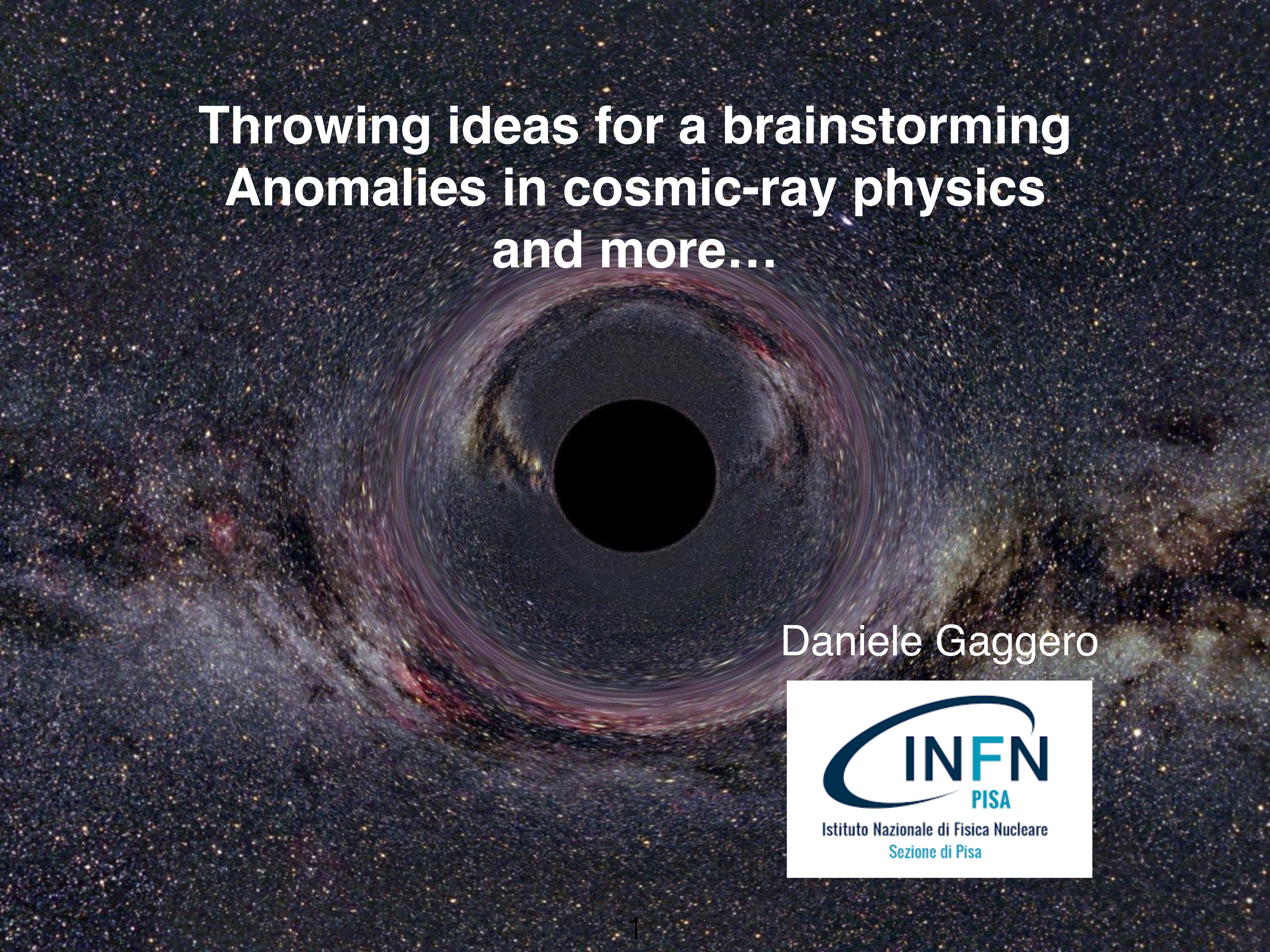
Throwing ideas for a brainstorming
Anomalies in cosmic-ray physics
and more…



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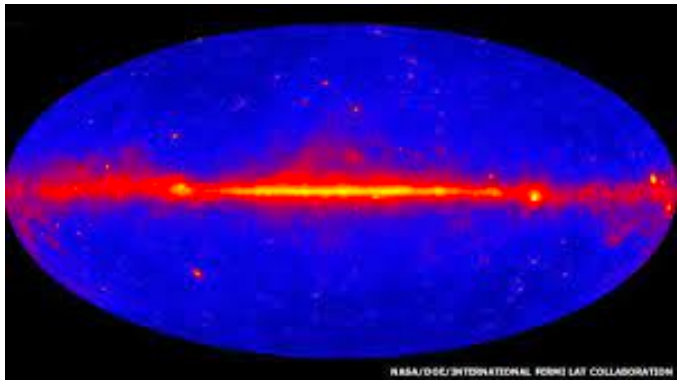
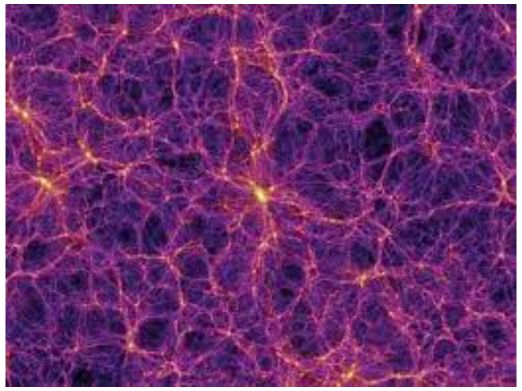
Sezione di Pisa

My research activity

High-energy Astrophysics

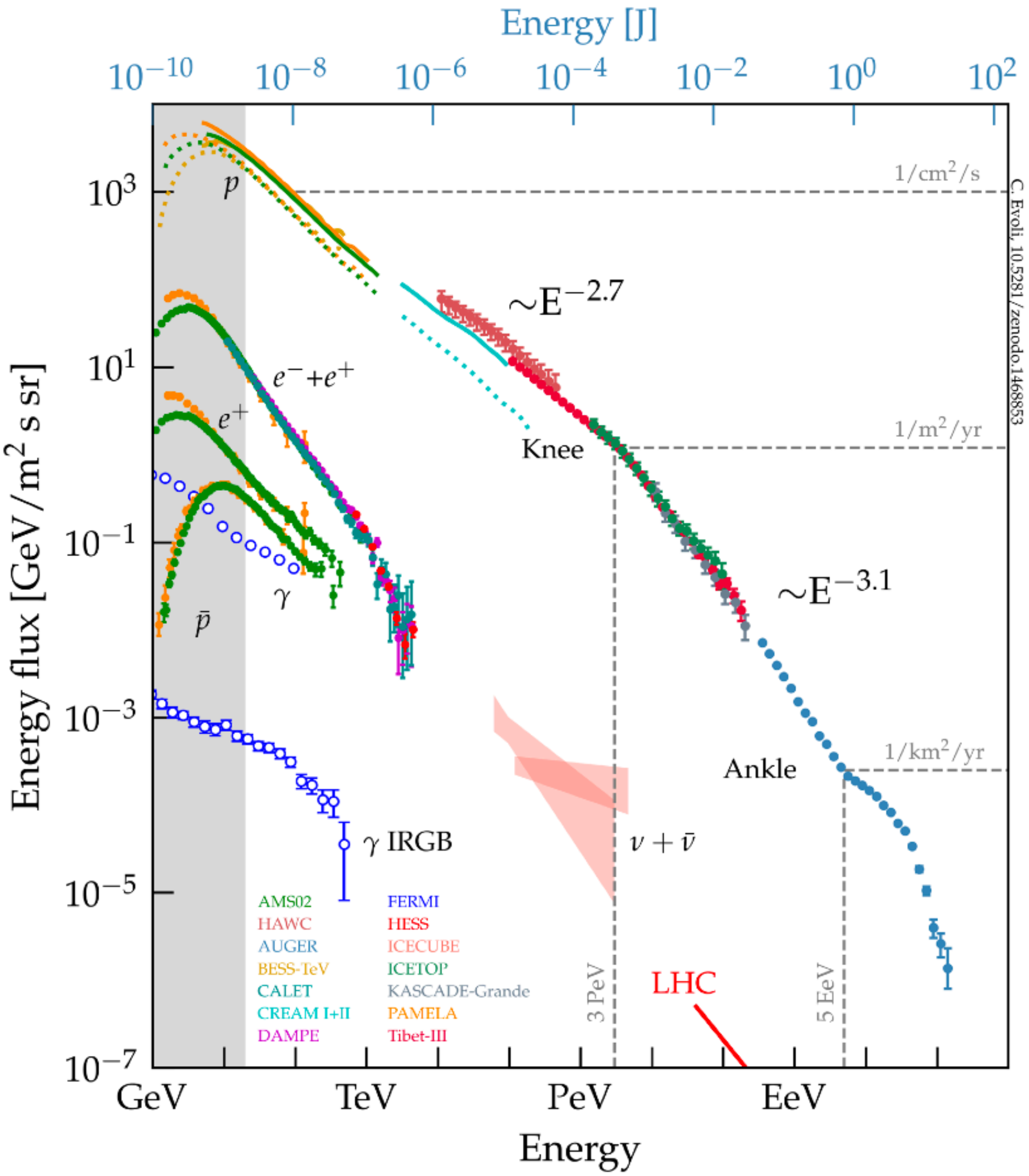


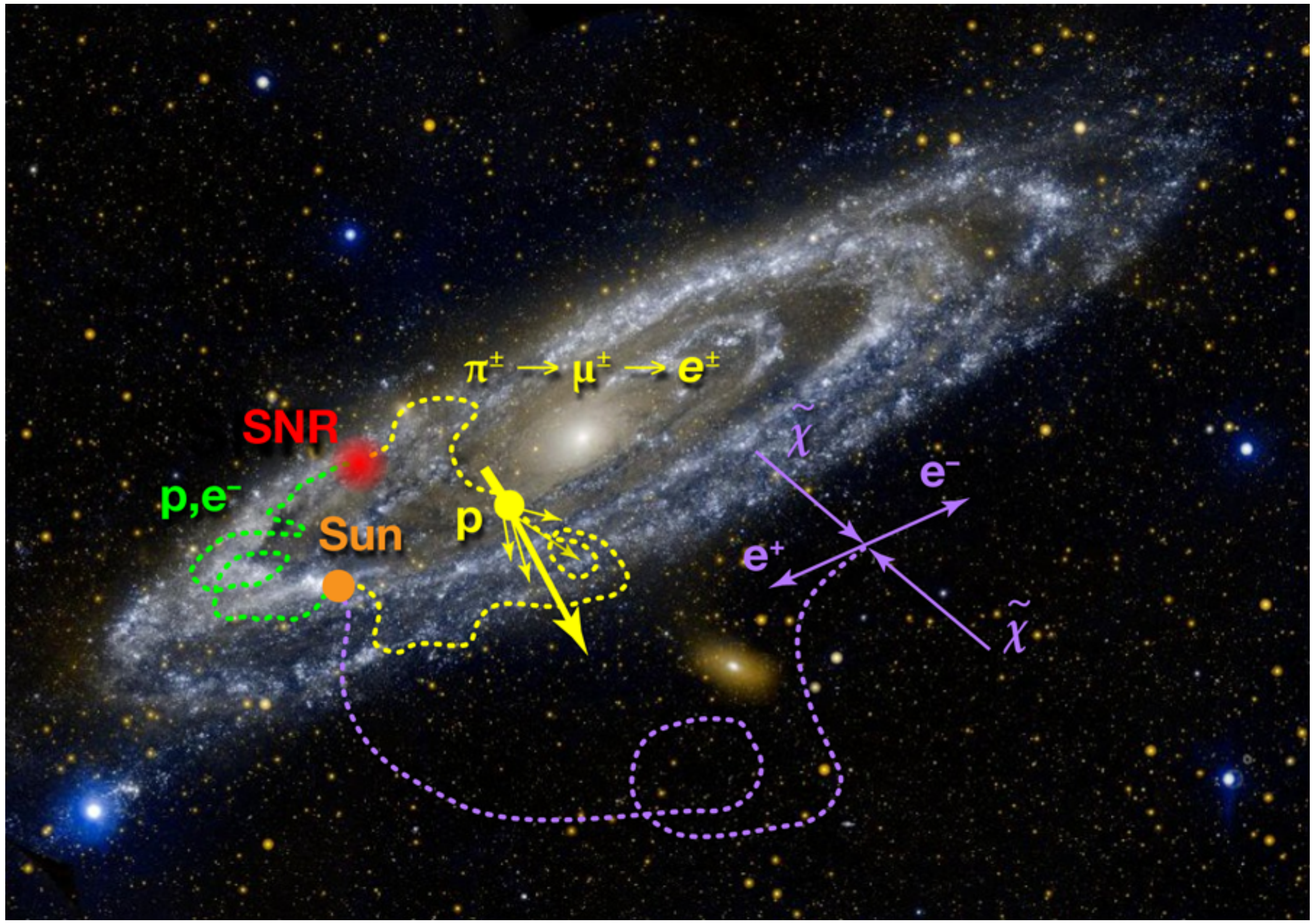
Quest for New Physics
Dark Matter searches



1. Phenomenology of **Black Holes** <—> indirect Dark Matter Searches
2. Galactic **Cosmic-ray** phenomenology <—>**WIMP searches**

Cosmic-ray propagation in the Galaxy



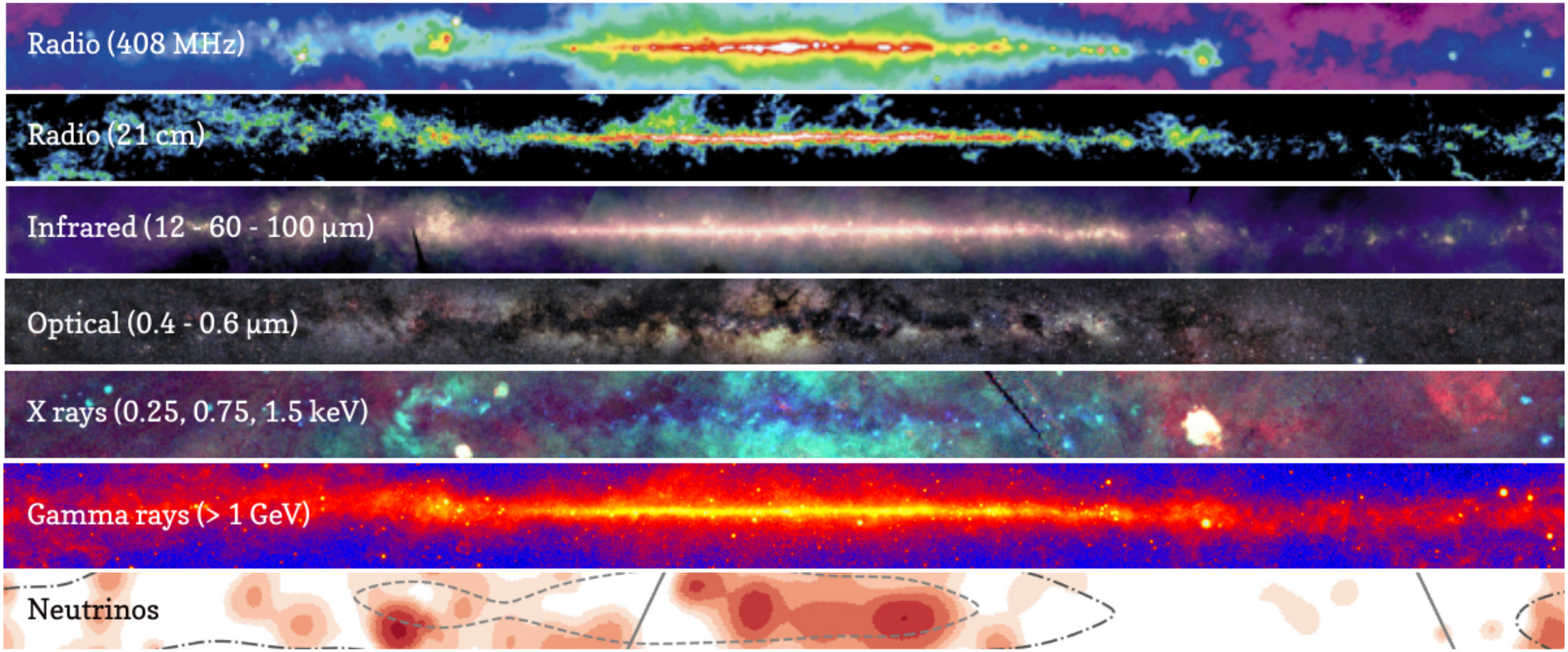


$$\nabla \cdot (\vec{J}_i - \vec{v}_w N_i) + \frac{\partial}{\partial p}\left[p^2 D_{pp} \frac{\partial}{\partial p}\left(\frac{N_i}{p^2}\right)\right] - \frac{\partial}{\partial p}\left[\dot{p} N_i - \frac{p}{3}\left(\vec{\nabla}\cdot\vec{v}_w\right) N_i\right] =$$

$$Q + \sum_{i<j}\left(c\beta n_{\rm gas}\,\sigma_{j\to i} + \frac{1}{\gamma\tau_{j\to i}}\right) N_j - \left(c\beta n_{\rm gas}\,\sigma_i + \frac{1}{\gamma\tau_i}\right) N_i$$

