Cosmic ray probes of fundamental physics

- **I.** Intro: Why should we look for fundamental physics in (high-energy) astrophysics?

- **II.** Surprises from what *should be there but ain't* (often forgotten example of NP found thanks to CR, not yet understood)

- **III. Surprises from excesses, i.e. *finding what should not be there ?***
  - a) The paradigmatic case of Dark Matter (DM) - Intro to DM
  - b) WIMP DM searches ⟵
  - c) Non-WIMP searches

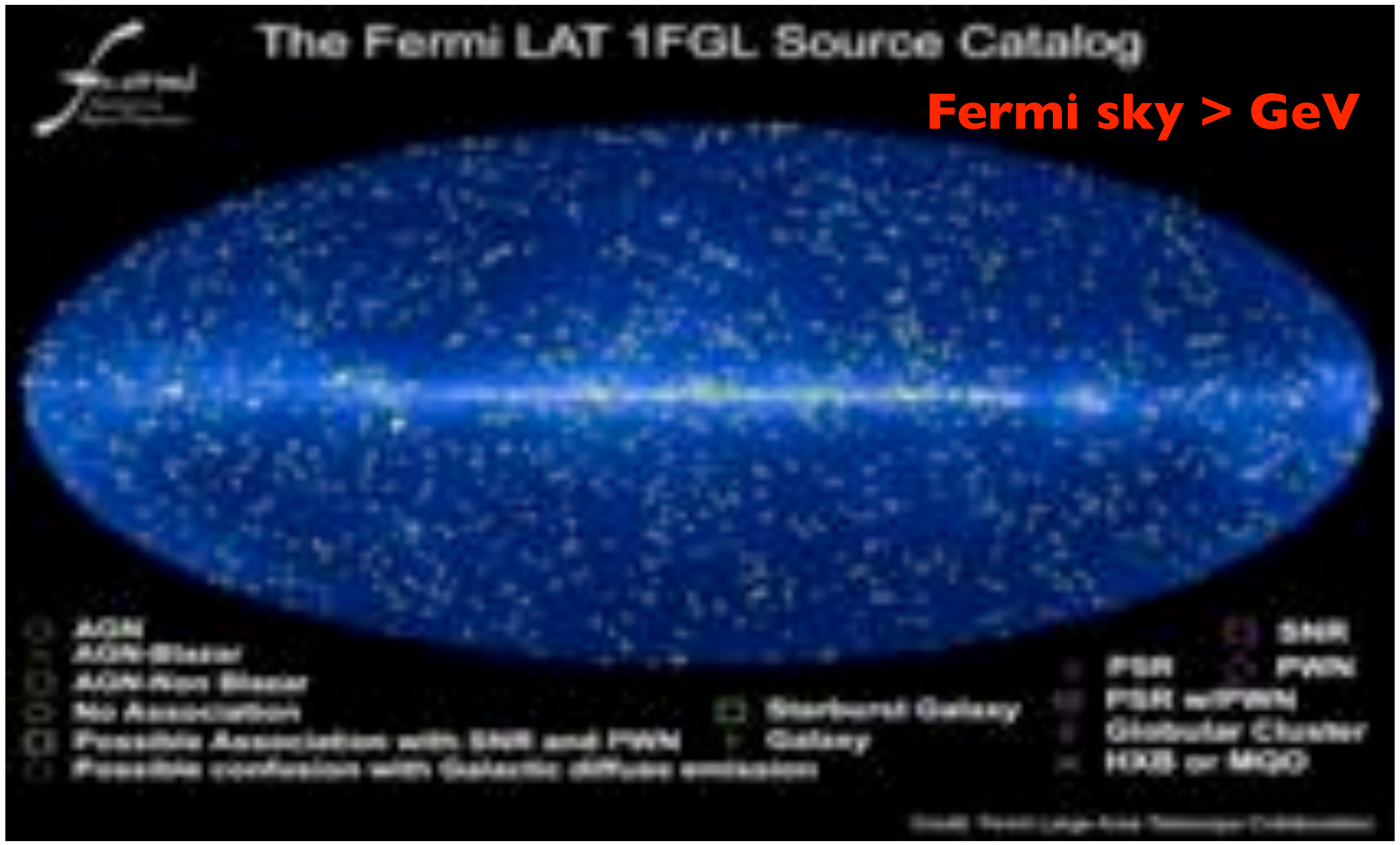
- **IV. *Something ain't working as it should*: Changes in SM-derived laws**

Pasquale Dario Serpico (Annecy, France)
ISAPP, Institut Pascal, 06/04/2022

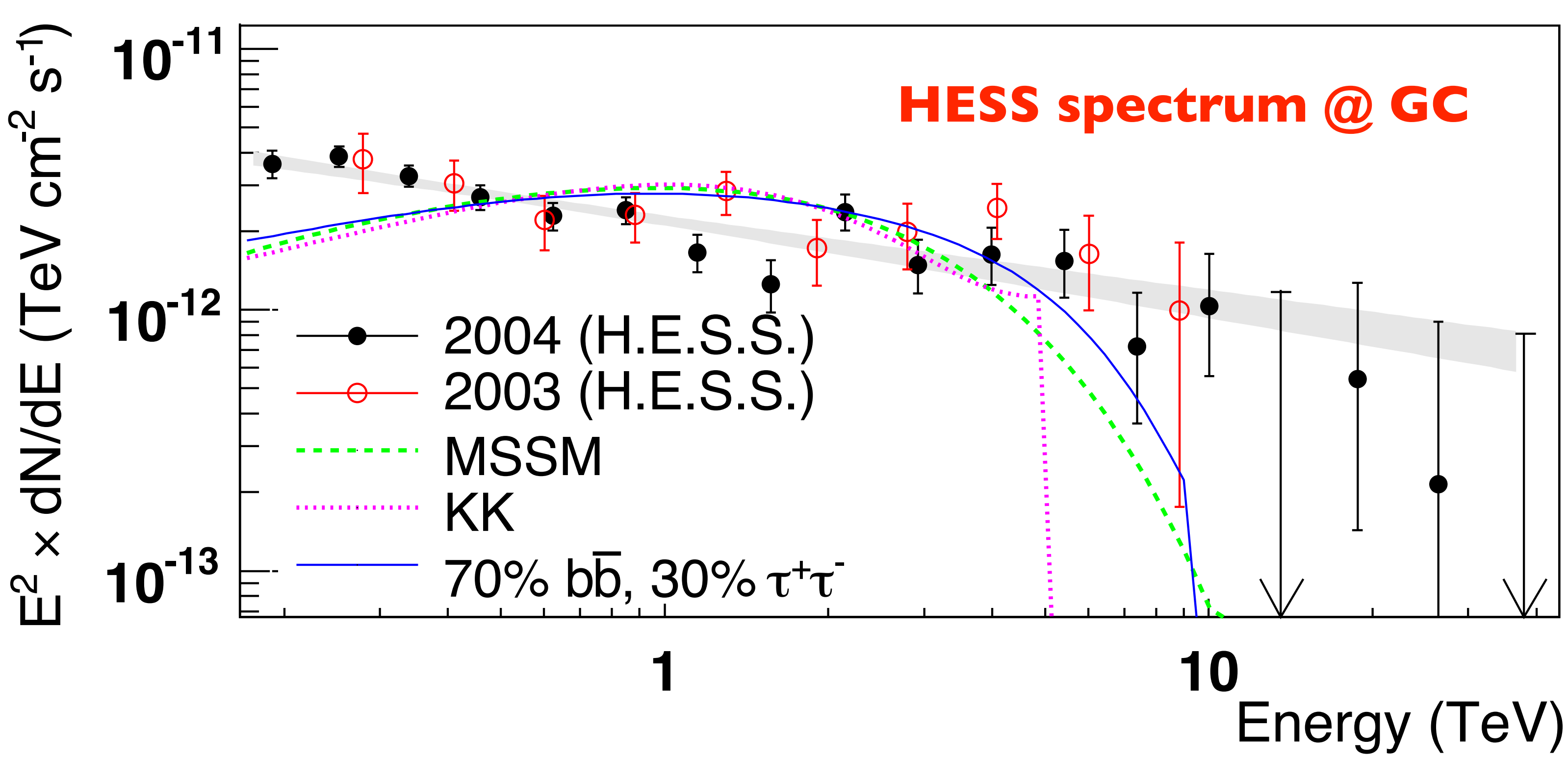
What do gamma-telescope reveal?

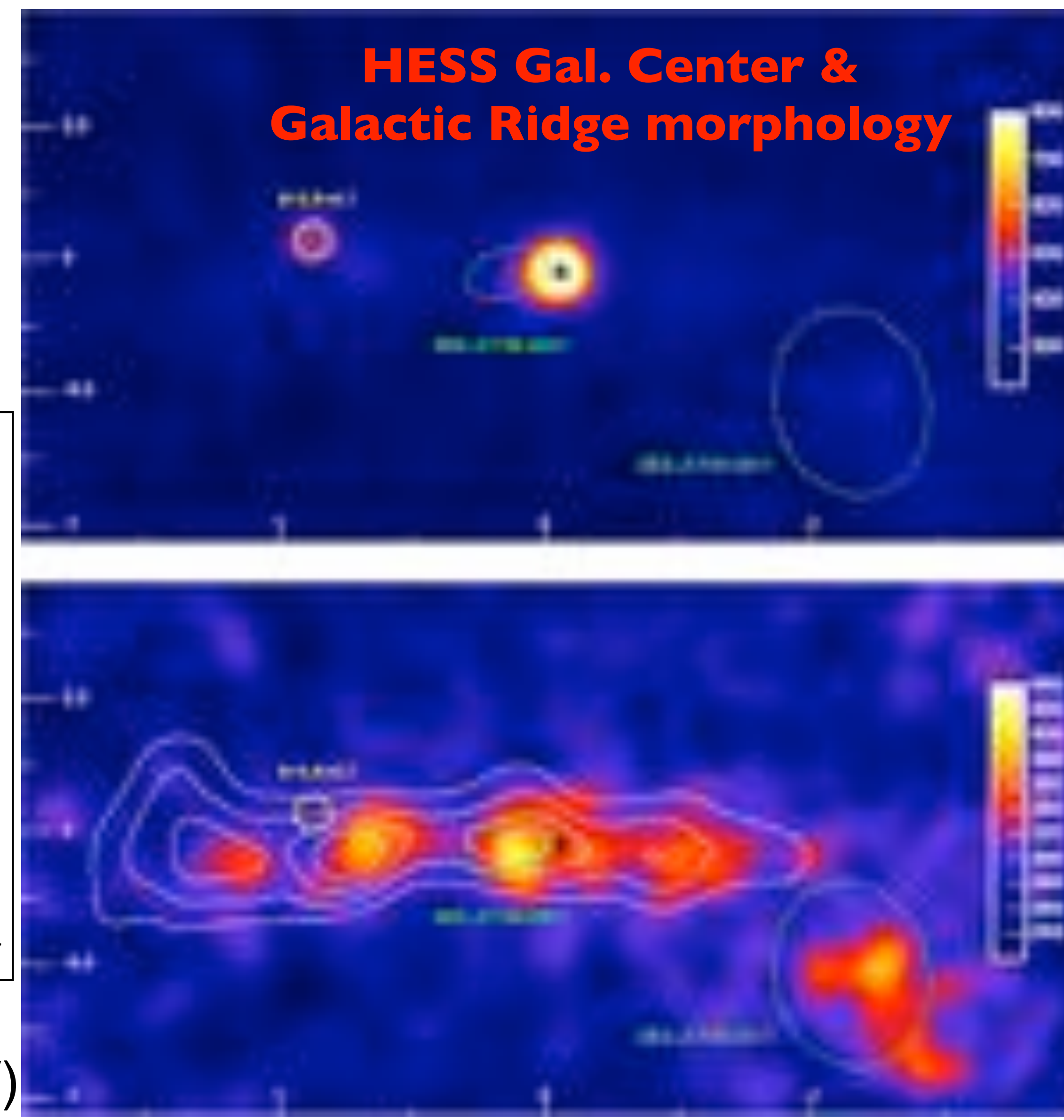
What Fermi or IACTs see looks nothing like DM expectations: backgrounds are often important!

their understanding is the main challenge in tightening IDM bounds (or interpreting some hints)



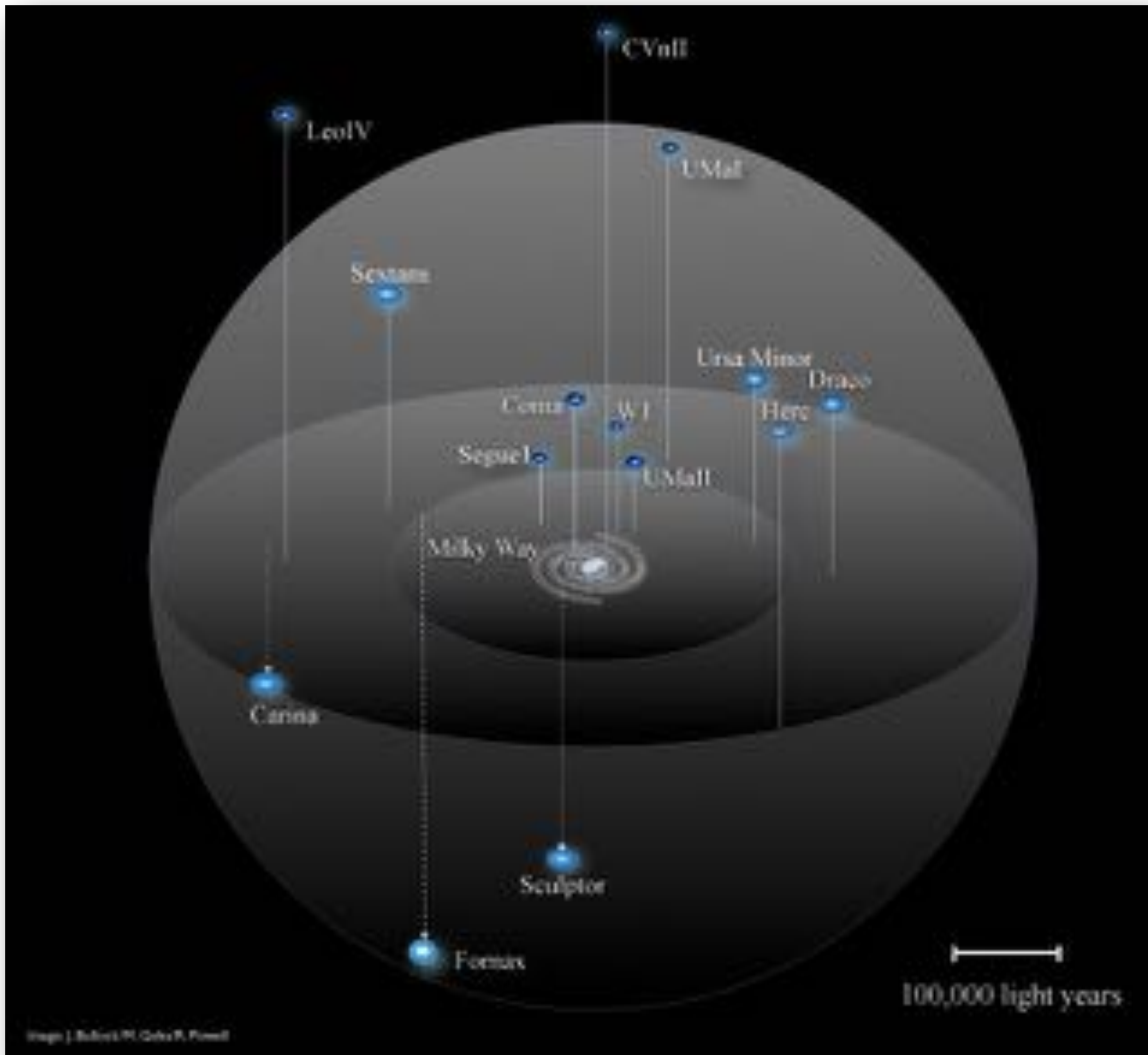
Emma de Ona Wilhelmi's & Elina Lindfors' lectures!

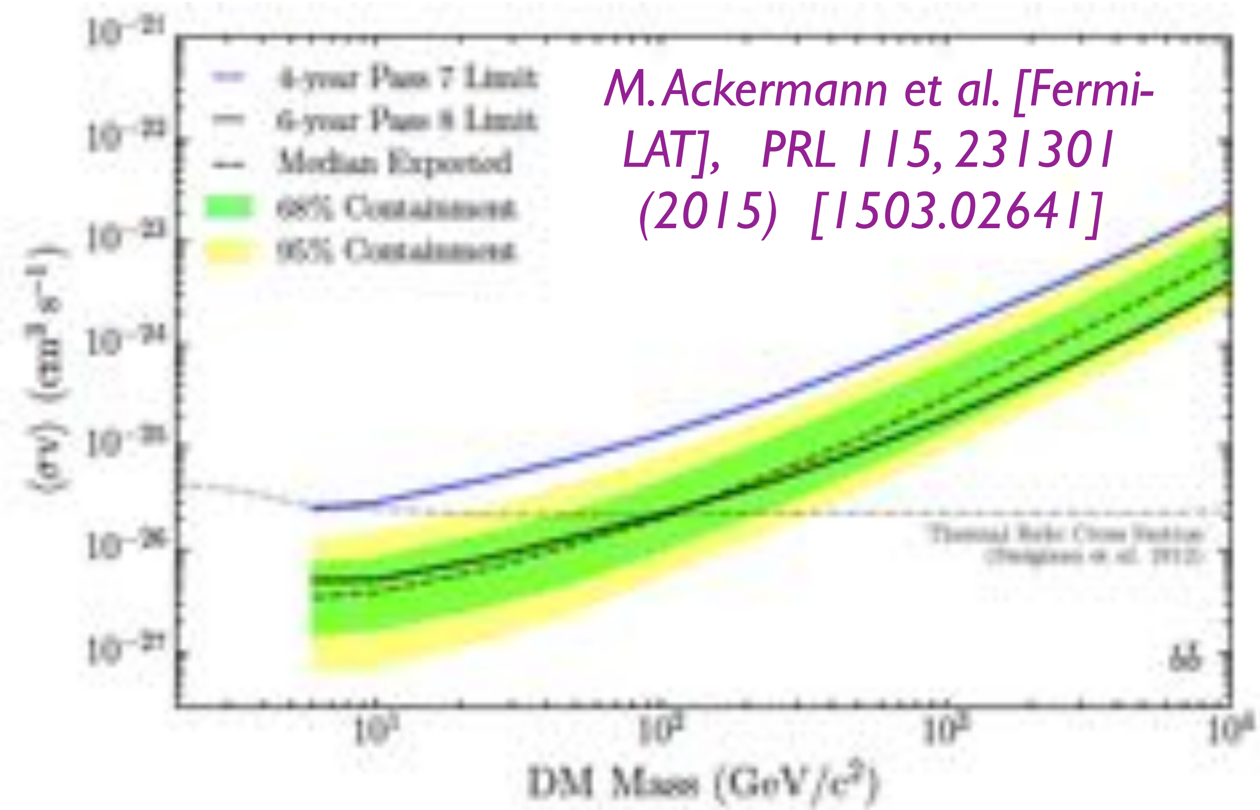




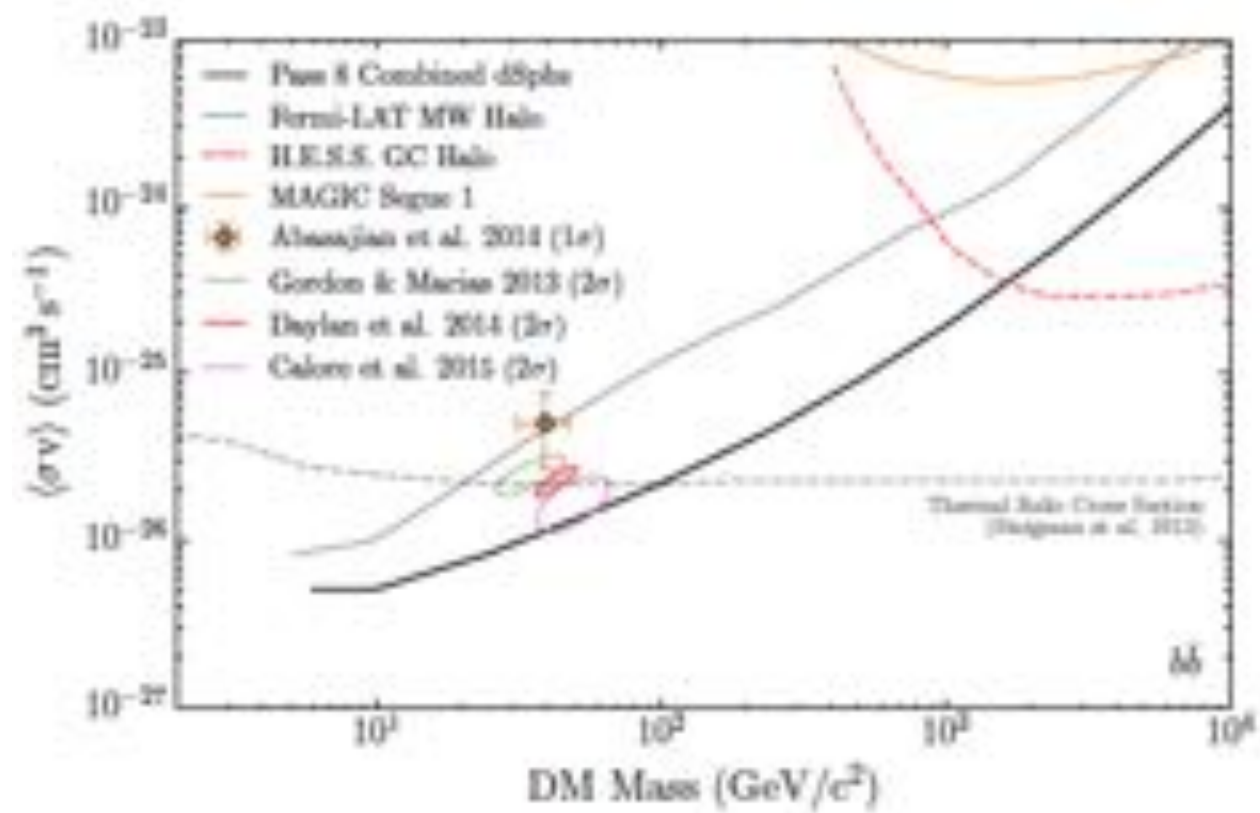
Satellites of the MW: Dwarf spheroidal galaxies

satellites of Milky Way with high DM/baryon content (1 to 3 orders of magnitude higher than the MW)
Almost ideal S/N, even better if stacking them (to beat uncertainties)!





M. Ackermann et al. [Fermi-LAT], PRL 115, 231301 (2015) [1503.02641]



Signal depends on _distance_ & _volume average of DM density_[2], (so-called _J-factors_). **Nominally exclude thermal s-wave relics annihilating into b's up to ~ 100 GeV (and in tension with GCE)**

Charged particles

Some advantage

☺ Relatively easy to detect

☺ Little (known) backgrounds in antiparticle channels

☹ More indirect, relying on astrophysics requiring modelling for propagation/losses

Computing fluxes at the Earth

Compare predicted and observed flux, to find indications of DM or constraints

Key hypothesis

Factorized problem (differences in time and spatial scales):
Sources ⊗ Propagation ⊗ Solar System effects *(solar modulation)*

While for neutral particles, even ignoring astro sources, one can still get conservative bounds, ***for charged particles no bound exists without propagation assumptions***

Propagation (symbolic)

Linear (***x*** & *t*-dependent) “Fokker-Planck like” PDEs (coupled) for fluxes

$$\left(P + L^{(i)}\right) \Phi_i = Q_i + A_{ij}\Phi_j$$

P. Blasi’s lectures!

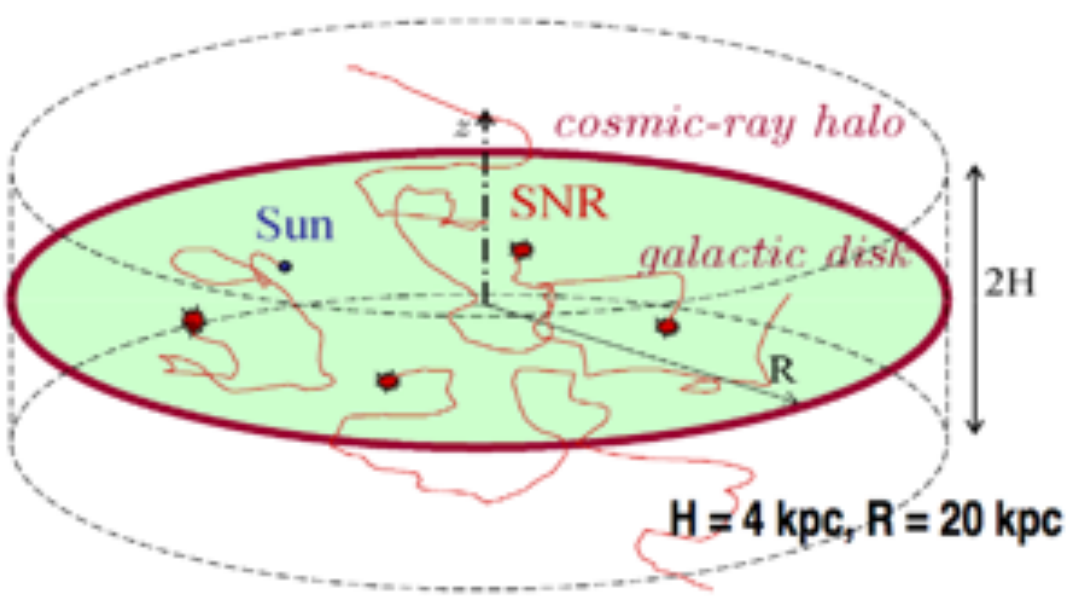
Spatial and momentum diffusion, advection…

Losses (Continuous, catastrophic) species-specific

Secondary sources (From losses of nuclei)

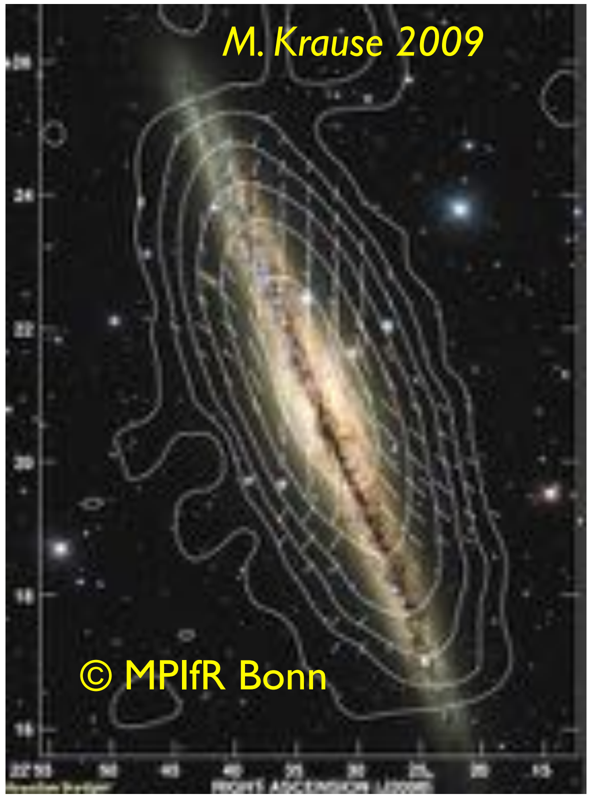
Coefficients are in general space-dependent (e.g. target densities)

Basically need the Green’s function obeying some boundary conditions



Often simplified geometry inspired by actual galactic magnetic halos

Solved numerically (GALPROP, DRAGON…) or semi-analytically (USINE…)



radio-I contours & B-field direction of NGC 891, MW-like Galaxy

How well do we know the sources?

