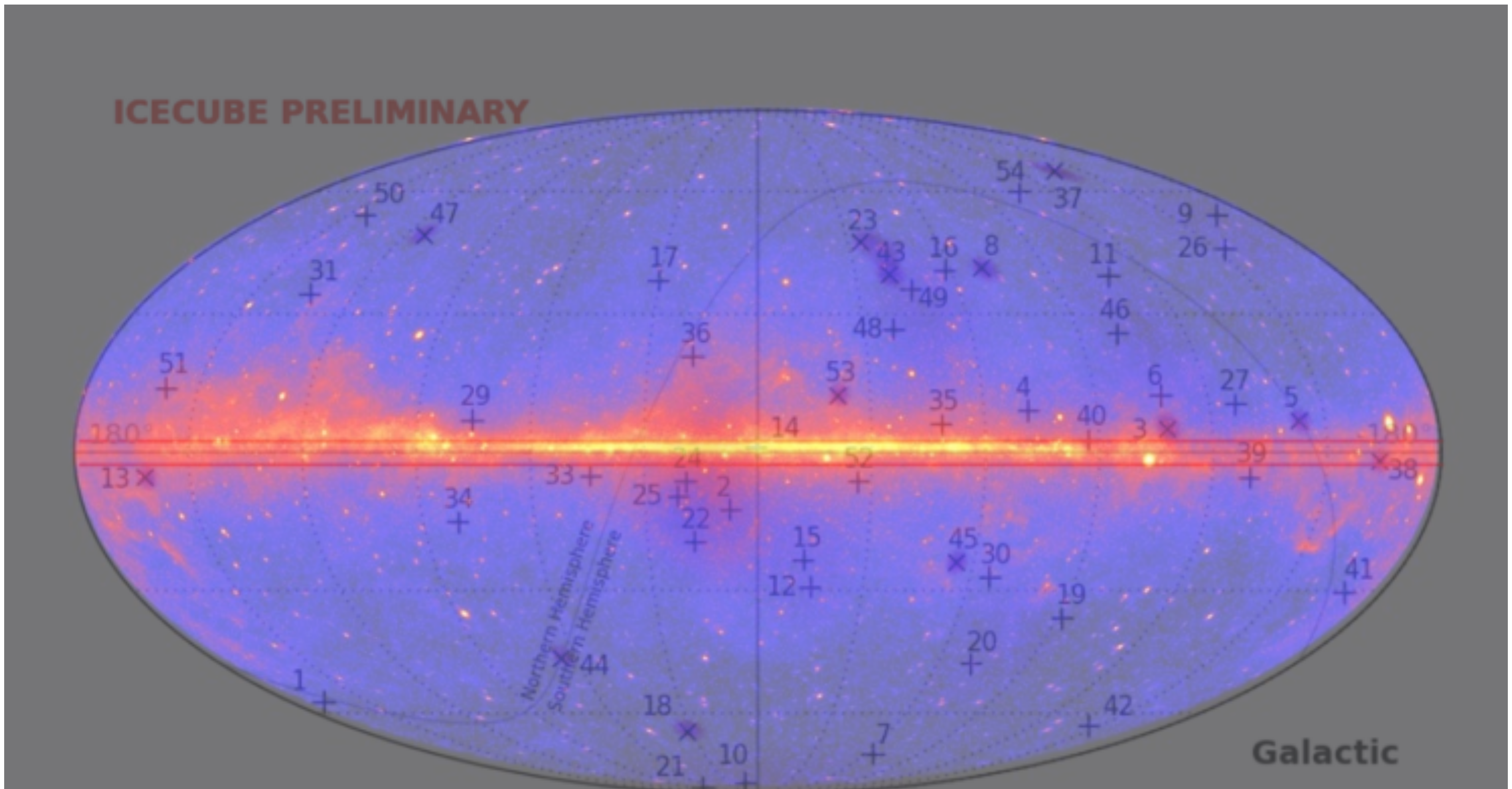
