NORDITA workshop
Particle Physics with Neutrons at the ESS
14/12/2018

~~*Cogenesis*~~ *Baryogenesis from Neutron - Dark Matter Oscillations*

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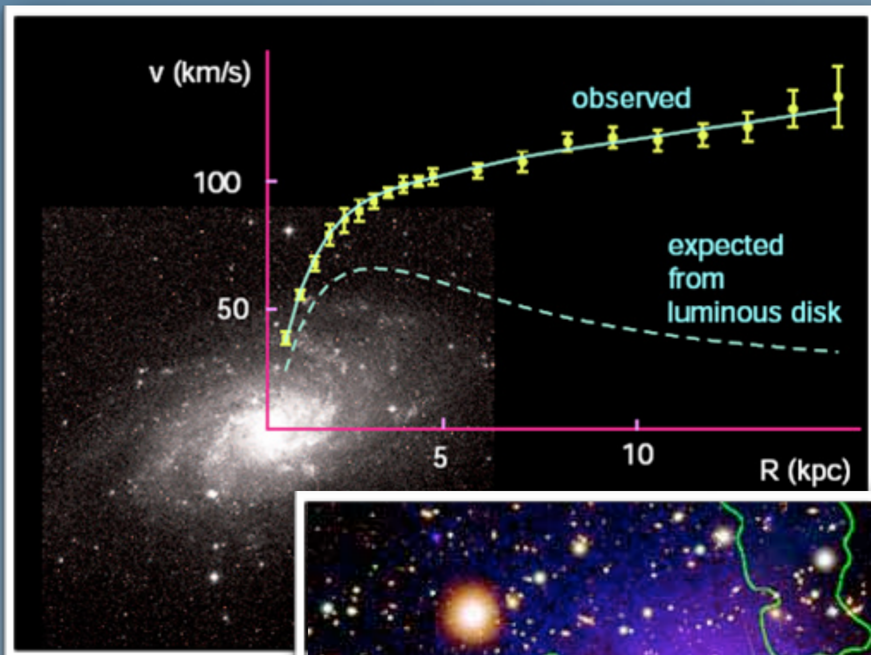
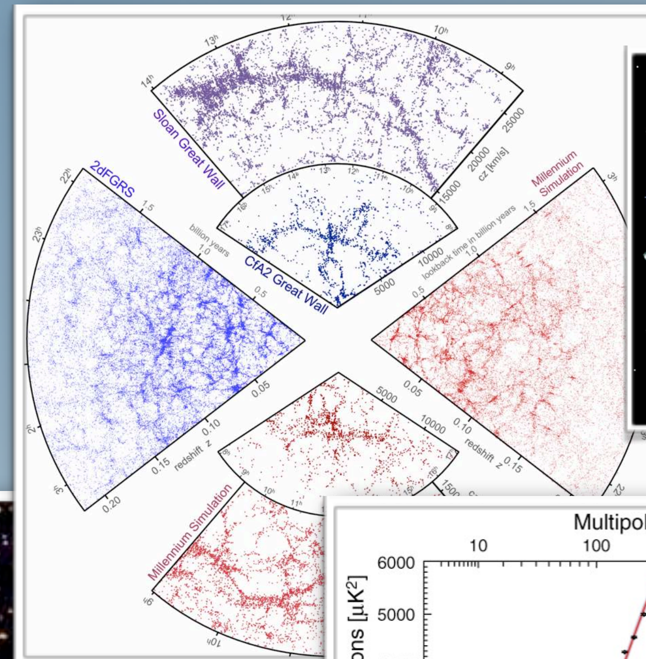
Based on:

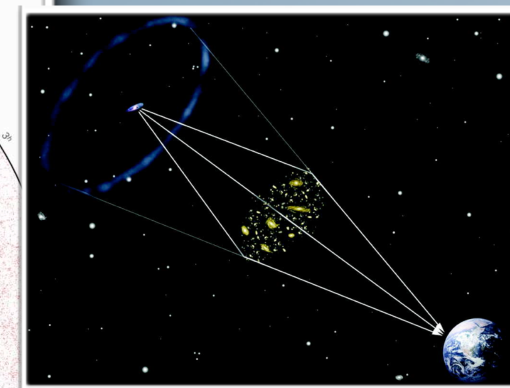
TB, Cline & Cornell, 1811.08215

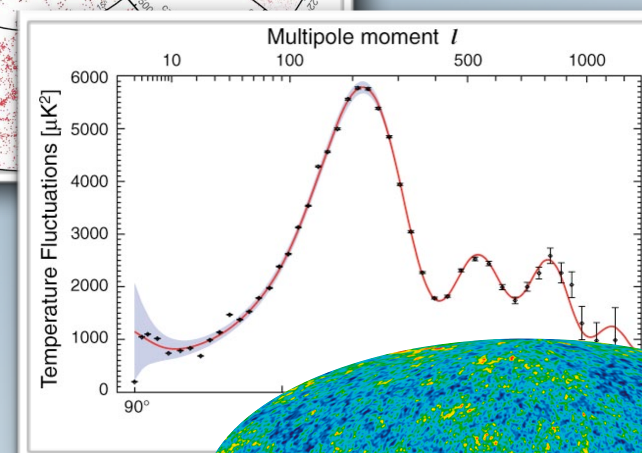
UiO : University of Oslo

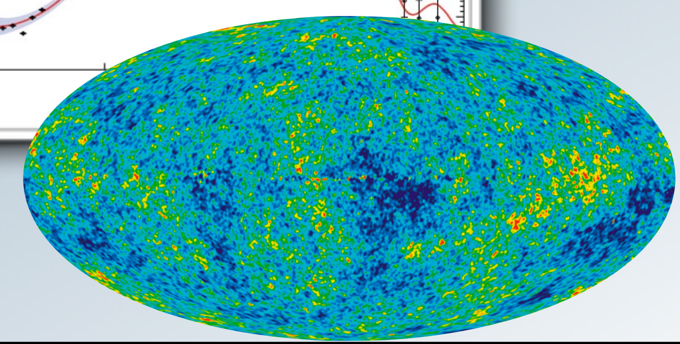
Dark matter all around











➡ *overwhelming evidence on **all** scales!*

$$\Omega_{\mathrm{CDM}} h^2 = 0.1188 \pm 0.0010$$

The WIMP 'miracle'