- Evoli, **DG**, et al. JCAP 2008 (DRAGON 1)
- **DG**, Evoli, et al., PRL 2013 (DRAGON3D)
- Evoli, **DG**, et al., JCAP 2016 (DRAGON 2)
- Evoli, **DG**, et al., 2017 (DRAGON 2 xsec)

Cosmic-ray propagation in the Galaxy



- **Synchrotron emission** (leptonic CRs)
- HI **21 cm** line
- **Thermal emission** from stars

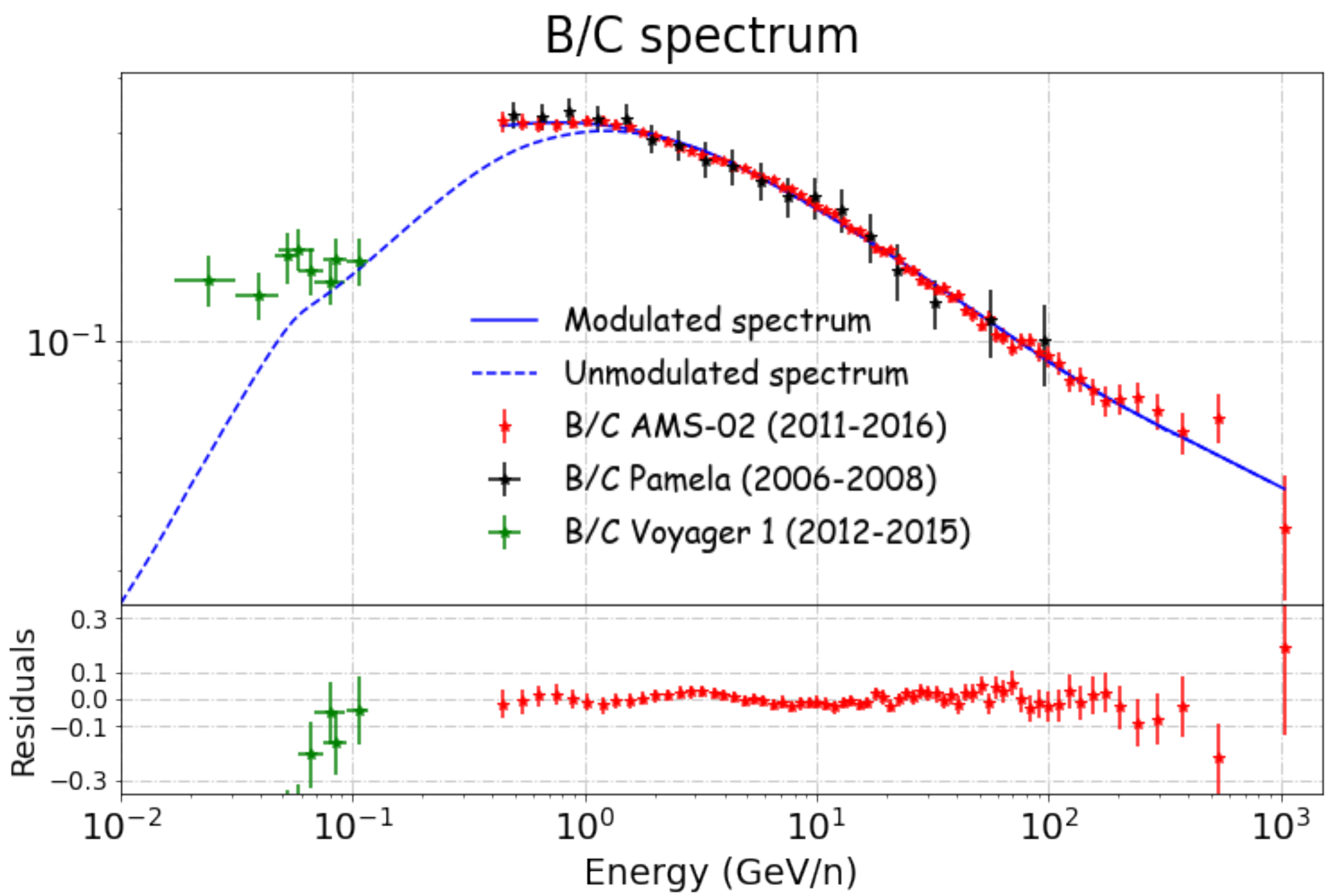
- **Pion decay** (hadronic CRs)
- **Inverse Compton scattering**, **Bremsstrahlung** (leptonic CRs)

Local Charged Cosmic Particles: The Orthodoxy

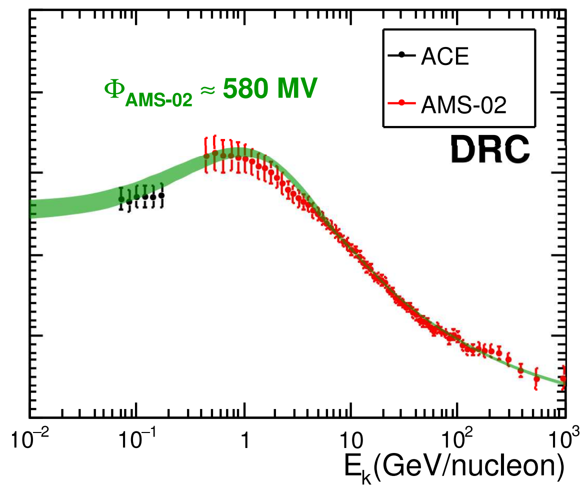
The three pillars [Gabici et al., 1903.11584]

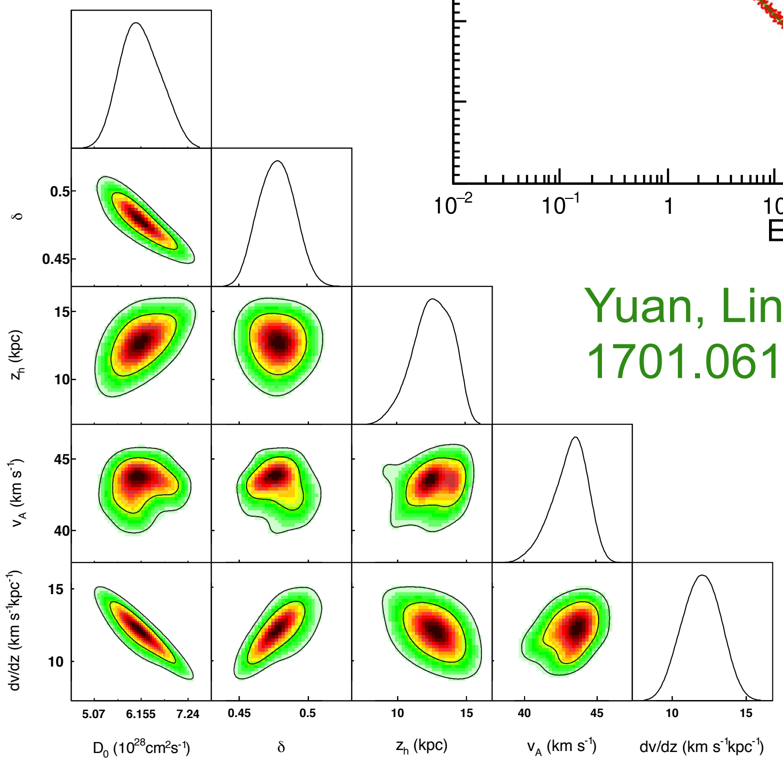
- The bulk of the **CR energy is released by SN explosions** in the Galactic disk
- CRs are accelerated via **diffusive shock acceleration** at work at SNR shocks
- CRs **diffuse** within an extended, turbulent and magnetized **halo in a isotropic and homogeneous way**
  —> A diffuse, homogeneous CR sea is present through the Galaxy

Good news: we fit most data



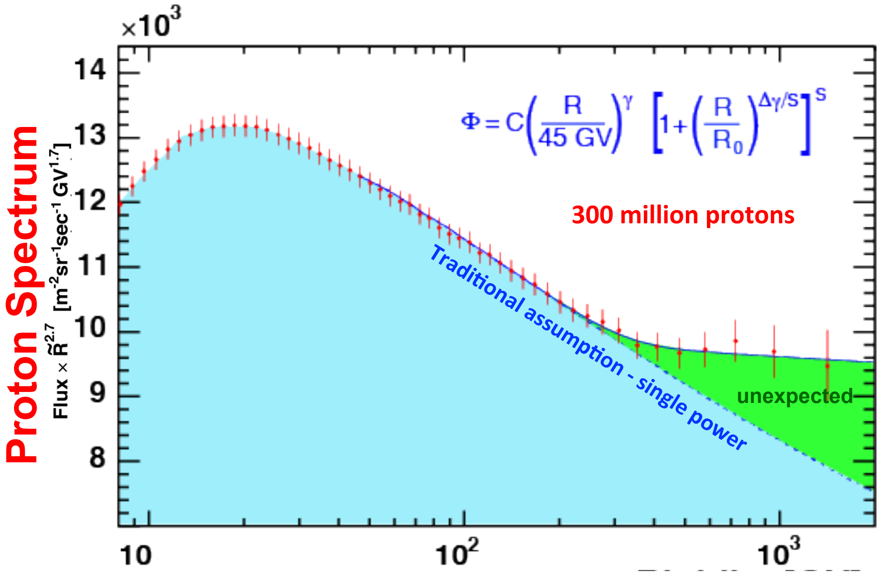
De La Torre et al *JCAP* 03 (2021) 099

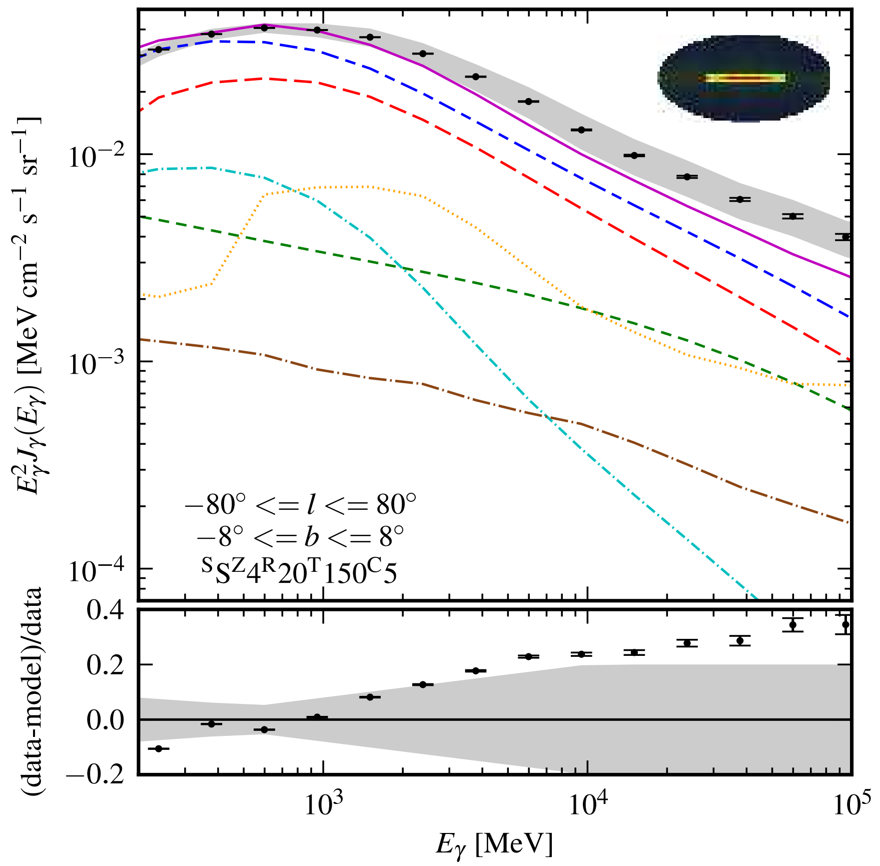


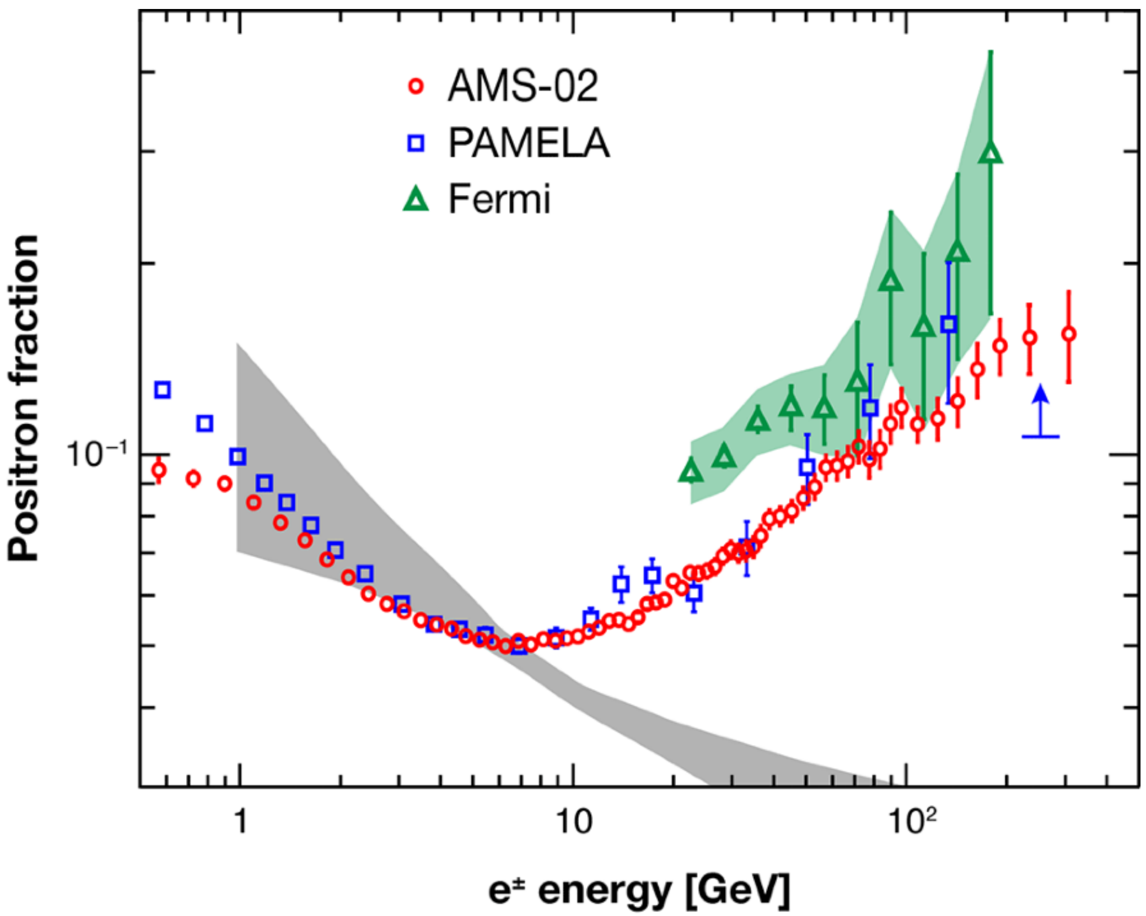


Yuan, Lin, Fang, Bi, 1701.06149

However, we have anomalies!

