INDIRECT SEARCHES FOR DARK MATTER WITH FUTURE GROUND-BASED GAMMA RAY EXPERIMENTS

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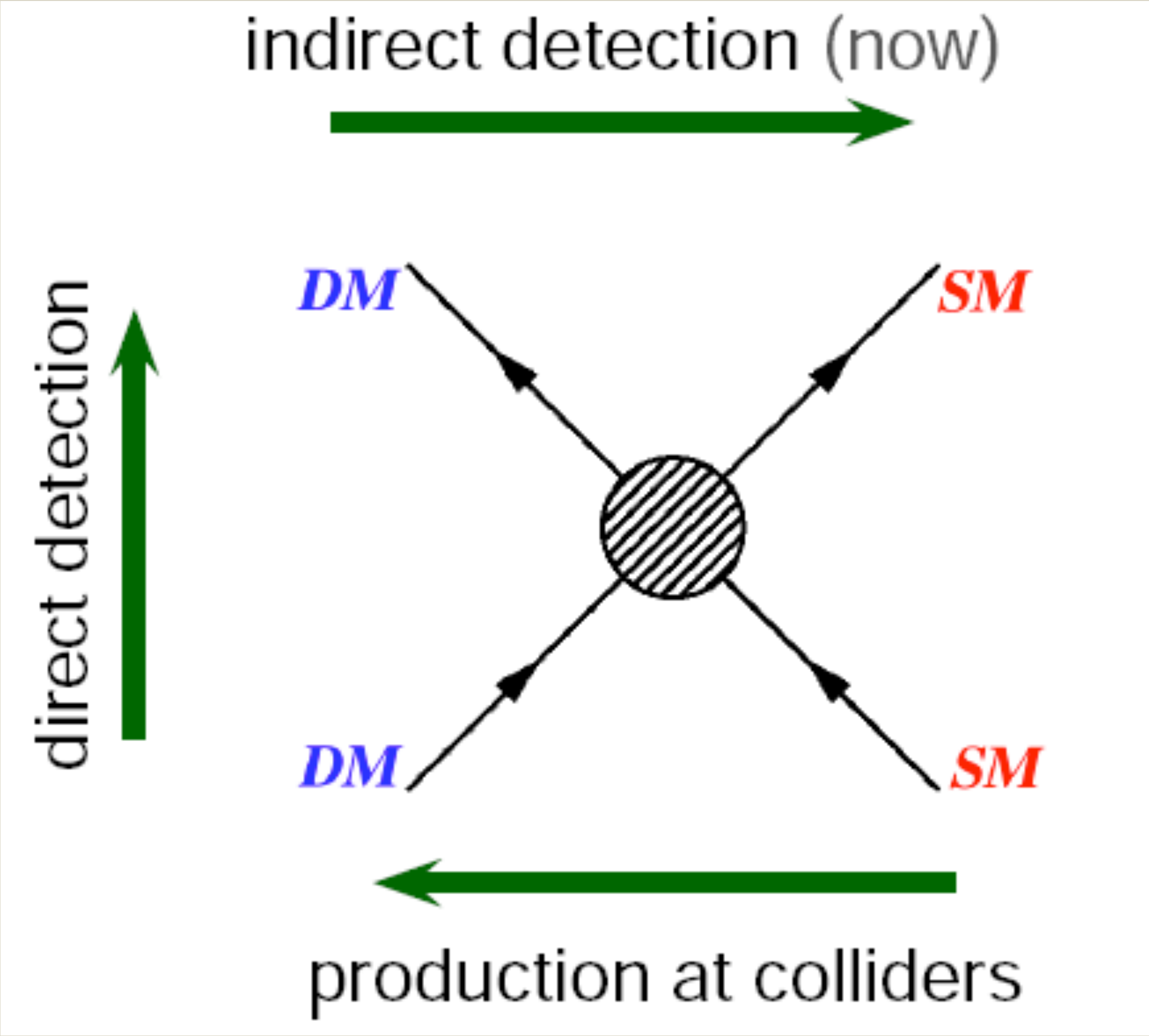
Latest Results on Dark Matter Conference, Stockholm, 2014/05/12-14

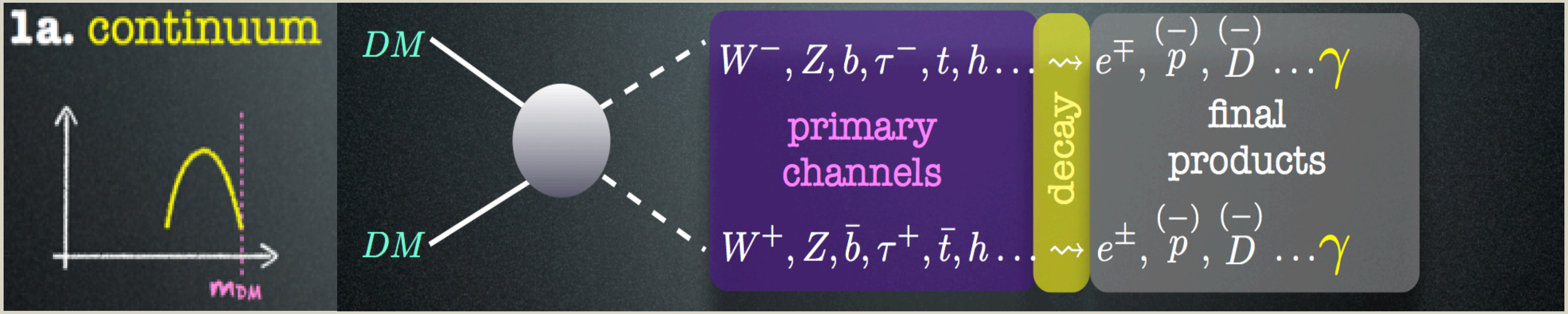
WHY GAMMA-RAYS ARE IMPORTANT

(for DM searches)

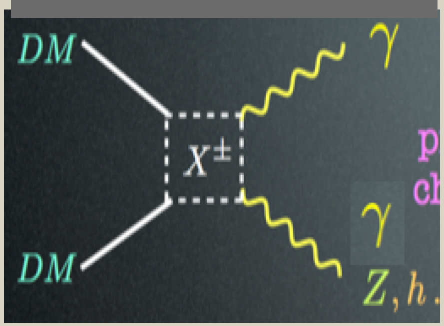
THREE WAYS TO RULE THEM ALL



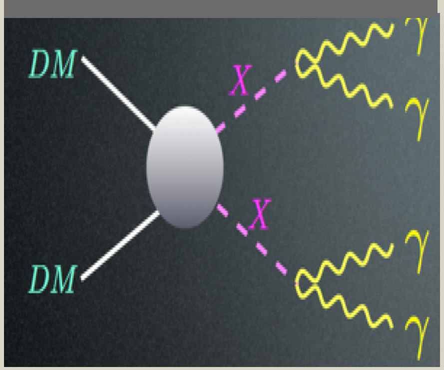
GAMMAS IN THE FINAL PRODUCTS

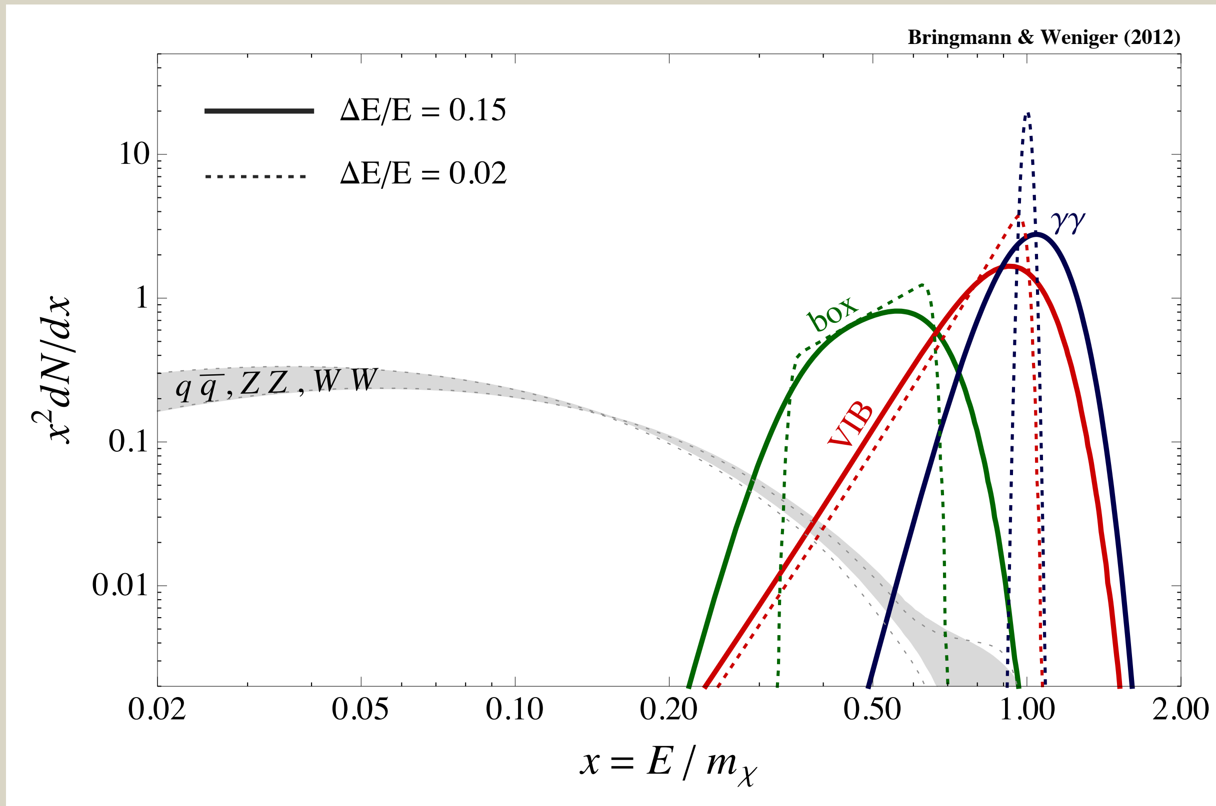


2. Lines



3. Other features





GAMMA RAYS PROVIDE SMOKING GUN

- **Universal**: they do not depend on the target
- **Peculiar features**: clearly identifiable (but: energy resolution)
- Gamma-ray are **neutral**: we can point the telescope where we know DM is
- **Identification** of dark matter with gamma rays is possible (besides detection!)
  - Measurement of dark matter mass
  - Measurement of dark matter nature

Worth fighting for!

FLUX AT THE EARTH

$$\frac{d\Phi_\gamma}{dE} = \frac{d\Phi_\gamma^{PP}}{dE} \times J(\Omega)$$

Rico 2013

Annihilation

$$\frac{d\Phi_\gamma^{PP}}{dE} = \frac{\langle \sigma v \rangle}{8\pi m_\chi^2} \frac{dN_\gamma}{dE}$$

$$J(\Omega) = \int_\Omega \int_{los} \rho^2(r) dr d\Omega$$

Decay

$$\frac{d\Phi_\gamma^{PP}}{dE} = \frac{1}{4\pi m_\chi \tau_\chi} \frac{dN_\gamma}{dE}$$

$$J(\Omega) = \int_\Omega \int_{los} \rho(r) dr d\Omega$$

$d\Phi_\gamma^{PP}/dE$ is the *particle-physics term*, determined by nature of DM particle
dN_γ/dE contains information of spectral shape
$J(\Omega)$ is the *astrophysical factor*, depends on DM distribution (and aperture)

Kolb 2013

Particle Dark Matter Taxonomy

• neutrinos (WIMPs exist!!!)	(hot)	thermal relics or decay of or oscillation from thermal relics
• sterile neutrinos, gravitini	(warm)	
• Lightest supersymmetric particle	(cold)	
• Lightest Kaluza-Klein particle	(cold)	
• Bose-Einstein condensates	coherent state of a scalar field	nonthermal relics
• axions, axion clusters		
• solitons (Q-balls, B-balls, …)		
• supermassive wimpzillas	from inflation	

Mass

10^{-22} eV (10^{-56} g) Bose-Einstein

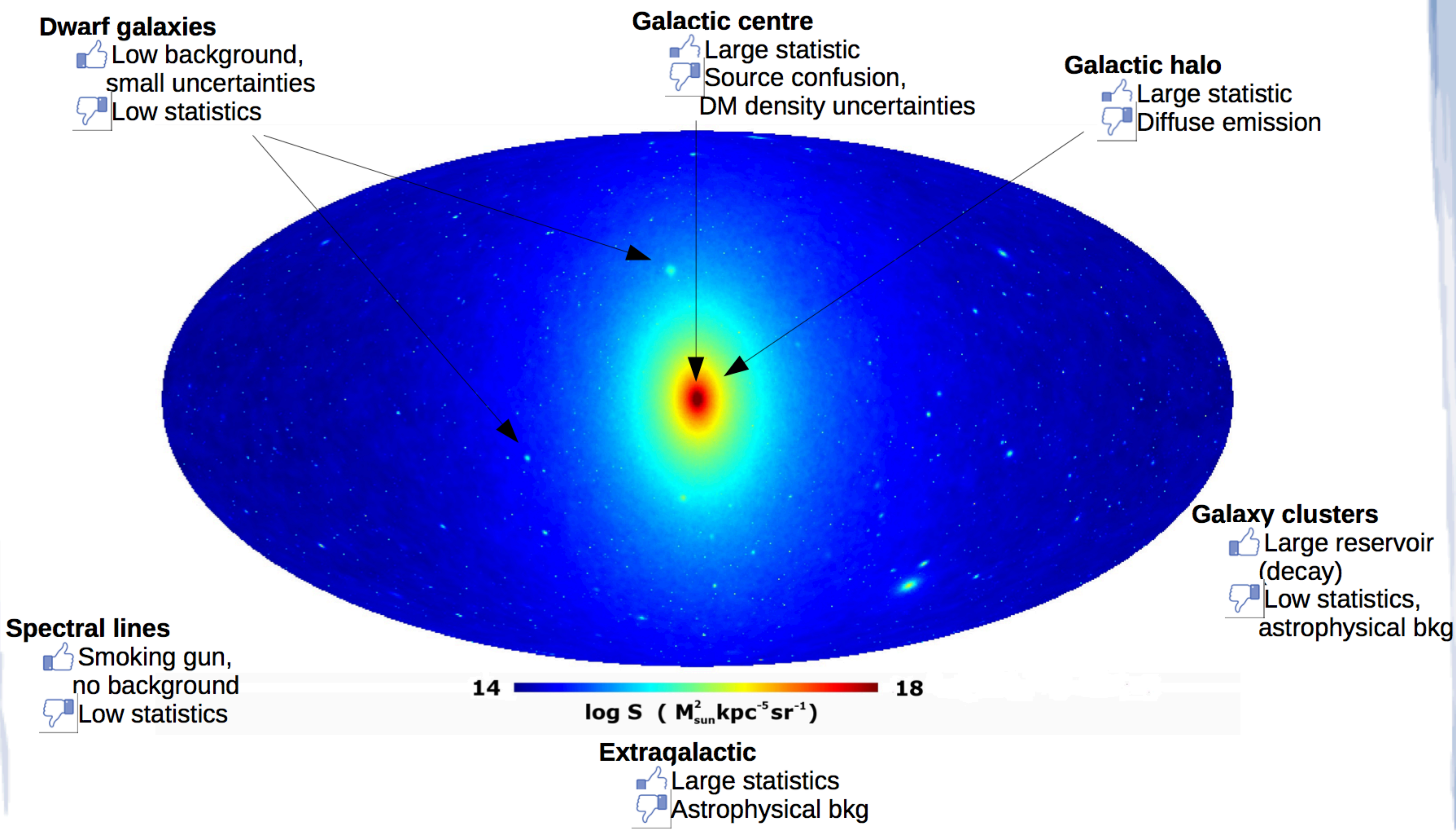
$10^{-8} M_{\odot}$ (10^{+25} g) axion clusters

Interaction Strength

only gravitational: wimpzillas

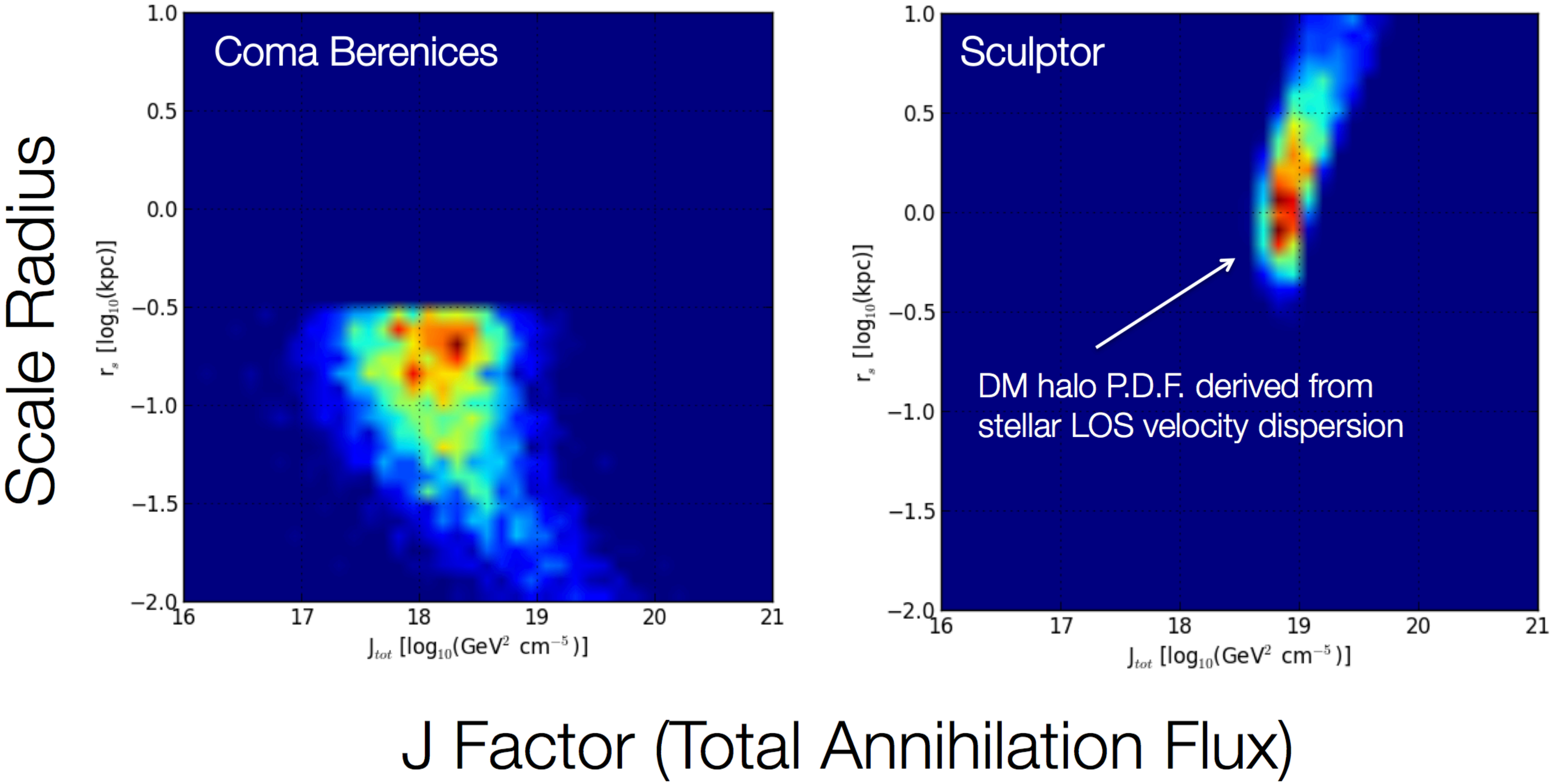
strongly interacting: B balls

WHERE TO POINT THE TELESCOPES



J-FACTOR

DM Halo Constraints (NFW)



