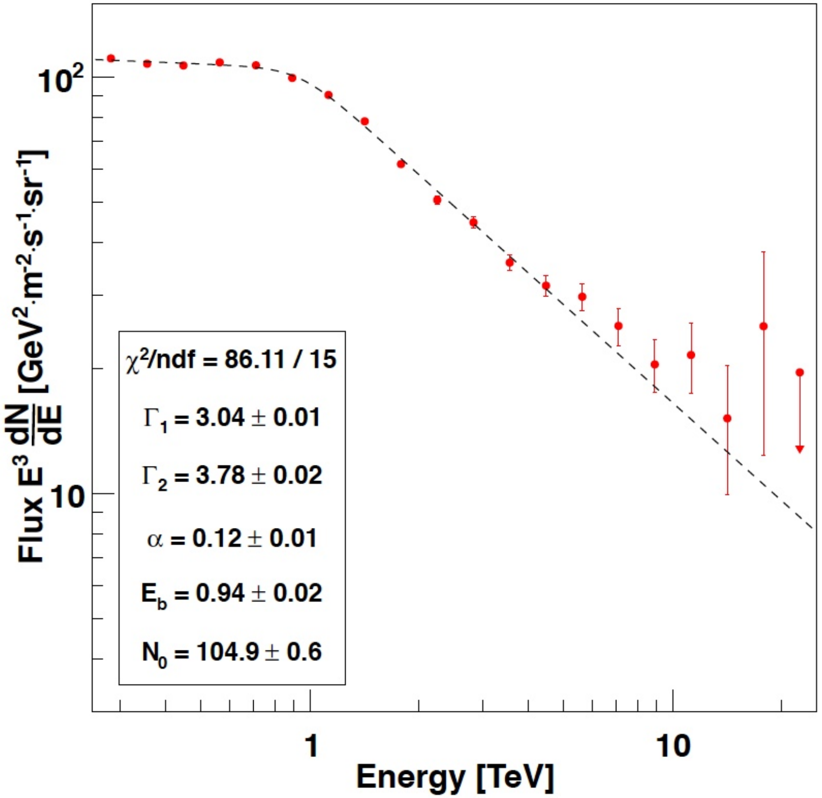
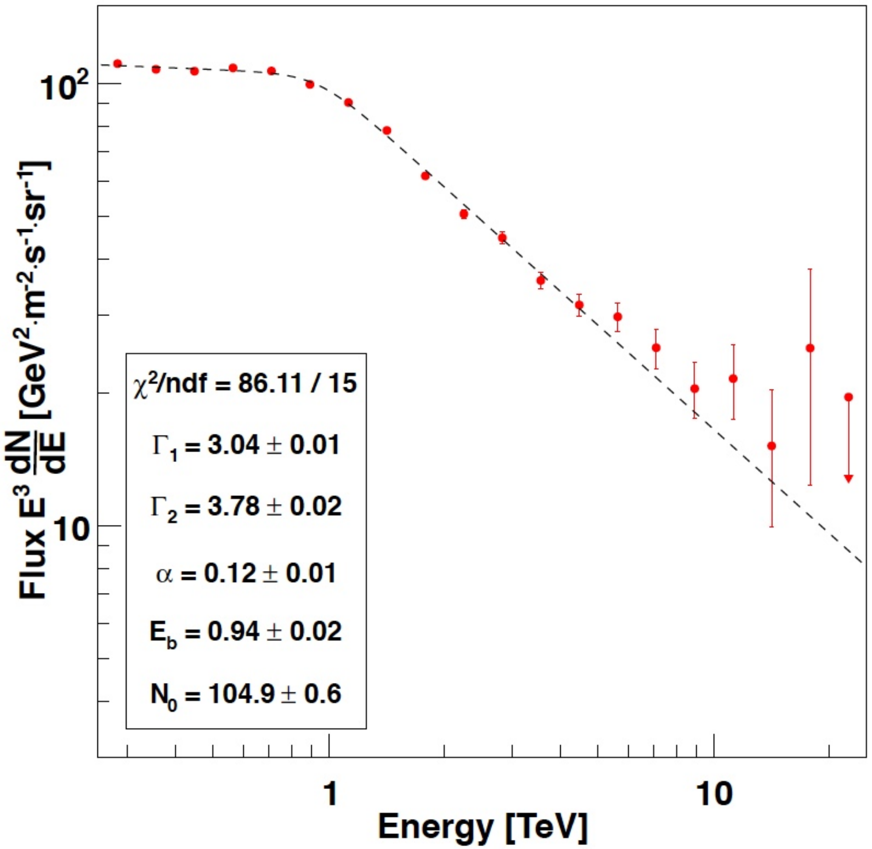
Electron + positron measurements by HESS 2004- March 2010



•HESS collab. 2017

Electron+ positron+ diffuse gamma measurements by HESS 2004- March 2010



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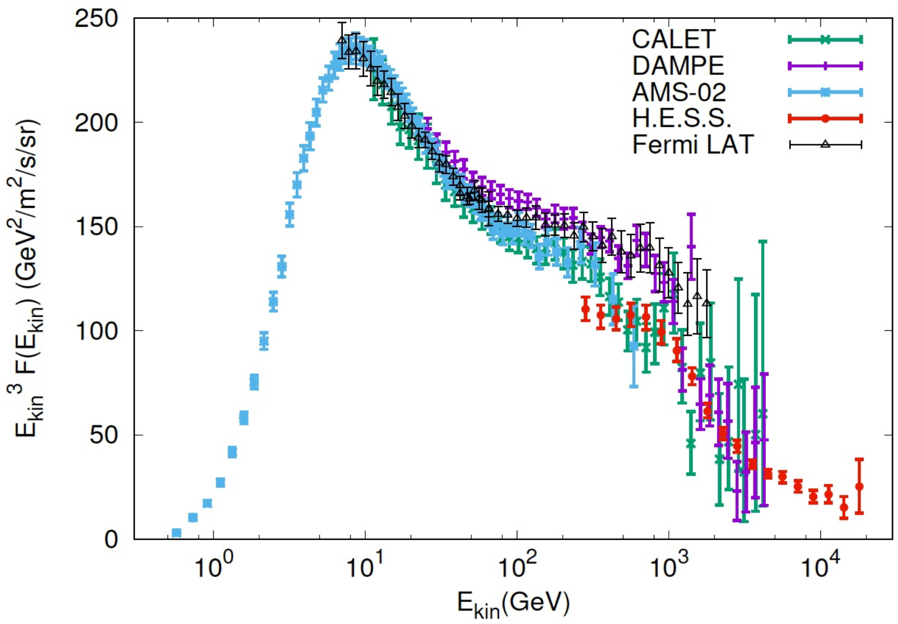
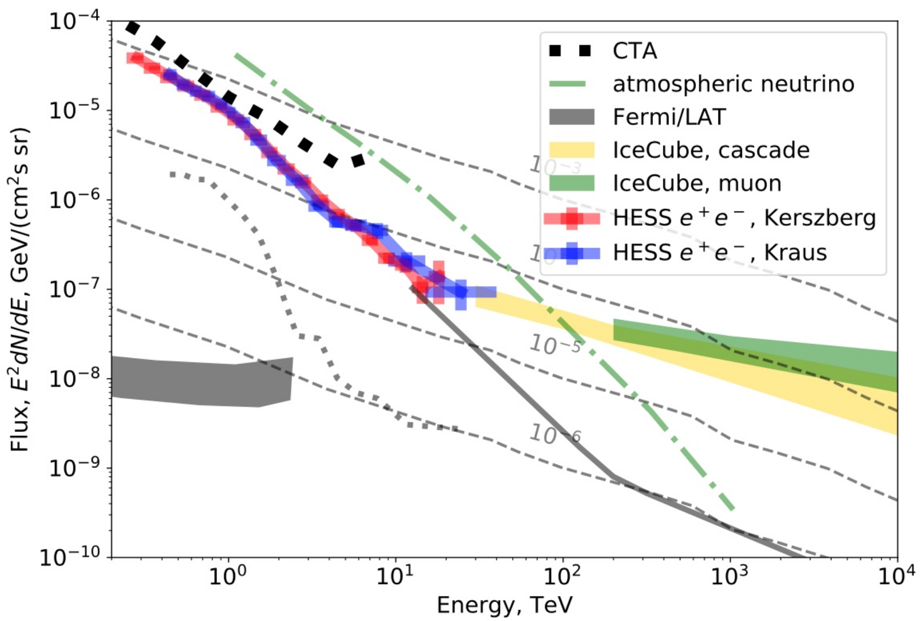


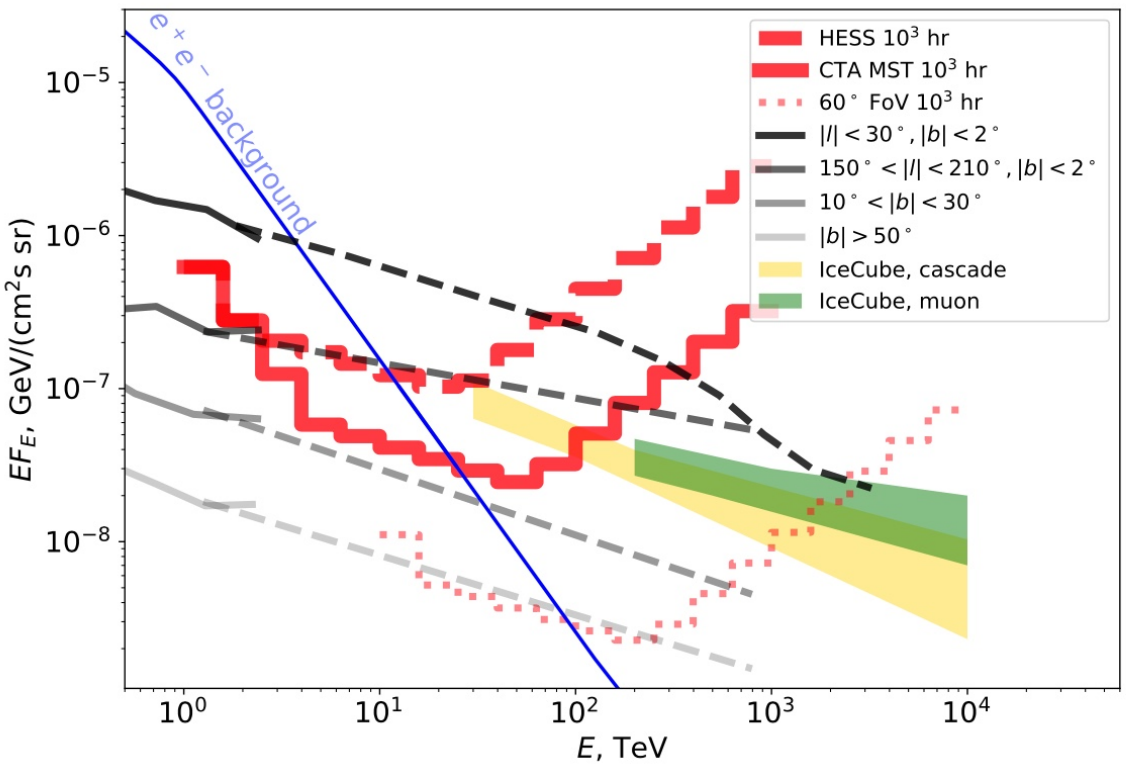


- M.Kachelriess and D.S.,
- Cosmic ray models,
- review astro-ph/1904.08160

- A.Neronov and D.S. ,
- astro-ph/2001.00922

Gamma-ray sky at 10-100 TeV with Cherenkov telescopes

Galactic diffuse flux at 10-100 TeV energies with Cherenkov



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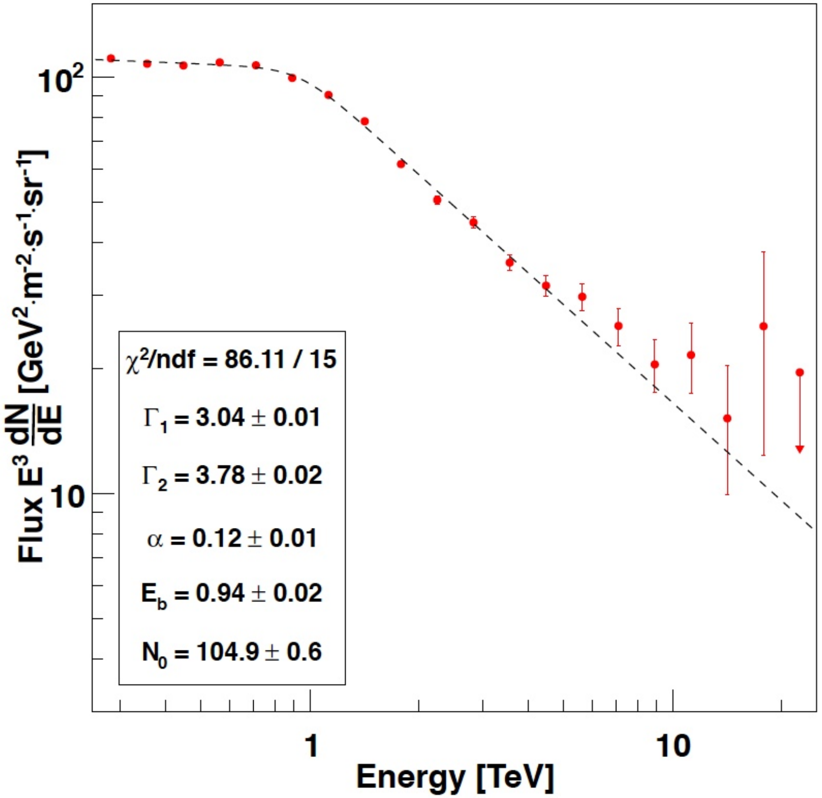

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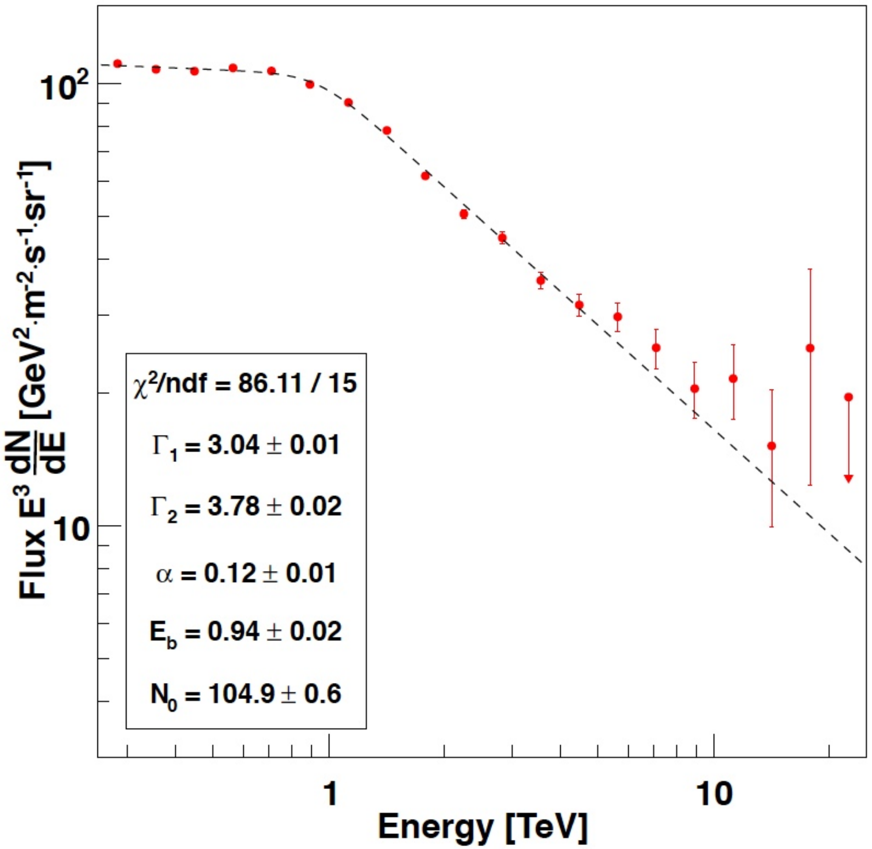

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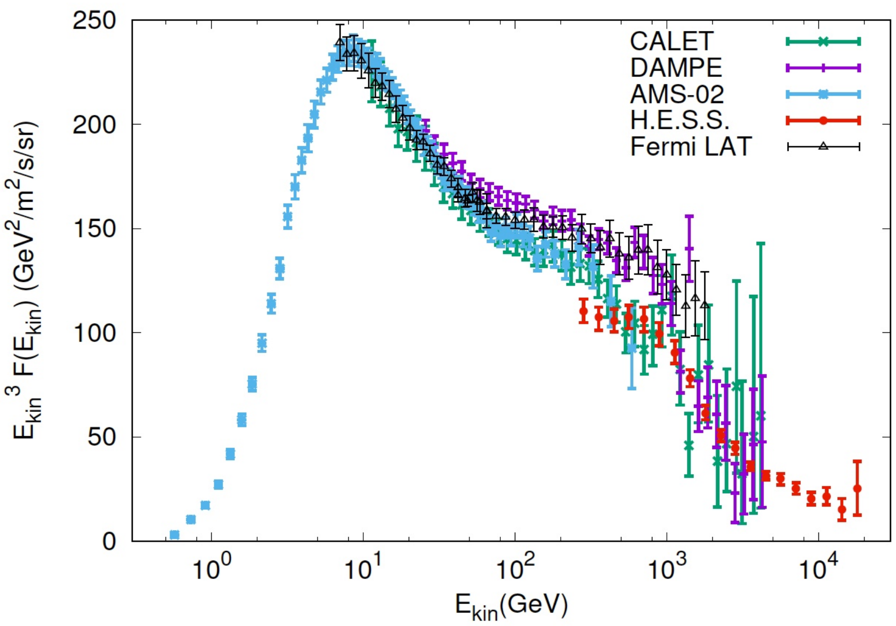

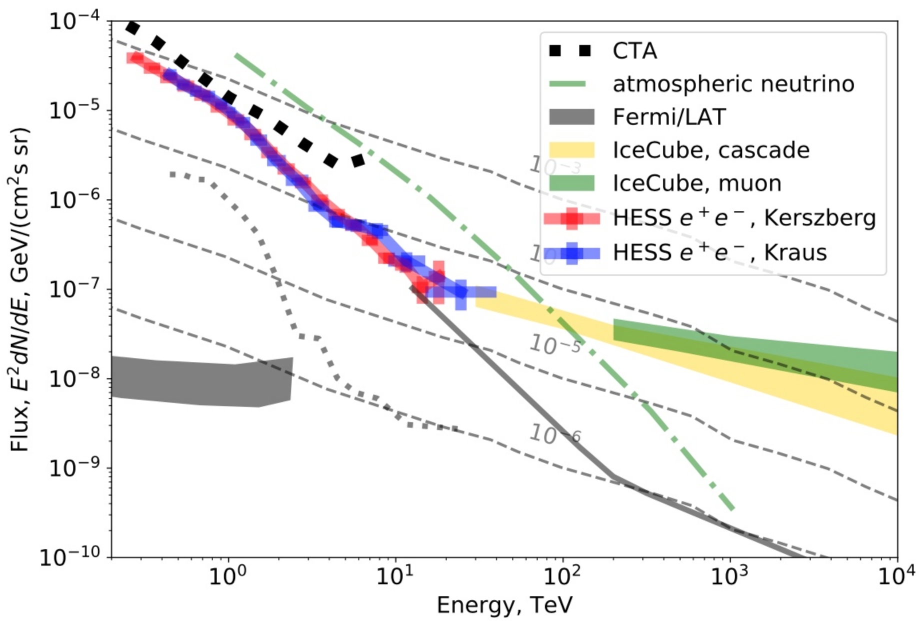

•M.Kachelriess and D.S.,
•Cosmic ray models,
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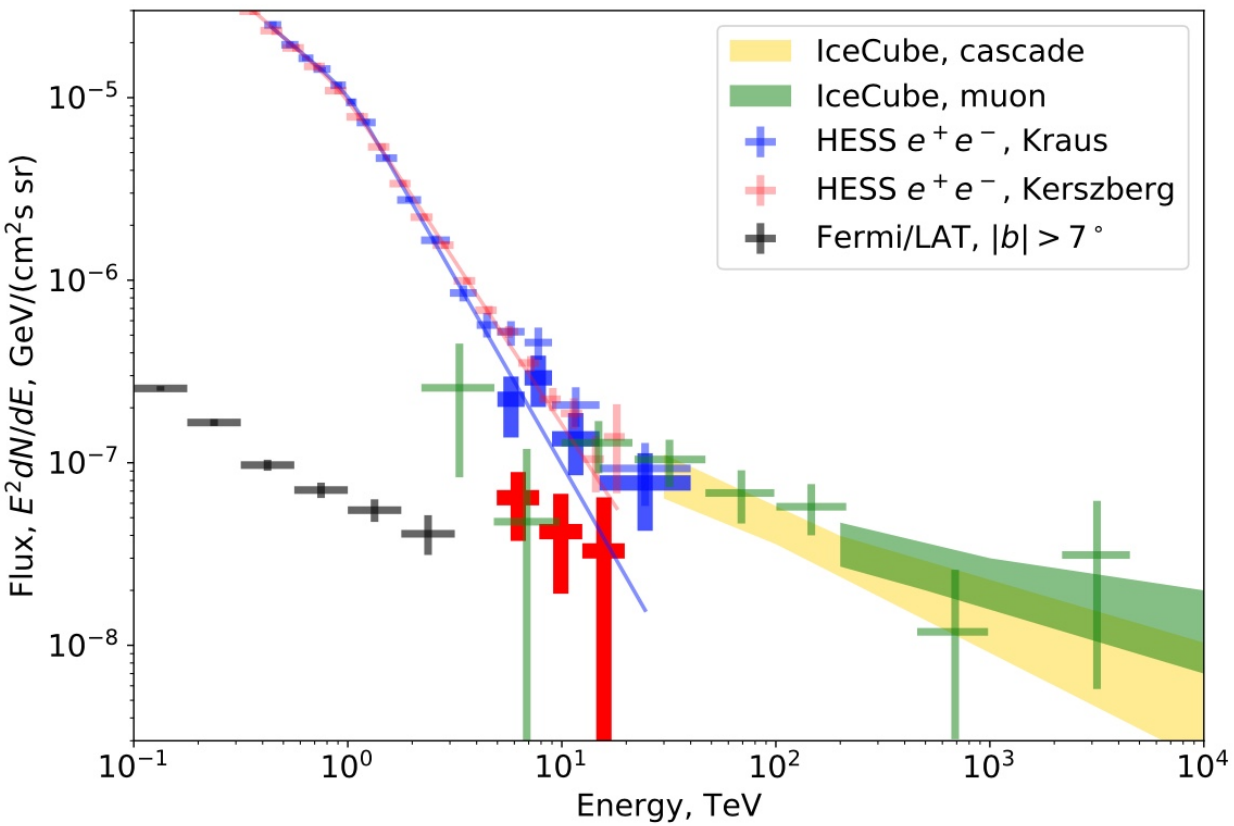
•A.Neronov and D.S. ,
•astro-ph/2001.00922

New component in HESS data

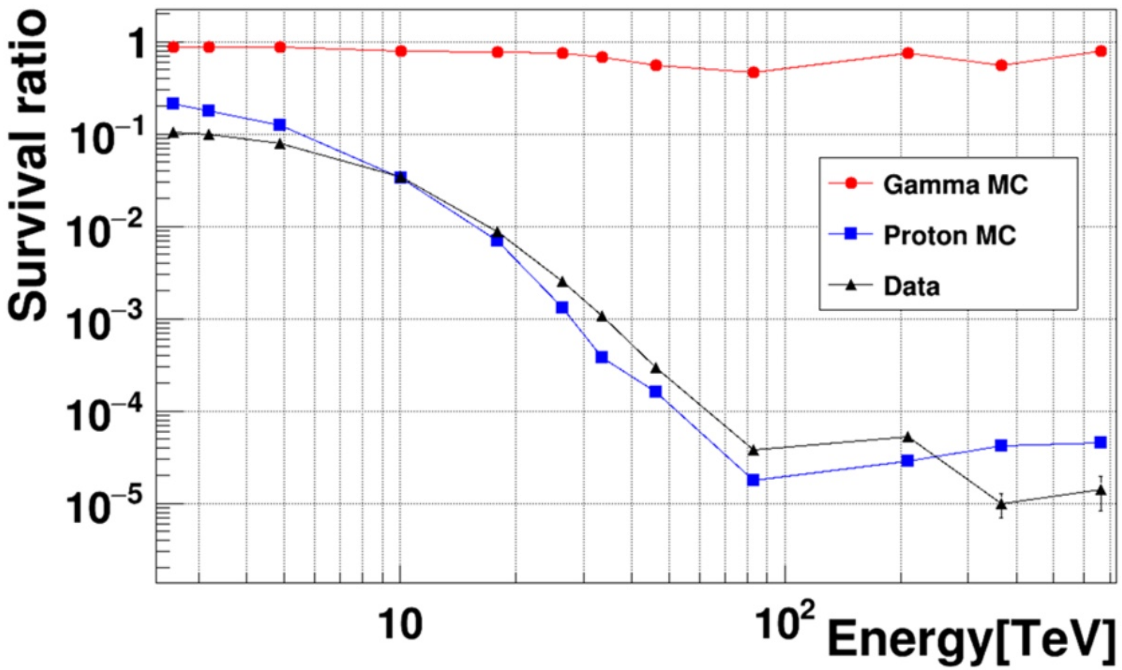


- A.Neronov and D.S. , astro-ph/2001.00922

Gamma-ray sky at 10-100 TeV with HAWC and LHAASO

γ/P discrimination of ¼ KM2A

Background rejection >10^4@100 TeV

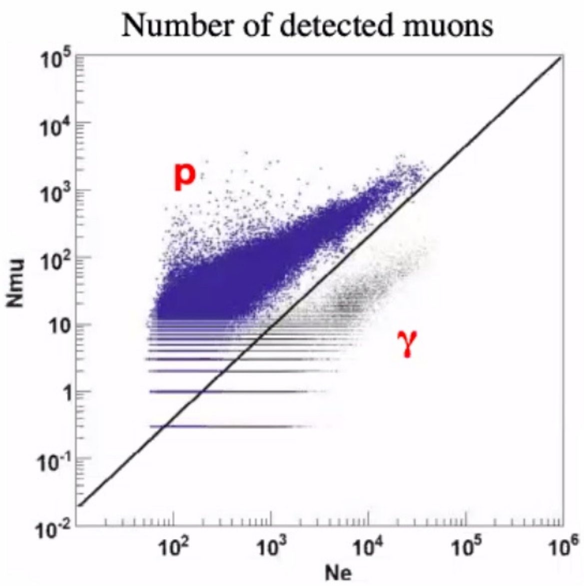


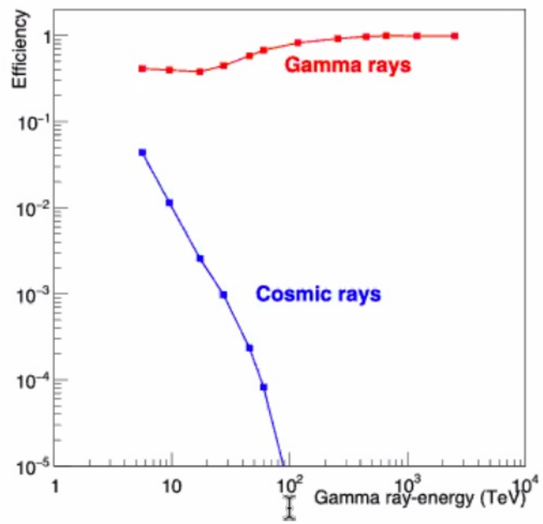
•LHAASO meeting Jan 2020

KM2A performance - 3

•Pino talk Yesterd

S. Cui et al./Astroparticle Physics 54 (2014) 86–92

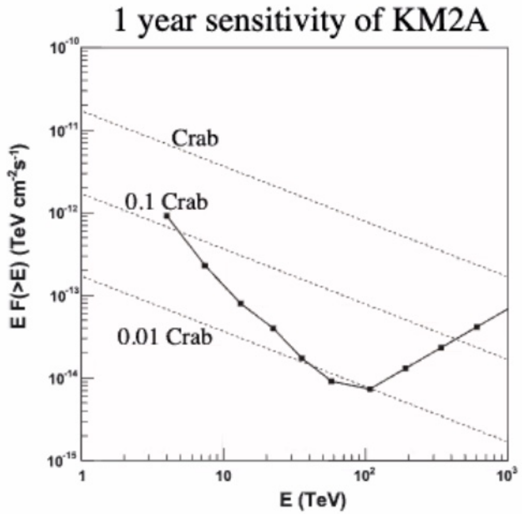




Fraction of surviving gamma and p-induced events after the selection cut.