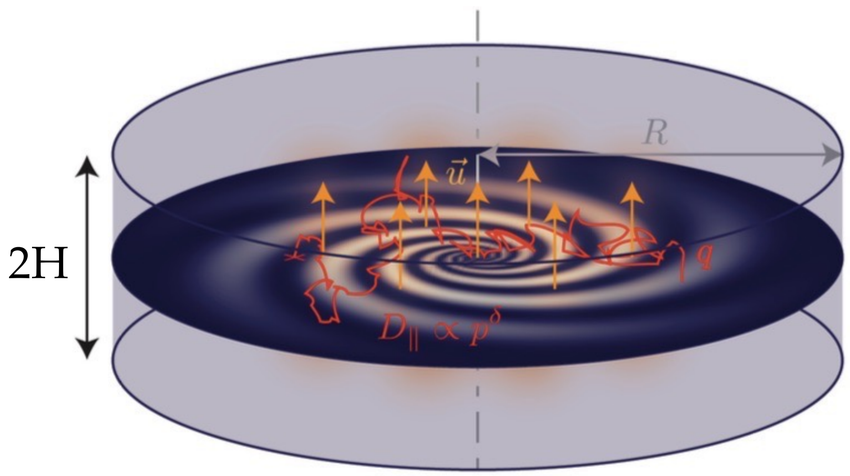


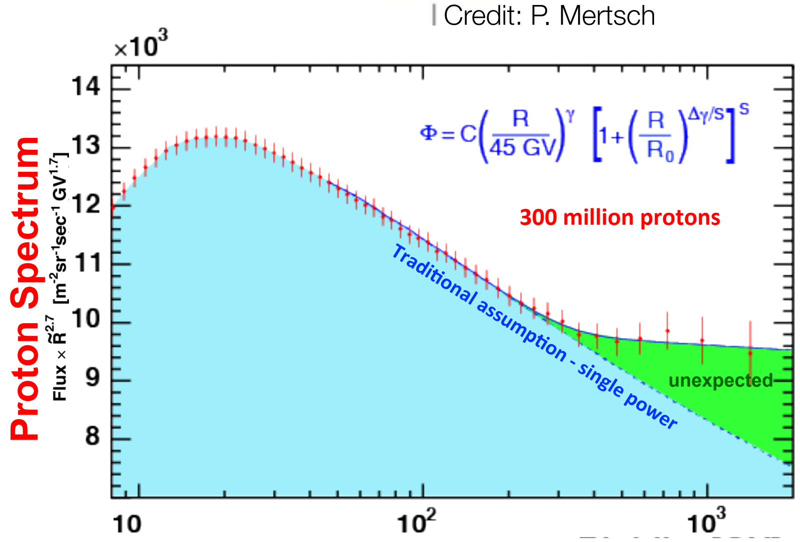




Anomalies with respect to what?

- Basic theories used as guidelines for *standard parametrizations*
- *S*et of "conventional models" —> anomalies "w.r.t. conventional model predictions"





$$-\frac{\partial}{\partial z}\left[D_\alpha(p)\frac{\partial f_\alpha}{\partial z}\right]+w\frac{\partial f_\alpha}{\partial z}-\frac{p}{3}\frac{\partial w}{\partial z}\frac{\partial f_\alpha}{\partial p}+\frac{\mu v(p)\sigma_\alpha}{m}\delta(z)f_\alpha+$$

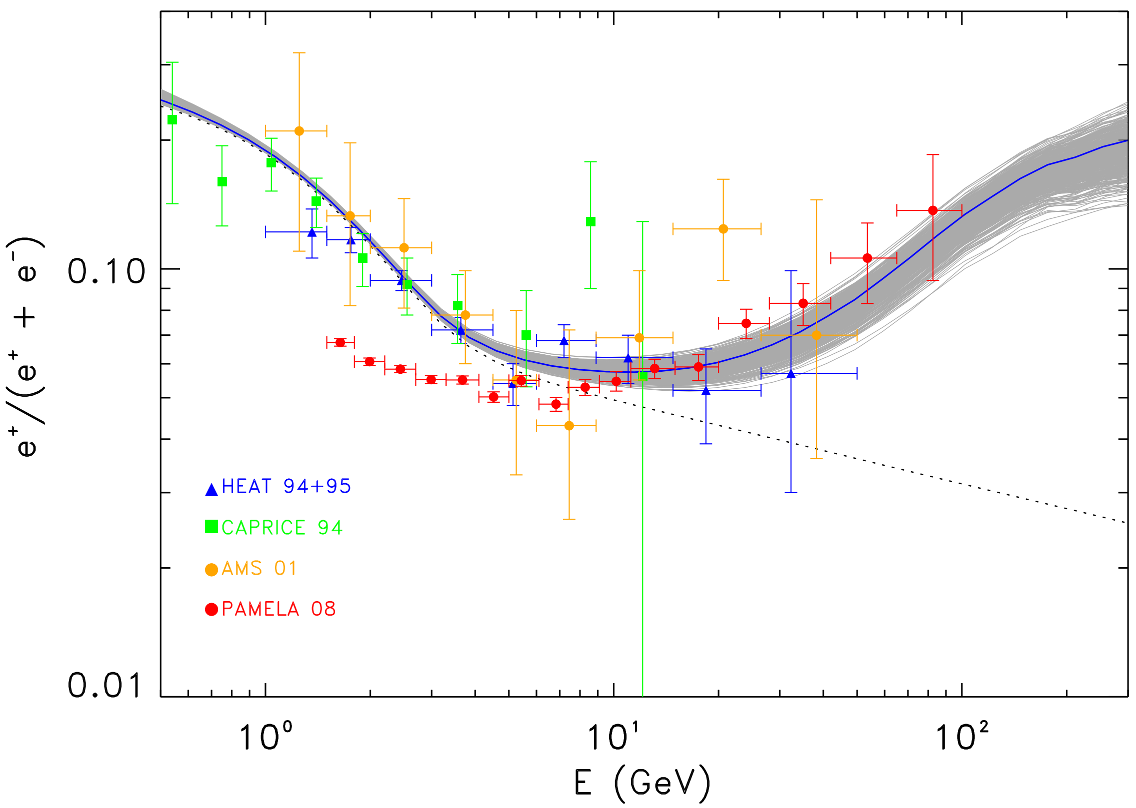
$$\frac{1}{p^2}\frac{\partial}{\partial p}\left[p^2\left(\frac{dp}{dt}\right)_{\alpha,ion}f_\alpha\right]=$$

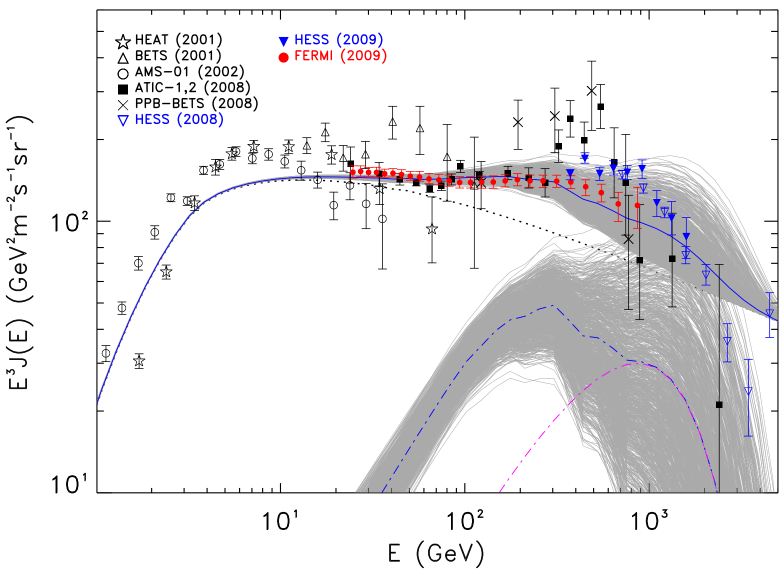
$$=2h_d q_{0,\alpha}(p)\delta(z)+\sum_{\alpha'>\alpha}\frac{\mu\, v(p)\sigma_{\alpha'\to\alpha}}{m}\delta(z)f_{\alpha'},$$

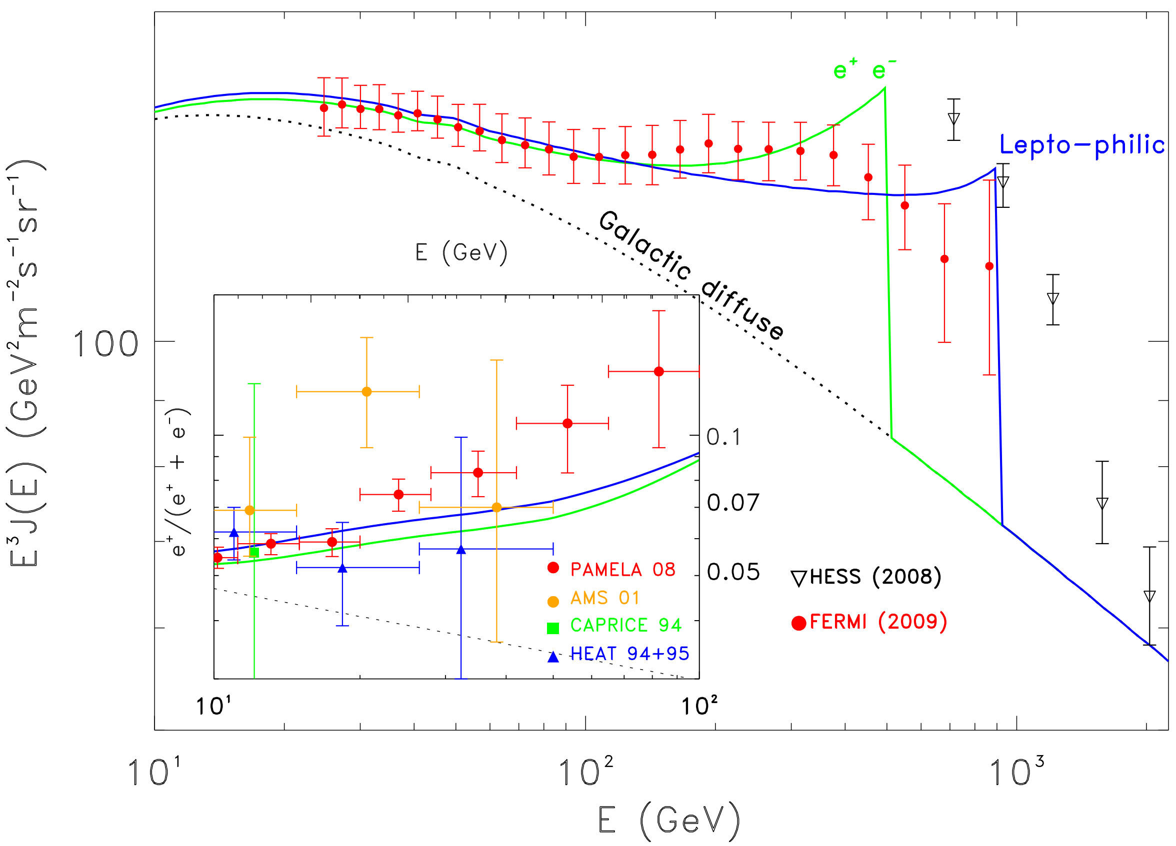
- 1 source class, universal featureless source spectrum *(but sometimes breaks are introduced)*

- Isotropic, homogeneous diffusion *(is it compatible with QLT?). Power-law in R*

