ν-dark forces: from Dwarf Galaxies to IceCube

Ian M. Shoemaker

CP^3 Origins
Cosmology & Particle Physics

[1411.1071]
[15XX.XXX]

with Los Alamos collaborators
JJ Cherry & Alex Friedland

MIAPP

DARK MALT 2015

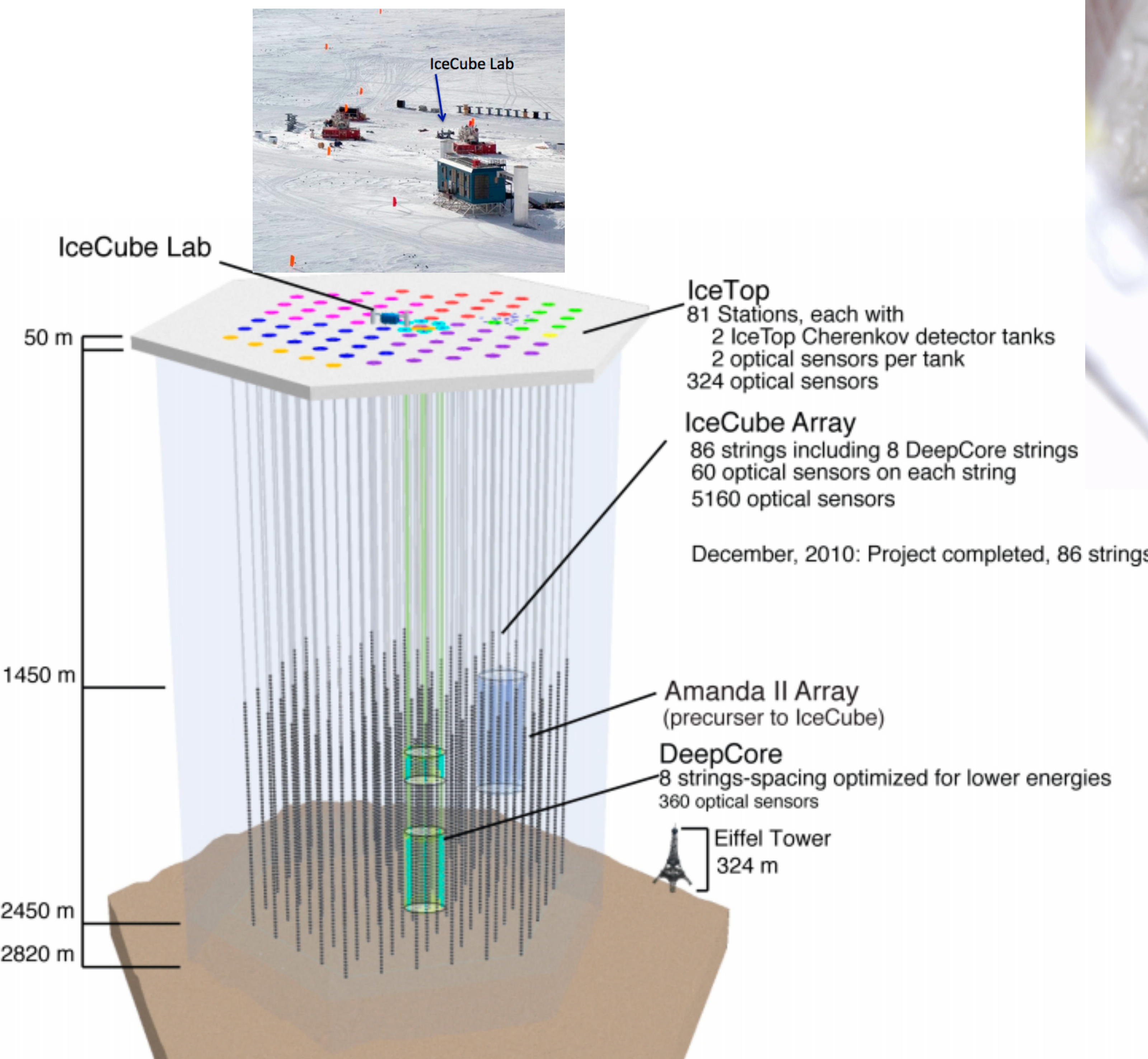
Previous related work:

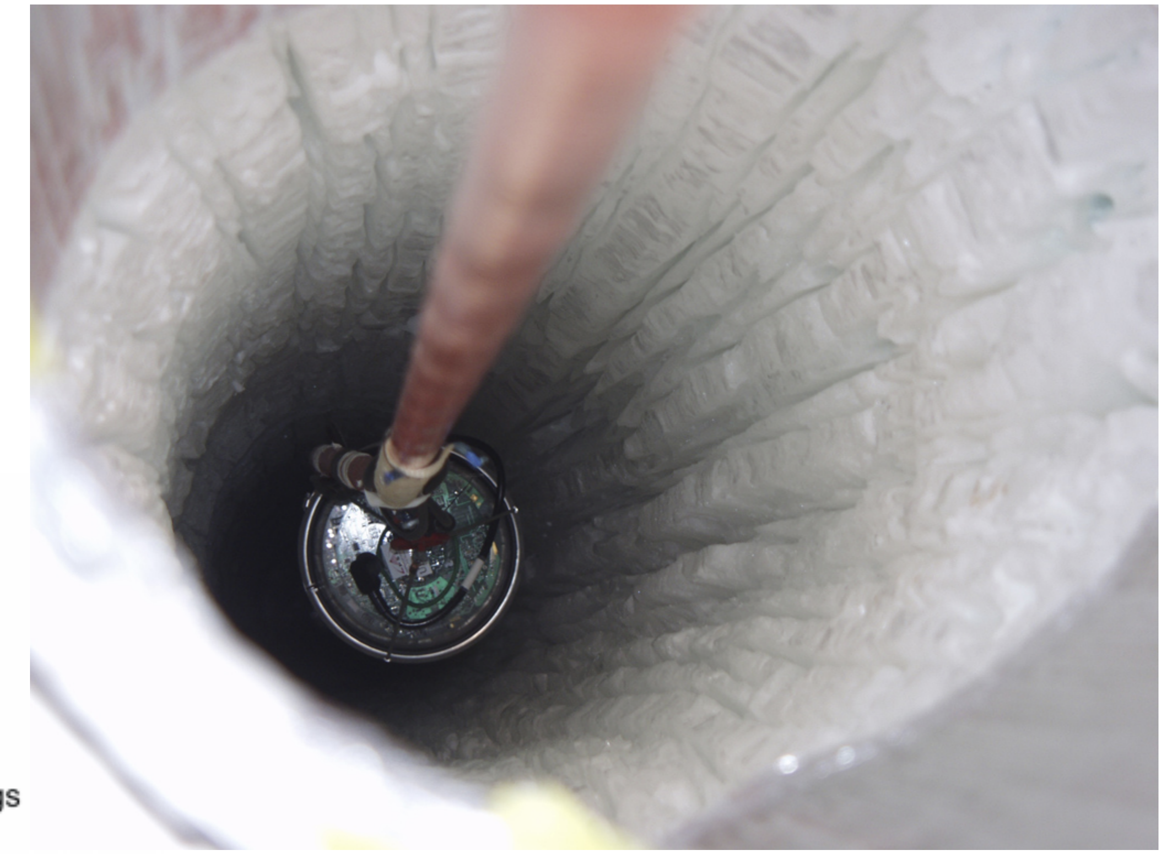
Boehm, Fayet, Schaeffer [astro-ph/0012504]
Boehm, Fayet [hep-ph/0305261]
van den Aarssen, Bringmann, Pfrommer [1205.5809]
Dasgupta, Kopp [1310.6337]
Bringmann, Hasenkamp, Kersten [1312.4947]
Ko, Tang [1404.0236]
Beacom, Ng [1404.2288]
Ioka, Murase [1404.2279]
Blum, Hook, Murase [1408.3799],
…

Spoiler

- IceCube has found an unusual neutrino signal.
  - Doesn’t fit generic astrophysical predictions.
- Very high energies and long baselines:
  - Can teach us about BSM neutrino interactions.
  - Present data can be accommodated if neutrinos couple to a new light force carrier.
- This same mediator may be responsible for the anomalies in the small-scale structure of dark matter, e.g. “missing satellites” & “cusp vs. core” problems.

The IceCube Detector





Need large volumes since:

i) these are rare events

ii) they are also large events

Just when IceCube was getting really good at placing limits...

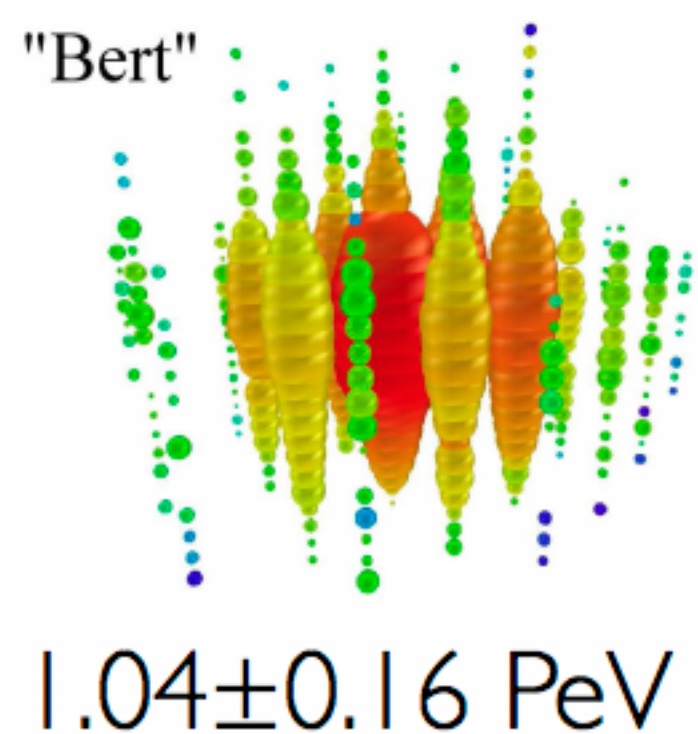
PRL 111, 021103 (2013) PHYSICAL REVIEW LETTERS week ending 12 JULY 2013

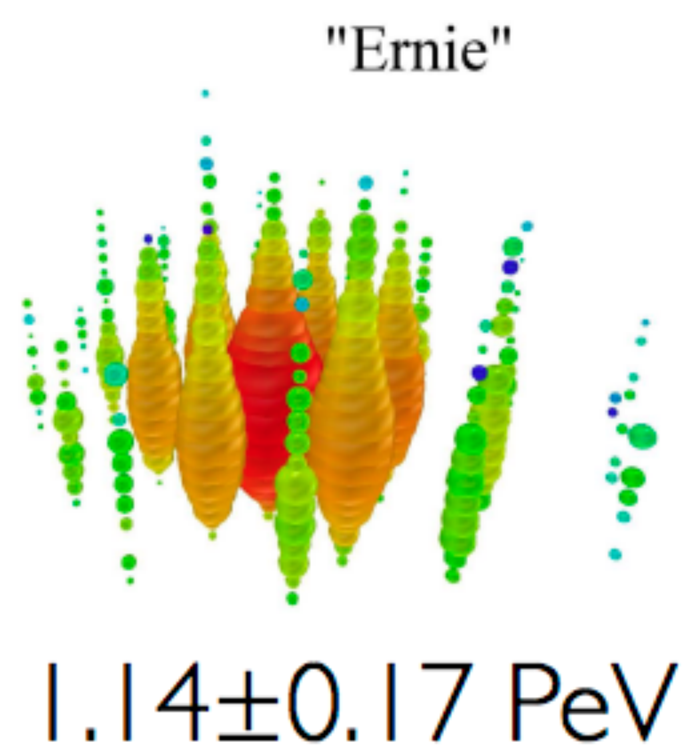
First Observation of PeV-Energy Neutrinos with IceCube

	Event 1	Event 2
date (GMT)	August 8, 2011	January 3, 2012
Number of Photoelectrons	7.0×10^4	9.6×10^4
number of recorded DOMs	312	354
reconstructed energy	1.04+-0.16 PeV	1.14+-0.17 PeV
reconstructed z vertex	121.8 m	24.6 m

Error on vertex position: ~ 5m

Given names befitting this monumental discovery:





[slide courtesy of N.Whitehorn]

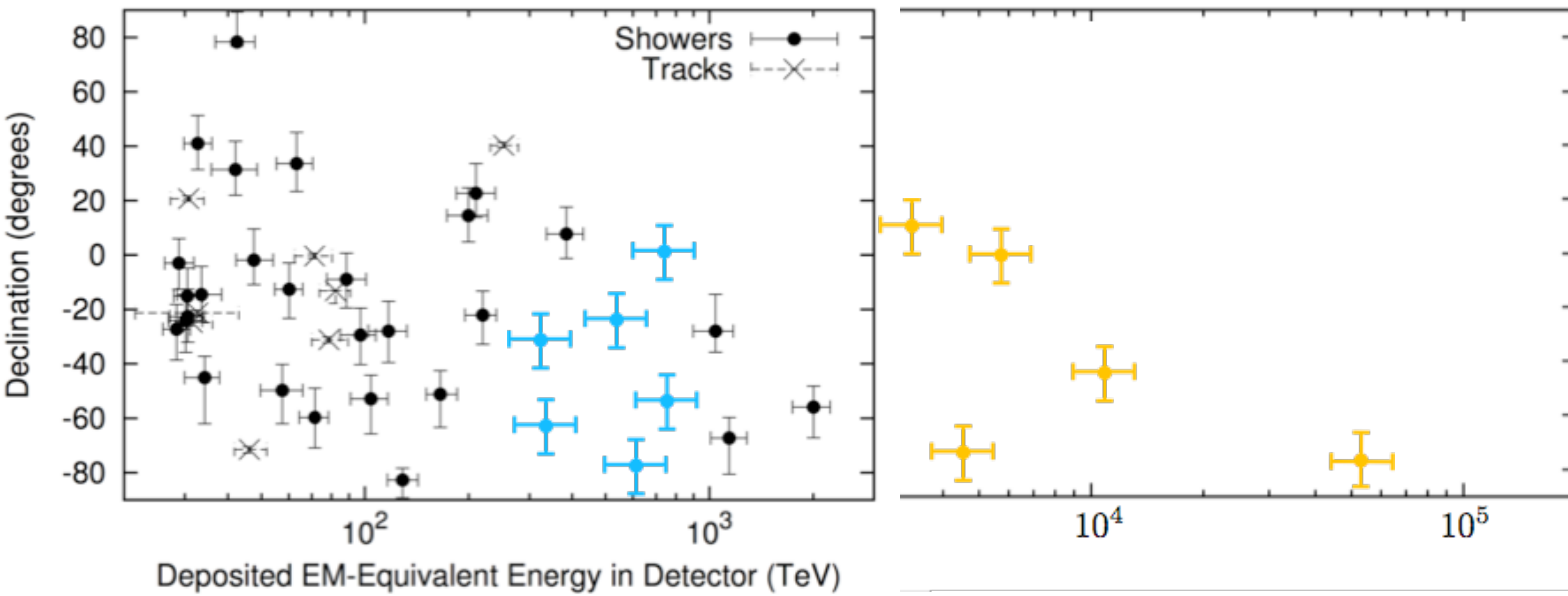
New Results

• IceCube has revealed much more: 35 more events (30 - 2000 TeV) for combined significance 5.7 σ above background.