The opposite cases of positrons and antiprotons

The positron rise era (~2008-2013)

Paradigm until ~13 years ago:

e^- : mostly ***primaries***, matching p spectra (at injection in SNRs) but for a normalisation

e^+ : ***secondaries*** dominated by pion production e.g. via $p_{CR} + H_{ISM} \rightarrow \pi + X$

Prediction: $e^+/(e^- + e^+)$ should decrease with E

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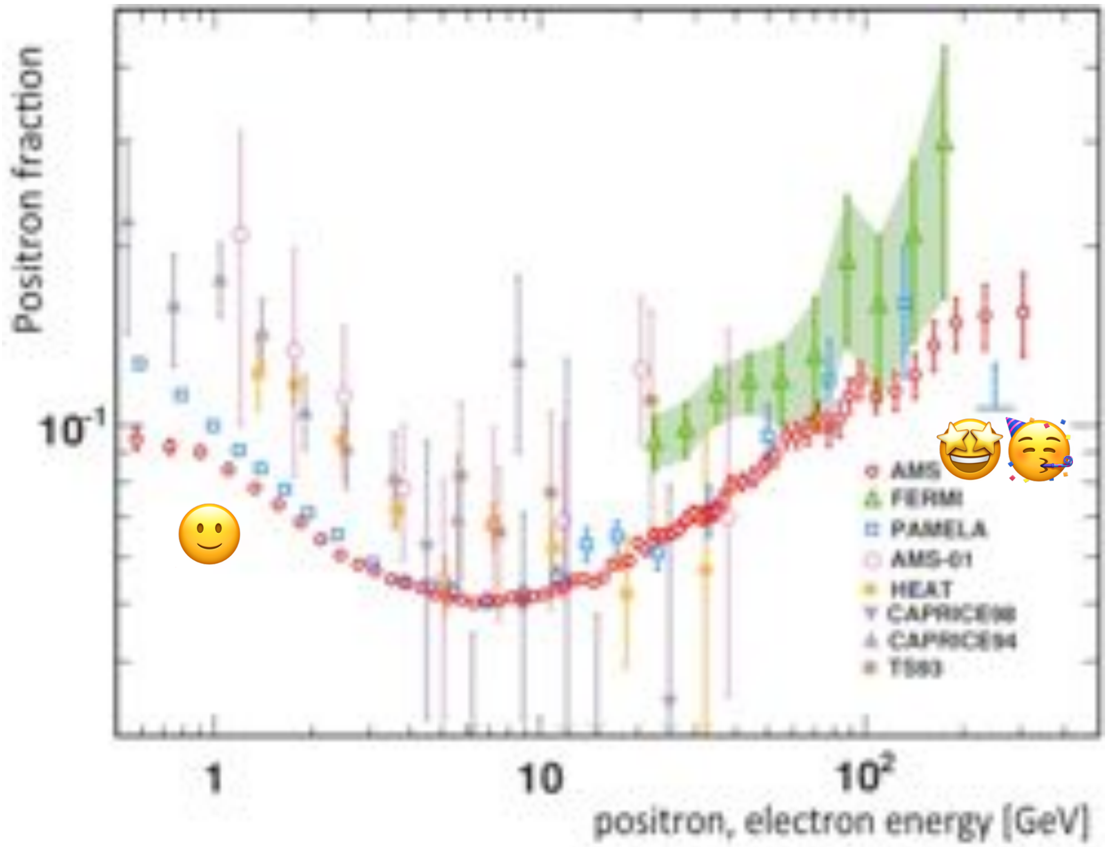

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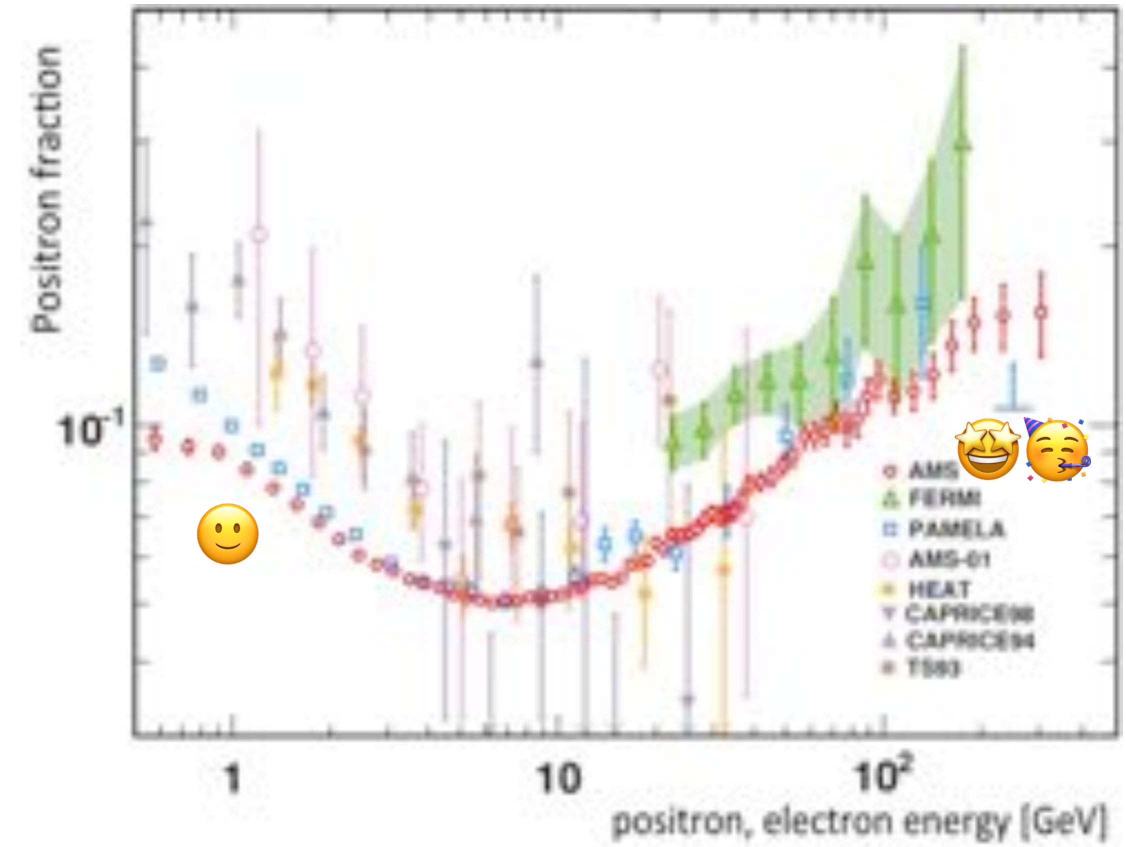

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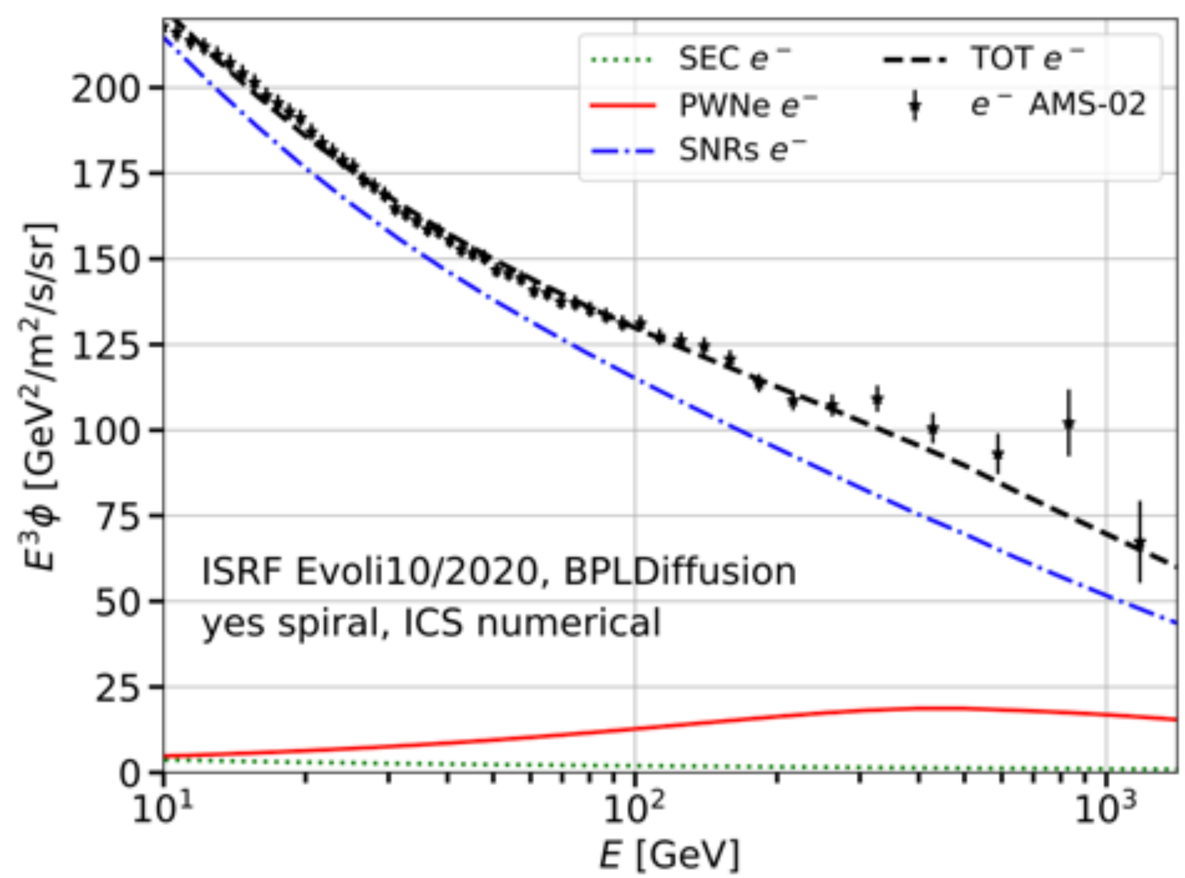
Over past decade, role of additional ***primary*** source(s) @ E> 10 GeV became clear

No single 'standard model', rather consistent with expectation from SNRs+PWN, but degeneracies in the source and propagation



M. Di Mauro, F. Donato, S. Manconi, "Novel interpretation of the latest AMS-02 cosmic-ray electron spectrum," [arXiv:2010.13825]

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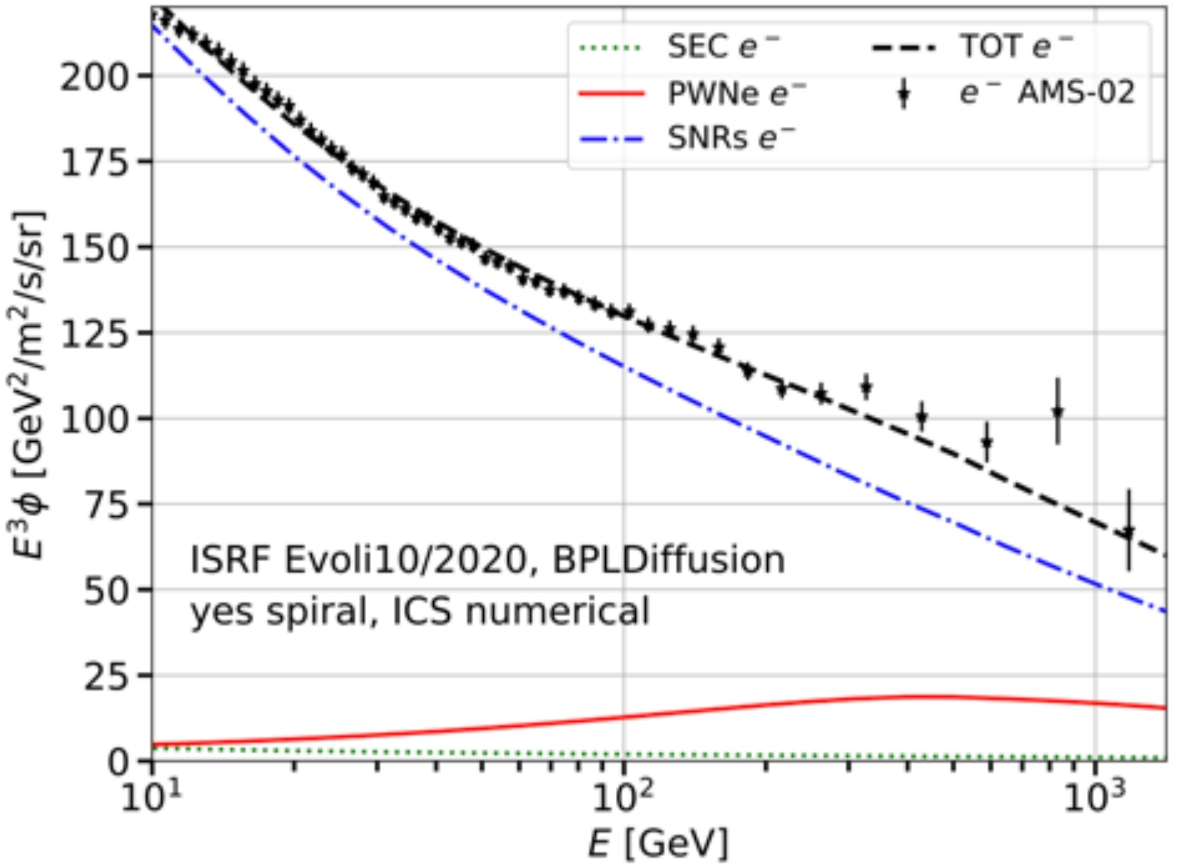
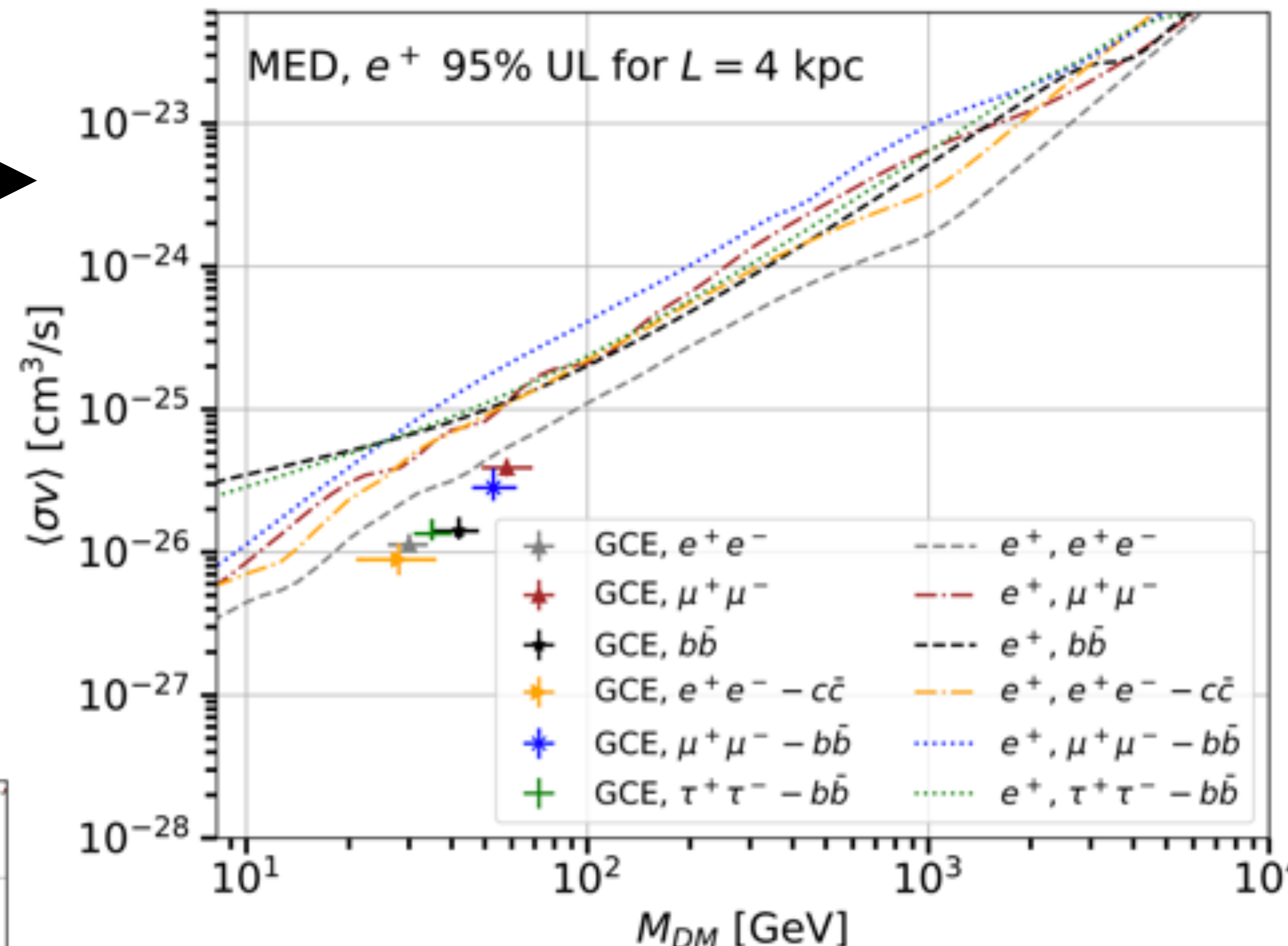
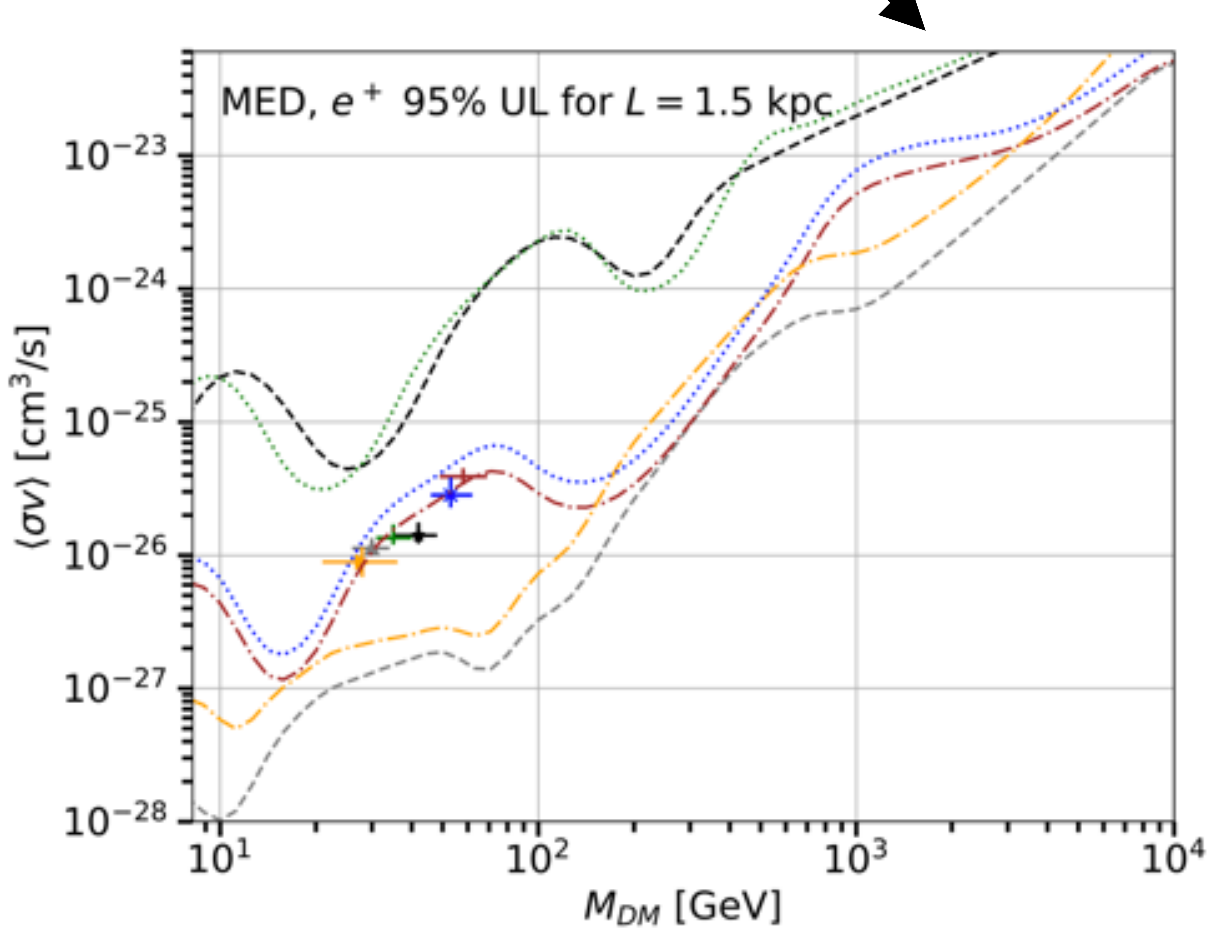


Can still set bounds from e⁺

e.g. conservatively accounting only for secondary e⁺



sensitive to prop. parameters (notably halo thickness *L*)
Assuming a "PWN-like" fit and different halo-size:



M. Di Mauro & M.W. Winkler, "Multimessenger constraints on the DM interpretation of the Fermi-LAT GC excess," Phys. Rev. D 103, 123005 (2021)[arXiv:2101.11027]

The situation is more under control for anti-*p*, but need to tackle issue of propagation parameters

Probing dark matter with antiprotons

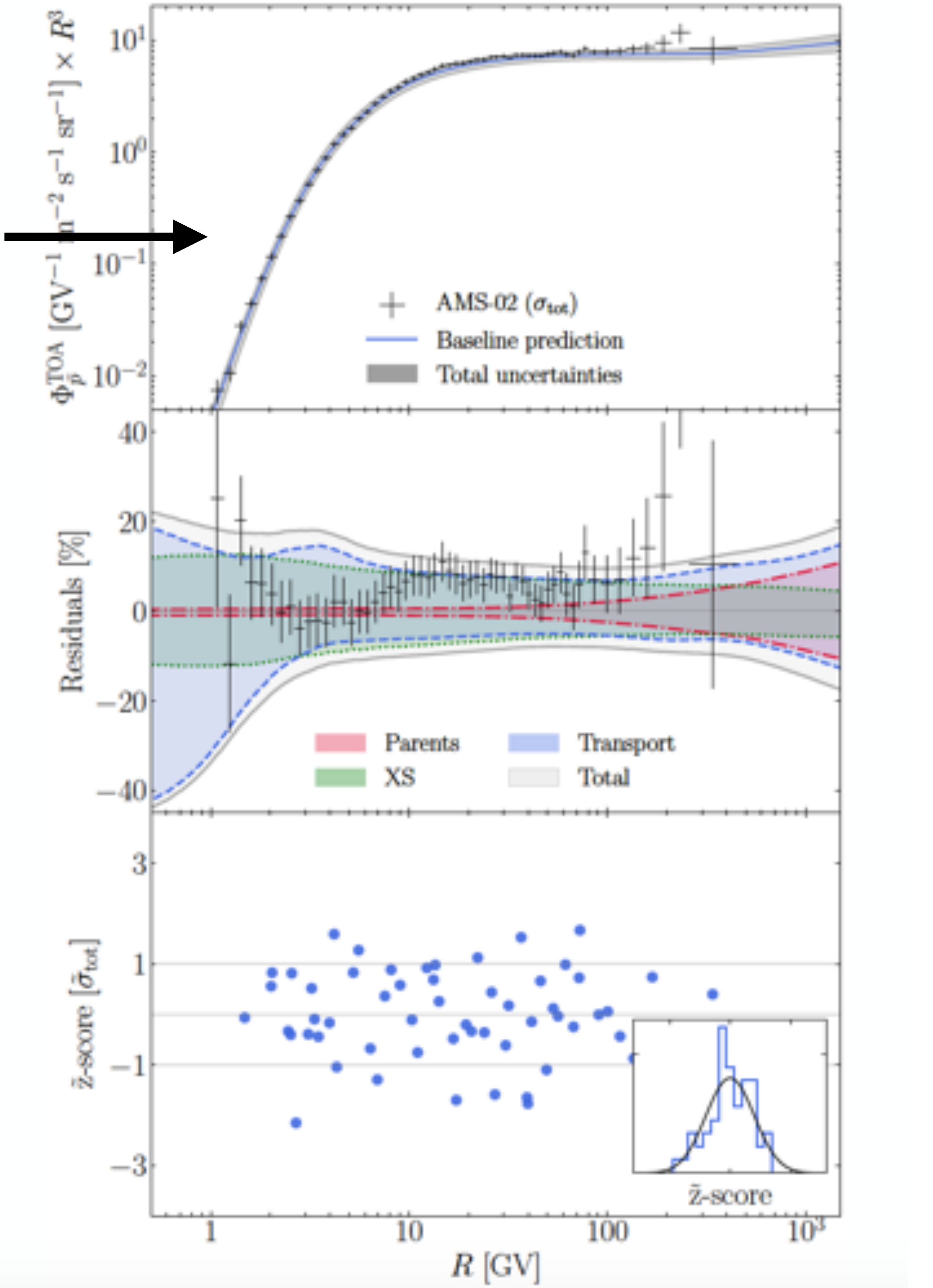
For a recent mini-review:

J. Heisig, "Cosmic-ray antiprotons in the AMS-02 era: A sensitive probe of dark matter," Mod. Phys. Lett. A 36 (2021) no.05, 2130003 [arXiv:2012.03956]

Prediction of the secondary antiproton flux (<u>not a fit!</u>)

M. Boudaud et al. Phys. Rev. Research 2, 023022 (2020) [1906.07119]

How often do you see that in astrophysics? →



Monte Carlo simulations to determine the errors (and correlations!) due to

- Production XS (fits to collider data)
- Transport (fit B/C)
- Parent CR fluxes

accounting for production from heavy nuclei, 'non-prompt' production (essentially anti-hyperons), isospin violation effect & uncertainties…