How my research started…

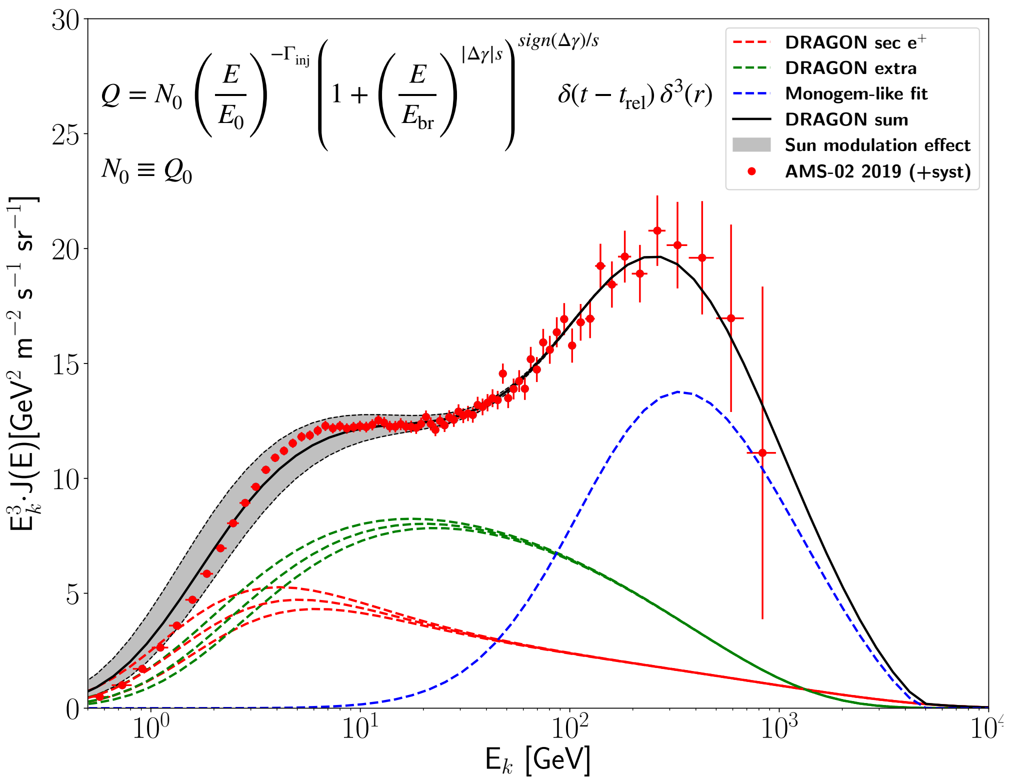




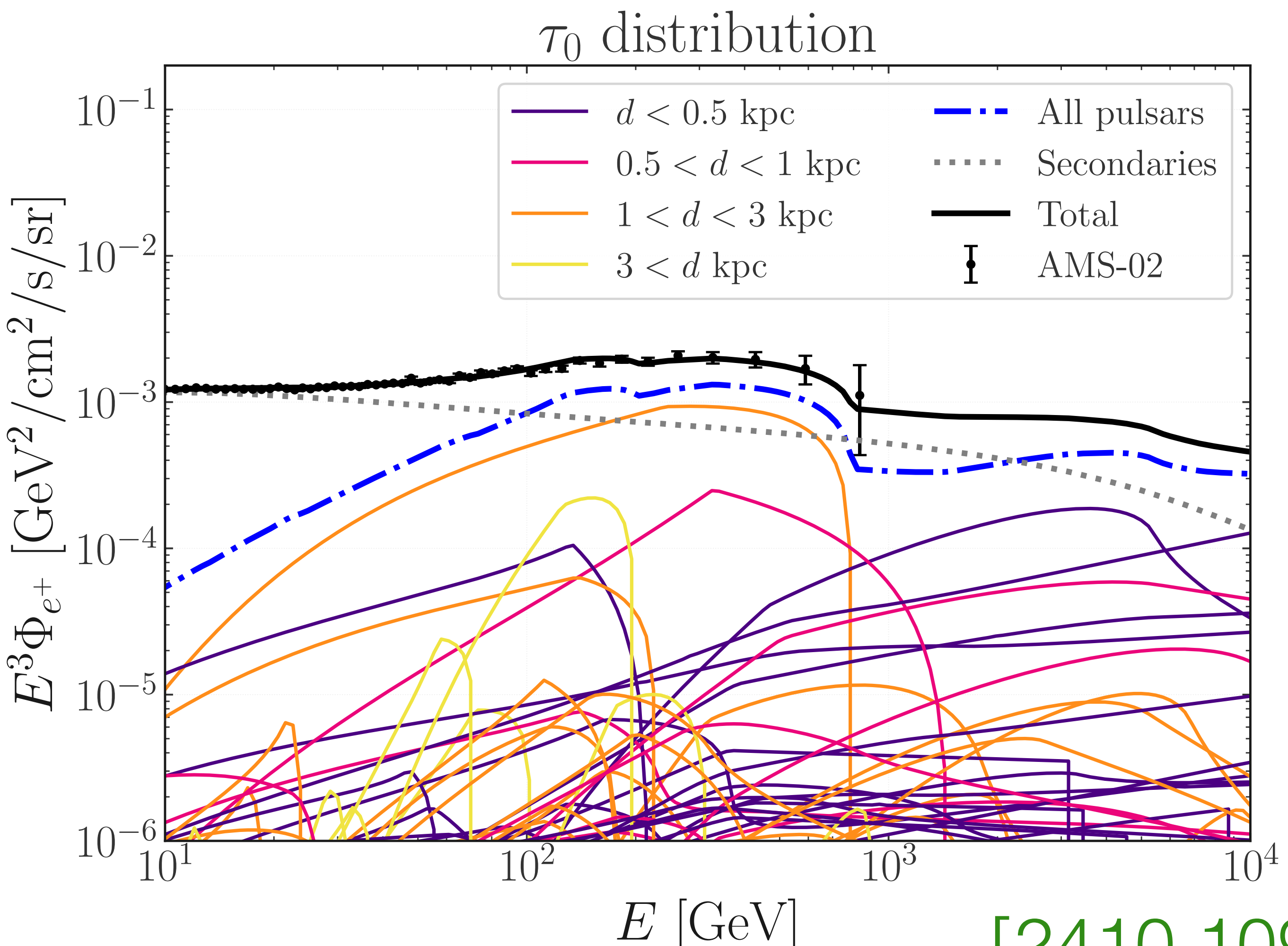


D. Grasso et al. 2009 [0905.0636]

The positron fraction now



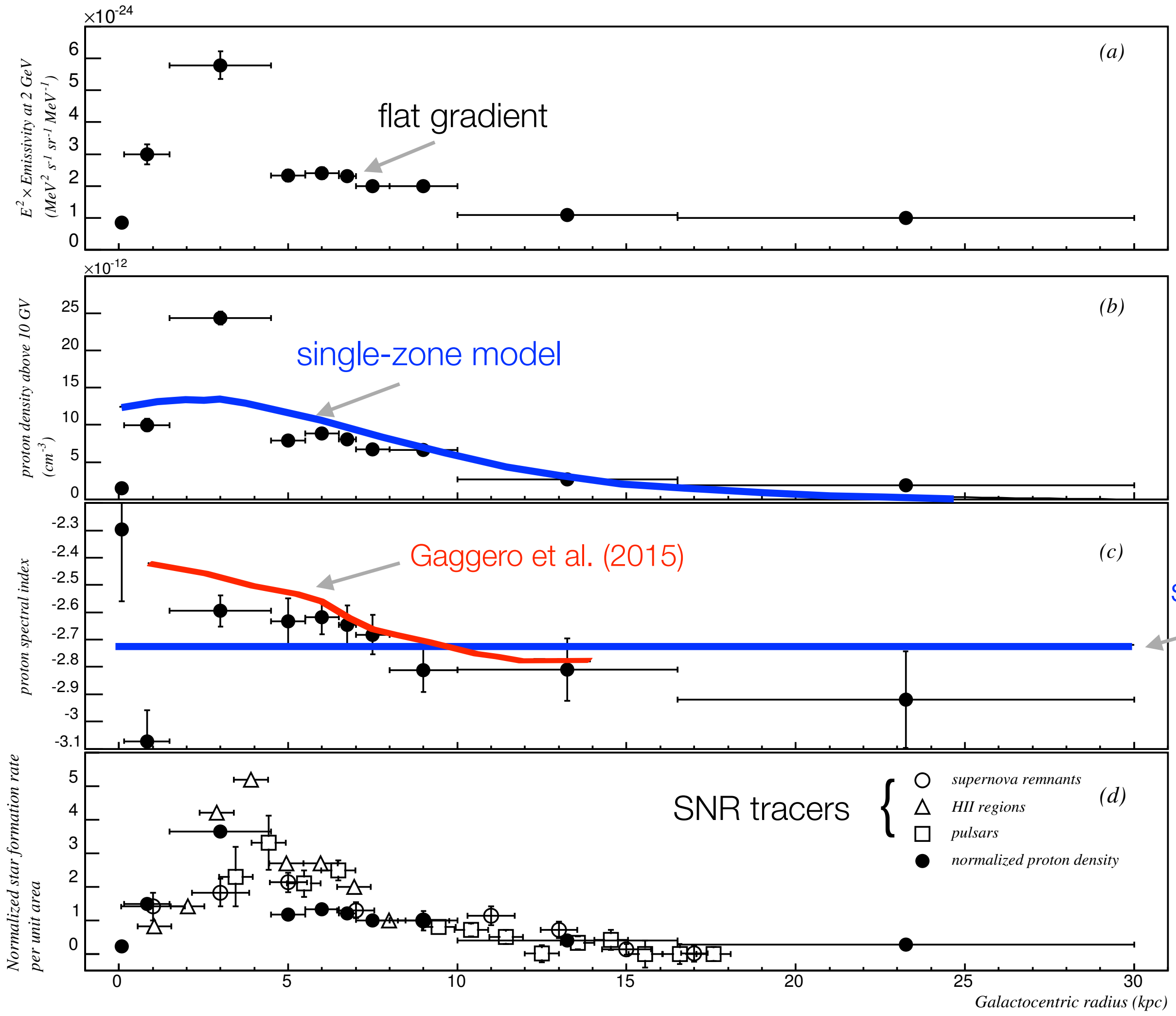
[1907.03696v2]



[2410.10951]

- How many sources contribute?
- How does transport near pulsars work?
- Is DM still viable?
- Can future data inform us?

Harder CR spectrum in the inner Galaxy?

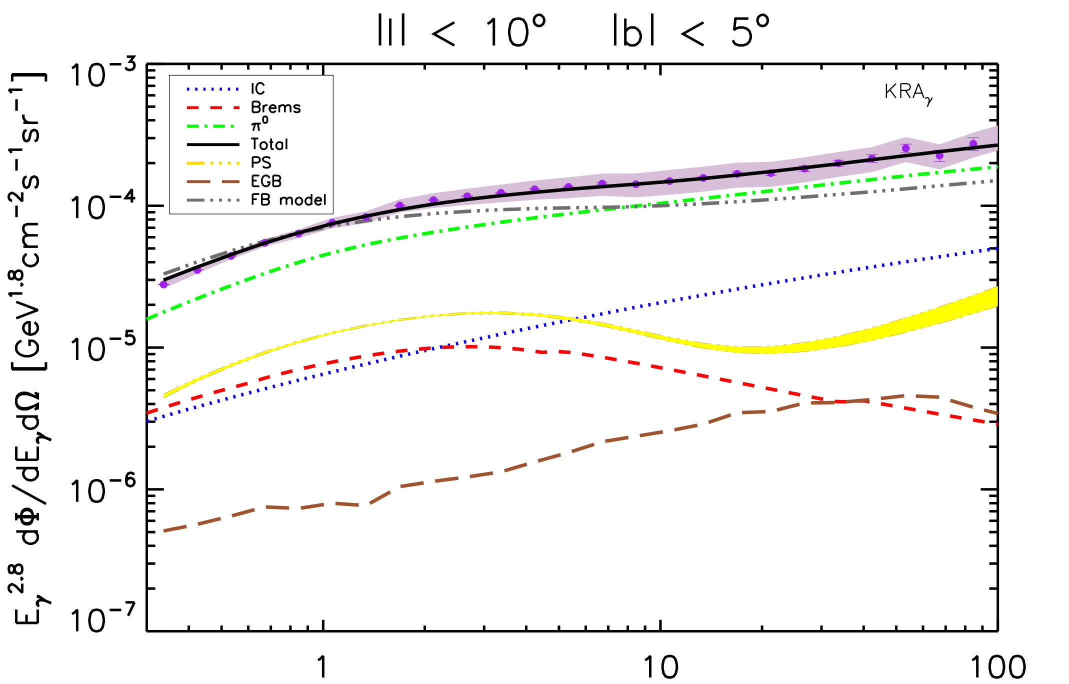


A **CR hardening** in the inner Galaxy inferred by gamma-ray data interpreted as a progressively harder scaling of the diffusion coefficient

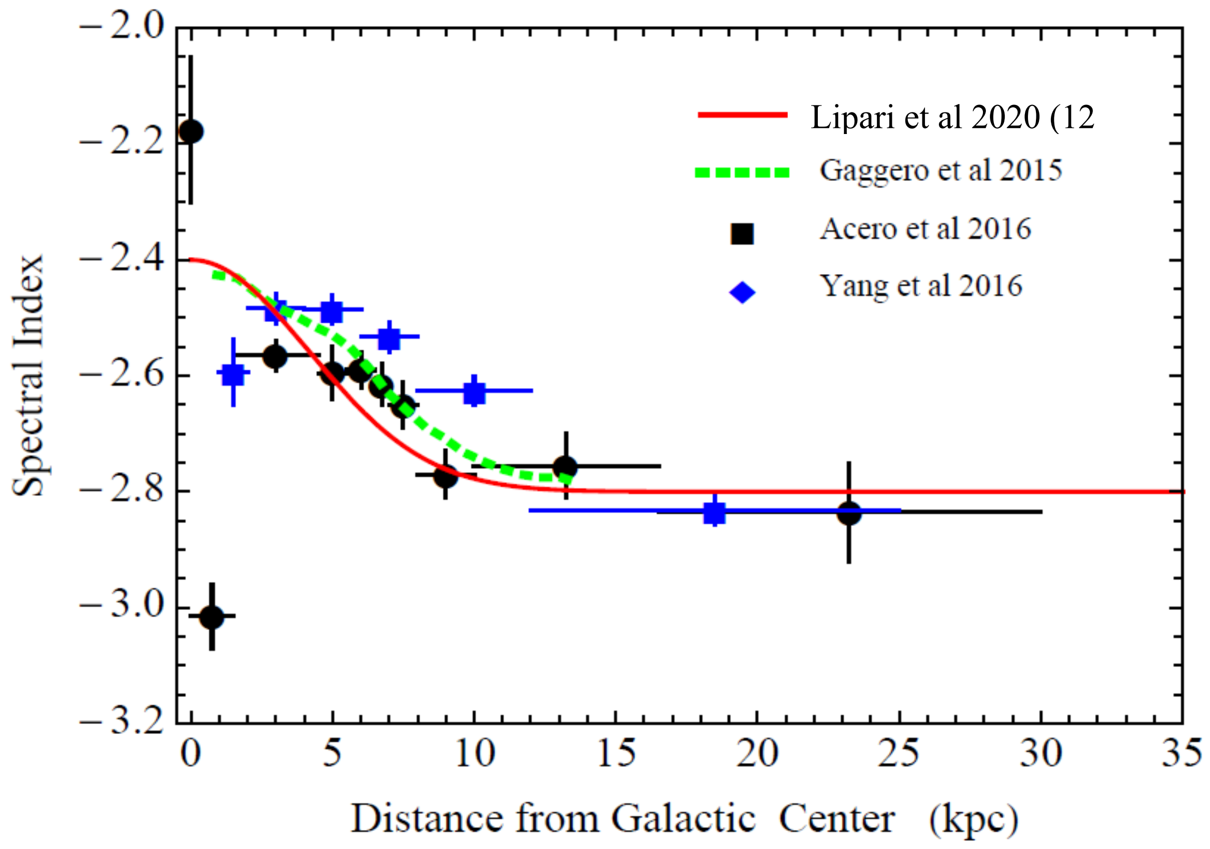
$$D(\rho) = D_0 \beta^\eta \left(\frac{\rho}{\rho_0}\right)^{\delta(r)}$$

$$\delta(r) = ar + b$$

DG, A. Urbano, M. Valli, P. Ullio, PRD 2015



Harder CR spectrum in the inner Galaxy?



