

INDIRECT DARK MATTER DETECTION: TALES OF SCALES

(across the desert)



Pasquale Dario Serpico (LAPTh, CNRS)

Planck 2014 - Paris

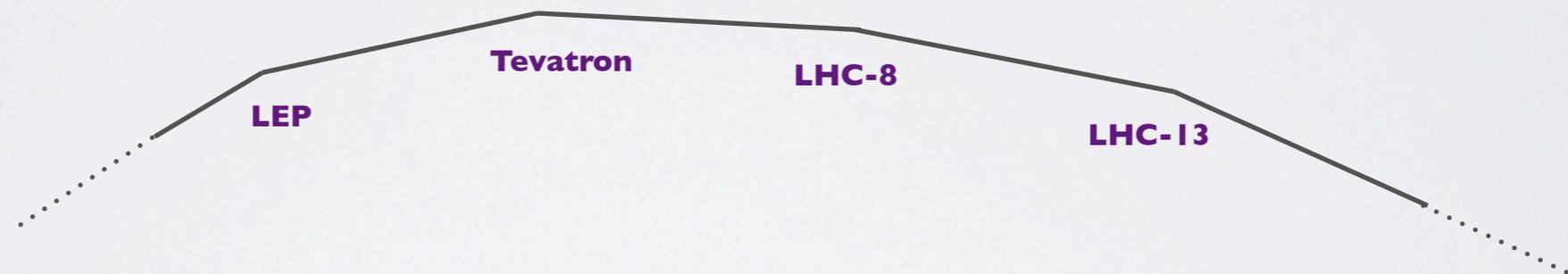
27/05/2014

LACK OF BSM PHYSICS FROM LAB: HOW TO INTERPRET IT?

The SM has proven to be a **successful* theory beyond expectations!**

The guiding principle to BSM from the “hierarchy problem” argument has failed, till now. It seems to me that there are **3 possible interpretations:**

- **Unlucky**: EW scale is '**a bit**' *fine-tuned* (0.1-1%?) & discoveries are around the corner: Let's just hope that the number of corners of the polygon is not too high...



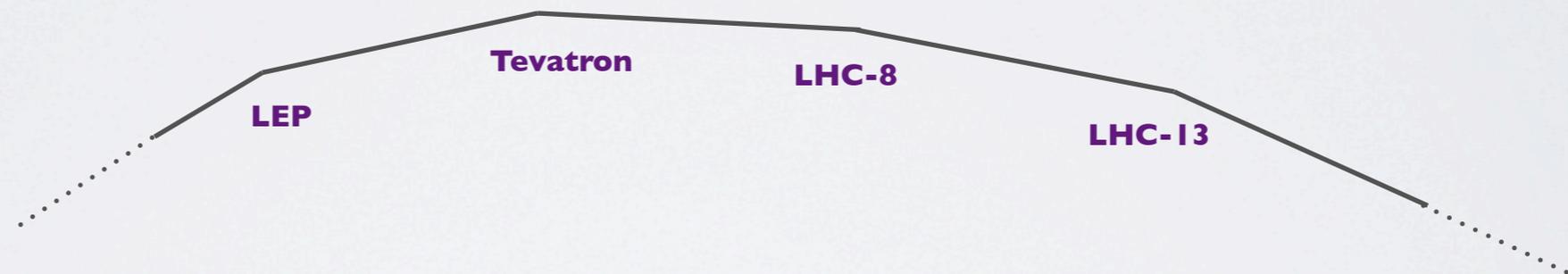
*but for neutrinos?

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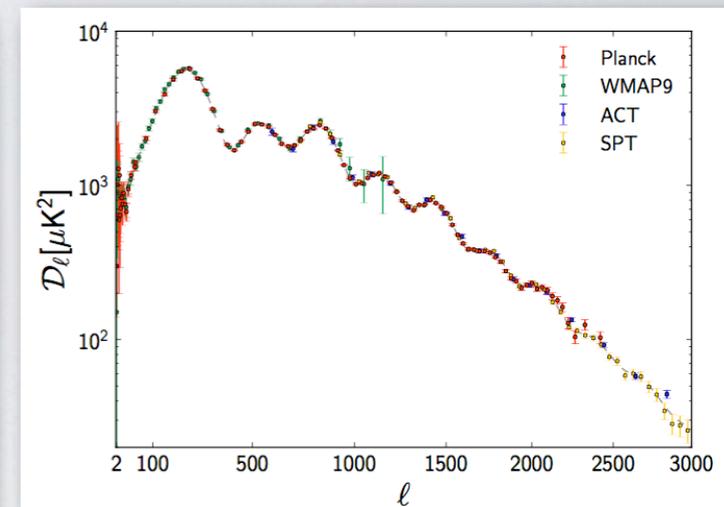
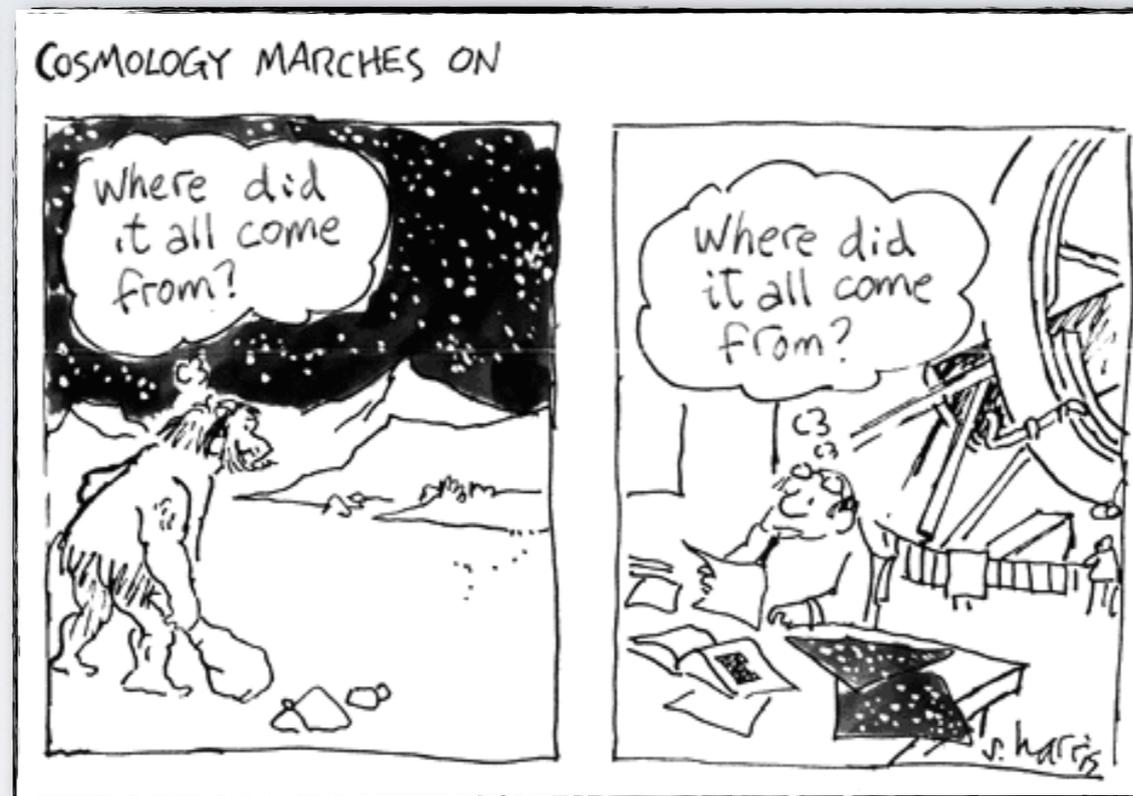
- **Humble:** we have misinterpreted/abused this *philosophical/aesthetic principle*, just **let the experiment** (if Nature is kind enough!) **tell us what the UV sector is.**
- **Shocking:** the reasoning is in principle correct, but there is **no problem** because **all the dof are at the EW scale** or below (i.e. light and very weakly coupled)

*but for neutrinos?

RESCUE FROM THE SKY?

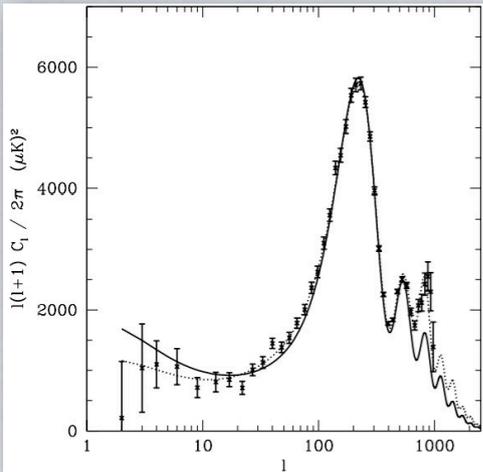
Perhaps a paradox: we have a simple **parametric model** (Λ CDM+inflation) that:

- ▶ **works incredibly well**
- ▶ **requires some new physics** (baryon asymmetry, **DM**,...) → Will concentrate on that in the following

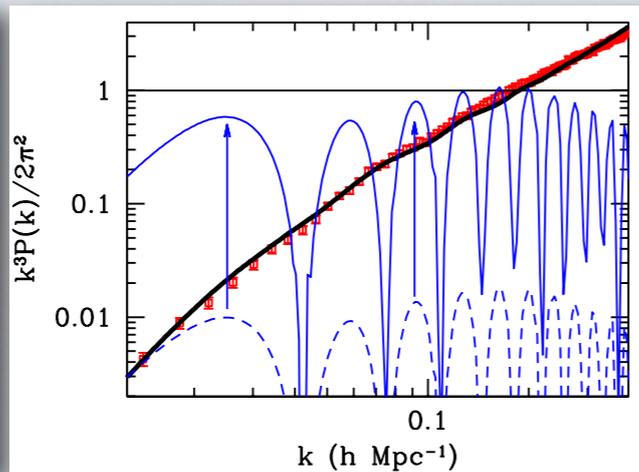


But getting a **handle on the scale** & coupling of this BSM has remained **beyond reach!**
(that would change if *BICEP 2* claimed detection of primordial *B* modes is confirmed...TBC...)

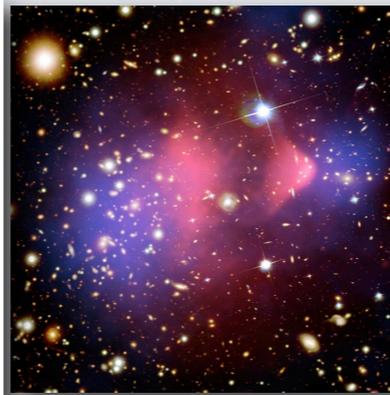
DM EVIDENCE @ MANY SCALES



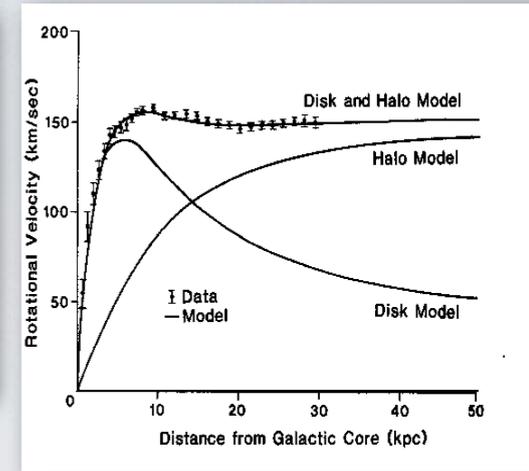
**CMB
anis.**



**(Growth & Pattern of)
Large Scale Structures**



**Clusters
(X-rays, lensing)**



**Galaxies Dwarfs
(rotation curves, fits...)**

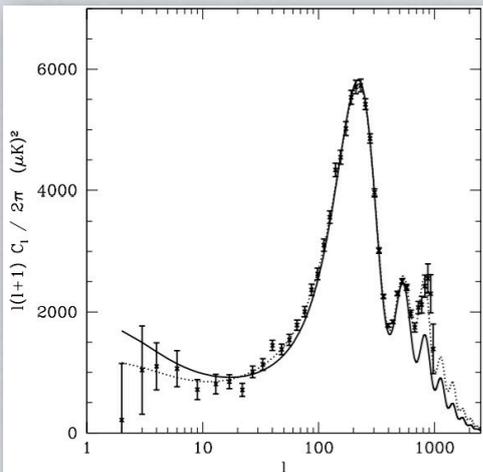
“Cosmological”

(growing effect of non-linearities, baryonic gas dynamics, feedbacks...)

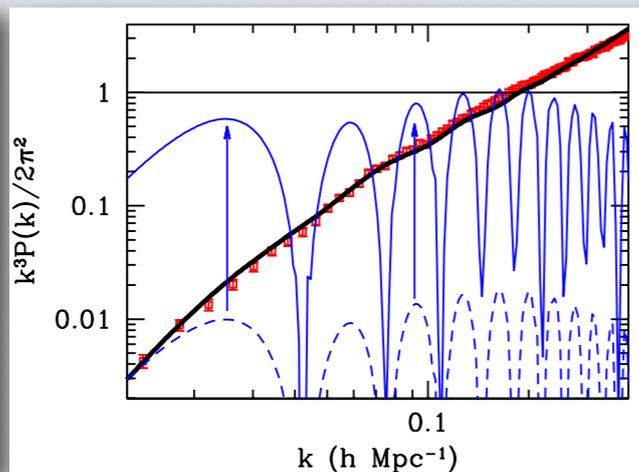


“Astrophysical”

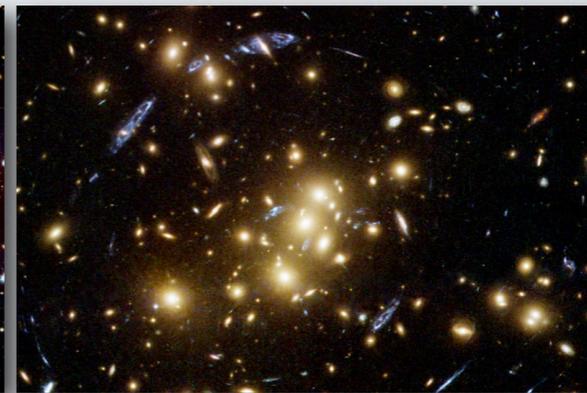
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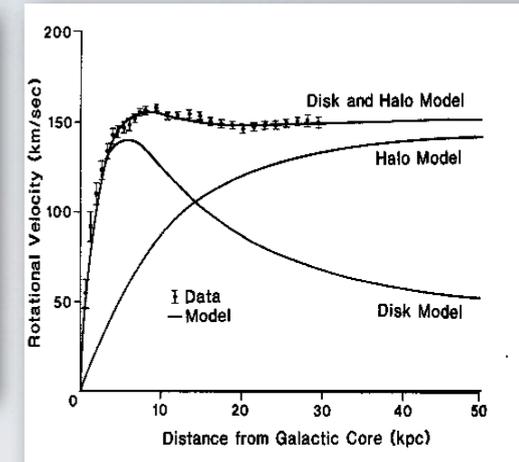
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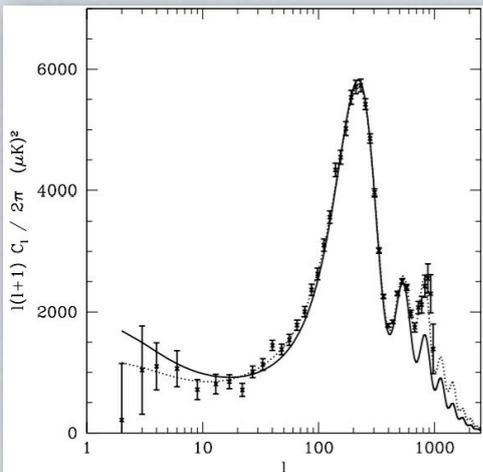
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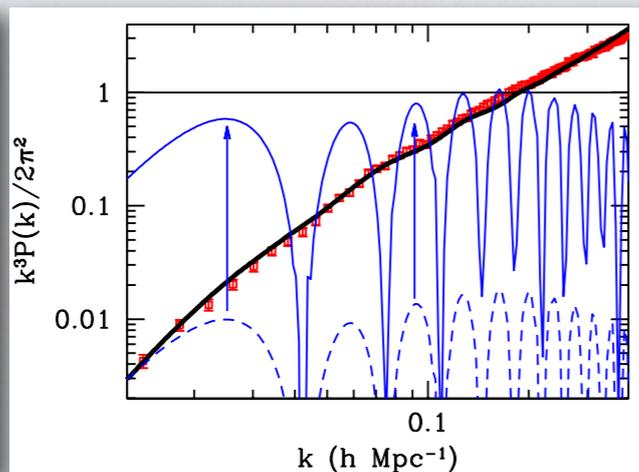
Especially cosmological evidence of paramount importance for Particle Physics!