Residuals which actually matter

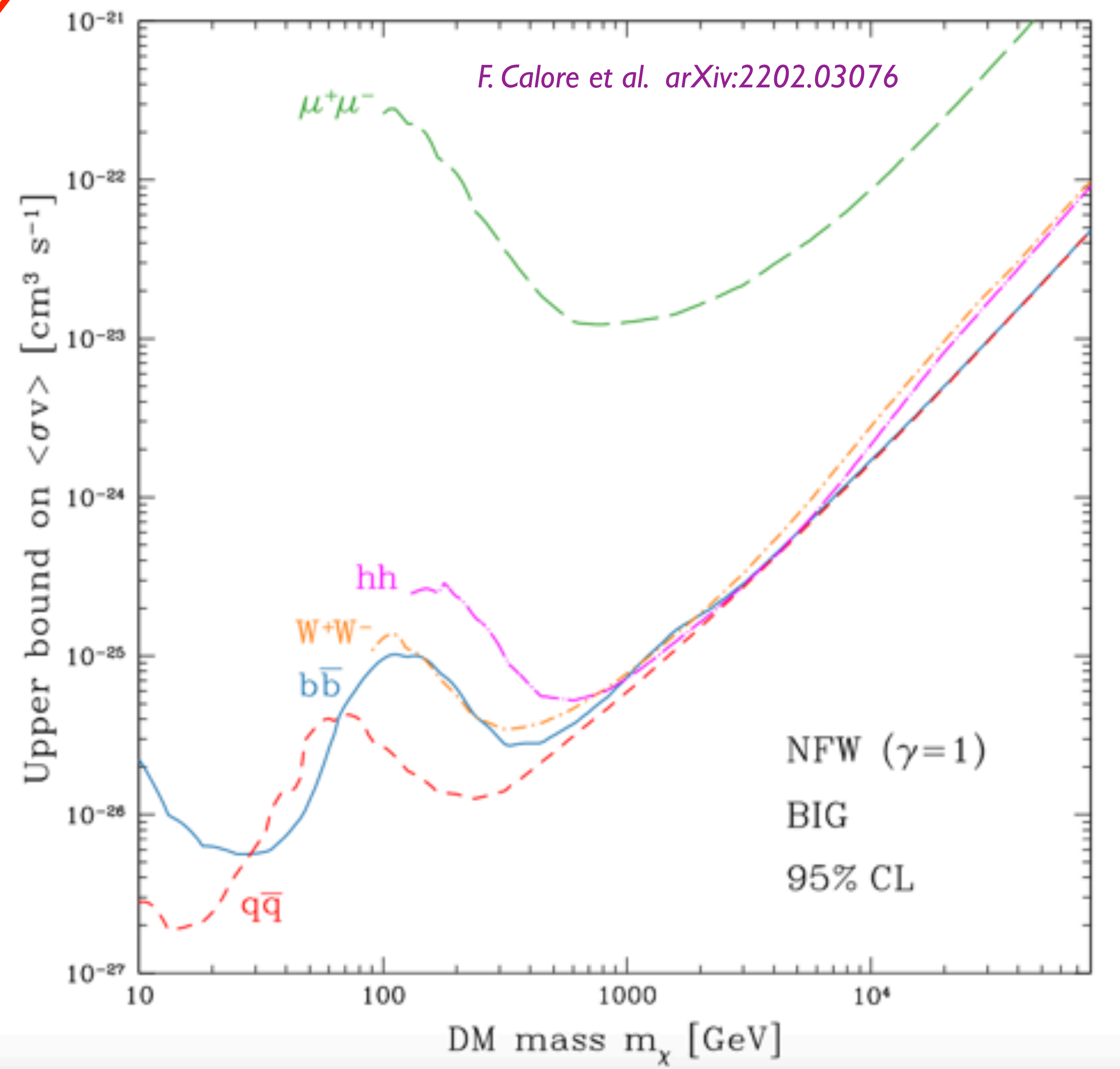
"rotated" z-score $\tilde{z}_i = \tilde{x}_i / \tilde{\sigma}_i$

in terms of "decorrelated" dof's

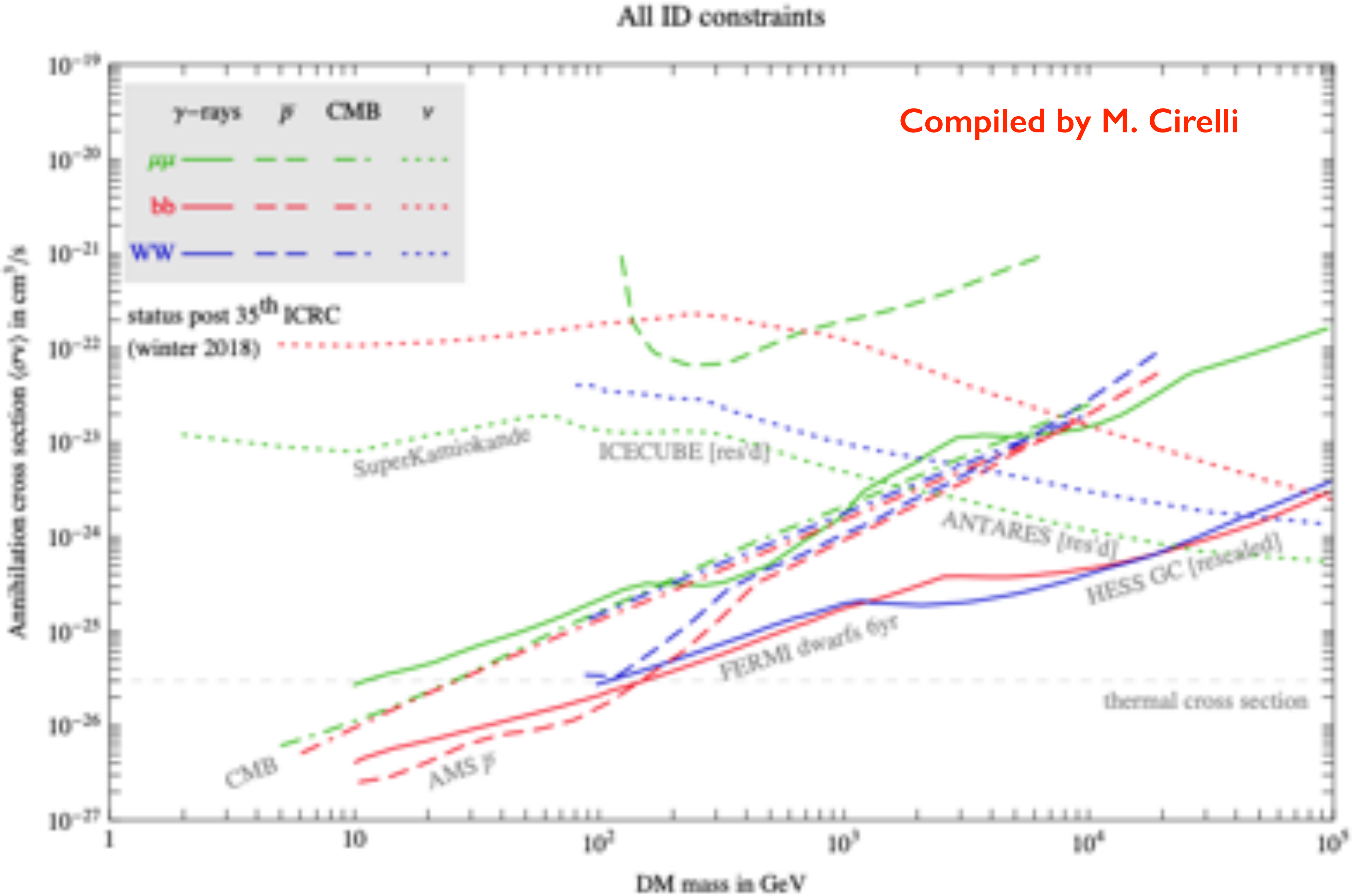
AMS-02 pbar data consistent with secondary origin!

Statistically irrelevant excess, bounds set

Past claims of significant DM-like excesses attributed largely to oversimplified treatment of errors (in particular, correlations are important)



Recap/summary: WIMP DM ind. searches



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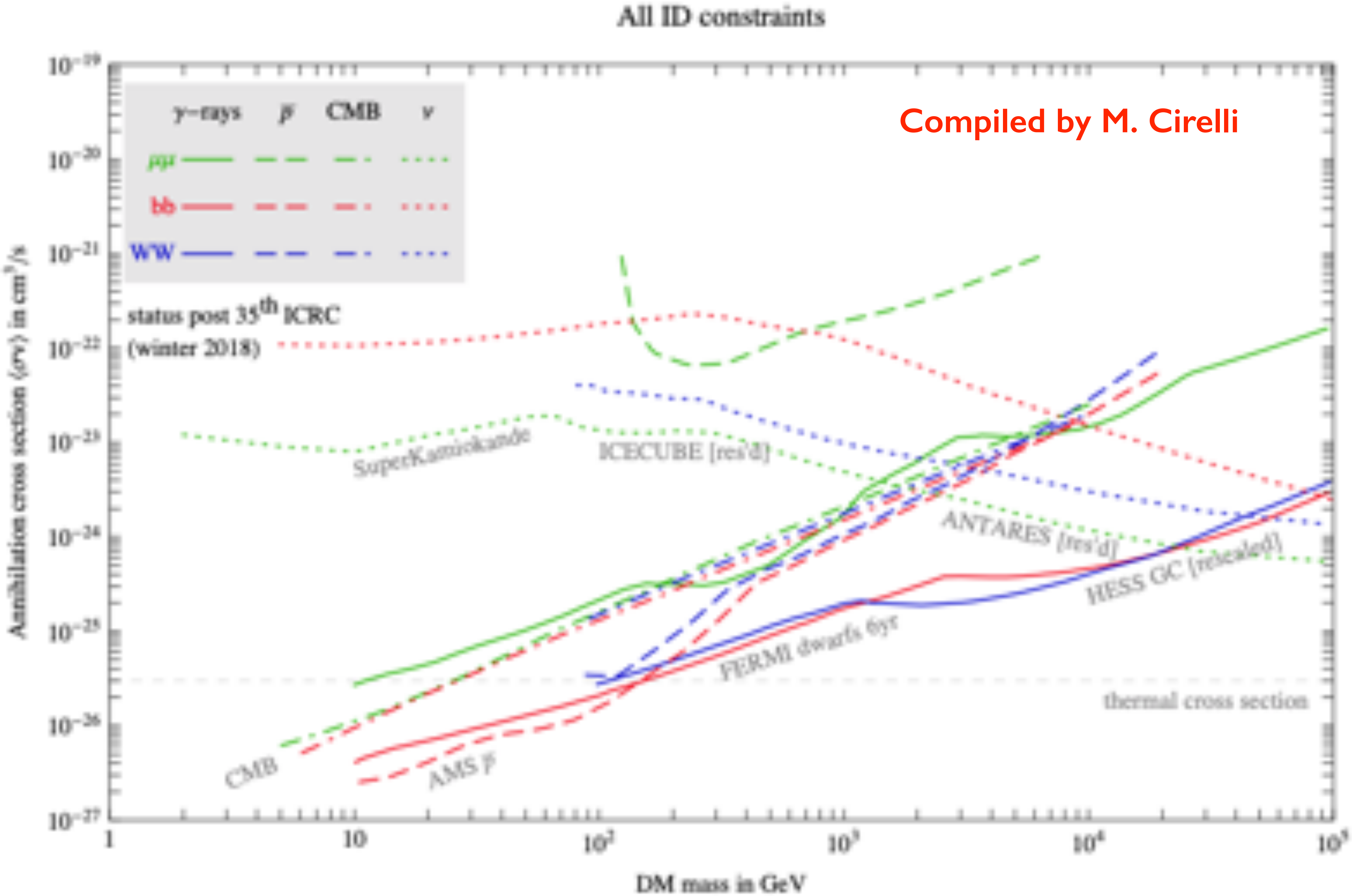

Null results till now *(in none of the channels)*

+

a number of more or less hyped claims

(notably in IDM, none of which confirmed independently, admitting alternative astrophysical or instrumental explanations)

So, what's next? Current trends in DM research

Loosely speaking, I can identify a couple of directions in model building and phenomenology

A. "Keep faith": WIMPy ideas ~correct, but we're unlucky, "mild" unexplained fine-tuning is present, e.g.:

1. BSM particles (slightly) too heavy to be produced at LHC, DM may be (multi)TeV, too…

2. … or accidentally light (after all, 1st gen. mass scale<< Higgs vev)

3. Almost mass-degenerate states (long-lived particle signals associated to DM?)

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B. "Get over it": DM unrelated to hierarchy prob., find inspiration in different theory or pheno

4. BSM too light and/or weakly coupled with the SM. Sufficient to explain lack of direct detection as well Motivations from neutrino physics? Axions from strong-CP and axion-like particles maybe from strings?

5. Problems at "small scales"? (Halo cores, satellite statistics and or variety…): hidden sector & new forces (dark gauge groups), links to the SM via "portal interactions"…

An important comment

Indirect detection is very far from a "critical coverage", even for "vanilla WIMPs"!

most models at few hundreds GeV scale still ok.

The (growing) **pessimism on WIMPs is not driven by IDM**.

If interested in pursuing a WIMP search program independently from negative results of EW-scale new physics searches, there is plenty of room in parameter space to justify it!

However, "traditional" WIMP IDM searches are limited by the systematic error with which we know (or can know, even in principle!) the "backgrounds" (*astrophysical signals*)

A commendable effort consists in "trying to squeeze the best we can", with (sometimes computationally painful) theoretical improvements.

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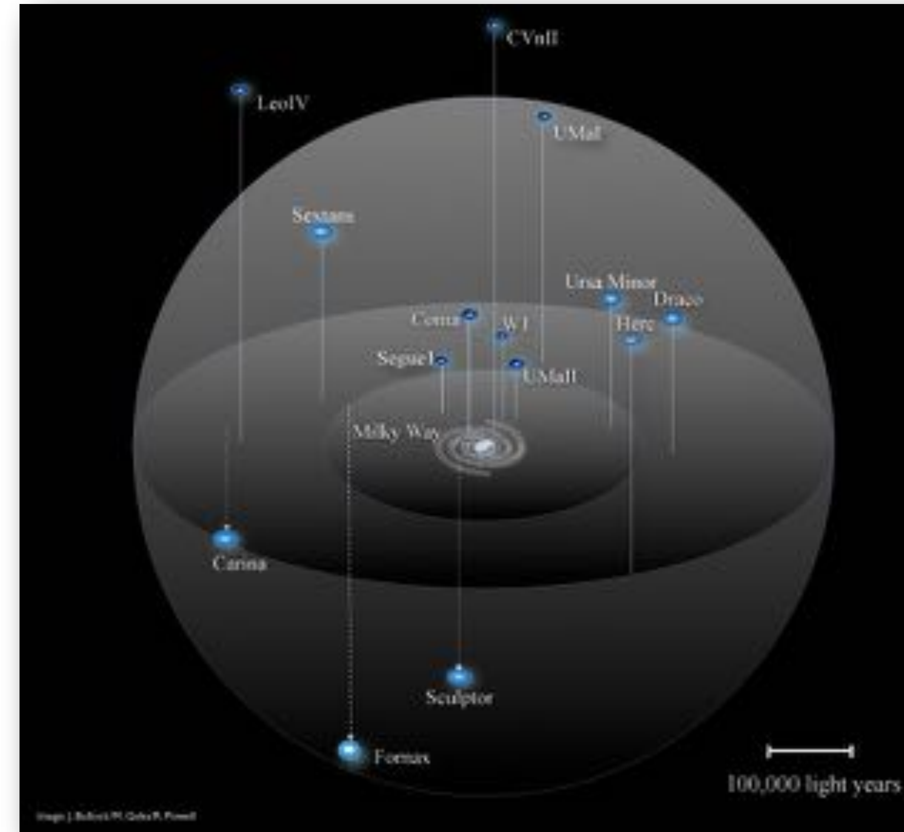
i.e. WIMP IDM searches are not dead

*but the "**return**" in explored parameter space over the "**investment**" (theory and experiments) is shrinking*

Expected anyway to go on in the next decade at very least as side advantage of new facilities

Take advantage of the existing/planned, ex. 1

Dwarf Spheroidals: satellites of Milky Way with high DM/baryon content, 1 to 3 orders of magnitude higher than the MW. Ideal Signal/Noise, even better if stacked! Best current gamma-ray limits



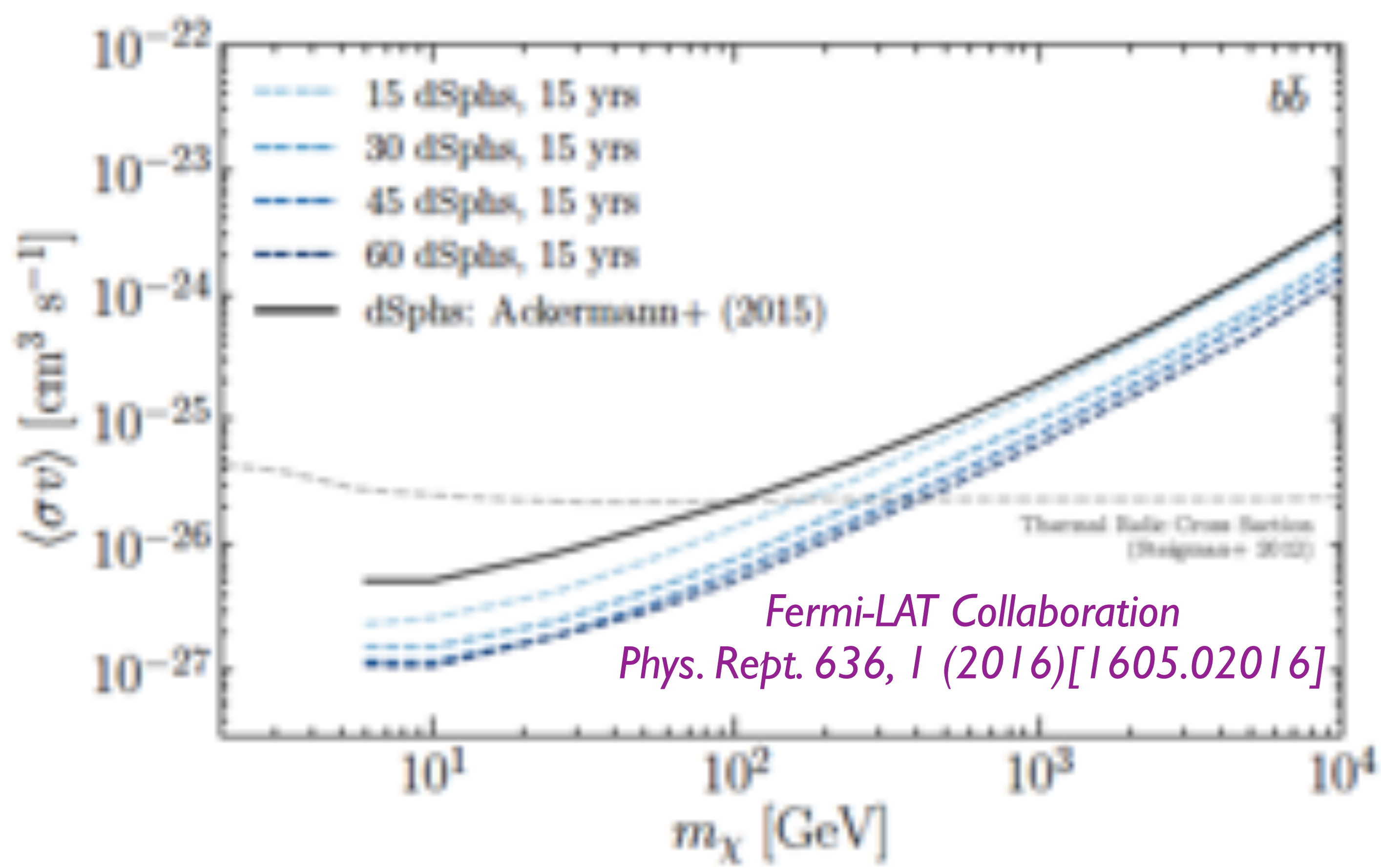
Surveys (e.g. LSST/VRO) could discover **hundreds new Dwarf Spheroidals;** even assuming only ~60 with good determination of DM distribution, improvement of a factor of a few expected by the end of Fermi lifetime

eventually (already now?) **background limited**, e.g. uncertainty in diffuse flux & unresolved sources along the l.o.s. Interest in alternative, **data-driven techniques**, see e.g

F. Calore, P.D.S., B. Zaldivar
JCAP 10 (2018) 029 [1803.05508]

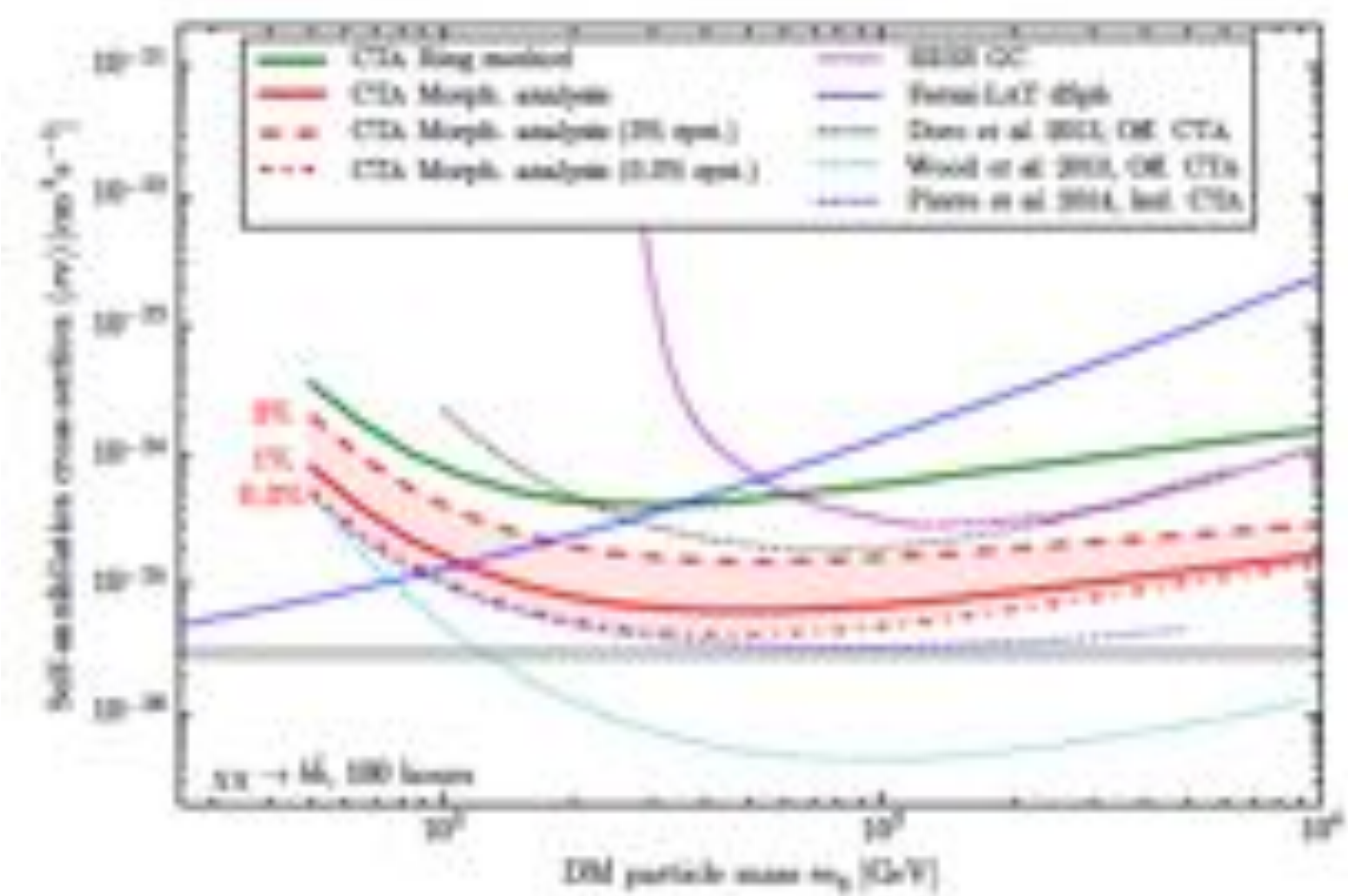
Extended to DM distribution measurements from surveys in

A. Alvarez et al. JCAP (2020), 004 [arXiv:2002.01229]



Take advantage of the existing/planned, ex. II

CTA will make us access to ~ "vanilla" WIMP x-sections in (multi)TeV mass range. Accounting for effects like Sommerfeld enhancement, bound state formation (e.g. *K. Petraki et al.*) crucial.



H. Silverwood, C. Weniger, P. Scott and G. Bertone,
"A realistic assessment of the CTA sensitivity to dark matter annihilation,"
JCAP 1503, 055 (2015)

III.c Beyond WIMPs

If not WIMPs, what else?

We cannot give up on (meta)stability if we want DM. Relax the condition of relic being in **equilibrium with SM** in the early universe.

Alone, this naturally explains negative results at LHC, see for instance:

F. Kahlhoefer, "On the LHC sensitivity for non-thermalised hidden sectors," 1801.07621

Since, typically, suppressing the x-sec entering production in the early universe also lowers the production at colliders. But where and how to search?

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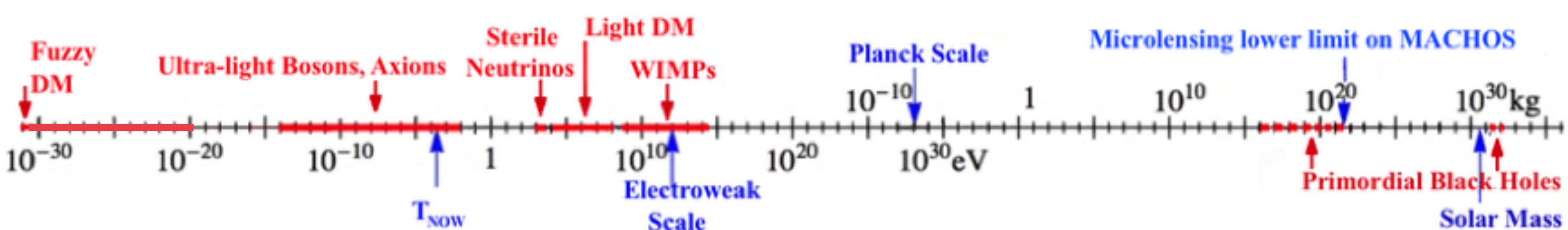

G. Gelmini

- Hard to search with conventional collider or direct searches, sometimes admit 'ad hoc' search programs (e.g. axions); usually precision frontier wins over energy frontier
- More frequently yield indirect signatures and/or astro/cosmo ones

Beware of the wrong inference "if DM not WIMP $\Longrightarrow$ no relevant astrophysical fluxes"!

Alternative production mechanisms I: Freeze-in

What if solving $$\frac{dn}{dt} + 3H\, n = -\langle \sigma v \rangle [n^2 - n_{\rm eq}^2]$$ without n=n_{eq} as initial condition? For example, using n=0?

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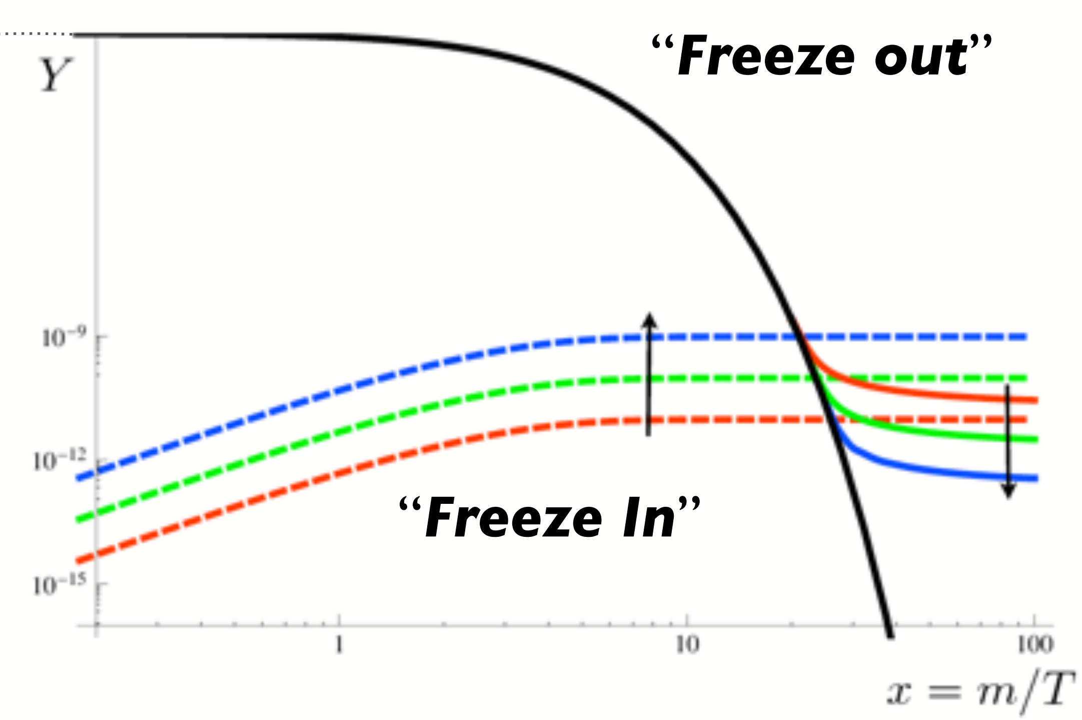

L. J. Hall, K. Jedamzik, J. March-Russell and S. M. West, "Freeze-In Production of FIMP Dark Matter," JHEP 1003, 080 (2010) [0911.1120]

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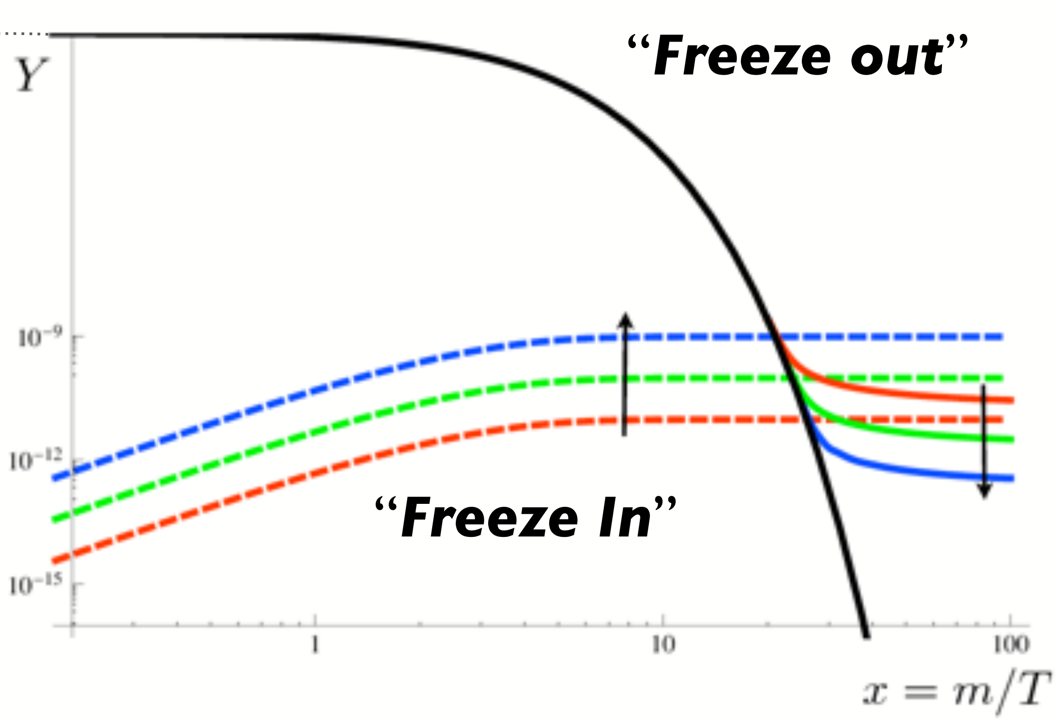

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- Note that now $$Y_\infty \propto \langle\sigma v\rangle$$ **inverse dependence** wrt WIMP freeze-out
- Y_∞ sensitive to **initial conditions** (reheating temperature, yield coming e.g. directly from inflation!)

