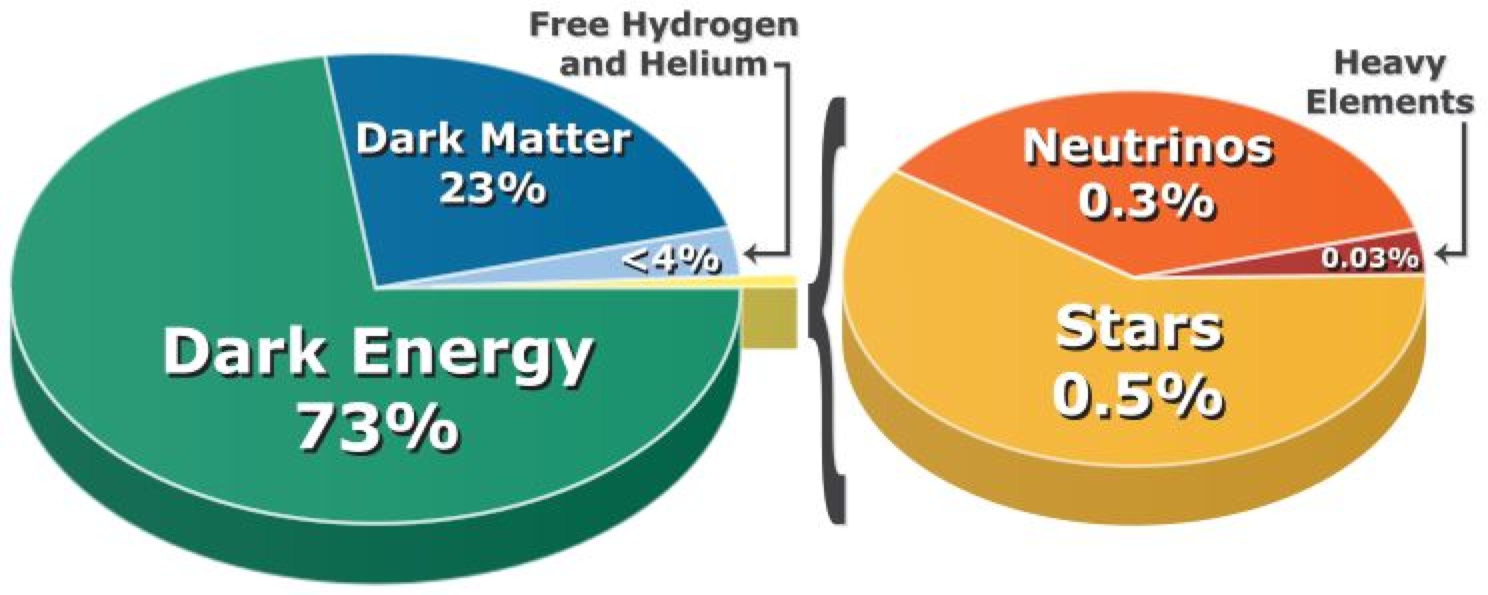
News from the dark and the bright universe

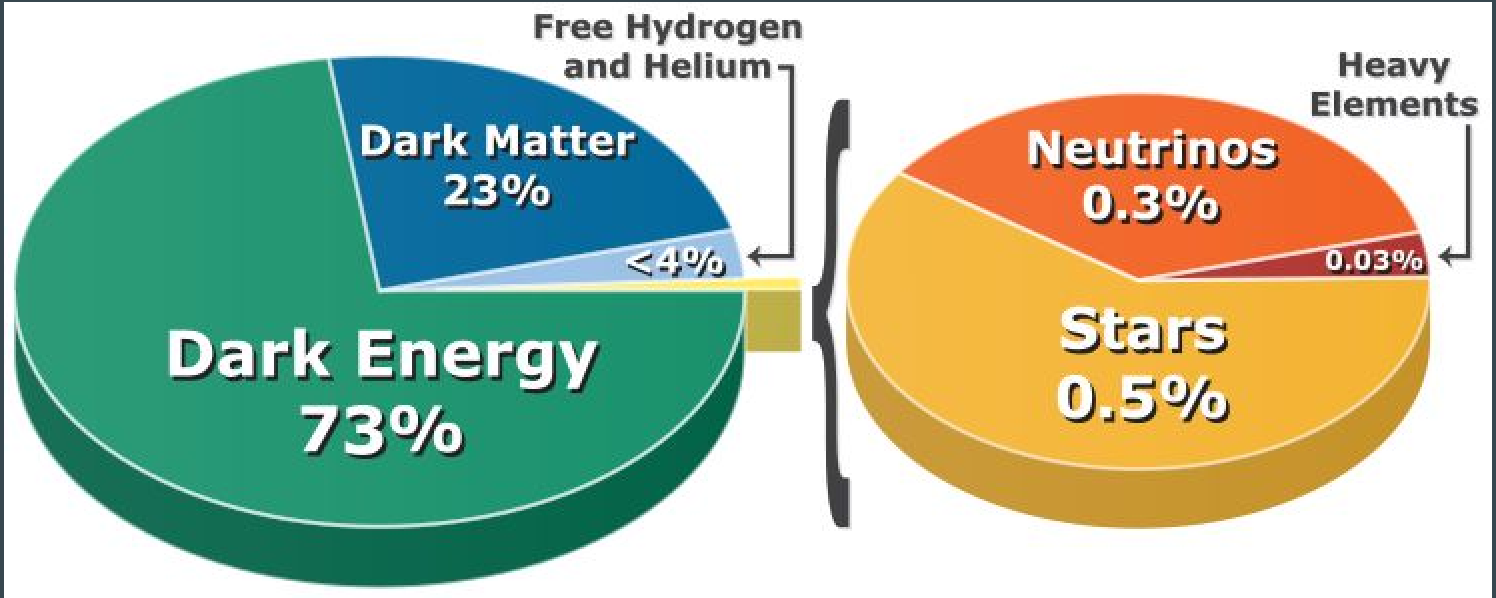
...

Alexander Kusenko
(UCLA and Kavli IPMU)

Universe: the energy composition



Universe: the energy composition



Cosmological uncertainty principle: (quantity) × (understanding) > 1

Different components – different expansion rates

radiation	$p = \frac{1}{3}\rho,\ w = 1/3$	$\rho \propto a^{-4}$	$a \propto t^{1/2}$
matter	$p = 0,\ w = 0$	$\rho \propto a^{-3}$	$a \propto t^{2/3}$
cosm. const.	$p = -\rho = \Lambda,\ w = -1$	$\rho \propto \text{const}$	$a \propto \exp(Ht)$

One can measure the composition of the universe by studying its expansion.

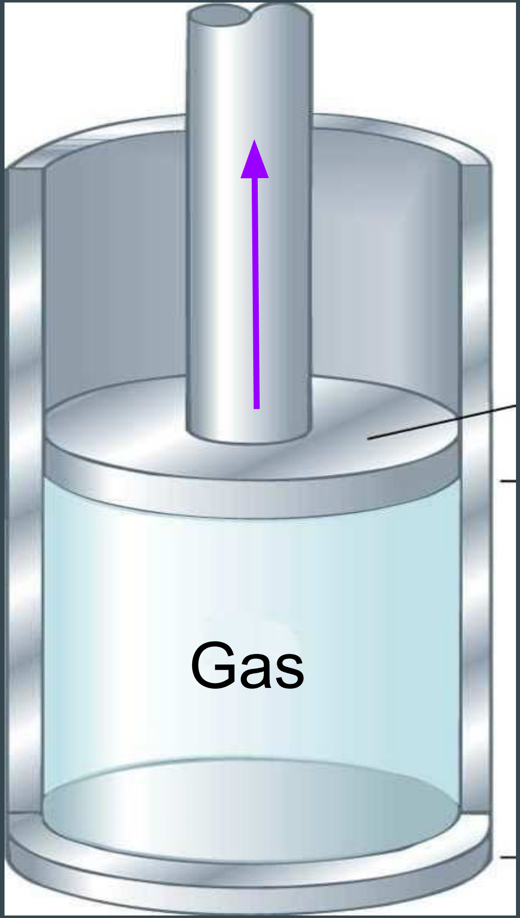
Most of the energy density is in dark energy which has negative pressure

Simple analogy

Expanding gas:

$$\Delta E = -p\Delta V$$

Expansion causes a decrease in E, which is in accord with p>0.

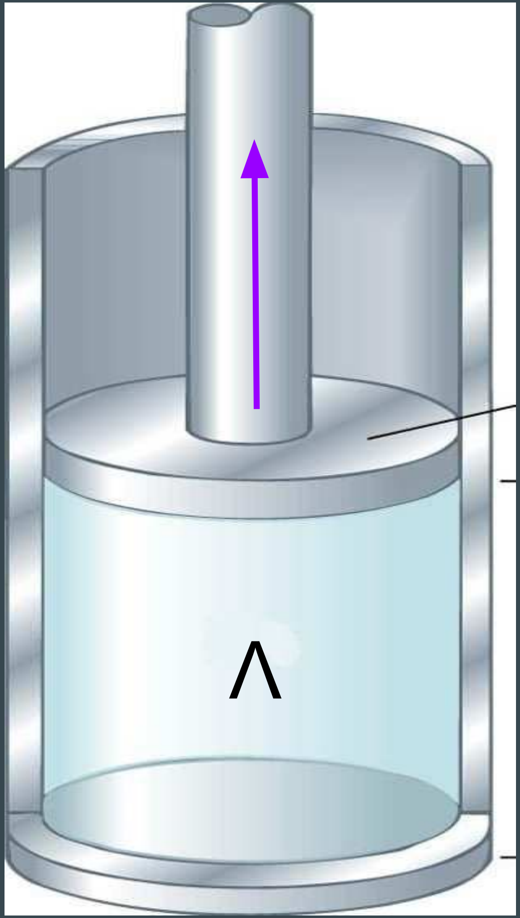


Simple analogy

Expanding gas: $$\Delta E = -p\Delta V$$

Cosmological constant: *$E = \Lambda \times V$* *energy increases!*

Work must be negative, which means $p < 0$



Constant (slowly varying) vacuum energy has negative pressure

Dark energy: is it a constant, or a slowly varying field?

Cosmological constant: introduced by Einstein in a flawed attempt to explain a static universe

Unnatural: "natural value" would be set by the Planck scale $m_{\rm Pl} \sim 10^{19}\ {\rm GeV}$

observed value is much smaller: $\Lambda^{1/4} \sim 10^{-11}\ {\rm GeV}$

Cosmological constant problem - a naturalness problem

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Cosmological constant problem - a naturalness problem

(You call this natural?..)

Dark energy: is it a constant, or a slowly varying field?

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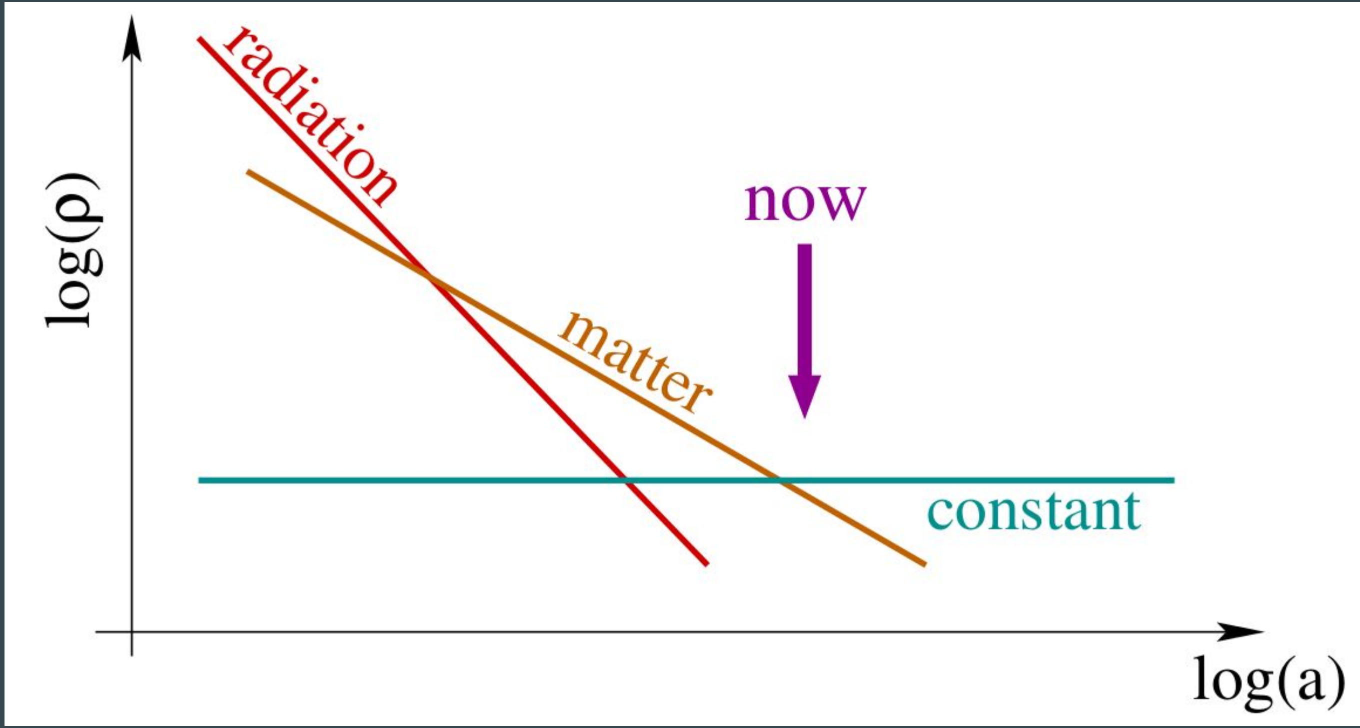
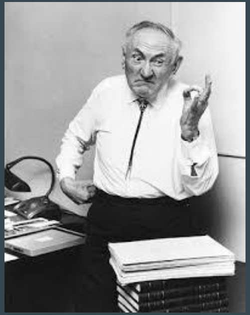
Cosmological constant problem - a naturalness problem

The only explanation that seems to work is anthropic - some people don't like this.

