ISAPP school 2013, Djurönäset/Stockholm

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Indirect Detection of Dark Matter

Outline

1st

- Prelude – WIMP dark matter
  - Thermal production and freeze-out
  - General principle of (in)direct detection
  - Dark matter distribution
- Gamma rays

2nd

  - *targets*: galactic center + halo, dwarf galaxies, galaxy clusters, ...
  - *signals*: continuum vs. "smoking gun" spectral features
- Neutrinos

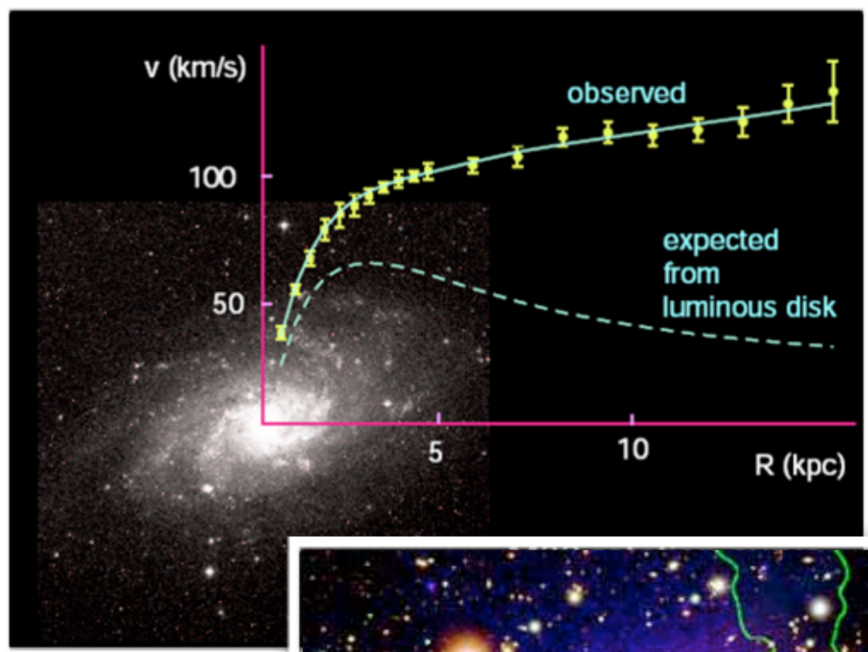
3rd

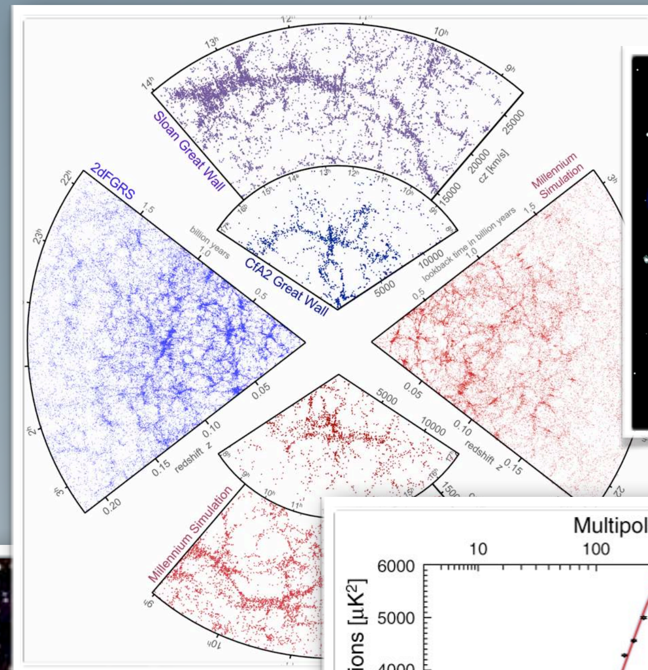
  - from galactic halo + sun/earth
- Charged cosmic rays
  - propagation of cosmic rays
  - positrons, antiprotons, [antideuterons]
  - multi-wavelength signals
- [Complementarity with direct and collider searches]

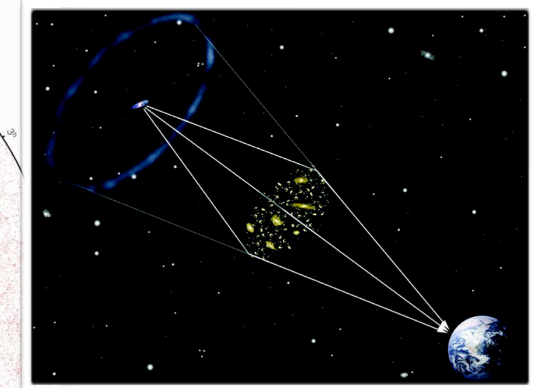
NB: Outline is preliminary...

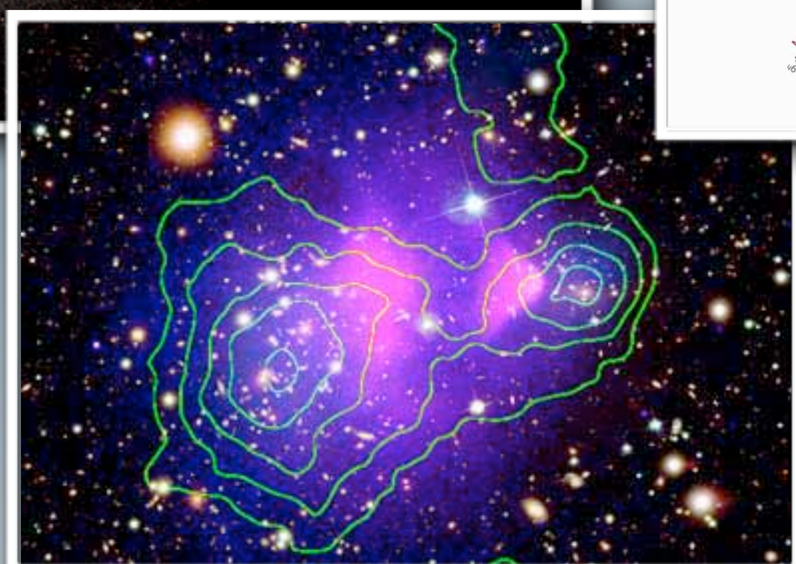
➡ *Please* *do* *interrupt!*

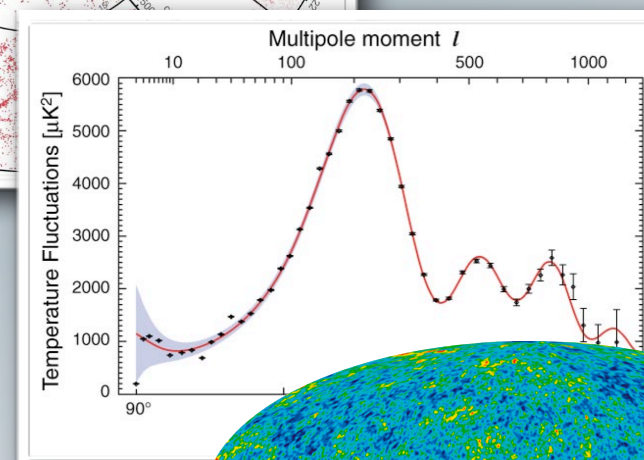
Dark matter all around

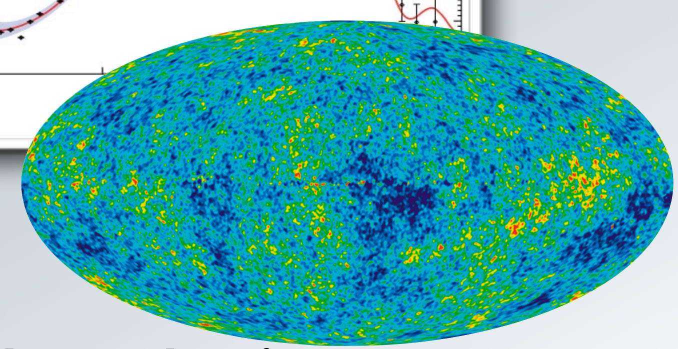












See lectures by S. Sarkar!

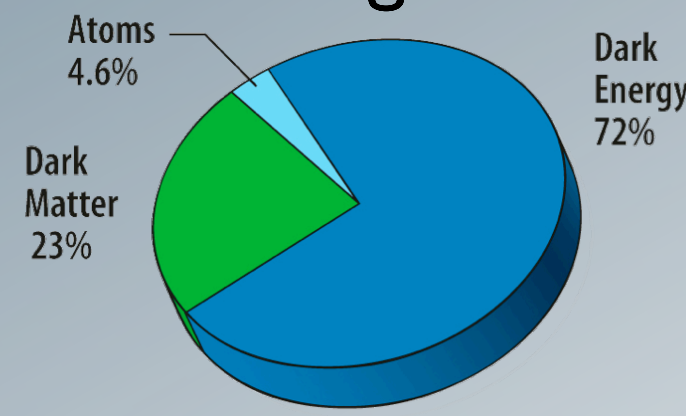
⇨ *overwhelming evidence on all scales!*

Dark matter properties

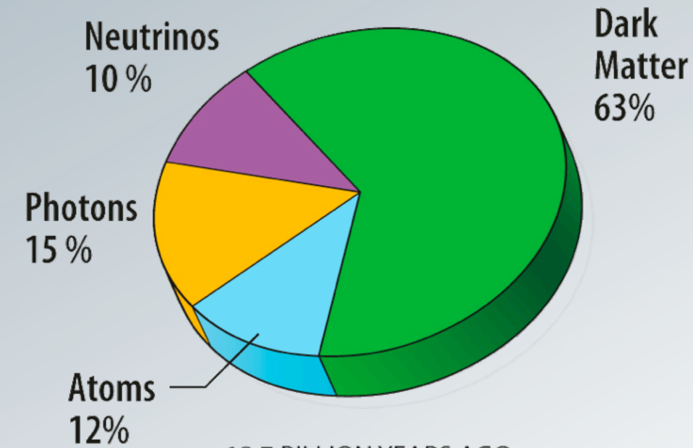
- *Existence* by now (almost) impossible to challenge!
  - $\Omega_{\rm CDM} = 0.233 \pm 0.013$ (WMAP)
  - electrically neutral (dark!)
  - non-baryonic (BBN, CMB)
  - cold – dissipationless and negligible free-streaming effects (structure formation)
  - 'collisionless' (bullet cluster)

But what is DM… ???

- Two options:
  - ~~Modify gravity~~ (but some people still try…)
  - Invoke some elementary(?) particle
- No candidate in standard model
  ➡ ***Evidence for physics beyond the SM!***



TODAY



13.7 BILLION YEARS AGO
(Universe 380,000 years old)

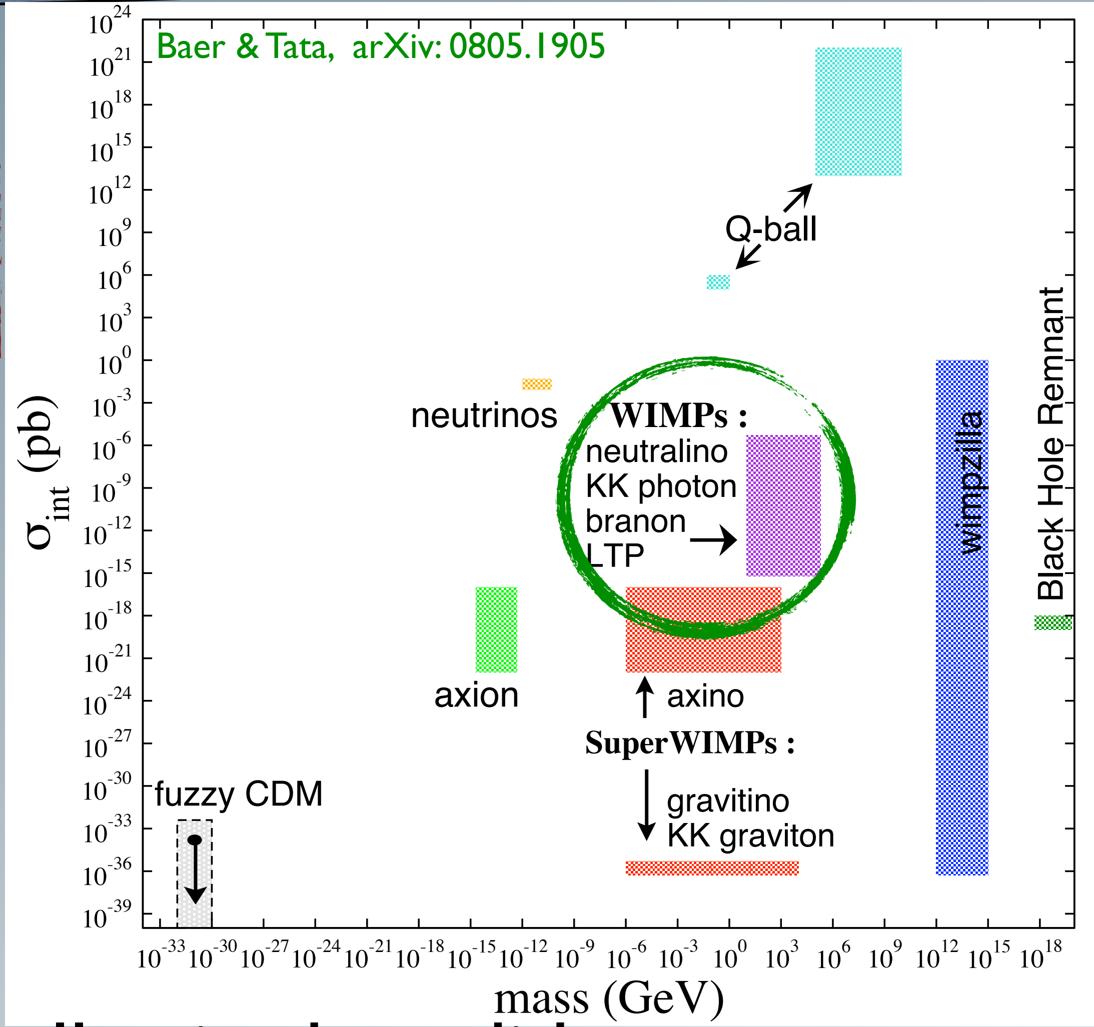
credit: WMAP

Candidates

- In principle many options...

See lectures by P. Gondolo!

- A good DM candidate should
  - explain 'all' observations
  - have an independent motivation from particle physics



- *WIMPs* are particularly well-suited candidates:
  - ✓ well-motivated: quasi 'by-products' in attempts to cure problems of SM [SUSY, EDs, little Higgs, ...]
  - ✓ thermal production 'automatically' leads to right relic abundance

The WIMP "miracle"

- The number density of **W**eakly **I**nteracting **M**assive **P**articles in the early universe:

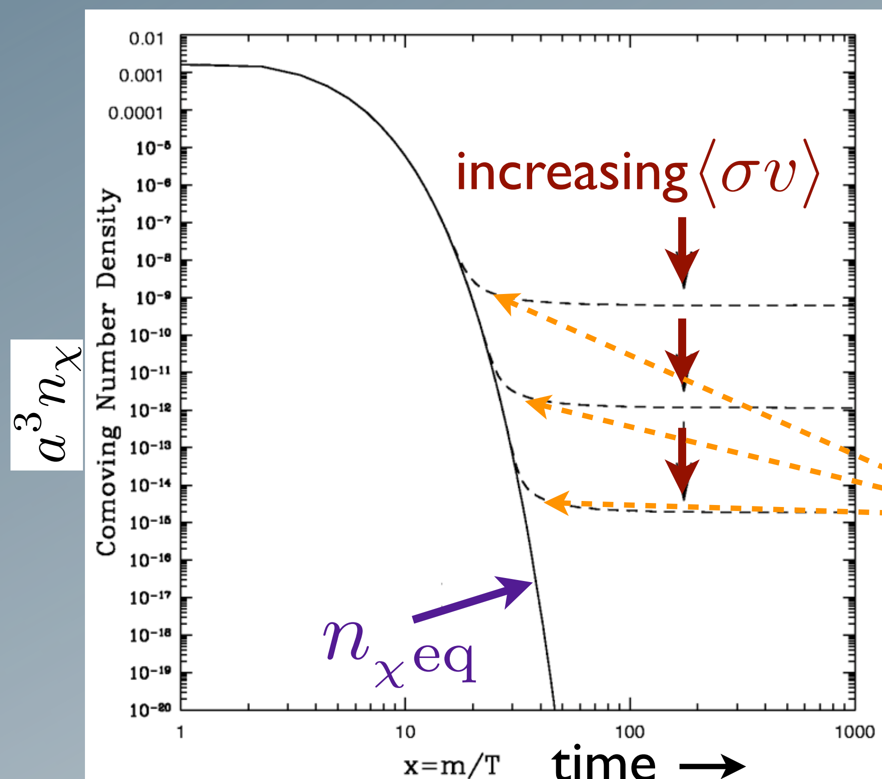


Fig.: Jungman, Kamionkowski & Griest, PR'96

$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle\sigma v\rangle \left(n_\chi^2 - n_{\chi\,\mathrm{eq}}^2\right)$$

$\langle\sigma v\rangle$: $\chi\chi \to \mathrm{SM\ SM}$ **(thermal average)**

"Freeze-out" when annihilation rate falls behind expansion rate ($\to a^3 n_\chi \sim \mathrm{const.}$)

- **Relic density** **(today):** $\Omega_\chi h^2 \sim \frac{3\cdot 10^{-27}\mathrm{cm}^3/\mathrm{s}}{\langle\sigma v\rangle} \sim \mathcal{O}(0.1)$ ← for weak-scale interactions!

Co-annihilations

- Typically, the DM particle is not the only new particle
- Order them such that $m_\chi \equiv m_1 \leq m_2 \leq \ldots \leq m_N$

$$\dot{n}_i + 3Hn_i = -\sum_{j=1}^{N} \langle \sigma_{ij} v_{ij} \rangle \left(n_i n_j - n_i^{\rm eq} n_j^{\rm eq} \right) - \sum_X \sum_{j \neq i} n_X^{\rm eq} [\langle \sigma'_{Xij} v_{ij} \rangle \left(n_i - n_i^{\rm eq} \right) - \langle \sigma'_{Xji} v_{ij} \rangle \left(n_j - n_j^{\rm eq} \right)] - \sum_{j \neq i} [\Gamma_{ij} \left(n_i - n_i^{\rm eq} \right) - \Gamma_{ji} \left(n_j - n_j^{\rm eq} \right)]$$

$$n \equiv \sum_{i=1}^{N} n_i$$

Eventually, everything will decay into the lightest state χ

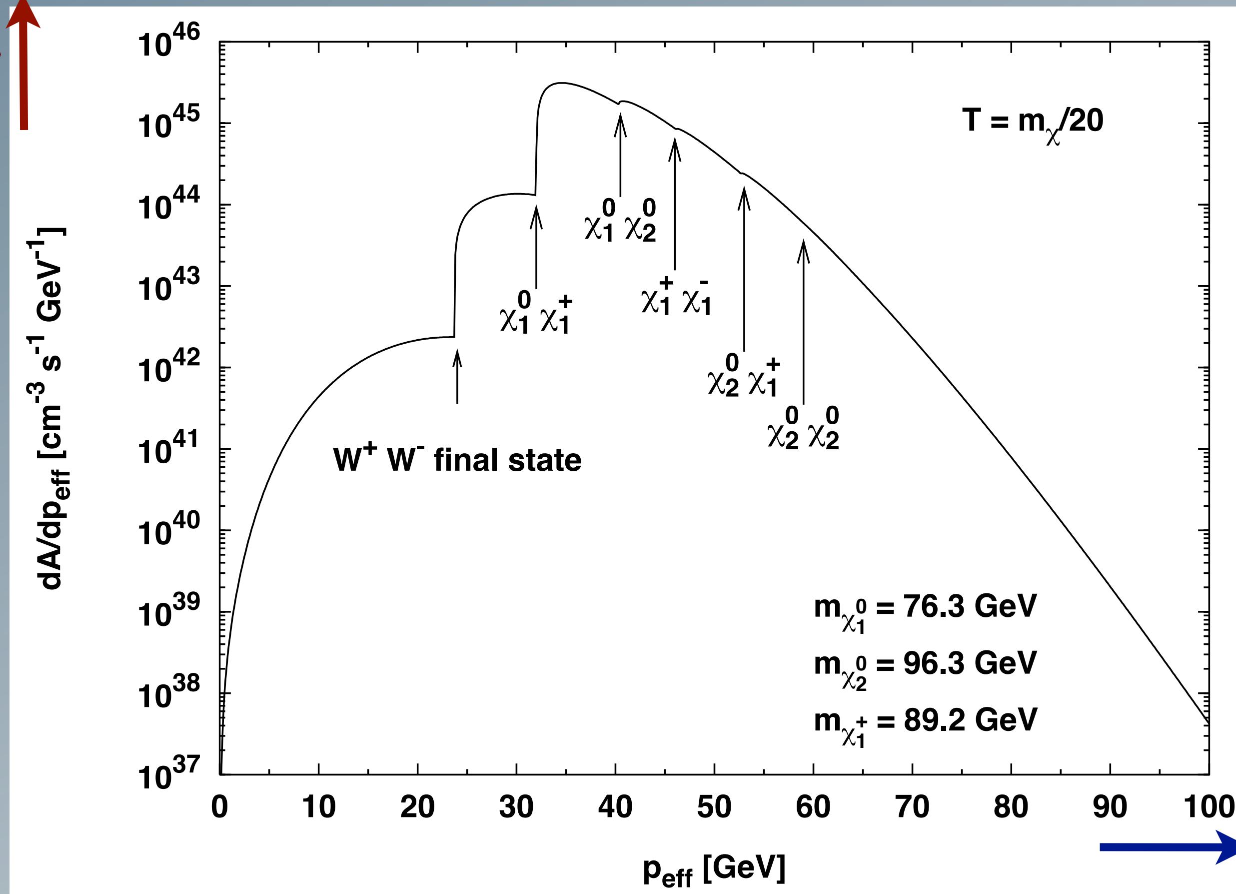
$$\dot{n} + 3Hn = -\langle \sigma_{\rm eff} v \rangle (n^2 - n_{\rm eq}^2)$$

$$\langle \sigma_{\rm eff} v \rangle = \sum_{ij} \langle \sigma_{ij} v_{ij} \rangle \frac{n_i^{\rm eq}}{n^{\rm eq}} \frac{n_j^{\rm eq}}{n^{\rm eq}}$$

where $n_{\rm eq} = \sum_i n_i^{\rm eq} \simeq \sum_i g_i \int \frac{dp}{(2\pi)^3} e^{-\frac{E_i}{T}}$

Co-annihilations (2)

$\sim n_{\rm eq}^2 \langle \sigma_{\rm eff} v \rangle$



WIMP momentum

Figure 4.2: Total differential annihilation rate per unit volume, $dA/dp_{\rm eff} = (T/\pi^4) p_{\rm eff}^2 K_1(p_{\rm eff}, T) W_{\rm eff}$, for the same model as in Fig. 4.1. We have chosen to evaluate $dA/dp_{\rm eff}$ for $T = m_\chi/20$ which is a typical value at freeze-out. The Boltzmann suppression at higher $p_{\rm eff}$ should be evident.

from Edsjö, hep-ph/9704384

Freeze-out ≠ decoupling !

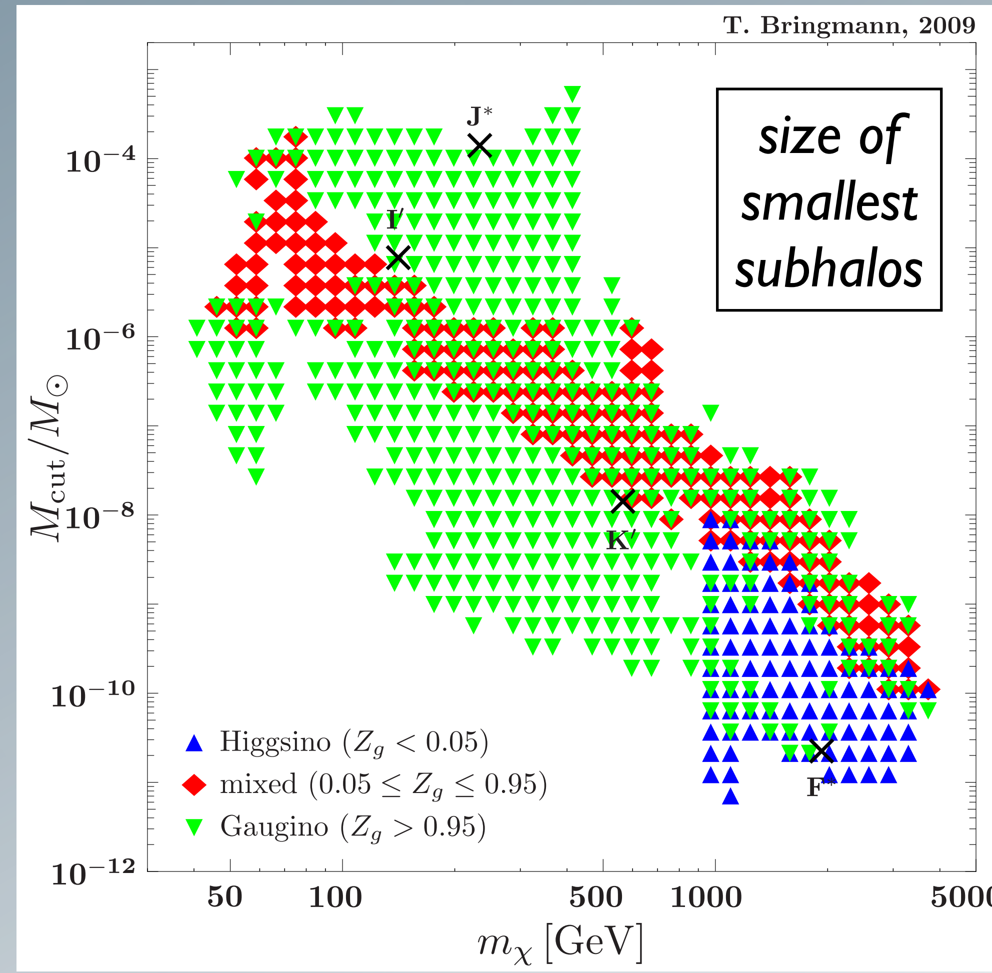
- WIMP interactions with heat bath of SM particles:

(annihilation) (scattering)

$$T_{\mathrm{cd}} \sim m_\chi/25 \qquad T_{\mathrm{kd}} \sim m_\chi/(10^2..10^5)$$

chemical decoupling — kinetic decoupling

$$\Omega_\chi \qquad M_{\mathrm{cut}}$$



- *Cut-off value highly model-dependent*

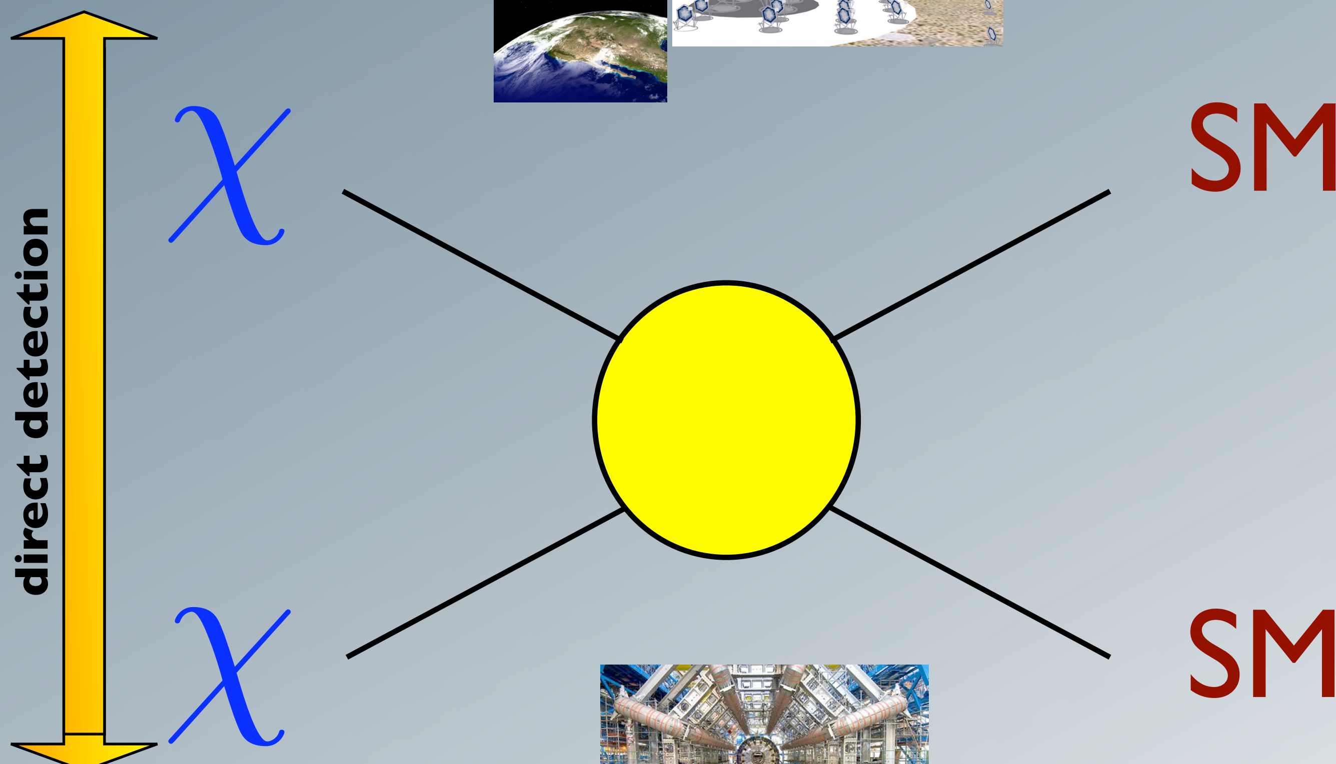
  [In principle values as large as the scale of dwarf-galaxies possible! van den Aarssen+ PRL'12]

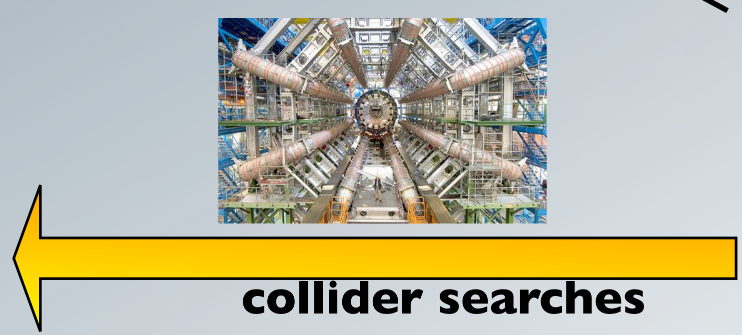
➡ *a window into the particle-physics nature of dark matter!?*

WIMPs do interact with the SM!

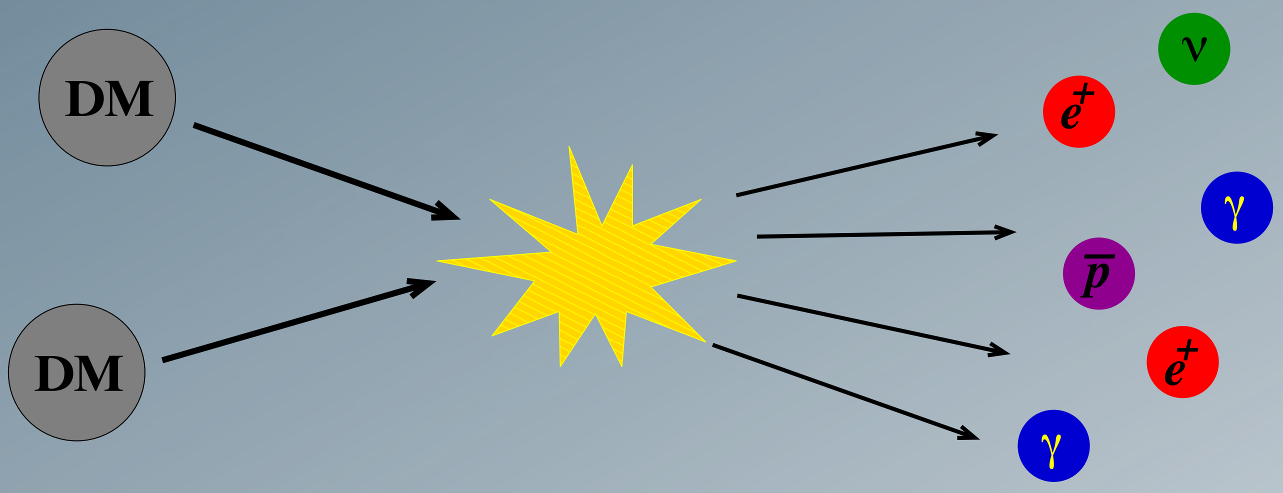
See also lectures by A. Melchiorri, J. Conrad, D. Boersma and F. Donato...

See lectures by J. Gascon





Indirect detection in one slide

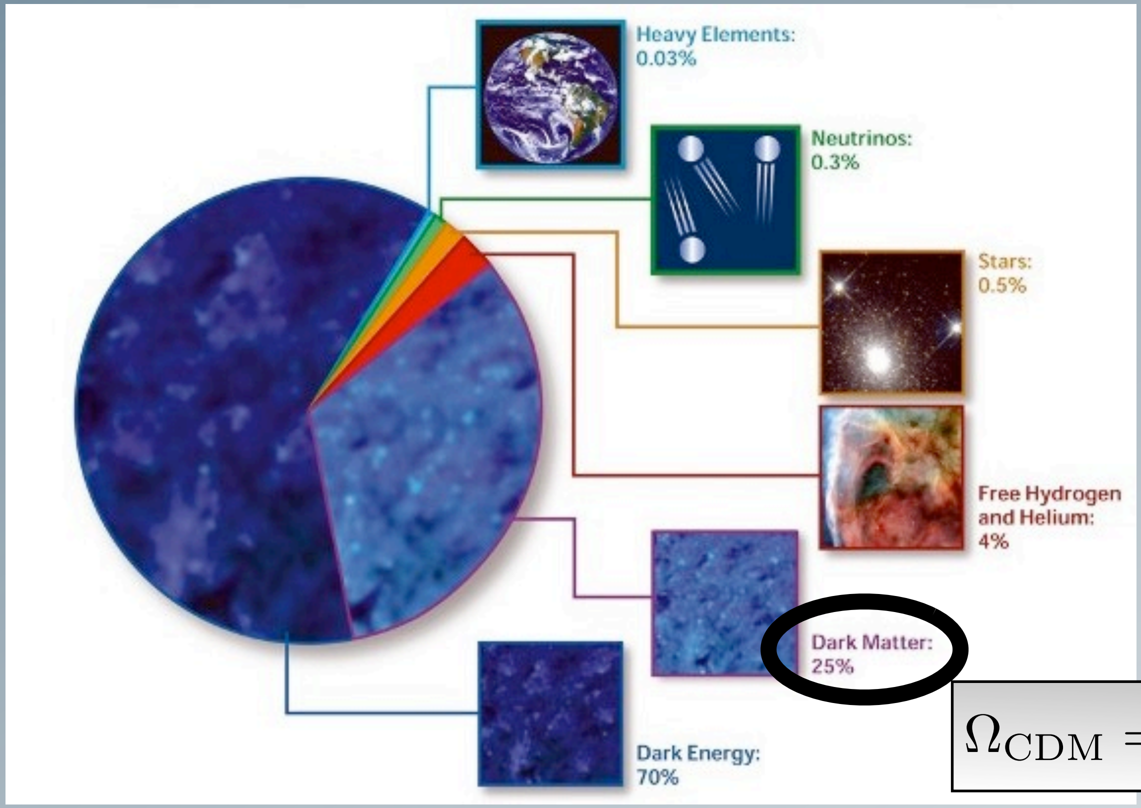


- DM has to be (quasi-)stable against decay...
- … but can usually pair-annihilate into SM particles
- Try to spot those in cosmic rays of various kinds
- The challenge: i) absolute rates
  $\rightsquigarrow$ regions of high DM density
  ii) discrimination against other sources
  $\rightsquigarrow$ low background; clear signatures

Distribution of dark matter

- Annihilation sensitive to DM density *squared*

  ➡ need to know this quantity very well!



NB: in general

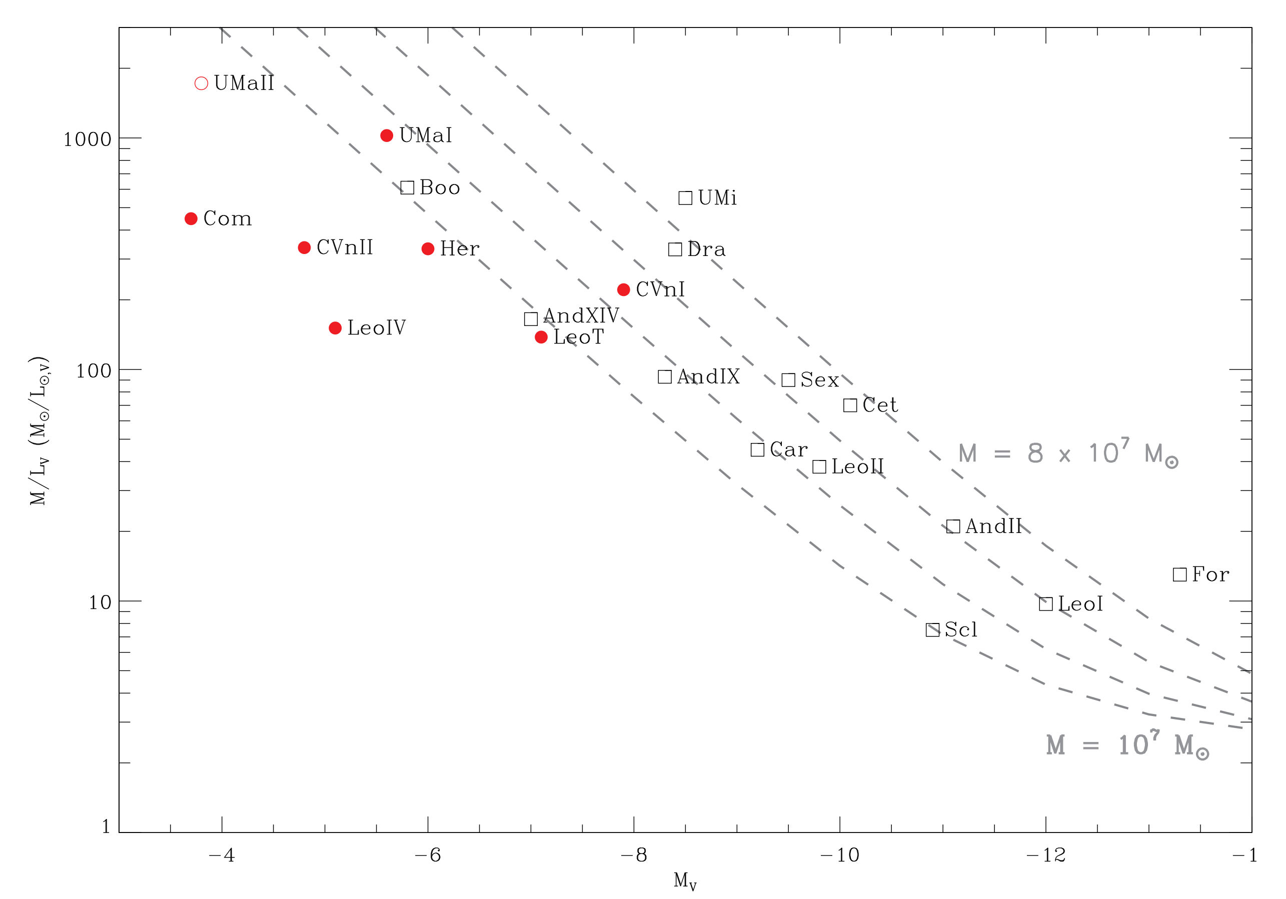
$$\Omega_\chi^{\rm local} \neq \Omega_{\rm CDM} \;!!!$$

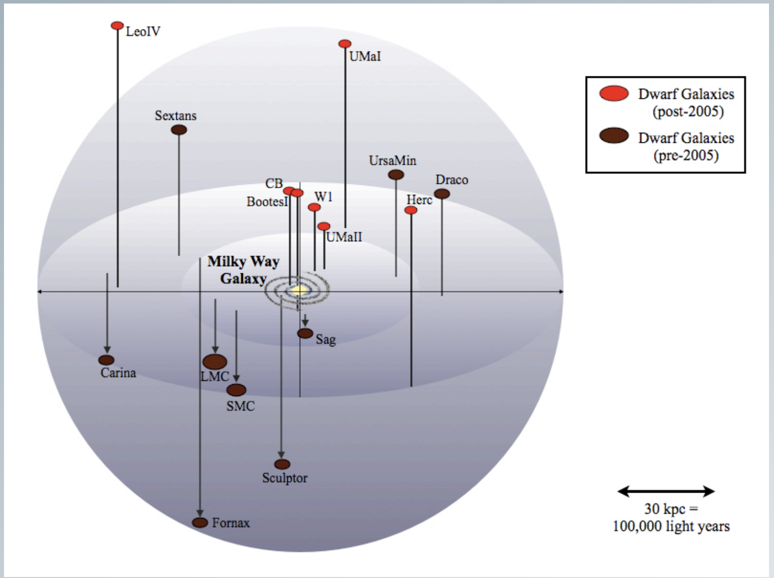
$$\Omega_{\rm CDM} = 0.233 \pm 0.013$$ on **large** scales

- [For comparison: *decaying* DM directly proportional to density]

Dwarf galaxies

- Use Jeans equation to relate observed velocity dispersion of stars to total mass distribution
  ➔ highest known mass-to-light ratios!





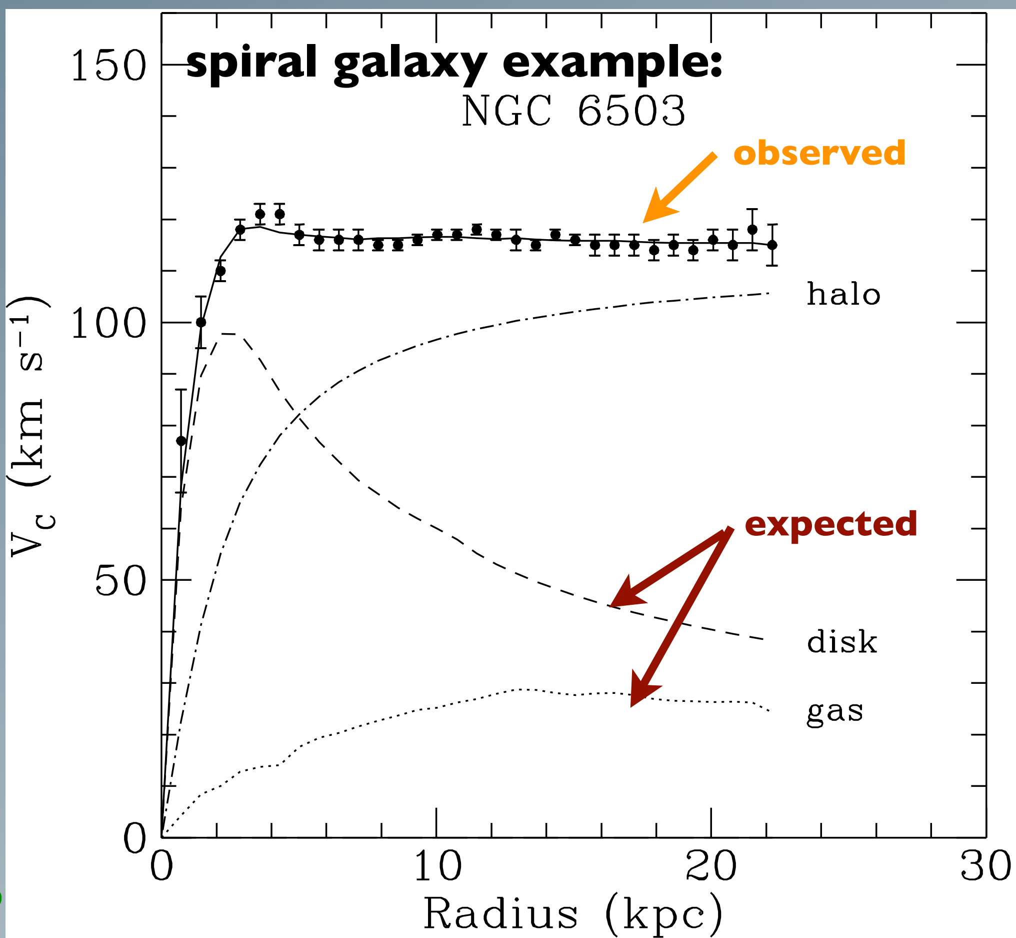
J.~D.~Simon, M.~Geha, ApJ 670, 313 (2007)

Galactic rotation curves

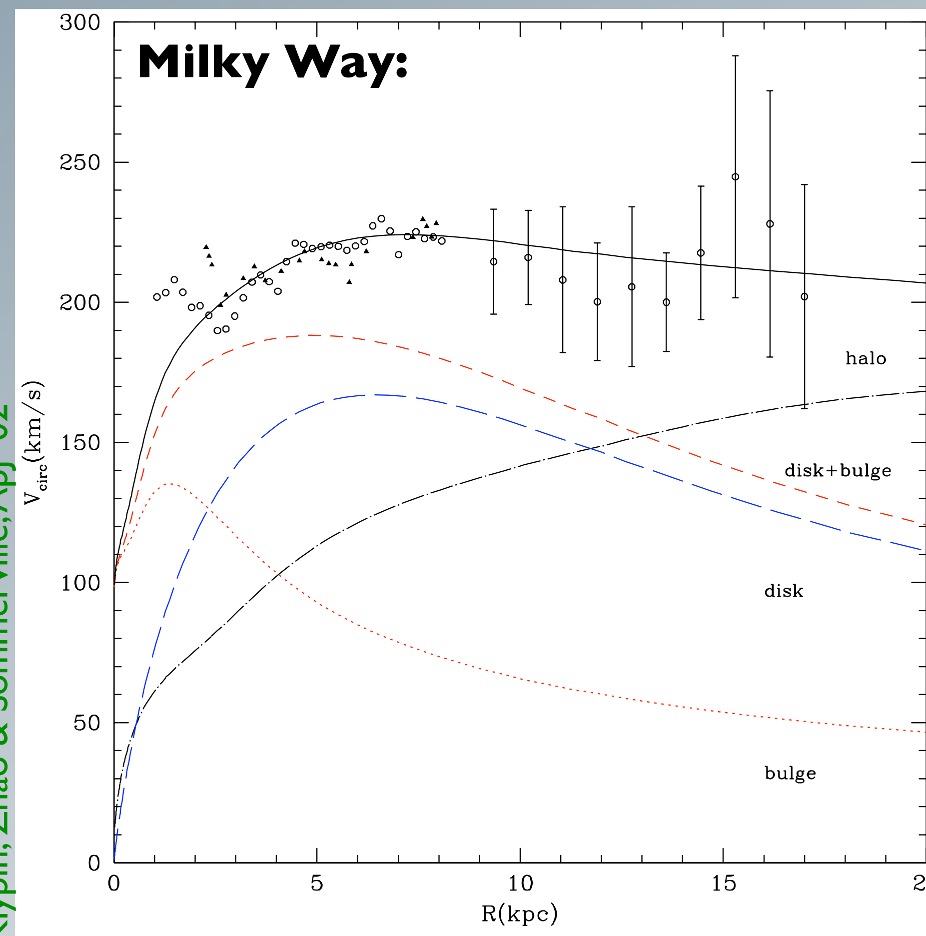
Standard Newtonian dynamics:

$$G_N m_\odot \frac{M(r<R)}{R^2} = m_\odot \frac{v^2}{R}$$

Begemann, Broeils & Sanders, MNRAS '91



Klypin, Zhao & Sommerville, ApJ '02



➡ *Observational determination of (inner) DM profile for MW ~ impossible!*

Inner halo profiles

See lectures by M. Vogelsberger!

ΛCDM *N*-body simulations

$$\rho_{\rm NFW} = \frac{c}{r(a+r)^2}$$

$$\rho_{\rm Einasto}(r) = \rho_s\, e^{-\frac{2}{\alpha}\left[\left(\frac{r}{a}\right)^\alpha - 1\right]}$$

$$(\alpha \approx 0.17)$$

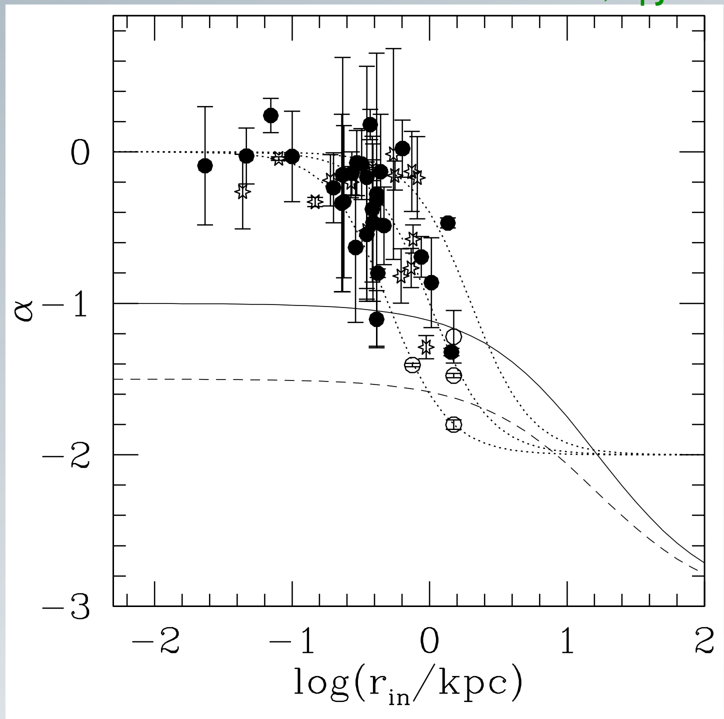
Fits to rotation curves?

$$\rho_{\rm Burkert} = \frac{c}{(r+a)(a^2+r^2)}$$

$$\rho_{\rm iso} = \frac{c}{(a^2+r^2)}$$

- Cuspy inner density profiles predicted by simulations not found in (all) observations
- Situation a bit unclear; effect of baryons?
  (But could also lead to a steepening of the inner profile!)

Blok *et al.*, ApJ '01



Substructure

- N-body simulations: The DM halo contains not only a smooth component, but a lot of substructure!
- Indirect detection effectively involves an averaging:

$$\Phi_{\rm SM} \propto \langle \rho_\chi^2 \rangle = (1 + {\rm BF}) \langle \rho_\chi \rangle^2$$

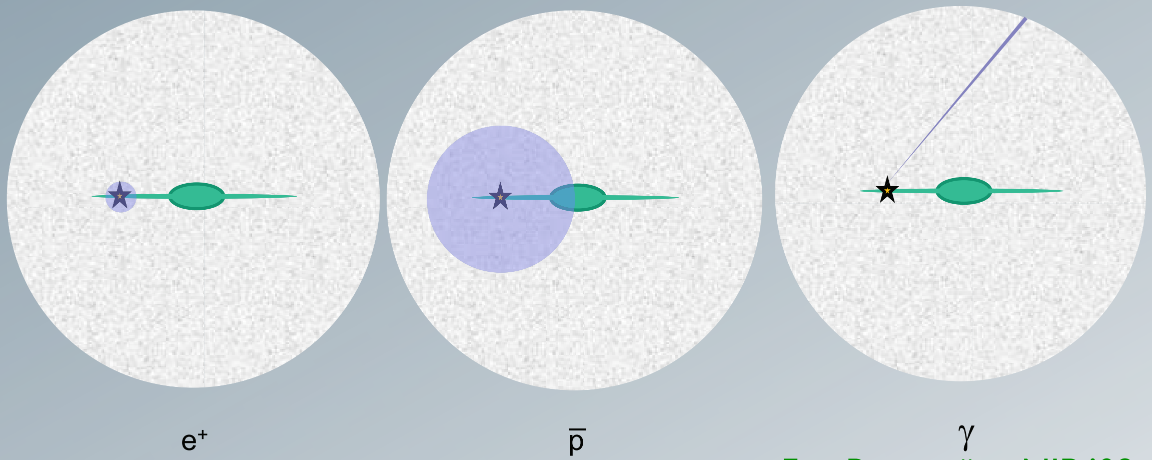


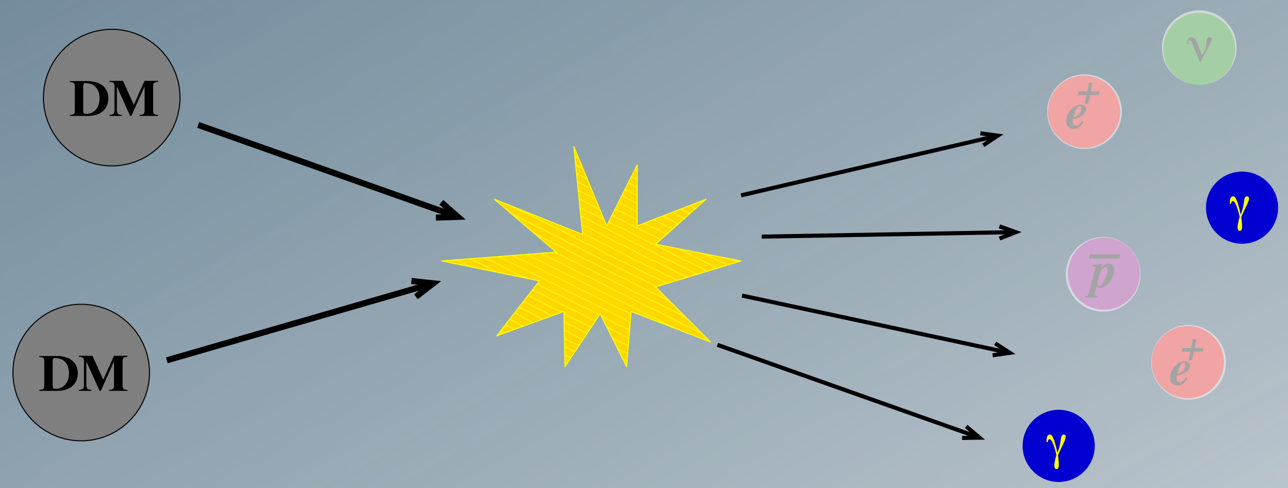
Fig.: Bergström, NJP '09

- "Boost factor"
  - each decade in $M_{\rm subhalo}$ contributes very roughly the same
    e.g. Diemand, Kuhlen & Madau, ApJ '07

    ⇨ *important to include realistic value for* $M_{\rm cut}$ *!*
  - depends on uncertain form of microhalo profile ($c_{\rm V}$ ...) and dN/dM (large extrapolations necessary!)

