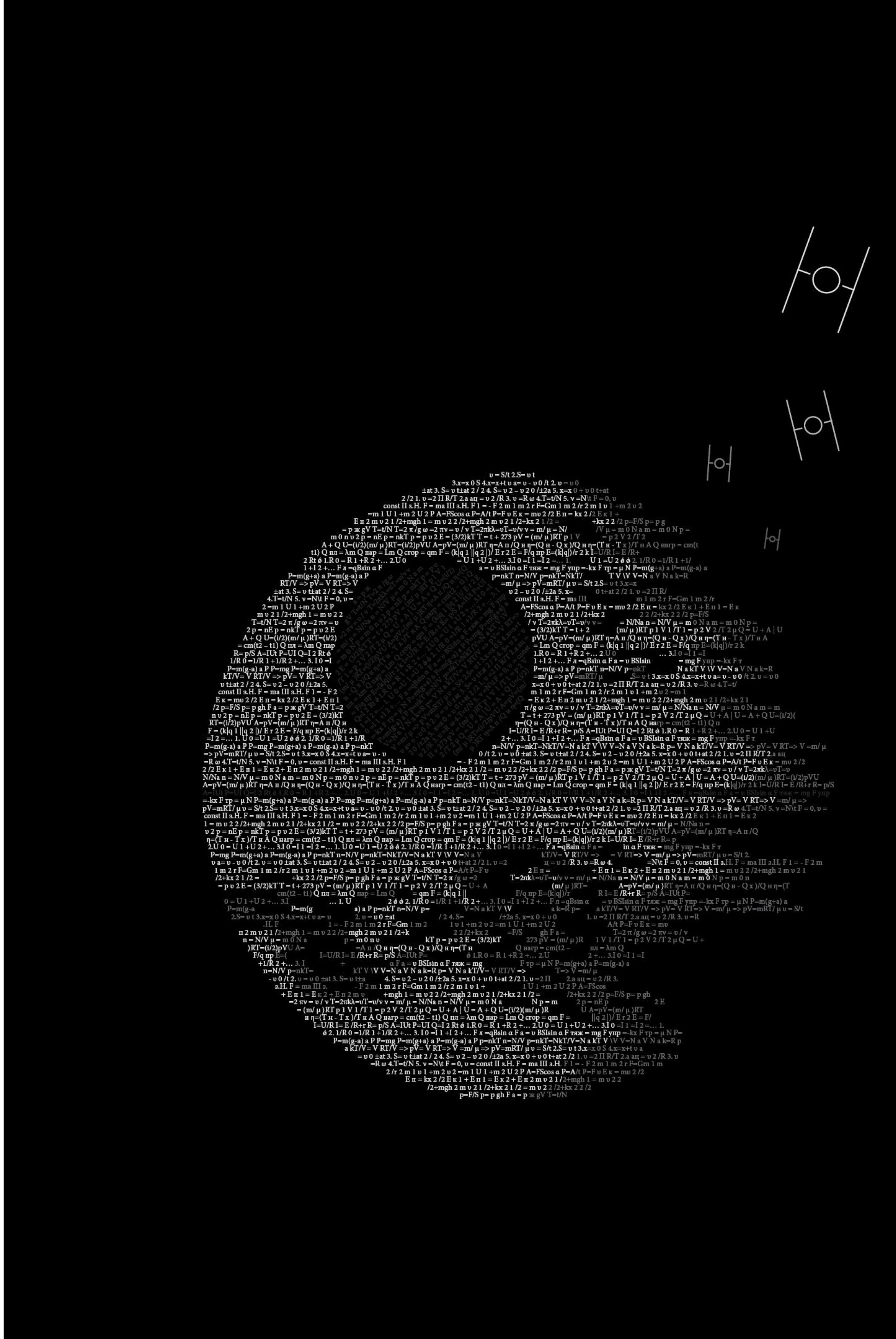
Light dark matter in the sky

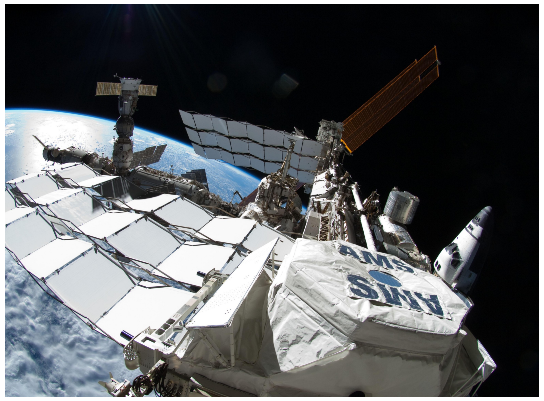
Aaron Vincent

LDMA '17
La Biodola, 26 May 2017

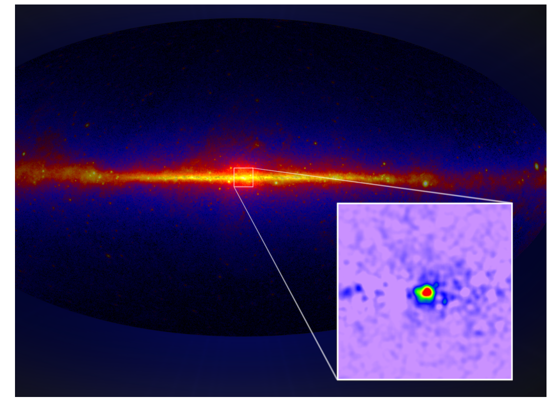
Imperial College London



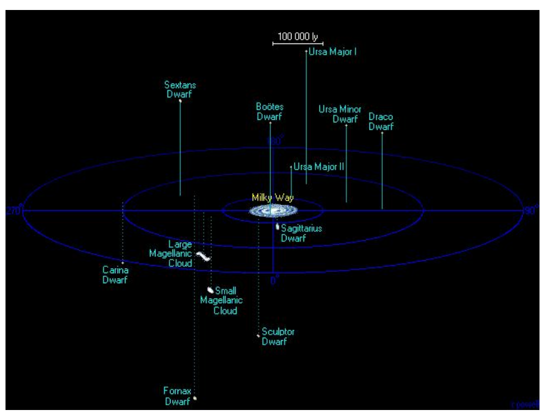
Indirect searches for dark matter



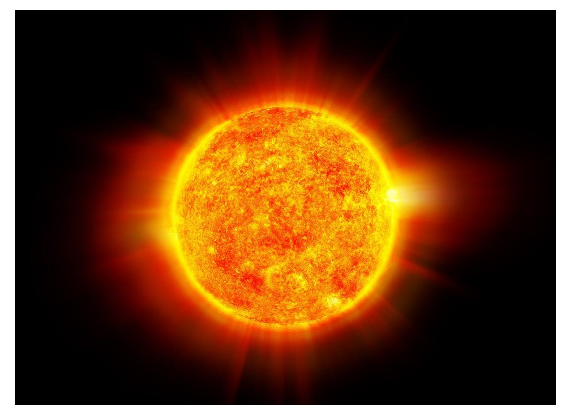
Local Cosmic Ray flux



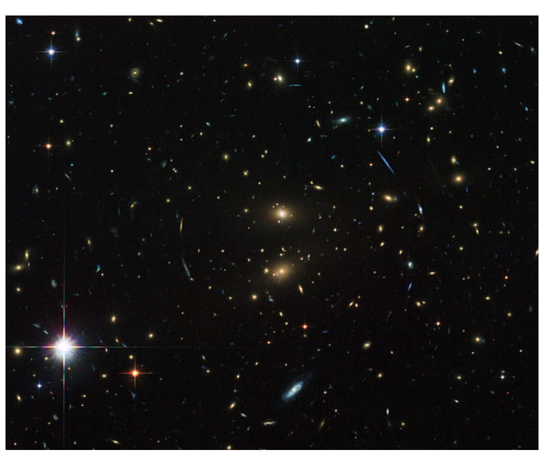
Galactic center



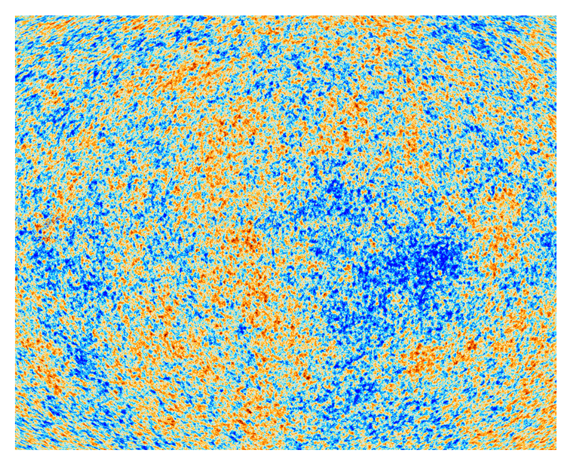
Dwarf galaxies



The Sun



Galaxy Clusters



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Overview

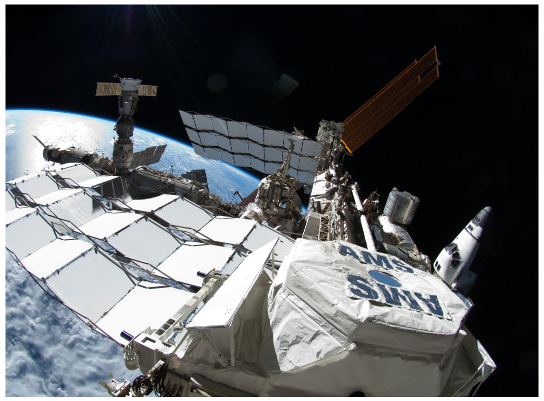
1. 511 keV: positrons from the dark side
   ACV, Cline, Martin 2012
   Siegert, … ACV 2016

2. Cosmology v. the MeV WIMP

   Escudero,…, ACV 2015
   Wilkinson, Boehm, McCabe, ACV 2016

3. PeV signals of low-mass dark matter at IceCube
   Argüelles, Kheirandish, ACV 2017

Indirect searches for dark matter



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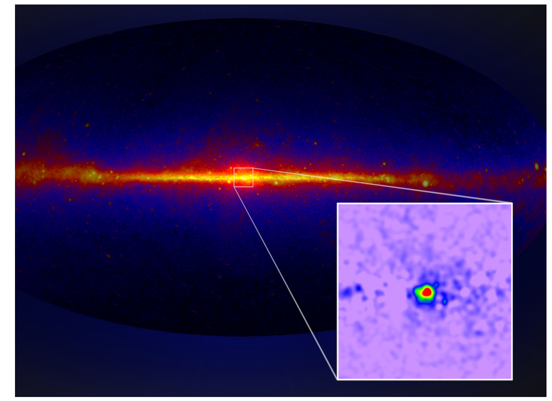

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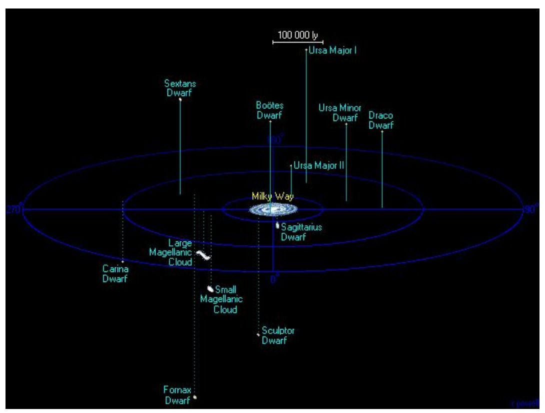

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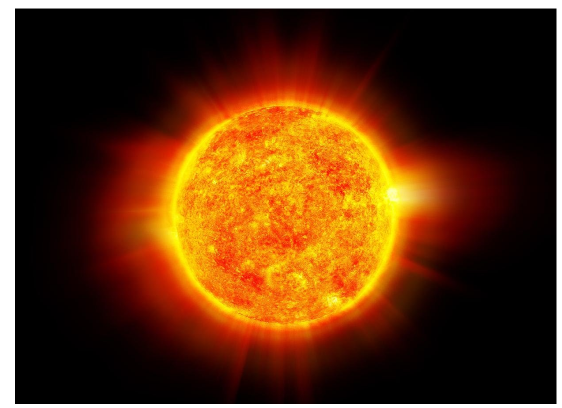

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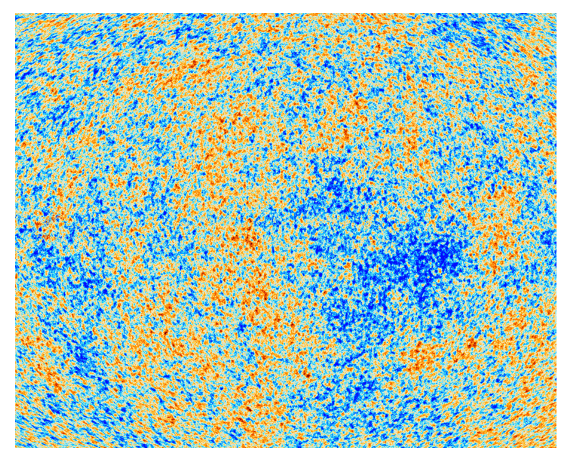

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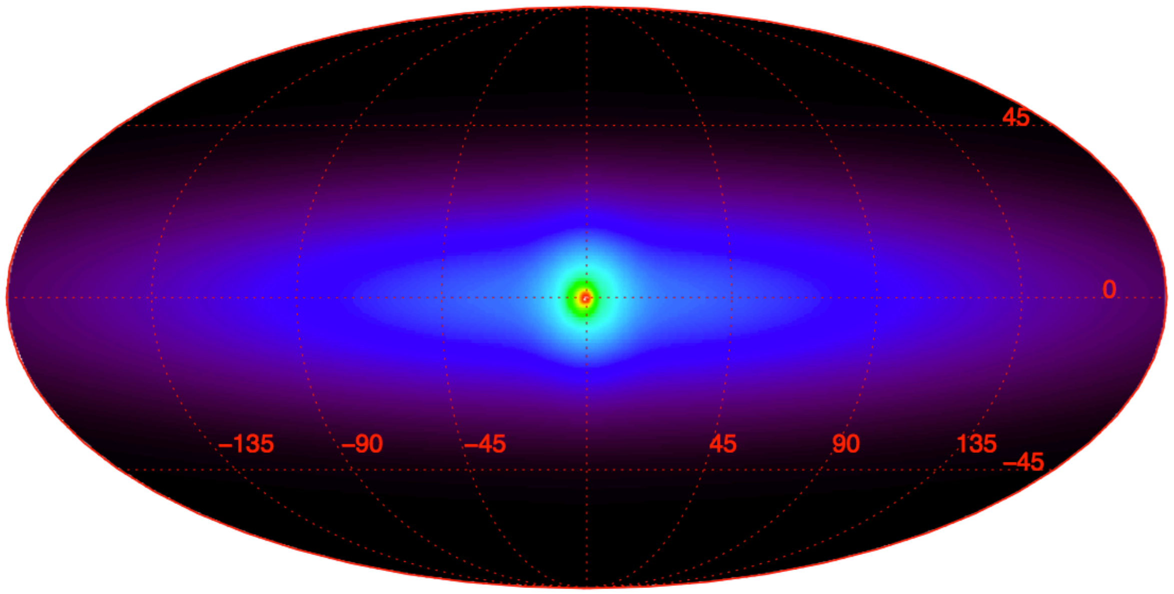
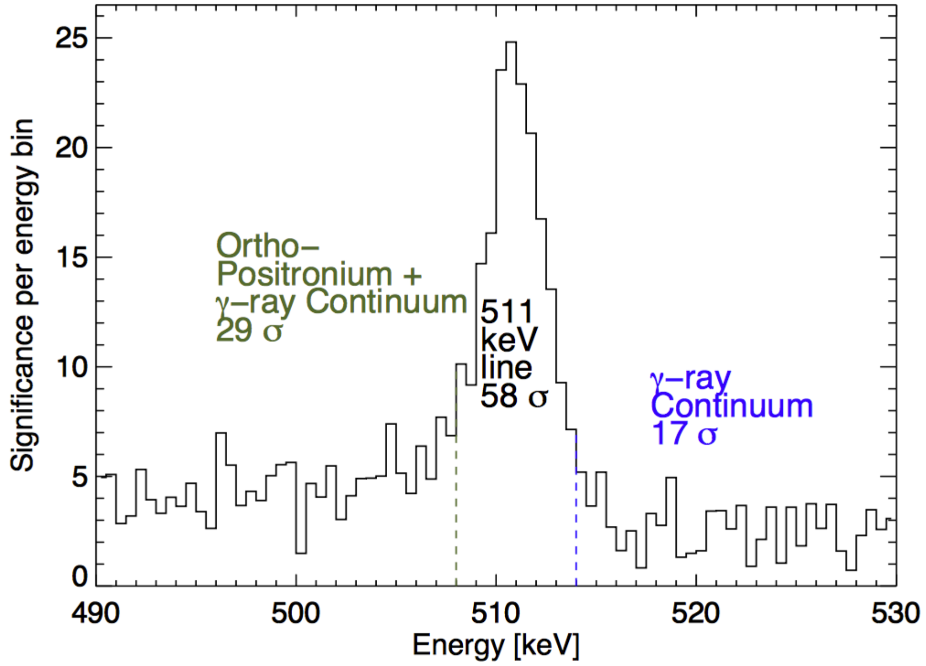
511 keV: INTEGRAL/SPI signal





Siegert et al. 2016

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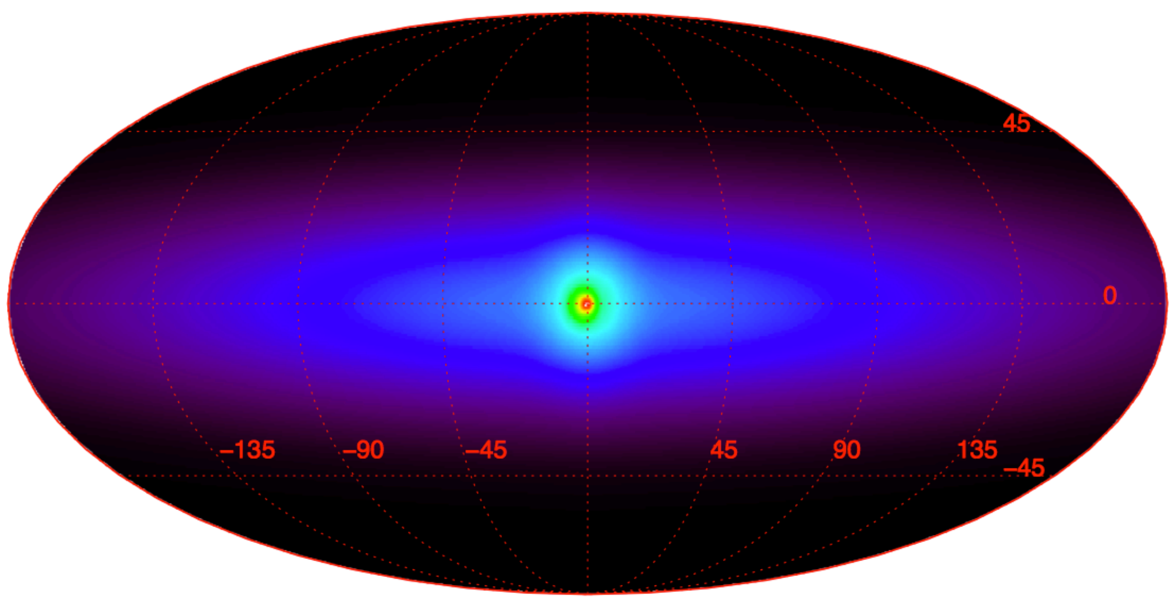
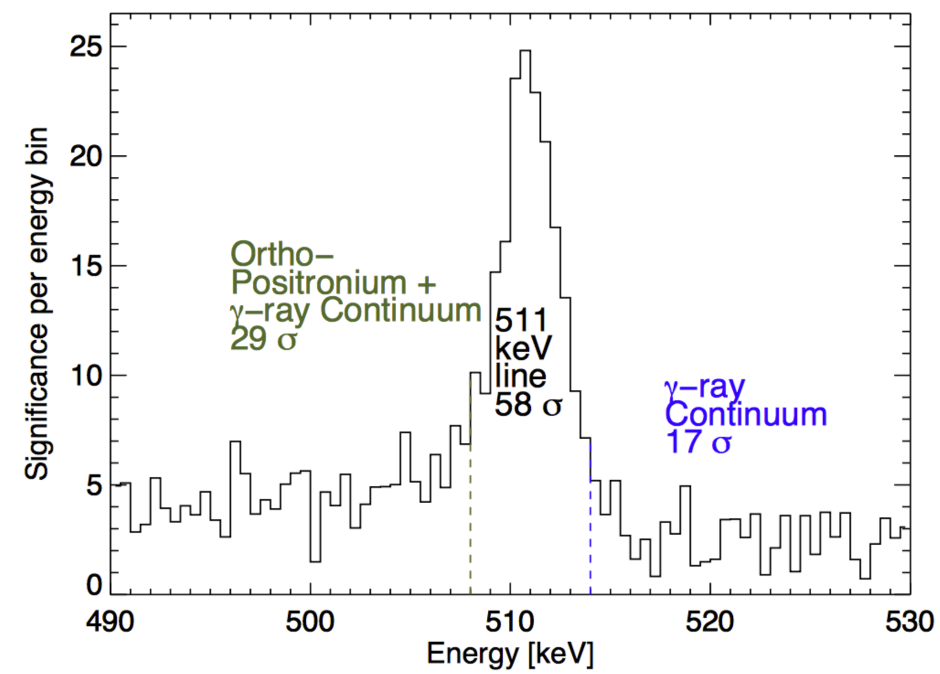