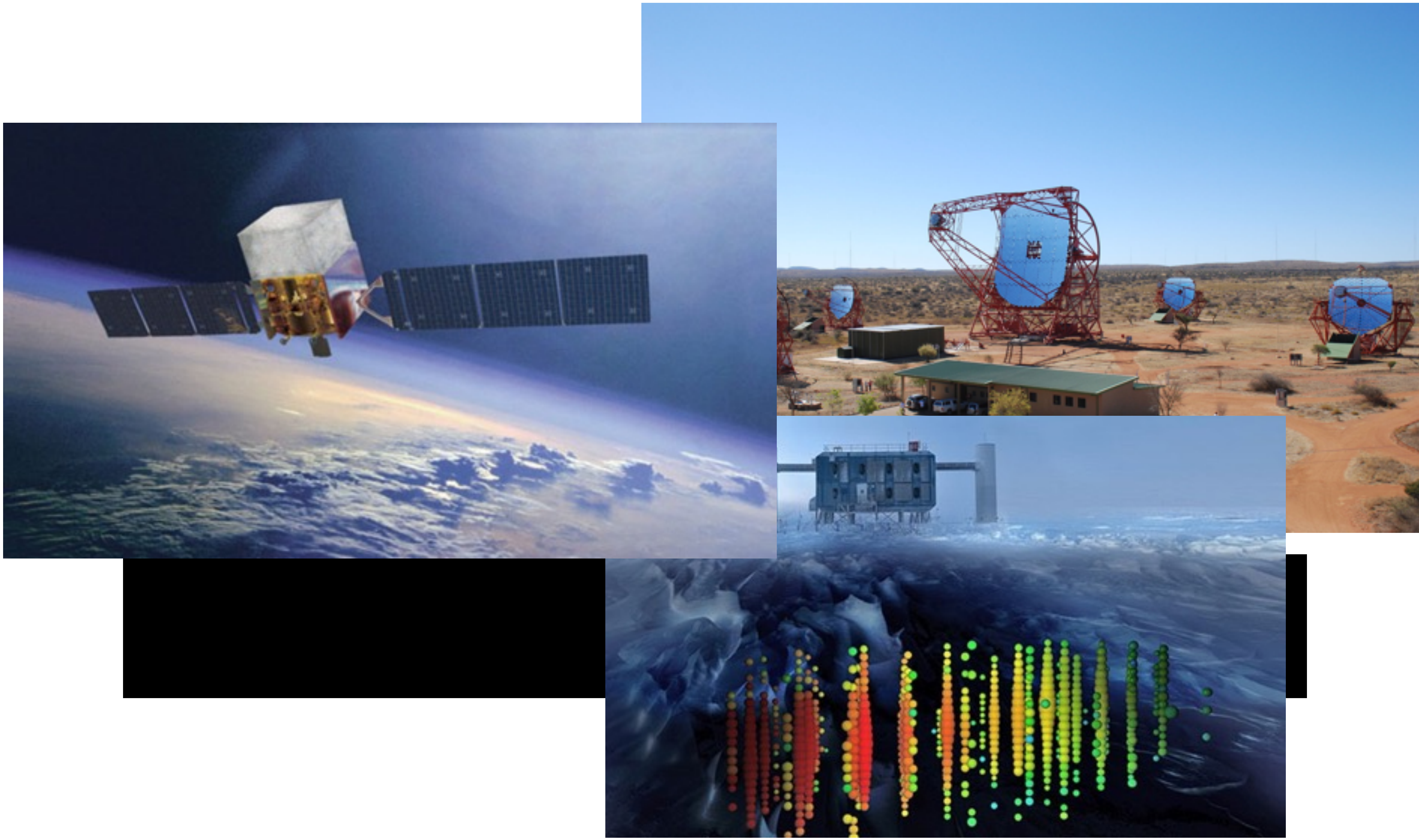