- Prelude – WIMP dark matter
  - Thermal production and freeze-out
  - General principle of (in)direct detection
  - Dark matter distribution
- Gamma rays
  - *targets*: galactic center + halo, dwarf galaxies, galaxy clusters, ...
  - *signals*: continuum vs. "smoking gun" spectral features
- Neutrinos
  - from galactic halo + sun/earth
- Charged cosmic rays
  - propagation of cosmic rays
  - positrons, antiprotons, [antideuterons]
  - multi-wavelength signals
- [Complementarity with direct and collider searches]

Indirect DM searches



Gamma rays:

- Rather high rates
- No attenuation when propagating through halo
- No assumptions about diffuse halo necessary
- Point directly to the sources: clear spatial signatures
- Clear spectral signatures to look for

Gamma-ray flux

The expected gamma-ray flux [GeV^{-1}cm^{-2}s^{-1}sr^{-1}] from a source with DM density ρ is given by

$$\frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma,\Delta\psi) = \int_{\Delta\psi}\frac{d\Omega}{\Delta\psi}\int_{\mathrm{l.o.s}} d\ell(\psi)\rho^2(\mathbf{r}) \; \frac{\langle\sigma v\rangle_{\mathrm{ann}}}{8\pi m_\chi^2}\sum_f B_f \frac{dN_\gamma^f}{dE_\gamma}$$

astrophysics | particle physics

for point-like sources:
$\simeq \left(D^2\Delta\psi\right)^{-1}\int d^3r\,\rho^2(\mathbf{r})$

$\Delta\psi$: angular res. of detector

D : distance to source

$\langle\sigma v\rangle_{\mathrm{ann}}$: total annihilation cross section

m_χ : WIMP mass $(50\,\mathrm{GeV} \lesssim m_\chi \lesssim 5\,\mathrm{TeV})$

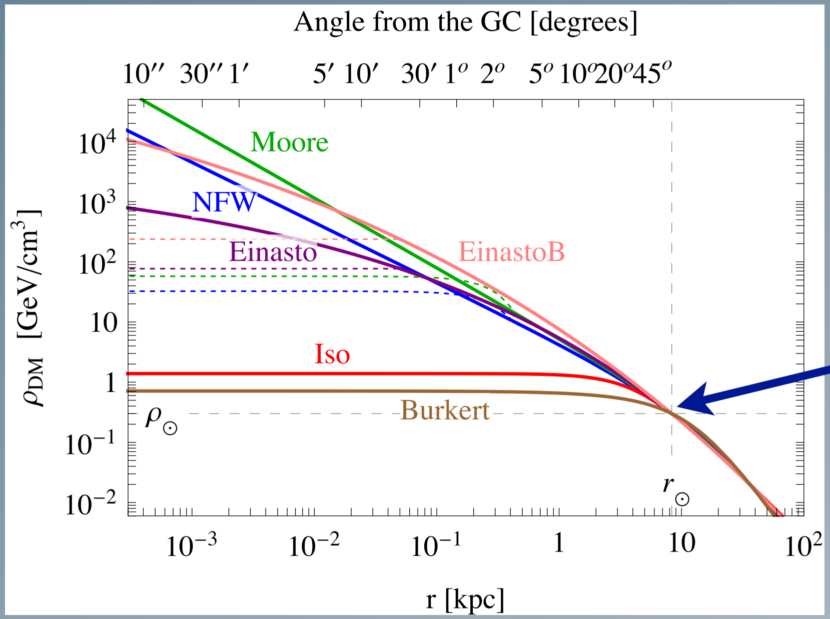
B_f : branching ratio into channel f

N_γ^f : number of photons per ann.

⇩ angular information + rather uncertain normalization

⇩ high accuracy spectral information

Halo profiles (2)



- Large uncertainties "only" in the very central region.

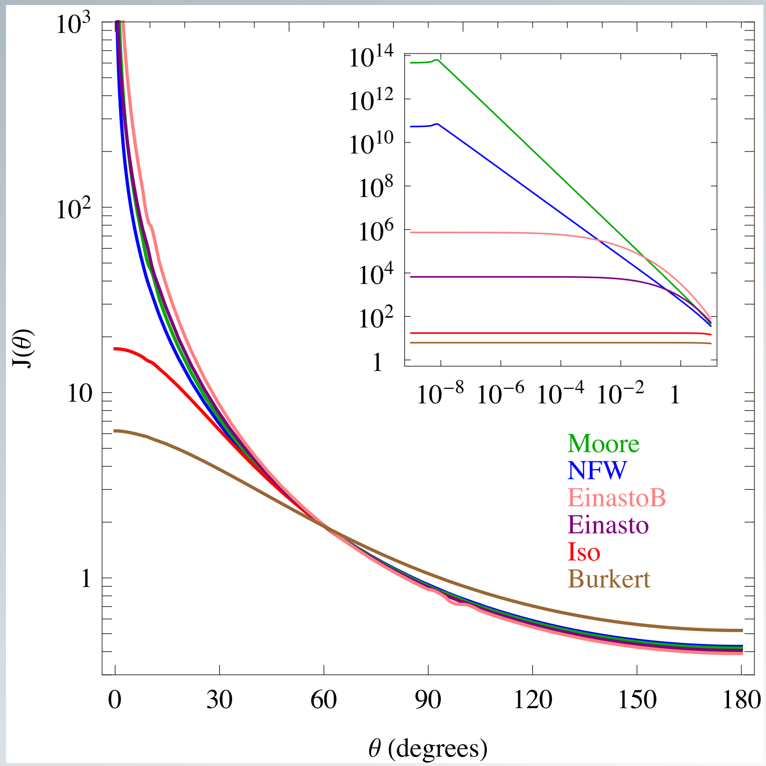
local DM density: $\rho_\odot \sim 0.4\,\mathrm{GeV/cm}^3$

- Difference in annihilation flux several orders of magnitude for the galactic center

  [NB: figure does not take into account cut-off due to self-annihilation!]

- Situation much better for e.g. dwarf galaxies

Cirelli et al., JCAP'11



Local DM density

- standard value:

$$\rho_\odot^{\rm DM} \sim 0.3 \to 0.4 \,\frac{\rm GeV}{\rm cm^3}$$

...

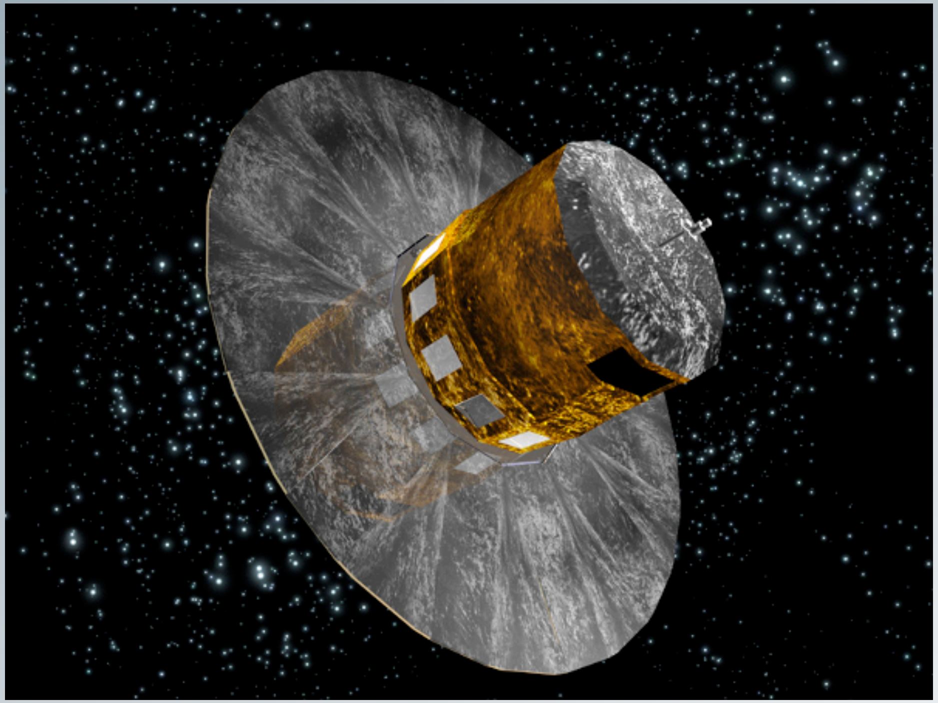
0.30 ± 0.05
Wydrow, Pim & Dubinski, ApJ '08

0.39 ± 0.03
Catena & Ullio, JCAP '10

0.43 ± 0.11 ± 0.10
Salucci et al, A&A '10

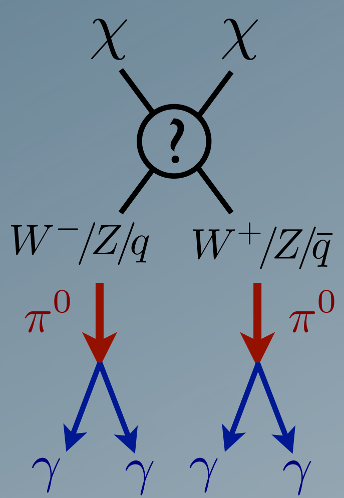
...

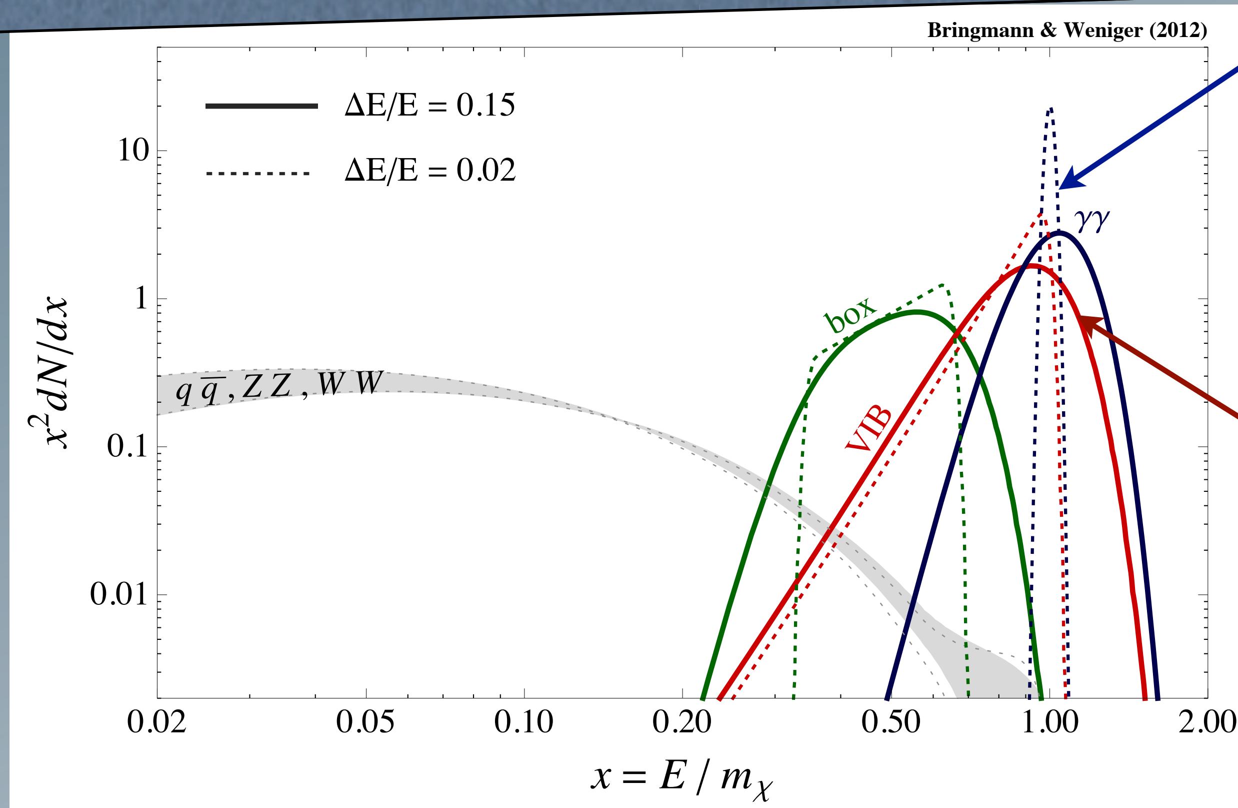
- Gaia (ESA mission, launch 11/13) will collect position and radial velocities of $\sim 10^8$ stars



⇨ *will settle the issue…!*

Annihilation spectra





Monochromatic lines

$\chi\chi \to \gamma\gamma, \gamma Z, \gamma H$

$\mathcal{O}(\alpha_{\rm em}^2)$

(Virtual) Internal Bremsstrahlung

$\chi\chi \to \bar{f}f\gamma, W^+W^-\gamma$

$\mathcal{O}(\alpha_{\rm em})$

- Secondary photons
  - *many* photons but
  - featureless & model-independent
  - difficult to distinguish from astro BG

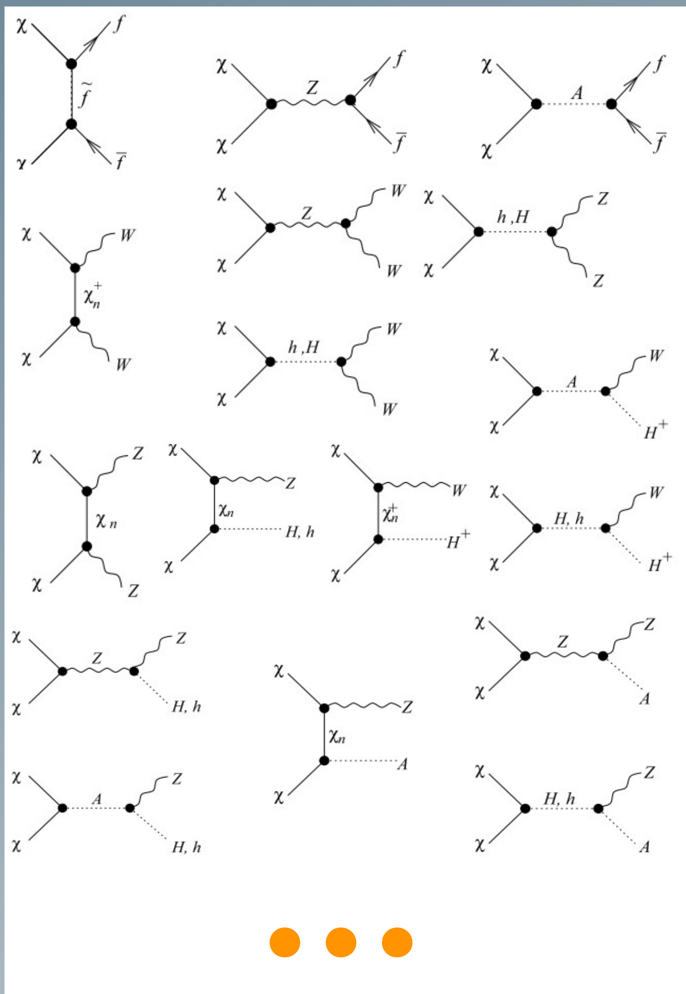
➡ *good constraining potential*

- Primary photons
  - direct annihilation to photons
  - model-dependent 'smoking gun' spectral features near $E_\gamma = m_\chi$

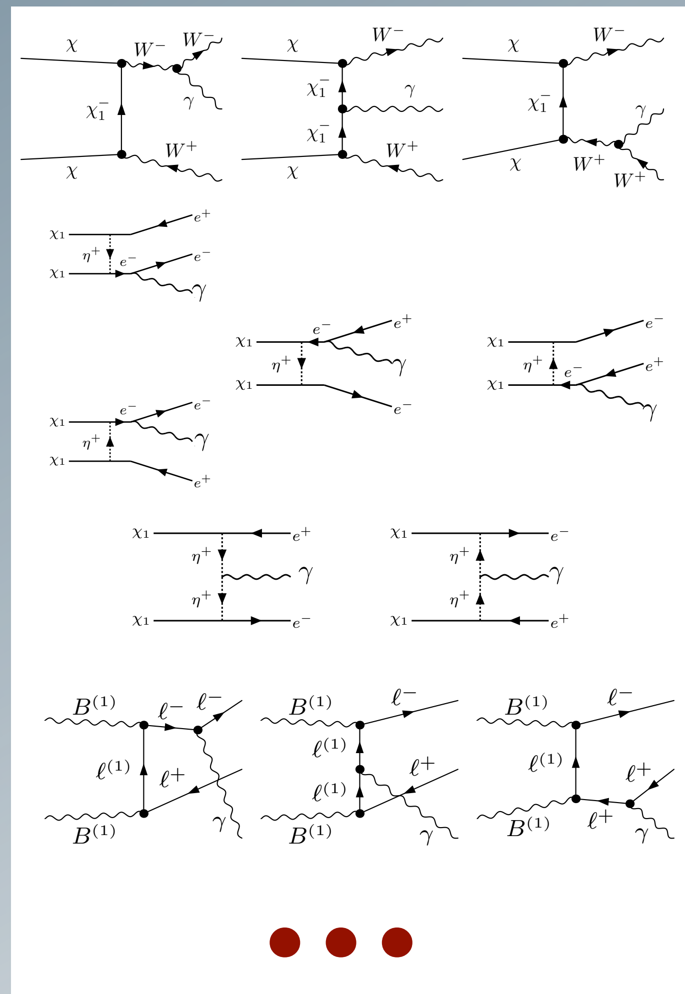
➡ *discovery potential*

The QFT point of view...

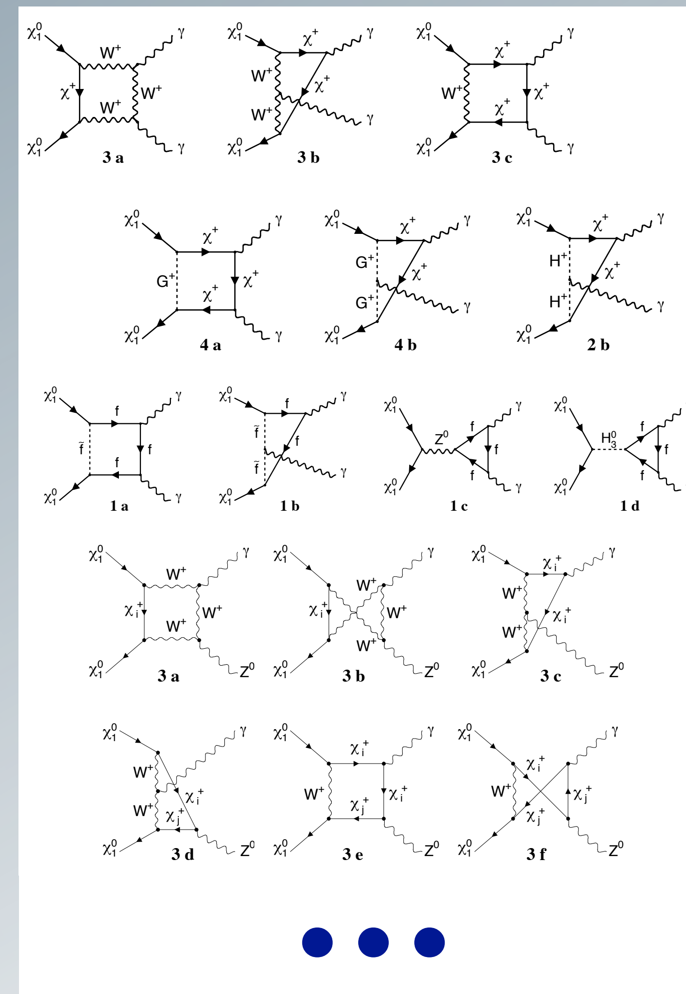
tree-level:



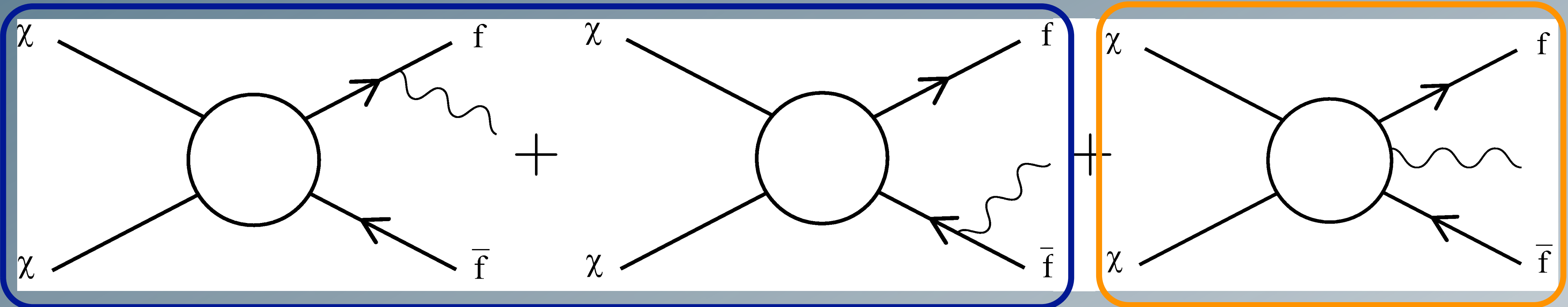
internal bremsstrahlung:



loops:



Internal bremsstrahlung



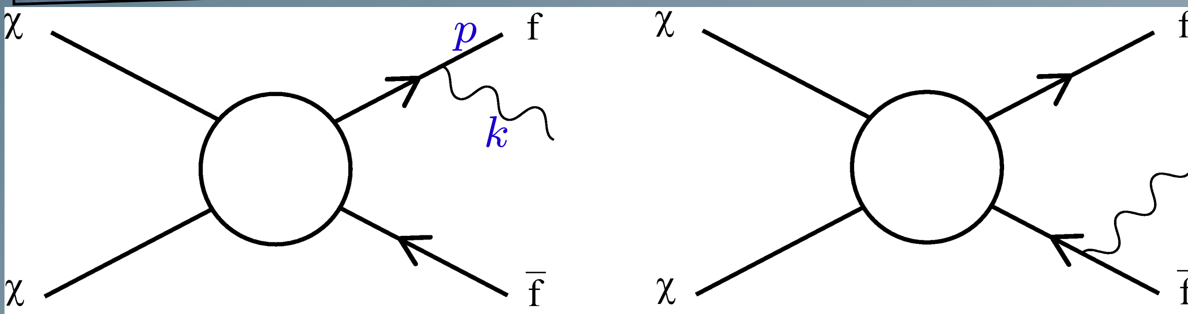
Final state radiation

- usually dominant for $m_\chi \gg m_f$
- mainly collinear photons
  $\rightsquigarrow$ model-independent spectrum
  Birkedal, Matchev, Perelstein & Spray, hep-ph/0507194
- important for high rates into leptons, e.g. Kaluza-Klein or "leptophilic" DM

"Virtual" IB

- dominant in two cases:
  i) f bosonic and *t*-channel mass degenerate with m_χ
  Bergström, TB, Eriksson & Gustafsson, PRL'05
  ii) symmetry restored for 3-body state Bergström, PLB '89
- model-dependent spectrum
- important e.g. in mSUGRA

Final state radiation



propagator for f:

$$\propto \frac{1}{(k+p)^2 - m_f^2} = \frac{1}{2k\cdot p}$$

For collinear photons, virtual particle f almost on-shell

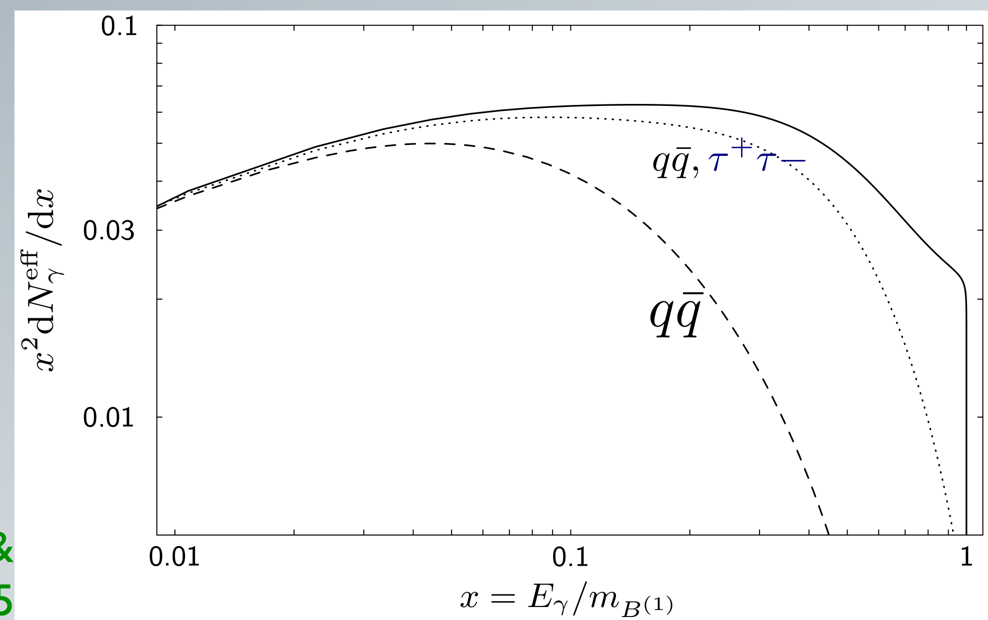
⇨ Logarithmic enhancement of cross section: $(x \equiv E_\gamma / m_\chi)$

$$\frac{dN}{dx} \sim \sigma(\chi\chi \to f\bar{f}) \cdot \frac{\alpha Q^2}{\pi} \mathcal{F}(x) \log \frac{s}{m_f^2}(1-x)$$

depends only on spin of f: model-independent

- Example:
  Lightest Kaluza-Klein particle (LKP) in UED

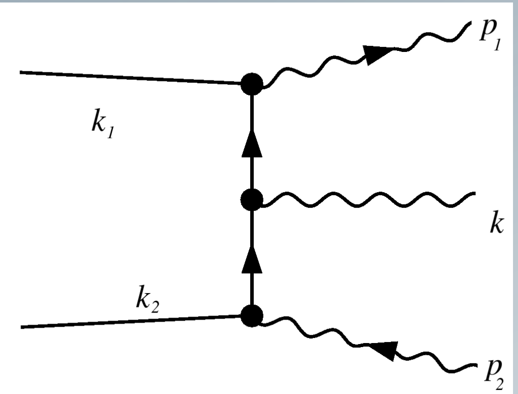
  (annihilation ~60% into leptons)

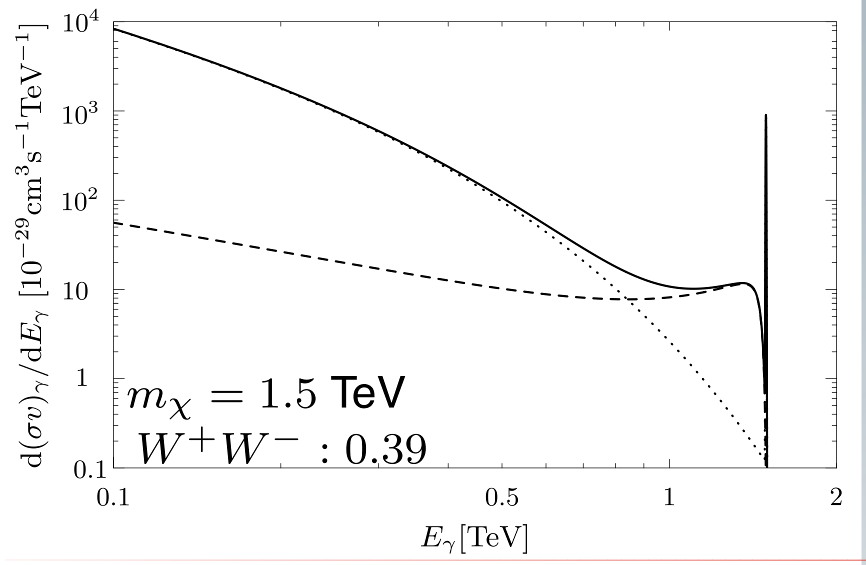


Bergström, TB, Eriksson & Gustafsson, PRL'05

Virtual IB

- Annihilation to "light" charged bosonic final states is enhanced for *t*-channel particles degenerate in mass with DM:
  - $\mathcal{M} \propto \frac{1}{k_1 \cdot p_1} \frac{1}{k_2 \cdot p_2} \approx \frac{1}{m_\chi^2 E_1 E_2}$
  - small E_1 or E_2 $\rightsquigarrow$ high E_γ
  - [Note that the contraction of fermionic final legs leads to an additional in the numerator...]

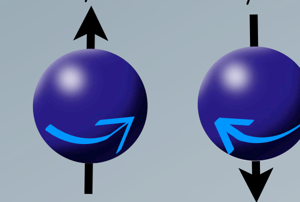




- Example: Higgsino
  - TeV mass $\rightsquigarrow m_\chi \gg m_W$
  - high branching ratio to W^+W^-

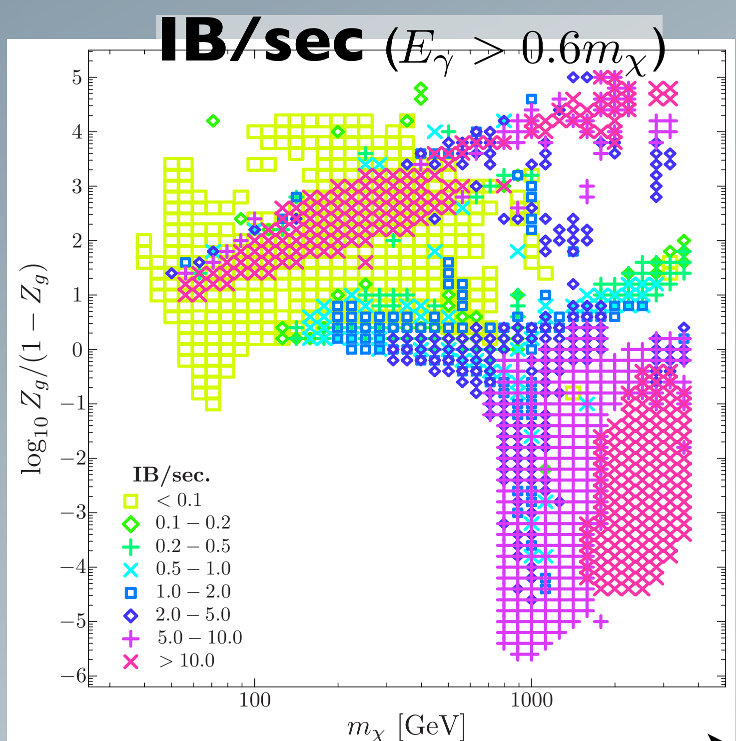
Bergström, TB, Eriksson & Gustafsson, PRL'05

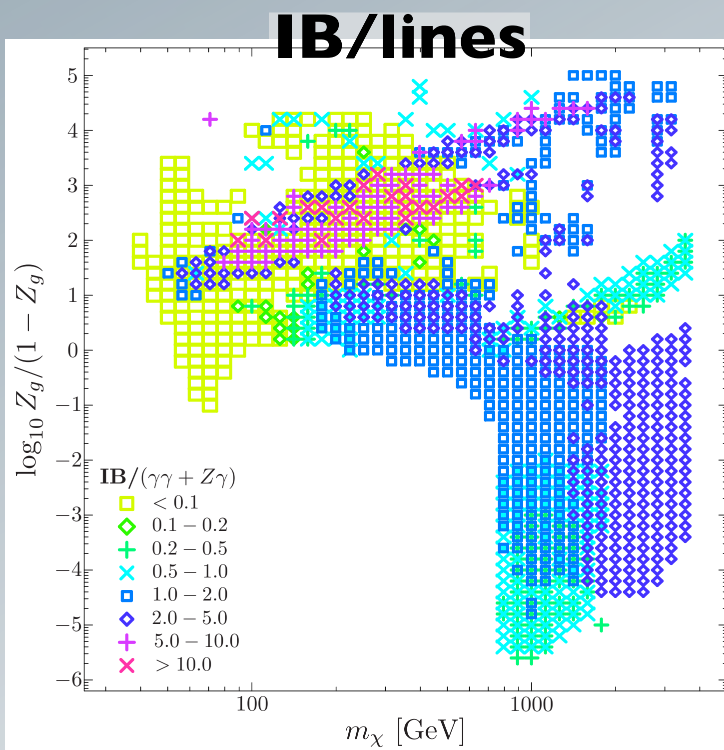
IB and SUSY



- Neutralinos are *Majorana* fermions,
  i.e. for $v \to 0$ a neutralino *pair* forms a $J^P = 0^-$ state
- Annihilation ~~helicity~~ suppressed: $\langle \sigma v \rangle \propto$ ~~$\frac{m_\ell^2}{m_\chi^2}$~~ $\frac{\alpha_{\text{em}}}{\pi}$
  ➩ $\langle \sigma v \rangle_{3-\text{body}} \gg \langle \sigma v \rangle_{2-\text{body}}$ *possible!*

cMSSM
+MSSM
scan





← Gaugino

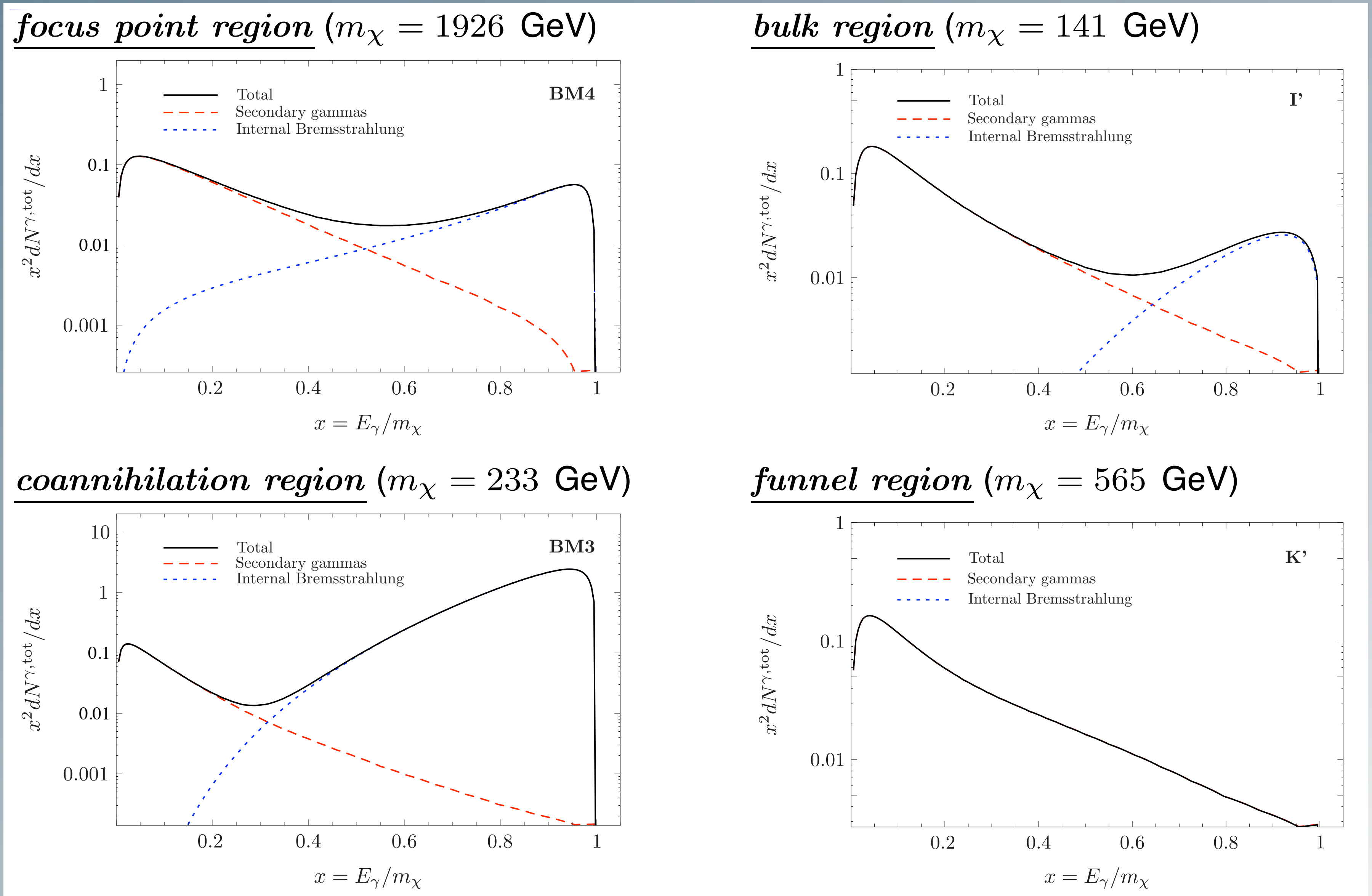
← mixed

← Higgsino

$\longrightarrow m_\chi$

TB, Edsjö & Bergström, JHEP '08

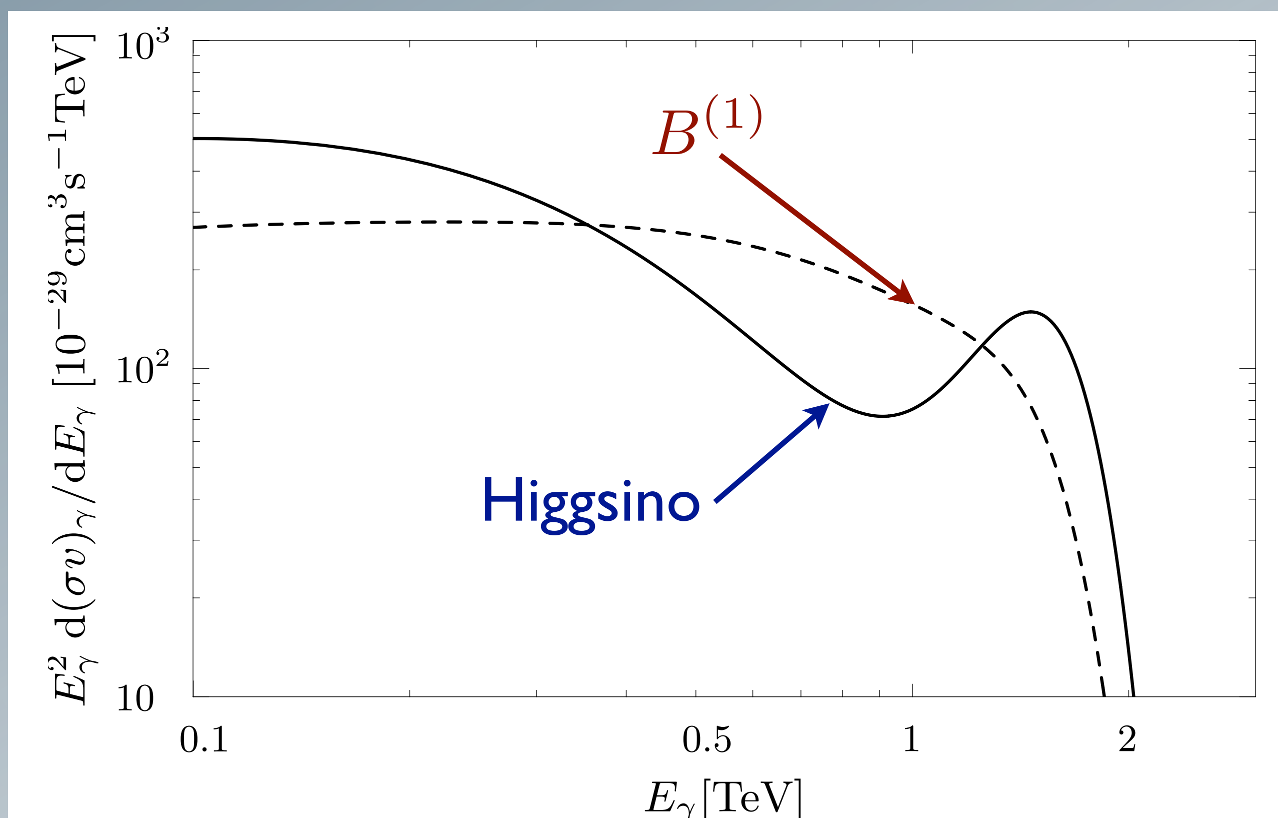
mSUGRA spectra



(benchmarks taken from TB, Edsjö & Bergström, JHEP '08 and Battaglia et al., EPJC '03)

Comparing DM spectra

- (Very) pronounced cut-off at $E_\gamma = m_\chi$
- Further features at slightly lower energies
- Could be used to distinguish DM candidates!
  - Example: mSUGRA benchmarks (assume energy resolution of 10%)
  - Example: Higgsino vs KK-DM (at same mass; assume $\Delta E = 10\%$)



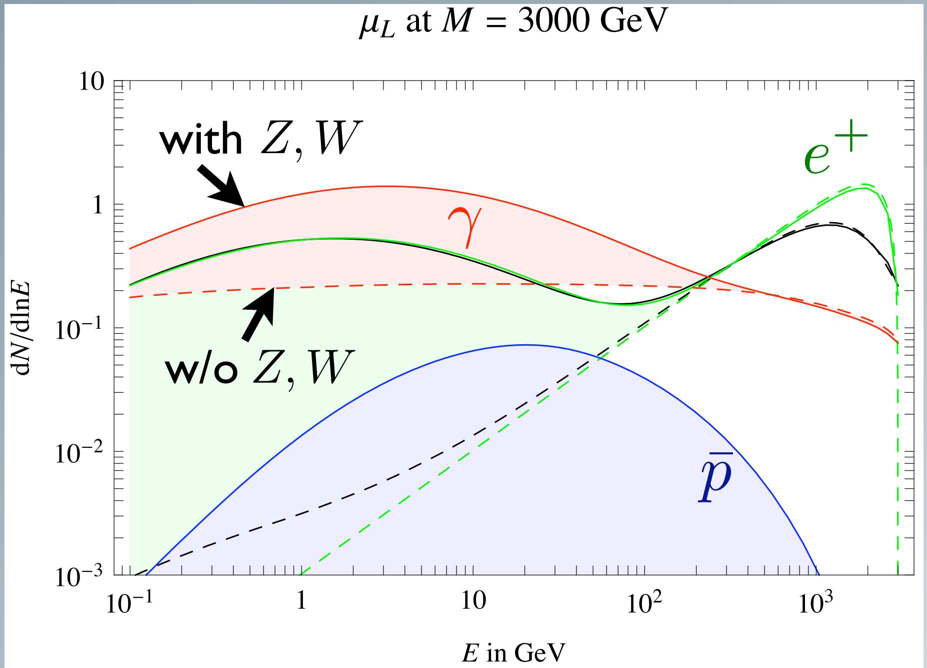
Bergström *et al.*, ’06

TB, ... ’08

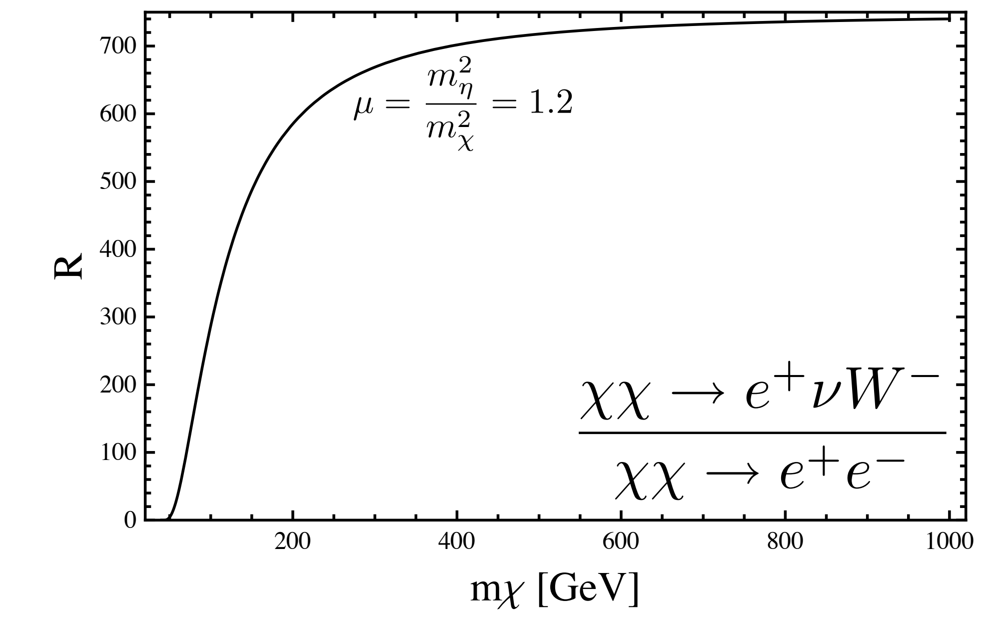
Electroweak corrections

- FSR of Z and $W^{\pm}$:
  - can open new channels like $\bar{p}$ (⇝ leptophilic models!)
  - sizable changes in spectrum for large m_χ (mostly at small E_γ)

Bell, Dent, Jacques & Weiler, PRD '08
Kachelriess, Serpico & Solberg, PRD '09
Ciafaloni & Urbano, PRD '10



Ciafaloni *et al.*, 1009.0224

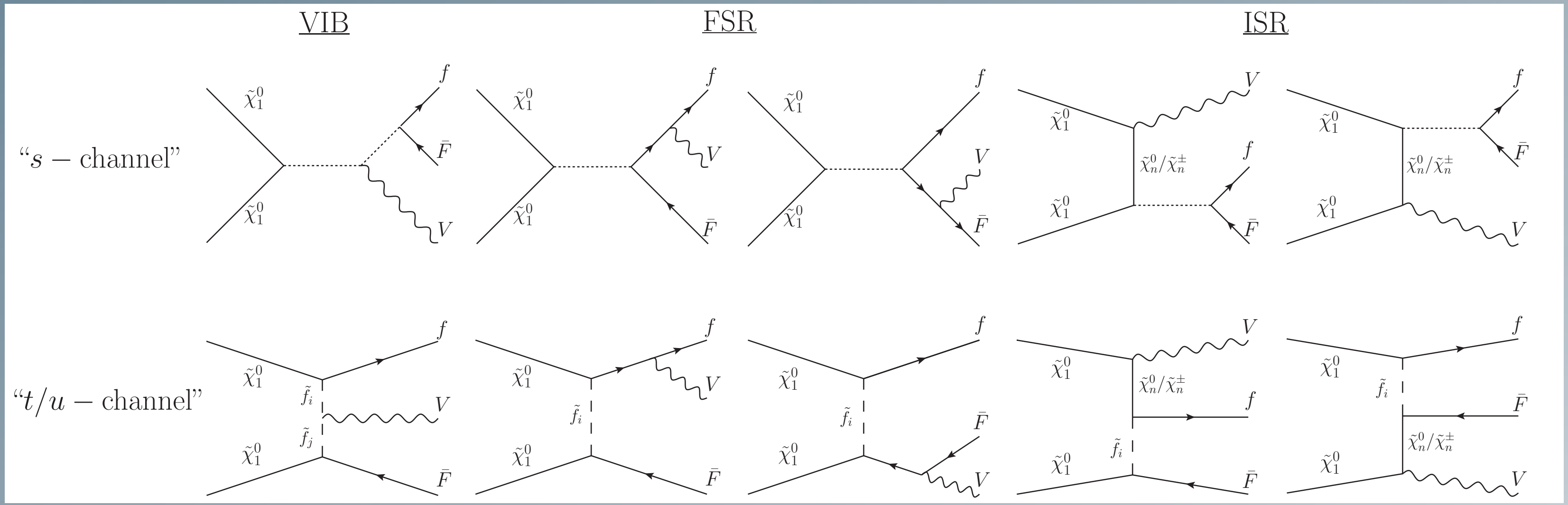


- VIB lifts helicity suppression (just like for photons, but numerically larger effect!)

Ciafaloni *et al.*, 1104.2996
Bell *et al.*, 1104.3823

EW corrections and SUSY

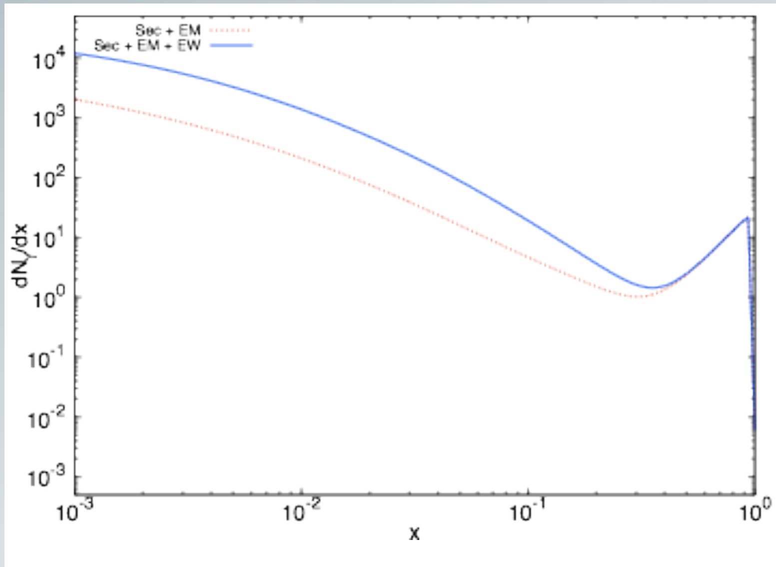
- *Much* more involved than for photon IB:



NB: in total these are **134 diagrams**!

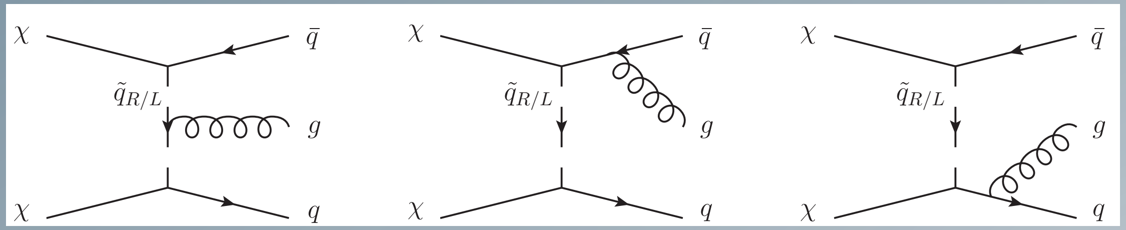
Figs. from F. Calore

- Impact on photon spectrum:
  - various enhancement effects (helicity suppression, resonances, longitudinal d.o.f)
  - Low-energy yield increases by up to ~100
  - Change in this part of the spectrum almost universal: no spectral features added

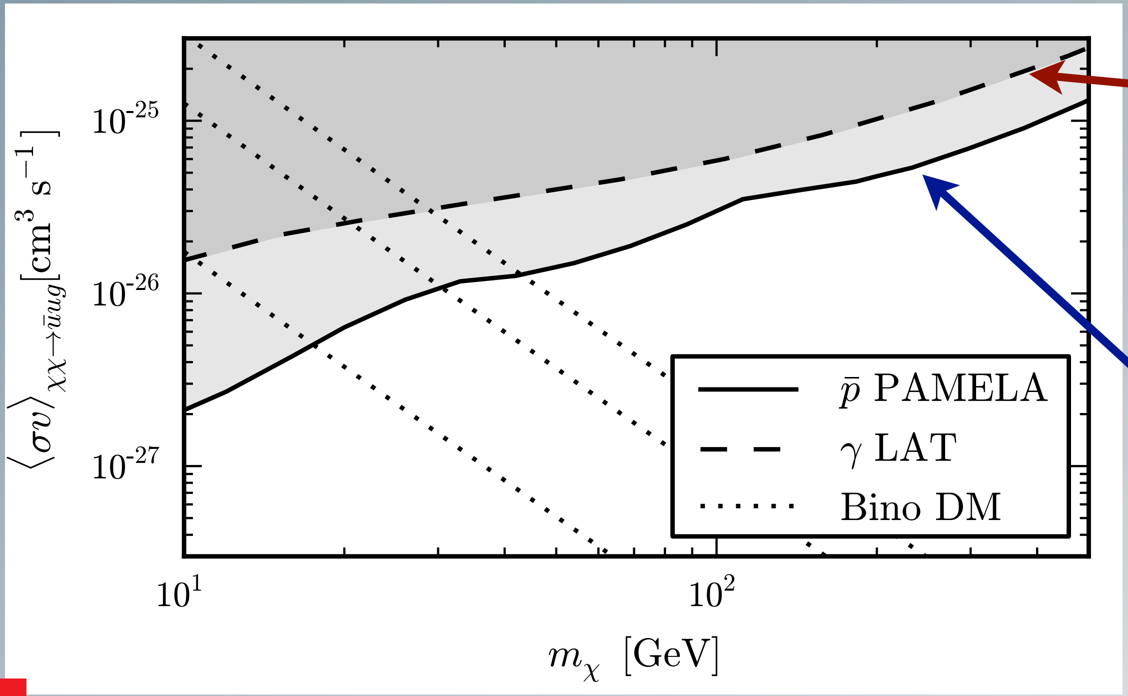


Gluon emission

- Subset of photon IB diagrams



- Photon spectrum very similar to $\bar{q}q$ final states
  ⇨ sufficient to consider total cross section!