Coincidence problem



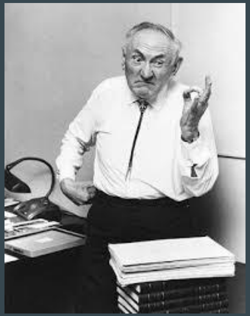
Dark matter



Fritz Zwicky

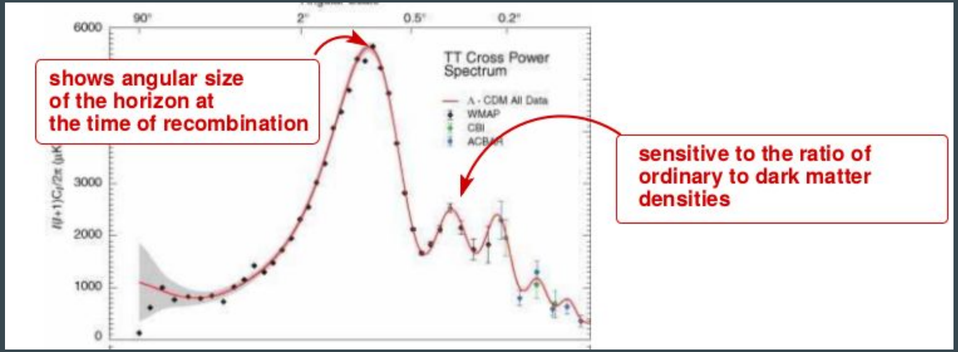
Most of the matter in the universe is not made of ordinary atoms

Dark matter

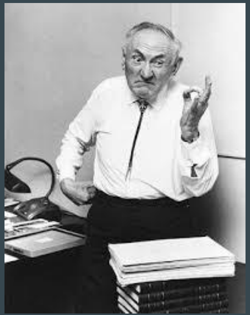


Most of the matter in the universe is not made of ordinary atoms

- Cosmic microwave background radiation

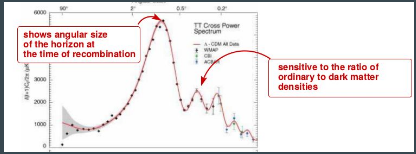


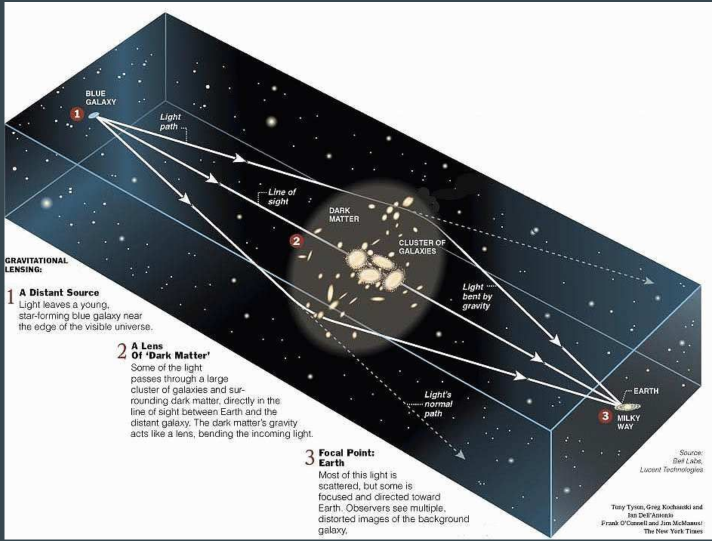
Dark matter

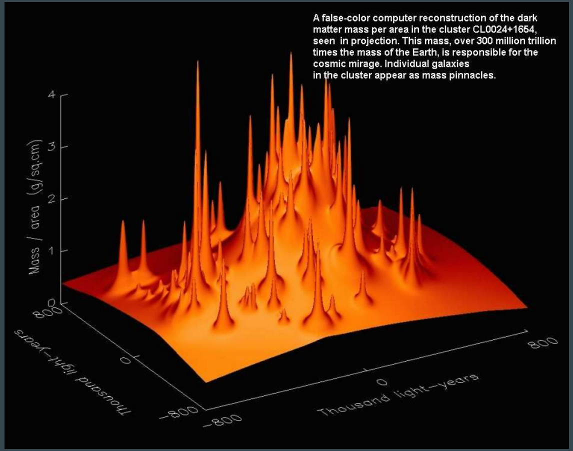


Most of the matter in the universe is not made of ordinary atoms

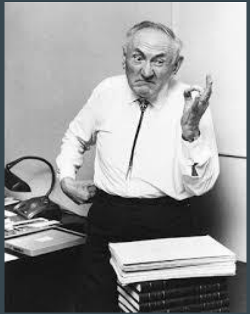
- Cosmic microwave background radiation
- Gravitational lensing





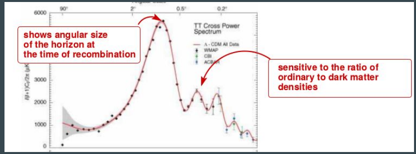


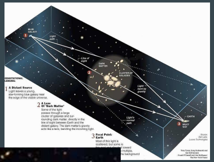
Dark matter

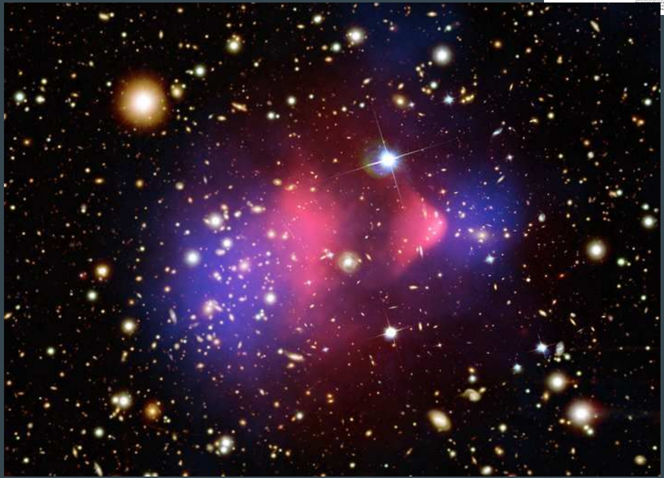


Most of the matter in the universe is not made of ordinary atoms

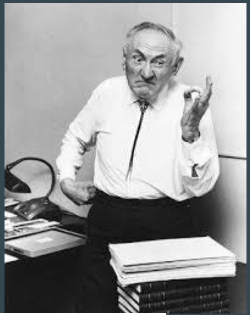
- Cosmic microwave background radiation
- Gravitational lensing
- Merging clusters



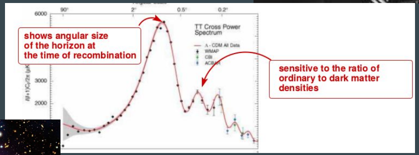




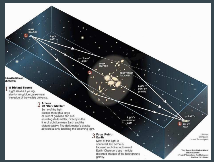
Dark matter



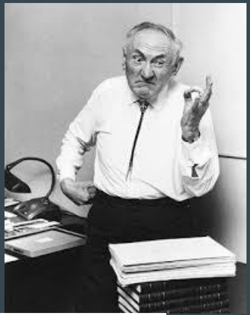
Most of the matter in the universe is not made of ordinary atoms



- Cosmic microwave background radiation
- Gravitational lensing
- Merging clusters
- X-ray emitting gas

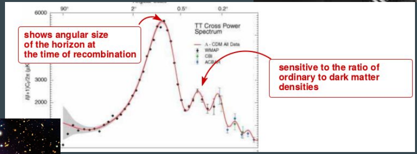


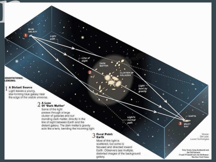
Dark matter

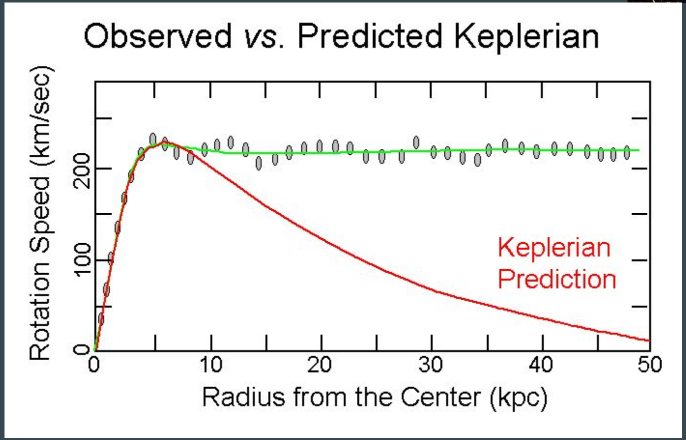


Most of the matter in the universe is not made of ordinary atoms

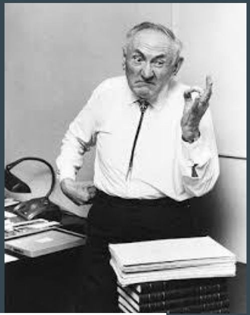
- Cosmic microwave background radiation
- Gravitational lensing
- Merging clusters
- X-ray emitting gas
- Rotation curves







Dark matter



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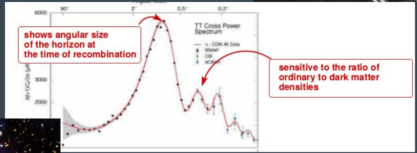
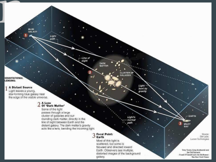
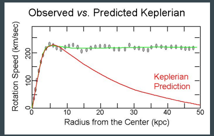
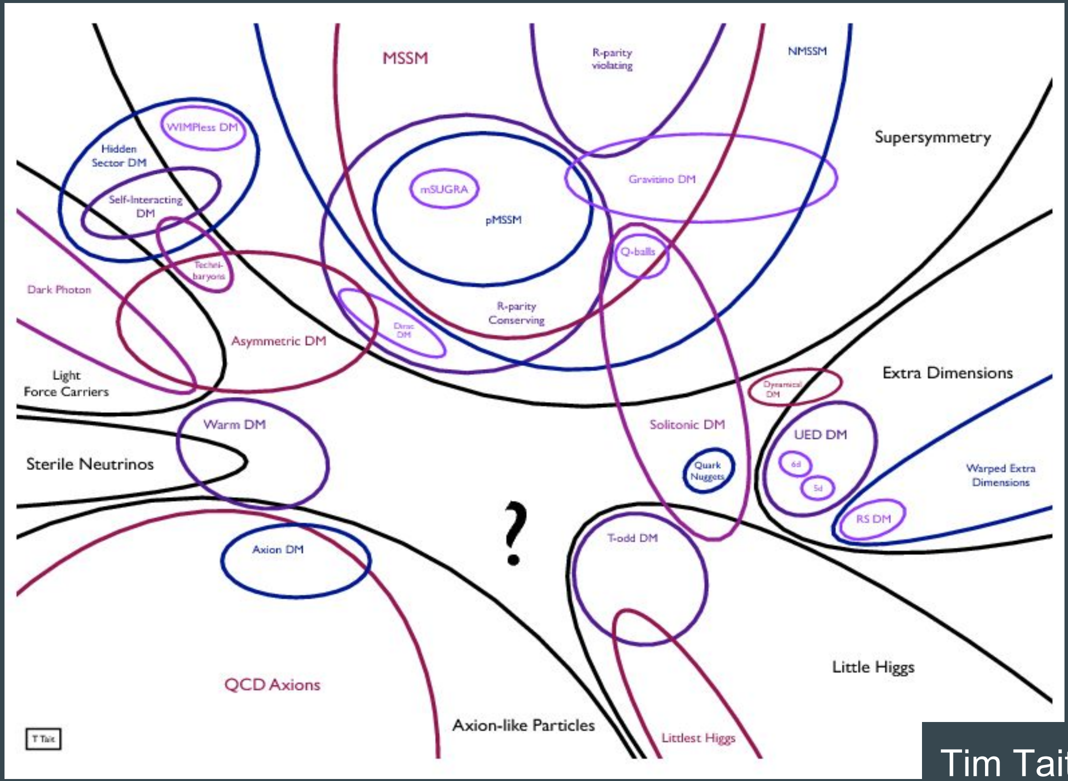






All observations point to the fact that dark matter outweighs normal matter by more than factor 5!

Dark matter: the landscape of possibilities



Tim Tait

WIMPs are popular:

- well motivated
- many detection techniques

non-WIMPs:

- equally well motivated, but
- often harder to search experimentally

“non-WIMP dark matter” is like a “non-dog animal”

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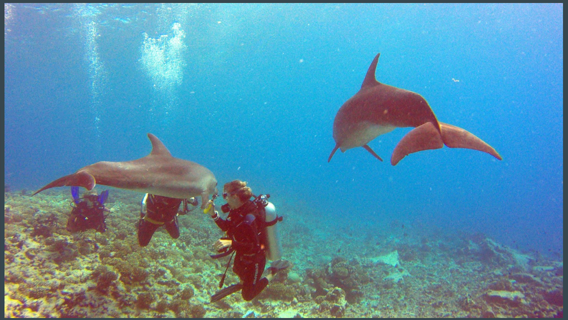
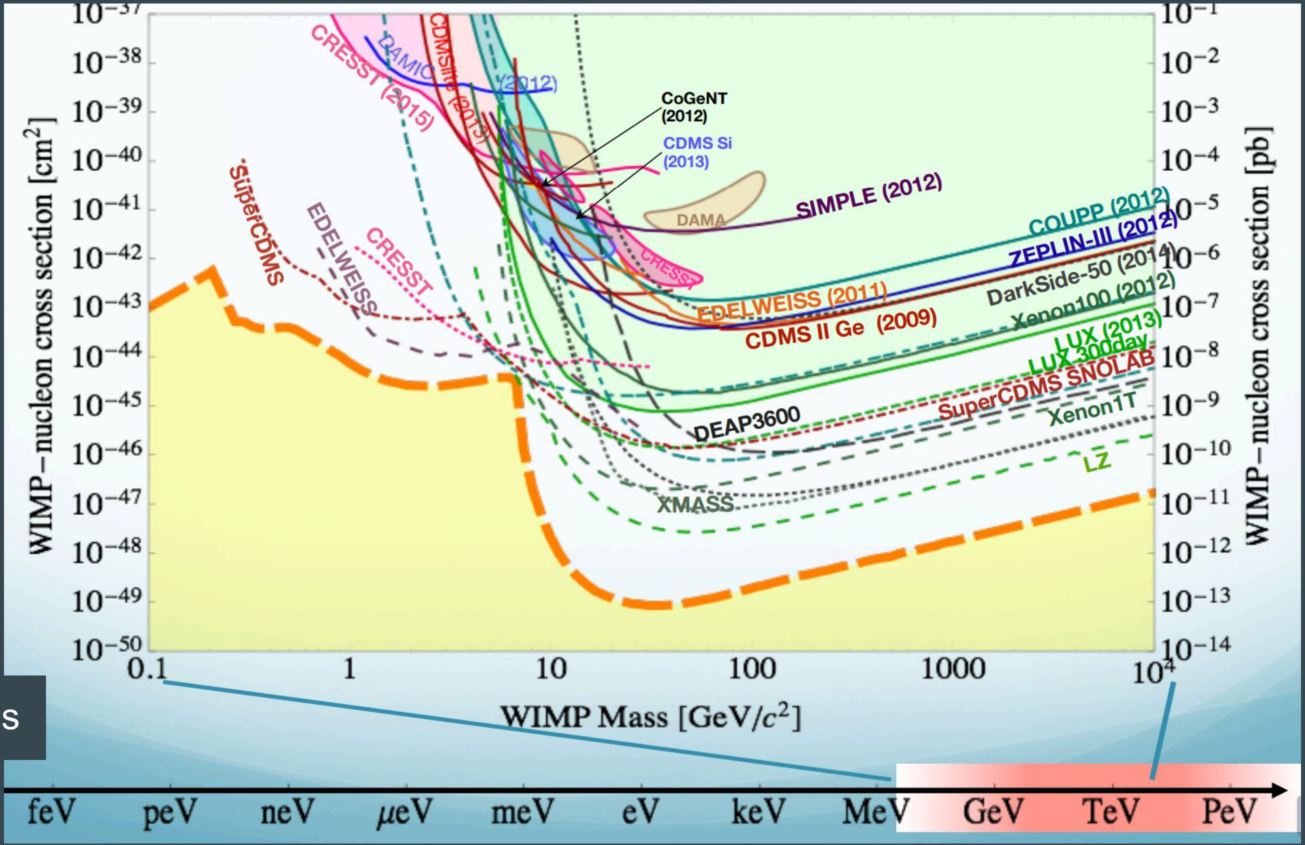