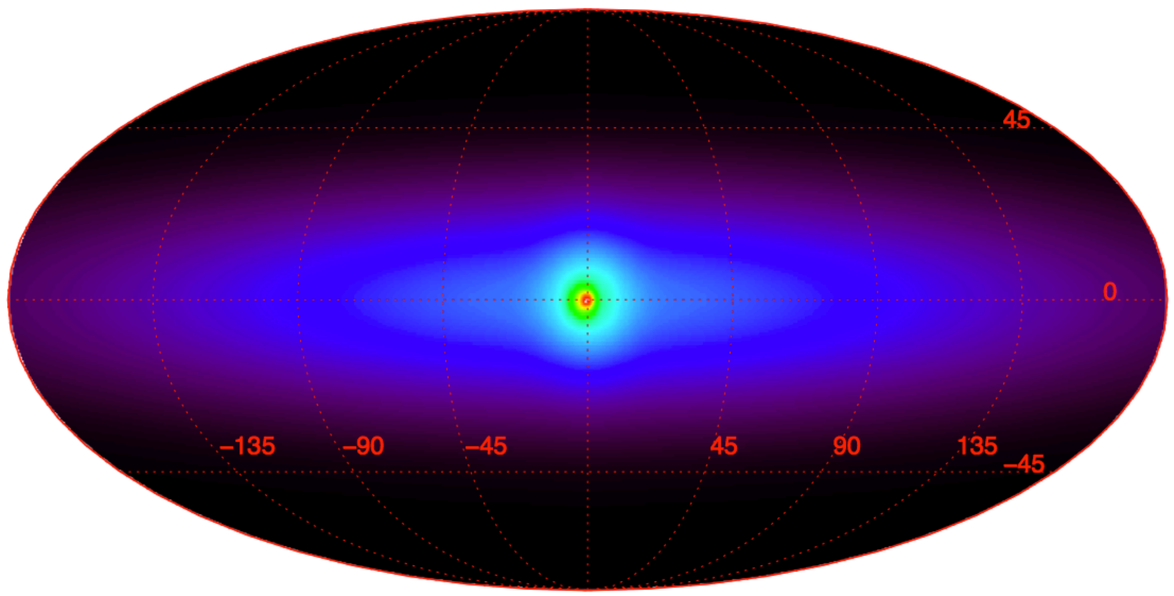


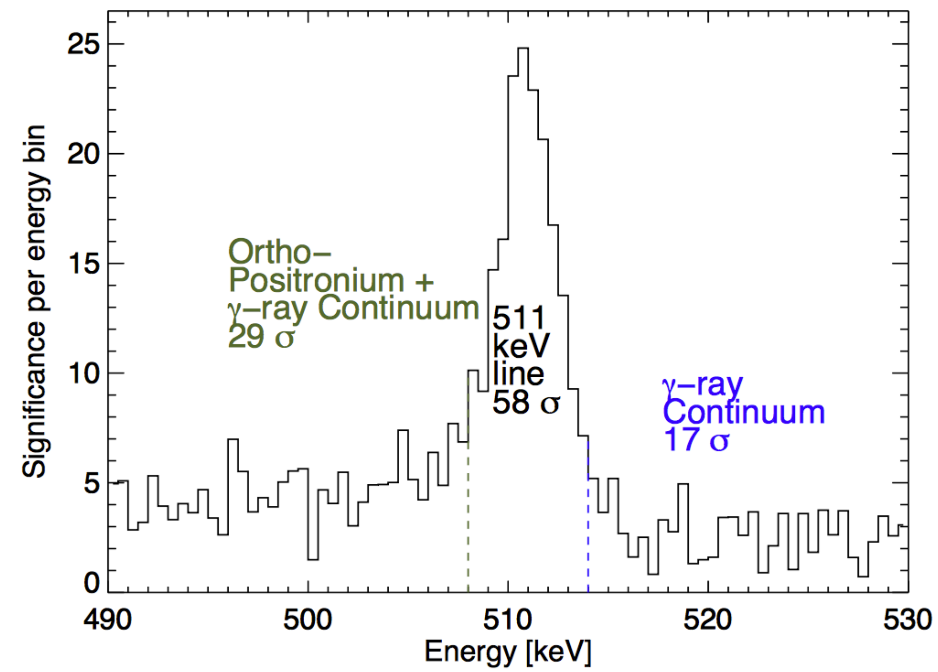
Siegert et al. 2016

Source	Process	Intensity	Spectrum	Morphology
(Requirement)		$\sim 10^{43} e^{+}\mathrm{s}^{-1}$	$E_{e^+} \lesssim 3$ MeV	B/D $\gtrsim 1.4$
Massive Stars	^{26}Al β^+ decay	✓	✓	×
SNe	^{44}Ti β^+ decay	✓	✓	×
SNIa	^{56}Ni β^+ decay	?	✓	×
Novae	β^+ decay	×	✓	×
Hypernovae/GRBs	^{56}Ni β^+ decay	?	✓	×
Cosmic rays	p–p collisions	?	×	×
Low-mass X-ray Binaries	γ–γ pair creation	✓	✓	×
Microquasars	γ–γ pair creation	✓	✓	×
Pulsars	γ–γ pair creation	✓	×	×
Central black hole	γ–γ pair creation	?	×	✓(?)
Dark Matter*	annihilation	?	✓	✓

Prantzos et al. 2011

511 keV: INTEGRAL/SPI signal





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Prantzos et al. 2011

511 keV: is it DM?

Morphology?

Spectrum?

Rate?

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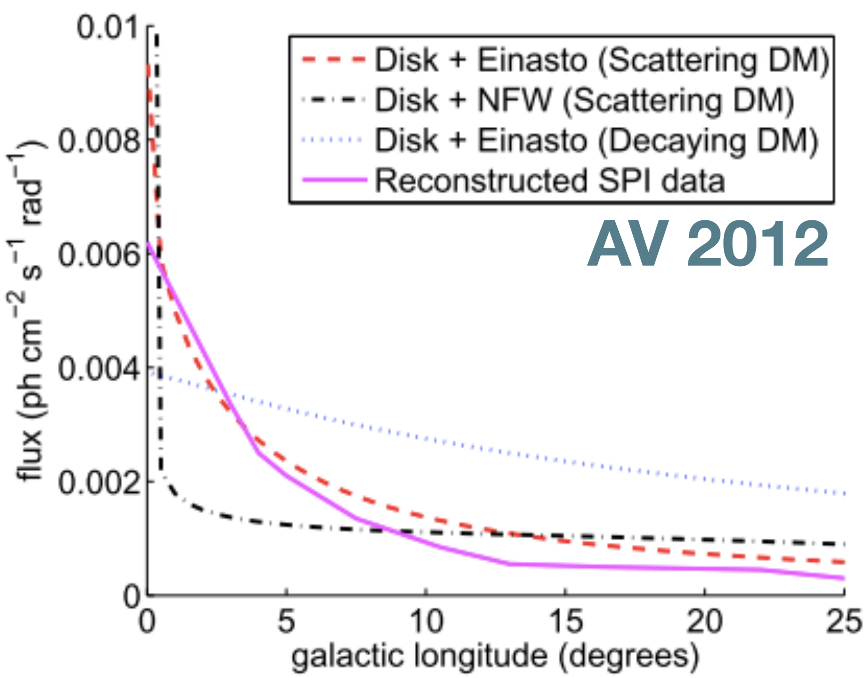

Better fit with DM
than the de facto gaussian model

Spectrum?

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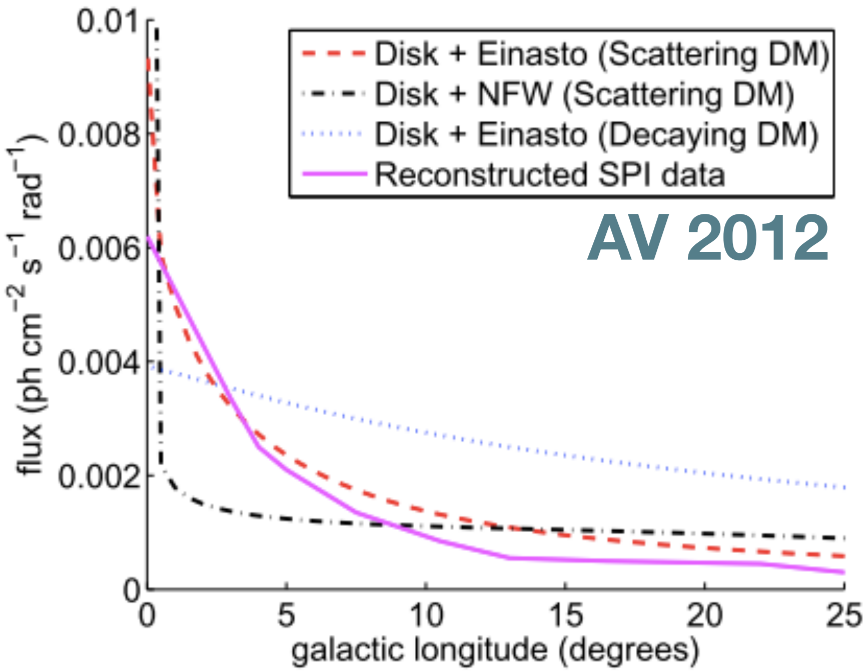

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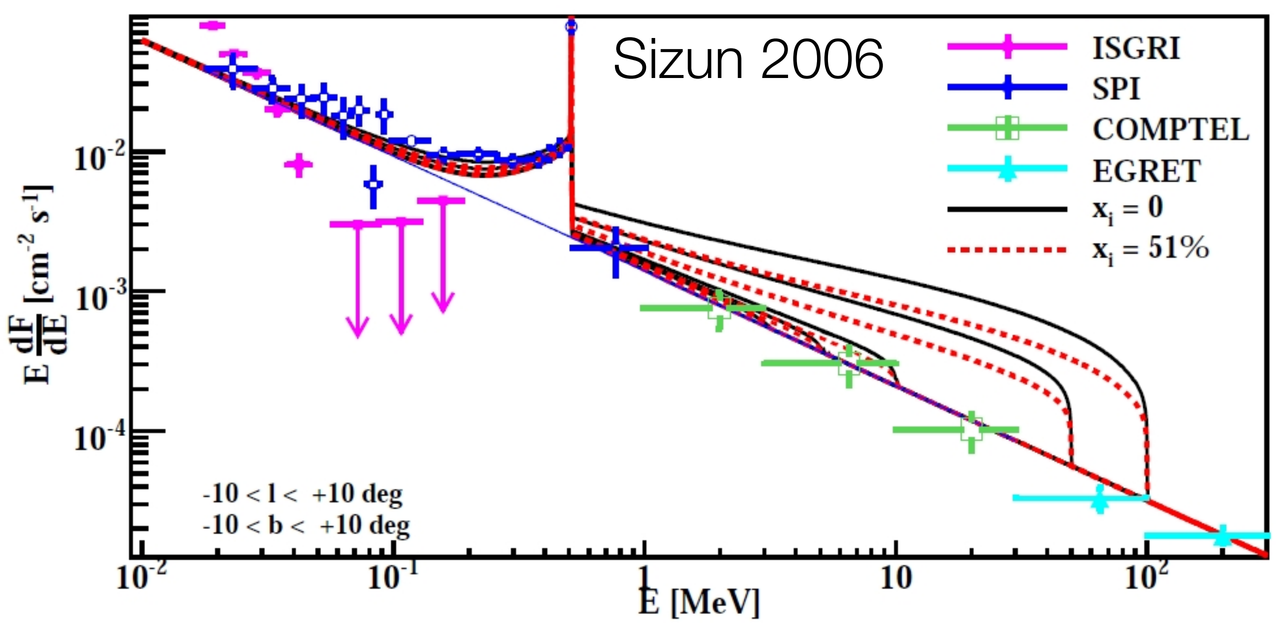

require **m <~ 10 MeV** to avoid
gamma ray overproduction

Rate?

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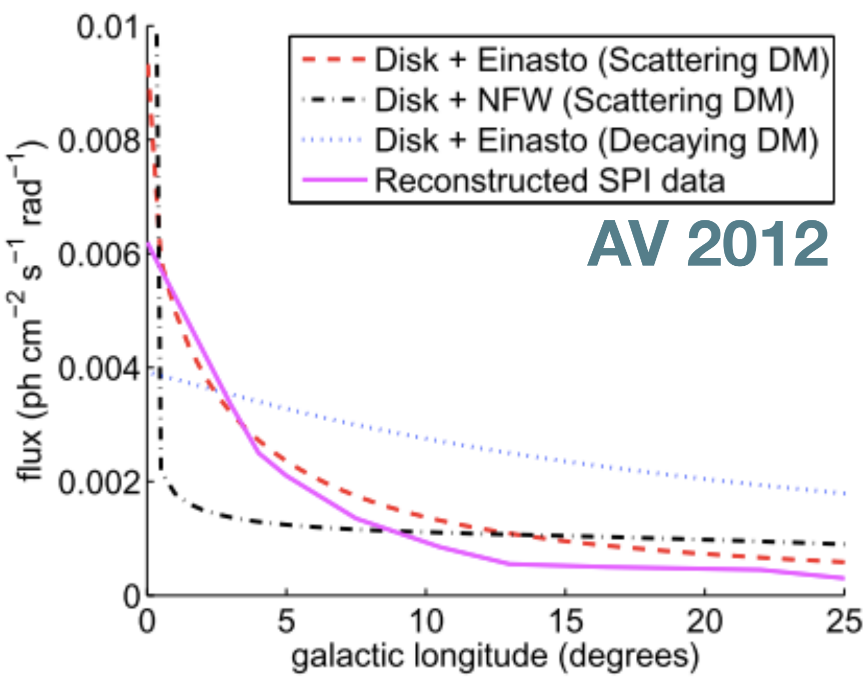

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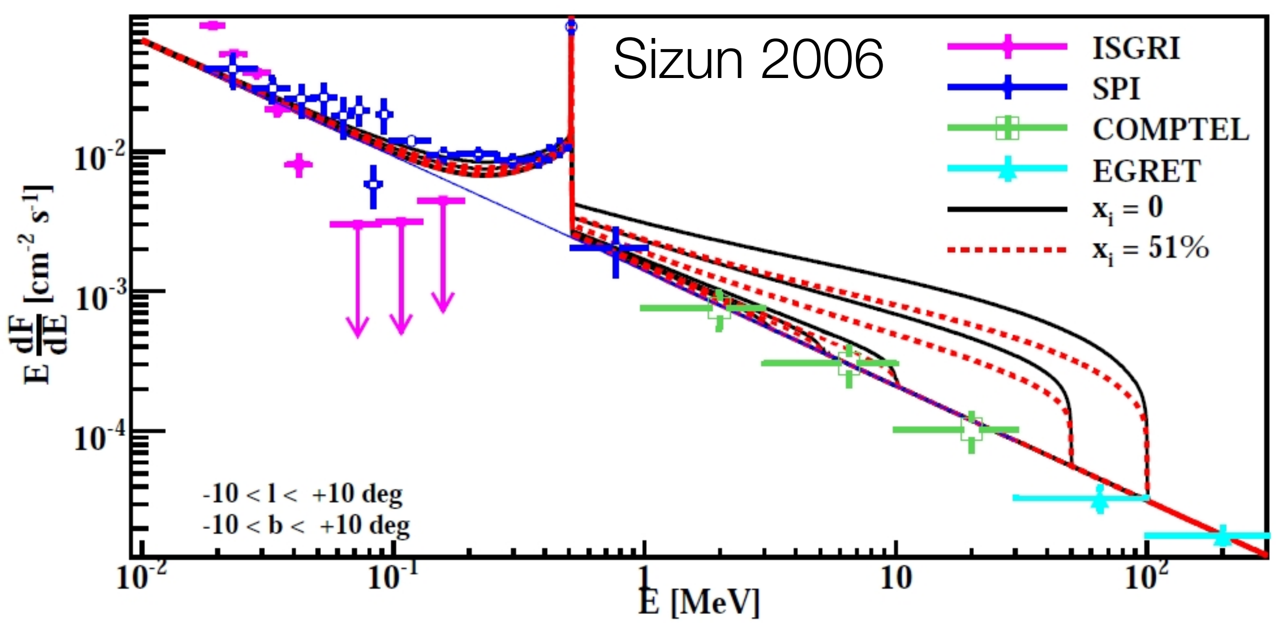

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Rate?

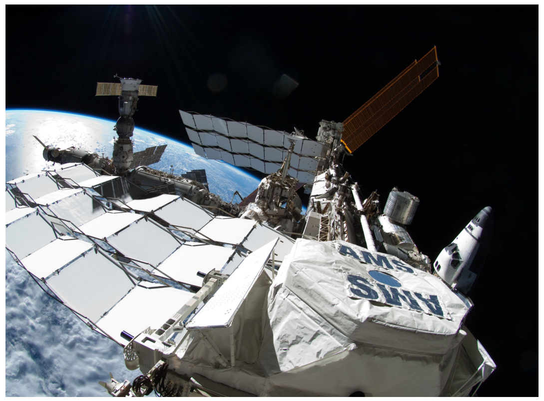
$$\dot{n}_{e^+} = 10^{43}\mathrm{s}^{-1}$$

$$\phi_{511} \propto \langle \sigma v \rangle \times J$$

$$J = \int d\Omega \int_{l.o.s.} \rho_{DM}^2 dx$$

$$\langle \sigma v \rangle \simeq 5 \times 10^{-31} \left(\frac{m_\chi}{\mathrm{MeV}} \right)^2 \mathrm{cm}^3\mathrm{s}^{-1}$$

Indirect searches for dark matter



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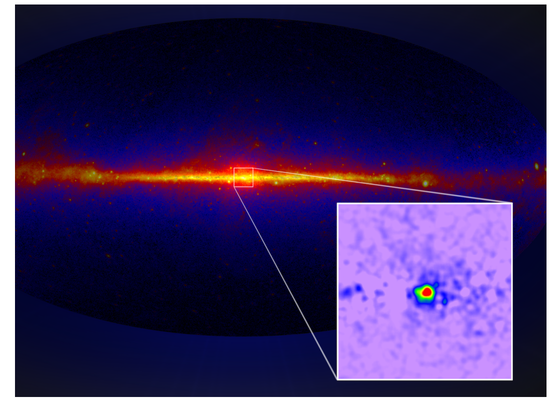

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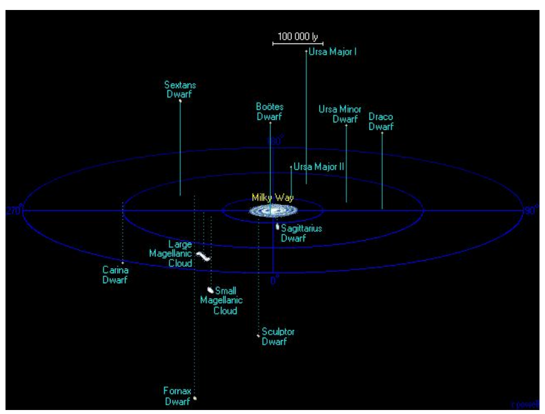

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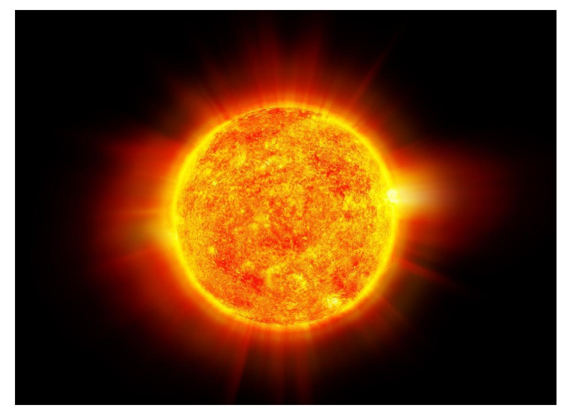