Asano, TB & Weniger, PLB '12

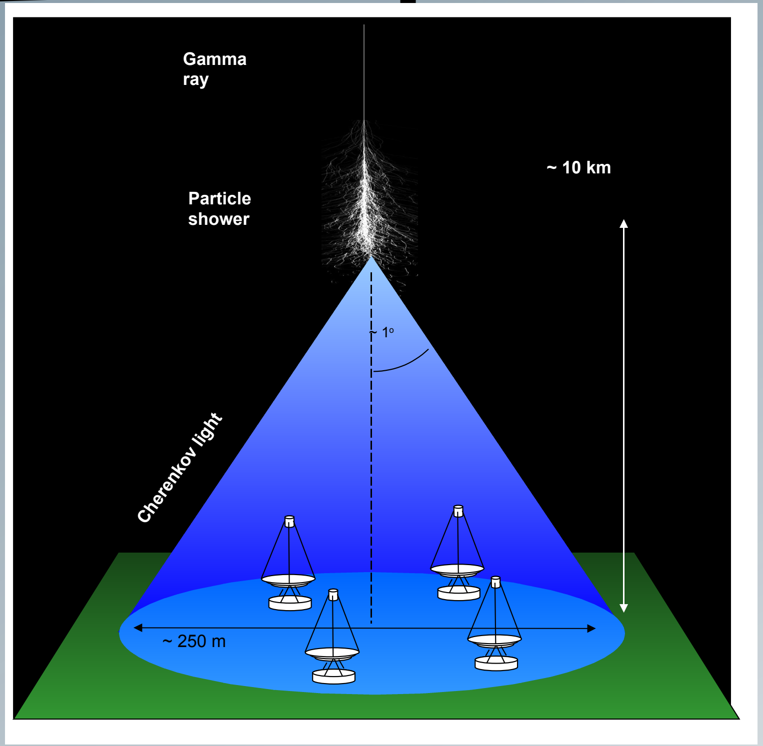
very strong limits from gamma ray observations with Fermi

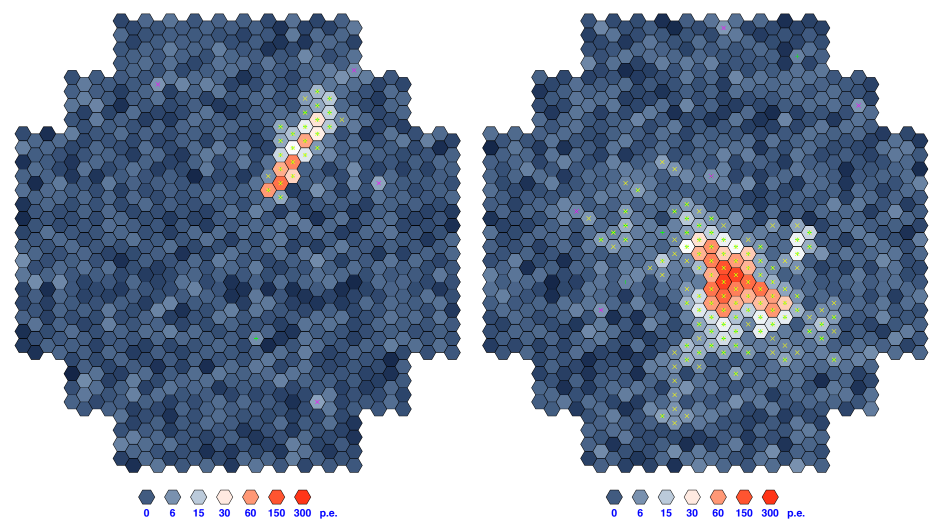
Limits from antiprotons are even stronger in this case

(See also Garny, Ibarra & Vogl, JCAP '12)

Air Cherenkov Telescopes

- Use the atmosphere as a calorimeter:
  - High-energy gamma rays $(E_\gamma \gg 10\,\mathrm{GeV})$ hit the atmosphere at high altitudes
  - this induces an electromagnetic shower of energetic charged particles
  - Resulting Cherenkov light pool, total light yield $\propto E_\gamma$

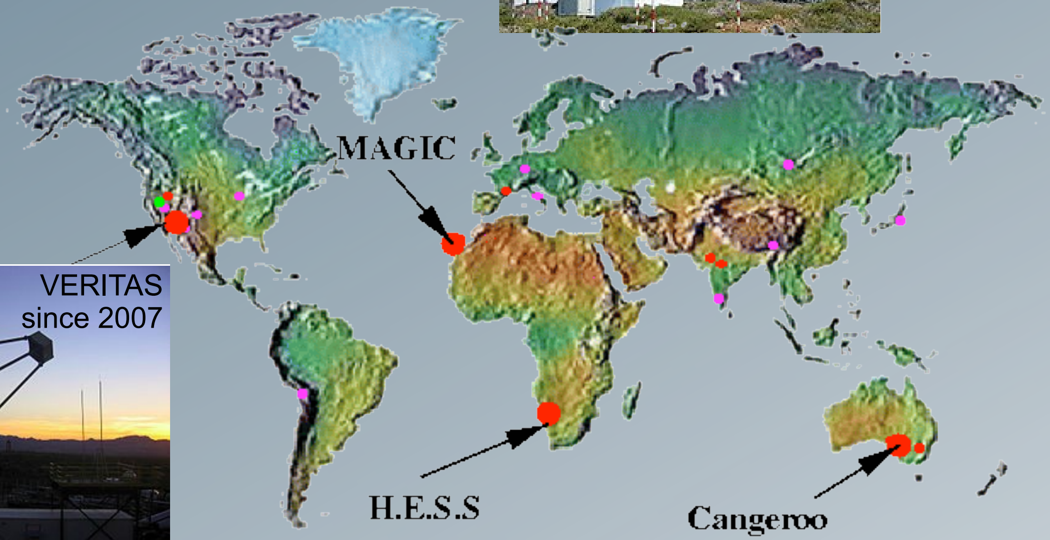




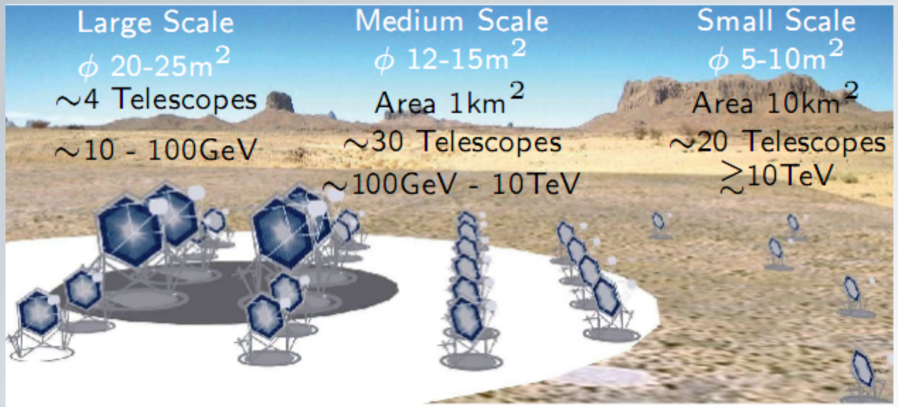
1.0 TeV gamma shower   2.6 TeV proton shower

- Background rejection
  - CR p vastly outnumber γ-rays
  - rejection efficiency $\epsilon_p \sim 10^{-1}..10^{-3}$ (use image properties & direction, improved for stereoscopic systems)
  - irreducible BG from CR $e^\pm$!

Operating and planned ACTs

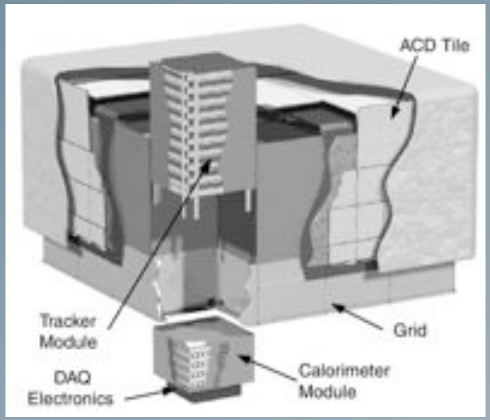


- The Cherenkov Telescope Array
  - planned open observatory, construction from 2015 ?
  - ~10 times better sensitivity than any existing instrument

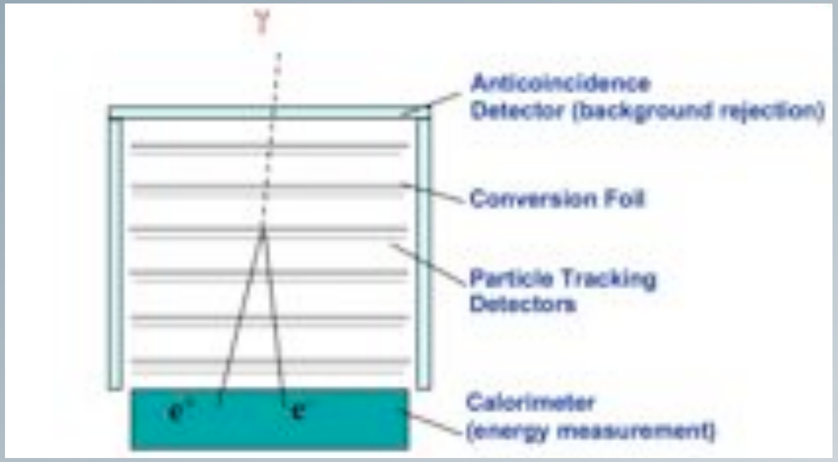


Space-based telescopes

- Going to space allows to very efficiently discriminate the CR background!
  - but of course one cannot build arbitrarily satellites...
    - leading instrument today: the **Fermi** gamma-ray space telescope:



- The ***LAT*** onboard Fermi is a pair-conversion telescope
  - anti-coincidence detector: plastic scintillator that produces flashes of light to veto charged CRs
  - reconstructing $e^{\pm}$ tracks allows to deduce direction of incoming γ-ray
  - Calorimeter measures total energy



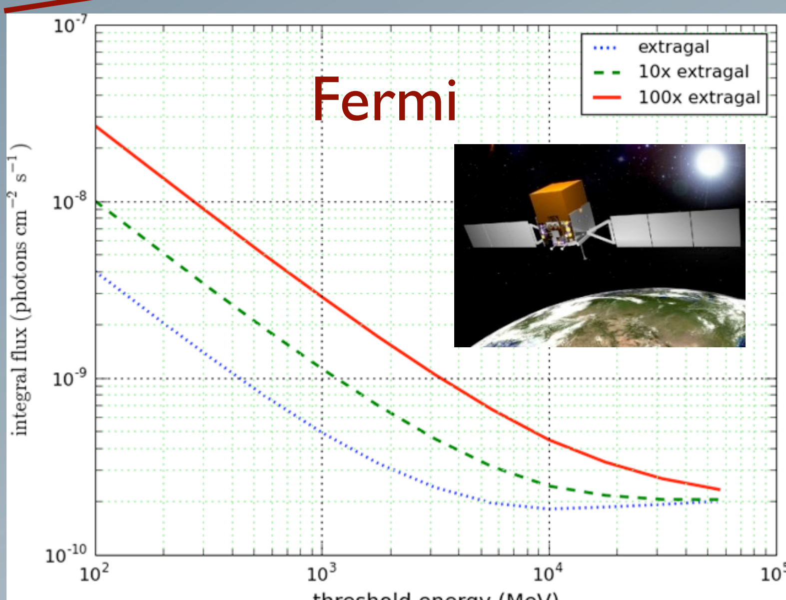
Main characteristics

Space-borne

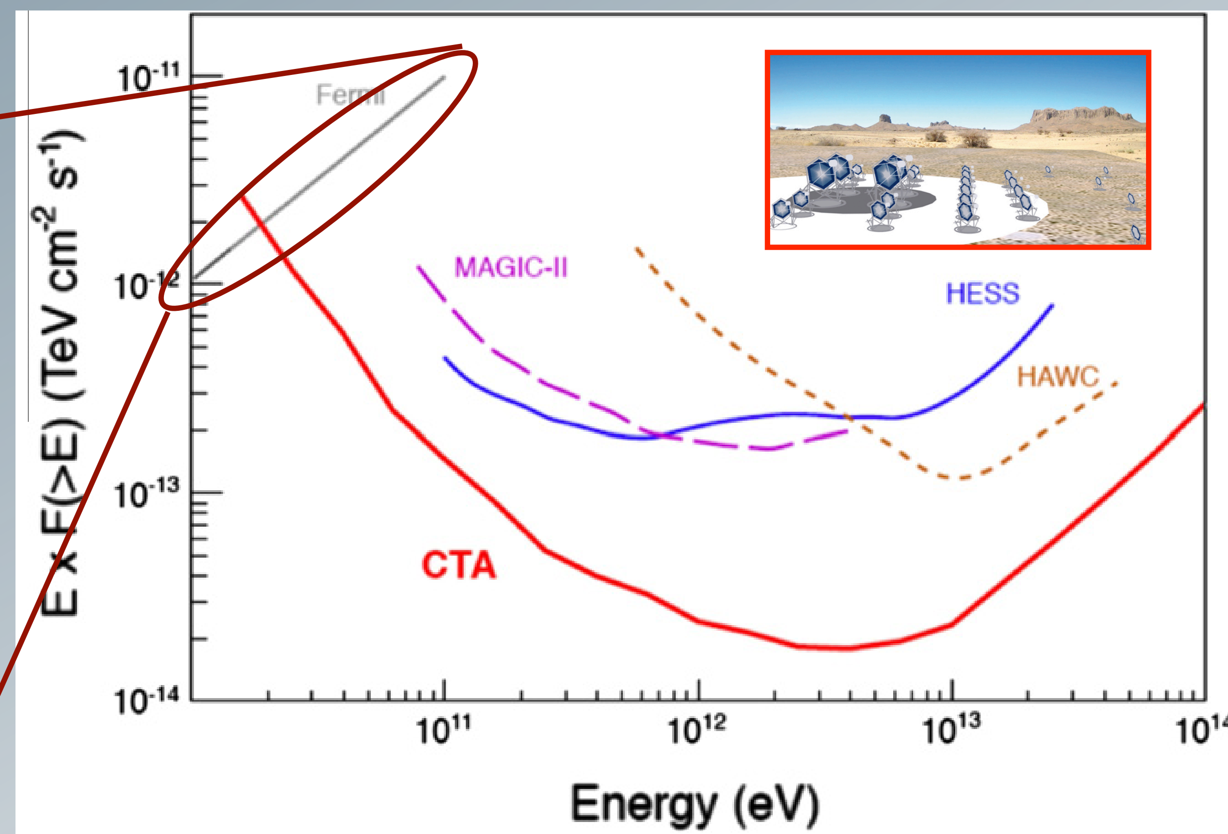
- small eff. Area (~m^2)
- large field of view
- upper bound on resolvable E_γ

Ground-based

- large eff. Area (~km^2)
- small field of view
- lower threshold $\gtrsim$ 40 GeV



(from the LAT webpage)

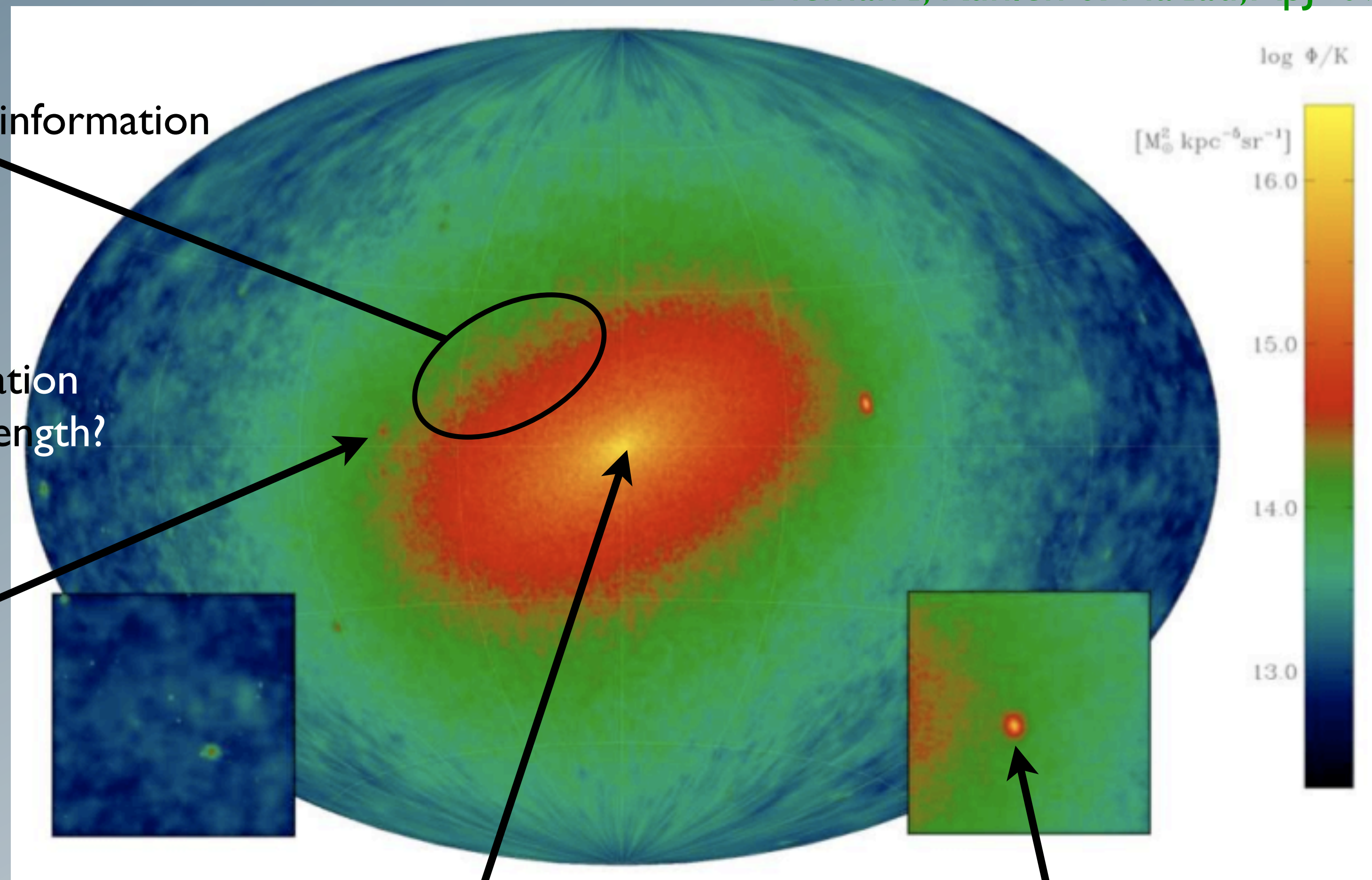


integrated sensitivity:
Fermi: 1*y* IACTs: 50*hrs*

Acharya *et al.*, AP '13

Possible targets

Diemand, Kuhlen & Madau, ApJ '07



Galactic halo

- good statistics, angular information
- galactic backgrounds?

Galaxy clusters

- cosmic ray contamination
- better in multi-wavelength?
- substructure boost?

Dwarf Galaxies

- DM dominated, M/L~1000
- fluxes soon in reach!

Extragalactic background

- DM contribution from all z
- background difficult to model
- substructure evolution?

Galactic center

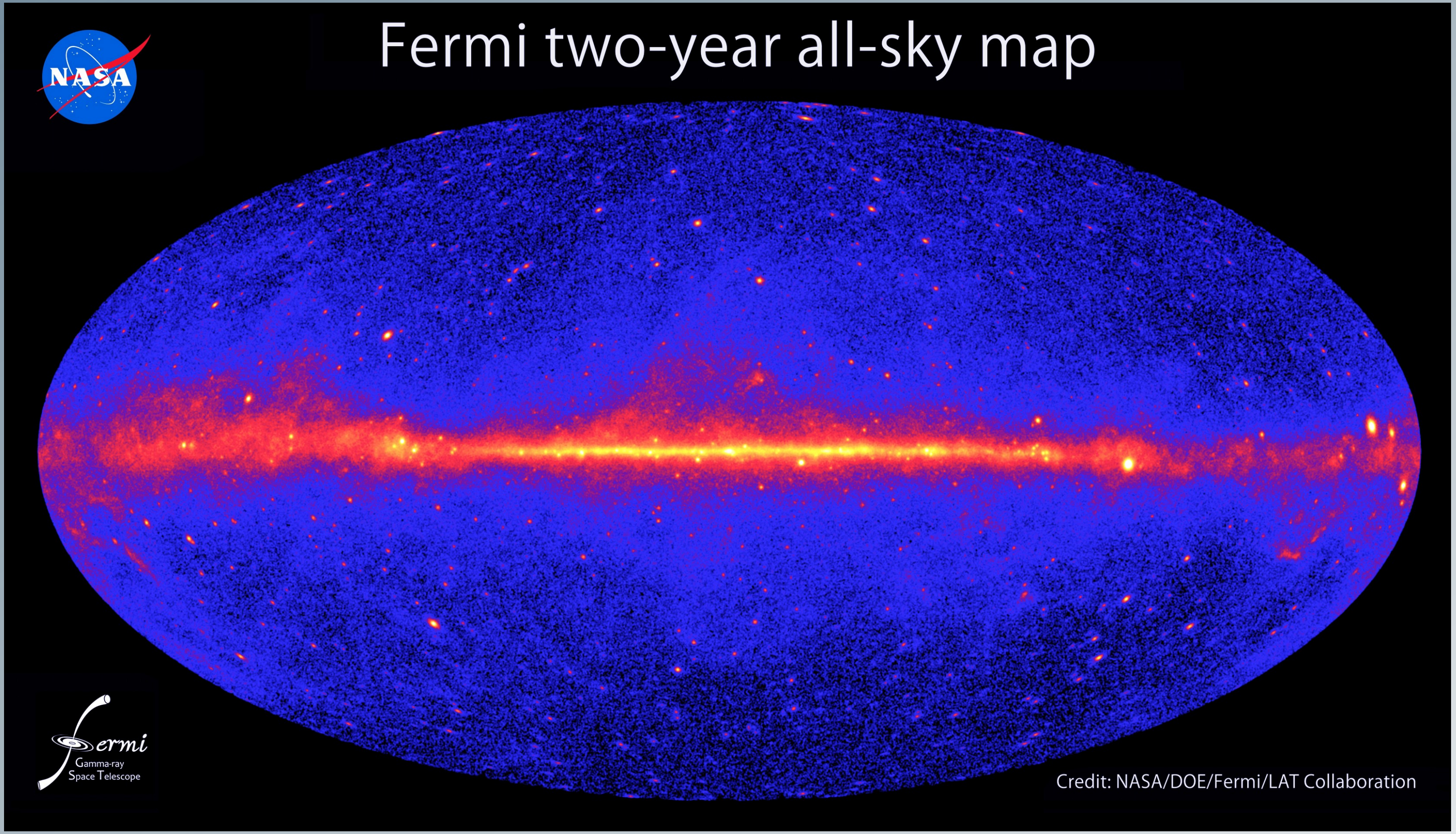
- brightest DM source in sky
- large background contributions

DM clumps

- easy discrimination (once found)
- bright enough?

Possible targets (2)

- NB: the reality looks quite different...



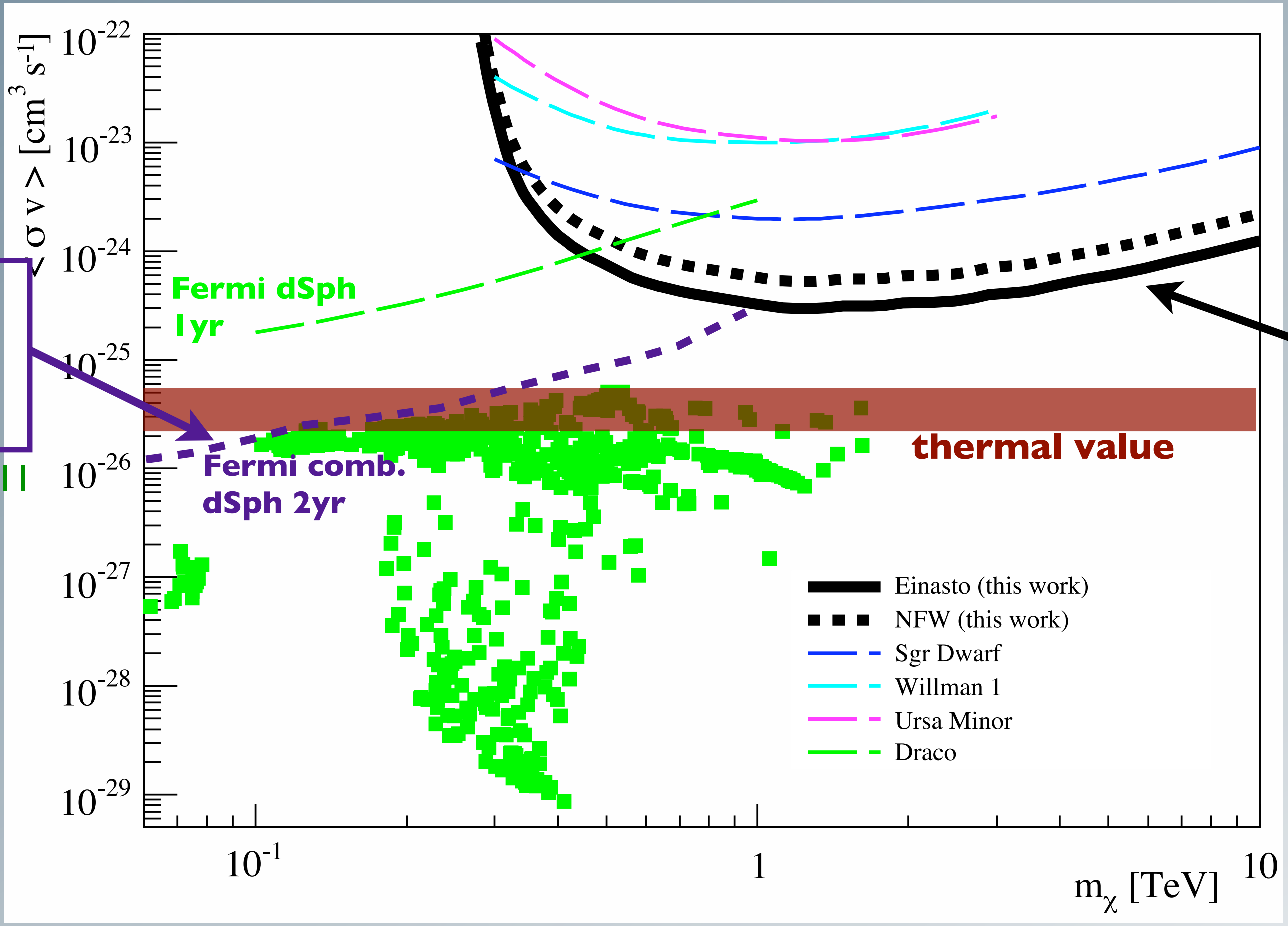
→ *Astrophysical processes certainly present significant backgrounds for DM searches!*

Constraints: current state

- Look for secondary photons from DM
  [typical assumption: 100% annihilation into $\bar{b}b$]

Dwarf galaxy observations by Fermi-LAT

Ackermann *et al*, PRL '11

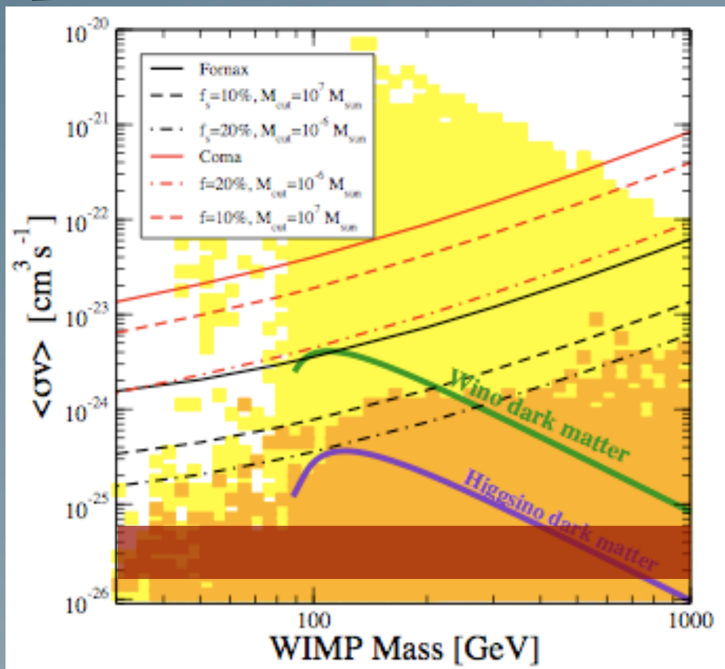


Galactic center observations with HESS

Abramowski *et al*, PRL '11

⇨ Indirect searches start to be very competitive!

More constraints



Almost as constraining: galaxy clusters

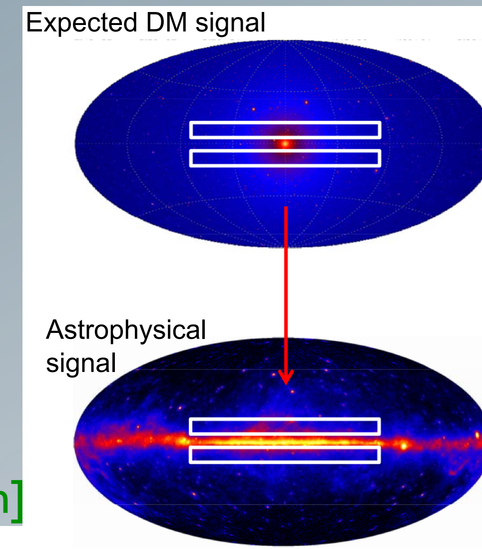
(NB: much better **discovery potential**!)

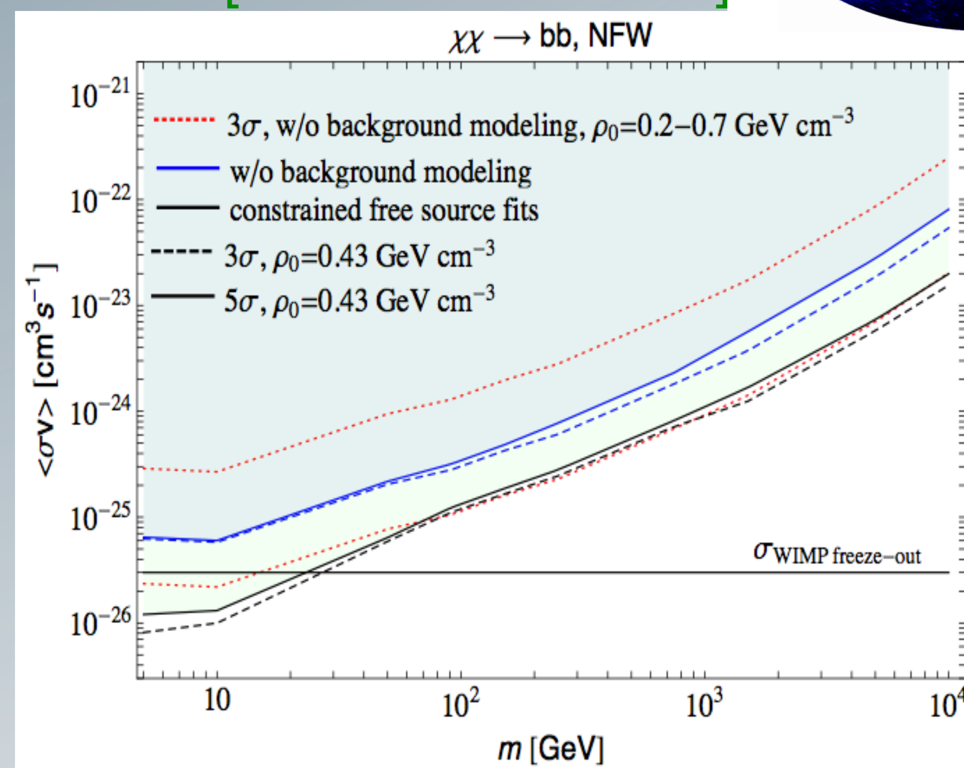
Ackermann *et al*, JCAP '10 [Fermi-LAT collaboration]

Getting close: the Milky Way halo

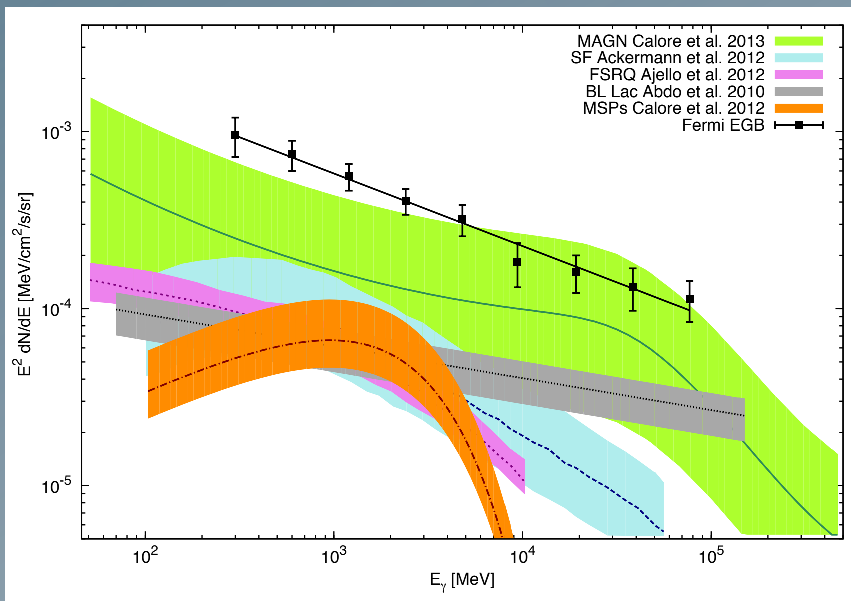
(NB: limits improved by factor of ~5 when including model for astrophysical emission)

Ackermann *et al*, ApJ '12 [Fermi-LAT collaboration]





Diffuse gamma-ray BG

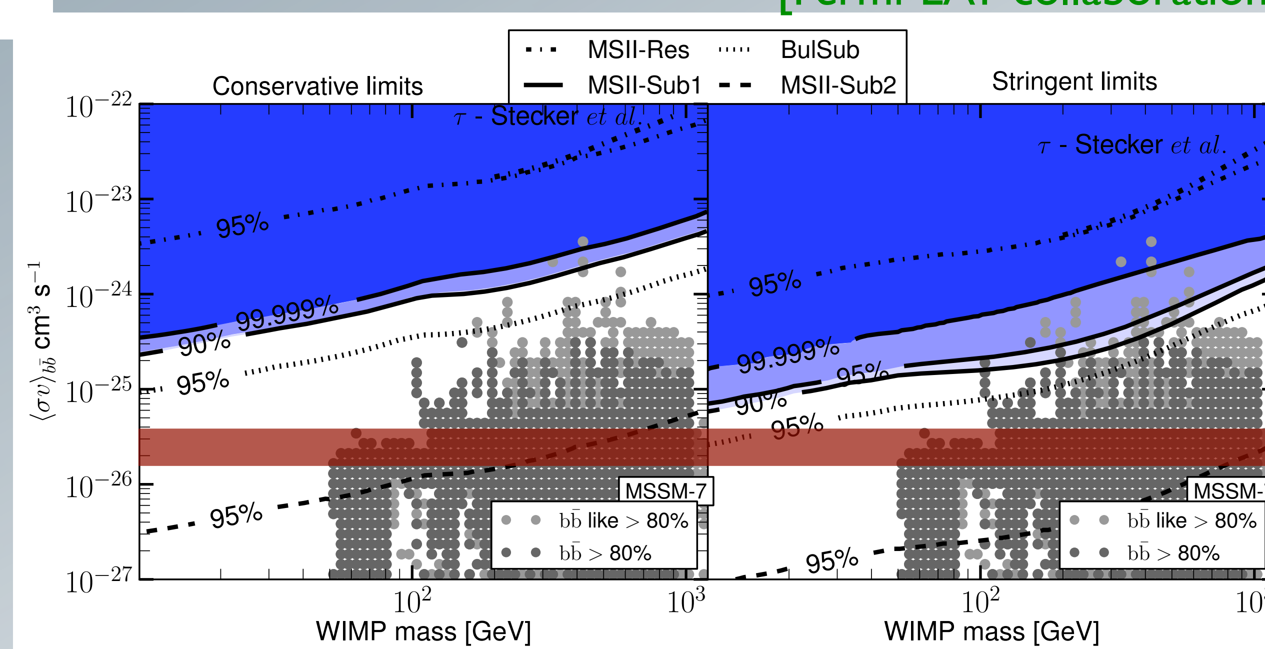


TB, Calore, Di Mauro & Donato, 1303.3284

Constraints from cosmological dark matter annihilation *also* depend strongly on subhalo model

(contribution from all halos at all redshifts)

Abdo *et al*, JCAP '10 [Fermi-LAT collaboration]



Significant systematic uncertainties in modeling source contributions to EGB!

(→ *see poster!*)

UCMHs

- Ultracompact Minihalos are DM halos that form shortly after matter-radiation equality Ricotti & Gould, ApJ '09
  - isolated collapse
  - formation by radial infall (Bertschinger, ApJS '95)

$$\longrightarrow \quad \rho \propto r^{-9/4}$$

- Excellent targets for indirect detection with gamma rays

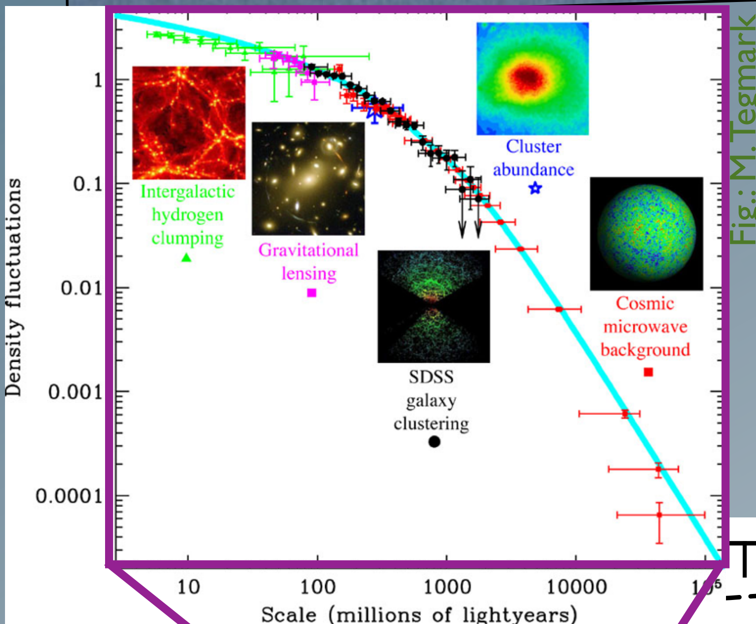
Scott & Sivertsson, PRL '09
Lacki & Beacom, ApJ '10

- Required density contrast at horizon entry:

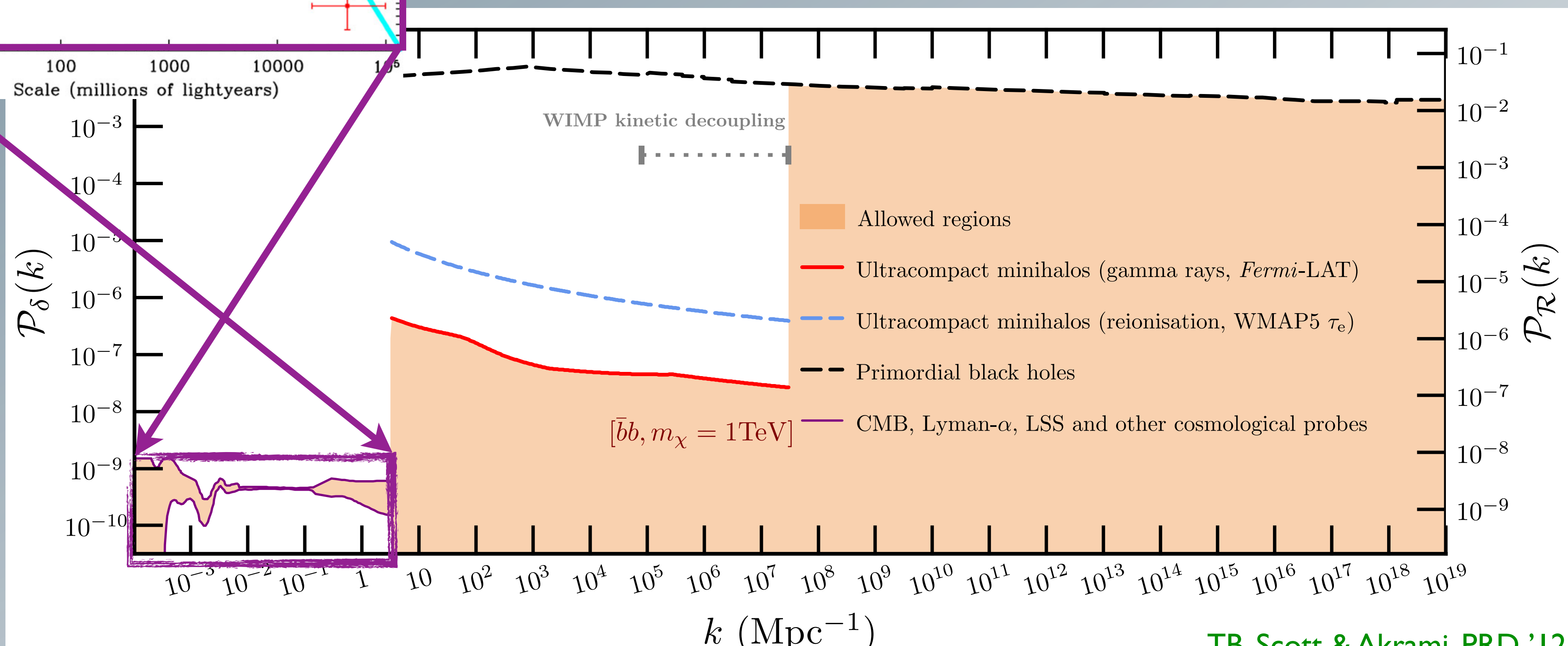
$$\delta \equiv \frac{\Delta\rho}{\rho} \sim 10^{-3} \quad @ \quad z \gg z_{\rm eq}$$

  - PBH: $\delta \gtrsim 0.3$
  - typical observed value: $\delta \sim 10^{-5}$ at 'large' scales

New constraints on $\mathcal{P}(k)$:



- Primordial (linear) power spectrum well measured at 'large' scales
- Below ~Mpc scales, only upper bounds available...



TB, Scott & Akrami, PRD '12

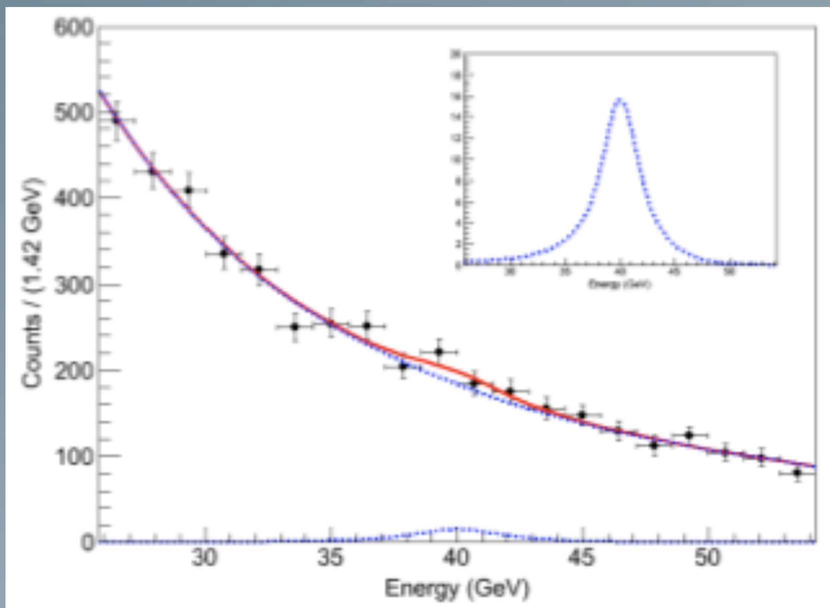
Recall:

We like distinct spectral features because they

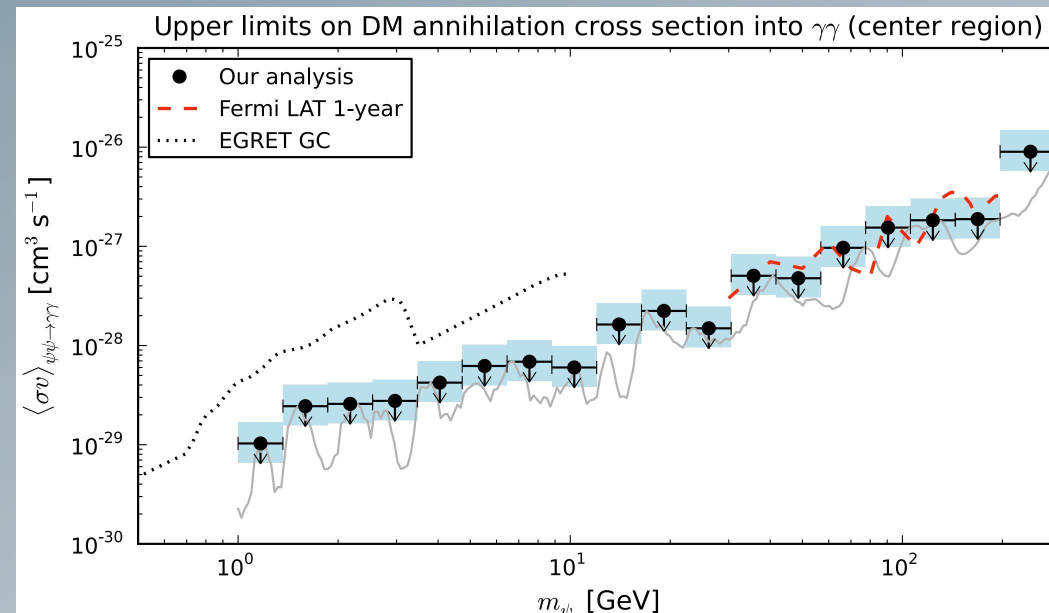
- make the discrimination of a signal from possible astrophysical backgrounds much more straightforward
- provide (potentially) very detailed information about the particle nature of dark matter

Line signals@ early 2012

- Fermi all-sky search for line signals:



Abdo *et al*, PRL '10



Vertongen & Weniger, JCAP 2011

- not (yet) probing too much of WIMP parameter space

(NB: natural expectation $\langle\sigma v\rangle_{\gamma\gamma} \sim \alpha_{\rm em}^2 \langle\sigma v\rangle_{\rm therm} \simeq 10^{-30}{\rm cm}^3{\rm s}^{-1}$)

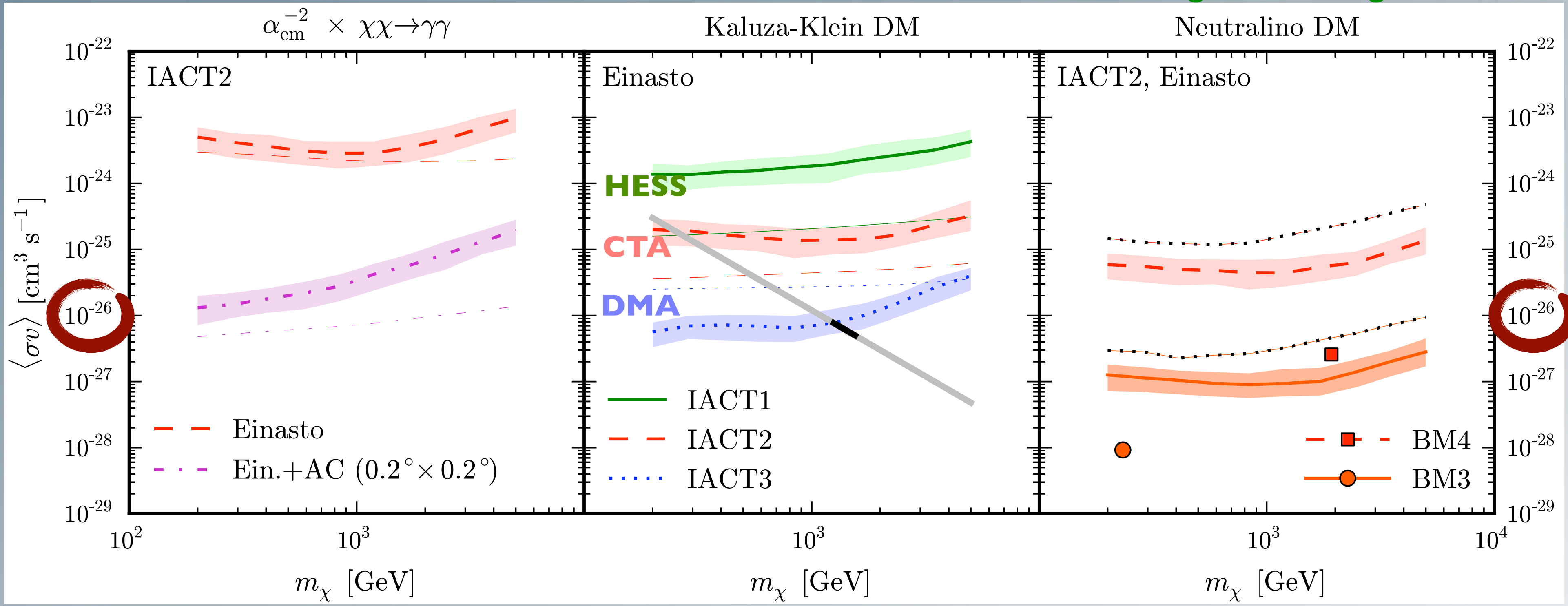
- NB: 1y data, simple choice of target region...
- No significant changes after 24 months of data...

Ackermann *et al*, 1205.2739

Other spectral features

- Searching for other signatures like sharp steps or IB "bumps" could be more promising:

TB, Calore, Vertongen & Weniger, PRD '10



Line signals **Kaluza-Klein DM (step)** **Neutralino DM (IB bump)**

⇨ Natural cross sections well within reach for ACTs!