One must search for many dark matter candidates

One looks for candidates that are well-motivated and compelling from the point of view of theory, which may show some observational hints, and for which an experiment is feasible

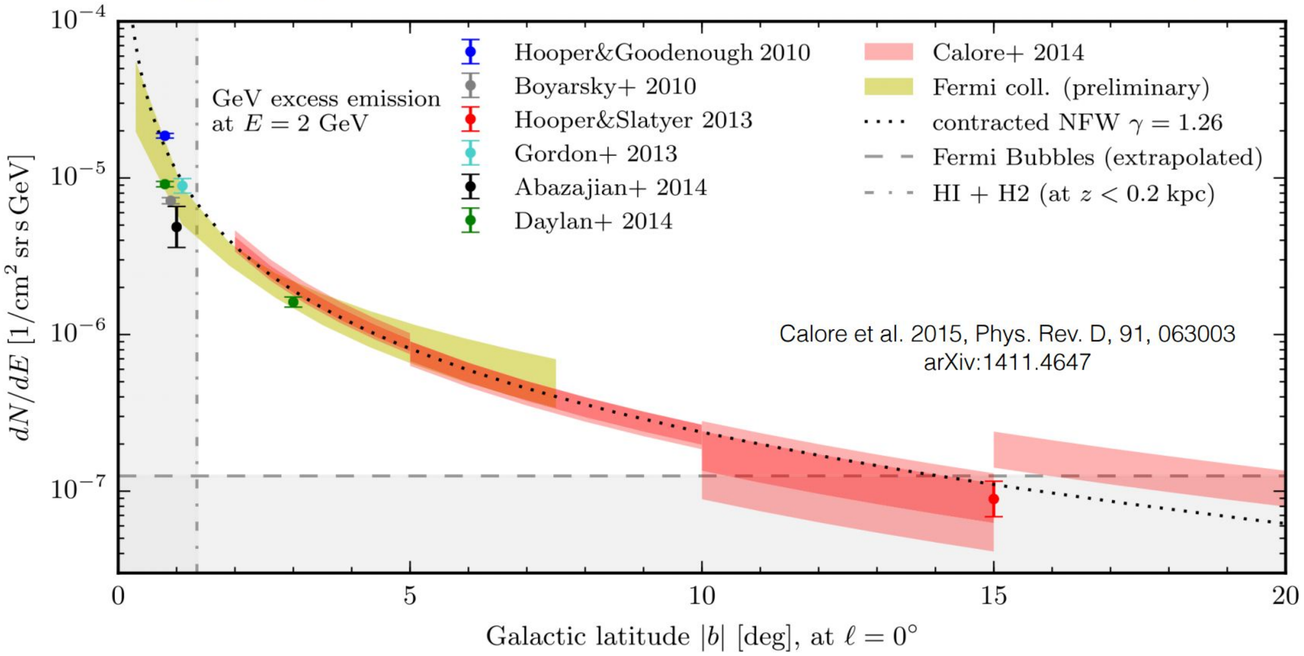
Direct detection of WIMPs: present and future



Serfass

Indirect detection of WIMPs: the Galactic Center excess

Many groups have reported a spatially extended excess of gamma-ray emission in the inner Galaxy peaking at ~2 GeV in E^2 dN/dE and consistent with a contracted NFW profile



Spectrum, spatial profile, and inferred annihilation cross section are consistent with WIMP hypothesis within uncertainties — *can an astrophysical interpretation be excluded?*

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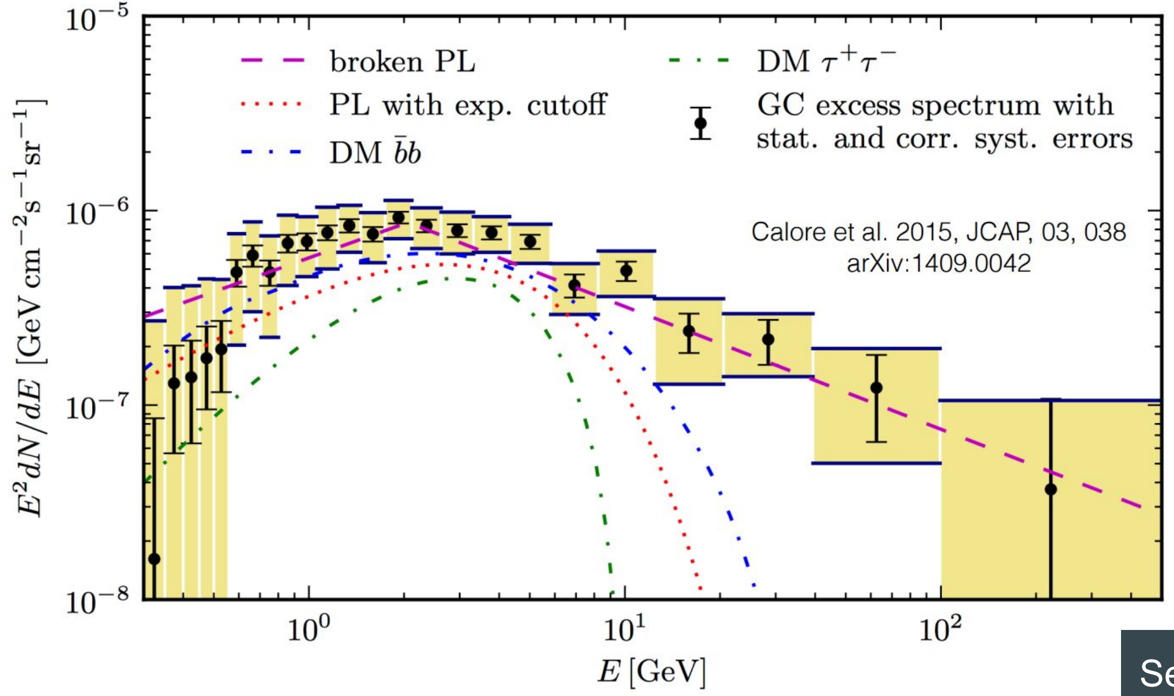
Indirect detection of WIMPs: the Galactic Center excess

Example: Ensemble of 60 interstellar emission models from GALPROP varying CR source distribution, gas tracers, interstellar radiation field, magnetic field, etc.



WIMP annihilation?

Astrophysical origin?

millisecond pulsars?

unresolved point sources seem to be favored by statistics [Lee, Lisanti, Safdi, 1412.6099]

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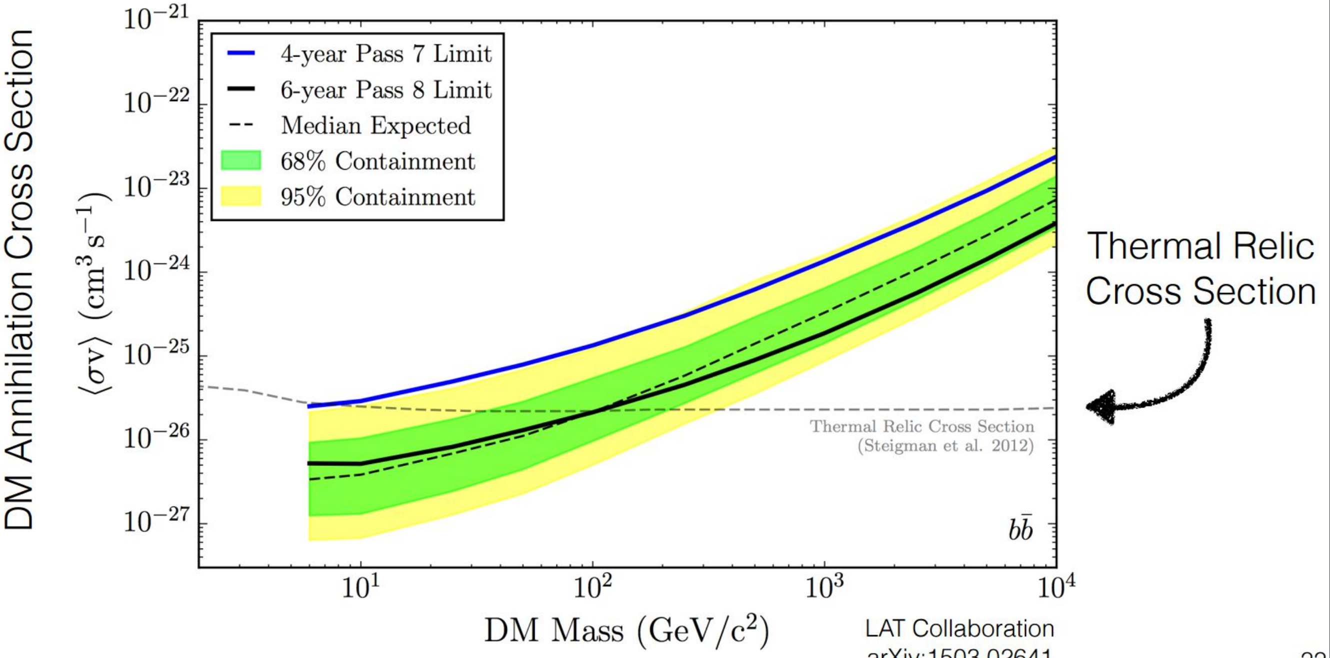
Indirect detection of WIMPs: dSphs limits

15 dSphs, 6 yrs of *Fermi*-LAT data, Pass 8, 500 MeV to 500 GeV

Only 20 to 30% overlap of events with 4-year Pass 7 analysis (~statistically independent)



LAT Collaboration
arXiv:1503.02641

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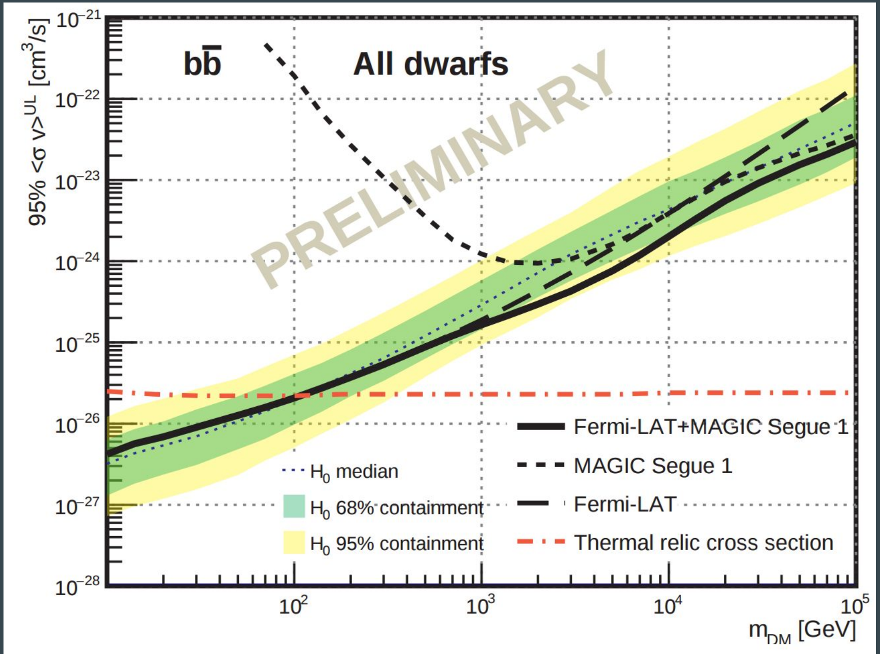
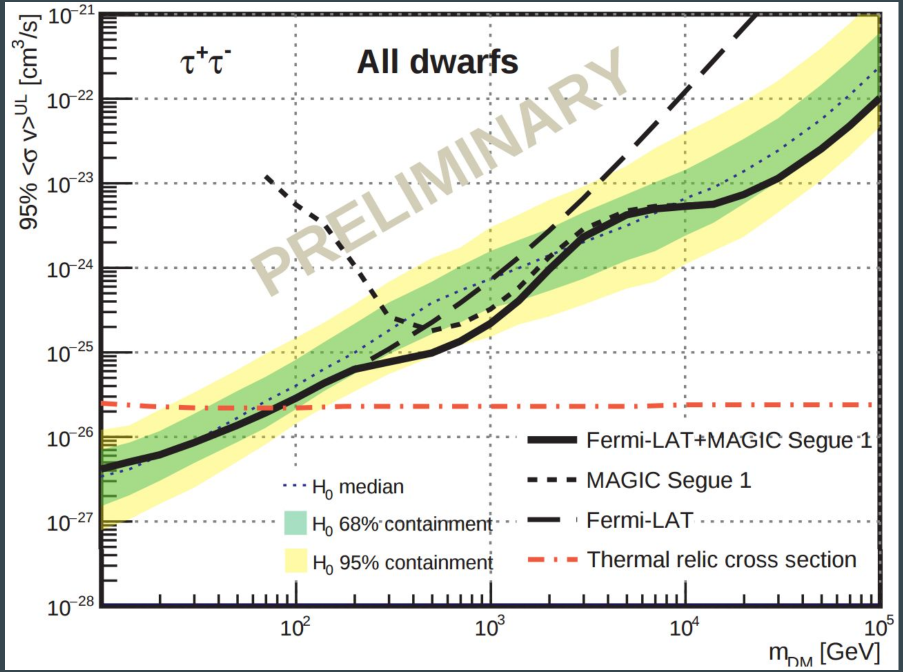
Indirect detection of WIMPs: dSphs limits

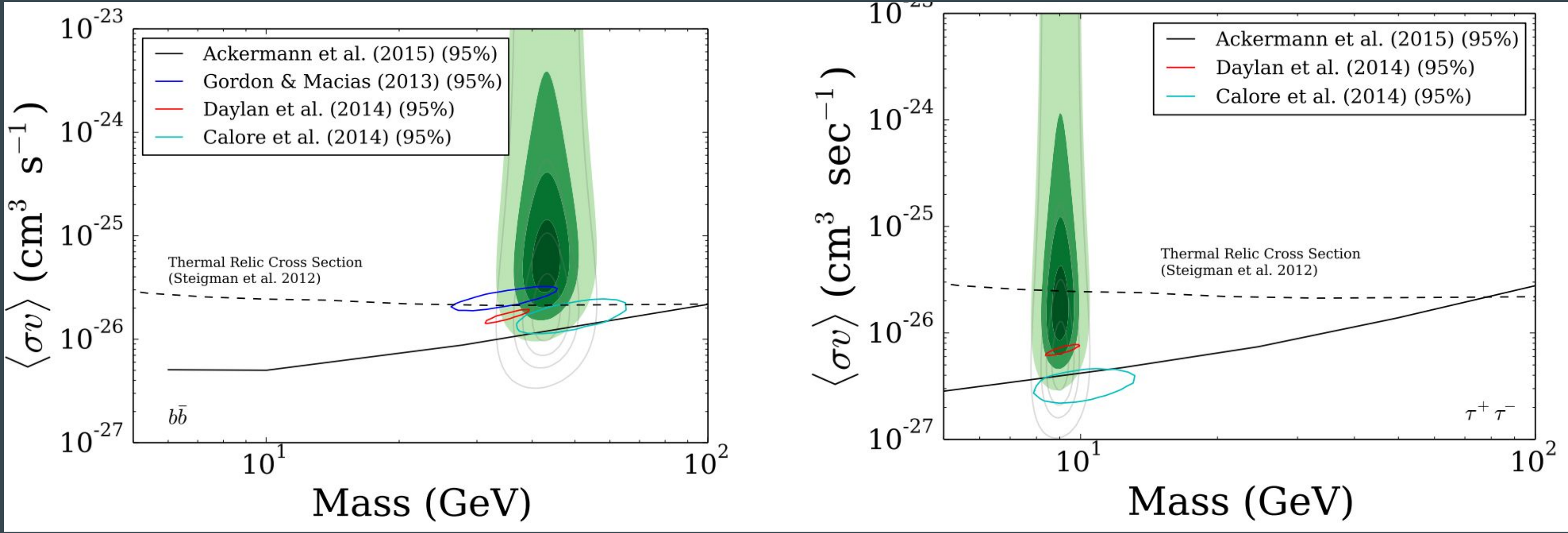




158 hours of observations of Segue 1 by MAGIC with 6-years observations of 15 dwarf satellite galaxies by the Fermi-LAT, Fermi and MAGIC, arXiv:1508.05827