Alternative mechanisms II: Gravitational production

A massive scalar field in FLRW metric can be described by an auxiliary scalar field in Minkowski metric with a “time-dependent mass”.

As a consequence, a ‘minimum energy’ state (vacuum) in the infinite past is not what a late time observer would define as vacuum, rather associated to some particle content.

Loosely speaking, you can think of *particle production at the expense of a time-dependent gravitational field*

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In general only relevant for massive particles and sufficiently 'hot' initial conditions post-inflation.
E.g. if $H_I \sim 10^{13}$ GeV is the Hubble parameter during inflation, numerically one finds

$$\Omega_X h^2 \approx \frac{T_R}{10^8\,\mathrm{GeV}} \begin{cases} (m_X/H_I)^2\,, & m_X \ll H_I \\ \exp(-m_X/H_I)\,, & m_X \gg H_I \end{cases}$$

D. J. H. Chung, E.W. Kolb and A. Riotto,
"Nonthermal supermassive dark matter," PRL 81, 4048 (1998)
"Superheavy dark matter," PRD 59, 023501 (1999)

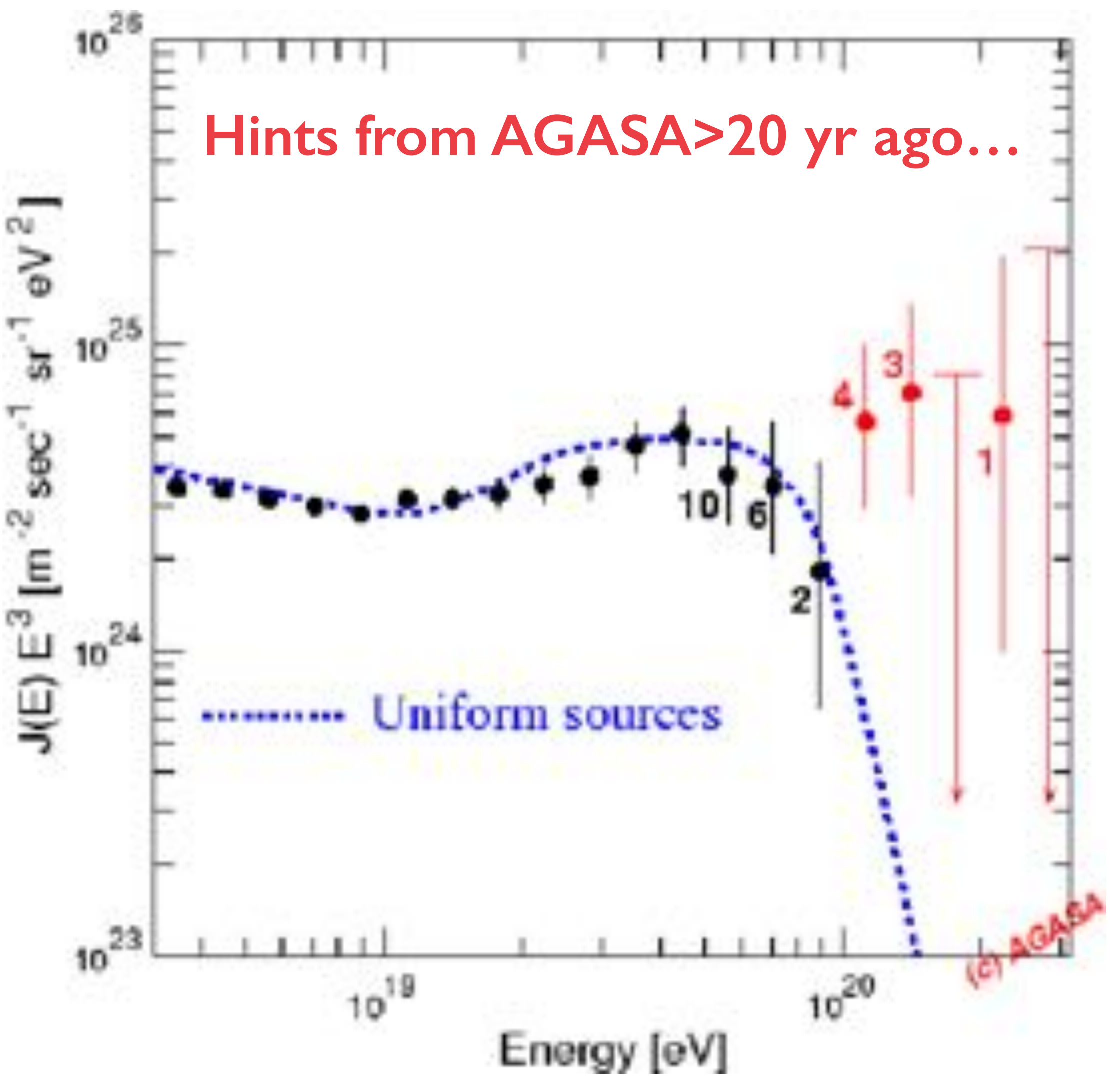
V. Kuzmin and I. Tkachev,
"Matter creation via vacuum fluctuations in the early universe and observed UHECR events,"
PRD 59, 123006 (1999)

For typical values $T_R \sim 10^9$ GeV one requires $m_X \sim 10^{14}$ GeV

If only gravitationally coupled (and we only need a gravitating, heavy particle for the mechanism to work) virtually untestable!

WIMP…zillas

If unstable but very long lived (e.g. think of protons in GUT: their decay could be mediated by high-dimension operators, or be purely non-perturbative) their ***decay*** products would be UHECR, beyond the cutoff expected due photopion production onto CMB photons for cosmologically distant protons!



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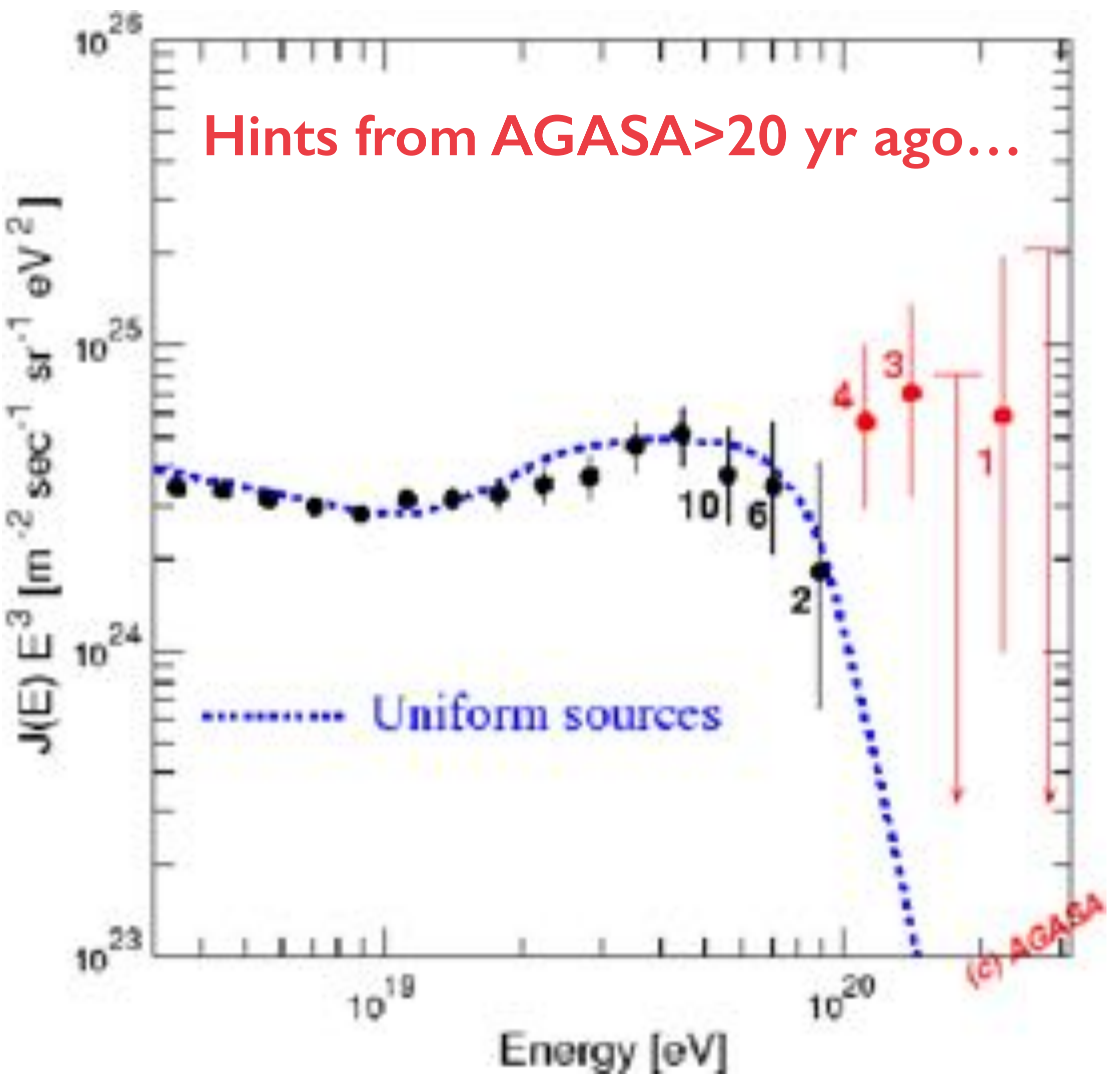


Some signatures:

- higher-than-standard fraction of photon and neutrino events,
- peculiar angular pattern (e.g. enhanced towards the Galactic Center). For a mini-review see e.g.

M. Kachelriess, "The rise and fall of top-down models as main UHECR sources," arXiv:0810.3017

A subdominant contribution still searchable in Auger, Telescope array, etc.

Technical comment: astro factor for Annihilation vs. Decay

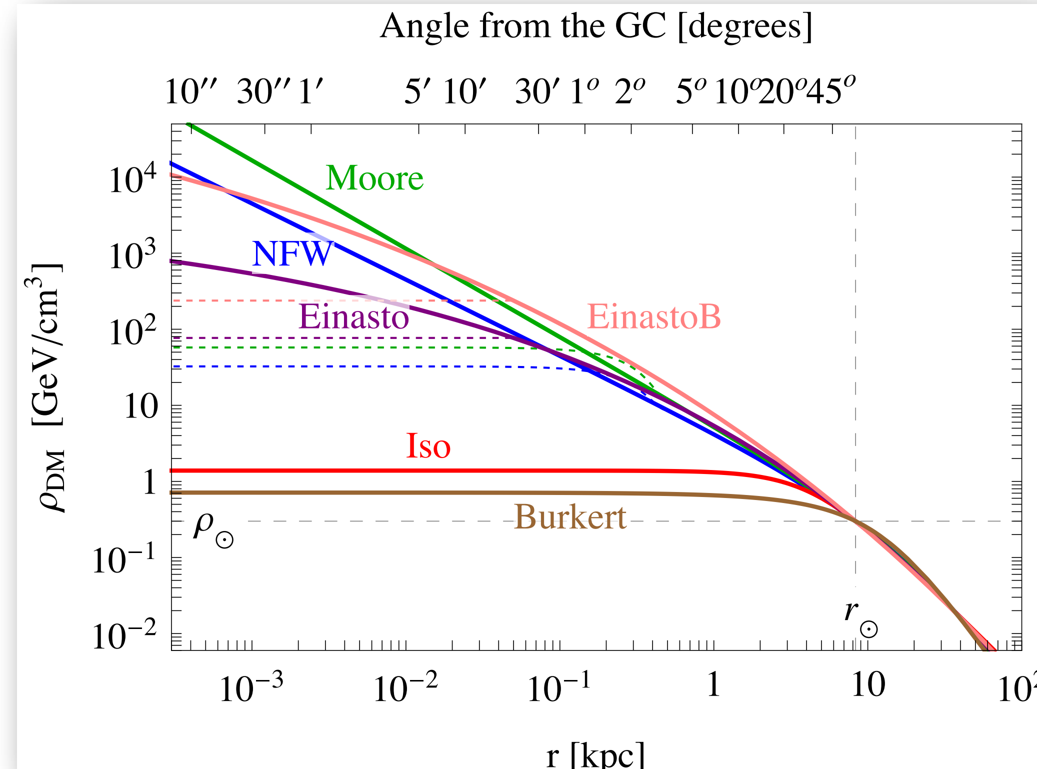
Annihilation depends quadratically on DM density, i.e. depends on poorly known **clumpiness** of DM, *prediction should rely heavily on simulation/theory*

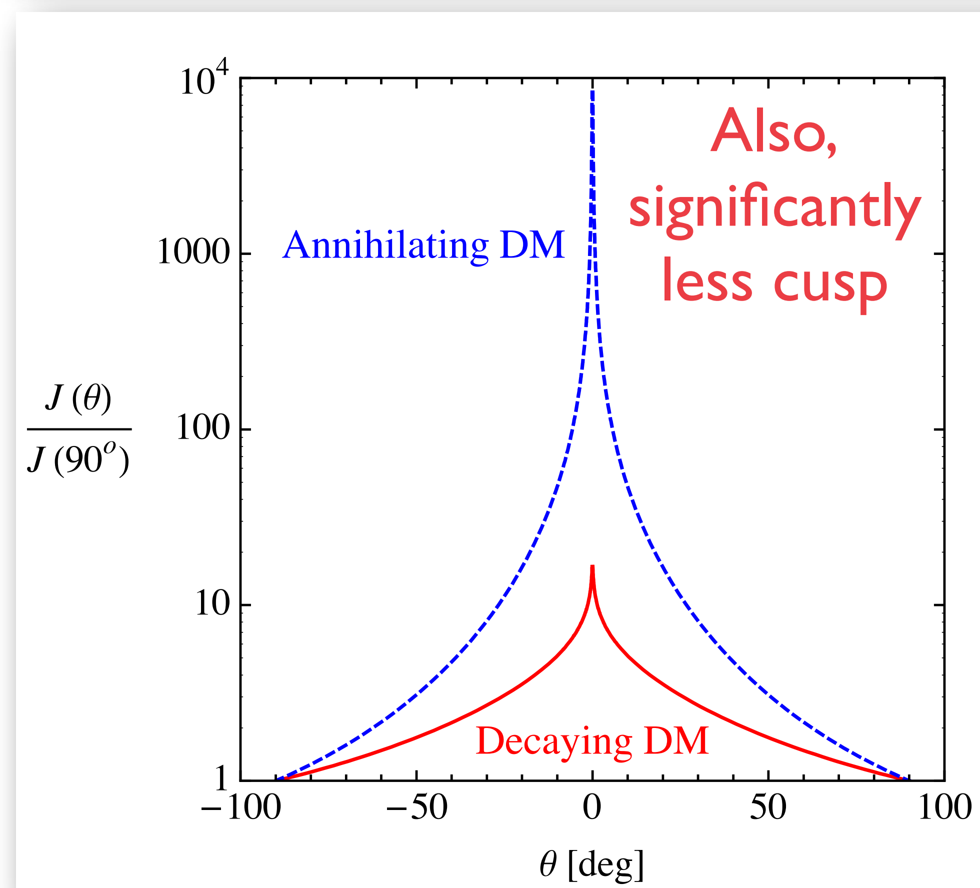
$$\Phi_\gamma(E_\gamma,\Omega) = \left[\frac{\mathrm{d}N_\gamma}{\mathrm{d}E_\gamma}(E_\gamma)\frac{\langle\sigma v\rangle}{8\pi m_X^2}\right]\int_{\mathrm{los}}\rho^2(\ell,\Omega)\,\mathrm{d}\ell$$

$$\langle\rho^2\rangle \geq \langle\rho\rangle^2$$

Decay signal depends on the integrated DM density, i.e. same source of DM gravitational effects. This is relatively well known, whenever DM is dynamically relevant.

$$\Phi_\gamma = \frac{\mathrm{d}N_\gamma}{\mathrm{d}E_\gamma}\frac{\Gamma}{4\pi\, m_X}\int_{\mathrm{los}}\rho(\ell,\Omega)\mathrm{d}\ell$$





An application to… “the Muppet show”

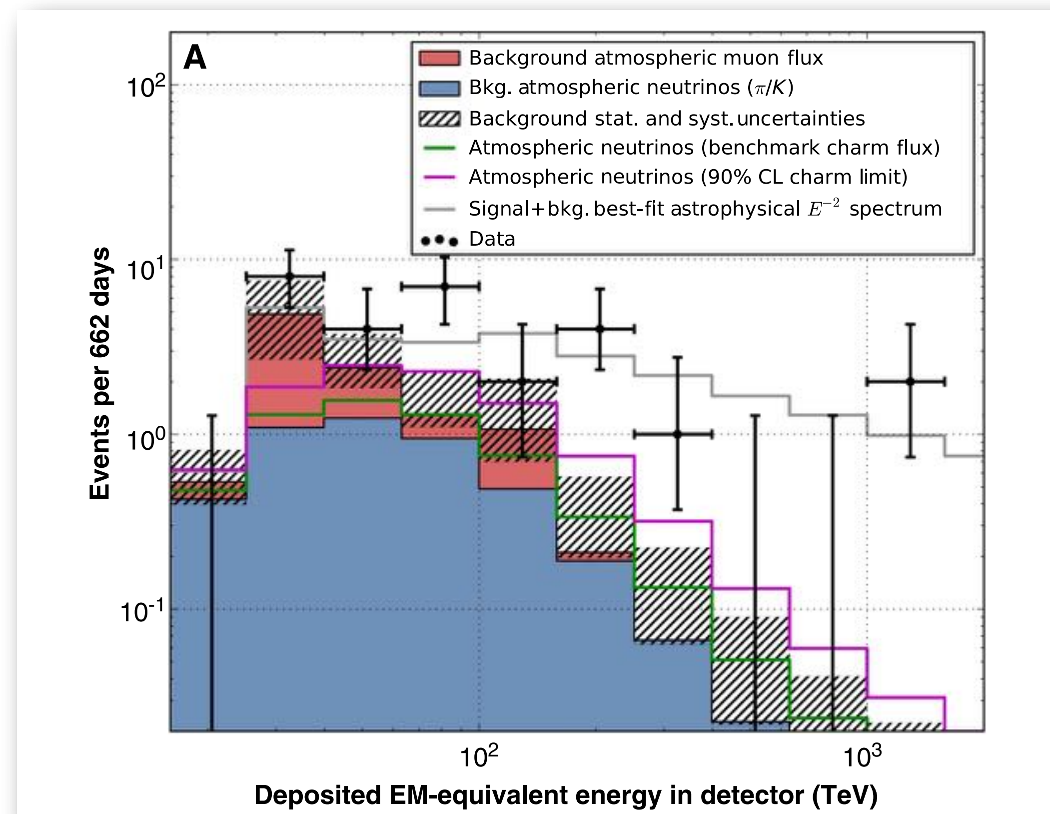
Goal is to show how alternatives to WIMPs may reserve rich pheno & multimessenger tests

A new window to the universe

M. Ahlers' lectures!

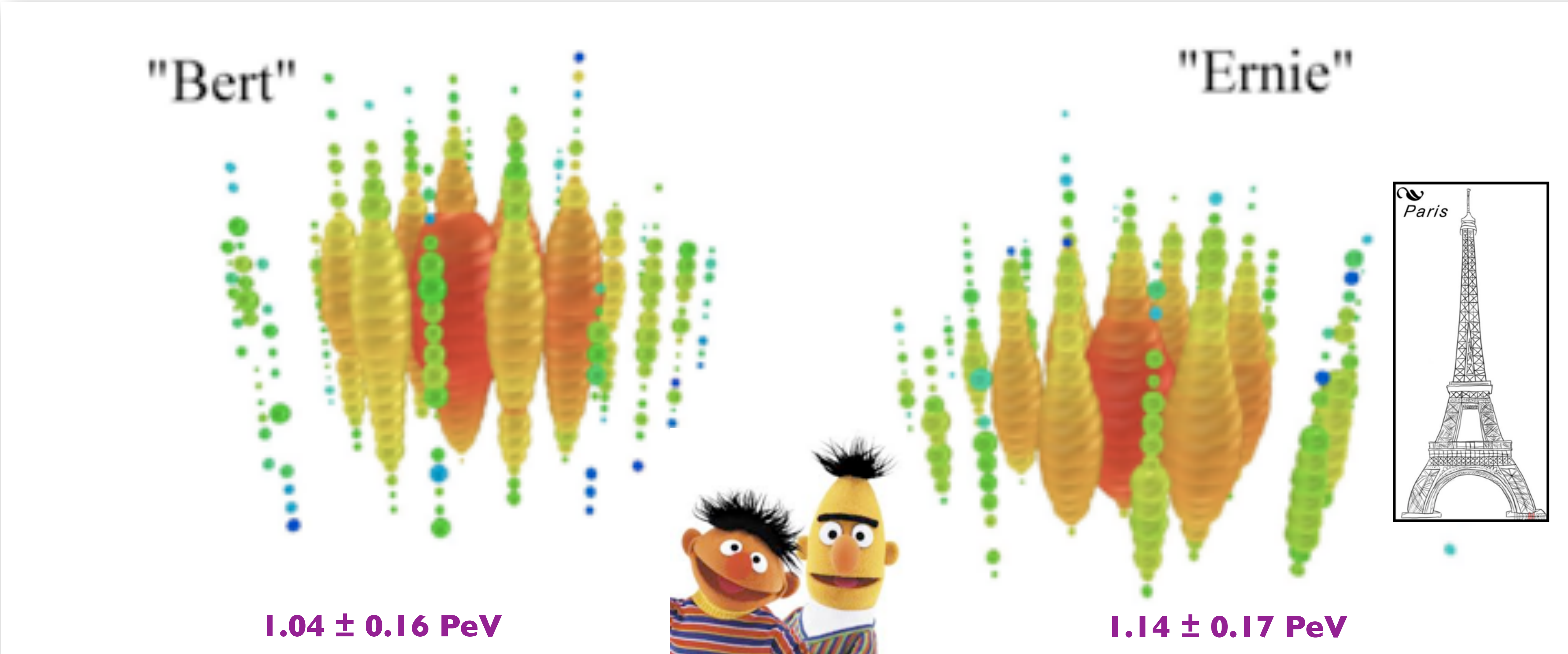
M. G. Aartsen et al. [**IceCube** Collaboration], "**Evidence for High Energy Extraterrestrial Neutrinos at the IceCube Detector,"** Science 342, no. 6161, 1242856 (2013) [arXiv:1311.5238]

- 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): **28 events** (both **showers & tracks**) wrt $10.6^{+5.0}_{-3.6}$ background expected (>**4 σ**!)
- Then 37 events including a ~2 PeV cascade event ("Big Bird", 1405.5303)… by now, ~yearly updates
- E-distribution, angular distribution and flavour composition consistent with a isotropic signal (fully Galactic plane disfavoured, but could have Galactic component)



Birth of high energy neutrino astronomy!

Reasons for the name…



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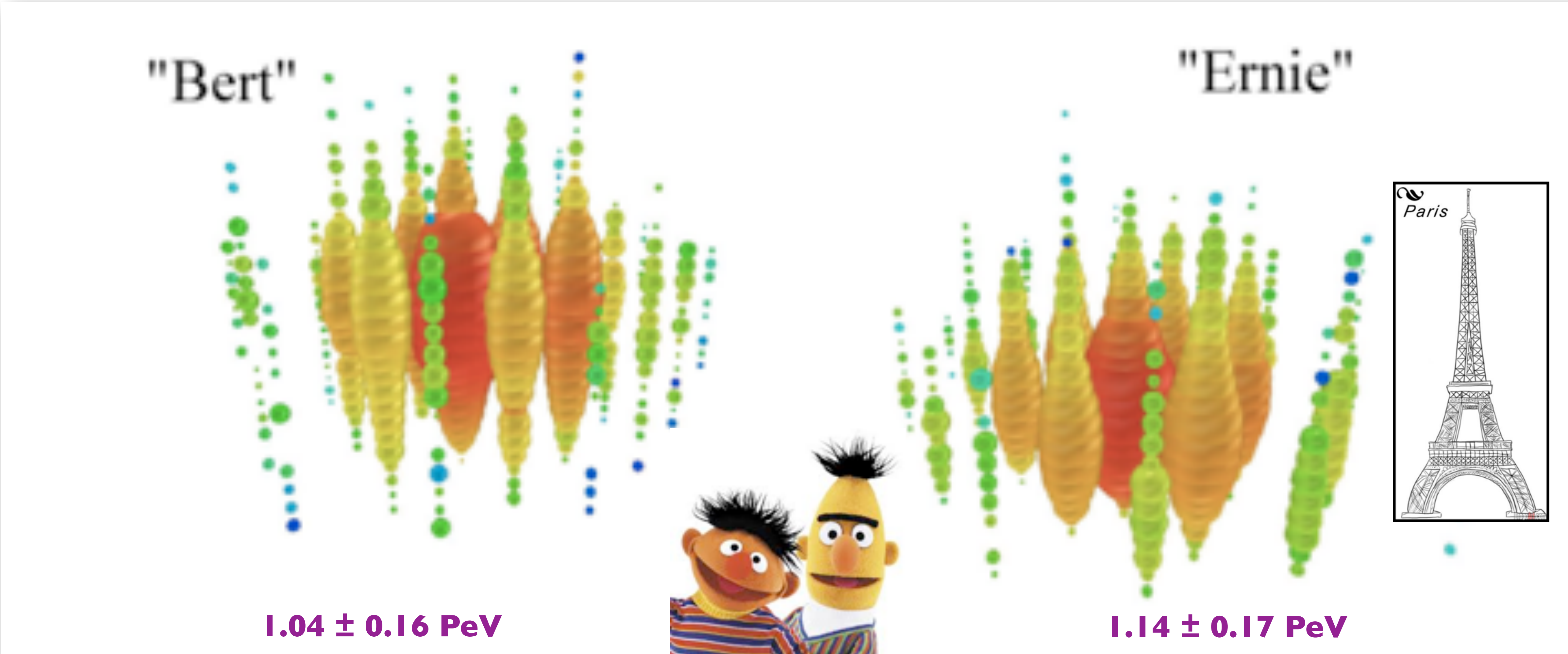

Third ~2 PeV cascade event ("Big Bird")
was found soon later…

Could they be due to DM?