Searching for spectral features

- Sliding energy window technique
  - standard in line searches
  - window size: few times energy resolution
  - main advantage: background can well be estimated by power law!
- Fit of 3-parameter model sufficient:

$$\frac{dJ}{dE} = S\frac{dN^{\mathrm{signal}}}{dE} + \beta E^{-\gamma}$$

- expected events:

$$\mu_i = \int_{E_0}^{E_1} dE \int dE'\, \mathcal{D}(E,E')\mathcal{E}(E')\frac{dJ}{dE'}$$

energy resolution **exposure**

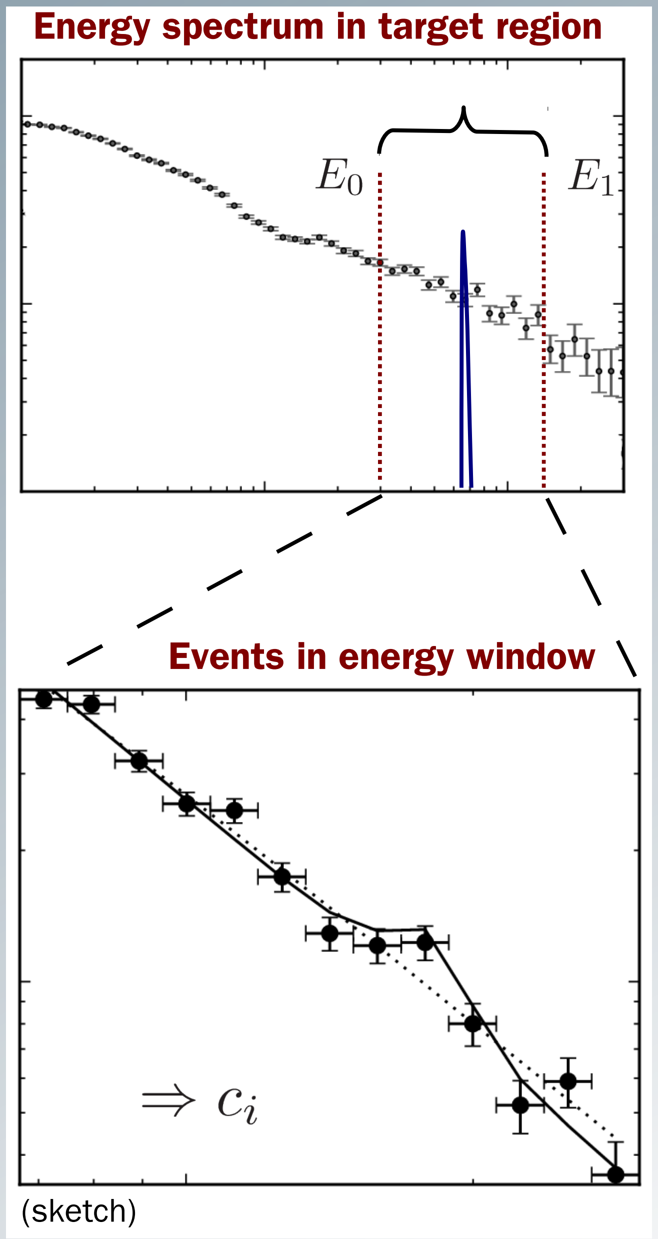


Fig.: C. Weniger

Likelihood analysis

- 'binned' likelihood
  - NB: bin size $\ll$ energy resolution $\rightsquigarrow$ same as un-binned analysis!

$$\mathcal{L} = \prod_i P(c_i|\mu_i)$$

observed (c_i), expected (μ_i)

$$P(c_i|\mu_i) = \frac{\mu_i^{c_i} e^{-\mu_i}}{c_i!}$$

- Significance follows from value of test statistic:

$$TS \equiv -2\ln\frac{\mathcal{L}_{\rm null}}{\mathcal{L}_{\rm DM}}$$

$\mathcal{L}_{\rm null}$: **best fit with** $S \overset{!}{=} 0$

$\mathcal{L}_{\rm DM}$: **best fit with** $S \geq 0$

⇨ significance (without trial correction): ~$\sqrt{TS}\sigma$

(95% *Limits* derived by profile likelihood method: increase S until $\Delta(-2\ln\mathcal{L})_{\rm DM} = 2.71$, while refitting/ 'profiling over' the other parameters)

because we take one-sided limits:

$$\int_{-\infty}^{\sqrt{2.71}} N(0,1,x) = 0.95$$

Target selection

- Galactic center by far brightest source of DM annihilation radiation
- Need strategy for large astrophysical backgrounds:
  - early focus on innermost region (but now: strong HESS source)
  - define optimal (S/N) cone around GC $\rightsquigarrow$ $\theta \sim 0.1^\circ - 5^\circ$
  - ~same, but for annulus (excluding the GC)
  - exclude galactic plane
  - ...
- New idea: data-driven approach

TB, Huang, Ibarra, Vogl & Weniger, JCAP '12

  - estimate background distribution from observed LAT *low-energy* photons $1\,\mathrm{GeV} \le E_\gamma \le 40\,\mathrm{GeV}$
  - Define grid with $1^\circ \times 1^\circ$
  - Optimize total S/N pixel by pixel:

$$\mathcal{R}_T \equiv \frac{\sum_{i\in T} \mu_i}{\sqrt{\sum_{i\in T} c_i^{E_\gamma \le 40\,\mathrm{GeV}}}}$$

signal

target region

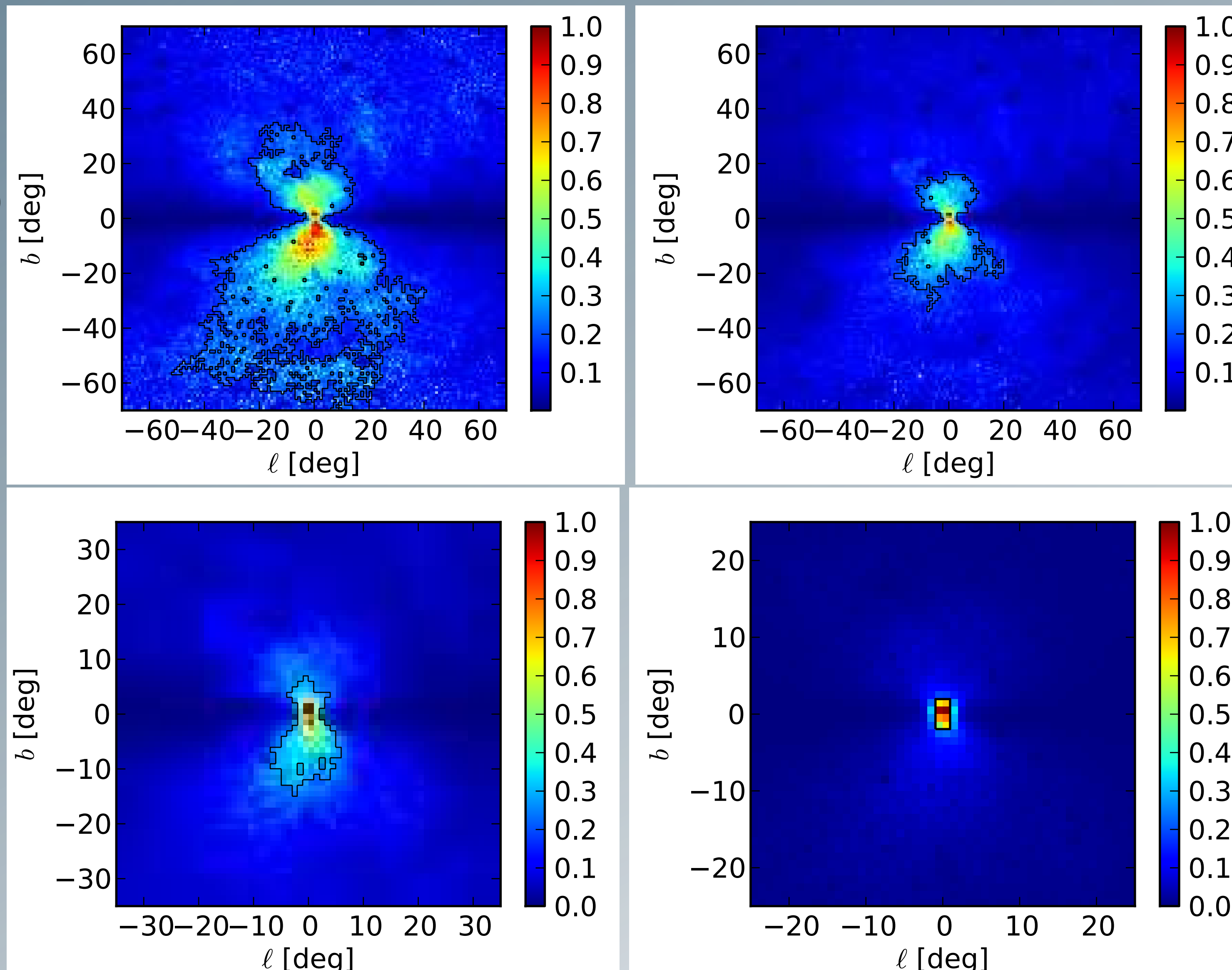
$\rho_\chi \propto r^{-\alpha}$

Optimal target regions

$\rho_\chi \propto r^{-1.0}$

'NFW'

$\rho_\chi \propto r^{-1.1}$



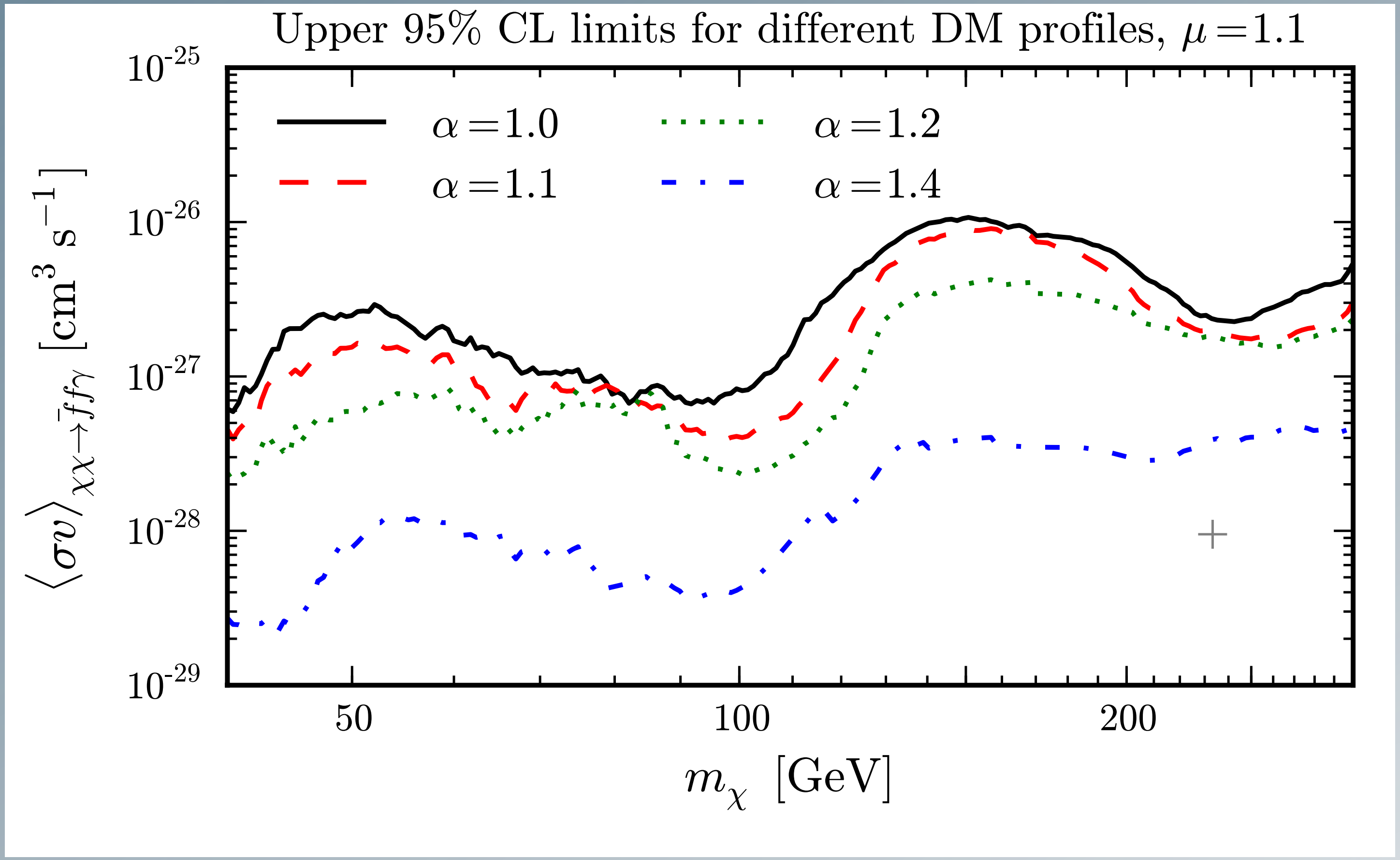
$\rho_\chi \propto r^{-1.2}$

$\rho_\chi \propto r^{-1.4}$

'adiabatic contraction'

Color scale: signal to *background*

IB limits from Fermi-LAT



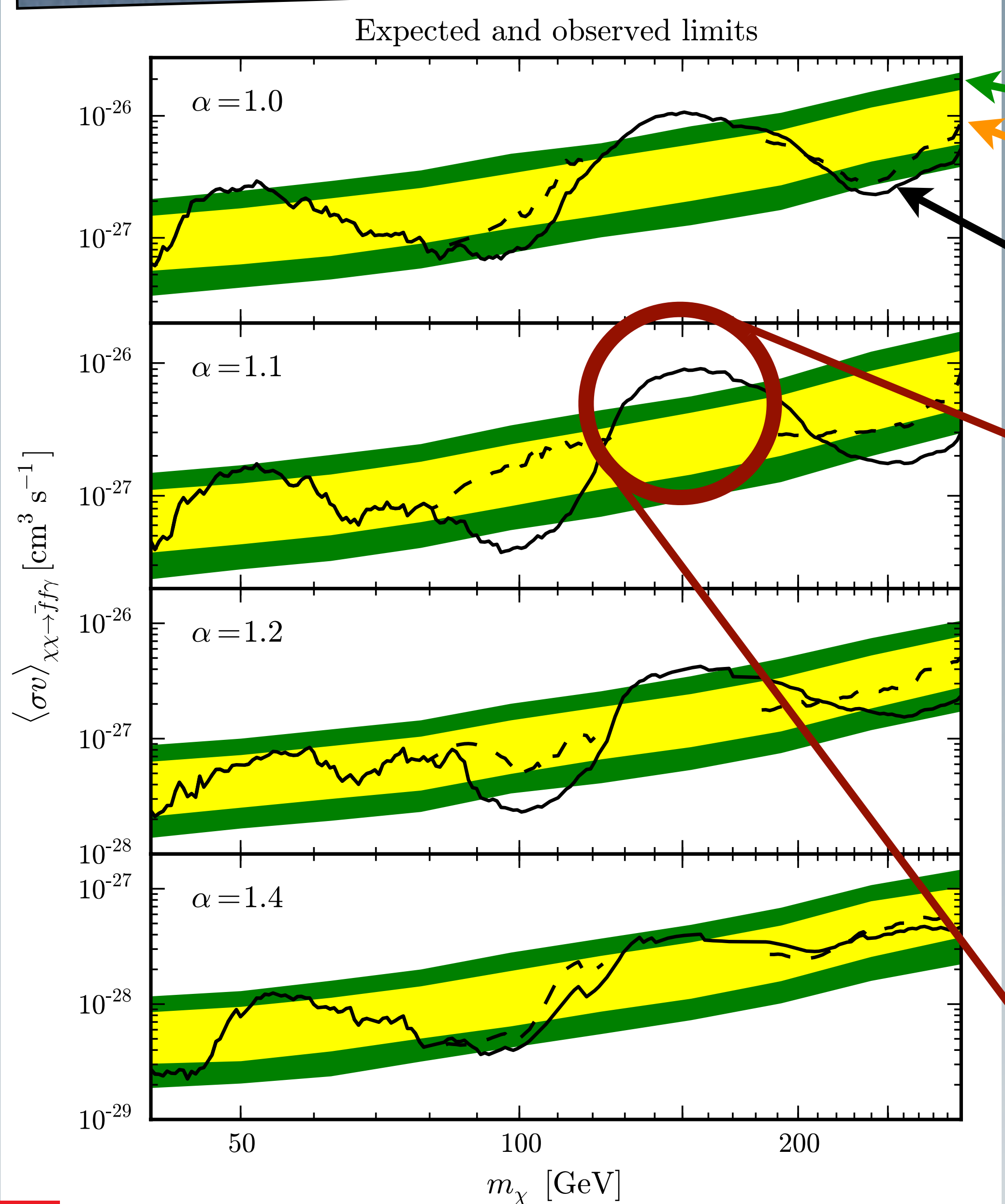
NB: 3-body x-section!

GC and halo region

$\rho_\chi \propto r^{-\alpha}$

- limits on $\ell^+\ell^-(\gamma)$ much stronger than for Fermi dwarfs!
- now let's compare this to the limits one should expect...
  (to do so, generate large number of mock data sets from null model)

Expected vs observed limits

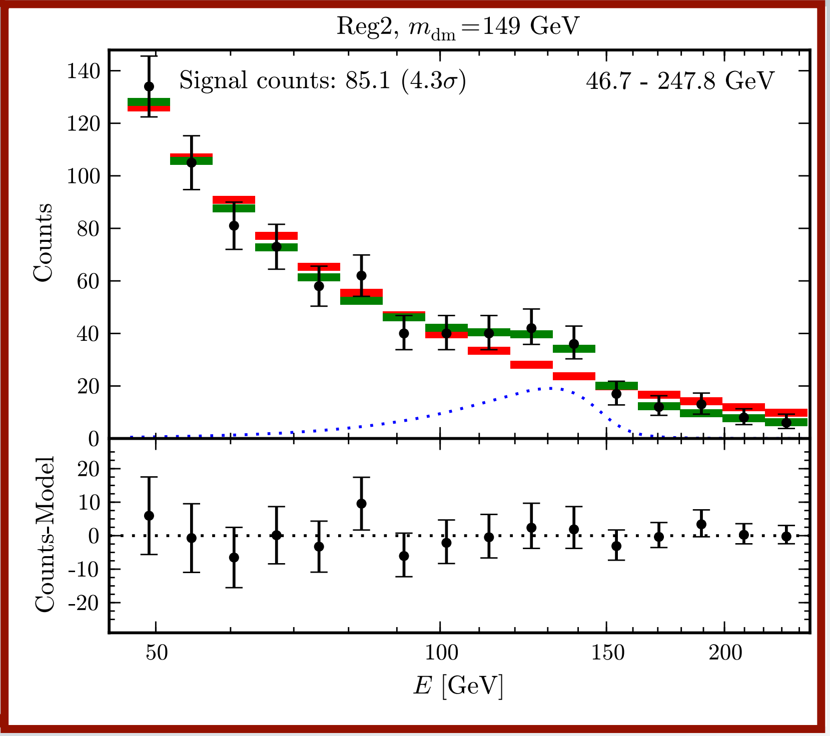


expected limits (95% CL)

expected limits (68% CL)

observed limits

(dashed: excluding data from 115 to 145 GeV)

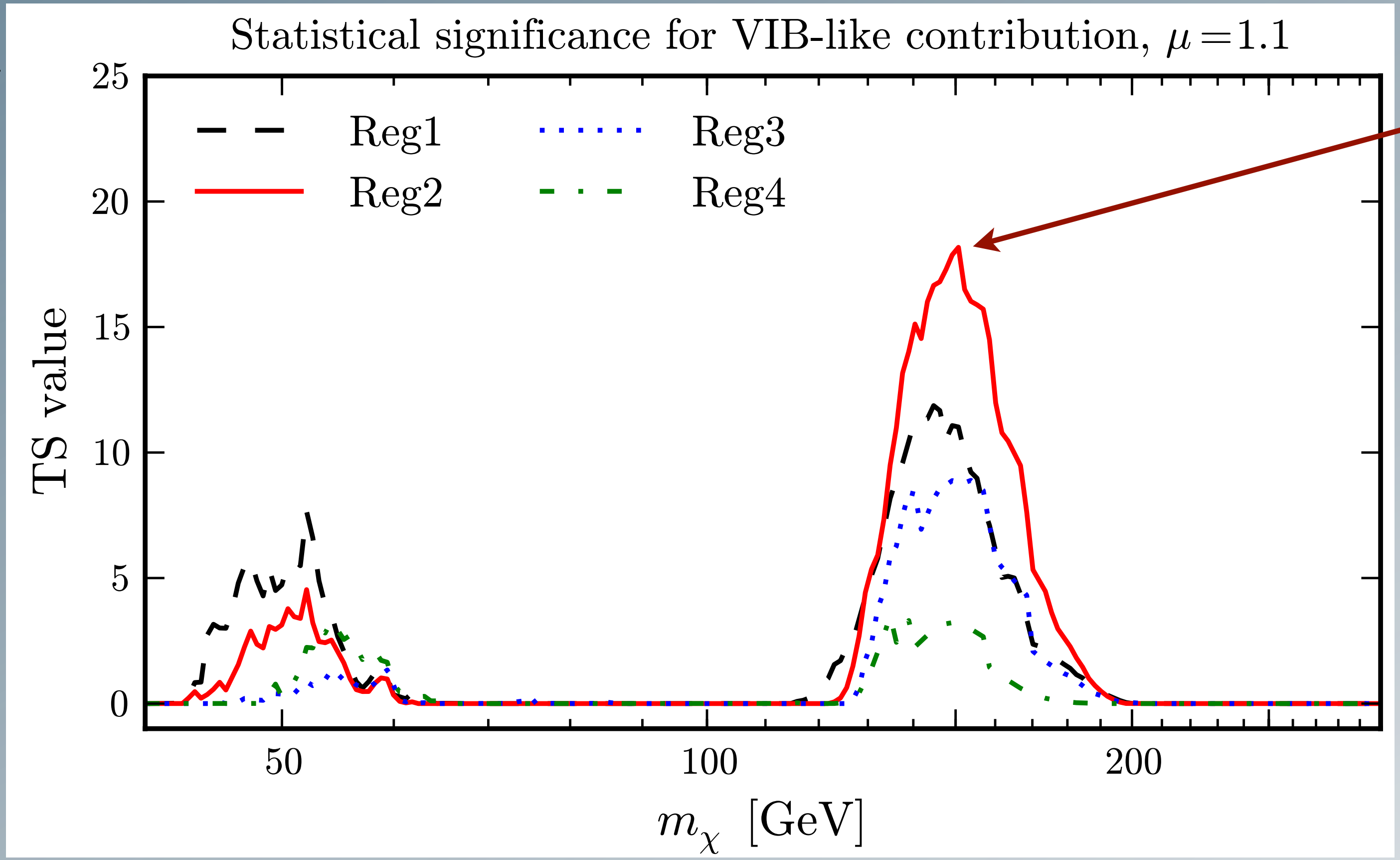


95% CL upper limits

A tentative signal!

$$\rho_\chi \propto \frac{1}{r^\alpha (1 + r/r_s)^{3-\alpha}}$$

Reg2: $\alpha = 1.1$



peak value nominally corresponds to signal significance of 4.3σ

- Best-fit values: $m_\chi = 149 \pm 4 \,{}^{+8}_{-15}\,\mathrm{GeV}$

  $\langle \sigma v \rangle_{\chi\chi \to \bar{f} f \gamma} = (5.7 \pm 1.4 \,{}^{+0.7}_{-1.0}) \times 10^{-27} \mathrm{cm}^3 \mathrm{s}^{-1}$

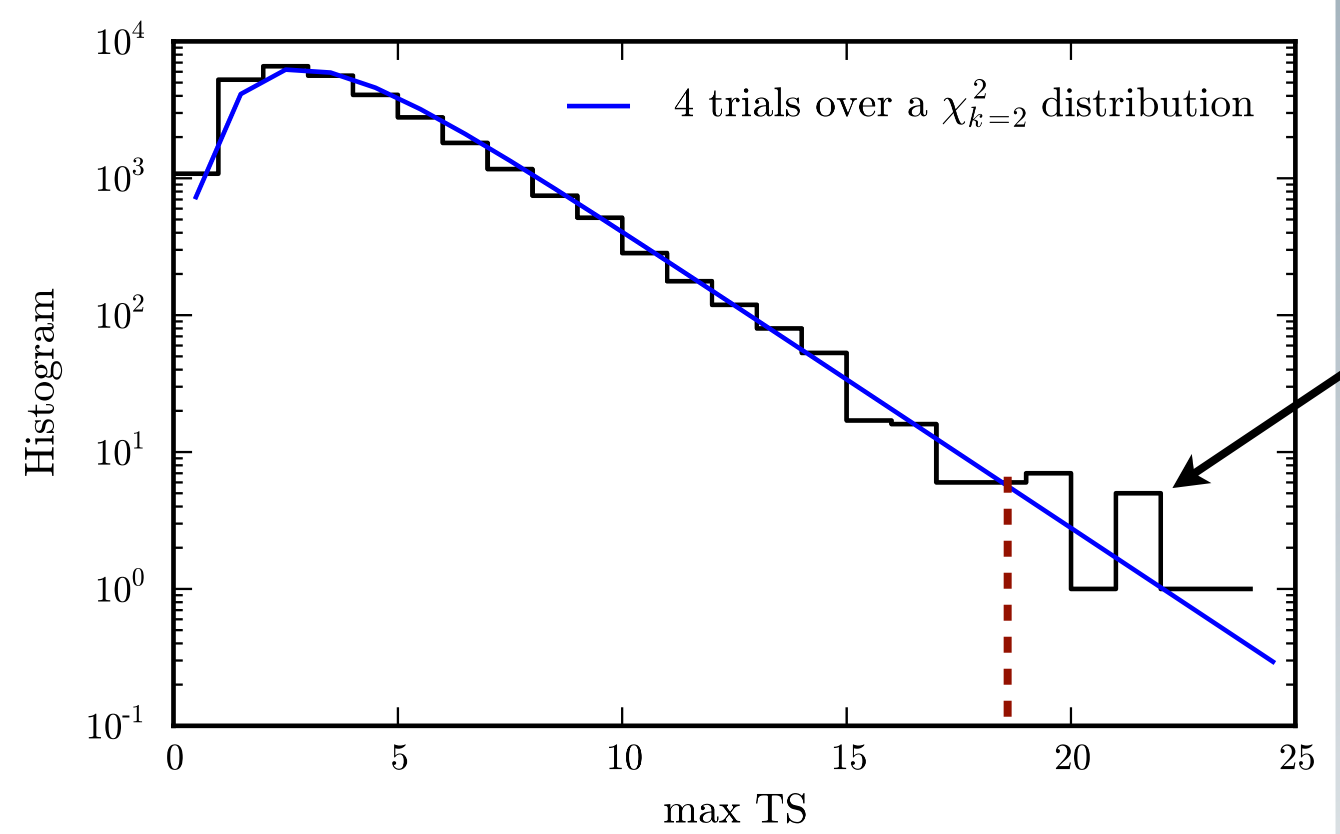
- NB: also very well fit by line with

$$m_\chi \sim 130\,\mathrm{GeV},\ \langle \sigma v \rangle \sim 10^{-27} \mathrm{cm}^3 \mathrm{s}^{-1}$$

TB, Huang, Ibarra, Vogl & Weniger, JCAP '12

Look-elsewhere effect

- Need to take into account that many independent statistical trials are performed!
  [i) scan over DM mass and ii) different test regions]



from subsampling analysis of galactic anticenter hemisphere

solve

$$P(\chi^2_k < TS)^t = P(\chi^2_1 < \sigma^2)$$

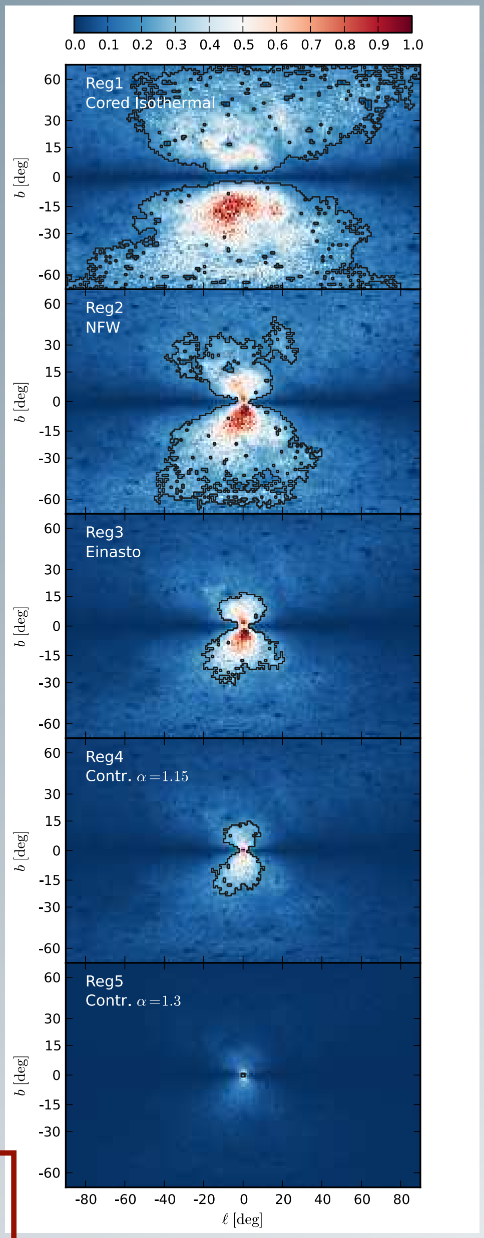
$t = 4 \times 4$

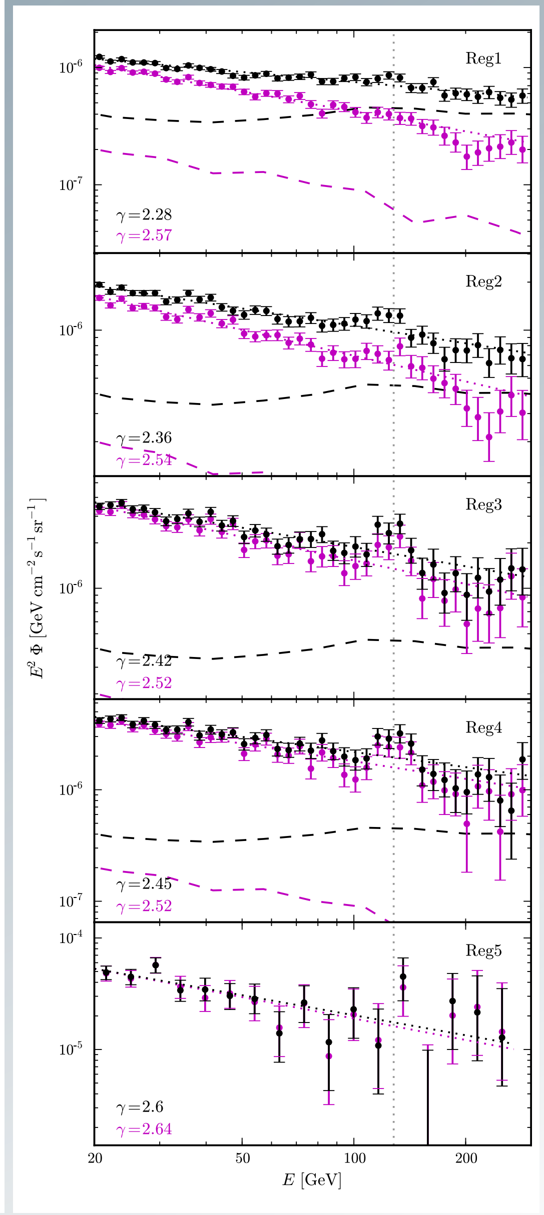
observed maximal TS value corresponds to significance of 3.1σ

Subsequent line analyses

Weniger, 1204.2797

- "A tentative gamma-ray line from DM @ Fermi LAT"
  - same data: 43 months Fermi LAT
  - very nice and extended description of (~same) method
  - extended discussion





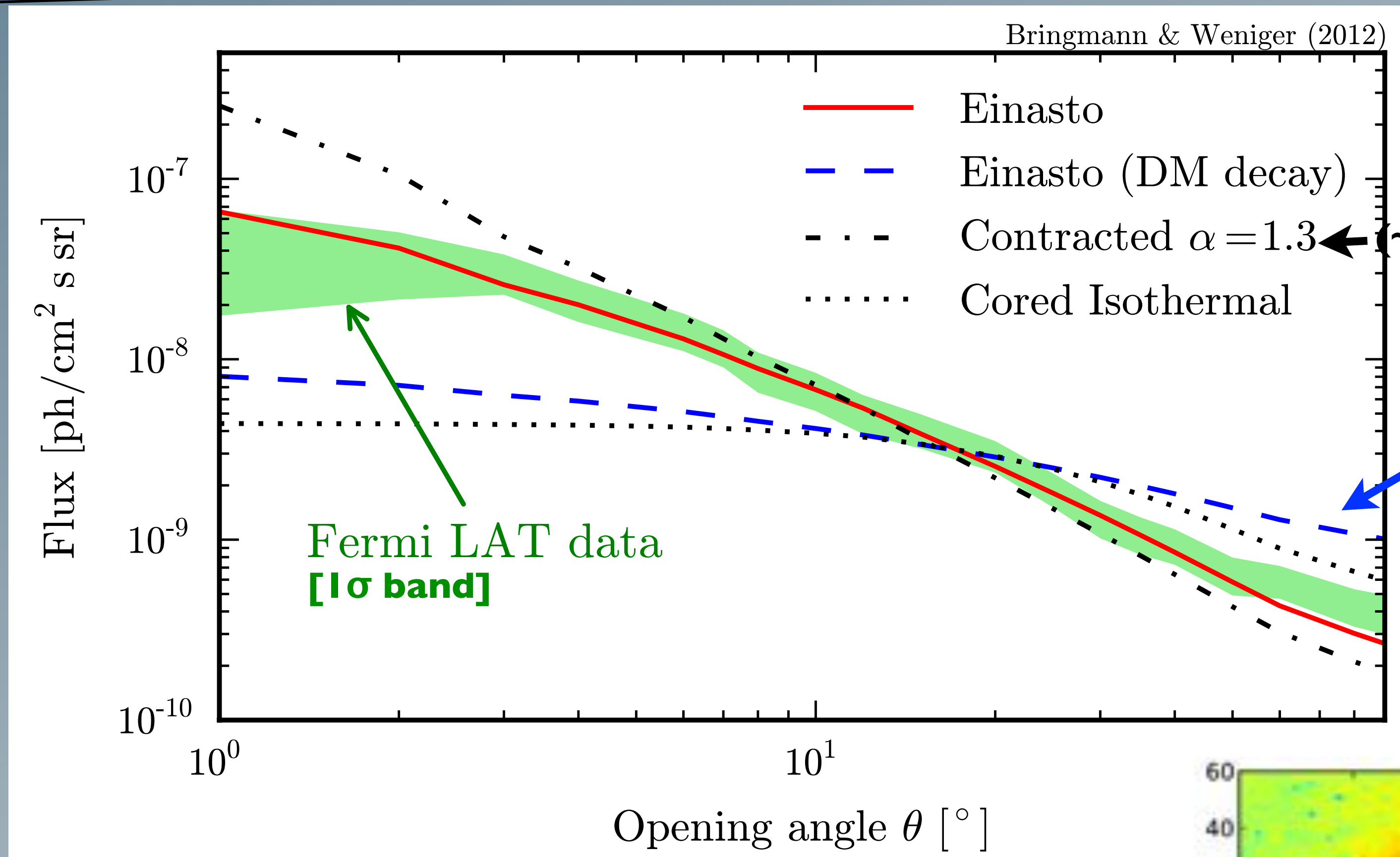
- bottom line:
  - $4.6\sigma\,(3.3\sigma)$ effect
  - $m_\chi = 129.8 \pm 2.4\,^{+7}_{-13}$ GeV
  - $\langle\sigma v\rangle_{\chi\chi\to\gamma\gamma} = (1.27 \pm 0.32\,^{+0.18}_{-0.28}) \times 10^{-27}\ \mathrm{cm}^3\ \mathrm{s}^{-1}$

- Excess also seen by:

  Tempel, Hektor & Raidal, 1205.1045
  Rajaraman, Tait & Whiteson, 1205.4723
  Su & Finkbeiner, 1206.1616 ←
  …

use spatial templates to infer *global* significance $> 5\sigma$!

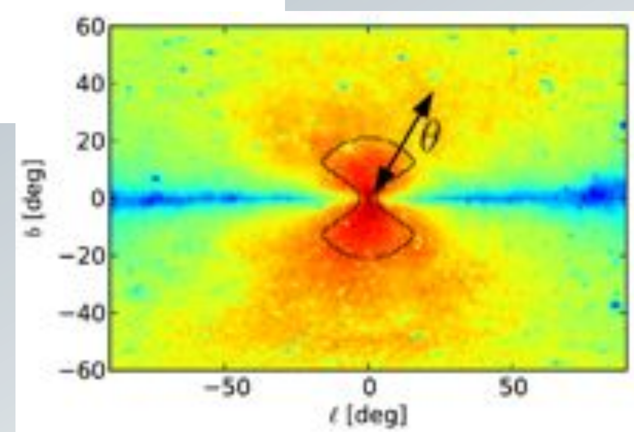
Signal profile



← (~same as NFW)

← (~same as point source)

NB: ***decaying DM no option!***



ROI [Color scale: signal to background]

⇨ Signal not compatible with point source, but (almost) *only* with standard NFW or Einasto profile!

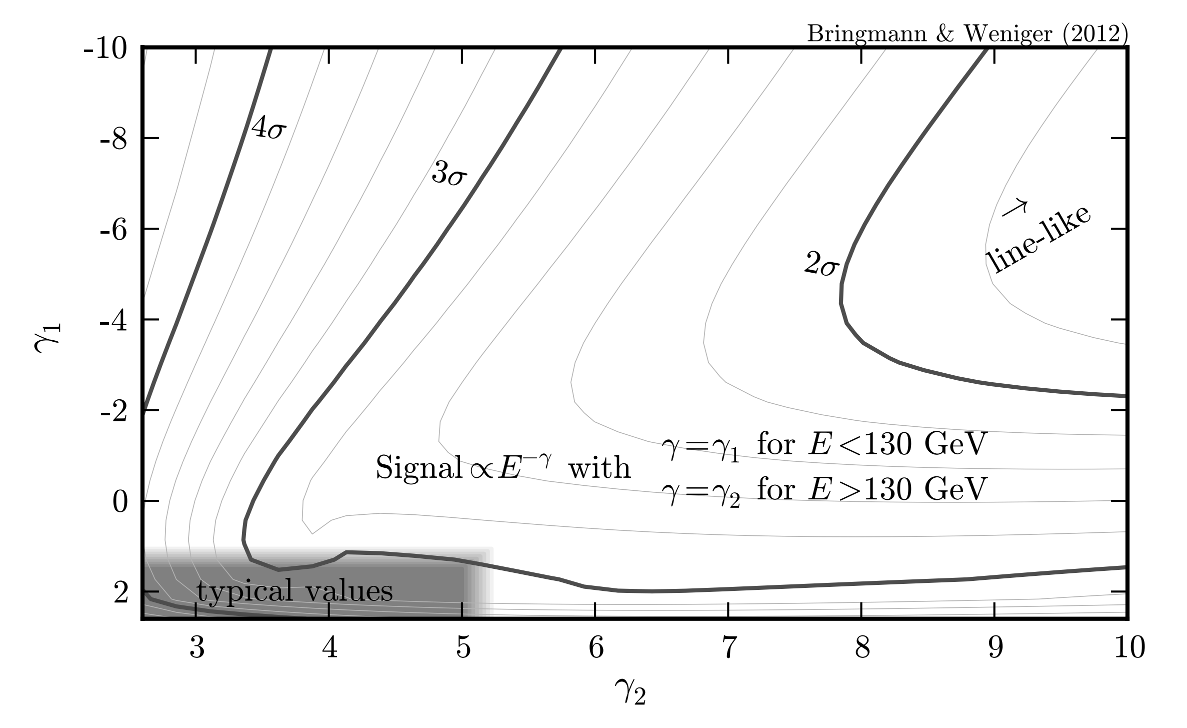
[Symmetry around GC checked by masking half ROIs]

Really a *line*?

- Intrinsic signal width: <18% @ 95% C.L.
  ⇨ not (yet) possible to distinguish between IB and line signal

- Broken power-law gives no reasonable fit to data!

- Signal proportional to $E^{-\gamma}\exp[-(E/E_{\rm cut})^2]$ also disfavored wrt line by at least 3σ
  [same for astro-physical toy example: ICS from mono-energetic $e^\pm$]

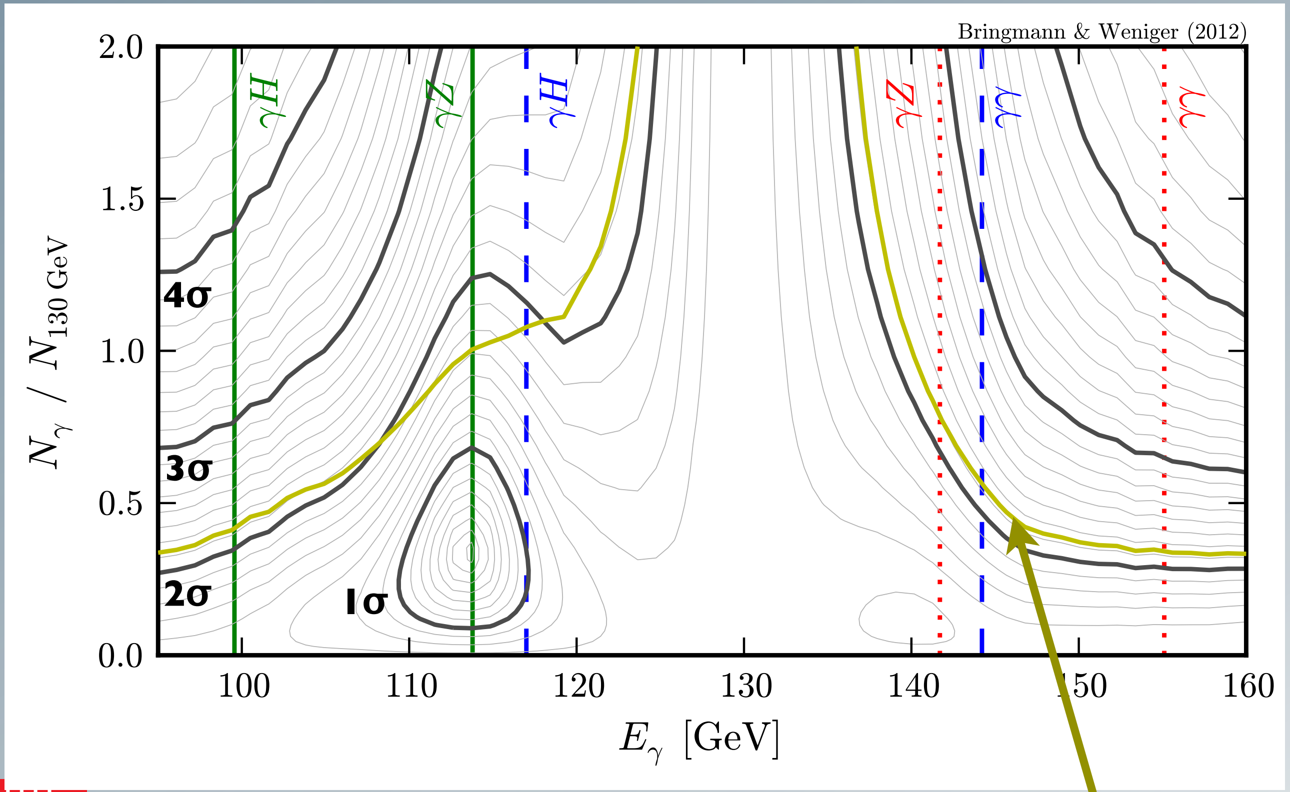


⇨ ***Extremely difficult to achieve with astrophysics!***

Which line(s)?

- DM mass and annihilation rate depend on channel

γX	m_χ [GeV]	$\langle\sigma v\rangle_{\gamma X}$ $[10^{-27}\mathrm{cm}^3\mathrm{s}^{-1}]$
$\gamma\gamma$	$129.8 \pm 2.4^{+7}_{-14}$	$1.27 \pm 0.32^{+0.18}_{-0.28}$
γZ	$144.2 \pm 2.2^{+6}_{-12}$	$3.14 \pm 0.79^{+0.40}_{-0.60}$
γH	$155.1 \pm 2.1^{+6}_{-11}$	$3.63 \pm 0.91^{+0.45}_{-0.63}$
IB	$149 \pm 4^{+8}_{-15}$	$5.2 \pm 1.3^{+0.8}_{-1.2}$



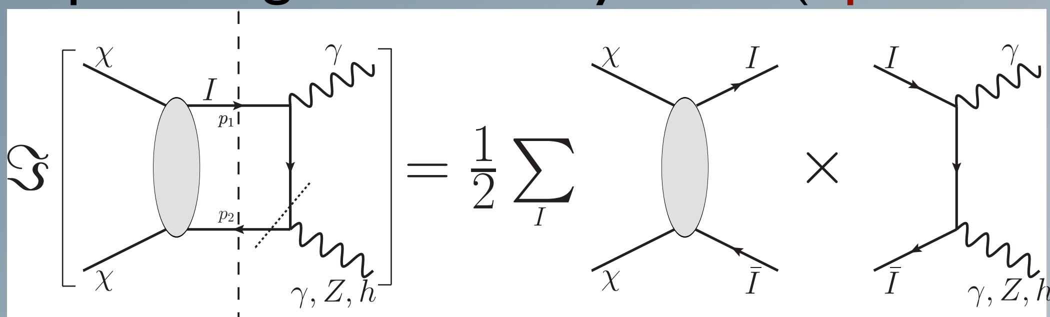
95%CL upper limit

- DM spectroscopy !?
  - usually at least two lines (eff. operators...)
  - relative rates provide important constraints on viable models
  - currently very *weak (1.4σ) indication* for 2nd line

see also:
Rajaraman, Tait & Whiteson, JCAP '12
Su & Finkbeiner, 1206.1616

More DM model implications

- Need rather large annihilation rate
  - implies resonances and/or large couplings (see e.g. Buckley & Hooper, PRD '12)
  - *difficult* to achieve for *thermally* produced DM!
  - expect large secondary rates (optical theorem!)



Asano, TB, Sigl & Vollmann, PRD '13

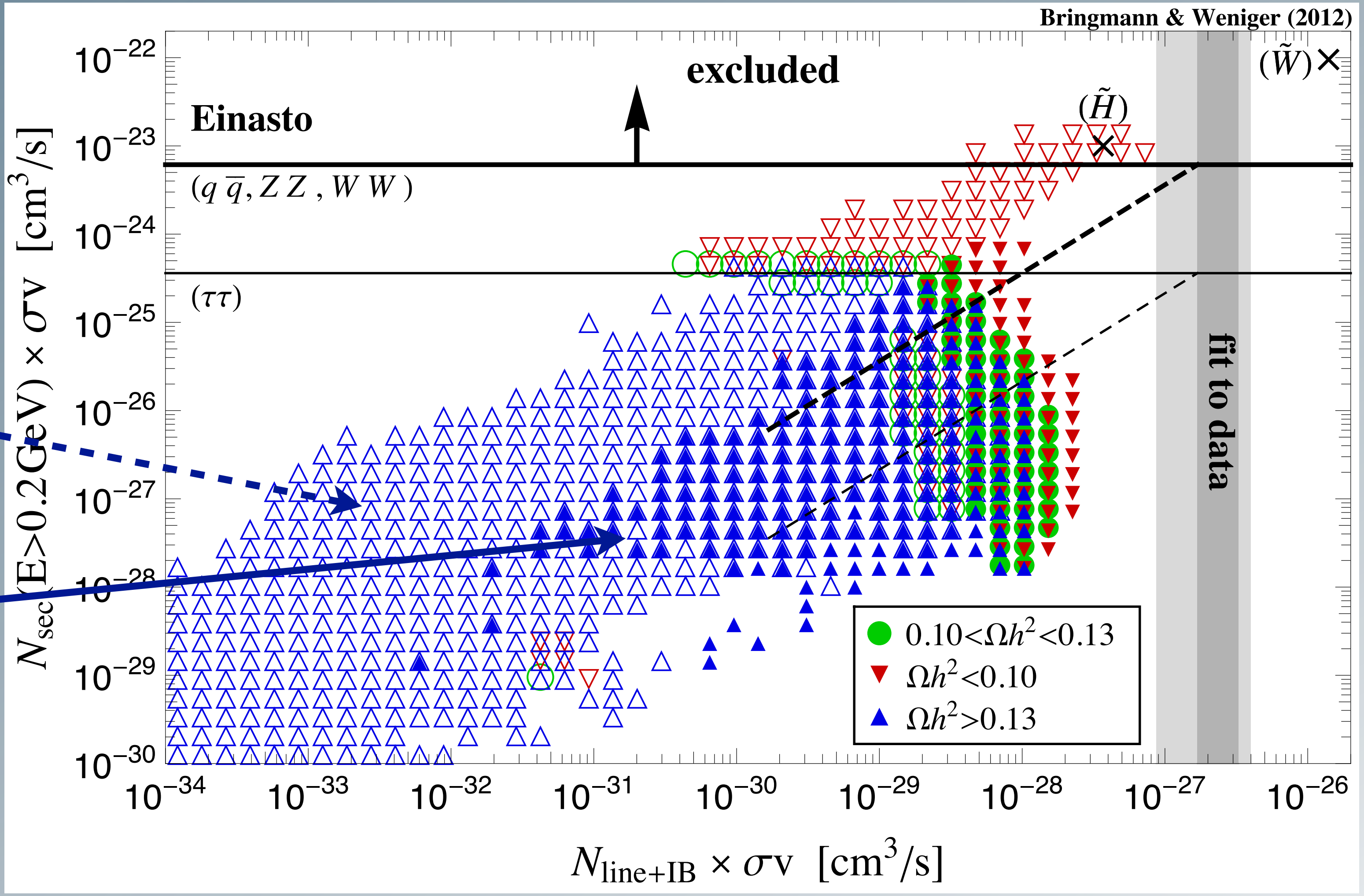
- Constraints from cont. γ-rays, antiprotons and radio!
  - E.g. neutralino DM already ruled out!?

Buchmüller & Garny, JCAP '12
Cohen *et al.*, JHEP '12
Cholis, Tavakoli & Ullio, PRD '12
Huang *et al.*, JCAP '12
Laha *et al.*, PRD '13

- Possible exceptions:
  - only new particles in loop (independent model-building motivation?)
  - cascade decays (fine-tuning to get narrow box!?)
  - Internal Bremsstrahlung

A SUSY scan

[cMSSM + MSSM-7; keep only models with correct mass and line-like spectra]



continuum gamma-ray constraints

open symbols: line-dominated

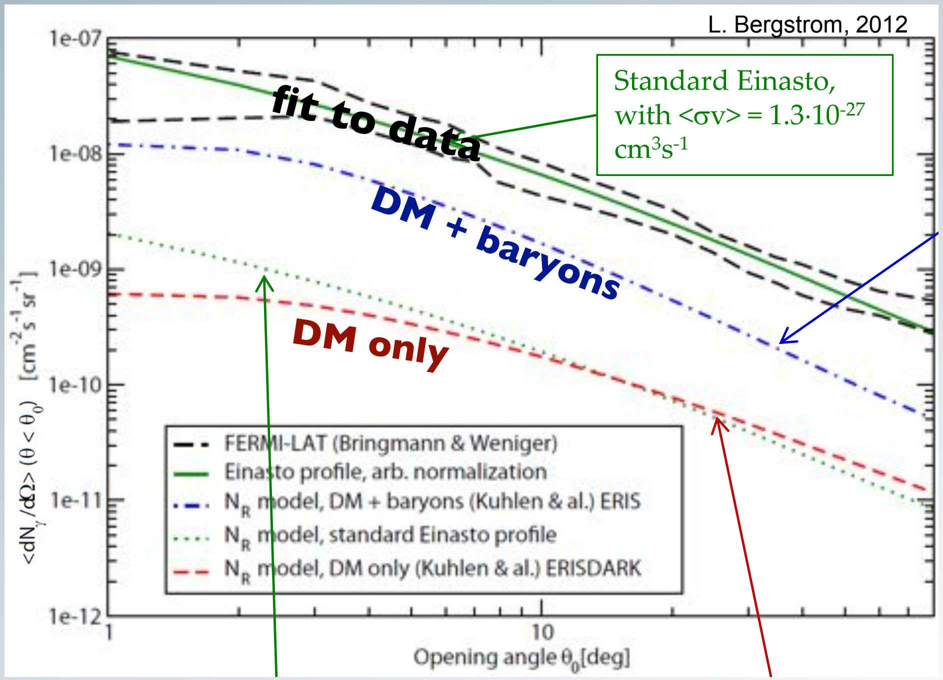
filled symbols: VIB-dominated

➡ *VIB more likely explanation than lines?*

(see also Bergström, PRD '12; Shakya 1209.2427, Tomar+ 1306.3646, Toma 1307.6181, Giacchino+ 1307.6480...)

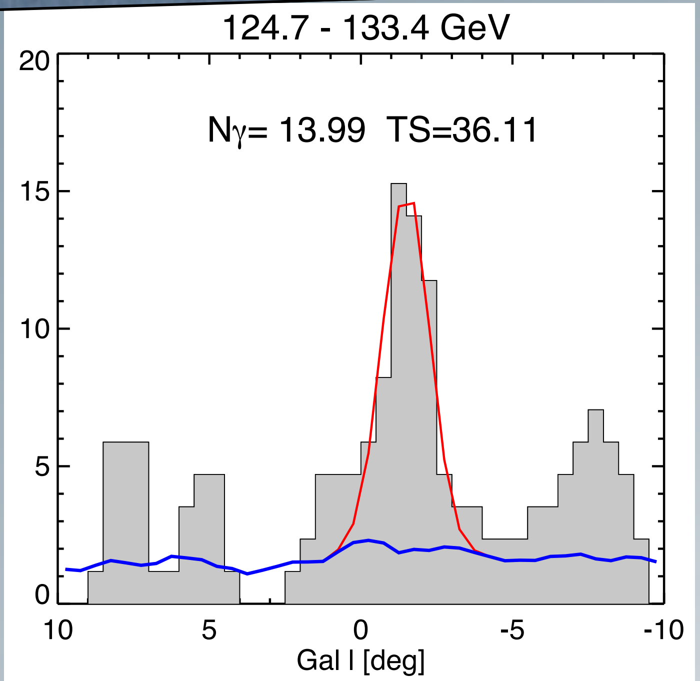
A note on absolute rates

- For standard (SUSY) couplings, still a missing factor of $\lesssim 10$ to obtain necessary rate
- Not possible to enhance signal by point-like cuspy profiles, nor large substructure boosts
[both result in wrong signal profile; latter is also highly unlikely in light of simulations]
- Still maybe possible through
  - larger *local DM density* than
  $$\rho_{\odot}^{\chi} = 0.4\,\mathrm{GeV/cm^3}$$
  (e.g. factor 2-3 claimed when including oblate halo and 'dark disk': Garbari *et al*, MNRAS '12)
  - Enhanced DM profile due to effect of baryons as in new ERIS simulation
  Kuhlen *et al.*, ApJ '13



Main caveats?