Daniele Gaggerc

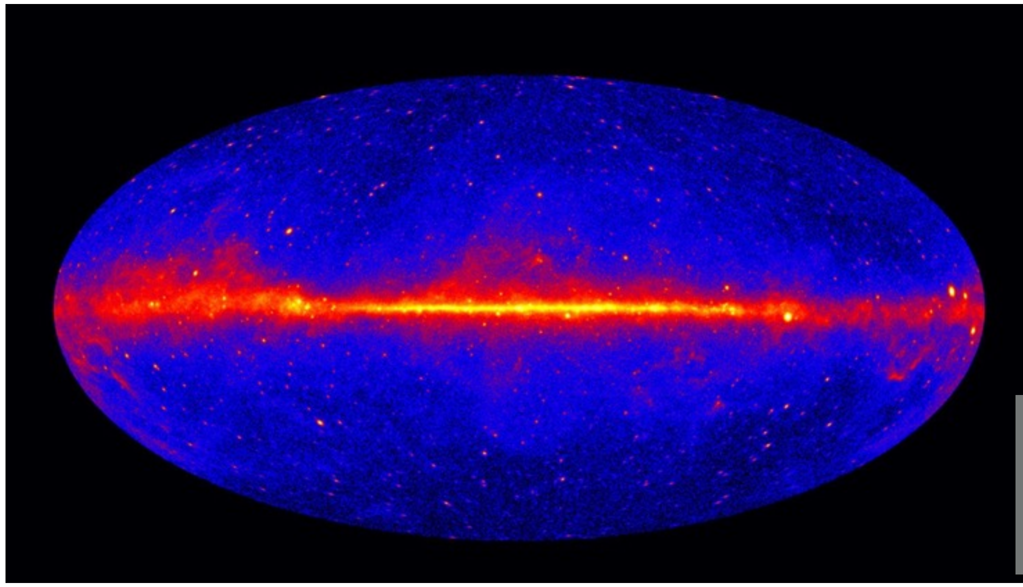
UNIVERSITEIT VAN AMSTERDAM

GRAPPA

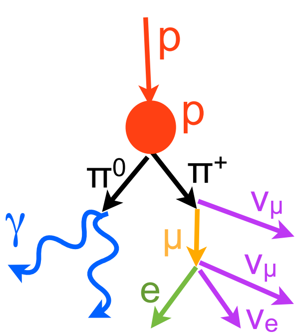
GRavitation AstroParticle Physics Amsterdam



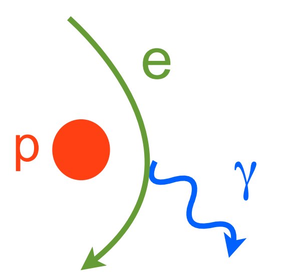
A tribute to the data: The multi-GeV gamma-ray sky