Some features allow one to entertain the possibility of a DM origin, notably

I. reduced flux beyond ~2 PeV
(below expectations from power-law extrapol.)

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

III. mild excess towards inner Galaxy

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 $<\sigma v>$ 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

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Note II : the **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...)

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

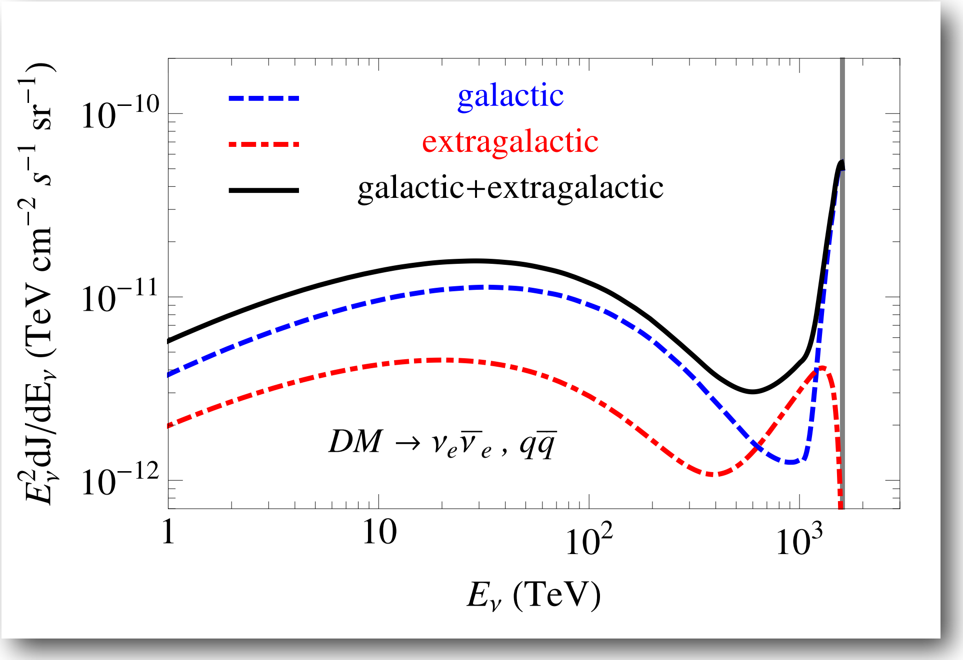
More details on model-building e.g. in Feldstein, A. Kusenko, S. Matsumoto and T.T. Yanagida, PRD 88, 1, 015004 (2013) [arXiv:1303.7320]
See also A. Esmaili, S. K. Kang and PS, arXiv:1410.5979

Some phenomenological aspects

- Both Galactic and extragalactic contributions, roughly comparable

$$\frac{\mathrm{d}J_{\mathrm{h}}}{\mathrm{d}E_\nu}(l,b) = \frac{1}{4\pi\, m_{\mathrm{DM}}\, \tau_{\mathrm{DM}}} \frac{\mathrm{d}N_\nu}{\mathrm{d}E_\nu} \int_0^\infty \mathrm{d}s\, \rho_{\mathrm{h}}[r(s,l,b)]$$

$$\frac{\mathrm{d}J_{\mathrm{eg}}}{\mathrm{d}E_\nu} = \frac{\Omega_{\mathrm{DM}}\rho_{\mathrm{c}}}{4\pi m_{\mathrm{DM}}\tau_{\mathrm{DM}}} \int_0^\infty \mathrm{d}z\, \frac{1}{H(z)} \frac{\mathrm{d}N_\nu}{\mathrm{d}E_\nu}[(1+z)E_\nu]$$



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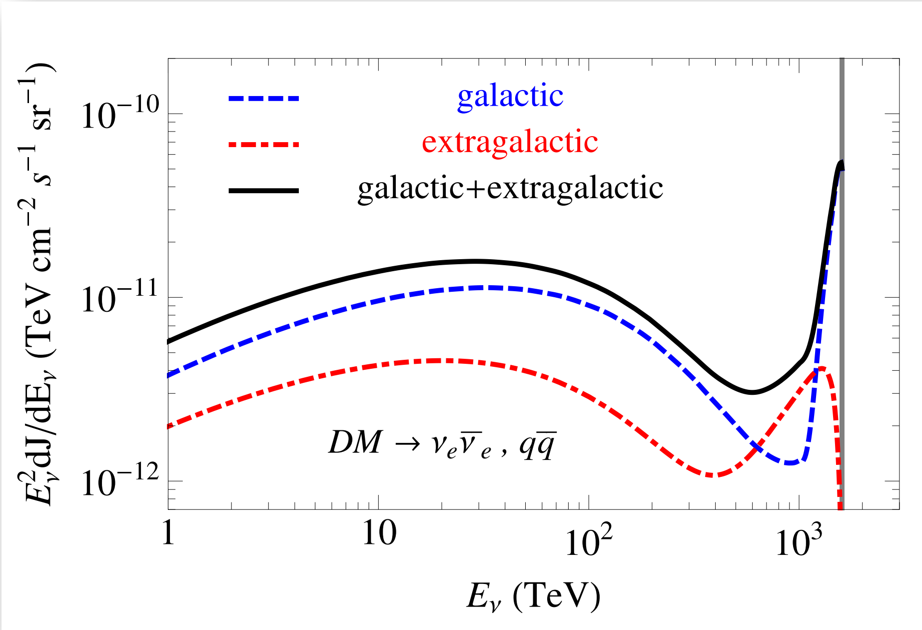
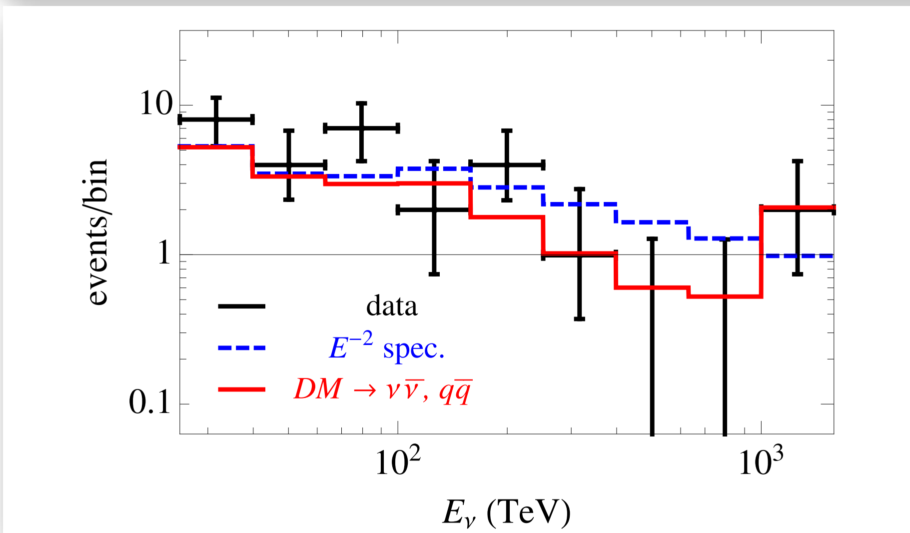
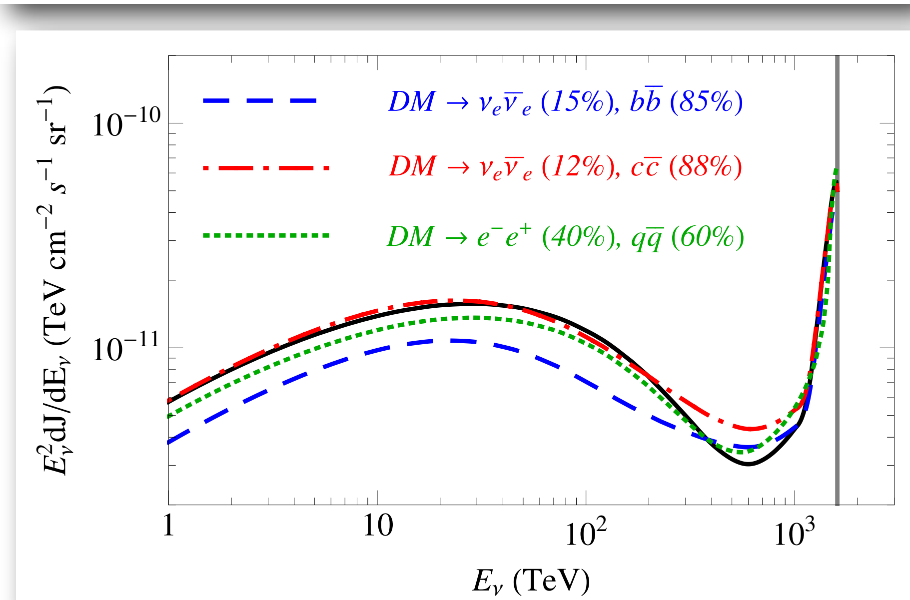
- almost isotropic, slight anisotropy towards inner Galaxy (much milder and less uncertain than for annihilation!)
- Abrupt energy cutoff expected (above DM mass)
- Dip expected for a mix of hard+soft channels, e.g. leptonic + hadronic/cascade contribution. Accommodated in a variety of final states/b.r./lifetimes (i.e. not particularly fine-tuned!)
- Associated to measurable gamma flux (but *early detection in neutrinos* quite *natural*...)







Further analyses

➡ Refined statistical tests on angular distribution, based on enlarged dataset.

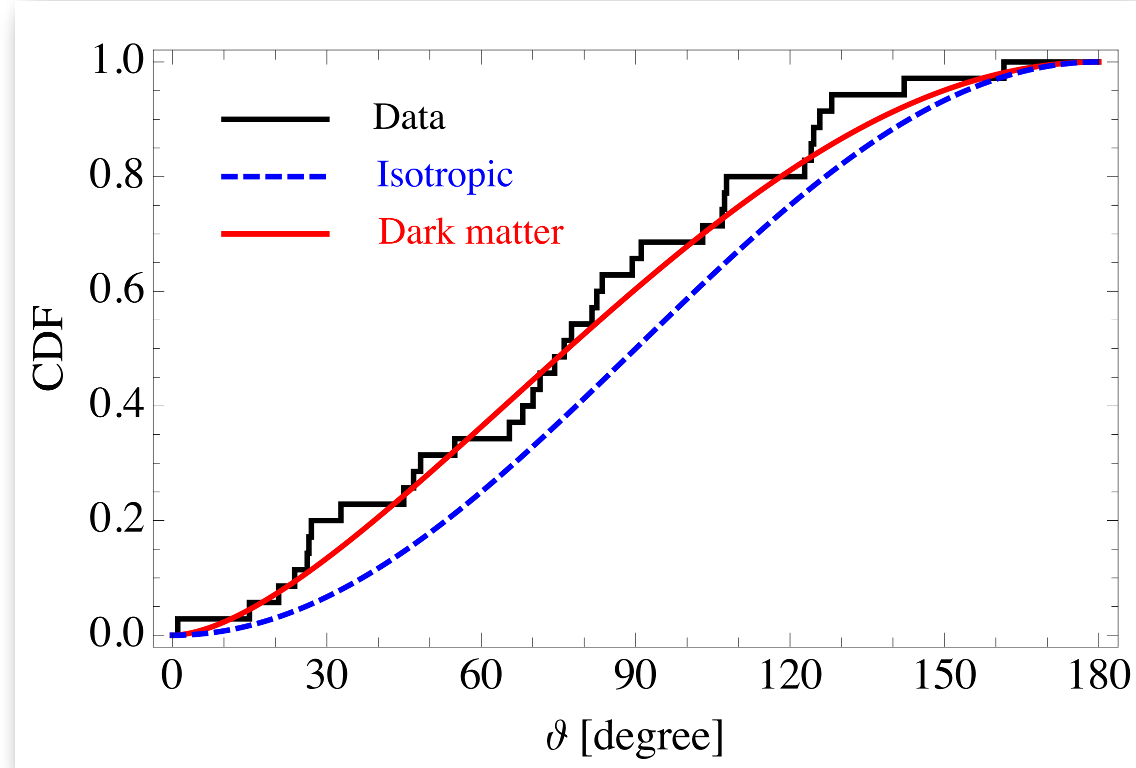
➡ Yet inconclusive, but ~2 sigmish preference for a DM-like distribution vs. isotropic one (~3 sigma level should be attainable within IceCube lifetime)

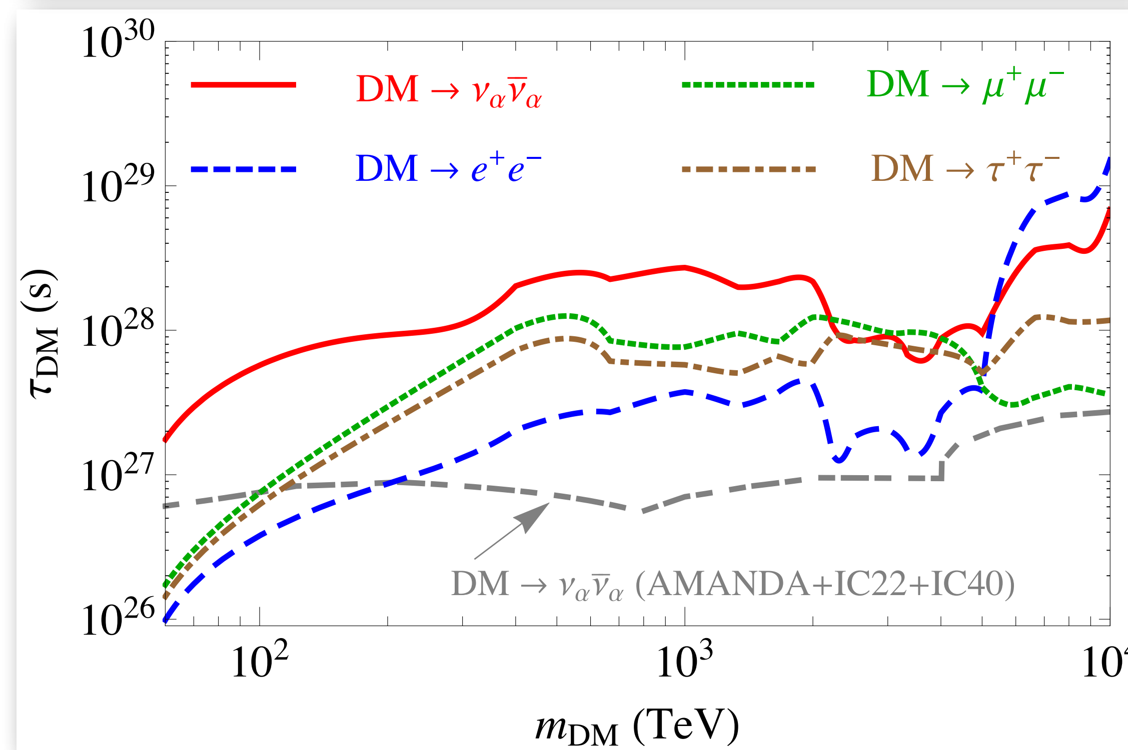
➡ Show that even the simplest model of the "portal type" can provide acceptable fits (lifetime and spectrum).
Production mechanisms: inflaton decay, freeze-in...

➡ Constraints from Galactic and extragalactic diffuse gamma bounds can be fulfilled (depend on decay channel)

➡ Even if signal is astrophysical, these data often provide best bounds to heavy DM lifetime!

This last point passed unnoticed, shows power of 'theory bias' even among experimentalists…



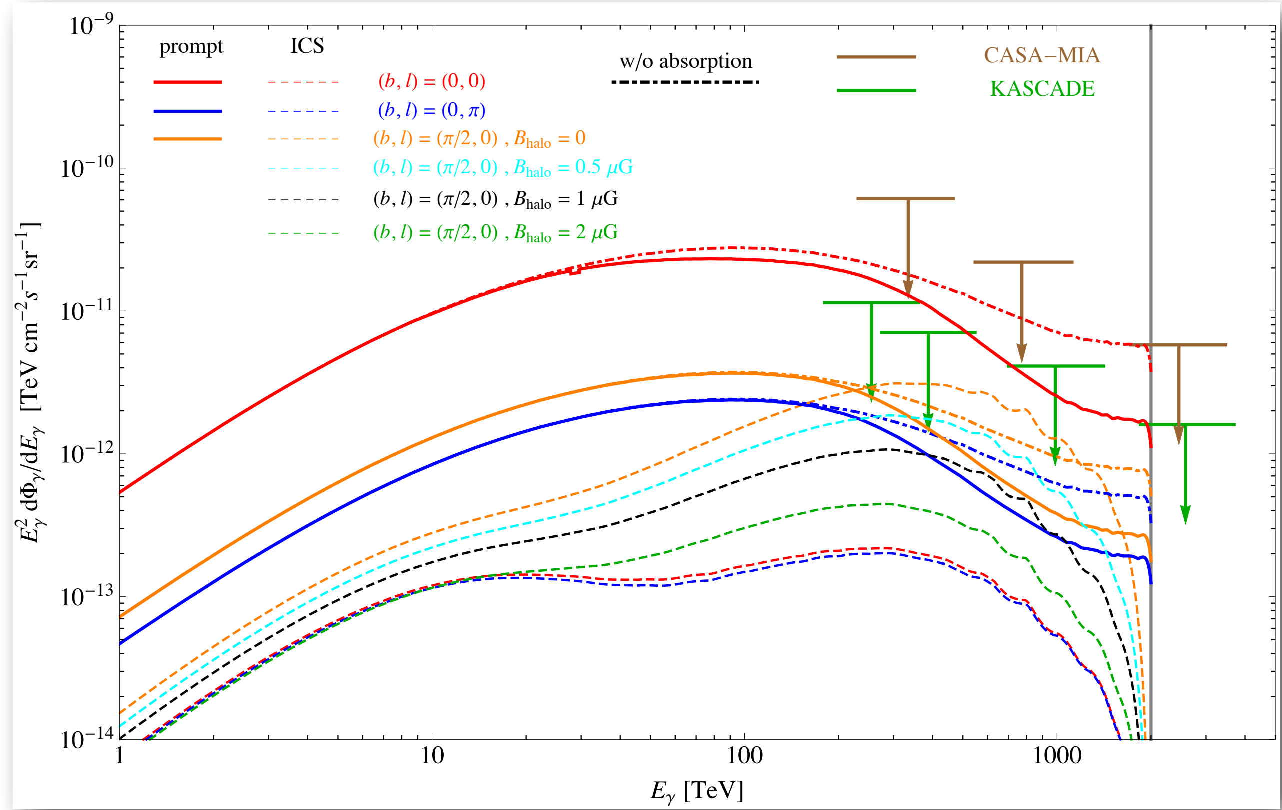


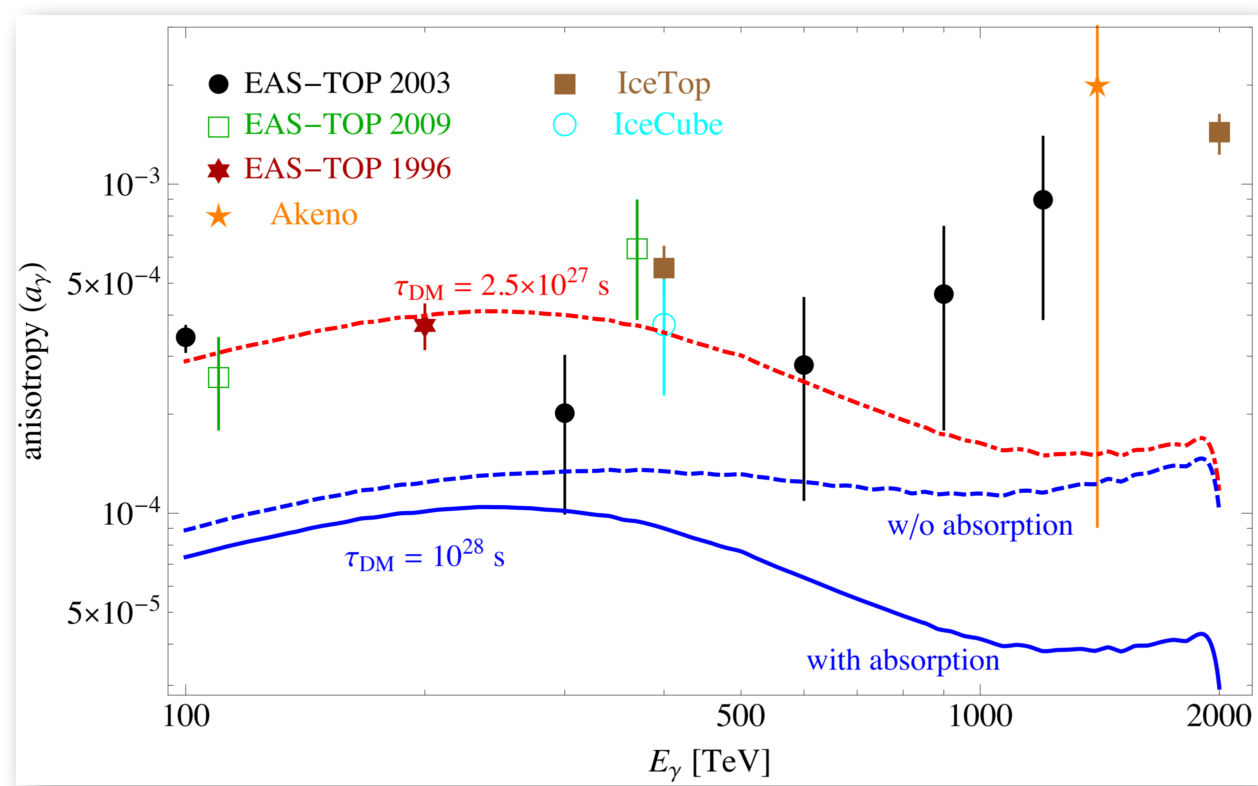
A. Esmaili, S. K. Kang and P. D. Serpico, arXiv:1410.5979, JCAP 12, 054 (2014)

Implications for VHE gamma astrophysics

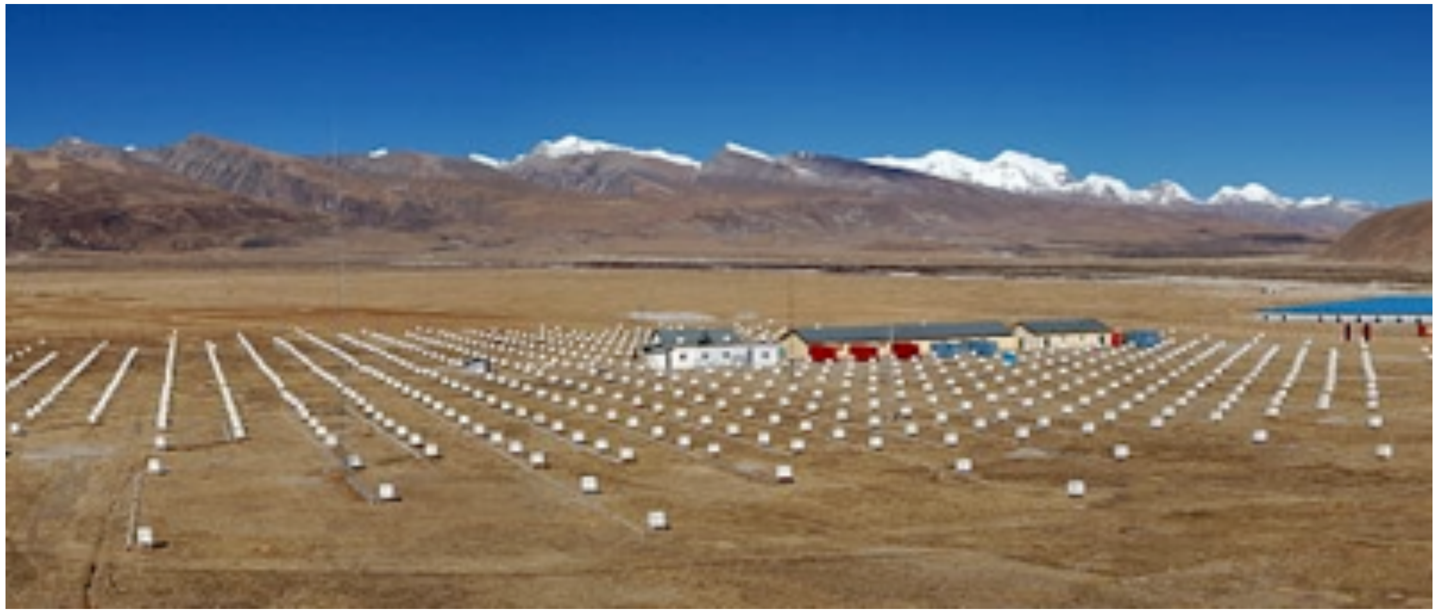
- Best hope for robust independent test comes from VHE (EAS) CR-gamma detectors
- The spectrum expected is deeply influenced by the *absorption* onto CMB and ISRF, which needs to be taken into account (2D/3D calc.)
- Surprisingly, similar sensitivity via CR anisotropy (despite CR/gamma ratio >>1!!!)
- Serendipitous DM discovery/constraining potential of ground based instruments like HAWC…

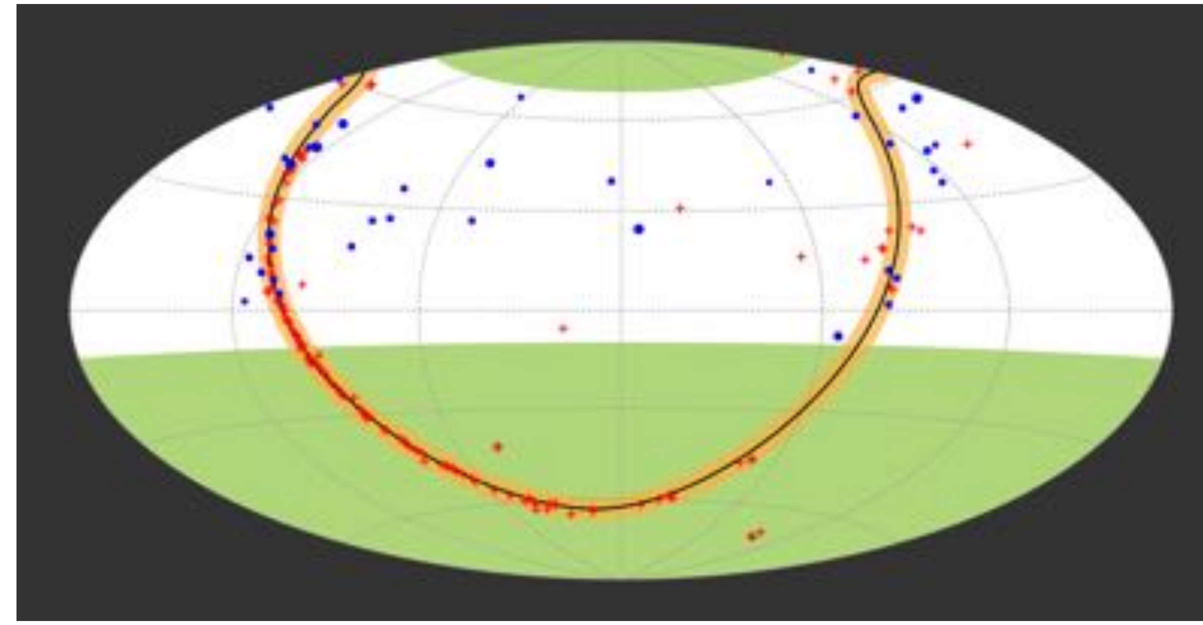
A. Esmaili and PS, JCAP 10, 014 (2015) [1505.06486]





2021 - TIBET AS$_\gamma$





Arrival directions of gamma-ray photons with energies between 0.4 and 1 PeV (blue solid dots). Most detections are clustered in the vicinity of the Galactic Plane (yellow shaded area). The red marks indicate the position of known TeV sources, while the green areas indicate the sky regions outside the field of view of the observatory.