The large area of the MD array of KM2A allow *rejection of cosmic ray background at a level of 10^{-5} at about 100 TeV*.

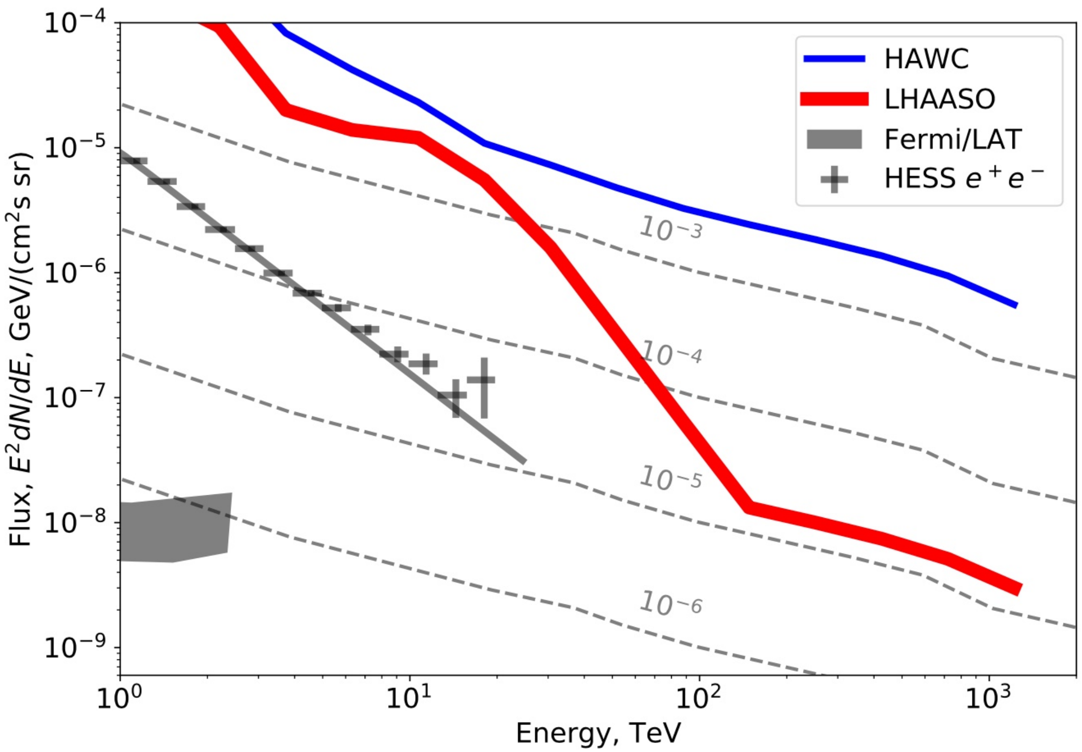
Above 100 TeV, in the *'back-ground free'* regime, 10 signal events are taken to measure the sensitivity of array.



At 50 TeV 1,700 events from Crab, expected

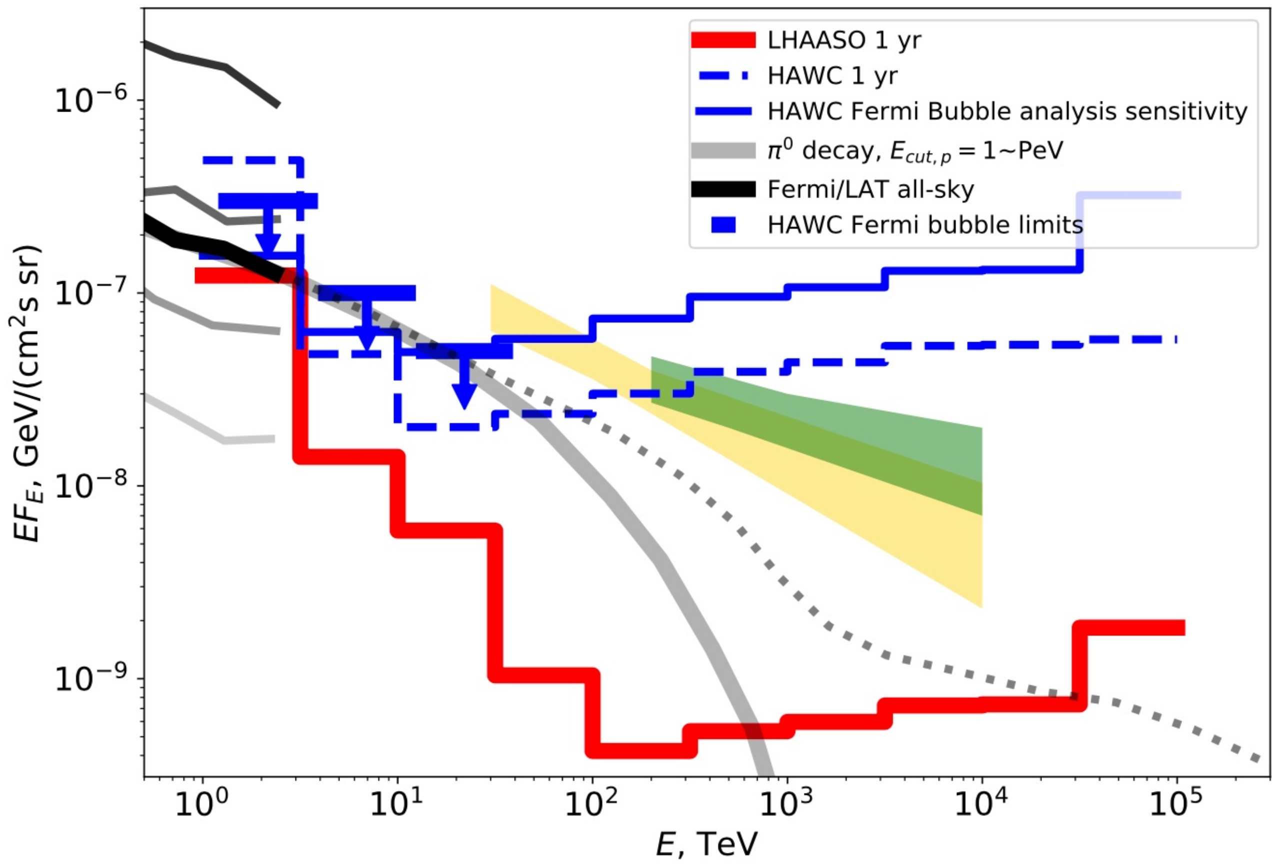
•LHAASO meeting Jan 2020

HAWC and LHAASO hadron cut



- A.Neronov and D.S. , astro-ph/2001.11881

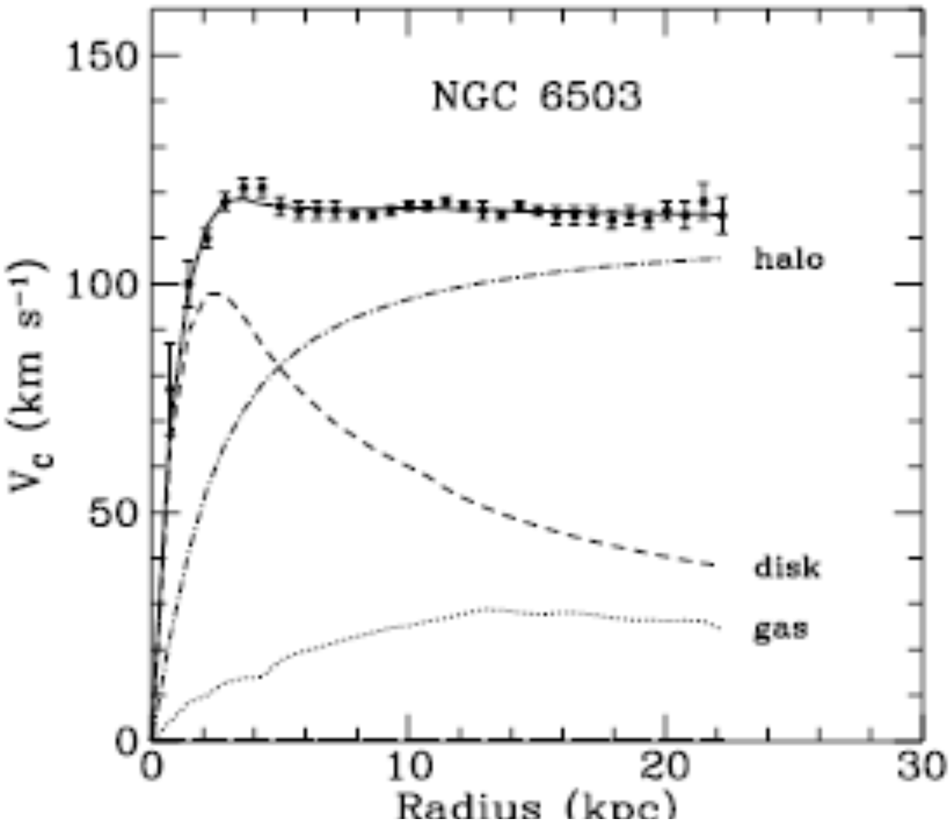
HAWC and LHAASO sensitivity to diffuse gamma

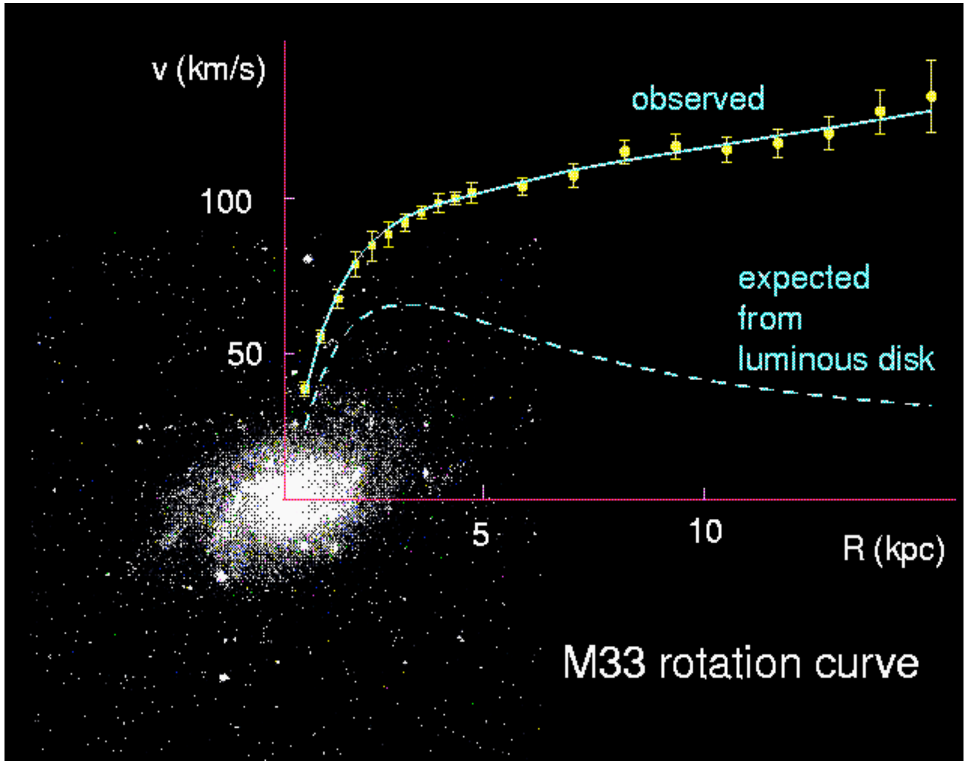


•A.Neronov and D.S. , astro-ph/2001.11881

Indirect detection of Dark Matter

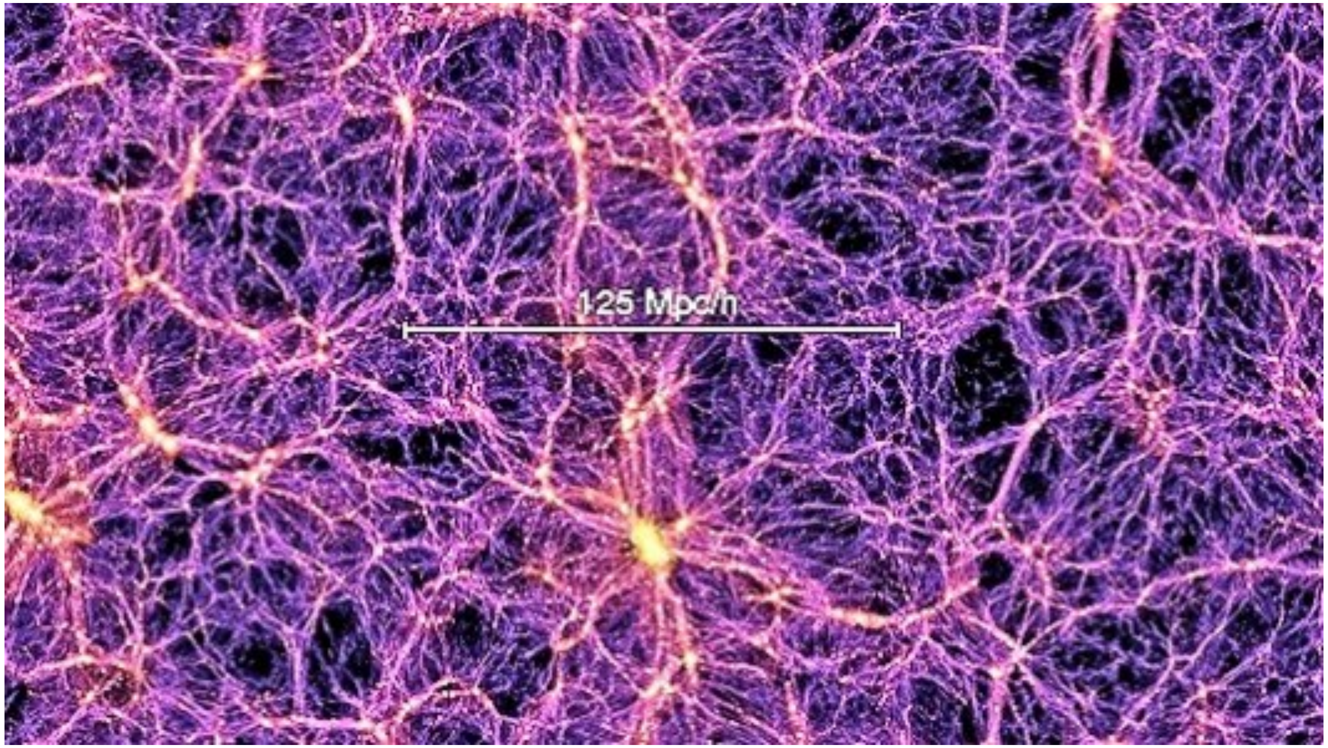
- Rotation Curves of galaxies





- Red Region: X Ray
- Blue Region: Gravitational lensing

- Large Scale Structure

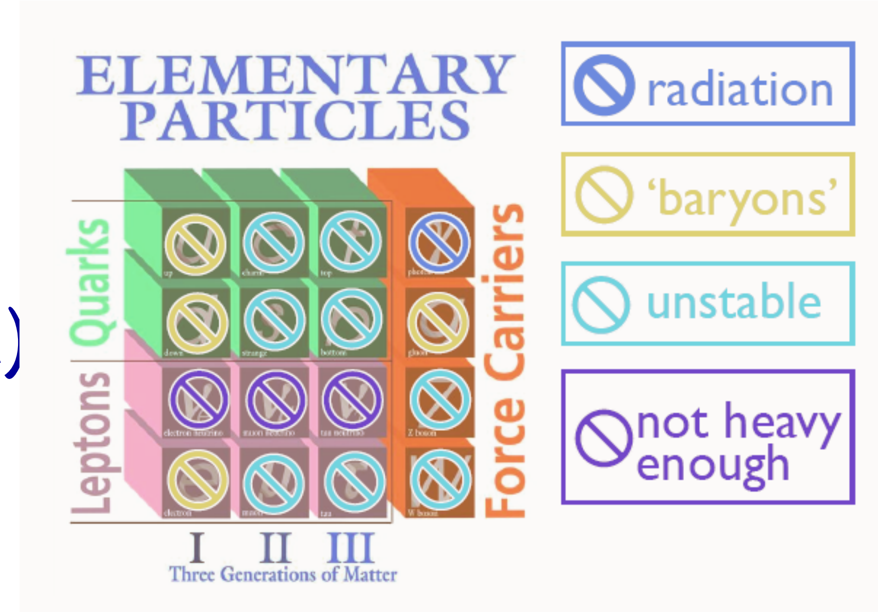


The N-body Simulation of Dark Matter Universe

Structure: Core, Filament and Cosmic Void.

•What we know about DM particles so far ?

- **neutral**



- **cold** (part of it can be warm)

- **weak interaction** (with itself and with ordinary matter) ? **Maybe!**

- **profile** (around us $\rho_{\chi} \approx 0.3 GeV/cm^3$ $V \approx 220$ km/s)

Neutrino dark matter

Neutrino seems to be a perfect dark matter candidate: neutral, stable, massive, abundantly produced in the early Universe

Cosmic neutrinos

- We know how neutrinos interact and we can compute their primordial number density $n_\nu = 112\,\mathrm{cm}^{-3}$ (per flavour)
- To give correct dark matter abundance the sum of neutrino masses, $\sum m_\nu$, should be $\sum m_\nu \sim 11\,\mathrm{eV}$

Tremaine-Gunn bound (1979)

- Such light neutrinos **cannot form small galaxies** – one would have to put too many of them and violated Pauli exclusion principle
- Minimal mass for fermion dark matter $\sim 300-400\,\mathrm{eV}$
- If particles with such mass were **weakly interacting** (like neutrino) – they would oveclose the Universe ($\Omega \sim 3!$)

Two roads from neutrino dark matter

Dark matter cannot be **light** and **weakly interacting** at the same time

Alternatives:

Light and necessarily **super-weakly** interacting — **HNL**

Heavy and weakly interacting — **WIMP**

...and of course other, completely orthogonal ideas, like axions

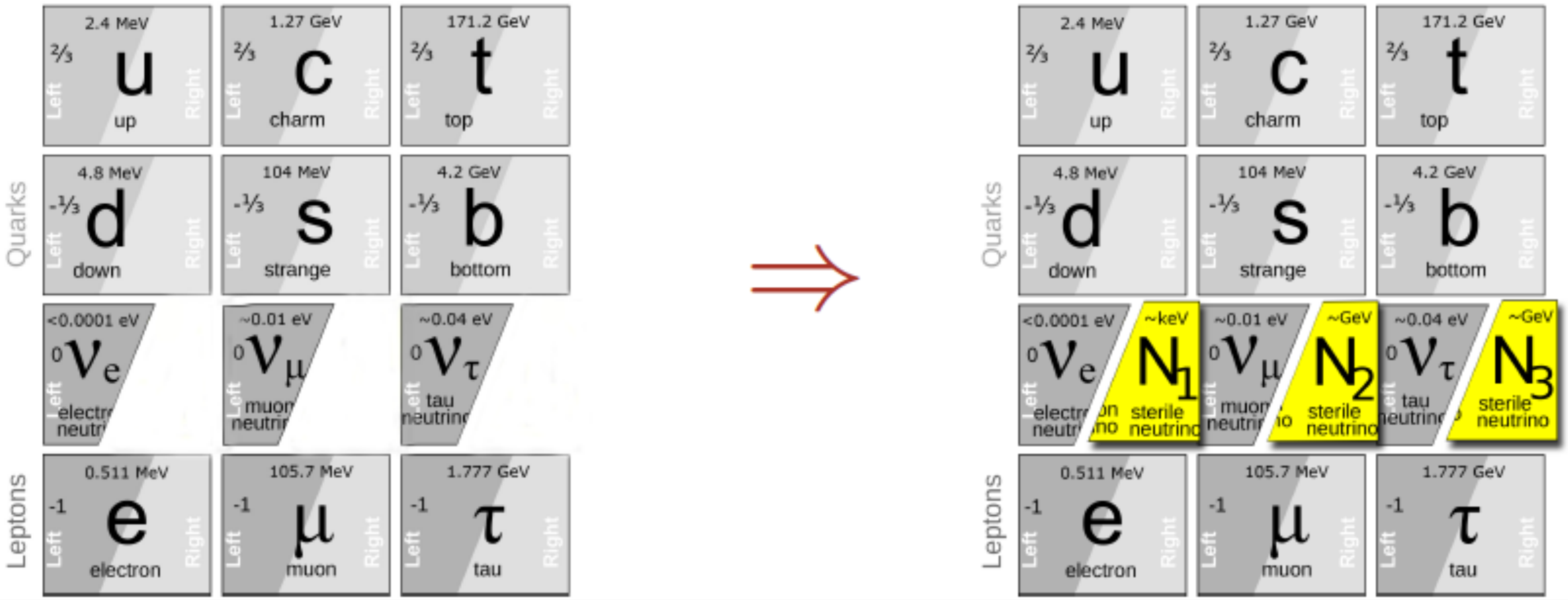
HNLs as dark matter

- **Can be light** (down to Tremaine-Gunn bound)
- **Can be warm** (born relativistic and cool down later)
- **Can be decaying** (stability is not required)
- **Can be produced** in correct amounts (via mixing with neutrinos)

Heavy neutral leptons

Extension of Standard Model with heavy neutral leptons

Asaka & Shaposhnikov'05. **Review:** Boyarsky+'09



Can this be a **unified Standard Model** of particle physics and cosmology

Sharing success of the Standard Model at accelerators and resolving major BSM problems: Neutrino masses and oscillations; Baryon asymmetry of the Universe; Dark matter

Type I seesaw model

Majorana mass term

$$\mathscr{L}_{\text{Seesaw Type I}} = \mathscr{L}_{\text{SM}} + i\bar{N}\partial\!\!\!/ N + Y\,\bar{N}(\tilde{H}\cdot L) + \frac{1}{2}\bar{N}\boldsymbol{M}N^c + \text{h.c.}$$

Dirac mass term

- Neutrinos are light because $m_{\text{Dirac}} \ll \boldsymbol{M}$:

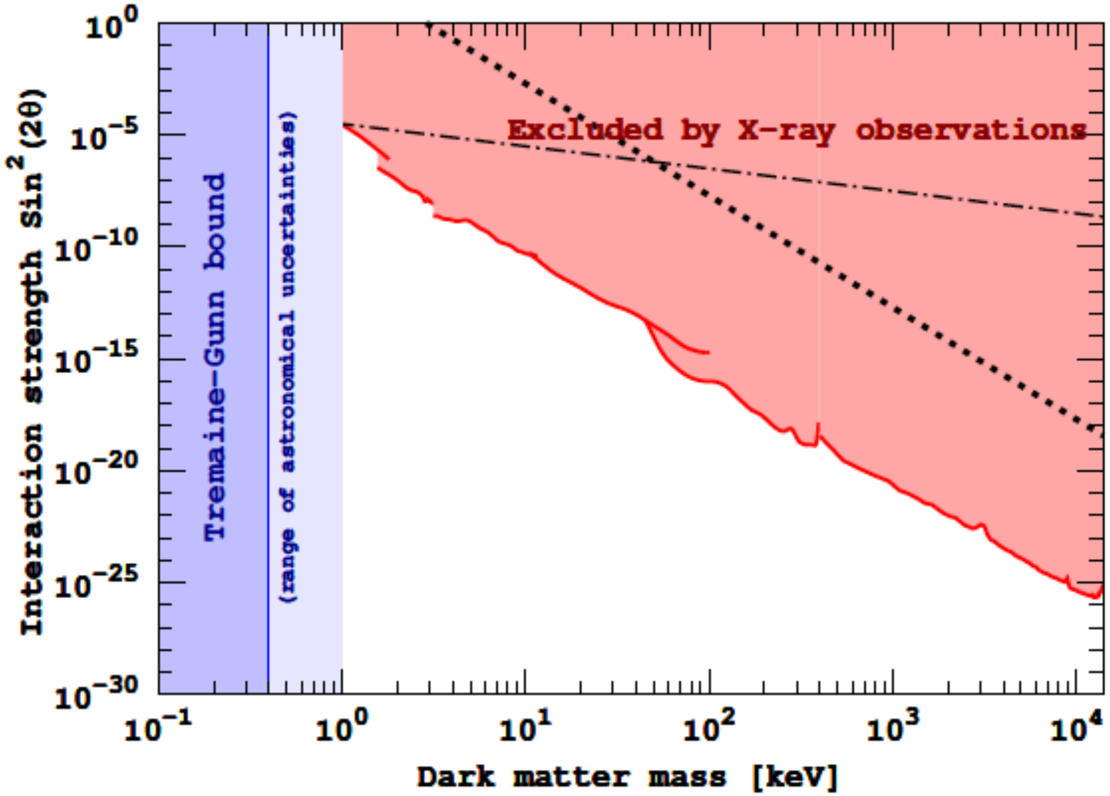
$$m_\nu \simeq \frac{(m_{\text{Dirac}})^2}{\boldsymbol{M}} = U^2\boldsymbol{M}$$

- active-sterile mixing angle

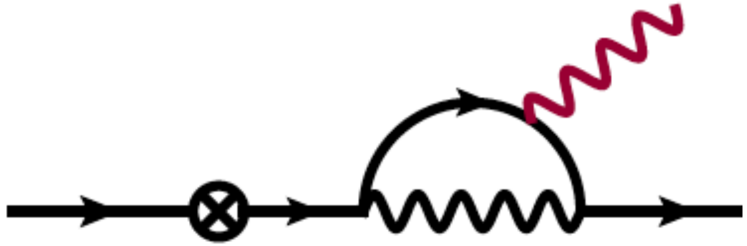
$$U = \frac{m_{\text{Dirac}}}{\boldsymbol{M}} \ll 1$$

The new particle is called "Sterile neutrino" or "heavy neutral lepton" or **HNL**

Parameter space of HNL dark matter I



- Non-observation of decay line $N \to \gamma + \nu$

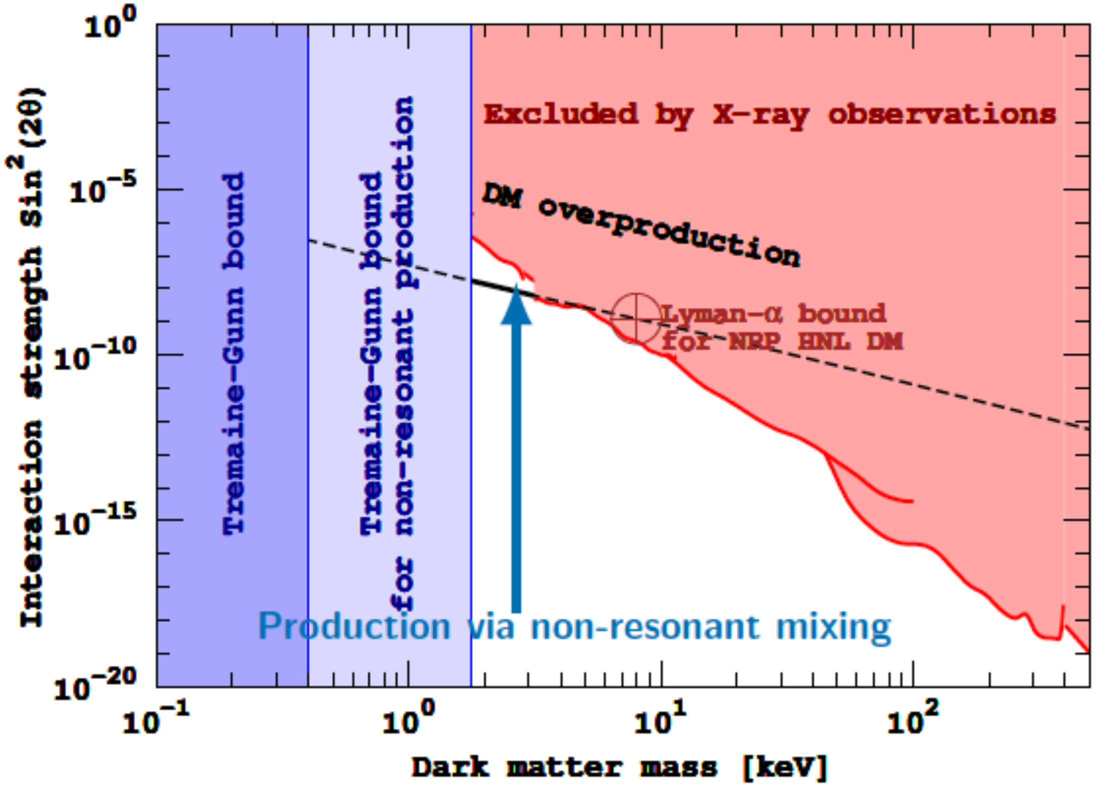


- Lifetime $\gg$ Age of the Universe (dotted line)
- Contribution to neutrino masses

$$m_{\odot} \sim U^2 M$$

[Asaka+'05; Boyarsky+'06]