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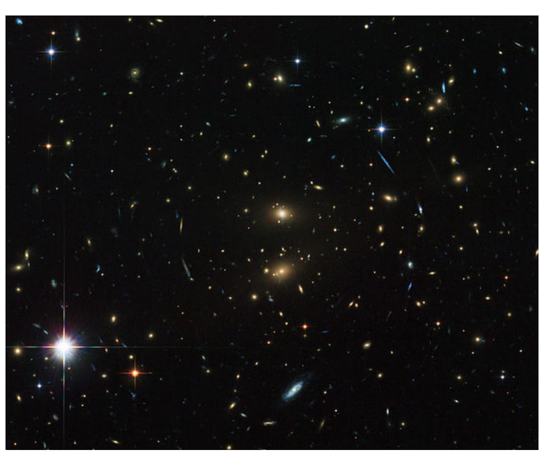

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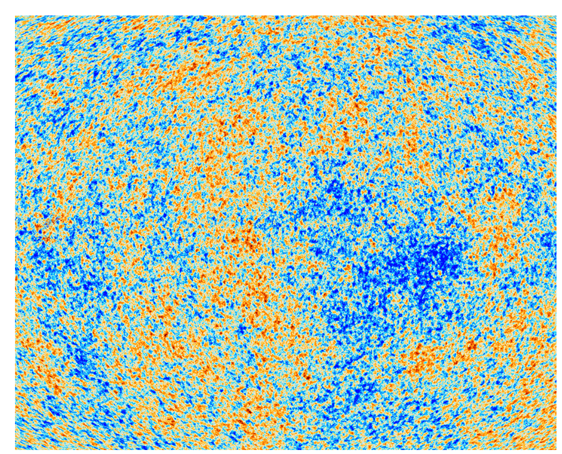

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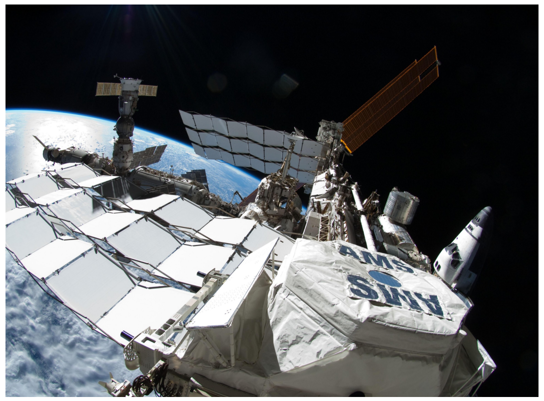

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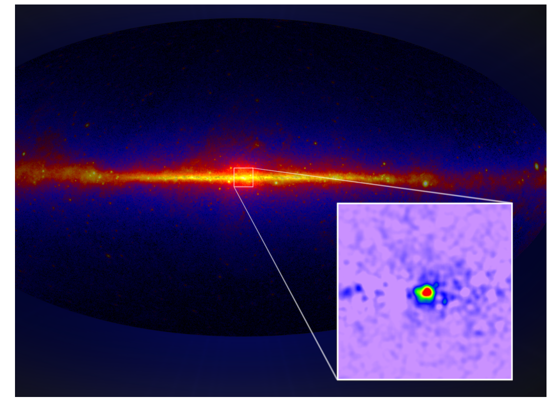

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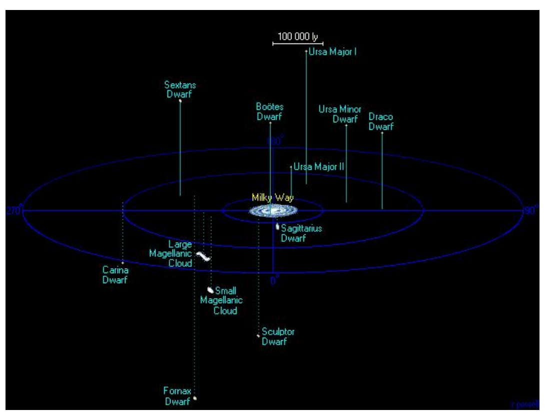

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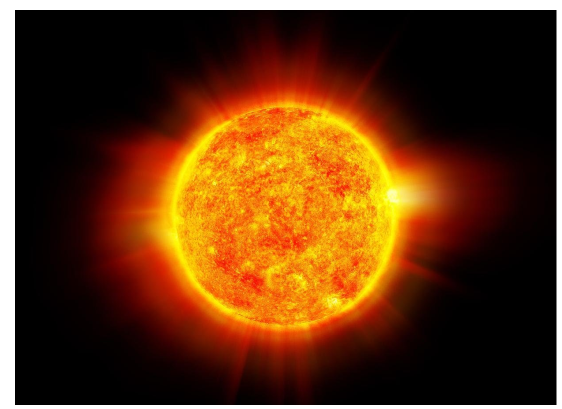

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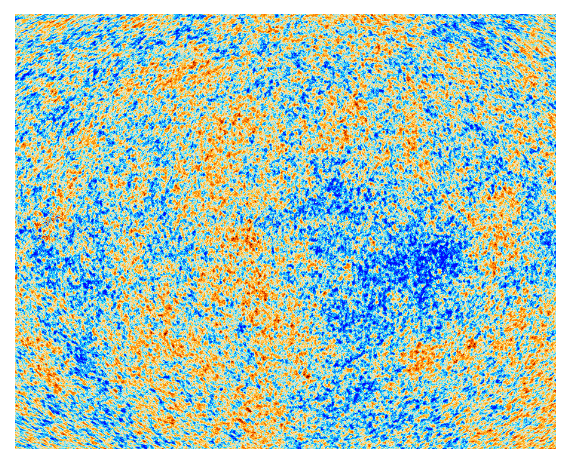

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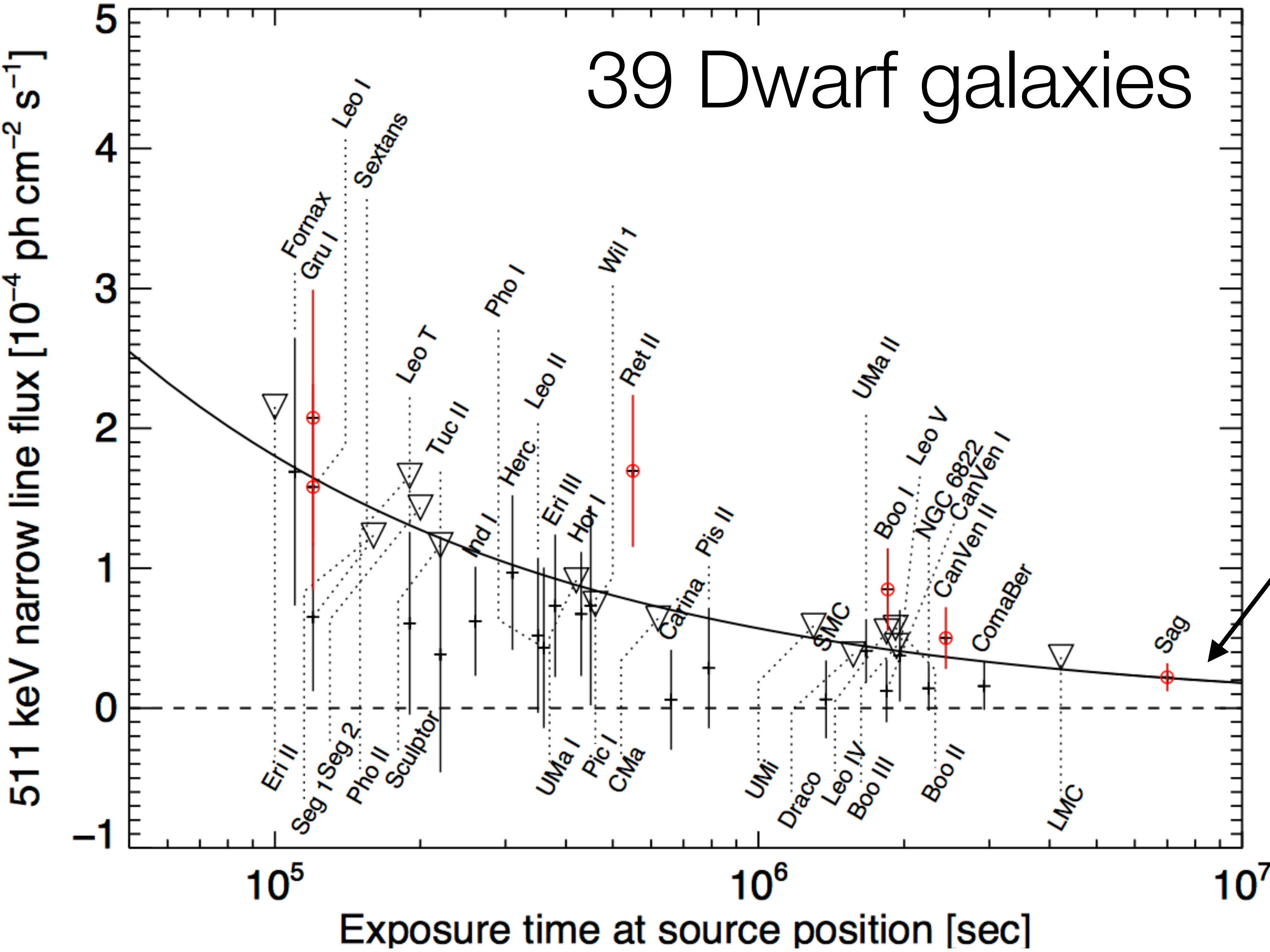
Search for 511 keV Emission in Satellite Galaxies of the Milky Way with INTEGRAL/SPI

Thomas Siegert[1★], Roland Diehl[1,2], Aaron C. Vincent[3], Fabrizia Guglielmetti[1,4], Martin G. H. Krause[5], and Celine Boehm[3]

$$\phi_{511} \propto \langle \sigma v \rangle \times J \qquad J = \int d\Omega \int_{l.o.s.} \rho^2_{DM} dx$$

$$J_{dwarf} \sim [10^{-3}, 10^{-2}] \times J_{MW}$$

INTEGRAL not sensitive to these fluxes, but we can still look



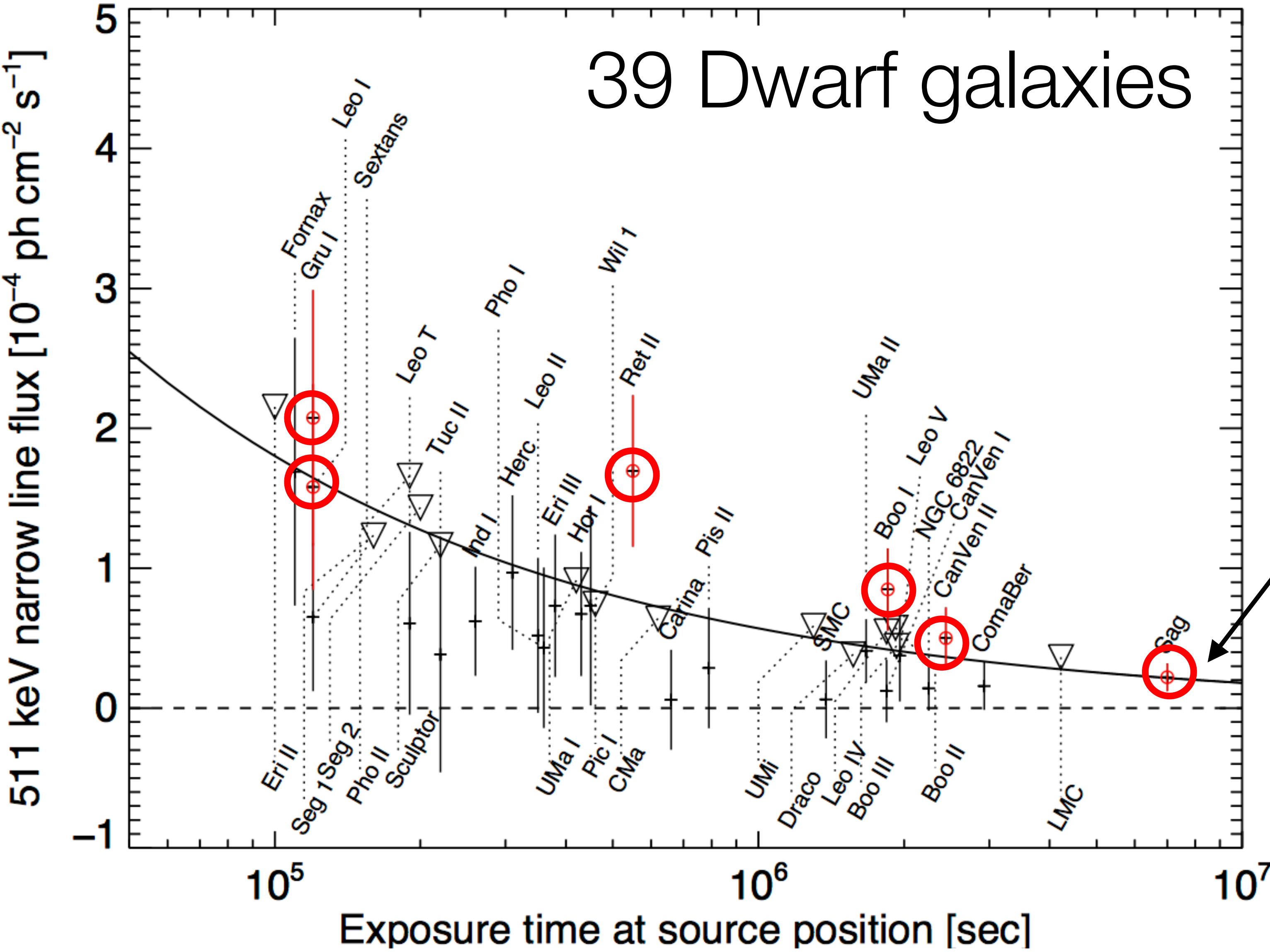
2 sigma detection threshold

Limit on cross section

$$\langle \sigma v \rangle < 5.6 \times 10^{-28} \left(\frac{m_{DM}}{\mathrm{MeV}} \right)^2 \mathrm{cm}^3\ \mathrm{s}^{-1}$$

Recall MW signal requires

$$\langle \sigma v \rangle \simeq 5 \times 10^{-31} \left(\frac{m_\chi}{\mathrm{MeV}} \right)^2 \mathrm{cm}^3 \mathrm{s}^{-1}$$



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But wait what's this?

6 dwarfs seen at > 2$\boldsymbol{\sigma}$

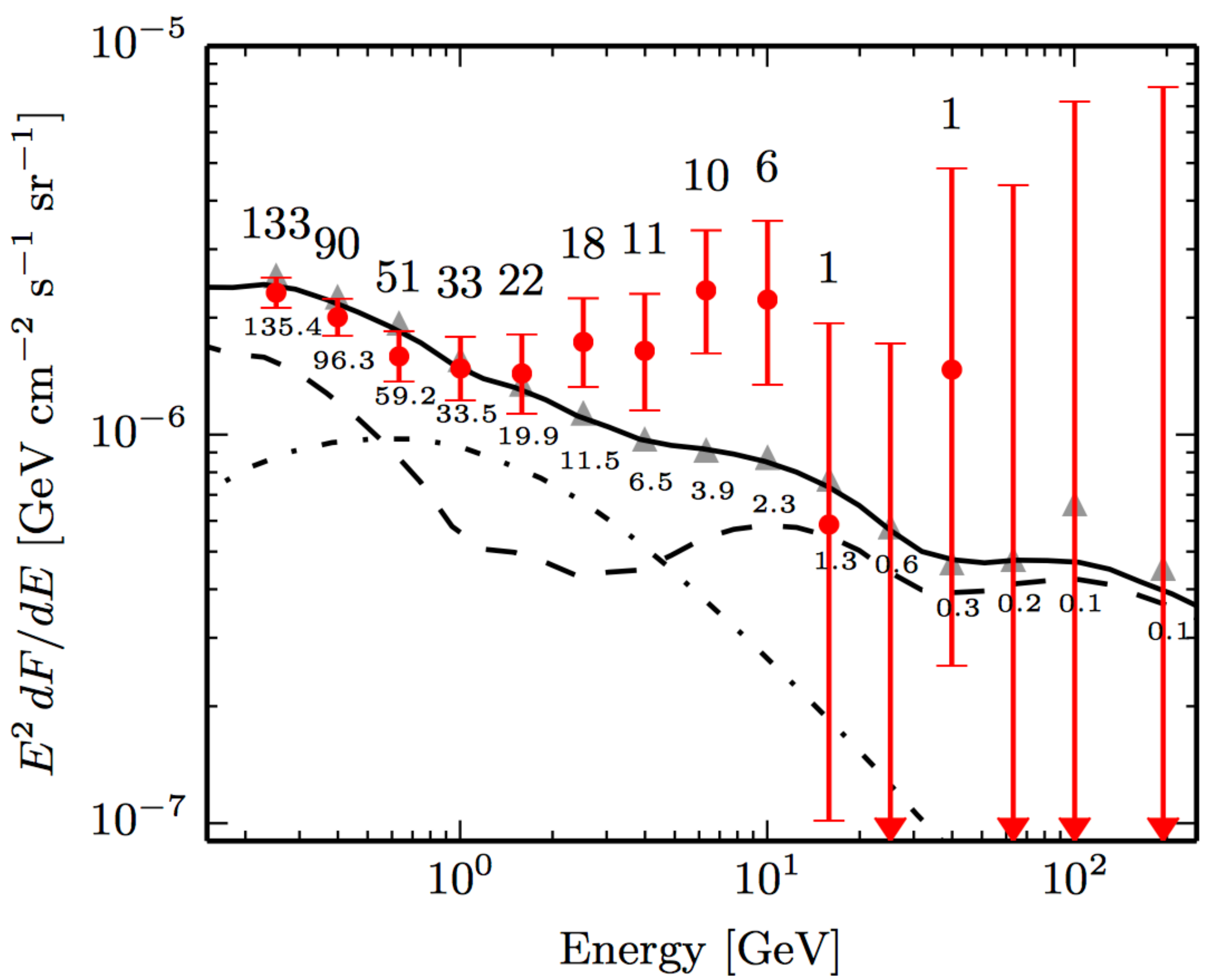
Two seen at > 3$\boldsymbol{\sigma}$

Boötes I

Reticulum II

Reticulum II

Recently discovered, and subsequently seen in gamma rays with Fermi LAT (Hooper & Linden 2015, Geringer-Sameth et al 2015)



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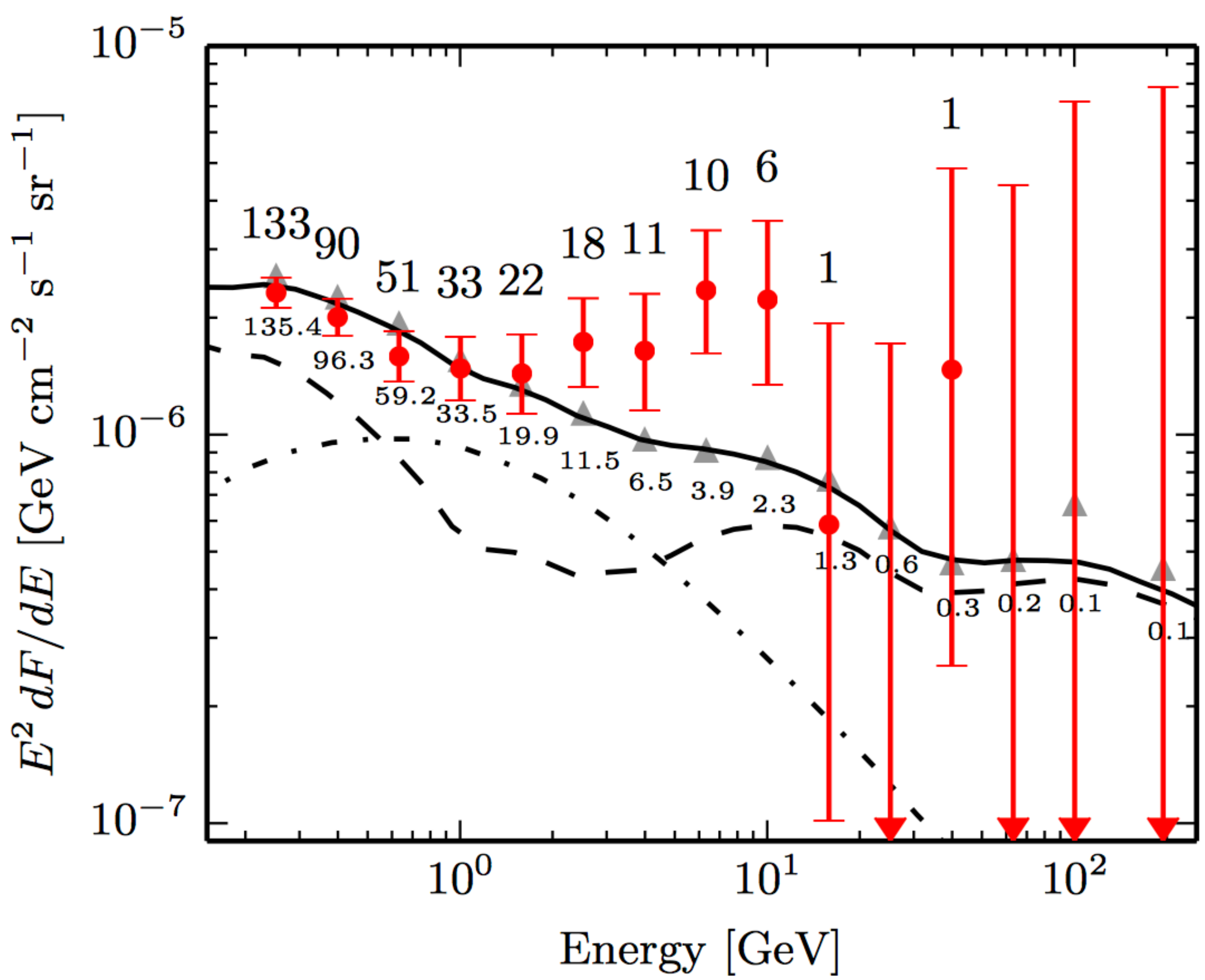


If light DM is producing 511 keV signal, cross section is 100x too large

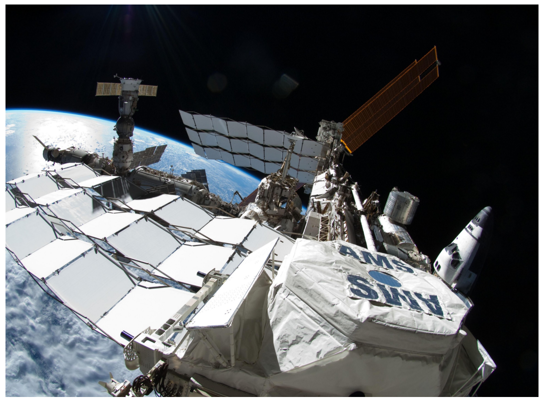
$$\dot{n}_{e^+,\mathrm{Ret\,II}} = 10^{43}\mathrm{s}^{-1}$$

$$\dot{n}_{e^+,\mathrm{GC}} = 10^{43}\mathrm{s}^{-1}$$

??!