- The number density of Weakly Interacting Massive Particles in the early universe:

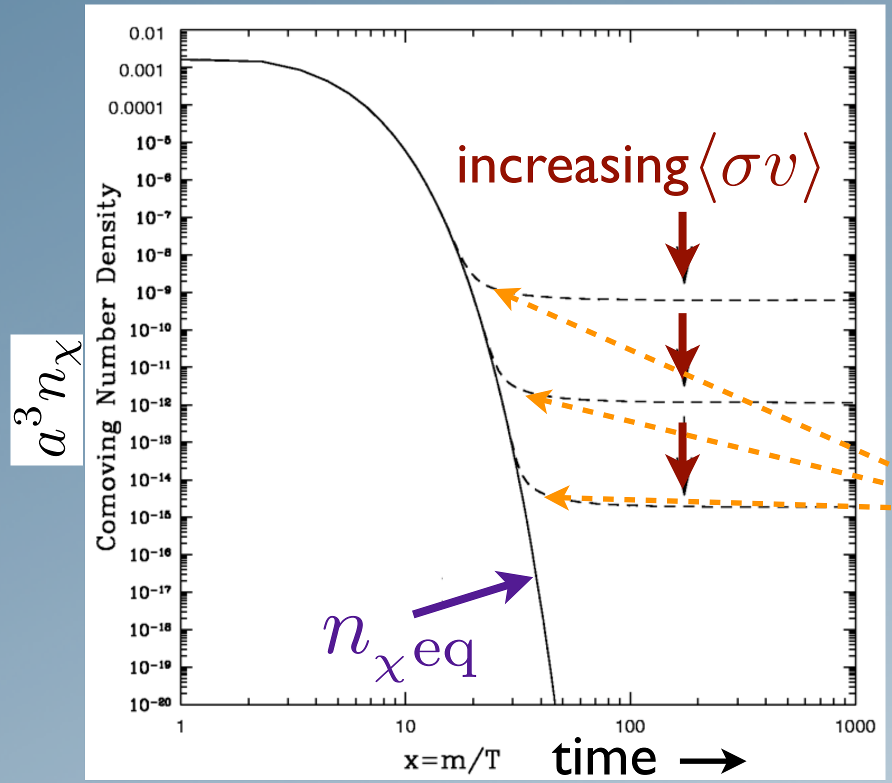


Fig.: Jungman, Kamionkowski & Griest, PR'96

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

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

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

for weak-scale interactions!

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

+ well-motivated from particle physics [SUSY, EDs, …]

Asymmetric DM

- But no independent evidence for such WIMPS (yet)…
- Also: ordinary matter ('baryons') is produced in a different way:
  - initial matter/antimatter asymmetry
  - cross sections much larger than 'thermal' value annihilate away the symmetric component
- Maybe dark and ordinary matter are not so different after all?

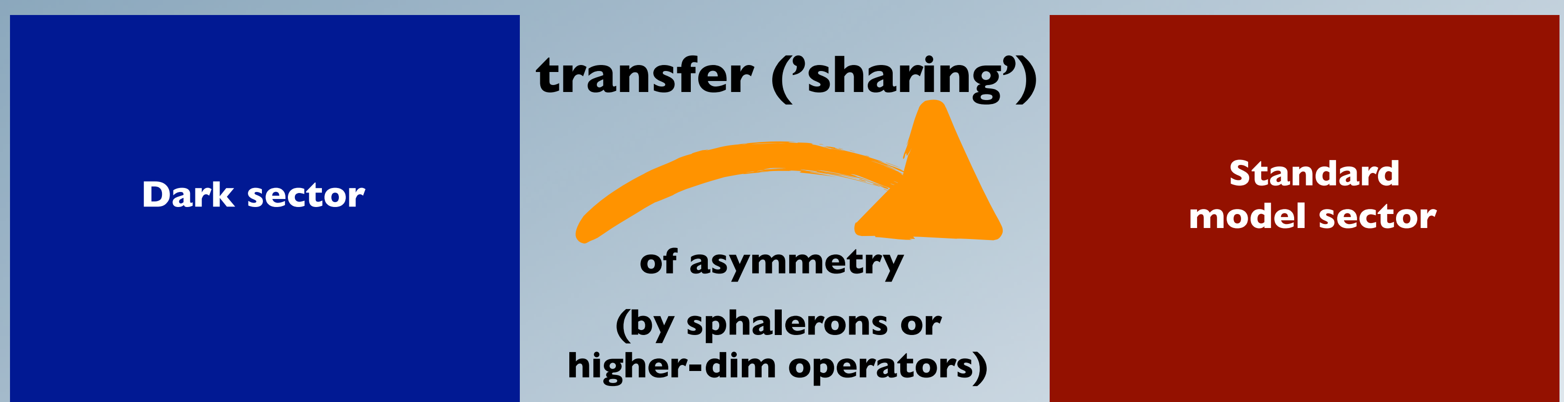
$$\Omega_\chi = 5.4\Omega_b = \mathcal{O}(1)\Omega_b$$

⇨ 'Asymmetric' dark matter (of Dirac fermions) ! review: Zurek, Phys.Rep.'14

But where does the asymmetry come from?

Creating asymmetries

- Origin of baryon asymmetry unknown
- Three necessary conditions: Sakharov, 1967
  - Baryon number violation
  - Violation of both *C and CP* ⟵ too small in standard model !
  - Departure from thermal EQ
- Often studied situation: review: Zurek, Phys.Rep.'14