- ▶ Exact solutions or linear perturbation theory applied to simple physical systems: credible and robust!
- ▶ Suggests **“cold”, collisionless additional species**, rather than a modification of gravity
- ▶ Tells that its majority is **non-baryonic**, rather than e.g. brown dwarf stars, planets...

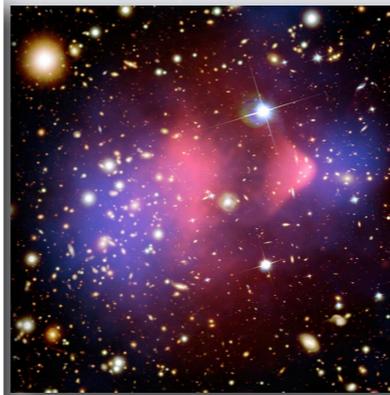
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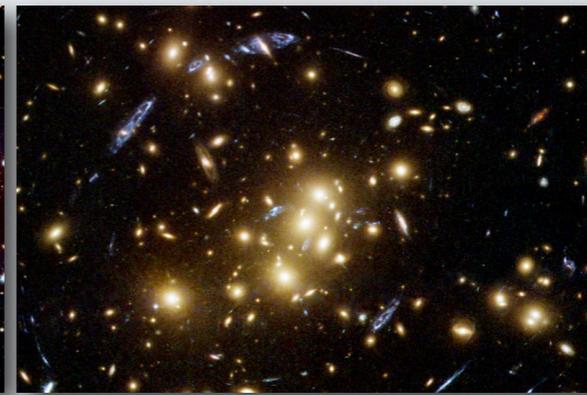
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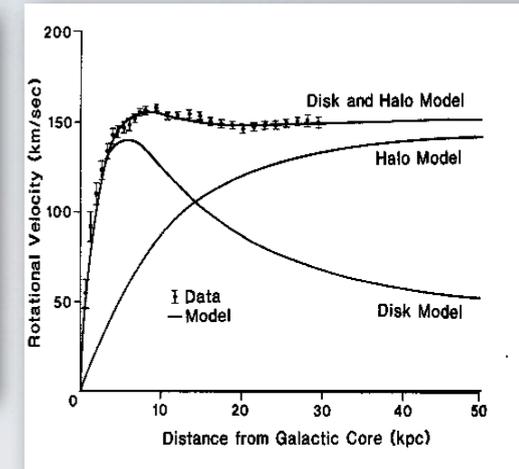
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BSM explanation **needed**, but **gravity is universal**: no particle identification!
discovery via other channels is needed **to clarify particle physics** framework

But what to look for depends on model-dependent “bias”

MAIN ARGUMENTS IN THIS TALK

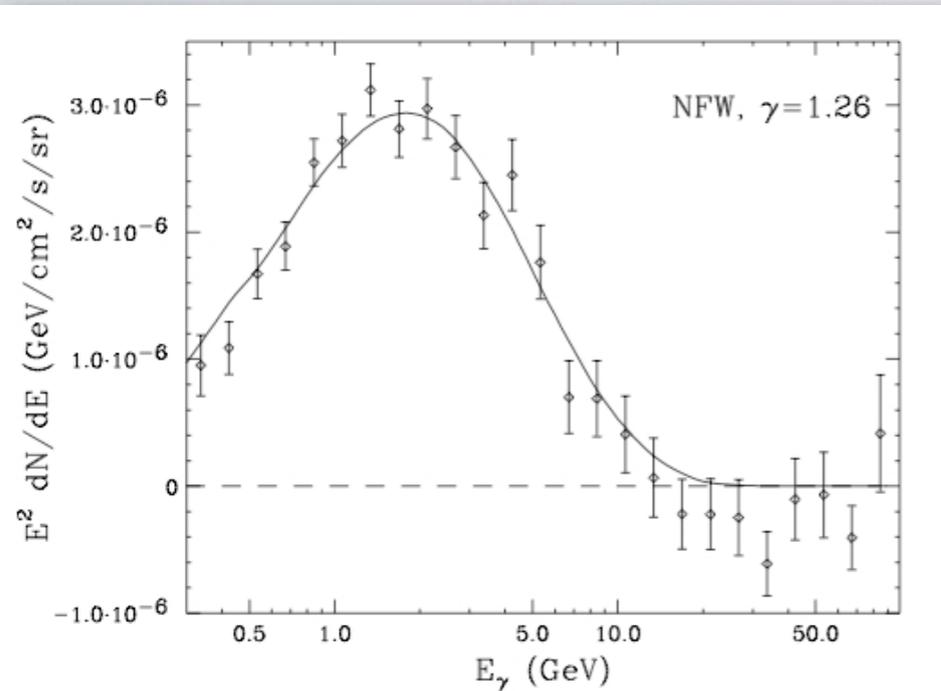
*detect SM byproducts of DM interactions
(with SM or DM)*



- ▶ *Indirect* DM detection **can help** discriminating among different scenarios for the BSM alternatives.
- ▶ Actually, we may be living that phase in real time! (3 examples will follow, falling in the 3 scenarios mentioned above)
- ▶ **Main difficulty:** How to conduct the quest productively (= progressing in the knowledge of nature) without being fooled (too often!)?
- ▶ I'll show how:
 - i) something looking like a “vanilla DM signal” may hide the ***devil in the details***.
 - ii) observables apparently unrelated to DM signal might be instead due to it!

CASE I: “VANILLA WIMP” FROM GC?

~3 independent groups claim (to a different degree) a statistically significant gamma-ray excess over diffuse emission plus known astrophysical sources.



L. Goodenough and D. Hooper, “**Possible Evidence** For Dark Matter Annihilation In The Inner Milky Way From The Fermi Gamma Ray Space Telescope,” arXiv:[0910.2998](https://arxiv.org/abs/0910.2998)

D. Hooper and L. Goodenough, PLB 697, 412 (2011) [arXiv:[1010.2752](https://arxiv.org/abs/1010.2752)]

K. N. Abazajian and M. Kaplinghat, PRD 86, 083511 (2012) [arXiv:[1207.6047](https://arxiv.org/abs/1207.6047)]

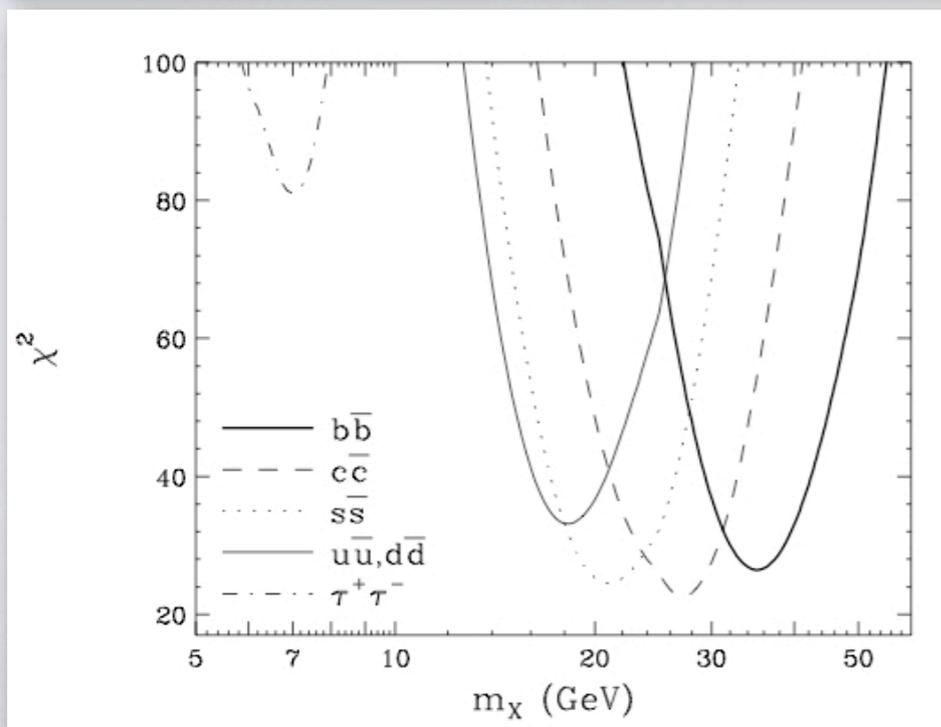
D. Hooper, I. Cholis, T. Linden, J. Siegal-Gaskins and T. Slatyer, PRD 88, 083009 (2013) [arXiv:[1305.0830](https://arxiv.org/abs/1305.0830)]

C. Gordon and O. Macias, PRD 88, 083521 (2013) [arXiv:[1306.5725](https://arxiv.org/abs/1306.5725)]

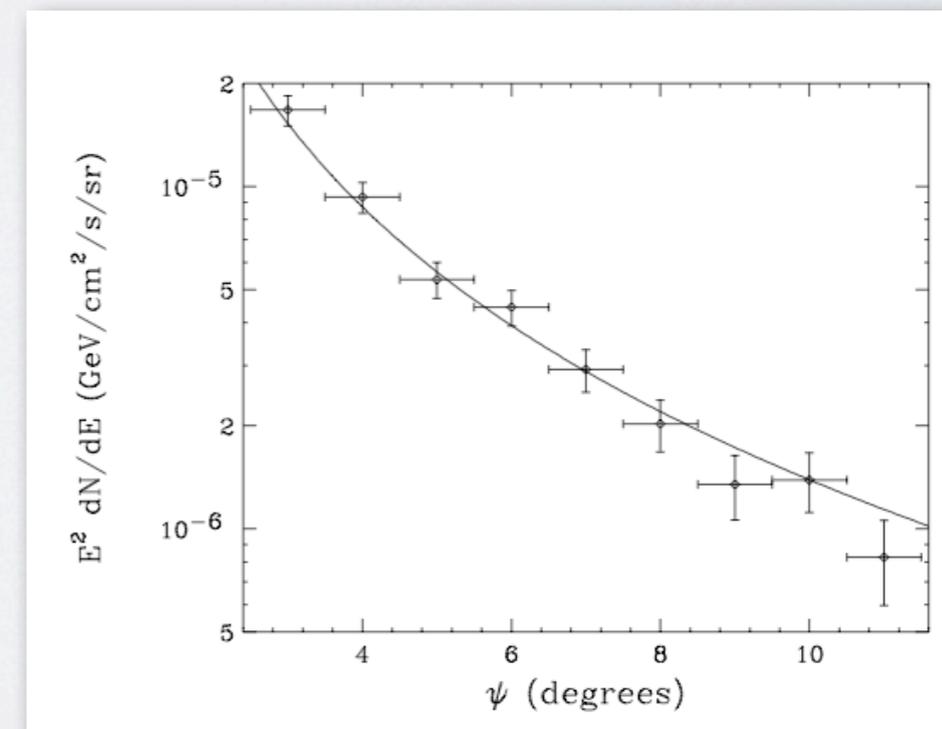
K. N. Abazajian, N. Canac, S. Horiuchi and M. Kaplinghat, arXiv:[1402.4090](https://arxiv.org/abs/1402.4090)

T. Daylan et al. “The Characterization of the Gamma-Ray Signal from the Central Milky Way: A **Compelling Case** for Annihilating Dark Matter”, arXiv:[1402.6703](https://arxiv.org/abs/1402.6703)

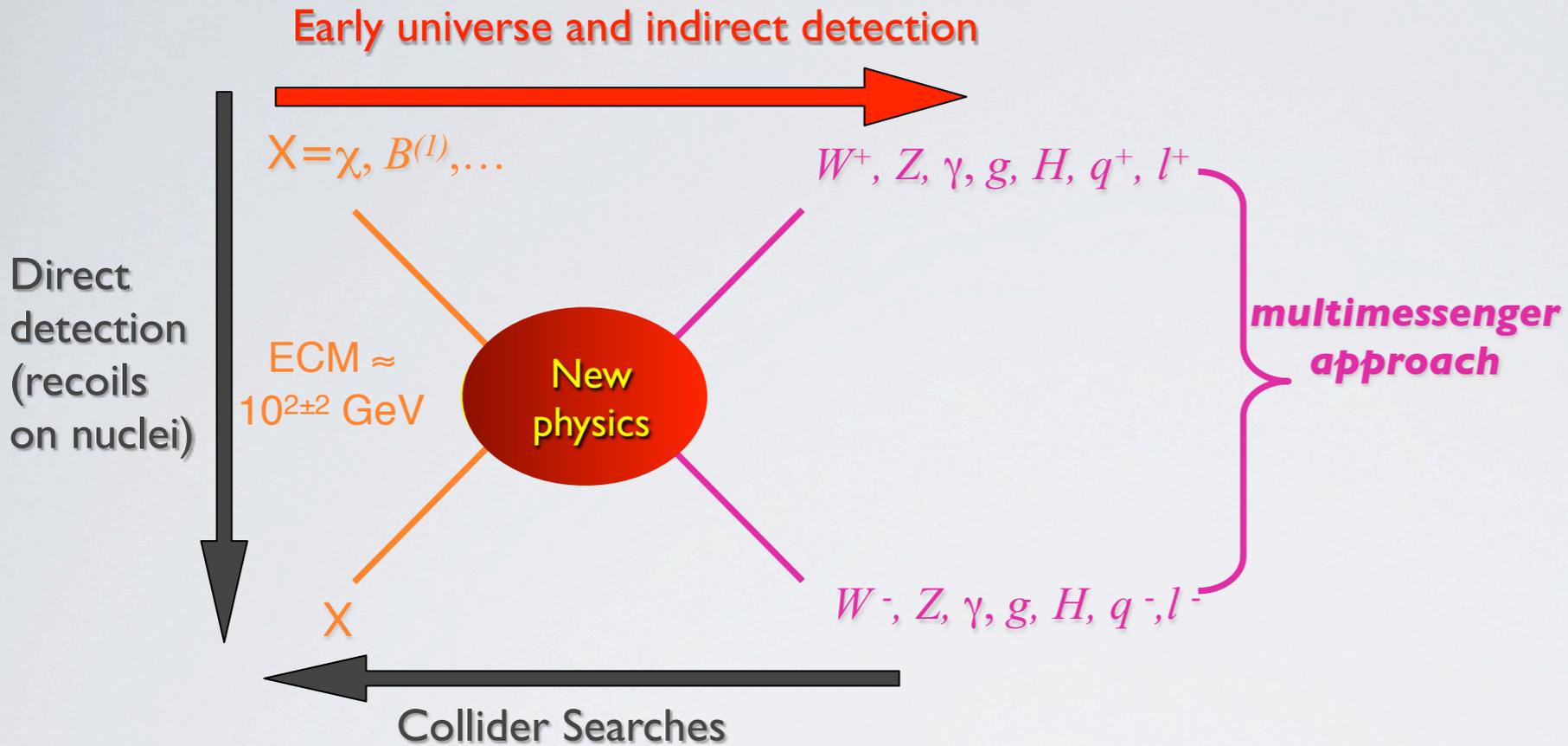
...