??!

Indirect searches for dark matter



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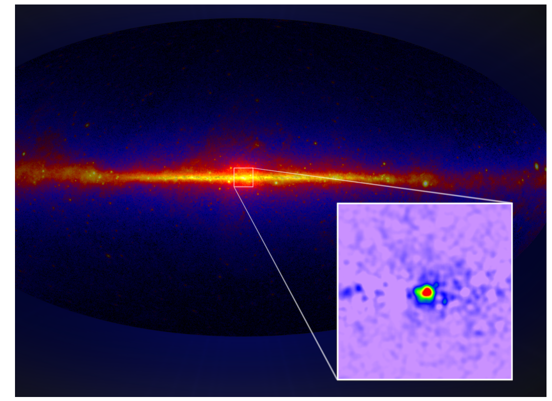

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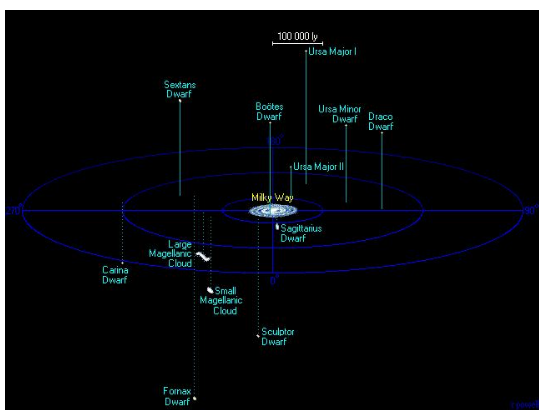

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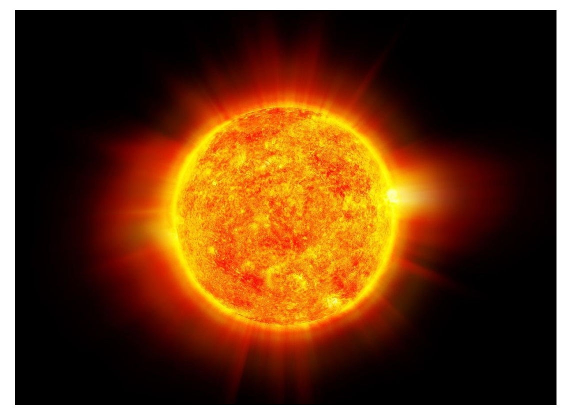

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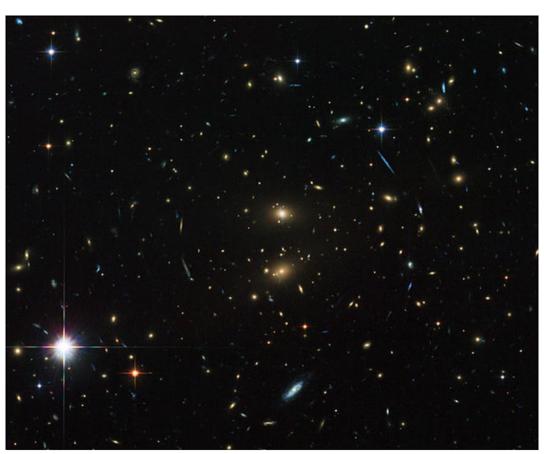

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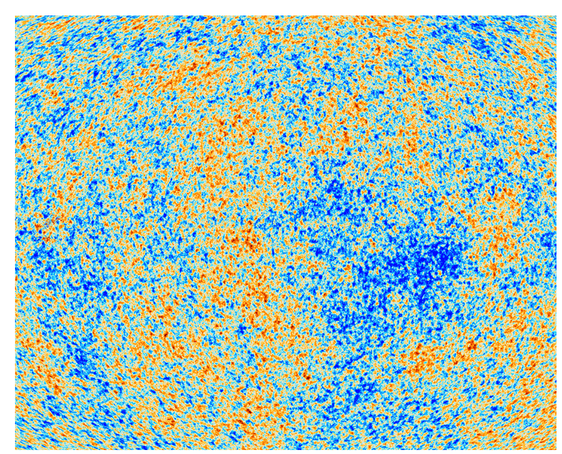

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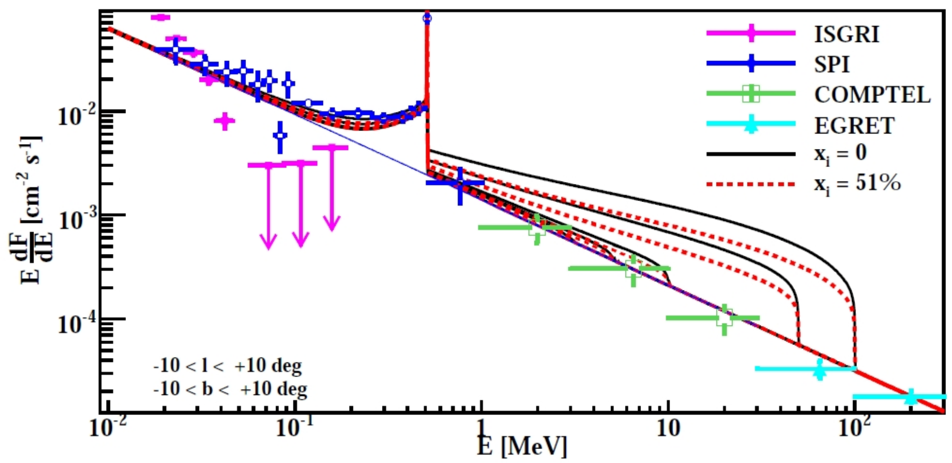
Could the galactic signal be a light WIMP?

$$\langle \sigma v \rangle \simeq 5 \times 10^{-31} \left(\frac{m_\chi}{\mathrm{MeV}} \right)^2 \mathrm{cm}^3 \mathrm{s}^{-1}$$



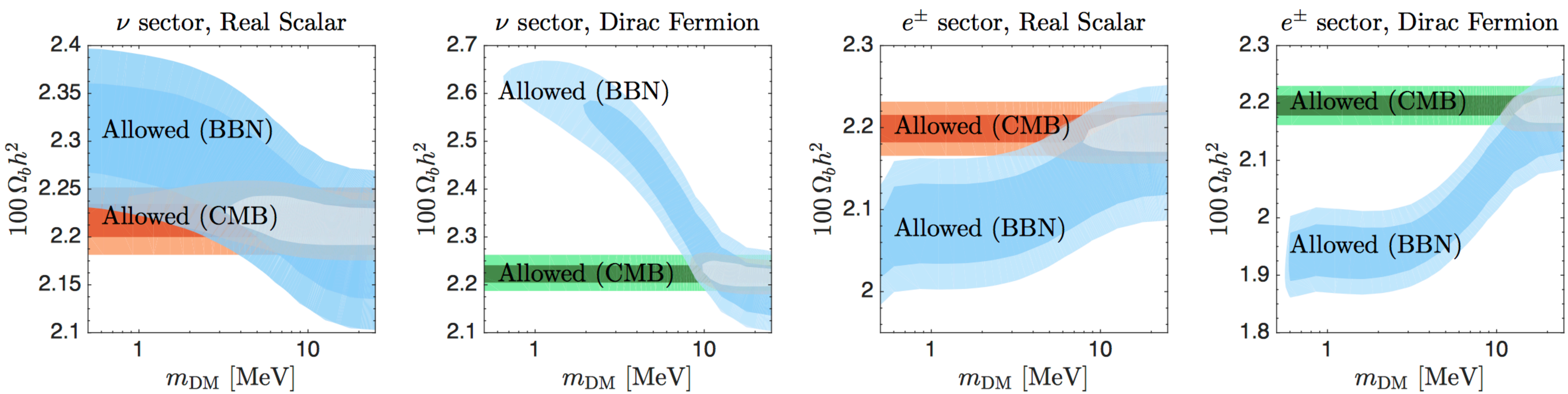
Require some extra piece to complete
the relic abundance cross section

$$\langle \sigma v \rangle \simeq 3 \times 10^{-26} \mathrm{cm}^3 \mathrm{s}^{-1}$$

could have

- p-wave annihilation to $e^{\pm}$ $\quad \langle \sigma v \rangle = a + b \left(\frac{v}{c} \right)^2$
- s-wave annihilation to neutrinos

Entropy transfer when light DM decouples



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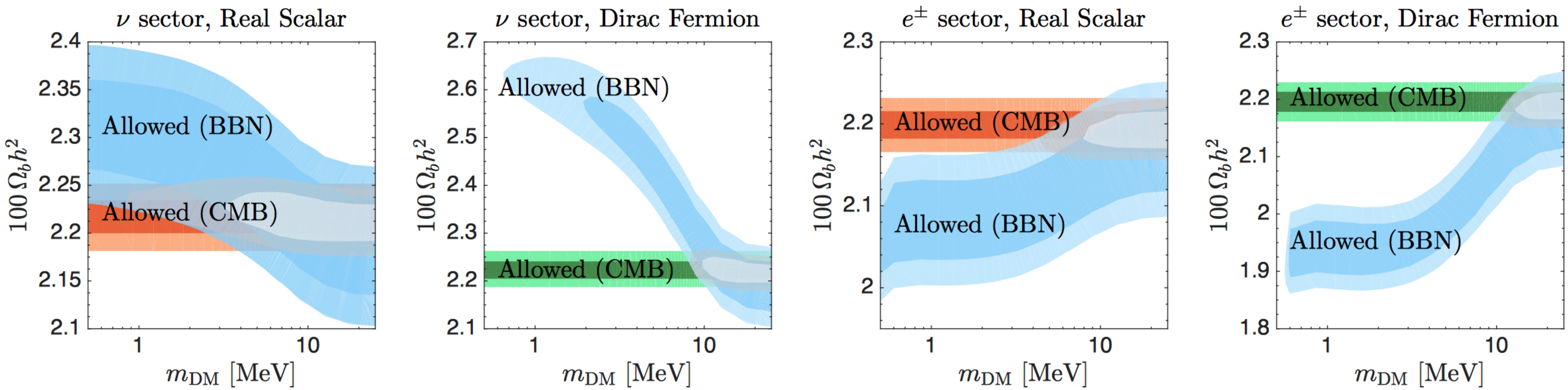
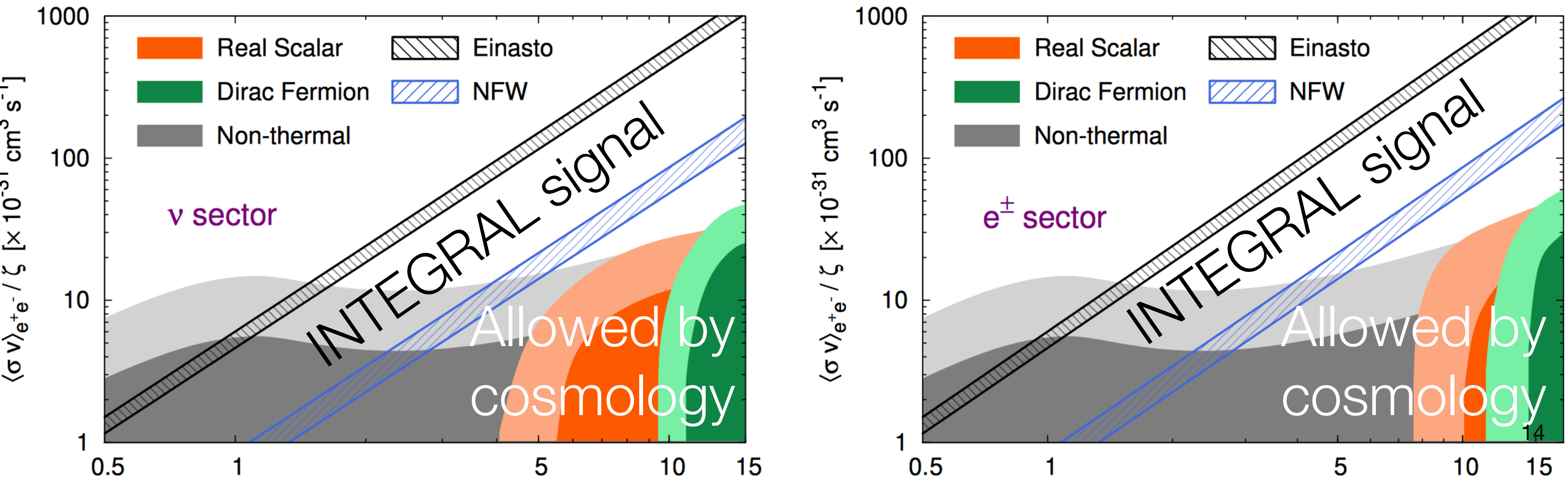
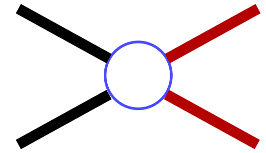


+ rescattering of CMB light during propagation to earth



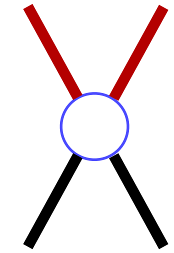
Probably not a thermal relic
but we can look at the effect of any
interaction between DM & the light particles

DM-neutrino interactions:



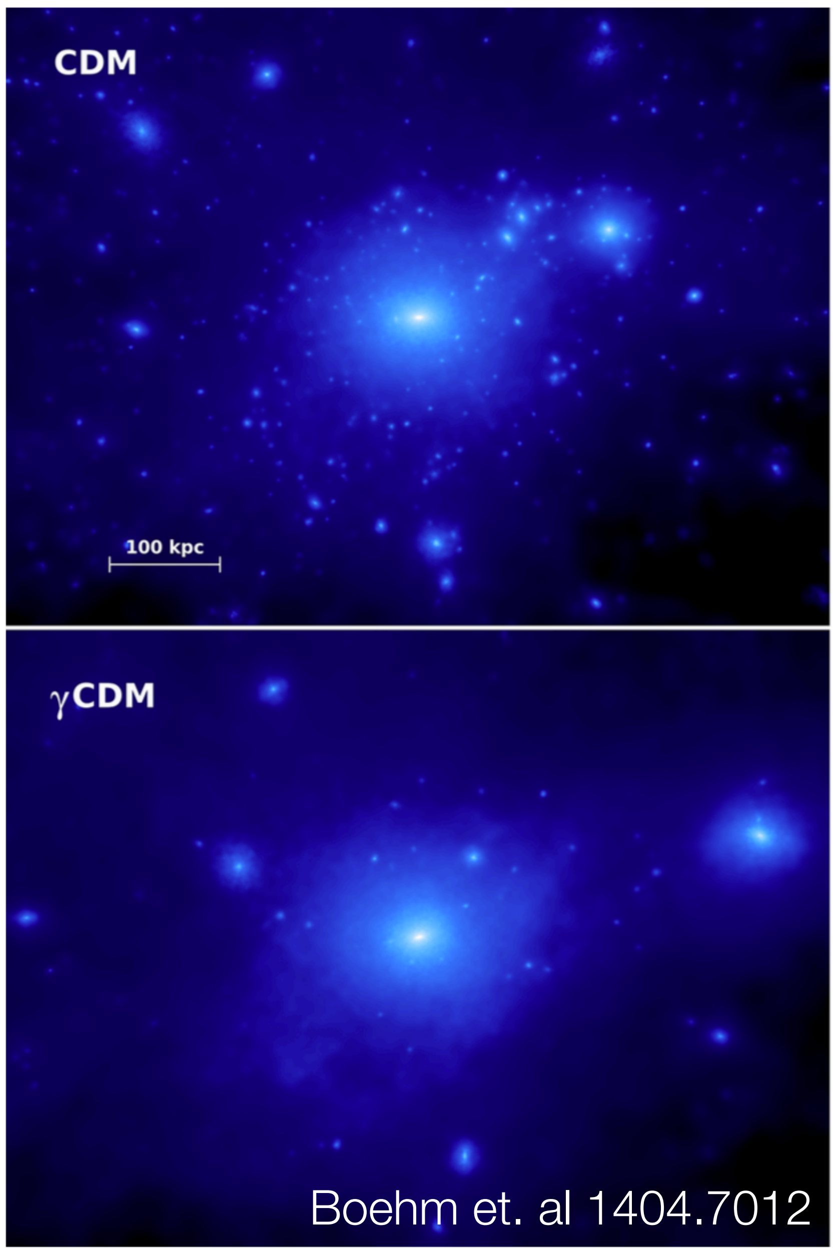
annihilation

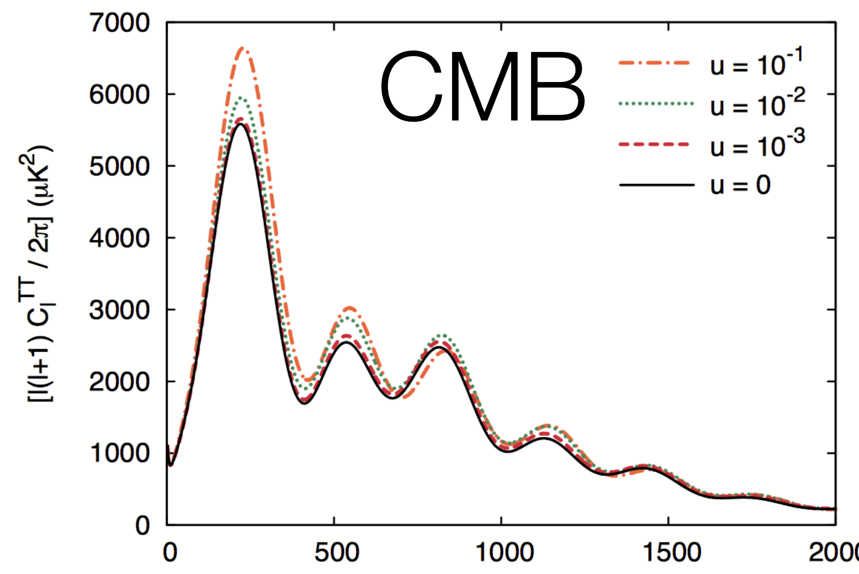
implies



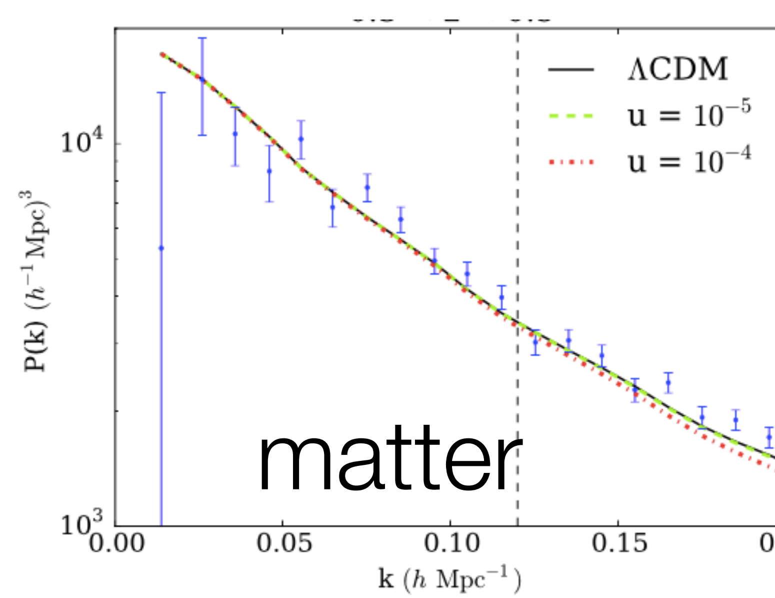
scattering

Power “bled away” on small scales
by neutrinos streaming away; increased correlations on large scales