  - Asymmetry very easy to achieve
  - E.g. strong phase transitions possible

Neutrons are special

- Neutrons provide the unique relevant operator to connect (Dirac) dark matter to the SM:

$$\mathcal{L}_{\rm mix} = -\delta m\, \bar{n}\chi + {\rm h.c.}$$

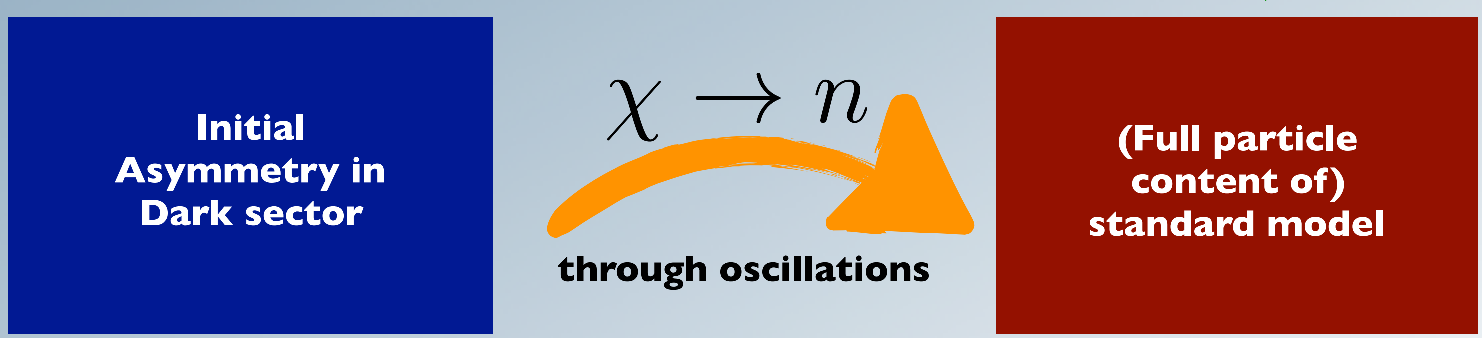
DM would carry baryon number !

- Oscillations to mirror partner — in analogy to neutrino oscillations — have been studied extensively

Berezhiani & Bento, PLB '06, EPC '09, …

- ***NEW***: means of successful low-scale baryogengesis!

TB, Cline & Cornell, 1811.08215

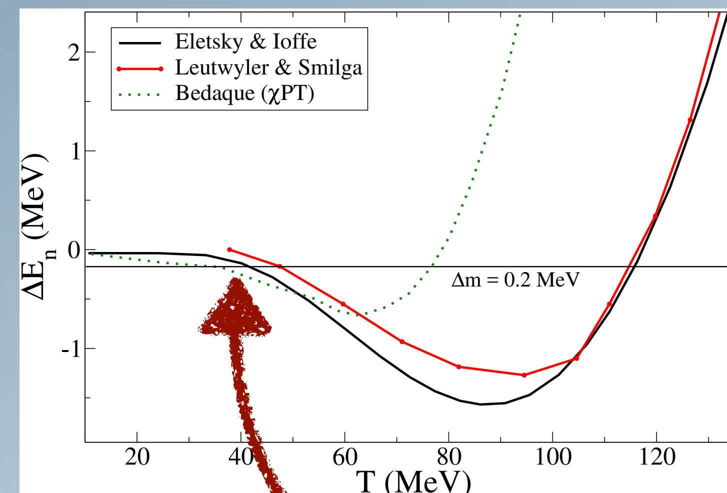


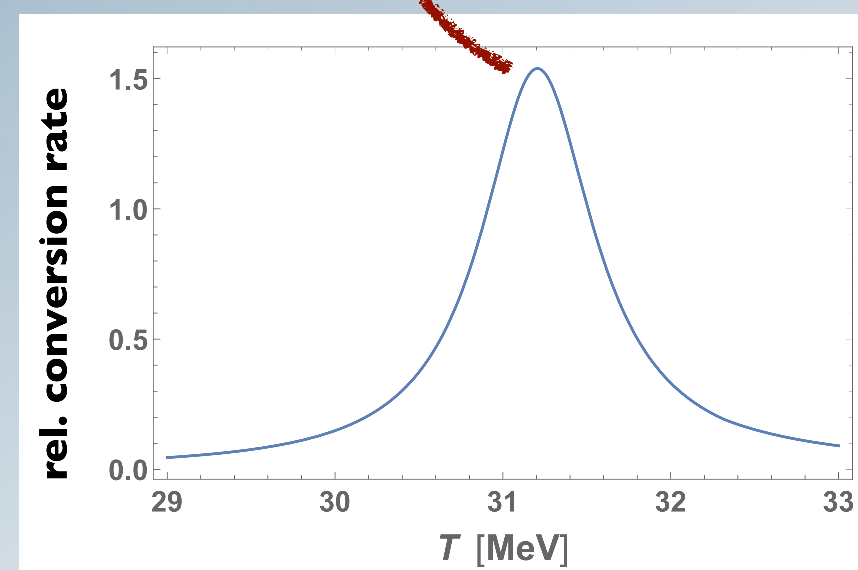
Oscillations at finite T

$$\mathcal{H} = \begin{pmatrix} \Delta E_n + m_n & \delta m \\ \delta m & \Delta E_\chi + m_\chi \end{pmatrix}$$

- Crucial ingredient: thermal corrections to particle masses

- For neutrons, the dominant contribution derives from pion scattering
  (combining dispersion relations with experimentally obtained scattering cross sections)
  Eletsky & Ioffe, PLB '97





- Mixing angle

$$\tan(2\theta) = \frac{\delta m}{(m_n - m_\chi) + (\Delta E_n - \Delta E_\chi)}$$

➡ resonant enhancement for $\Delta E_n \approx m_\chi - m_n < 0$

Converting DM to neutrons

- Heuristic approach:
  1. Coherent oscillation probability:

$$P_n(t) = \sin^2(2\theta)\,\sin^2(\delta\omega\, t/2)$$

difference between (thermal) mass eigenvalues

  2. Average over mean free time between scatterings $n\pi \to n\pi$

$$\bar{P}_{\chi\to n} = \int dt\, e^{-\Gamma_n t} P_{\chi\to n}(t) = \frac{2(\delta m)^2}{(\delta\omega)^2 + \Gamma_n^2}$$