30 ± 10 GeV with “thermal cross section” ~few 10^{-26} cm^3/s into quarks, preferentially, with slightly steeper than NFW halo profile

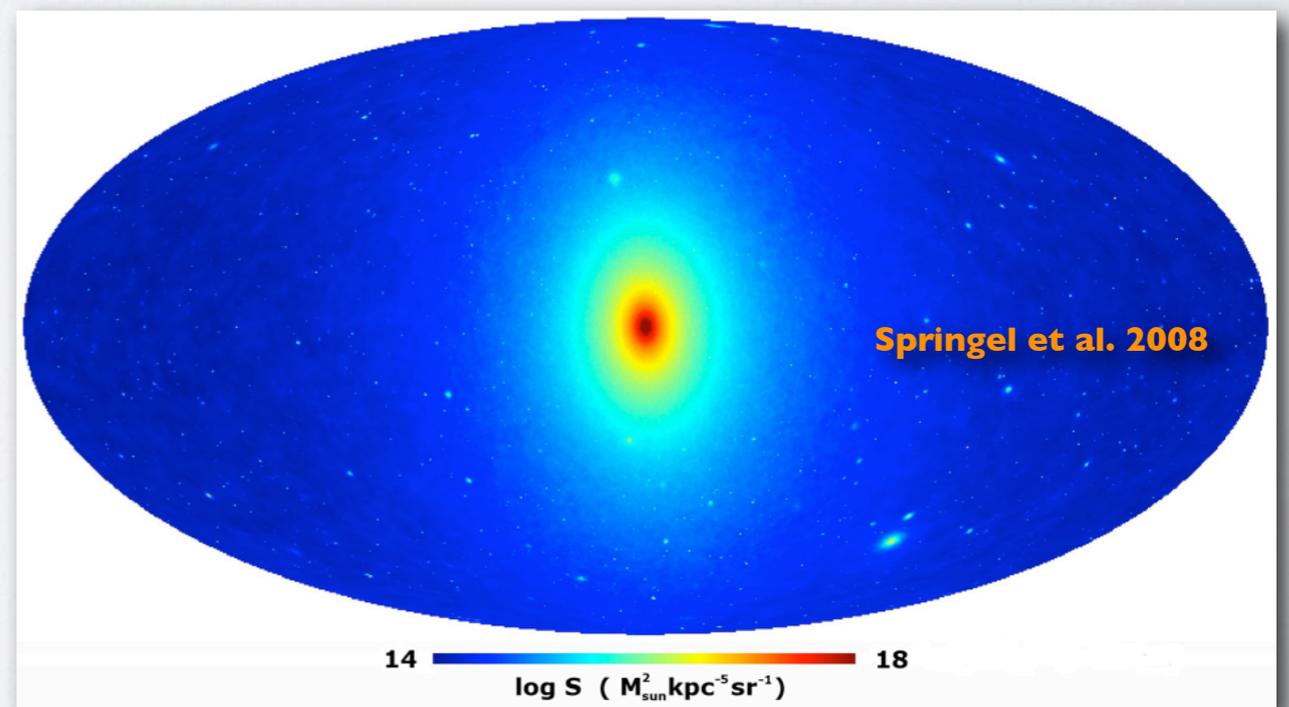


GAMMA RAYS FROM WIMPS?!



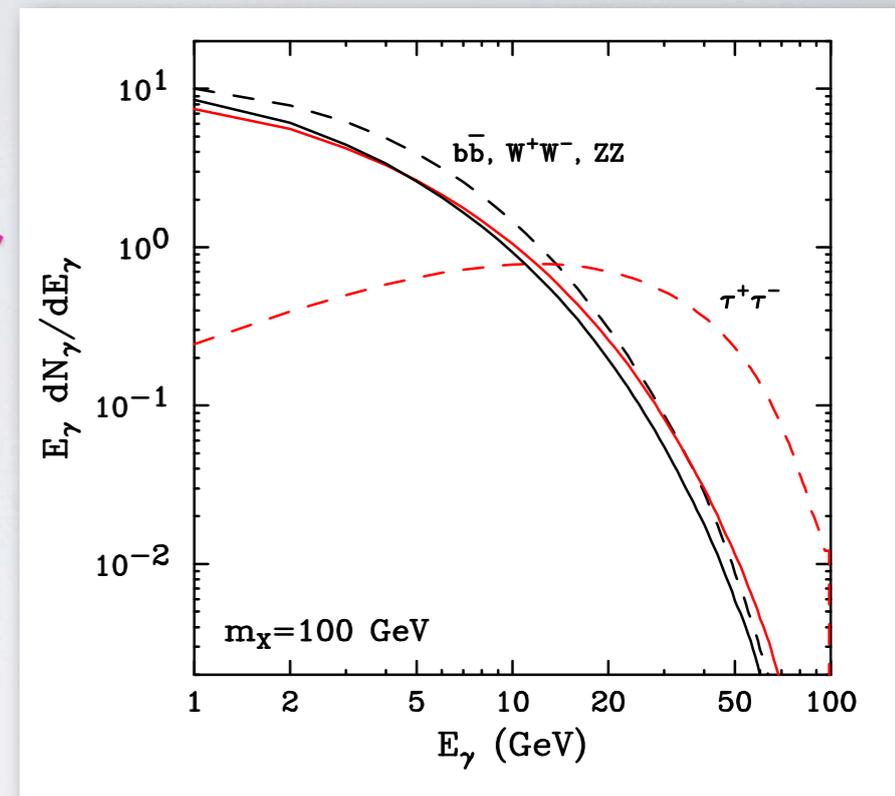
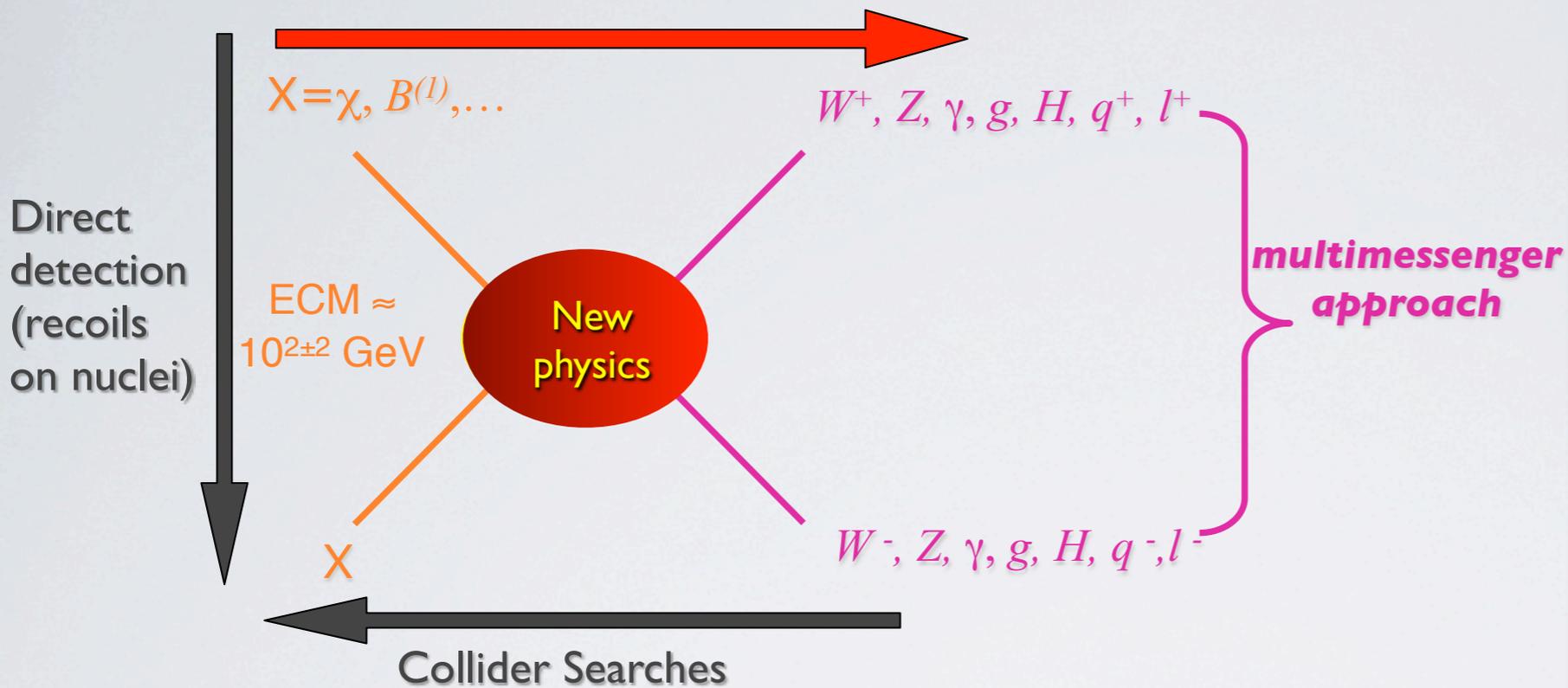
Annihilations may still take place nowadays, particularly in sufficiently deep potential wells (inferred from simulations or kinematical constraints...)

Differently from charged particles, gammas retain directionality



GAMMA RAYS FROM WIMPS?!

Early universe and indirect detection



Often written:

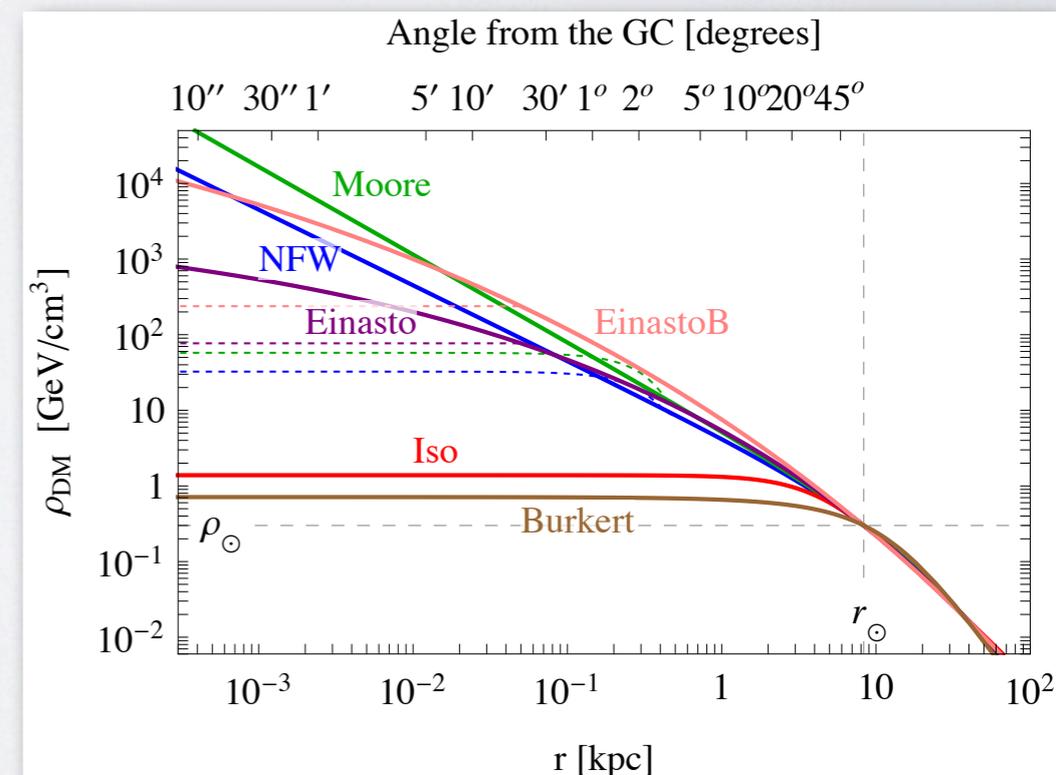
particle physics

astrophysics

$$\Phi_\gamma(E_\gamma, \Omega) = \left[\frac{dN_\gamma}{dE_\gamma}(E_\gamma) \frac{\langle \sigma v \rangle}{8\pi m_X^2} \right] \int_{\text{los}} \rho^2(l, \Omega) dl$$

[particle] \otimes (astro) factorization holds if

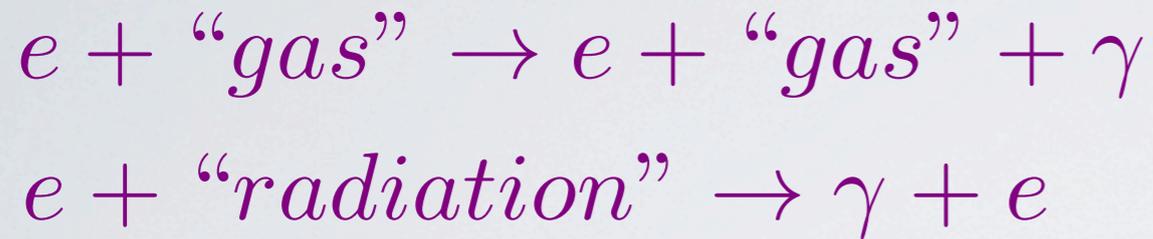
- ▶ σv is v -independent
- ▶ **if prompt emission dominates**



AN EXAMPLE WHERE IT FAILS

Even “what signal and what background should look like” is difficult!