First Detection of sub-PeV Diffuse Gamma Rays from the Galactic Disk: Evidence for Ubiquitous Galactic Cosmic Rays beyond PeV Energies

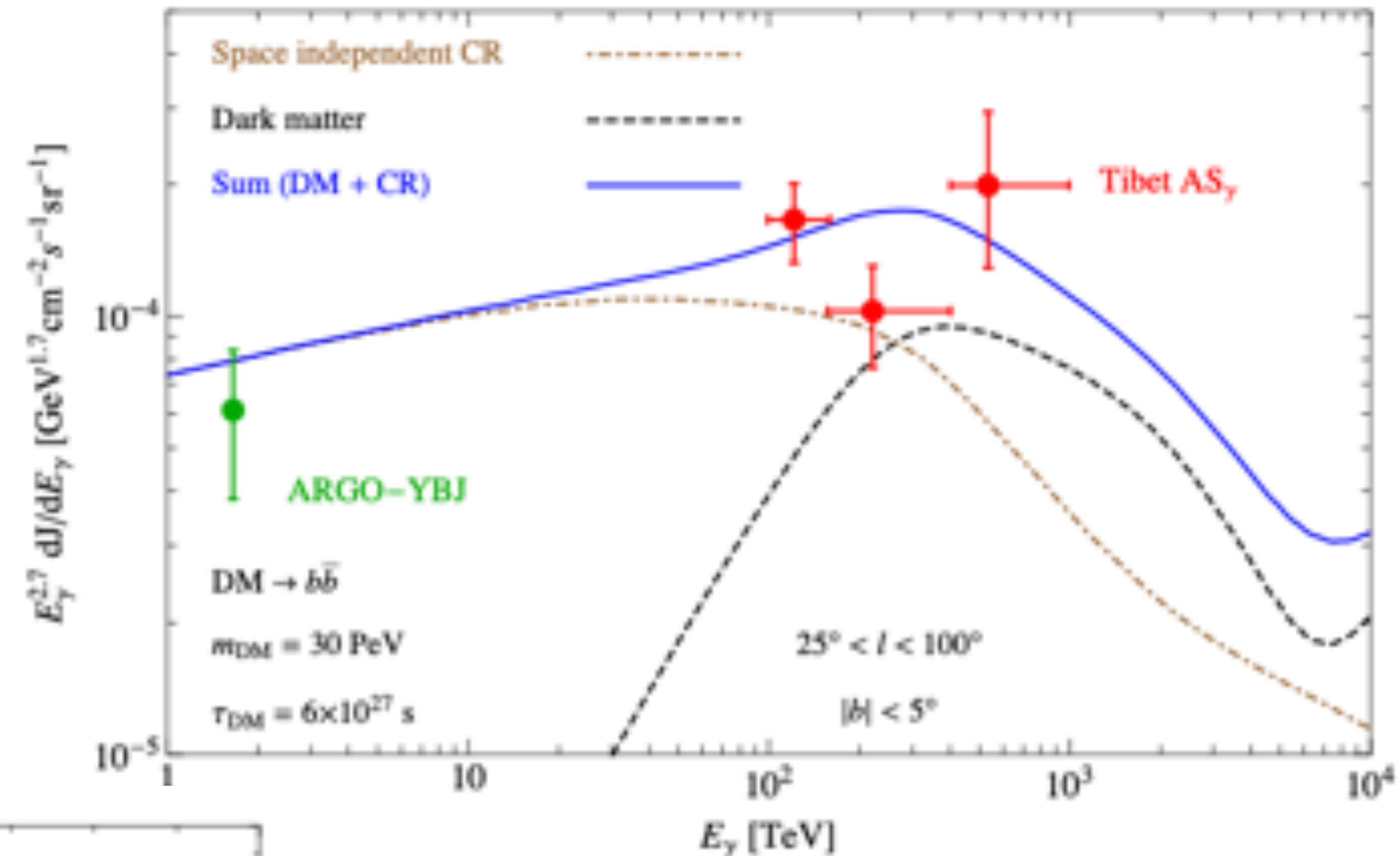
M. Amenomori *et al.* (Tibet AS$_\gamma$ Collaboration)

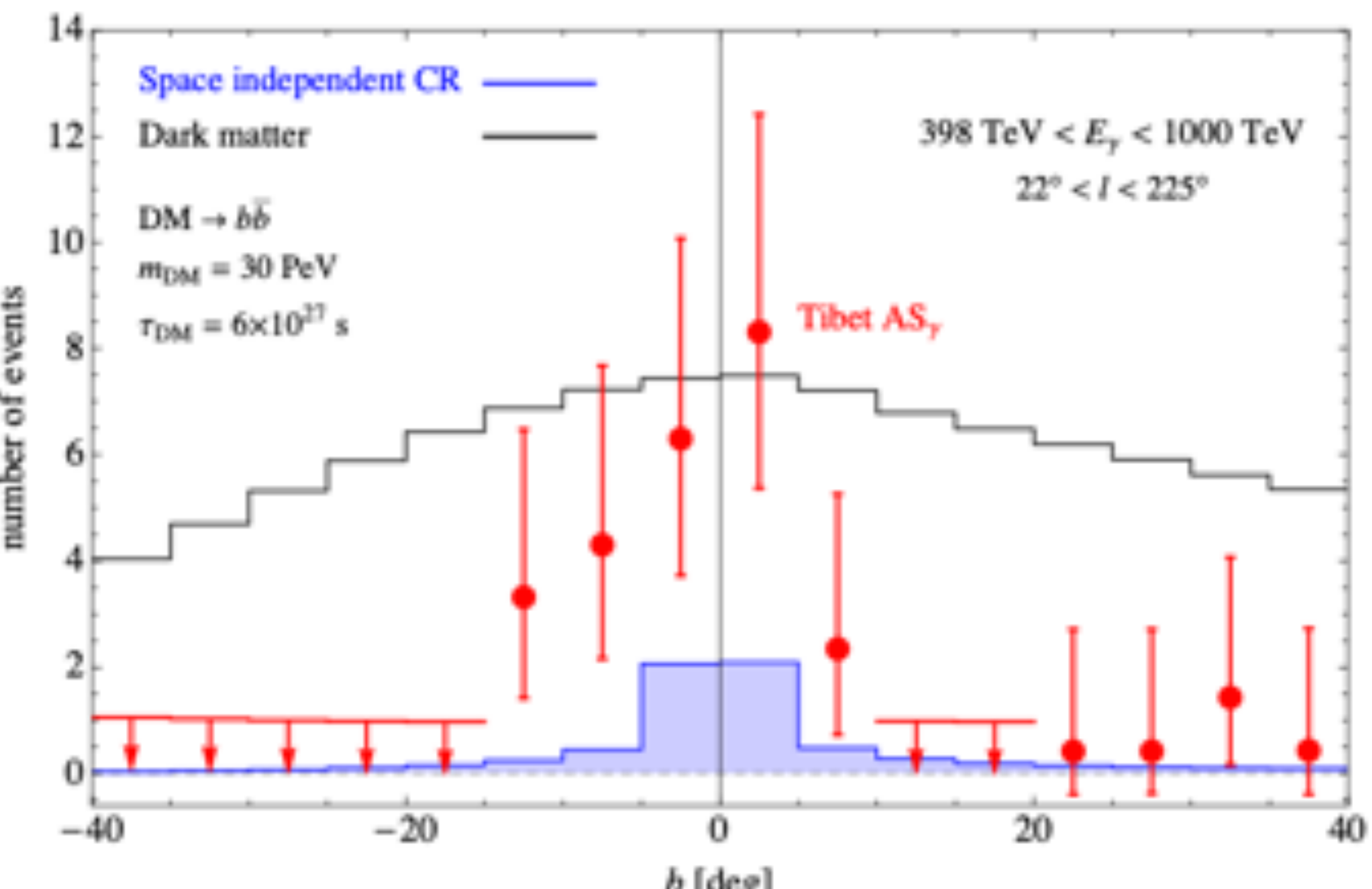
Phys. Rev. Lett. **126**, 141101 – Published 5 April 2021

Added power of angular information

DM naively allowed (or favoured!) at spectral level…

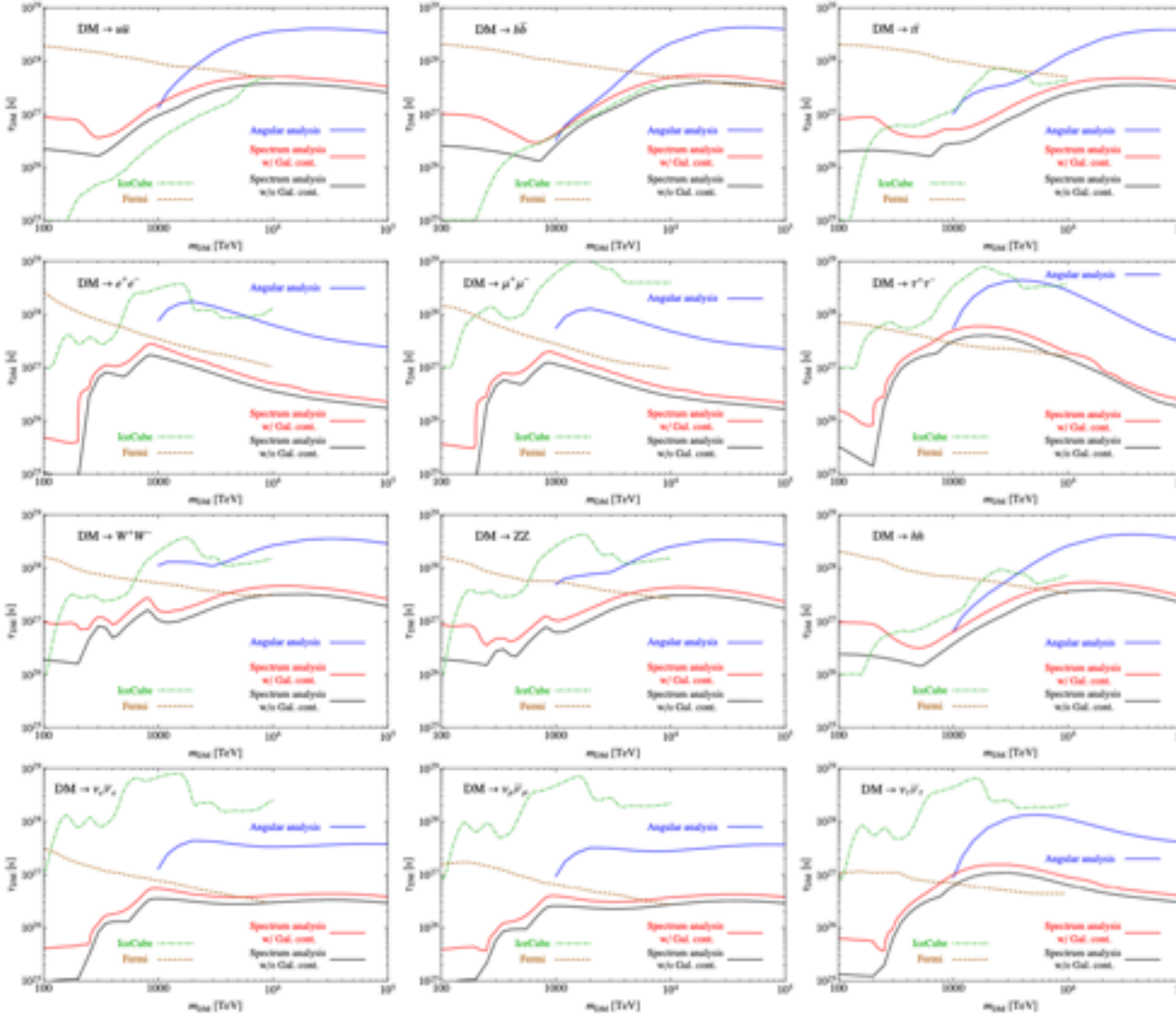
A. Esmaili and PDS, Phys. Rev. D 104 L021301 (2021) [2105.01826]





…may be unacceptable at angular level!

First proof that ground-based (not IACTs) can lead the DM (non-WIMP!) constraints in some parameter space



DM → $u\bar{u}$
DM → $b\bar{b}$
DM → $t\bar{t}$
DM → e^+e^-
DM → $\mu^+\mu^-$
DM → $\tau^+\tau^-$
DM → W^+W^-
DM → ZZ
DM → hh
DM → $\nu_e\bar{\nu}_e$
DM → $\nu_\mu\bar{\nu}_\mu$
DM → $\nu_\tau\bar{\nu}_\tau$
Angular analysis
Spectrum analysis w/ Gal. cont.
Spectrum analysis w/o Gal. cont.
IceCube
Fermi
$m_{\rm DM}$ [TeV]
$\tau_{\rm DM}$ [s]
100
1000
10^4
10^5
10^{25}
10^{26}
10^{27}
10^{28}
10^{29}

“More” exotic DM

No need for the DM to be collection of ‘particles’, either!
(A couple of exemples)

Case III: Primordial Black Holes (PBH)

PBH from gravitational collapse of sufficiently large density fluctuations, at scales much smaller than the CMB ones (*Zeldovich & Novikov 67, Carr & Hawking 74, Carr 75…*)

Associated to non-trivial inflationary dynamics and/or phase transitions
(change of EOS, string loops, bubble collisions…)

Simple argument:
free-fall time of a density perturbation of Hubble size shorter than pressure counterbalance timescale

$$\tau_{\rm fall} < \tau_{\rm press} \Leftrightarrow \frac{\delta\rho}{\rho} \gtrsim \mathcal{O}(1) c_s^2 \simeq \frac{1}{3}\,(\mathrm{RD})$$

where

$$\tau_{\rm fall} \simeq (4\pi G \delta\rho)^{-1/2}$$

$$\tau_{\rm press} \simeq \frac{R_H}{c_s} \simeq \frac{\sqrt{3}}{c_s\sqrt{8\pi G\rho}}$$

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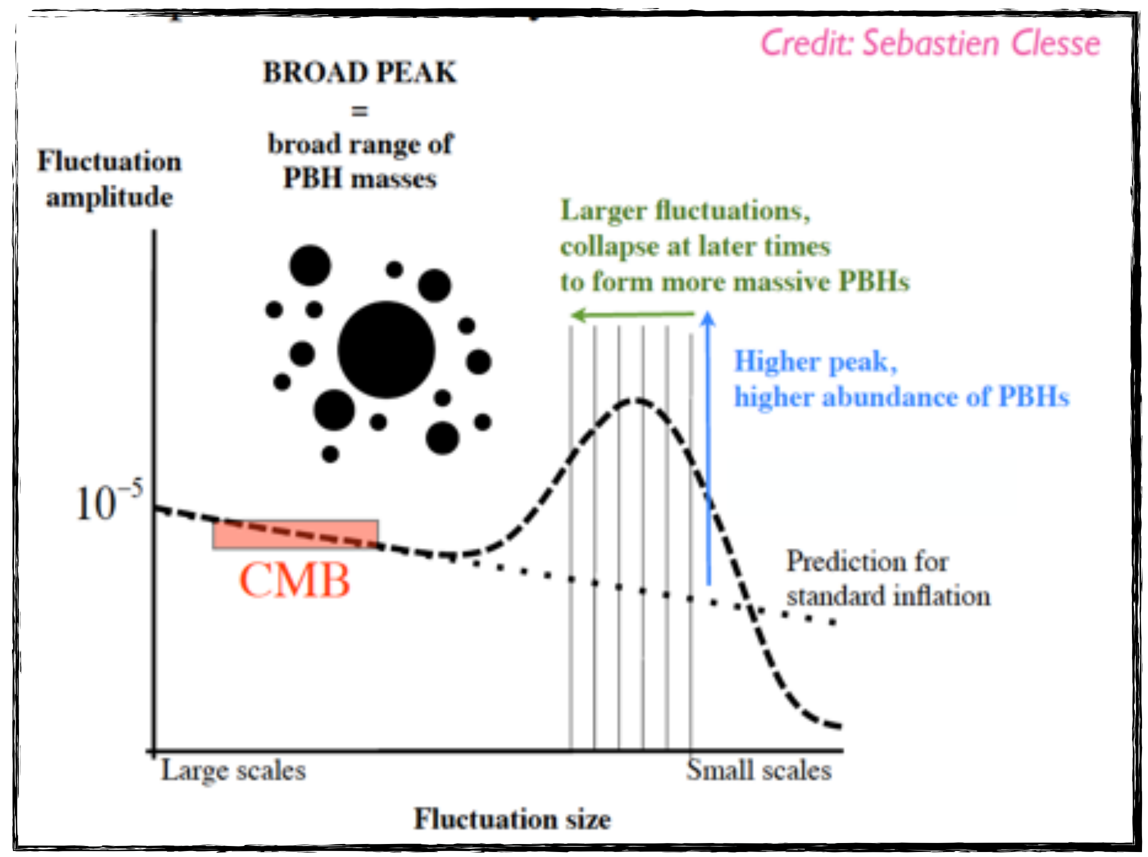
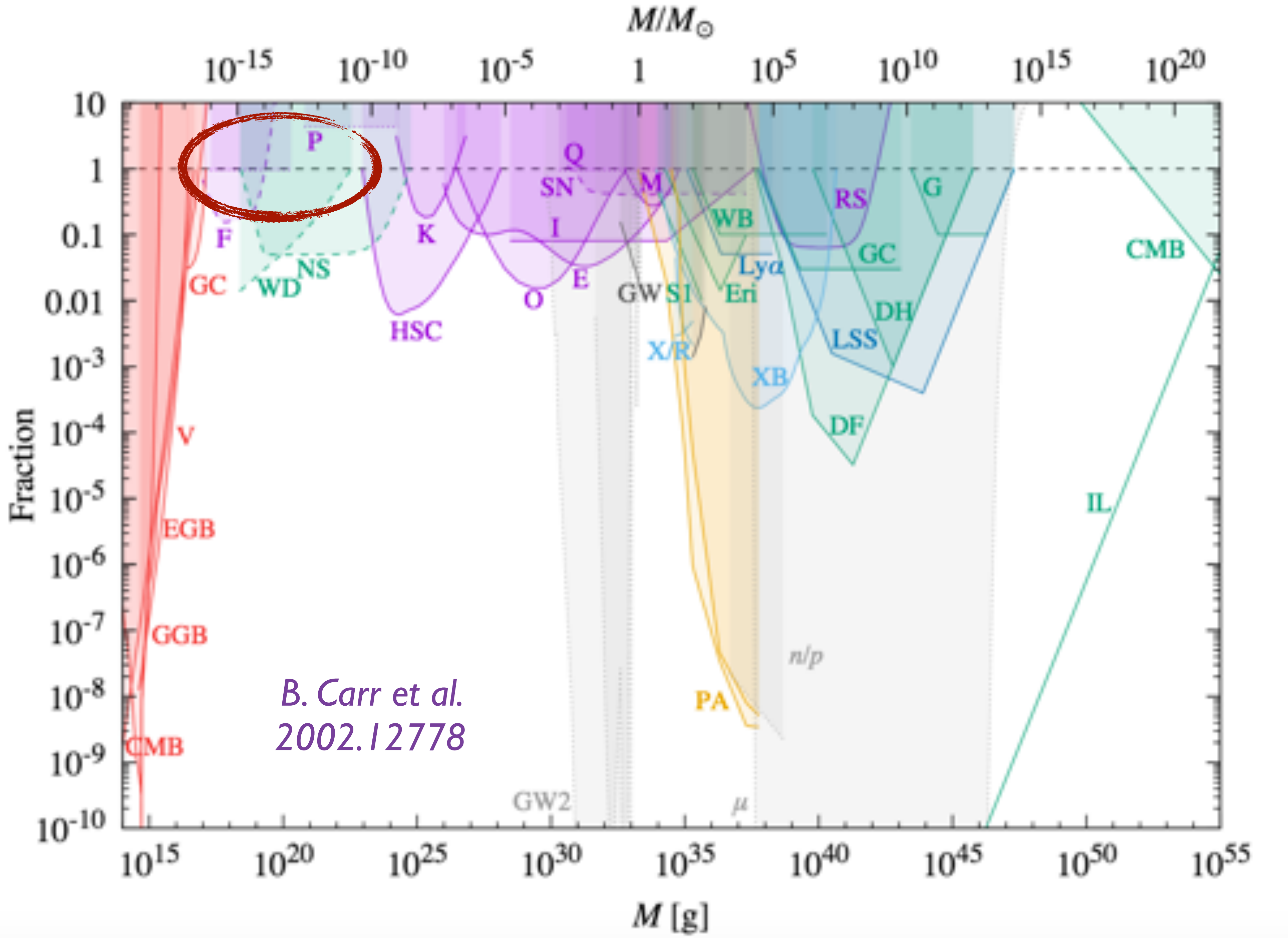
$$M_{\rm PBH} \sim M_H\Big|_{\rm cross} \sim \rho H^{-3}\Big|_{\rm cross} \propto H^{-1}\Big|_{\rm cross} \propto k_{\rm peak}^{-2}$$



Requires density contrast >> CMB-level ones!
(early matter phase would help, too!)

Overall bounds: current situation



Constraints on f(M) from evaporation (red), lensing (magenta), dynamical effects (green), accretion (light blue), CMB distortions (orange), large-scale structure (dark blue) and background effects (grey). Evaporation limits come from the extragalactic gamma-ray background (EGB), the Galactic gamma-ray background (GGB) and Voyager e± limits (V). Lensing effects come from femtolensing (F) and picolensing (P) of gamma-ray bursts, microlensing of stars in M31 by Subaru (HSC),in the Magellanic Clouds by MACHO (M) and EROS (E), in the local neighbourhood by Kepler (K), in the Galactic bulge by OGLE (O) and the Icarus event in a cluster of galaxies (I), microlensing of supernova (SN) and quasars (Q), and millilensing of compact radio sources (RS). Dynamical limits come from disruption of wide binaries (WB) and globular clusters (GC), heating of stars in the Galactic disk (DH), survival of star clusters in Eridanus II (Eri) and Segue 1 (S1), infalling of halo objects due to dynamical friction (DF), tidal disruption of galaxies (G), and the CMB dipole (CMB). Accretion limits come from X-ray and radio (X/R) observations, CMB anisotropies measured by Planck (PA) and gravitational waves from binary coalescences (GW). Background constraints come from CMB spectral distortion (μ), 2nd order gravitational waves (GW2) and the neutron-to-proton ratio (n/p). The incredulity limit (IL) corresponds to one hole per Hubble volume.

A QFT effect in curved spacetimes: Hawking evaporation

Black Holes are not black (Hawking '74)
they emit a blackbody radiation with

$$T_{\rm BH} = \frac{1}{8\pi G M} \simeq 1.06 \left(\frac{10^{13}\,{\rm g}}{M}\right) {\rm GeV}$$

as a consequence, BHs
lose mass at a rate

$$\frac{dM}{dt} = -5.34 \times 10^{-11} \mathcal{F}(M) \left(\frac{M}{10^{13}\,{\rm g}}\right)^{-2} {\rm s}^{-1}$$

emitted particle spectra follow
black body-like forms.

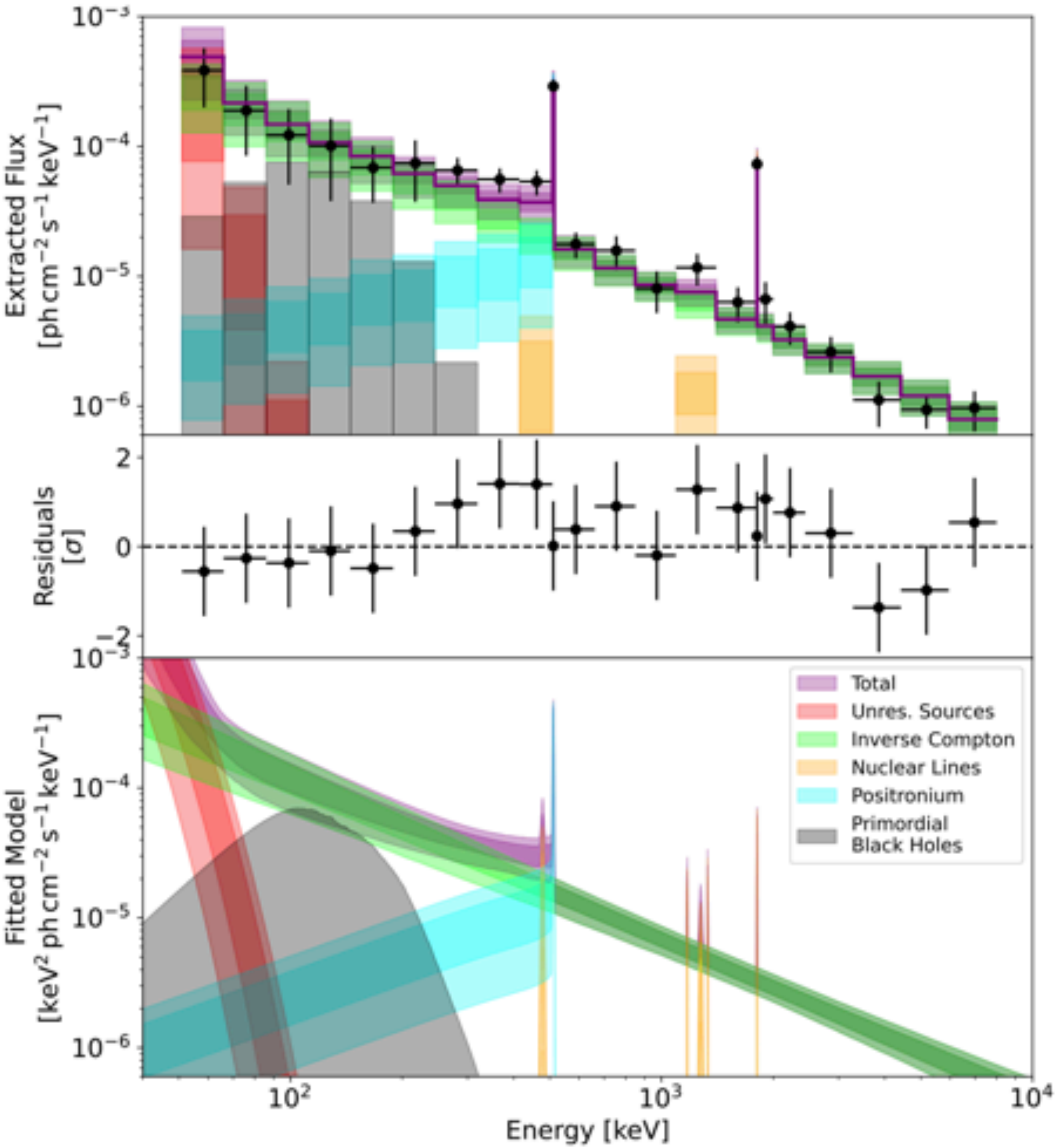
$$\frac{d\dot{N}_s}{dE} \propto \frac{\Gamma_s}{e^{E/T_{\rm BH}} - 1(-1)^{2s}}$$