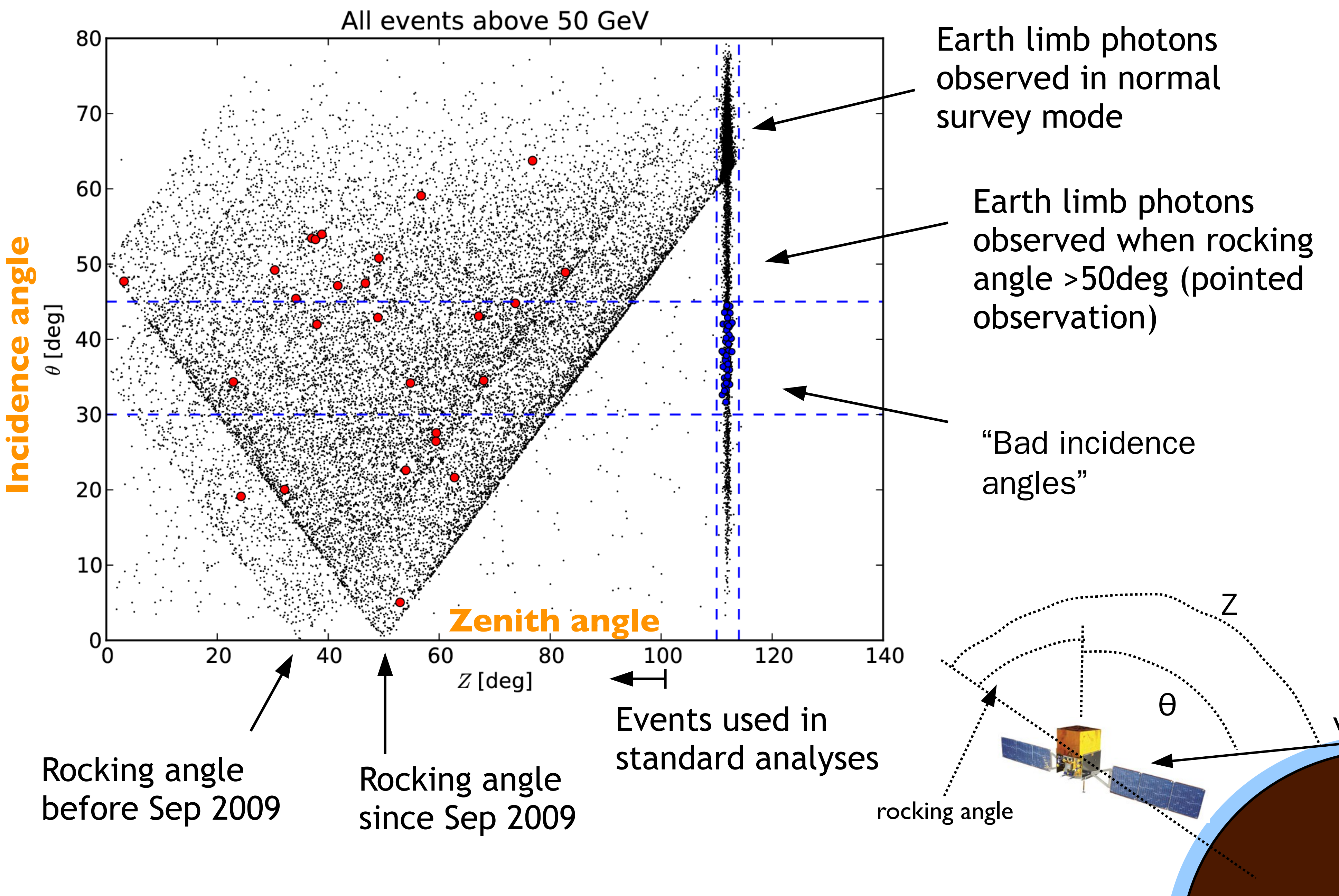
- Signal appears offset from the (dynamical) galactic center!
  - possibility surprisingly little discussed in literature (but ~1.5° ~ 200 pc is a lot)!
  - Baryons affected by star formation & supernovae, shock during galaxy mergers
  - OK for 'realistic' numerical simulations of late-type spiral galaxy formation ?!?



Su & Finkbeiner, 1206.1616

- A contamination from the earth albedo?
  - (weak?) indication by Su & Finkbeiner, confirmed by Fermi collaboration
  - would be a serious challenge to the DM interpretation
  - atm completely unknown what could cause such a line...
- Analysis relies on public Fermi tools...
  - ⇨ need independent confirmation by collaboration!

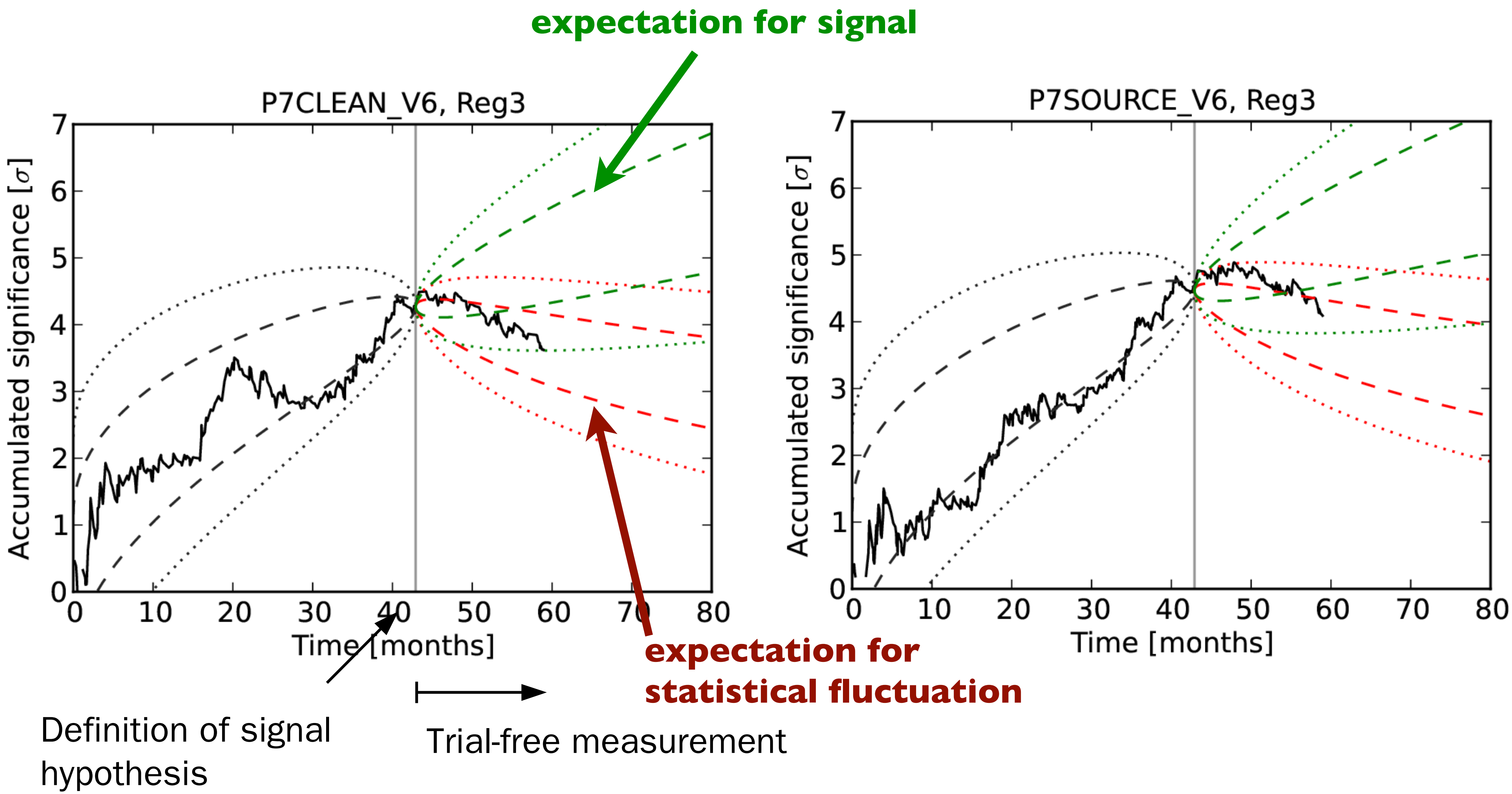
The incidence angle vs zenith angle plane



- **Red** events: Galactic center line
- **Blue** events: a suspicious line in the Earth limb...

slide from Christoph Weniger

Our analysis (P7V6), until July 2013



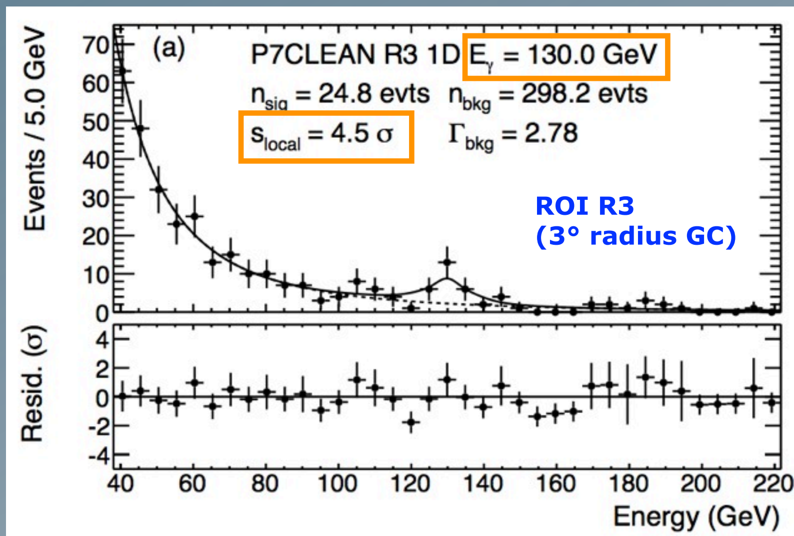
Bands: Analytical projection for ±1σ and ±2σ bands, assuming Gaussian noise with S/B~0.35 (details in CW 2013, 1303.1798); projections do not take into account expected improvements with PASS8

65-260 GeV energy range;
129.8 GeV line energy;
1D PDF

slide from Christoph Weniger

Updated Fermi line search

Fermi LAT coll., 1305.5597



➡ Line signal confirmed!

(for same 3.7 years of data)

local significance: 4.5σ

- But...
  - use 3.7 yr re-processed data
    (re-calibration of calorimeter)
  - use 2D fit
    (add additional parameter P_E for energy dispersion)
  - 3.7 yr ⟶ 4.4 yr of data

4.5σ ↓ 4.1σ ↓ 3.3σ ↓ 2.9σ

<u>NB</u>: *relative* importance of effects depends on the ROI, but net result is always ~the same...

➡ *there <u>is</u> 'something', but things look much worse than 1yr ago...*

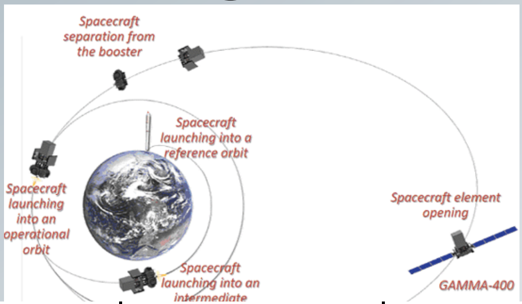
and <u>nothing</u> in the inverse ROI...!

Future confirmation?

- ‘Tentative evidence’ based on <100 photons
  - ⇨ need a few years more data to either confirm or firmly rule out signal…
  - …but maybe much faster if Fermi collaboration publishes PASS8 event selection before and/or changes observation strategy!
- HESS II is looking at GC as one of the first targets
- final word possibly by GAMMA-400 Galper *et al.*, 1210.1457
  - launch around 2018
  - greatly improved angular and energy resolution (at the expense of sensitivity)
  - $\sim 5\sigma$ signal significance after 10 months ! Bergström *et al.*, JCAP ’12

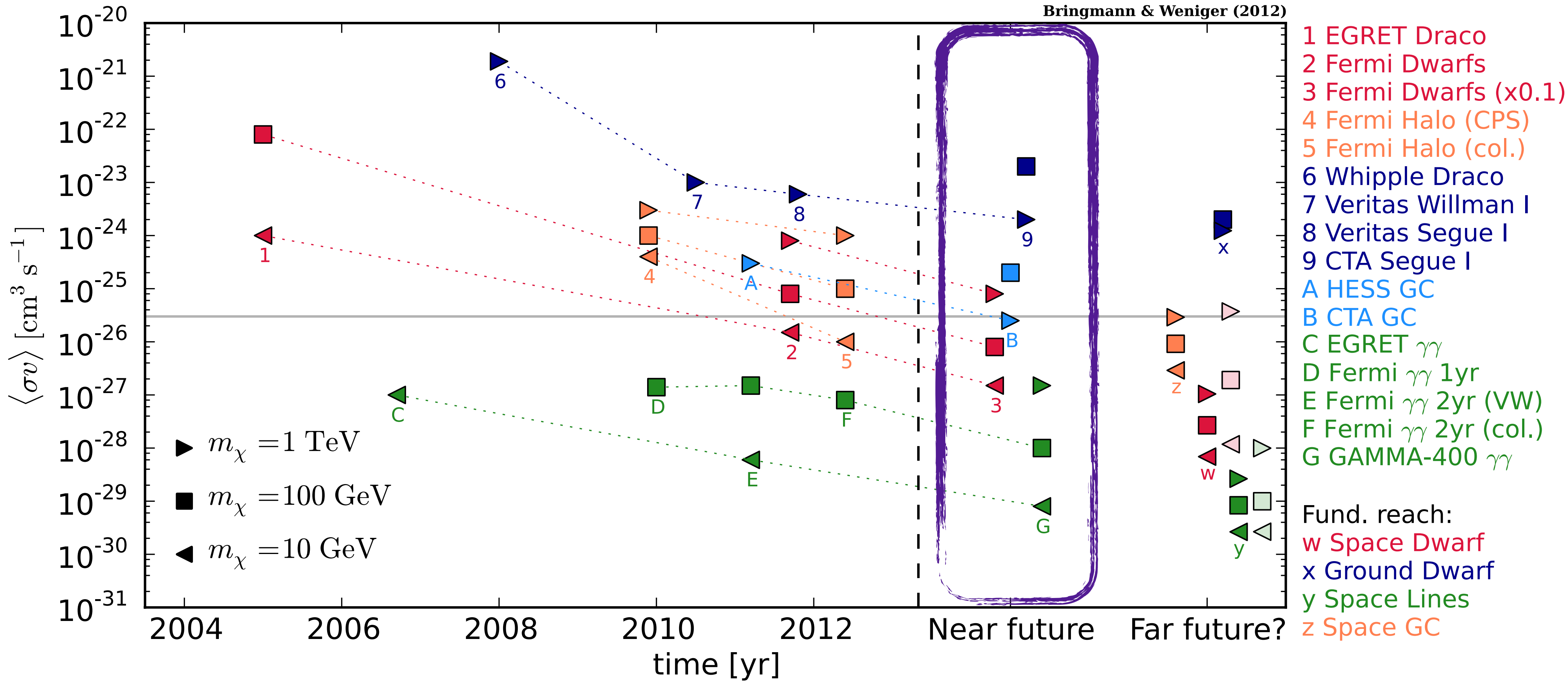
⇨ may also provide further information about the spectrum!

[NB: Similar performance expected by chinese DAMPE & HERD!]



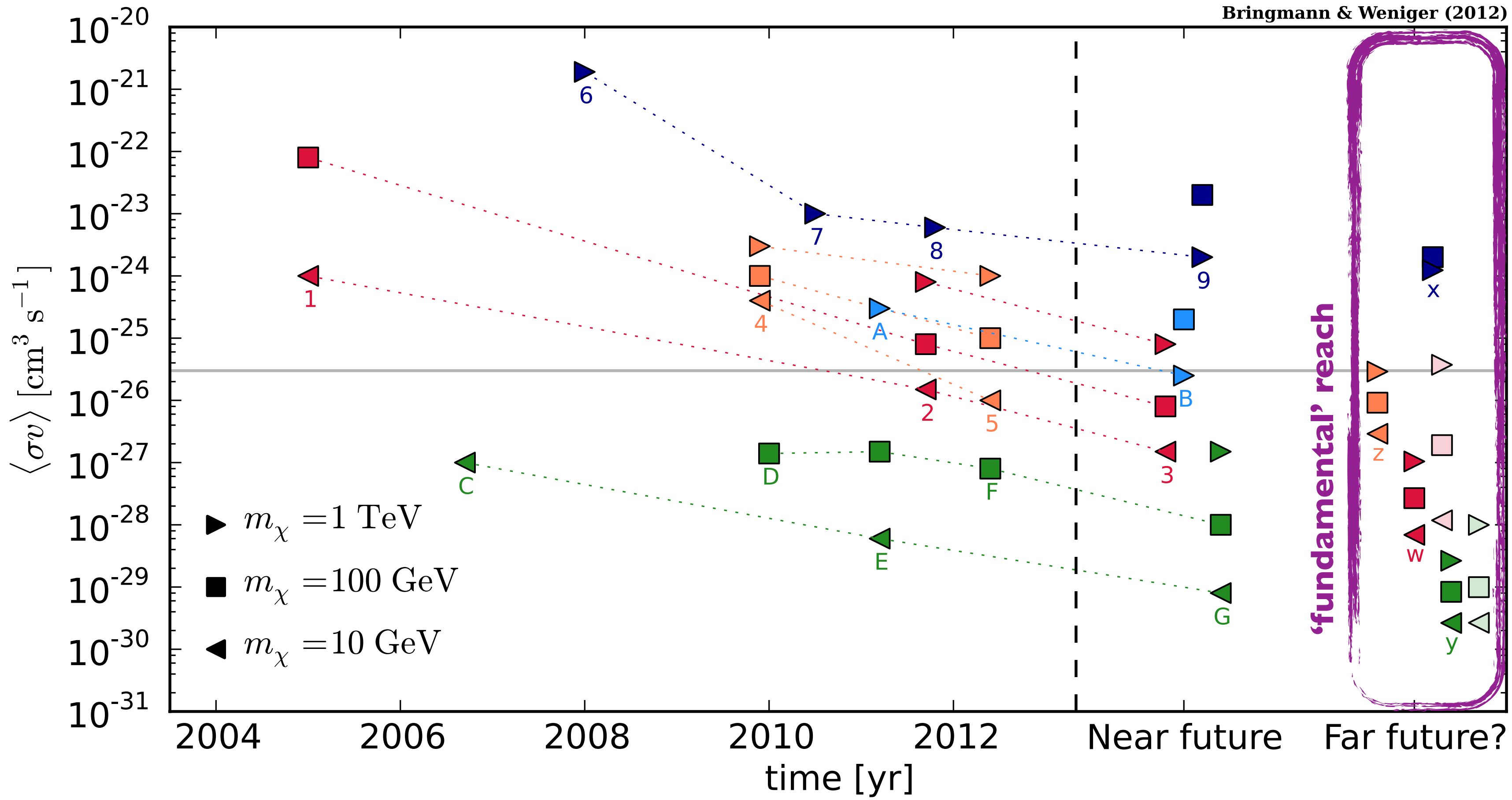
	Fermi	GAMMA-400	H.E.S.S.
Energy range, GeV	0.1-300	**0.1-3000**	>100
Angular resolution, deg (E_γ > 100 GeV)	0.1	**~0.01**	0.1
Energy resolution, % (E_γ > 100 GeV)	10	**~1**	15

(Far) future of DM searches



- Roughly one order of magnitude improvement during last decade, expect ~same for next decade

(Far) future of DM searches



:= systematics under control at 1% level
[light: 100x10yr Fermi]

- further significant improvement possible with current technology
  - in particular space-based instruments (but need very large exposures)
  - earth-based soon systematics-limited ⇝ need to e.g. reject e⁻-background!

Commercial break...

want to read up on gamma rays from DM?

*Check out a dedicated recent **review**!*

[arXiv:1208.5481]

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ELSEVIER

Gamma ray signals from dark matter: Concepts, status and prospects

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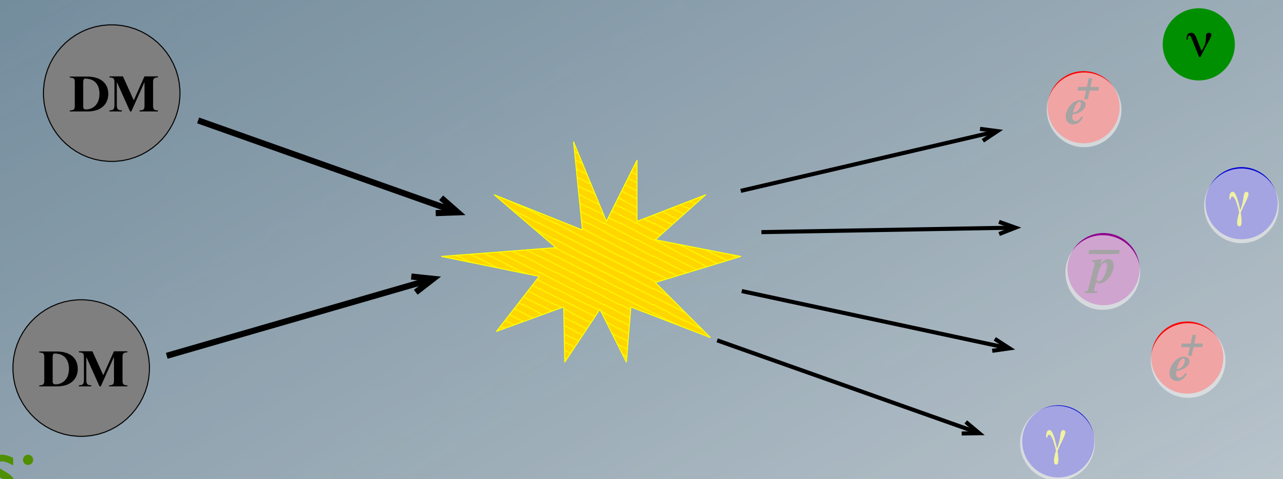
ARTICLE INFO

ABSTRACT

Weakly interacting massive particles (WIMPs) remain a prime candidate for the cosmological dark matter (DM), even in the absence of current collider signals that would unambiguously point to new physics below the TeV scale. The self-annihilation of these particles in astronomical targets may leave observable imprints in cosmic rays of various kinds. In this review, we focus on gamma rays which we argue to play a pronounced role among the various possible messengers. We discuss the most promising spectral and spatial signatures to look for, give an update on the current state of gamma-ray searches for DM and an outlook concerning future prospects. We also assess in some detail the implications of a potential signal identification for particle DM models as well as for our understanding of structure formation. Special emphasis is put on the possible evidence for a 130 GeV line-like signal that we recently identified in the data of the Fermi gamma-ray space telescope.

- Prelude – WIMP dark matter
  - Thermal production and freeze-out
  - General principle of (in)direct detection
  - Dark matter distribution
- Gamma rays
  - *targets*: galactic center + halo, dwarf galaxies, galaxy clusters, ...
  - *signals*: continuum vs. "smoking gun" spectral features
- **Neutrinos**
  - **from galactic halo + sun/earth**
- Charged cosmic rays
  - propagation of cosmic rays
  - positrons, antiprotons, [antideuterons]
  - multi-wavelength signals
- [Complementarity with direct and collider searches]

Indirect DM searches



Neutrinos:

- Unperturbed propagation like for photons
- But signal significance (for the same target) usually considerably worse
- New feature: signals from the center of sun or earth!

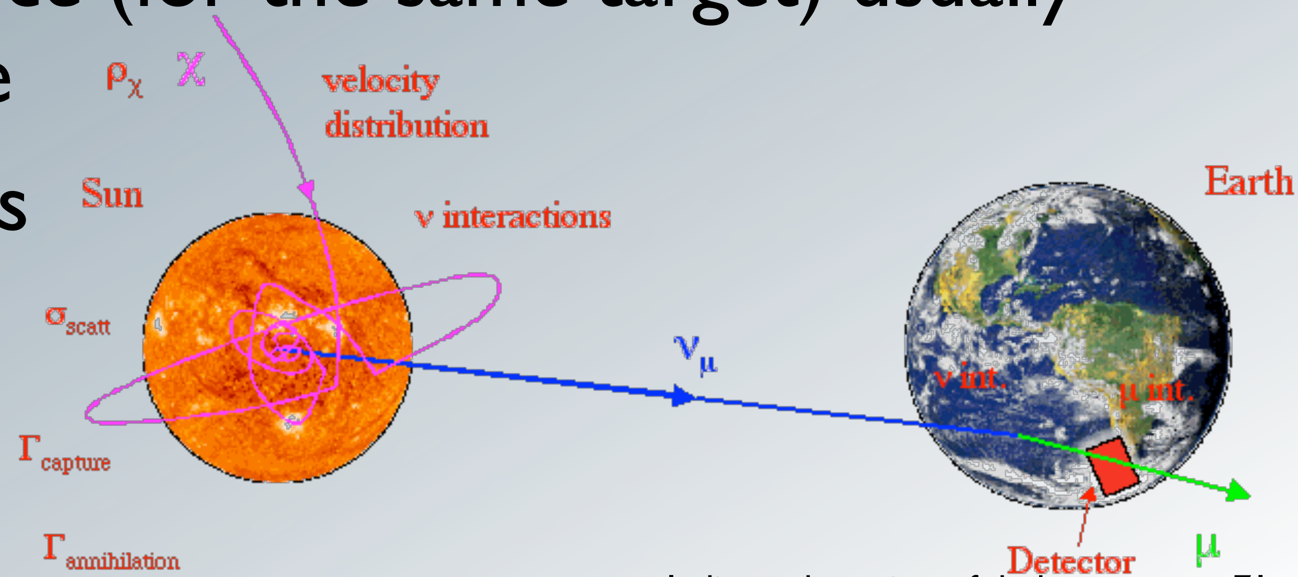
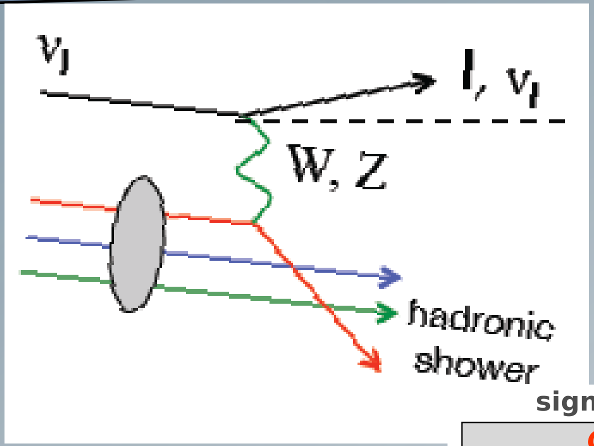


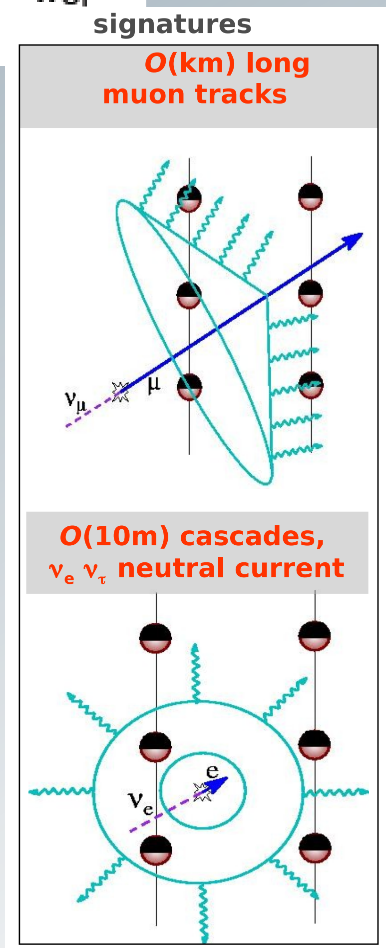
Fig. from J.Edsjö

Detection principle

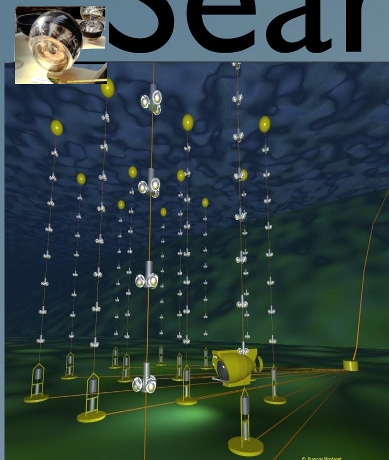


- Array of optical modules in transparent medium (ice/water) to detect Cherenkov light from relativistic secondaries
  (mostly sensitive to muons because they have the longest tracks)
- opening angle: $\Theta_{\mu\nu} \approx 0.7° \cdot (E_\nu / \mathrm{TeV})^{-0.7}$
  ⇨ possible to do neutrino astronomy!
- tiny *x*-sections & fluxes: *need HUGE volumes*!
- background muons:
  - down-going: atmospheric neutrinos
  - up-going: also induced by cosmic rays (hitting the atmosphere the far side of the earth)

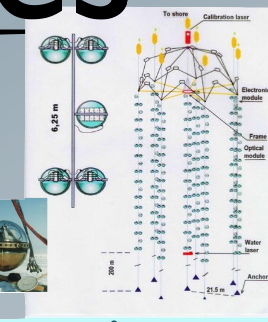
⇝ look for excesses in any given direction

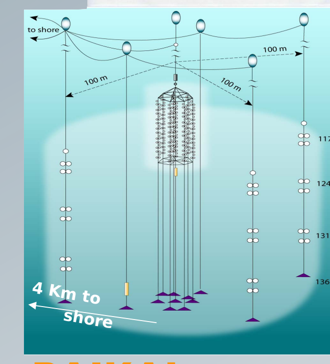


Searches with ν telescopes

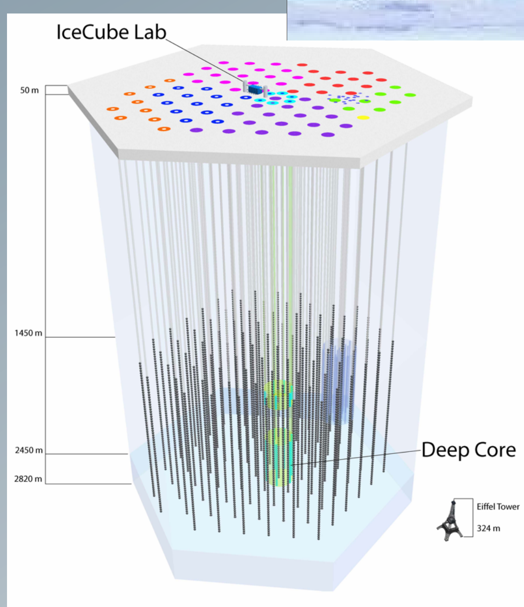


ANTARES





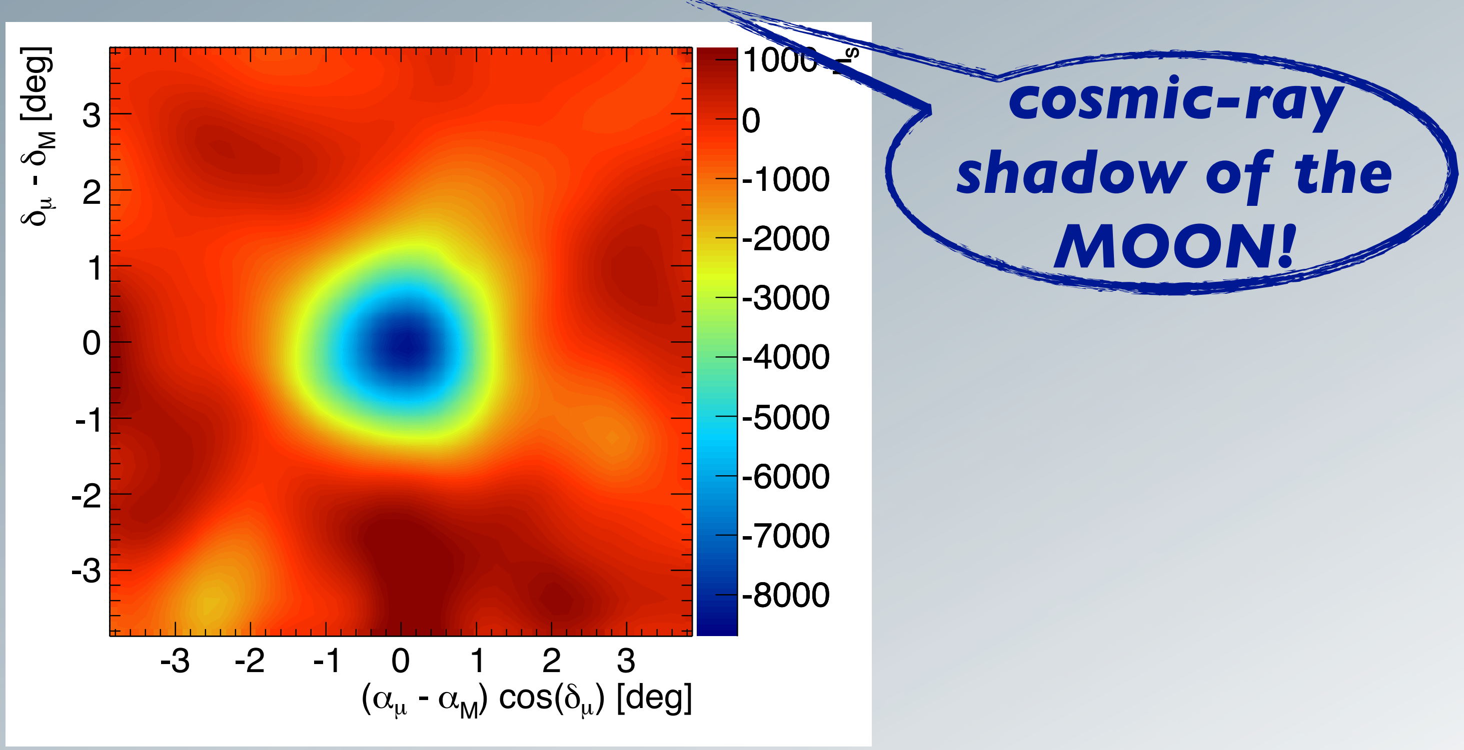
BAIKAL



- IceCube
  - 80+6 strings and 5160 optical modules probe a volume of ~1 km3
  - ~100 GeV energy threshold (lower: Deep Core)
  - ~1° angular resolution

Side note

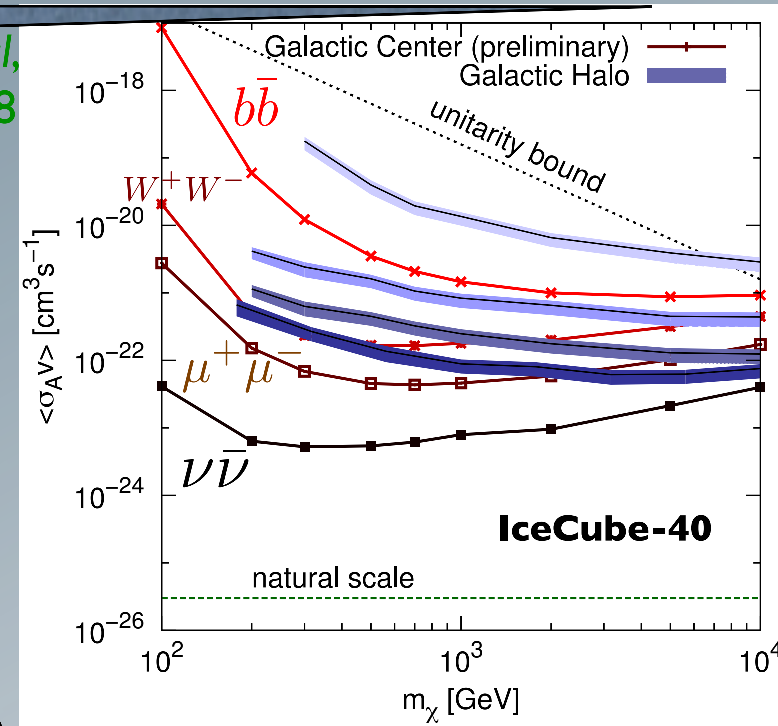
- At such high energies, the sun is not visible in neutrinos...
- … but IceCube can see the ~~MOON!~~



Aartsen *et al.*, 1305.6811

Galactic center neutrinos

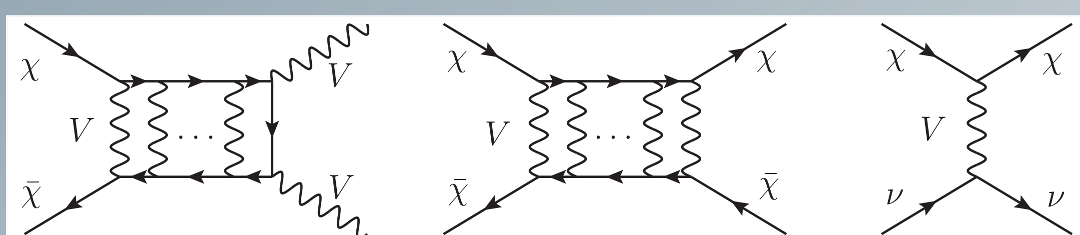
Bissok *et al*, 1111.2738



- Neutrinos from GC usually not competitive with photons
  - expect factor ~10 better for IceCube-79

→ Only interesting for very large annihilation rates into neutrinos!

- Such a model was recently proposed as possible solution to *all* ΛCDM small-scale problems!

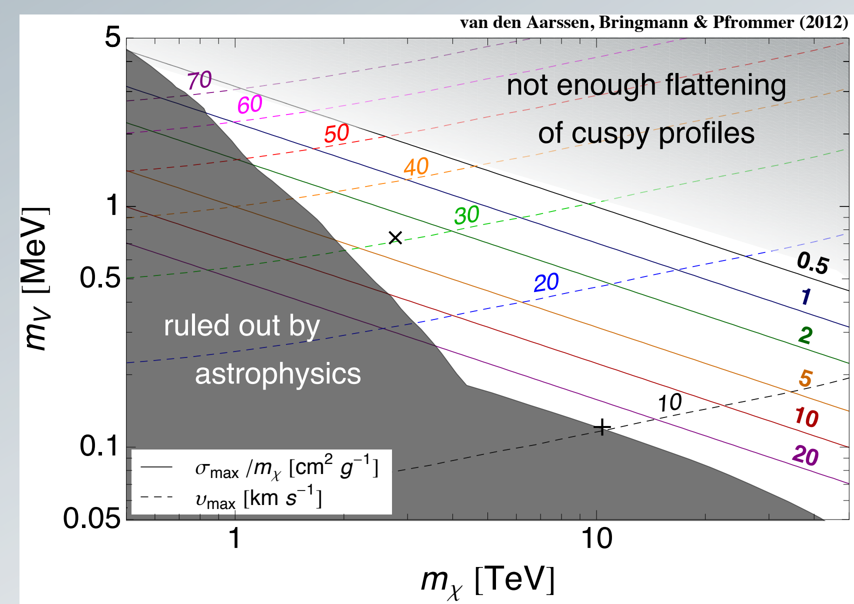


$(\sigma v)_{\nu\bar{\nu}} \sim 10^{-24}\mathrm{cm}^3/\mathrm{s}$

larg(ish) velocity-dependent self-interaction

$M_{\rm cut} \lesssim 10^{10} M_\odot$

van den Aarssen+, PRL '12



Gravitational diffusion

Figs. from J. Edsjö

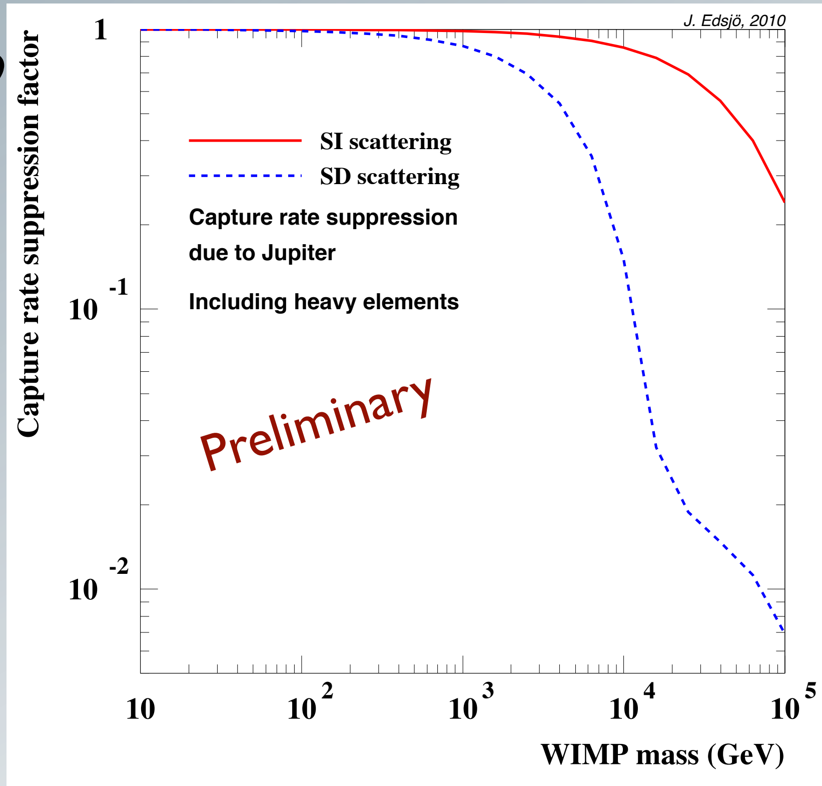
- Is a particle with $v' < v_{\rm esc}$ captured?
  - Jupiter may give it a 'kick' to throw it out of the solar system
  - [in principle also reverse possible, but smaller(?) effect]

↓

no!

Sivertsson & Edsjö, PRD '12

Lundberg & Edsjö, PRD '04
Peter & Tremaine, 0806.2133
Peter, PRD '09



Neutrino signals

$$\dot{N} = C - \underbrace{C_A N^2}_{2\Gamma_A} - C_E N$$

capture rate

[evaporation rate]

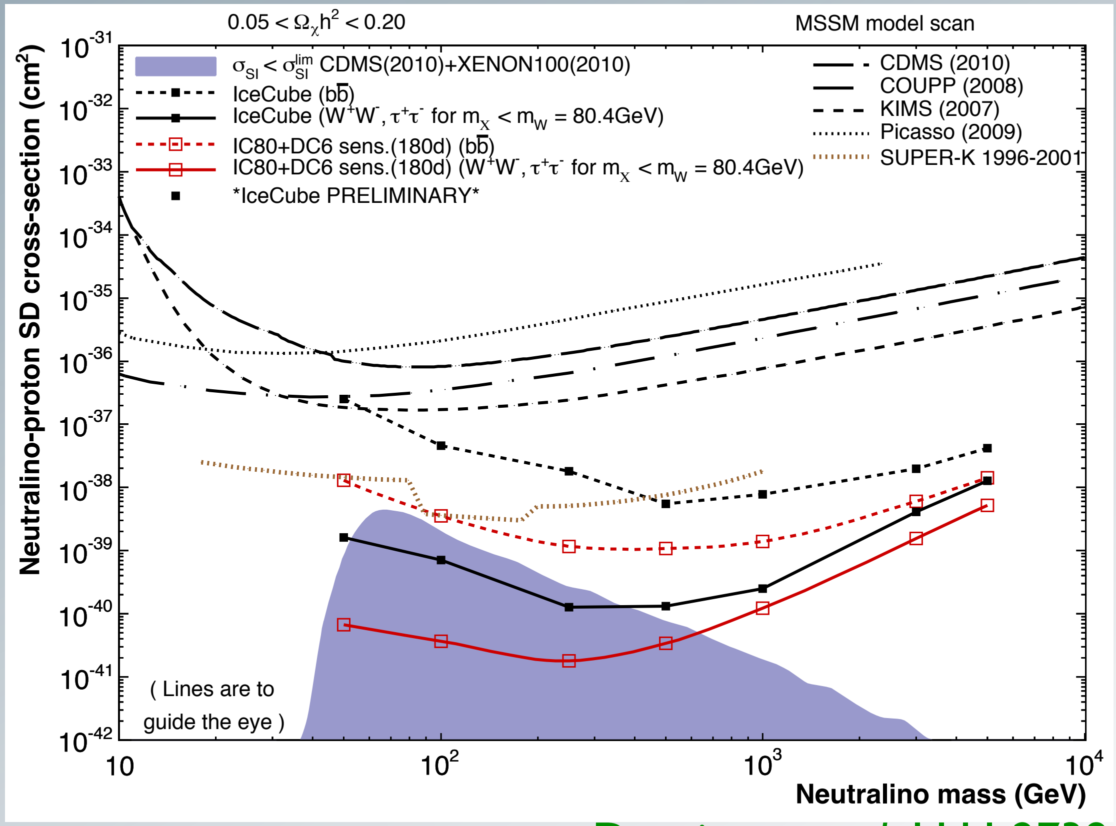
Annihilation rate:

$$\Gamma_A = \frac{1}{2} C \tanh^2 \frac{t}{\sqrt{C_A C}}$$

$C/2$ in equilibrium
(=maximal signal)

- Neutrino signal from center of earth not competitive with direct detection
  (equilibrium typically not yet reached)

- Neutrino signal from sun leads to very competitive limits on spin-dependent scattering rates



Danninger *et al*, 1111.2738

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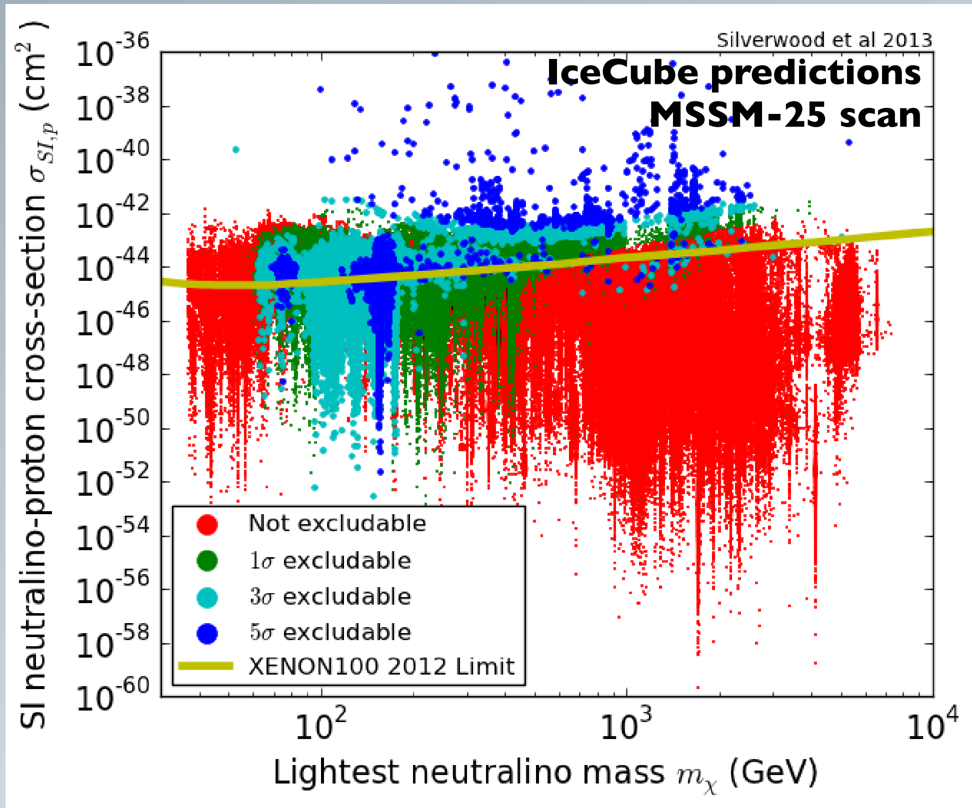

Silverwood *et al*, JCAP '13

More about neutrinos from DM:

See lecture by D. Boersma…!

- Prelude – WIMP dark matter
  - Thermal production and freeze-out
  - General principle of (in)direct detection
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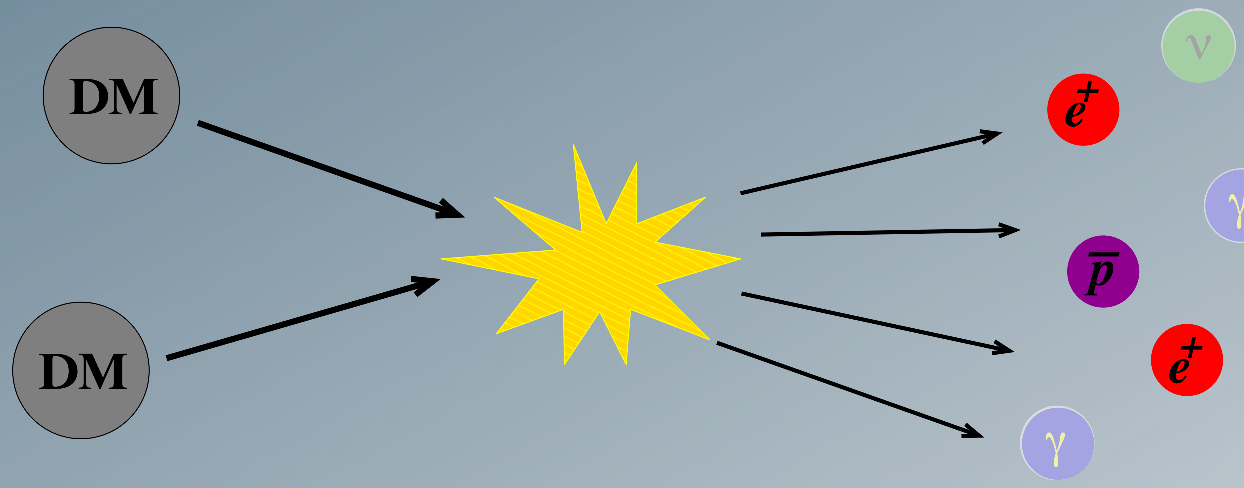
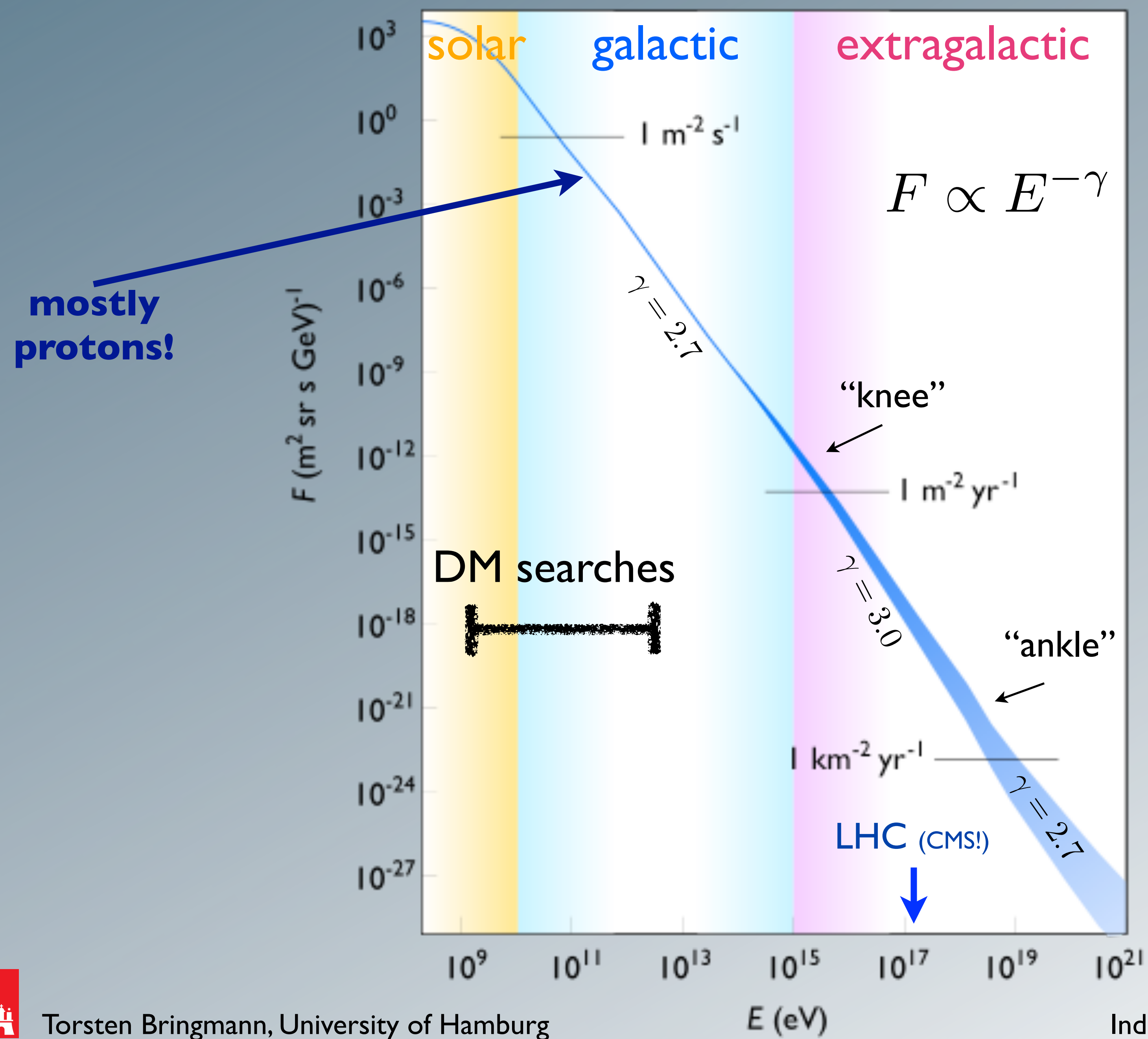
  - *targets*: galactic center + halo, dwarf galaxies, galaxy clusters, ...
  - *signals*: continuum vs. "smoking gun" spectral features
- Neutrinos
  - from galactic halo + sun/earth
- **Charged cosmic rays**
  - **propagation of cosmic rays**
  - **positrons, antiprotons, [antideuterons]**
  - **multi-wavelength signals**
- [Complementarity with direct and collider searches]

Charged cosmic rays



- GCRs are confined by galactic magnetic fields
- After propagation, no directional information is left
- Also the spectral information tends to get washed out
- Equal amounts of matter and antimatter
  ⇨ focus on antimatter (low backgrounds!)