Wood 2014

HESS, MAGIC AND VERITAS

Current telescopes

CURRENT MAJOR IACT EXPERIMENTS

VERITAS (Arizona, USA)

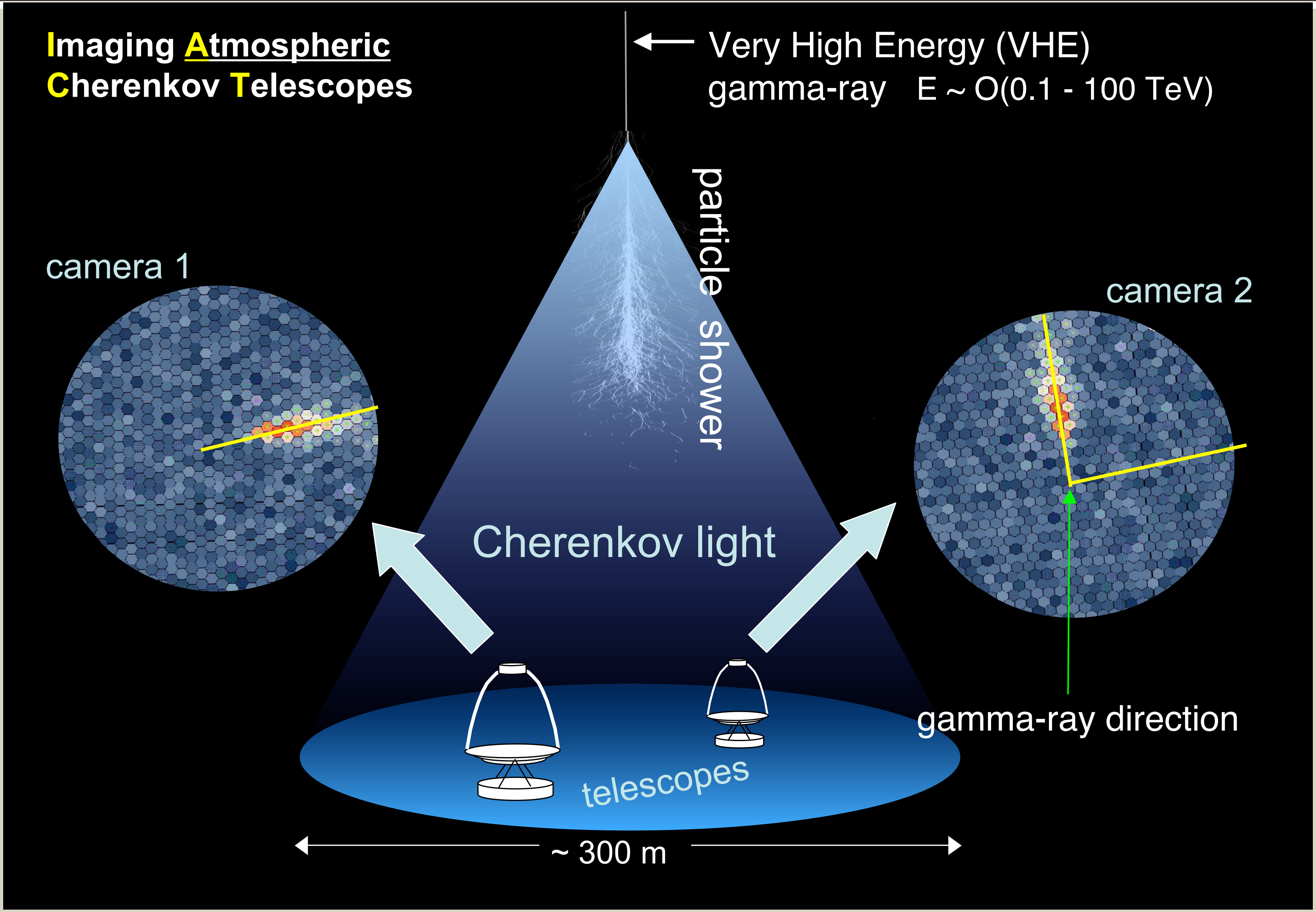
Array 4 telescopes of 12m diam.
Central mast mounting
1300 m asl
>2007

Array 2 telescopes
17m diameters
2200 m asl
>2004

HESS (Namibia)

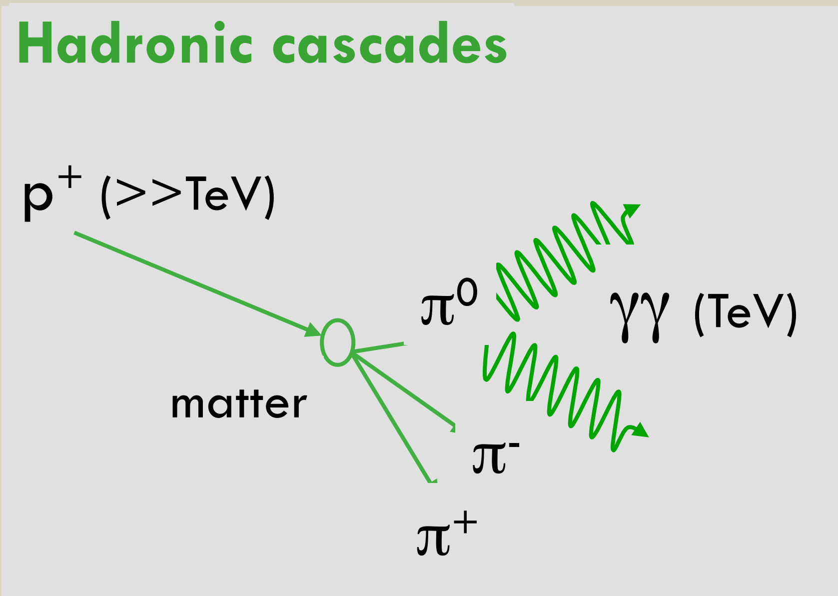
HESS I: Array 4 tel. of 12m
HESS II: 28m diameter (2013?)
1800 m asl
> 2003

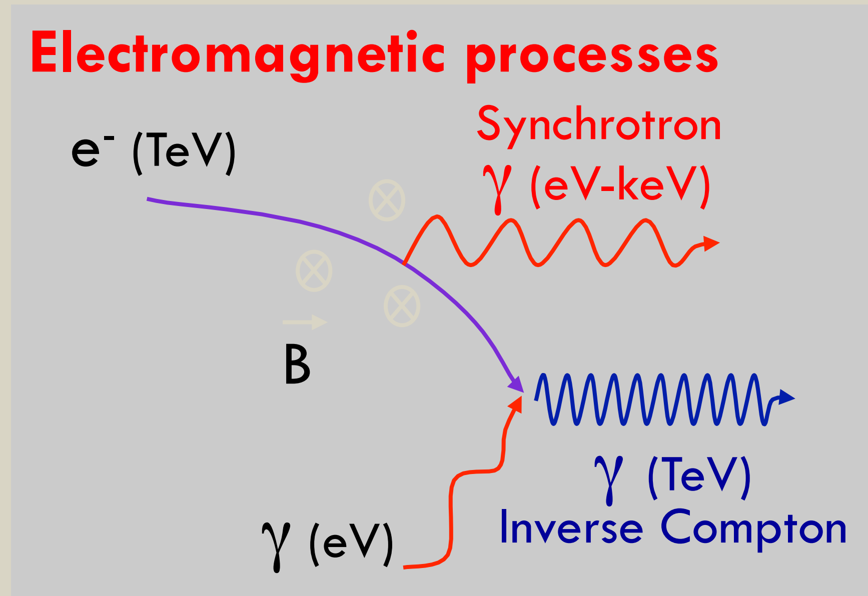
THE IACT TECHNIQUE



GAMMA RAYS TRACE COSMIC RAYS

- Gamma rays trace charged cosmic rays

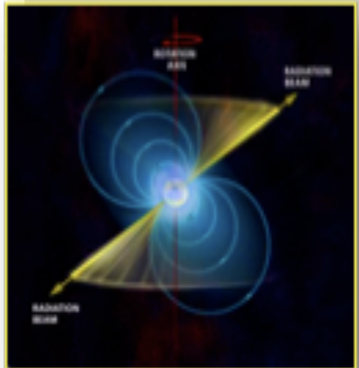




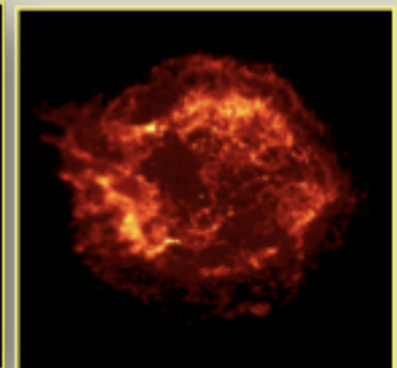
- Cosmic-ray physics (origin, mechanisms)
- Jet physics, magneto hydrodynamics, magnetic turbulence, etc.
- Fundamental physics (DM, ALPs, LIV)

TARGETS

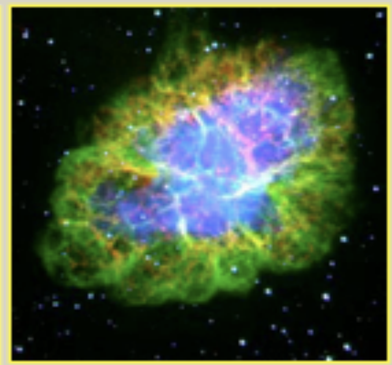
- Galactic targets



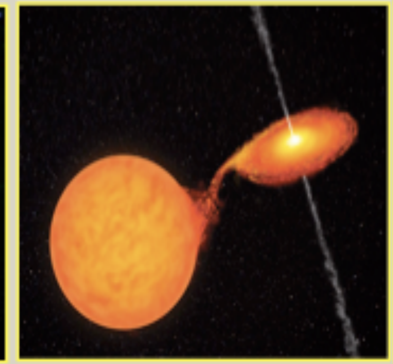
Pulsar



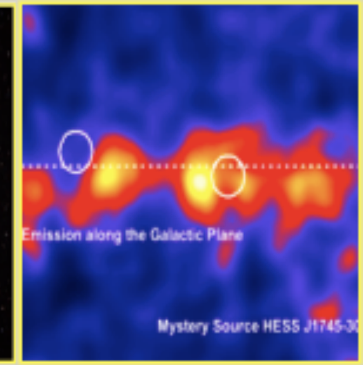
Supernova Remnants



Pulsar wind nebulae



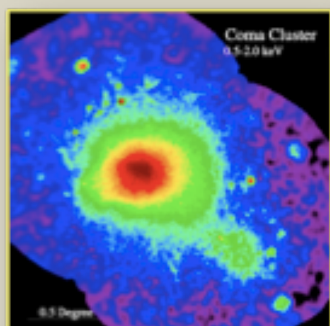
Micro-quasars



Galactic center

- Extragalactic targets

Active Galactic Nuclei



Galaxy Cluster

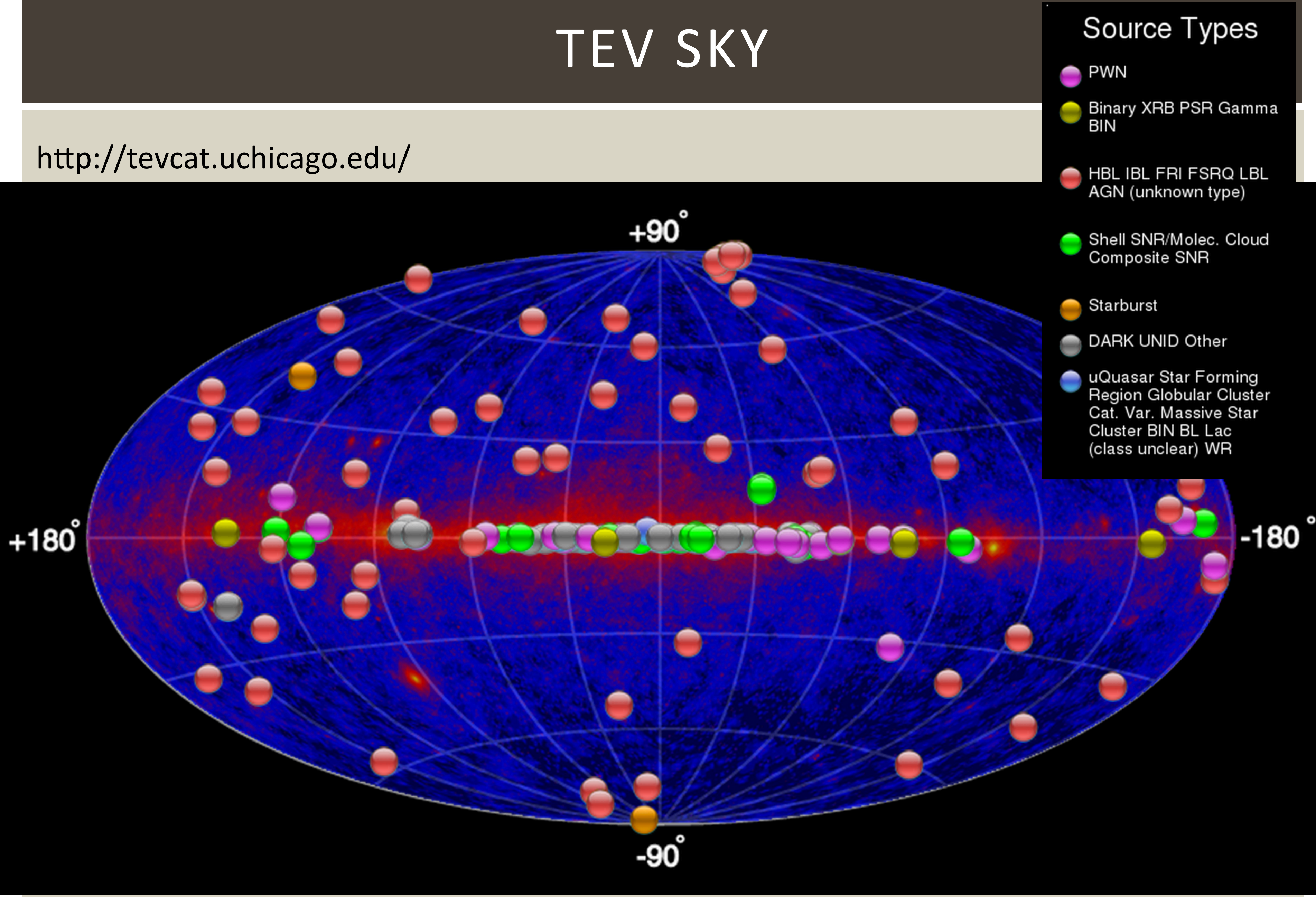
Starburst galaxies

Merging Galaxies

Gamma-ray Bursts

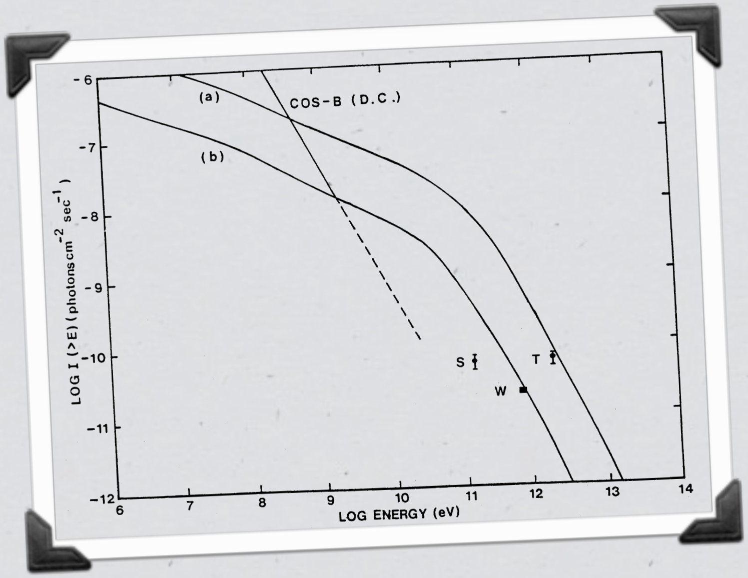
TEV SKY

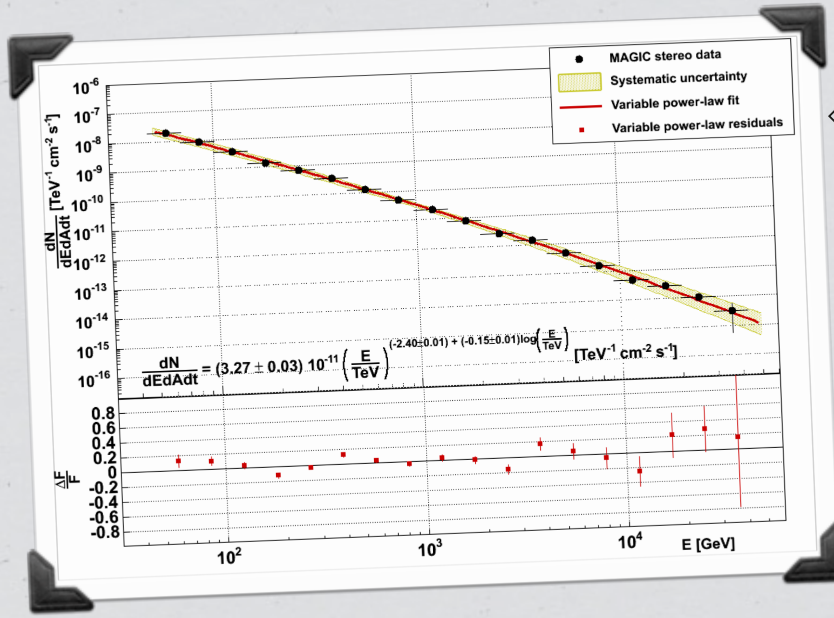
http://tevcat.uchicago.edu/

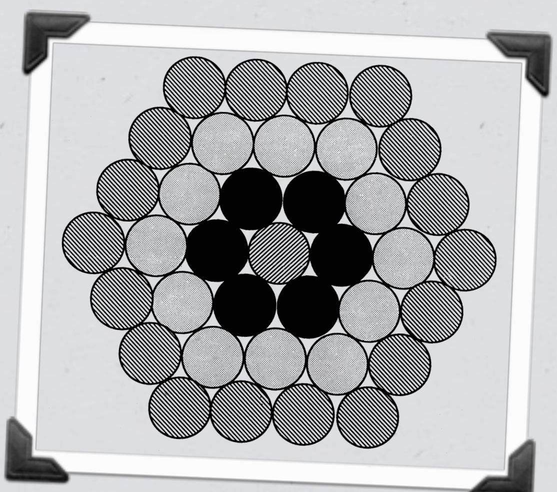


Family album

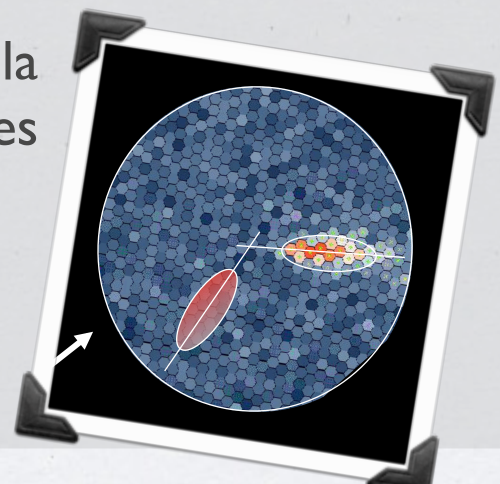
1989: When I first saw the Crab Nebula with Whipple