Ibarra

Indirect detection of WIMPs: dSphs limits, tension w/GC



b-quark channel (left), τ channel (right) [Abazajian, Keeley, 1510.06424]

Sterile neutrinos as dark matter

A well-motivated dark matter candidate

- neutrino masses are most easily explained if right-handed neutrinos exist. If one of them has mass in the keV mass range, it can be dark matter
- models exist, in which the abundance is “natural” (a non-WIMP miracle)
- depending on the production mechanism, can be warm or (practically) cold dark matter
- can explain the observed pulsar velocities
- can be discovered by a radiative decay line using X-ray telescopes:

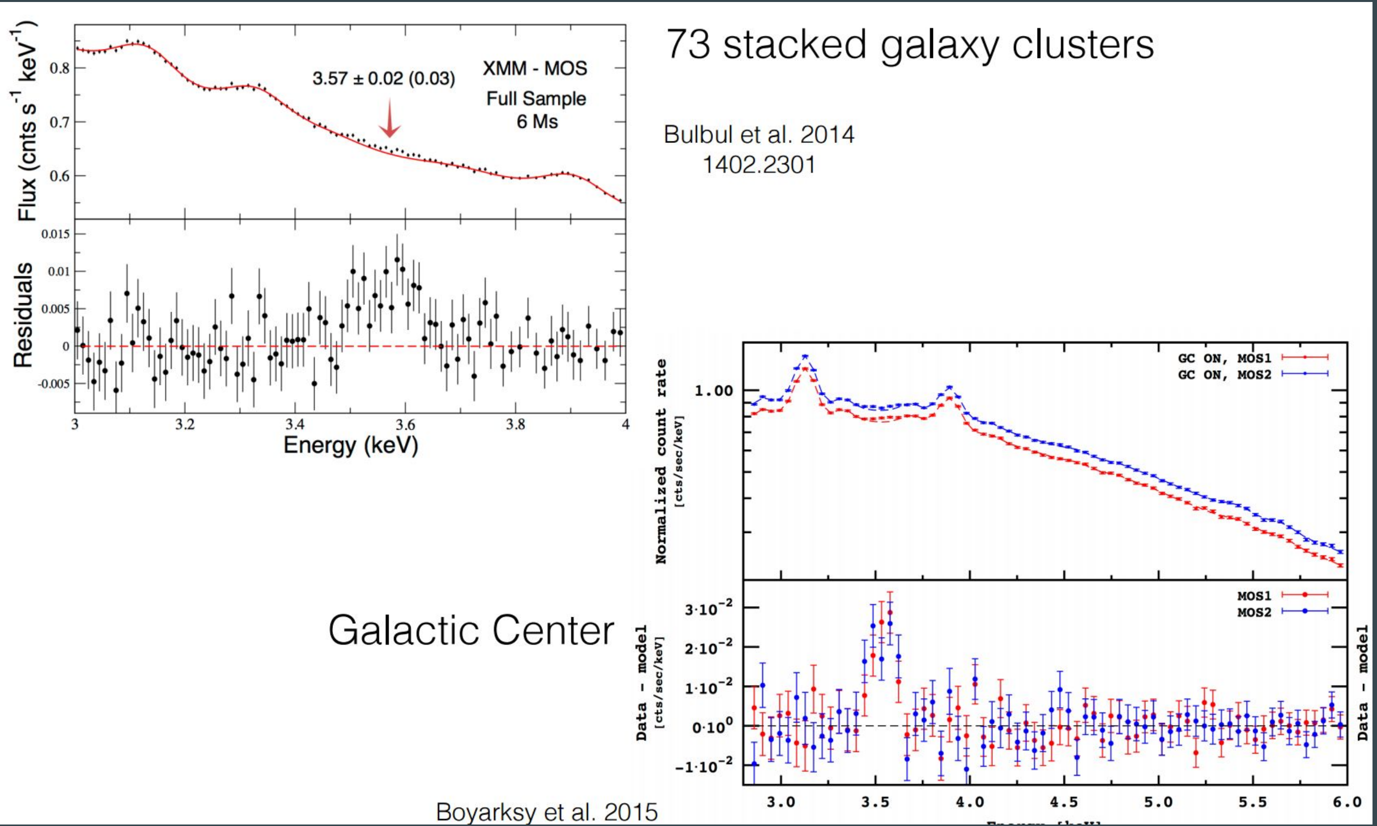
$$\nu_s \to \nu_{e,\mu,\tau}\gamma, \quad E_\gamma = \frac{m_s}{2} \Rightarrow \text{narrow spectral line}$$

For review, see, e.g., *A.K., Sterile neutrinos: the dark side of the light fermions, Phys. Rept. 481 (2009) 1*

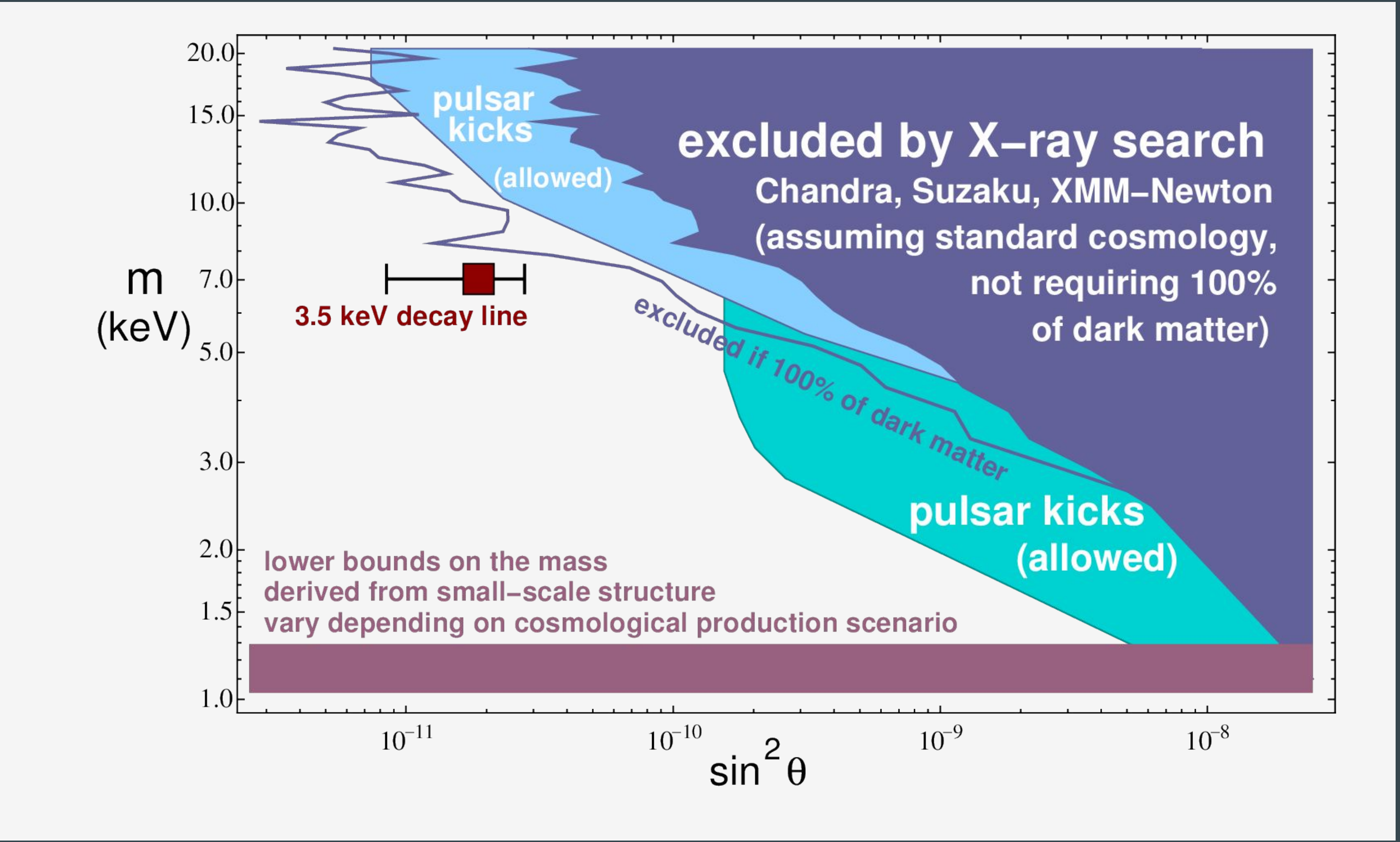
Same signature -- from supersymmetry/strings moduli dark matter

[Murayama et al.; Loewenstein, AK, Yanagida]

Unidentified 3.5 keV line: is it dark matter?



Interpretation as a dark-matter sterile neutrino



3.5 keV line: detected or not?

Target	Instrument	Significance (σ)	Reference
M31	XMM-Newton/MOS	3.2	Boyarsky 2014 1402.4119
Perseus Cluster (outskirts)	XMM-Newton/MOS XMM-Newton/PN	2.6 2.4	Boyarsky 2014 1402.4119
Perseus Cluster (center)	Chandra/ACIS	3.5	Bulbul 2014 1402.2301
Perseus Cluster (center)	Suzaku	3	J. Franse (TAUP 2015)
Galactic Center	XMM-Newton/MOS	5.7	Boyarksy 2014 1408.2503
73 Stacked Clusters (z<0.4)	XMM-Newton/MOS XMM-Newton/PN	5 4	Bulbul 2014 1402.2301
8 Stacked dSphs	XMM-Newton/MOS XMM-Newton/MOS	Non-detection	Malyshev et al. 2015 1408.3531
M31	Chandra/ACIS	Non-detection	Horiuchi et al. 2014 1311.0282
Blank Sky	XMM-Newton/MOS	Non-detection	Boyarsky 2014 1402.4119

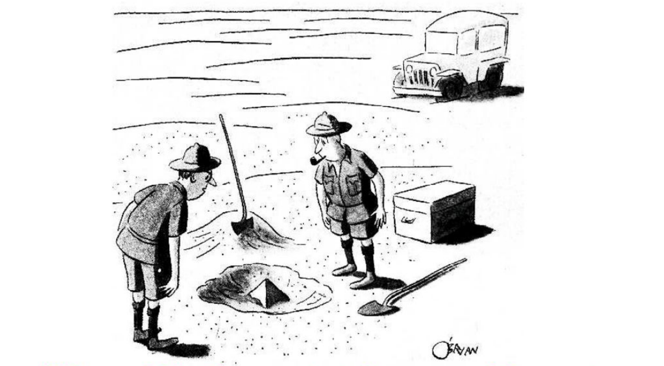
Not a consensus, see, e.g., Jeltema & Profumo 2015, MNRAS, 450, 2143 (arXiv:1408.1699)

Conflicting claims

dark matter?

instrumental effects?

gas lines?



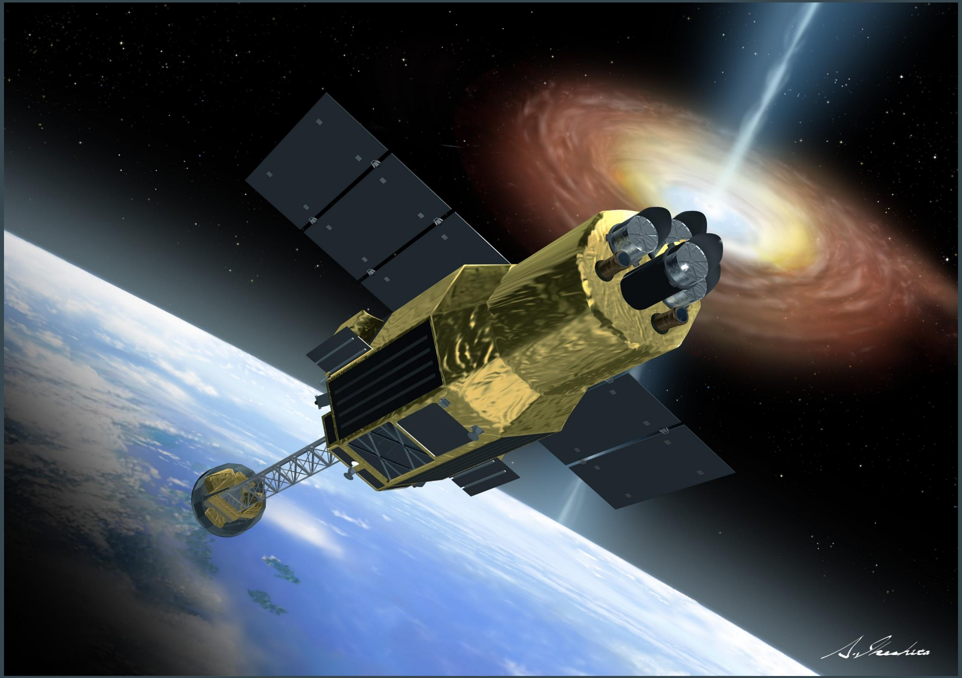
This could be the greatest discovery of the century. Depending, of course, on how far down it goes.

Serfass

Astro-H: sterile neutrinos and/or keV moduli search

Astro H will have a fantastic energy resolution -- a boon to a search for a line from decay of sterile neutrinos and/or string/supersymmetry moduli

The line profile can distinguish Doppler broadening from gaseous lines

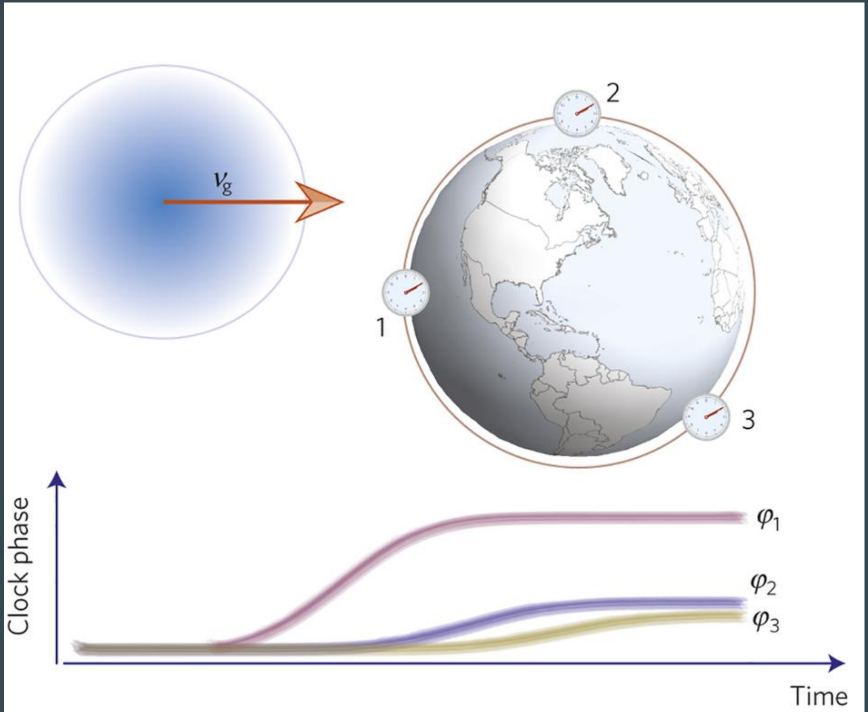


An intriguing possibility: dark matter lumps

Dark matter can be made up of extended objects (topological defects, nontopological solitons, etc.)