•First indication of a new astrophysical source.

•Distribution consistent with extra-galactic source.

[1405.5303]



Who ordered a gap and a cutoff?

Potential astro sources

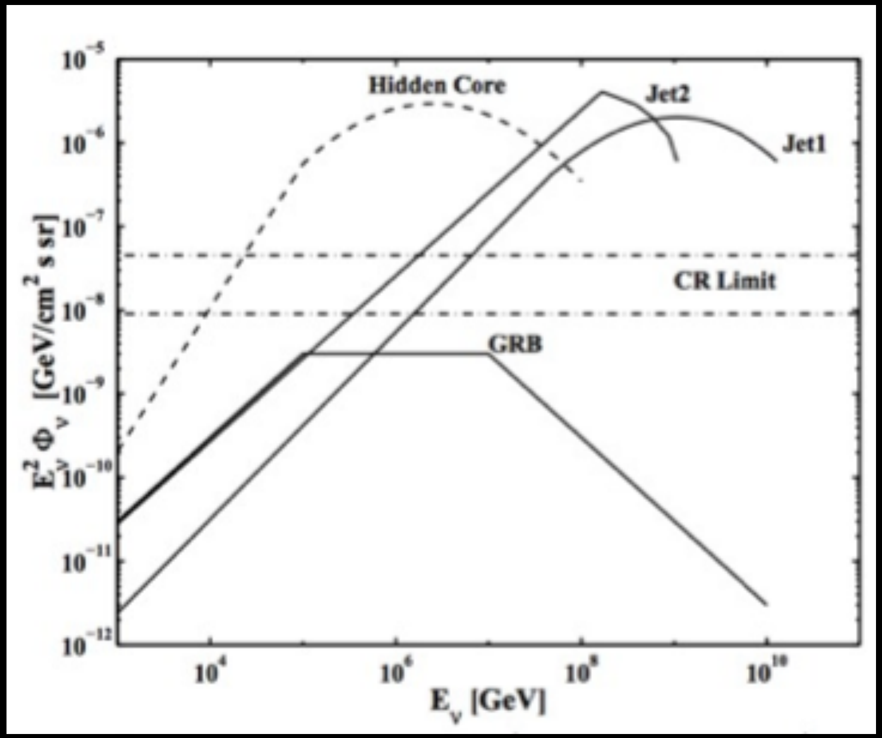
- *Gamma ray bursts (GRBs)*

Fast rotating star goes supernova $\longrightarrow$ shock wave

shock accelerates protons $\longrightarrow$ $p + \gamma \to n\pi^+$

$$\pi^+ \to \mu^+ \nu_\mu$$

$$\mu^+ \to e^+ + \nu_e + \overline{\nu}_\mu$$



Shock acceleration yields:

$$\phi_\nu \propto E_\nu^{-2}$$

[Waxman, Bahcall, PRL **59**, 023002 (1999)]

Potential astro sources

- *Active galactic nuclei (AGNs)*
  - Similar, but can accelerate protons to even higher energies, and photo-pion produce $\nu' s$.

NEUTRINO FLUXES FROM ACTIVE GALAXIES: A MODEL-INDEPENDENT ESTIMATE

F. HALZEN
Department of Physics, University of Wisconsin, Madison, WI 53706
AND
E. ZAS
Departamento de Física de Partículas, Universidad de Santiago, E-15706 Santiago, Spain

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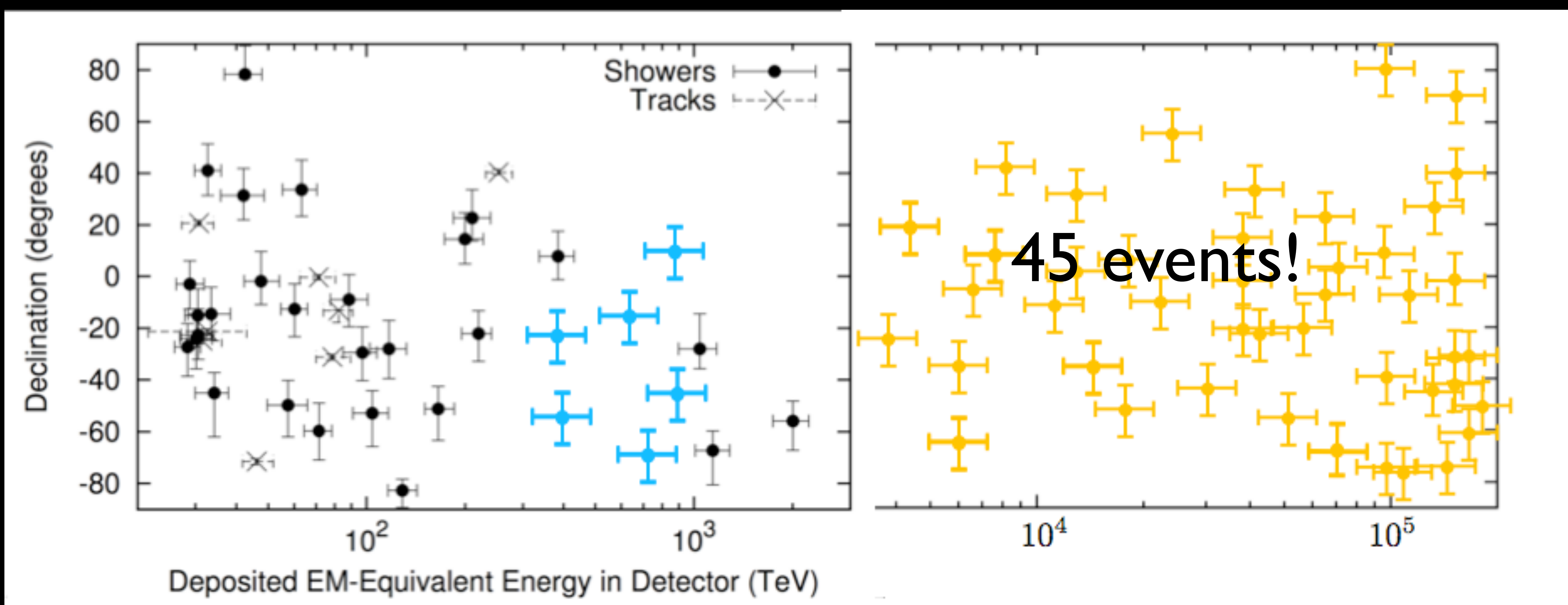
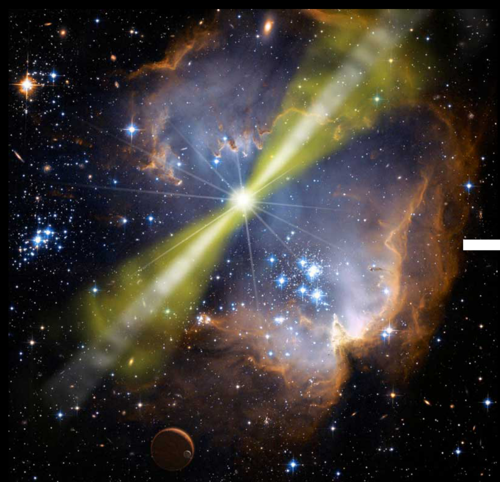
ABSTRACT

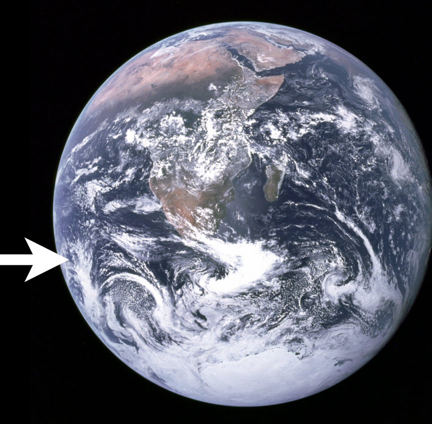
There are tantalizing hints that jets, powered by supermassive black holes at the center of active galaxies, are true cosmic proton accelerators. They produce photons of TeV energy, possibly higher, and may be the enigmatic source of the highest energy cosmic rays. Photoproduction of neutral pions by accelerated protons on UV light may be the source of the highest energy photons in which most of the bolometric luminosity of some galaxies is emitted. The case that proton beams power active galaxies is, however, far from conclusive. Neutrinos from the decay of charged pions represent an incontrovertible signature for the proton-induced cascades. We show that their flux can be estimated by model-independent methods, based on dimensional analysis and textbook particle physics. Our calculations also demonstrate why different models for the proton blazar yield very similar results for the neutrino flux that are consistent with the ones obtained here. As regards astrophysics, they illustrate that proton beams are required to generate TeV photons without fine-tuning.



Standard picture
(pre-IceCube data)



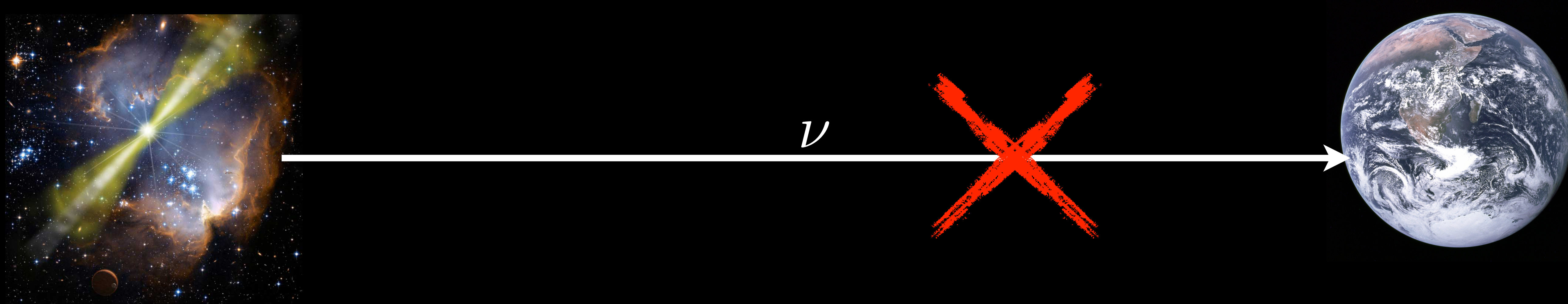
ν



***Source*:**
e.g. GRBs/
AGNs

***Detection*:**
SM charged-
current and
neutral-current
to see events.

New picture =???



Source:
decaying PeV DM?

[Feldstein, Kusenko, Matsumoto, Yanagida, 2013]

[Esmaili, Serpico, 2013]

...

Propagation:

???

Minimal implementation

↓

Only modify ν interactions

Detection:
heavy leptoquarks?

[Barger, Keung, 2013]

An old idea…

PHYSICAL REVIEW D
PARTICLES AND FIELDS

THIRD SERIES, VOLUME 36, NUMBER 10 — 15 NOVEMBER 1987

Supernova 1987A and the secret interactions of neutrinos

Edward W. Kolb
Osservatorio Astronomico di Roma, via del Parco Mellini 84, 00136 Rome, Italy
and NASA/Fermilab Astrophysics Center, Fermi National Accelerator Laboratory, P.O. Box 500, Batavia, Illinois 60510
and Department of Astronomy and Astrophysics, The University of Chicago, Chicago, Illinois 60637

Michael S. Turner
NASA/Fermilab Astrophysics Center, Fermi National Accelerator Laboratory, P.O. Box 500, Batavia, Illinois 60510
and Department of Astronomy and Astrophysics, The University of Chicago, Chicago, Illinois 60637
and Department of Physics and the Enrico Fermi Institute, The University of Chicago, Chicago, Illinois 60637
(Received 13 July 1987)

By using SN1987A as a "source" of neutrinos with energy ~ 10 MeV we place limits on the couplings of neutrinos with cosmic background particles. Specifically, we find that the Majoron–electron-neutrino coupling must be less than about 10^{-3}; if neutrinos couple to a massless vector particle, its dimensionless coupling must be less than about 10^{-3}; and if neutrinos couple with strength g to a massive boson of mass M, then g/M must be less than 12 MeV^{-1}.