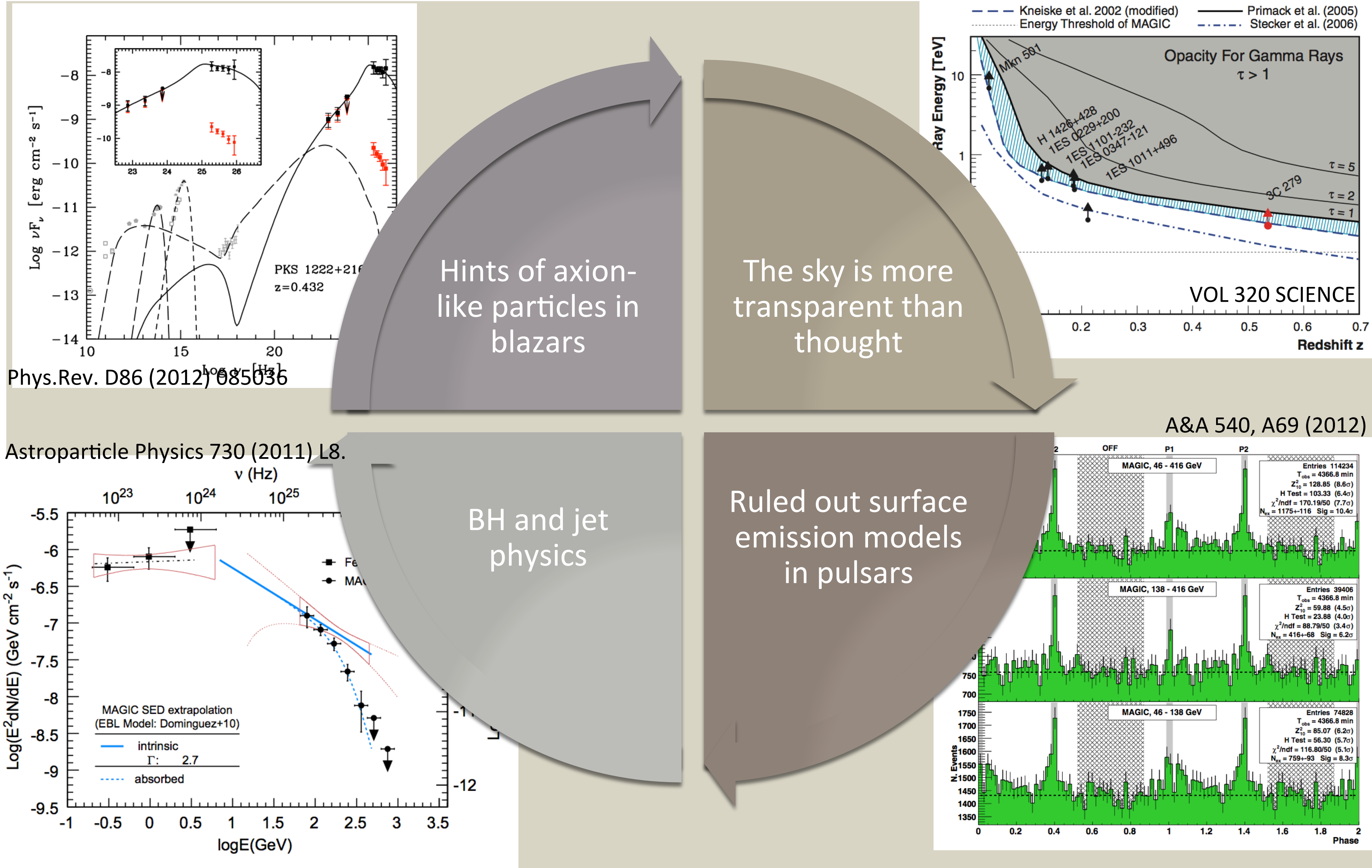




2012: Crab Nebula with MAGIC eyes

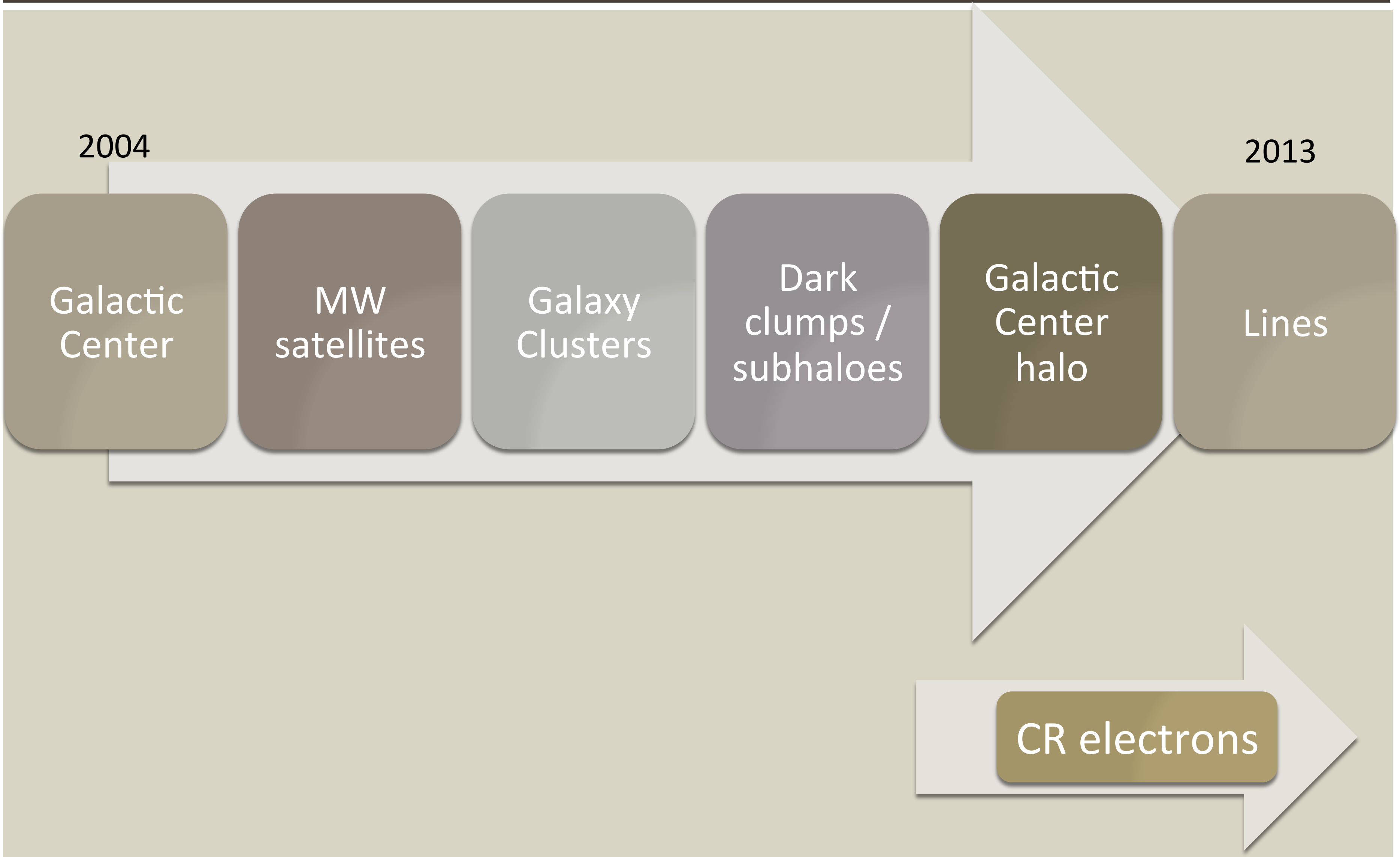


SOME RESULTS



DARK MATTER SEARCHES

(APPROX.) HISTORY OF A HUNT



Target	Year	Time	Experiment	Ref.
Globular Clusters				
M15	2002	0.2	Whipple	[5]
	2006 – 2007	15.2	H.E.S.S.	[6]
M33	2002 – 2004	7.9	Whipple	[5]
M32	2004	6.9	Whipple	[5]
NGC 6388	2008 – 2009	27.2	H.E.S.S.	[6]
Dwarf Satellite Galaxies				
Draco	2003	7.4	Whipple	[5]
	2007	7.8	MAGIC	[7]
	2007	18.4	VERITAS	[8]
Ursa Minor	2003	7.9	Whipple	[5]
	2007	18.9	VERITAS	[8]
Sagittarius	2006	11	H.E.S.S.	[9]
Canis Major	2006	9.6	H.E.S.S.	[10]
Willman 1	2007 – 2008	13.7	VERITAS	[8]
	2008	15.5	MAGIC	[11]
Sculptor	2008	11.8	H.E.S.S.	[12]
Carina	2008 – 2009	14.8	H.E.S.S.	[12]
Segue 1	2008 – 2009	29.4	MAGIC	[13]
	2010 – 2011	48	VERITAS	[14]
	2010 – 2013	158	MAGIC	[15]
Boötes	2009	14.3	VERITAS	[8]
Galaxy Clusters				
Abell 2029	2003 – 2004	6	Whipple	[16]
Perseus	2004 – 2005	13.5	Whipple	[16]
	2008	24.4	MAGIC	[17]
Fornax	2005	14.5	H.E.S.S.	[18]
Coma	2008	18.6	VERITAS	[19]
The Milky Way central region				
MW Center	2004	48.7	H.E.S.S.	[20]
MW Center Halo	2004 – 2008	112	H.E.S.S.	[21]
Other searches				
IMBH	2004 – 2007	400	H.E.S.S.	[22]
	2006 – 2007	25	MAGIC	[23]
Lines	2004 – 2008	112	H.E.S.S.	[24]
	2010 – 2013	158	MAGIC	[15]
UFOs	–	–	MAGIC	[25]
	–	–	VERITAS	[26]
All-electron	2004 – 2007	239	H.E.S.S.	[27, 28]
	2009 – 2010	14	MAGIC	[29]
Moon-shadow	–	–	MAGIC	[30]

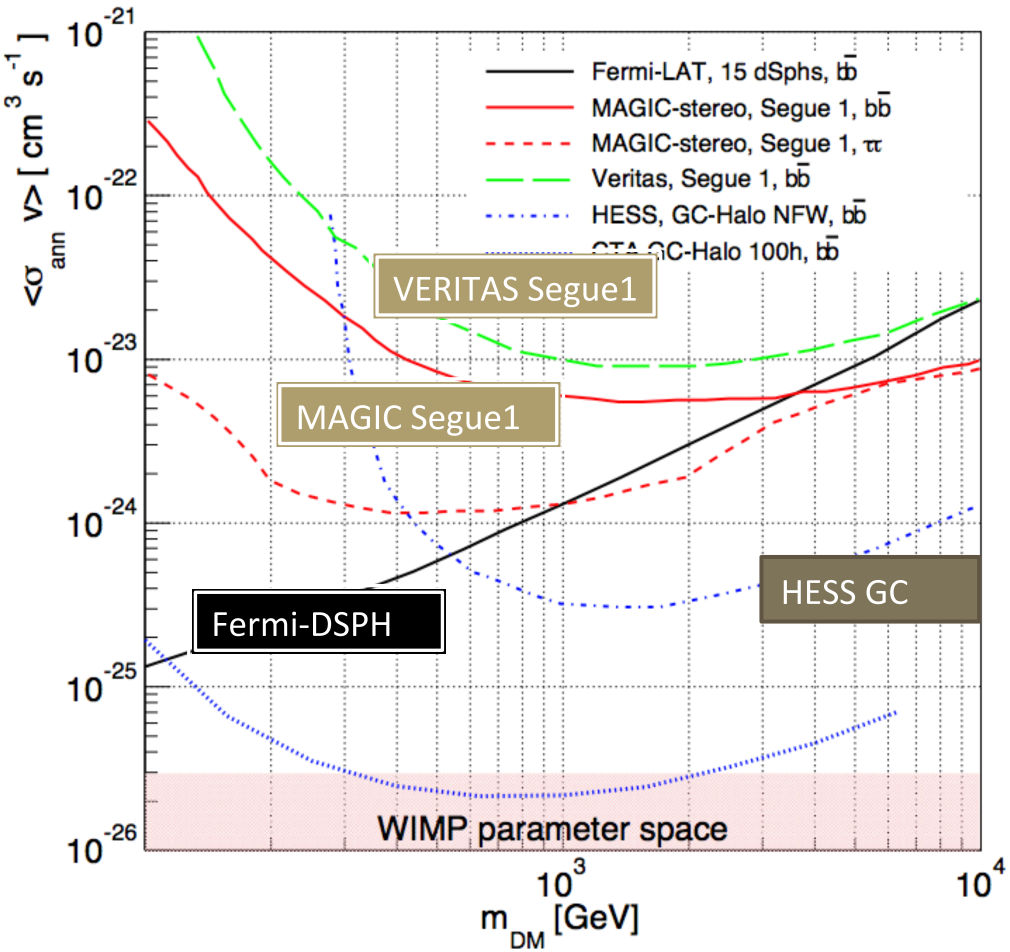
OUR CATALOG

- Several targets
- Tens of sources
- Thousands hour
- No hint
- Shall we stop? I will try to answer

M.Doro, NIMA 2014

ONE PLOT

- IACT versus FERMI-LAT

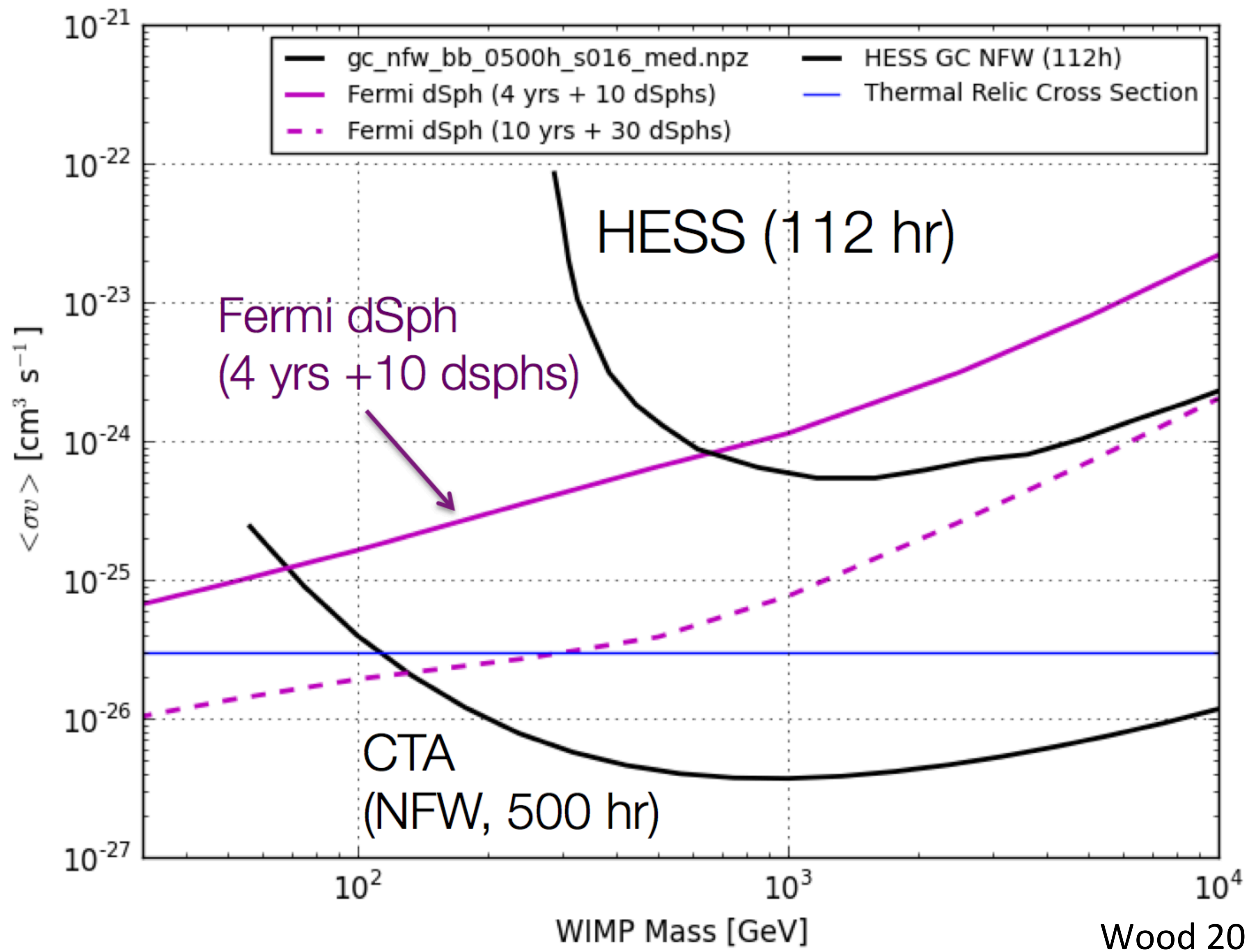


a-

Figure 2: Comparison of some exclusion lines for the Fermi-LAT observation of 15 combined DSGs for $b\bar{b}$ (solid black) [85], H.E.S.S. observation of the galactic center halo for the NFW (dot-dashed blue [21]) for the $b\bar{b}$ channel, MAGIC-stereo observations of the Segue 1 DSG for the $b\bar{b}$ (solid red) and $\tau^+\tau^-$ (dashed red) channels [15], Veritas observations of the Segue 1 DSG for $b\bar{b}$ (dashed green) [14], and for the estimation for 100 h observation at the galactic center halo with CTA (thick dashed blue) [54]. More details in the text.

M.Doro, NIMA 2014

CTA: NOW WE TALK SERIOUS!

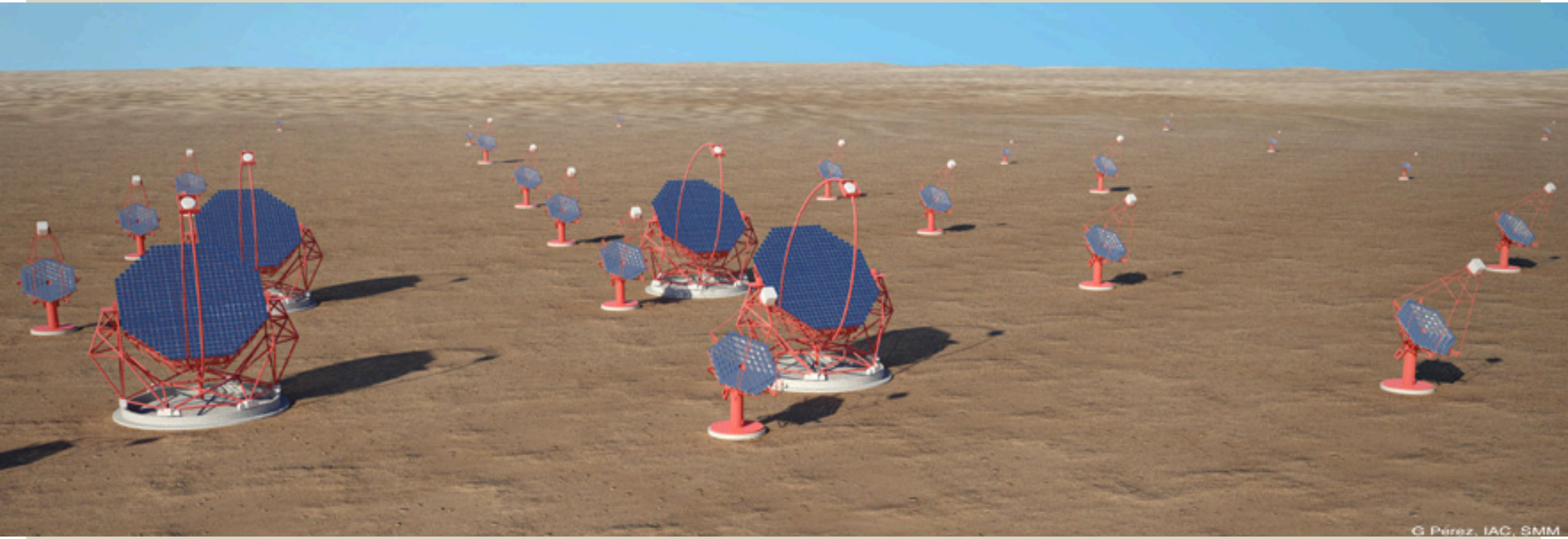


Wood 2014

WHAT IS CTA?