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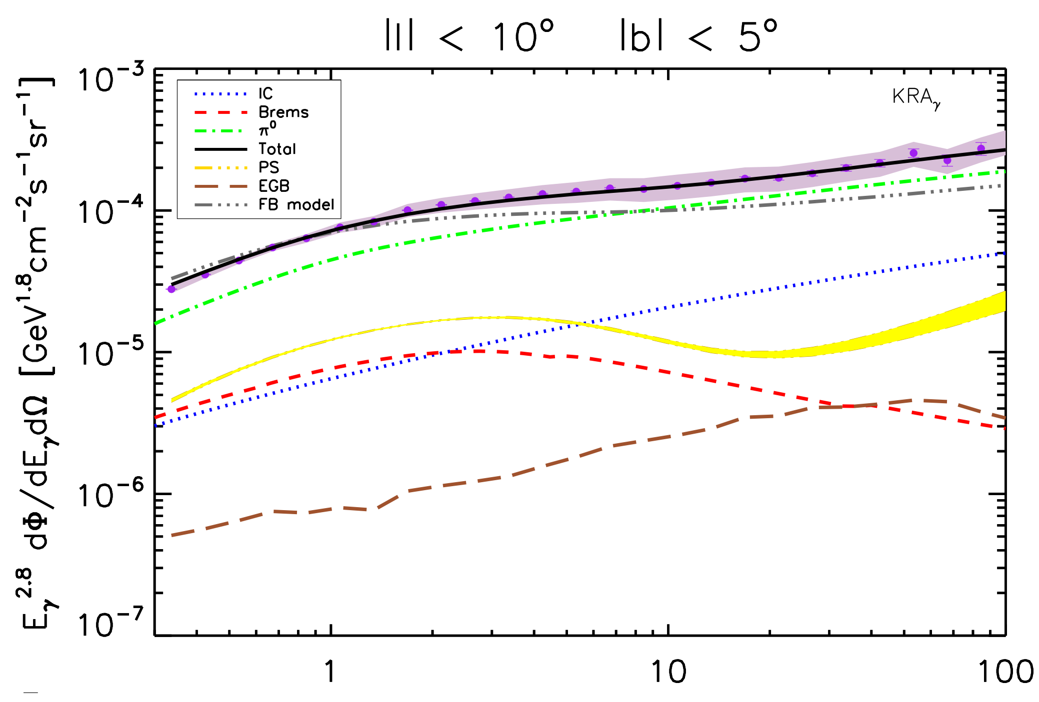
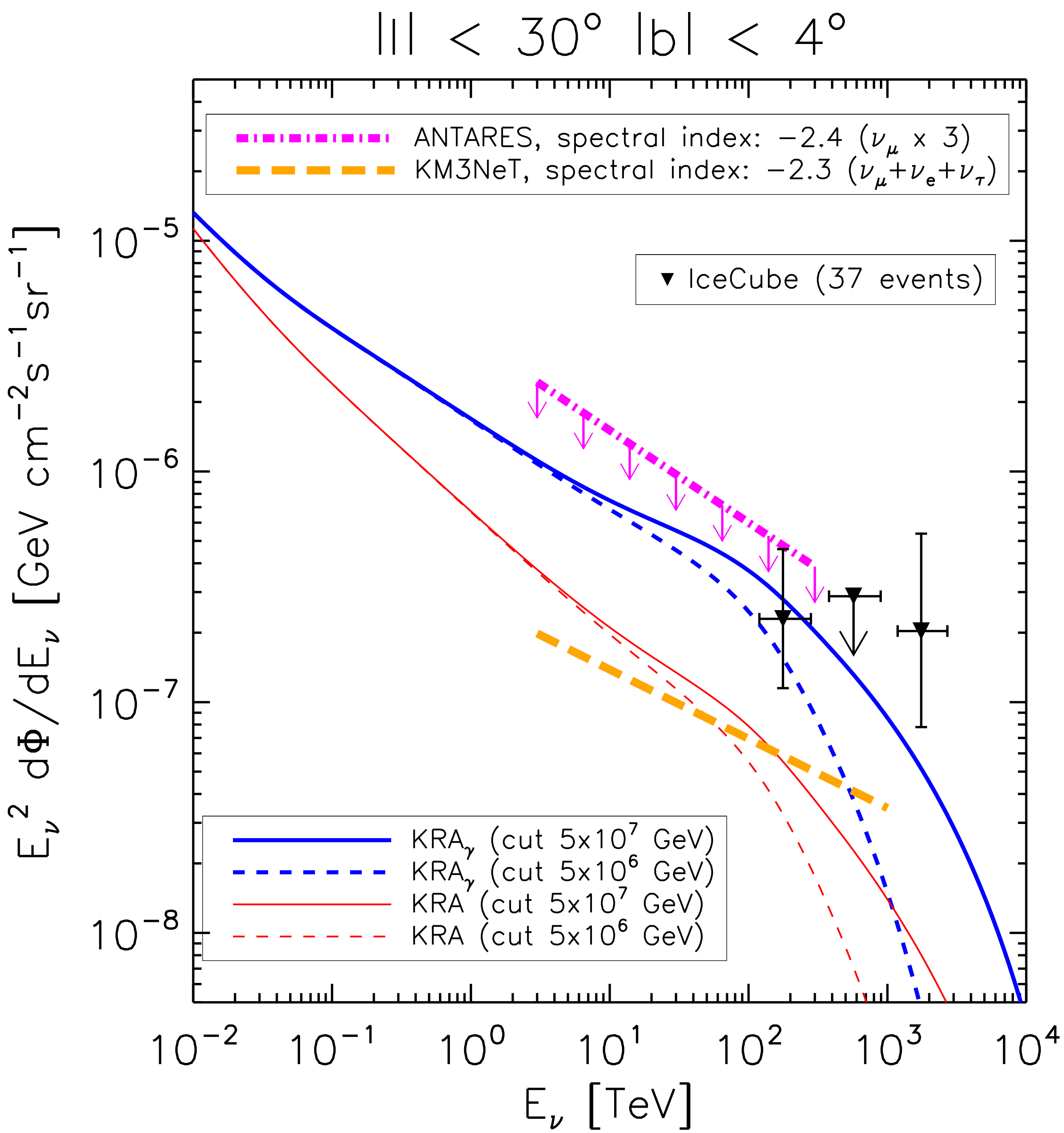
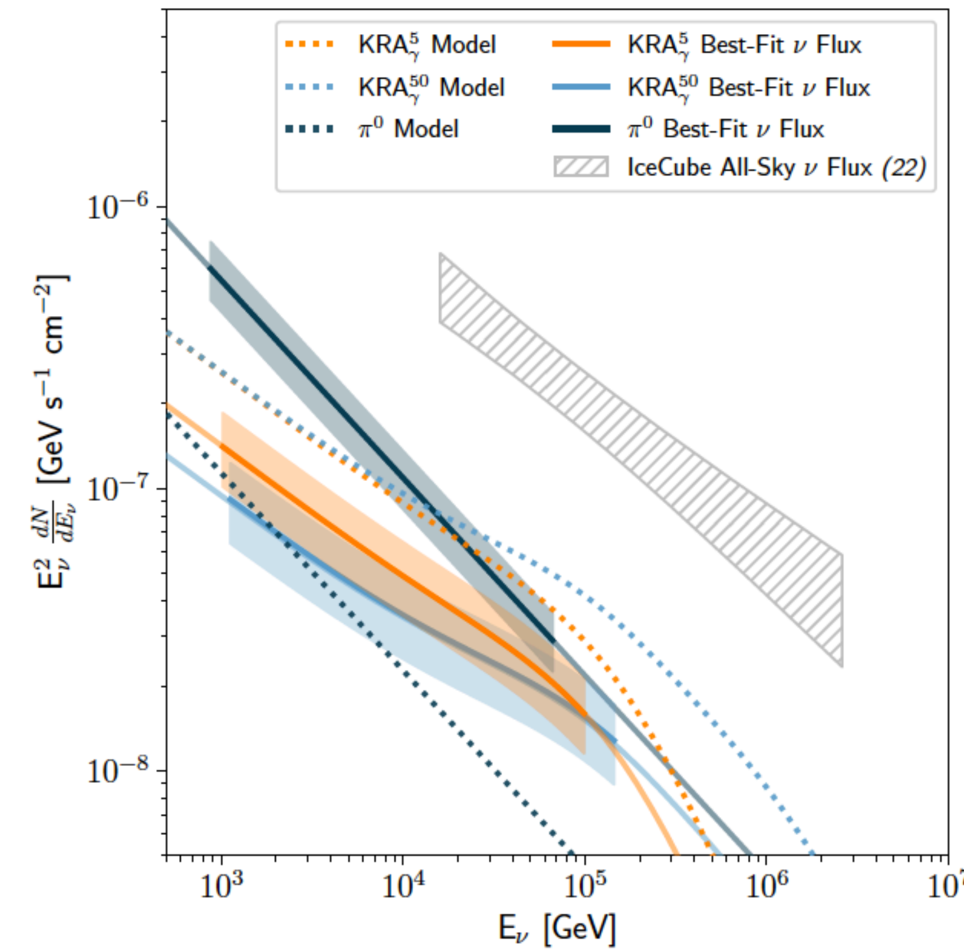


Neutrino connections

Base ("pi0"/"Conventional") **models VS Gamma** ("KRAgamma") **models**

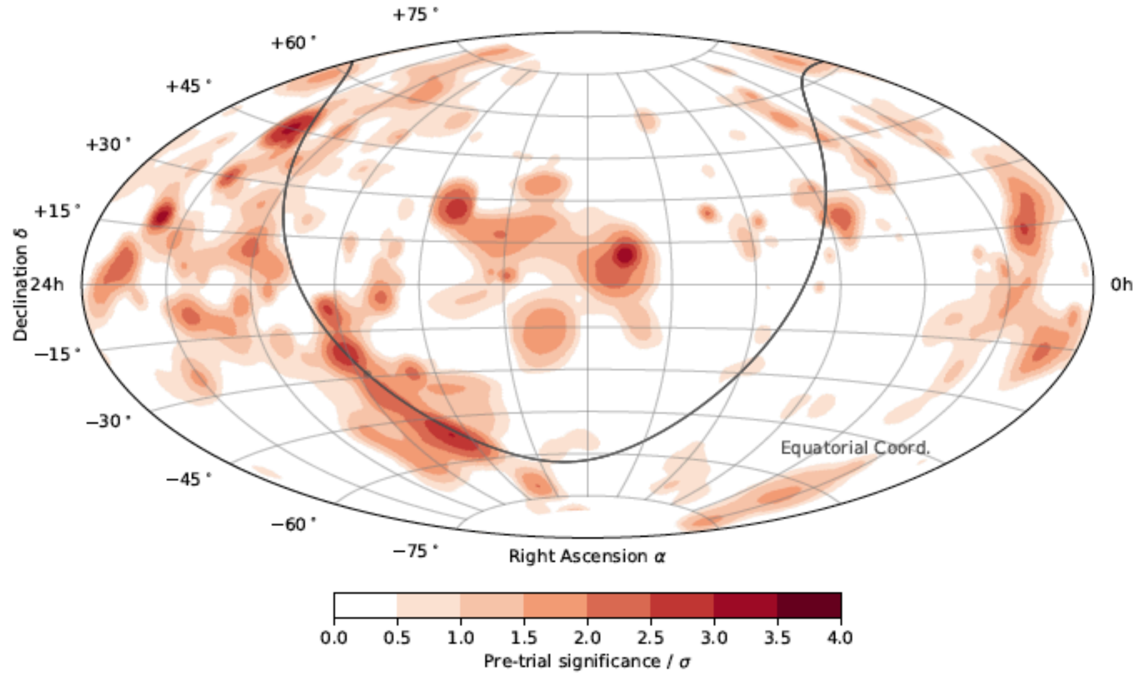


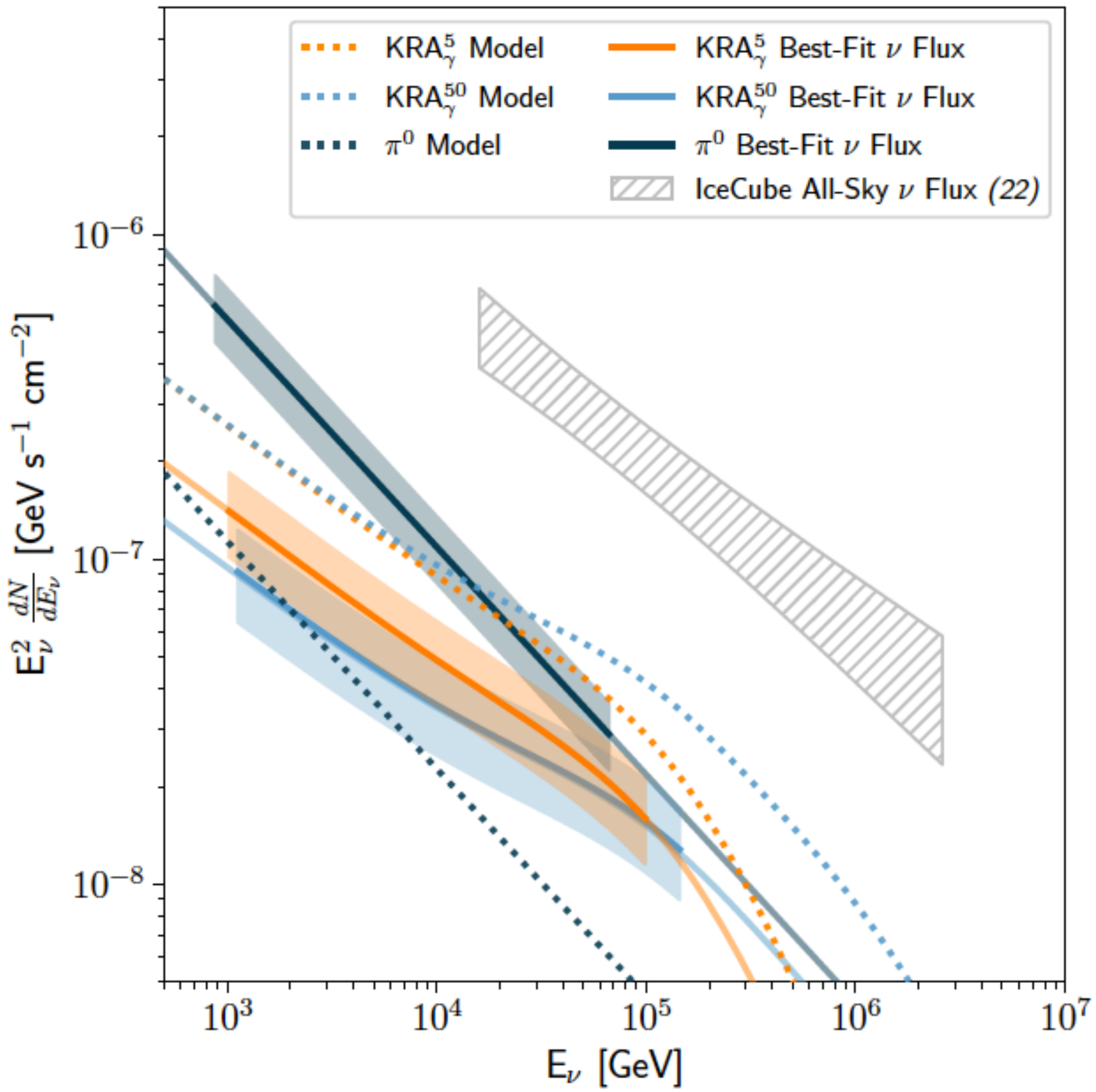
DG, D. Grasso, A. Marinelli, A. Urbano, M. Valli, ApjL, 2016



"our model also provides a different interpretation of the full-sky neutrino spectrum measured by IceCube with respect to the standard lore, since ***it predicts a larger contribution of the Galactic neutrinos to the total flux****, compared to conventional models. These predictions will be* ***testable in the near future*** *by neutrino observatories such as ANTARES, KM3NeT, and* ***IceCube itself*** *via dedicated analyses that are focused on the Galactic plane"*