Back of the envelope

Perhaps some neutrinos were lost en route.

For significant scattering to occur:

$$\lambda \approx \frac{1}{\sigma_{\nu\nu} n_\nu} < \text{source distance} \sim \mathrm{Gpc}$$

Neutrino relic density is huge:

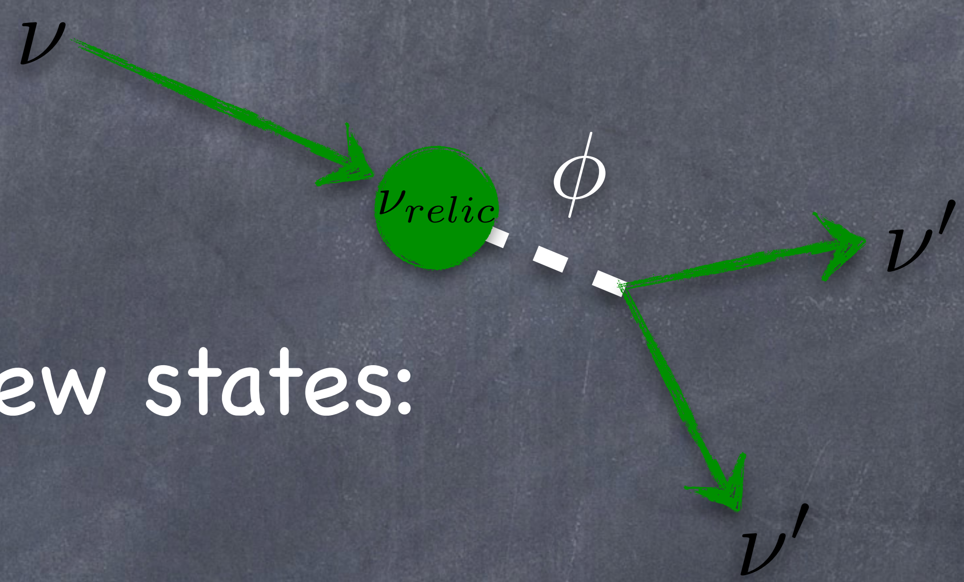
$$n_\nu \sim 300 \ \mathrm{cm}^{-3}$$

c.f. $n_{DM} \sim 10^{-8} \ \mathrm{cm}^{-3}$ for a 100 GeV WIMP

$$\Rightarrow \sigma_{\nu\nu} \gtrsim 10^{-31} \ \mathrm{cm}^2$$

SM is not enough: $\sigma_{\nu\nu}^{SM} \sim E_\nu^2 G_F^2 \sim 10^{-42} \ \mathrm{cm}^2$

MeV-scale resonance



Use PeV neutrinos to produce new states:

$$2m_\nu E_\nu = m_\phi^2$$

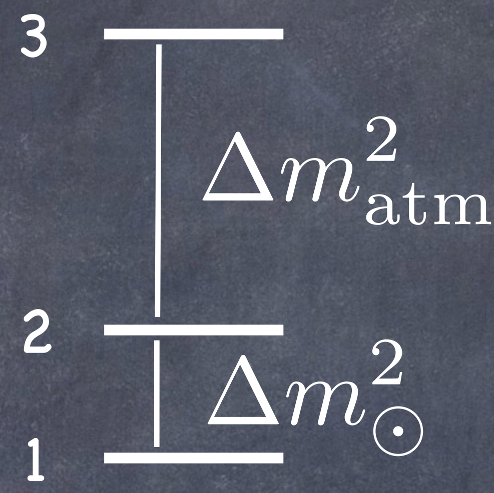
Unknown, though $m_\nu \lesssim 0.5 \text{ eV}$

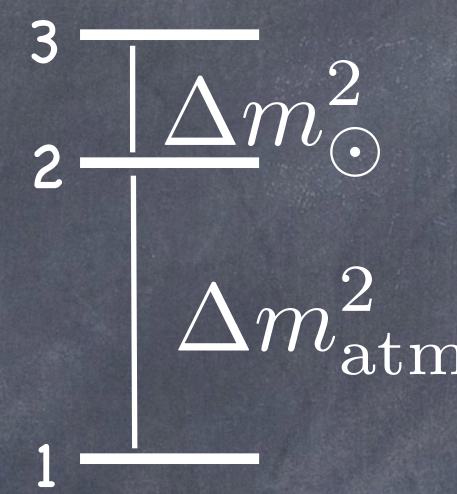
As an example, take $m_\nu \approx \sqrt{\Delta m_\odot^2} \approx 50 \text{ meV}$

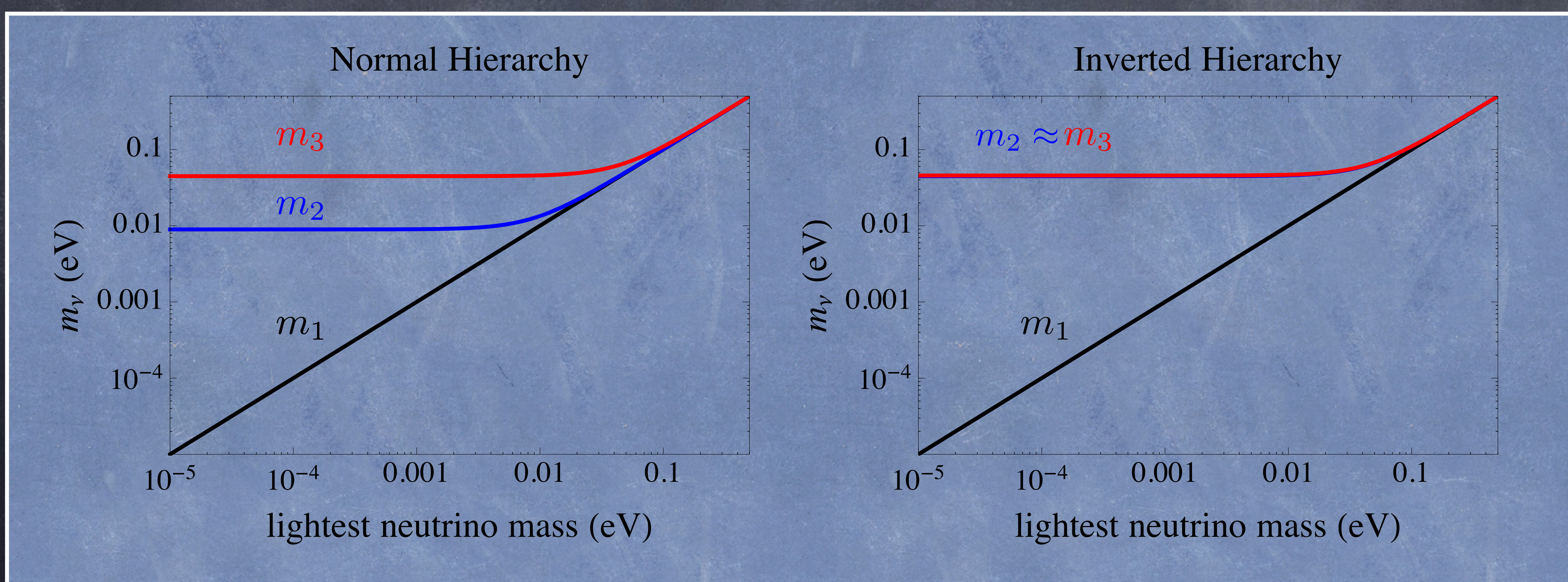
@ $E_\nu \sim 10^6 \text{ GeV} \Longrightarrow m_\phi \sim 10 \text{ MeV}$

Known unknowns

Only know two mass splittings…







Scattering on a thermal background

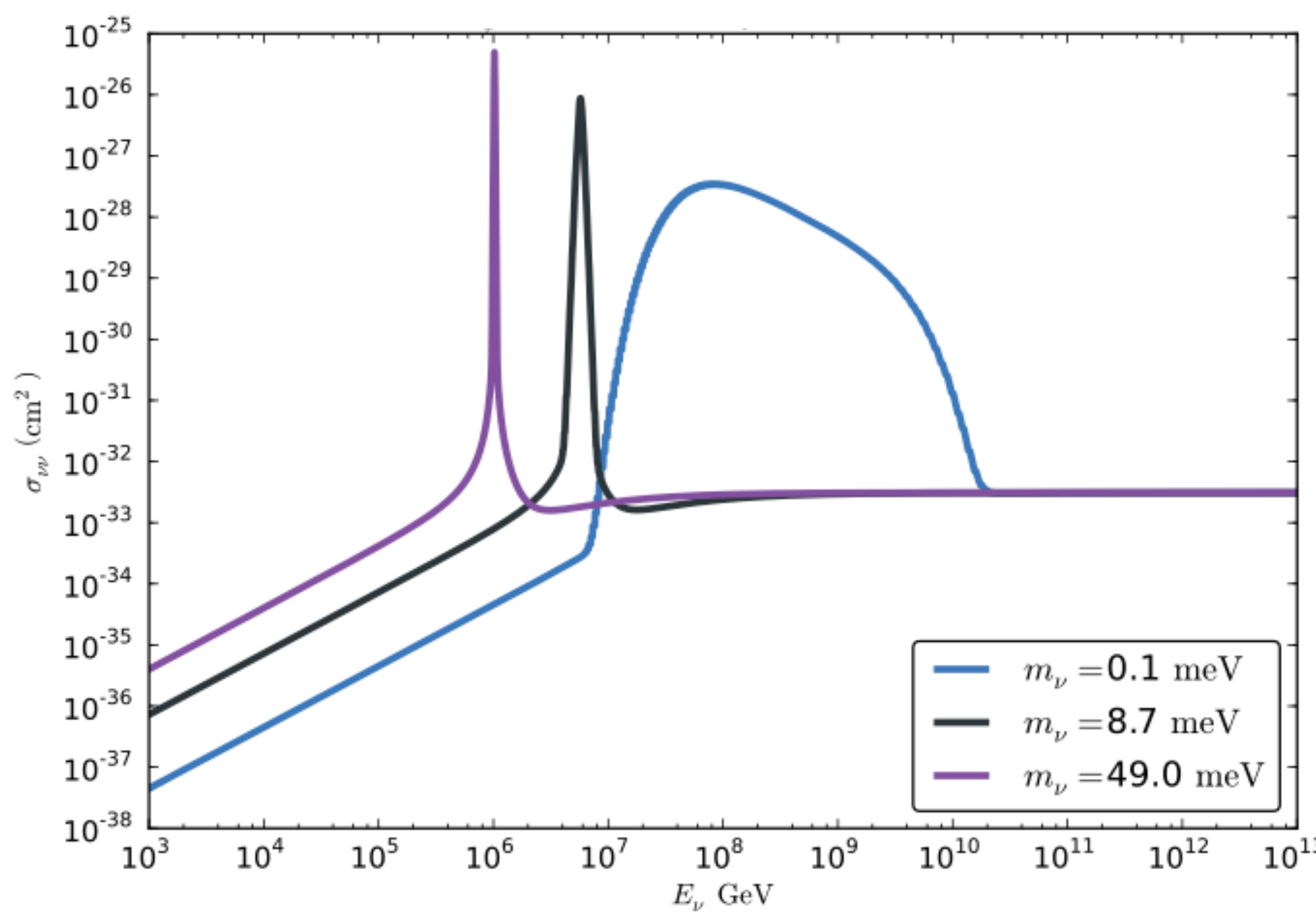
- The thermal neutrino relic background has a temperature: $T_\nu = \left(\frac{4}{11}\right)^{1/3} T_\gamma \approx 0.2\ \text{meV}$
- The lightest nu can easily be relativistic, leading to thermally broadened resonance.

Non-relativistic:

$$s \approx 2E_\nu m_\nu$$

Relativistic:

$$s \approx 2E_\nu \left(\sqrt{p_\nu^2 + m_\nu^2} - p_\nu \cos\theta\right)$$



Constraints BSM neutrino interactions

- Supernovae (1987A):

  [Kolb & Turner (1987)]

  No scattering between here and the LMC

  $$g_\nu \lesssim 12 \left(\frac{m_\phi}{\mathrm{MeV}}\right)$$

- Rare decays

  [Laha, Dasgupta, Beacom (2013)]

  Don't modify Z/meson decays. → Easily satisfied for SM sterile neutrinos.

- BBN/CMB N_{eff}

  Model dependent.