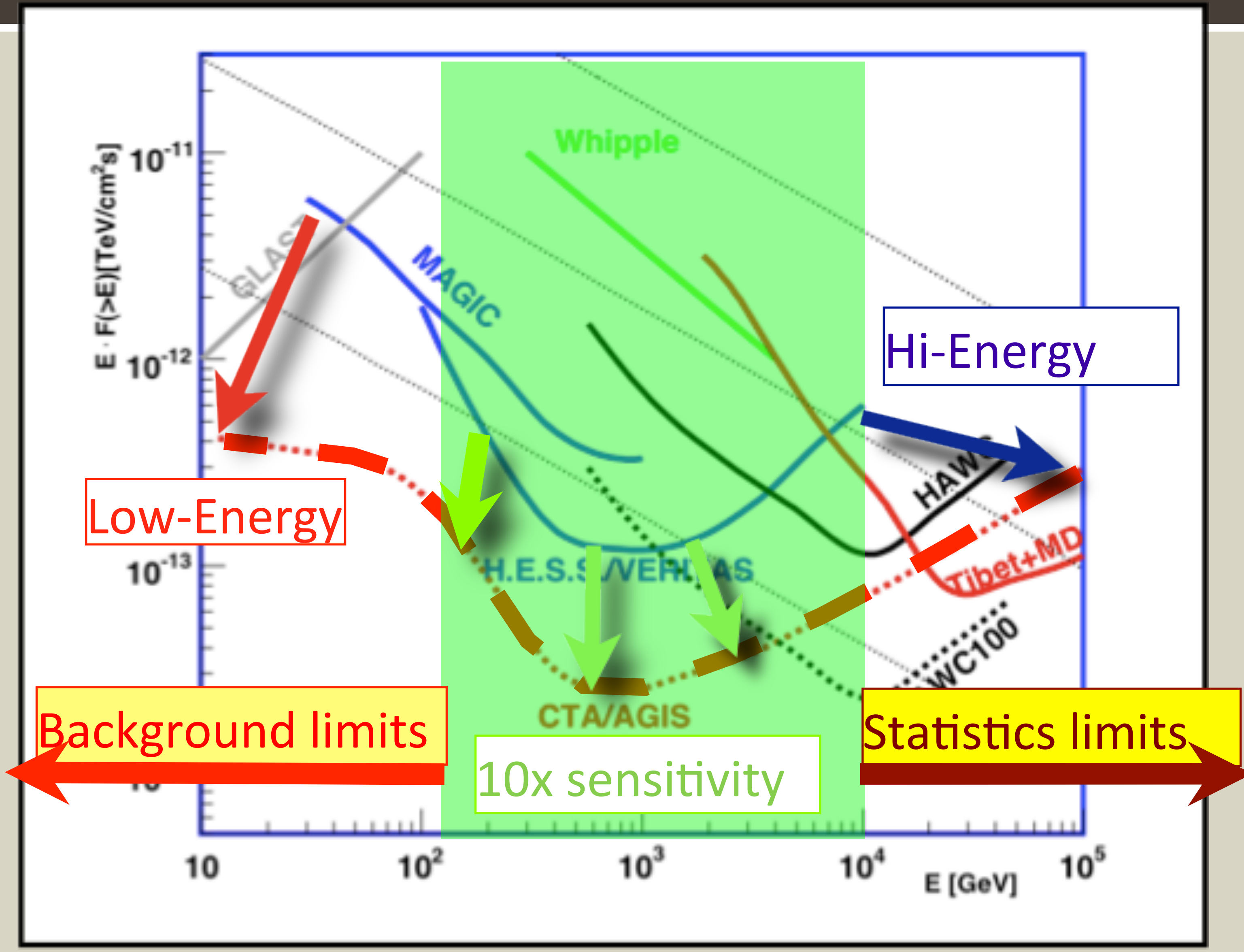
CHERENKOV TELESCOPE ARRAY

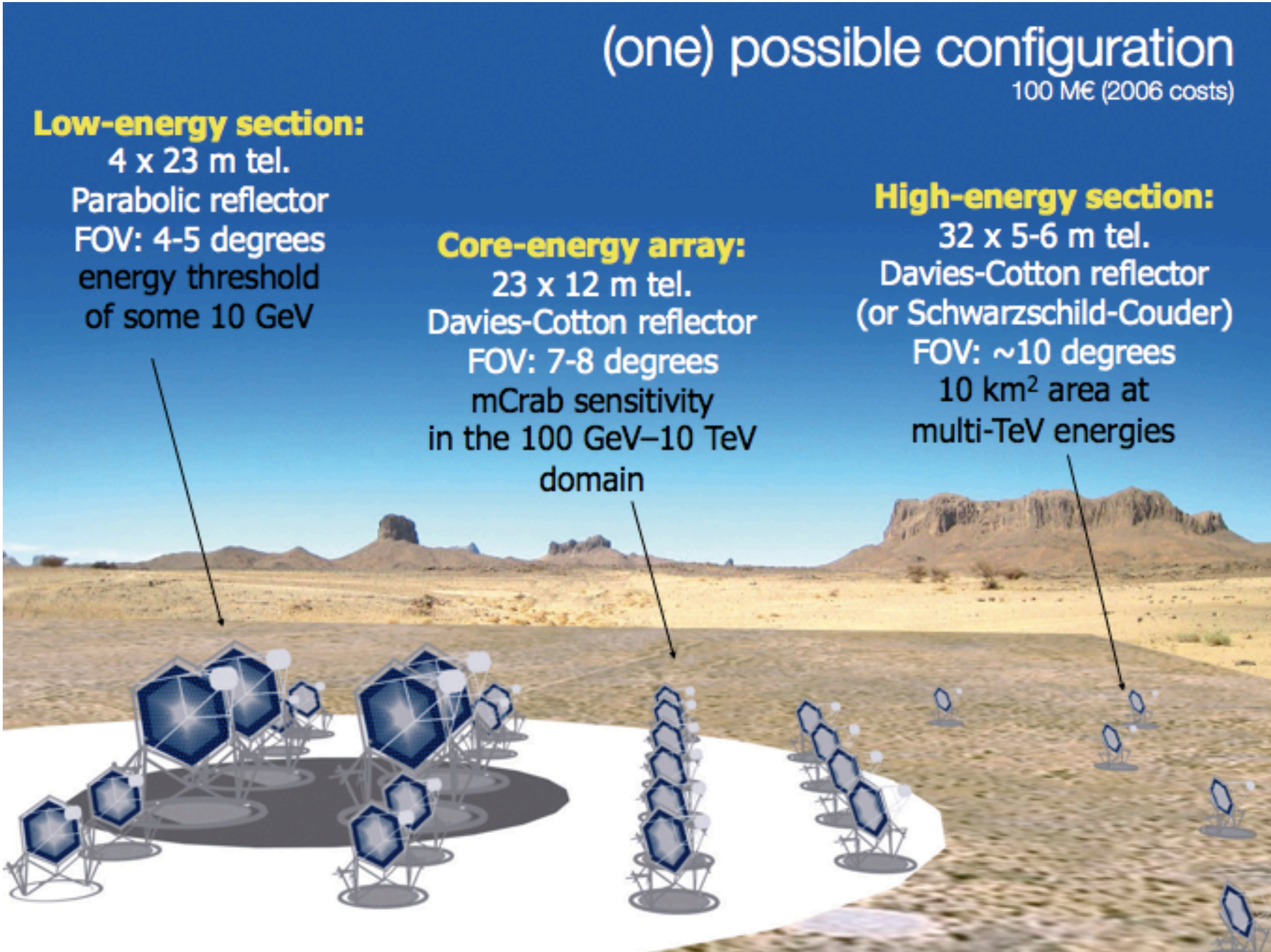
- A project for a new generation of Cherenkov Telescopes
- Precision gamma-ray astronomy and astrophysics from few tens of GeV to >100 TeV
- Two sites: one Southern and one Northern with about a hundred telescopes in total



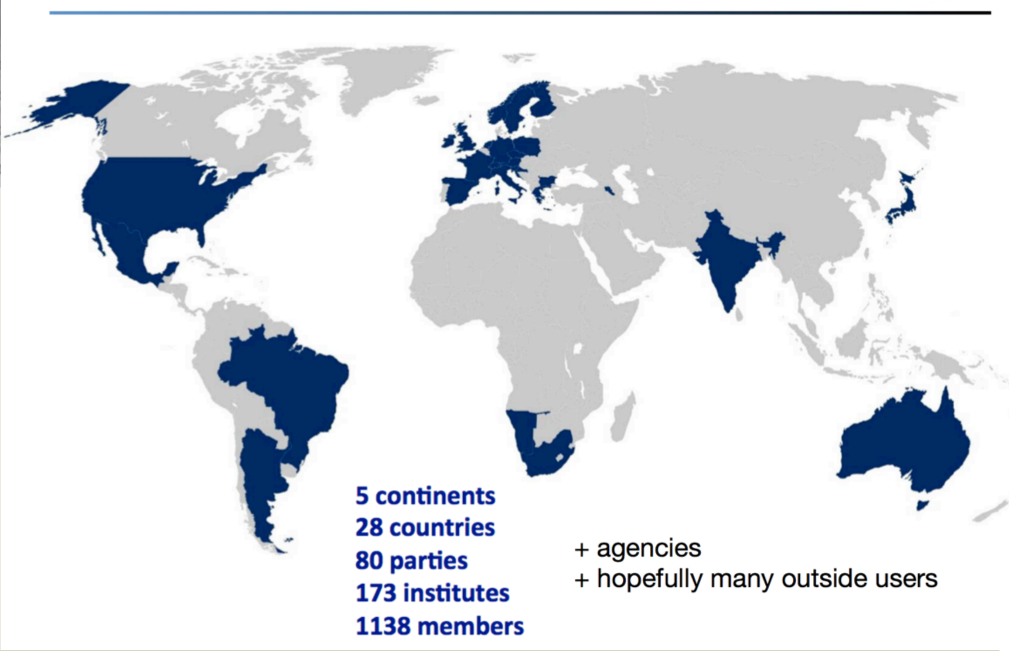
http://www.cta-observatory.org/

CTA SENSITIVITY IN 3 REGIMES




(one) possible configuration
100 M€ (2006 costs)
Low-energy section:
4 x 23 m tel.
Parabolic reflector
FOV: 4-5 degrees
energy threshold
of some 10 GeV
Core-energy array:
23 x 12 m tel.
Davies-Cotton reflector
FOV: 7-8 degrees
mCrab sensitivity
in the 100 GeV–10 TeV
domain
High-energy section:
32 x 5-6 m tel.
Davies-Cotton reflector
(or Schwarzschild-Couder)
FOV: ~10 degrees
10 km² area at
multi-TeV energies

A COLLABORATION THAT GROWS



* HESS+MAGIC+VERITAS collaborations + Europe + world interest (Japan, Argentina)
* US AGIS (Advanced Gamma-ray Imaging System) converged to CTA
* already ~170 institutes, ~28 countries (~ 1100 scientists)
* Regular meetings since 2007.

DESIGN CONCEPTS AND STATUS

Design Concepts for the Cherenkov Telescope Array

The CTA Consortium

(Submitted on 22 Aug 2010 (v1), last revised 21 Oct 2010 (this version, v2))

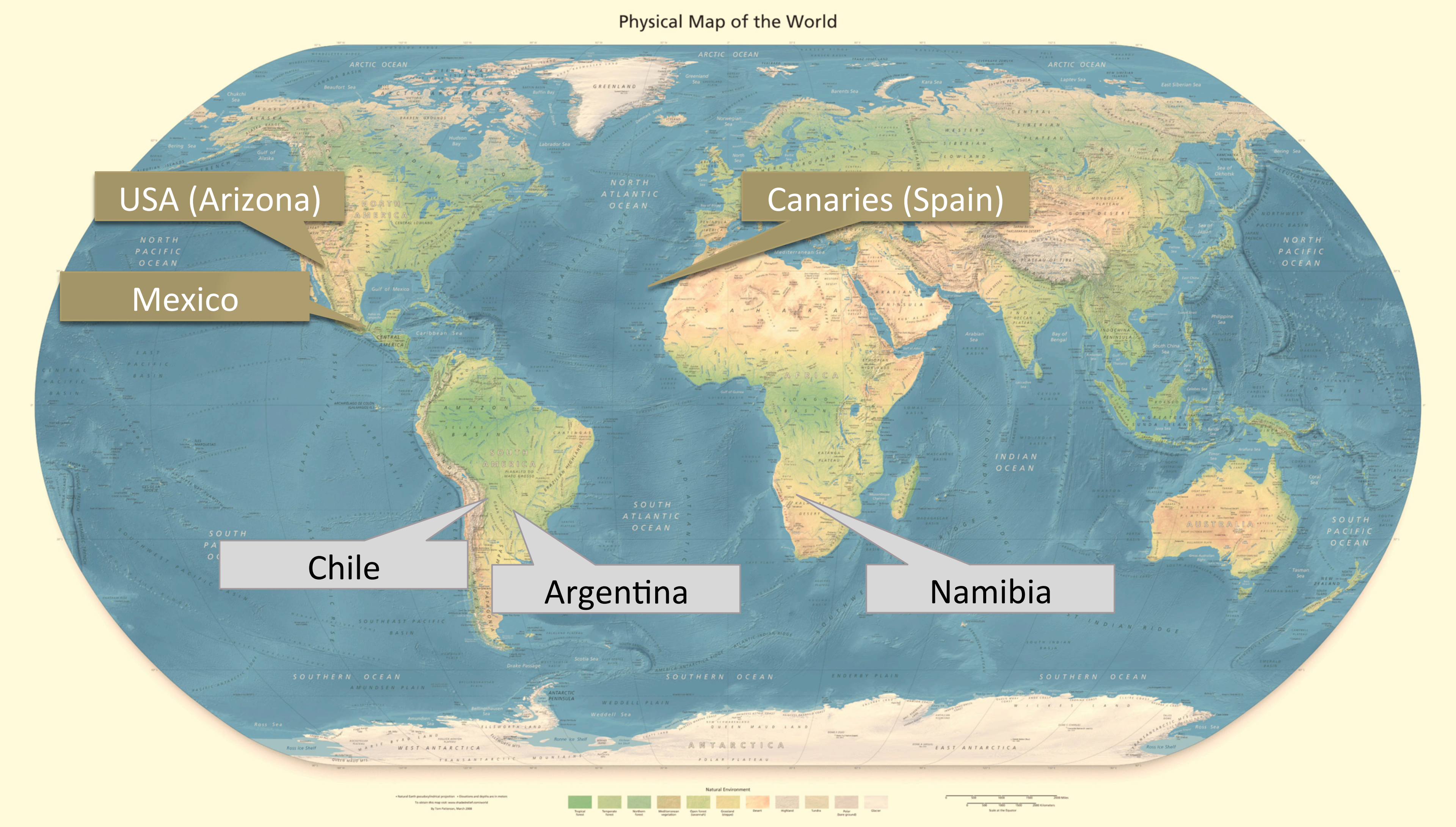
Ground-based gamma-ray astronomy has had a major breakthrough with the impressive results obtained using systems of imaging atmospheric Cherenkov telescopes. Ground-based gamma-ray astronomy has a huge potential in astrophysics, particle physics and cosmology. CTA is an international initiative to build the next generation instrument, with a factor of 5-10 improvement in sensitivity in the 100 GeV to 10 TeV range and the extension to energies well below 100 GeV and above 100 TeV. CTA will consist of two arrays (one in the north, one in the south) for full sky coverage and will be operated as open observatory. The design of CTA is based on currently available technology. This document reports on the status and presents the major design concepts of CTA.

Comments: 120 pages, 54 figures, 5 tables (with minor editorial changes)
Subjects: **Instrumentation and Methods for Astrophysics (astro-ph.IM)**; High Energy Astrophysical Phenomena (astro-ph.HE)
Cite as: **arXiv:1008.3703v2 [astro-ph.IM]**

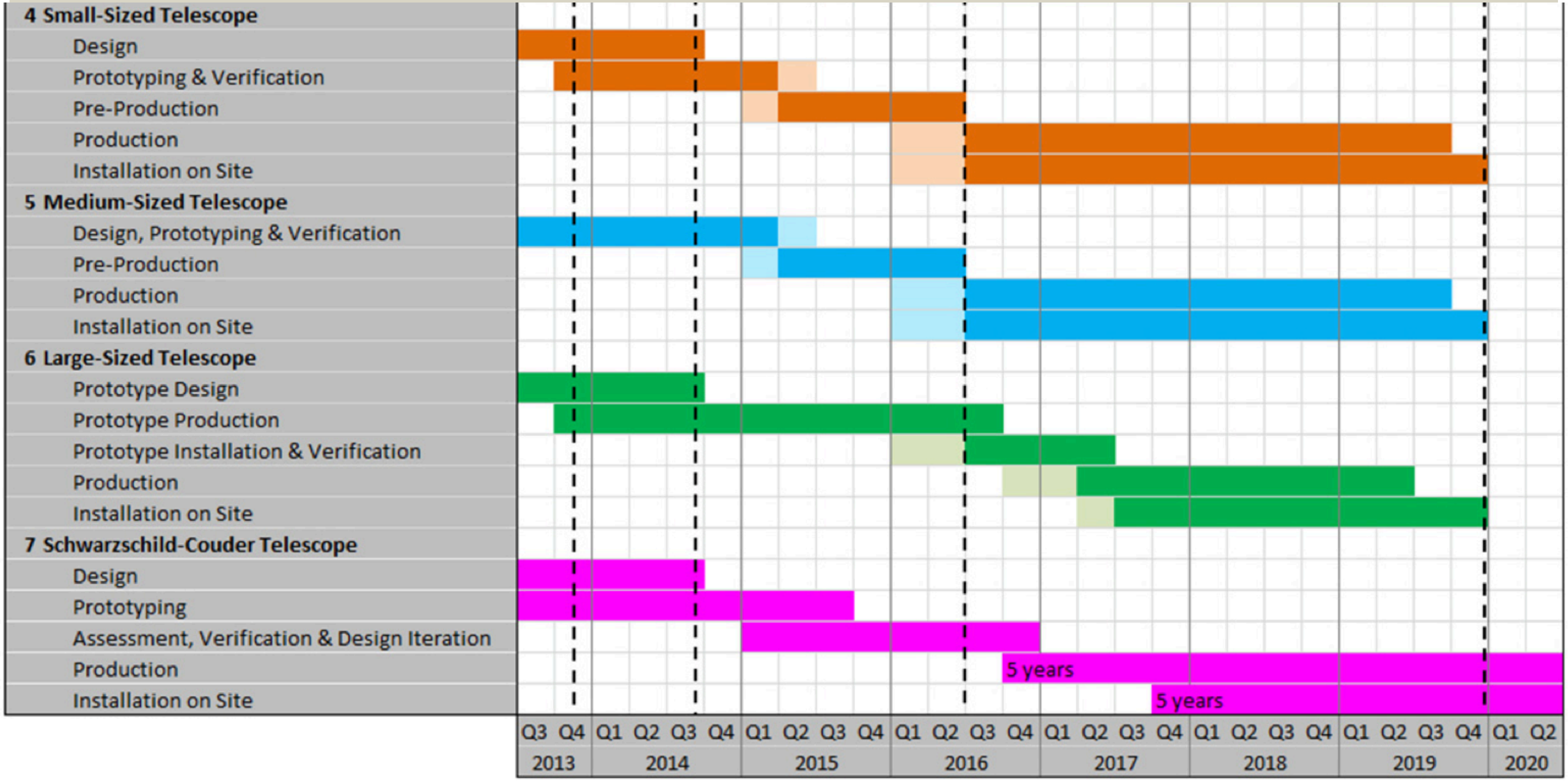
FP7-supported Preparatory Phase: Fall 2010 – Fall 2013
➜ Technical design, sites, construction and operation cost
➜ Legal, governance and finance schemes
➜ Small + medium-sized telescope prototypes