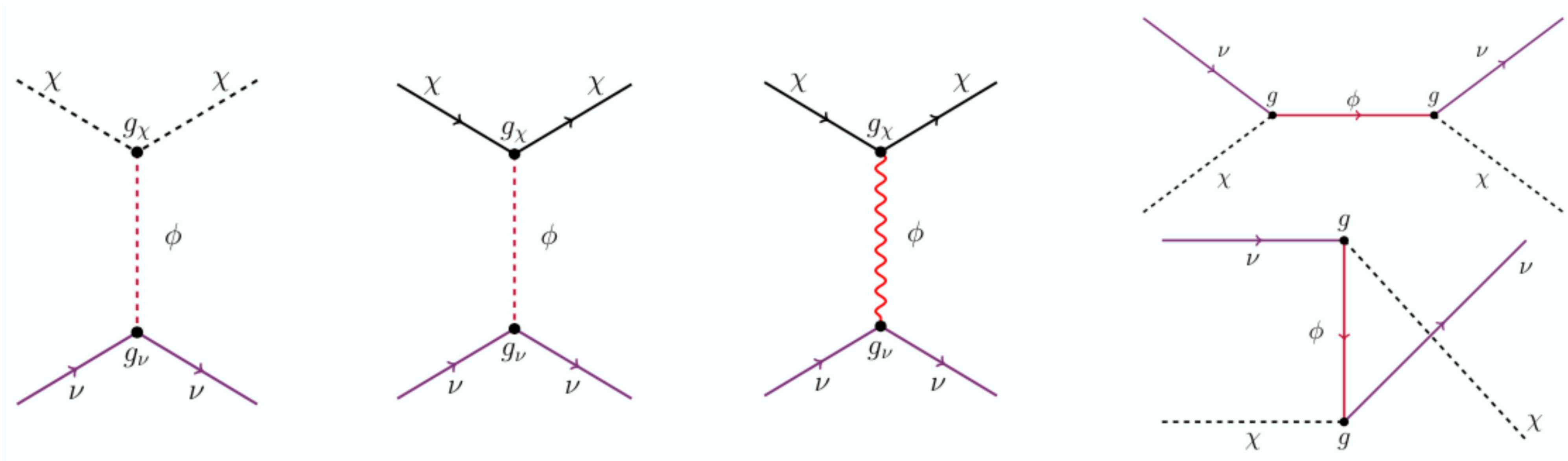




Wilkinson et al. 1401.7597



Escudero … ACV 1505.06735



Generic scattering cross section:

$$E_\nu \ll m_\chi$$

1) $\sigma \rightarrow const.$

2) $\sigma \rightarrow const. \times E_\nu^2$

Perturbation damping limits:

$$\sigma_{\mathrm{DM}-\nu,0}^{(WiggleZ)} \lesssim 4 \times 10^{-31} \, (m_{\mathrm{DM}}/\mathrm{GeV}) \;\; \mathrm{cm}^2$$

$$\sigma_{\mathrm{DM}-\nu,2}^{(WiggleZ)} \lesssim 1 \times 10^{-40} \, (m_{\mathrm{DM}}/\mathrm{GeV}) \;\; \mathrm{cm}^2 \times (T_\nu / T_{\mathrm{today}})^2$$

Escudero+ACV++

$$c.f. \; \sigma_{Thomson} = 10^{-26} \mathrm{cm}^2$$

Mangano 2006 + many others

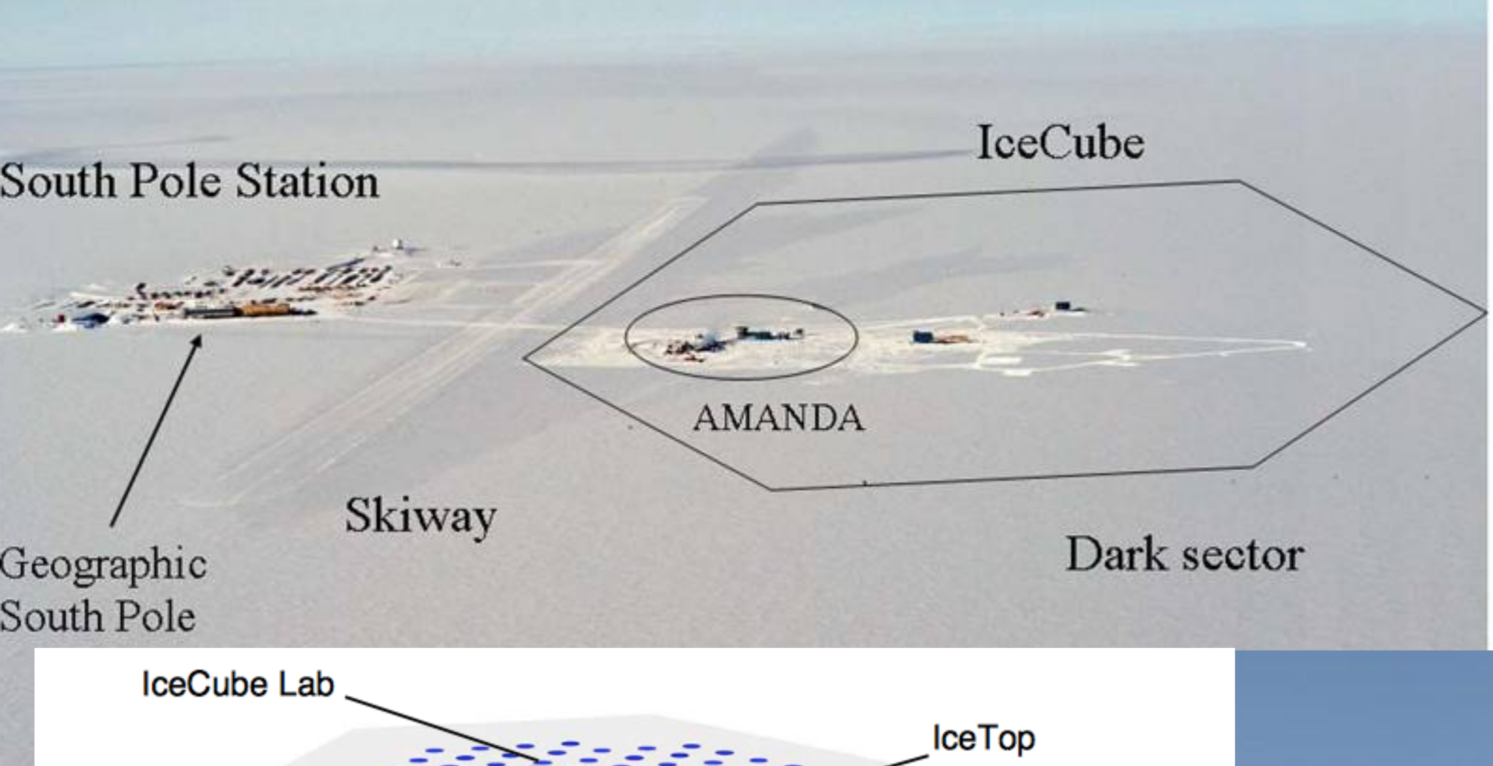
$$\sigma_{DM-\nu} \propto E_\nu^2$$

IceCube has seen events above a PeV….

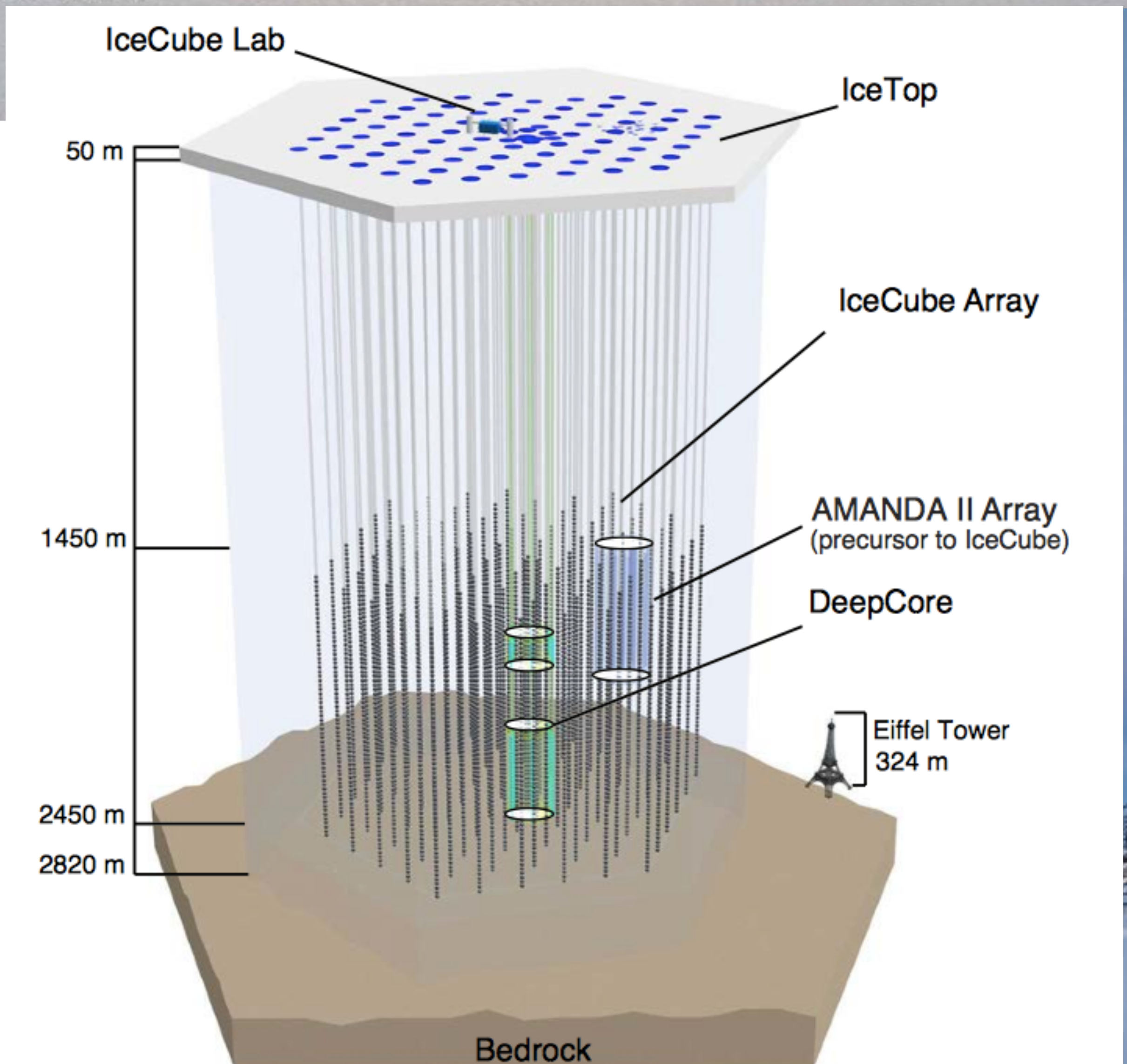
$$\left(\frac{\mathrm{PeV}}{T_{\nu,recomb.}}\right)^2 \sim 10^{30}$$

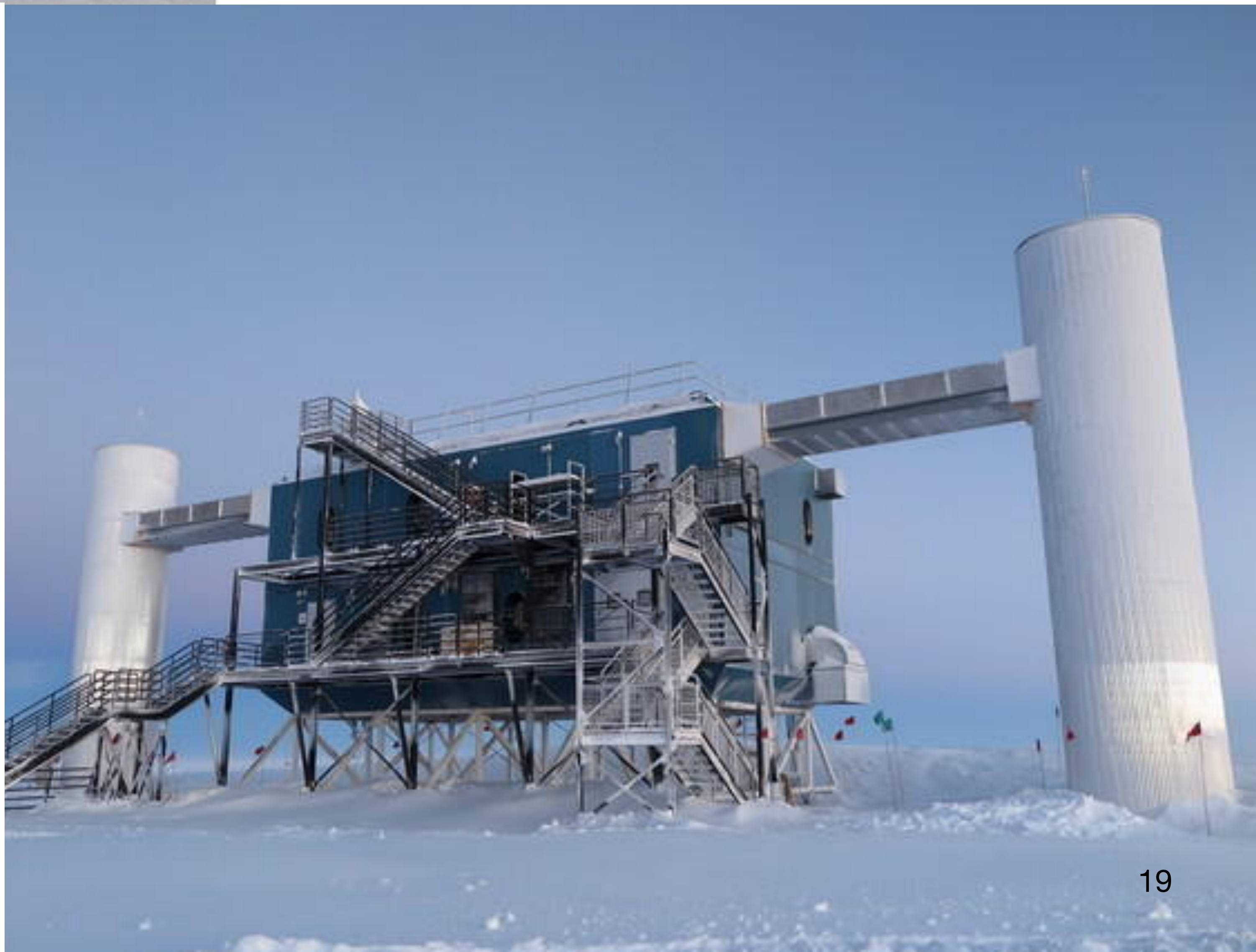
Let’s look there!