Neutrino Portal DM

New sterile sector, charged under a U(1)

$$g_\nu \bar{\nu}_s \gamma_\mu \nu_s \phi^\mu$$

$$\Delta \mathscr{L}_M = y_\alpha \frac{(L_\alpha H)(h_X \nu_s)}{\Lambda}$$

SM mass mixing

Effectively endows SM neutrinos with new BSM interactions: $\sim \theta_s^2 g_\nu$

[For similar work, see e.g. Nelson, Walsh; Pospelov; Kopp, Harnik, Machado; Pospelov, Pradler; Dasgupta, Kopp]

Suppressing Sterile Production

- No active-to-sterile oscillation when there is a large matter potential:

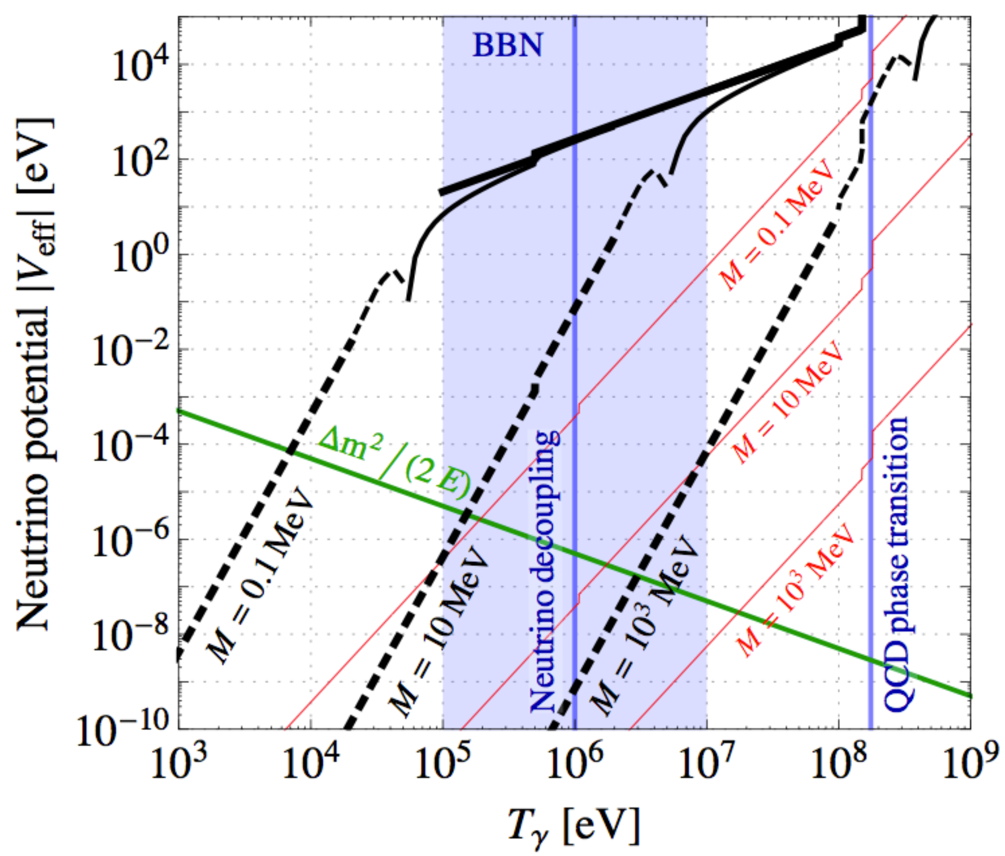
$$\sin^2 2\theta_m = \frac{\sin^2 2\theta_0}{\left(\cos 2\theta_0 + \frac{2E}{\Delta m^2} V_{\rm eff}\right)^2 + \sin^2 2\theta_0}$$

$$|V_{\rm eff}| \gg \left| \frac{\Delta m^2}{2E} \right| \quad \Rightarrow \quad \theta_m \longrightarrow 0$$

$$\boxed{\begin{aligned} \Delta N_\nu \equiv \frac{\rho_{\nu_s} + \rho_{A'}}{\rho_\nu} &= \frac{(g_{\nu_s} + g_{A'})\, T_s^4}{g_\nu\, T_\nu^4} \\ &= \frac{\left(\frac{7}{8} \times 2 + 3\right) \times \left(\frac{10.75}{106.7}\right)^{\frac{4}{3}}}{\left(\frac{7}{8} \times 2\right) \times \left(\frac{4}{11}\right)^{\frac{4}{3}}} \simeq 0.5 \end{aligned}}$$

Dasgupta, Kopp [2013]

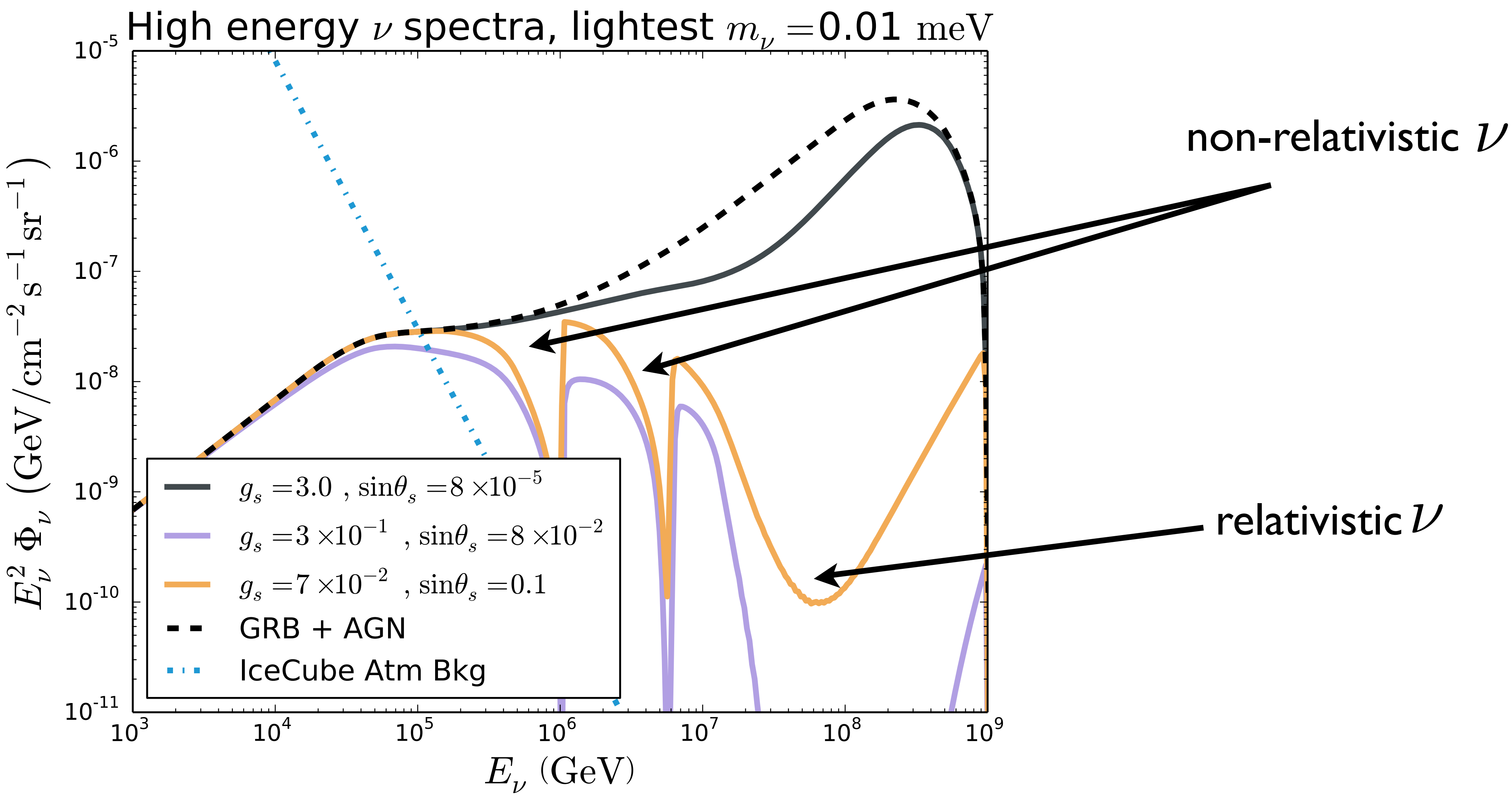
Hannestad, Hansen, and Tram [2013]



Propagation results

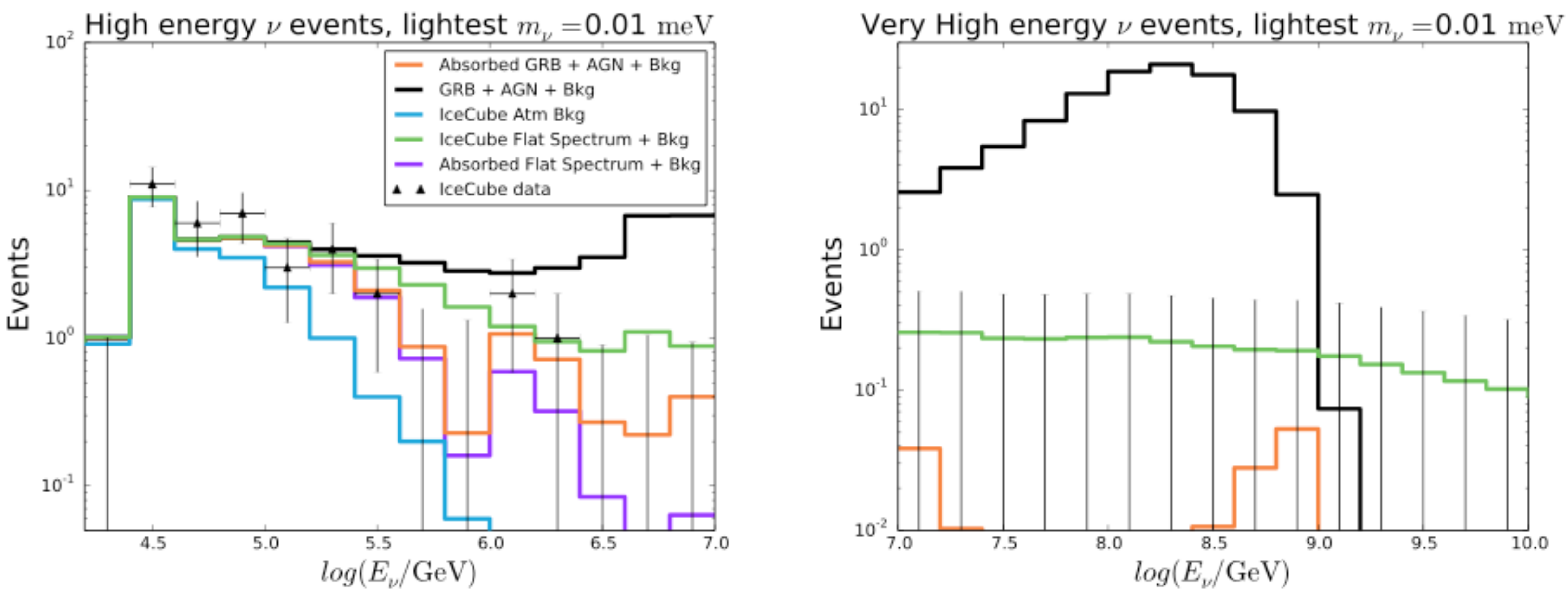
Absorption: $\overline{\nu}_a \nu_a \to \phi \to \overline{\nu}_s \nu_s$

$$m_\phi = 10\ \mathrm{MeV}$$



Event spectra

IceCube detector mock-up: include energy/ flavor dependent exposures.



Future data will tell if the gap and the cutoff are real.

A ν-redshift horizon

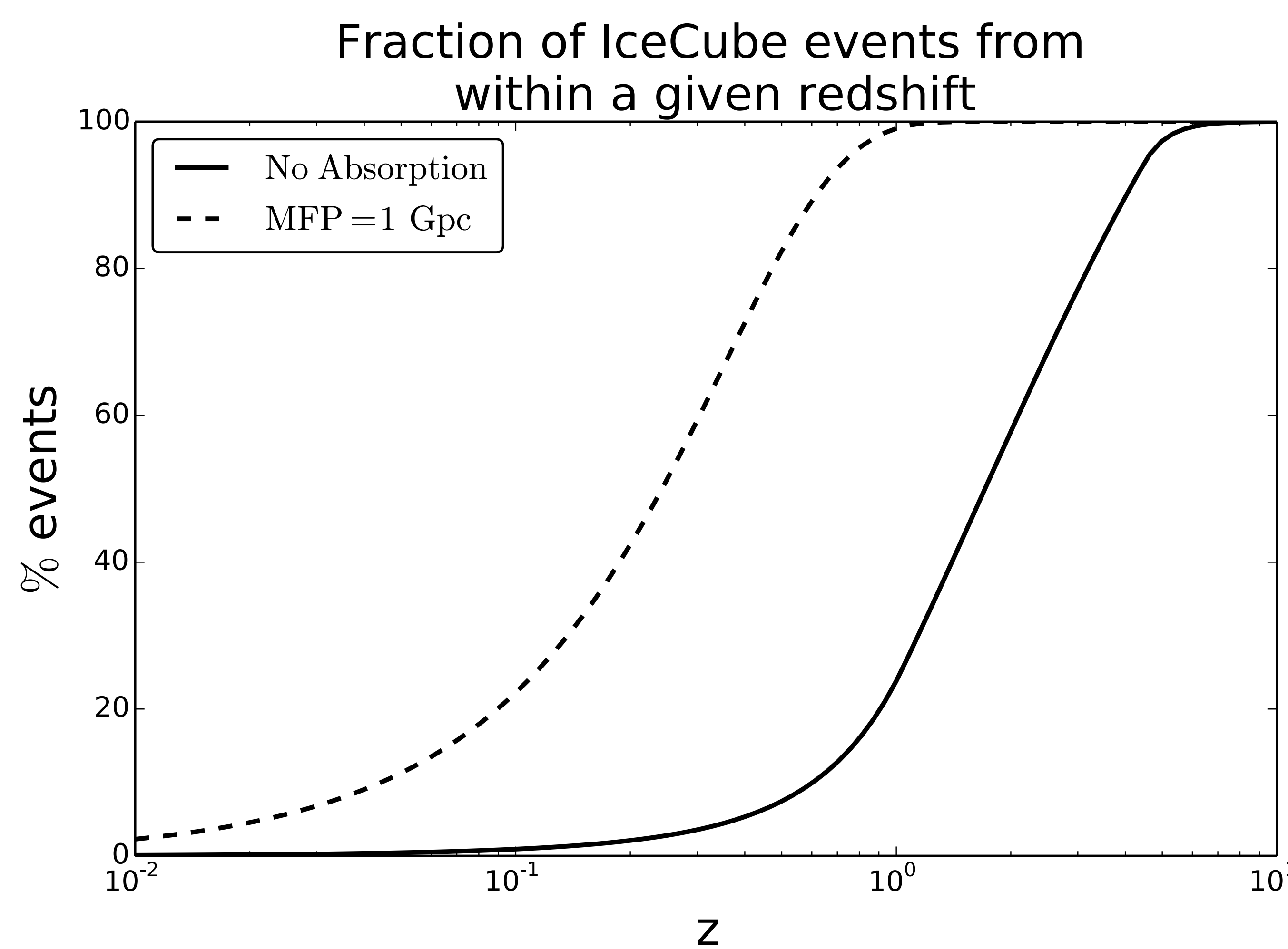
If the mean free path is too small, can only see very nearby sources and isotropy is ruined.