Spectrum and origin of CRs



Cosmic ray propagation

- Little known about Galactic magnetic field distribution
- Magnetic fields confine CRs in galaxy for $E \lesssim 10^3\,\mathrm{TeV}$
- Random distribution of field inhomogeneities
  $\rightsquigarrow$ propagation well described by diffusion equation

$$\frac{\partial\psi}{\partial t} - \nabla\cdot(D\nabla - v_c)\psi + \frac{\partial}{\partial p} b_{\mathrm{loss}}\psi - \frac{\partial}{\partial p} K \frac{\partial}{\partial p}\psi = q_{\mathrm{source}}$$

often set to 0 (stationary config.)

Diffusion coefficient, often $D \propto \beta(E/q)^\delta$

convection

energy losses

diffusive reacceleration $K \propto v_a^2 p^2/D$

Sources (primary & secondary)

Analytical vs. numerical

How to solve the diffusion equation?

- **Numerically**
  - ⊕ 3D possible
  - ⊕ any magnetic field model
  - ⊕ realistic gas distribution, full energy losses
  - ⊖ computations time-consuming
  - ⊖ for most users a "black box"

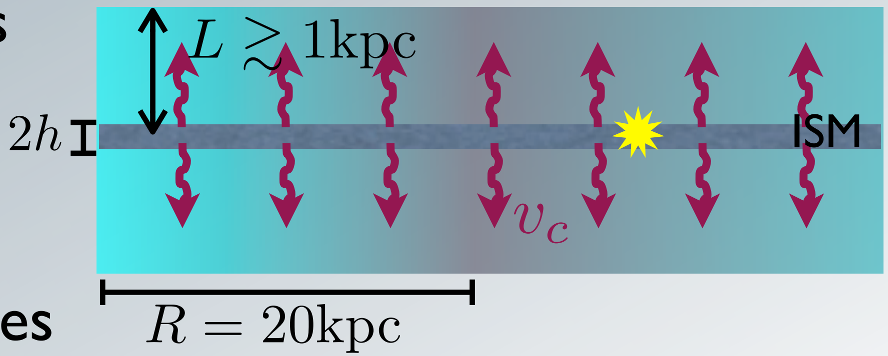
e.g.

Strong, Moskalenko, …

DRAGON
Evoli, Gaggero, Grasso & Maccione

- **(Semi-)analytically**
  - ⊕ Physical insight from analytic solutions
  - ⊕ fast computations allow to sample full parameter space
  - ⊖ only 2D possible
  - ⊖ simplified gas distribution, energy losses

e.g. Donato, Fornengo, Maurin, Salati, Taillet, ...



GCR composition

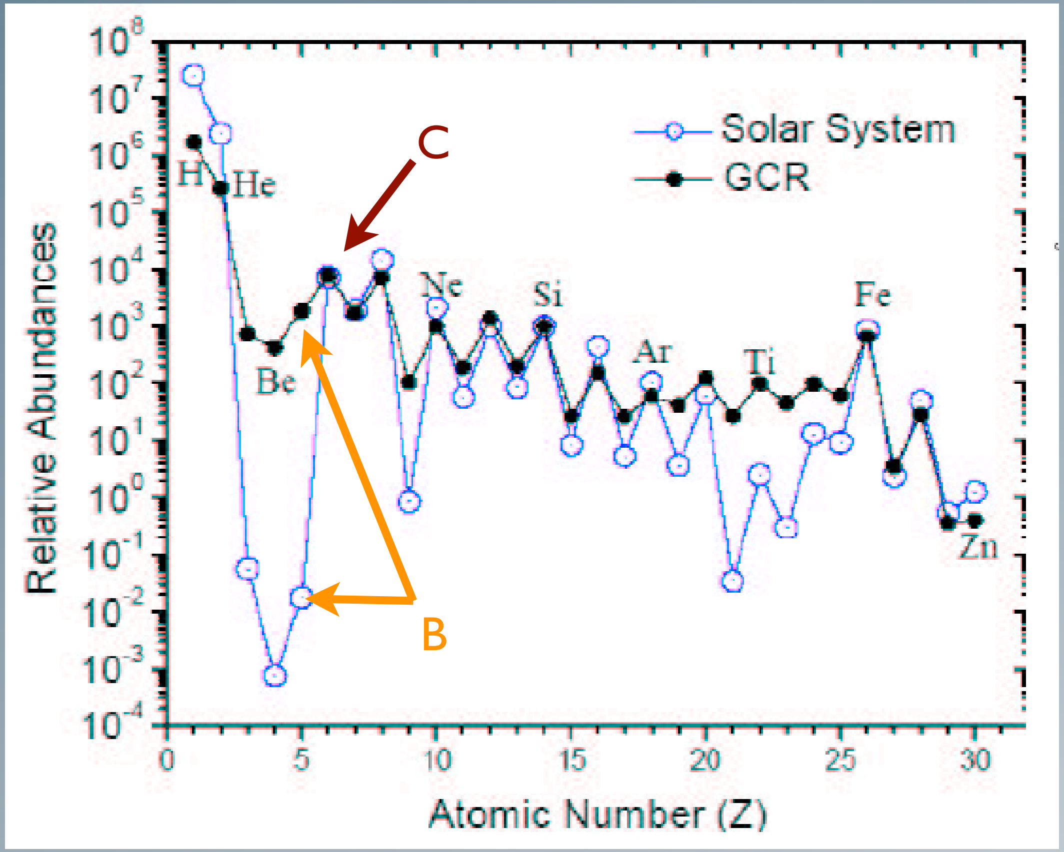
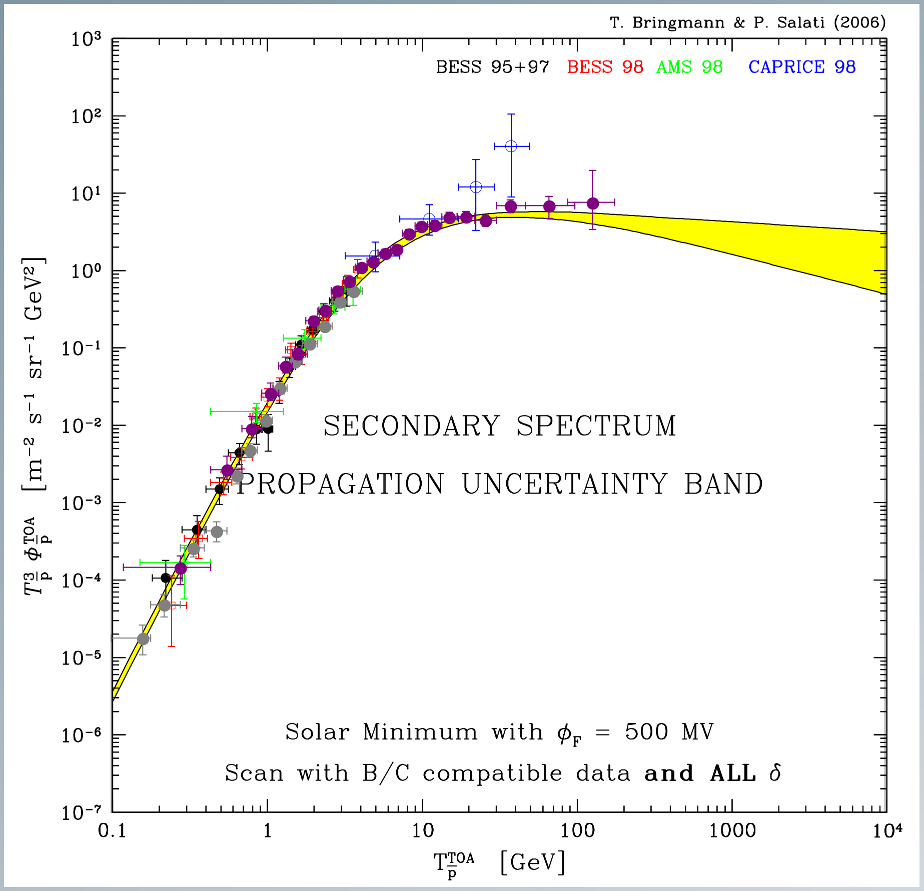


Fig. from D. Maurin

- Primary species
  - present in sources
  - element distribution following stellar nucleosynthesis
  - accelerated in supernova shockwaves
- Secondary species
  - much larger relative abundance than in stellar environments
  - produced by interaction of primary cosmic rays with interstellar medium

E.g. secondary antiprotons

- Propagation parameters $(K_0, \delta, L, v_a, v_c)$ of two-zone diffusion model strongly constrained by B/C
  Maurin, Donato, Taillet & Salati, ApJ '01
- This can be used to predict fluxes for other species:



TB & Salati, PRD '07

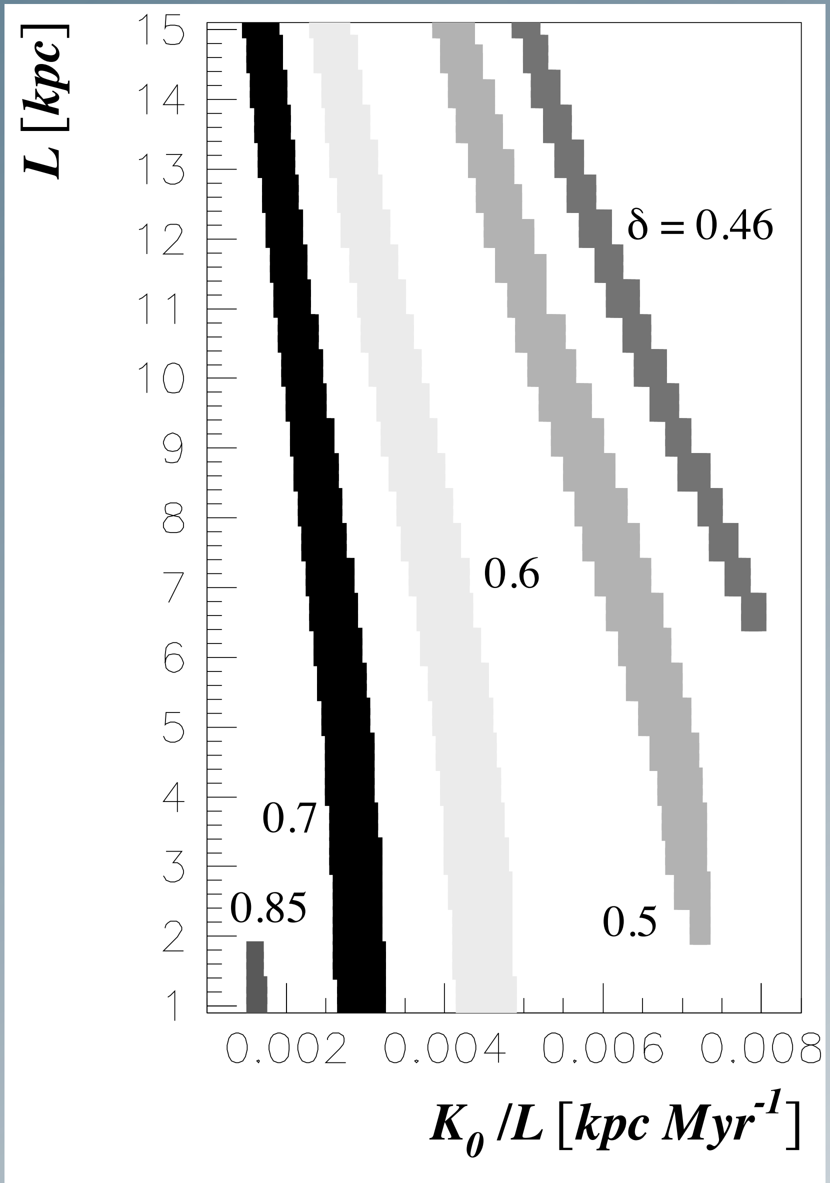
excellent agreement with new data:

BESSpolar 2004
Abe *et al.*, PRL '08

PAMELA 2008
Adriani *et al.*, PRL '10

➩ very nice test for underlying diffusion model!

Degeneracies



Maurin, Donato, Taillet & Salati, ApJ '01

- B/C analysis leaves large degeneracies in propagation parameters that
  - (almost) do not affect standard CR fluxes (~everything produced in the disk)
  - but can have a large impact on, e.g., antiprotons from DM annihilations:

Donato, Fornengo, Maurin, Salati & Taillet, PRD '04

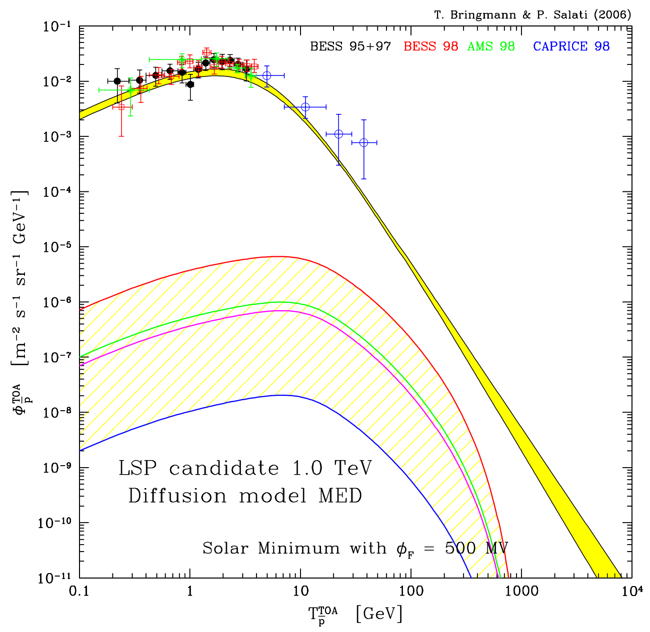
case	δ	K_0 (kpc^2/Myr)	L (kpc)	V_c (km/sec)	V_A (km/sec)
max	0.46	0.0765	15	5	117.6
med	0.70	0.0112	4	12	52.9
min	0.85	0.0016	1	13.5	22.4

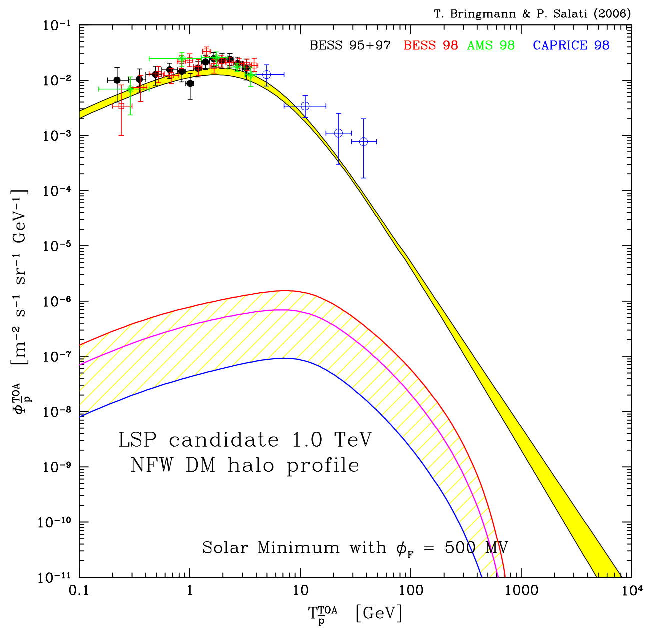
⇩

$\mathcal{O}(10^2)$ change in predicted $\bar{p}$ flux from DM!

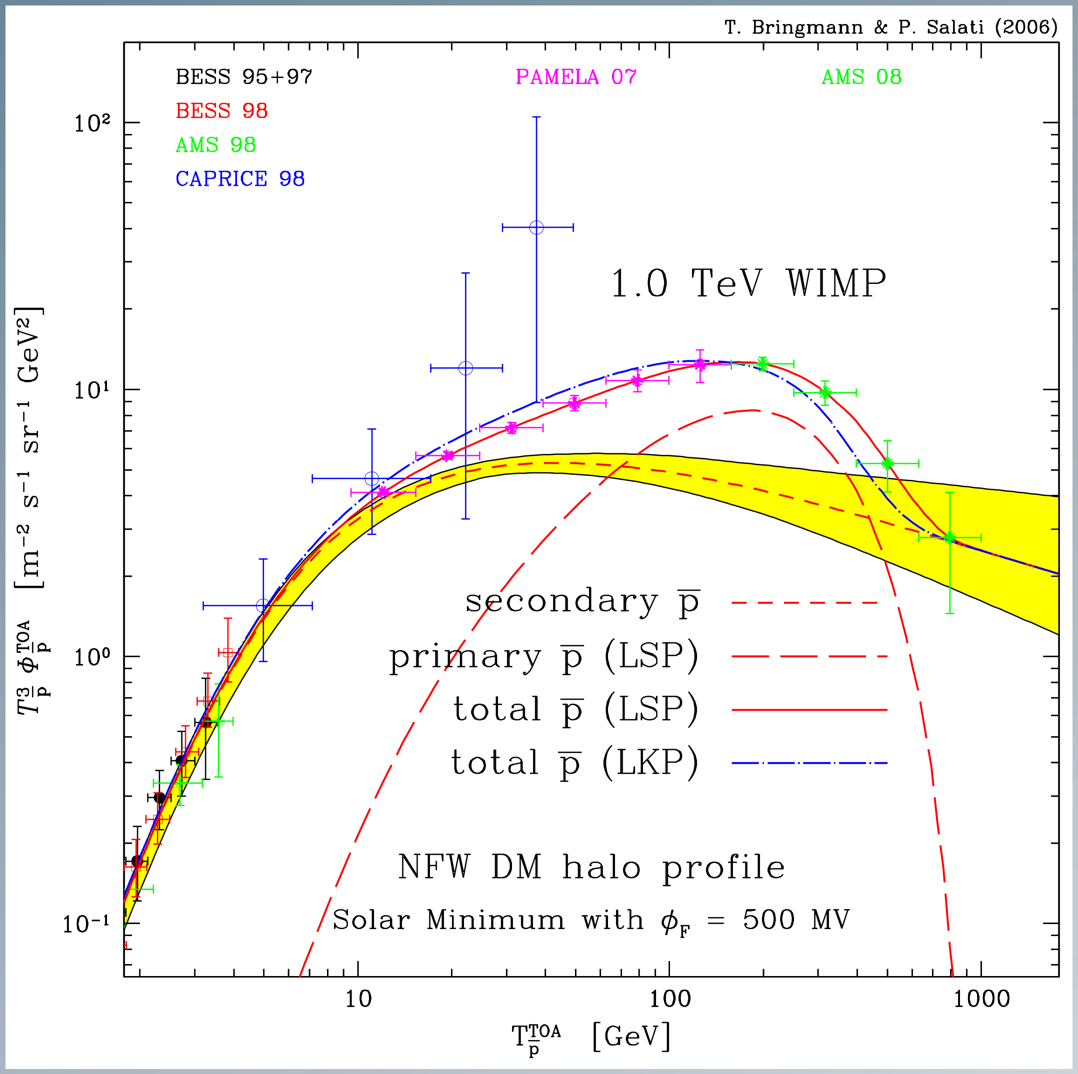
Antiprotons

- Rather straightforward to handle:
  - no significant astrophysical sources
  - for $E_{\bar{p}} \gtrsim 10\,\mathrm{GeV}$ completely diffusion dominated
- Uncertainties in $\bar{p}$ flux from DM annihilation much larger than for secondaries!
  - up to ~100 from DM profile
  - up to ~40 from range of propagation parameters compatible with B/C





Antiprotons

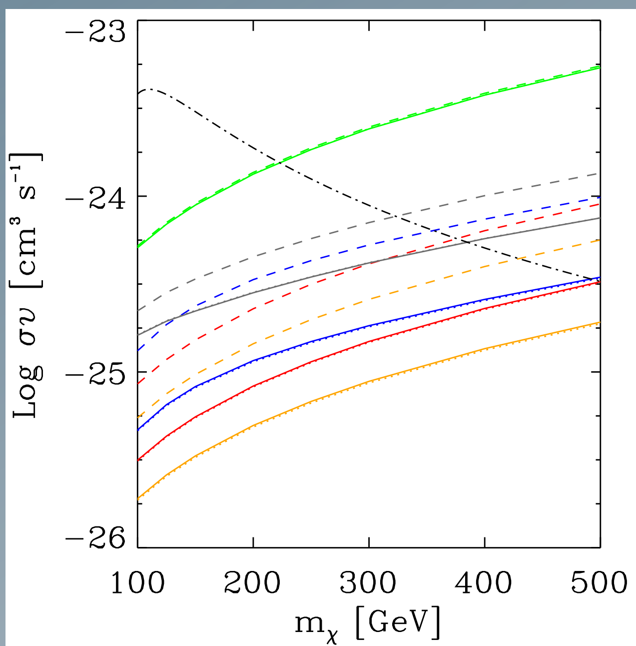


- Cannot be used to discriminate between DM candidates...
- ...but are quite efficient in settings constraints!
  - light SUSY DM
    Bottino *et al.*, PRD '98+05
  - non-standard DM profile proposed by deBoer
    Bergström *et al.*, JCAP '06
  - DM explanations for the PAMELA e^+/e^- excess
    Donato *et al.*, PRL '09
  - "Evidence" for DM seen in Fermi data towards the GC
    TB, 0911.1124
  - ...

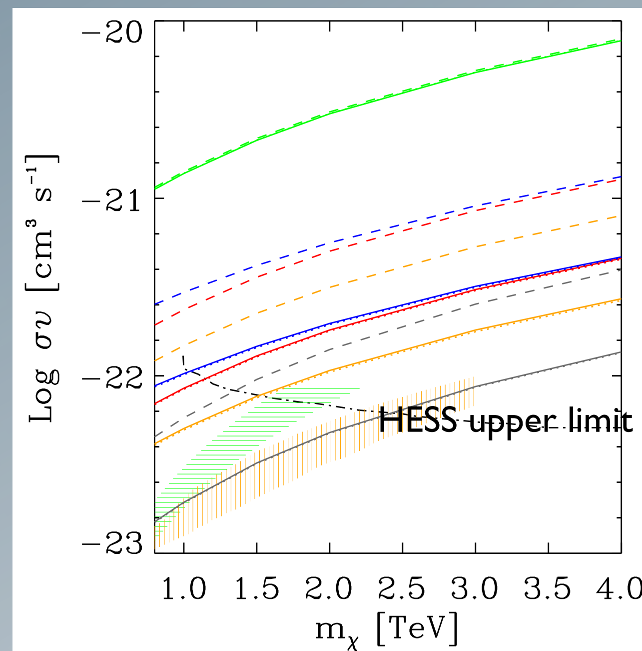
Antiproton constraints

- Updated limits on annihilation cross section:
  [reference model in red]

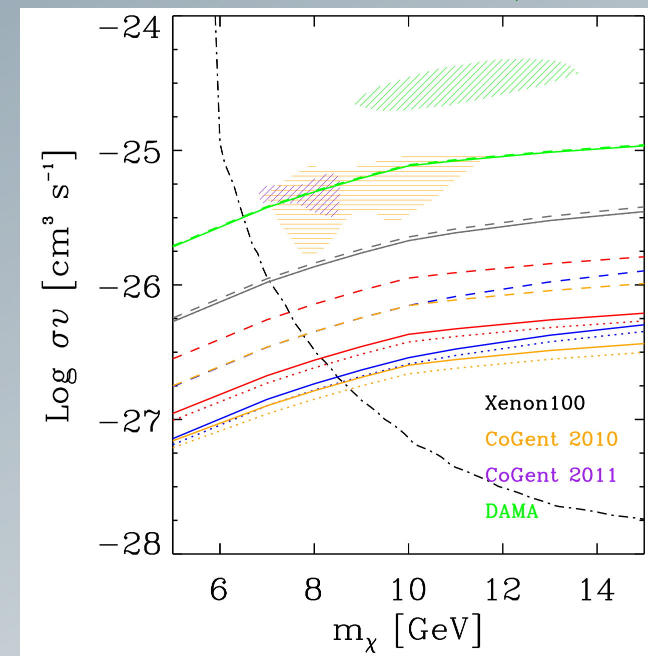
Evoli *et al.*, PRD ’12



Wino DM



$\mu^+\mu^-$



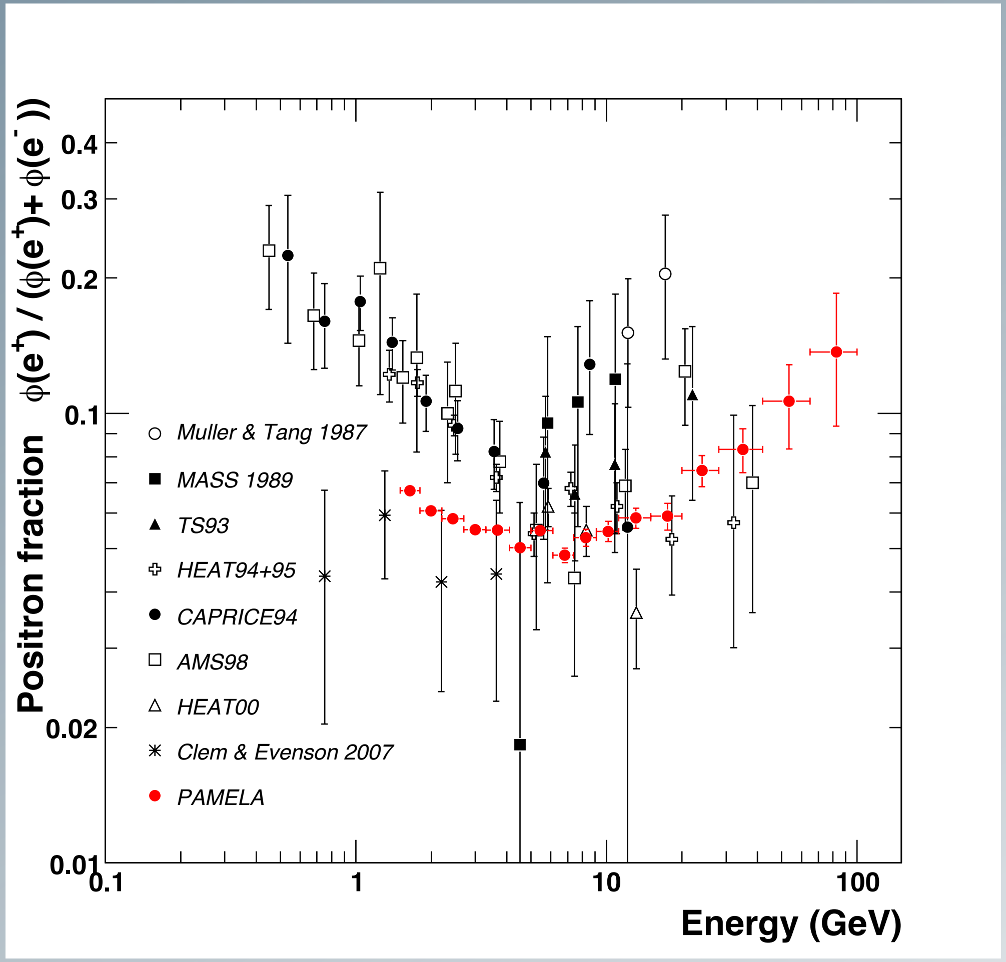
$b\bar{b}$

➡ need to constrain propagation parameters better, in particular the halo height L

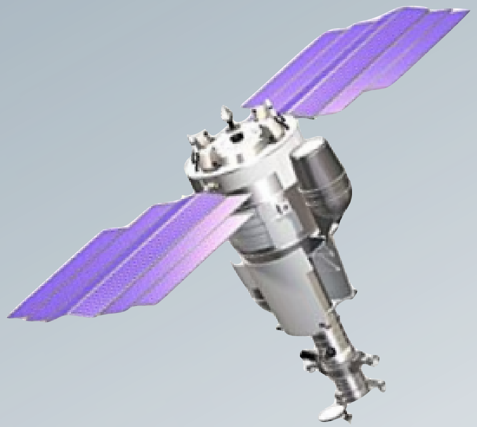
more in lecture by F. Donato…!

Positrons

Excess in cosmic ray positron data has triggered great excitement:



PAMELA

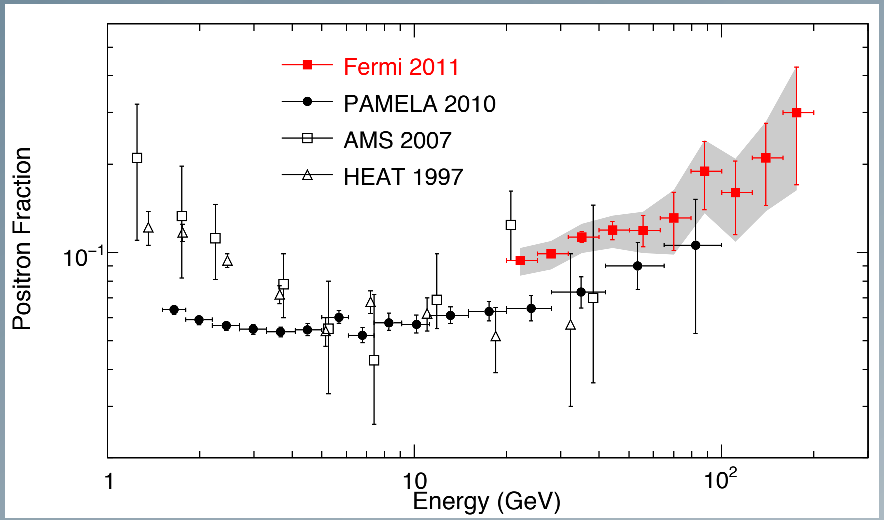


Adriani *et al.*, Nature '09

⇨ Are we seeing a DM signal ???

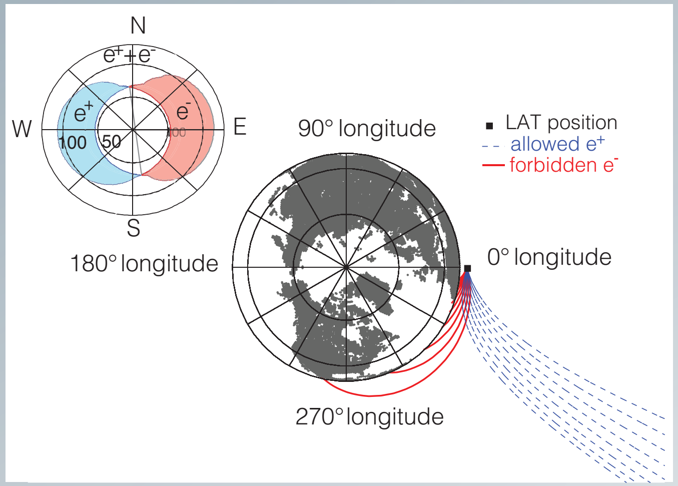
Independent confirmation

- By Fermi (!):

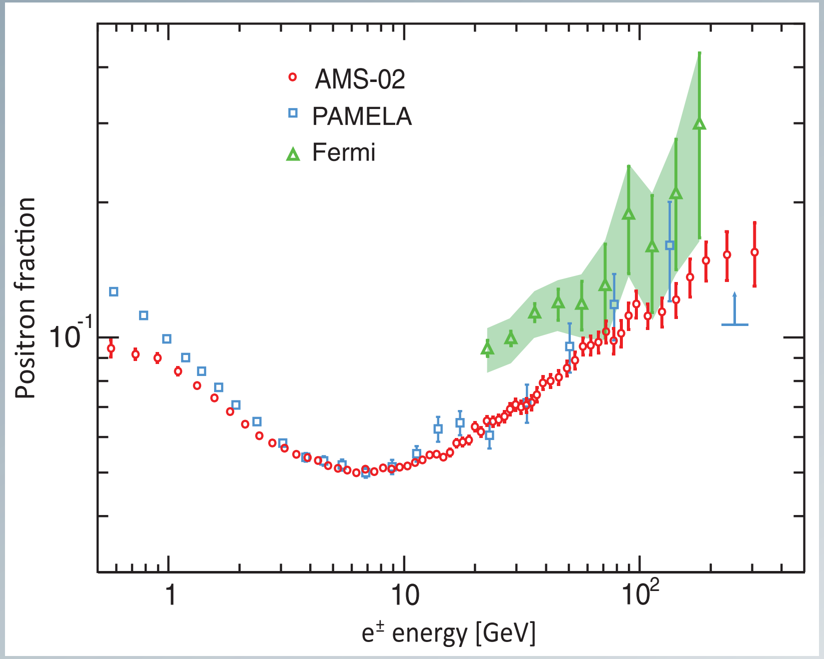


Ackermann *et al.*, PRL '12

NB: Fermi does not have a magnet on board, but uses the earth magnetic field!



- By AMS:

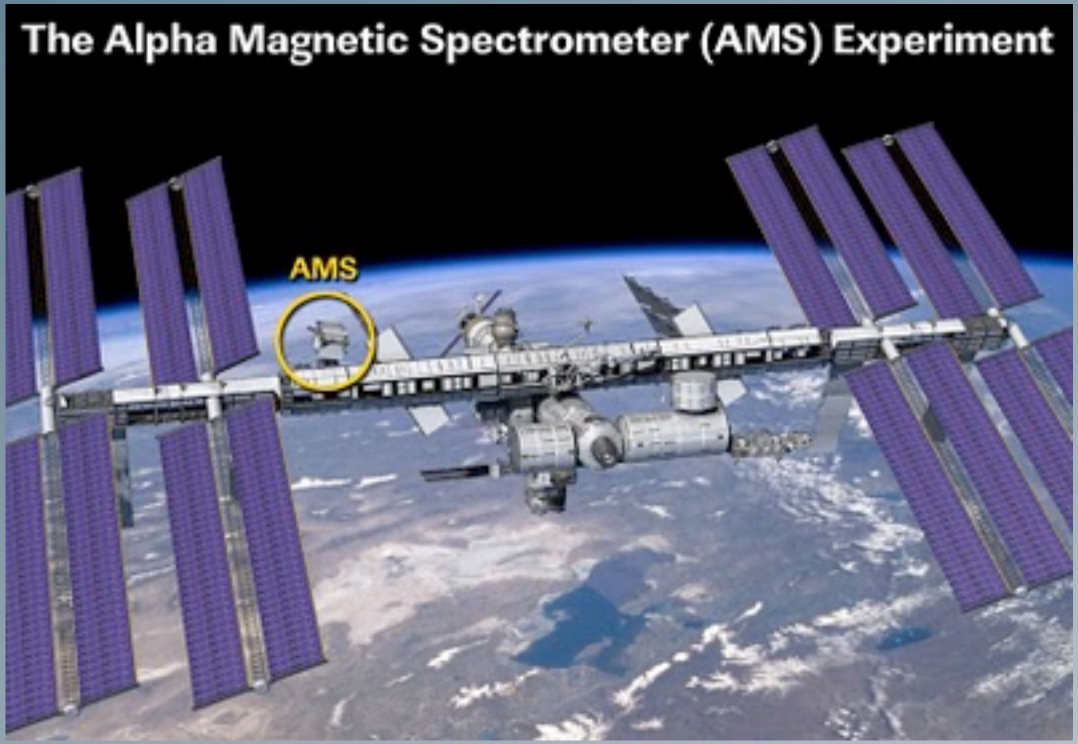


Aguilar *et al.*, PRL '13

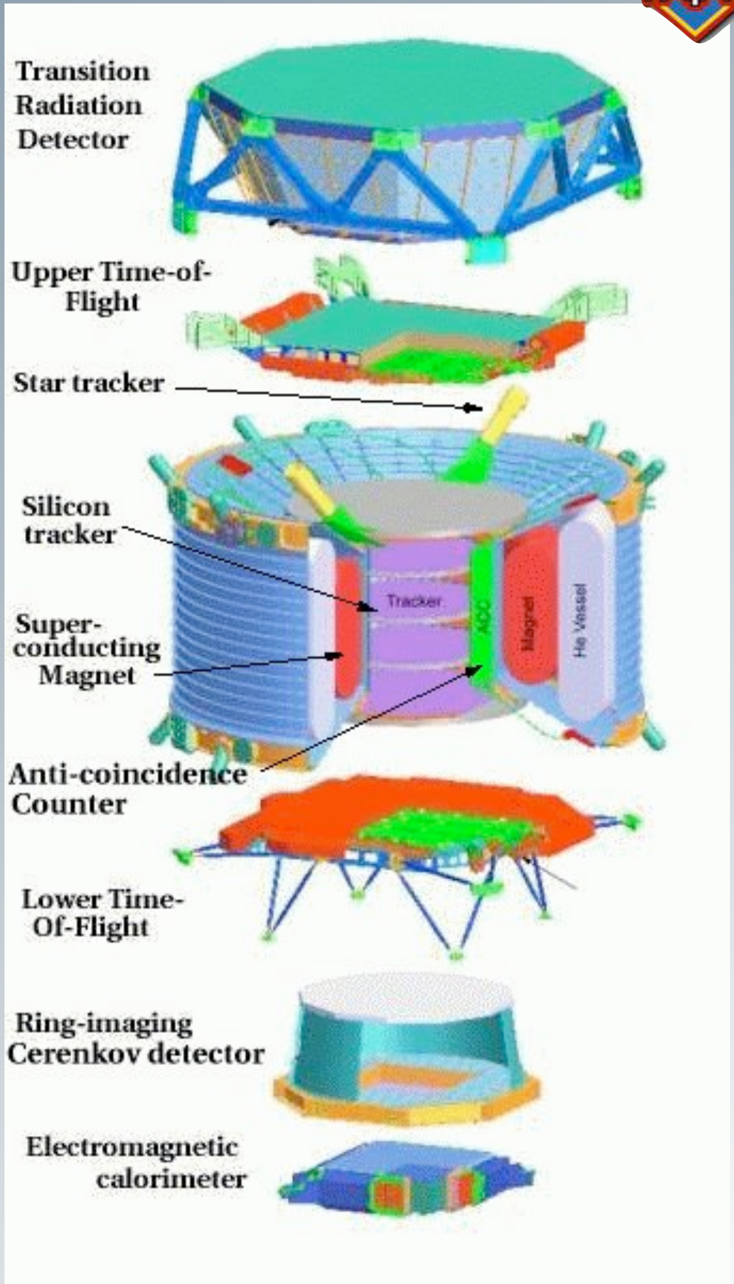
S.Ting:

"Over the coming months, AMS will be able to tell us conclusively whether these positrons are a signal for dark matter, or whether they have some other origin"

Alpha Magnet Spectrometer



- installed on ISS in 05/11, first data release 03/13
- uses a 0.14 T permanent magnet
- designed for CR spectra precision measurements for the next 18 yrs



Lepton propagation

- $e^{\pm}$ can also be described in same framework as $\bar{p}$!

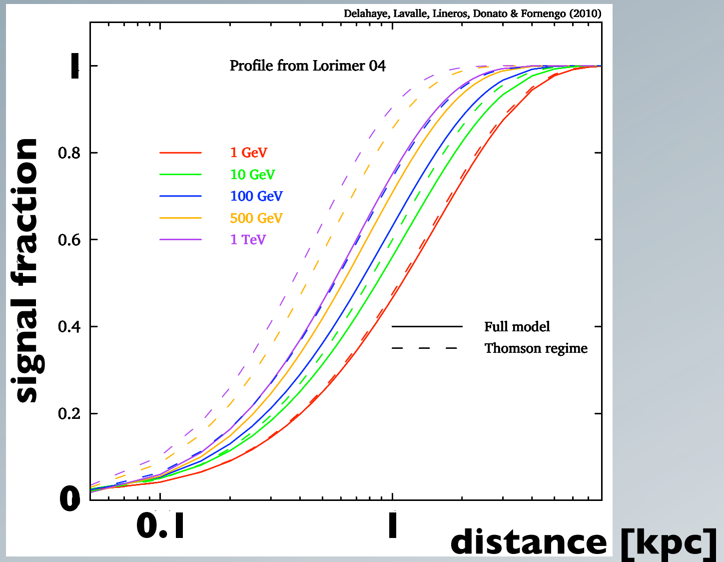
Delahaye *et al.*, PRD '08, A&A '09, A&A '10

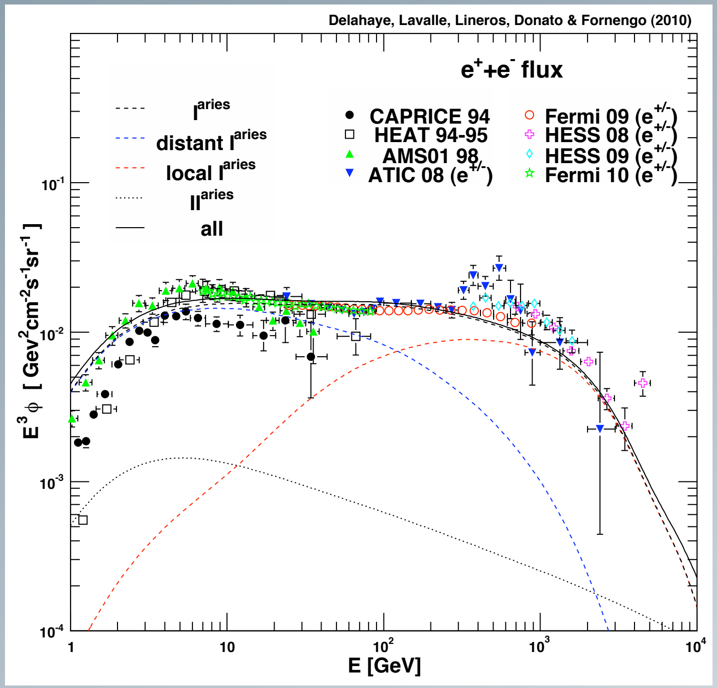
- Main difference to nuclei:

  energy losses are dominant

  [synchrotron + inverse Compton]

  ⇨ mainly locally produced (~kpc for 100 GeV leptons)





- propagation uncertainties:
  - secondaries ~ 2-4
  - primaries ~5

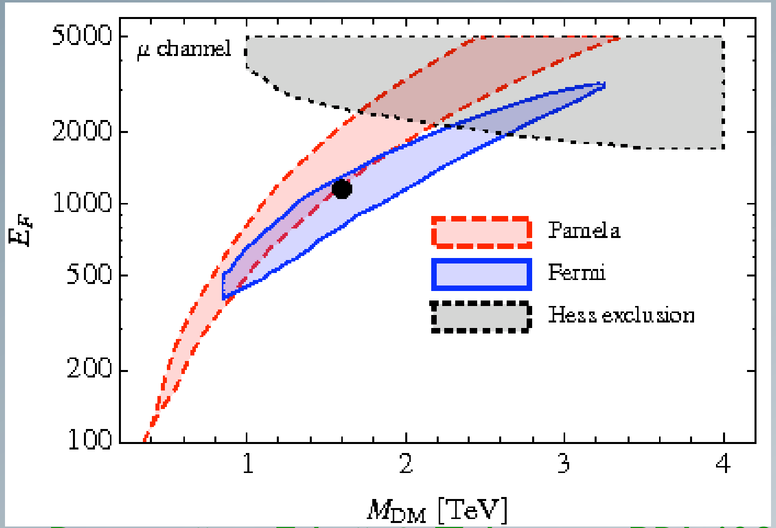
⇨ need for local primary source(s) to describe data well above ~10 GeV

DM explanations

- Model-independent analysis:
  - strong constraints on hadronic modes from $\bar{p}$ data
  - $\chi\chi \rightarrow e^+e^-$ or $\mu^+\mu^-$ favoured
  - large boost factors *generic* – $\mathcal{O}(10^3)$

➡ highly non-conventional DM!

+ significant radio/IC constraints, see later!



Bergström, Edsjö & Zaharijas, PRL '09

- *and*: many good astrophysical candidates for primary sources in the cosmic neighbourhood:
  - pulsars Grasso *et al.*, ApP '09; Yüksel *et al.*, PRL '09; Profumo, 0812.4457
  - old SNRs Blasi, PRL '09; Blasi & Serpico, PRL '09
  - and further proposals...

take home message:

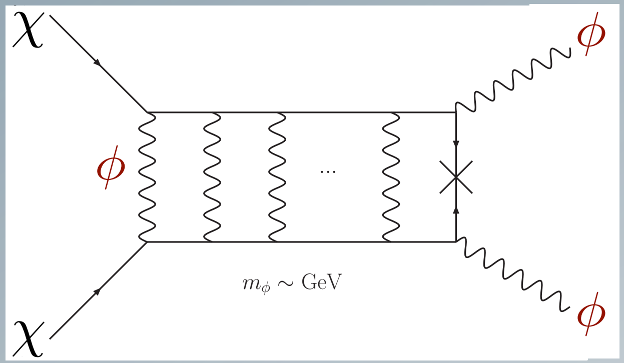
Positrons are certainly not the best messengers for DM searches!

(...

"A theory of dark matter"

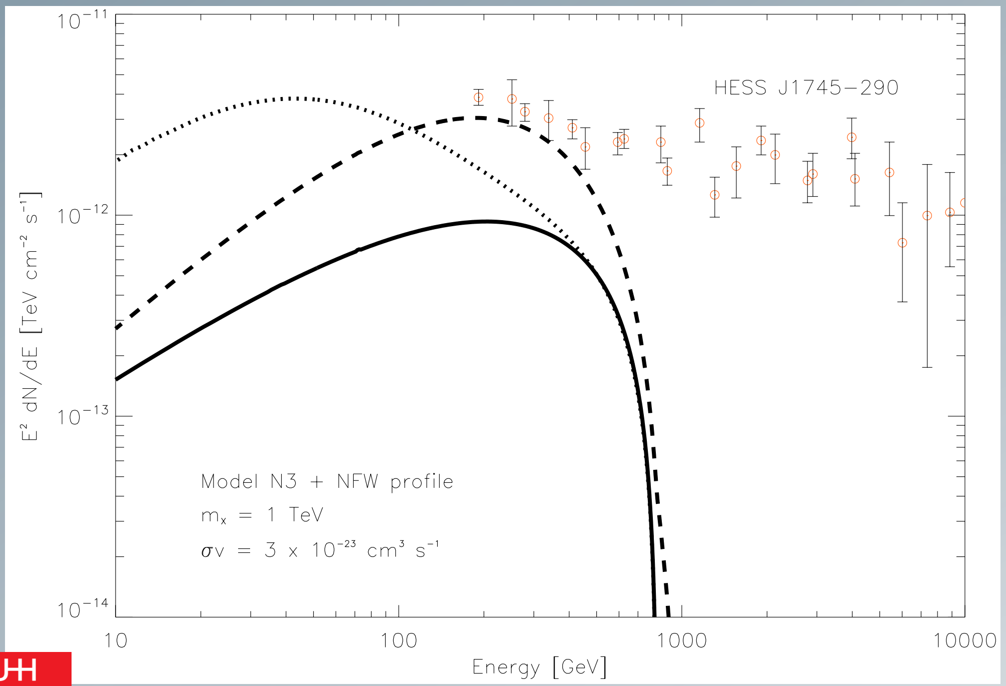
Arkani-Hamed, Finkbeiner, Slatyer & Weiner, PRD '09

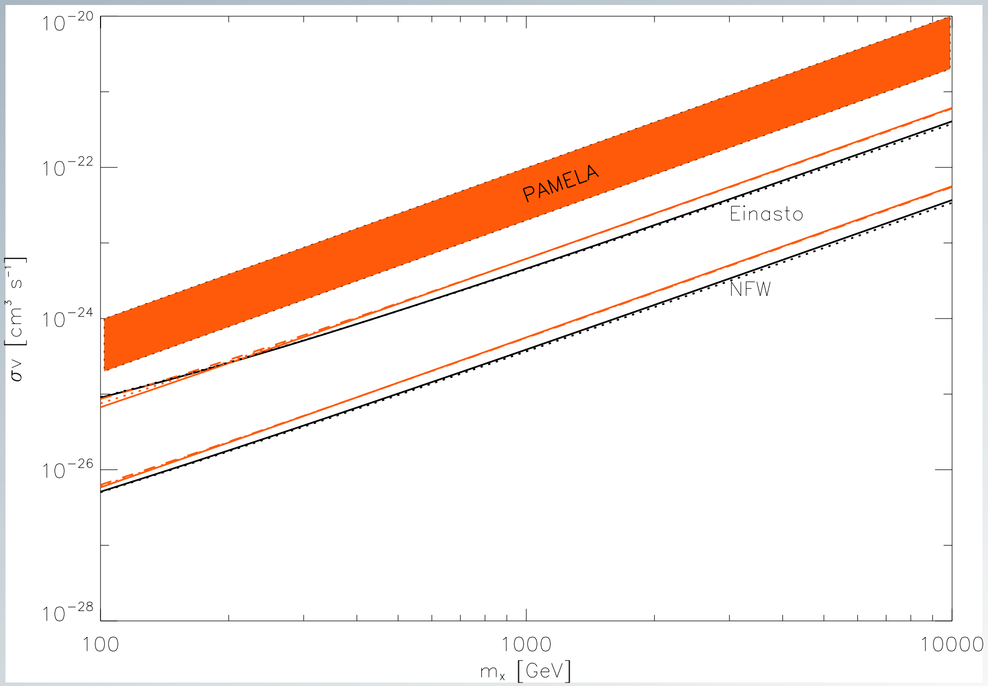
- ***idea***: introduce new force in dark sector, with $m_\phi \lesssim 1\,\mathrm{GeV}$
  - large annihilation rates (Sommerfeld enhancement)
  - later decay: $\phi \to e^+e^-$ or $\mu^+\mu^-$ (kinematics!)



- ***but***: strong constraints from γ (IB) and radio (synchroton)!