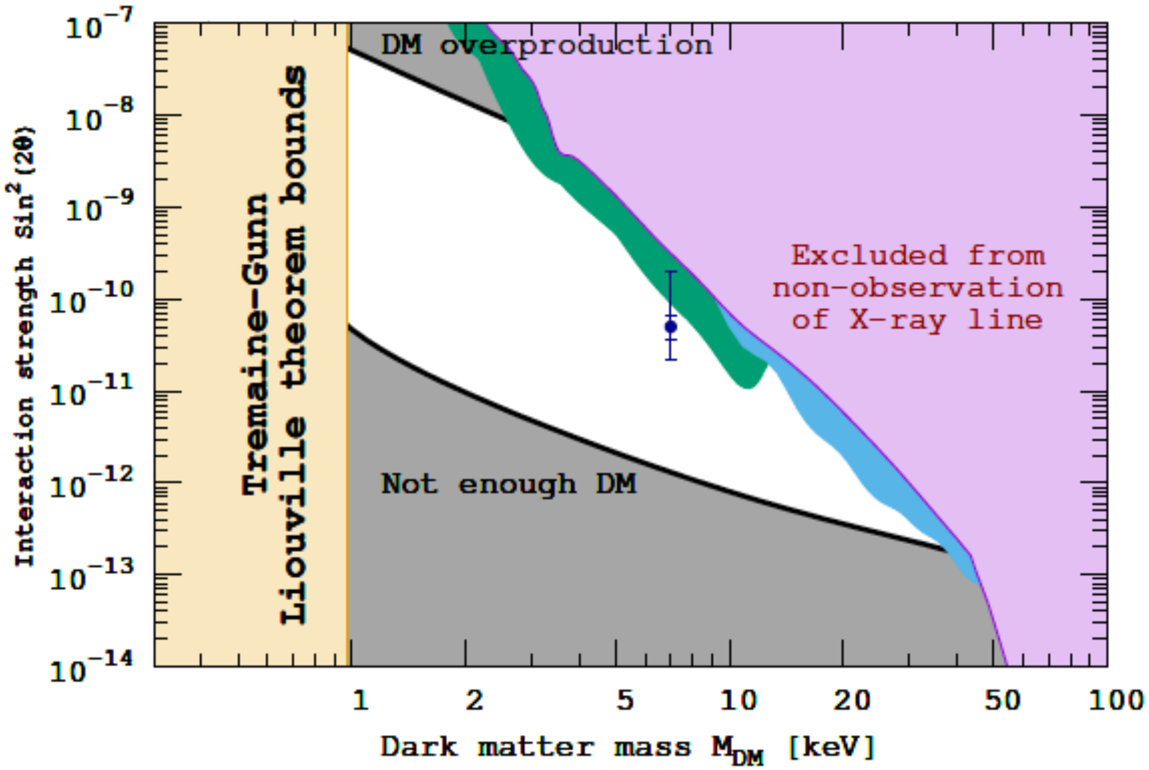
Parameter space of HNL dark matter II



– Production via non-resonant mixing [Dodelson & Widrow'93; Asaka, Laine, Shaposhnikov'06]
– Liouville bound (neglecting feedback from baryons) [Boyarsky, O.R. et al.'08; Gorbunov+'08]
– Lyman-α bound [Boyarsky, Lesgourgues, O.R., Viel'08]

- Production via mixing and decay signal depend on the same mixing angle U^2
- X-ray bounds grow very fast with mass (flux $\sim M_N^5$)

Parameter space of HNL dark matter III



- White region: production via **resonant** mixing [Shi & Fuller'93; Laine & Shaposhnikov'08]
- Requires: lepton asymmetry exceeding η_{baryon} by many orders of magnitude at $T \sim 100 - 500\,\mathrm{MeV}$

In summary

- HNL DM is **light** ($1 - 50$ keV) if there are no other particles
- Yukawa of HNL DM are tiny ($\mathcal{O}(10^{-10})$ or below)

Reminder: 3.5 keV line story

Two groups reported an identified feature in the X-ray spectra of dark matter-dominated objets

DETECTION OF AN UNIDENTIFIED EMISSION LINE IN THE STACKED X-RAY SPECTRUM OF GALAXY CLUSTERS

Esra Bulbul[1,2], Maxim Markevitch[2], Adam Foster[1], Randall K. Smith[1] Michael Loewenstein[2], and Scott W. Randall[1]
[1] Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138.
[2] NASA Goddard Space Flight Center, Greenbelt, MD, USA.
Submitted to ApJ, 2014 February 10

ApJ (2014) [1402.2301]

An unidentified line in X-ray spectra of the Andromeda galaxy and Perseus galaxy cluster

A. Boyarsky[1], O. Ruchayskiy[2], D. Iakubovskyi[3,4] and J. Franse[1,5]
[1]Instituut-Lorentz for Theoretical Physics, Universiteit Leiden, Niels Bohrweg 2, Leiden, The Netherlands
[2]Ecole Polytechnique Fédérale de Lausanne, FSB/ITP/LPPC, BSP, CH-1015, Lausanne, Switzerland

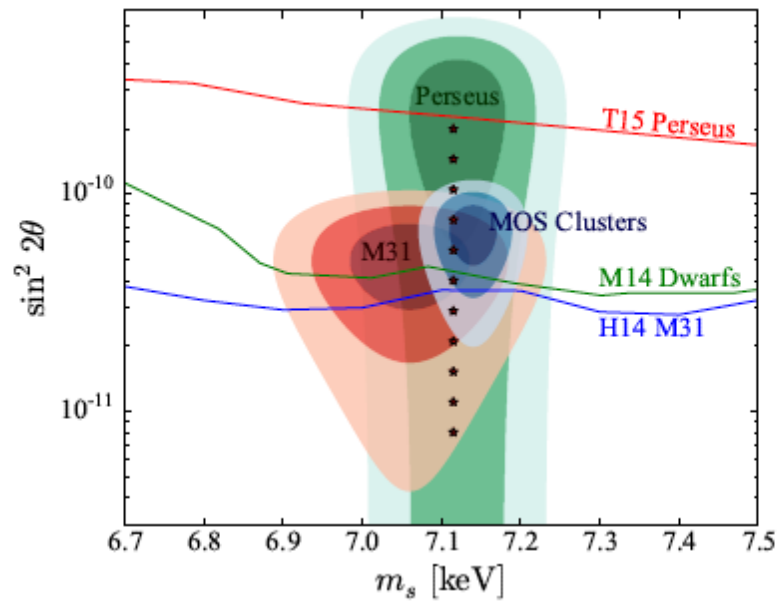
PRL (2014) [1402.4119]

- **Energy:** 3.5 keV. Statistical error for line position $\sim 30-50$ eV.
- **Lifetime:** $\sim 10^{28}$ sec (uncertainty: factor ~ 3)
- **Possible origin:** decay $DM \to \gamma + \nu$ (fermion) or $DM \to \gamma + \gamma$ (boson)

Subsequent works

For overview see e.g. [1602.04816] "A White Paper on keV Sterile Neutrino Dark Matter"

- Subsequent works confirmed the presence of the 3.5 keV line in some of the objects
  Boyarsky O.R.+, Iakubovskyi+; Franse+; Bulbul+; Urban+; Cappelluti+
- challenged it existence in other objects
  Malyshev+; Anderson+; Tamura+; Sekiya+
- argued astrophysical origin of the line
  Gu+; Carlson+; Jeltema & Profumo; Riemer-Sørensen; Phillips+



[1507.06655]

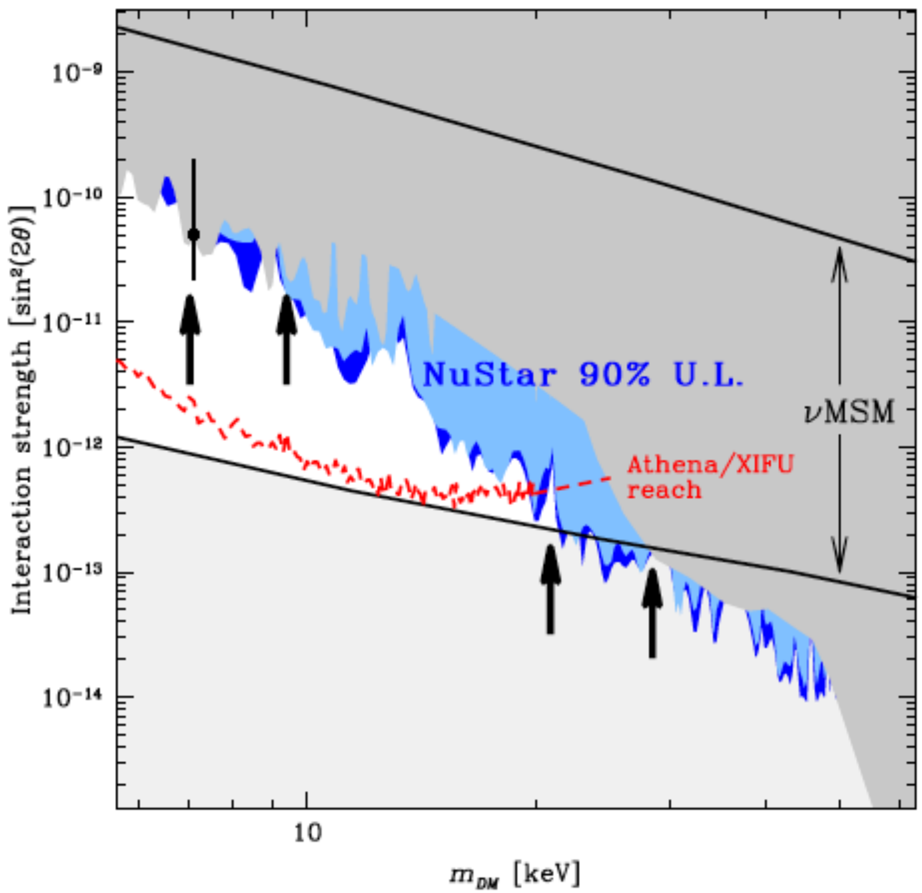
A common explanation for every detection and non-detection?

- When comparing bounds from different objects one should be careful — dark matter content in each of them uncertain by a factor $2-3$

Line in NuStar

Milky Way halo. Neronov & Malyshev [1607.07328]. Also Ng+ [1609.00667]

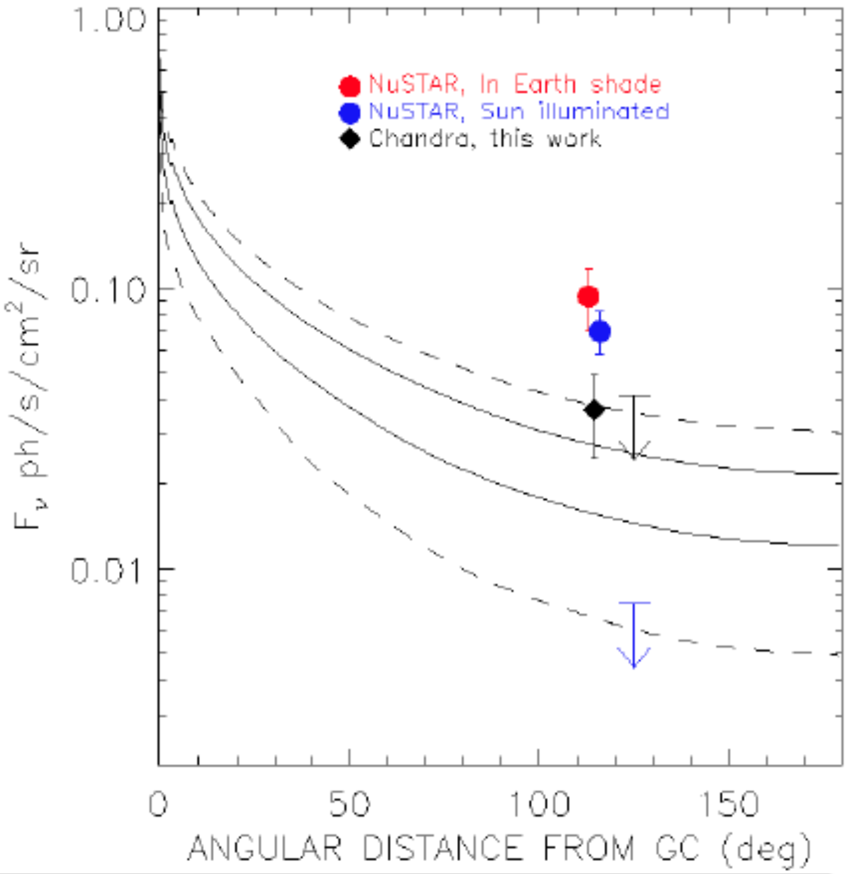
- The 3.5 keV is present in the spectrum with 11σ significance
- The spectrum of NuStar ends at 3 keV, so this is a lower edge of sensitivity band
- The 3.5 keV line has been previously attributed to reflection of the sunlight on the telescope structure
- However, in the dataset when Earth shields satellite from the Sun the line is present with the same flux



Line in Chandra

Cappelluti+'17

- Most recently: 10 Msec of Chandra observation of Chandra Deep Fields
- 3σ detection of a line at ~ 3.5 keV
- If interpreted as dark matter decay – this is a signal from Galactic halo outskirts ($\sim 115°$ off center)
- Chandra has mirrors made of Iridium (rather than Gold as XMM or Suzaku) – absorption edge origin becomes unlikely

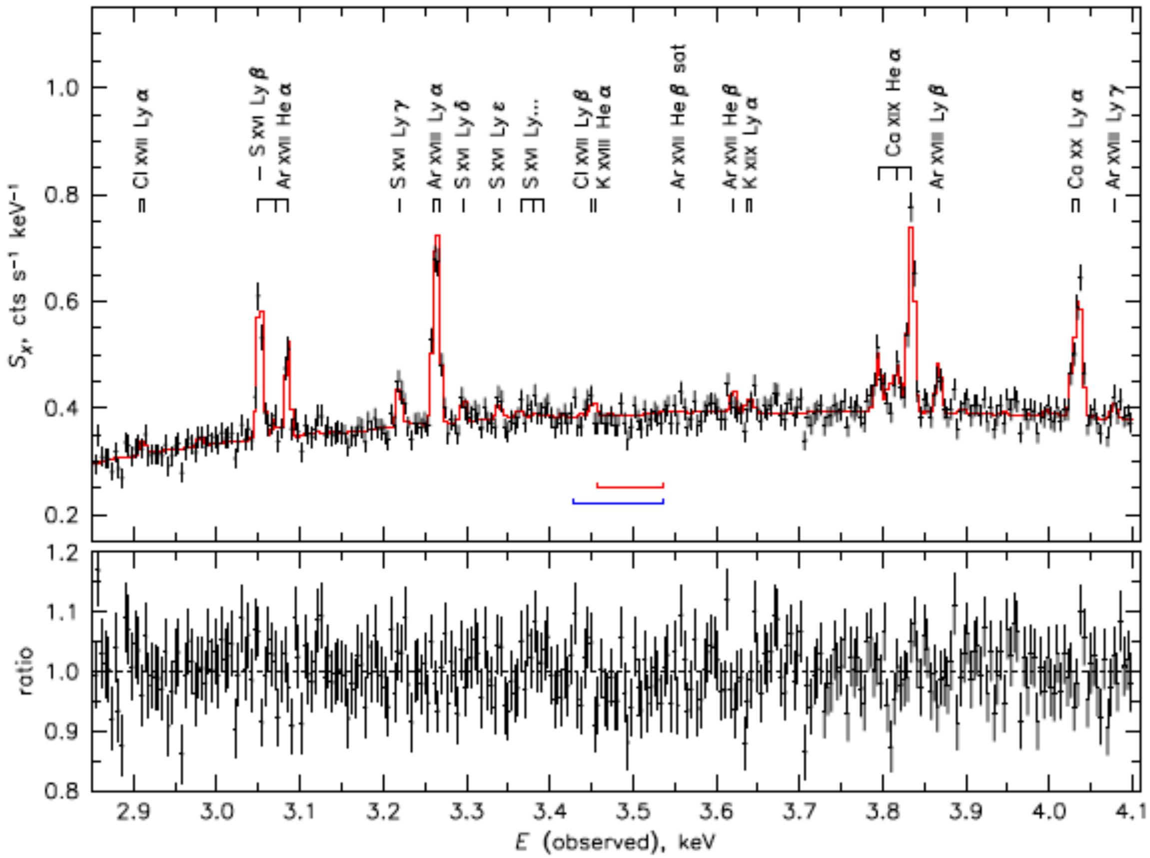


By now the 3.5 keV line has been observed with 4 existing X-ray telescopes, making the systematic (calibration uncertainty) origin of the line highly unlikely

Next step for 3.5 keV line: resolve the line

- Astro-H/Hitomi – new generation X-ray spectrometer with a superb spectral resolution
- Launched February 17, 2016
- ☹ Lost few weeks later
- Before its failure observed the center of Perseus galaxy cluster
- The observations was in calibration phase (additional filters block most of X-ray below 3 keV)

Perseus center spectrum [1607.07420]



What did we learn with existing Hitomi data?

- Due to its super energy resolution, *Hitomi* can distinguish between atomic line broadening (thermal velocities $\sim 10^2\,\mathrm{km/sec}$) and decaying dark matter line broadening (virial velocity $\sim 10^3\,\mathrm{km/sec}$)
- Even the short observation of Hitomi showed that Potassium, Clorium, etc. do not have super-solar abundance in Perseus cluster $\Rightarrow$ 3.5 keV line is **not** astrophysical
- Bounds much weaker for a **broad** (dark matter) line $\Rightarrow$ not at tension with previous detections

- This does not seem to be astrophysics (Hitomi spectrum)
- This does not seem to be systematics (4 different instruments)
- ???

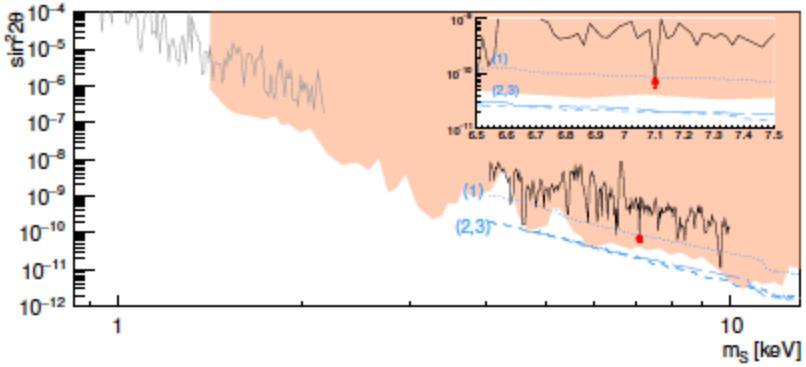
Future of decaying dark matter searches in X-rays

Another Hitomi

JAXA is planning to send a replica of Hitomi satellite (within about 2 years)

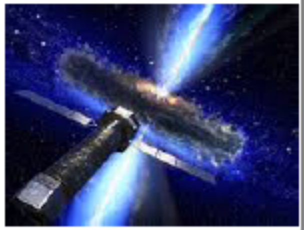
Microcalorimeter on sounding rocket (2017)

- Large field-of-view and very high spectral resolution
- Can resolve narrow lines from diffuse sources
- Flying time $\sim 10^2$ sec



Athena+

- Large ESA X-ray mission (2028) with X-ray spectrometer (X-IFU)
- Very large collecting area ($10\times$ that of XMM)



ALPs

Physics case for axions: Strong CP problem

> Most general gauge invariant Lagrangian of QCD up to dimension four:

$$\mathcal{L} = -\frac{1}{4} G^a_{\mu\nu} G^{a,\mu\nu} + \overline{q}\,(i\gamma_\mu D^\mu - \mathcal{M}_q)\, q - \frac{\alpha_s}{8\pi}\,\theta\, G^a_{\mu\nu}\tilde{G}^{a,\mu\nu}$$

- Fundamental parameters of QCD: strong coupling α_s, quark masses m_u, m_d, ..., and theta parameter

$$\overline{\theta} = \theta + \arg\,\det\,\mathcal{M}_q$$

> Theta term $\propto G^a_{\mu\nu}\tilde{G}^{a,\mu\nu} \propto \mathbf{E}^a \cdot \mathbf{B}^a$ odd under P and T, i.e. leads to CP violation in flavor conserving interactions

> Most sensitive probe of P and T violation in flavor conserving interactions: electric dipole moment (EDM) of neutron; experimentally

$$|d_n| < 2.9 \times 10^{-26}\ e\,\mathrm{cm}$$

> Strong CP problem:

$$d_n(\overline{\theta}) \sim \frac{e\overline{\theta} m_u m_d}{(m_u + m_d) m_n^2} \sim 6 \times 10^{-17}\ \overline{\theta}\ e\,\mathrm{cm} \Rightarrow |\overline{\theta}| \lesssim 10^{-9}$$

Physics case for axions: Strong CP problem

- Peccei-Quinn solution of strong CP problem based on observation that the vacuum energy in QCD, inferred from effective chiral Lagrangian,

$$V(\overline{\theta}) = \frac{m_\pi^2 f_\pi^2}{2} \frac{m_u m_d}{(m_u + m_d)^2} \overline{\theta}^2 + \mathcal{O}(\overline{\theta}^4)$$

has localised minimum at vanishing theta parameter:

If theta were a dynamical field, its vacuum expectation value (vev) would dynamically relax to zero

- Introduce field a(x) as dynamical theta parameter, enjoying a shift symmetry, $a \to a + \text{const.}$, broken only by anomalous couplings to gauge fields,

$$\mathcal{L} \supset \frac{1}{2} \partial_\mu a \, \partial^\mu a - \frac{\alpha_s}{8\pi} \left(\bar{\theta} + \frac{a}{f_a} \right) G^b_{\mu\nu} \tilde{G}^{b,\mu\nu} - \frac{\alpha}{8\pi} C_{a\gamma} \frac{a}{f_a} F_{\mu\nu} \tilde{F}^{\mu\nu} + \ldots$$

  - Can eliminate theta by shift $a(x) \to \overline{a}(x) \equiv a(x) + \overline{\theta} f_a$; QCD dynamics (see above) leads to vanishing vev, $\langle \overline{a} \rangle = 0$, i.e. P, T, and CP conserved
  - Elementary particle excitation of field around vev: axion (Weinberg 78; Wilczek 78)

Physics case for axions: Strong CP problem

$$\mathcal{L} \supset \frac{1}{2}\partial_\mu a\, \partial^\mu a - \frac{\alpha_s}{8\pi}\left(\bar{\theta} + \frac{a}{f_a}\right) G^b_{\mu\nu}\tilde{G}^{b,\mu\nu} - \frac{\alpha}{8\pi} C_{a\gamma}\frac{a}{f_a} F_{\mu\nu}\tilde{F}^{\mu\nu} + \ldots$$

- For large decay constant f_a: prime paradigm of a WISP (Kim 79; Shifman et al 80; Zhitnitsky 80; Dine et al 81)

$$g_{a\gamma} = \frac{\alpha}{2\pi f_a}\left(C_{a\gamma} - \frac{2}{3}\frac{m_u + 4m_d}{m_u + m_d}\right) \sim 10^{-12}\ \mathrm{GeV}^{-1}\left(\frac{10^9\,\mathrm{GeV}}{f_a}\right)$$

$$m_a = \frac{m_\pi f_\pi}{f_a}\frac{\sqrt{m_u m_d}}{m_u + m_d} \simeq 6\,\mathrm{meV} \times \left(\frac{10^9\,\mathrm{GeV}}{f_a}\right)$$

- Strong constraints from astrophysics (non-excessive energy loss of stars):

$$f_a \gtrsim 10^9\ \mathrm{GeV}$$

Physics case for axions and ALPs: NGBs of SSB

- In 4D field theoretic extensions of the Standard Model (SM), axion field realised as phase of a complex $SU(2)_L \times U(1)_Y$ singlet scalar field whose vev breaks a global anomalous chiral $U(1)_{\mathrm{PQ}}$ symmetry,

$$\Phi(x) = \frac{v_{\mathrm{PQ}} + \rho(x)}{\sqrt{2}} \, \mathrm{e}^{ia(x)/f_a}$$

  - At energies much below the symmetry breaking scale v_{PQ} the low-energy effective field theory is that of a (pseudo-)Nambu-Goldstone Boson (NGB) with decay constant

$$f_a = v_{\mathrm{PQ}}/C_{ag}$$

- More axion-like particles (ALPs) may arise as NGBs from the breaking of more than one anomalous $U(1)_{\mathrm{PQ}}$

$$\mathcal{L} = \frac{1}{2}\,\partial_\mu a_i\,\partial^\mu a_i - \frac{\alpha_s}{8\pi}\left(\overline{\theta} + C_{ig}\frac{a_i}{f_{a_i}}\right) G^b_{\mu\nu}\tilde{G}^{b,\mu\nu} - \frac{\alpha}{8\pi}C_{i\gamma}\frac{a_i}{f_{a_i}}\,F_{\mu\nu}\tilde{F}^{\mu\nu} + \ldots$$

Photon/axion conversions

- Axions proposed as a by-product of the Peccei-Quinn solution of the strong-CP problem.
- Axion-like particle (ALP): mass and coupling not related.
- Can be suitable dark matter candidates.
- Expected to convert into photons (and vice-versa) in the presence of magnetic fields.

Probability of conversion (e.g.Raffelt & Stodolsky 88, Mirizzi+07):

$$P_0 = (\Delta_B s)^2 \frac{\sin^2(\Delta_{\rm osc} s/2)}{(\Delta_{\rm osc} s/2)^2}.$$

with

$$\Delta_B = \frac{B_t}{2M} \simeq 1.7 \times 10^{-21} M_{11} B_{\rm mG}\ {\rm cm}^{-1},$$

$$\Delta_{\rm osc}^2 \simeq (\Delta_{\rm CM} + \Delta_{\rm pl} - \Delta_a)^2 + 4\Delta_B^2,$$

Photon/axion conversions the main vehicle used in axion searches at present (ADMX, CAST...).