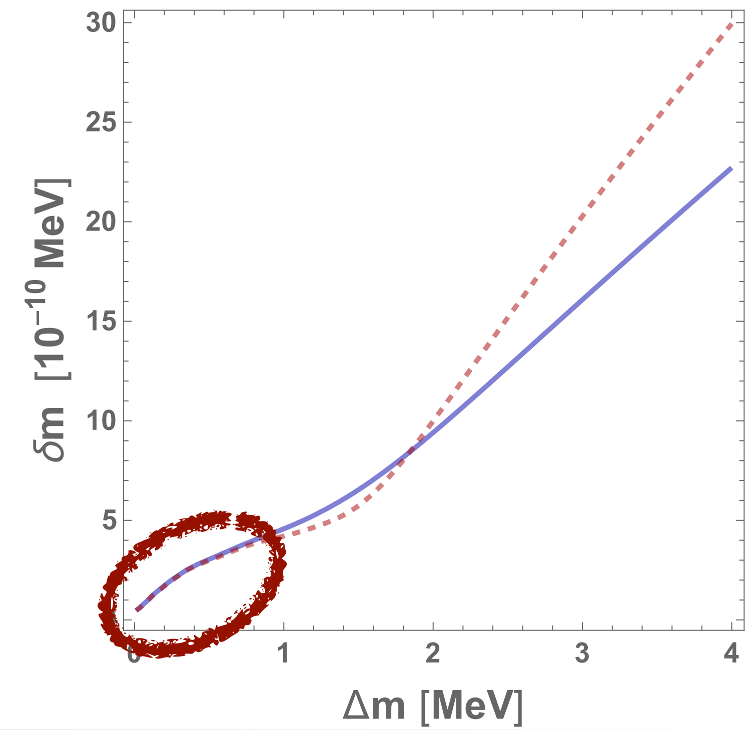
  3. Solve simple Boltzmann equation for the conversion of χ to *n:*

$$\dot{n}_n = -\dot{n}_\chi = \Gamma_{\rm osc}(n_\chi - n_n)$$

$\Gamma_n \bar{P}_{\chi\to n}$

start with $n_n = 0$

demand $n_\chi/n_n = 5.4$ **'today'**

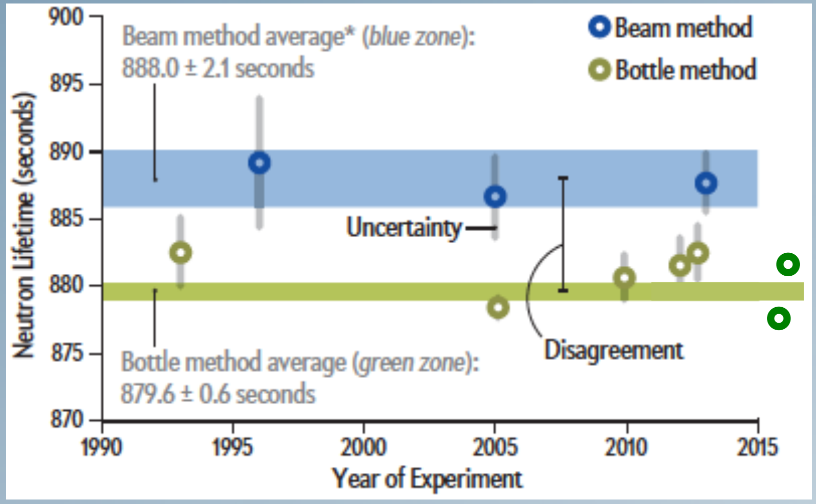


- Very good agreement with full (Matrix) Boltzmann approach

[when conversion probability is highly peaked]

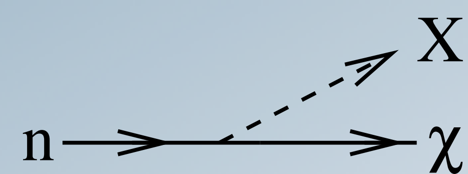
Neutron lifetime anomaly

- Long-standing discrepancy of lifetime measurements in *p*-appearance (beam) vs *n*-disappearance (bottle) experiments



Green & Geltenbort, '16

- Additional decay channel to DM may explain this, if $BR(n \to X\chi) = 0.9\%$



Fornal & Grinstein, PRL '18

- Only small mass window available ($\Delta m \equiv m_n - m_\chi$):
  - Avoid decay to protons ($\chi \to p e^- \nu_e$)
  - Neutron stability inside nuclei (^{9}Be)

$$0.79\,\mathrm{MeV} < \Delta m < 1.67\,\mathrm{MeV}$$

- All possible visible channels ($X = \gamma$ and $X = e^+e^-$) experimentally ruled out

Tang *et al*, PRL '18
Sun *et al*, PRC '18

Adding a *U(1)*

- Let's assume that DM couples to some new light (vector) particle

$$\mathcal{L} \supset g' \bar{\chi} \gamma^\mu \chi A'_\mu$$

➡ $\Gamma_{n\to\chi\gamma'}/\Gamma_{n\to\chi\gamma} \propto (g'/\mu_n)^2 \gg 1$

$m_{\gamma'}$ ~~0.79 MeV~~ $< \Delta m < 1.67\,\mathrm{MeV}$

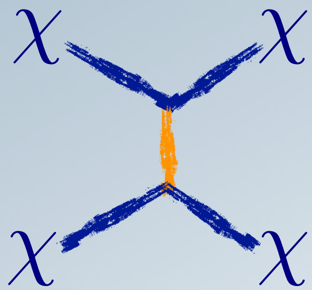
- Pressure loss in neutron stars from $n \to \chi$ problematic