MFP > 50 Mpc

Assume that sources track star-formation history.

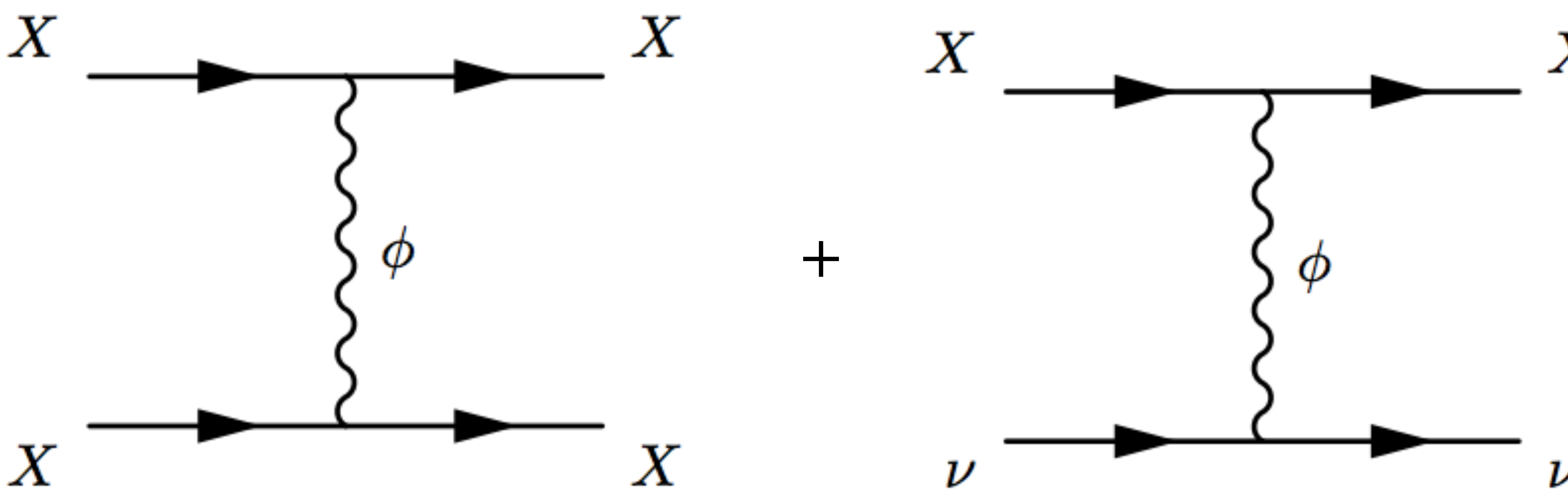
Most sources are at z~1-5.

Thus if correlations with nearby sources are seen, we should have seen many more events in total



Dark Matter Connections

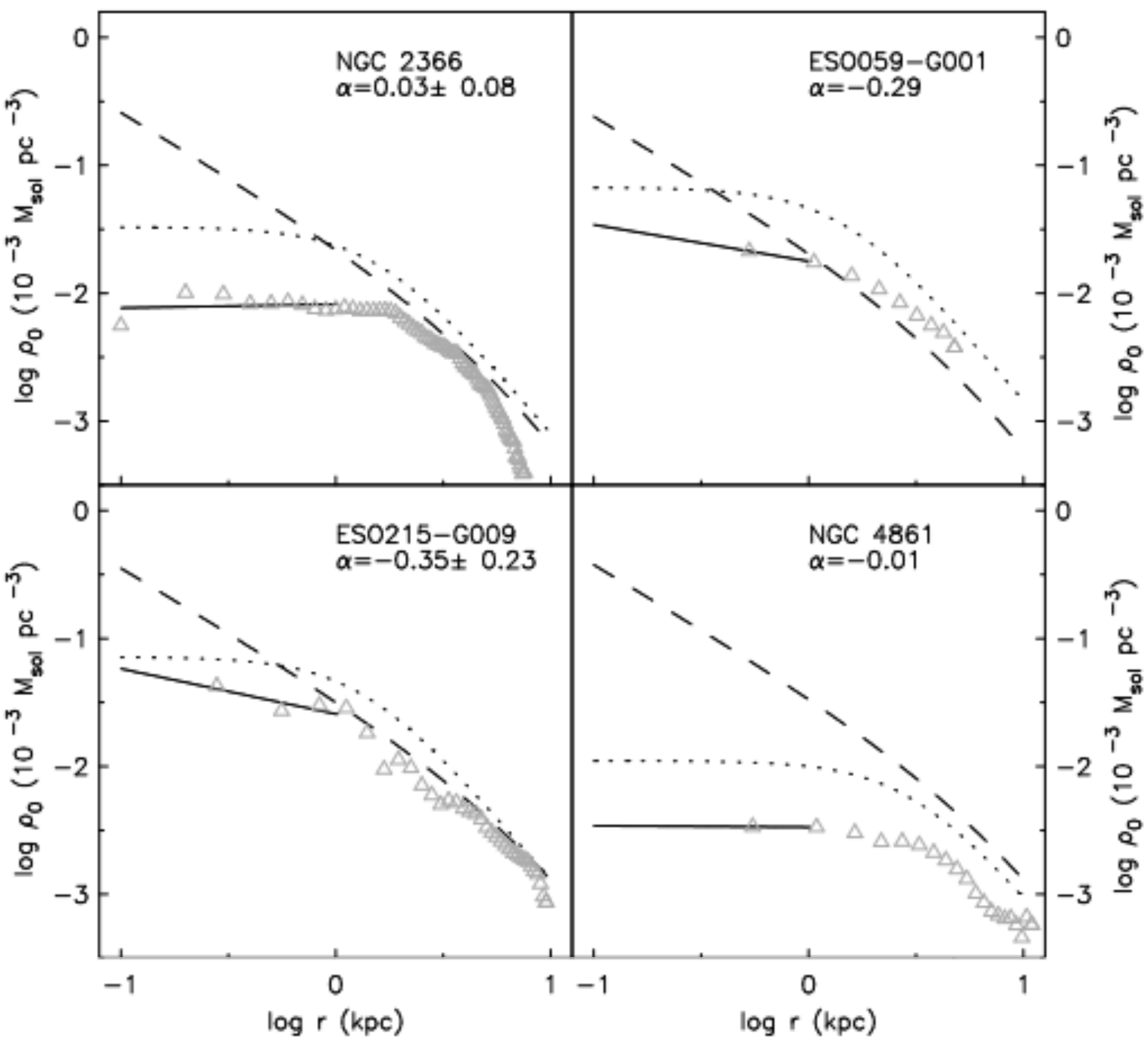
$$\mathcal{L} \supset g_X \bar{X} \gamma^\mu X \phi_\mu$$



Is collisionless cold dark matter in trouble?

Problem 1: Cusps versus Cores

[J. van Eymeren, C. Trachternach, B. S. Koribalski, R.-J. Dettmar (2009)]



Observations of dwarf galaxies have favored core-like density profiles.

N-body simulations of cold DM predict more cuspy profiles.

Problem 2: Missing Satellites

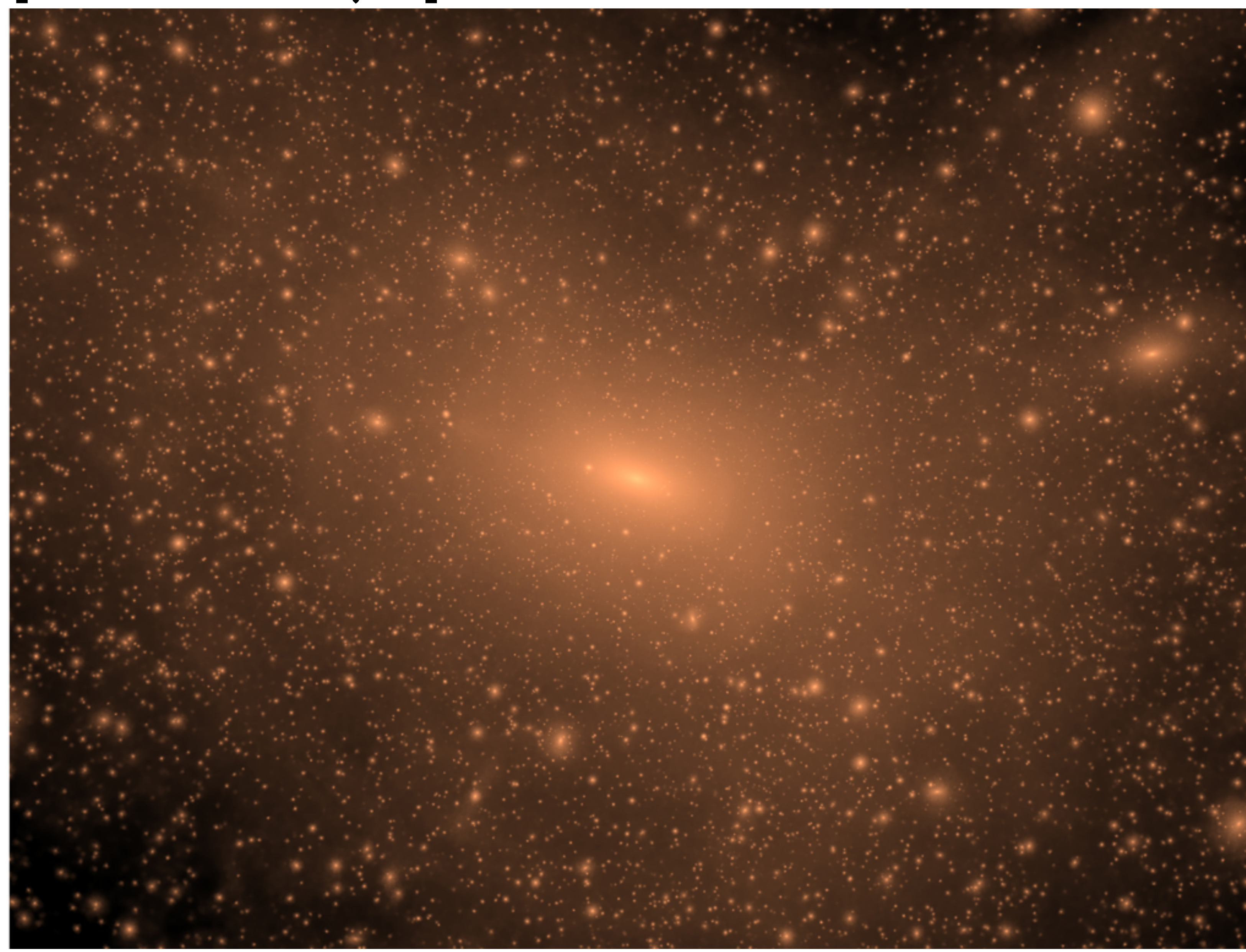
Cold Dark Matter N-body simulations predict many more satellites than observed.

-Could be undiscovered due to faintness or limited sky coverage.

-No baryons in this simulation. Processes like SN can reduce star formation.

Simulated Galactic Halo

[Via Lactea II Project]



Problem 3: Too big to fail*

*(from the point of view of star formation)

- "…dissipationless ΛCDM simulations predict that the majority of the most massive subhaloes of the Milky Way are too dense to host any of its bright satellites."

[Boylan-Kolchin, Bullock, Kaplinghat (2011)]

But should be luminous given the observed dwarfs.