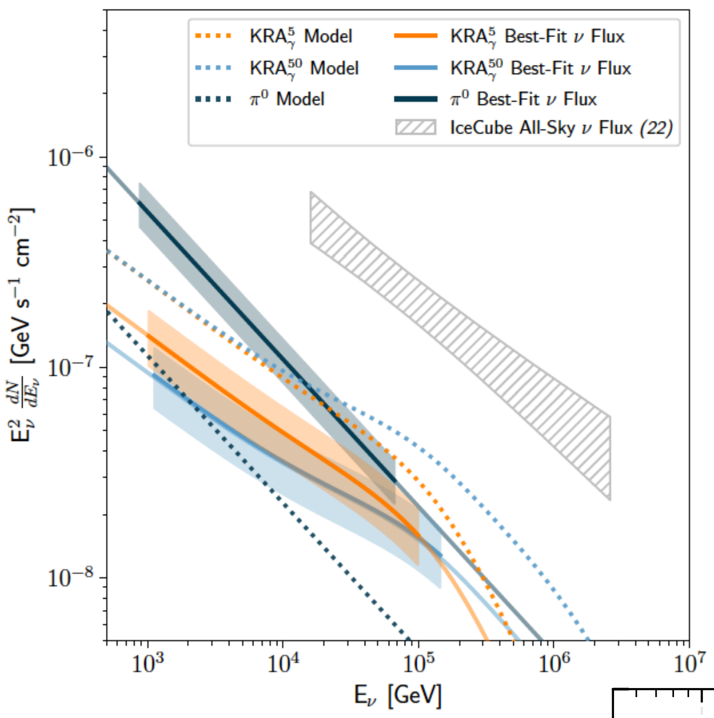
Neutrino connections



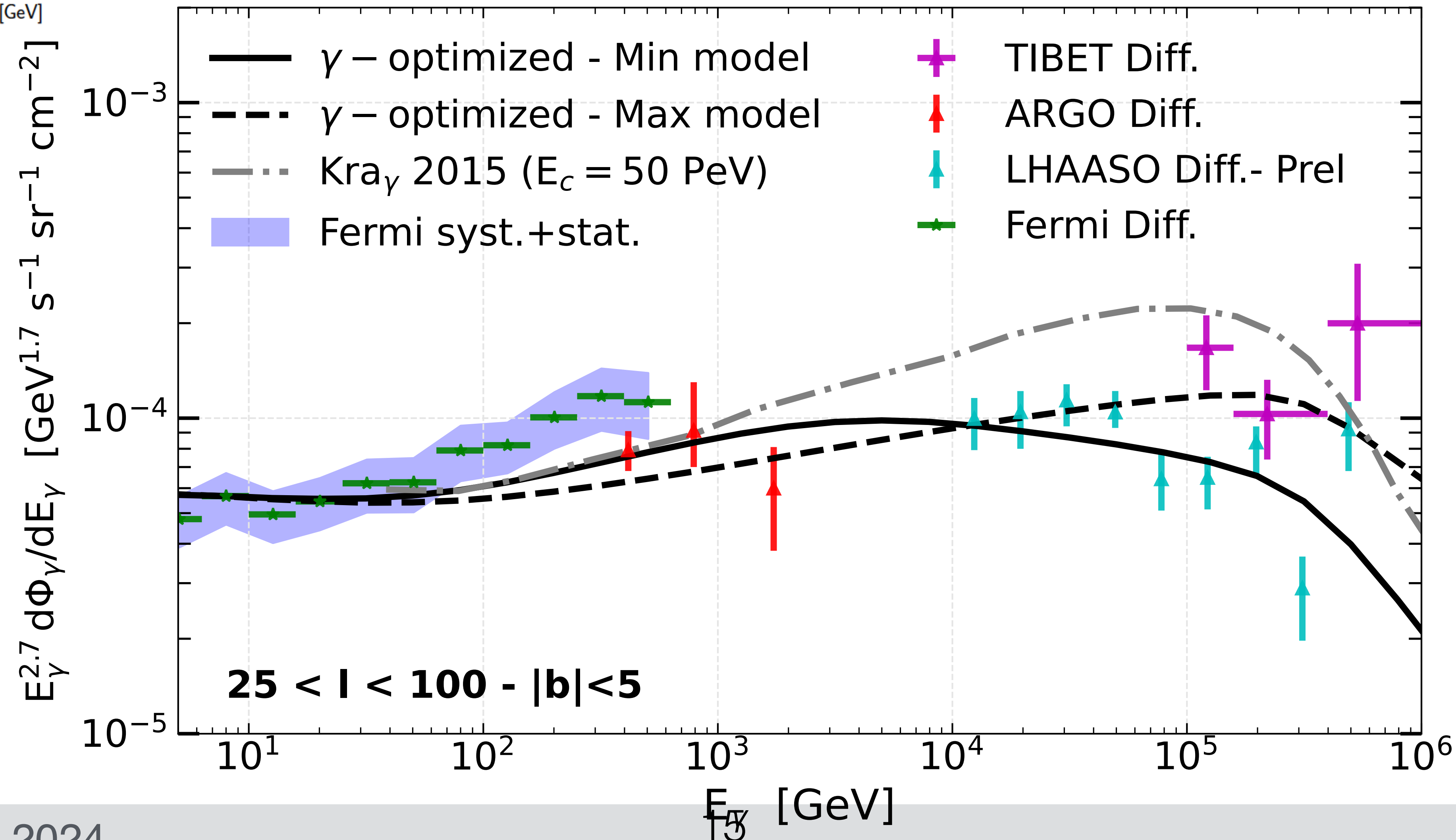


- 10 years of data
- *Cascade* events were analyzed *(lower background, better energy resolution, and lower energy threshold of cascade events compensate for their inferior angular resolution)*
- Neutrino emission from GP is **detected**. Three models tested.

Neutrino connections + Multi-messenger

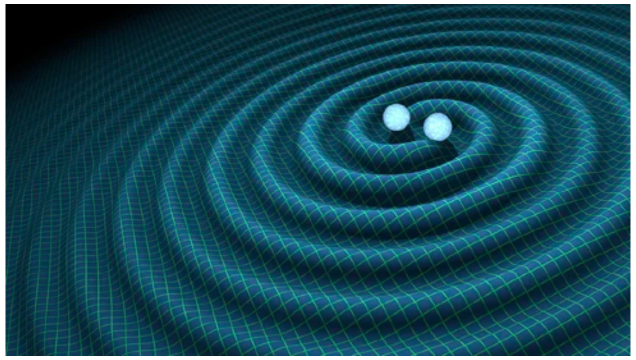


- Conventional models or models with hardening? Gamma ray may help to find the answer.
- How to deal with high-energy uncertainties? Position of the knee?
- Role of unresolved sources? **New ideas needed!!**



Part II: Black Holes and Dark Matter

Black Holes phenomenology:
- Study of Black Hole *inspirals*
- Accretion physics



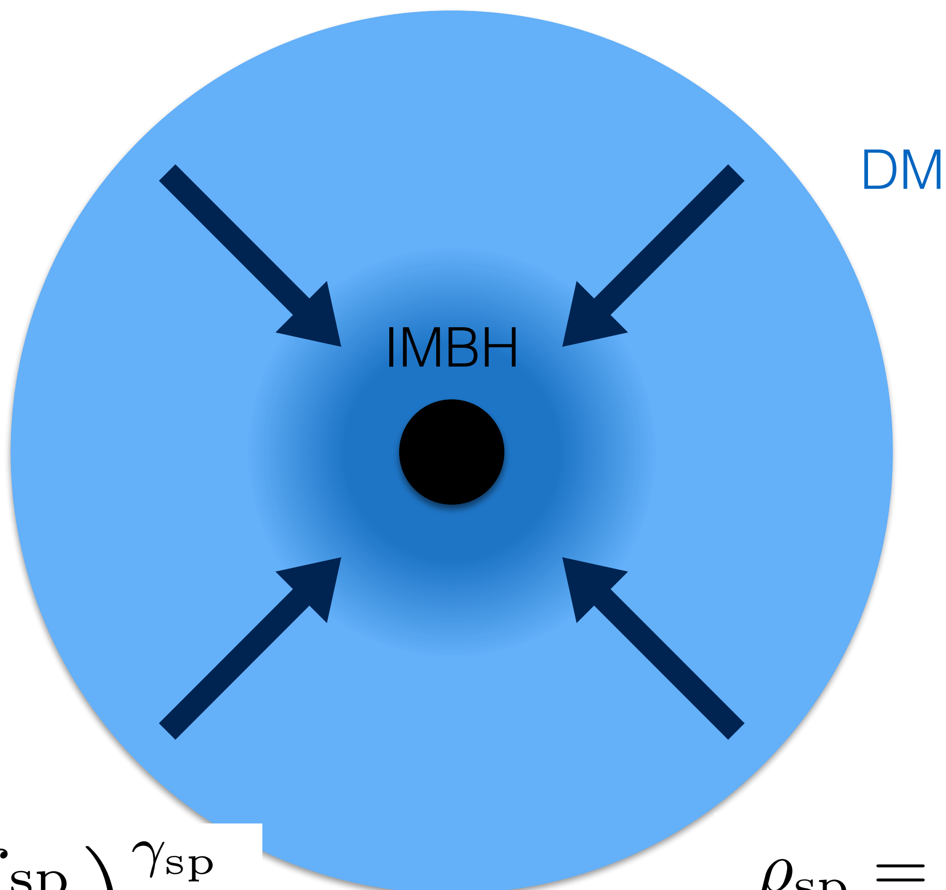
Dark Matter searches
- *Can Black holes of primordial origin be a part of the Dark Matter?*
- *Can we learn something on the nature of the Dark Matter by studying Black Hole physics?*

Multi-messenger astronomy
- Gravitational Waves
- Radio waves/ X-rays/ Gamma rays/ Neutrinos

Black Holes as Portals to new Physics

- Intermediate-Mass Black Holes may exist in the Universe.
- Dark-Matter overdensities can form around them [Gondolo&Silk 9906391, Zhao&Silk 0501625, Hannuksela+ 1906.11845].

$M_{IMBH} = 1000\ M_{Sun}$

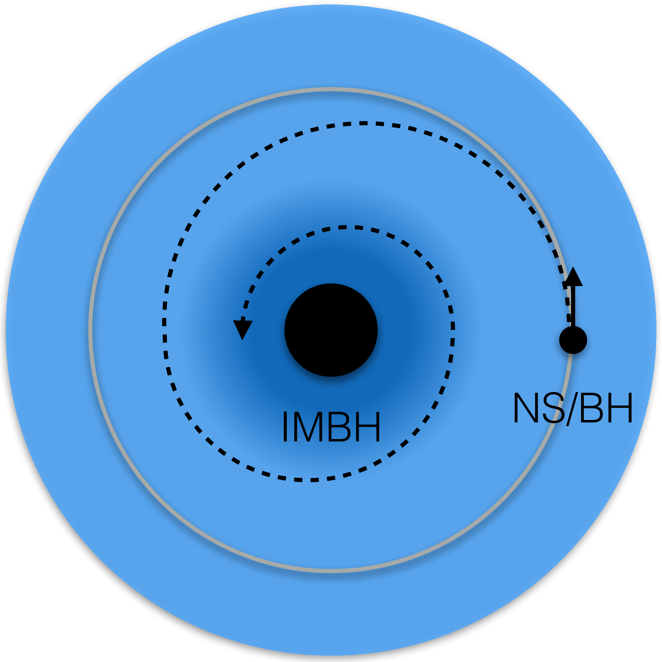


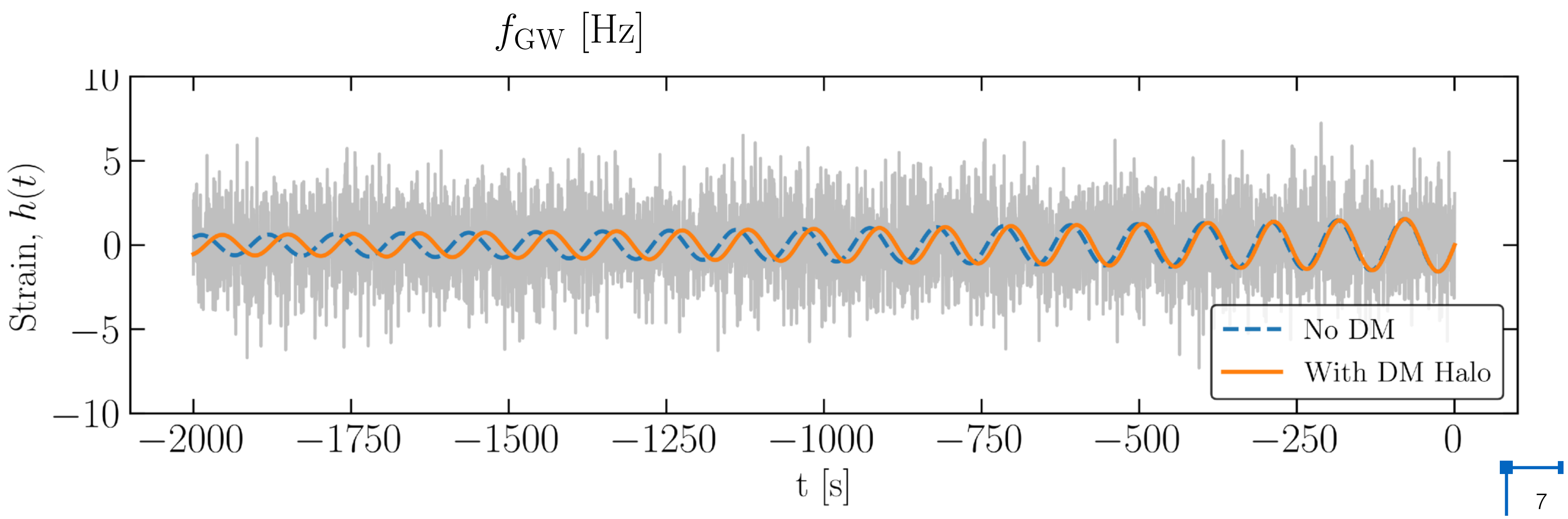
$$\rho_{\rm DM}(r) = \rho_{\rm sp}\left(\frac{r_{\rm sp}}{r}\right)^{\gamma_{\rm sp}}$$

$$\rho_{\rm sp} = 200\, M_\odot\, {\rm pc}^{-3}$$
$$r_{\rm sp} = 0.5\, {\rm pc}$$

Black Holes as Portals to new Physics

- Stellar-mass black holes that inspiral around IMBHs can trace the presence of either accretion disks or Dark Matter overdensities (DM "dresses" or "spikes")



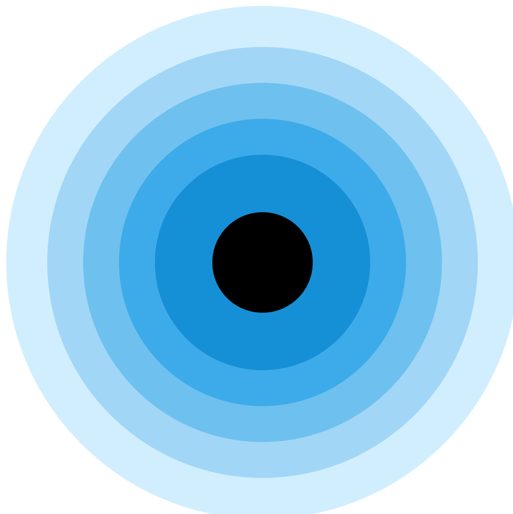


- Dephasing of the waveform w.r.t. GR in vacuum
- Physical process: Dynamical Friction

- Kavanagh+ 2002.12811 (PRD)
- Coogan+ 2108.04154 (PRD)
- Cole+ 2211.01362 (Nature Astronomy)

$$\frac{\mathrm{d}E_{\rm DF}}{\mathrm{d}t} = 4\pi (G m_2)^2 \rho_{\rm DM}(r_2)\, \xi(v)\, v^{-1} \log \Lambda$$