We are entering the Pre-Construction Phase

CANDIDATE SITES



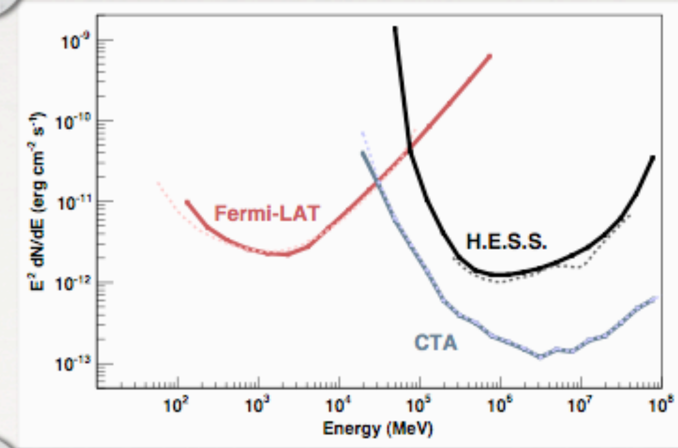
TELESCOPES (PRELIMINARY)

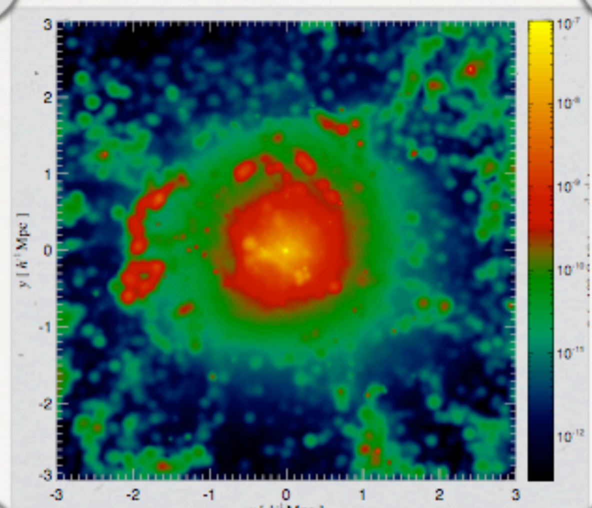


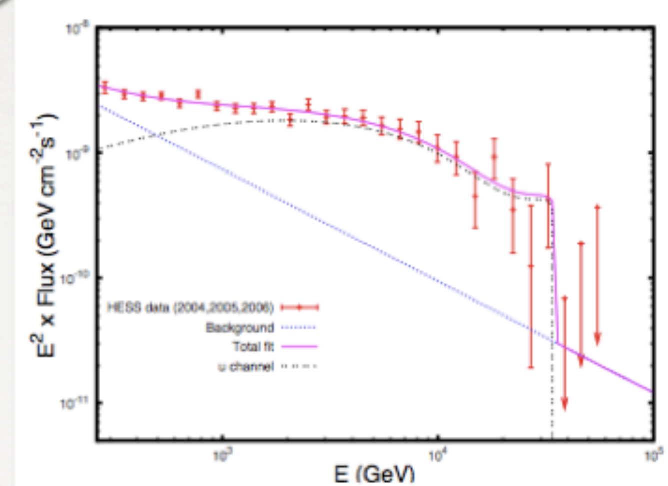
2019

CTA IS WELL-SUITED FOR DM SEARCHES

- Of course, the **sensitivity**
- **Energy threshold:** more photons per DM annihilation
- **Energy resolution**: Spectral features and discrimination with astrophysical sources
- **FOV and angular resolution:** morphology







CTA prospects

MD et atl. Astroparticle Physics 43 (2013) 189–214

Dark Matter and Fundamental Physics with the Cherenkov Telescope Array

M. Doro, J. Conrad, D. Emmanoulopoulos, M. A. Sánchez-Conde, J.A. Barrio, E. Birsin, J. Bolmont, P. Brun, S. Colafrancesco, S. H. Connell, J.L. Contreras, M.K. Daniel, M. Fornasa, M. Gaug, J.F. Glicenstein, A. González-Muñoz, T. Hassan, D. Horns, A. Jacholkowska, C. Jahn, R. Mazini, N. Mirabal, A. Moralejo, E. Moulin, D. Nieto, J. Ripken, H. Sandaker, U. Schwanke, G. Spengler, A. Stamerra, A. Viana, H.-S. Zechlin, S. Zimmer, for the CTA collaboration.

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Abstract

The Cherenkov Telescope Array (CTA) is a project for a next-generation observatory for very high energy (GeV–TeV) gro[...] gamma-ray astronomy, currently in its design phase, and foreseen to be operative a few years from now. Several tens of t[...] of 2–3 different sizes, distributed over a large area, will allow for a sensitivity about a factor 10 better than current instruments such as H.E.S.S, MAGIC and VERITAS, an energy coverage from a few tens of GeV to several tens of TeV, and a field of view of up to 10 deg. In the following study, we investigate the prospects for CTA to study several science questions that can profoundly influence our current knowledge of fundamental physics. Based on conservative assumptions for the performance of the different CTA telescope configurations currently under discussion, we employ a Monte Carlo based approach to evaluate the prospects for detection and characterisation of new physics with the array.

First, we discuss CTA prospects for cold dark matter searches, following different observational strategies: in dwarf satellite galaxies of the Milky Way, which are virtually void of astrophysical background and have a relatively well known dark matter density; in the region close to the Galactic Centre, where the dark matter density is expected to be large while the astrophysical background due to the Galactic Centre can be excluded; and in clusters of galaxies, where the intrinsic flux may be boosted significantly by the large number of halo substructures. The possible search for spatial signatures, facilitated by the larger field of view of CTA, is also discussed. Next we consider searches for axion-like particles which, besides being possible candidates for dark matter may also explain the unexpectedly low absorption by extragalactic background light of gamma-rays from very distant blazars. We establish the axion mass range CTA could probe through observation of long-lasting flares in distant sources. Simulated light-curves of flaring sources are also used to determine the sensitivity to violations of Lorentz Invariance by detection of the possible delay between the arrival times of photons at different energies. Finally, we mention searches for other exotic physics with CTA.

Keywords: CTA, Dark Matter, Dwarf satellite galaxies, Galactic centre, Galactic halo, Galaxy clusters, Axion-like Particles, Lorentz Invariance Violations, Neutrino, Magnetic monopoles, Gravitational Waves

[1] Sent off-print requests to Michele Doro (michele.doro@uab.cat) and Jan Conrad (conrad@fysik.su.se)

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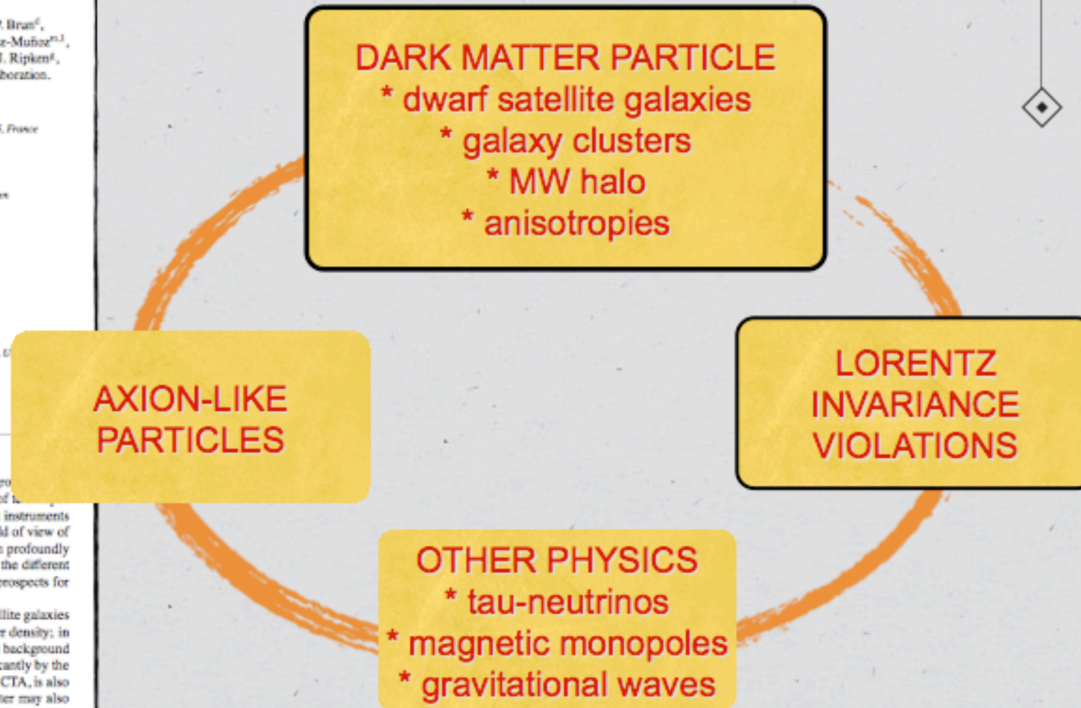
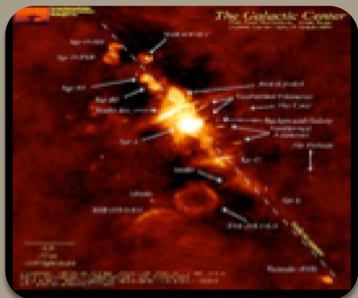


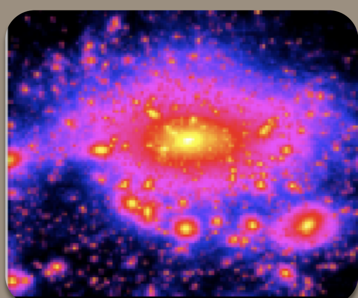
TEST MODEL AGAINST CTA PROPOSED ARRAYS

BEST TARGETS



GALACTIC CENTER+GALACTIC HALO (300-500h) Very good prospects if:

- Profile is **cusp,** i.e. baryons do not reduce the DM density



DARK CLUMPS/DSPH (100 h per year in 5 years on few of the best targets)

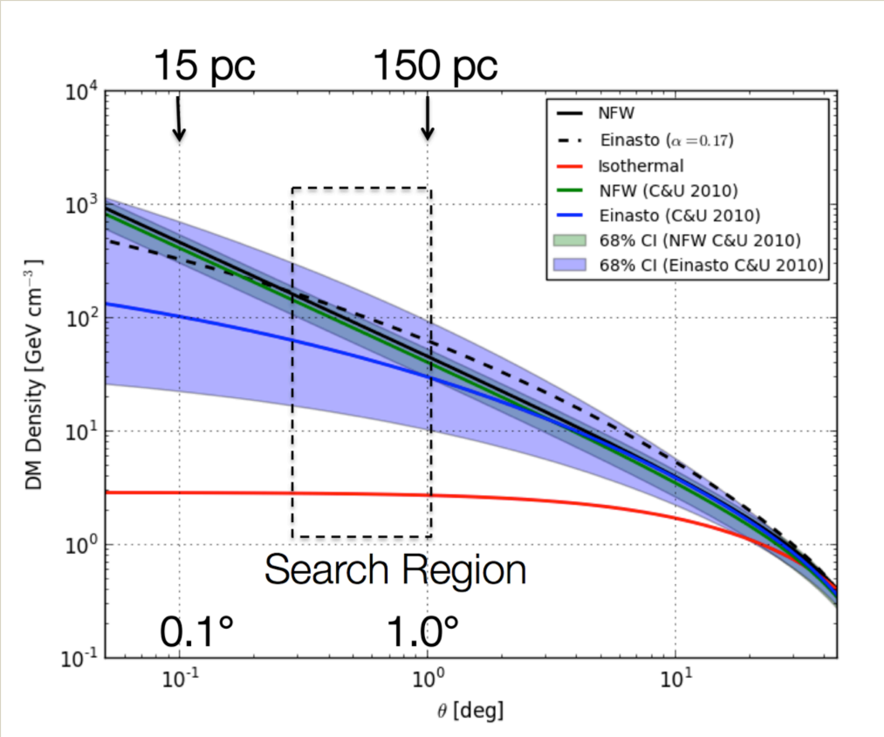
- There can be new dsphs and close by dark clumps which larger expected flux
- Cleanest from astrophysical sources and less background systematics
- There will be news in the future before CTA era

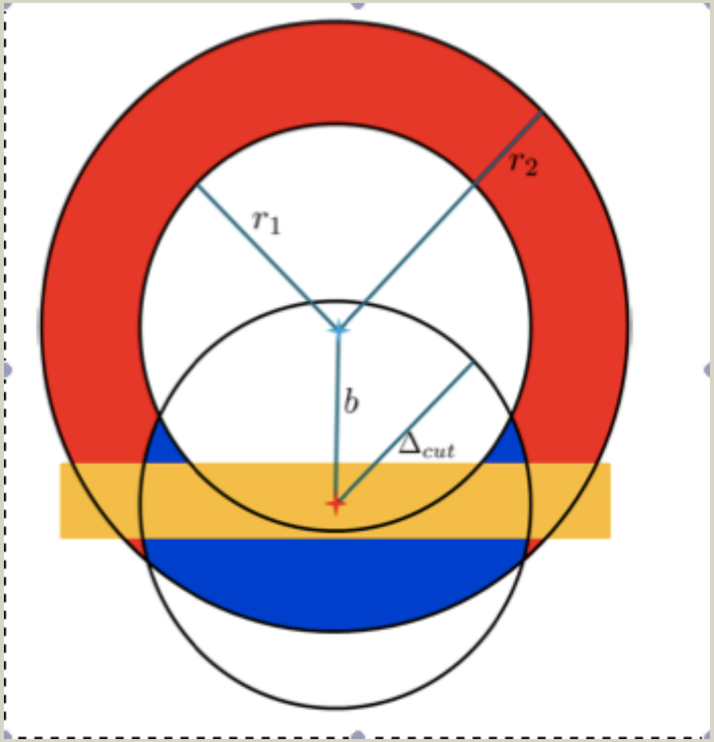
CLUSTERS

- No way for annihilating DM
- maybe promising targets for **decaying** DM

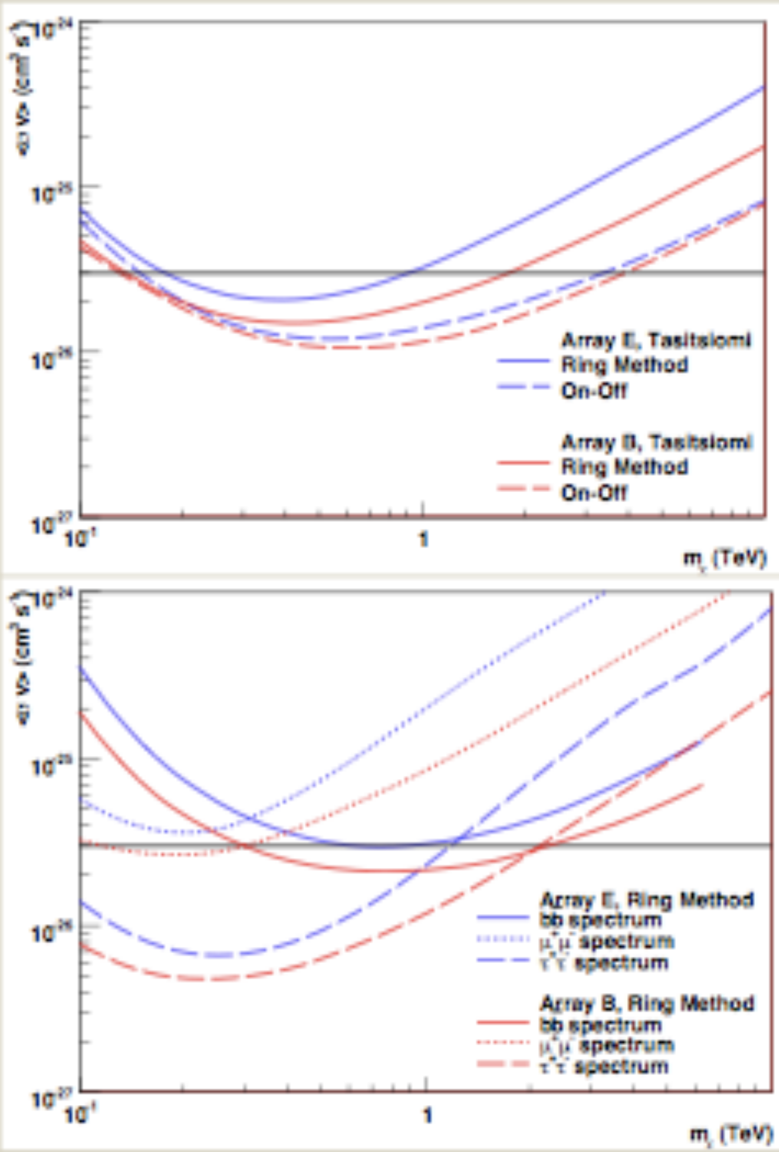
GALACTIC HALO

- Galactic center obvious target for DM searches, but crowded region
- Galactic halo at short distance from GC is well-defined
- HESS envisaged a strategy: Abramowski+, et al. PRL 106 (2011) 161301–+.