Large lumps can be detected by their effects of clocks

A. Derevianko & M. Pospelov, Nature Physics 10, 933–936 (2014)



Neutrino physics

Photo © Takaaki Kajita

Takaaki Kajita

Prize share: 1/2

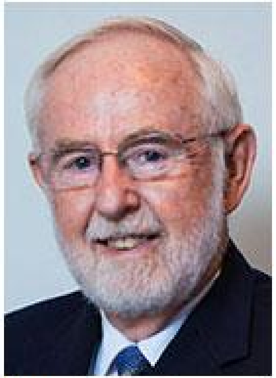


Photo: K. MacFarlane. Queen's University /SNOLAB

Arthur B. McDonald

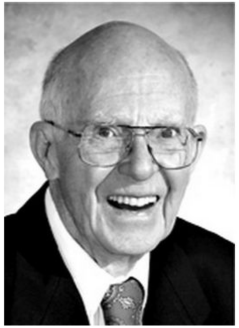
Prize share: 1/2

The Nobel Prize in Physics 2015

- Takaaki Kajita
- Arthur B. McDonald

"for the discovery of neutrino oscillations"

The 2002 Nobel Prize



Raymond Davis Jr.
Prize share: 1/4

Masatoshi Koshiba
Prize share: 1/4

Riccardo Giacconi
Prize share: 1/2

The Nobel Prize in Physics 2002 was divided, one half jointly to Raymond Davis Jr. and Masatoshi Koshiba *"for pioneering contributions to astrophysics, in particular for the detection of cosmic neutrinos"* and the other half to Riccardo Giacconi *"for pioneering contributions to astrophysics, which have led to the discovery of cosmic X-ray sources"*.

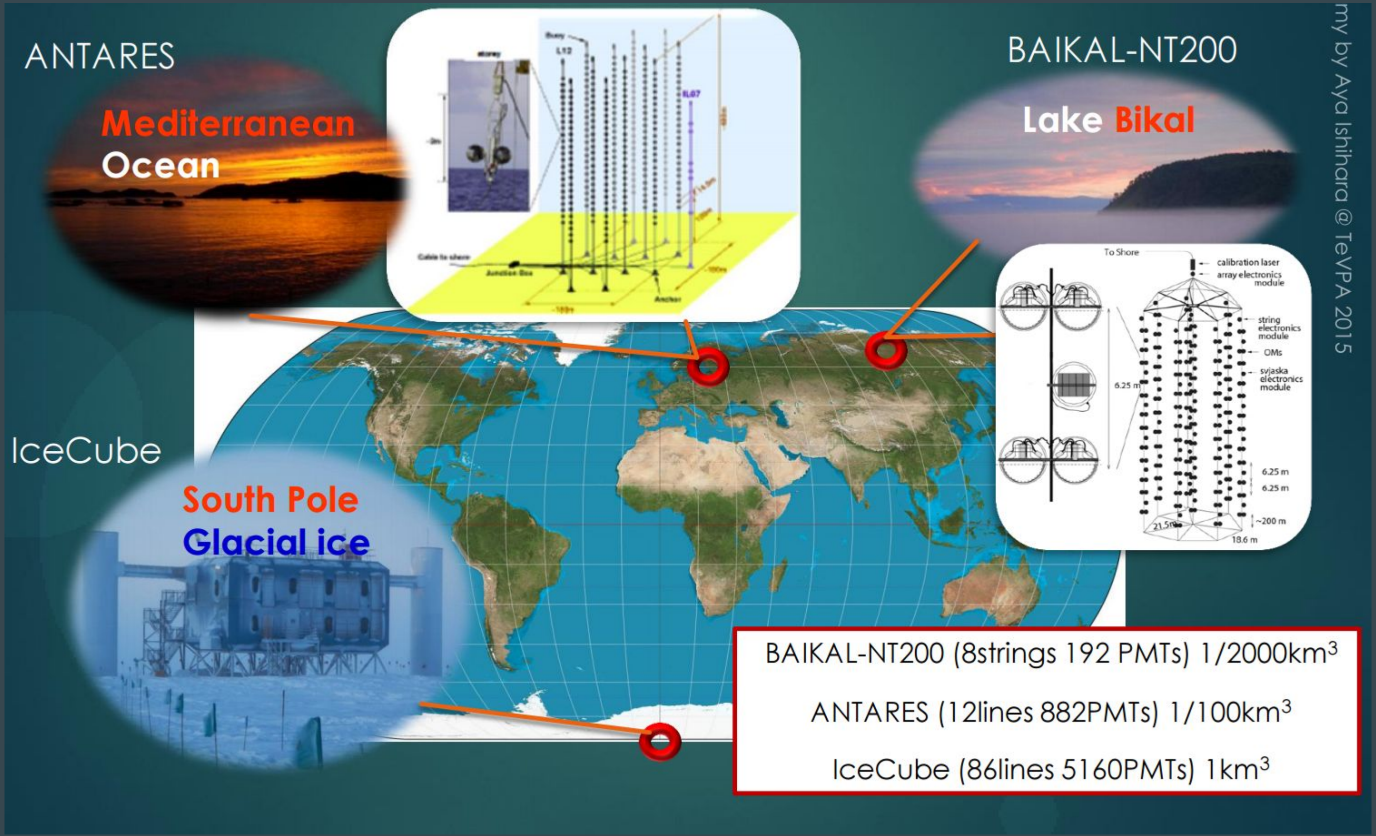
Two New Windows on the Universe

The Earth lies in the path of a continuous flux of cosmic particles and other types of radiation. This year's Nobel Laureates in Physics have used these very smallest components of the universe to increase our understanding of the very largest: the Sun, stars, galaxies and supernovae. The new knowledge has changed the way we look upon the universe.

(Press release, 2002)

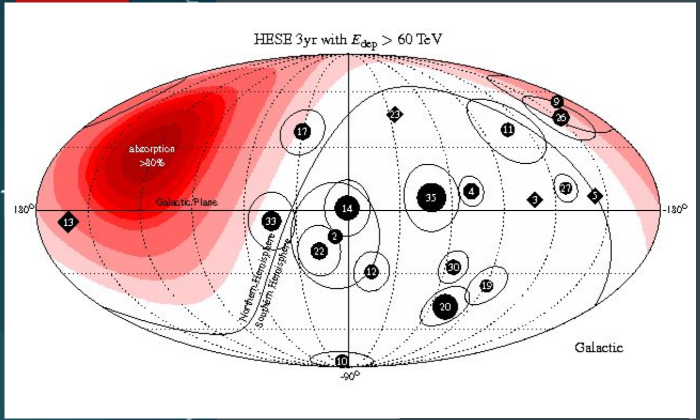
KUNGL.
VETENSKAPSAKADEMIEN
THE ROYAL SWEDISH ACADEMY OF SCIENCES

The golden age of neutrino astronomy

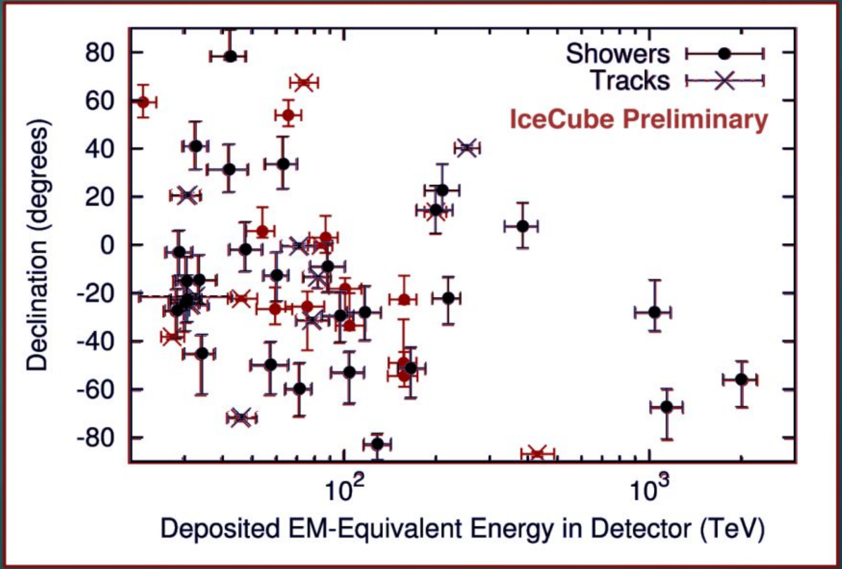


Starting event channel

- Use outer layer of IceCube detector as muon veto
  - Updated from previous publication (3 year sample, PRL 1[…] 101101) with additional one year of data
- Glowing significance: 4.1σ(2y) →5.7σ(3y) →6.5σ(4y)
- Increasing number of events: 28(2y) →36+1(3y) →53+1(4y)
- No new over PeV event



Ahlers et al.

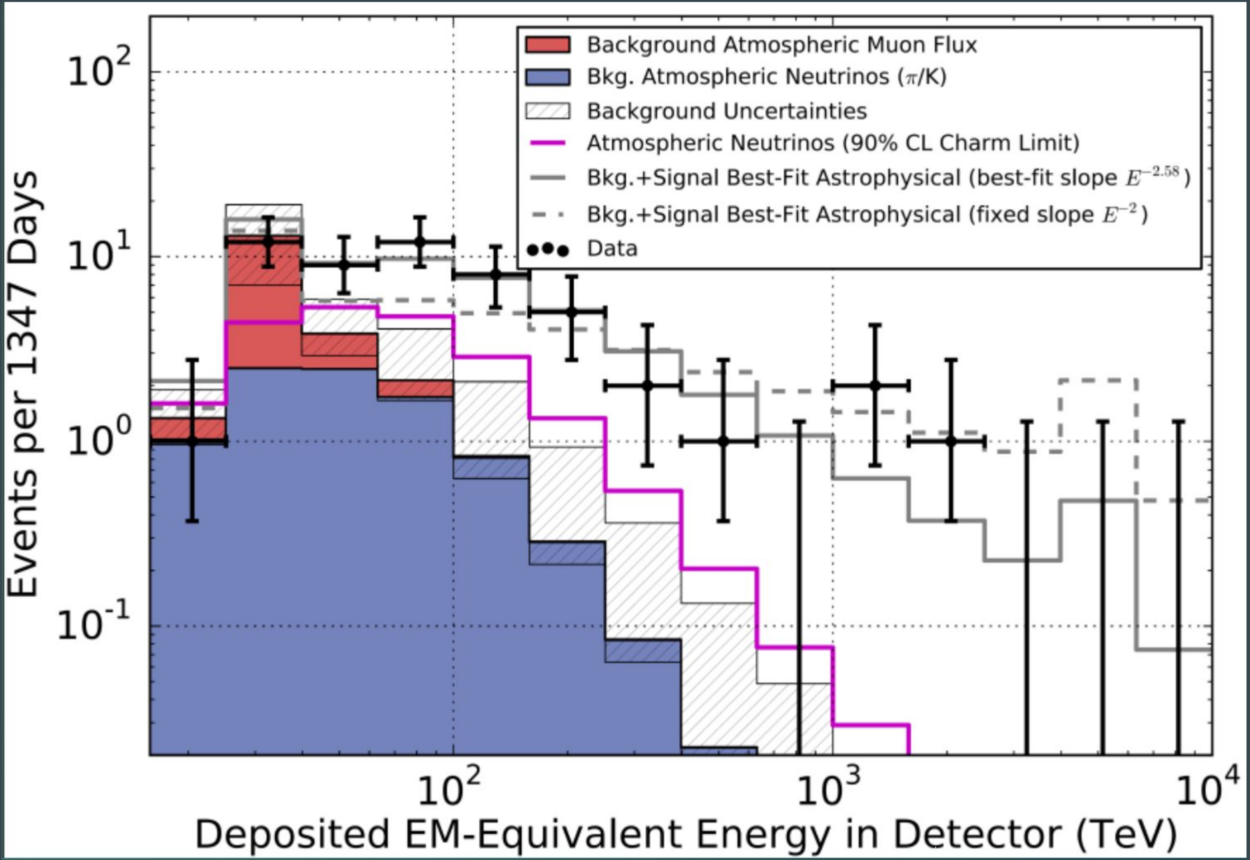


Ishihara

High significance; small backgrounds: atmospheric neutrino backgrounds would appear primarily in the northern sky (top), also at low energies and predominantly as tracks.

The attenuation of high-energy neutrinos in the Earth is visible in the top right of the figure

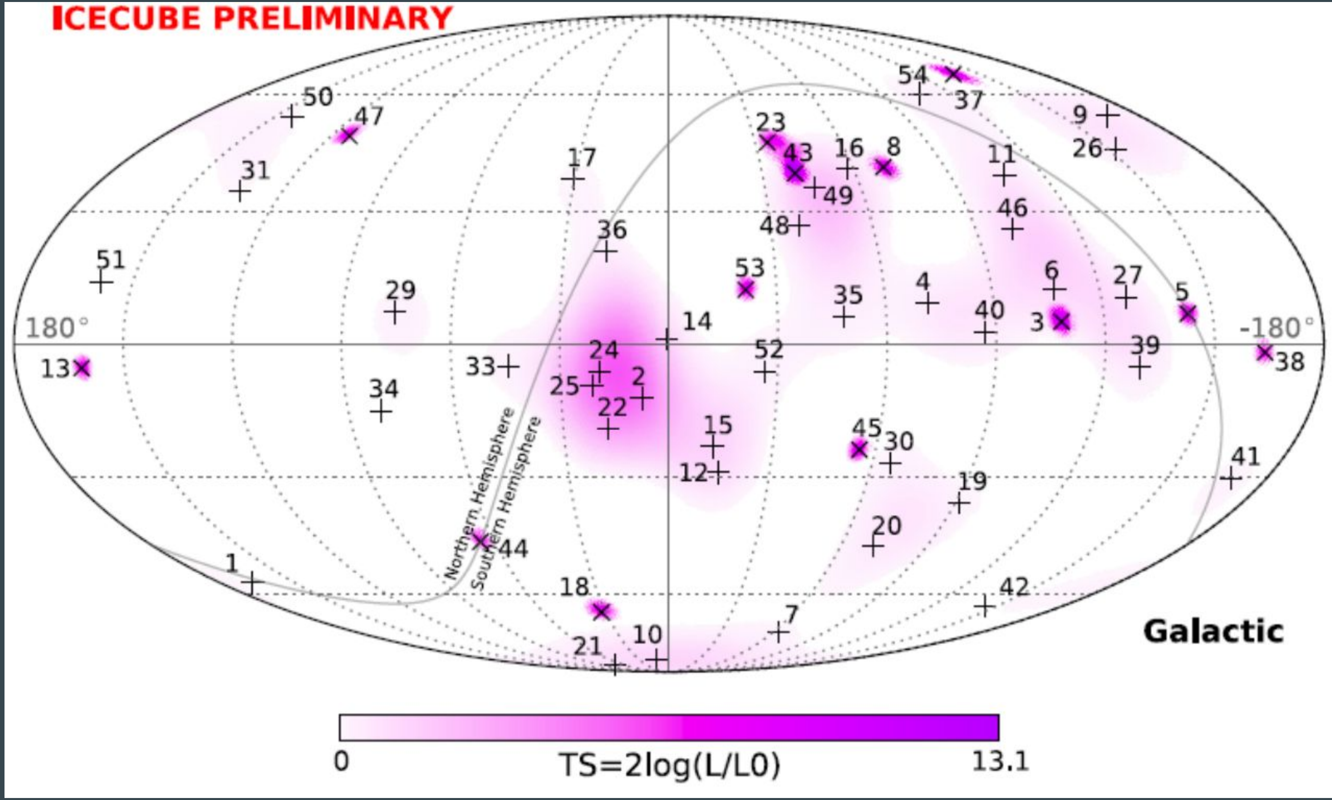
IceCube neutrinos: the spectrum



Power law with a cutoff?