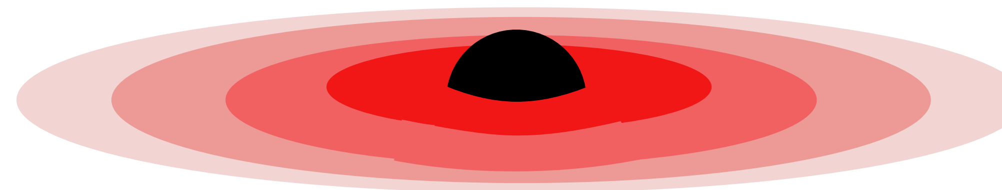
LISA can discriminate environmental effects



Particle Dark Matter
'**Spikes**' or '**Dresses**'

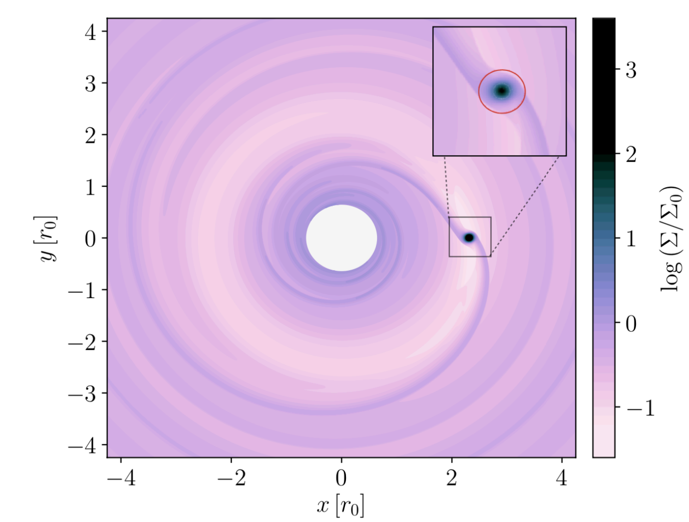
- **Collisionless** DM overdensity
- **Spherical** symmetry
- **Dynamical friction** at work
- **Feedback** on the halo is important

$$\frac{\mathrm{d}E}{\mathrm{d}t} = m_2 v_0 \frac{\mathrm{d}v}{\mathrm{d}t} = -\frac{4\pi (G_N m_2)^2 \rho_{\mathrm{DM}}(r) \xi(v_0)}{v_0} \log \Lambda$$



Baryonic
Accretion Disks

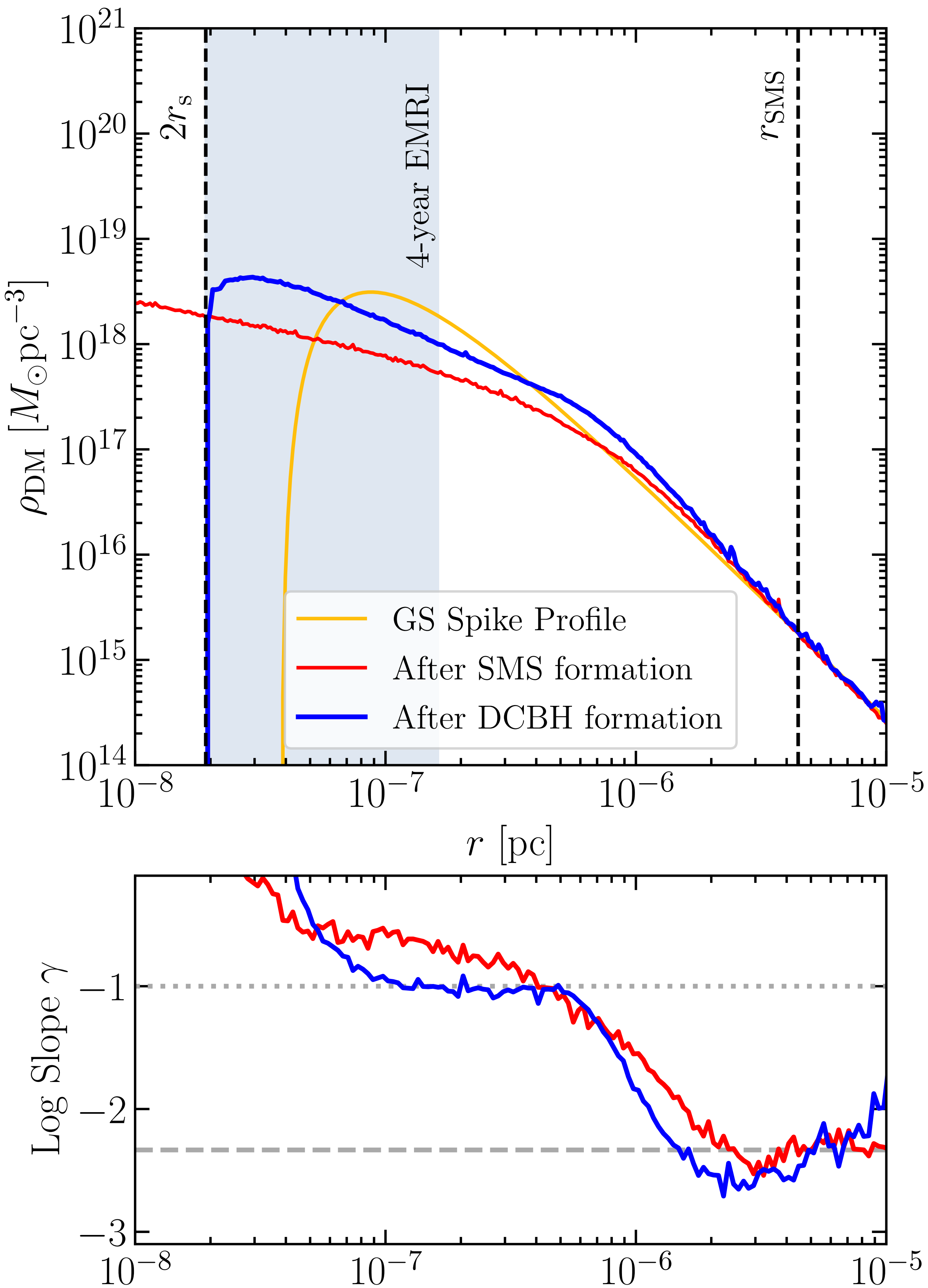
- Differentially rotating **baryonic** disk
- Disk is perturbed by the inspiralling object. Asymmetric "wake"
- Perturbation back-reacts and exerts **torques**



$$T_{\mathrm{I}} = -\Sigma(r) r^4 \Omega^2 q^2 \mathcal{M}^2$$

$$\frac{\mathrm{d}E_{\mathrm{torque}}}{\mathrm{d}t} = \frac{1}{4} m_1 T_{\mathrm{I}} \left(\frac{G_N}{r^3 M} \right)^{1/2}$$

Formation of DM overdensities



- **Formation of a supermassive star:** profile is shallower compared to GS solution, because the potential of the SMS star is more extended

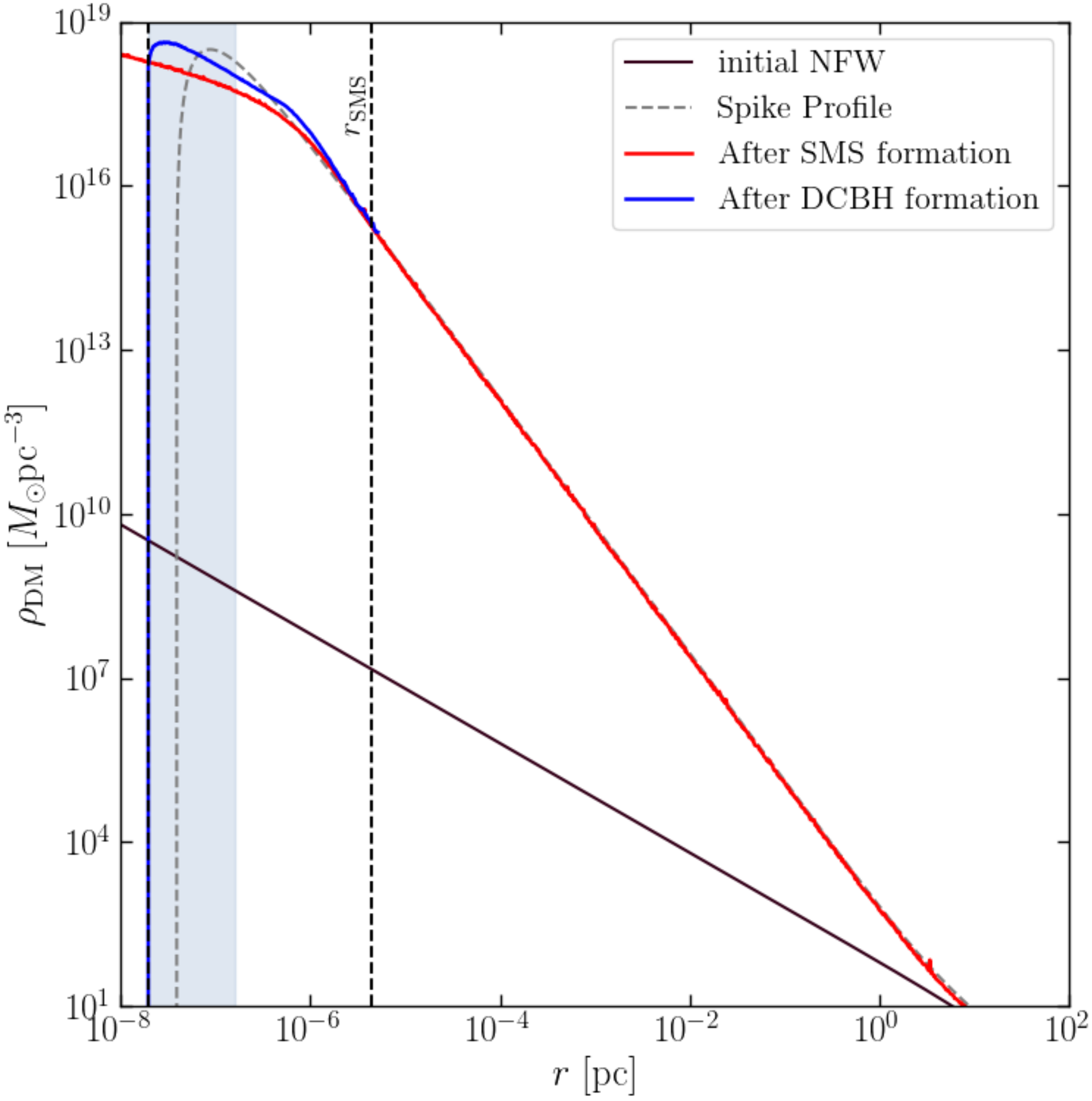
- **Direct Collapse Black Hole:** mild steepening

Orbits with $r < 2r_S$ **captured** by the BH, as in fully relativistic computation 1305.2619 *(radius of the unstable circular orbit in the Schwarzschild geometry for a marginally bound particle*)

Gianfranco Bertone, Renske Wierda, DG, Bradley Kavanagh, Marta Volonteri, Naoki Yoshida, *2404.08731*

Formation of DM overdensities

- How does the nature of the DM candidate change this picture?