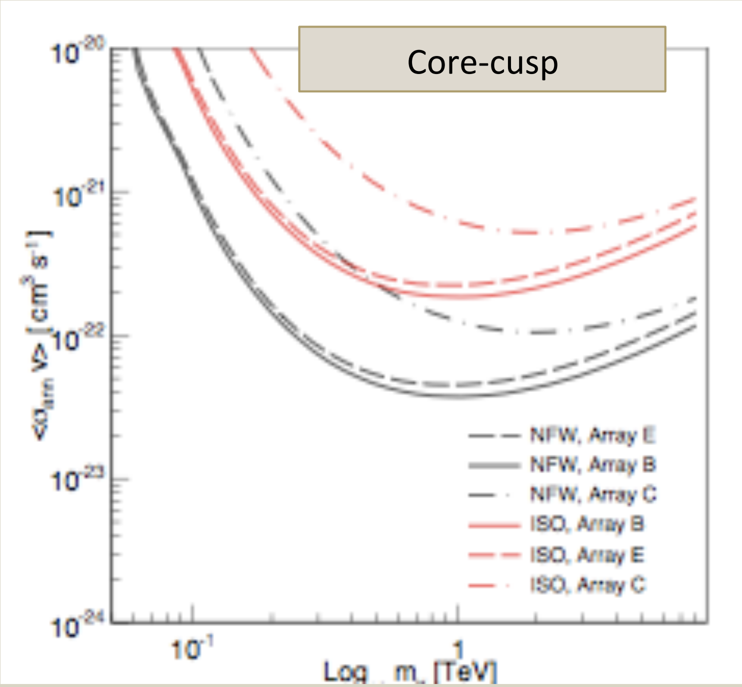


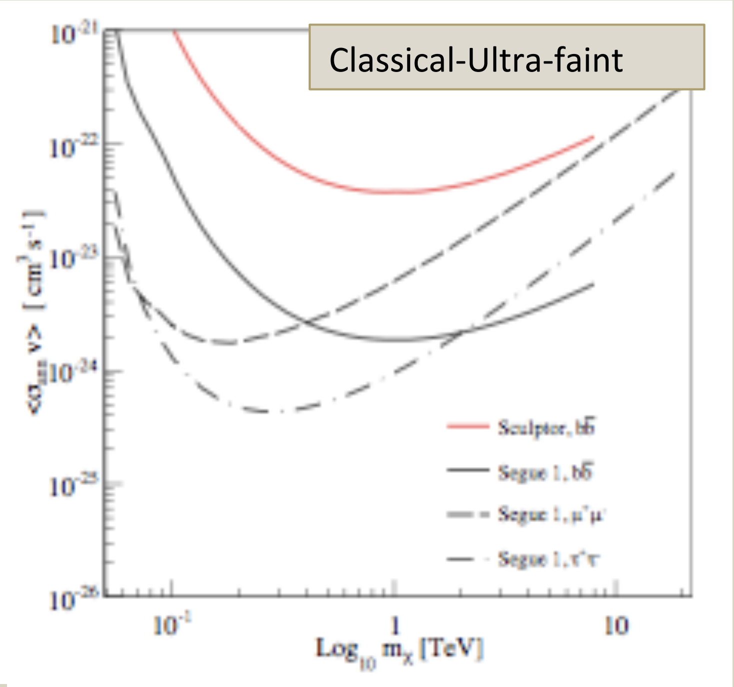
CTA PROSPECTS



- Careful selection of the signal and background region
- Control of diffuse gamma-ray background
- Control of background systematics
- Results are robust for cusp profile, but are not valid for core profiles

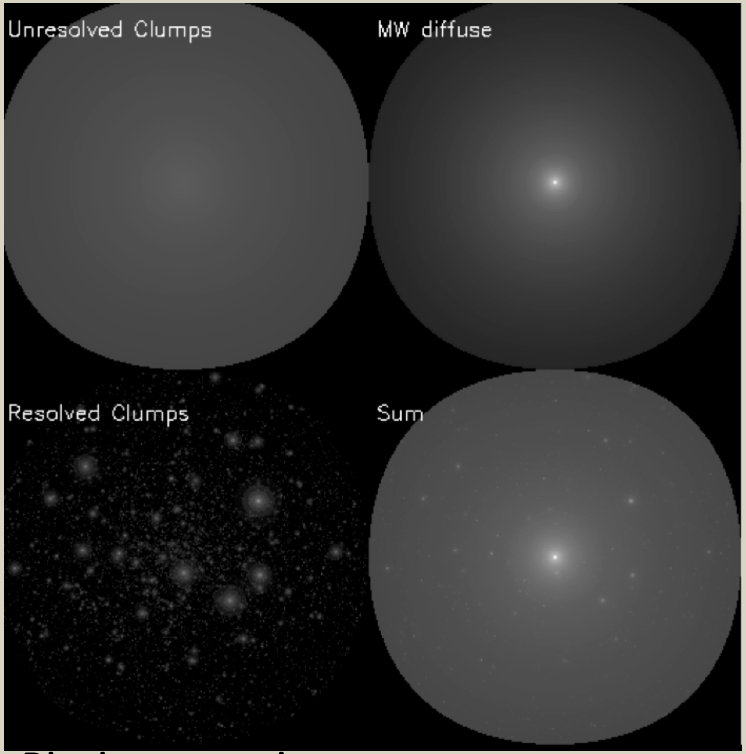
DSPHS





New experiments will surely detect new dsphs (and better constraints known) in the time from here to CTA

DARK CLUMPS



Pieri+ some time ago

- **Clumps of DM could be dark emitter (only gamma-ray)**
- Some of them could Unidentified Fermi sources
- Or Fermi could be blind to them if DM is above few hundreds GeV

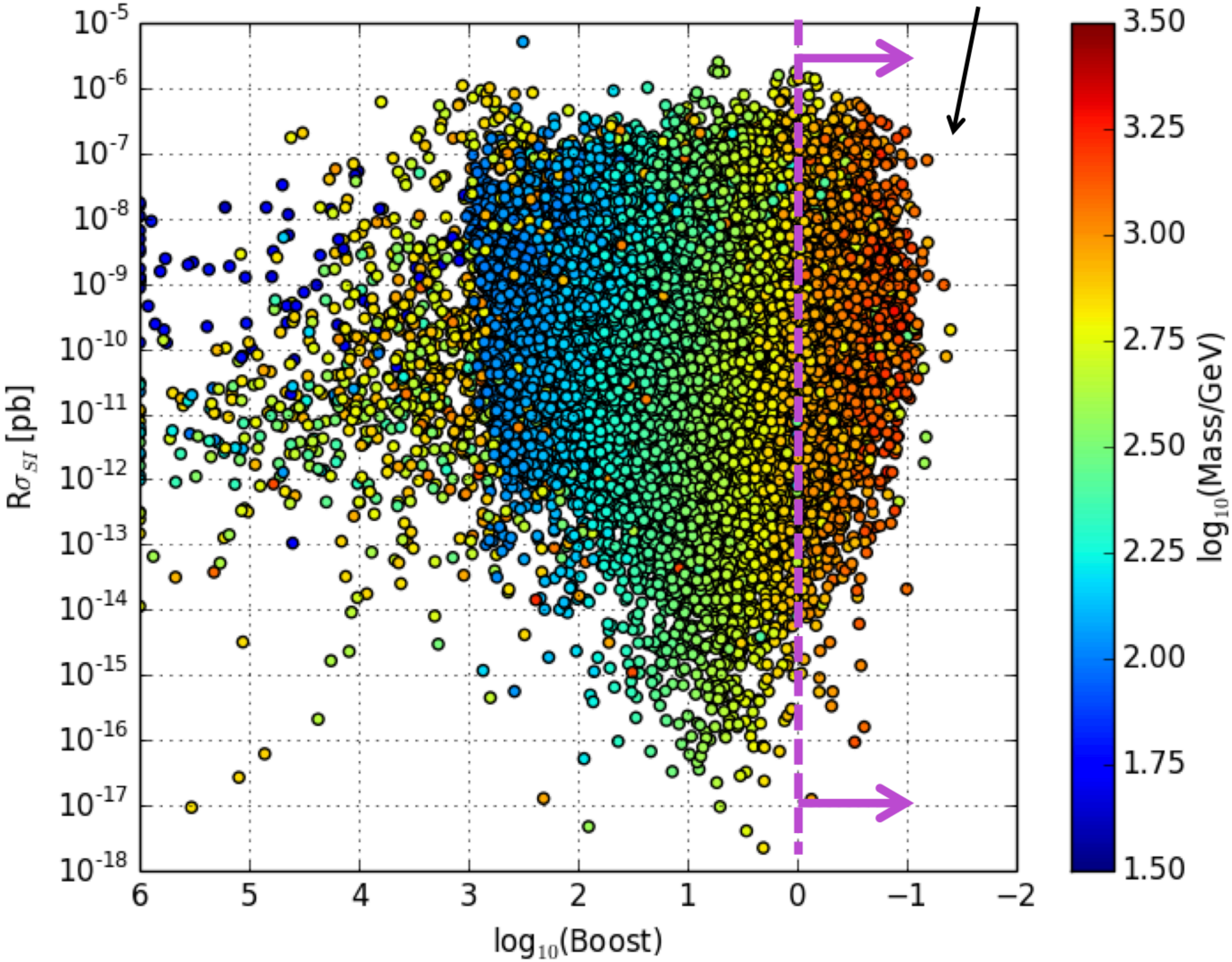
H. Zechlin (very very preliminary)

Survey [mCrab]	Boost $\langle\sigma v\rangle / \langle\sigma v\rangle_{\rm th}$	$N(\Delta M, \|b\| \geq 10°)$ $\chi\chi \to b\bar{b}$ 0.5 TeV	$\chi\chi \to b\bar{b}$ 1.0 TeV	$\chi\chi \to b\bar{b}$ 5.0 TeV	$\chi\chi \to \tau\bar{\tau}$ 0.5 TeV	$\chi\chi \to \tau\bar{\tau}$ 1.0 TeV	$\chi\chi \to \tau\bar{\tau}$ 5.0 TeV
5	≤ 10	0.00	0.01	0.00	0.19	0.05	0.00
	≤ 100	0.31	0.74	0.26	6.91	2.63	0.03

WILL CTA BE COMPETITIVE?

Constraints: XENON100

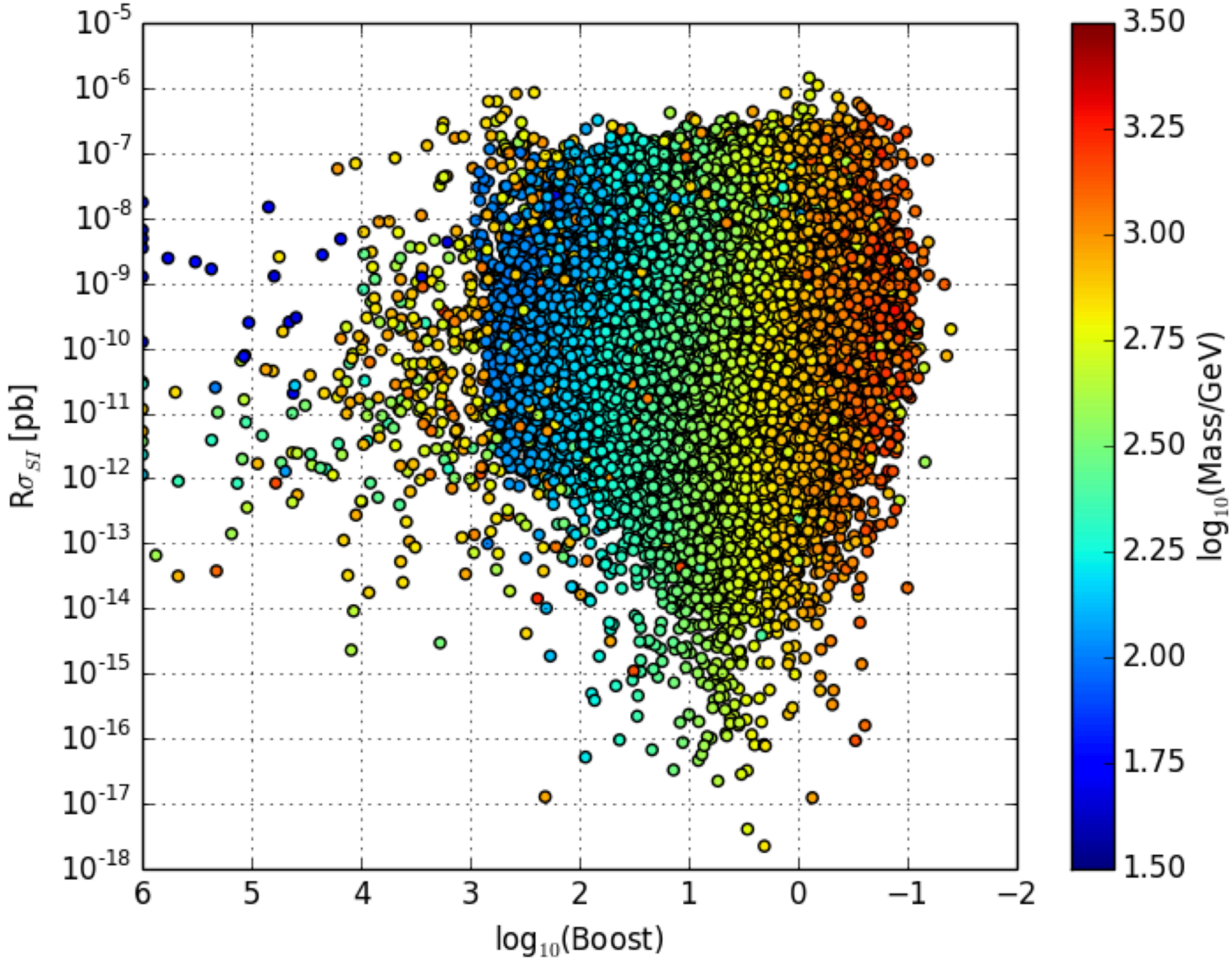
Models Excluded by CTA



Log_{10}(CTA Boost)

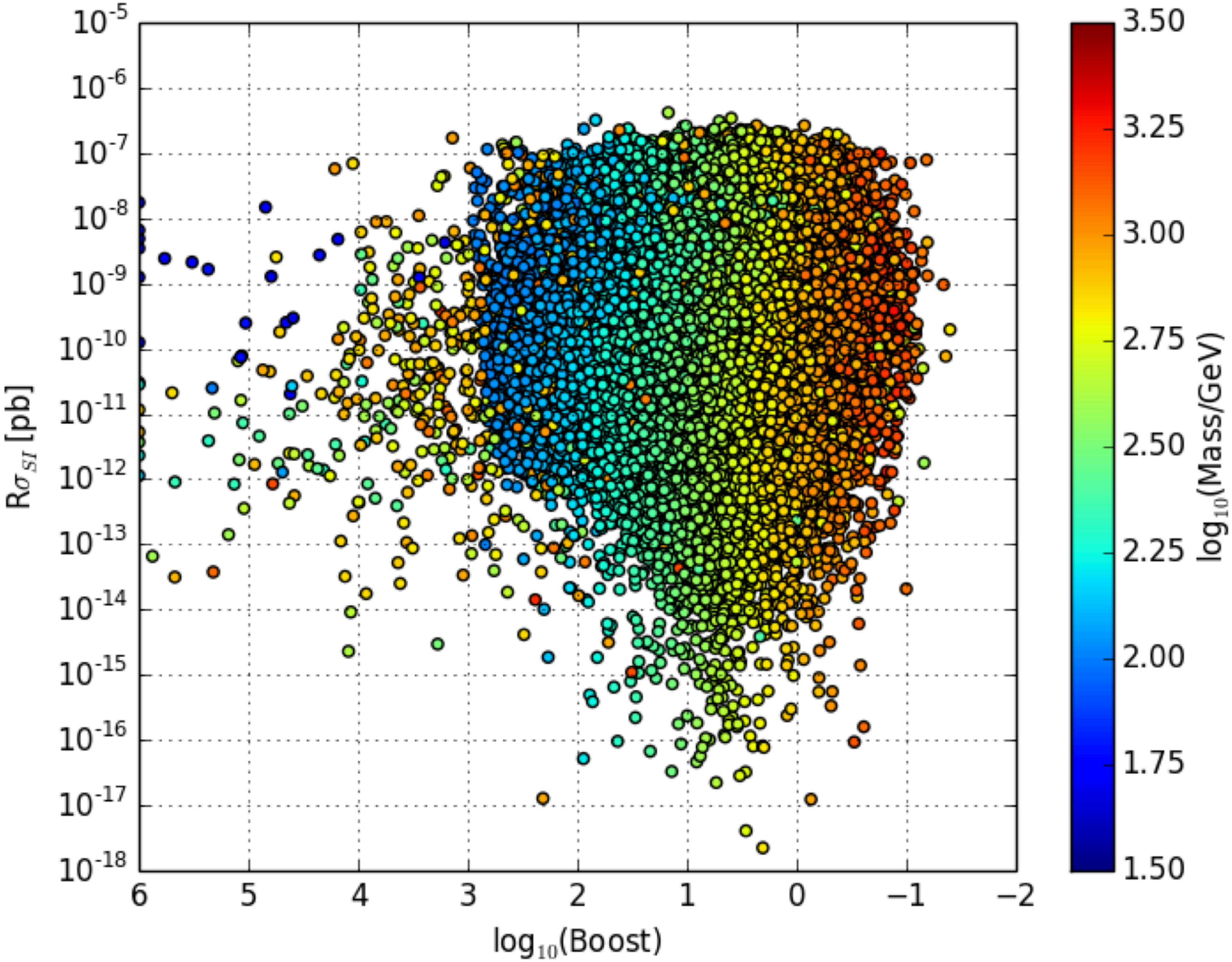
Cahill-Rowley+ 2014 (and in next slides)

Constraints: XENON100, ATLAS+CMS 7/8 TeV



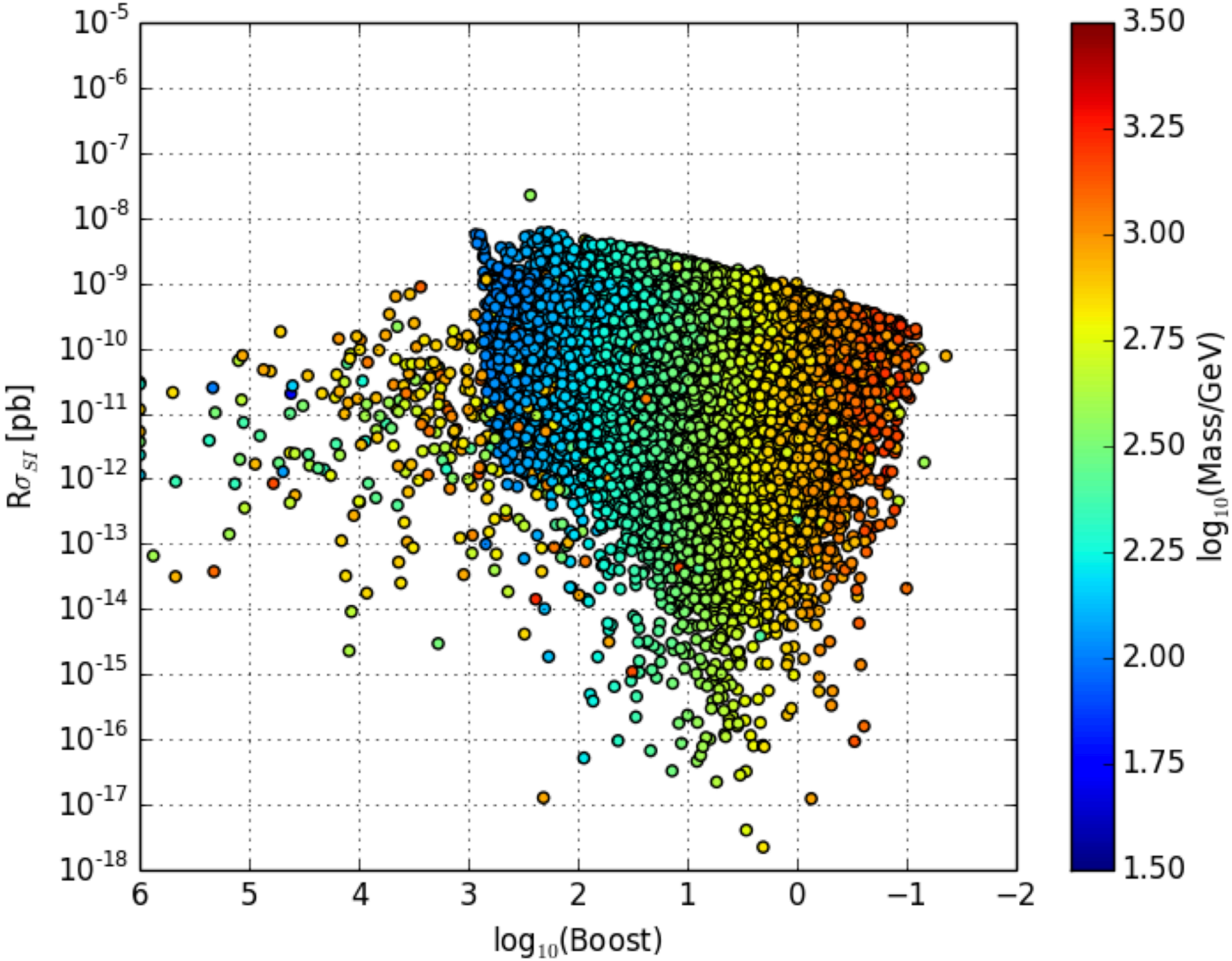
Log_{10}(CTA Boost)