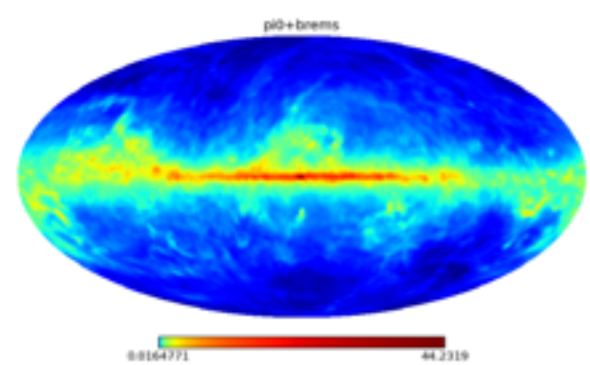
- **Diffuse Galactic emission:**

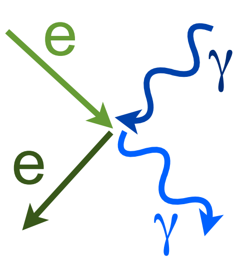


Proton-Proton Interactions

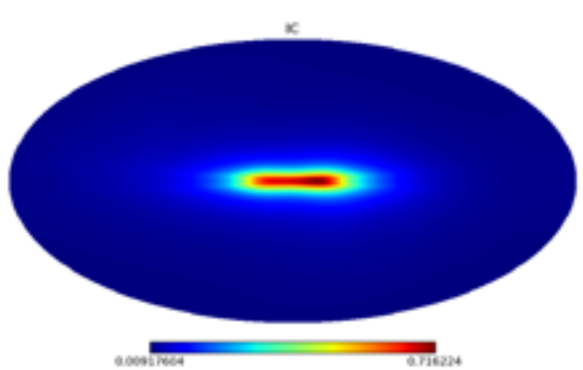


Bremsstrahlung

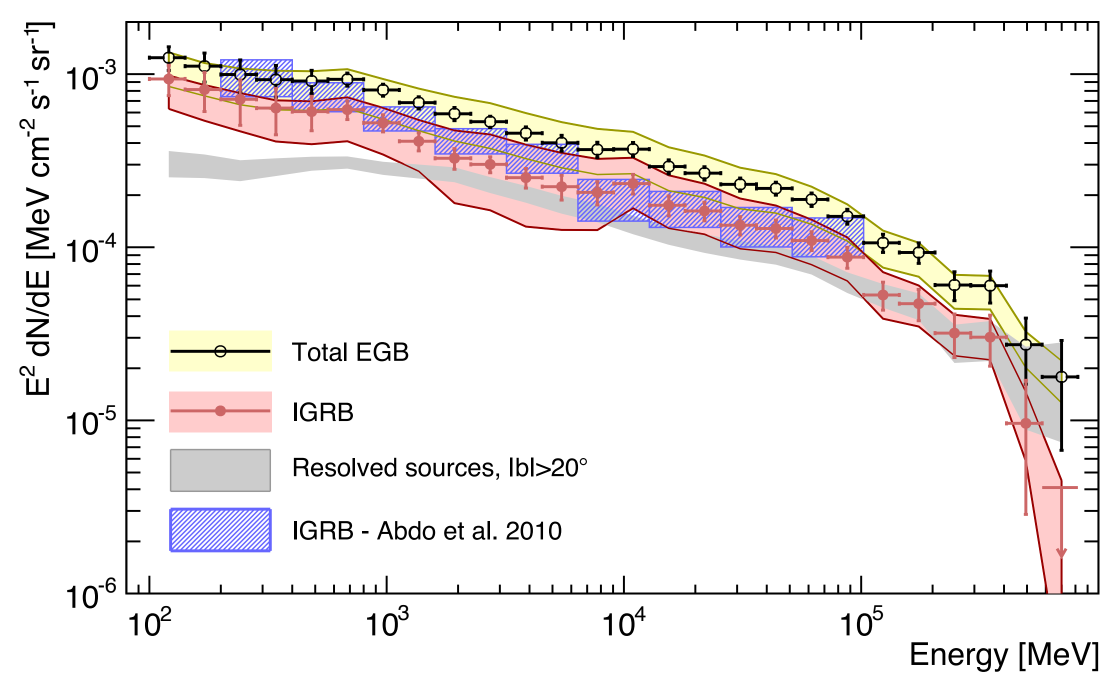