Two components?

IceCube neutrinos: the arrival directions



Anisotropy is key to identifying the sources, and also the production mechanism (in some cases).

Consistent with isotropy.

Small anisotropy possible

Two components?

IceCube neutrinos: the origin?

IceCube neutrinos: the origin?

Astrophysical origin?
Dark matter decays?
pγ interactions? pp interactions?
Galactic or extragalactic?
Blazars (at the sight)?
Blazars (CRs along the line of sight)?
Hypernovae?
Hidden neutrino sources (opaque to γ rays)?
Galactic cosmic rays?
Fermi Bubble?
...

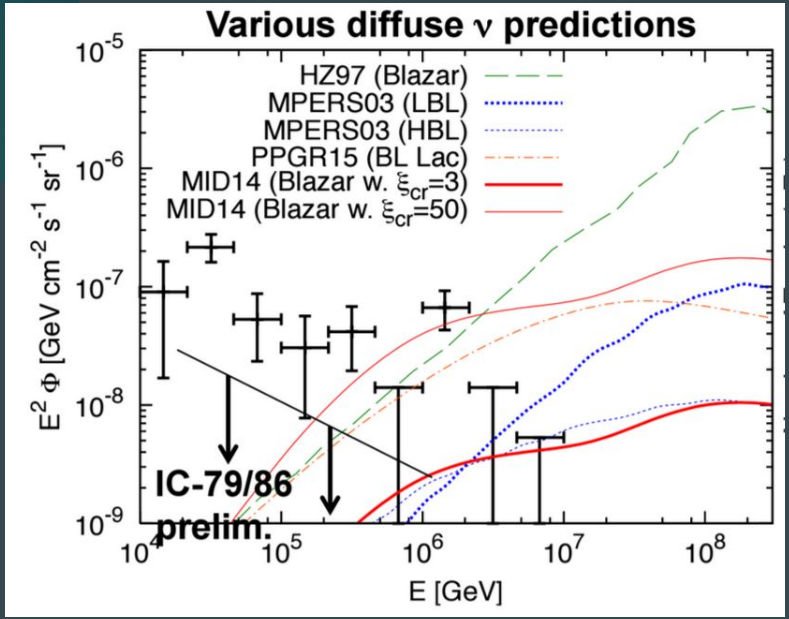
IceCube neutrinos: AGN?

FERMI blazar stacking results

	p-values $w_{source} \propto F_\gamma$	p-values $w_{source} = 1$	No. of sources
All 2LAC Blazars	36 %	6 %	862
FSRQs	34 %	34 %	310
LSPs	36 %	28 %	308
ISP/HSPs	>50 %	11 %	301
LSP-BLLACs	13 %	7 %	62

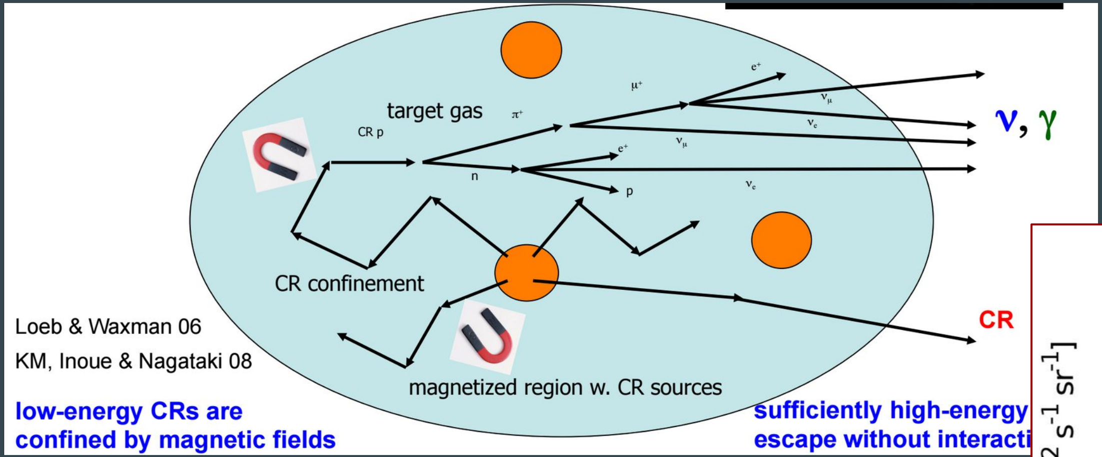
Ishihara

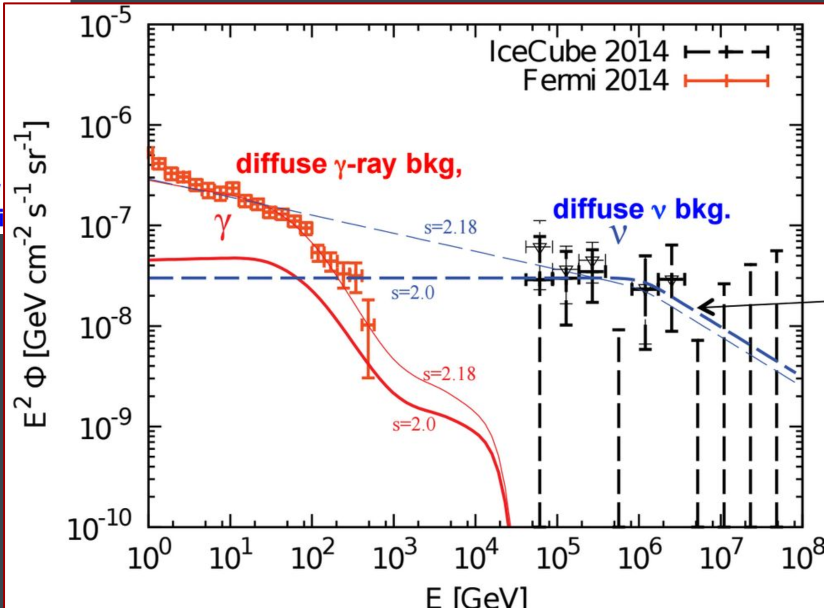
Blazar models (simplest) tend to produce very hard spectra.



Murase

Cosmic ray reservoirs: starburst galaxies, clusters



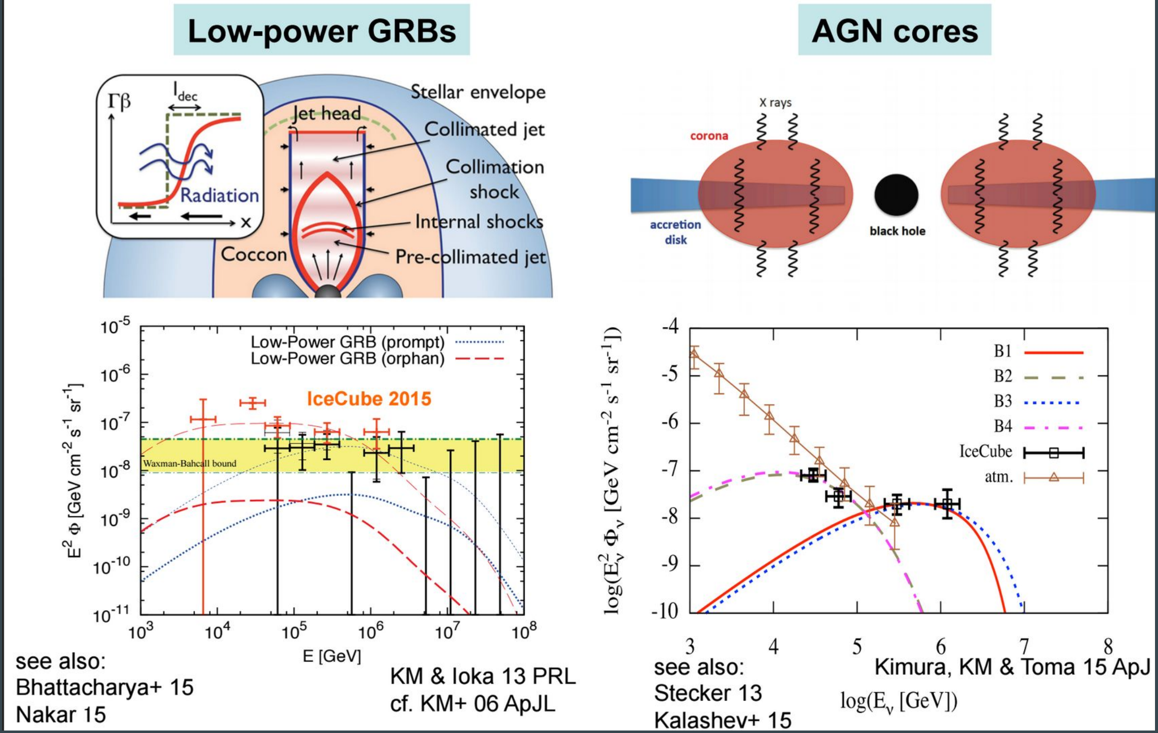


The spectral break can arise from diffusive escape. Large contribution to diffuse extragalactic γ-ray background.

Murase

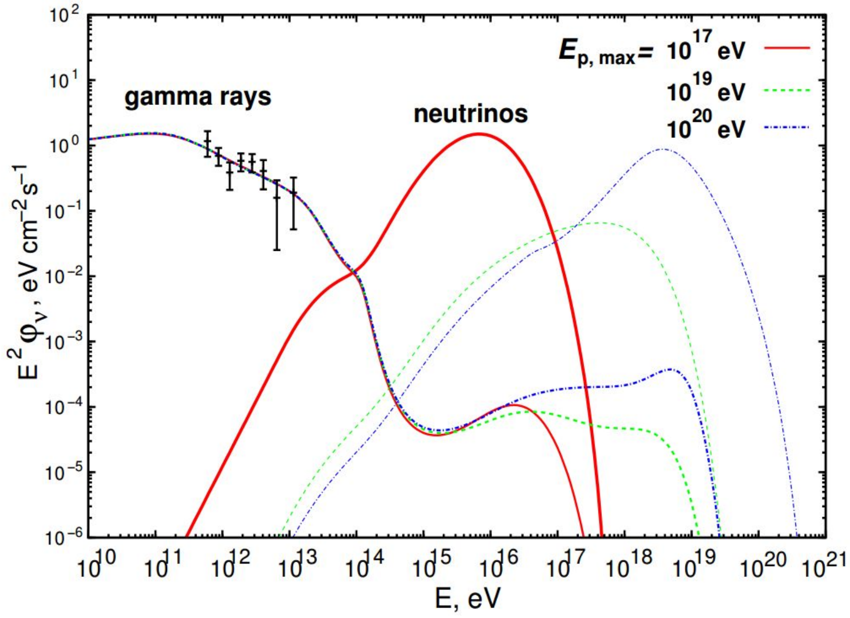
IceCube neutrinos: the origin

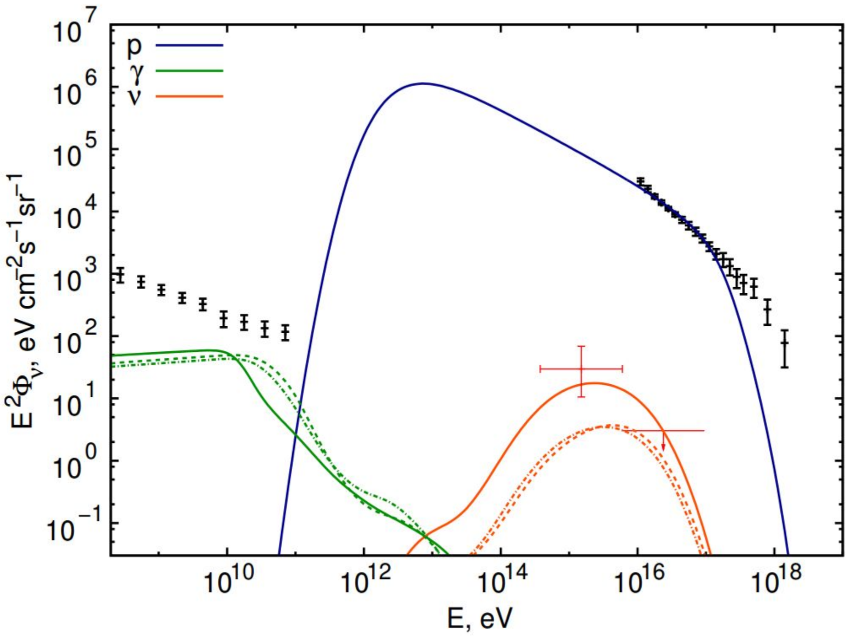
Possible hidden neutrino factories can evade the constraints form γ rays and cosmic rays



Murase

Line-of-sight interactions of CRs from blazars





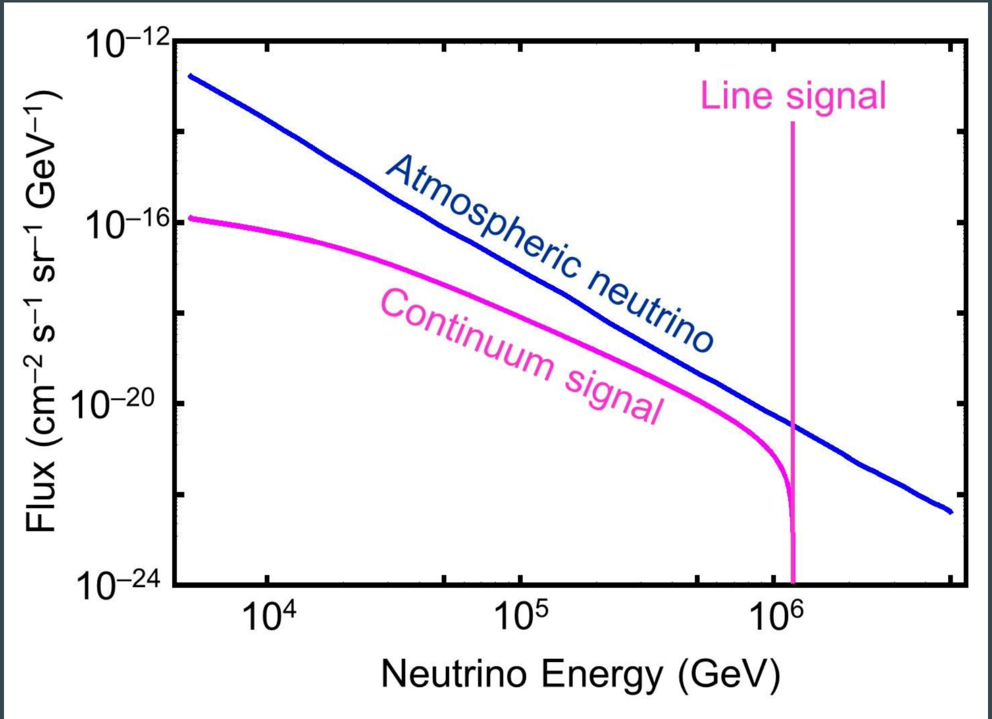
Essey et al. Phys.Rev.Lett. 104 (2010) 141102; Kalashev et al., Phys.Rev.Lett. 111 (2013) 4, 041103

Decaying dark matter

Superheavy dark matter, including particles with PeV mass can be produced in the early universe. It can decay on cosmologically long time scales.