Constraints: LUX (2013), ATLAS+CMS 7/8 TeV



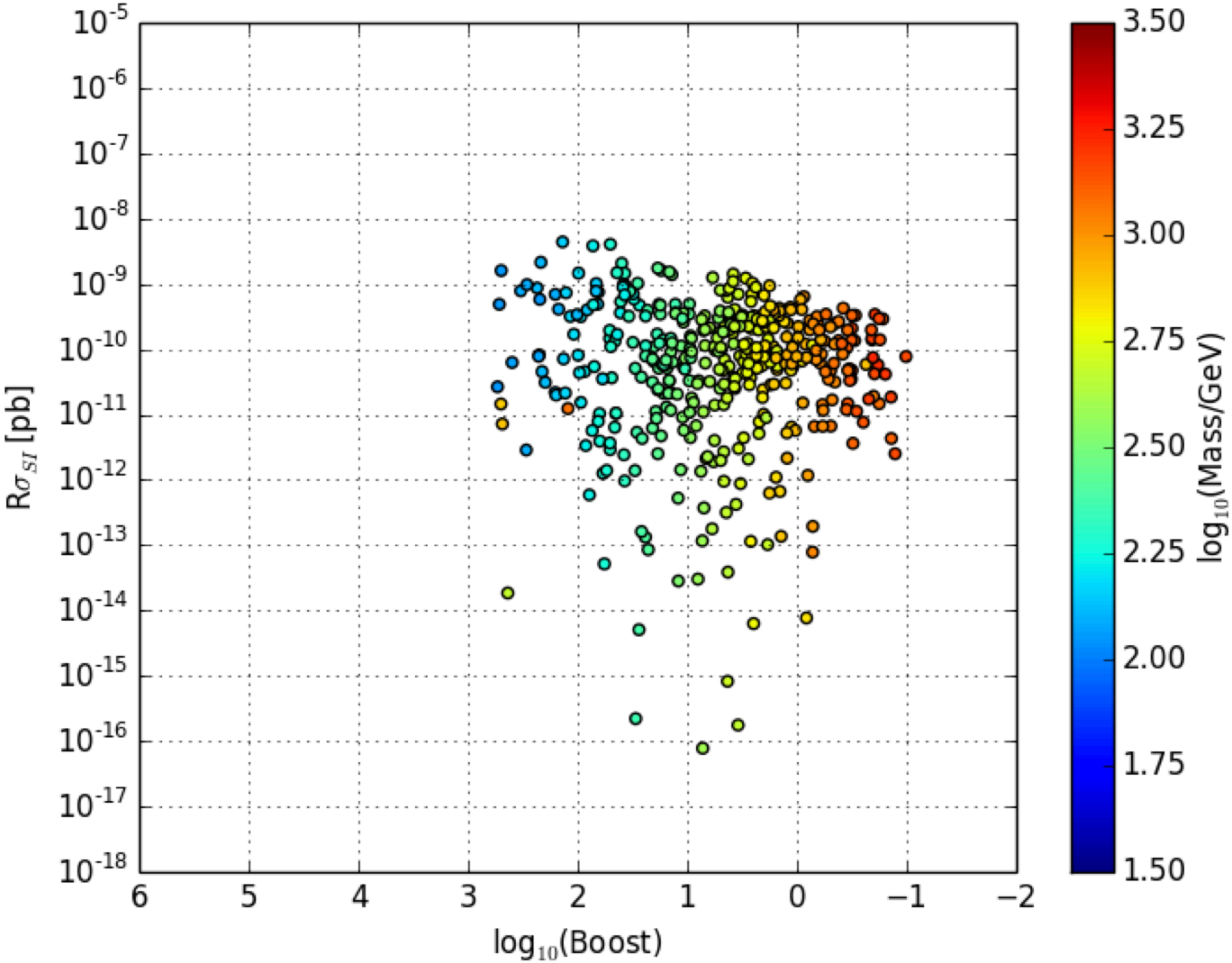
Log_{10}(CTA Boost)

Constraints: LZ 1000 days, ATLAS+CMS 7/8 TeV

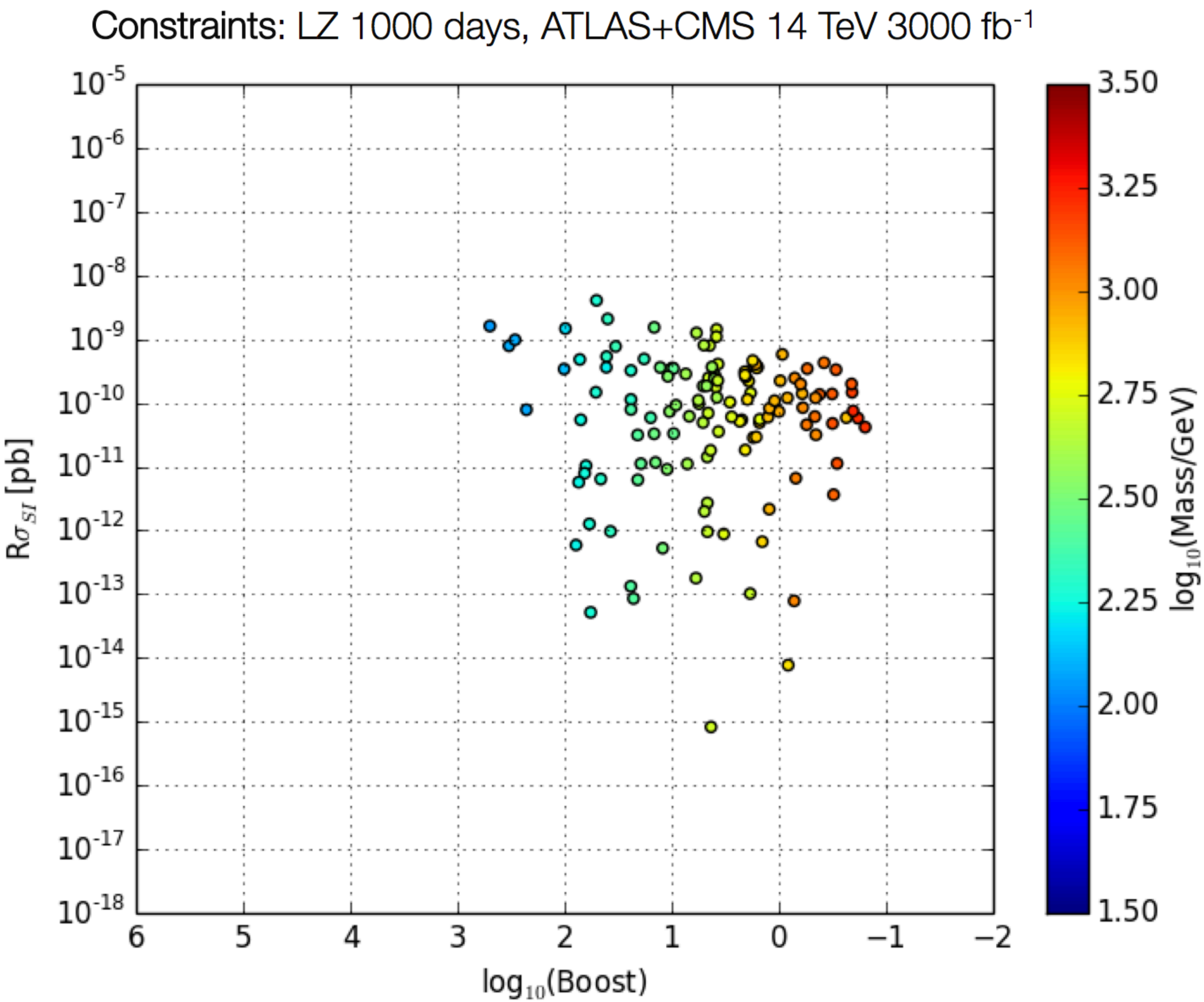


Log$_{10}$(CTA Boost)

Constraints: LZ 1000 days, ATLAS+CMS 14 TeV 300 fb^{-1}

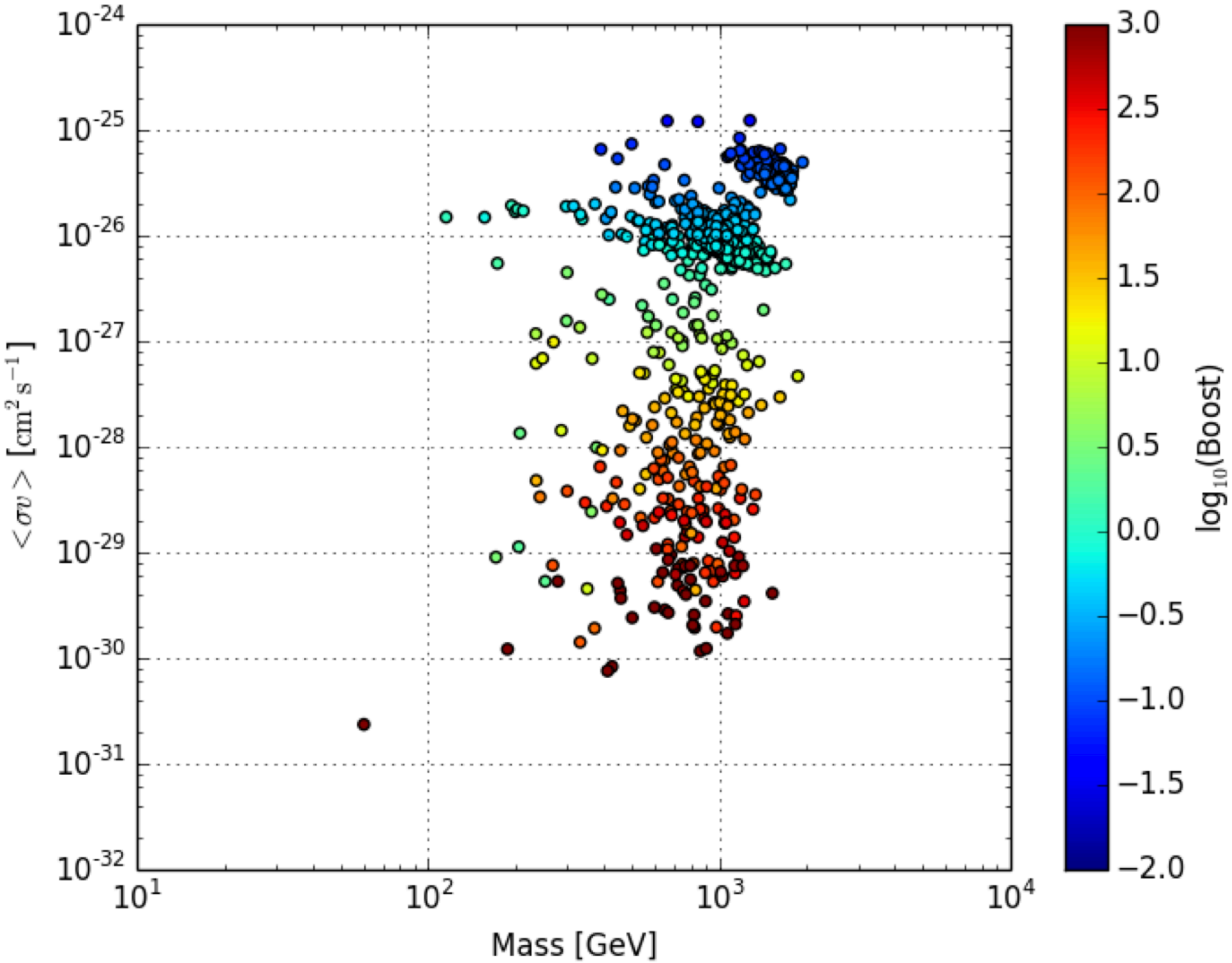


Log$_{10}$(CTA Boost)

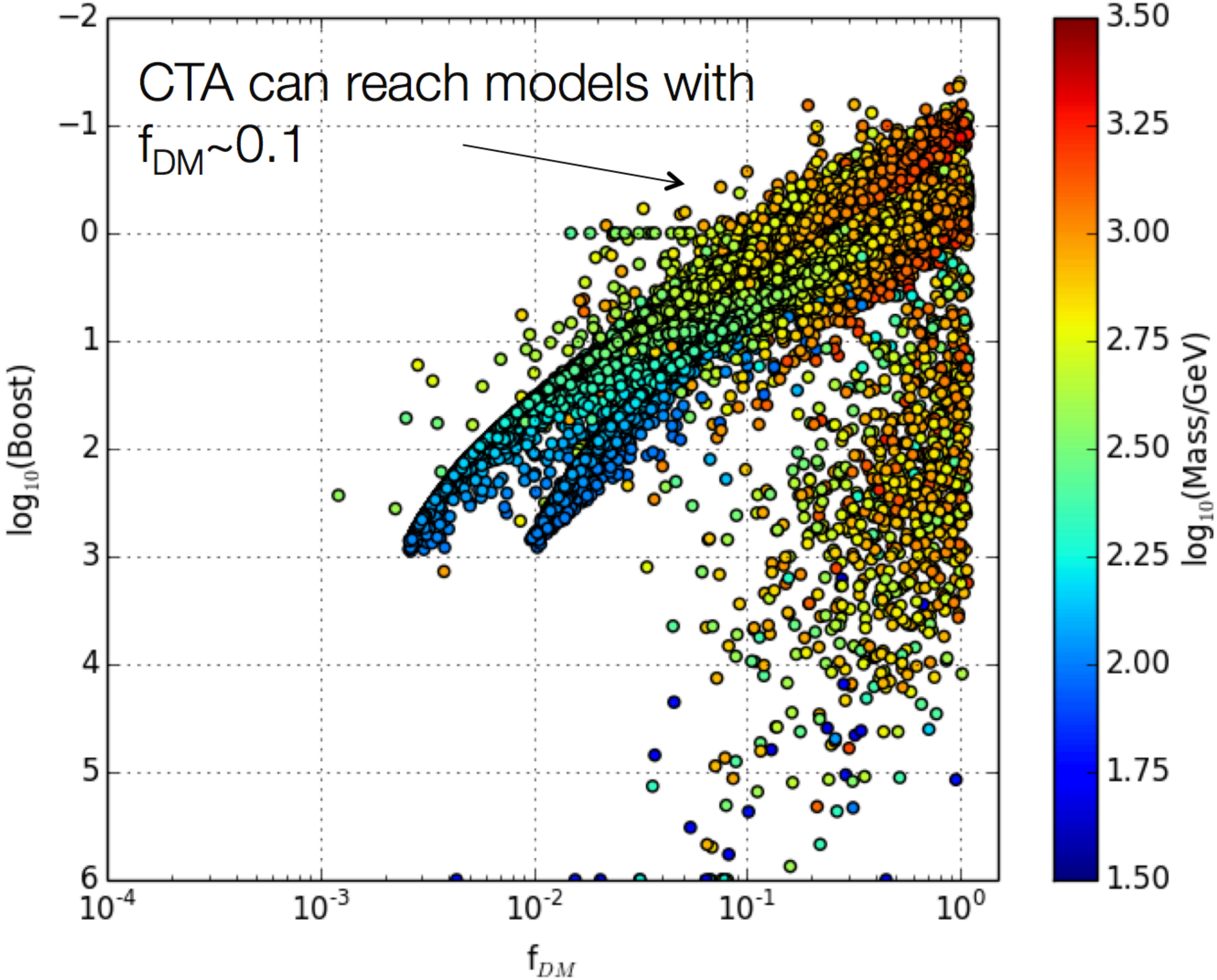


Log_{10}(CTA Boost)

Constraints: LUX (2013), ATLAS+CMS 7/8 TeV, $f_{DM} > 0.9$



Constraints: LUX (2013), ATLAS+CMS 7/8 TeV



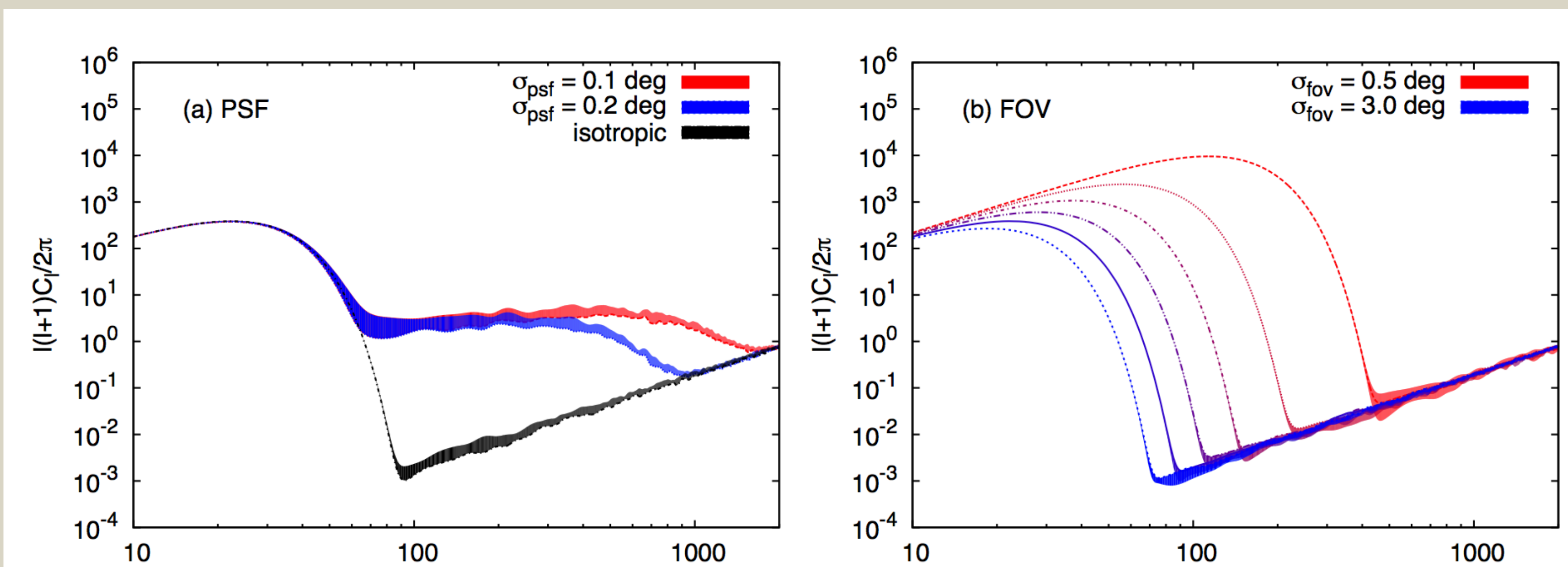
$f_{DM}=\Omega h^2/\Omega_{DM}h^2$

ANISOTROPIES

IACT CAN PLAY THE GAME

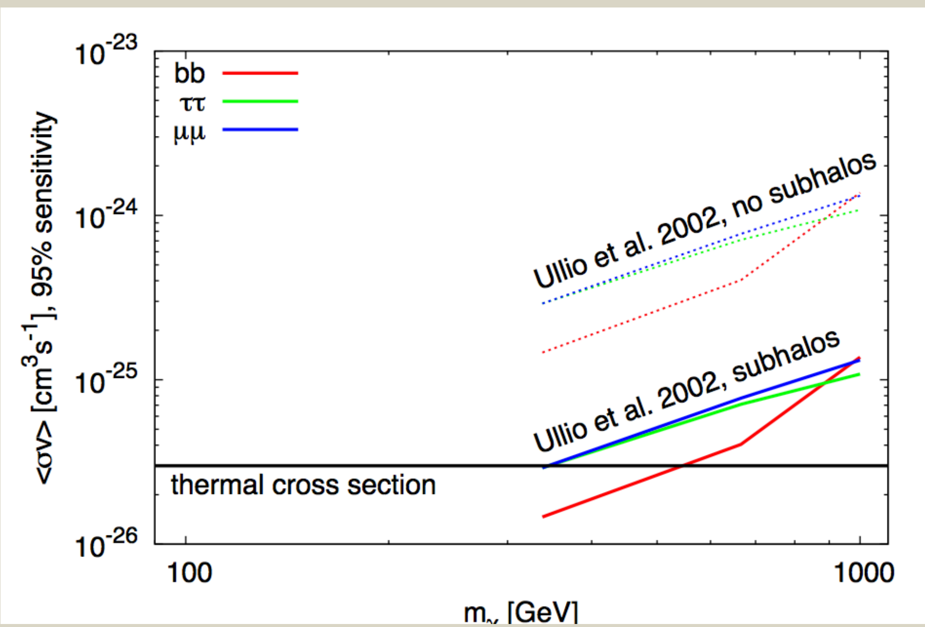
JCAP01(2014)049

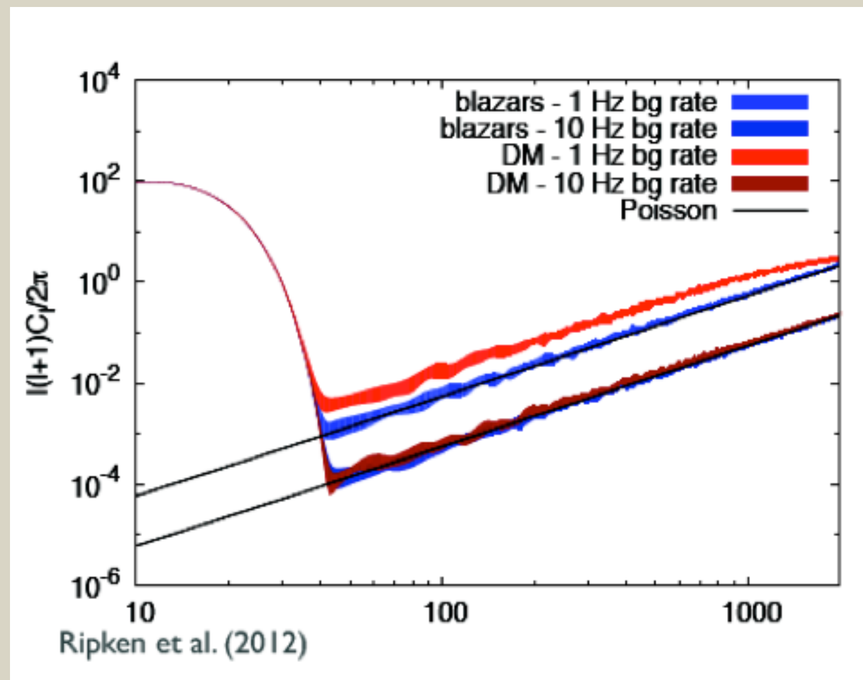
- Self-annihilating DM could leave its signature in the angular power spectrum of the EDGB
- PSF and FOV of the IACTs are not killer: multipoles in the range between 100 and 1000 can be probed
- At the same time, the background is expected to be isotropic at small scales and therefore no fundamental obstacle either.