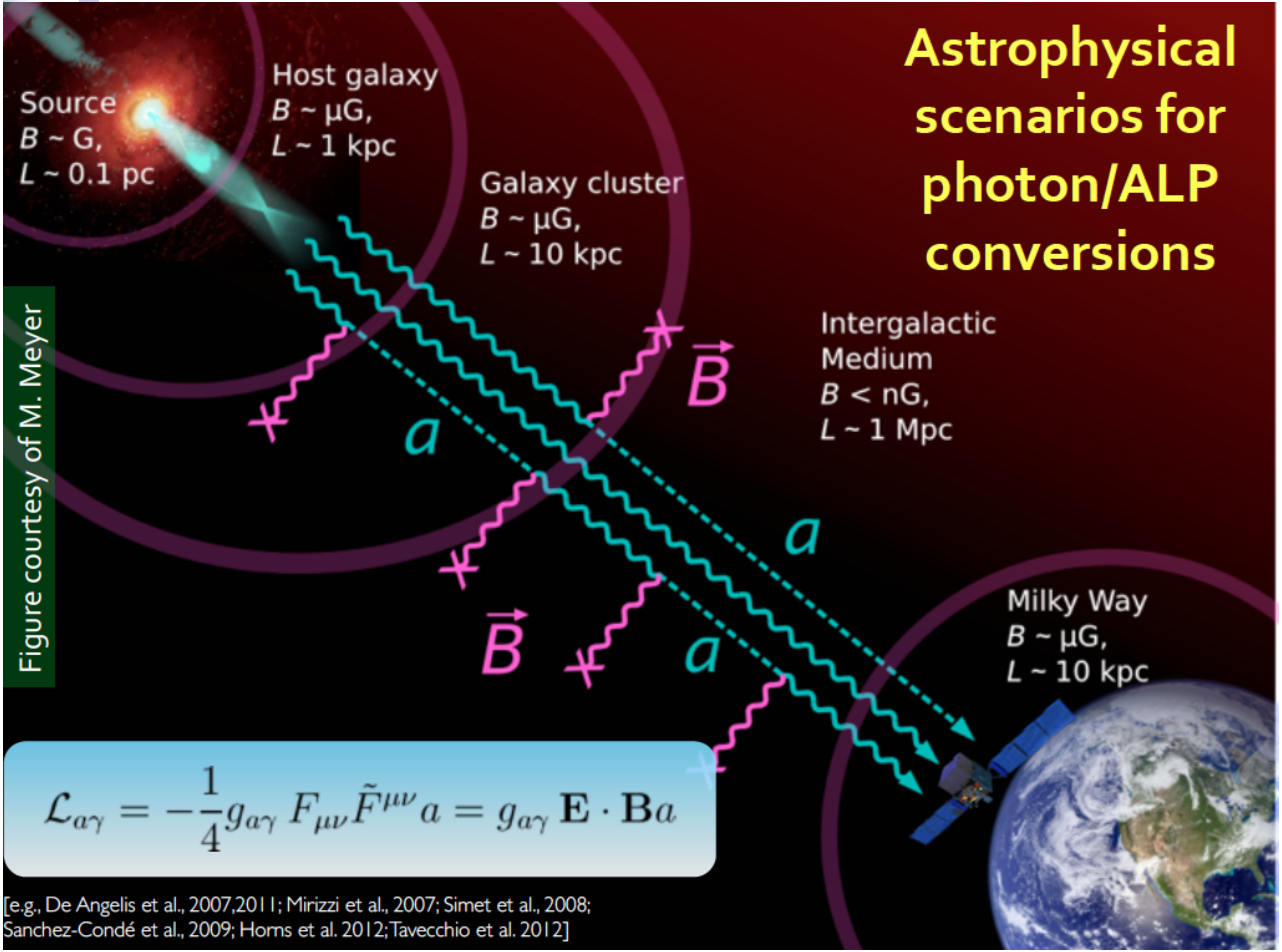
Some astrophysical environments fulfill the mixing requirements

$$\frac{15 \cdot B_G \cdot s_{pc}}{M_{11}} \geq 1$$

$M_{11} \geq 0.114$ GeV (CAST limit)

- M_{11}: coupling constant inverse ($g_{ag}/10^{11}$ GeV)
- B_G: magnetic field (G)
- s_{pc}: size region (pc)

Astrophysical scenarios for photon/ALP conversions



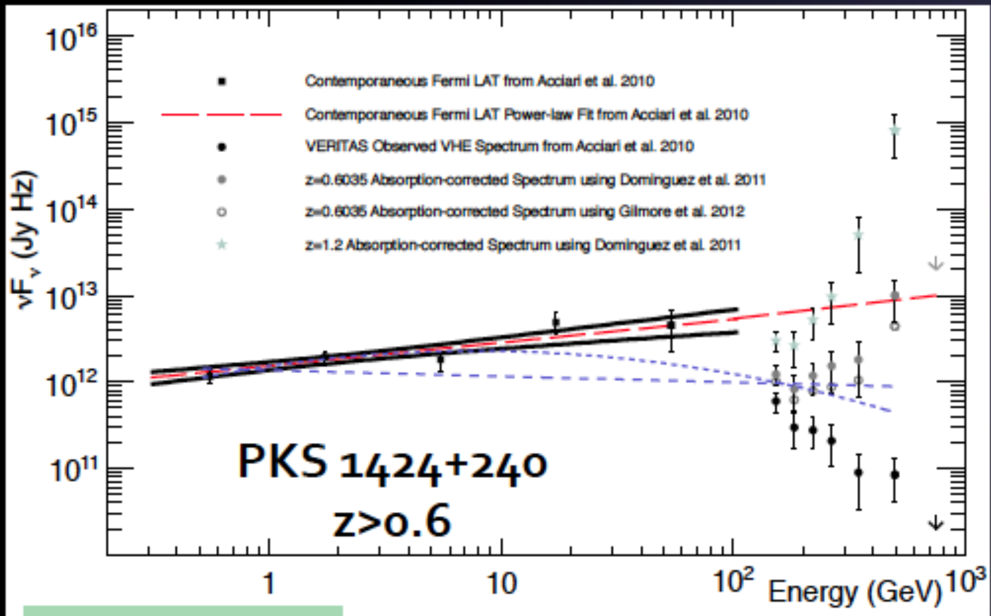
$$\mathcal{L}_{a\gamma} = -\frac{1}{4} g_{a\gamma} F_{\mu\nu} \tilde{F}^{\mu\nu} a = g_{a\gamma} \mathbf{E} \cdot \mathbf{B} a$$

[e.g., De Angelis et al., 2007,2011; Mirizzi et al., 2007; Simet et al., 2008; Sanchez-Condé et al., 2009; Horns et al. 2012; Tavecchio et al. 2012]

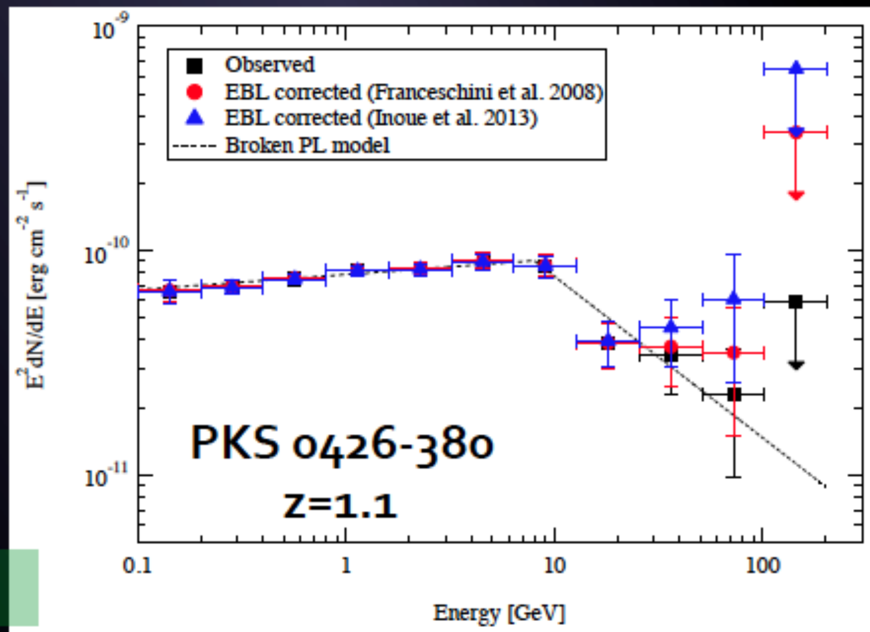
Hints of new Physics in γ-ray data?

SPECTRAL "HARDENING" at high τ

Some de-absorbed, *intrinsic* AGN spectra are best described by power laws with spectral indices smaller than 1.5 – **too "hard" AGN spectra**



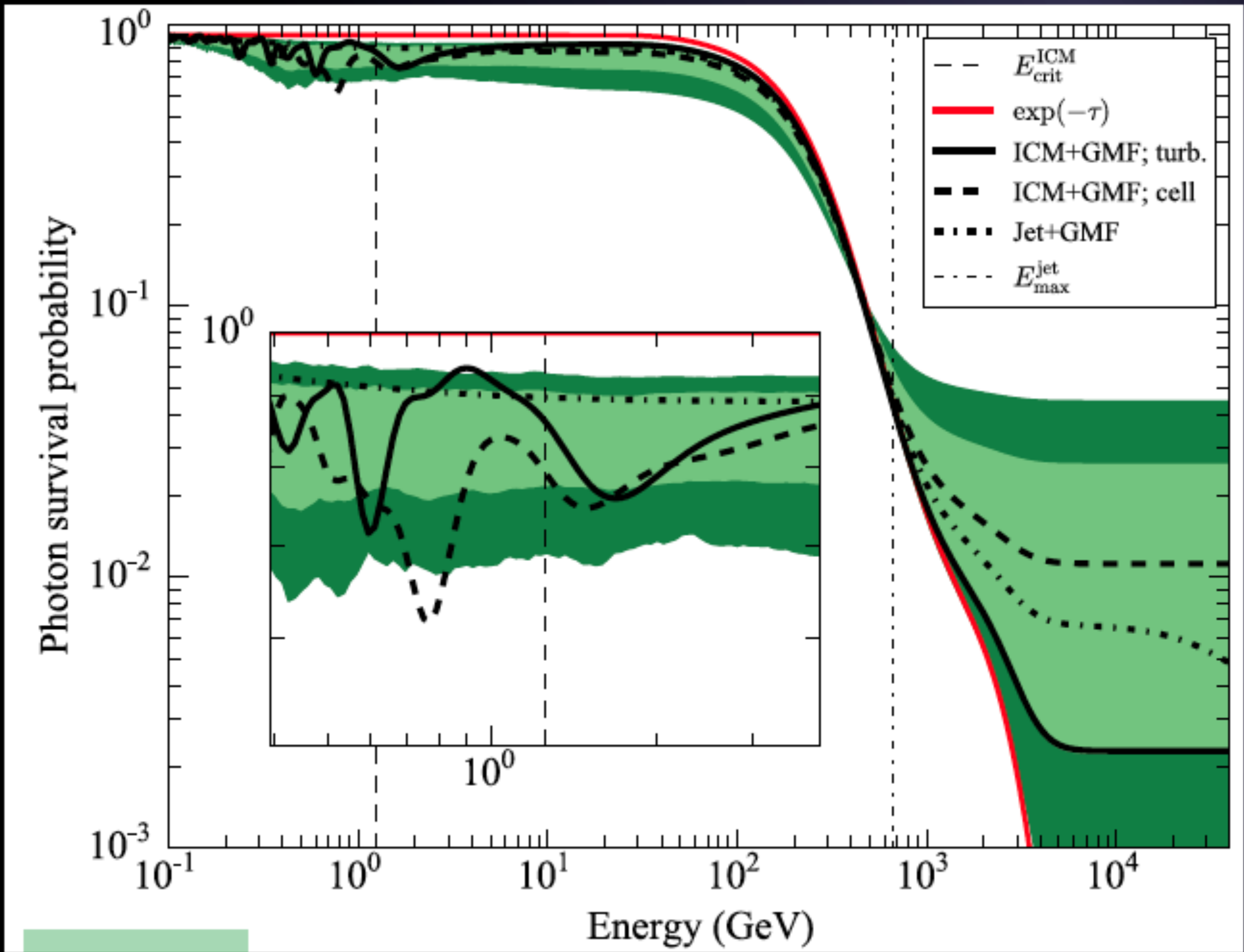
Furniss+13c



Tanaka+13

Note that the last data points give τ ~ 5 !!

ALPs modify the spectrum of AGNs

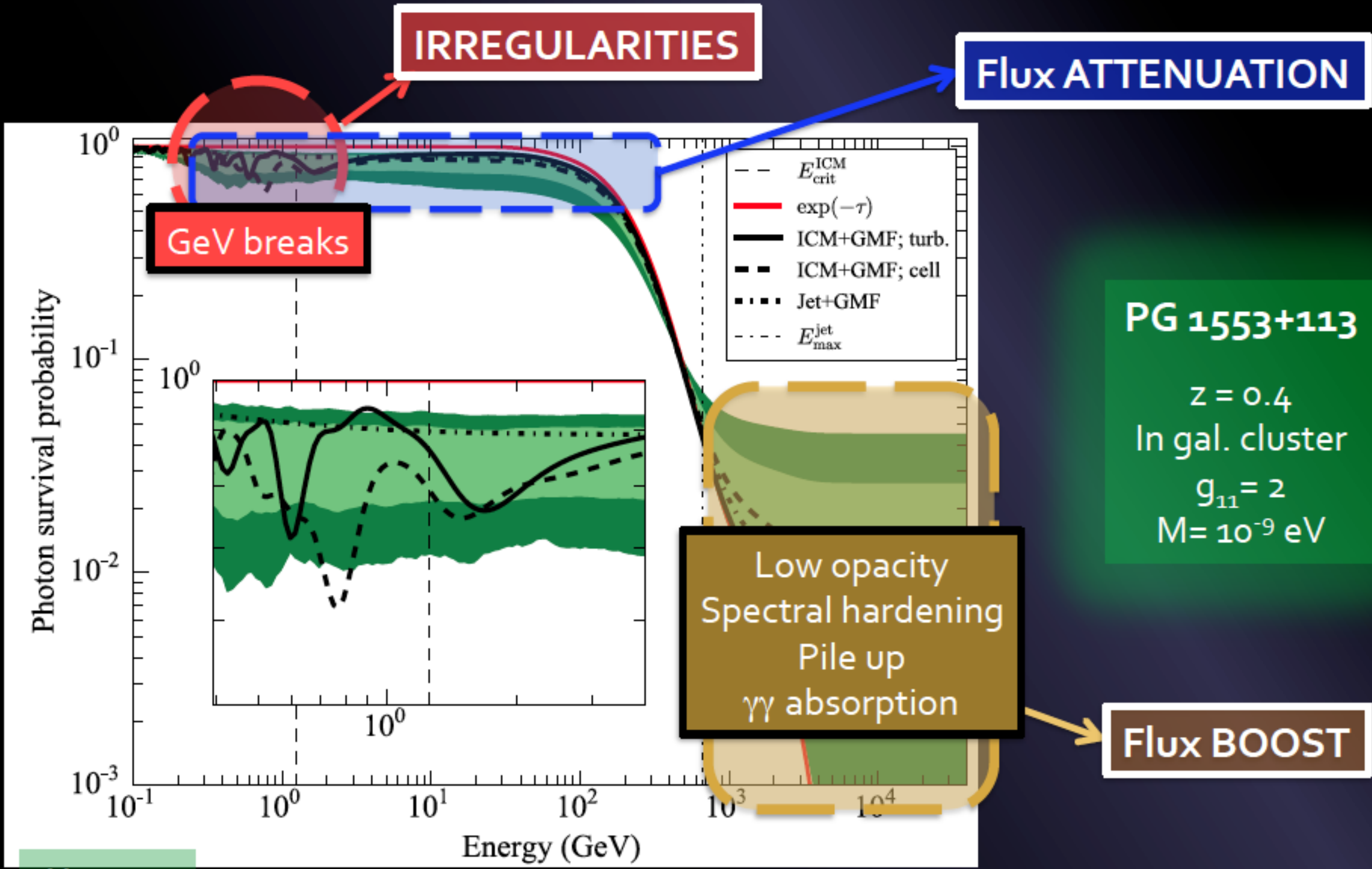


Meyer+14

PG 1553+113

z = 0.4
In gal. cluster
g_{11}= 2
M= 10^{-9} eV

ALPs could explain these anomalies



PG 1553+113

z = 0.4

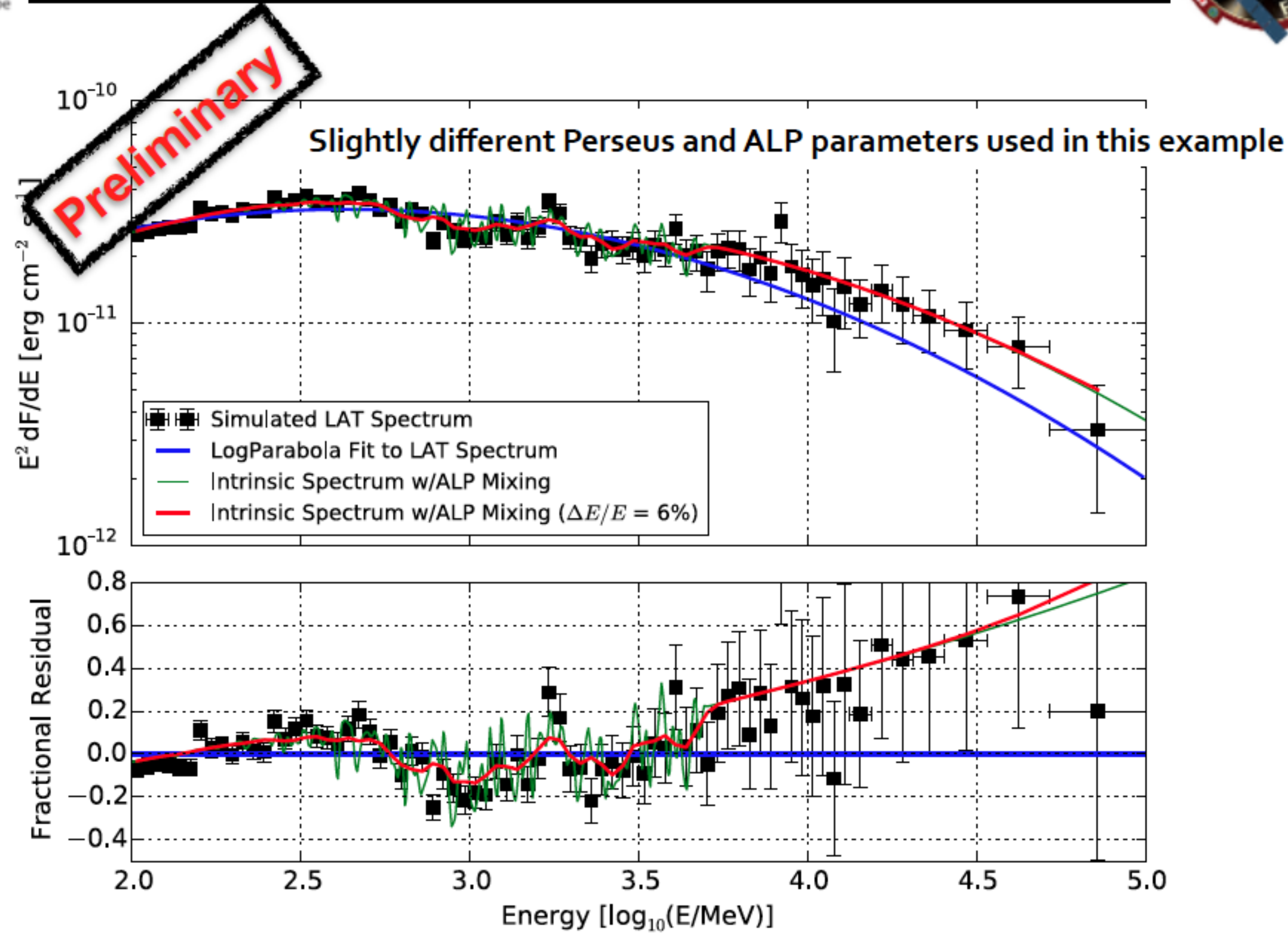
In gal. cluster

g_{11} = 2

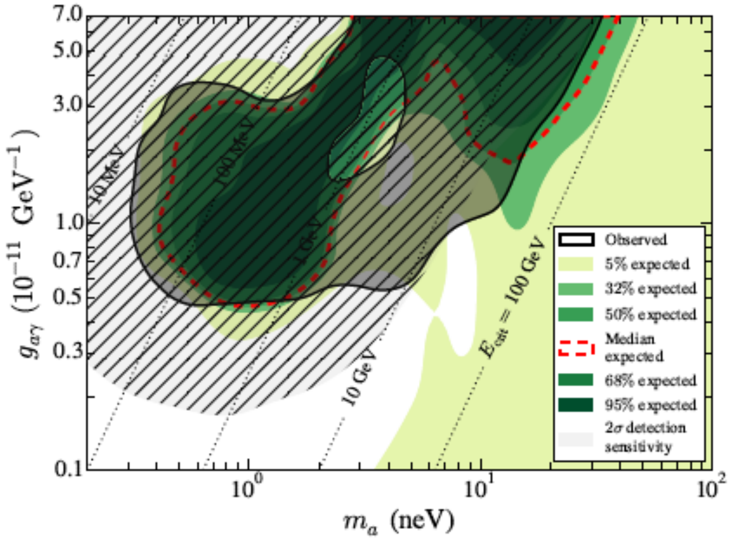
M= 10^{-9} eV

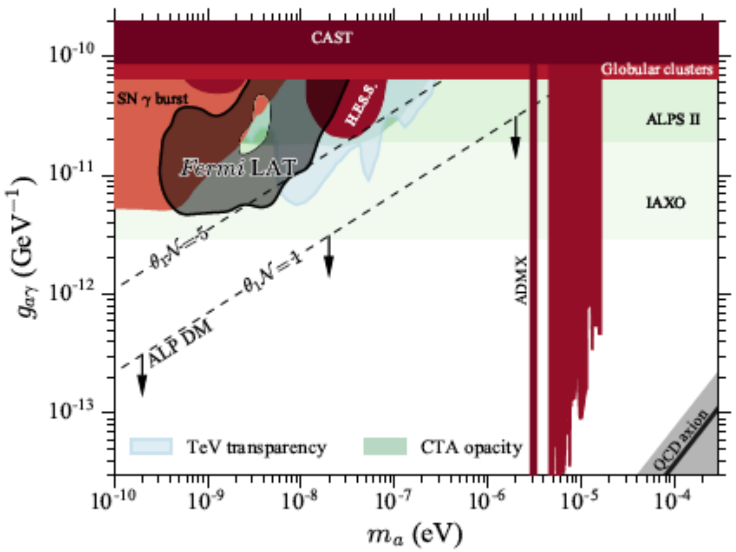
Meyer+14

Simulated LAT spectrum of NGC1275 including Axion-like particles



Fermi search for ALPs





WIMPs

Basic Concepts

A. dark matter particles could interact with standard model particles and reach thermal equilibrium. Non-thermal processes are also OK.

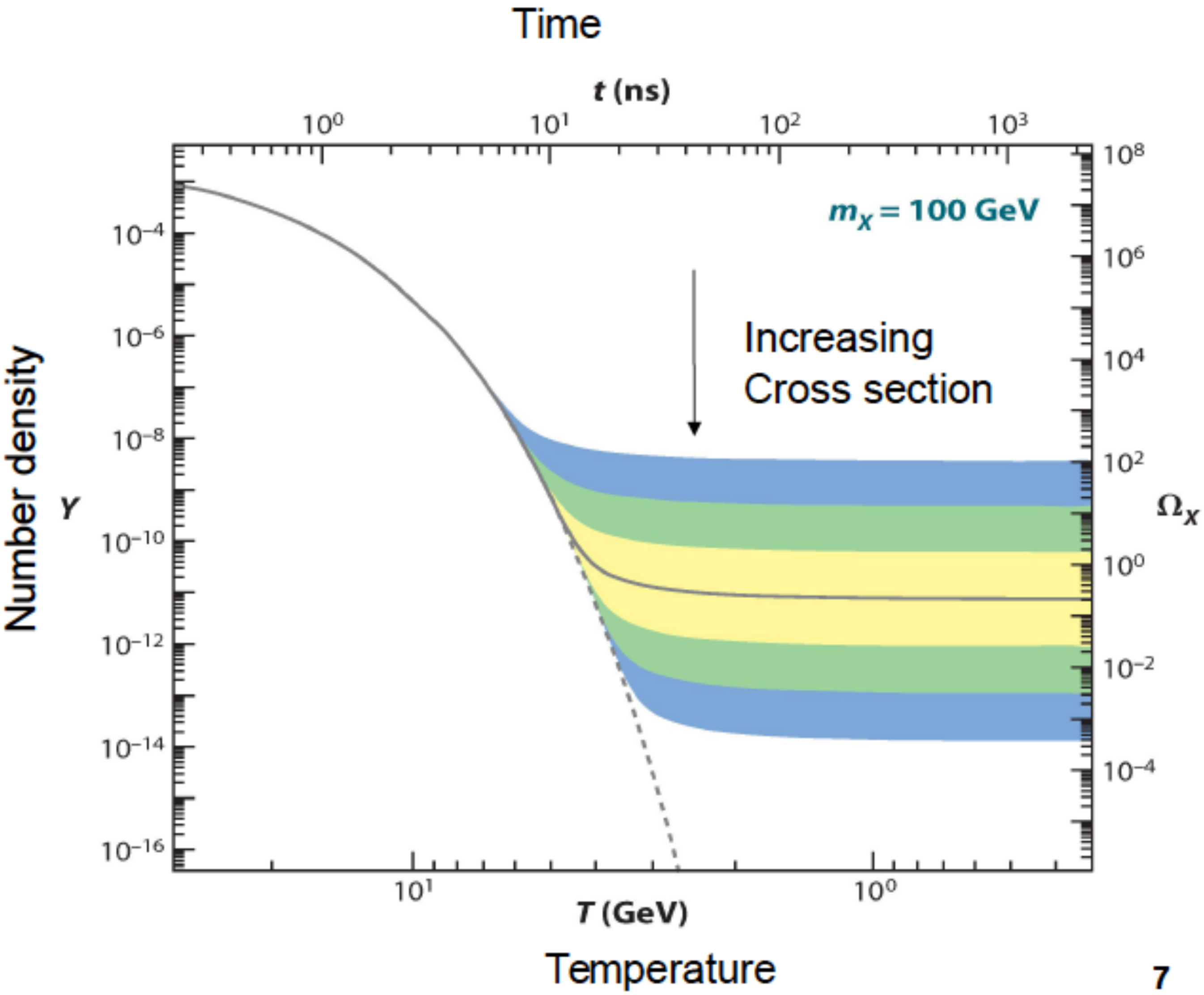
B. After the universe cooled down and expanded, eventually the expansion rate equaled the interaction rate → freeze-out.