McKeen+, 1802.08244
Baym+, 1802.08282
Motta, Guichon & Thomas, 1802.08427

➡ sufficient counter-pressure for

$$m_{\gamma'/g'} \lesssim (45-60)\,\mathrm{MeV}$$

Cline & Cornell, JHEP '18

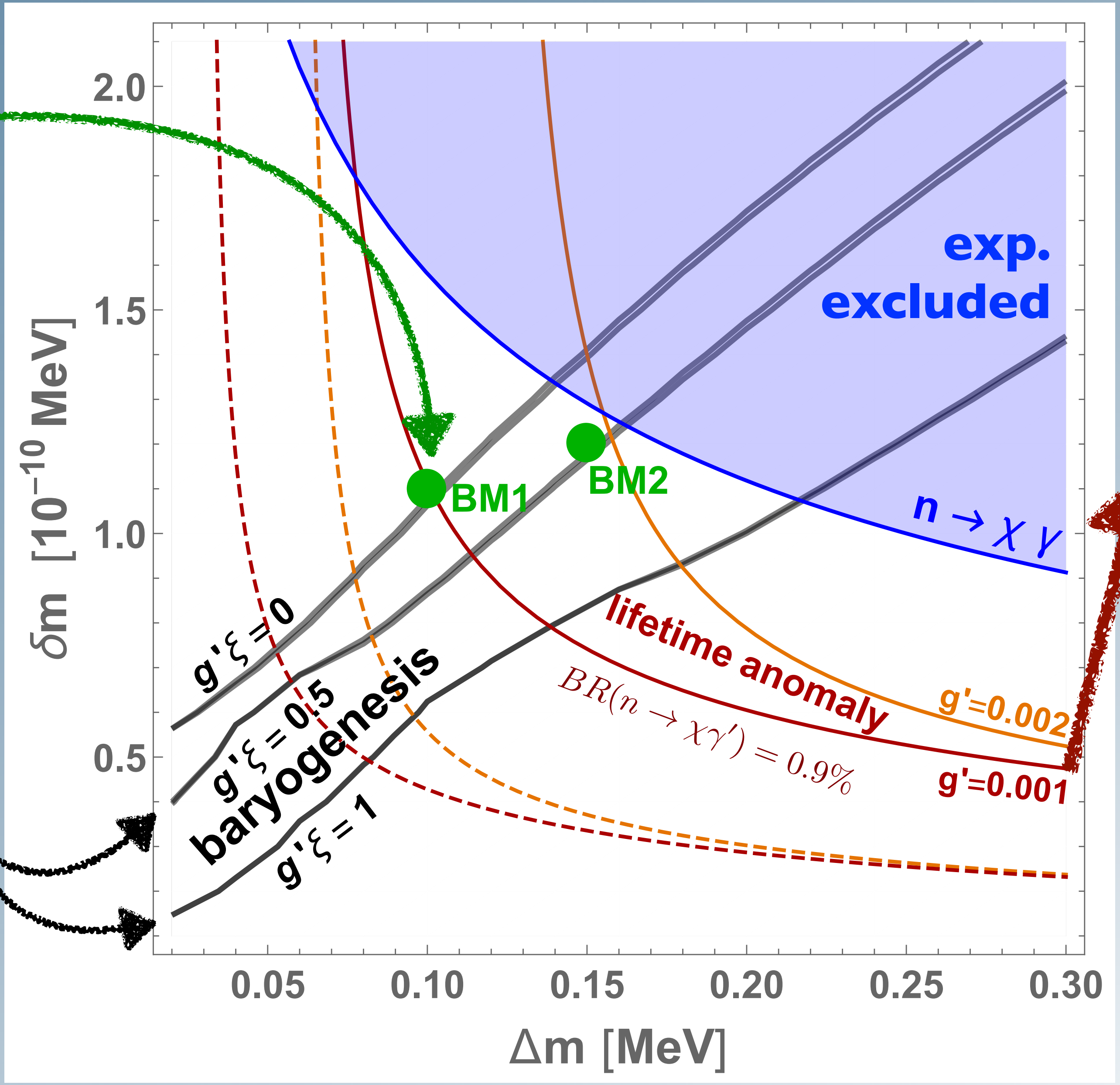


- Now also the DM mass receives thermal corrections from $\chi\gamma' \to \chi\gamma'$

Baryogenesis & lifetime anomaly

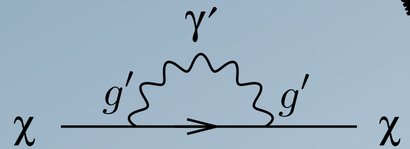
BM1: successful baryogenesis, address lifetime anomaly, satisfy all constraints

BM2: 'minimal' version for successful baryogenesis (no lifetime anomaly!): large coupling and 50 MeV dark photon.



explaining lifetime anomaly requires $m_{\gamma'}/g' > 60\,\mathrm{MeV}$, in conflict with neutron star constraints

thermal corrections



$$\xi \equiv T_{\gamma'}/T_\gamma$$

Possible UV completion

Cline & Cornell, JHEP '18

$$\mathcal{L}_{\rm UV} = \lambda_1 \bar{d}^a P_L \chi \Phi_{1,a} + \lambda_2 \epsilon^{abc} \bar{u}^C_a P_R d_b \Phi_{2,c} + \mu \phi \Phi_{1,a} \Phi_2^{*a} + \text{H.c.}\,.$$

heavy *SU(3)* triplets

$m_\Phi \gtrsim 1.5\,\text{TeV}$ (LHC)

$B = -2/3$

Φ_1 also carries U(1) charge

'dark Higgs'

gives mass to γ'

benchmark B1: $m_\phi \sim 60\,\text{MeV}$

- Mass mixing ($\mathcal{L}_{\rm mix} = -\delta m\ \bar{n}\chi + \text{h.c.}$) induced as $\langle\phi\rangle \equiv v' \neq 0$:

$$\delta m = \frac{\beta\mu\lambda_1\lambda_2 v'}{m^2_{\Phi_1} m^2_{\Phi_2}} \cong 8 \cdot 10^{-10}\,\text{MeV} \left(\frac{v'}{60\,\text{MeV}}\right)\left(\frac{\lambda_1\lambda_2\mu}{\text{TeV}}\right)\left(\frac{\text{TeV}^4}{m^2_{\Phi_1} m^2_{\Phi_2}}\right)$$

[$\beta = \langle n | udd | 0 \rangle = 0.014\,\text{GeV}^3$ from lattice QCD: Aoki+, PRD '17]

- U(1) phase transition indeed happens before resonance temperature — TB, Cline & Cornell, 1811.08215
  - For benchmark B1 at around 100 MeV