Some DM candidates can decay predominantly into neutrinos (gravitino with R-parity violation, hidden sector gauge boson, singlet fermion in extra dimensions, right-handed neutrino).

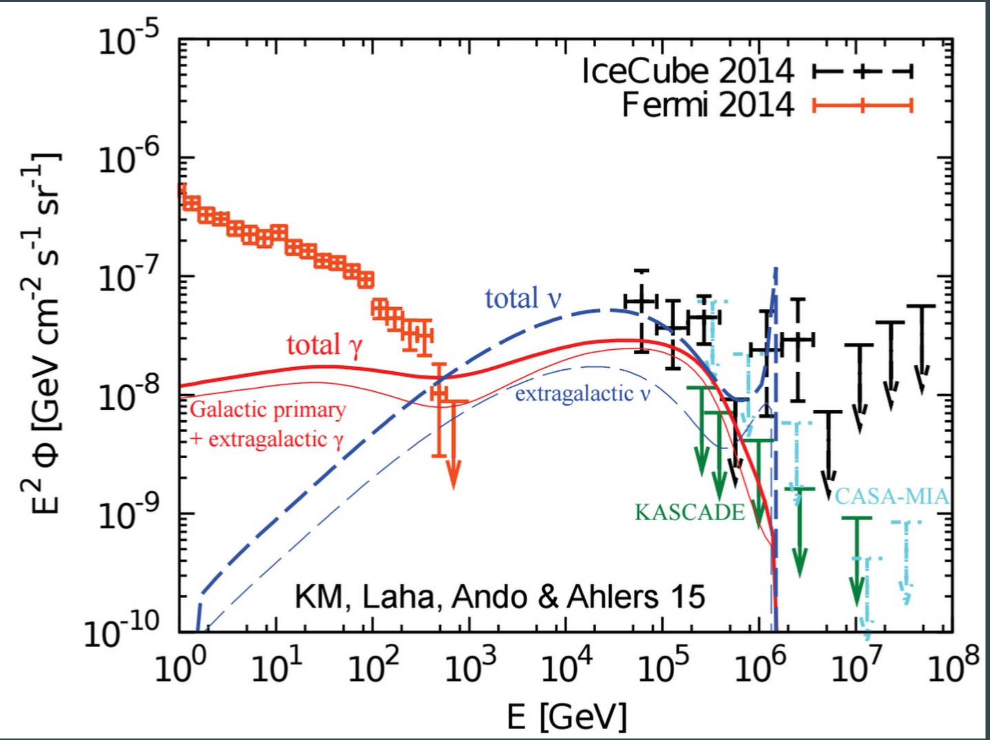
Can produce a spectral feature at a PeV



Feldstein et al. Phys.Rev. D88 (2013) 1, 015004

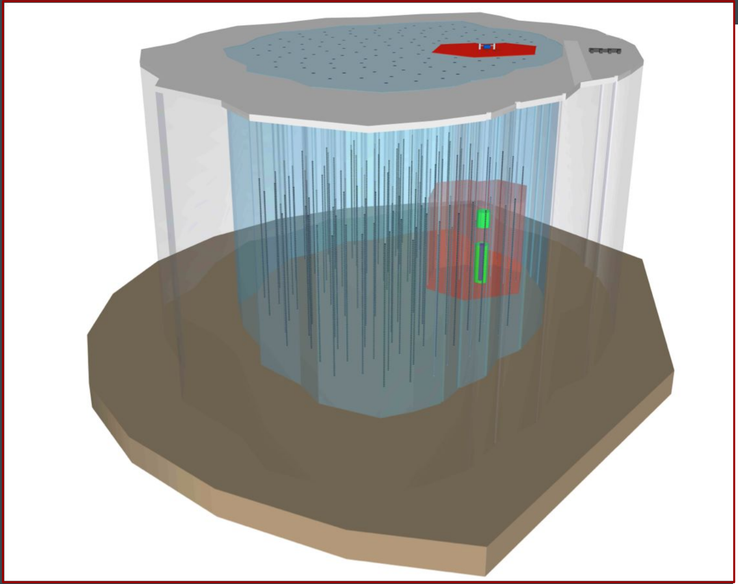
Decaying dark matter

If decay products include non-neutrino channels, gamma rays can provide a strong constraint (or confirmation)

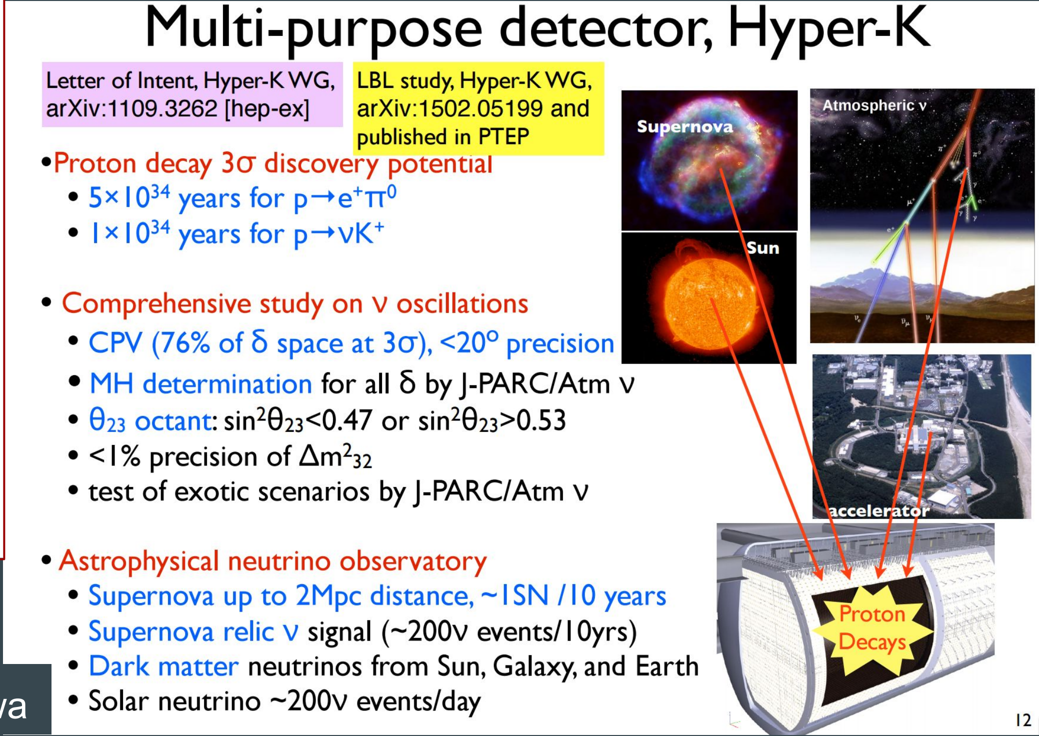


Murase et al., Phys. Rev. Lett. 115, 071301

Future: IceCube Gen-2, Hyper-K, double-βdecay…



Kelley

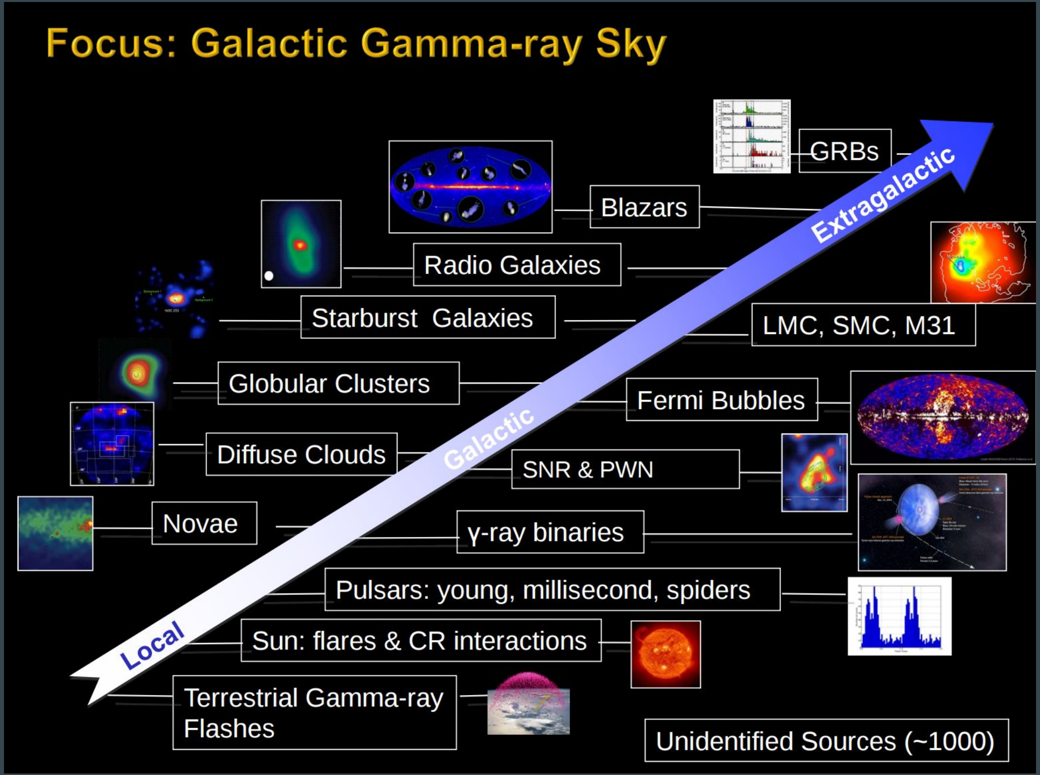


Shiozawa

γ-ray astronomy: rich with discoveries

blazars,
GRBs,
radio galaxies
...

pulsars millisecond,
radio loud γ,
radio faint γ,
novae (6),
Fermi Bubble



Reimer

understanding
leptonic vs hadronic

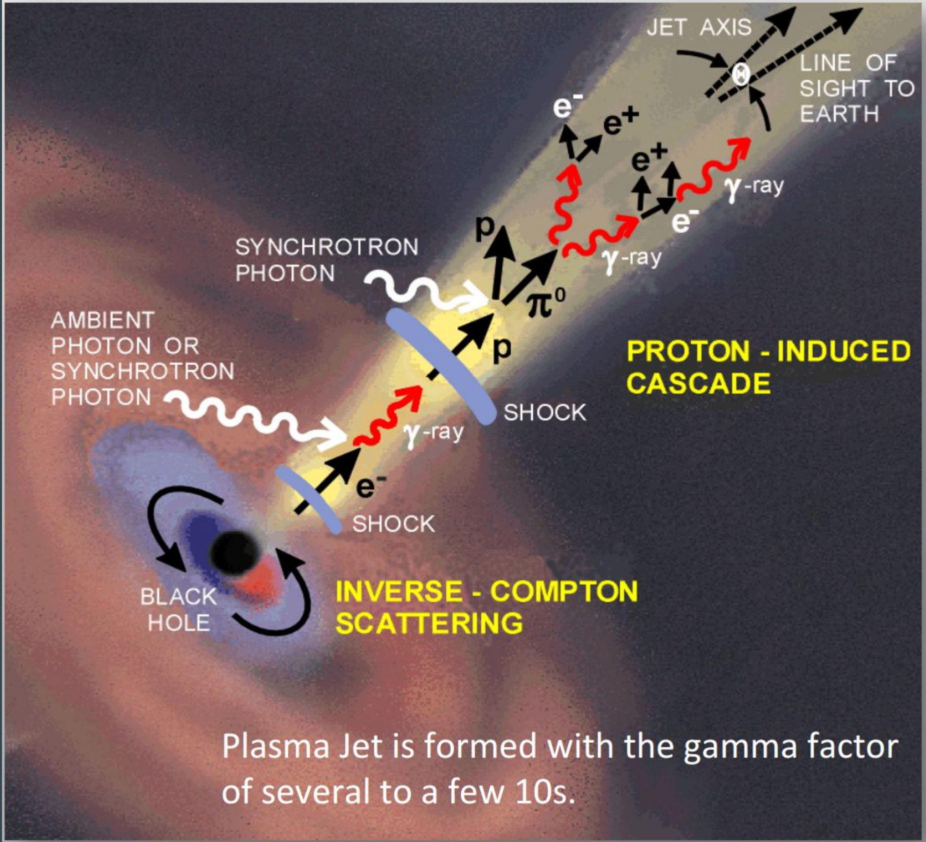
understanding
gamma emission and
acceleration of CRs