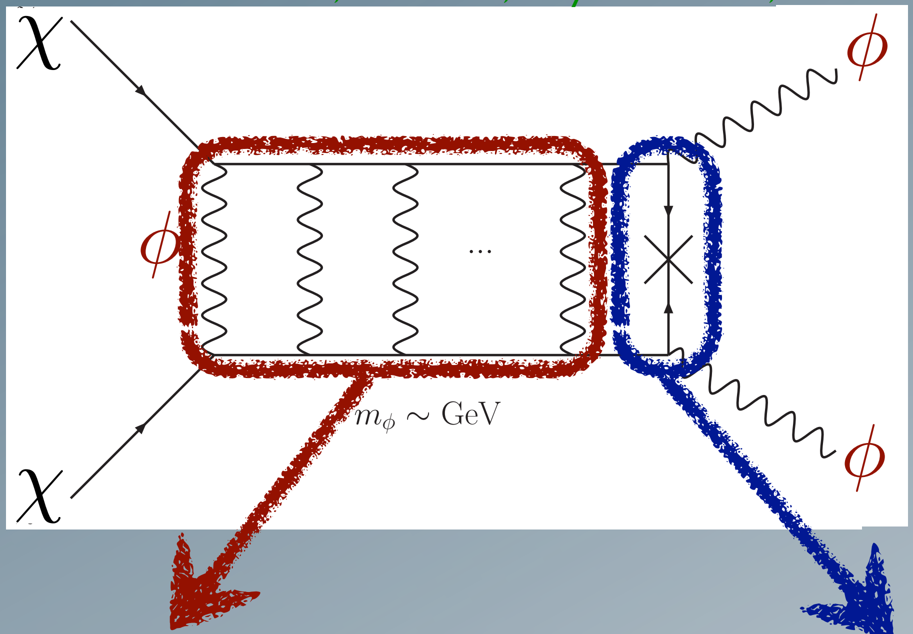
Bertone, Bergström, TB, Edsjö & Taoso, PRD '09





Sommerfeld effect

Arkani-Hamed, Finkbeiner, Slatyer & Weiner, PRD '09



- Kinematical situation:
  - non-relativistic DM particle χ
  - light exchange particle, $m_\phi \ll m_\chi$

➡ each 'rung' of ladder contributes at

$$\mathcal{O}(\alpha/v)$$

➡ resummation necessary!

long range interaction, potential distorts wave function:

$$\left(-\frac{\nabla^2}{m_\chi} + V\right)\psi(r) = m_\chi v^2\,\psi(r)$$

short range interaction, standard QFT result:

$$\sigma_0$$

$$\sigma = S(v)\sigma_0$$

$$S(v) = |\psi(0)|^2$$

Enhancement factor

- Coulomb potential
  - analytic solution

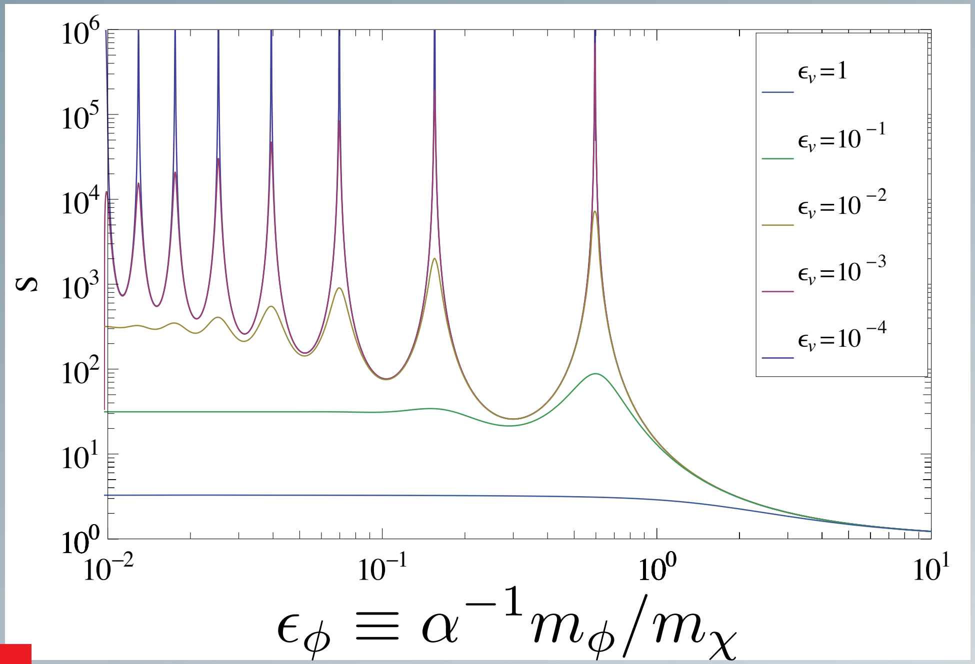
$$S(v) = \frac{\pi\alpha/v}{1 - e^{-\pi\alpha/v}} \quad \underset{v\to 0}{\longrightarrow} \quad \frac{\pi\alpha}{v} \equiv \frac{\pi}{\epsilon_v}$$

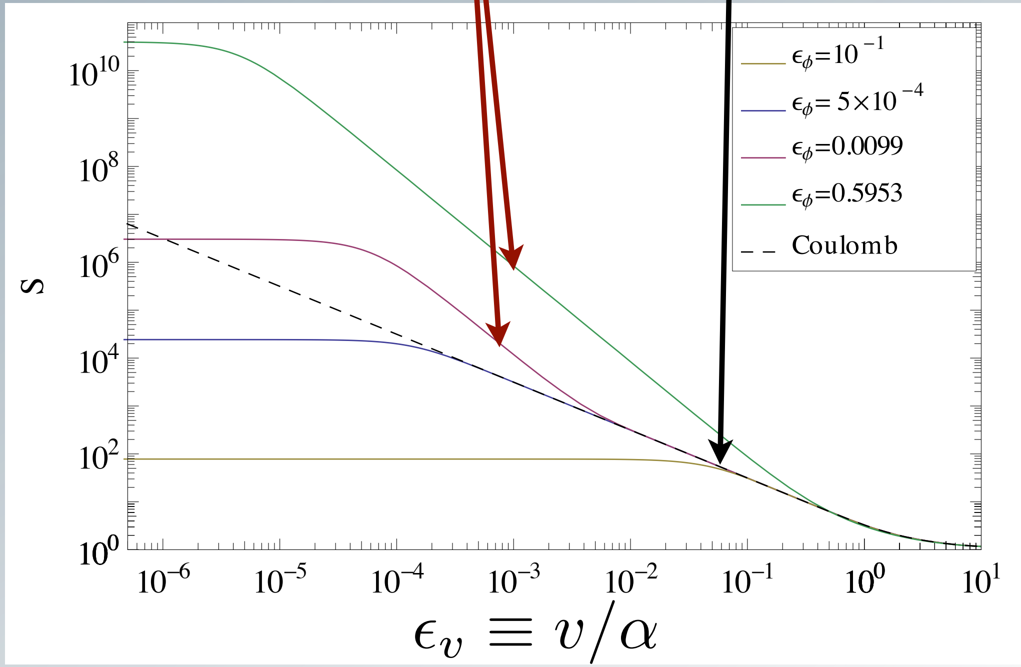
- Yukawa potential
  - numerical solution
  - appearance of resonances

saturation for small *v*

on resonance: $S \propto v^{-2}$

off resonance: $S \propto v^{-1}$





Figs.: van den Aarssen

A rich and interesting phenomenology!

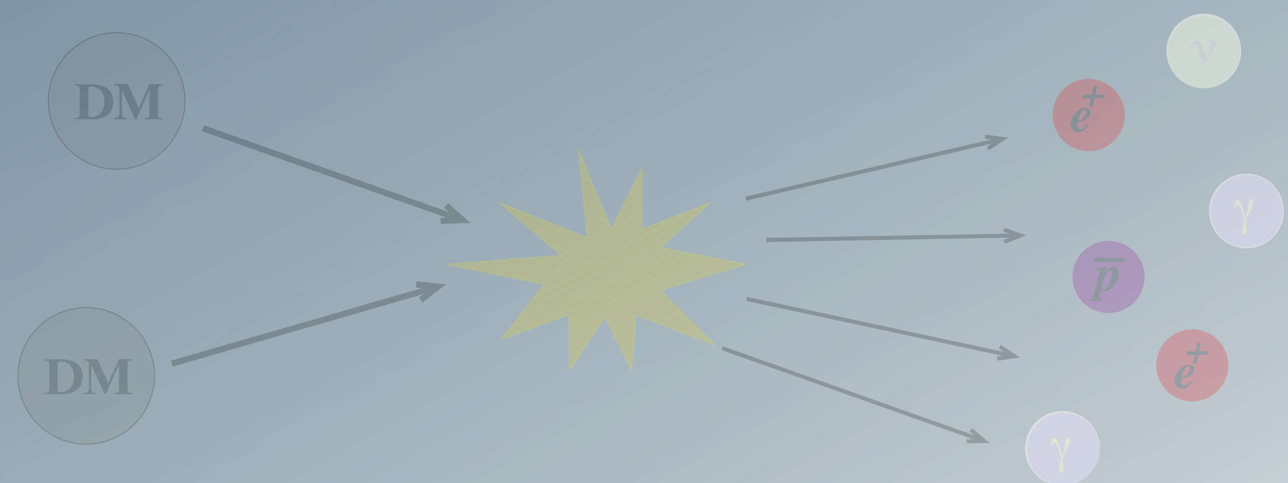
- Introduced in DM context long before PAMELA
  - TeV neutralinos can annihilate resonantly to gauge bosons! — Hisano, Matsumoto, Nojiri, Saito, ... '03 - '06
- No simple 'factorization' of particle physics and astrophysics in gamma-ray flux
  - E.g. much larger 'boost-factors' from substructure than for s-wave annihilators! — E.g. Bovy, PRD '09
- Significant effects on thermal history
  - Factor 2-3 changes in relic density possible (despite $v \sim \sqrt{3/x_{\rm cd}} \sim 0.3$) — Hisano *et al.*, PLB '07; Cirelli, Strumia & Tamburini, NPB '07; March-Russell *et al.*, JHEP '08
  - New era of annihilation after kinetic decoupling possible — Dent, Dutta & Scherrer, PLB '10; Zavala, Vogelsberger & White, PRD '10; Feng, Kaplinghat & Yu, PRD '10; van den Aarssen, TB & Goedecke, PRD '12; ...
  - Substructure cut-off can be as large as the scale of dwarf spheroidals — van den Aarssen, TB & Pfrommer, PRL '12
- Change of DM profiles — Feng, Kaplinghat & Yu, PRL '10; Loeb & Weiner, PRL '11; Vogelsberger, Zavala & Loeb, MNRAS '12

…)

Charged cosmic rays

take home message:

> *Positrons are certainly not the best messengers for DM searches!*



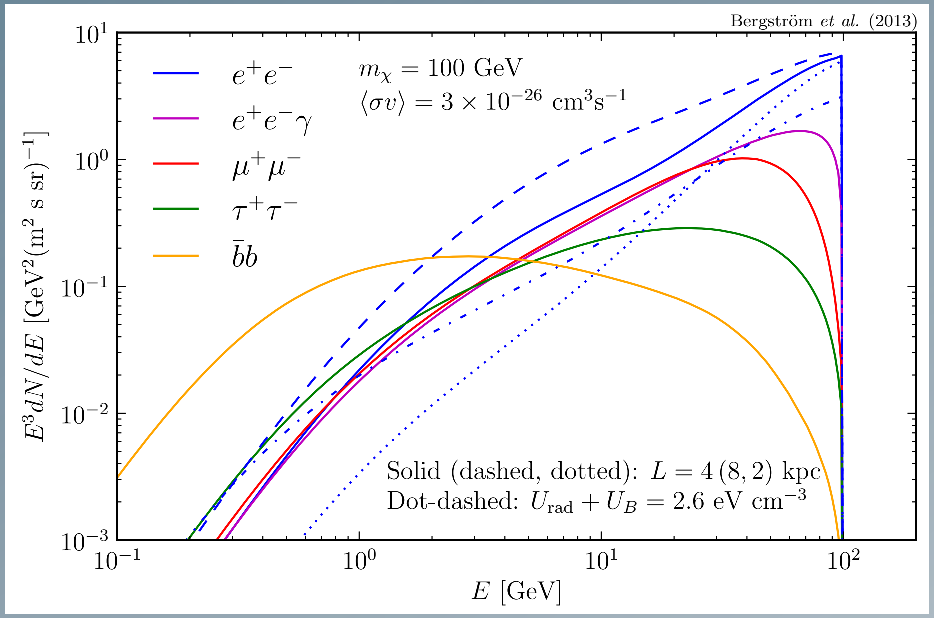
- GCRs are confined by galactic magnetic fields
- After propagation, no directional information is left
- ➡ Also the spectral information tends to get washed out
- Equal amounts of matter and antimatter

  ➡ focus on antimatter (low background!)

Is that actually always true???

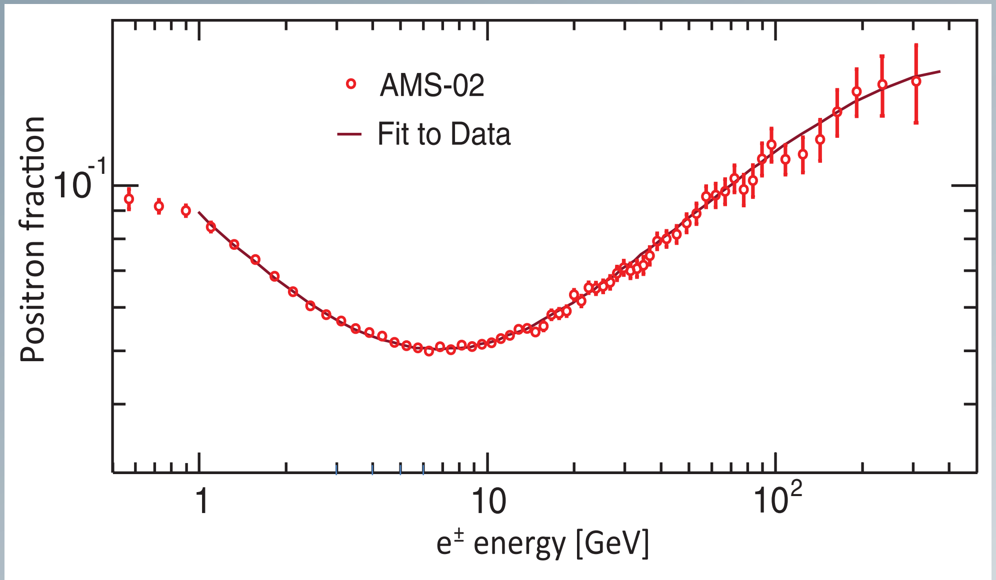
Re-assessing the e$^+$ channel

- Simple observation #1:



Sharp spectral features do exist, for leptonic channels, even after propagation!

- Simple observation #2:



AMS provides data
i) with extremely high statistics
ii) for which a simple (5 param) smooth BG model provides an excellent fit

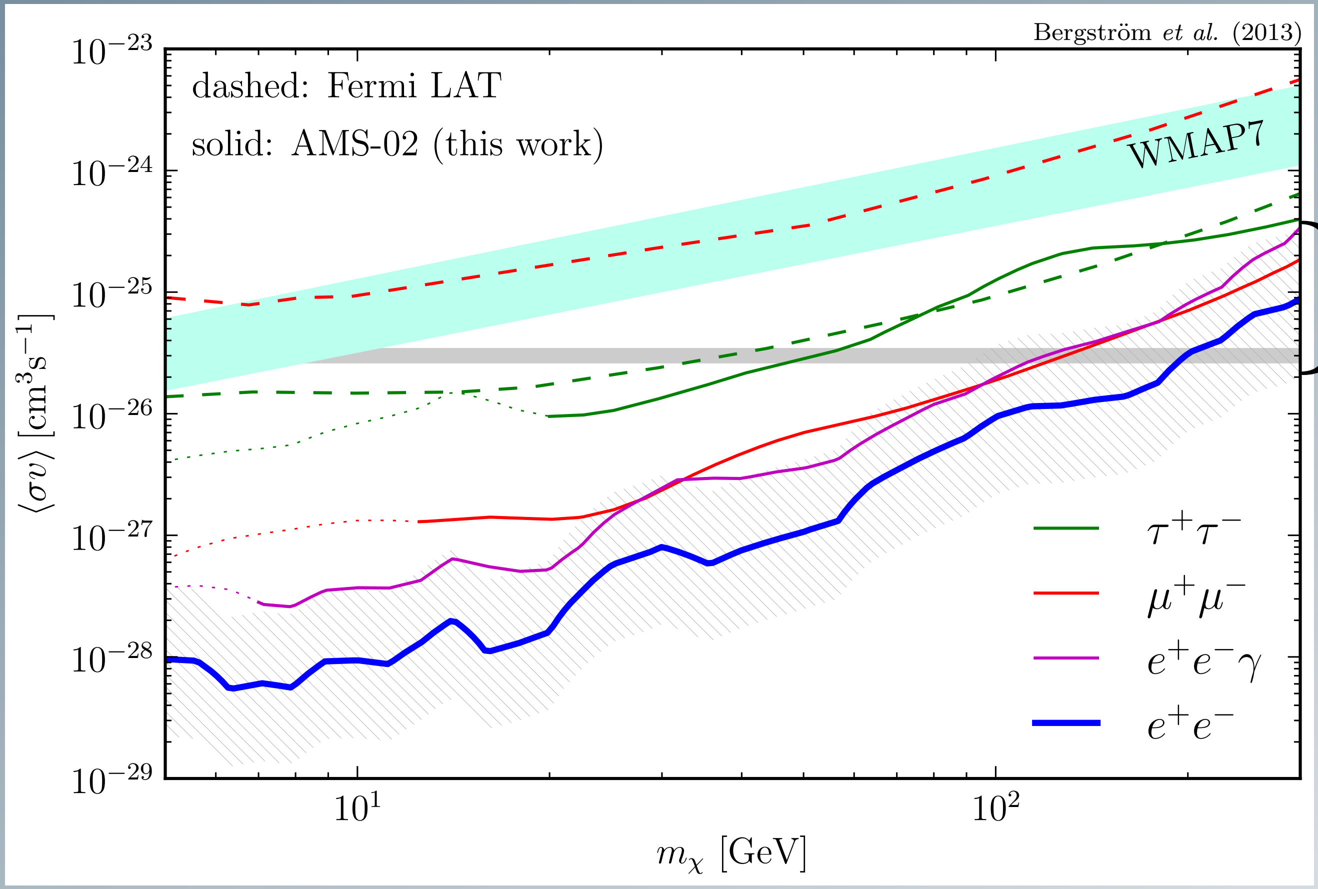
Let's try a spectral fit!

Spectral fit with positrons

Bergström, TB, Cholis, Hooper & Weniger, 1306.3983

- ~same procedure as for gamma rays...

[profile likelihood; *no* sliding energy window, 5 params for BG instead of 2]



represents uncertainty in
i) local DM density
ii) local radiation density

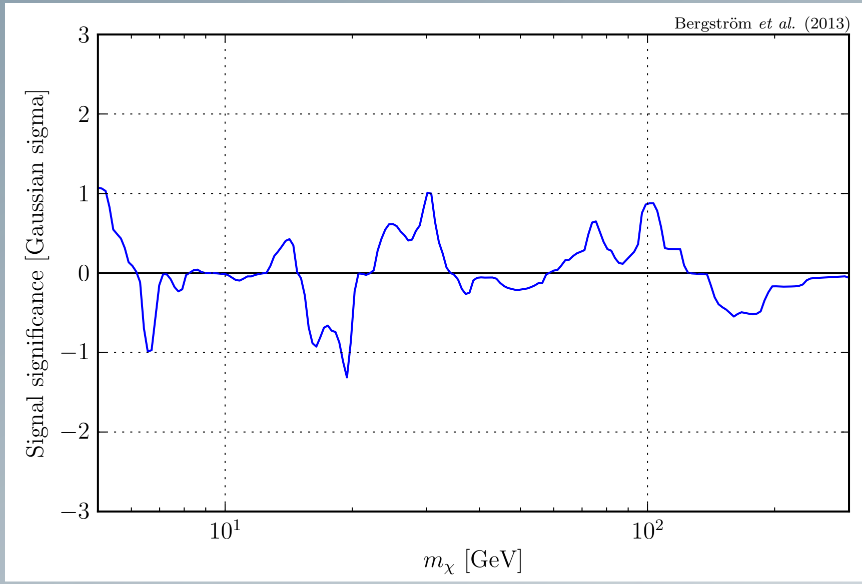
<u>NB</u>: this method gives very robust limits – but only for spiky signals!

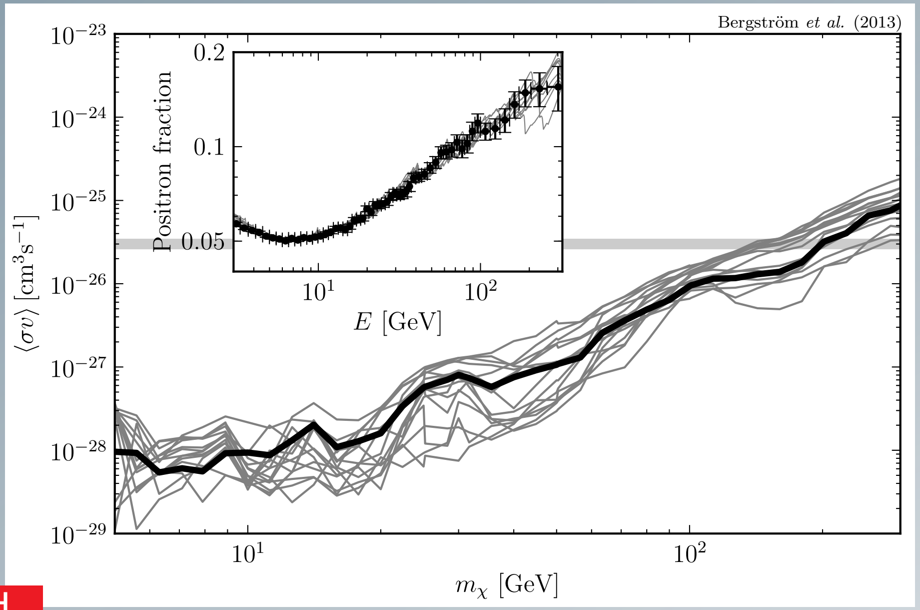
➡ *Most stringent existing limits on (light) leptonic states!*

Spectral fit with positrons

Bergström, TB, Cholis, Hooper & Weniger, 1306.3983

- *No signal* this time…
  [BG only: χ^2/d.o.f. = 28.5/57]
- Using 'physical' background models (GALPROP)
  + varying diffusion parameters:
  no big effect on limits





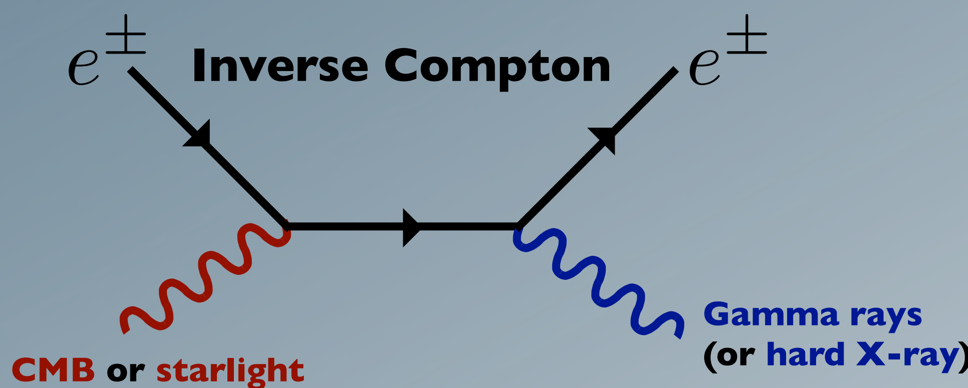
- Largest effect (~factor 3): high energy part of e^+ fraction is superposition of many pulsars and dip in BG conspires with DM signal at same place

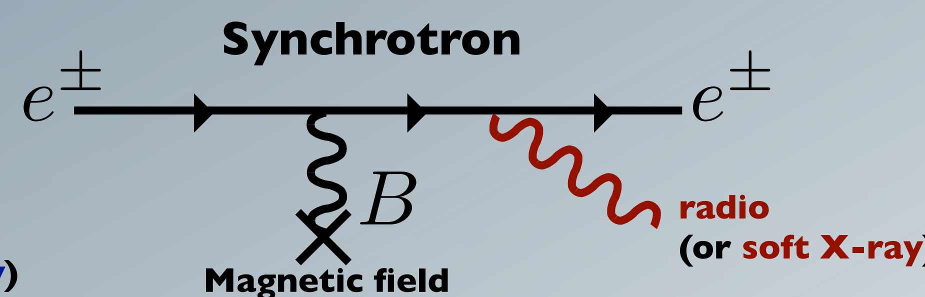
- Prelude – WIMP dark matter
  - Thermal production and freeze-out
  - General principle of (in)direct detection
  - Dark matter distribution
- Gamma rays
  - *targets*: galactic center + halo, dwarf galaxies, galaxy clusters, ...
  - *signals*: continuum vs. "smoking gun" spectral features
- Neutrinos
  - from galactic halo + sun/earth
- Charged cosmic rays
  - propagation of cosmic rays
  - positrons, antiprotons, [antideuterons]
  - **multi-wavelength signals**
- Complementarity with direct and collider searches

more in lecture by F. Donato…!

Multi-wavelength approaches

- In principle, high-energy positrons (and electrons!) from DM annihilations could induce further signals:





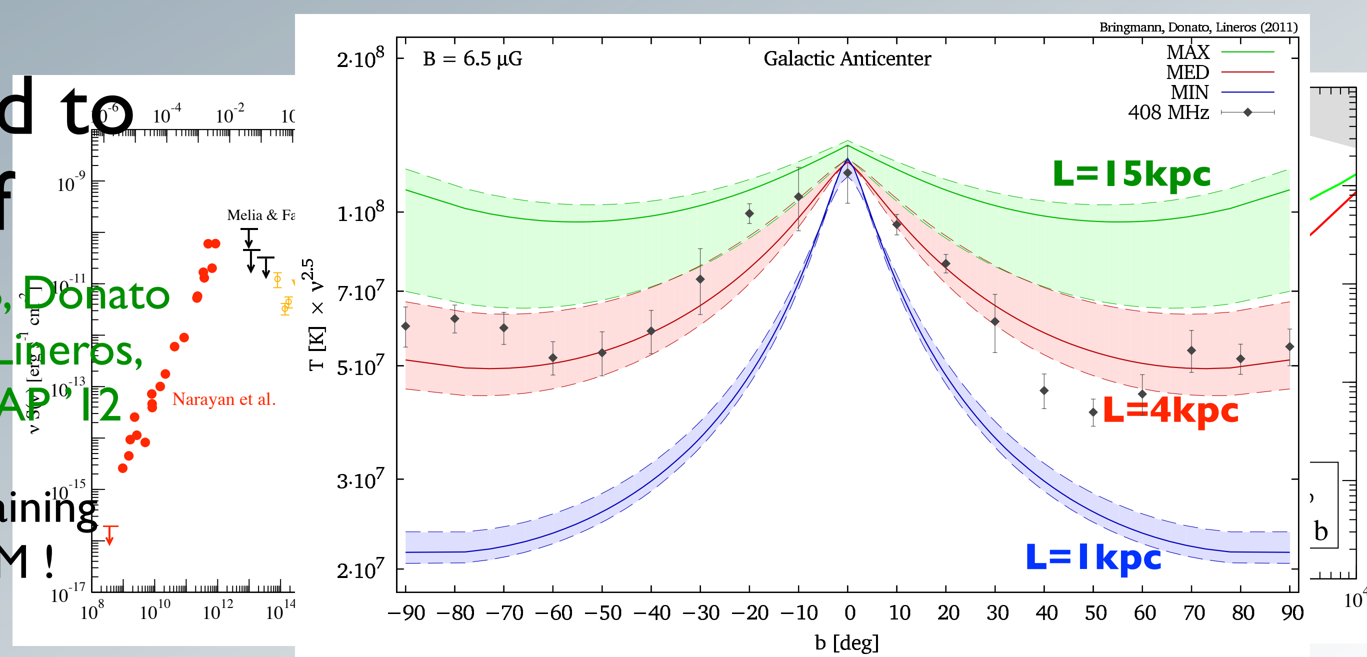
- E.g. the Galactic Center:
- Can also be used to constrain size of diffusive halo:

Gamma rays not necessarily most constraining!

Regis & Ullio, PRD '08

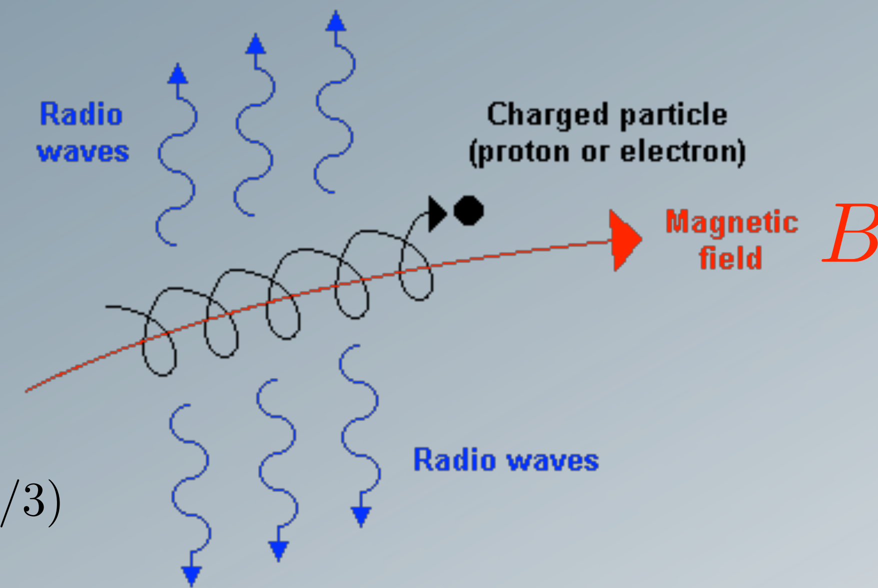
TB, Donato & Lineros, JCAP '12

➡ Important for constraining (in particular light) DM !



Synchrotron radiation

- Synchrotron emission power:



$$\frac{dw}{d\nu} = \frac{\sqrt{3}\, e^3 B}{m_e c^2} \frac{2}{\pi} \int_0^{\pi/2} d\theta \, \sin\theta \; F\left(\frac{\nu}{\nu_c \sin\theta}\right)$$

(angular average for isotropic e⁻ distribution)

$$F(x) = x \int_x^\infty d\zeta \; K_{5/3}(\zeta) \approx \frac{8\pi}{9\sqrt{3}} \delta(x - 1/3)$$

➡
- peak production at resonance $\nu \approx \nu_c$
- power scales roughly like B^2

$$\nu_c = \frac{3eBp_e^2}{4\pi m_e^3 c} = 16\,\mathrm{MHz} \left(\frac{B}{\mu\mathrm{G}}\right)\left(\frac{E_e}{\mathrm{GeV}}\right)^2$$

- Intensity:

$$I_\nu = \frac{1}{\Delta\Omega} \int_{\Delta\Omega} d\Omega \int d\ell \; J_\nu(\mathbf{x}) \, e^{-\int_0^\ell d\ell' \, \alpha_\nu(\mathbf{x}')} = 2\nu^2 k_B T_b / c^2$$

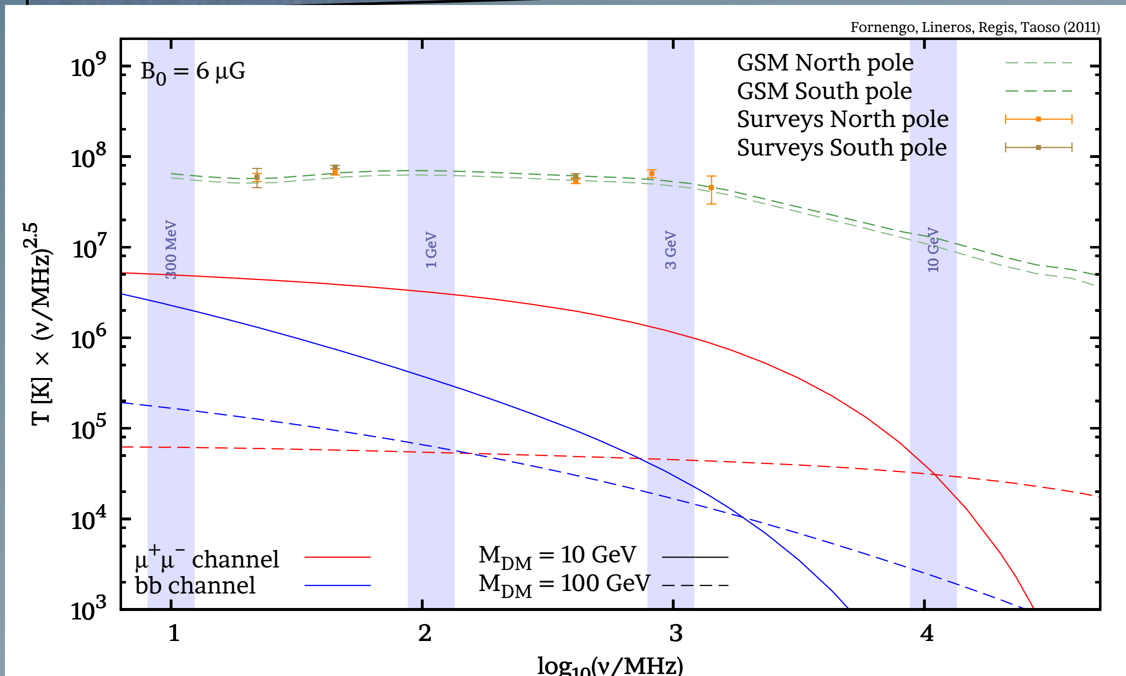
emissivity $J_\nu = \int \frac{dn_e}{dE} \frac{dw}{d\nu} dE$

(absorption length)⁻¹

- power laws:

$$\frac{dn_e}{dE} \propto E^{-\gamma} \quad \Rightarrow \quad T_b \propto \nu^{-\frac{\gamma+3}{2}}$$

Synchrotron from DM



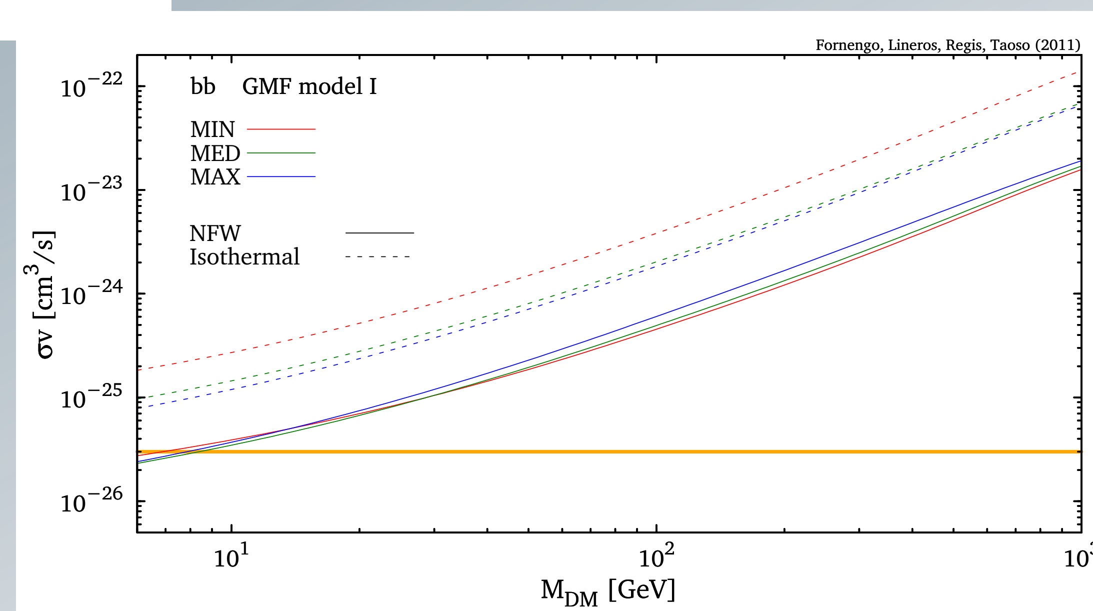
- Galactic halo: low frequencies are most constraining

Fornengo, Lineros, Regis & Taoso, JCAP '12

- constraints rather competitive

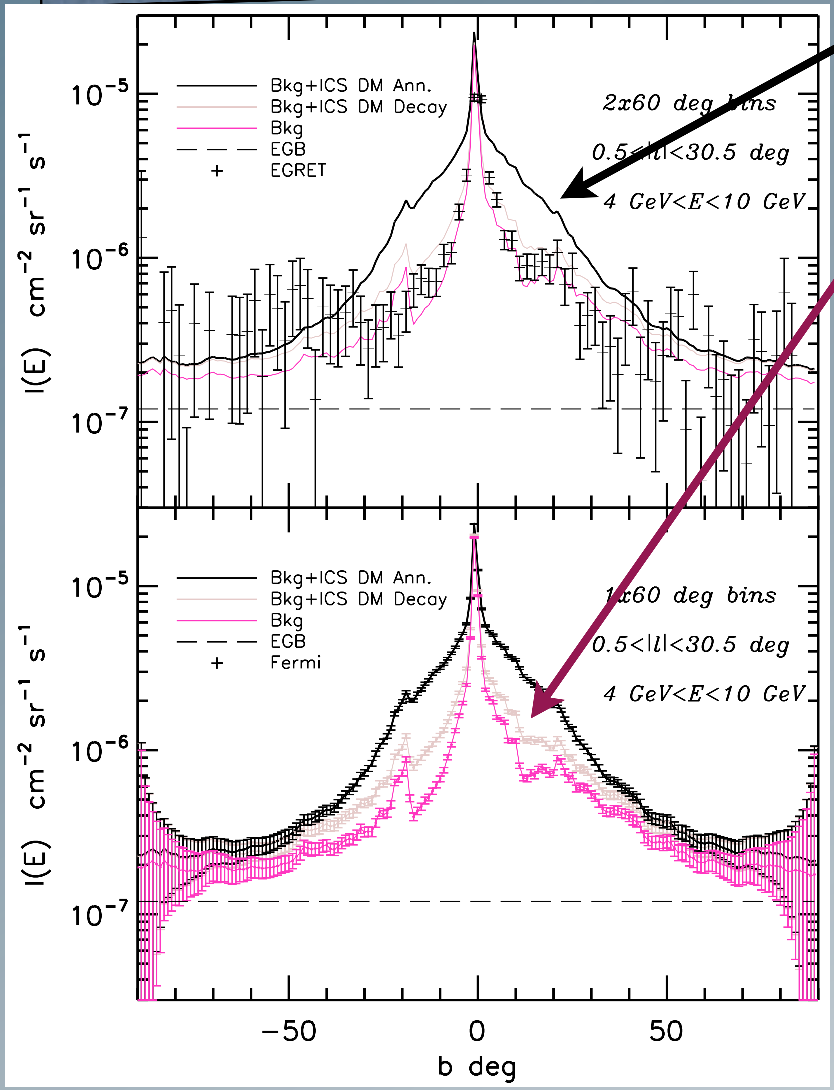
- GC constraints much more stringent – but strongly dependent on DM profile for r<1 pc!

Bertone, Sigl & Silk, MNRAS '01
Bertone, Cirelli, Strumia & Taoso, JCAP '09
...

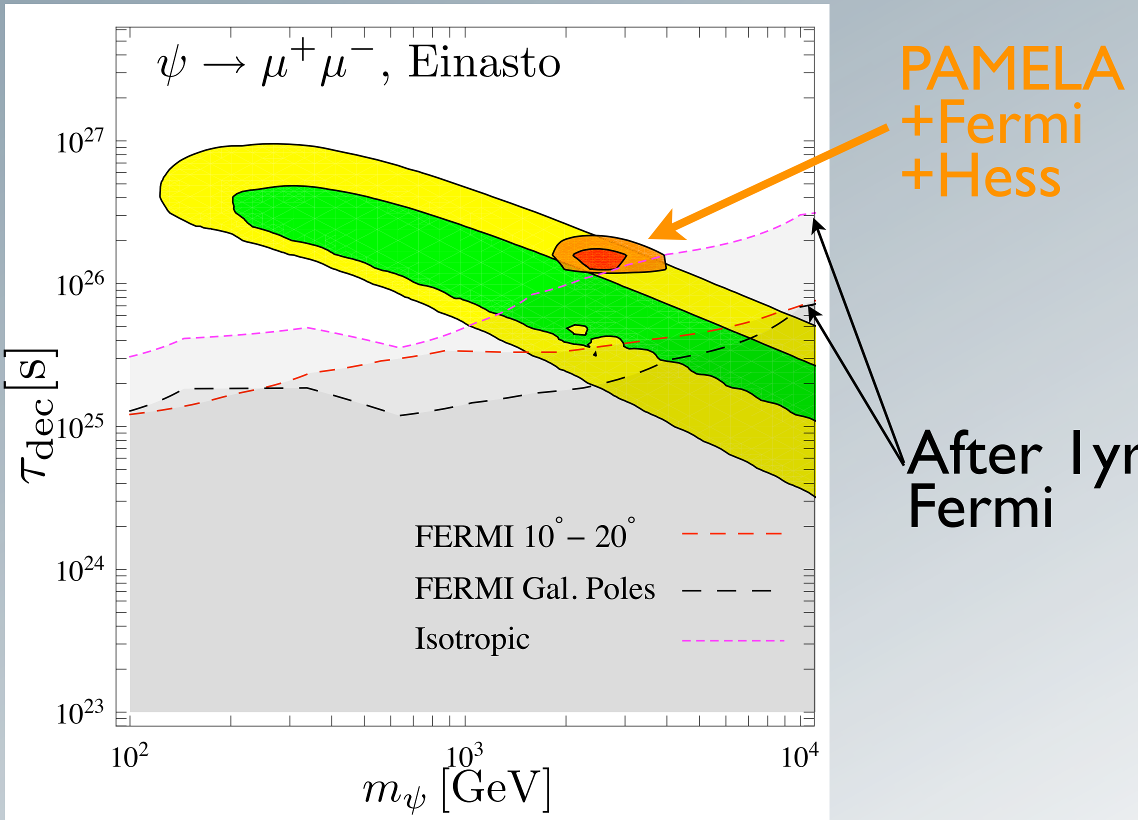


IC constraints on diffuse γ-rays

- Already EGRET data in some tension with annihilating WIMP explanation of PAMELA
- Prediction for Fermi: even decaying DM could be excluded!



Borriello, Cuoco & Miele, PRL '09



Cirelli, Panci & Serpico, NPB '10

⇨ *mostly important for heavy leptophilic DM*

Dark Stars *'Indirect detection at early times'*

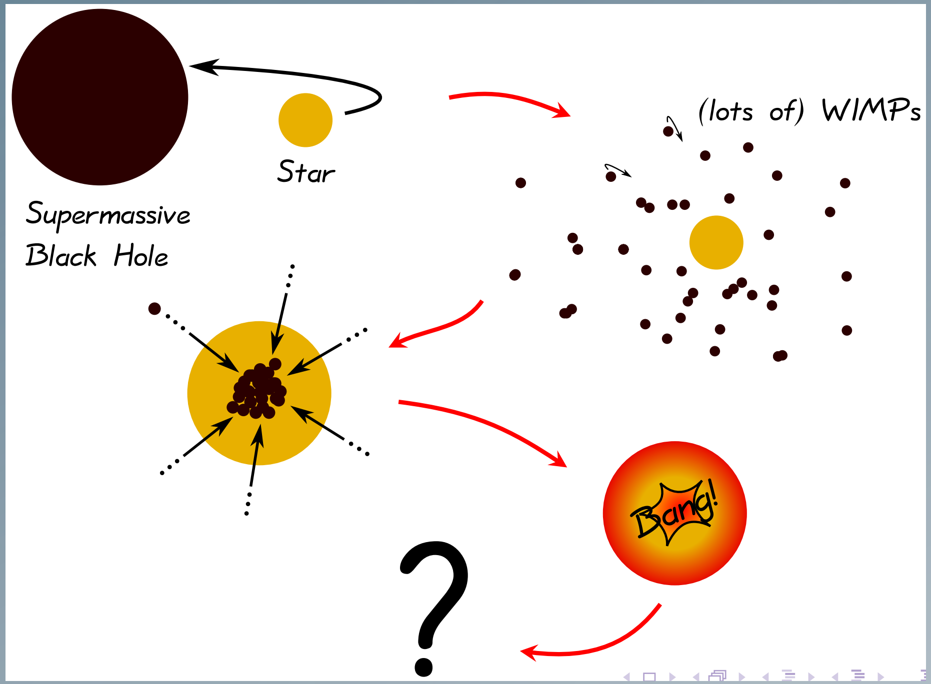


Fig.: Pat Scott

or

- Stars in dense environments may collect so many WIMPs that their annihilation starts to fuel the star

Salati, Silk 1989
Moskalenko, Wai 2006
Fairbairn, Scott, Edsjo 2007
Spolyar, Freese, Aguirre 2008
Iocco 2008
Bertone, Fairbairn 2008
Yoon, Iocco, Akiyama 2008
Taoso et al 2008
Iocco et al 2008
Casanellas, Lopes 2009

- the first stars in the universe might have been supported by DM annihilation rather than fusion

Spolyar, Freese, Gondolo 2008
Freese, Gondolo, Sellwood, Spolyar 2008
Freese, Spolyar, Aguirre 2008
Freese, Bodenheimer, Spolyar, Gondolo 2008
Natarajan, Tan, O'Shea 2009
Spolyar, Bodenheimer, Freese, Gondolo 2009

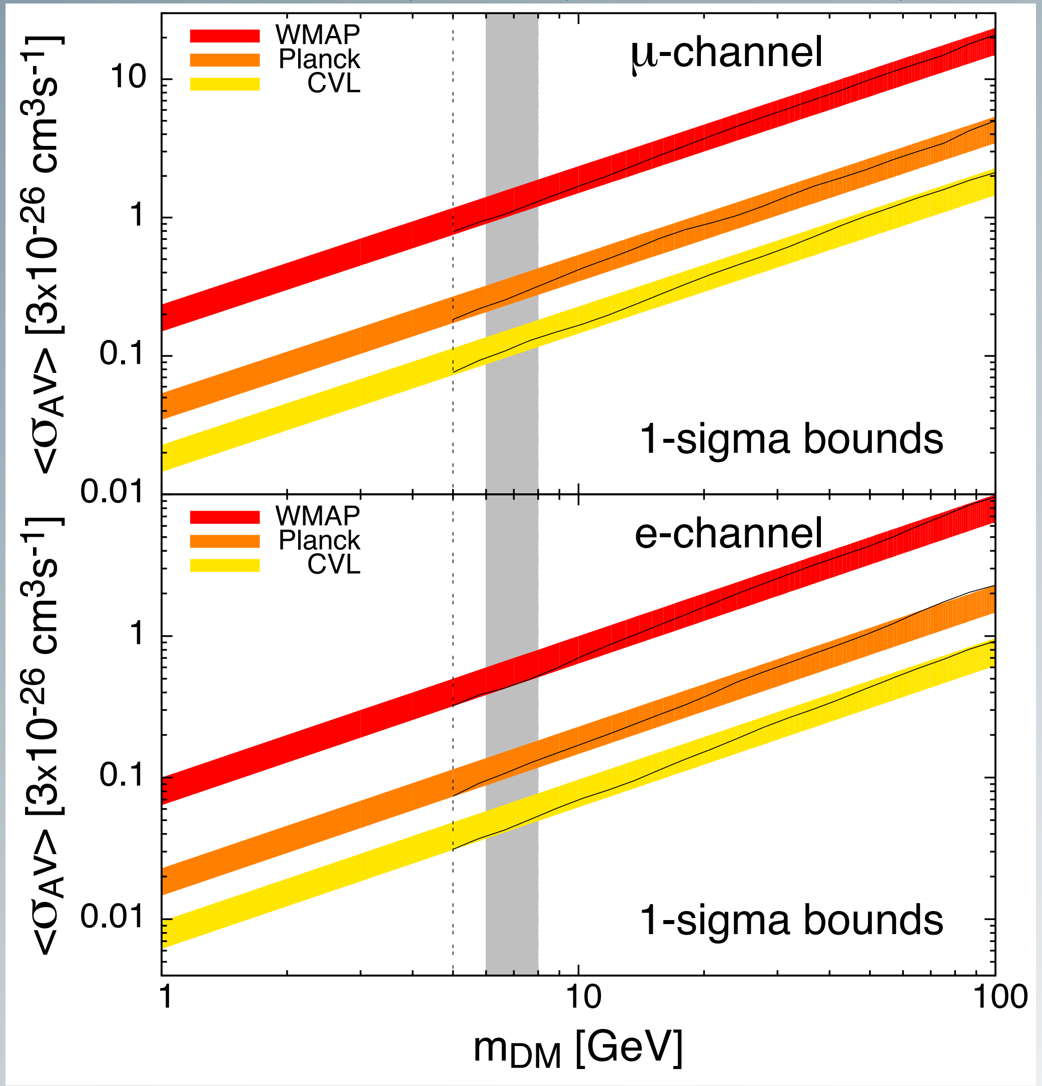
CMB constraints

- DM annihilation at high z injects energy that effects the CMB photons by
  - ionizing the thermal gas
  - inducing Ly-a excitations of H
  - heating the plasma

↓

- Significant constraints on light DM!
  - (other channels bracketed by the two cases shown)

Hütsi, Chluba, Hektor & Raidal, AA '11

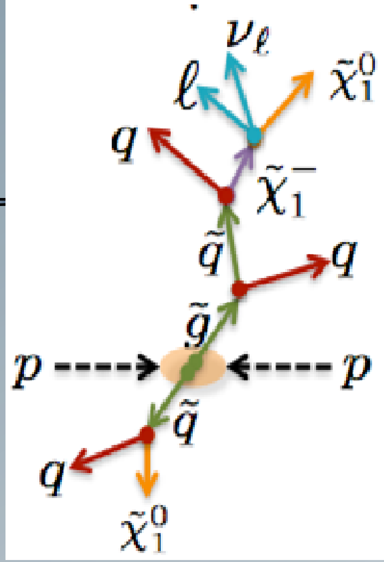


~direct detection?

- Prelude – WIMP dark matter
  - Thermal production and freeze-out
  - General principle of (in)direct detection
  - Dark matter distribution
- Gamma rays
  - *targets*: galactic center + halo, dwarf galaxies, galaxy clusters, ...
  - *signals*: continuum vs. "smoking gun" spectral features
- Neutrinos
  - from galactic halo + sun/earth
- Charged cosmic rays
  - propagation of cosmic rays
  - positrons, antiprotons, [antideuterons]
  - multi-wavelength signals
- Complementarity with direct and collider searches

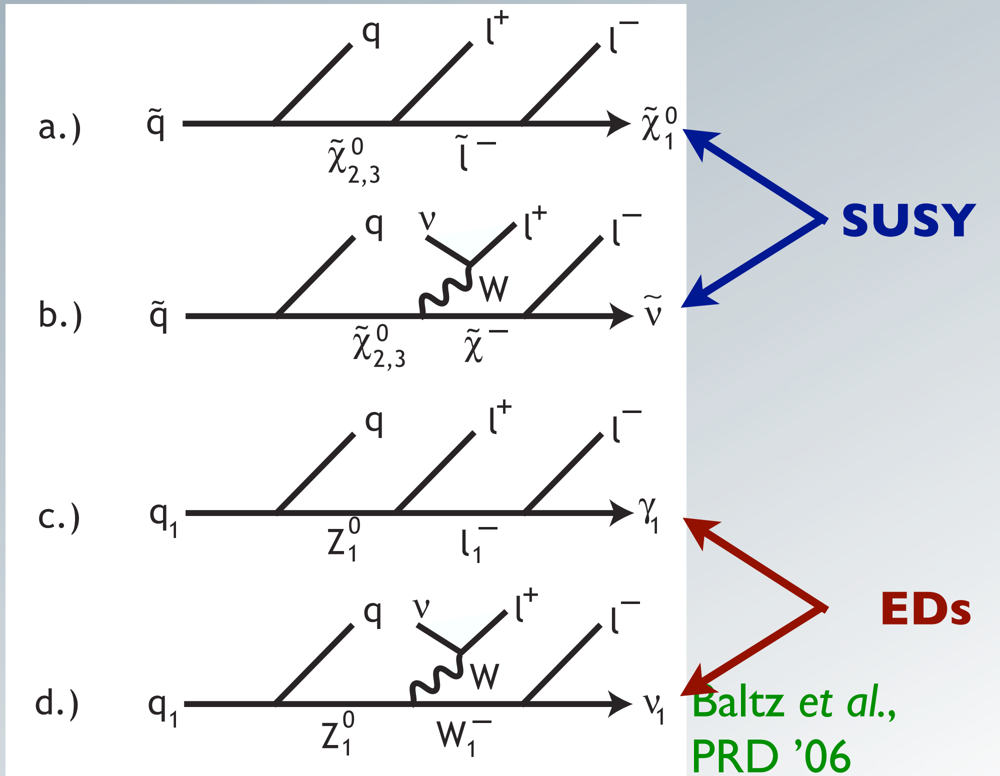
Accelerator searches

- Process: $\overline{\mathrm{SM}}\,\mathrm{SM} \rightarrow \chi\chi + X$
- WIMP Signal: missing (transverse) energy $\not{E}_T$
  - extract additional information from other produced particles
  - NB: also SM processes!



- Constraints very powerful but model-dependent
- Hard to unambiguously identify WIMP in accelerator-only approach!

  (though shapes of invariant mass distributions help)



Baltz *et al.*, PRD '06

LHC model reconstruction

Extremely difficult to confirm that WIMP=DM even for very constrained frameworks like the CMSSM! Baltz *et al.*, PRD '06

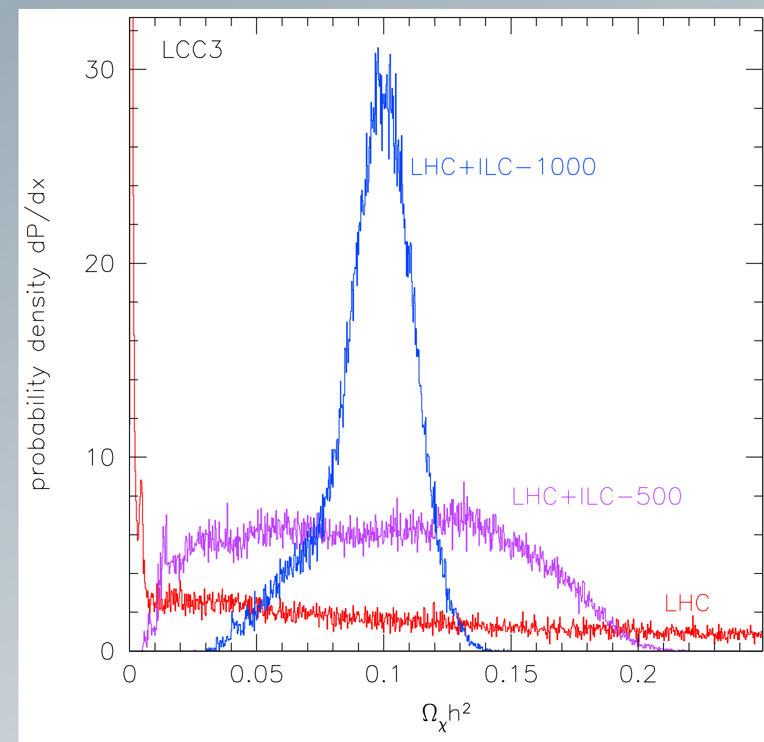
choose model
↓
create fake data
↓
reconstruct model parameters
↓
calculate relic density

already excluded by LHC...

need in any case independent confirmation
from direct and/or indirect searches
!!!