Goldman Sachs

Possible solutions

- Baryonic physics
- Observations
- *Go beyond collisionless cold dark matter*:
    - ***Self-interacting dark matter*** [Spergel, Steinhardt, …]
    - Warm dark matter [Bode, Ostriker, Turok, …]
    - DM late decays [Sigurdson, Kamionkowski, …]
    - "Fuzzy" cold dark matter [Hu, Barkana, Gruzinov]

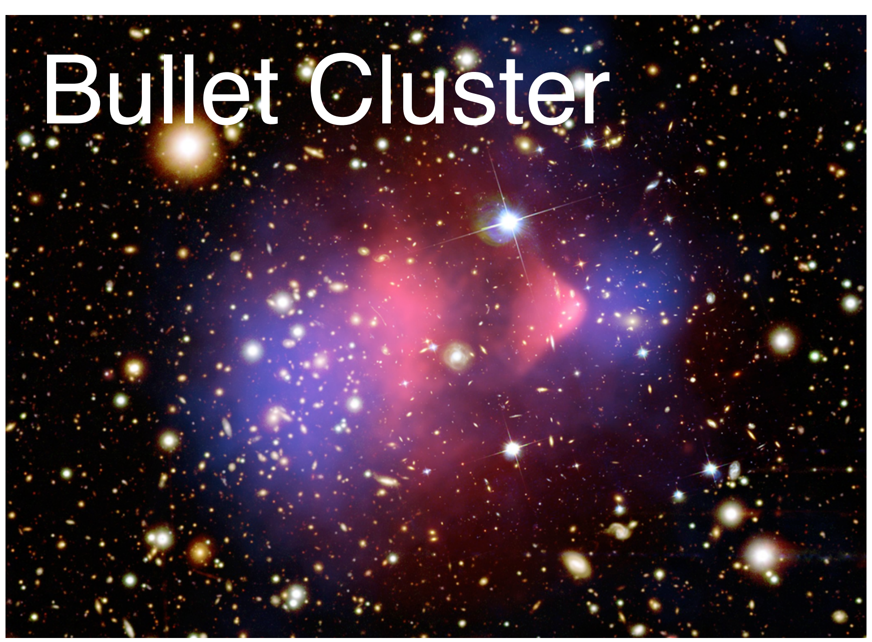
Potential Problems

Rate estimate for impacting dwarfs:

$$\Gamma_{scat} \simeq n\sigma v \sim (\rho/m_X)\,\sigma v \simeq H_0$$

✓ $\sigma/m_X \sim (1-10)\ \mathrm{cm^2/g}$ @ $v \sim 10\ \mathrm{km/s}$

X Clusters



$\sigma/m_X \lesssim 1\ \mathrm{cm^2/g}$

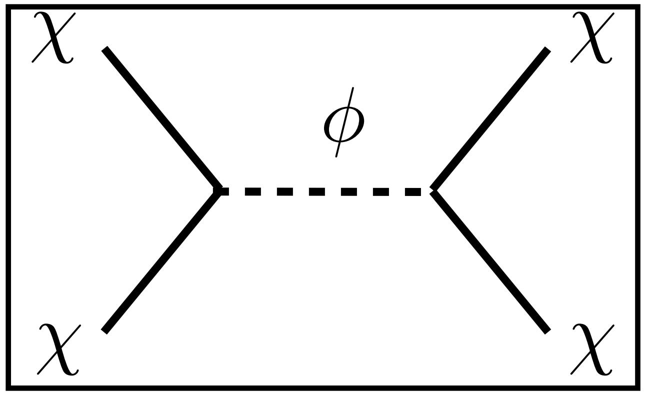
@ $v \sim 3000\ \mathrm{km/s}$

X Isotropizes halos

$\sigma/m_X \lesssim 1\ \mathrm{cm^2/g}$

@ $v \sim 300\ \mathrm{km/s}$

Yukawa Interacting Dark Matter

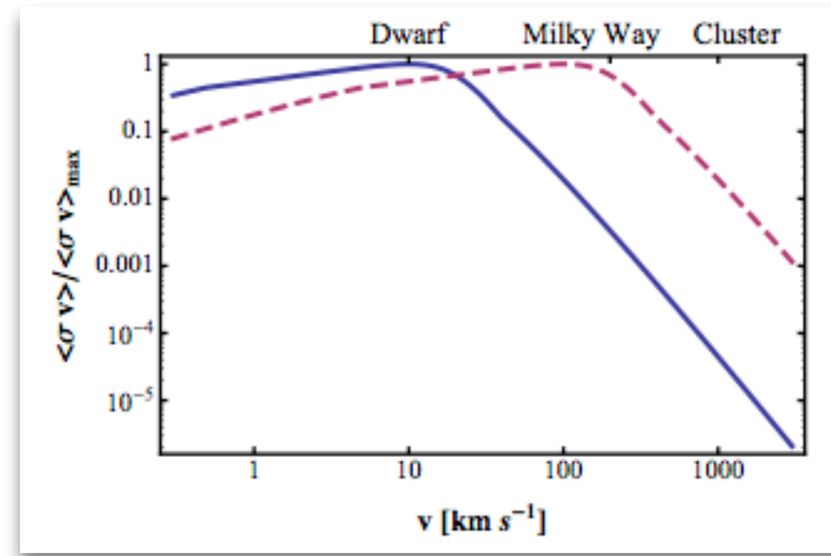


$$V(r) = \pm \frac{\alpha_X}{r} e^{-m_\phi r}$$

dwarf:

$$v \sim 10 \text{ km/s}$$

Loeb, Weiner (2010)



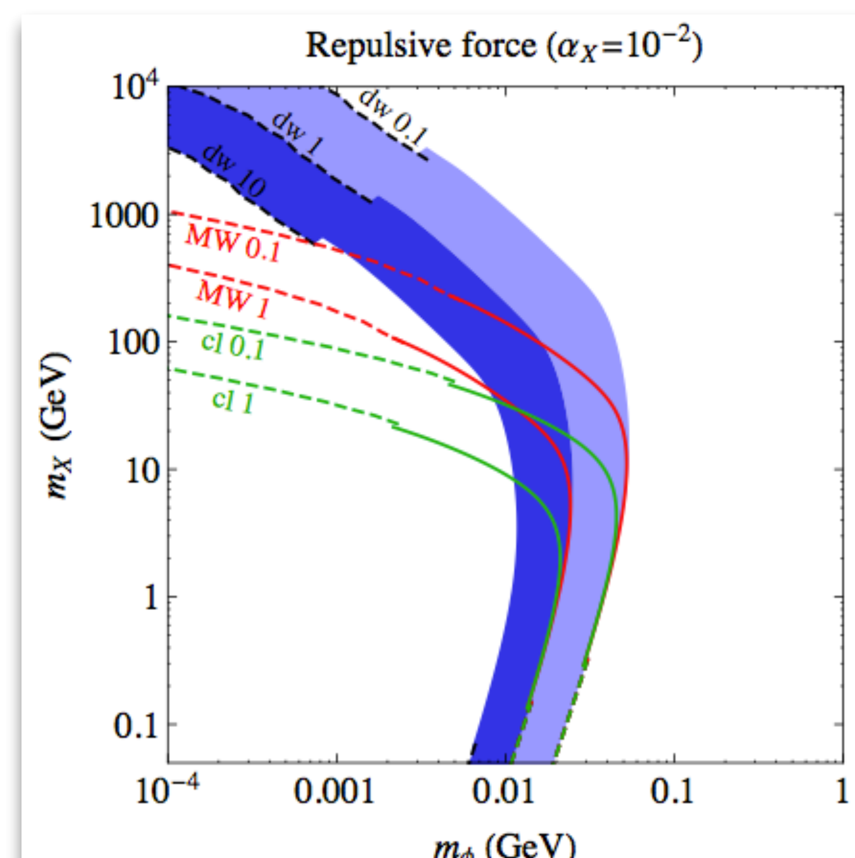
✓ SIDM gives efficient exchange of energy between hotter/outer region to the cold/inner region.

In the small mediator mass limit, DM-DM scattering is Rutherford-like

$$\sigma \sim \frac{\alpha_X^2}{m_X^2 v^4} \quad (m_X v \gg m_\phi)$$

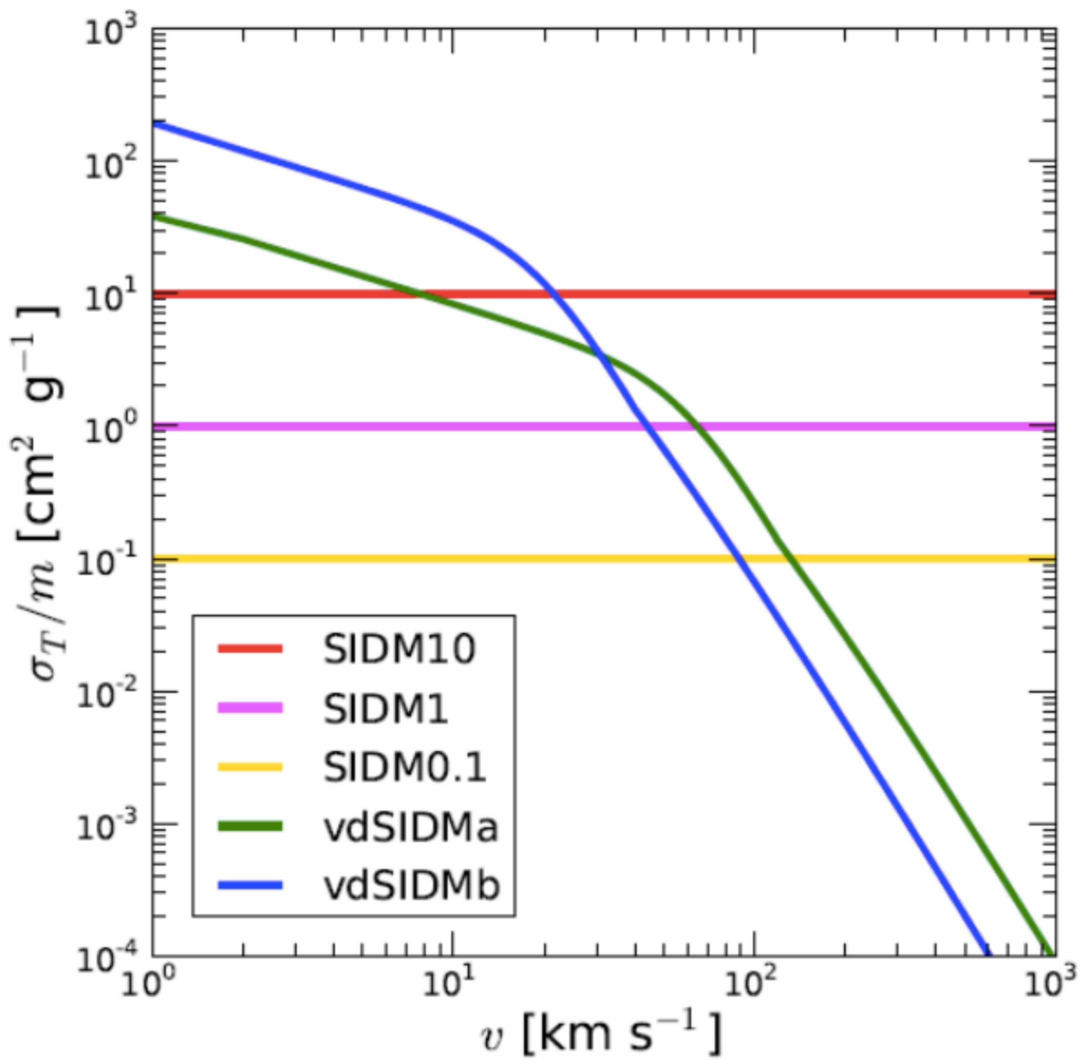
✓ Strong velocity dependence can give significant scattering in dwarfs but small scattering rate in clusters.

Tulin, Yu, Zurek (2013)



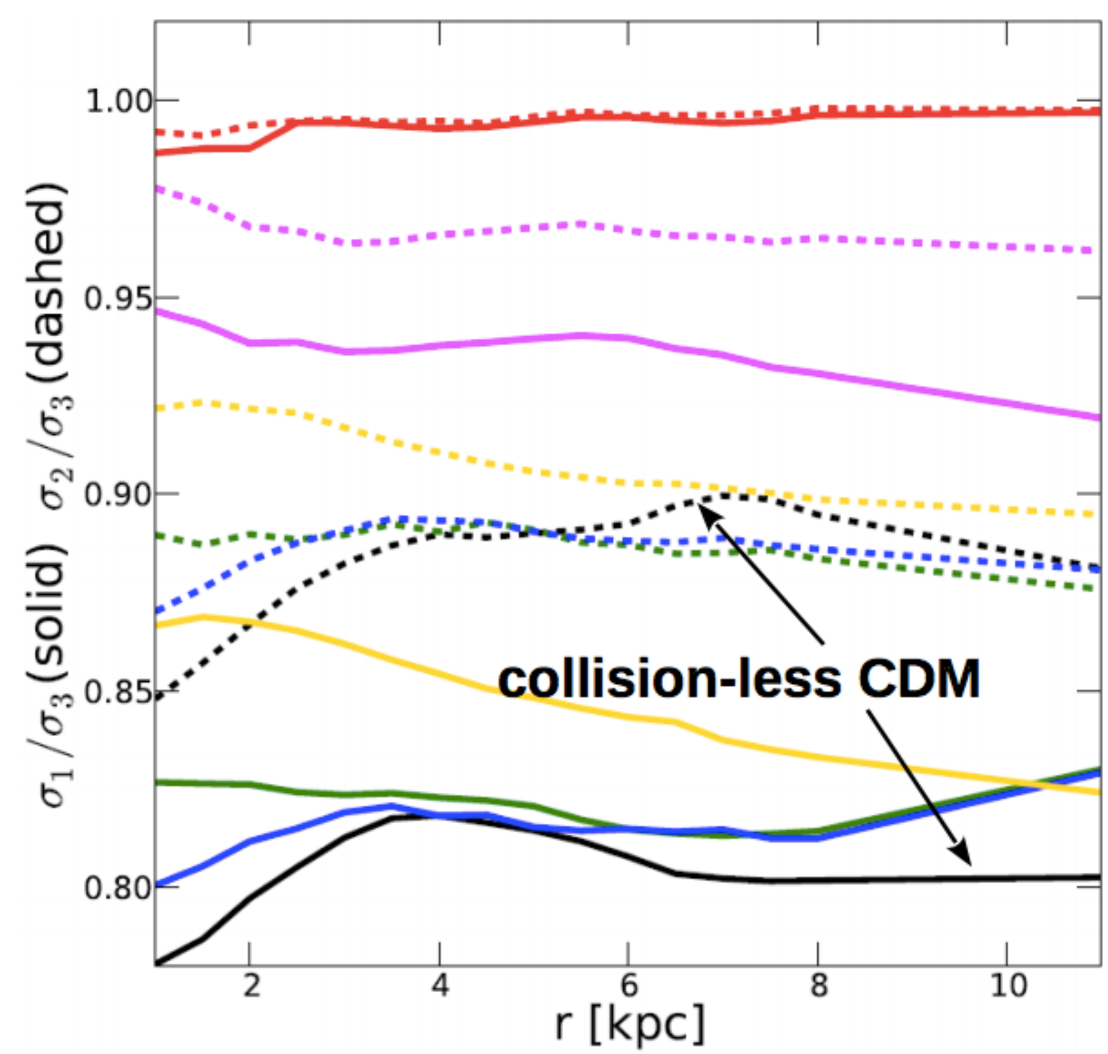
Retaining Isotropy

Self-interactions cross section

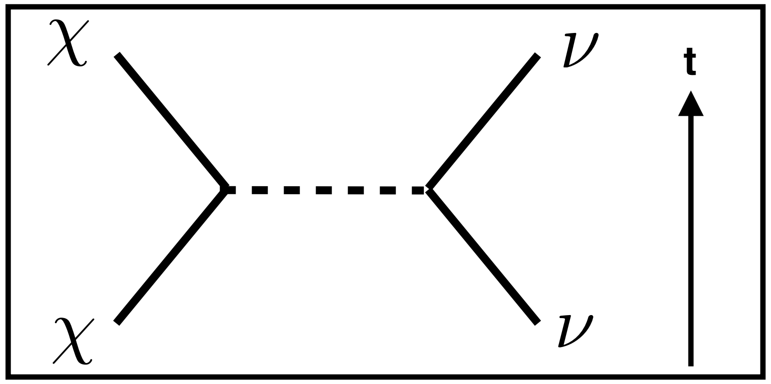


Halo ellipticity

velocity dispersion (main halo)