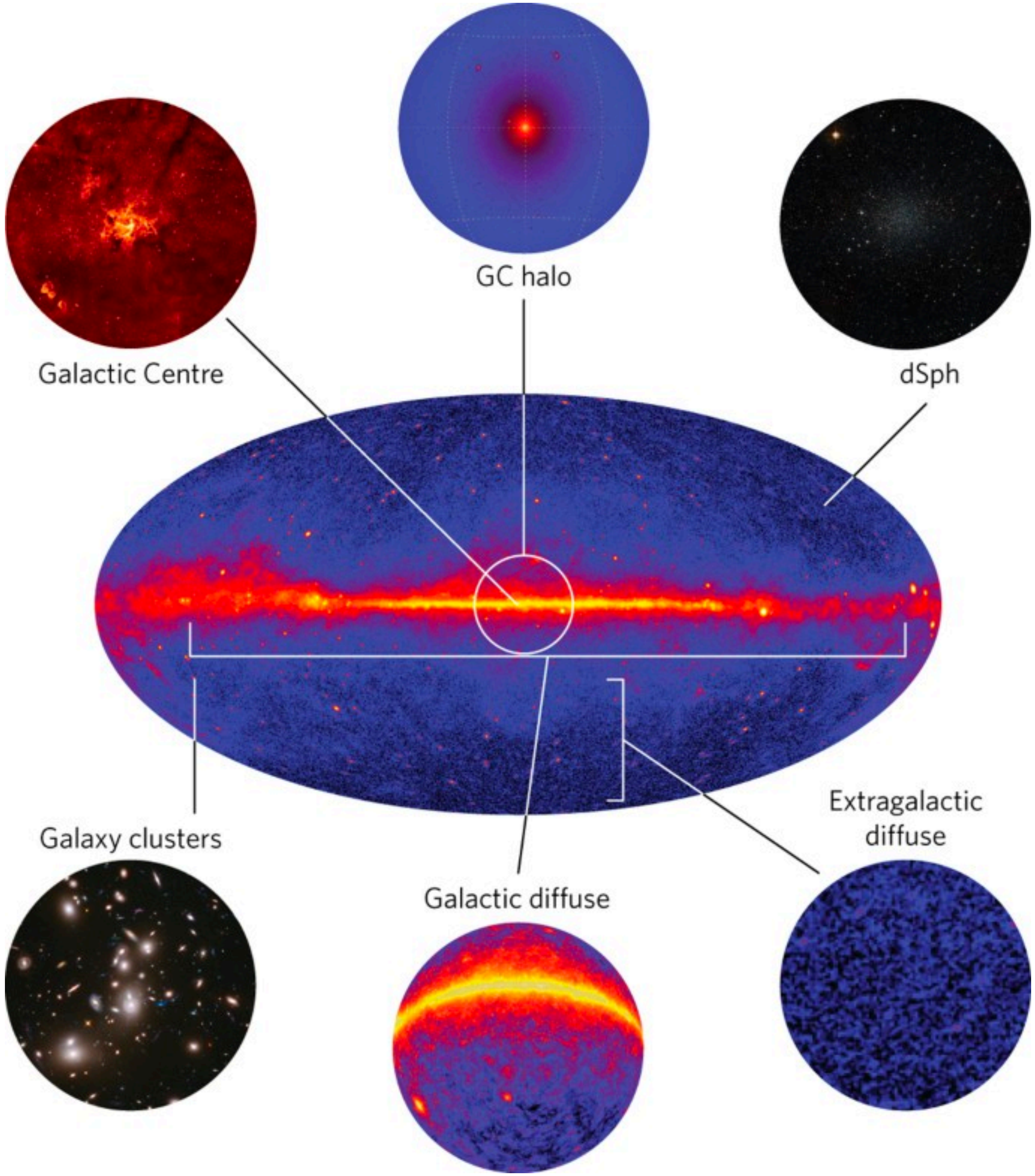


Conclusions

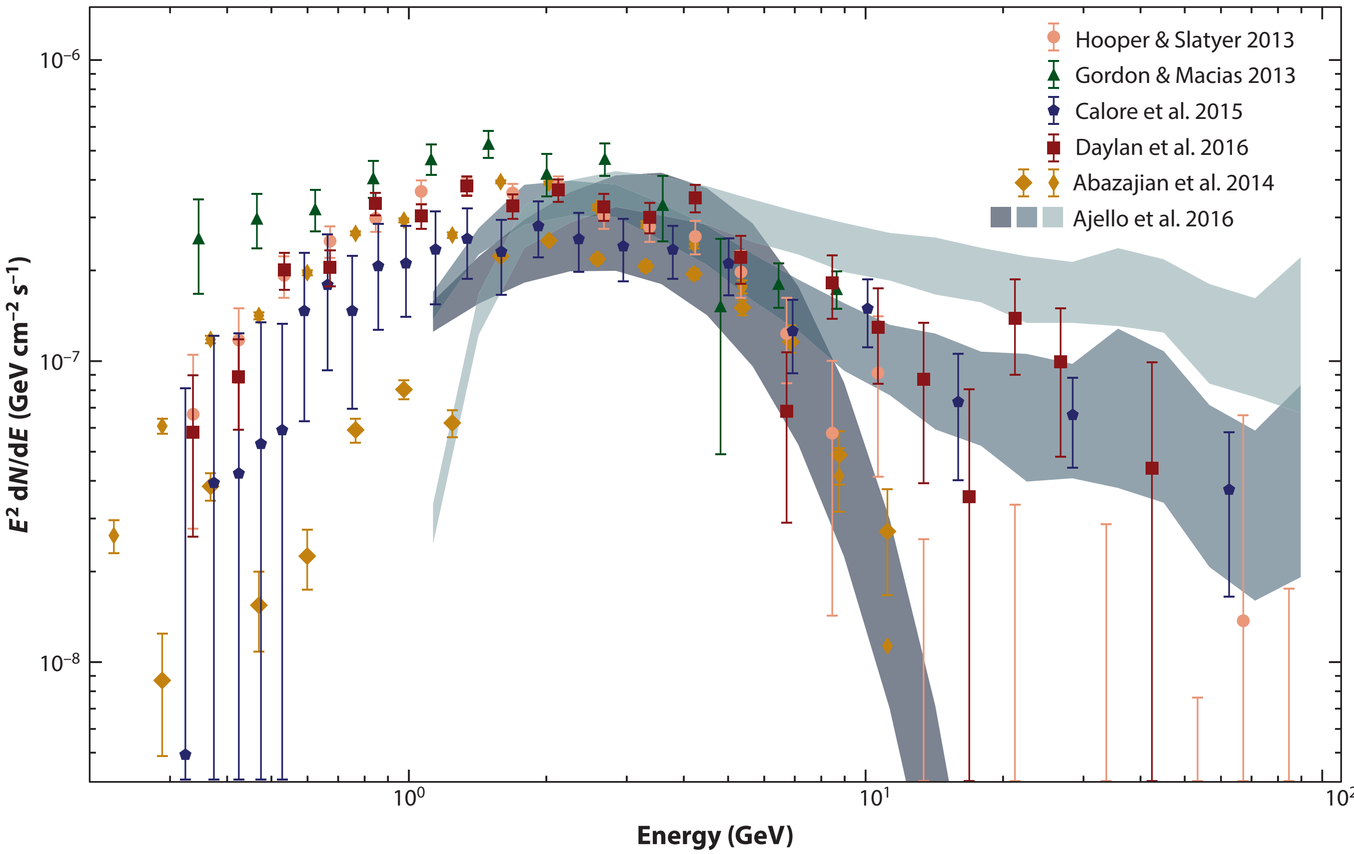
- Can CR anomalies point to new physics? or interesting new astrophysics?

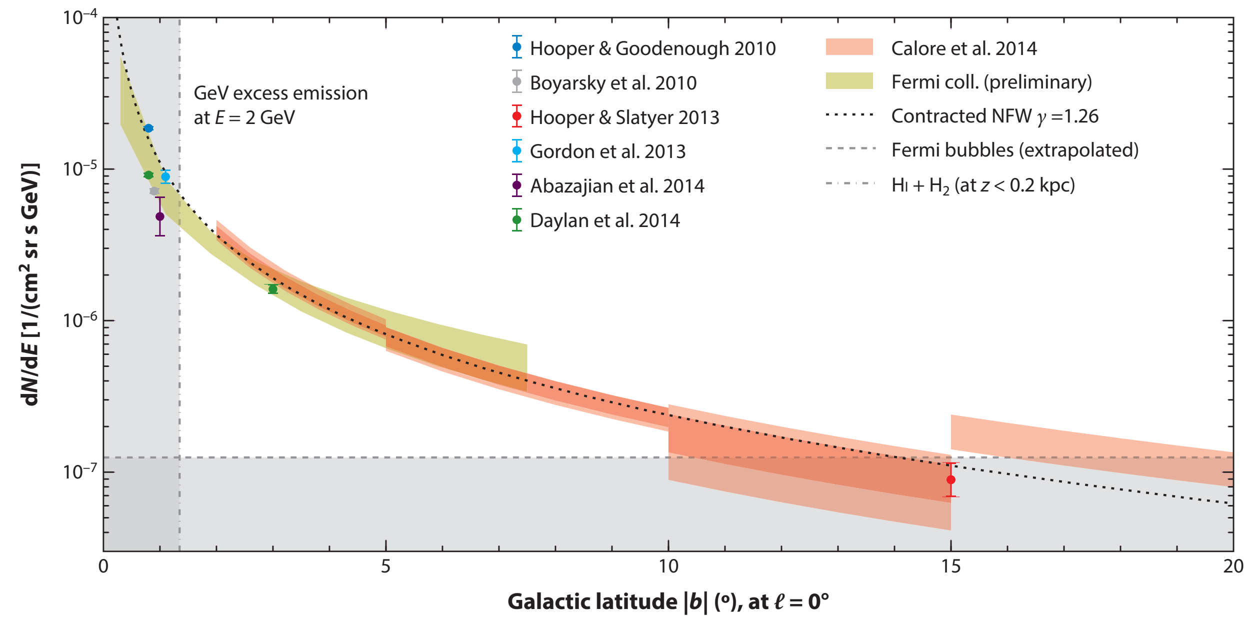
- Can BH phenomenology inform us about dark matter?

New physics searches



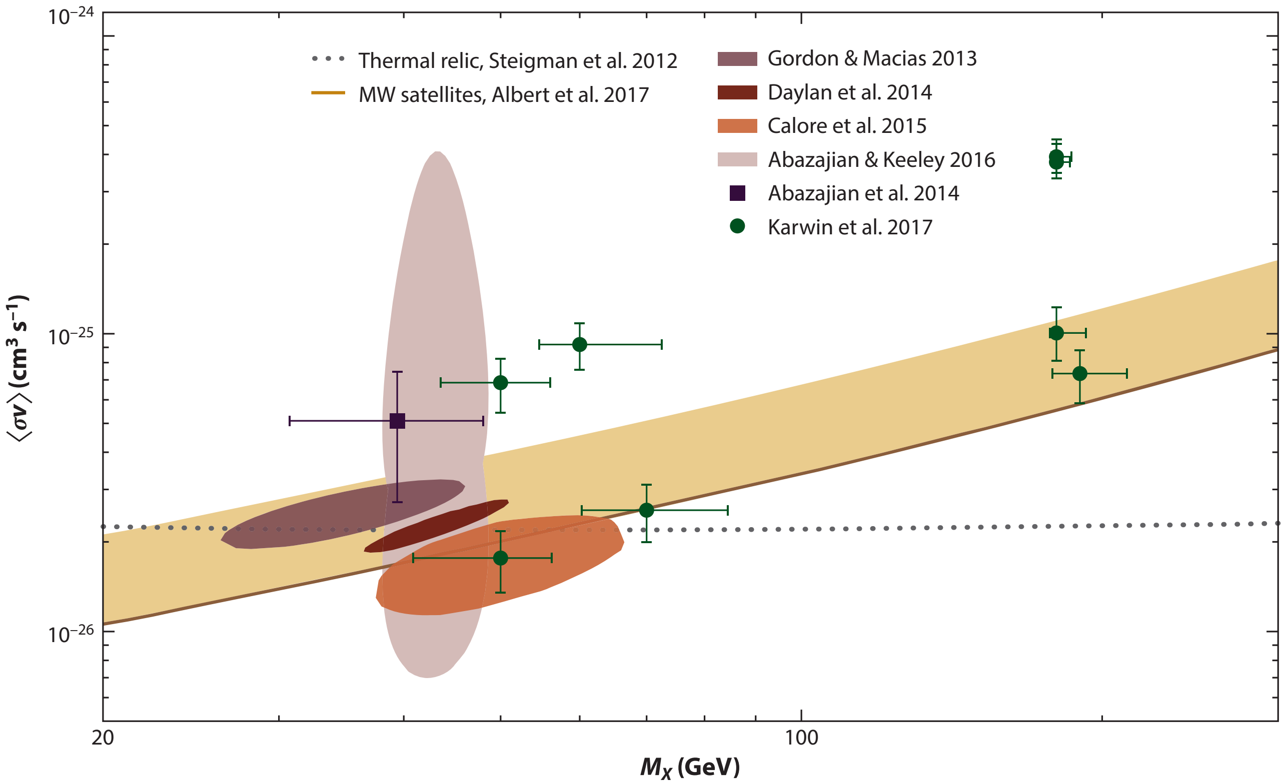
Debate about a GeV excess





- An extended, spherical **signal** from the **inner Galaxy**
- Outlined by a ***template fitting*** technique
- **DM interpretation**: $M_{DM} \sim 30$ GeV; σ_{ann} close to thermal cross section
- Very rich literature!

D. Dixon et al. 1998 [arXiv:9803237]; V. Vitale et al. 2009 [arXiv:0912.3828]; L Goodenough and D. Hooper, 2009; D. Hooper and L. Goodenough, 2010 D. Hooper and T. Linden, 2011; K. N. Abazajian and M. Kaplinghat, 2012 D. Hooper and T. R. Slatyer, 2013; C. Gordon and O. Macias, 2013 T. Daylan, D. P. Finkbeiner, D. Hooper, T. Linden; S. Portillo, N. L. Rodd and T. R. Slatyer, 2014 [arXiv:1402.6703]; F. Calore, I. Cholis, C. Weniger, 2014 [arXiv:1409.0042]; F. Calore et al. 2015 [arXiv;1411.4647]



- **DM interpretation**

tension with constraints from dwarf spheroidal galaxies?
connection with other channels?

- **MSP interpretation**

suggested by wavelet analyses and photon statistics. Probably: new astrophysics found!

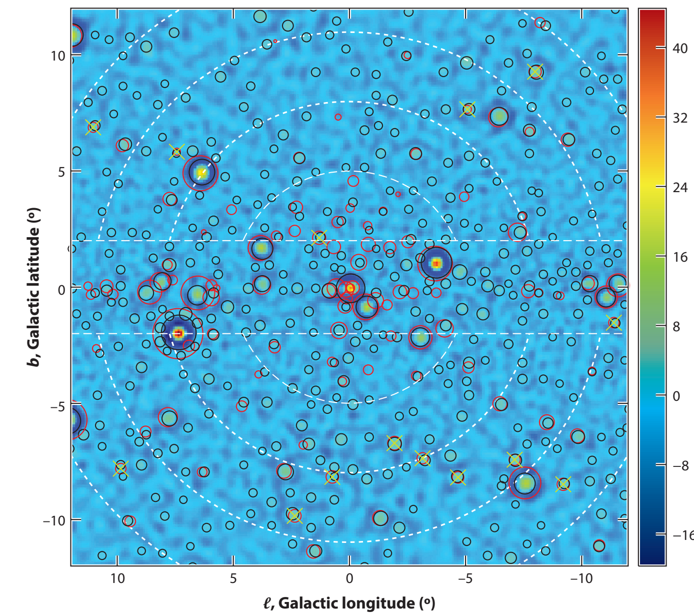
R. Bartels et al. 2016 [1506.05104]
S. Lee et al. 2016 [1506.05124]
F. Calore et al. 2021 [2102.12497]

- **Is it really an excess** (normalization issues)**?**

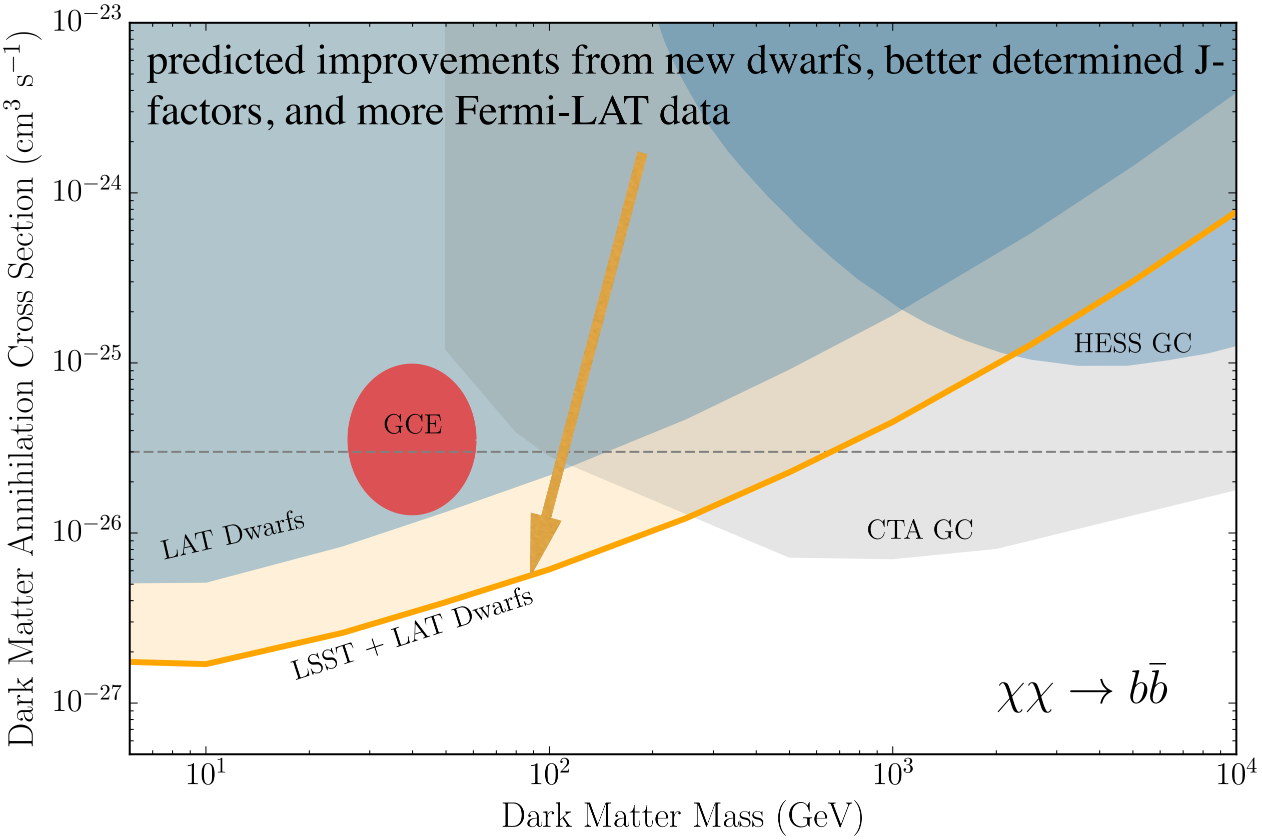
D. Gaggero et al. 2015 [1507.06129]
E. Carlson et al. 2015 [1510.04698]

- **Is it really spherically symmetric** (morphology issues)**?**

R. Bartels et al. 2017 [1711.04778]
O. Macias et al. 2017 [1611.06644]



Future prospects (LSST+Fermi, CTA)



arXiv:1902.01055