But B1 needs further d.o.f…

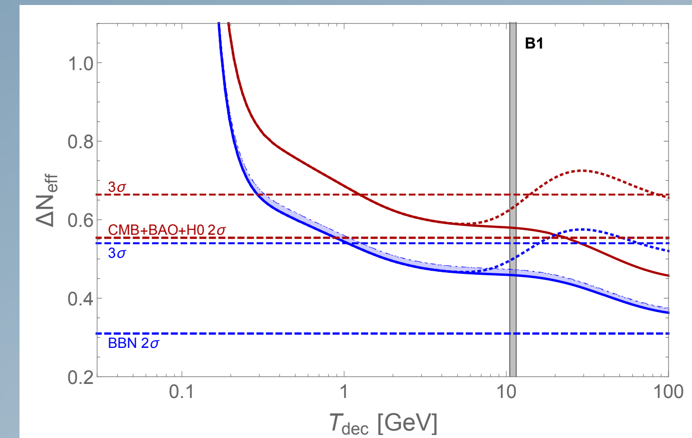
TB, Cline & Cornell, 1811.08215

- Need ~100 GeV Majorana fermion ψ' to avoid transferring original asymmetry *before* oscillations
  - Problematic 'low-energy' process: $\chi\phi^* \to udd$
  - Cure: $\mathcal{L} \supset \lambda' \bar{\chi}\phi\psi'$ sets $\mu_\chi = \mu_\phi \rightsquigarrow \mu_{\rm SM} = 0$
- Need ~100 GeV Dirac fermion ψ to get rid of symmetric DM component
  - Freeze-out from $\chi\chi \to \gamma'\gamma'$ not efficient enough for small g'
  - Cure: freeze-out from $\chi\chi \to \psi\psi$
- Need ~massless sterile neutrinos ν' as an invisible decay channel for thermally produced γ'
  - $\gamma' \to e^+e^-$ not kinematically accessible $\rightsquigarrow$ quasi-stable $\rightsquigarrow$ overclosure
  - Cure: any light inert d.o.f. that cannot mix with χ

Late-time cosmology

- Additional light d.o.f. currently lead to 2σ tension w/ CMB+BBN

  ⇨ firmly testable in near future!

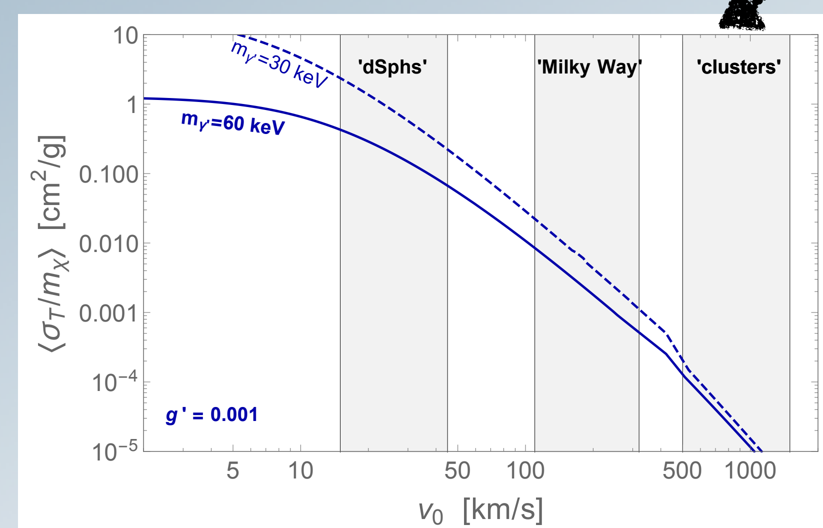


- Late-time $\chi\nu' \to \chi\nu'$ induces cutoff in power-spectrum of matter density perturbations

  ⇨ address missing satellites problem?

- Late-time $\chi\chi \to \chi\chi$ can affect DM distribution in dwarf galaxies

  ⇨ address further ΛCDM small-scale problems?

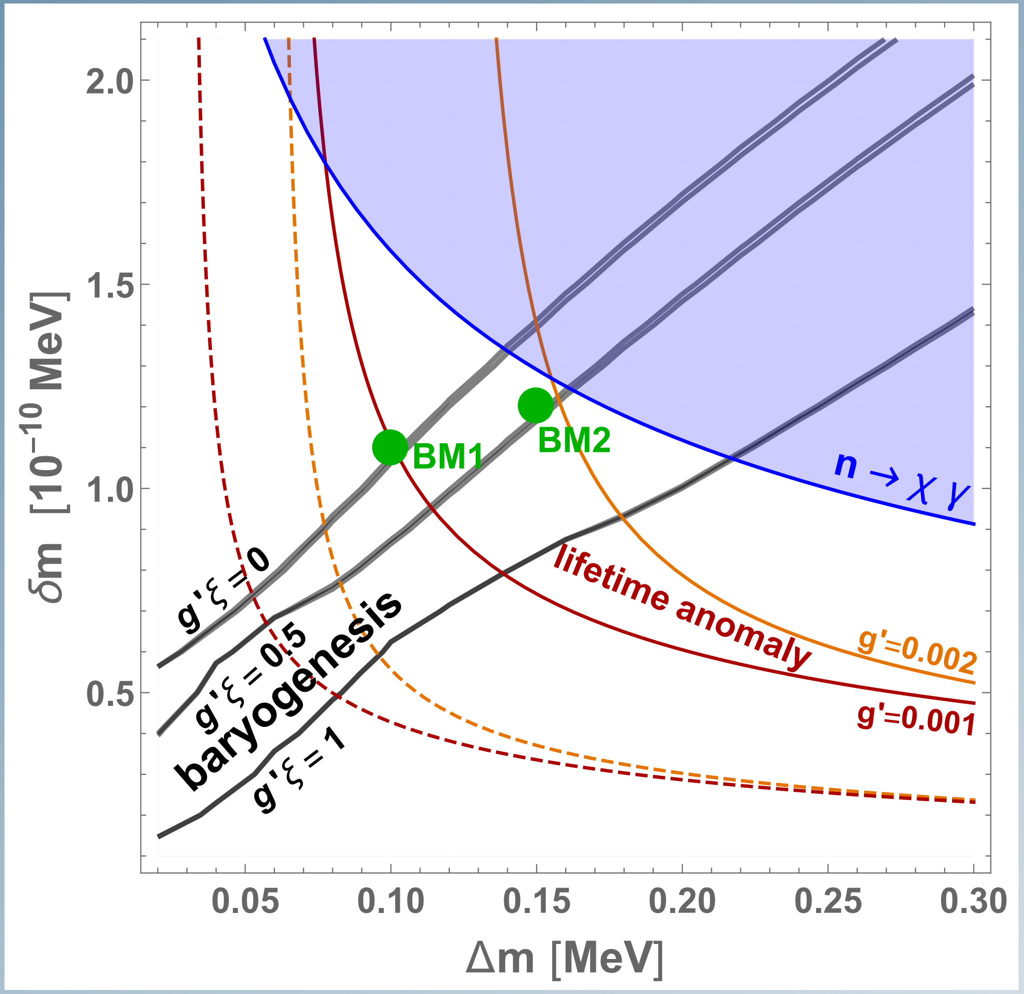


Conclusions

BM1

'light dark photon, small DM coupling'

- low-scale **baryogenesis** through χ-*n* oscillations
- explain neutron **lifetime anomaly**
- address ΛCDM **small-scale problems**
- **UV complete** model (with proliferation of new dof ?)