53 high-energy neutrinos in 4 years



IceCube Neutrino Observatory





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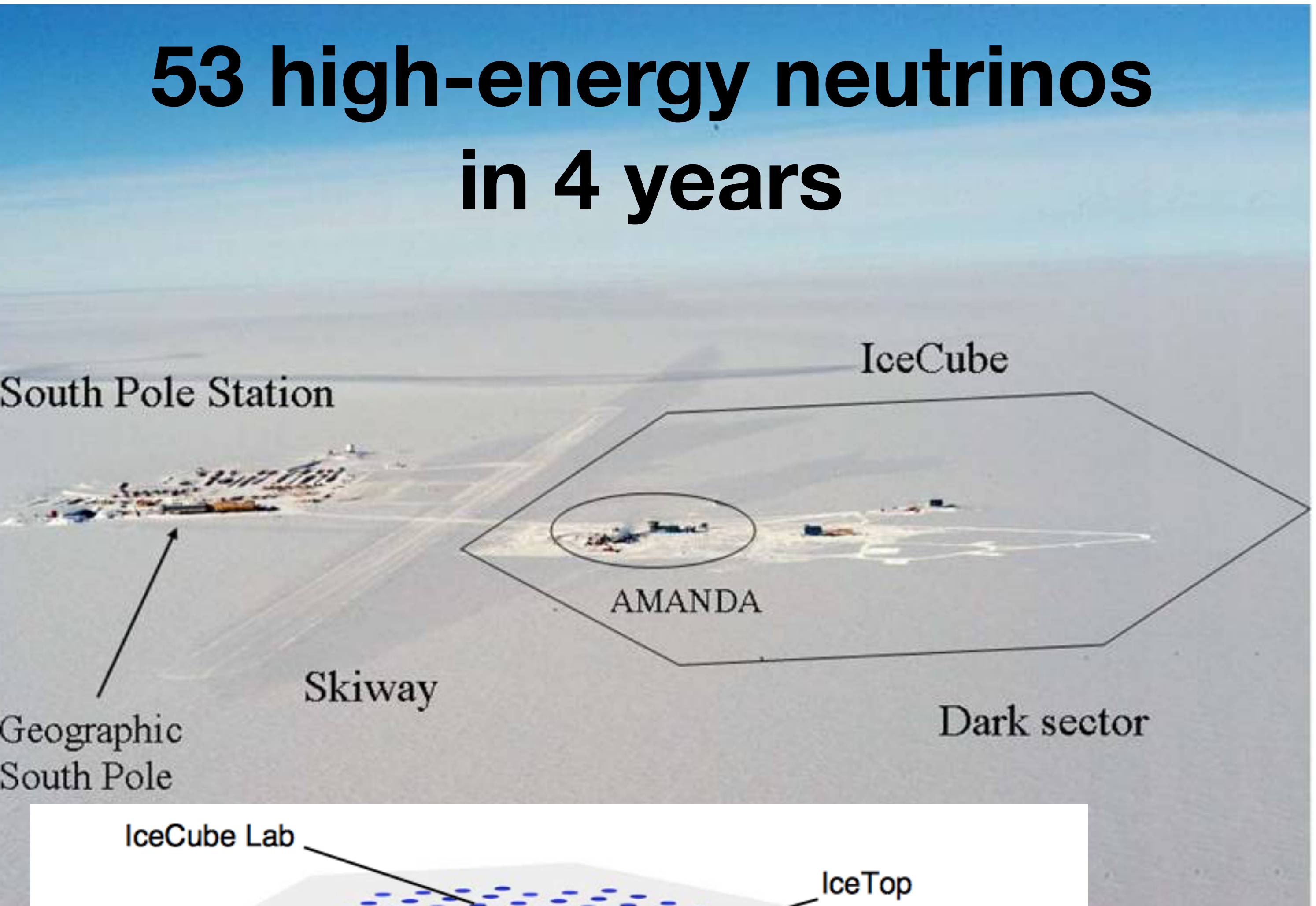
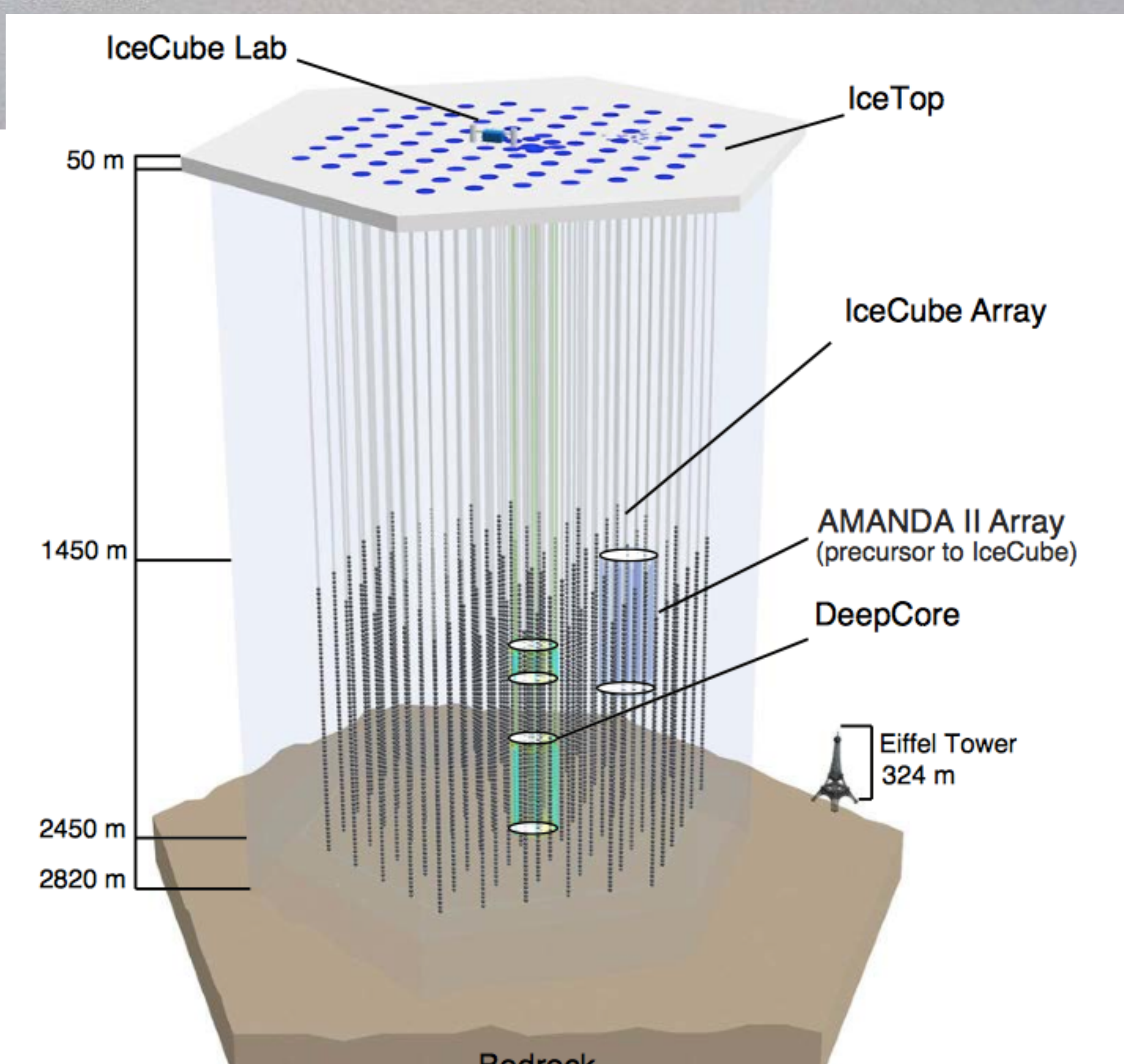
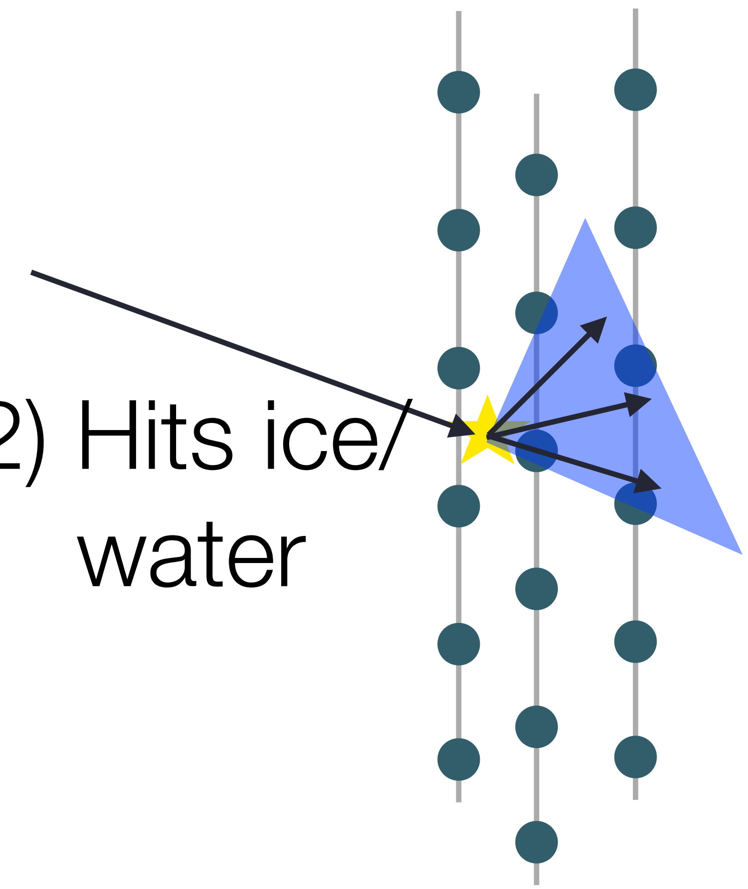




IceCube Neutrino Observatory

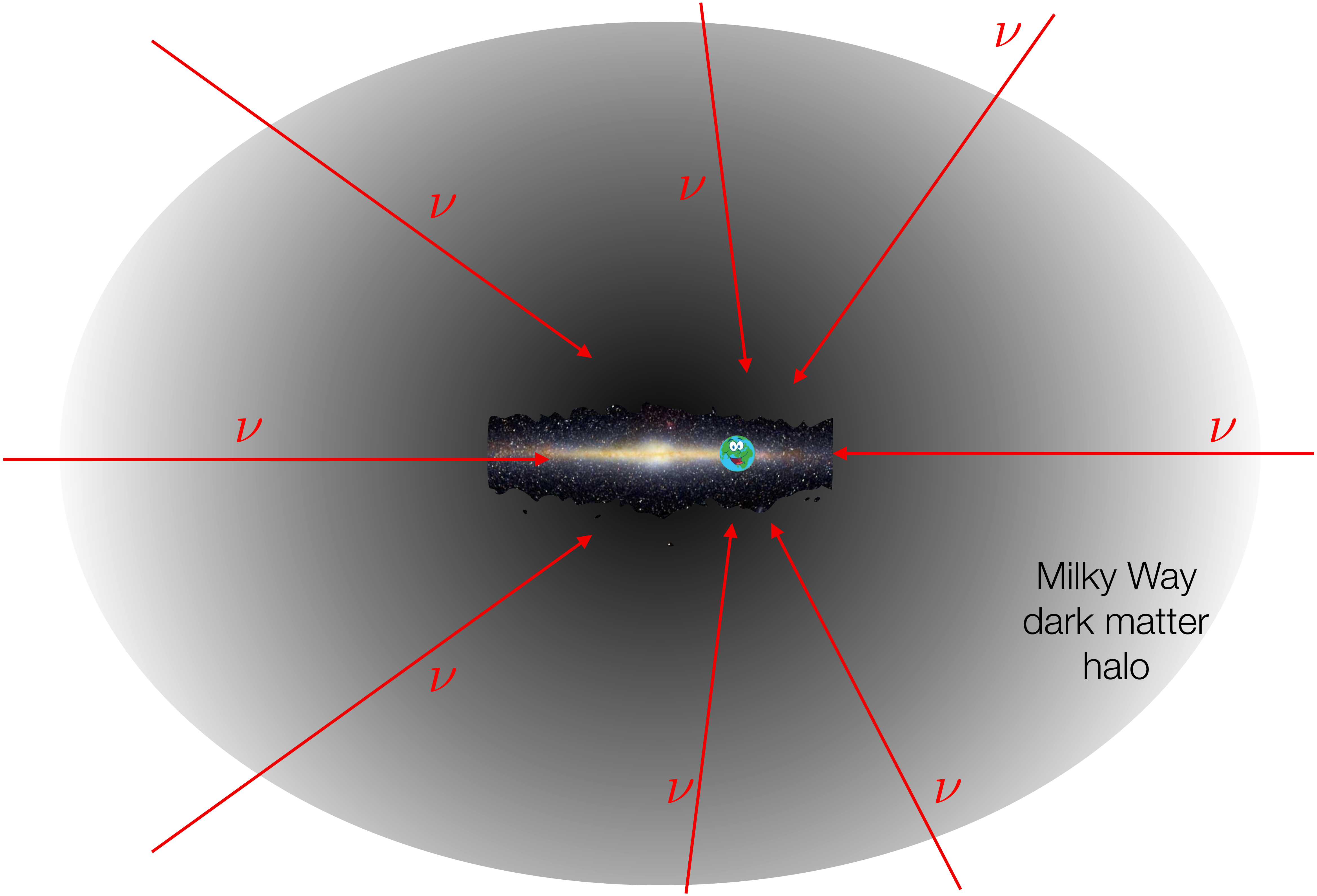
1) Neutrino arrives

2) Hits ice/ water

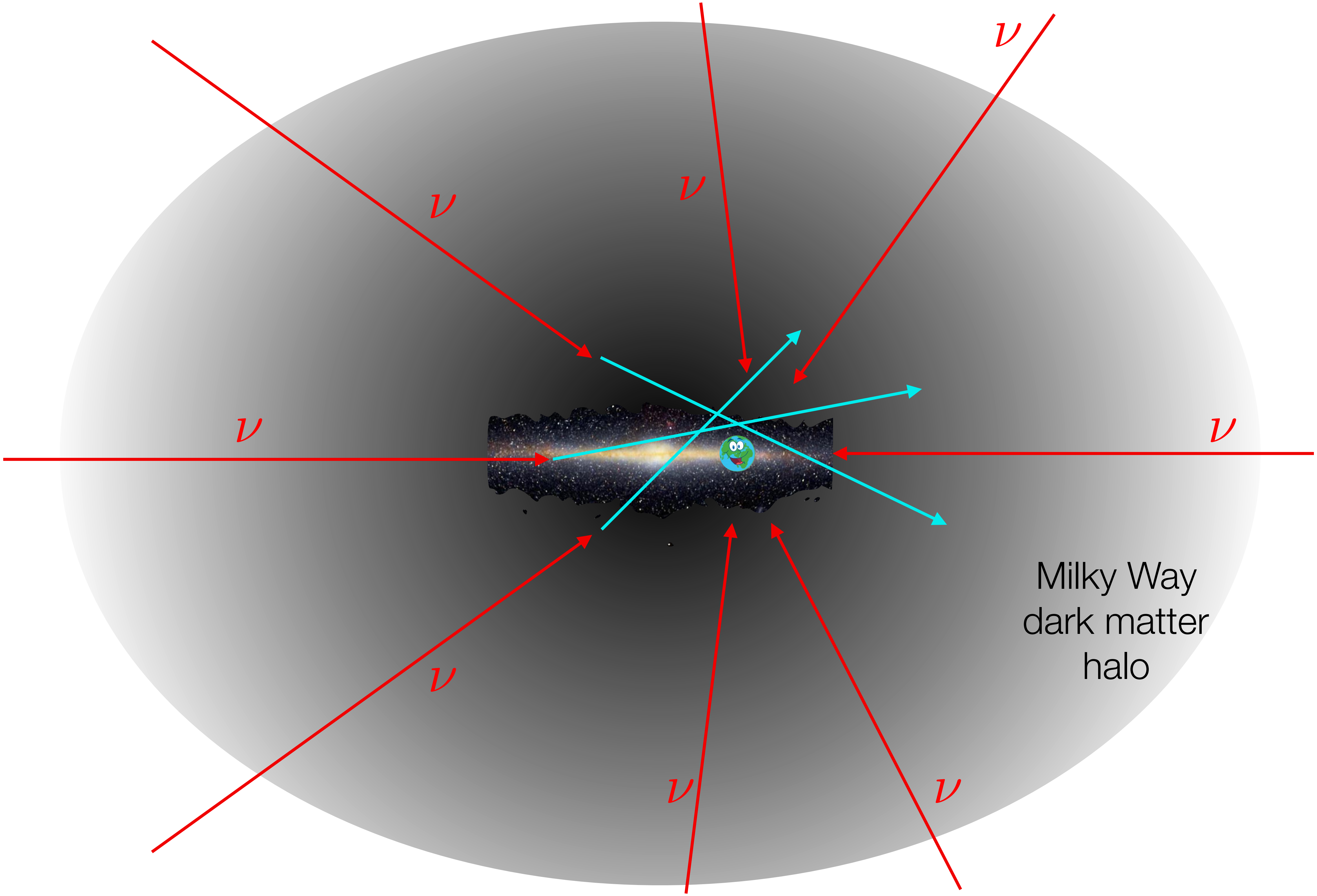


3) DOMs see Čerenkov light from electrons, muons

Isotropic extragalactic neutrino flux



Isotropic extragalactic neutrino flux



Anisotropic deflection/energy loss

In practice

b, l: galactic latitude, longitude

column density: $$\tau(b,l) = \int_{l.o.s} n_\chi(x;b,l)\ dx.$$

$$\frac{d\Phi(E,\tau)}{d\tau} = -\sigma(E)\Phi(E,\tau) + \int_E^\infty d\tilde{E}\,\frac{d\sigma(\tilde{E},E)}{dE}\Phi(\tilde{E},\tau)$$

$$\downarrow \qquad\qquad \downarrow$$

scattering **from** *E* to any energy

scattering **to** *E* from any energy $\tilde{E}$

Solve to find flux at earth at energy E and direction (b,l)

What about cross section?

$$\sigma_{DM-\nu} \propto E_\nu^2 \quad \xrightarrow[??]{} \left(\frac{\text{PeV}}{T_{\nu,recomb.}}\right)^2 \sim 10^{30}$$

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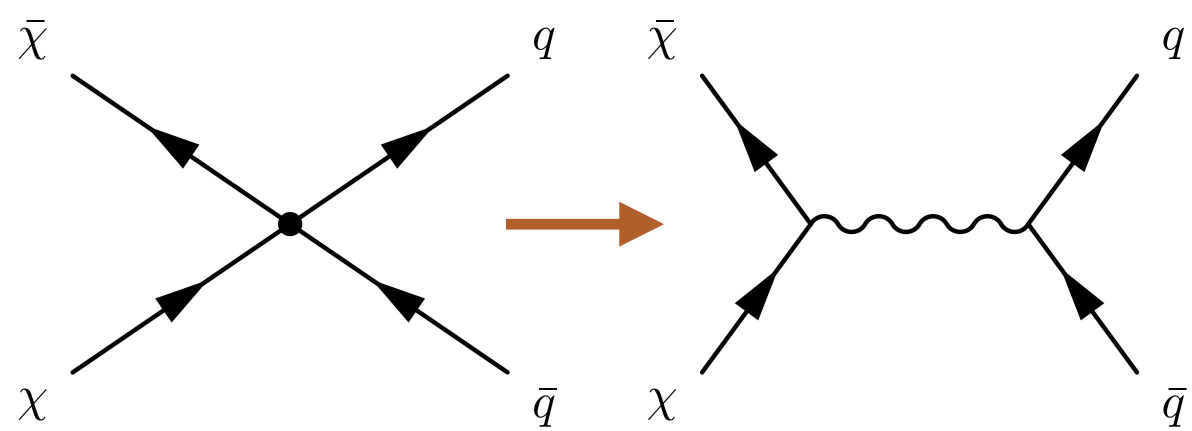
No!

What about cross section?

$$\sigma_{DM-\nu} \propto E_\nu^2 \quad \xrightarrow[??]{} \left(\frac{\text{PeV}}{T_{\nu,recomb.}}\right)^2 \sim 10^{30}$$

No!

$$E \to \Lambda_{New\,physics}$$

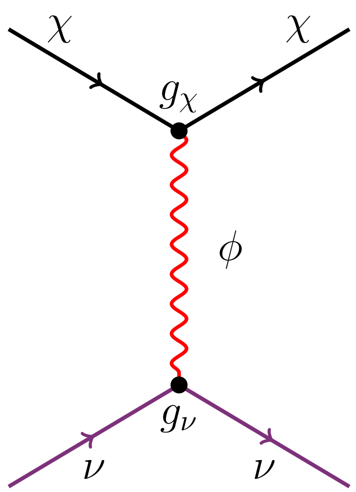


The low energy approximation does not work at a PeV!!

Begin to resolve microphysics: **need more concrete model**

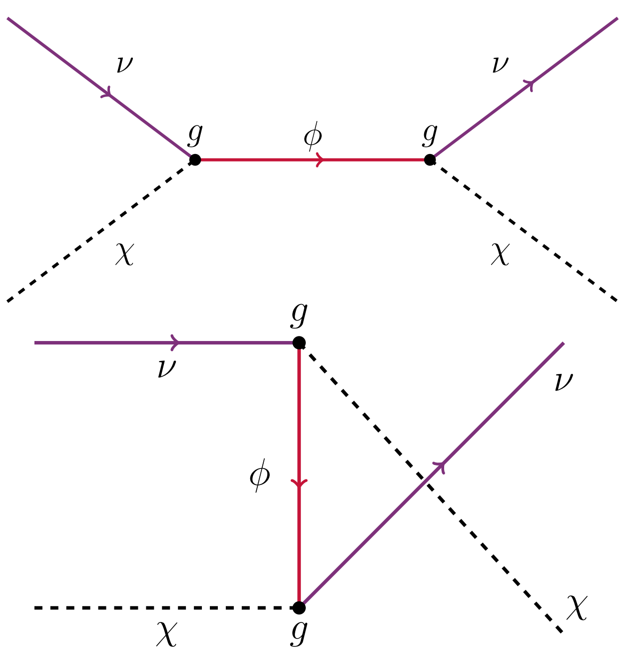
Two fiducial simplified models

1)



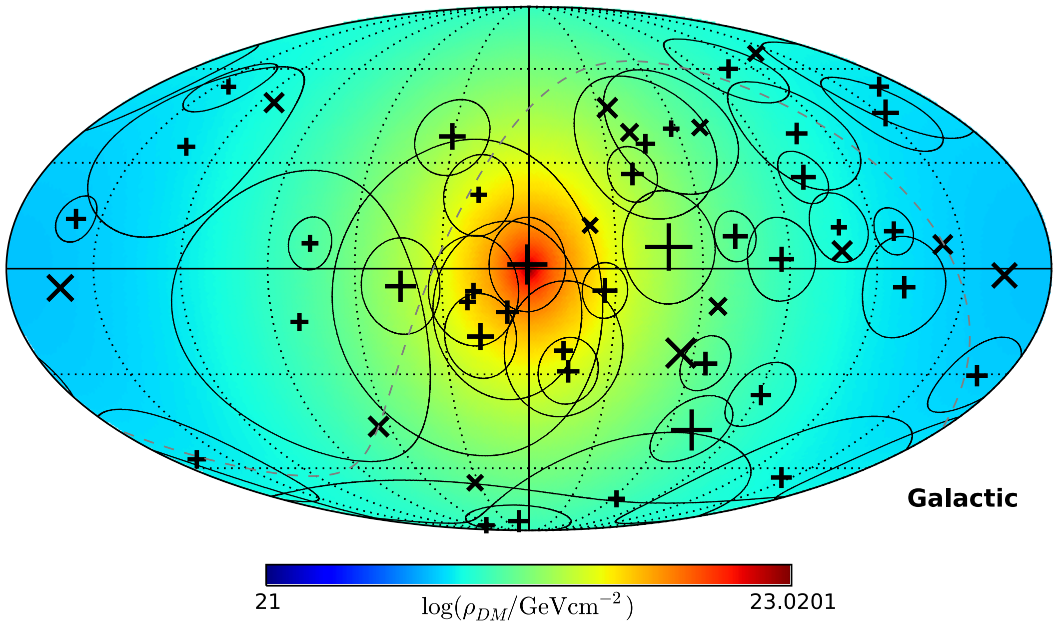
Fermion DM, **vector mediator**: similar to a leptophillic Z' model
Scales strongly with *E*

2)