"nice model"

SPS1a' – *bulk* (/coann.), $m_\chi = 96$ GeV



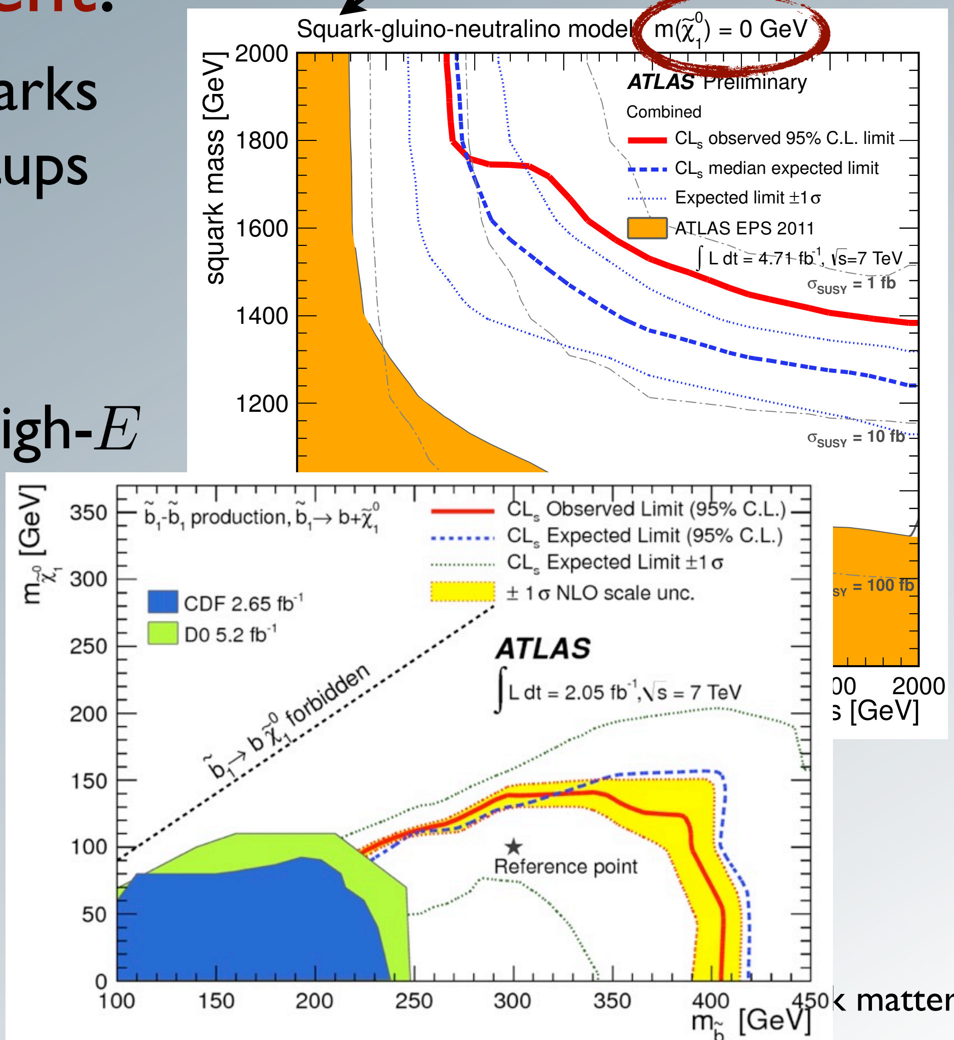
"bad model"

LCC3 – *coannihilation*, $m_\chi = 143$ GeV

LHC limits on new particles

- So far, no sign for new physics at LHC...
- ...but impressive limits on new particles (e.g. SUSY)!
- These are model-dependent!
  - All limits but for gluinos and squarks are derived/follow in minimal setups
  - ...
- *Have* to cut on soft jets!
  - Usually, limits are derived from high-E jet + $\not{E}_T$ signature, i.e. $M_{\tilde{\chi}^1_0} = 0$

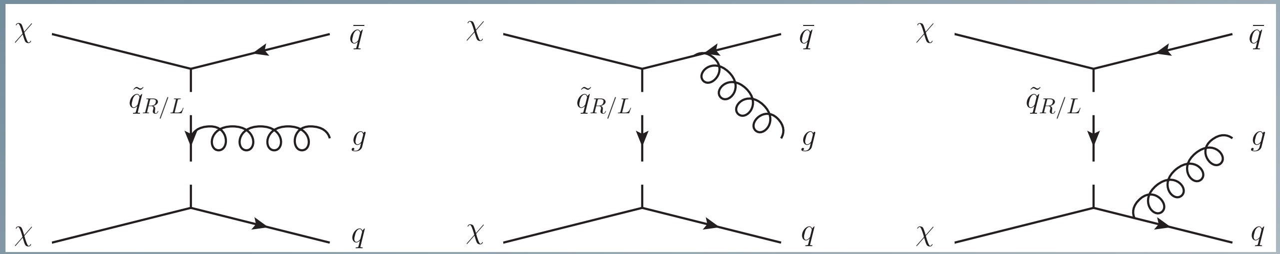
degenerate 1st and 2nd generation...



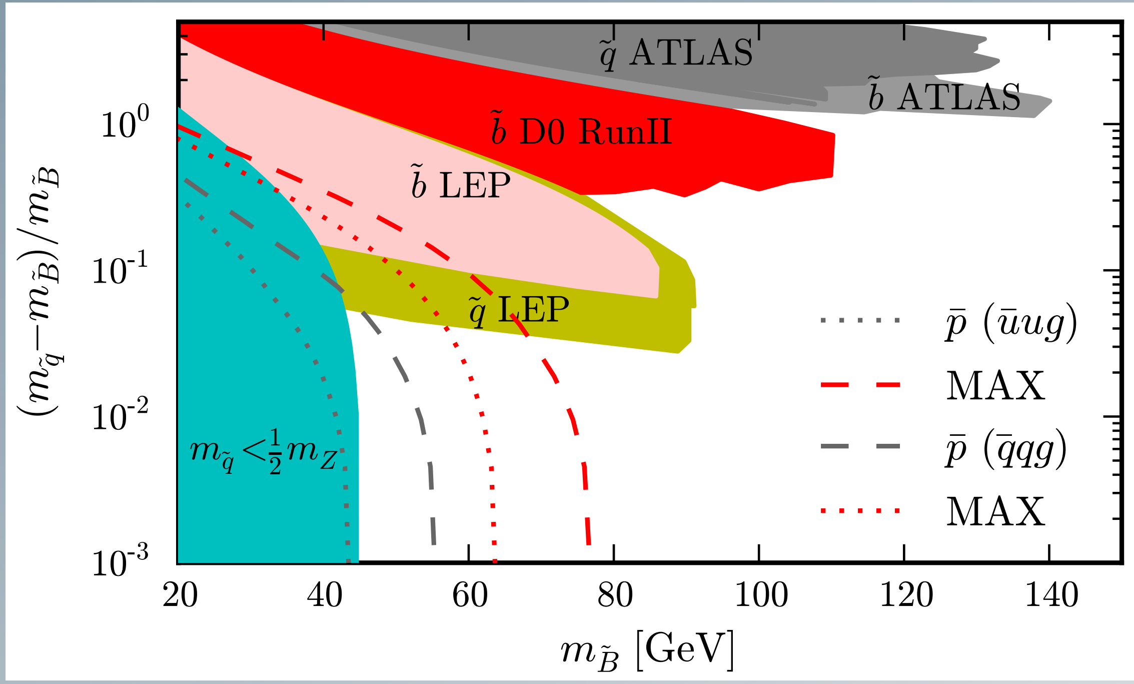
> *Mass degeneracies between colored new states and lightest new state generically difficult to test with LHC!*

Degenerate spectra

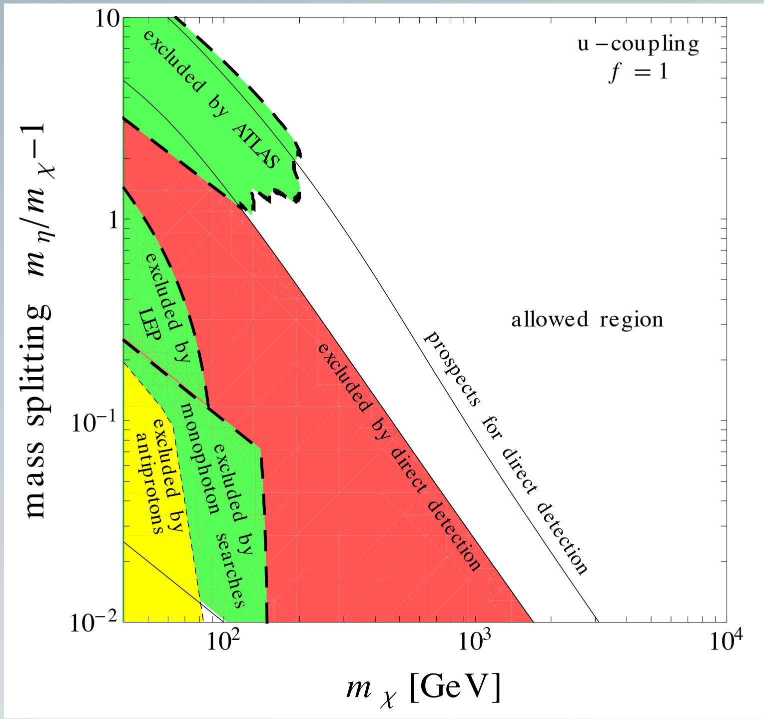
- Indirect searches could probe the small mass differences not accessible by colliders:



} → **antiprotons...**



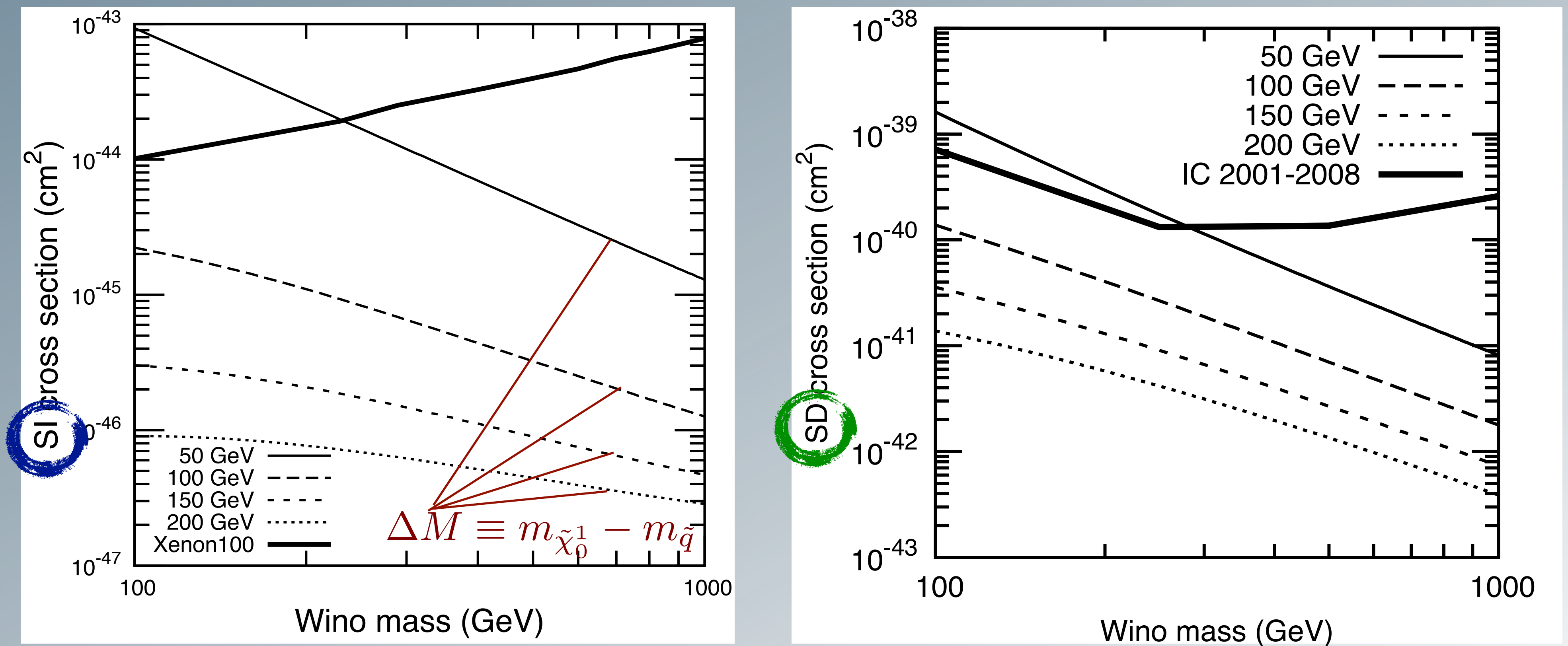
Asano, TB & Weniger, PLB '12



Garny, Ibarra, Pato & Vogl, JCAP '12

Degenerate spectra (2)

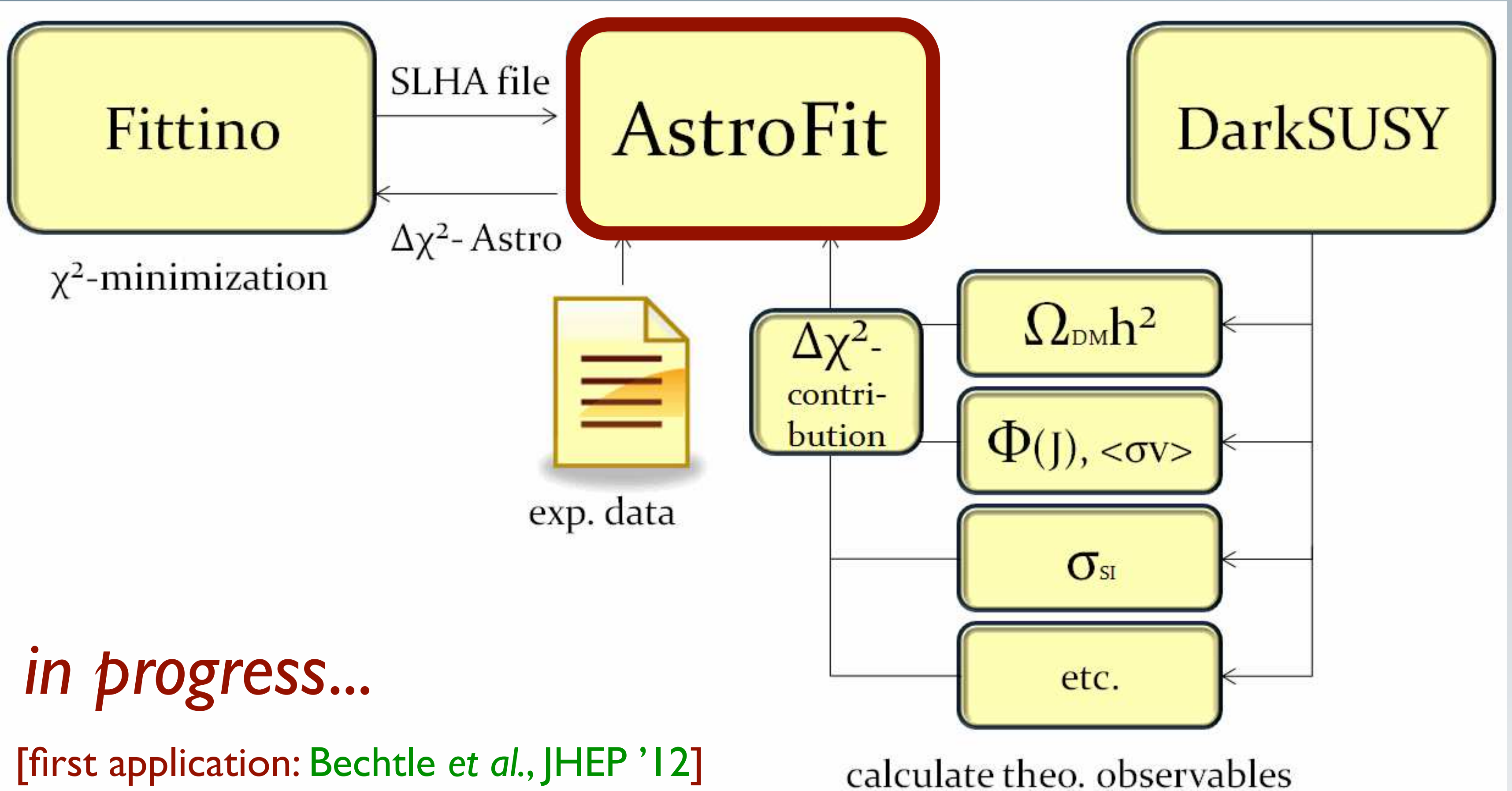
- Direct scattering rate with degenerate squarks enhanced through s-channel resonance
  - ⇨ maybe even more constrained: Hisano, Ishiwata & Nagata, PLB '11



direct detection with Xenon100 **indirect detection with IceCube**

Complementarity

- Systematic treatment: link numerical tools from particle physics and codes like DarkSUSY:



in progress...

[first application: Bechtle *et al.*, JHEP '12]

TB, Nguyen, Horns

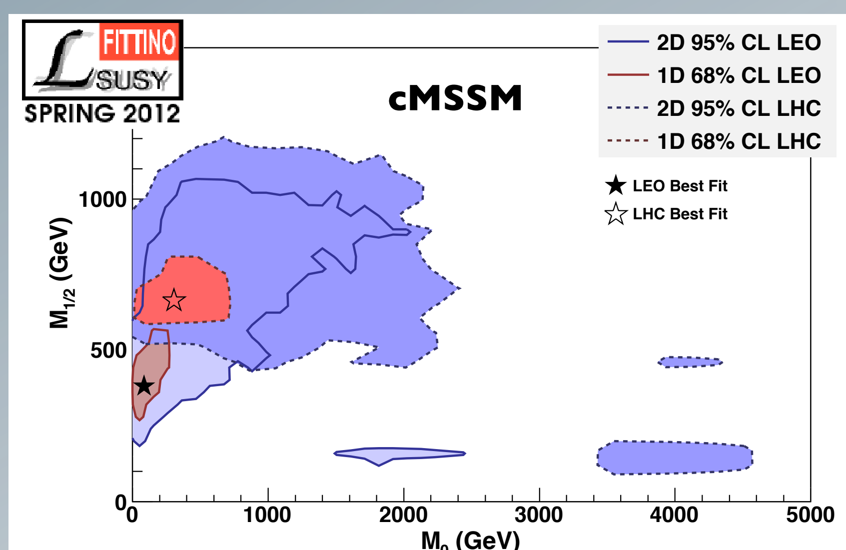
LHC implications

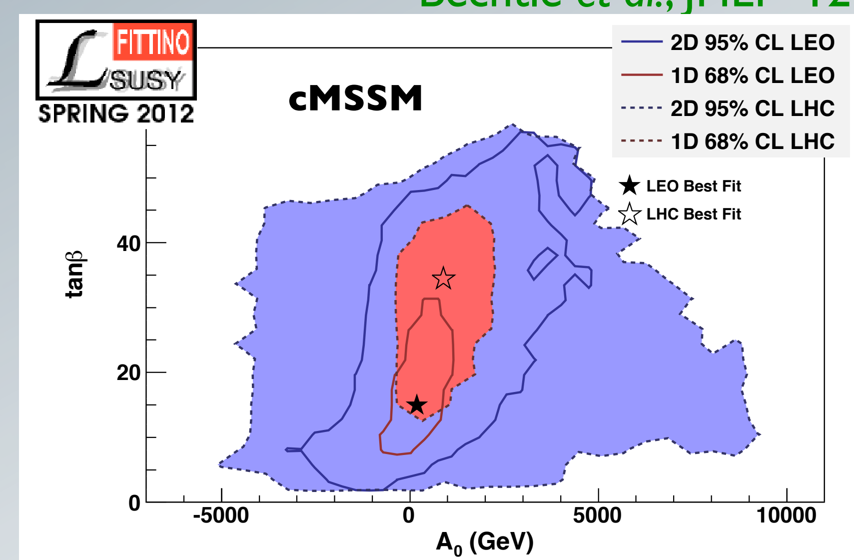
- LHC limits on sparticles imply that new colored states must be heavy
- Low-energy observables, in particular g−2, indicate necessity of light new states coupling to leptons

➜ *constrained* SUSY scenarios already in some tension with data!

Bechtle *et al.*, JHEP '12

	χ^2/ndf
☆ LHC 5 fb^{-1}	13.1/9
★ LEO	10.3/8

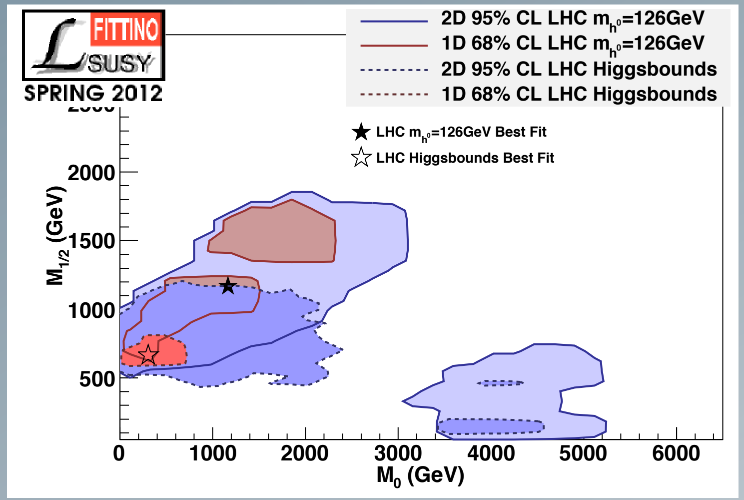


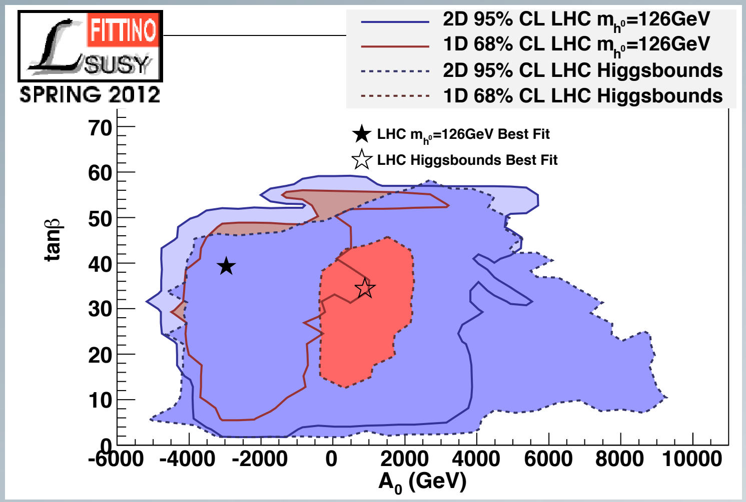


LHC+Higgs implications

- m_H=126 GeV requires even higher mass scale
  (mainly from scalar top contribution)
  ➔ *constrained* SUSY scenarios in significant tension!

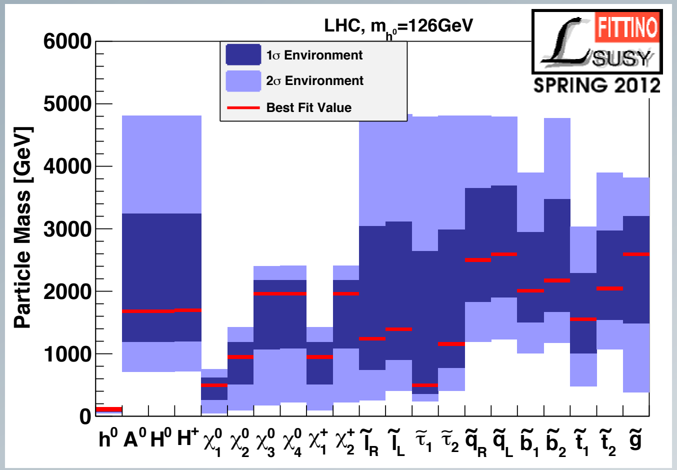
	χ^2/ndf
★ LHC +Higgs	18.4/9
☆ LHC	13.1/9

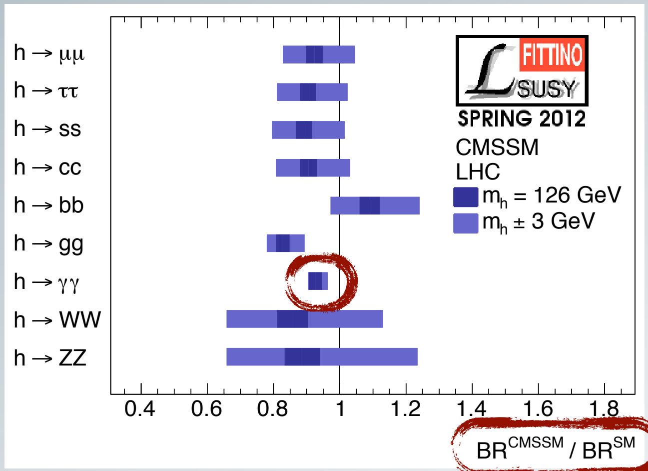




cMSSM global fits

Bechtle *et al.*, JHEP '12



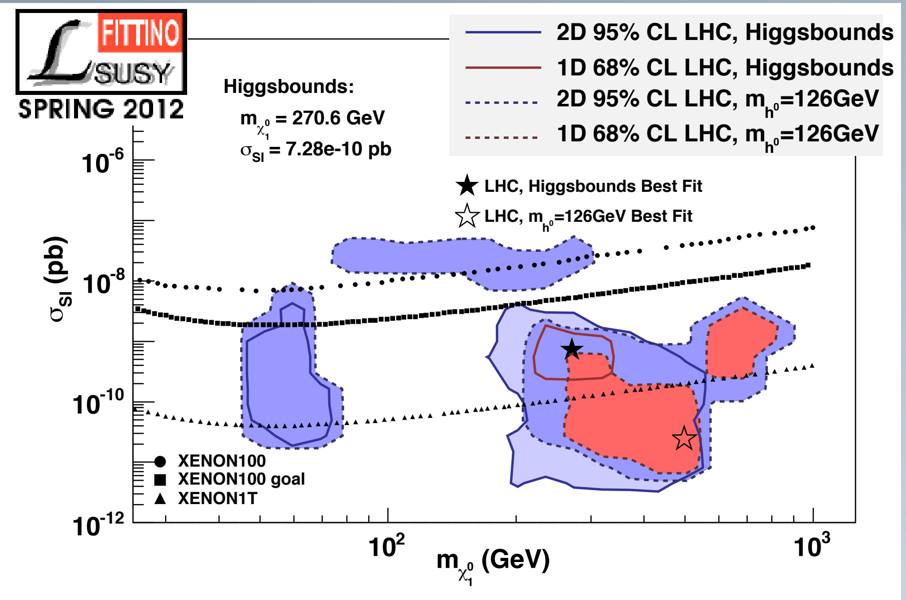


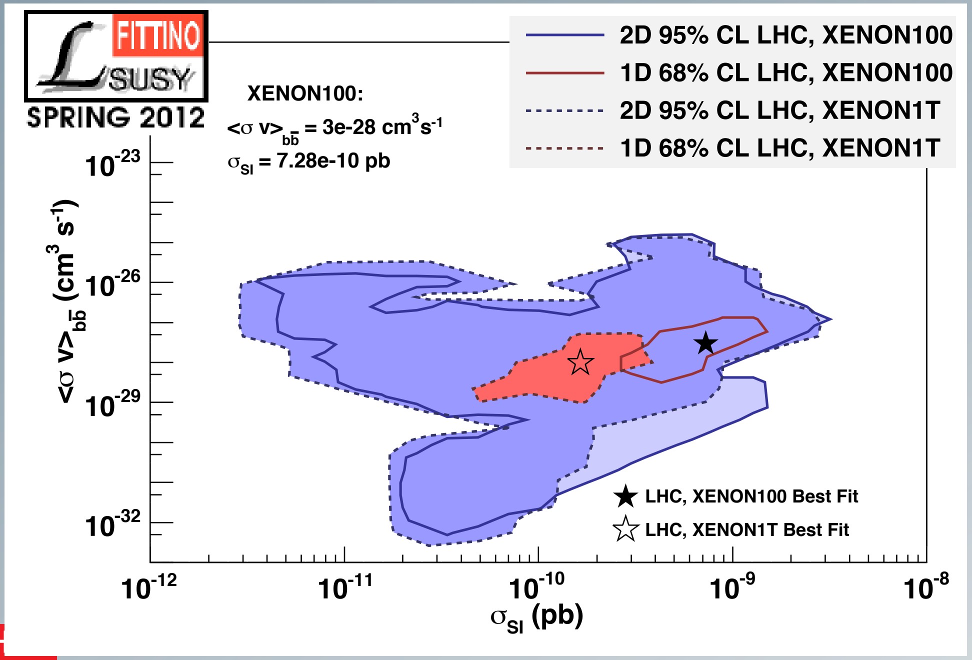
Decay channels will constrain the cMSSM even further...

Direct vs. indirect searches

Implications of a 126 GeV Higgs for direct searches:

(Note that present data – Xenon100 – does not provide any constraints beyond LHC+LEO)





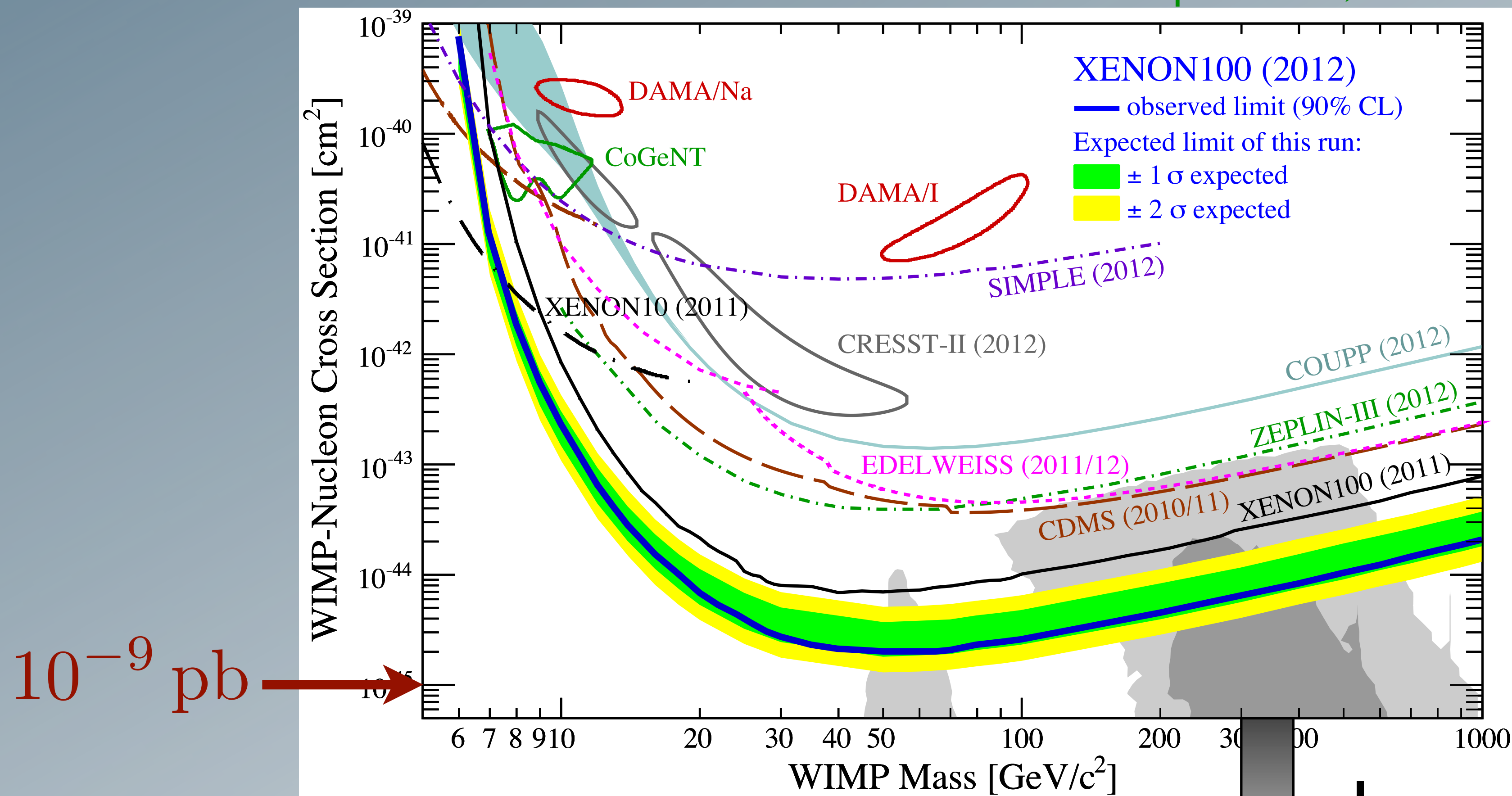
Indirect searches (Fermi Dwarfs limits) just start to touch this area from above

➪ *complementarity of direct and indirect searches!*

Direct searches

- Impressive improvements of direct detection limits in recent years:

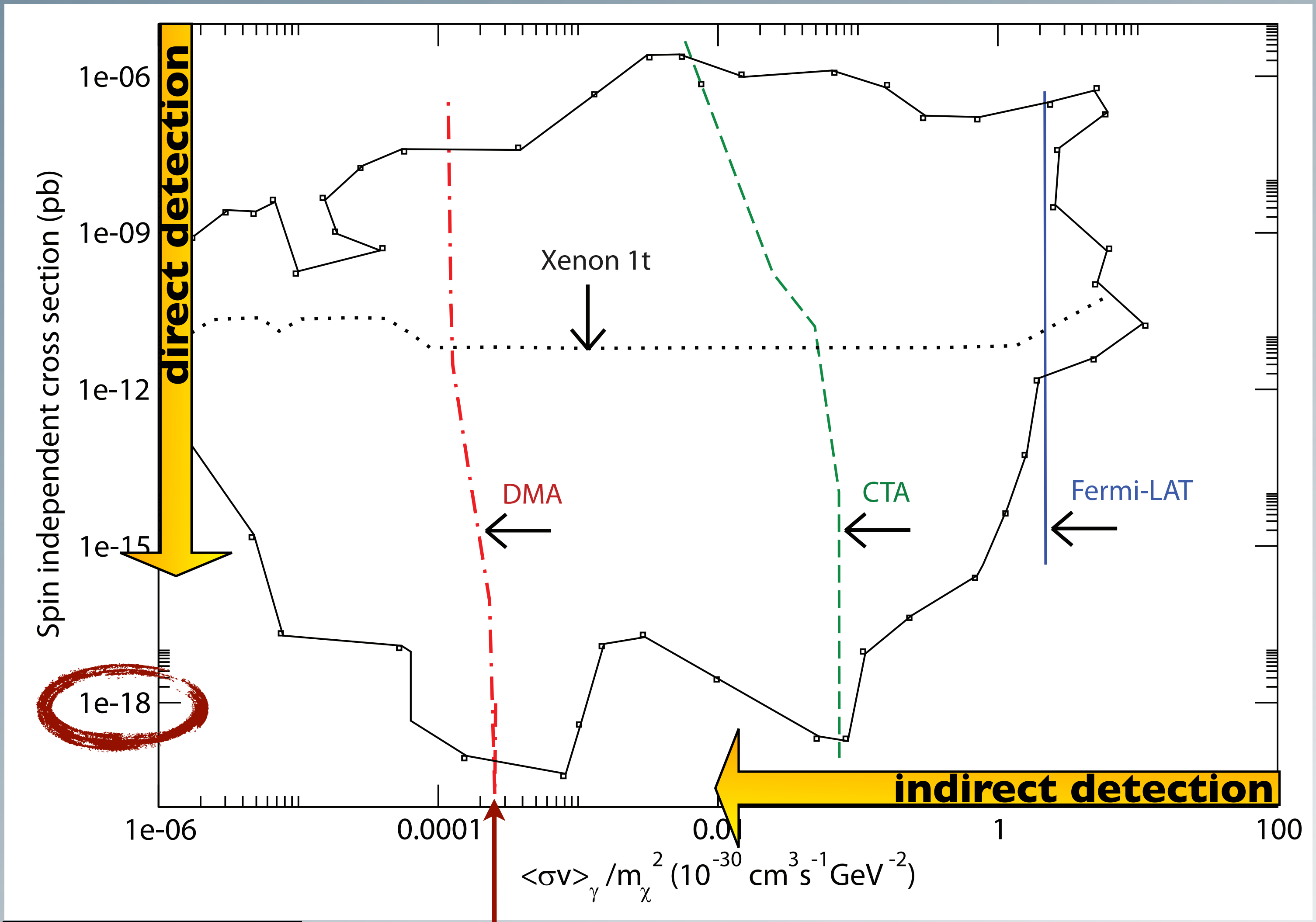
Aprile *et al.*, PRL '12



lower limit to $\sigma_{\rm SI}$?

(Far) future of DM searches

- MSSM scan
  - relic density, pre-LHC bounds OK
- Galactic center:
  - NFW
  - no boost factor
- The "Dark Matter Array":
  - 10 x A_{eff}(CTA)
  - E > 10 GeV
  - dedicated: t_{obs} ~5000 hrs



Bergström, TB & Edsjö, PRD '11
Bergström, 1205.4882

health warning: this assumes zero systematic uncertainty!

DarkSUSY

P. Gondolo, J. Edsjö, P. Ullio, L. Bergström, M. Schelke, E.A. Baltz, T. Bringmann and G. Duda

FREE DOWNLOAD ;)

http://darksusy.org

- Fortran package to calculate "all" DM related quantities:
  - *relic density + kinetic decoupling*
  - *generic SUSY models + laboratory constraints implemented*
  - *cosmic ray propagation*
  - *indirect detection rates: gammas, positrons, antiprotons, neutrinos*
  - direct detection rates
  - ...

➡ *new (more modular) version 6 to come!*

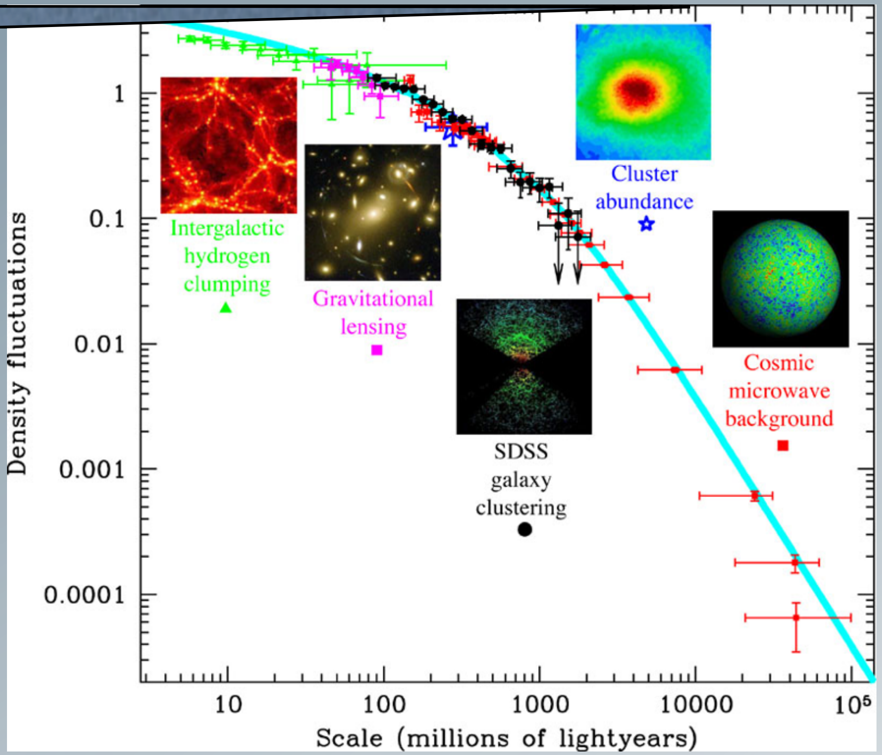
Backup slides

Density perturbations

- Observed structures in the universe seeded by tiny primordial inhomogeneities:

$$\rho(\mathbf{x},t) = \bar\rho(t)\left[1+\delta(\mathbf{x},t)\right]$$

- Gravity makes δ grow...
  - only 'inside the horizon' ($\rightsquigarrow$ full GR!)
  - Evolution of δ_i depends on both a) background *and* b) component *i*



M. Tegmark

e.g.: $\delta_\chi(t) \propto \begin{cases} \ln a(t) & \text{for } t < t_{\rm eq} \\ a(t) & \text{for } t > t_{\rm eq} \end{cases}$

- Spectrum usually assumed uncorrelated and isotropic:

$$\langle \delta_{\mathbf{k}} \delta^*_{\mathbf{k}'} \rangle \equiv \frac{2\pi^2}{k^3} \mathcal{P}_\delta(k)\, \delta(\mathbf{k}-\mathbf{k}')$$

  - scale-free spectrum: $\mathcal{P}_\delta(k) \propto k^{n+3}$
  - For $n=1$, the mass variance $\left\langle |\delta_R(\mathbf{x})|^2 \right\rangle$ *at horizon crossing* is independent of R

IB features with Fermi?

TB, Huang, Ibarra, Vogl & Weniger, JCAP '12

- Introduce simplified toy model with minimal field content to get strong IB signals
  [~same as sfermion co-annihilation region in SUSY]

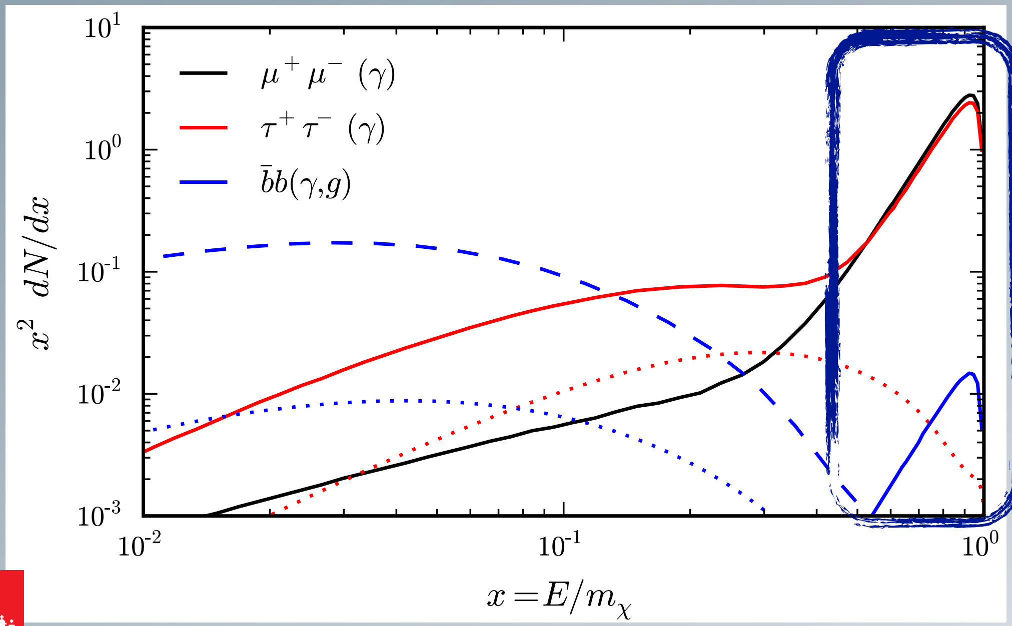
$$\mathcal{L}_\chi = \frac{1}{2}\bar{\chi}^c i\partial\!\!\!/ \chi - \frac{1}{2} m_\chi \bar{\chi}^c \chi$$ Majorana DM particle

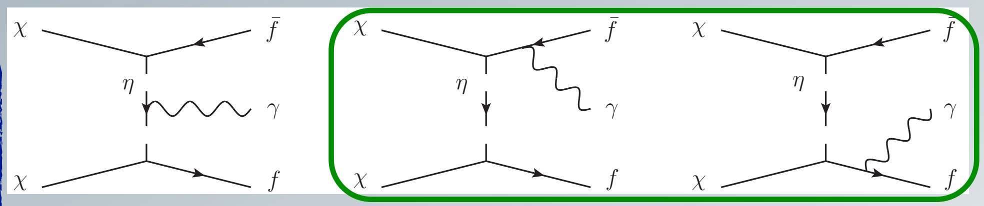
$$\mathcal{L}_\eta = (D_\mu \eta)^\dagger (D^\mu \eta) - m_\eta^2 \eta^\dagger \eta$$ SU(2) singlet scalar

$$\mathcal{L}_{\rm int} = -y \bar{\chi} \Psi_R \eta + {\rm h.c.}$$ τ, μ, b Yukawa interaction term

~MSSM: $\eta \rightarrow \tilde{f}_L, \tilde{f}_R$

couplings $y_{R,L}$ *fixed!*





solid: full 3-body

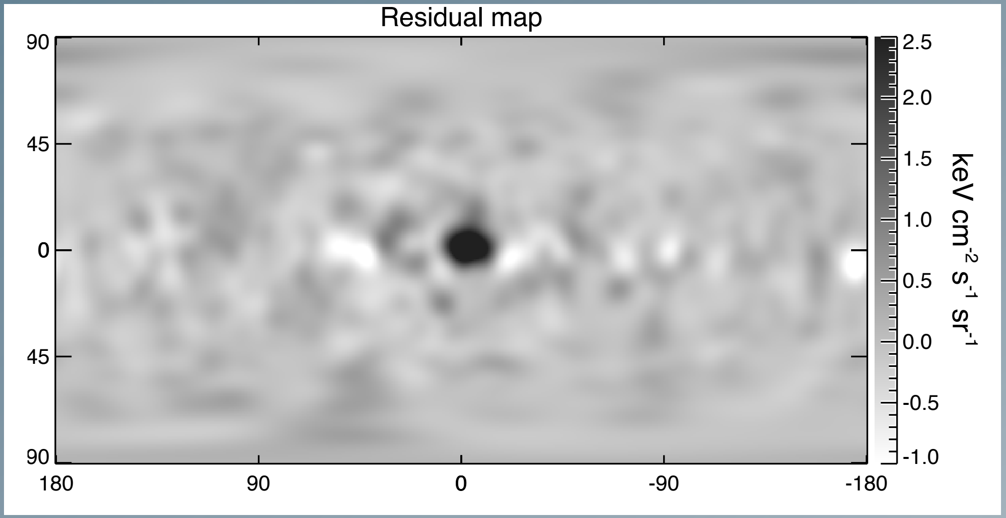
dotted: 2-body + FSR

(dashed: photons from $\bar{b}bg$)

focus on this part!

'Strong evidence'

Su & Finkbeiner, 1206.1616

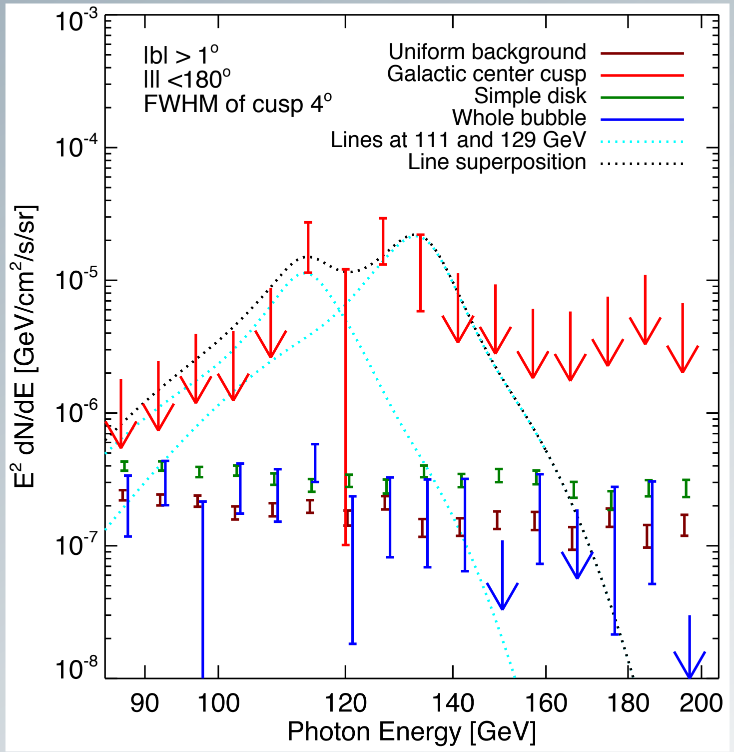


- 120-140 GeV residual map
  - created by subtracting background estimate = $E^2 dN/dE$ average of (80-100,100-120, 160-180) maps
  - all maps smoothed with FWHM=10°
  - no similar structure seen elsewhere
  - ~no difference with(out) point sources

- Template regression analysis (fit linear combinations of spatial templates)

- *Global* significance in σ

	one line	two lines
Gauss	3.7	4.3
NFW	4.5	4.9
Einasto	5.1	5.5



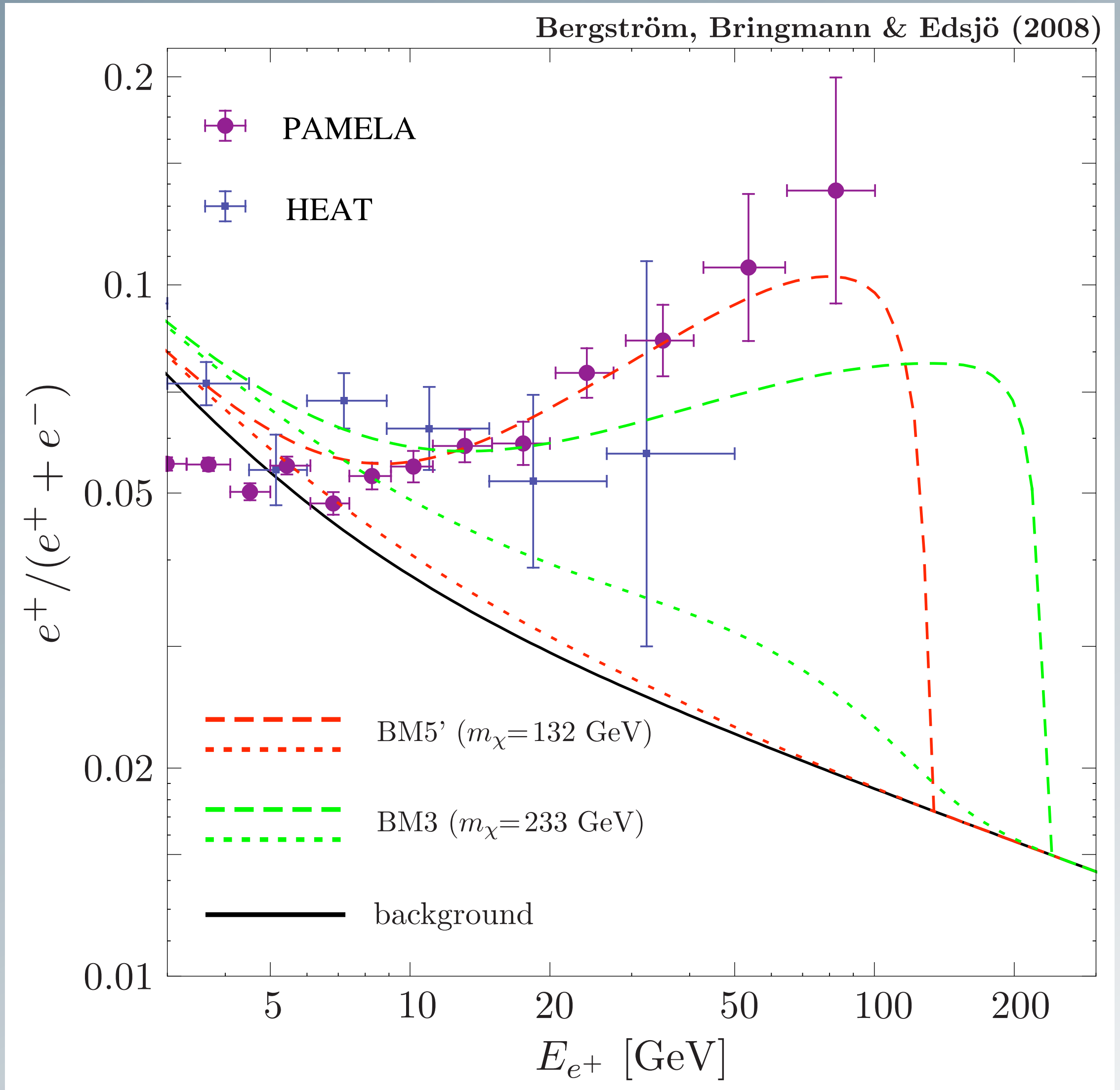
SUSY DM and PAMELA

- Neutralino annihilation ~~helicity~~ suppressed:

$$\langle \sigma v \rangle \propto \frac{m_\ell^2}{m_\chi^2} \quad \frac{\alpha_{\rm em}}{\pi}$$

- Surprisingly hard spectra possible if $\chi\chi \to e^+ e^- \gamma$ dominates!
  [first attempt to connect PAMELA to DM]

- ***but***: enormous boost factors needed w.r.t. thermal cross section...



Bergström, TB & Edsjö, PRD '08