C. After the freeze-out the dark matter particles clustered forming the structures we observe today.

D. In the WIMP paradigm the abundance is connected to the annihilation cross section at freeze-out.

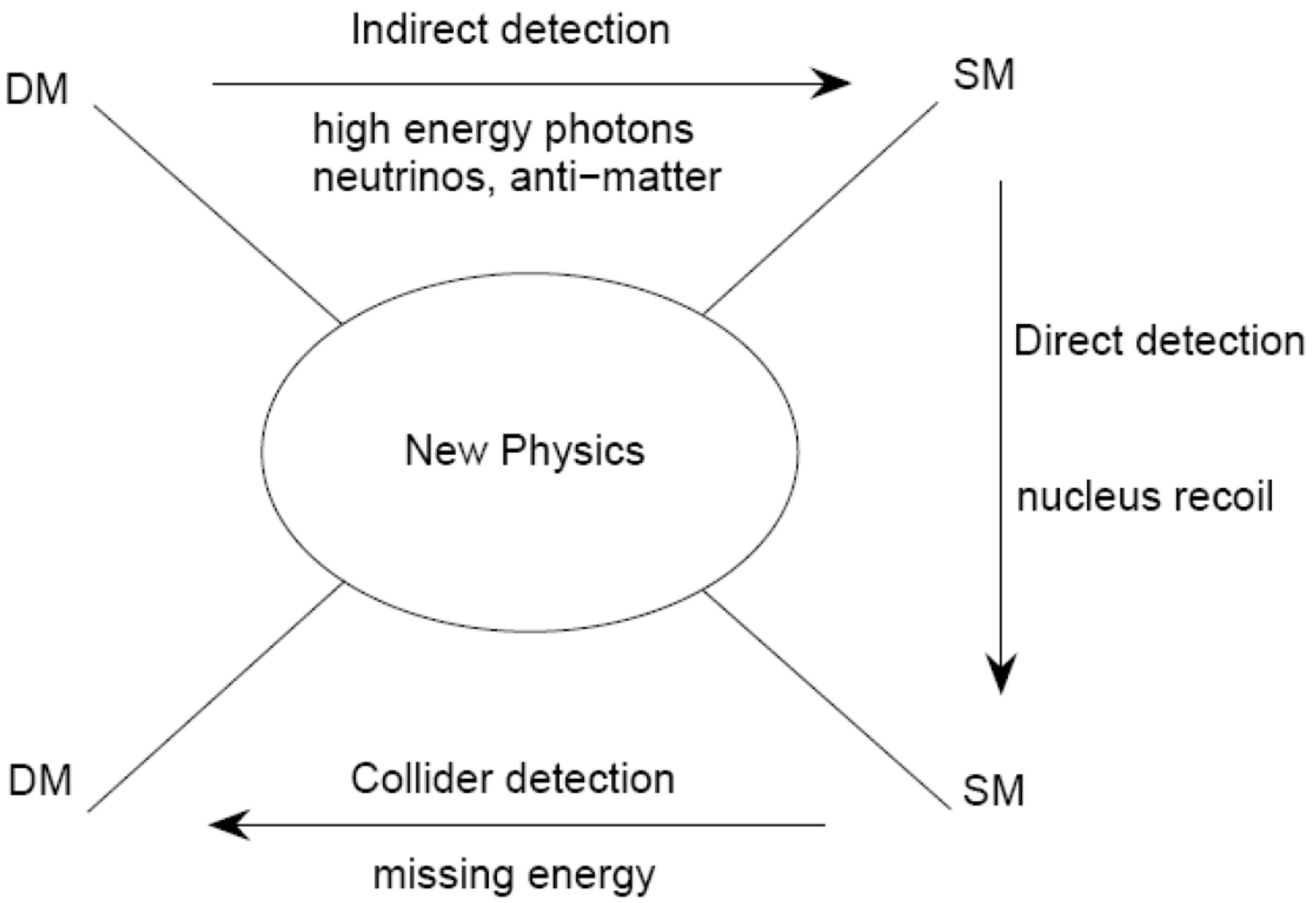
Dark Matter Abundance (WIMP)

Right relic abundance → Annihilation cross section at the weak scale



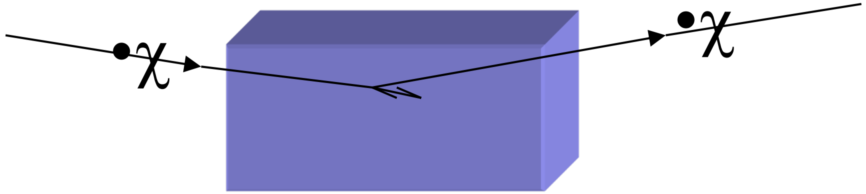
• The methods of detecting Dark Matter

Detection of particle dark matter

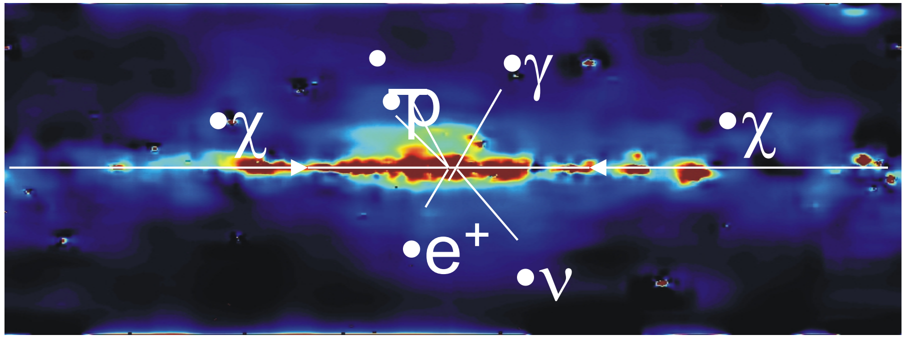


The detection of dark matter

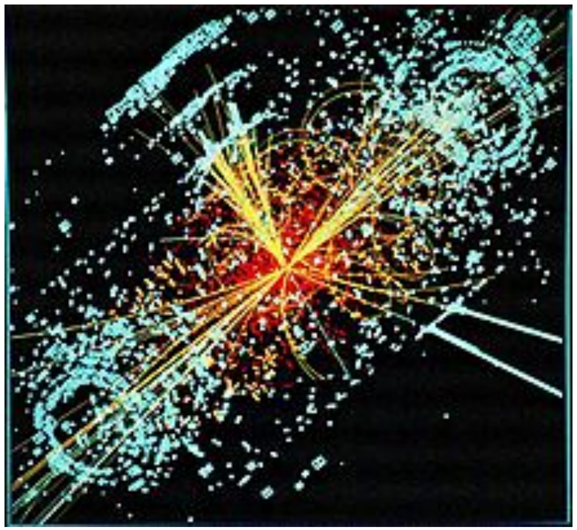
- Direct detection：PandaX， CDEX，Xenon, CDMS, DAMA, COGENT and so on



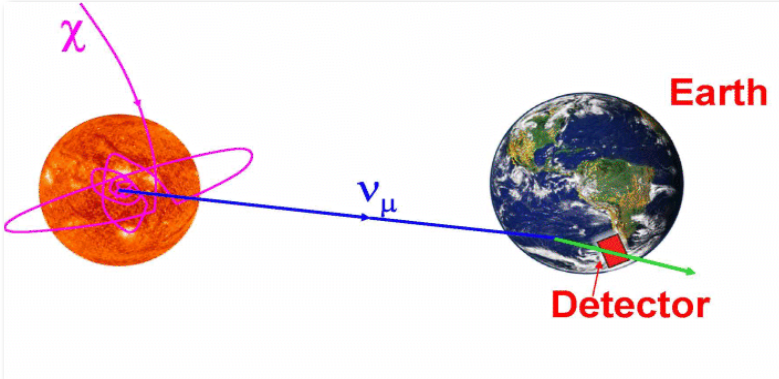
- Indirect detection ：Pamela ,ATIC, Fermi, HESS， AMS02，DAMPE and so on



- Collider: LHC



Indirect Detection of Dark Matter



Neutrinos
in the core of the Sun

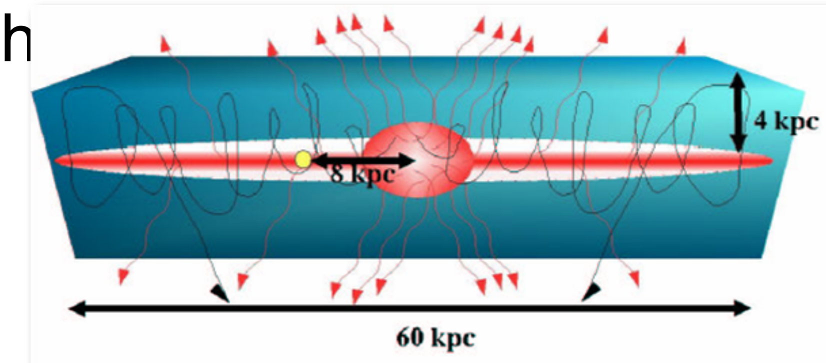
Gamma Rays from annihilations
in the galactic halo, near the

galactic center, in dwarf galaxies, etc.

Positrons/Antiprotons from annihilations
throughout the galactic halo

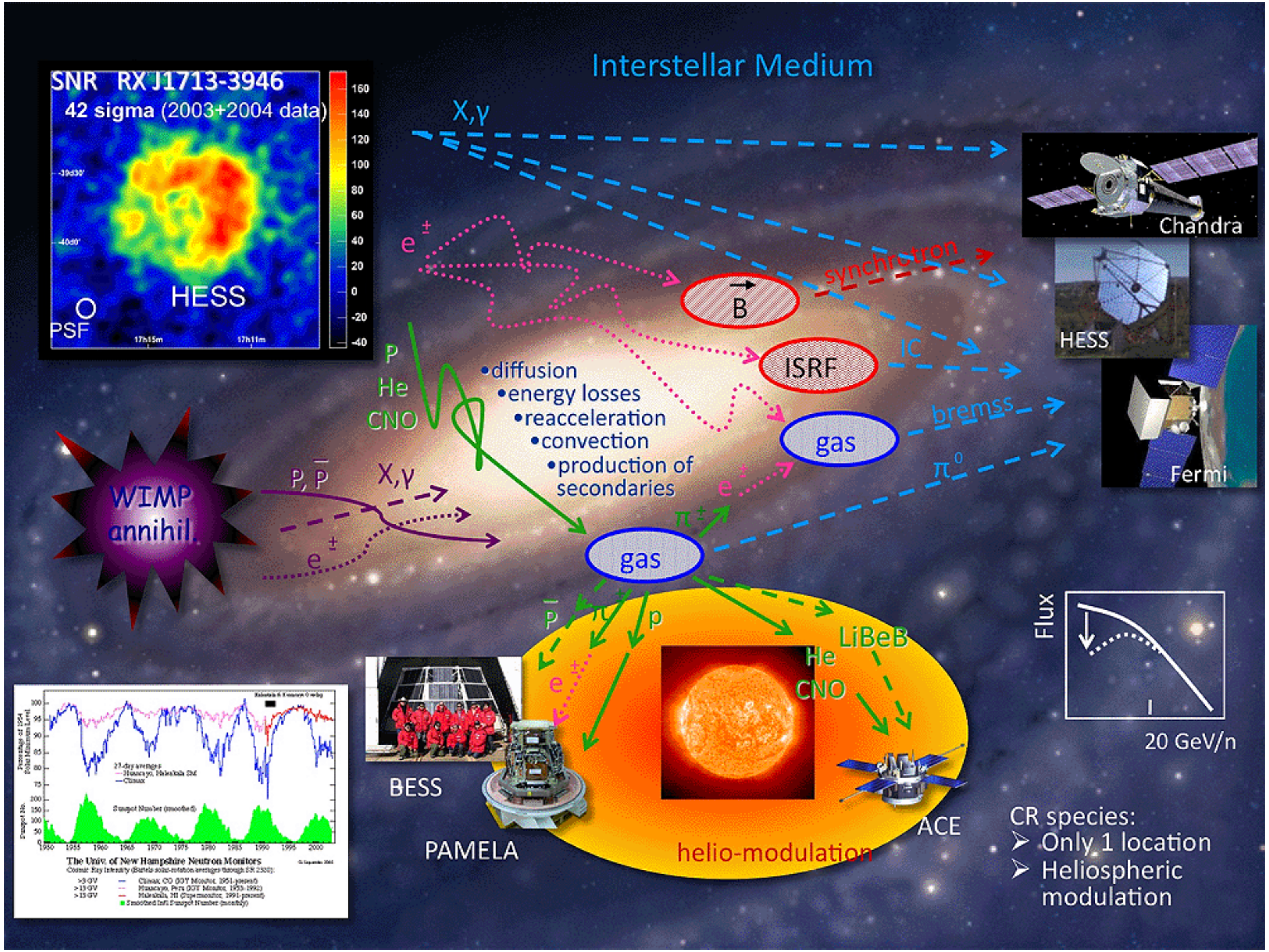
Synchrotron Radiation from
electron/positron interactions with
magnetic fields of the inner

galaxy

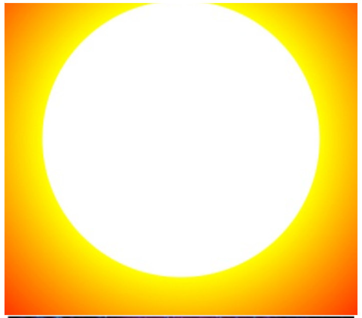


•**From Dan Hooper**

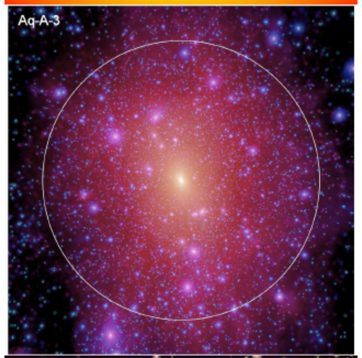
•Cosmic Ray Propagation



•Targets to detect dark matter particles

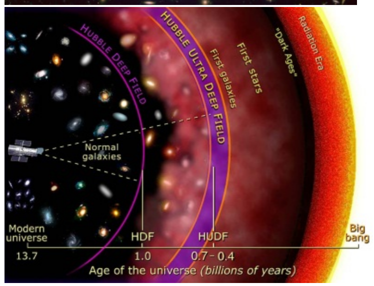


•Sun

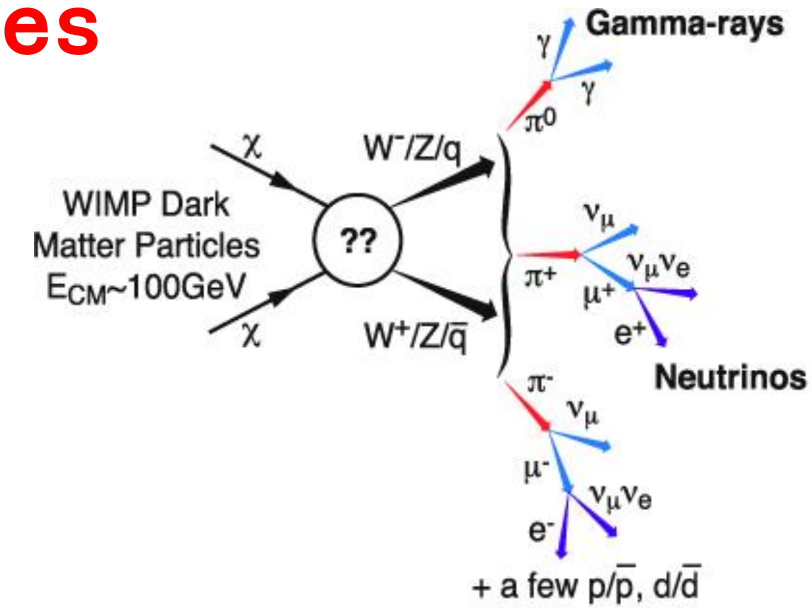


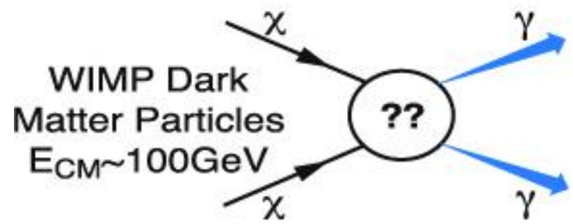
•Galaxy

•Galaxy Cluster



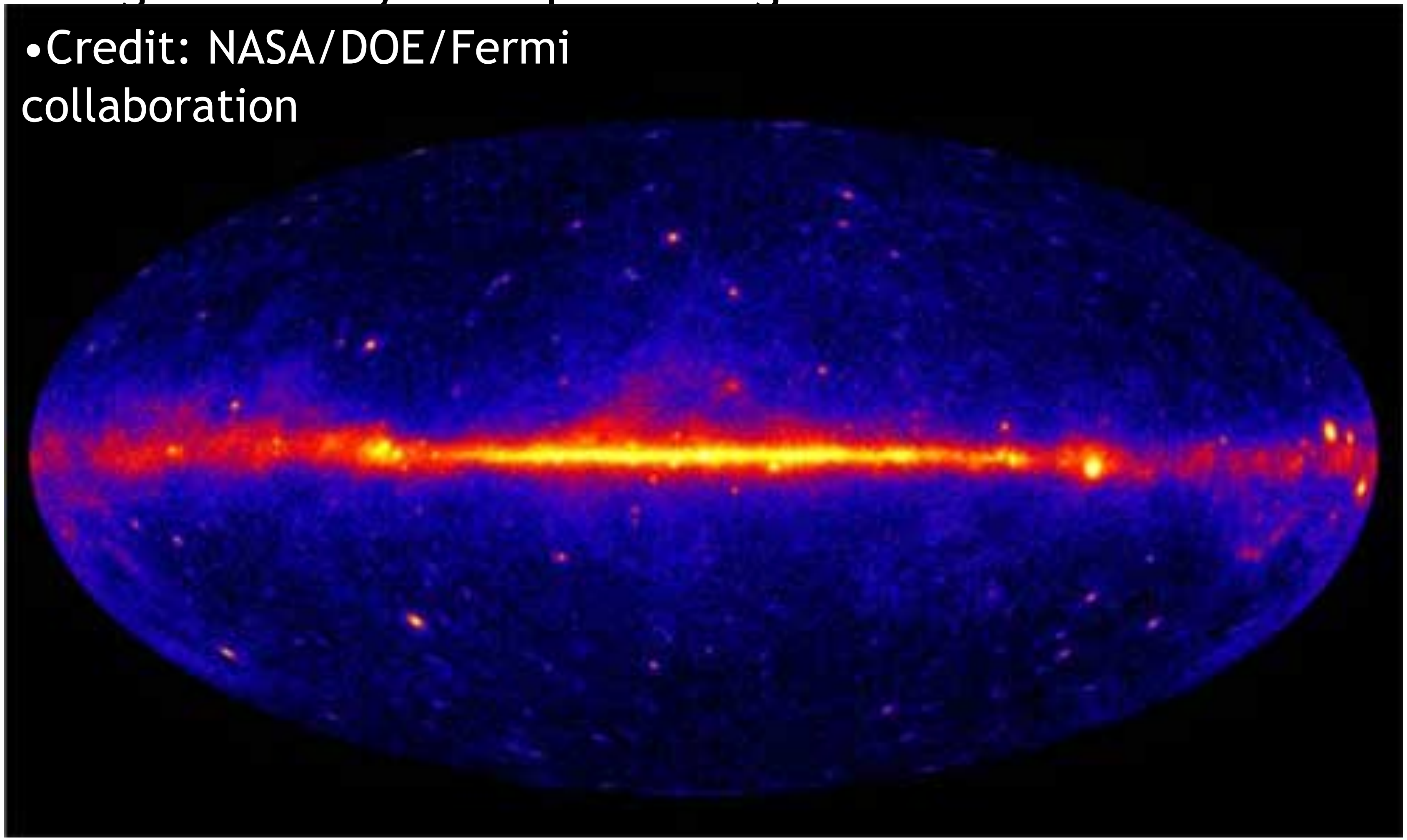
•Deep extragalactic space and early Universe





•Baltz et al. 2008

- Fermi gamma-rays can provide good test of the DM models

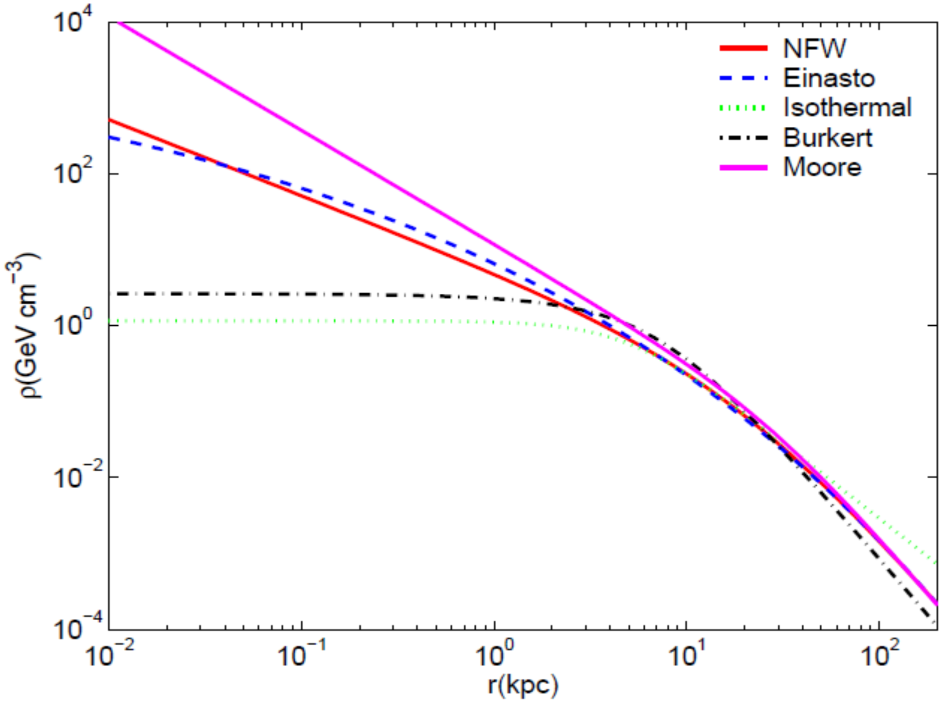


•Credit: NASA/DOE/Fermi collaboration

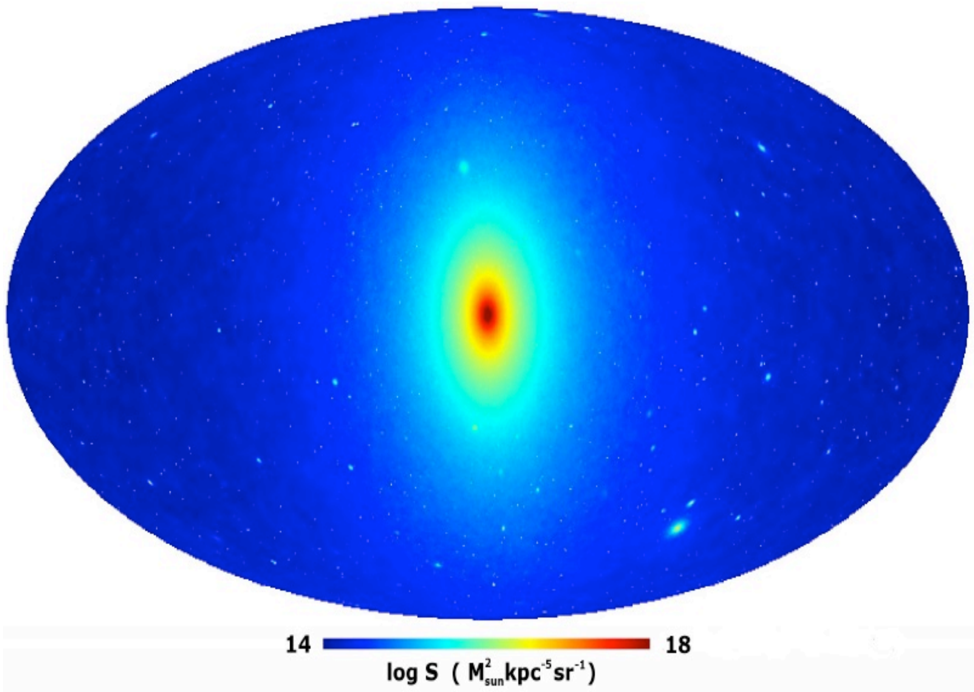
- Galactic center
- Galactic halo
- Dwarf galaxies

- Clusters
- Extra-galactic diffuse
- Line search

The gamma-ray sky map produced by dark matter annihilation in our Galaxy

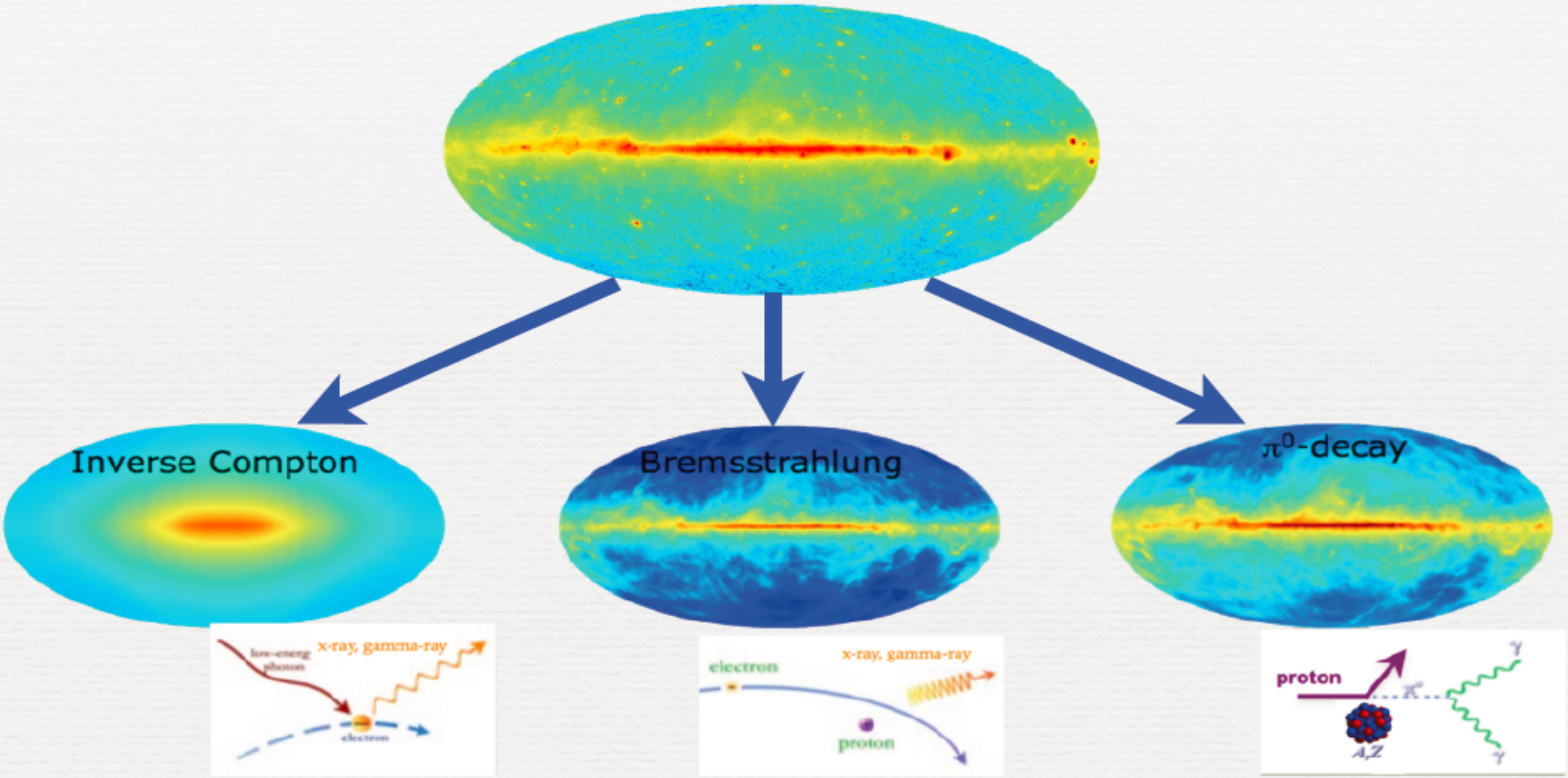


•The J-Factor of different dark matter profile models.



•The Galaxy center is the best region to detect dark matter.