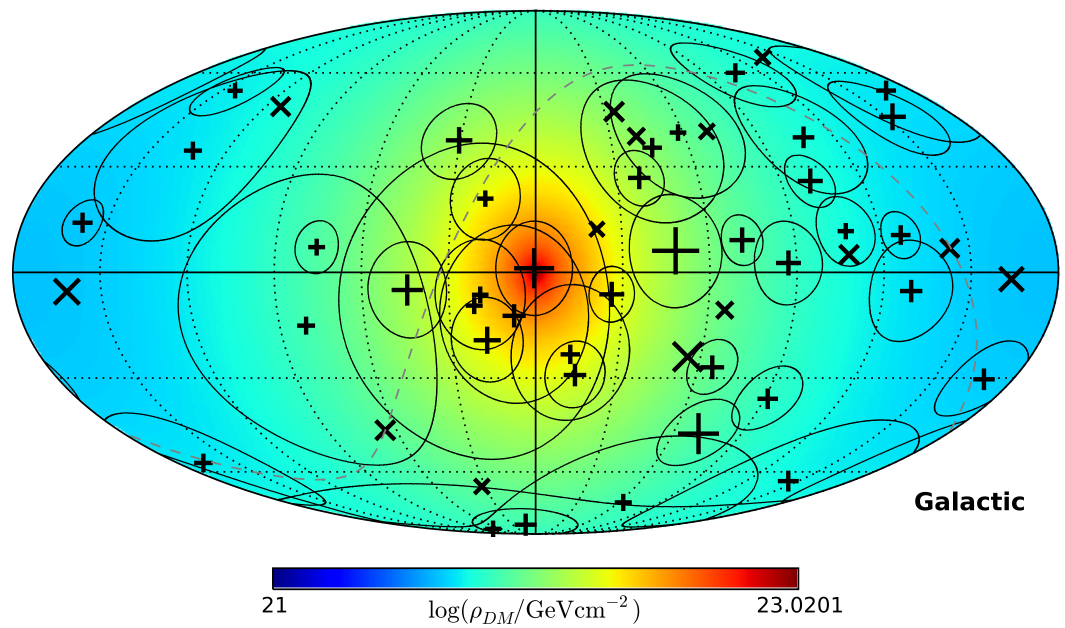


Scalar DM, **fermionic mediator**:
e.g. sneutrino dark matter, neutralino mediator. Resonant Behaviour (s-channel)

Dark matter column density seen from Earth

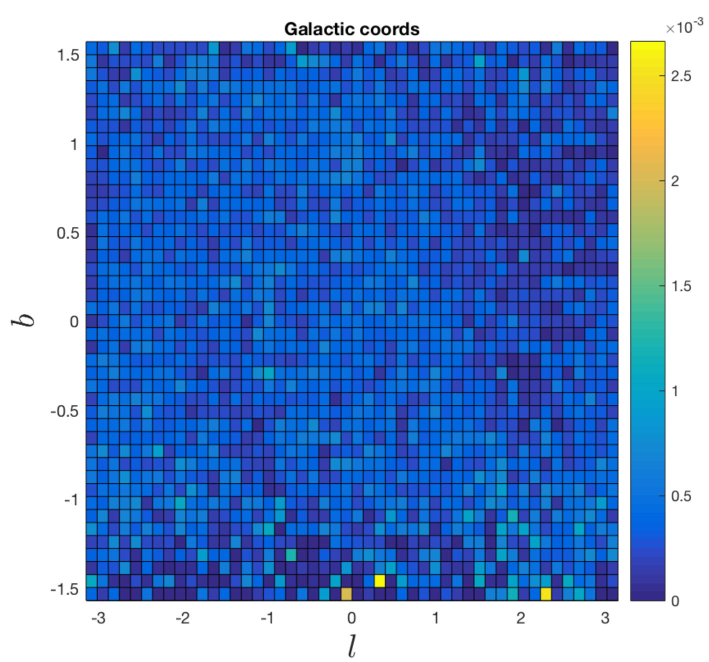


Dark matter column density seen from Earth

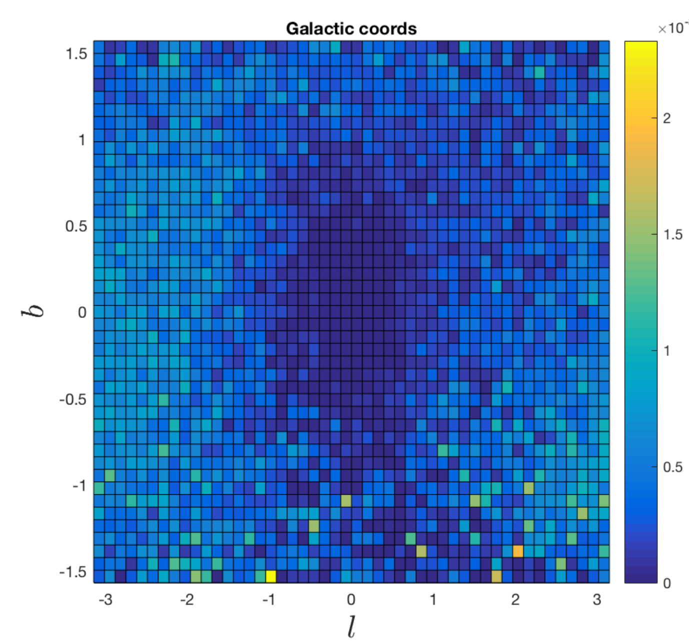


Simulation including effects of detector, Earth

no interaction

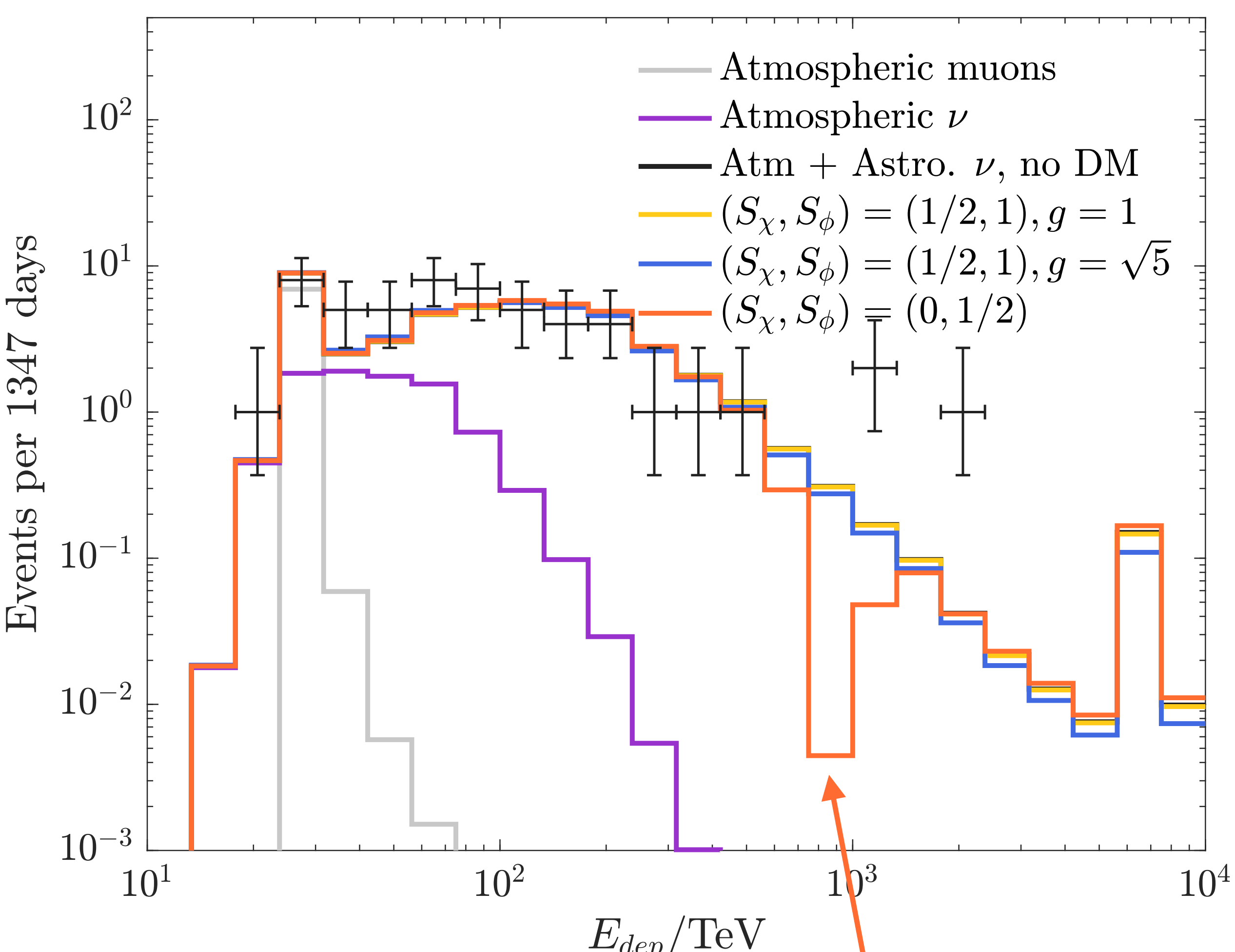


strong interaction



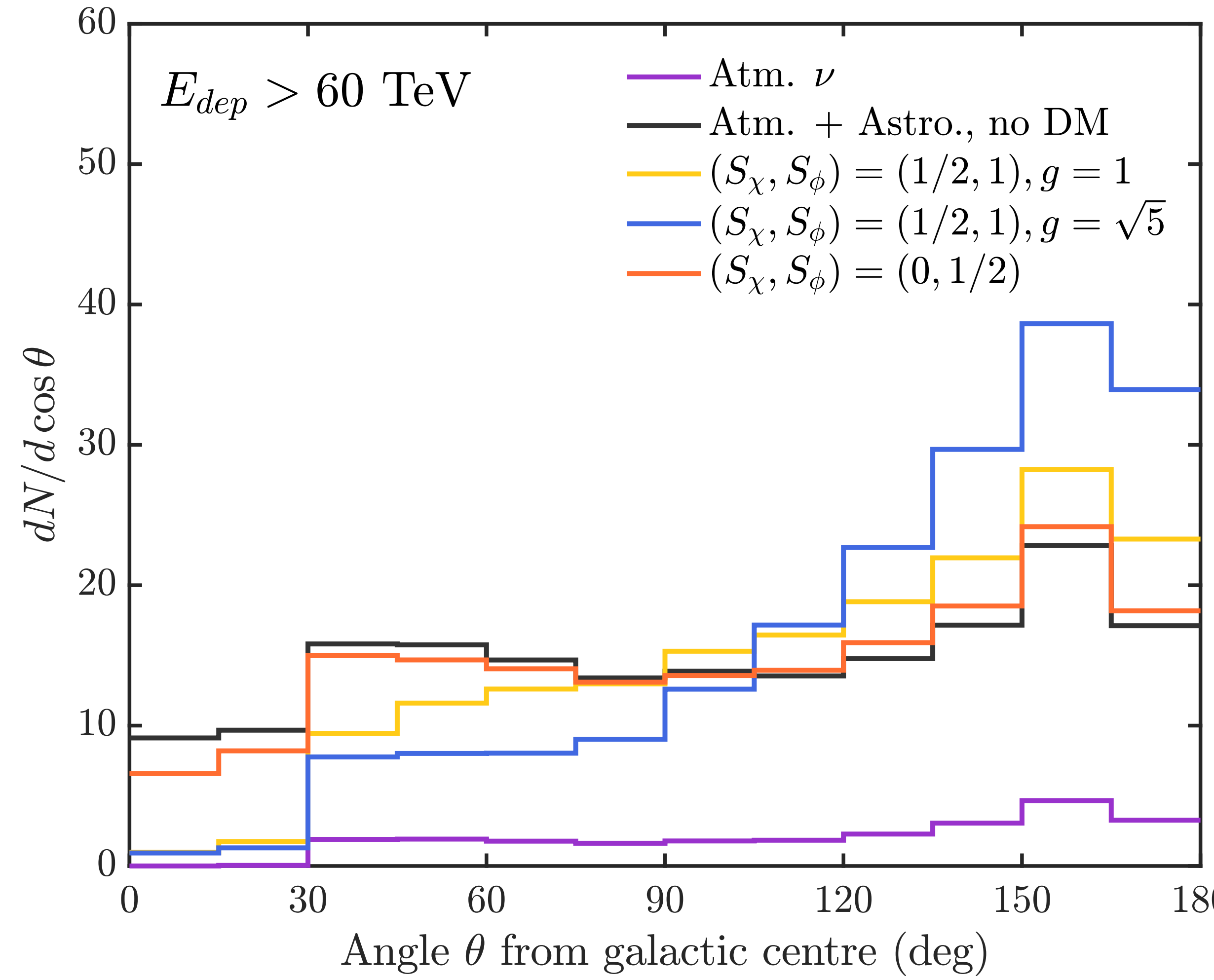
Energy & morphology

Energy



Resonance @ 810 TeV

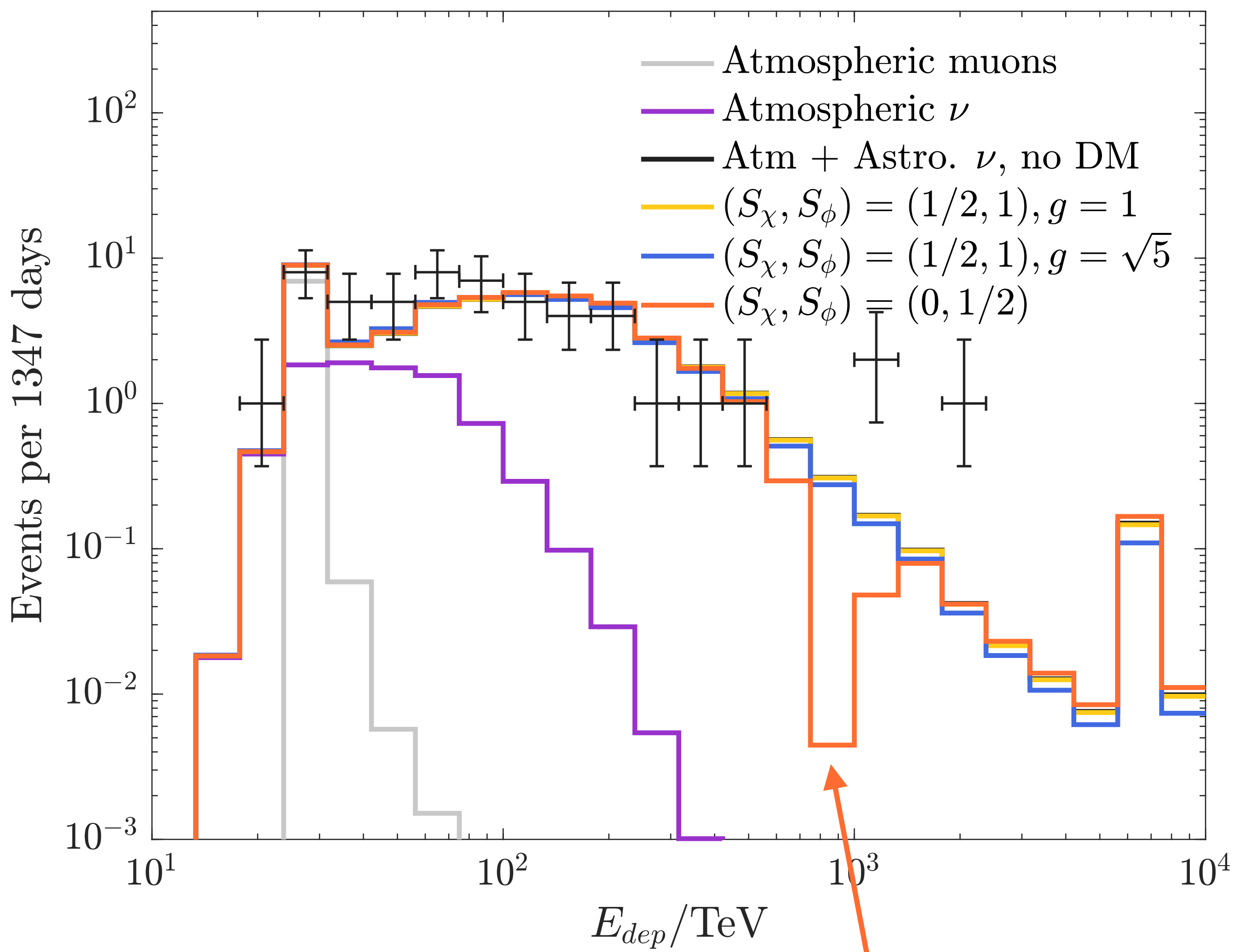
Angle from galactic centre



IceCube HESE events

Energy & morphology

Energy



Resonance @ 810 TeV

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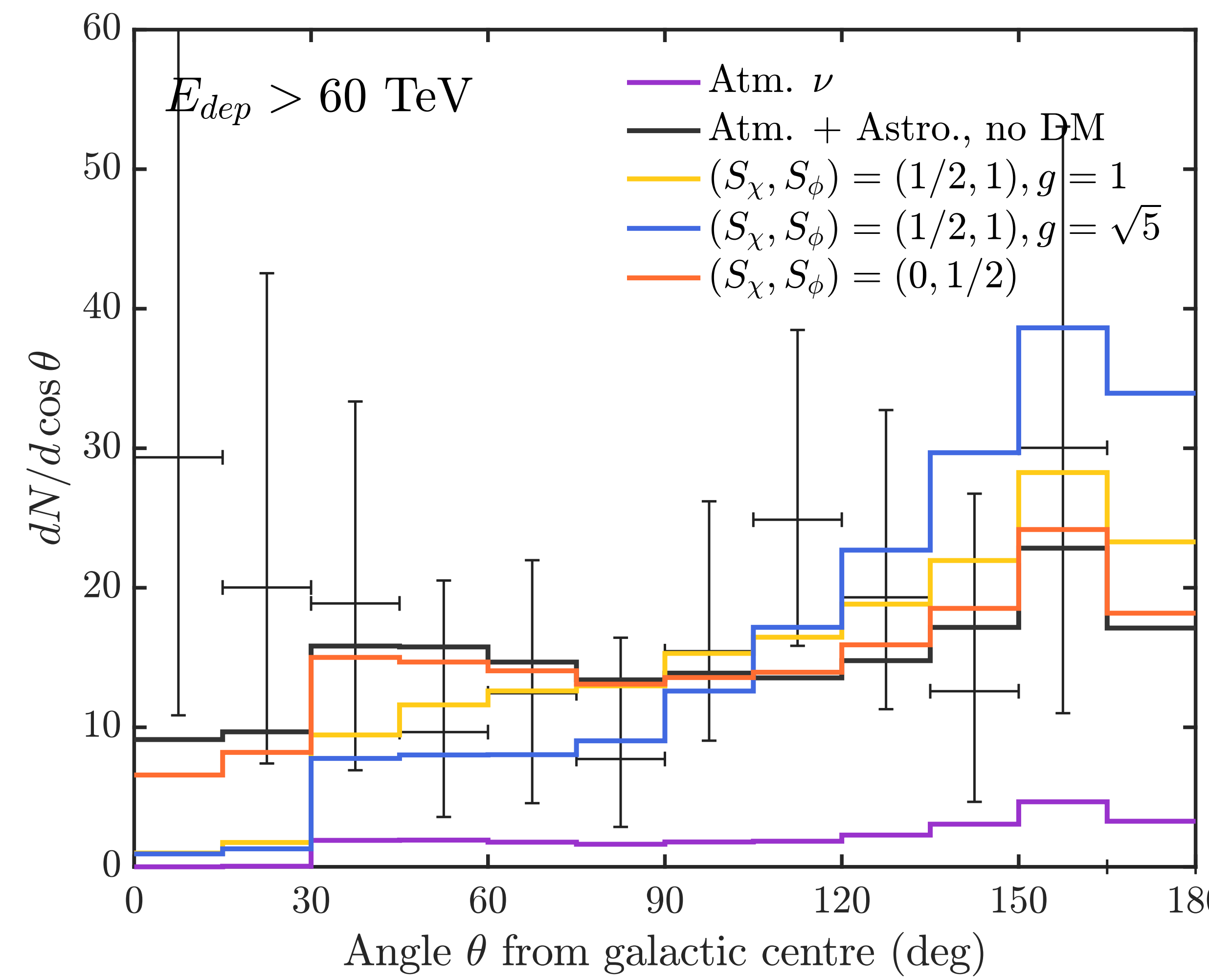