A NOVELTY WITH CHANCES

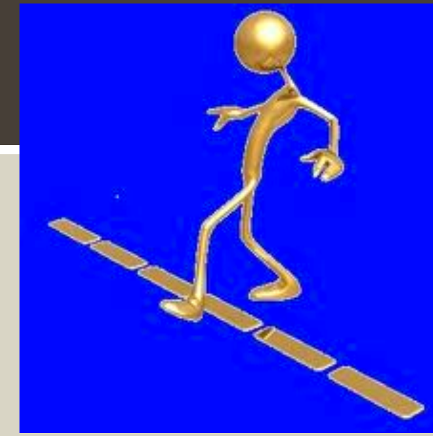
- All depends on
  - a) DM real anisotropy level
  - b) background suppression capability of CTA
- **Best strategy**: multiple ROI obtained from standard extragalactic observation (e.g. 10x100h) above 300 GeV.



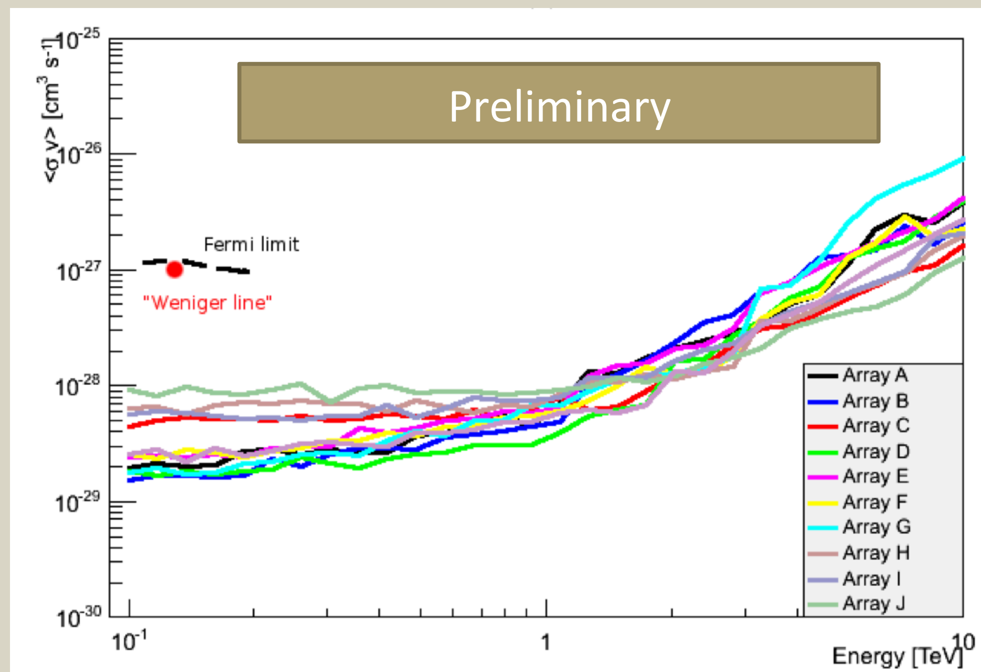


LINES

DO NOT CROSS THE LINE



- A large effort is currently at place in CTA to improve the energy resolution and bias through through instrument and atmospheric calibration
- Low-energy threshold and larger sensitivity go along well with line searches
- All configurations see the Bringmann-Weniger line



THE UGLY DUCKLING

SMITH CLOUD

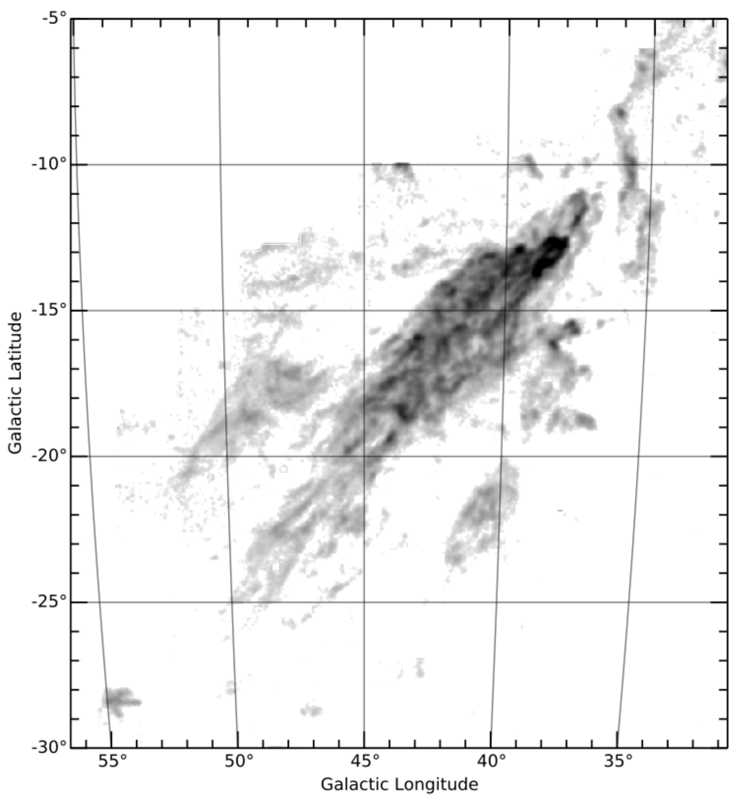


Figure 1. GBT HI image of the Smith Cloud integrating over all $V_{\rm GSR} > 220$ km s^{-1}. The grey scale is proportional to the square root of the HI column density to reveal the extended cometary morphology.

arXiv:1404.3209v1

- The Smith Cloud is exceptionally massive, compared to standard HV cloud
- If not encapsulated by a DM halo, stellar content should be disrupted by passage through the Galactic disk
- Nichols+ 2014

WHY NOT

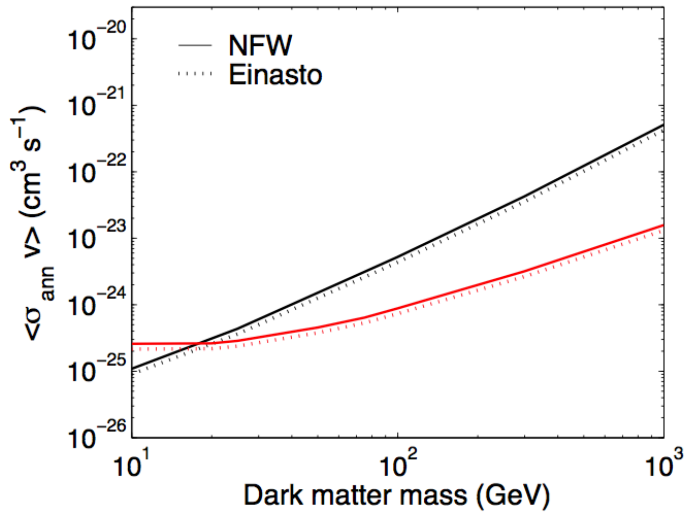
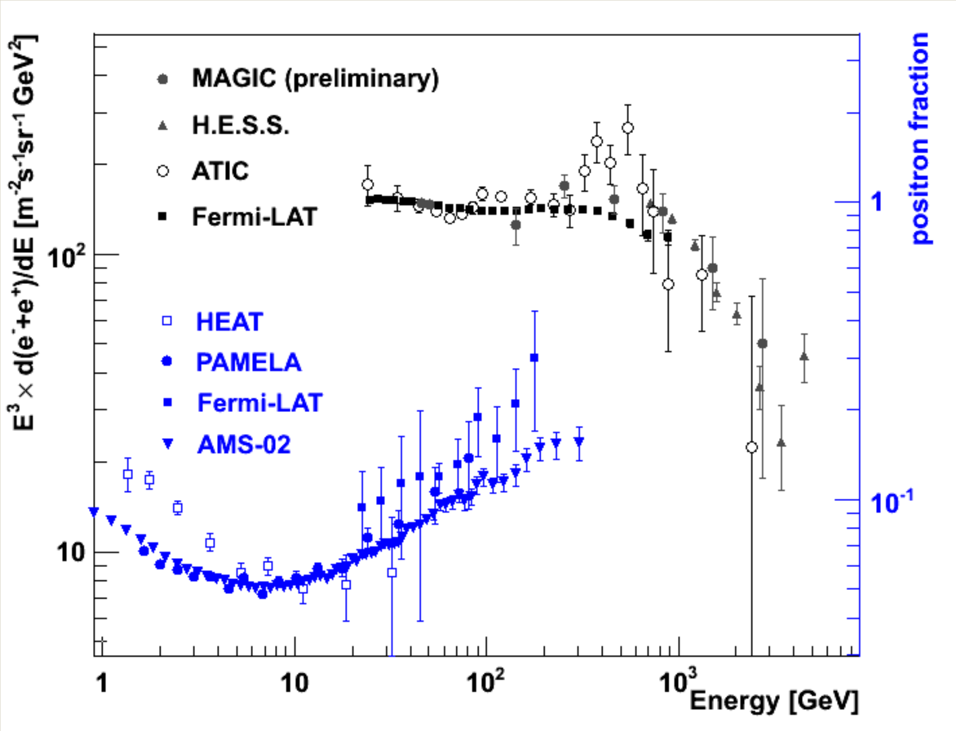


Figure 8. Derived upper limits for $\langle \sigma v \rangle_\chi$ versus dark matter mass for both the NFW and Einasto profiles. $\tau^+\tau^-$ (black) and $b\bar{b}$ (red) channels are shown.

- "Upcoming experiments such as the Cherenkov Telescope Array (CTA) will be able to achieve improved angular resolution and sensitivity around the Smith Cloud for energies above 100 GeV" Nichols+ 2014

A DM FLIRT: DOING IT WITH THE ELECTRONS

DM SEARCHES VIA CR ELECTRON(S)



- Many experiments find anomalies in CRs fluxes
  - PAMELA, AMS+: rising e+/e± ratio above 10 GeV
  - Fermi, HESS: rising e± spectrum above 100 GeV

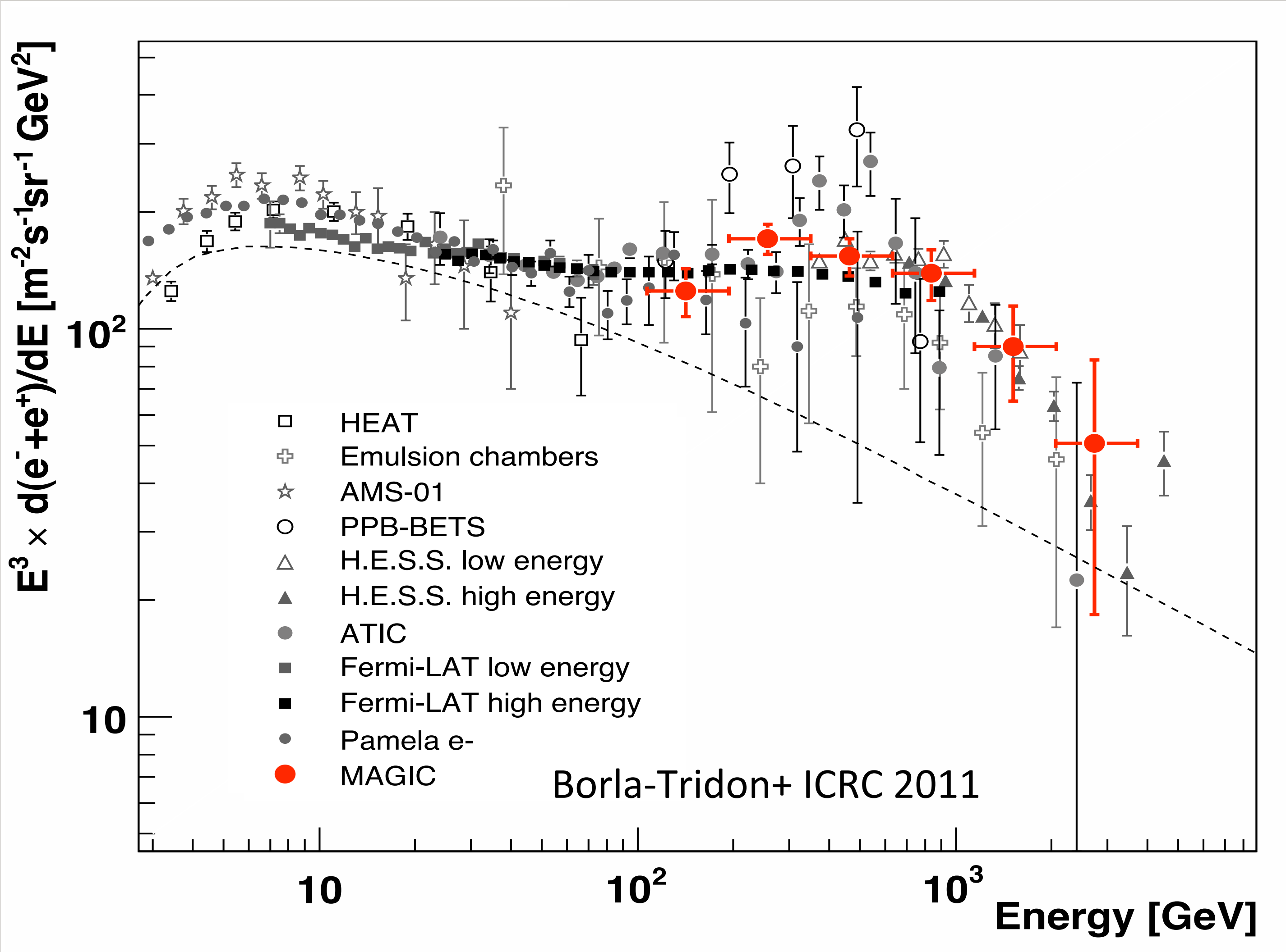
Explanations

Nearby astrophysics sources

Dark Matter annihilation/decay

Different CR propagation

ALL-ELECTRONS MEASURED BY IACTS



COMMENTS AND CONCLUSIONS

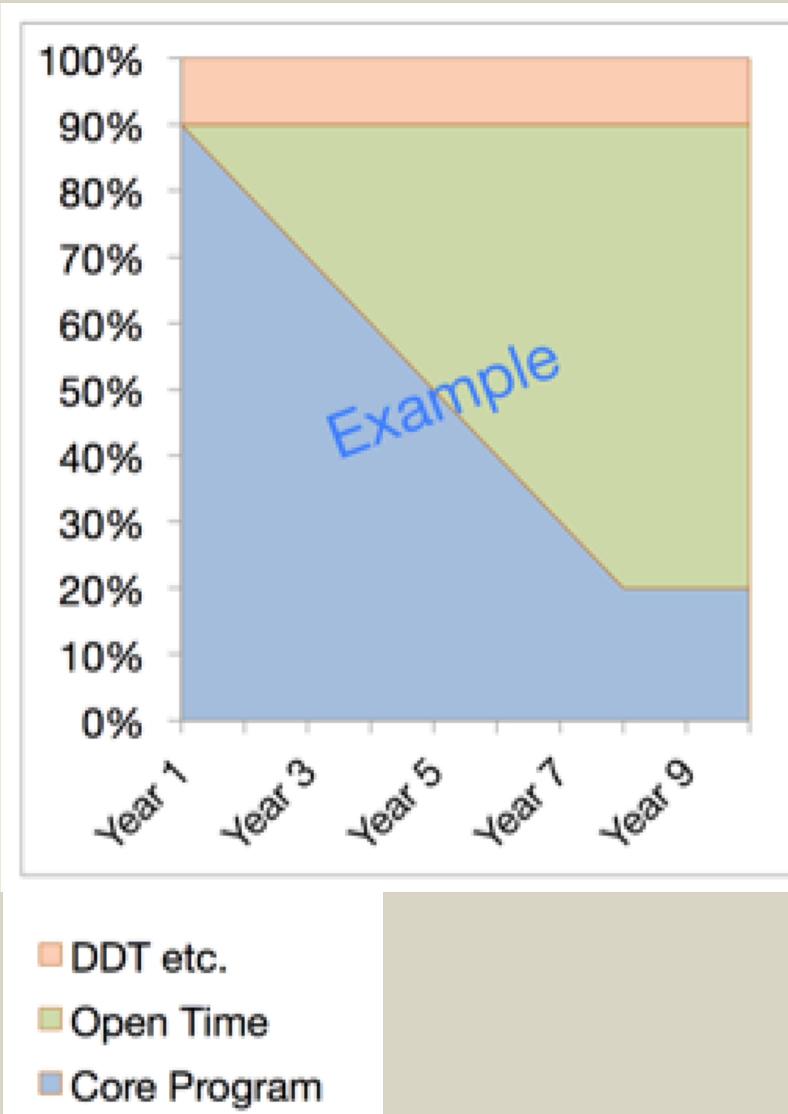
DM SEARCHES WITH CTA

1. We have shown that there is at least a part (for now) of the parameter space that we can curb with CTA (DM at the GC-halo)
2. In case LHC-14 do not discover DM, CTA has still chance if DM is heavy
3. CTA can be the only player if DM is heavy for 2020-2030.
4. Others can make detection of DM, but in case, CTA can make **identification**

CONCLUSIONS #1

- CTA has good prospects for reaching WIMP models with thermal relic cross section and mass > 100 GeV
- Dwarf Galaxies: need high boost factor or new sources discovered (possibly dark clumps?)
- Galactic Center: Fraction of parameter space finally accessible with CTA – particularly at high LSP masses (>1 TeV)
- Other probe (electrons, anisotropy) or weirdo targets could appear (Smith!)
- CTA will be complementary to LHC and direct detection searches and can be unique player in some regions of the parameter space

CONCLUSIONS #2



- CTA science community is currently working on Key-Science Projects definitions:
  - To define core program
  - To secure proprietary time
  - To define schedule
- Guest time relevant!
- Photons will be distributed along with analysis tools a-la Fermi
- First time of a the first Cherenkov *observatory*!

THANKS!