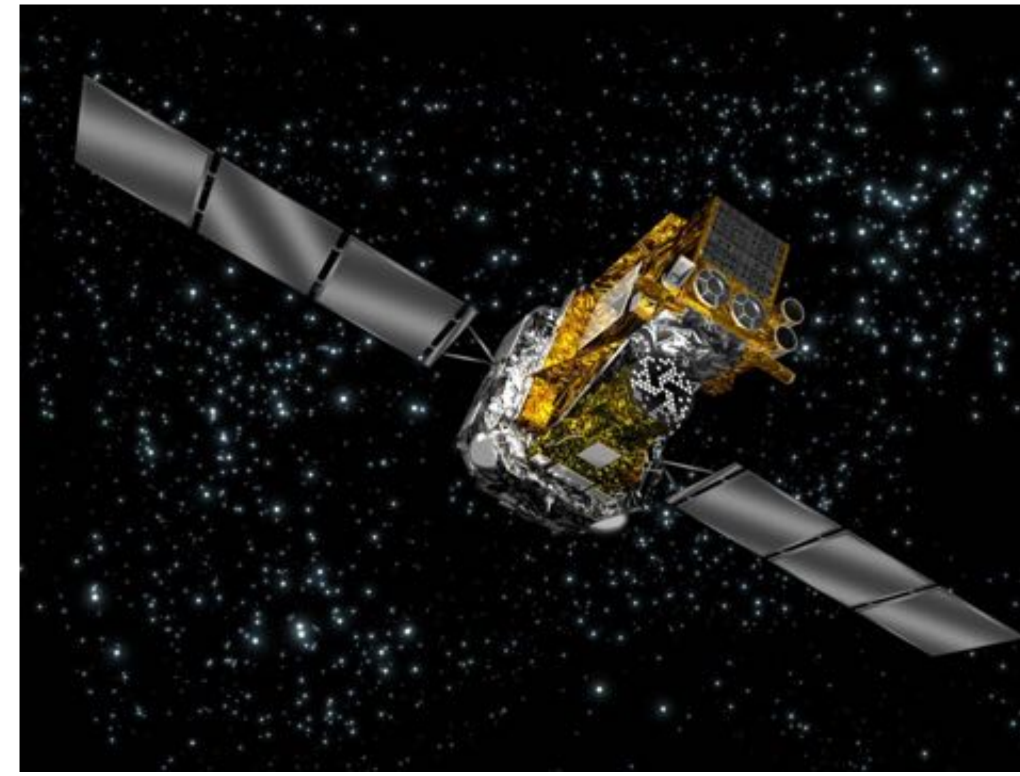
At high energies, one has

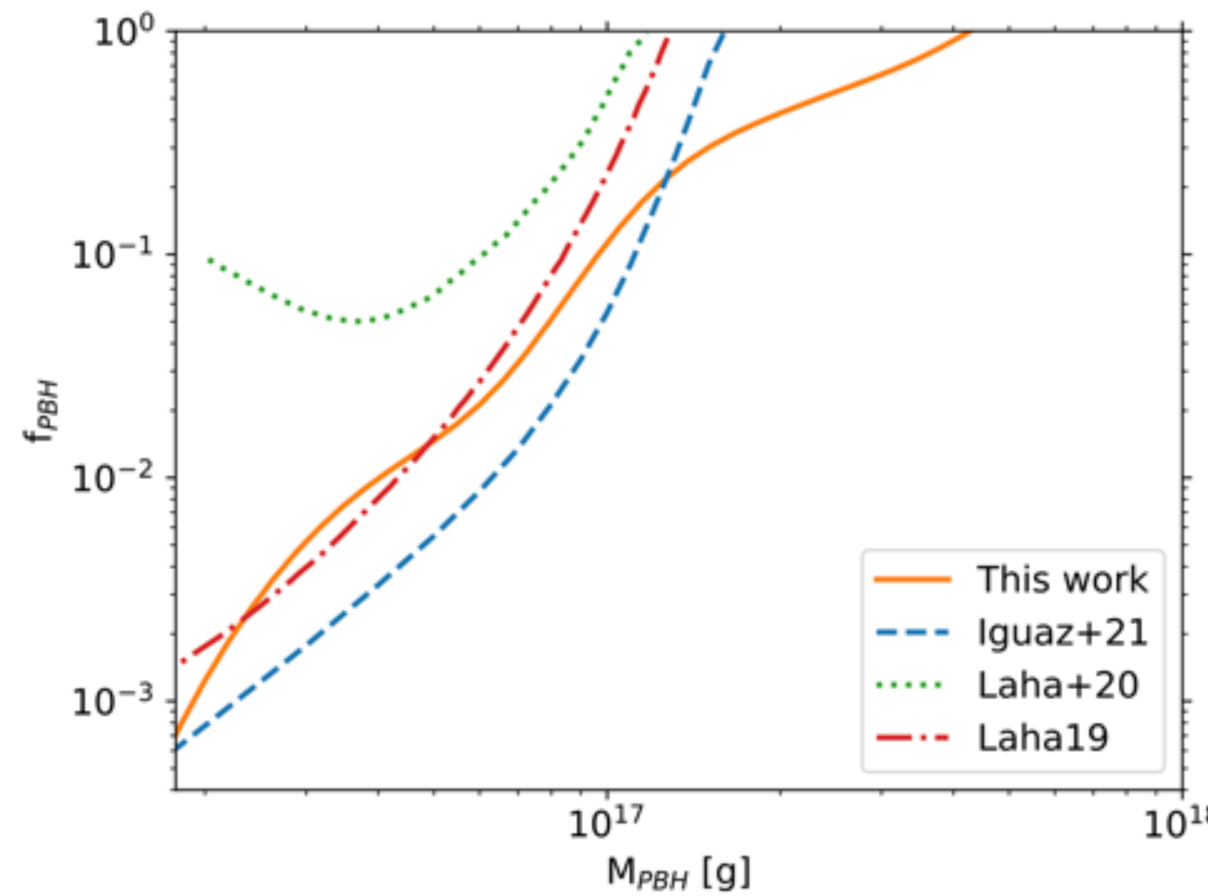
$$\Gamma_s(M,E) = 27E^2G^2M^2$$

This is all very nice, but for astrophysical BH it's purely of academic interest (too low!)
However, if "light" primordial BH produced in the early universe, the energy injection rate via evaporation may be detectable!

Can use X-rays to soft gammas to search for PBH







J. Berteaud et al. "Strong constraints on PBH dark matter from 16 years of INTEGRAL/SPI observations," arXiv:2202.07483

Case IV: A (scalar) classical field as DM

Key notions and difference with respect to WIMPs

- **The DM behaviour is obtained as the "classical field" limit of a new dof**
- **The implementation often involves light mass terms and BSM physics** (e.g. new symmetry breaking) **at very-high energies,** typically no link with EW scale/collider ones

What I want to show you:

- **The conditions under which a scalar field in the early universe behaves as DM**
- **The conditions needed to match the DM abundance**

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Action of scalar field X with minimal coupling in a flat FLRW $ds^2 = dt^2 - a(t)^2 d\mathbf{x}^2$

$$S = \int \mathrm{d}t\, a^3 \int \mathrm{d}^3\mathbf{x} \left[\frac{\dot{X}^2}{2} - V(X) \right]$$

Eq. of motion and stress-energy of a scalar field *X*

For simplicity, consider
free massive particle potential

$$V = M_X^2 X^2/2$$

$$a^3[\ddot{X} + 3H\,\dot{X} + M_X^2 X] = 0$$

A scalar field *X* is also associated to a stress-energy tensor.
FRLW symmetries require it to be of the "perfect fluid" form

$$T_{\alpha\beta}(X) = (\rho + P)u_\mu u_\nu - P g_{\mu\nu}$$

One can prove that:

$$\rho = \frac{1}{2}\dot{X}^2 + V(X)$$

$$P = \frac{1}{2}\dot{X}^2 - V(X)$$

Early time solution

$$a^3[\ddot{X} + 3H\,\dot{X} + M_X^2 X] = 0$$

if mass term negligible wrt expansion rate (i.e. at sufficiently high temperatures)

$$H^2 \gg M_X^2$$

by setting $\dot{X} = W$ the equation reduces approximately to

$$\dot{W} + 3H\,W \simeq 0$$

whose solution is a constant (plus a transient)

$$X(t) = X_1 + W_1 \int_{t_1}^{t} \left(\frac{a_1}{a}\right)^3 dt$$

X "gets frozen" due to the high expansion rate, acting like friction (overdamping)

Late time solution

$$a^3[\ddot{X} + 3H\,\dot{X} + M_X^2 X] = 0$$

If mass term large wrt expansion rate
(i.e. at sufficiently low temperatures)

$$H^2 \ll M_X^2$$

The field oscillates fast, on the top of which "slow" evolution driven by *H*

In fact, consider the energy density

$$\rho = \frac{1}{2}(\dot{X}^2 + M_X^2 X^2)$$

From Fried. Eq., averaging over times much longer than M_X^{-1} but shorter than H^{-1}

$$\langle\dot{\rho}\rangle = -3\,H\,\langle\dot{X}^2\rangle$$

and using virial theorem

$$\langle\dot{X}^2\rangle = 2\langle K\rangle = \langle K\rangle + \langle V\rangle$$

valid for harmonic potential

$$\langle\dot{\rho}\rangle = -3\,H\,\langle\rho\rangle \Rightarrow \langle\rho\rangle = \langle\rho\rangle_1\left(\frac{a_1}{a}\right)^3$$

The **field average energy** density evolves as the one for **cold dark matter**!

DM from 'misalignment'

$$\rho_0 = M_X\, n_X^* \left(\frac{a_*}{a}\right)^3 \simeq M_X \frac{\rho_*}{M_X} \left(\frac{a_*}{a}\right)^3 \simeq M_X^2 A_*^2 \left(\frac{a_*}{a_0}\right)^3$$

↓

$$\rho_0 \simeq M_X^2 A_*^2 \frac{g_S(T_0) T_0^3}{g_S(T_*) T_*^3}$$

↓

where T* is given roughly by the condition ***$3H(T^*)=M_X$***, which clearly yields (in the radiation era) ***$T^* \sim (M_{Pl}\, M_X)^{1/2}$***. The scaling is thus

$$\rho_0 \propto M_X^{1/2} A_*^2 \,,$$

$$\rho_0 \sim 10^{-5} \mathrm{GeV\,cm^{-3}} \sqrt{\frac{M_X}{\mathrm{eV}}} \left(\frac{A_*}{10^{12}\,\mathrm{GeV}}\right)^2 , \Leftrightarrow \Omega_X h^2 \sim 0.1 \sqrt{\frac{M_X}{100\,\mathrm{meV}}} \left(\frac{A_*}{10^{12}\,\mathrm{GeV}}\right)^2$$

Note: light particles + large values for the initial field displacement work!

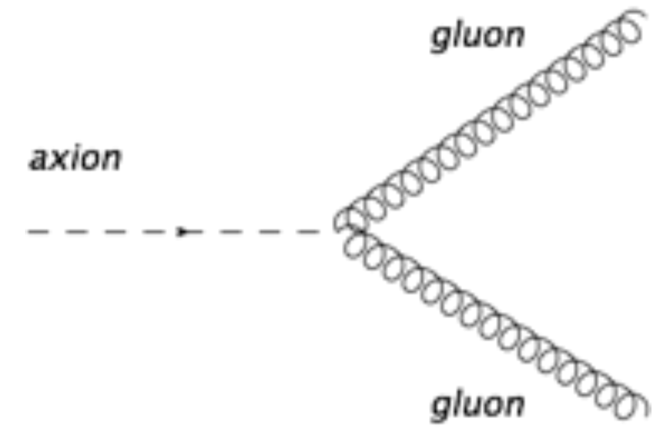
'Morally analogous' to the axion case (scaling different for the potential, etc.…)

The case of axion (and axionlike particles, ALPs)

As a dynamical solution to the absence of CP violation in the strong sector (smallness of θ term) Peccei & Quinn introduced a new axial $U(1)_{PQ}$ symmetry (1977) spontaneously broken at a scale f_a the **axion** is the corresponding Nambu-Goldstone mode (Weinberg, Wilczek '78)

"Defining coupling": Axions couple to gluons (and mix with π^0)

$$\theta G_{\mu\nu}\tilde{G}_{\mu\nu} \rightarrow \frac{a}{f_a} G_{\mu\nu}\tilde{G}_{\mu\nu}$$



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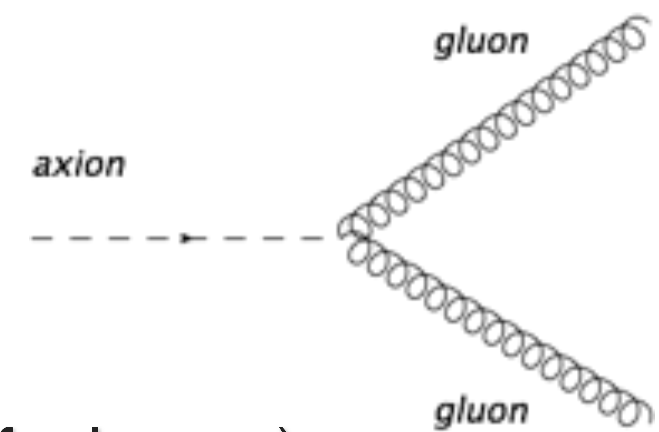
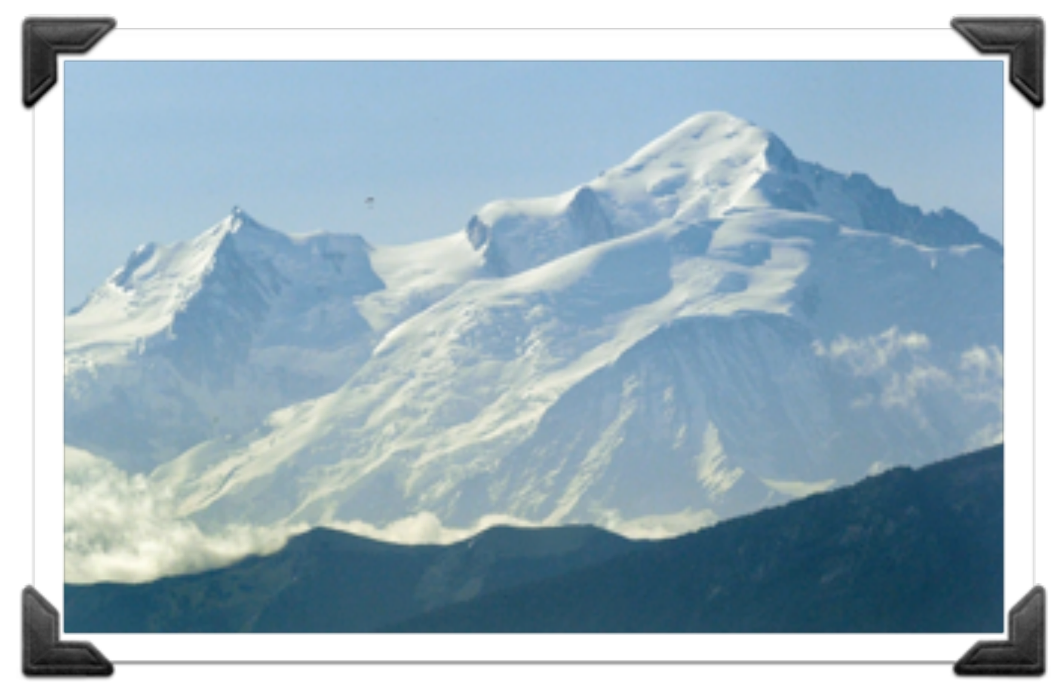


- Axions satisfy $m_\pi f_\pi \sim m_a f_a$
- They can couple to fermions, but more model-dependent (especially for leptons)
- effective 2-γ coupling $g_{a\gamma\gamma} = \xi\, \alpha/(2\pi f_a) \propto m_a$ (important for phenomenology)

Rich phenomenology: can be cold DM, subleading hot DM, affect stars, cosmology...

Search extended to axion-like particles (ALPs)≡
Light (pseudo)scalars with a 2-γ coupling $g_{a\gamma\gamma}$ with generic relation with m_a



Rather than relating it to DM, let me use this to illustrate some example of

IV. Something ain't working as it should: Alteration in SM-derived laws

and discuss its impact on high-energy astrophysics observables

Unrelated (?!) topic: Hillas plot

Any accelerator (including cosmic ray ones!) must be able to contain the particle: Larmor Radius must be smaller than the size of the accelerator: $r_L < s$

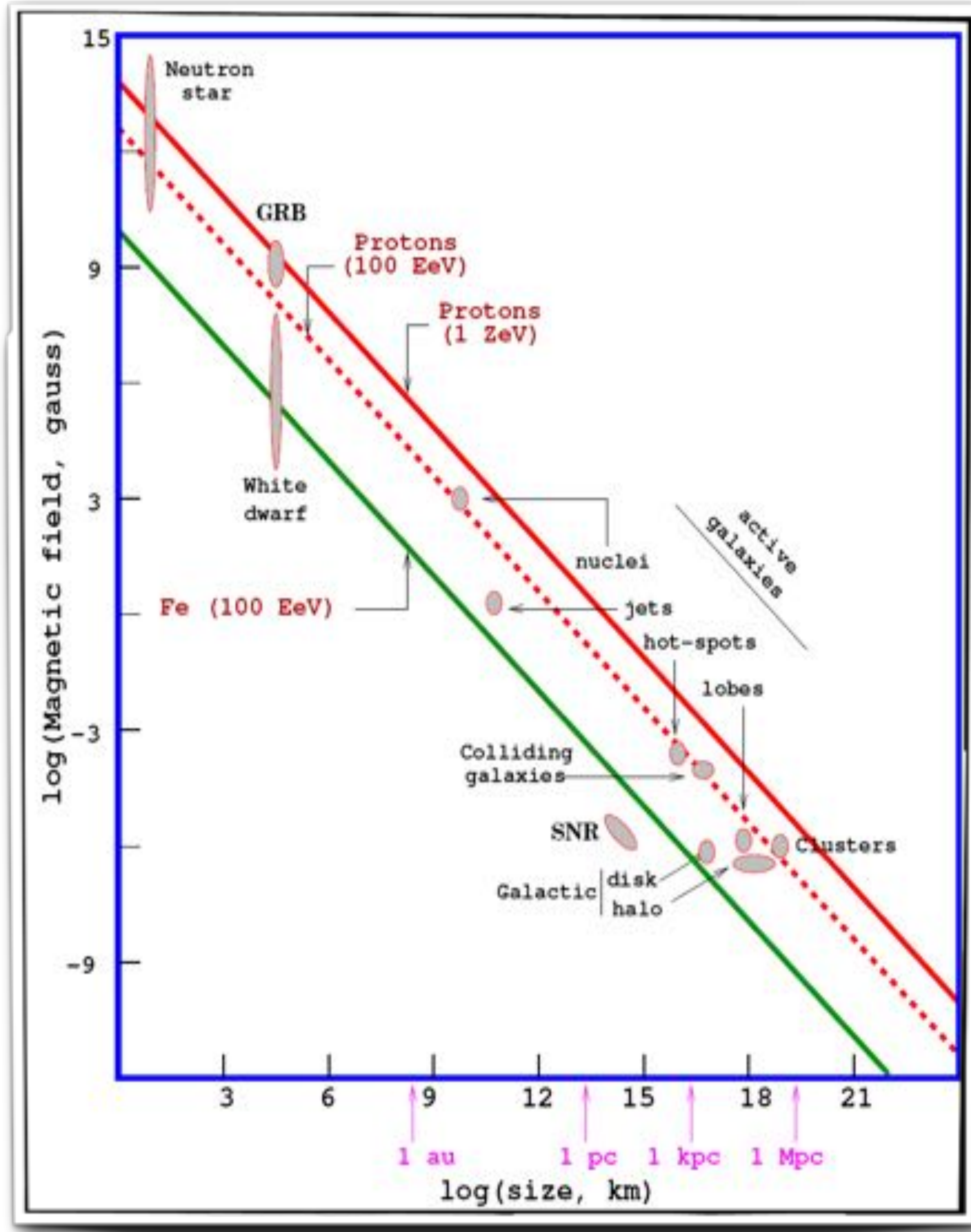
$$r_L = \frac{p_\perp}{Z\,e\,B} \approx \frac{1\,\text{pc}}{Z}\left(\frac{p_\perp}{\text{PeV}/c}\right)\left(\frac{1\mu\text{G}}{B}\right)$$

UHECRs extend at least up to ~3 10^{20} eV

$$E_{\max} \approx 9.3\times10^{20}eV \times B_G s_{pc}$$

$$B_G s_{pc} \geq 0.3$$

should be realized in nature...



Alps, UHECRs sources…and gamma-astrophysics!

For a photon propagating in a domain of size *s* with uniform field *B* along its direction, neutrino-like oscillation probability formula holds (leading to up to~30% flux distortions...)

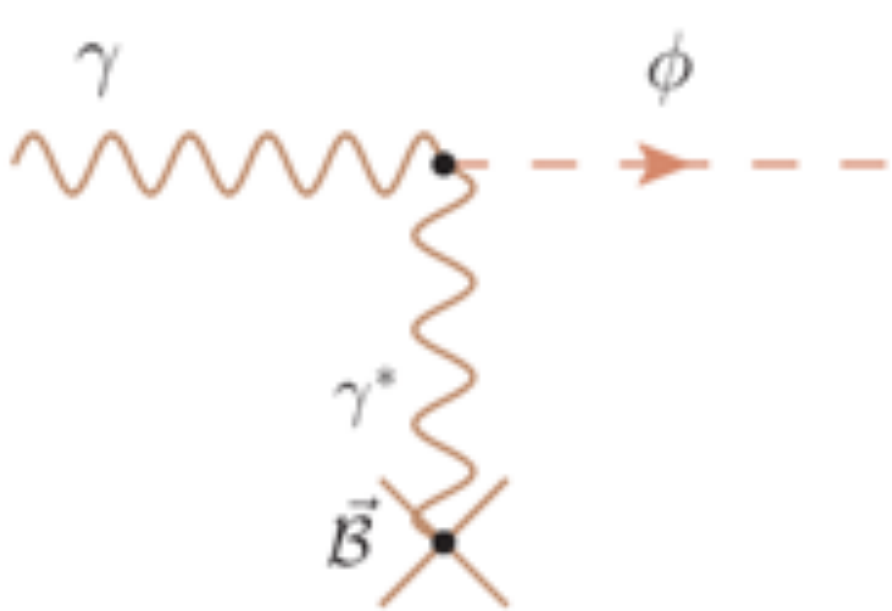
$$P_{osc} = \sin^2(2\theta)\sin^2\left[\frac{g_{a\gamma}Bs}{2}\sqrt{1+\left(\frac{K}{E}\right)^2}\right]$$

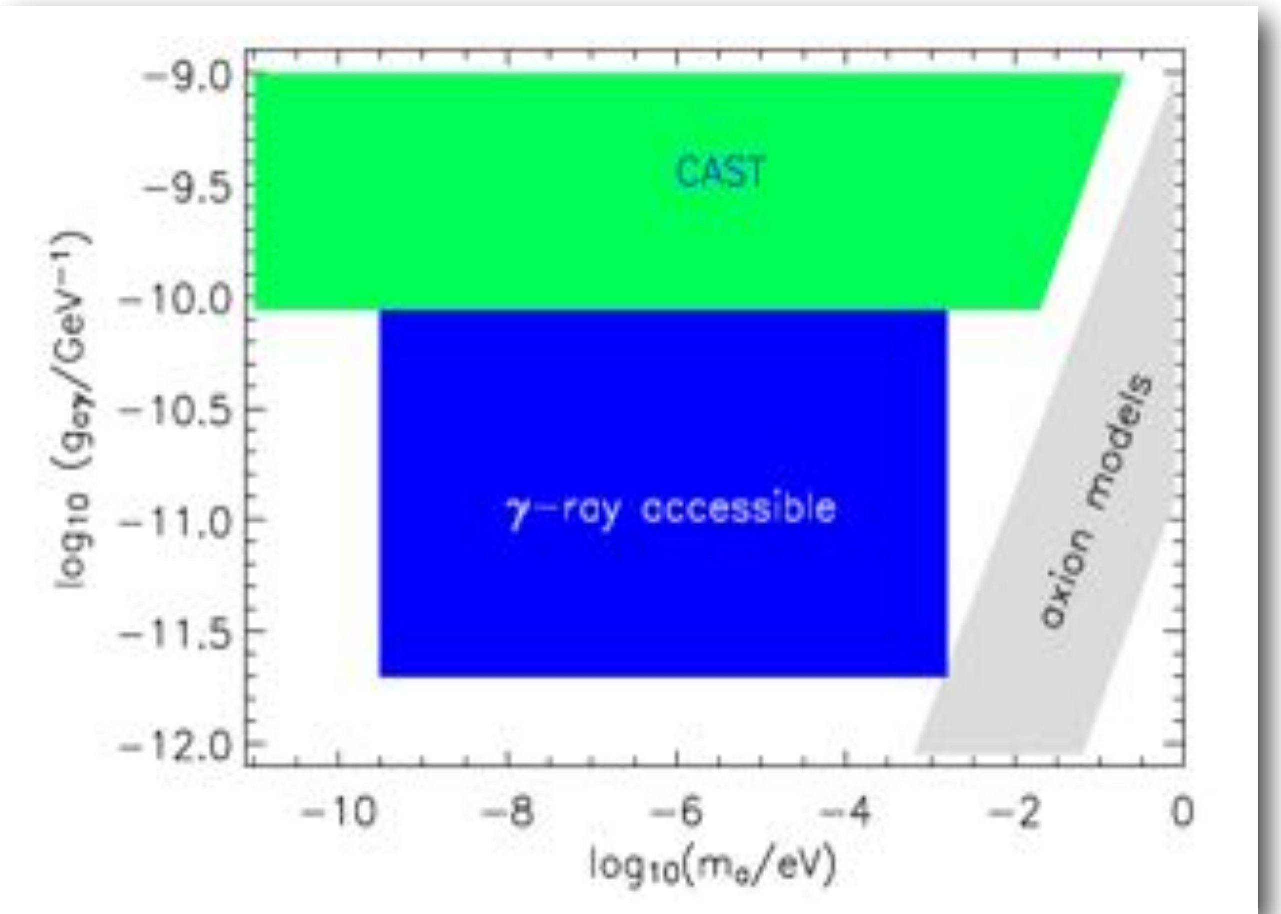
$$\sin^2(2\theta) = \frac{1}{1+(K/E)^2} \qquad K = \frac{m^2}{2g_{a\gamma}B}$$

Hooper & PDS, Phys. Rev. Lett. 99, 231102 (2007)

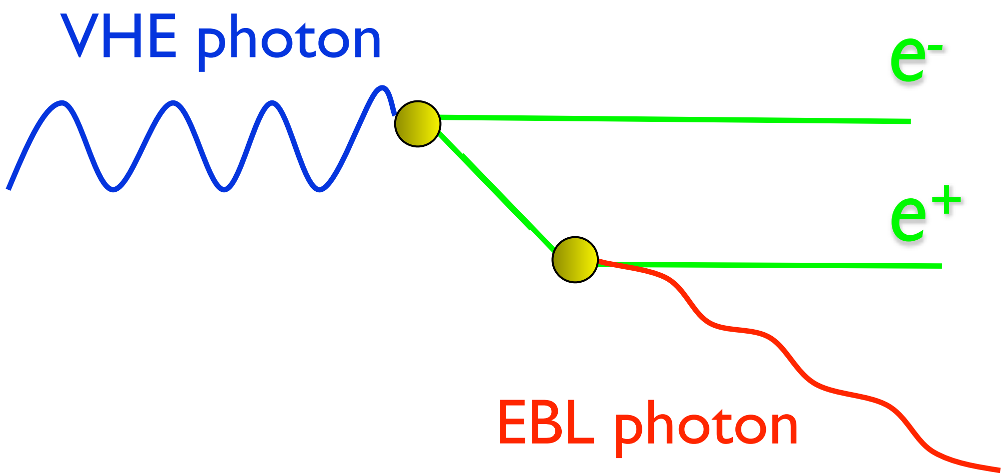
Large phases (→*large conversions*) for unexplored range of coupling naturally *expected for Hillas-efficient accelerators*!