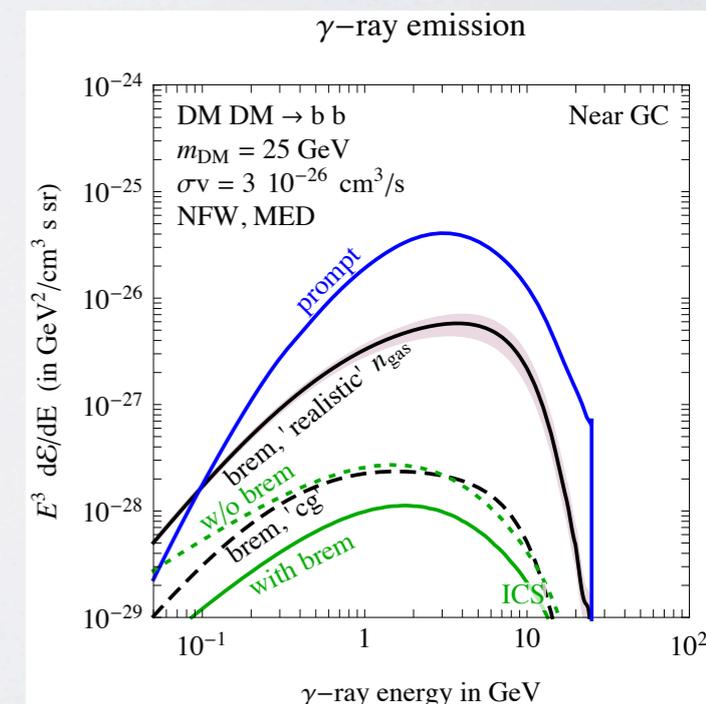
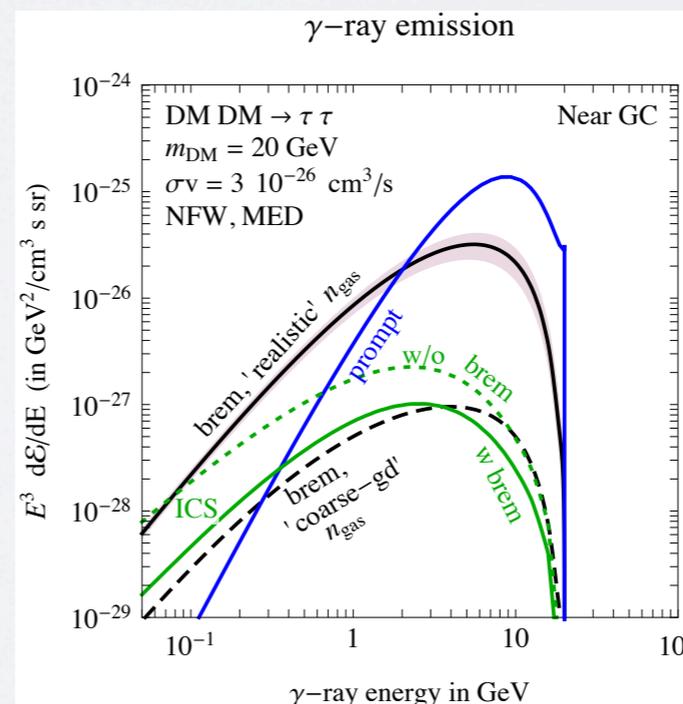
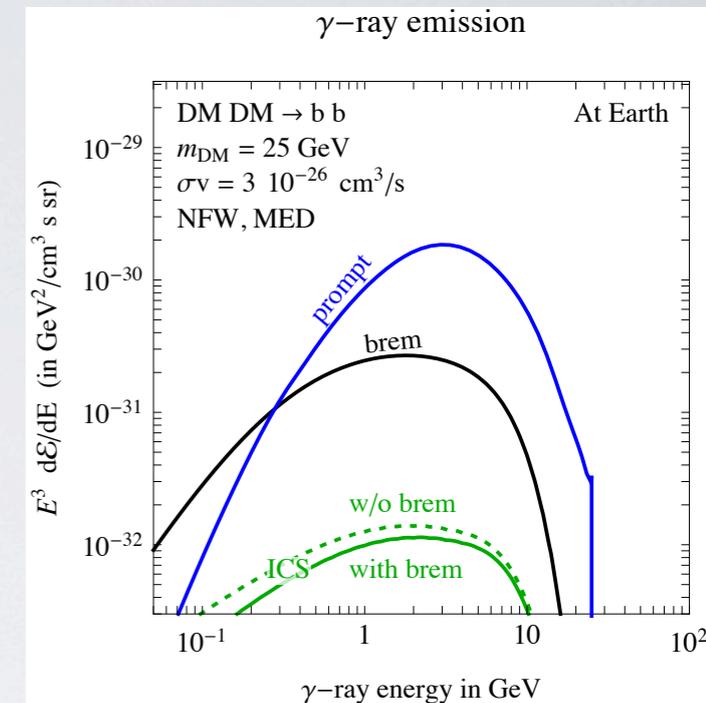
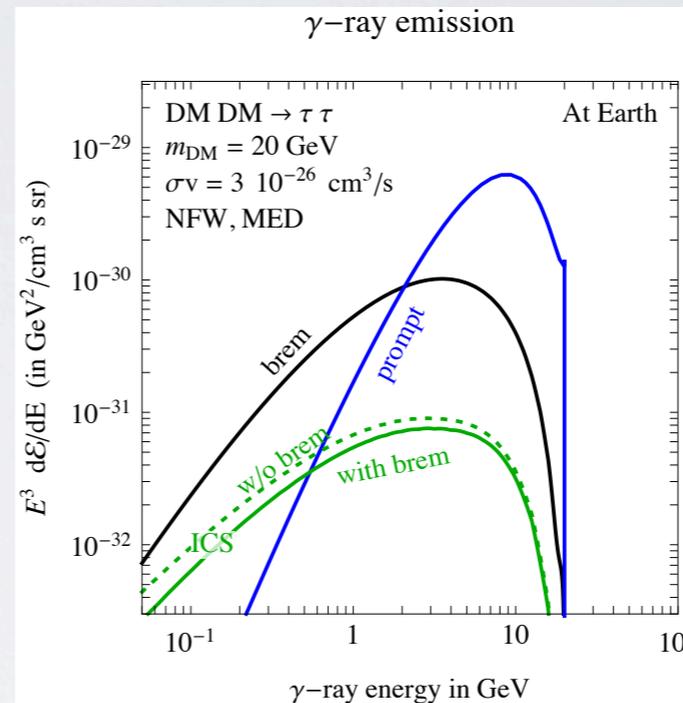
DM signal computation depends from astrophysics! (especially @ $E \leq \text{few GeV}$)



We recently highlighted that knowing e.g. the gas distribution is important to gauge the **bremsstrahlung** contribution (and the **IC**).

M. Cirelli, PS and G. Zaharijas, “Bremsstrahlung gamma rays from light Dark Matter,” JCAP 1311, 035 (2013) [arXiv:1307.7152].

Technical note (beware of black boxes!)
 optimized Galprop models fitting gas distribution in the inner galaxy assume no DM contribution. A priori not self-consistent when DM added: “Diffusion-loss and signal maps not the same”



MORE CAVEATS ABOUT GAL. CENTER

Before getting too excited, remember that many ingredients enter these results, e.g.:

- ▶ diffuse background modeling
- ▶ properties of unresolved sources (number, distribution...)
- ▶ point-like source spectra (at low-E, bad angular resolution!)
- ▶ time dependence?
- ▶ new type of sources?
- ▶ ...

“There are more things in heaven and earth, Horatio, Than are dreamt of in your philosophy.” - Hamlet, W. Shakespeare

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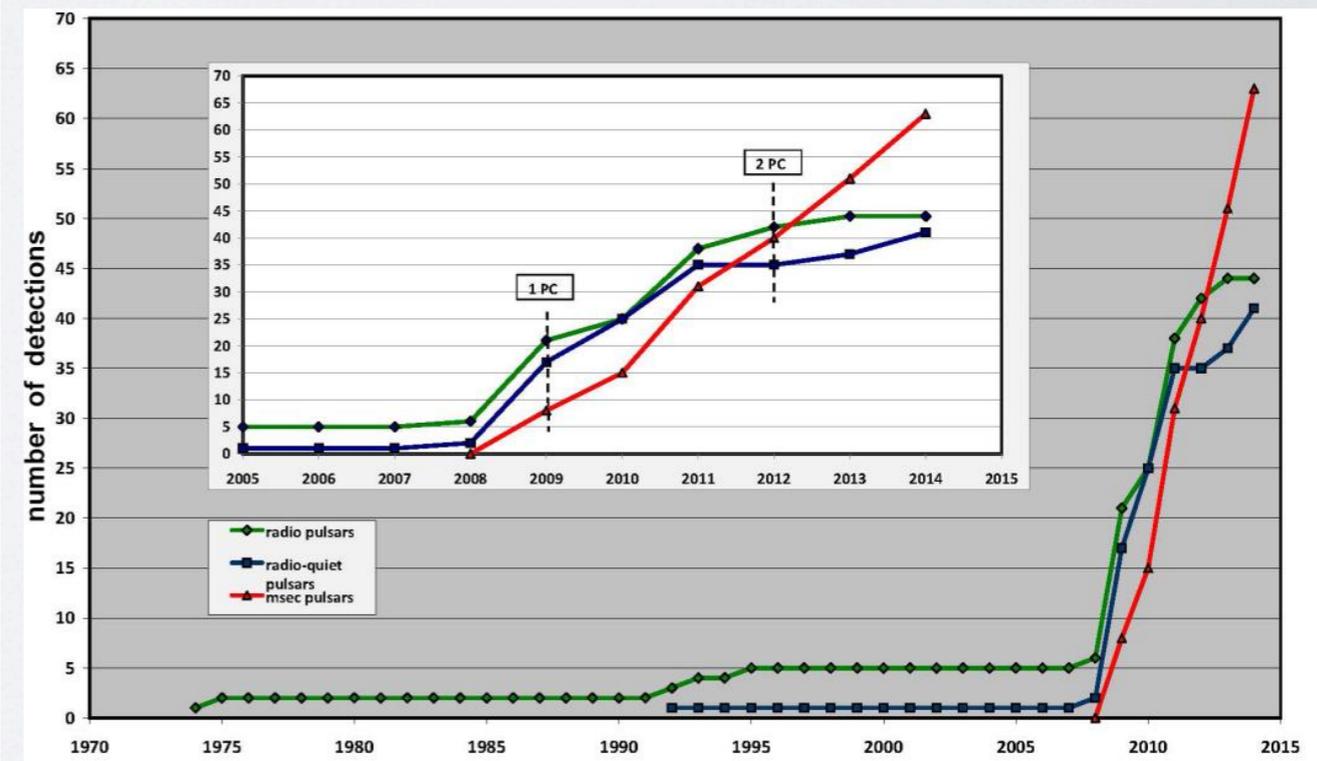
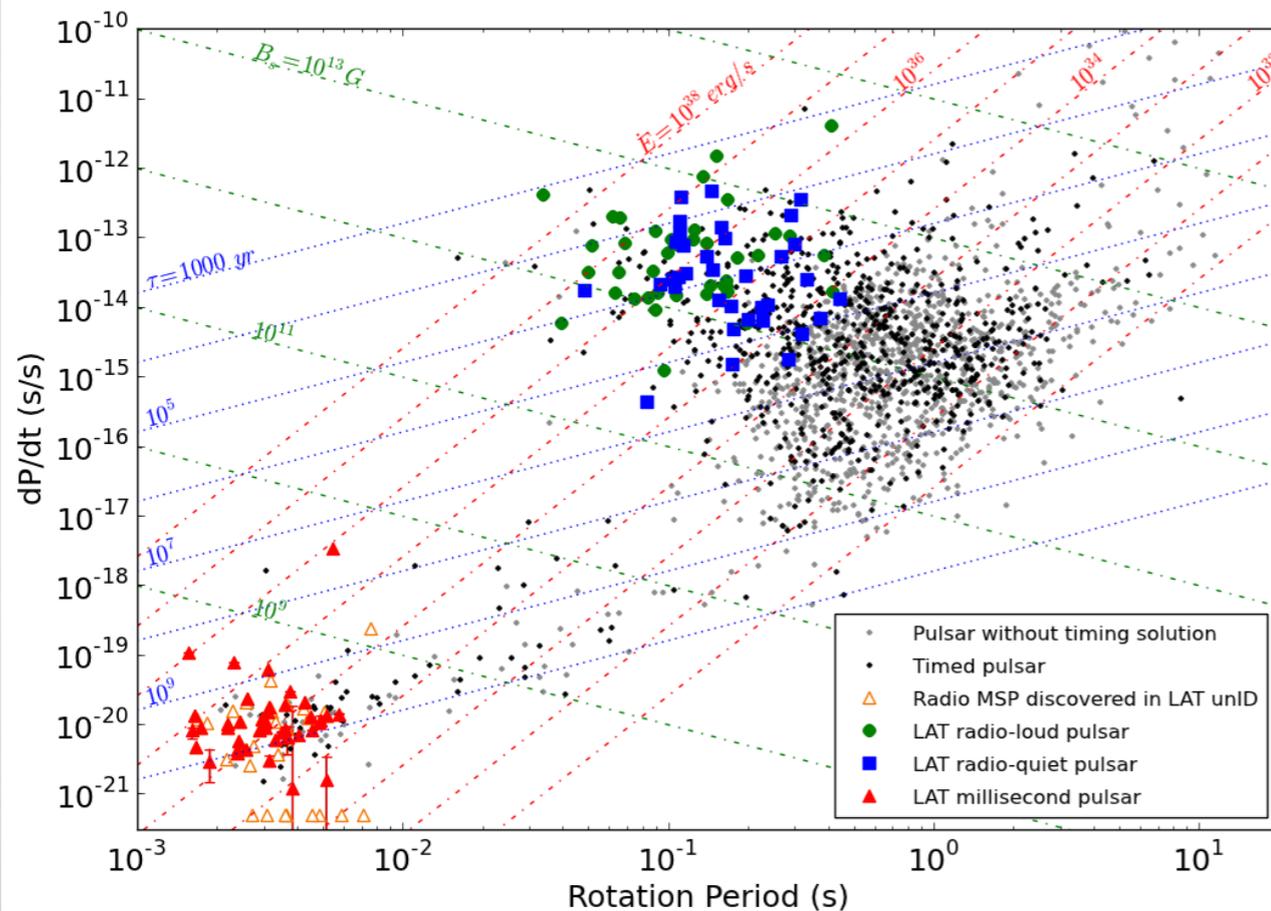
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P.A. Caraveo, “Gamma-ray Pulsar Revolution,”

Annual Review of Astronomy and Astrophysics 52 (2014) [arXiv:1312.2913]

I mean... literally!

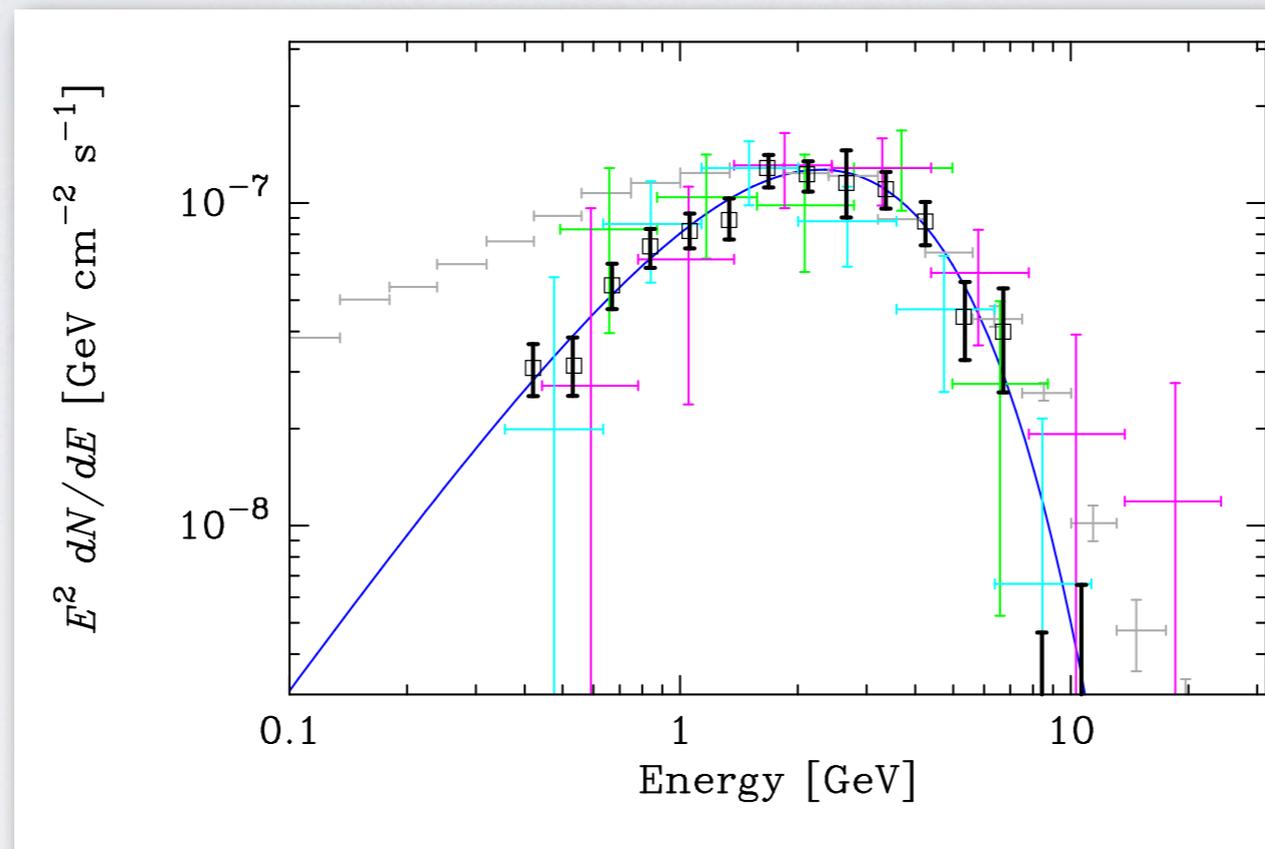


EXAMPLE OF “STRANGE BEASTS”

→ Could be due to new population of MSP?

✓ Spectrum (above GeV, at least) very similar to signals from globular clusters, attributed to MSP, i.e. recycled pulsars, spun up due to accretion from companion star.

⦿ Normalization would require $\sim 10^{3.4 \pm 0.4}$ MSP. (Qualitatively ok: high stellar density in inner bulge!) Traditional models do not predict so many pulsars, but note that MSP field revolutionized in the Fermi era...



K.N.Abazajian, JCAP 1103 (2011) 010 [1011.4275]

“The Consistency of Fermi-LAT Observations of the Galactic Center with a Millisecond Pulsar Population in the Central Stellar Cluster,”

Q.Yuan and B. Zhang, “Millisecond pulsar interpretation of the Galactic center gamma-ray excess,” arXiv:1404.2318 [astro-ph.HE]
(suggest that also profile matches the one of low mass X-ray binaries...)