Inverse Compton



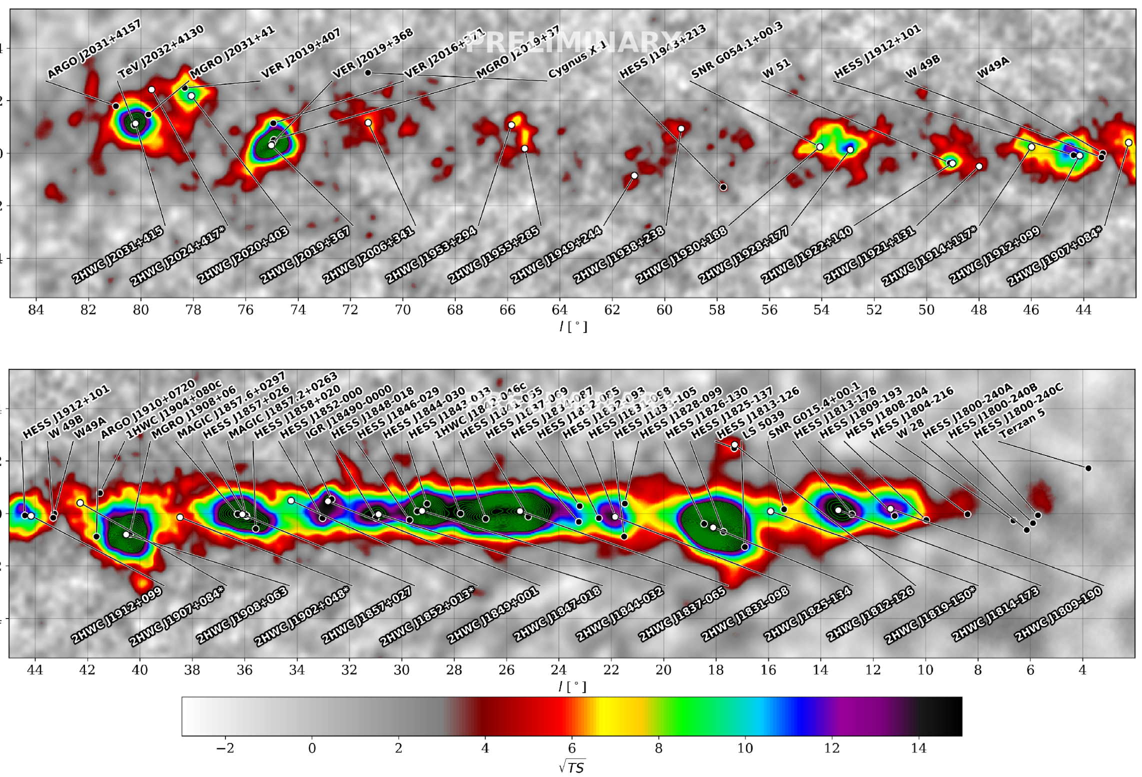
- **Extra-Galactic emission:**

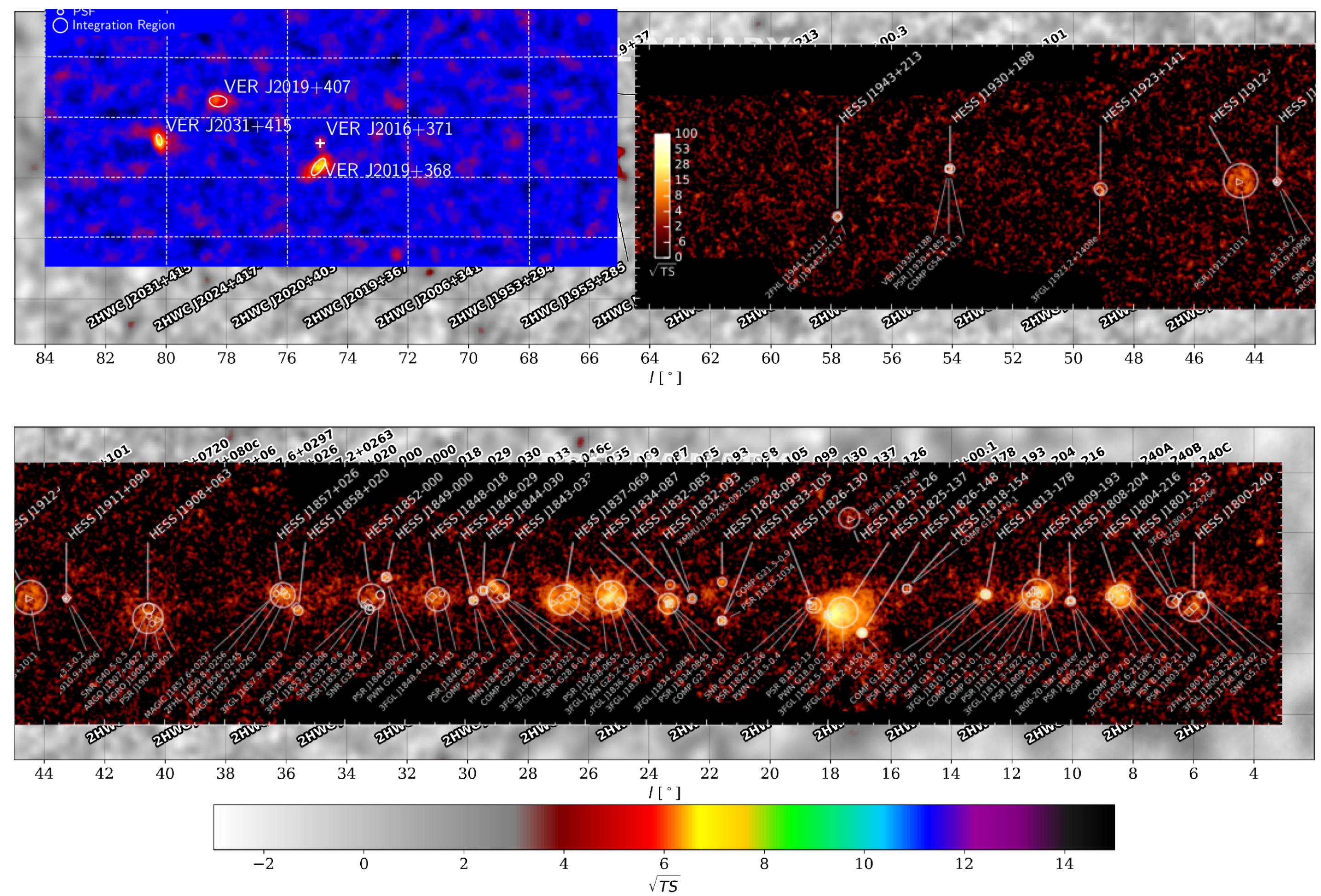


Fermi-LAT collab., arXiv:1410.3696

A tribute to the data: The multi-TeV gamma-ray sky