[Zavala, Vogelsberger, Walker (2012); Zavala, Vogelsberger (2012)]



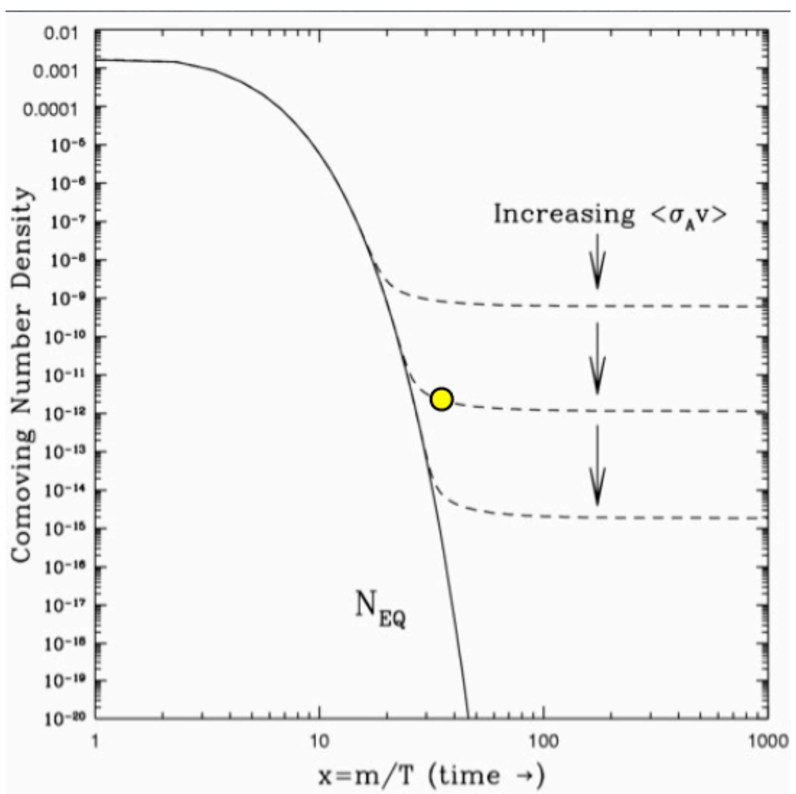
Suppressing small-scale structure

[L. Aarssen, T. Bringmann, C. Pfrommer, PRL **109** 231301 (2012)]

Relic abundance

set by epoch of ***chemical*** decoupling:

$$X\overline{X} \leftrightarrow \overline{f} f$$

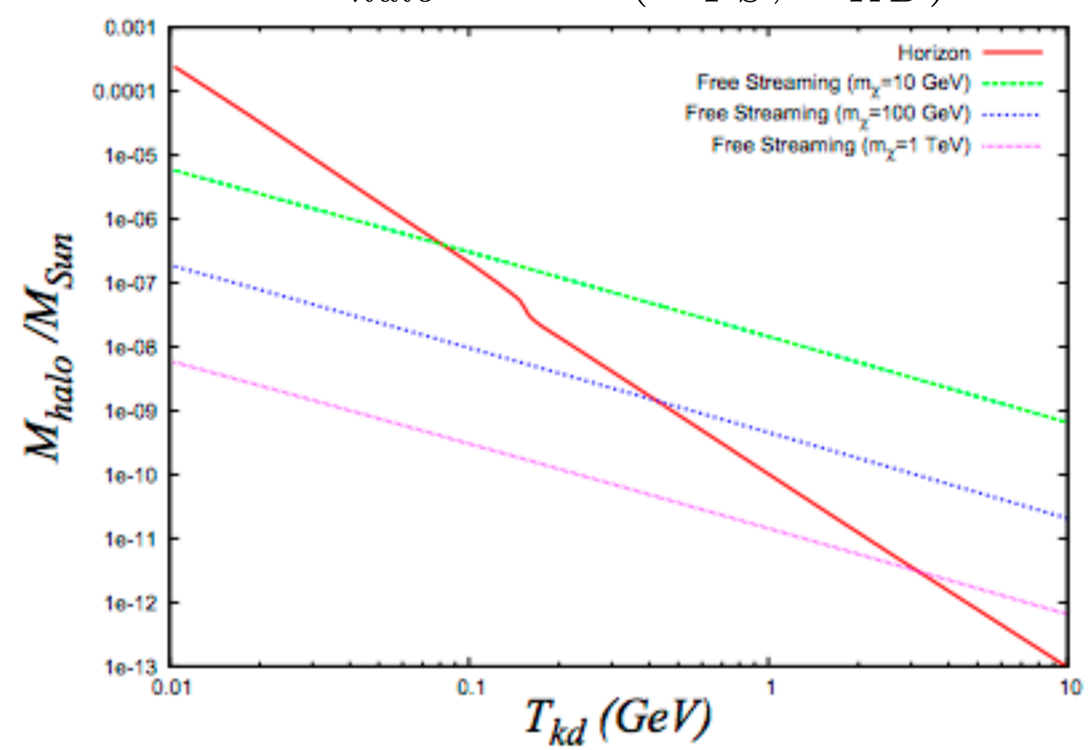


Smallest DM protohalos

set by epoch of ***kinetic*** decoupling:

$$X f \leftrightarrow X f$$

$$M_{halo} \equiv \max\left(M_{FS}, M_{KD}\right)$$

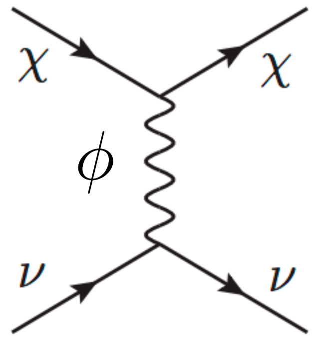


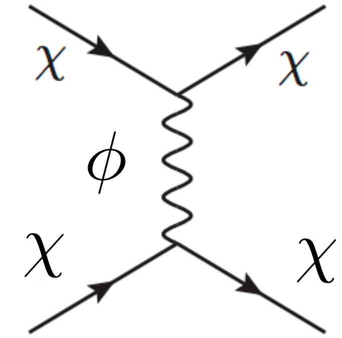
[Gondolo, Hisano, Kadota (2012)]

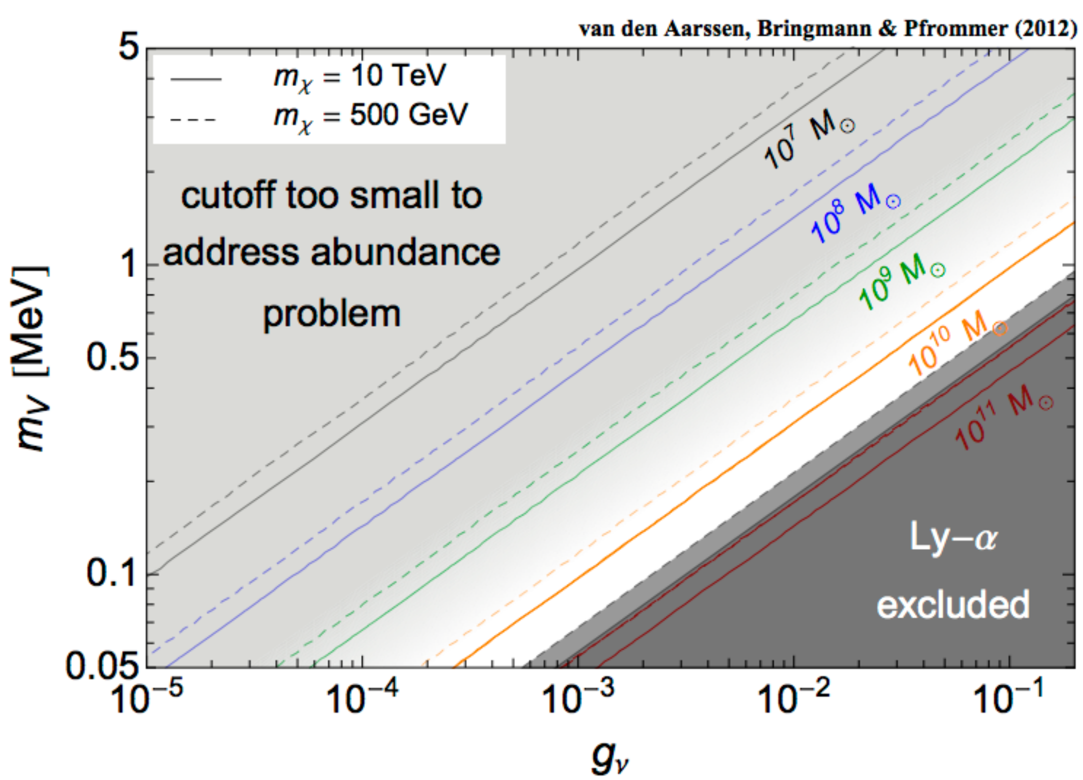
Late kinetic decoupling requires large g_X

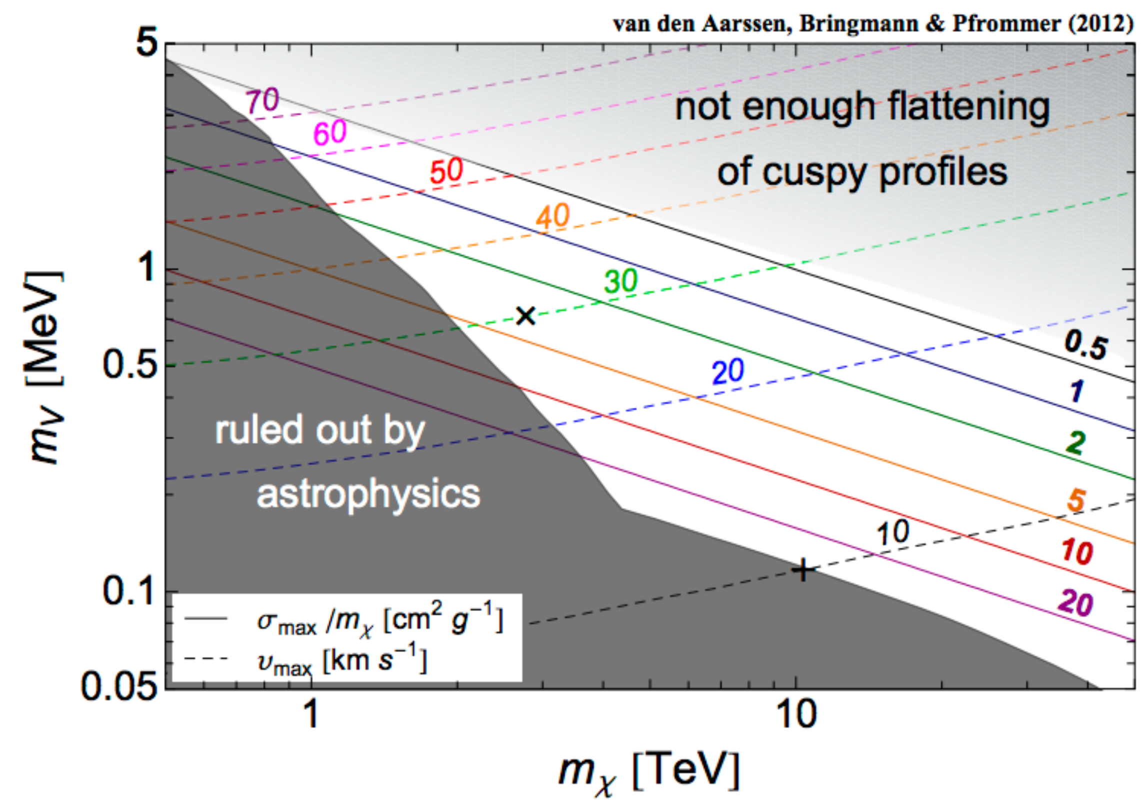
Solving the problems of CDM

[L. Aarssen, T. Bringmann, C. Pfrommer, PRL **109** 231301 (2012)]



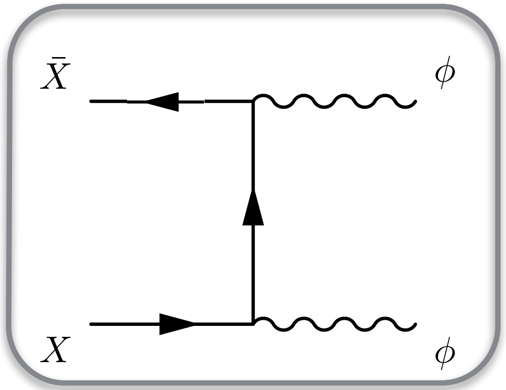






DM-neutrino interactions decouple late, and disallow for very small subhalos to form.