BM2

'heavy dark photon, large DM coupling'

- low-scale **baryogenesis** through χ-*n* oscillations

Thanks for your attention!

BACKUP

DarkSUSY

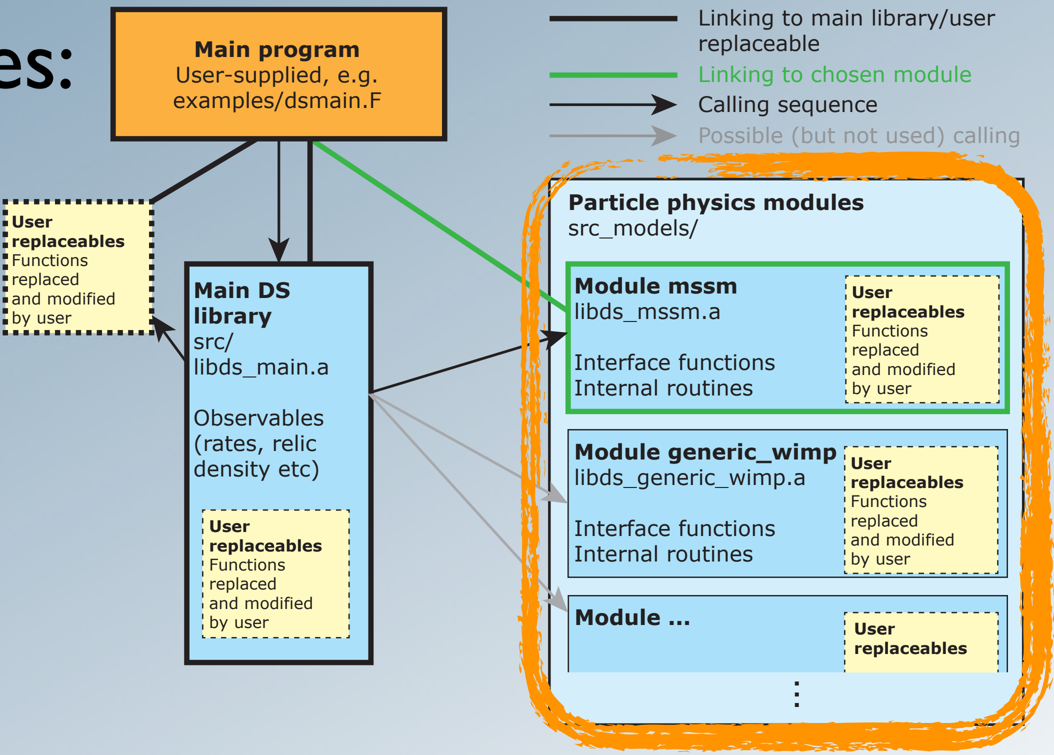
FREE DOWNLOAD ;)

TB, Edsjö, Gondolo, Ullio & Bergström, 1802.03399 (JCAP)

http://darksusy.org

Significantly revised version 6 earlier this year!

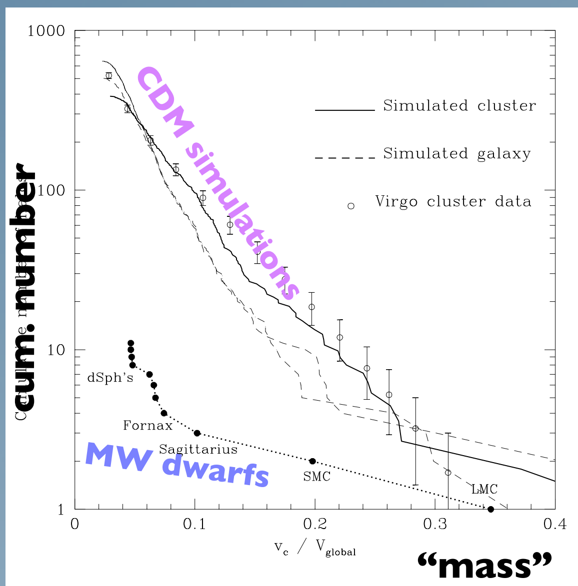
- Fortran package to calculate "all" DM related quantities:
  - *relic density + kinetic decoupling* **(also for $T_{\rm dark} \neq T_{\rm photon}$)**
  - *generic SUSY models + laboratory constraints implemented*
  - *cosmic ray propagation*
  - *indirect detection rates: gammas, positrons, antiprotons, neutrinos*
  - *direct detection rates*
  - ...



since 6.1: DM self-interactions

Small-scale problems

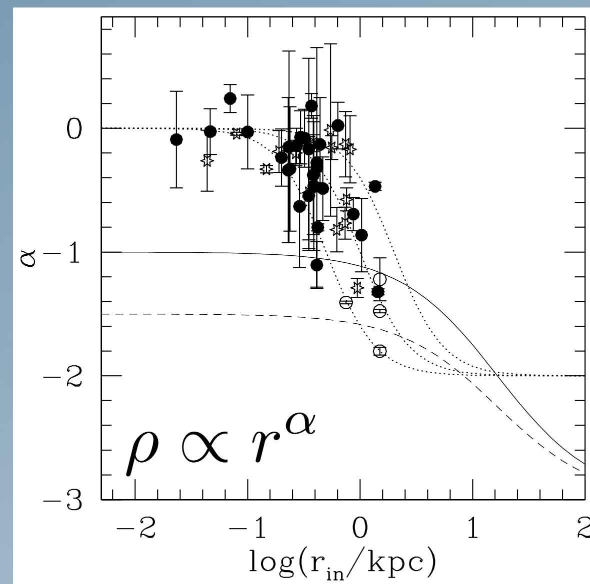
1. Missing satellites?