Diffuse Galactic γ-ray Emission: Origin



Dark Matter Annihilation: Gamma-ray Excess at the Galactic Center

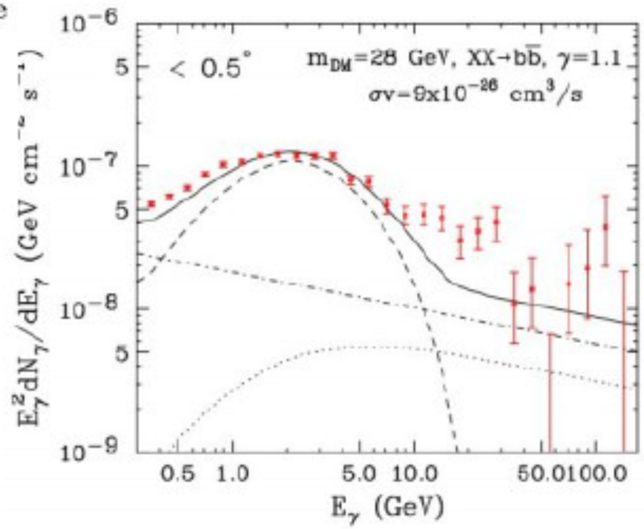
First observation (2009)

Possible Evidence For Dark Matter Annihilation In The Inner Milky Way From The Fermi Gamma Ray Space Telescope

Lisa Goodenough[1] and Dan Hooper[2,3]

[1] Center for Cosmology and Particle Physics, Department of Physics, New York University, New York, NY 10003
[2] Center for Particle Astrophysics, Fermi National Accelerator Laboratory, Batavia, IL 60510
[3] Department of Astronomy and Astrophysics, University of Chicago, Chicago, IL 60637

We study the gamma rays observed by the Fermi Gamma Ray Space Telescope from the direction of the Galactic Center and find that their angular distribution and energy spectrum are well described by a dark matter annihilation scenario. In particular, we find a good fit to the data for dark matter particles with a 25-30 GeV mass, an annihilation cross section of $\sim 9 \times 10^{-26}$ cm^3/s, and that are distributed with a cusped halo profile, $\rho(r) \propto r^{-1.1}$, within the inner kiloparsec of the Galaxy. We cannot, however, exclude the possibility that these photons originate from an astro-



First Fermi-LAT team members – report (2009)

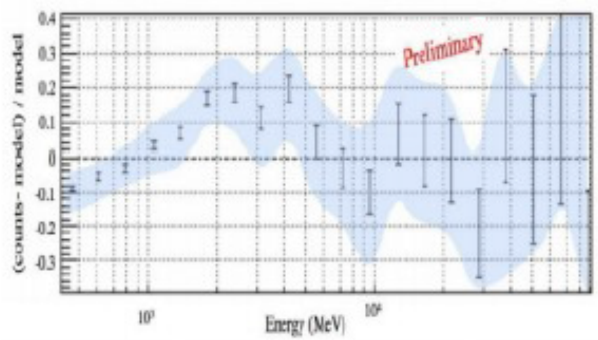
2009 Fermi Symposium, Washington, D.C., Nov. 2-5

Indirect Search for Dark Matter from the center of the Milky Way with the Fermi-Large Area Telescope

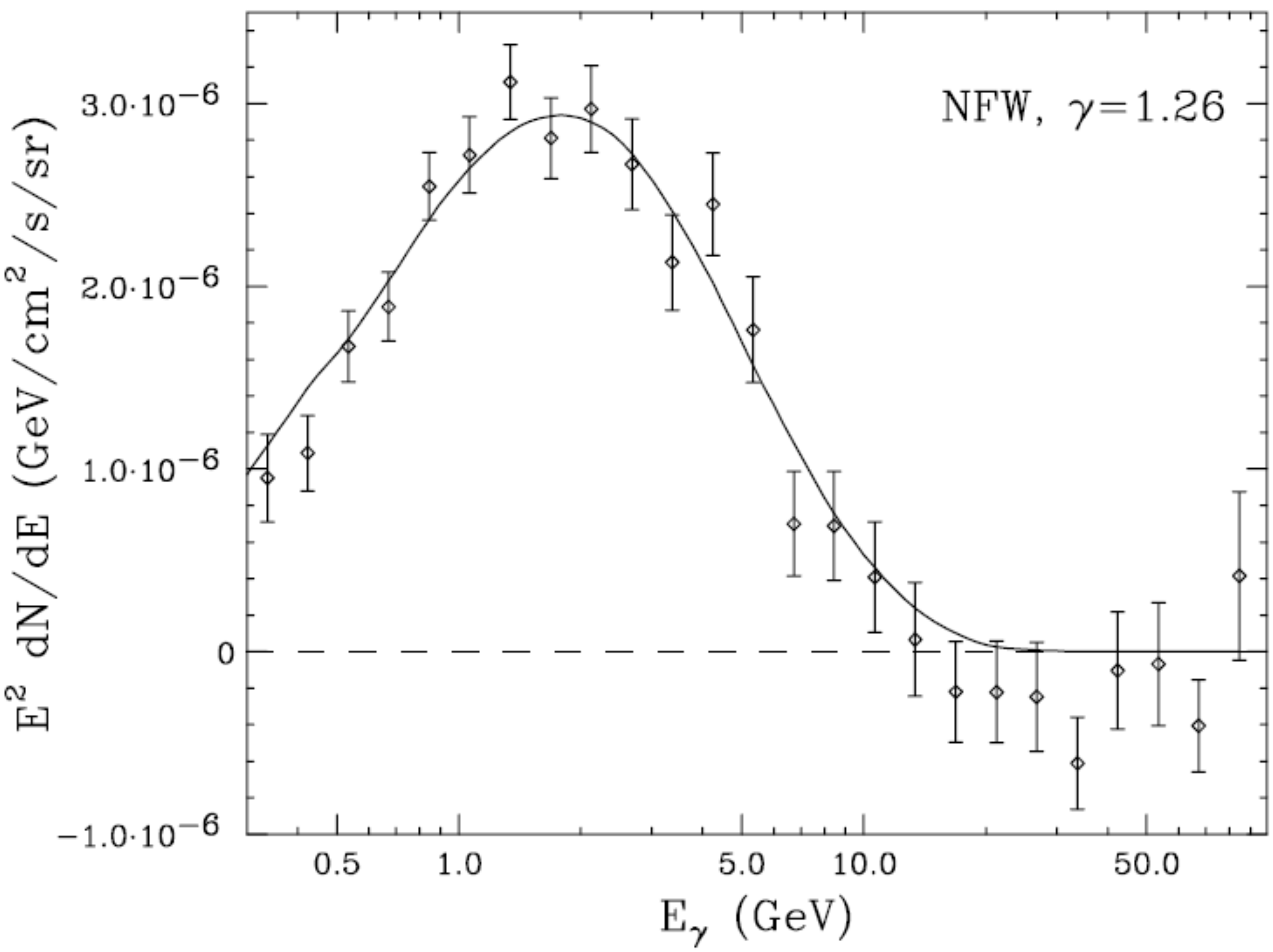
Vincenzo Vitale and Aldo Morselli, for the Fermi/LAT Collaboration
Istituto Nazionale di Fisica Nucleare, Sez. Roma Tor Vergata, Roma, Italy

ciations, is reported. The diffuse gamma ray backgrounds and discrete sources, as we know them today, can account for the large majority of the detected gamma-ray emission from the Galactic Center. Nevertheless a residual emission is left, not accounted for by the above models.

An improved model of the Galactic diffuse emission and a careful evaluation of new (possibly unresolved) sources (or source populations) will improve the sensitivity for a DM search.

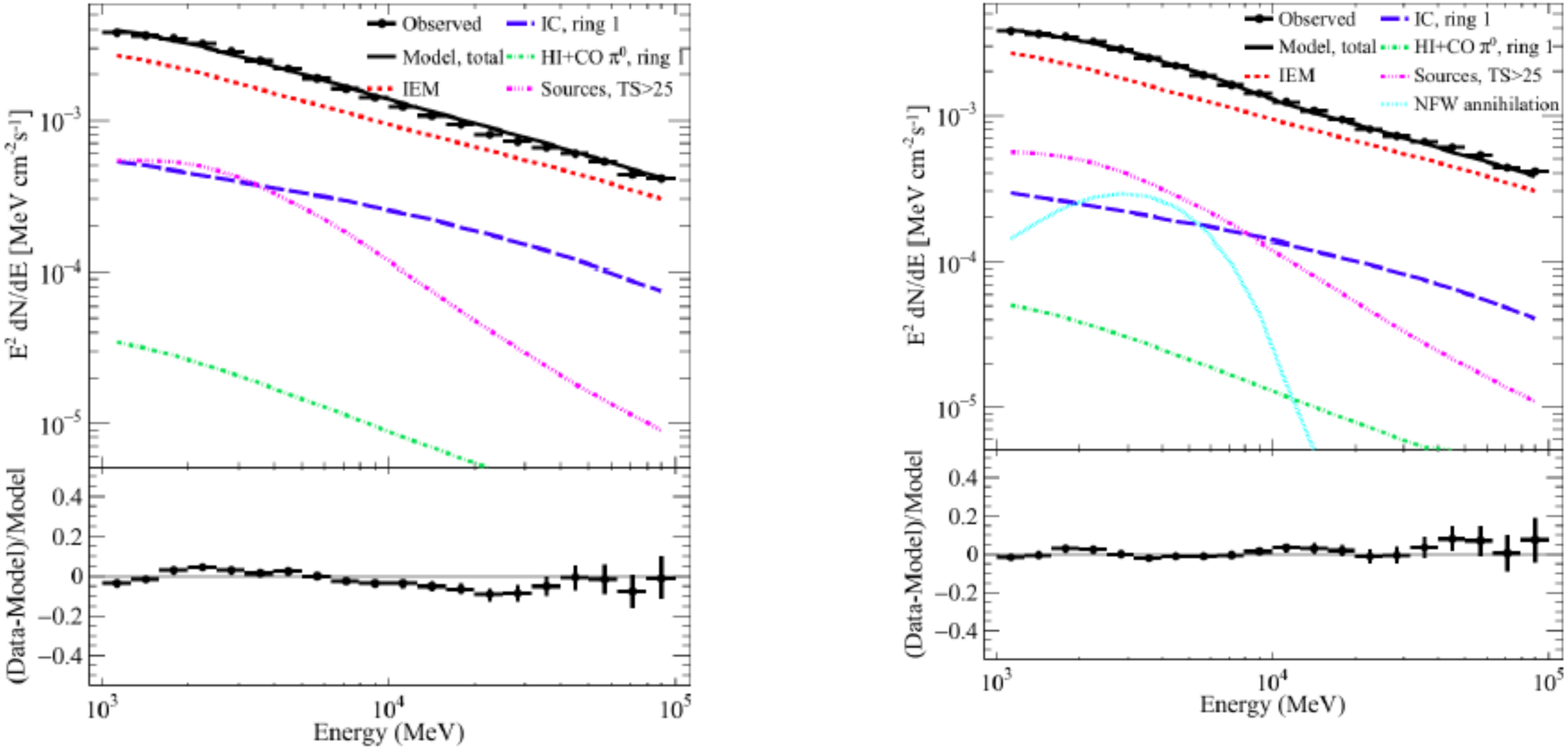


The GeV Excess



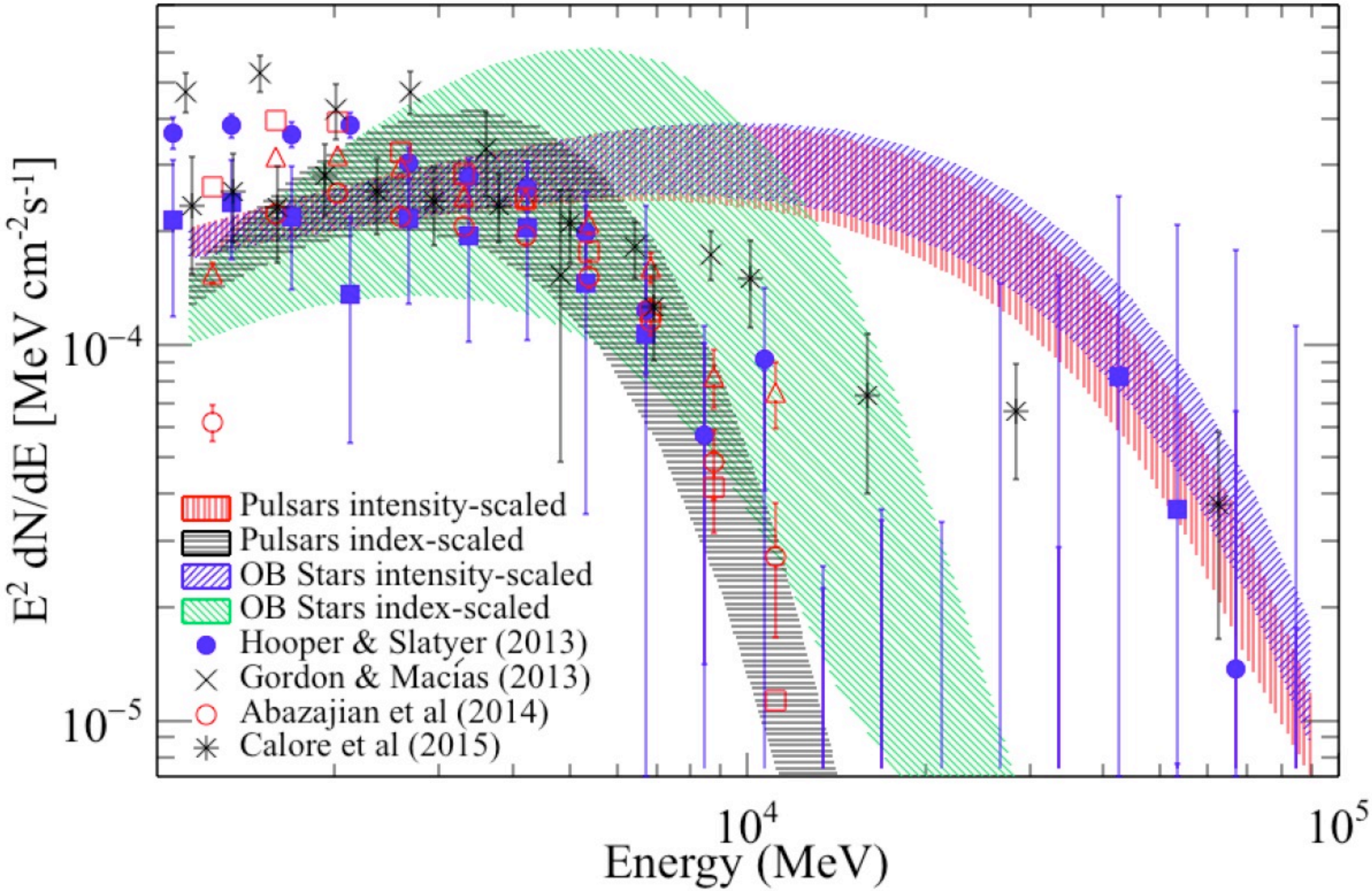
- Daylan et al. 2015

The GeV Excess



- Fermi collaboration 2015

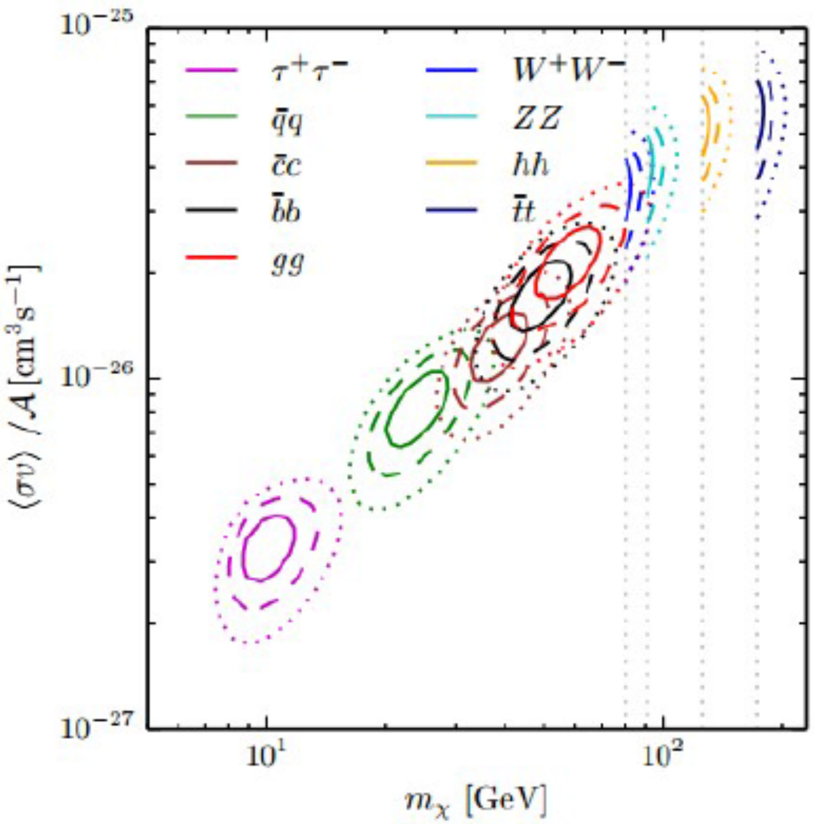
GeV excess in Fermi Pass 8 data



arXiv:1511.02938v1

Gamma-ray Excess in the Galactic Center

Dark Matter | **Interpretations** | **Other Sources**



F. Calore et al, 1411.4647

Many dark matter models fit the Galactic excess easily, but only some are consistent with direct detection and collider bounds.

1. Young Pulsars

   K. N. Abazajian+, 1402.4090.
   R. Bartels+, 1506.05104;
   S. Lee+,1506.05124;

2. Collisions between gas with protons accelerated by a black holes.

   T. Linden+, 1203.3539;
   O. Macias+, 1410.1678

3. Collisions between gas with cosmic-rays (e.g. non-thermal bremsstrahlung from a population of electrons scattering off neutral molecular clouds)

   F. Yusef-Zadeh+,1206.6882

4. Series of Burst-like events during an active past of our galaxy

   E. Carlson+,1405.7685
   J. Petrovic+, 1405.7928

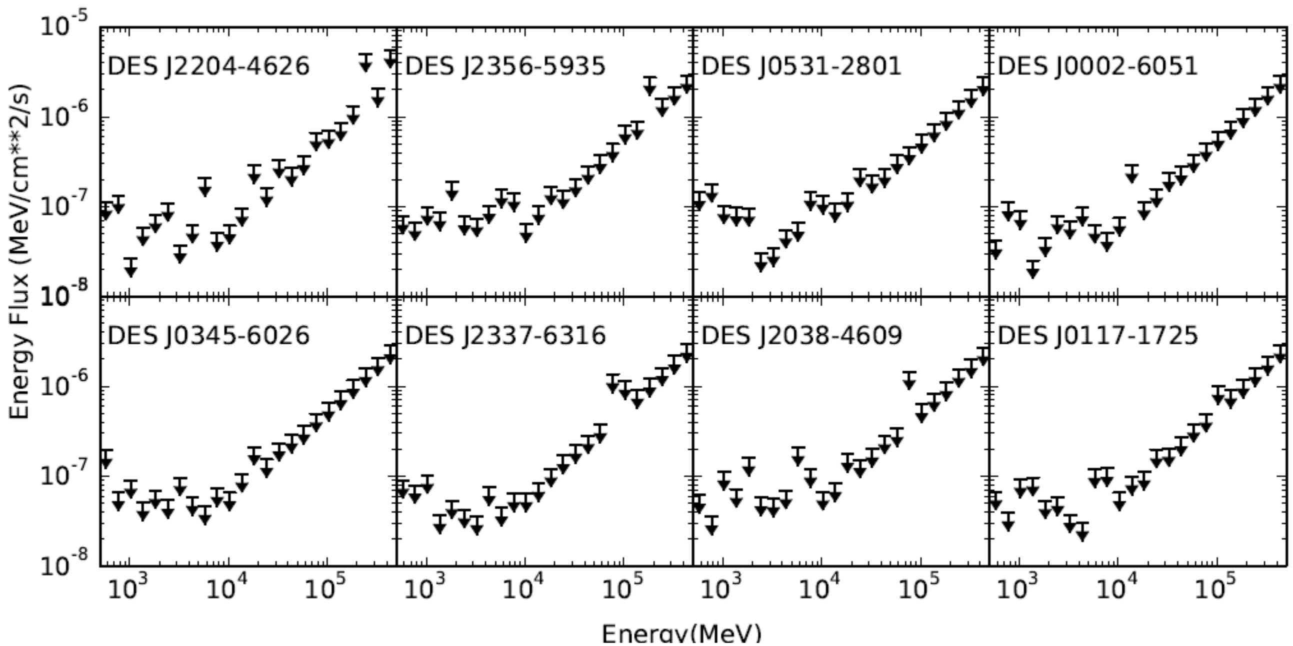
5. Different distributions of distribution cosmic-ray sources

   E. Carlson+,1510.04698
   D. Gaggero+, 1507.06129

GeV Excess in the dwarf galaxies?

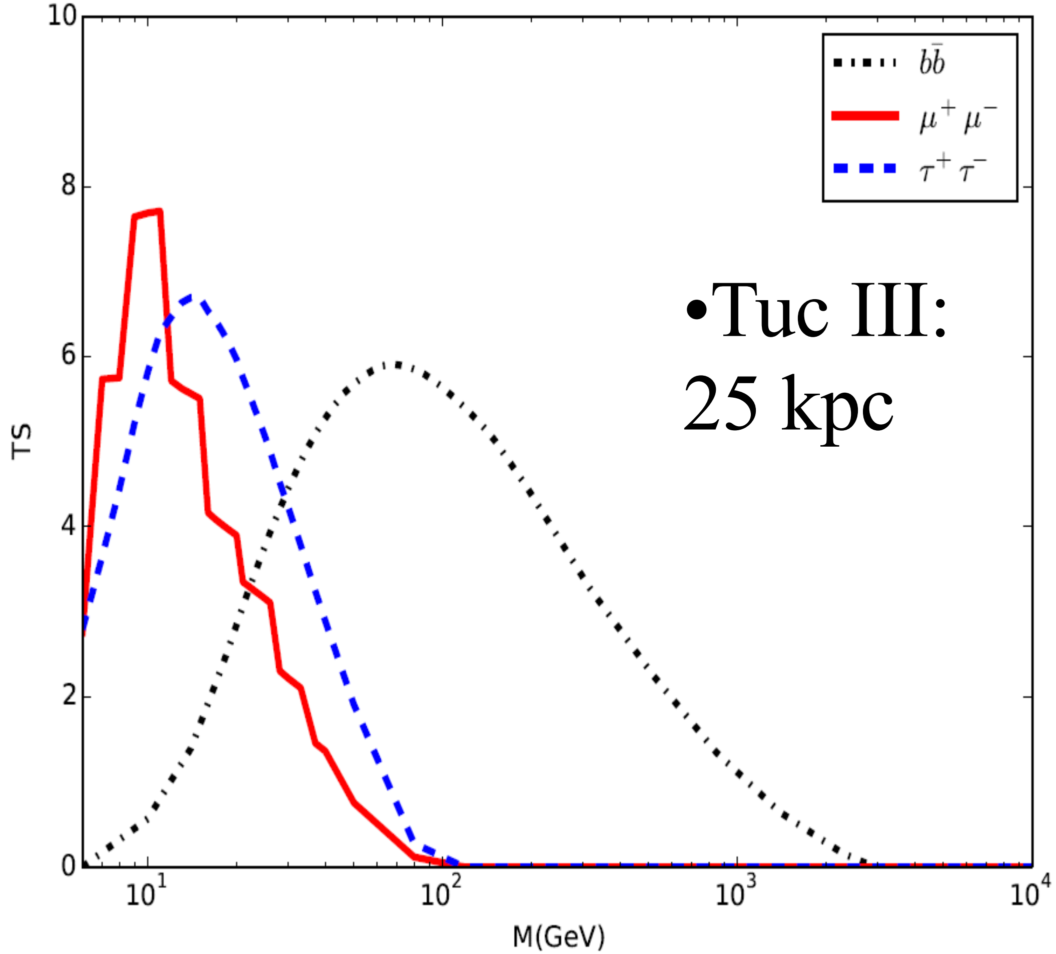
TABLE I: DES2 dSph Candidates and the Estimated J-factors

Name	(l, b)[a] (deg)	Distance[b] (kpc)	$\log_{10}$ (Est.J)[c] log 10(GeV^2cm^{-5})
DES J2204-4626	(351.15,-51.94)	53 ± 5	18.8
DES J2356-5935	(315.38,-56.19)	25 ± 2	19.5
DES J0531-2801	(231.62,-28.88)	182 ± 18	17.8
DES J0002-6051	(313.29,-55.29)	48 ± 4	18.9
DES J0345-6026	(273.88,-45.65)	92 ± 13	18.3
DES J2337-6316	(316.31,-51.89)	55 ± 9	18.8
DES J2038-4609	(353.99,-37.40)	214 ± 16	17.6
DES J0117-1725	(156.48,-78.53)	30 ± 3	19.3



•**Shang Li 1511.09252**

•GeV Excess in the Dwarf Galaxies?



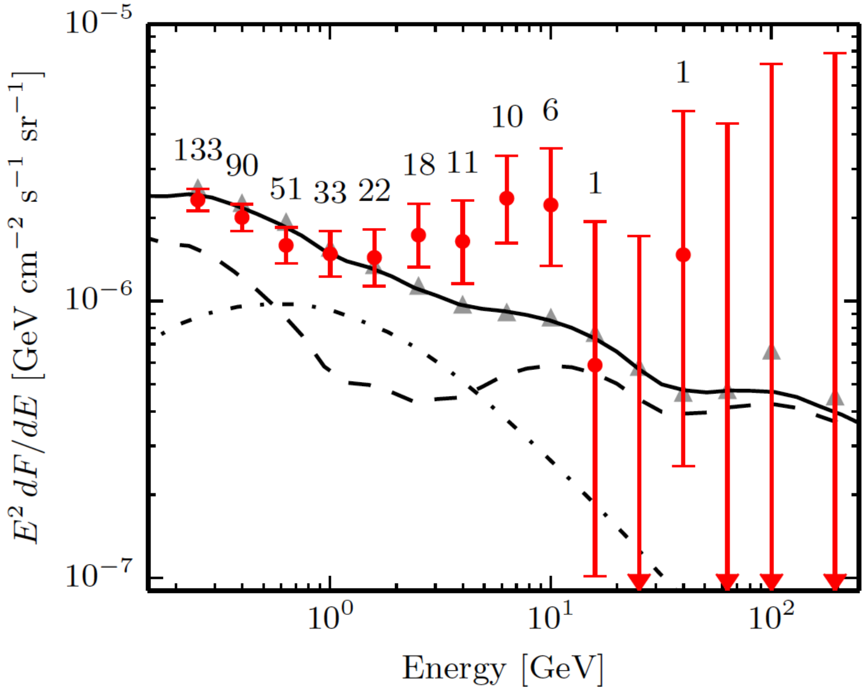
•(Li, S. et al. 2016)

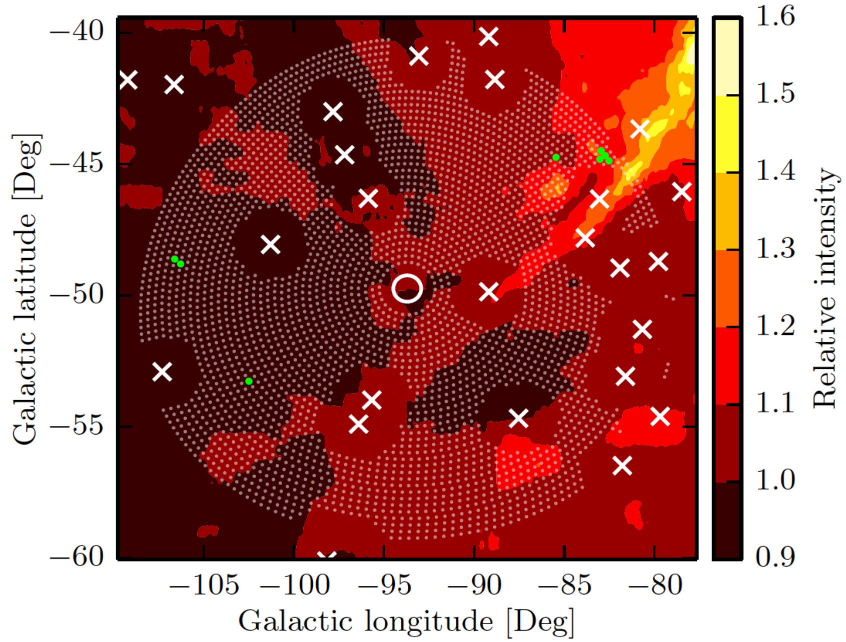
Evidence for Gamma-ray Emission from the Newly Discovered Dwarf Galaxy Reticulum 2

Alex Geringer-Sameth* and Matthew G. Walker†
McWilliams Center for Cosmology, Department of Physics, Carnegie Mellon University, Pittsburgh, PA 15213, USA

Savvas M. Koushiappas‡
Department of Physics, Brown University, Providence, RI 02912, USA

Sergey E. Koposov, Vasily Belokurov, Gabriel Torrealba, and N. Wyn Evans
Institute of Astronomy, University of Cambridge, Cambridge, CB3 0HA, UK
(Dated: March 10, 2015)