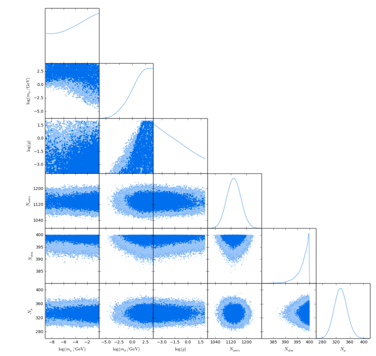
IceCube HESE events

Compare Likelihood to real events

$\ln \mathcal{L}$
$+$

*

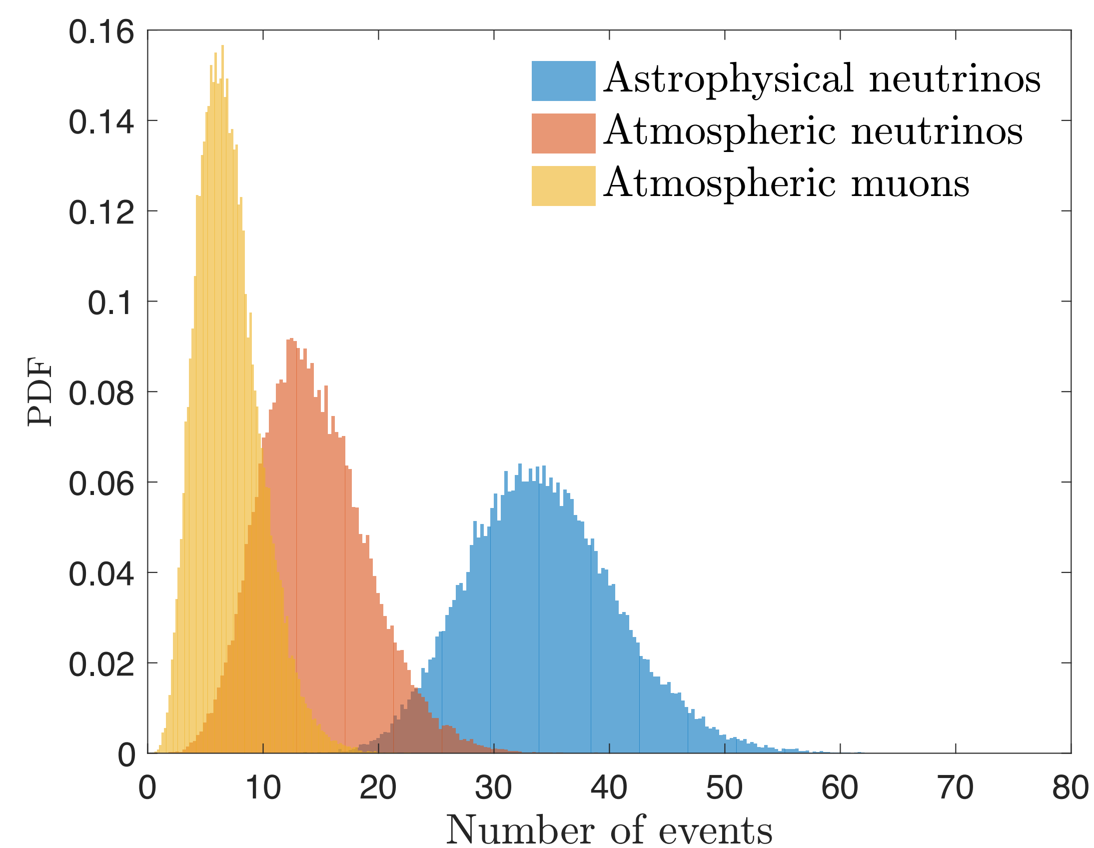
emcee
The MCMC Hammer



$$\mathcal{L}(\{t, E, \vec{x}\}|\vartheta) = e^{-\sum_b N_b} \prod_{i=1}^{N_{obs}} \sum_a N_a P_a(t_i, E_i, \vec{x}_i|\vartheta).$$

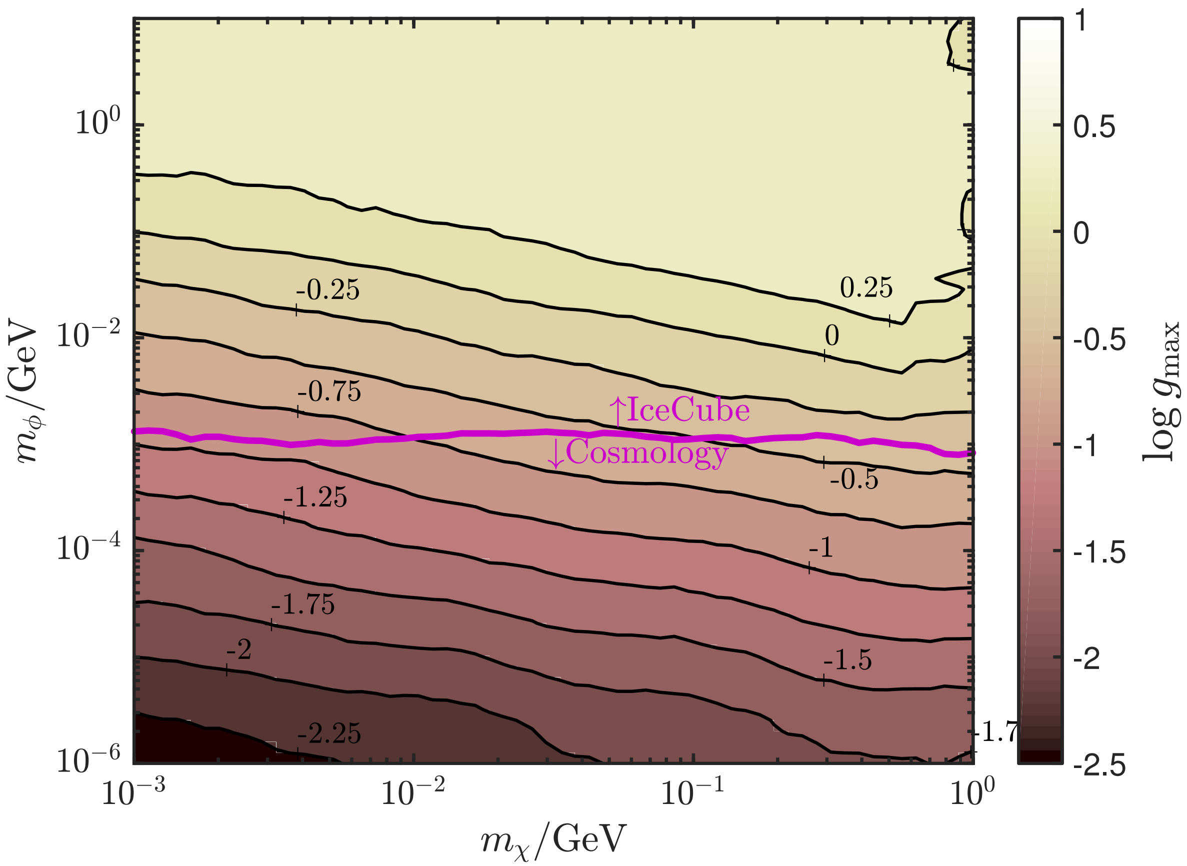
Parameters:

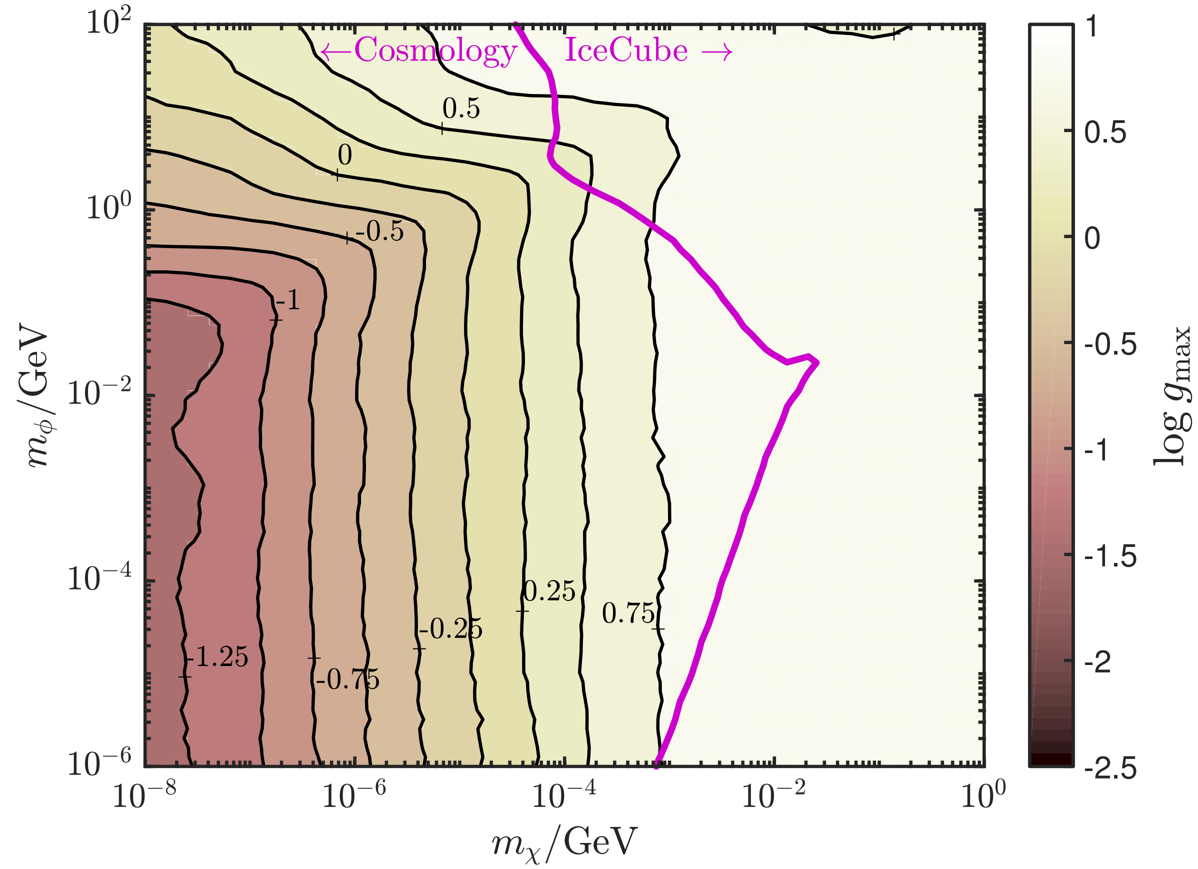
$$m_\chi \; m_\phi \; g \; N_{astro} \; N_{atmo} \; N_{\mu^\pm}$$

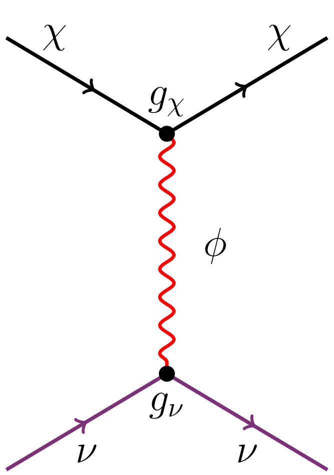


*IceCube data

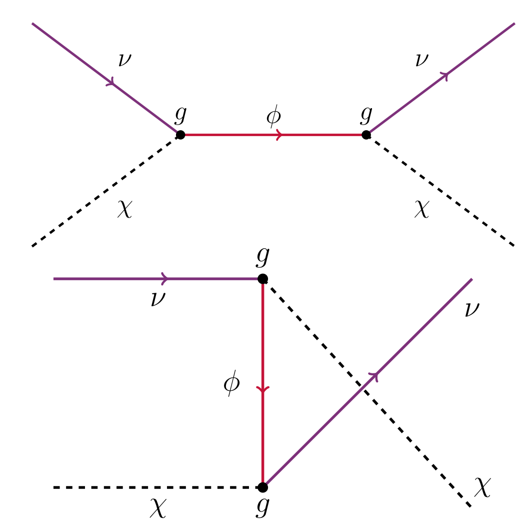
Limits from IceCube



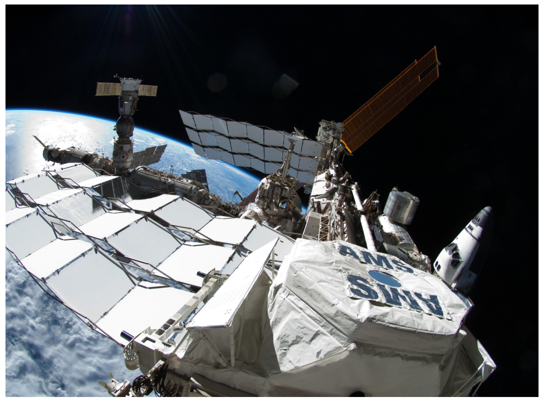




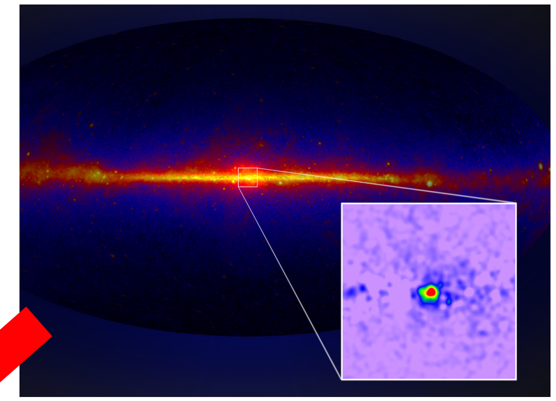
Only 53 events: already eating into cosmology parameter space



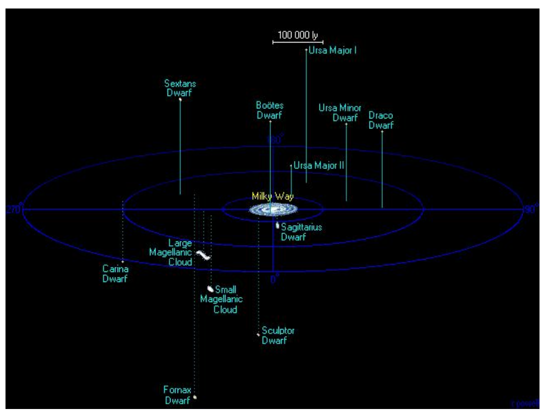
Indirect searches for dark matter



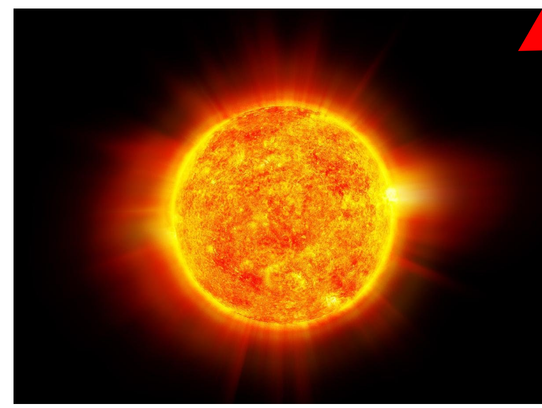
Local Cosmic Ray flux



Galactic center

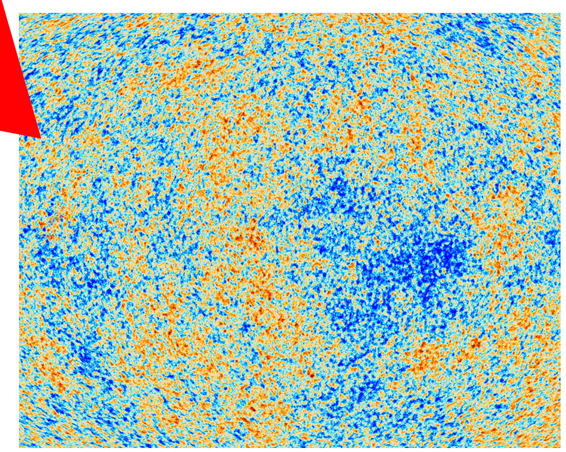


Dwarf galaxies



The Sun

Galaxy Clusters



CMB

Summary

- Over 4 decades after its first detection, 511 keV signal from the galactic centre is still there!
- There's a similar (but incompatible?) signal in two dwarf galaxies
- Cosmology makes a DM interpretation difficult
- PeV neutrinos from IceCube give us complementary and competitive information

Thank you

Name	d	F_{511}	M_{Dyn}	M_V	σ	l	b	T_{Exp}	Ref.
Canis Major[b]	9	< 4.1	> 49	−14.4	–	239.99	−8.00	0.62	(1),(16),(17)
Segue 1[b]	23	< 12.4	0.26	−1.5	–	220.48	50.43	0.16	(1),(12),(60),(61),(62),(63)
Sagittarius Dwarf	**28**	**2.2(1.0)**	**190**	**-13.4**	**2.3**	**5.57**	**-14.17**	**7.00**	(1),(44),(45),(46)
Reticulum II[c]	**30**	**17.0(5.4)**	**0.24**	**-2.7**	**3.1**	**266.30**	**-49.73**	**0.55**	(22),(23),(27),(42),(43)
Ursa Major II[c]	34	4.1(2.3)	3.9	−4.2	1.9	152.46	37.44	1.67	(1),(57),(58),(59)
Segue 2[c]	35	< 14.4	0.23	−2.5	–	149.43	−38.14	0.20	(1),(48)
Willman 1[c]	42	7.3(7.1)	0.39	−2.7	1.0	158.58	56.78	0.45	(1),(62),(64),(65)
Coma Berenices[c]	44	1.6(1.7)	0.94	−4.1	1.0	241.89	83.61	2.93	(1),(6),(12),(18)
Boötes III	48	< 4.4	> 0.017	−5.8	–	35.41	75.35	1.93	(1),(8),(9),(10)
Boötes II[a]	49	< 5.8	3.3	−2.7	–	353.69	68.87	1.92	(1),(5),(6),(7)
Large Magellanic Cloud	50	< 3.6	> 1500	−18.1	–	280.47	−32.89	4.22	(1),(37),(38)
Tucana II[c]	57	3.8(8.4)	*N/A*	−3.8	0.5	328.08	−52.32	0.22	(22),(23)
Small Magellanic Cloud	61	0.6(2.8)	1400	−16.8	0.2	302.80	−44.30	1.38	(1),(37),(52),(53)
Boötes I[a c]	**62**	**8.5(2.9)**	**0.81**	**-6.3**	**3.0**	**358.08**	**69.62**	**1.85**	(1),(2),(3),(4)
Ursa Minor[c]	73	< 5.8	9.5	−8.8	–	104.97	44.80	1.30	(1),(29)
Horologium I[c]	79	6.7(4.4)	0.55	−3.4	1.6	271.39	−54.73	0.43	(22),(23),(27)
Draco[c]	82	< 3.8	11	−8.8	–	86.37	34.72	1.57	(1),(19),(20),(21)
Phoenix II	83	< 16.6	*N/A*	−2.8	–	323.68	−59.75	0.19	(22),(23)
Sculptor[c]	83	< 11.6	14	−11.1	–	287.54	−83.16	0.22	(1),(47)
Sextans[c]	85	6.5(5.3)	10.6	−9.3	1.2	243.50	42.27	0.12	(1),(49),(50),(51)
Eridanus III	87	7.3(5.1)	*N/A*	−2.0	1.5	274.95	−59.60	0.38	(22),(23)
Indus I	100	6.2(3.9)	*N/A*	−3.5	1.6	347.15	−42.07	0.26	(23),(23)
Ursa Major I[c]	101	< 9.2	11	−5.5	–	159.43	54.41	0.42	(1),(6),(54),(55),(56)
Carina[c]	103	0.6(3.6)	6.3	−9.1	0.2	260.11	−22.22	0.66	(1),(14),(15)
Pictoris I	114	< 7.4	*N/A*	−3.1	–	257.29	−40.64	0.46	(22),(23)
Grus I[c]	**120**	**20.8(9.1)**	**N/A**	**-3.4**	**2.3**	**338.68**	**-58.25**	**0.12**	(22),(23)
Hercules	136	9.7(5.5)	2.6	−6.6	1.8	28.73	36.87	0.31	(1),(6),(12),(26)
Fornax[c]	139	16.9(9.6)	56	−13.4	1.8	237.10	−65.65	0.11	(1),(24),(25)
Canes Venatici II[c]	**153**	**5.0(2.2)**	**0.91**	**-4.9**	**2.3**	**113.58**	**82.70**	**2.44**	(1),(6),(12),(13)
Leo IV[c]	155	< 5.4	1.3	−5.8	–	265.44	56.51	1.84	(1),(6),(12),(13)
Pisces II[c]	182	2.9(4.3)	> 0.0086	−5.0	0.7	79.21	−47.11	0.79	(1),(39),(40),(41)
Leo V[c]	186	3.7(3.3)	1.1	−5.2	1.1	261.86	58.54	1.96	(1),(35),(36)
Canes Venatici I[c]	216	1.2(2.2)	19	−8.6	0.6	74.31	79.82	1.84	(1),(6),(11)
Leo II[c]	218	5.0(5.5)	4.6	−9.8	0.9	220.17	67.23	0.35	(1),(31),(32)
Leo I[c]	**246**	**15.8(7.4)**	**12**	**-12**	**2.2**	**225.99**	**49.11**	**0.12**	(1),(28),(29),(30)
Eridanus II	380	< 21.6	*N/A*	−6.6	–	249.78	−51.65	0.10	(22),(23)
Leo T[c]	412	6.1(6.5)	3.9	−8.0	1.0	214.85	43.66	0.19	(1),(33),(34)
Phoenix I	418	4.3(5.7)	9.7	−9.9	0.8	272.16	−68.95	0.36	(1),(66),(67),(68),(69)
NGC 6822	498	1.4(1.6)	3500	−15.2	0.9	25.34	−18.40	2.25	(1),(29),(69),(70),(71),(72)