Moore *et al.*, ApJ '99

Many *more* *satellites in simulations* of MW-like galaxies than observed

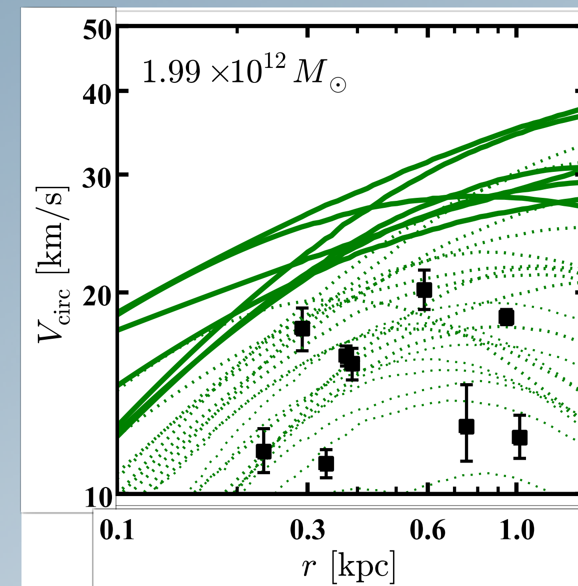
2. Cusps or cores?



Blok *et al.*, ApJ '01

Cuspy inner density profiles predicted by simulations not found in (all) observations

3. Too big to fail?



Boylan-Kolchin, Bullock & Kaplinghat, '11

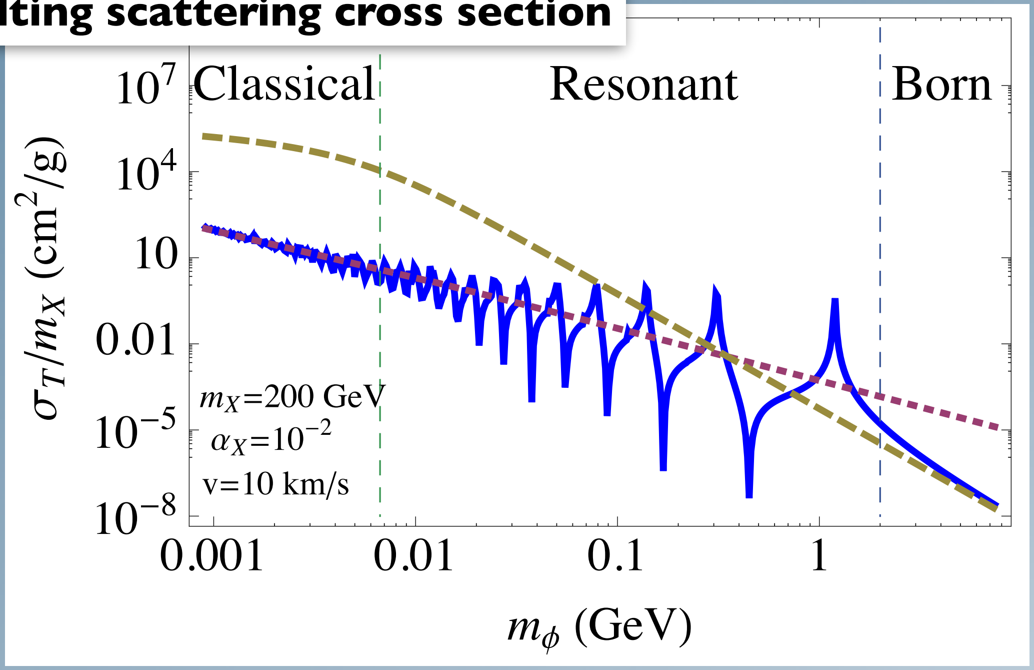
Most massive subhalos in simulations are too dense to form observed brightest dwarf galaxies

Self-interacting dark matter

- Massive mediators induce a Yukawa potential between DM particles.

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

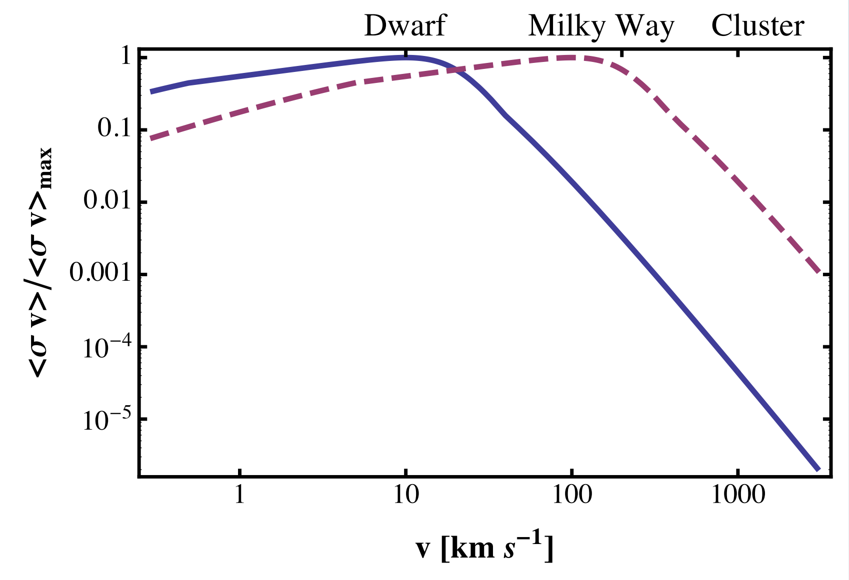
Resulting scattering cross section



[resonances only for attractive potential]

$$\sigma_T \equiv \int d\Omega(1-\cos\theta)\frac{d\sigma}{d\Omega}$$

see e.g. Tulin, Yu & Zurek, PRD '13



Loeb & Weiner, PRL '11

+ *characteristic velocity dependence !*

This can address the cusp-core and too-big-to-fail problems!

Feng, Kaplinghat & Yu, PRL '10
Loeb & Weiner, PRL '11
Vogelsberger, Zavala & Loeb, MNRAS '12

Adding one more light particle

- A stable massive mediator would overclose the universe (c.f. cosmological bound on massive neutrinos)
- Decay to SM particles essentially not possible
  - severe CMB bounds due to Sommerfeld-enhanced annihilation
    TB, Kahlhoefer, Schmidt-Hoberg & Walia, PRL '17
  - scalar mediators (*p*-wave) evade those, but are typically excluded by direct detection
    Kaplinghat, Tulin & Yu, PRD '14
    Bernal+, JCAP '16
- Invisible decay also leads to *very late kinetic decoupling*, and thereby addresses the missing satellites problem!
  van den Aarssen, TB & Pfrommer, PRL '12
  TB, Hasenkamp & Kersten, JCAP '14