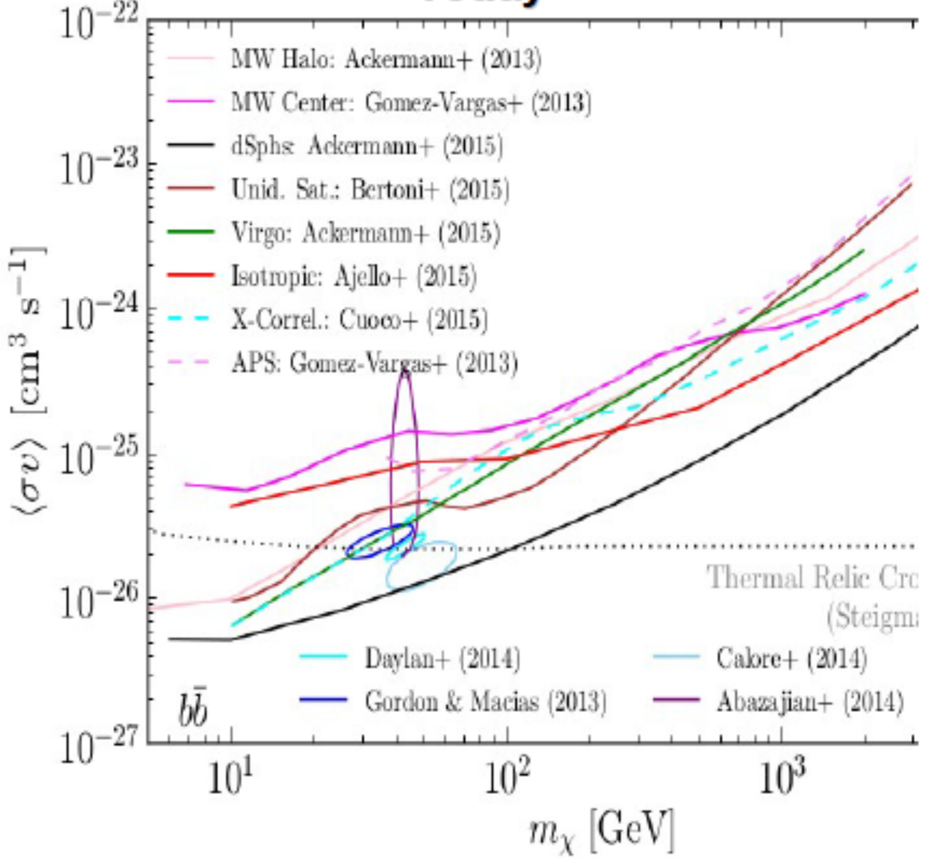




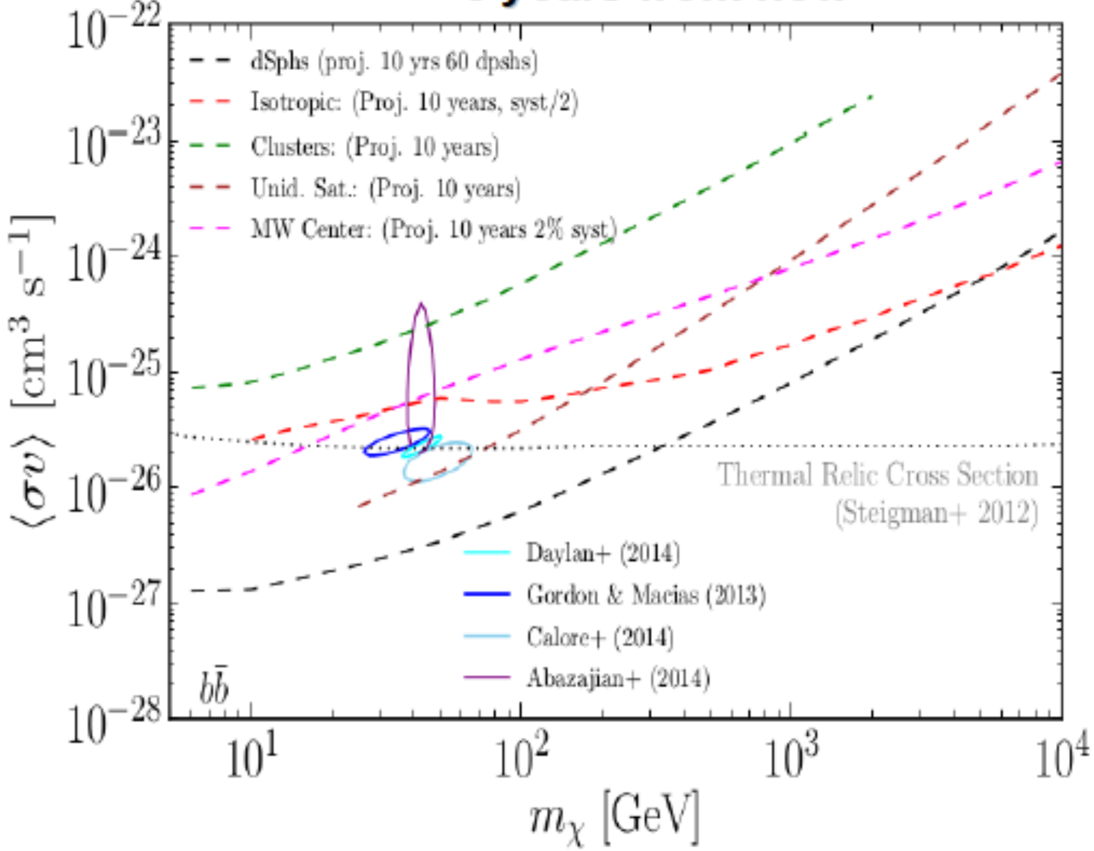
FERMI-LAT

Status of the Gamma-ray Excess in the Galactic Center

Today



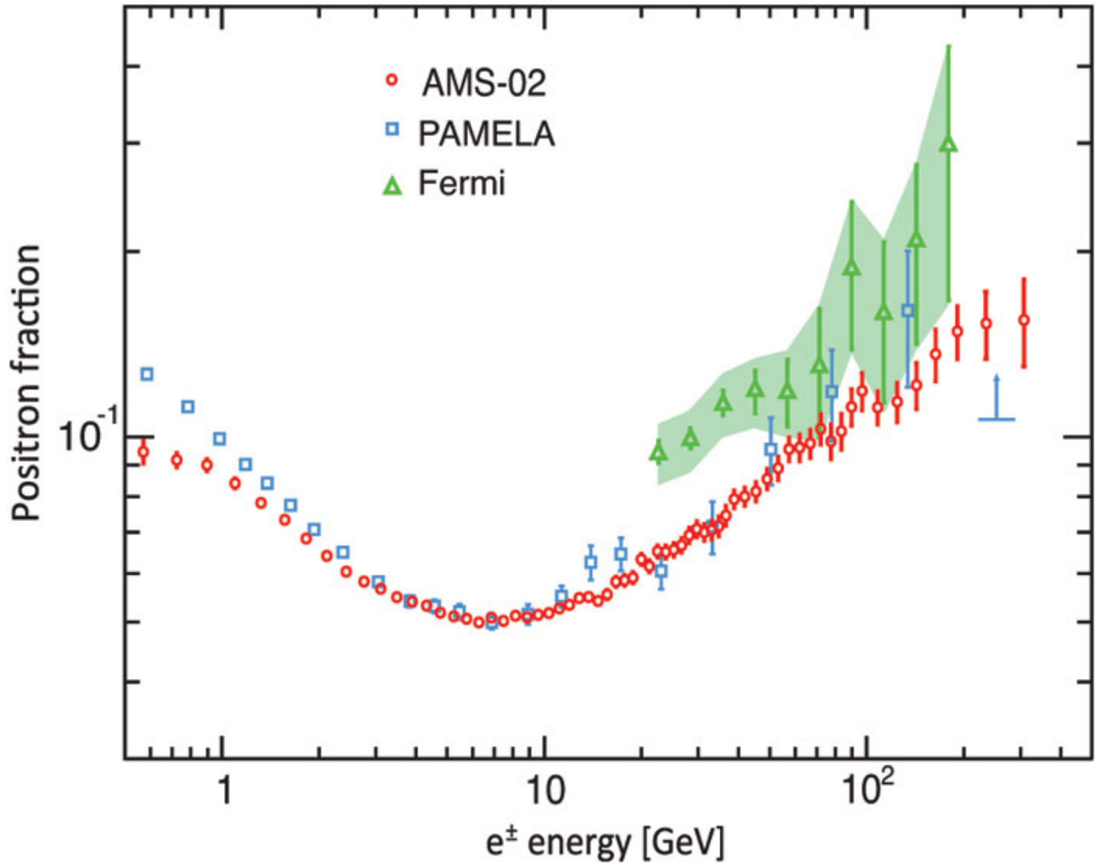
3 years from now



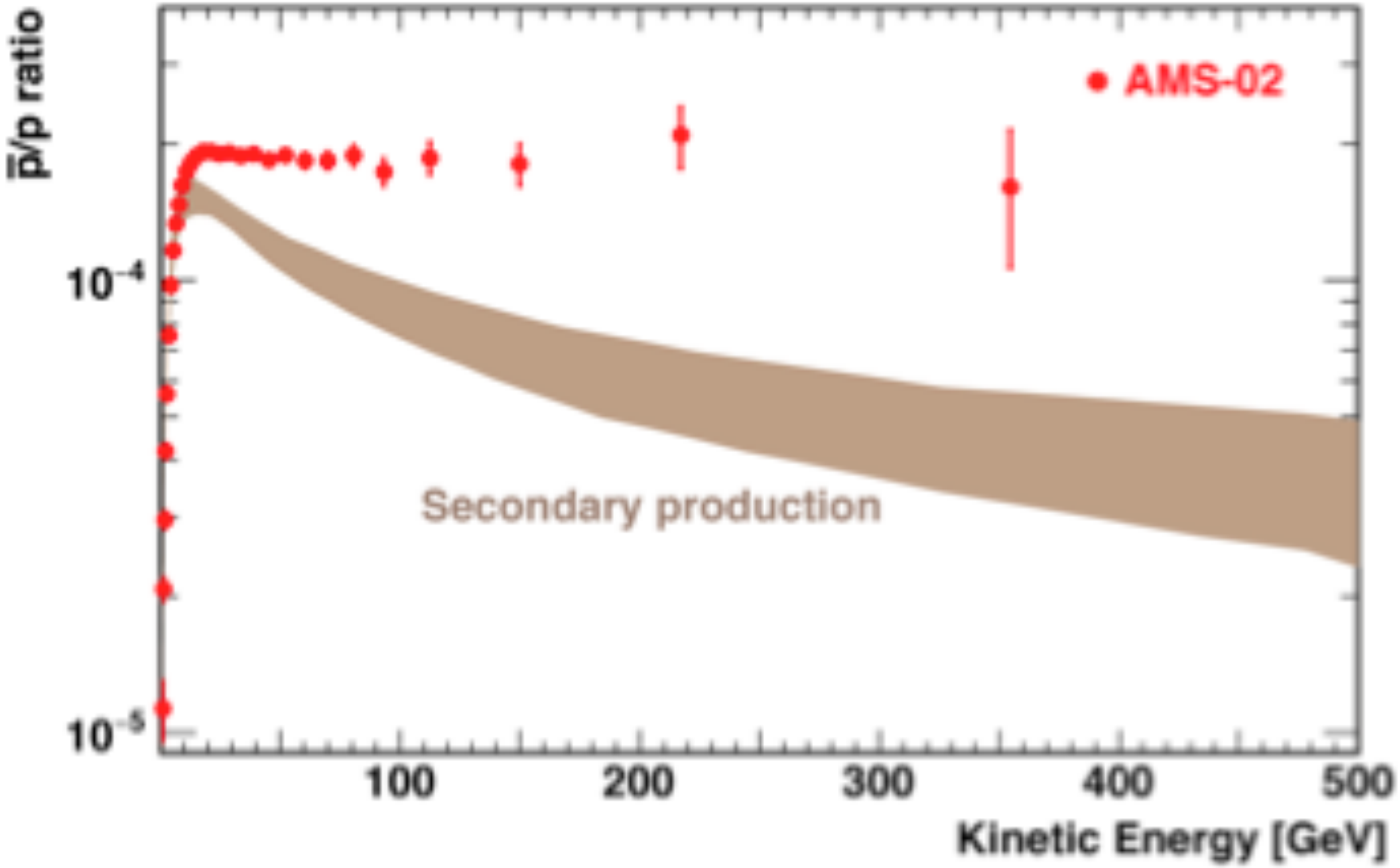
From the right panel, one could conclude that the dark matter interpretation of the galactic center excess will be decisively confirmed or ruled in the near future.

Positron and anti-proton excess

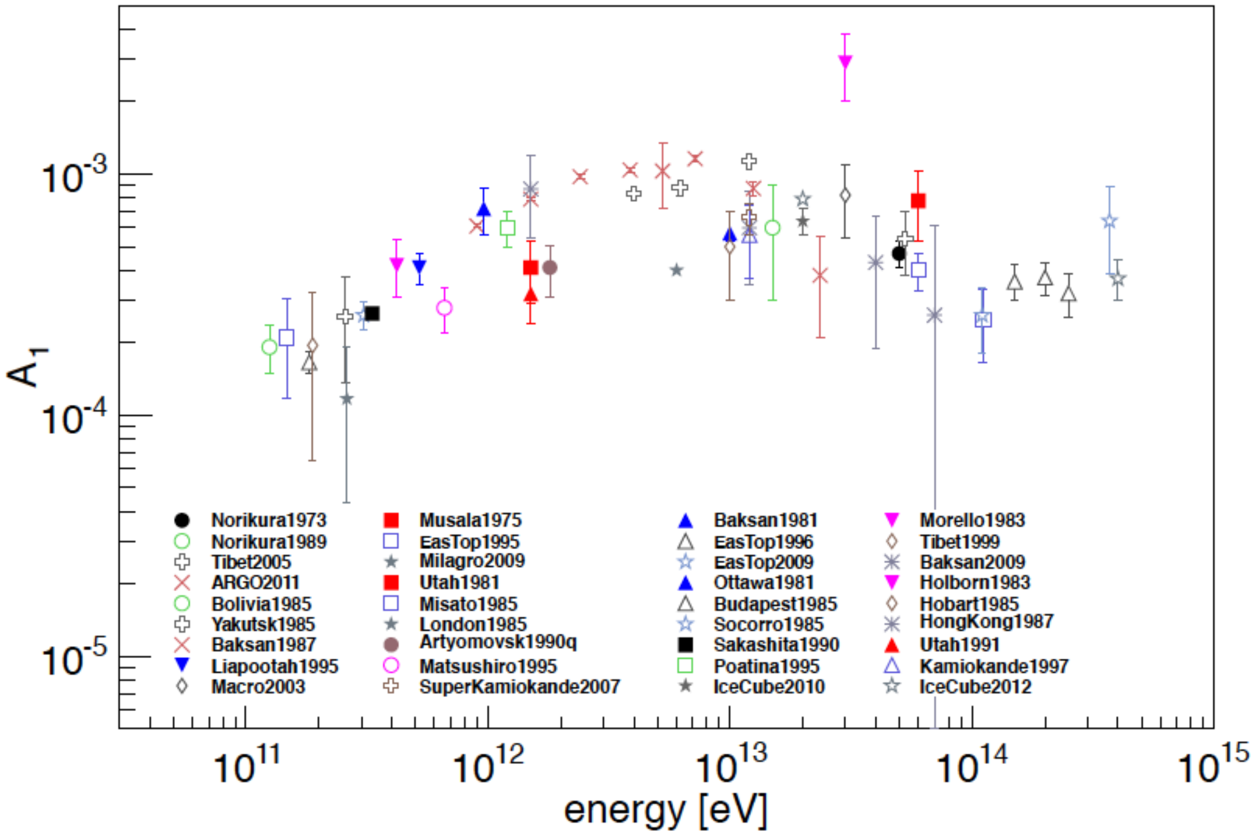
Positron to (electron + positron) ratio by PAMELA, Fermi, AMS-2