À la Loeb/Weiner, DM self-scattering is large in dwarfs but small on larger scales.

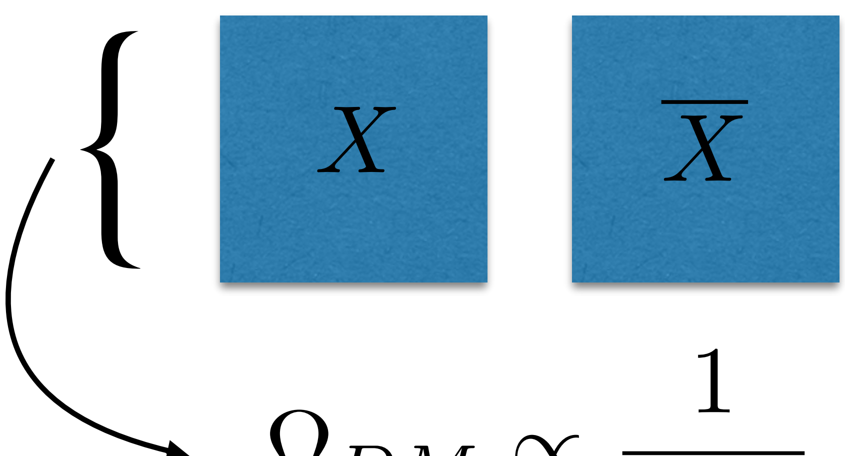


Asymmetric Relic Abundance

(see Petraki, Volkas [1305.4939]; Zurek [1308.0338])

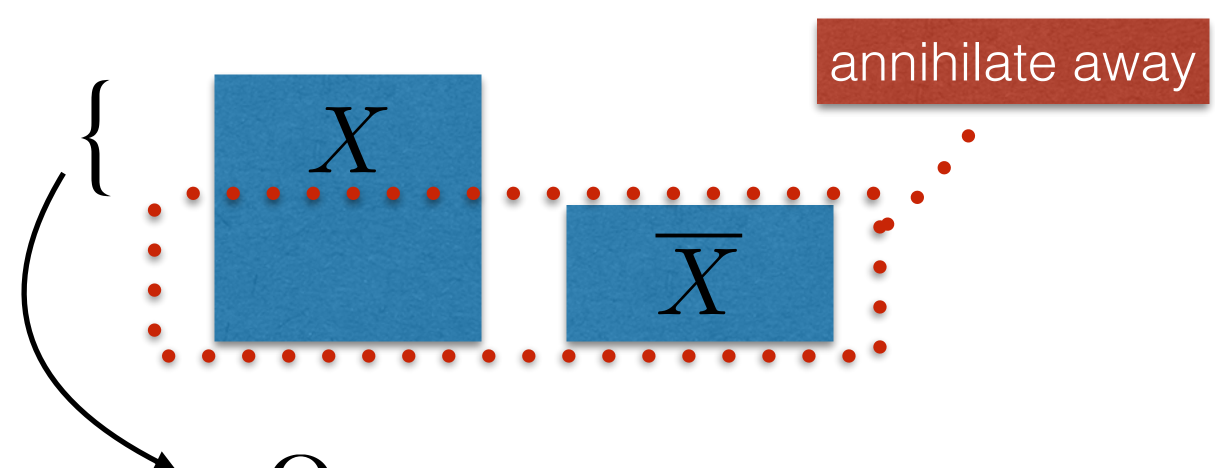
Particle/anti-particle asymmetries are generically possible. → $\eta_X = (n_X - n_{\bar{X}})/s \neq 0$

symmetric DM

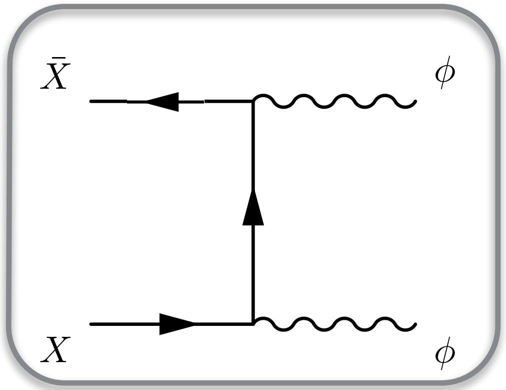


$$\Omega_{DM} \propto \frac{1}{\langle \sigma v \rangle}$$

asymmetric DM



$$\Omega_{DM} \propto \text{excess}$$



Asymmetric Relic Abundance

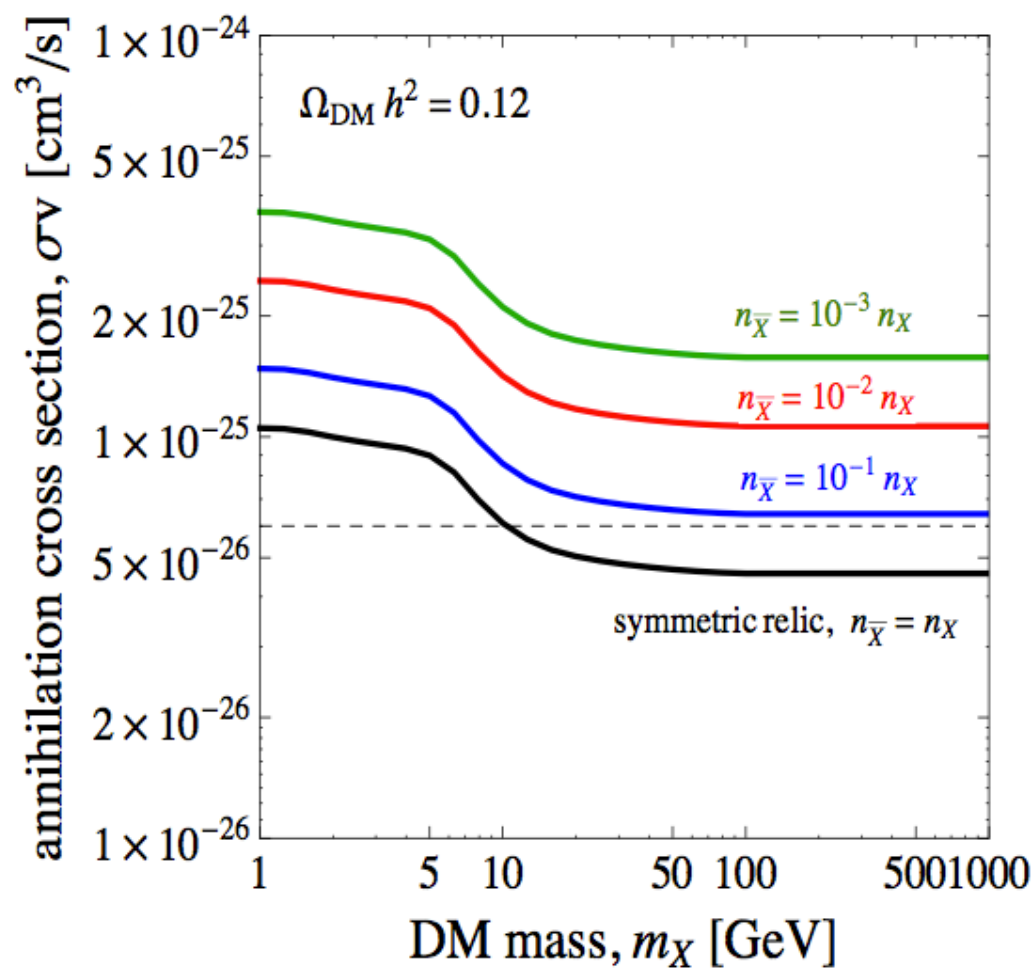
Particle/anti-particle asymmetries are generically possible.

$\eta_X = (n_X - n_{\bar{X}})/s \neq 0$

Solve the coupled Boltzmann equations of X and anti-X.

Generic requirement

$$\langle \sigma v \rangle_{ADM} > \langle \sigma v \rangle_{SDM}$$



In a complete model, final abundance is set by the asymmetry ***and*** annihilation cross section:

$$Y_{\pm}(\infty) \simeq \frac{\pm\eta_X}{1 - [1 \mp \eta_X / Y_{\pm}(x_f)]\, e^{\mp \eta_X \lambda \sqrt{g_*} x_f^{-n-1}/(n+1)}}$$

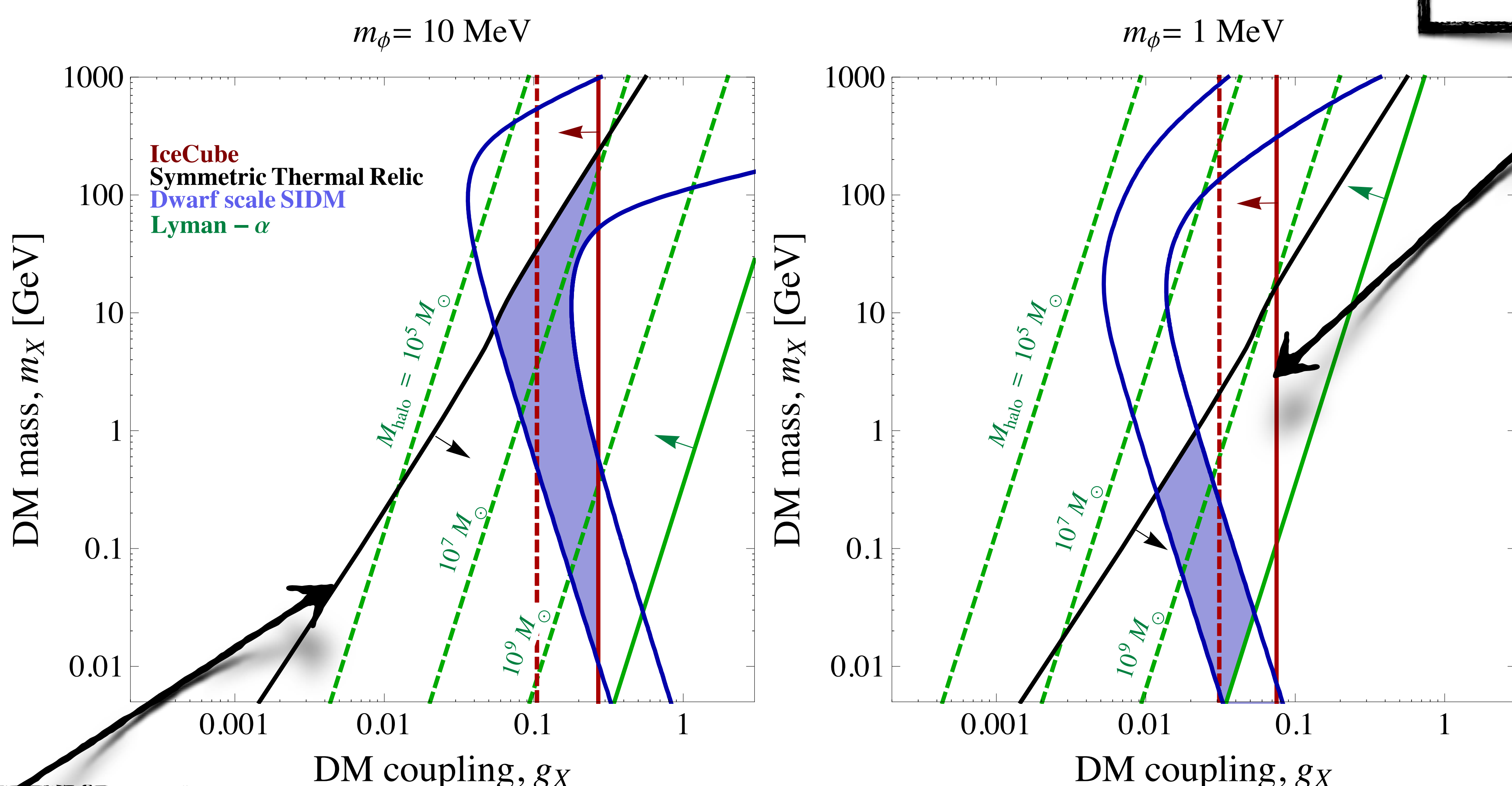
$$\lambda \equiv 0.264 M_{\rm pl} m_X \sigma_0$$

Bell, Horiuchi, IMS [1408.5142]

Graesser, IMS, Vecchi [1103.2771]

Summary of constraints

Isotropy of IceCube signal



symmetric relic from
$\overline{X}X \to \phi\phi$

Summary

- IceCube has found a new neutrino source with an unusual spectrum.
  - Could be "ordinary" astrophysics with novel neutrino self-interactions.
  - Gaps and a cutoff are generic in this model.
  - May also produce a neutrino horizon, screening far away sources.
- The same mediator can alleviate small-scale structure problems of CDM.