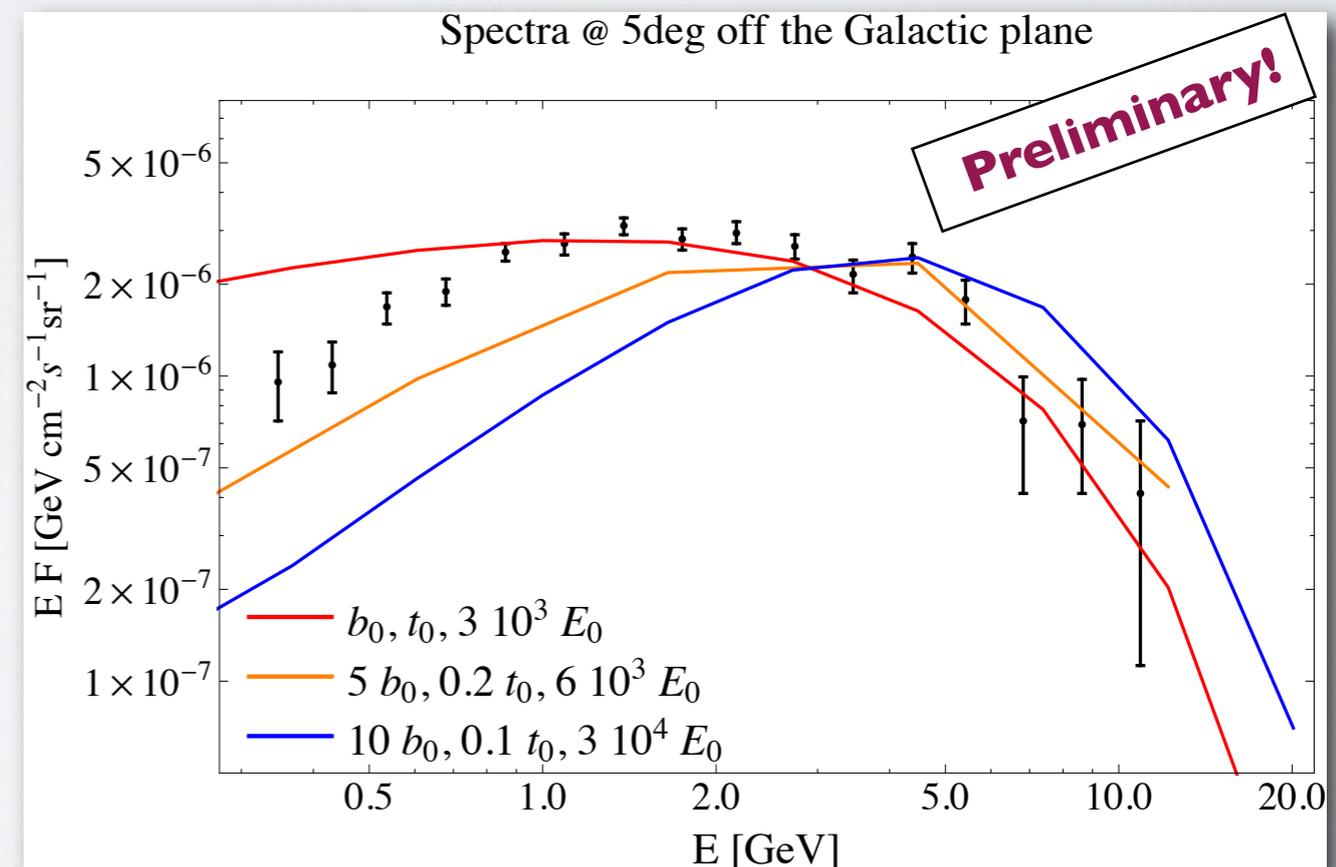
AN ANCIENT GALACTIC BURST?

✓ Maybe what we see is not the result of **stationary** non-thermal phenomena, rather the **forensic evidence** of some **bursting event** happened in the past at the GC. Cosmic rays “stay around” for $>$ Myrs after the event!

✓ Preliminary results indicate that $O(10^{52})$ erg injected “rapidly” a few Myrs ago (accretion +jet activity? Starburst episode?) producing a “standard” astrophysical power-law $\sim E^{-2.\varepsilon}$ can fully explain the excess via Inverse Compton onto starlight at $E >$ GeV.

✓ **Energy cutoff and angular extension** (up to $\sim 10^\circ$) simultaneously explained by the same age parameter.

✓ There seem to be other evidence for GC activity with the same timescale in the past...



Work in progress with G. Zaharijas

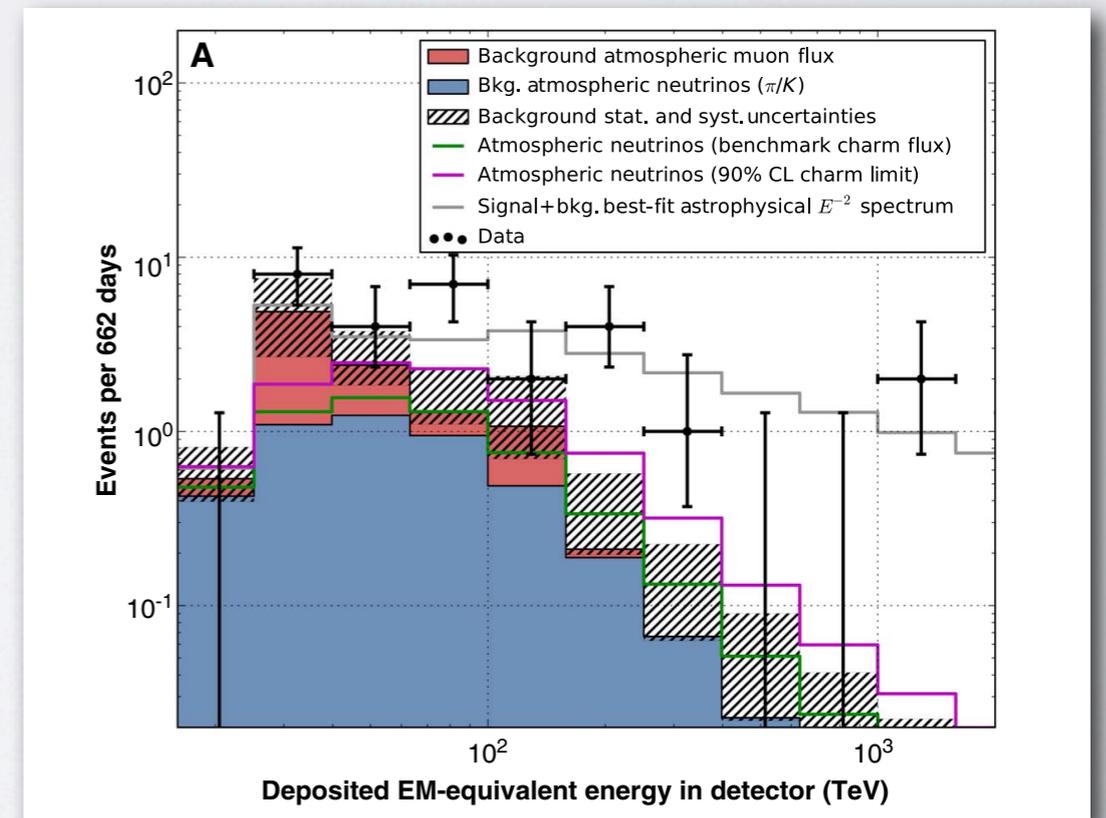
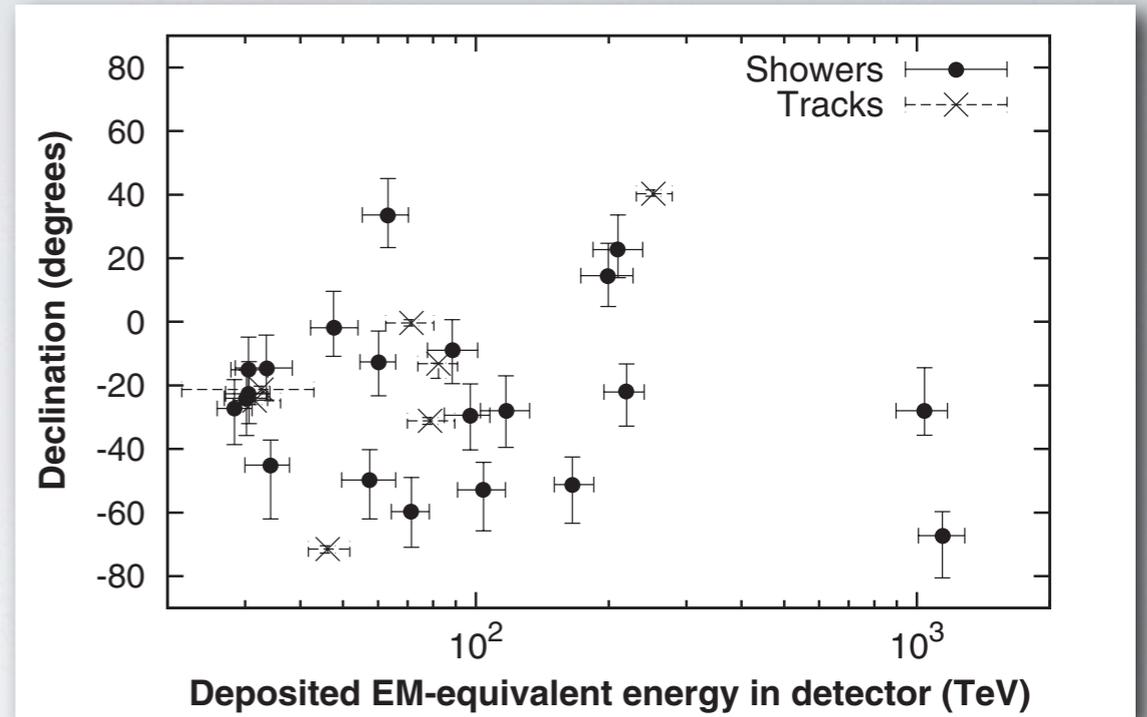
A NEW WINDOW TO THE UNIVERSE!

M. G. Aartsen et al. [IceCube Collaboration], "Evidence for High Energy Extraterrestrial Neutrinos at the IceCube Detector," Science 342, no. 6161, 1242856 (2013) [arXiv:1311.5238]

▶ First, **2 shower** events just above the **PeV** found at the lower edge of a search motivated by cosmogenic neutrinos, **2.8 σ excess**

▶ Later, extension to **lower energies** (down to 30 TeV): overall **28 events** (both **showers and tracks**) wrt $10.6^{+5.0}_{-3.6}$ background expected (**>4 σ !**)

▶ E-distribution, angular distribution and flavour composition consistent with a isotropic signal (fully Galactic plane disfavored, but could have Galactic component)

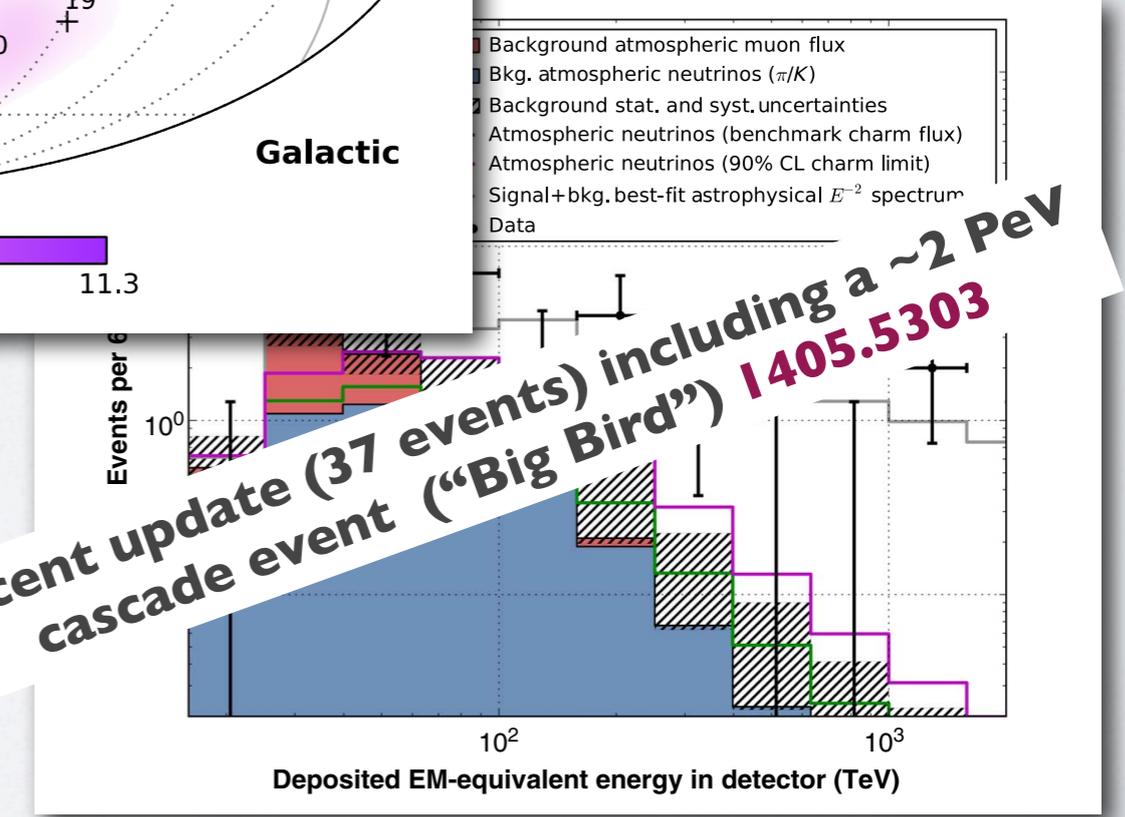
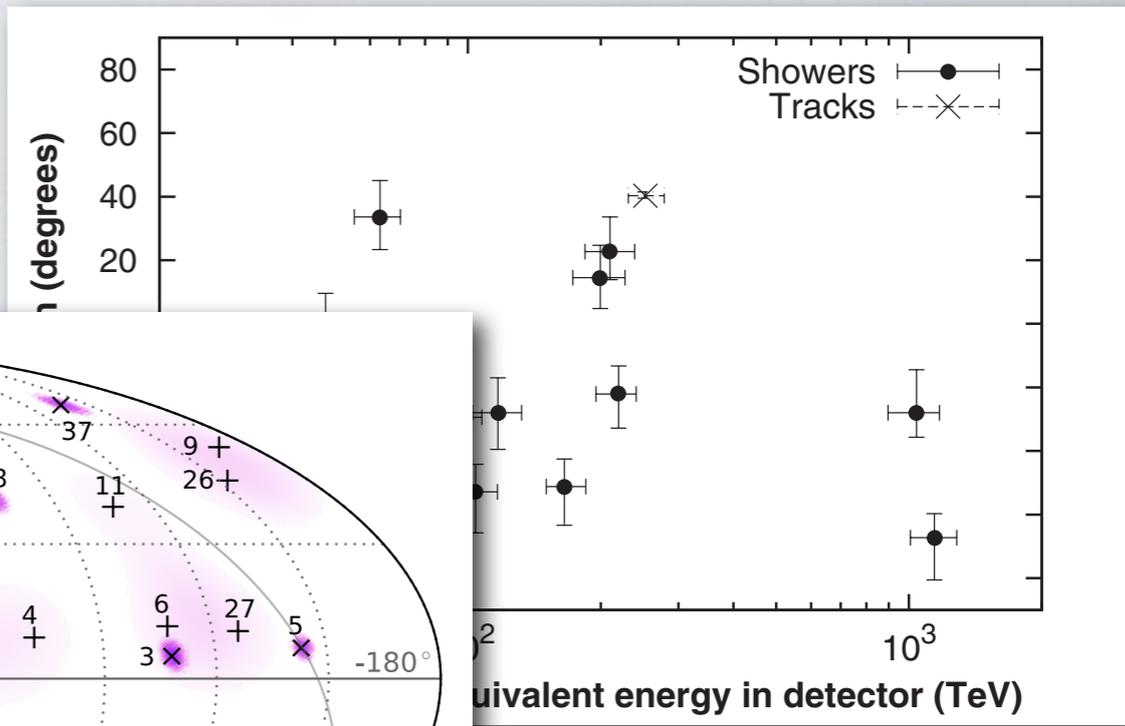
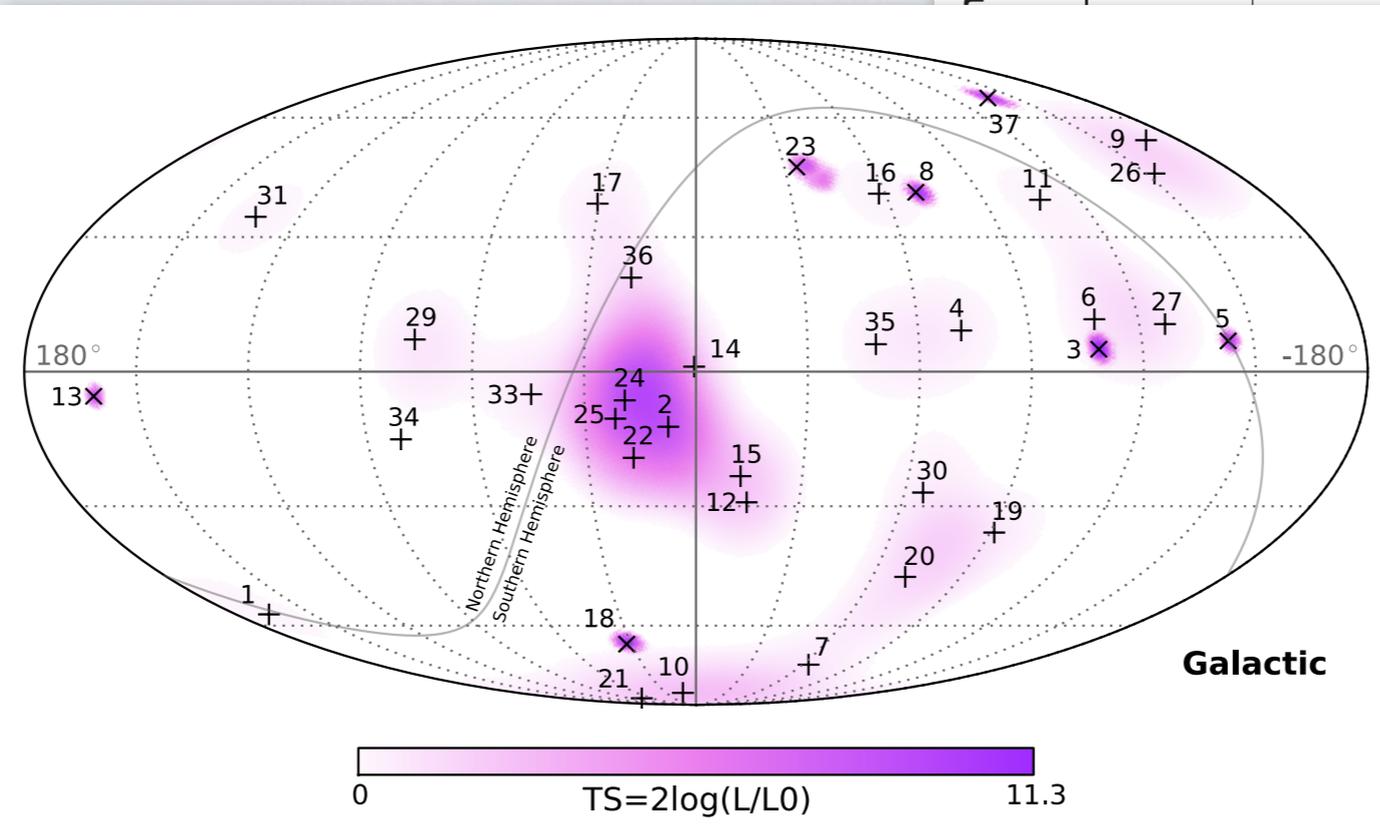