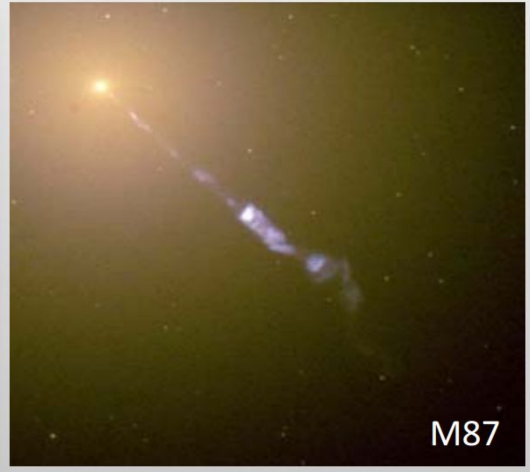
better diffuse
modeling
in Milky Way

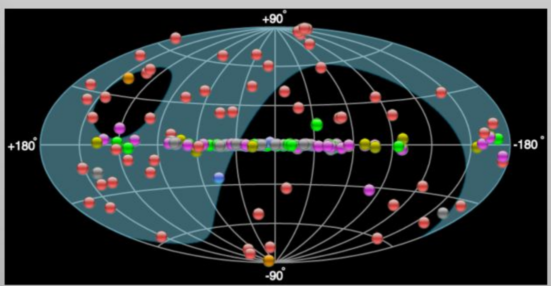
EBL studies

search for
dark matter

Blazars

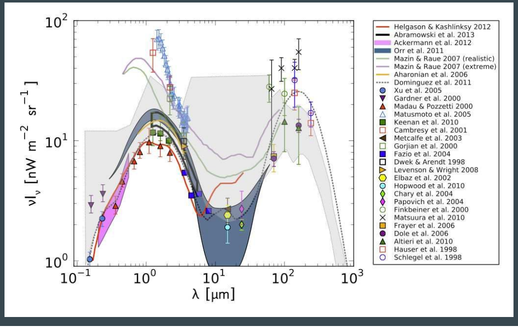


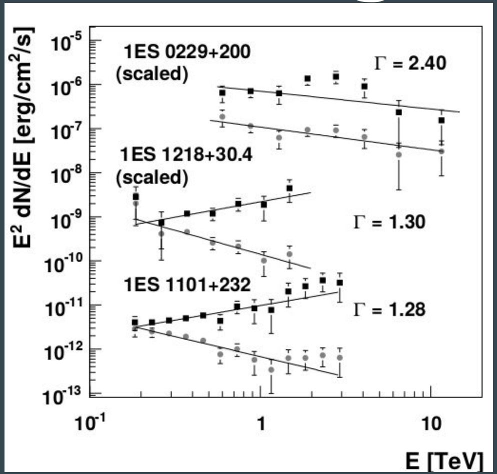


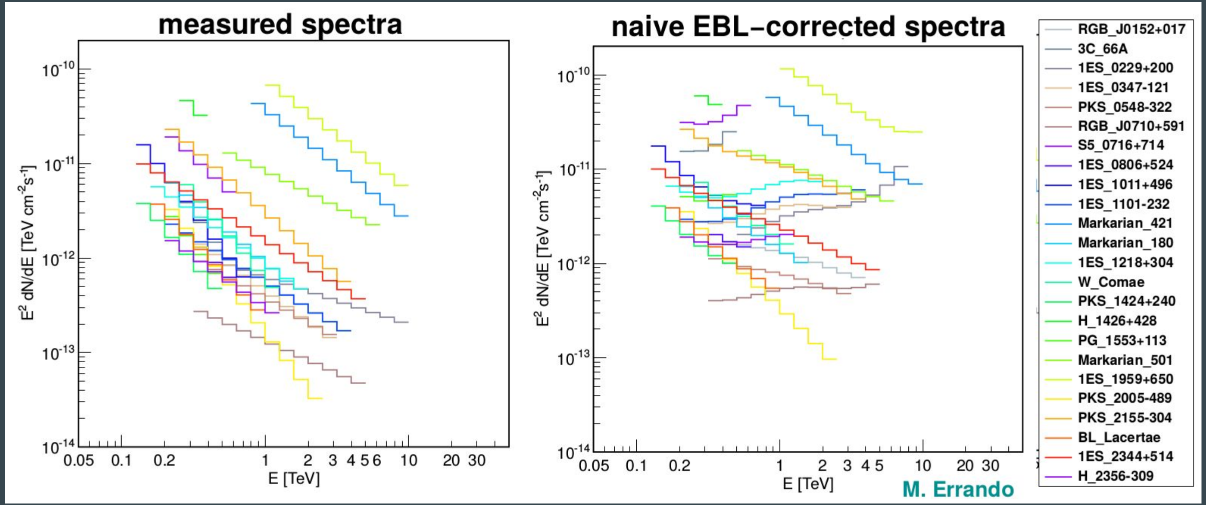


Teshima

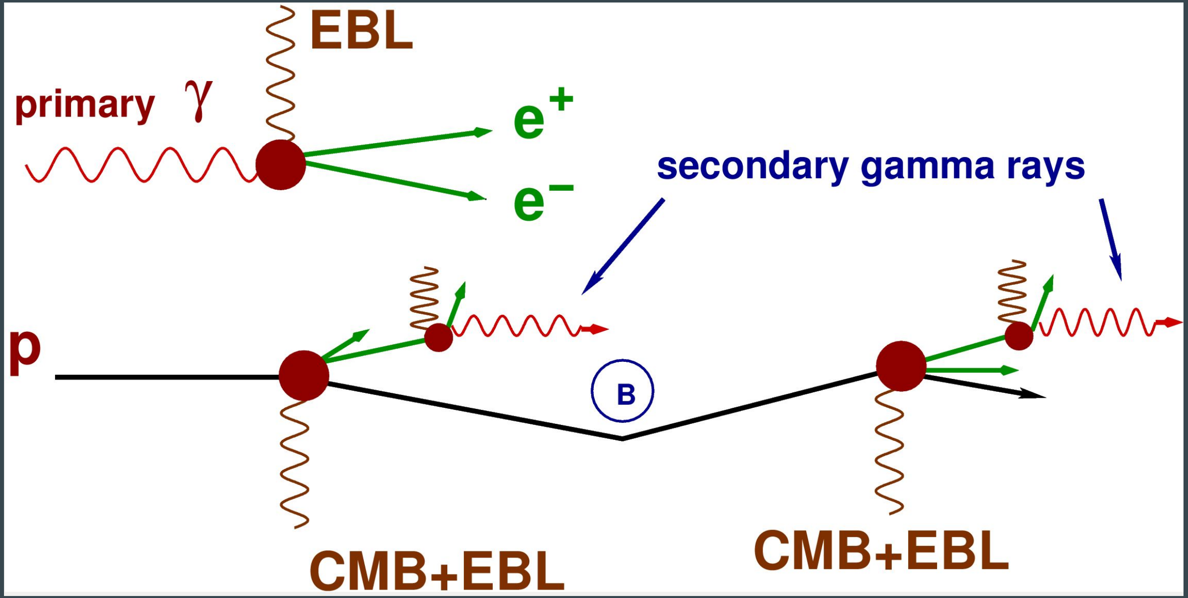
TeV gamma rays must interact with EBL and lose energy







γ rays and cosmic rays



Secondary gamma rays from line-of-sight interactions of CRs

[Essey & AK (2010)]

Different scaling

$$F_{\text{primary},\gamma}(d) \propto \frac{1}{d^2}\exp\{-d/\lambda_\gamma\}$$

$$F_{\text{secondary},\gamma}(d) = \frac{p\lambda_\gamma}{4\pi d^2}\left[1 - e^{-d/\lambda_\gamma}\right] \propto \begin{cases} 1/d, & \text{for } d \ll \lambda_\gamma, \\ 1/d^2, & \text{for } d \gg \lambda_\gamma. \end{cases}$$

$$F_{\text{secondary},\nu}(d) \propto (F_{\text{protons}} \times d) \propto \frac{1}{d}.$$

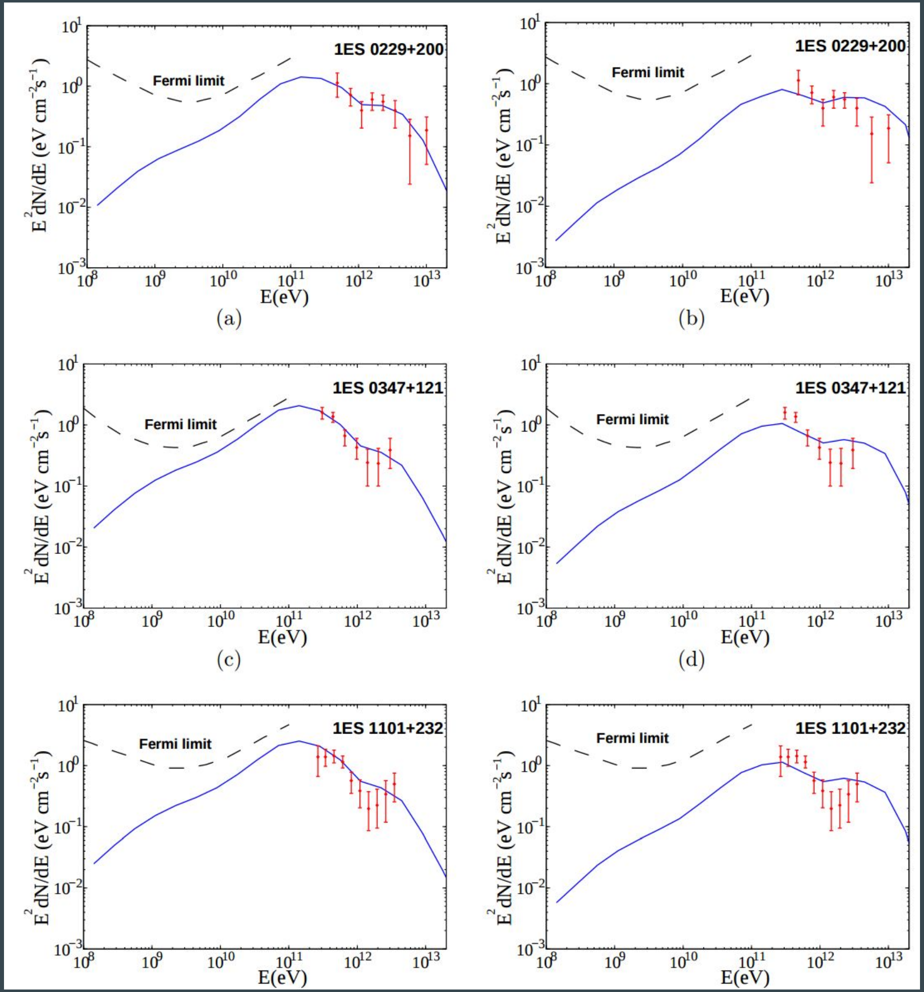
For distant sources, the secondary signal wins!

One-parameter fit (power in CR) for each source
[Essey & AK (2010); Essey, Kalashev, AK, Beacom (2011)]

Good agreement with data for high-redshift blazars (both “high” and “low” EBL models).

Reasonable CR power for a source up to z~1
[Aharonian, Essey, AK, Prosekin (2013);
Razzaque, Dermer, Finke (2012);
Murase, Dermer, Takami, Migliore (2012)]

Consistent with data on time variability
[Prosekin, Essey, AK, Aharonian (2012)]



Essey, Kalashev, AK, Beacom, ApJ (2011)

Implications for intergalactic magnetic fields

Magnetic fields along the line of sight:

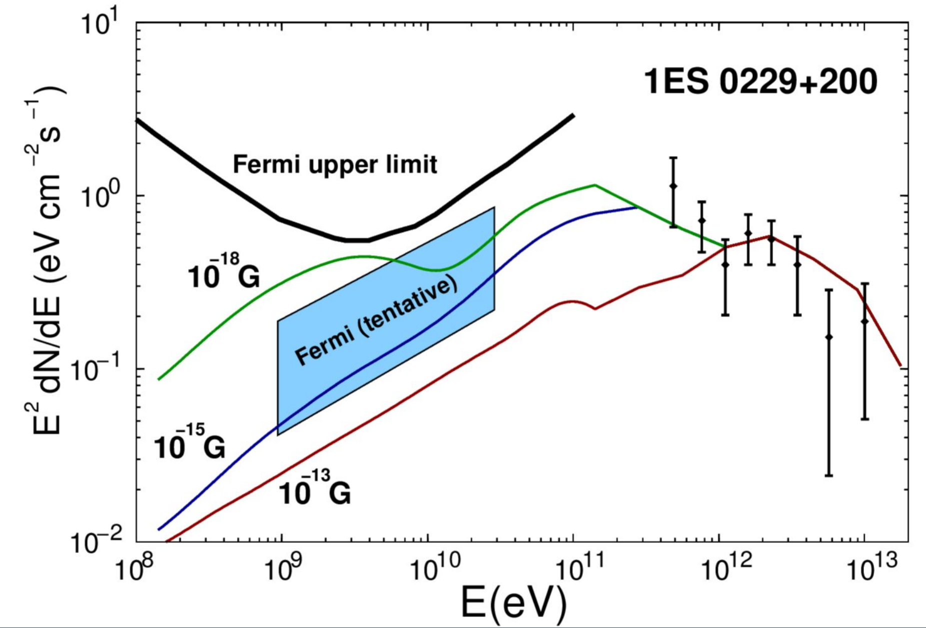
$$1 \times 10^{-17}\ \mathrm{G} < B < 3 \times 10^{-14}\ \mathrm{G}$$

Essey, Ando, AK, arXiv:1012.5313

Lower limits: see also Finke et al. (2015)

If an intervening filament deflects protons, then no secondary component is expected. (Cf. MAGIC observations of 1ES1011+496, talk by Teshima)

However, even a source at z~1 has an order-one probability to be unobscured by magnetic fields, and can be seen in secondary gamma rays [Aharonian, Essey, AK, Prosekin, arXiv:1206.6715]



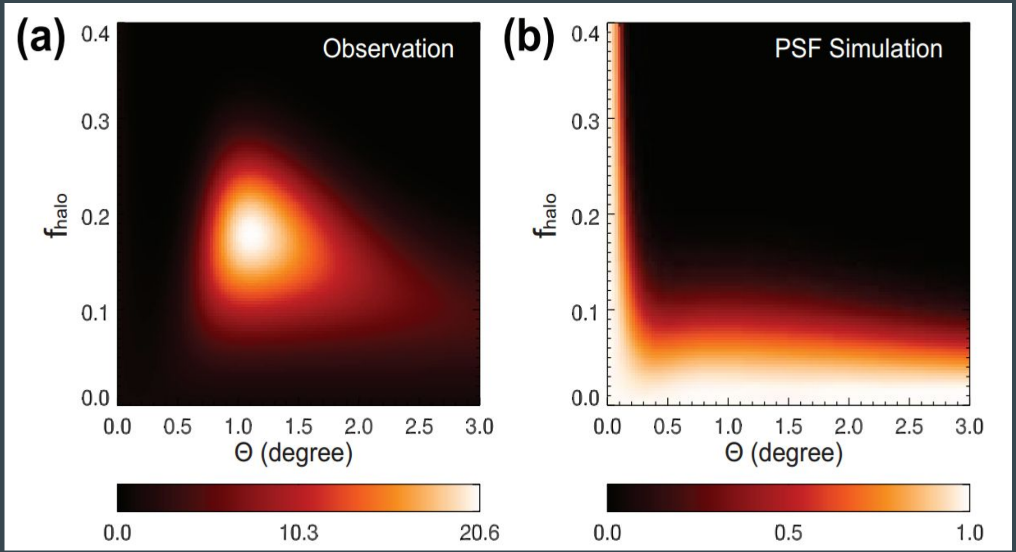
Essey, Ando, AK (2011), arXiv:1012.5313

Blazar halos: an independent measurement of IGMFs

Halos around stacked images of blazars implying **B~10^{-15} G** were reported (3.5σ) in 1st year Fermi data [Ando & AK, ApJL 722 (2010) L39].

Now the same technique was applied to the much larger Fermi data set, detecting lower energy halos of z< 0.5 blazars. The results, **B~10^{-17} -- 10^{-15} G** [Chen, et al. (2015)], confirm earlier results of Ando & AK, arXiv:1005.1924.

Consistent with independent measurement based on the gamma-ray spectra of blazars [Essey, Ando, AK, arXiv:1012.5313]



Chen, Buckley, Ferrer, Phys. Rev. Lett. (2015) confirm halos, IGMFs in the **B~10^{-17} -- 10^{-15} G** range

Extragalactic magnetic fields: a new window on the early universe?

Conclusion

- We have not identified the building blocks of most of the matter in the universe
- We have no understanding of dark energy, which dominates the expansion
- We are discovering new high-energy messengers of the most energetic objects in the universe