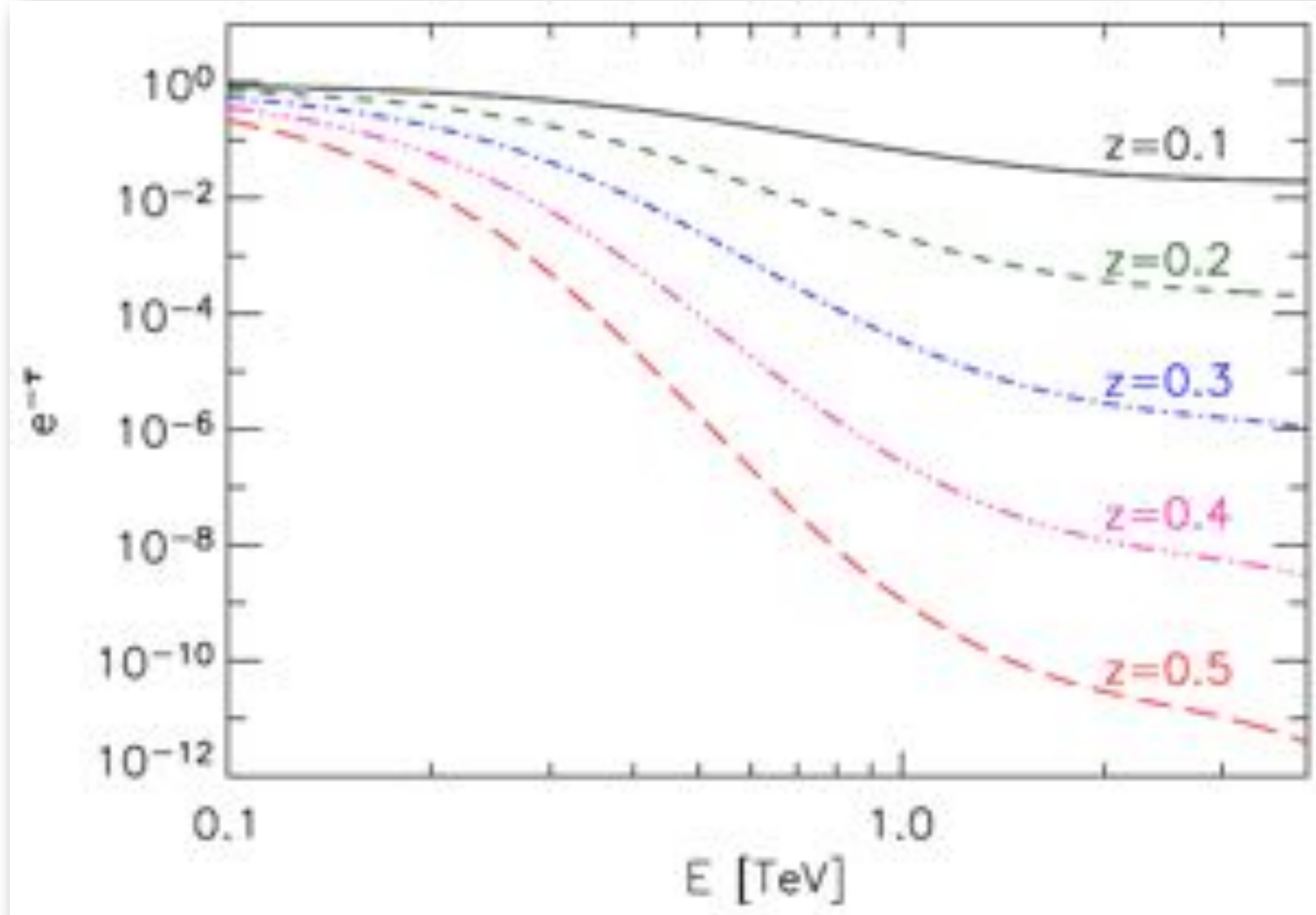
$$K_{GeV} = \frac{m^2_{\mu eV}}{0.4 g_{11} B_G} \qquad 15 g_{11} B_G s_{pc} \geq 1$$





BSM to go beyond TeV horizon?





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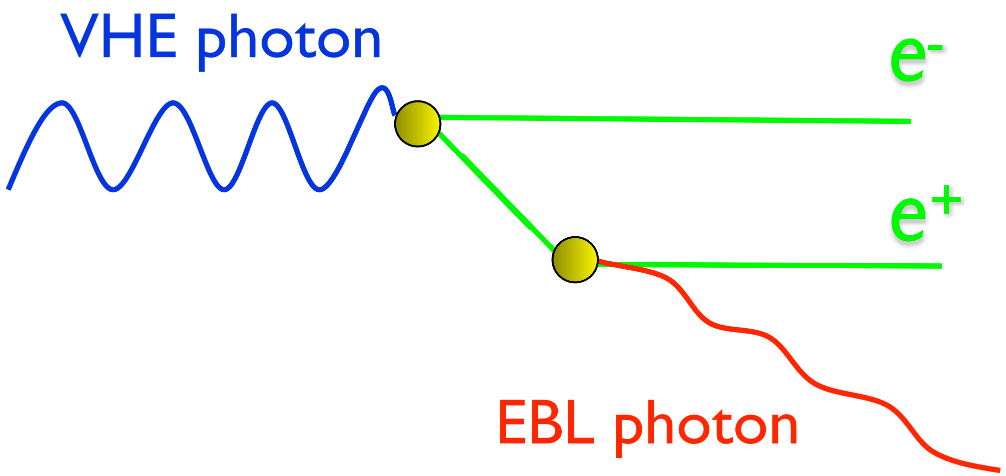
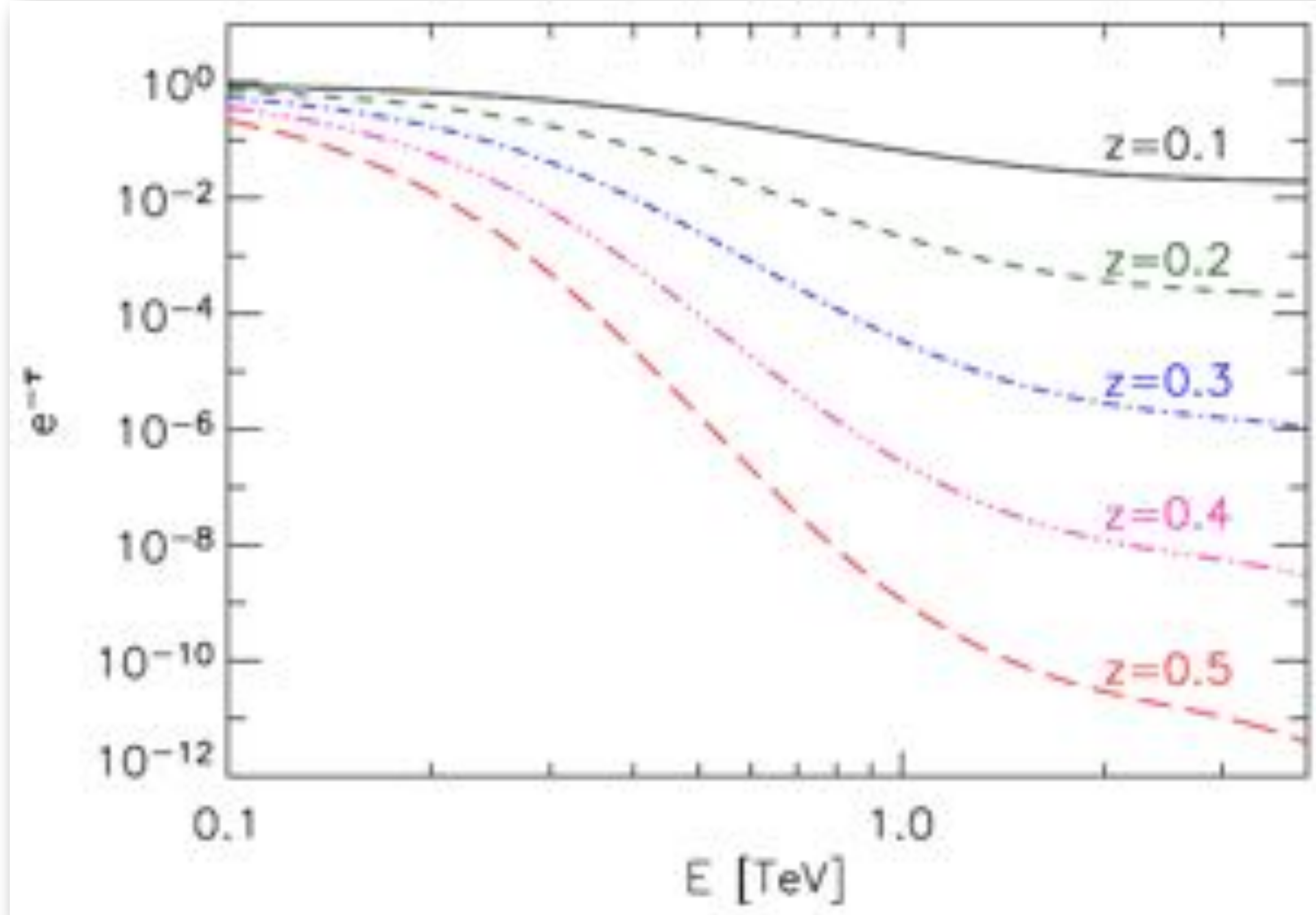
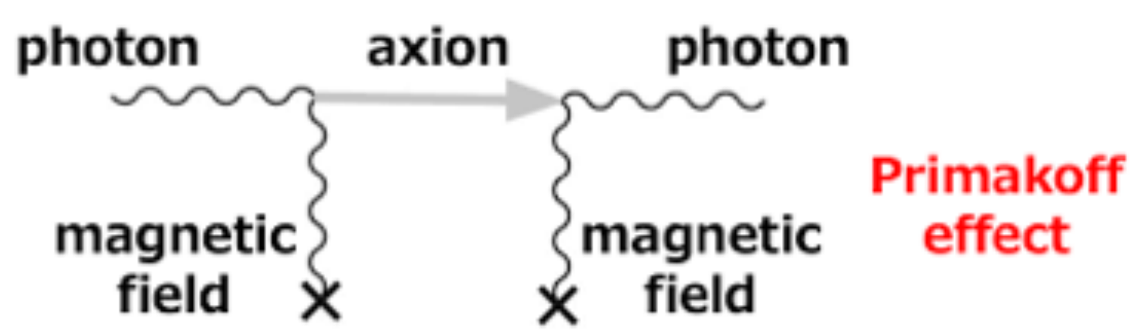
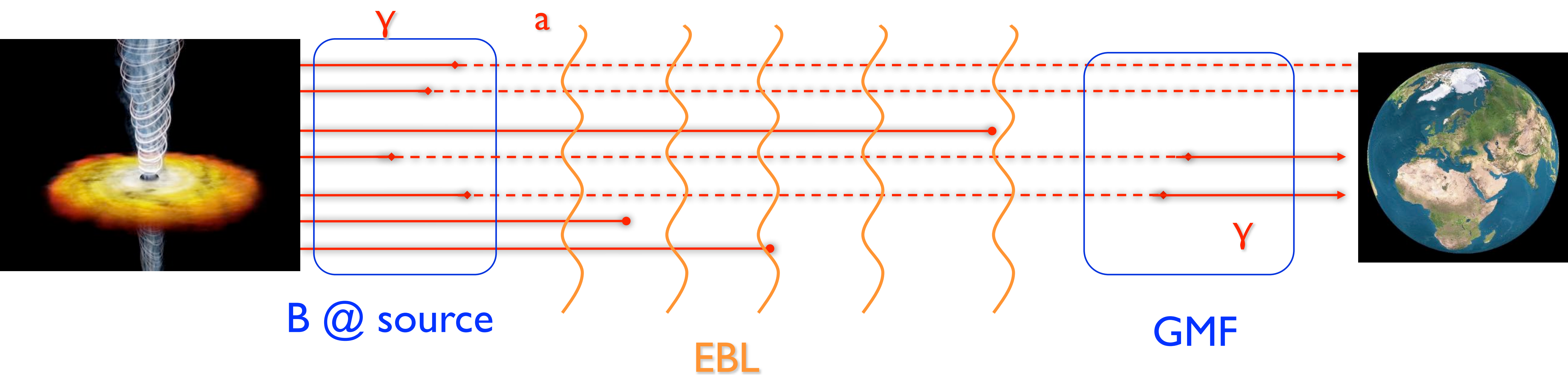




The ALP-photon coupling, used on Earth to search for axions with "Light shining through wall" experiments, can be similarly exploited at astrophysical scales!



A Galactic axionscope!

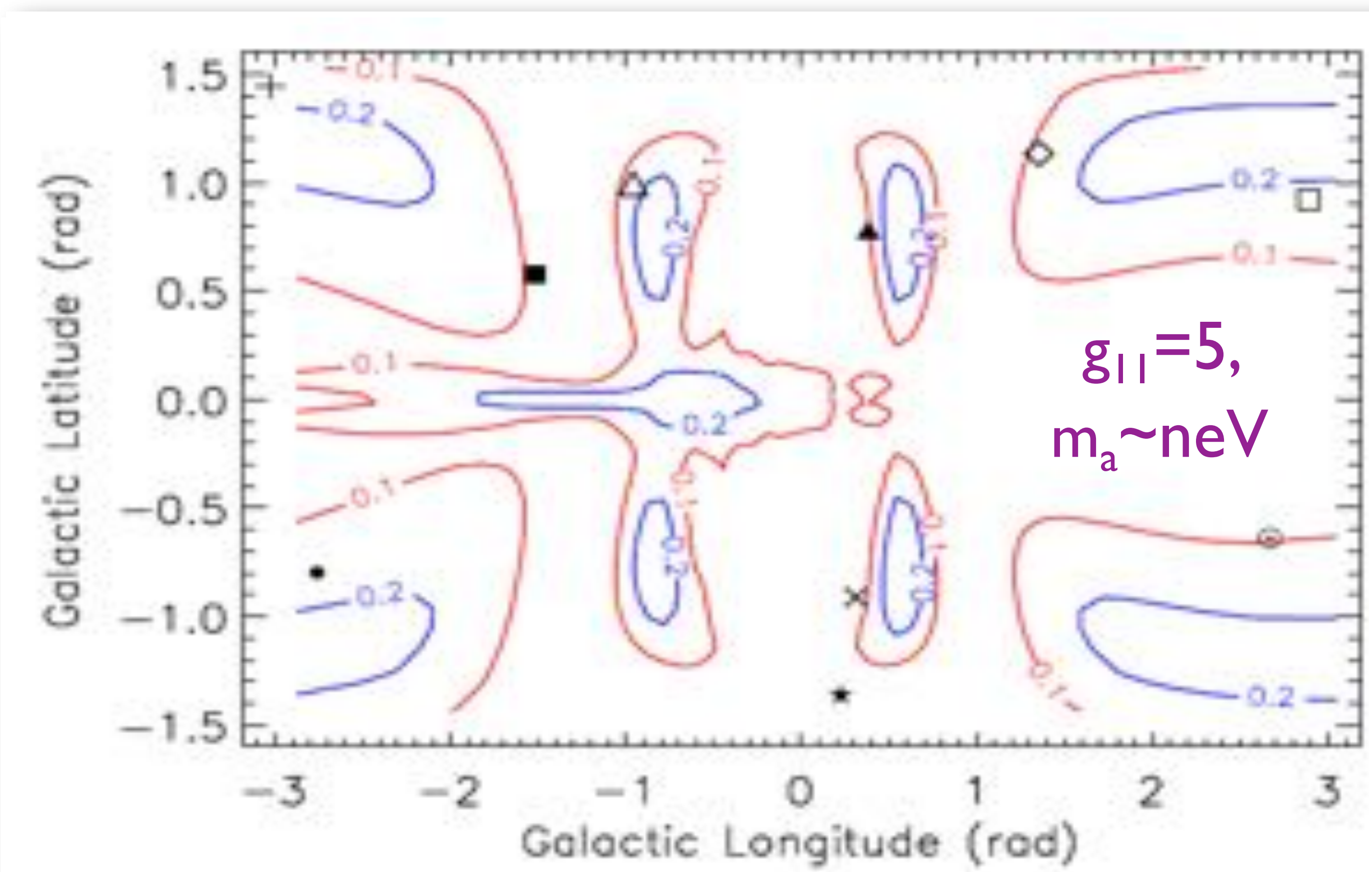


Argued that astrophysical accelerators (e.g. involved in UHECRs) produce ALP fluxes.

Is a significant TeV back-conversion in Galactic Magnetic Field possible?

Simet, Hooper, PDS
PRD 77, 063001, 2008

Yes!
Could see remote sources in gammas, where no flux expected within SM!



Object	z	Symbol
3C279	0.536	△
PG 1553+113	> 0.25	▲
1ES1011+496	0.212	□
1ES 0347-121	0.188	●
1ES1101-232	0.186	■
1ES1218+304	0.182	+
H 2356-309	0.165	⋆
1ES 0229+200	0.140	⊙
H 1426+428	0.129	◇
PKS 2155-304	0.117	×

Let me conclude with another example of:

IV. Something ain’t working as it should: Alteration in SM-derived laws

Parameterising Lorentz-invariance violation

Lorentz invariance violation (LIV) effect can be phenomenologically parametrized in terms of **δ**

$$\delta = \left(\frac{v}{v_0}\right)^2 - 1\,, \quad v = \frac{\partial E}{\partial p}\,, v_0 = \frac{p}{\sqrt{p^2+m^2}}\,,$$

assuming that there is at least one frame in which space and time translations and spatial rotations are exact symmetries (typically the lab one), there one can write

$$E^2 = p^2 + m^2 + f(p, \ldots)$$

with *f* containing e.g. cubic or quartic powers of *p* inducing "linear" (n=1) or "quadratic" (n=2) deviations, respectively, from LI occurring at a mass scale M_{QG}.

$$\delta = \left(\frac{v}{v_0}\right)^2 - 1 \simeq \frac{v_0}{E}\frac{\partial f}{\partial p} \simeq \pm\left(\frac{E}{M_{\rm QG}}\right)^n$$

Remember OPERA?

Initial claim of evidence for	$\delta \simeq 5 \times 10^{-5}$	OPERA collab.1109.4897
argued internally inconsistent with CERN beam survival due to fast allowed "Cherenkov" decay	$\nu \to \nu\, e^+\, e^-$	A. G. Cohen and S. L. Glashow, PRL 107, 181803 (2011) [1109.6562]

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For finite (but much smaller!) **δ**, same channel open at PeV scale if:

$$E_\nu \gtrsim 2\, m_e/\sqrt{\delta} \simeq \mathrm{PeV}\sqrt{10^{-18}/\delta}$$

with a loss rate

$$\Gamma_{e^\pm} = \frac{1}{14}\frac{G_F^2 E^5 \delta^3}{192\,\pi^3} = 2.55 \times 10^{53} \delta^3 E_{\mathrm{PeV}}^5 \ \mathrm{Mpc}^{-1}$$

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Little Problem: here we do not know the initial beam flux!
How to translate this observation into a constraint?

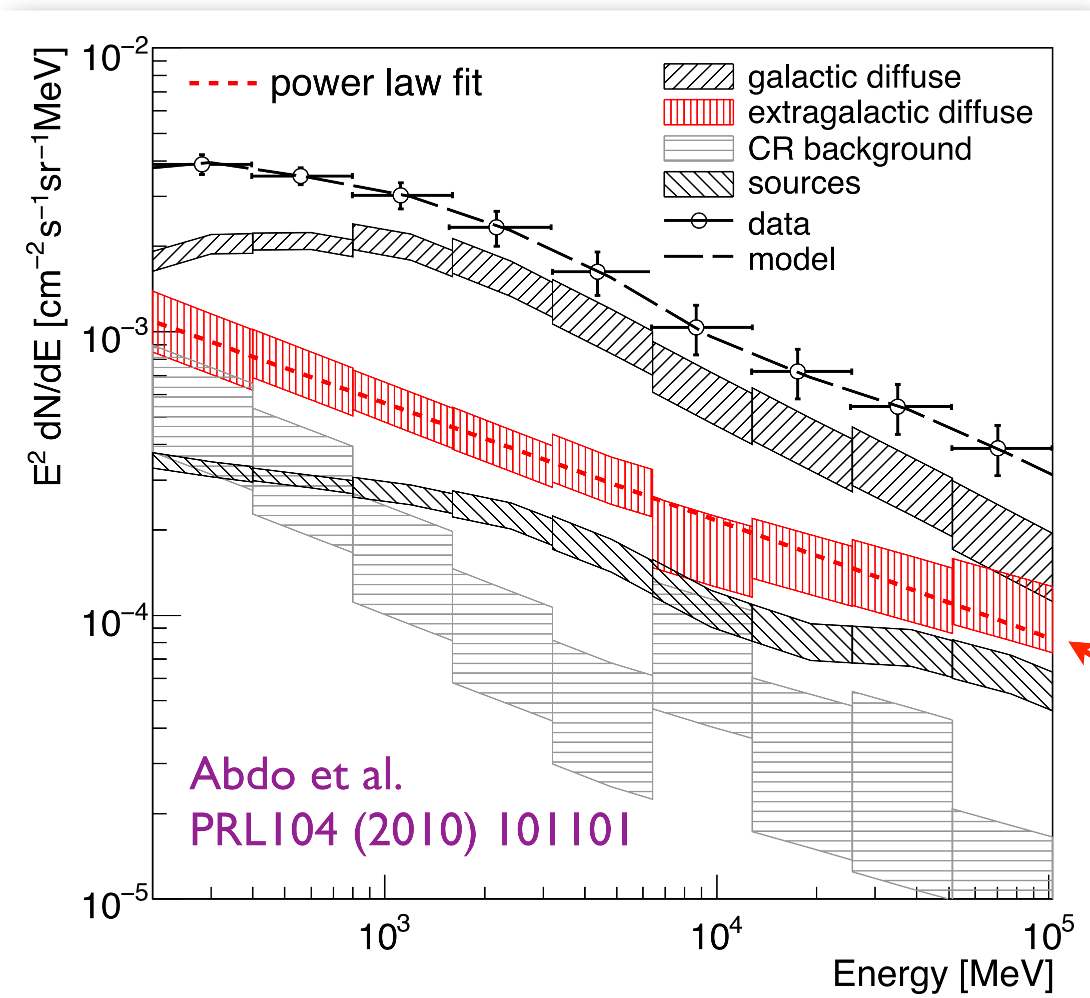
E. Borriello, S. Chakraborty, A. Mirizzi and PDS, Phys. Rev. D 87, no. 11, 116009 (2013)

Cosmic application

The e± pairs from the decay induce e.m. cascades, with gammas being reprocessed in the ~1-100 GeV band of the gamma extragalactic background.

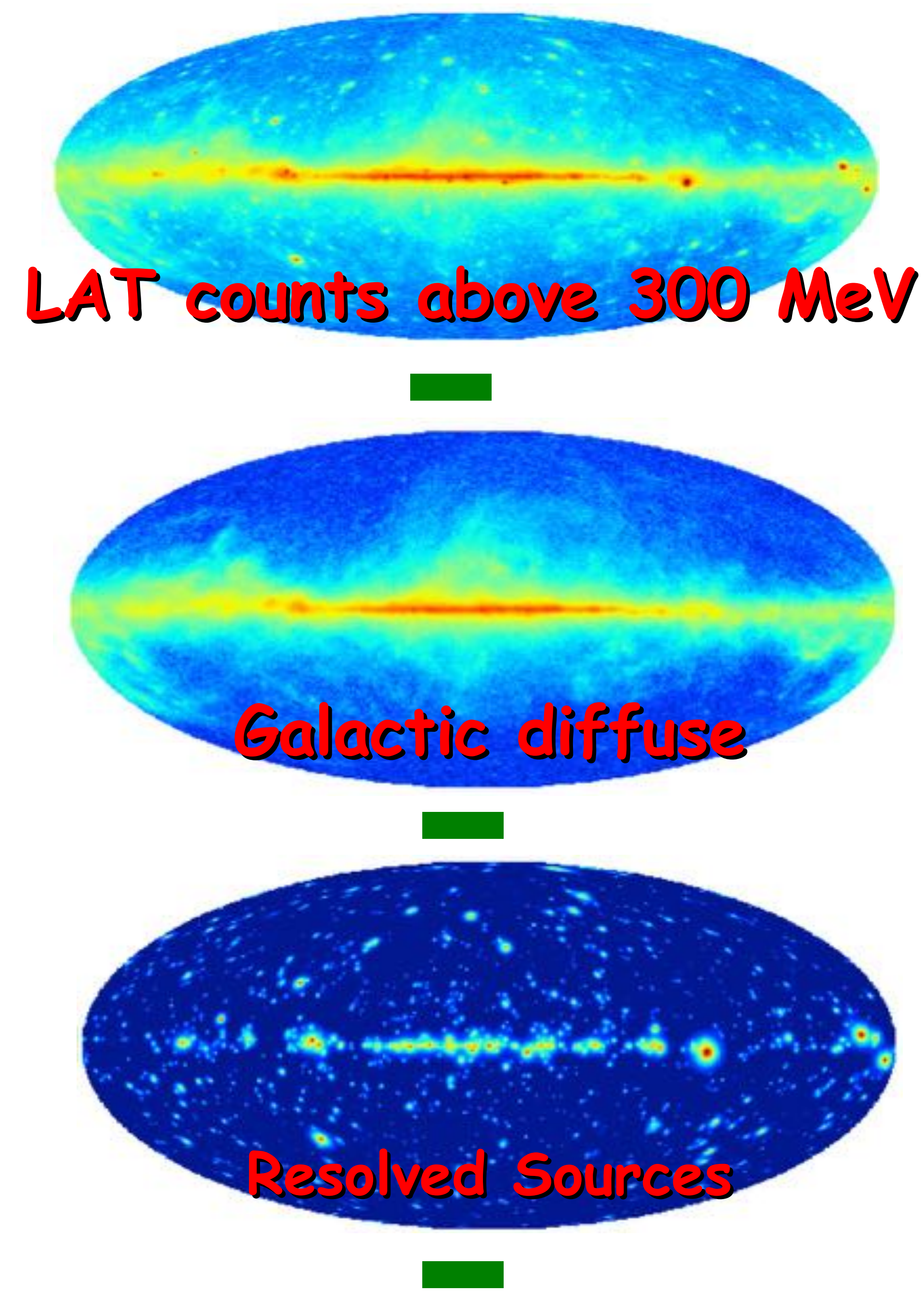
Fermi-LAT puts an **upper limit** to the total energy density stored in the initial **neutrino** flux!

$$\omega_\gamma = \frac{4\pi}{c}\int_{E_1}^{E_2} E\,\frac{d\varphi_\gamma}{dE}\,dE \lesssim 5.7\times 10^{-7}\,\mathrm{eV/cm^3}\,.$$



spectrum
$\sim E^{-2.41\pm0.05}$
$I(>0.1\,\mathrm{GeV}) = (1.03\pm0.17)\times 10^{-5}\ \mathrm{cm^{-2}\,s^{-1}\,sr^{-1}}$

IGRB
(consistent with being isotropic)
=



−
Solar emission
−
CR background

Huge jump in constraints from 2 ~PeV neutrinos!

Energy density inferred from the observed 2 events is:

$$\omega_\nu^{\rm obs} = \frac{4\pi}{c}\int_{1\,\rm PeV}^{1.2\,\rm PeV} E\,\frac{d\varphi_E}{dE}\,{\rm d}E \simeq 2.7\times 10^{-9}\,{\rm eV/cm^3}\,,$$

So, if this is the relic of a huge, suppressed flux, the maximum tolerable suppression is

$$e^{-\Gamma\, d} \gtrsim \frac{\omega_\nu^{\rm obs}}{\omega_\gamma} \sim 10^{-2}$$

For cosmologically distant sources* d> Gpc, this implies that

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weaker bound (but better than existing ones) follows from the process $\nu \to \nu\gamma$
which is however independent on the assumptions on the LIV bound in the e-sector
(this also follows from direct bounds from Crab flare, see F.W. Stecker, APP 56, 16 (2014))

*A purely Galactic origin for the totality of the signal excluded by angular distribution study, plus lack of plausible origin... and even in that case one would gain over existing bounds

Note: for δ close to the opening of the channel, one may clearly 'induce a PeV cutoff' via LIV, F.W. Stecker and S.T. Scully, 1404.7025

Concluding remarks

‘Cosmic Rays’ for fundamental physics

DM

No conclusive identification of DM, but enormous progress in astrophysical sensitivity

WIMP paradigm dominated the searches for several decades. Still alive, but not alone anymore!

WIMP exploration will continue, likely more moderate return over investment due to limitations in our understanding of the ‘background’ (aka astrophysics)

Alternative candidates given less attention, perhaps due to theory bias, perhaps thinking that if DM is no WIMP, low chances for indirect detection. This is not true!

Showed rich pheno with ~PeV DM from freeze-in+Decay; but also case of PBH…

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Example of LIV bounds from HE neutrino events (plus gamma information, multimessenger)

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Finally, CR can contribute to the discovery of new physics, even if they don’t help us in understanding what lies behind it (case of baryon asymmetry)

Thank you for your attention!

Everything we see hides another thing, we always want to see what is hidden by what we see.

R. Magritte