Birth of high energy neutrino astronomy!

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- ▶ First, 2 shower events found at the lower energy range (by cosmogenic neutrinos)
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CASE II: SERENDIPITOUS UV SCALE?

While it is likely that astrophysical sources are responsible for those events, some features allow one to entertain the possibility of a DM origin, notably

I. no events beyond ~ 2 PeV (vs. ~ 8 expected if flux set to a $\sim E^{-2}$ astrophys. benchmark)

II. dip of events in the 0.4-1 PeV range (but still $\leq 2\sigma$ fluct.)

III. Observed ratio downgoing/upgoing (>1 due to Earth absorption) events ~ 6

Accounting for μ contamination, down to **4.5 \pm 1.0**

Expected for an isotropic E^{-2} astro-background ~ 1.8

P. Lipari, arXiv:1308.2086

IV. Some excess towards GC, but no Galactic Plane correlation
(7 of the contained events in $30^\circ \times 30^\circ$, 8% chance prob.)

$L_\nu(0.06-2 \text{ PeV}) \sim 5 \cdot 10^{36} \text{ erg/s}$
 $L_\nu(>1 \text{ TeV}) \sim 7 \cdot 10^{34} \text{ erg/s}$

Glimpses of Dark Matter?

B. Feldstein, A. Kusenko, S. Matsumoto and T.T. Yanagida, PRD 88, 1, 015004 (2013) [arXiv:1303.7320] (“PeV line” only)

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....

Note I: must be **non-thermal DM!** For $m > 300$ TeV thermal DM should have annihilating $\langle \sigma v \rangle$ larger than unitarity bound.

K. Griest and M. Kamionkowski, PRL 64, 615 (1990).

Viable production mechanisms exist, e.g. directly from inflaton decay in low-scale reheating scenarios, see for example

K. Harigaya, M. Kawasaki, K. Mukaida and M. Yamada, “Dark Matter Production in Late Time Reheating,” arXiv:1402.2846

SIGNAL SHOULD COME VIA DECAY

The right o.o.m. can be obtained by invoking Planck suppressed operators
(plus GUT-related or B-L breaking or...)

$$\Gamma \sim \left(\frac{\Lambda}{m_{\text{Pl}}} \right)^2 \left(\frac{m_X}{m_{\text{Pl}}} \right)^4 m_X$$

More details on model-building e.g. in
Feldstein, A. Kusenko, S. Matsumoto and T.T. Yanagida,
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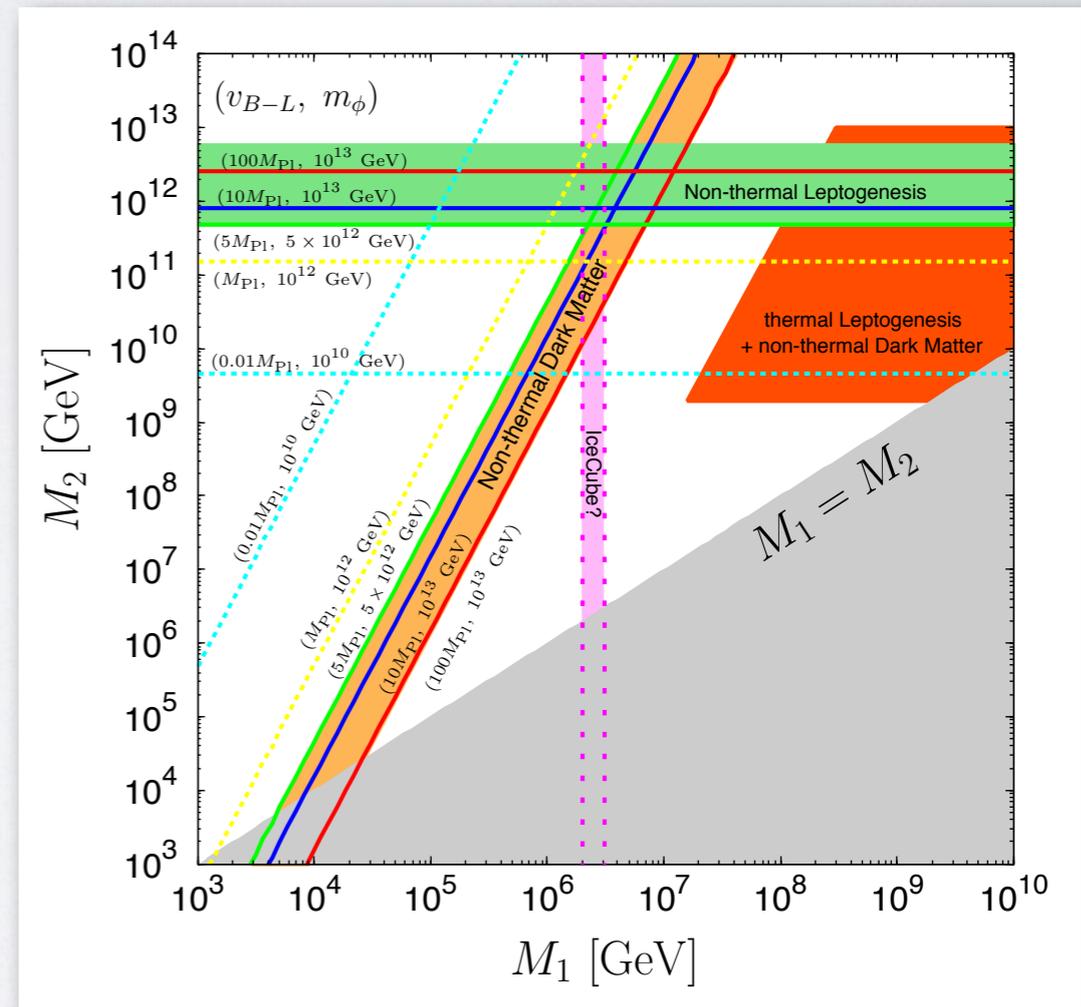
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Alternatively, from “right-handed” neutrino decays
(in leptons and gauge bosons/higgses)

$$\Gamma \sim \frac{|y|^2 m_X}{16\pi} \quad y \sim 10^{-29}$$

Caveat: many unnatural small parameters... still
a problem for anyone?

Plus: can “embed” it into a more complete model,
also accounting for inflation (B-L breaking “higgs”),
leptogenesis, even BICEP 2...



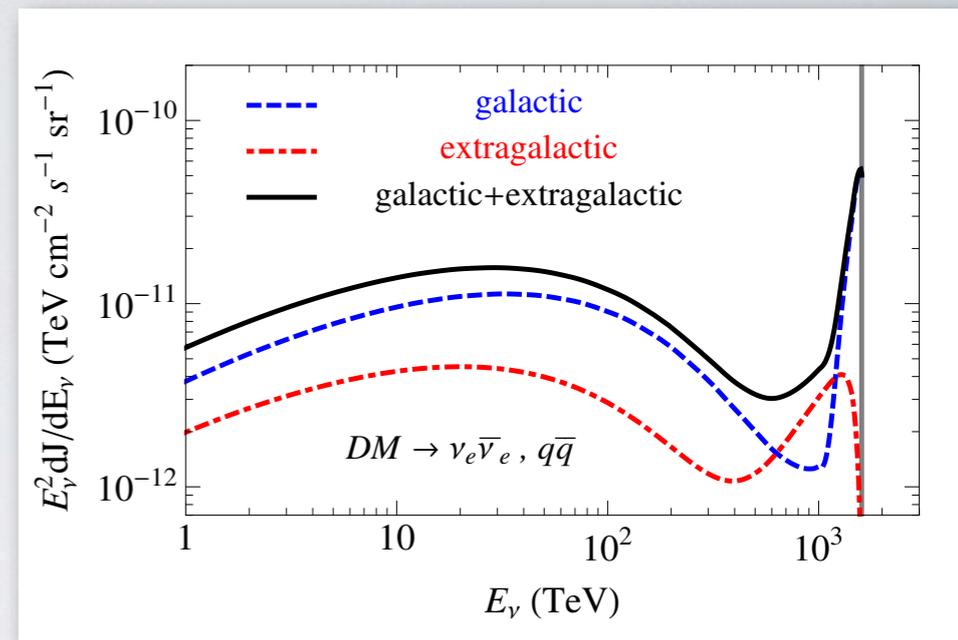
T. Higaki, R. Kitano and R. Sato,
“Neutrino Universe,” arXiv:1405.0013

SOME PHENO ASPECTS

- ▶ Both Galactic and extragalactic contributions, roughly comparable

$$\frac{dJ_h}{dE_\nu}(l, b) = \frac{1}{4\pi m_{\text{DM}} \tau_{\text{DM}}} \frac{dN_\nu}{dE_\nu} \int_0^\infty ds \rho_h[r(s, l, b)]$$

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SOME PHENO ASPECTS

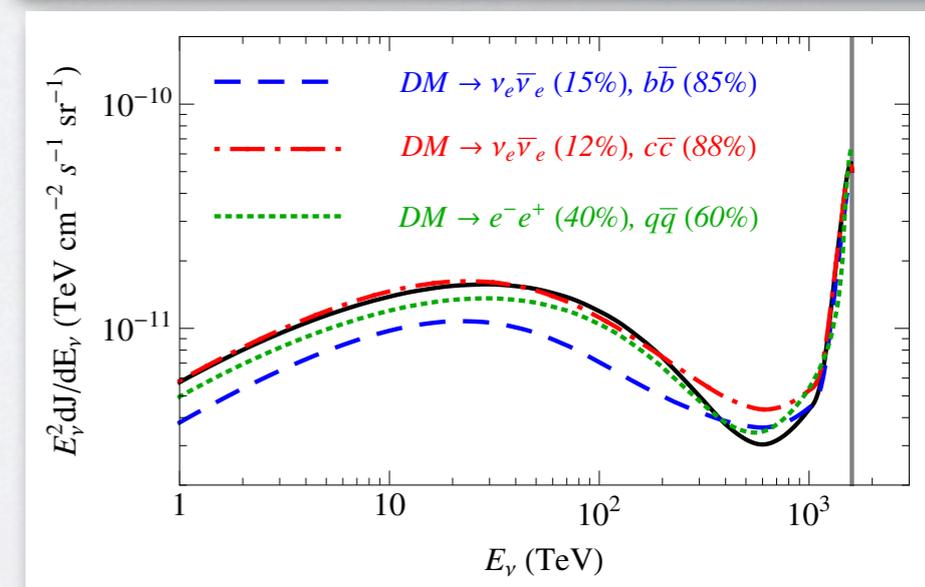
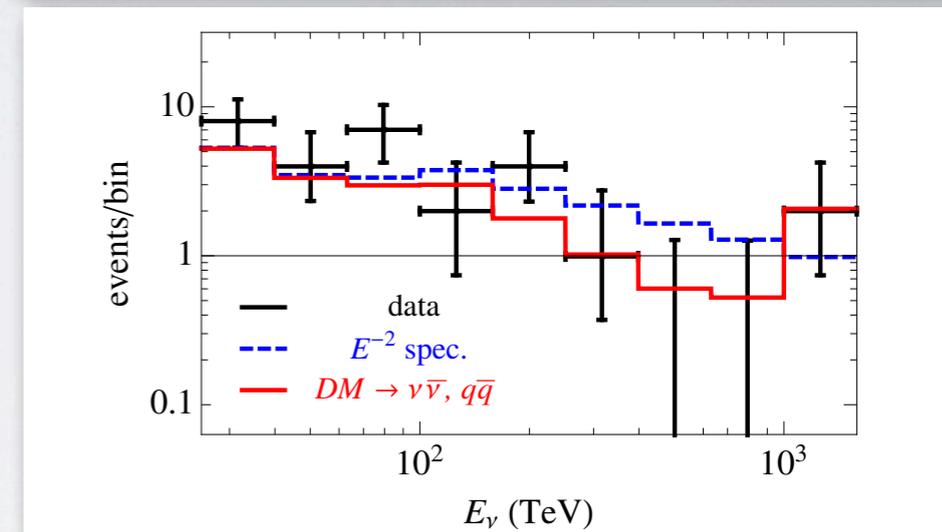
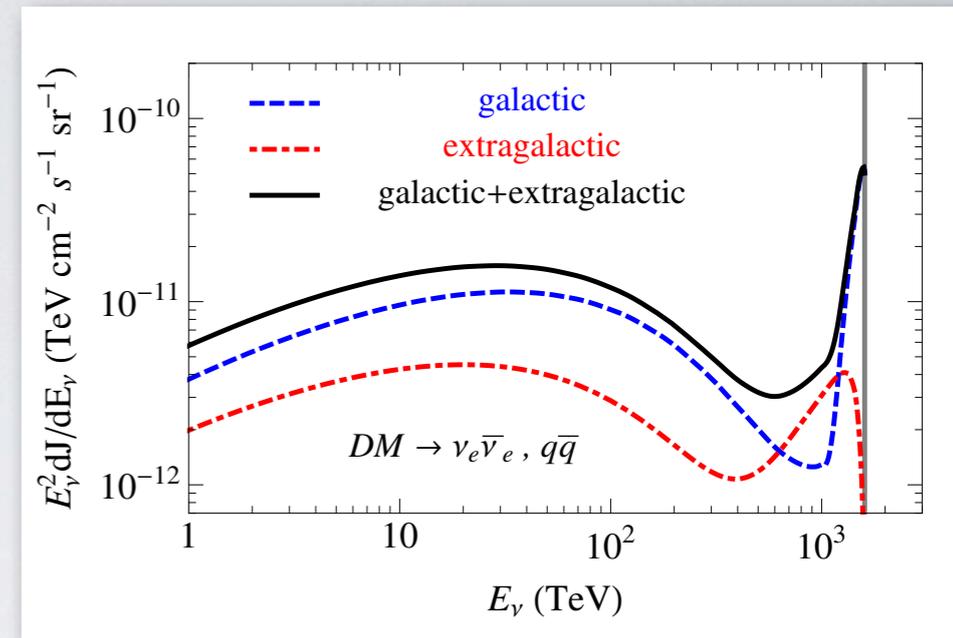
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- ▶ In a 30° aperture cone around the Gal. Center, ~ twice the events than for an isotropic flux (~15% vs 7%), much milder and less uncertain than for annihilation!
- ▶ Abrupt energy cutoff expected (at few PeV at most)
- ▶ Accommodated in a variety of final states/b.r./lifetimes (i.e. not particularly fine-tuned, e.g. decay via operators containing LH OK, no specific flavor structure)
- ▶ Possibly (likely) associated to measurable gamma flux (but early detection in neutrinos quite natural...)