Anti-protons by AMS-2

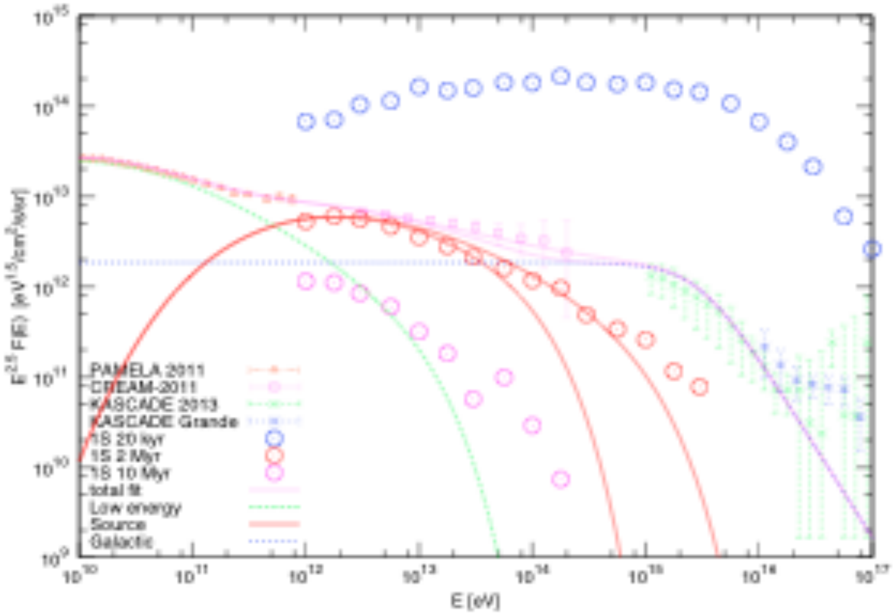


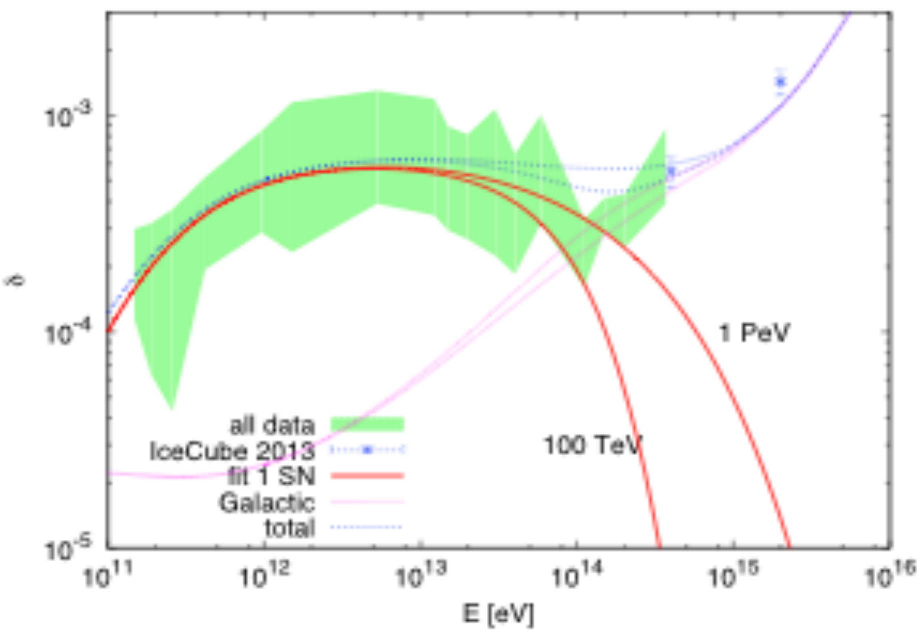
Dipole anisotropy of cosmic rays



- **G.Di Sciascio and R. Iuppa, arXiv: 1407.2144**

Anisotropy and flux from 2 Myr SN

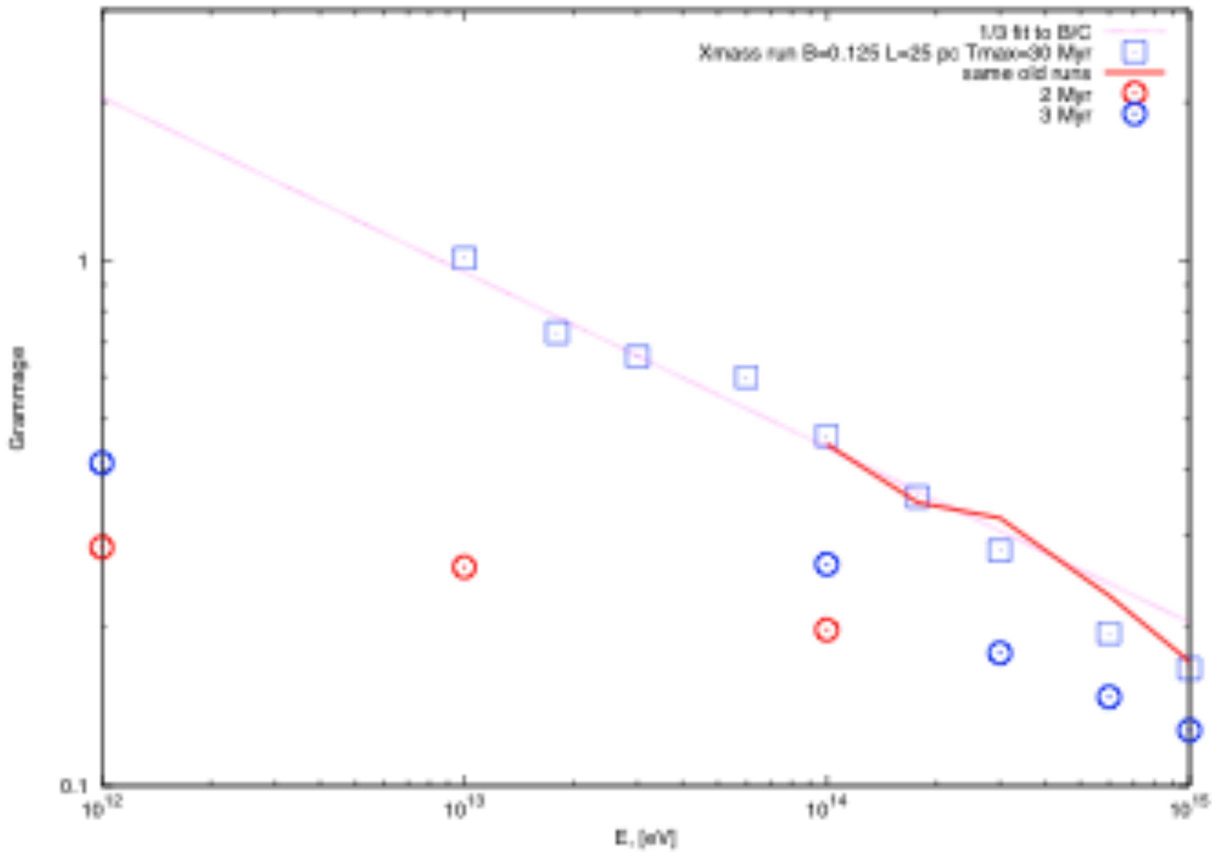




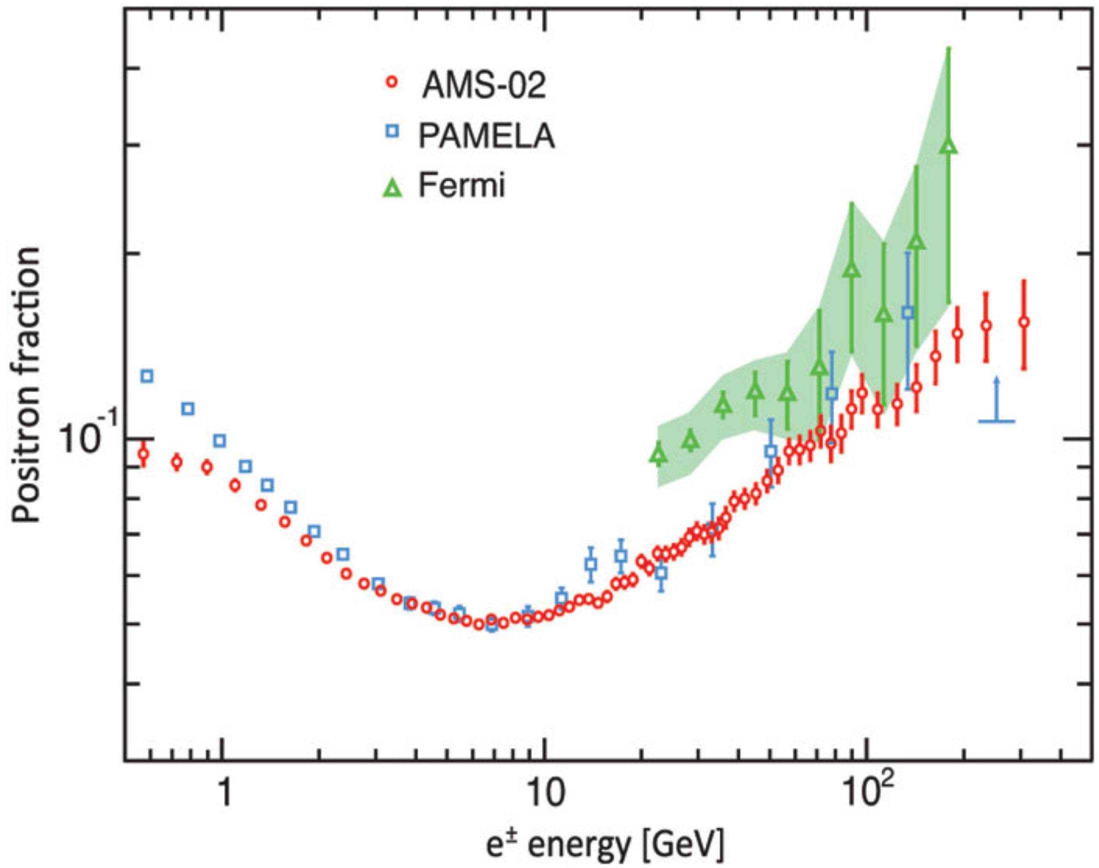
•A=3/2 R/T

- V.Savchenko, M.Kachelriess, and D.Semikoz, arXiv:1505.02720

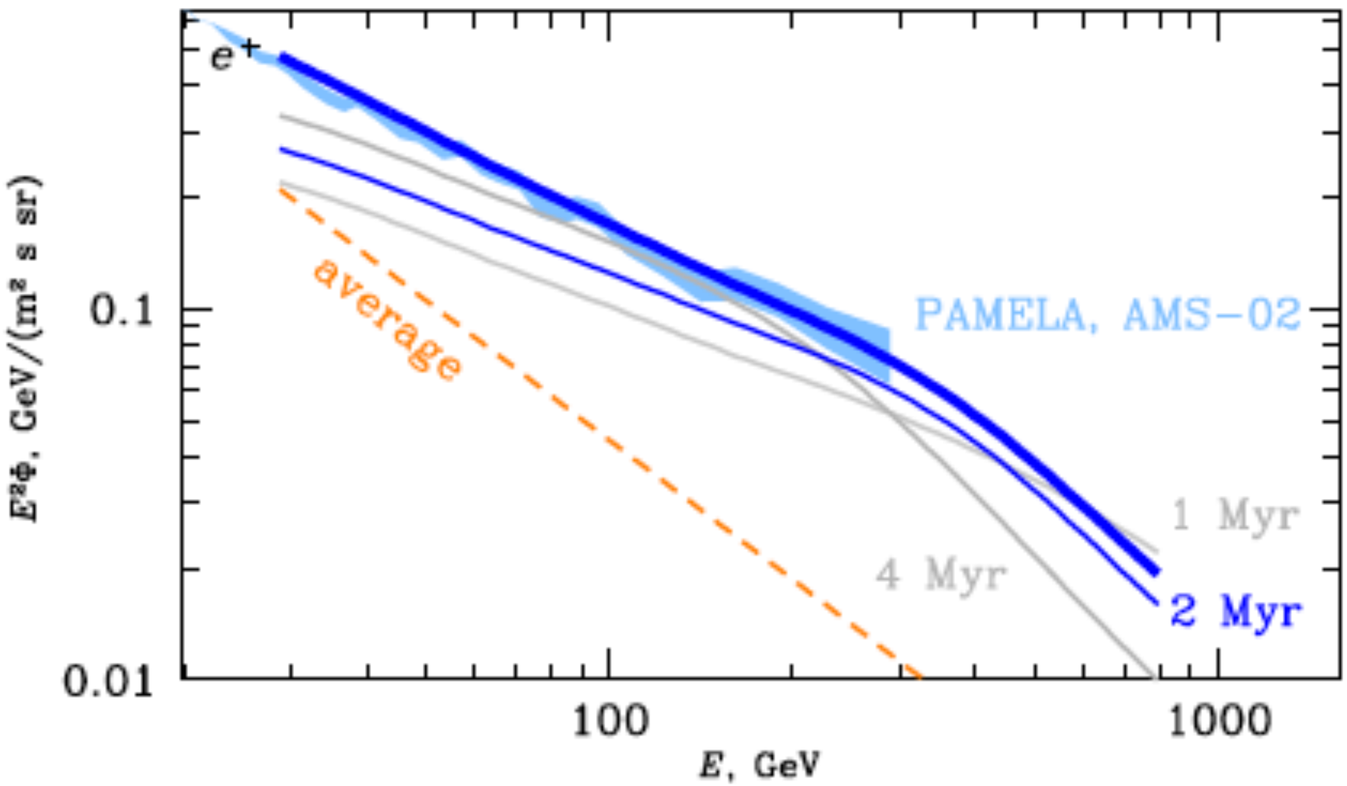
Grammage to create secondaries



Positron to (electron + positron) ratio

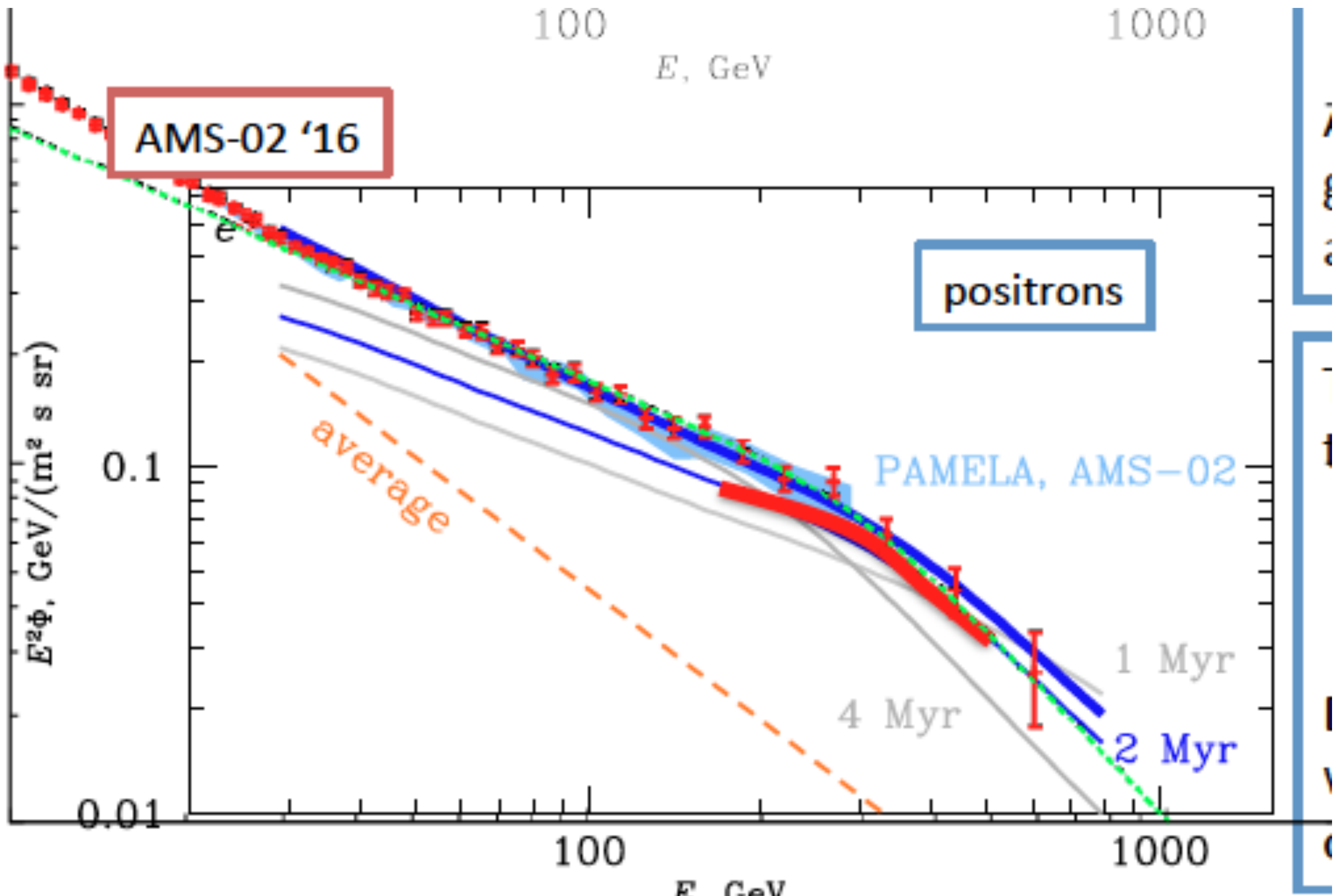


Positron flux PAMELA/AMS-II



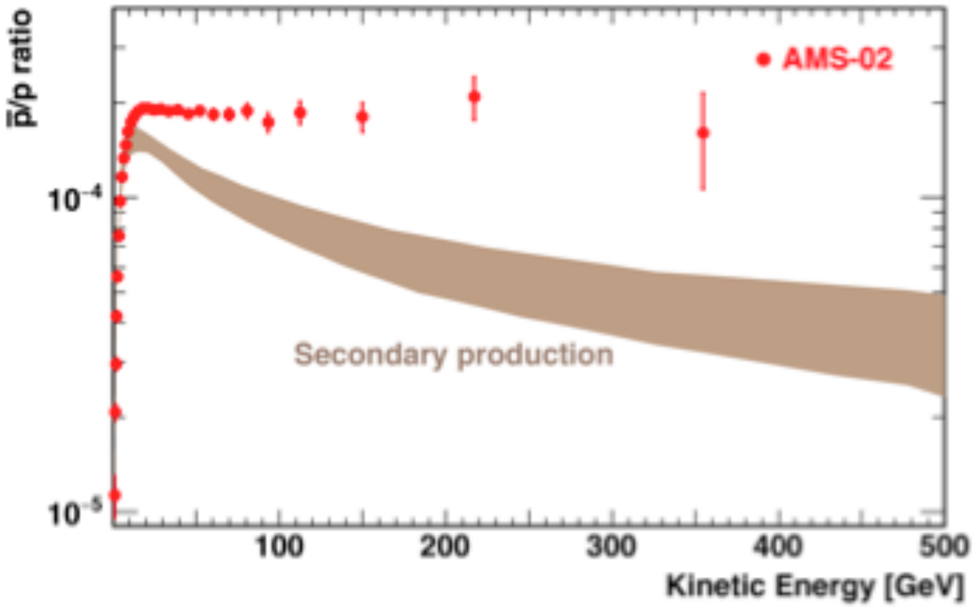
- M.Kachelriess, A. Neronov and D.Semikoz, arXiv:1504.06472

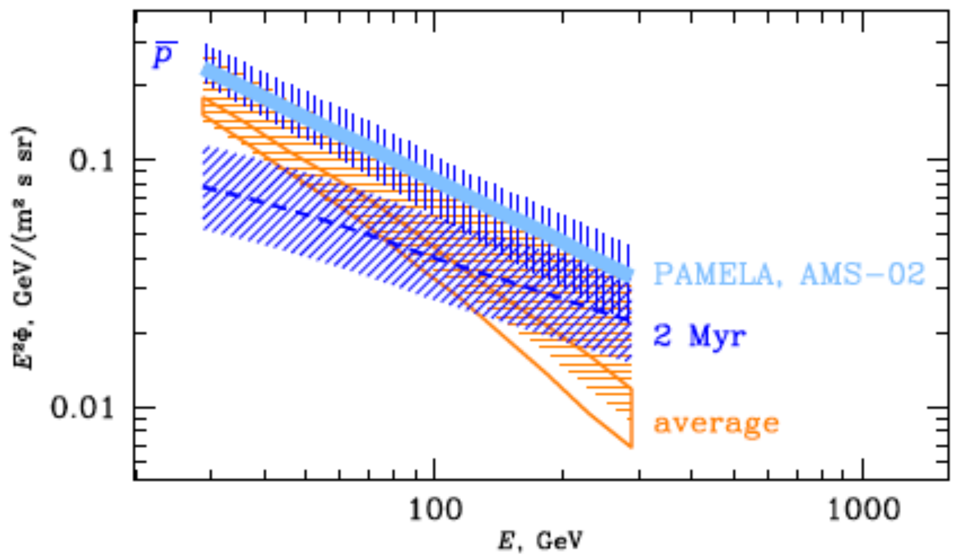
Positron flux PAMELA/AMS-II



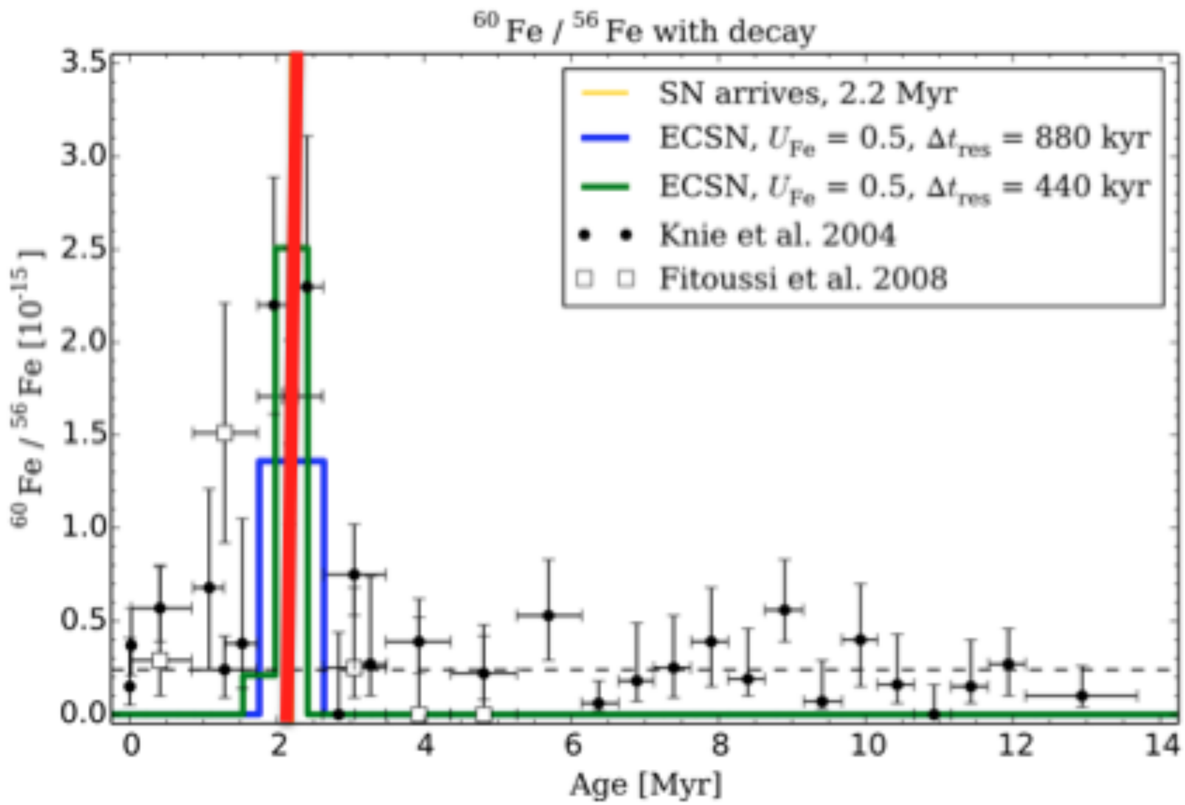
Kachelriess et al. '15

Antriprotons





Nearby SN from Fe60 in ocean crust



•Knie et al. ‘99, ’04, Fry et al. ‘15

Conclusions:

- Gamma-ray astronomy works
- Will help to understand hadronic component in different kind of astrophysical sources
- helps to establish extragalactic IR/O backgrounds
- Diffuse gamma-ray background dominated by unresolved sources
- Will allow to study magnetic field in the voids of large scale structure: primordial magn. field!
- Give constraint/signature on Dark Matter

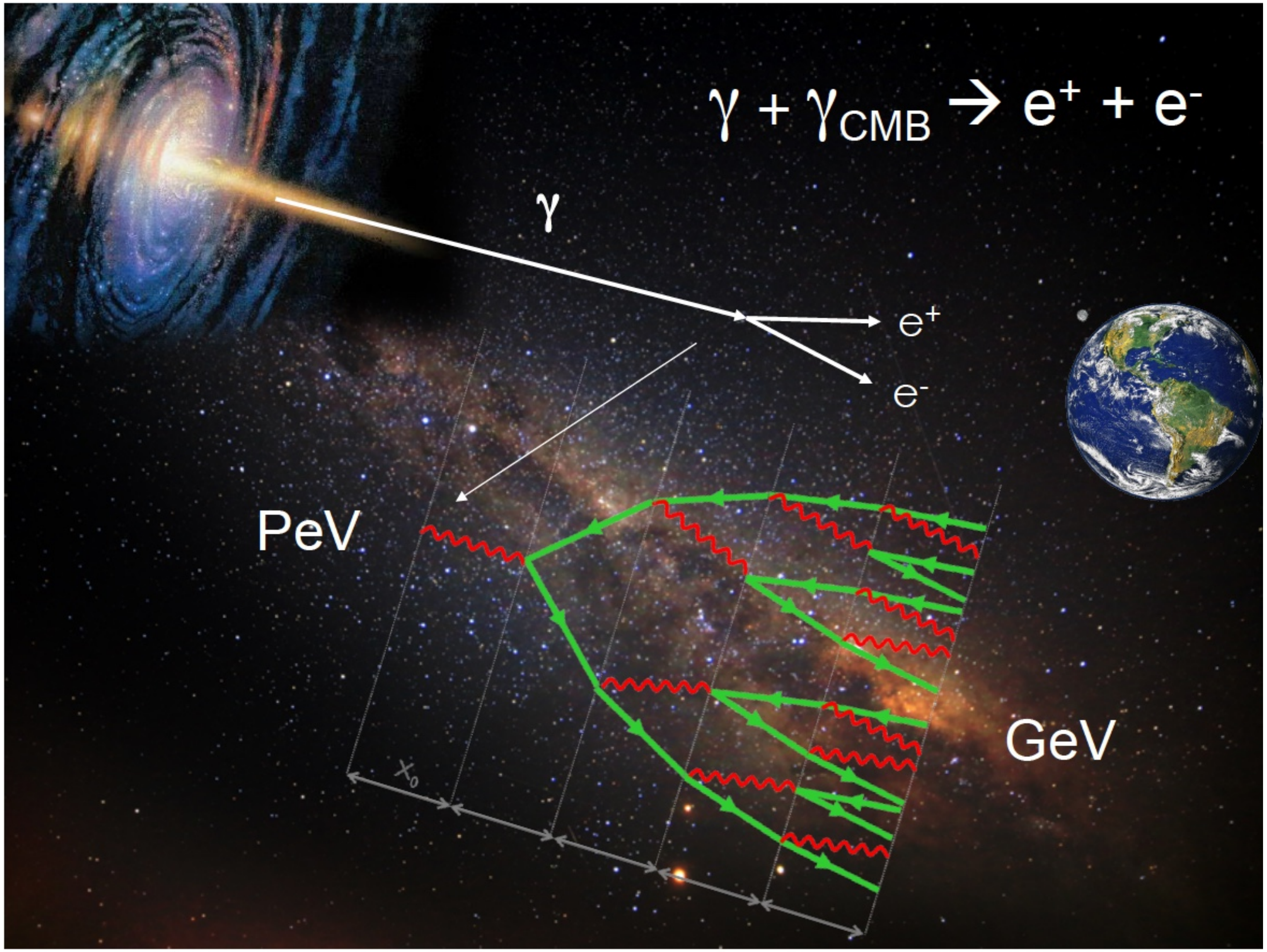
Seminar: Gamma-ray optical depth

Ultra High Energy \\ Cosmic Rays

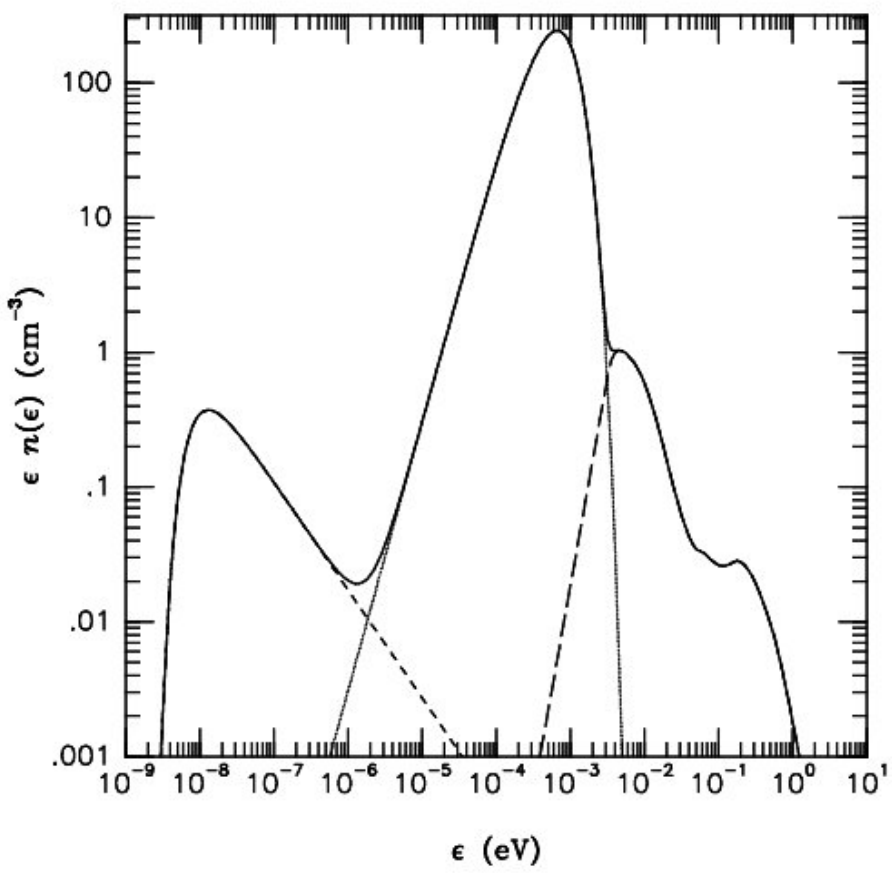
Dmitry Semikoz

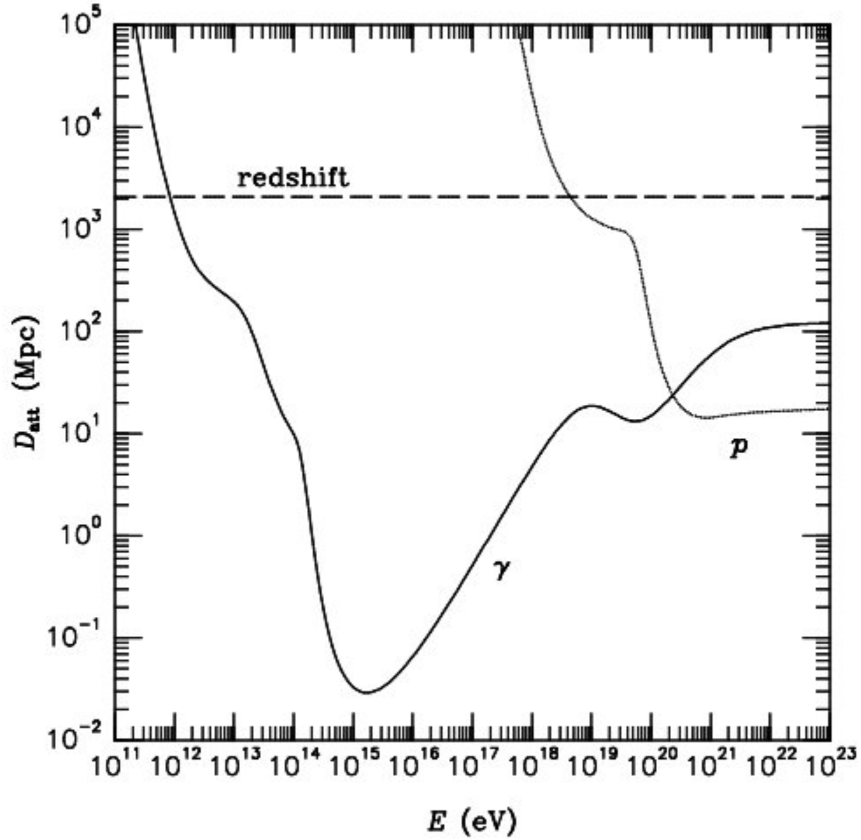
APC (Paris)

Electromagnetic cascade



Diffuse backgrounds





Electromagnetic cascade

$$\gamma + \gamma_B \Rightarrow e^- + e^+$$

$$e^{\pm} + \gamma_B \Rightarrow e^{\pm} + \gamma$$

Gamma-ray optical depth

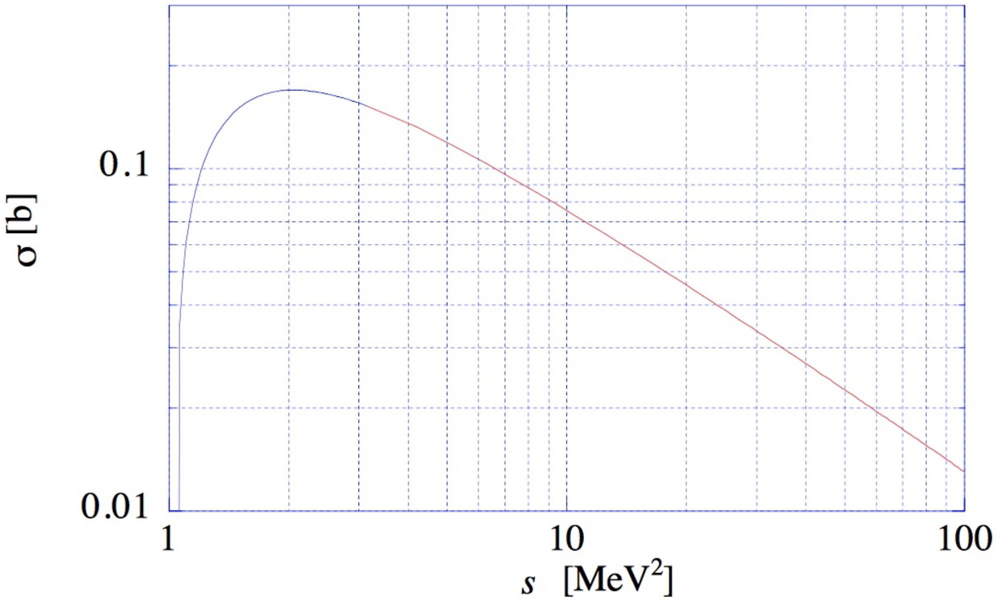
$$\tau(E_\gamma, z_0) = \frac{1}{2}\int_0^{z_0} \mathrm{d}z\, \frac{\mathrm{d}l}{\mathrm{d}z} \int_{-1}^{1} \mathrm{d}(\cos\theta)\,(1-\cos\theta) \times \int_{E_{\mathrm{min}}}^{\infty} \mathrm{d}E_{\mathrm{bg}}\, n(E_{\mathrm{bg}}, z)\, \sigma[E_\gamma(1+z), E_{\mathrm{bg}}, \theta],$$

where we have

$$E_{\mathrm{min}} = E_{\mathrm{th}}\,(1+z)^{-1} = \frac{2m_{\mathrm{e}}^2 c^4}{E_\gamma(1+z)(1-\cos\theta)}$$

$$\frac{dt}{dz} = \frac{1}{H_0(1+z)} \frac{1}{\sqrt{\Omega_M(1+z)^3 + \Omega_\Lambda}}$$

Cross section



$$\sqrt{2E_1E_2(1-\cos\theta)} \geq 2m_ec^2$$

$$E_{th} = \frac{2m_e^2c^4}{E_\gamma(1-\cos\theta)}.$$

$$\sigma(E_1, E_2, \theta) = \frac{3\sigma_T}{16}(1-\beta^2) \times \left[2\beta(\beta^2-2) + (3-\beta^4)\ln\left(\frac{1+\beta}{1-\beta}\right)\right]$$

$$\beta = \sqrt{1 - \frac{2m_e^2c^4}{E_1E_2(1-\cos\theta)}}$$

$$\sigma_T = \frac{8\pi}{3}\left(\frac{e^2}{m_ec^2}\right)^2 = 6.65\times10^{-25}\ \mathrm{cm}^2$$

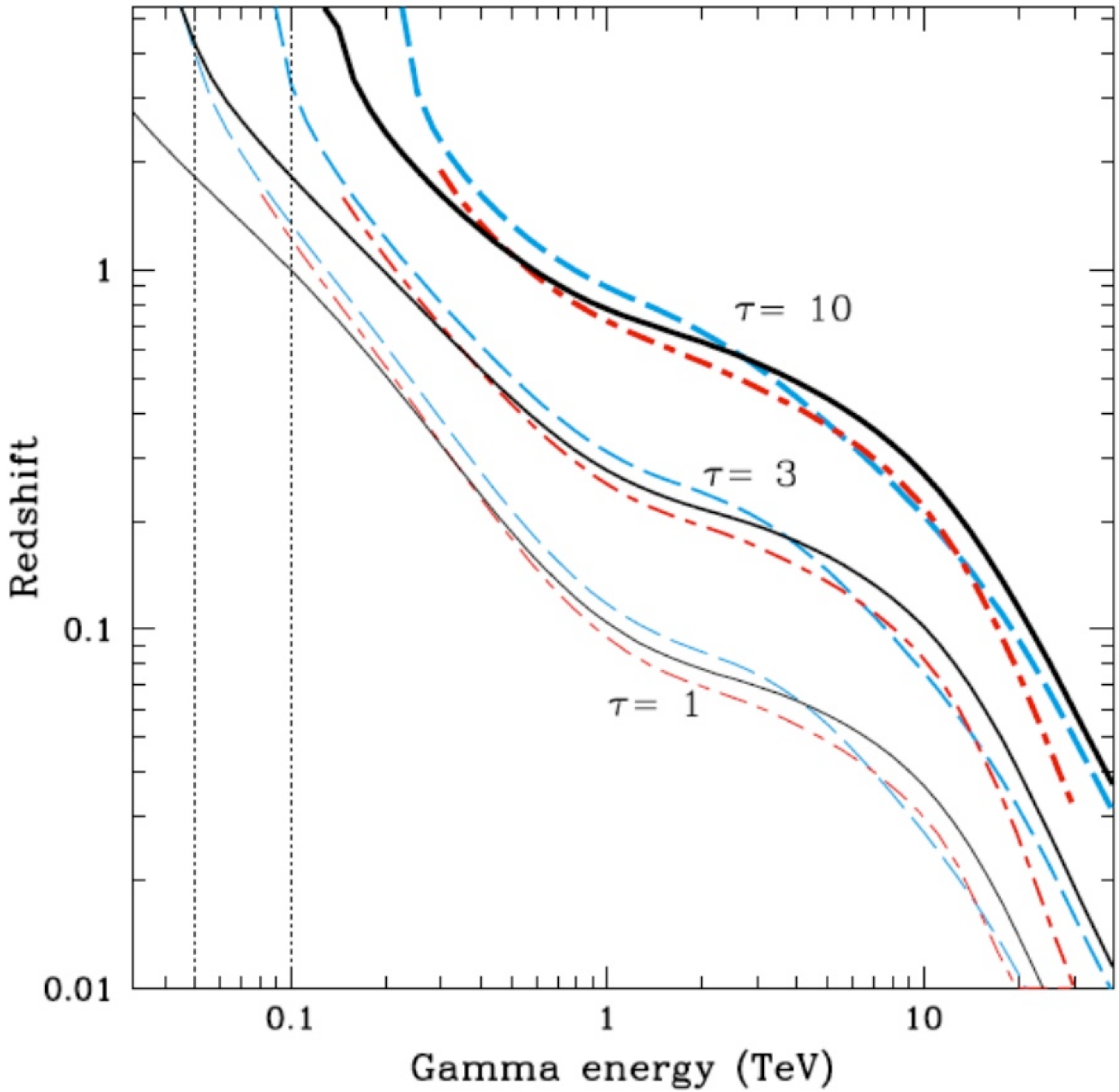
Gamma-ray travel distance

$$D_\gamma(E'_{\gamma 0}, z)^{-1} = < \sigma_{\gamma\gamma} n_{\mathrm{EBL}} >$$

$$= \int_{\epsilon'_{min}}^{\infty} d\epsilon' \frac{dn_{EBL}(\epsilon', z)}{d\epsilon'} \int_{-1}^{1} d\mu (1-\mu) \sigma_{\gamma\gamma}(s),$$

$$n_{EBL}(\epsilon, z) \approx (1+z)^{-2} n_{EBL}$$

$$D_\gamma(E'_{\gamma 0}, z) = 40 \frac{\kappa}{(1+z)^2} \left[\frac{E'_{\gamma 0}}{20\ \mathrm{TeV}} \right]^{-1} \mathrm{Mpc}$$



Redshift
1
0.1
0.01
0.1
1
10
Gamma energy (TeV)
τ= 10
τ= 3
τ= 1

Gamma-Ray Attenuation

$$\left.\frac{dN}{dE}\right|_{obs} = \left.\frac{dN}{dE}\right|_{int} \exp\left[-\tau(E,z)\right]$$

$$\tau(E,z) = \int_0^z \left(\frac{dl'}{dz'}\right) dz' \int_0^2 d\mu \frac{\mu}{2} \int_{\varepsilon_{min}}^{\infty} d\varepsilon' \, \sigma_{\gamma\gamma}(\beta') n(\varepsilon', z')$$

Distance (cosmology)

Interaction angle

Cross section

EBL photon density evolution (cosmology)