Testable with forthcoming IceCube data!



CASE III: SHOCKING?

- SM Neutrinos do not work as DM, but have some good properties (almost Ok!)
Easy to add one extra neutrino state which works!
- SM singlet, but for mixing with active (one needs ≥ 2 of these to give mass to ν 's...)

$$\delta\mathcal{L} = \bar{N}i\partial_\mu\gamma^\mu N - \lambda_\ell H\bar{N}L^\ell - \frac{M}{2}\bar{N}^c N + h.c.$$

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- Astrophysically interesting candidate:
- “cold-to-warm”, may suppress structures at sub-kpc scales;
- can be searched for via X-ray line (rare loop-suppressed decay)
- can be embedded in a “minimal extension” of the SM with only 3 right-handed neutrinos (two GeV-ish ones explaining baryon asymmetry...)

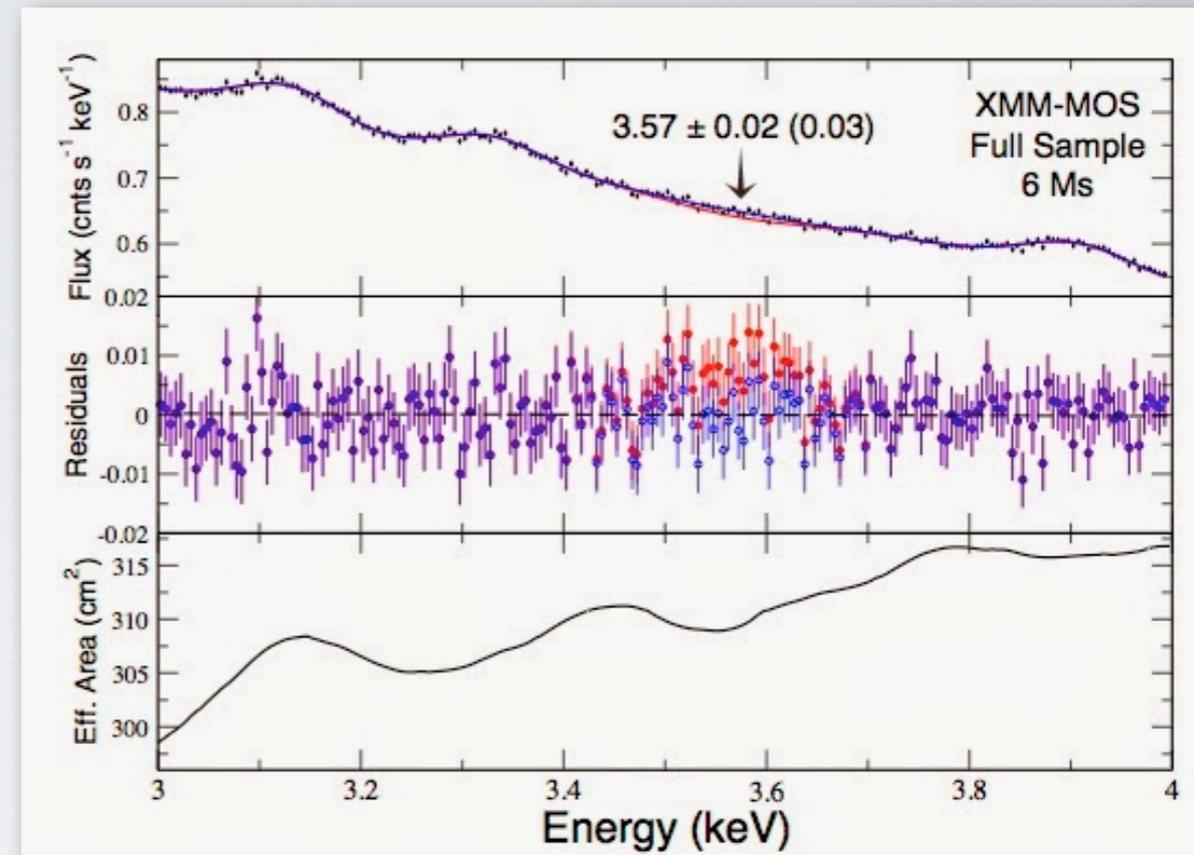
$$N \rightarrow \nu + \gamma$$

ν MSM, for a review, A. Boyarsky, O. Ruchayskiy and M. Shaposhnikov,
Ann. Rev. Nucl. Part. Sci. 59, 191 (2009)

Note: no physics above the electroweak scale is required

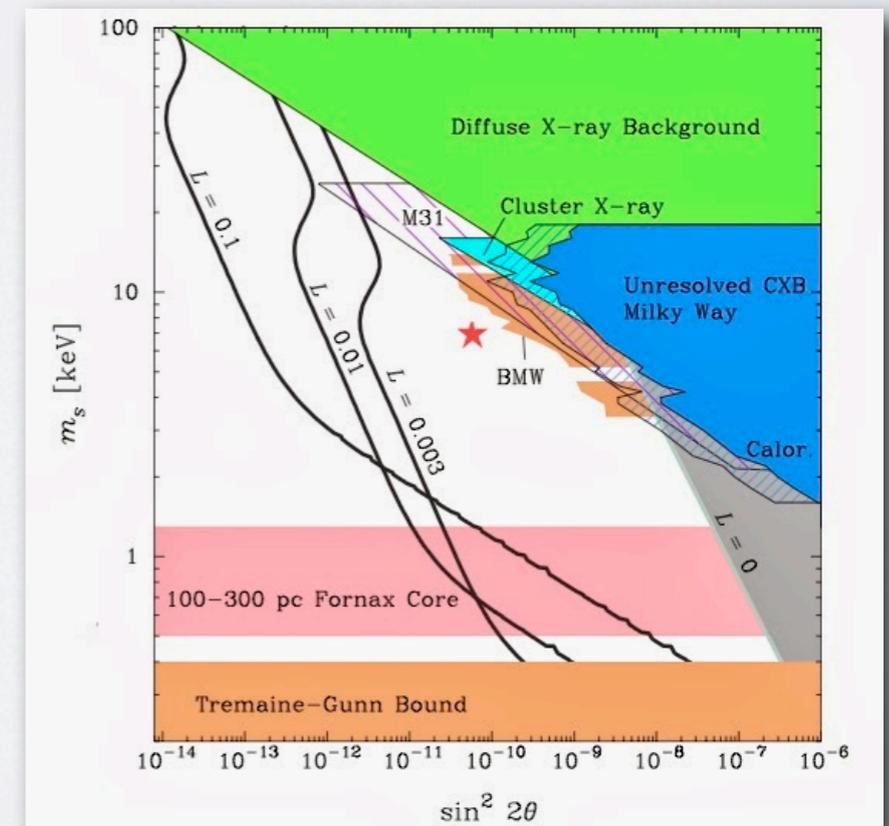
CASE III: THE LINE OF THE YEAR (2014)

a recent analysis of X-ray spectrum of galactic clusters claims the presence of a monochromatic 3.55 keV photon line which can be interpreted as a signal of a 7.1 keV sterile neutrino



E. Bulbul, M. Markevitch, A. Foster, R. K. Smith, M. Loewenstein and S.W. Randall, "Detection of An Unidentified Emission Line in the Stacked X-ray spectrum of Galaxy Clusters," arXiv:1402.2301

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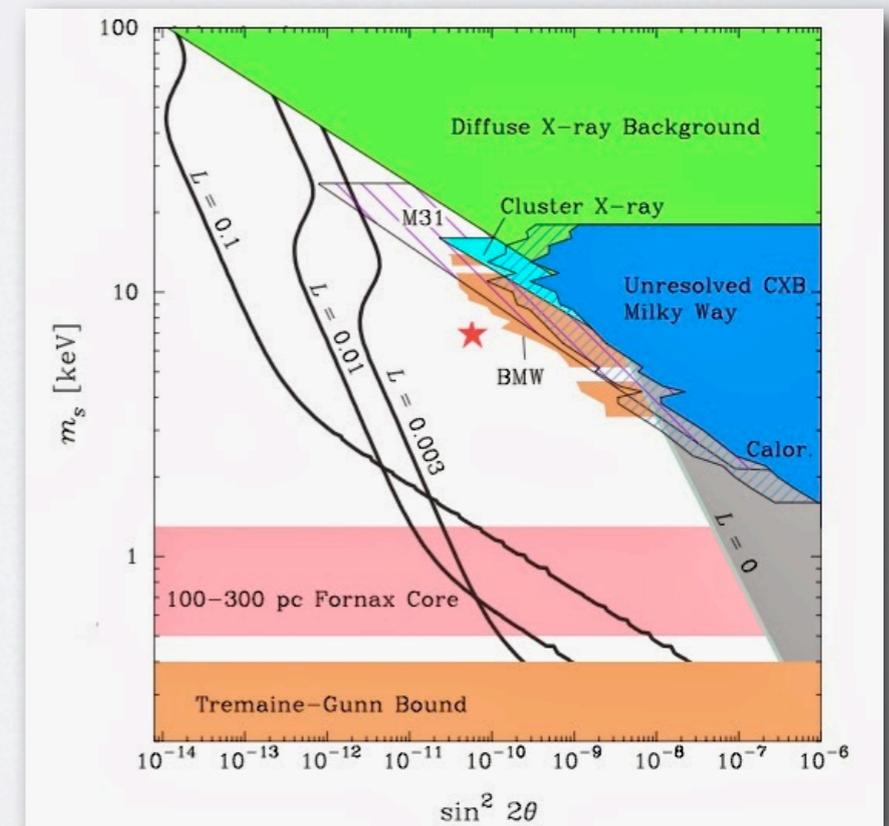
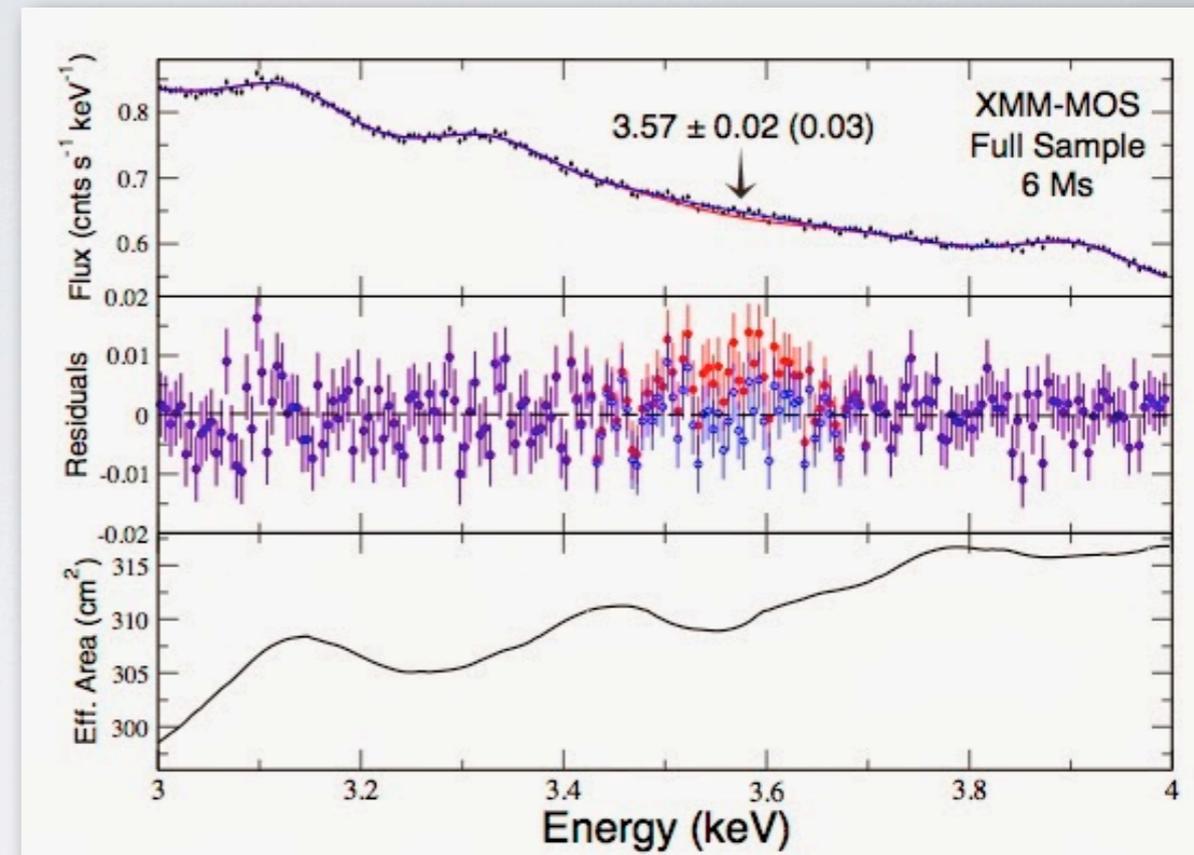
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- ▶ stack clusters (“shuffling” via z-dependence)
- ▶ need to parameterize “effective” background to better than % level (but argued OK)
- ▶ Overall consistent with DM, but some anomaly in normalization of Perseus?
- ▶ Would require “resonant” (non-thermal) production mechanism, via asymmetry? Or not ν_s ?
- ▶ Further tests needed (wait for *Astro-H*...)

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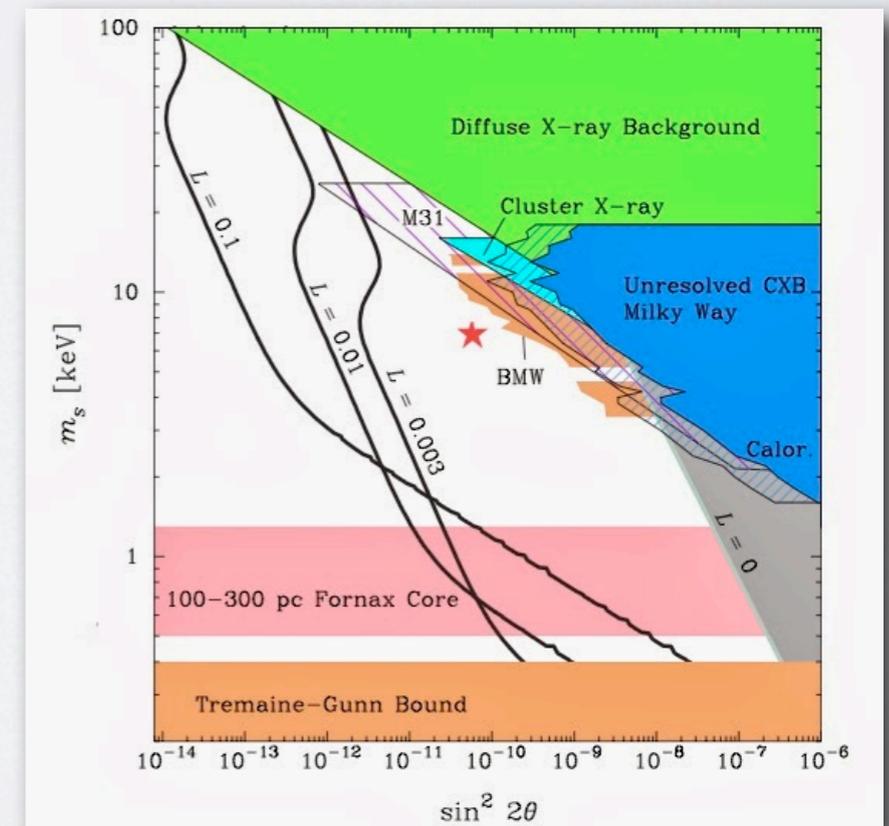
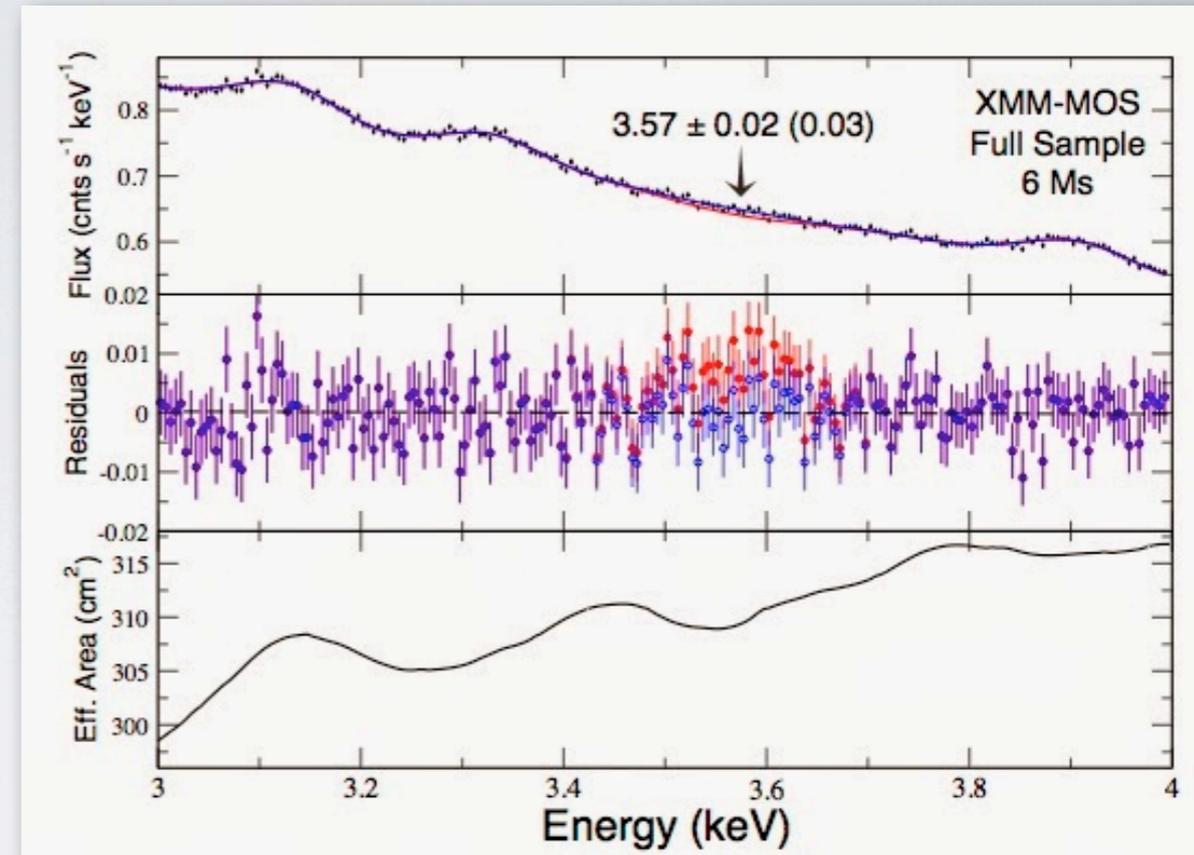
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See also DM parallel session!

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MESSAGE TO BRING BACK

Differently from colliders (till now!) “Cosmic Lab” **guarantees** that BSM physics is there! (in particular I stressed the DM case)

What is limiting progress is not the lack of theoretical ideas, but the **firm** identification of **clues** to select the right scale (& “path across the desert”).

What I showed (with concrete, literature inspired, examples!) is that Indirect DM detection **can help** discriminating among different scenarios for the BSM alternatives.
(but no “Theorem” that guarantees success, true of most post-Higgs searches!)

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For the astroparticle quest to be successful, we have to search:

better, in known channels. This means computing better signals but also better understanding of astrophysical “foregrounds”, themselves opportunities for discoveries

elsewhere: Astrophysics and Cosmology fortunately offer plenty of windows to be fully exploited (CMB polarization, spectral distortions, tomographic surveys, 21 cm, high energy gamma rays, neutrinos, gravitational waves, underground detectors...)

Thank you for your attention!



INDEPENDENT TESTS

Collider bounds & direct detection bound can be evaded (but testable at LHC-13!) with Dirac DM and pseudoscalar mediator a (e.g. via $t t a \sim tt E_{mis}$)

C. Boehm, M. J. Dolan, C. McCabe, M. Spannowsky and C. J. Wallace,
 “Extended gamma-ray emission from Coy Dark Matter,”
arXiv:1401.6458 [hep-ph].

AMS positrons:

Good possibilities to test it according to D. Hooper and W. Xue,
 “Possibility of Testing the Light Dark Matter Hypothesis with the Alpha Magnetic Spectrometer,”
PRL 110, 041302 (2013) [arXiv:1210.1220]

but bounds for hadronic modes not shown (!?) in

L. Bergstrom, T. Bringmann, I. Cholis, D. Hooper and C. Weniger,
 “New limits on dark matter annihilation from AMS cosmic ray positron data,”
PRL 111, 171101 (2013) [arXiv:1306.3983]

Below sensitivity according to

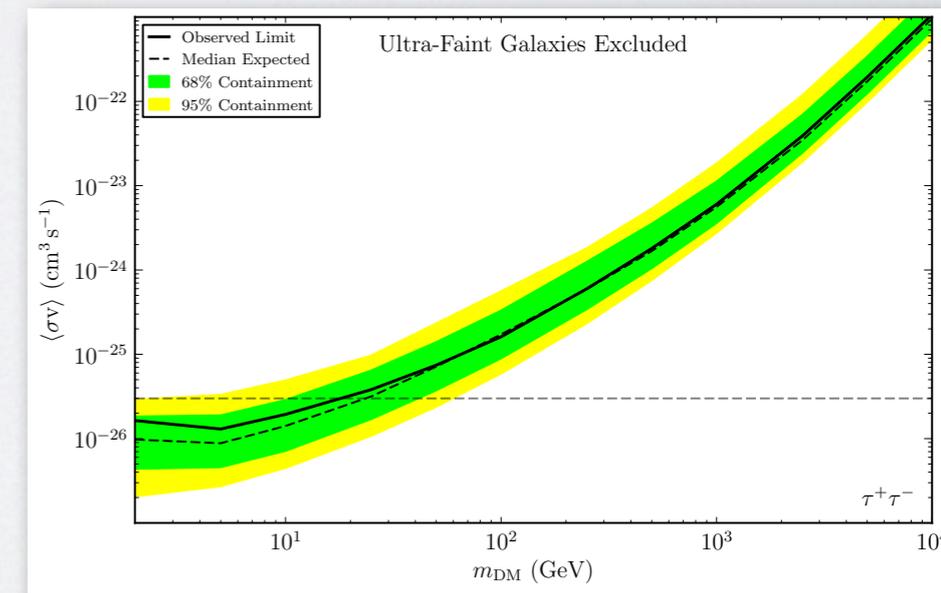
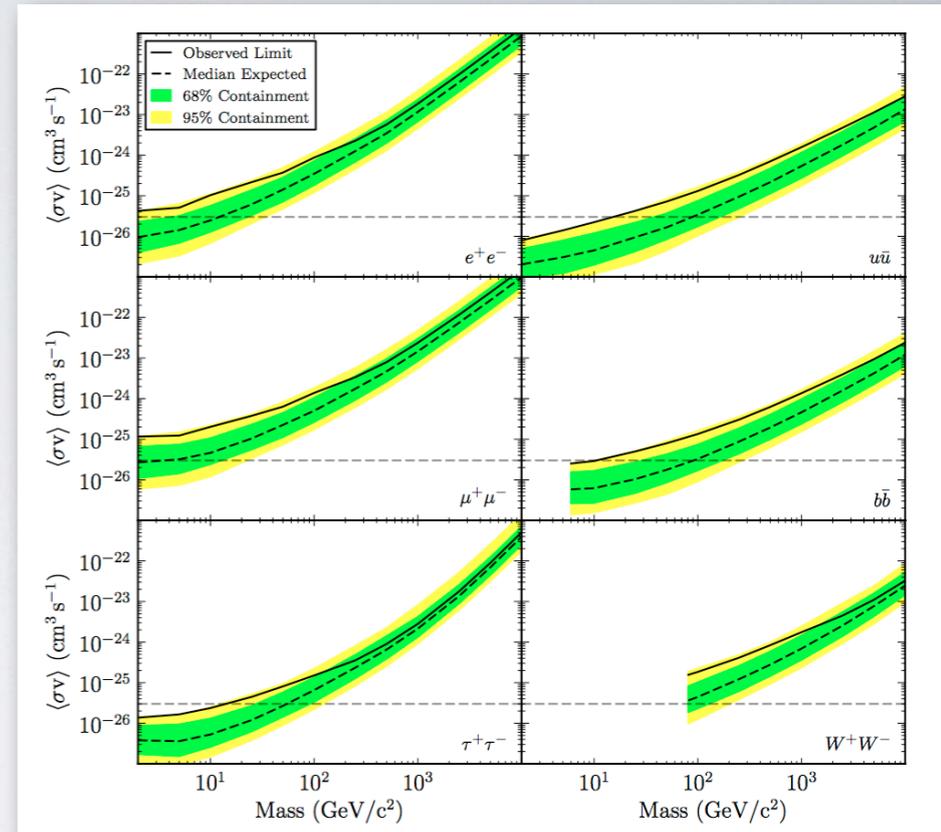
A. Ibarra, A. S. Lamperstorfer and J. Silk,
 “Dark matter annihilations and decays after the AMS-02 positron measurements,”
[arXiv:1309.2570].

Part of parameter space testable with AMS-02 antiprotons, see

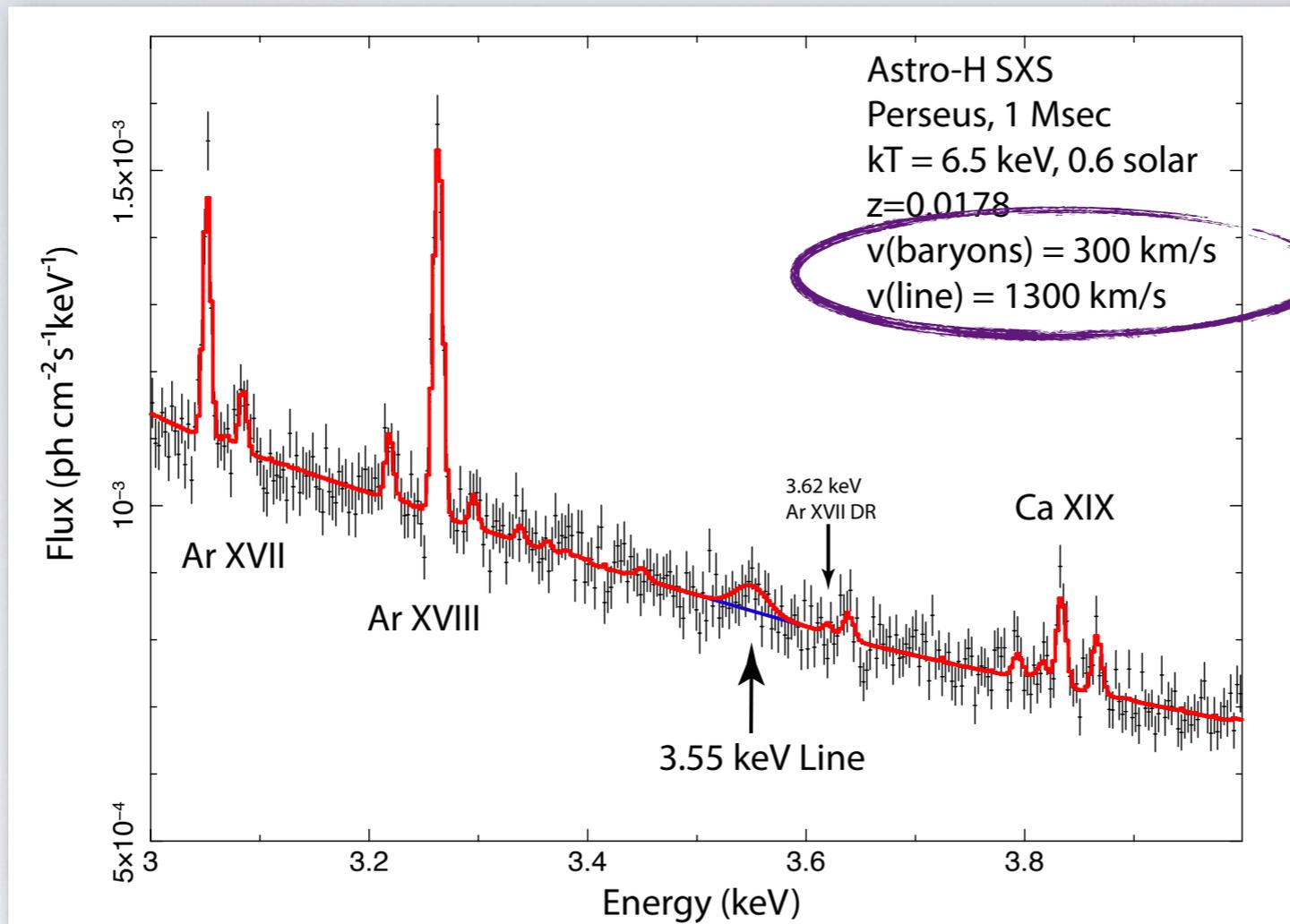
M. Cirelli and G. Giesen,
 “Antiprotons from Dark Matter: Current constraints and future sensitivities,”
JCAP 1304, 015 (2013) [arXiv:1301.7079]

Gammas from dwarfs in Fermi, some of which show a little excess?

Fermi-LAT, Phys. Rev. D 89, 042001 (2014) [1310.0828]



A SMOKING GUN?



Simulation astro-H

With sufficient spectral resolution, can distinguish broadening due to thermal plasma effect from DM velocity dispersion (virial theorem)!

E. Bulbul, M. Markevitch, A. Foster, R. K. Smith, M. Loewenstein and S.W. Randall, "Detection of An Unidentified Emission Line in the Stacked X-ray spectrum of Galaxy Clusters," arXiv:1402.2301