- Many ongoing and planned experiments. Magic, H.E.S.S., Veritas, CTA, HAWC…



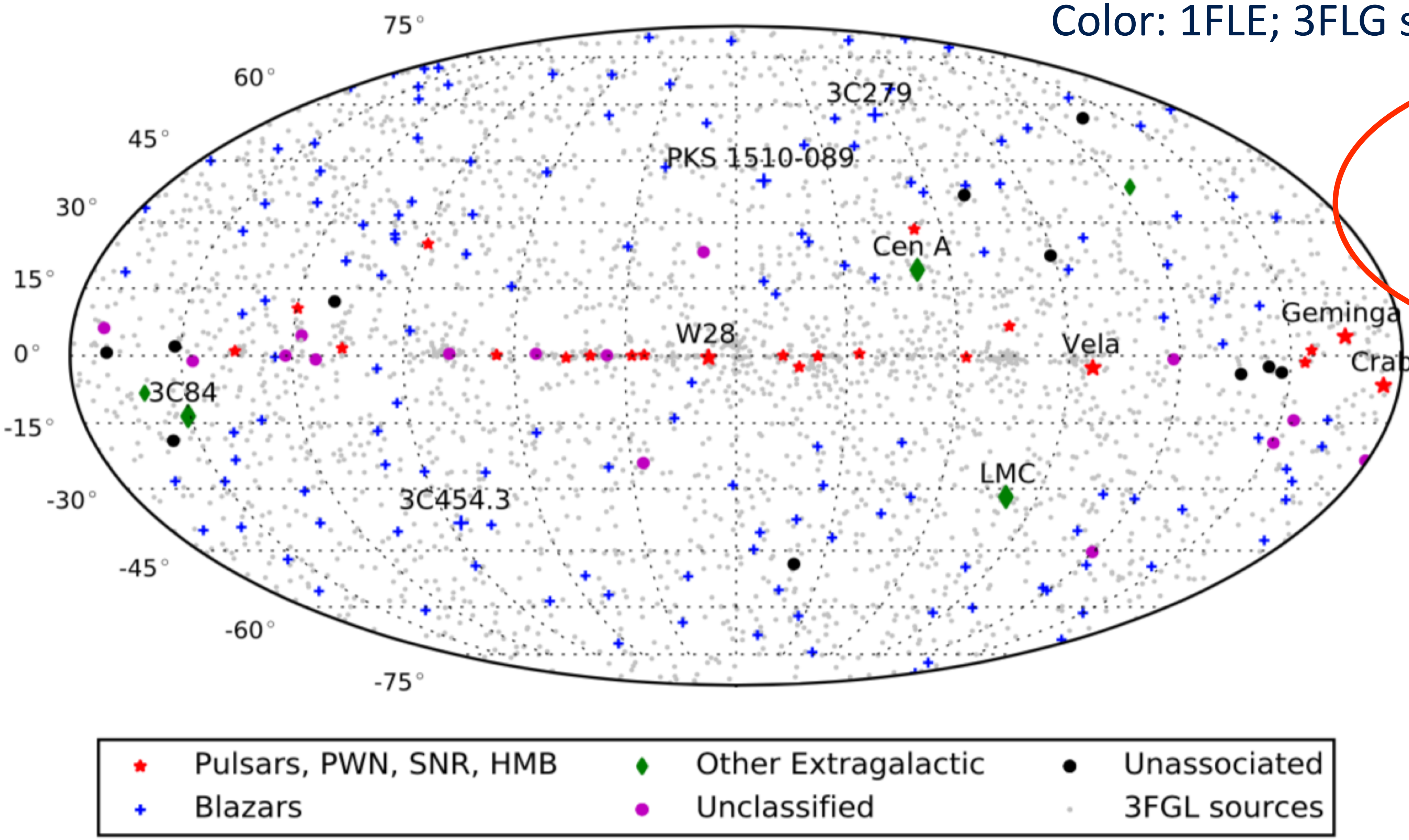


HAWC collaboration

H.E.S.S. collaboration

from TeVPa 2018

GeV-TeV Gamma-ray point sources



Color: 1FLE; 3FLG sources in grey

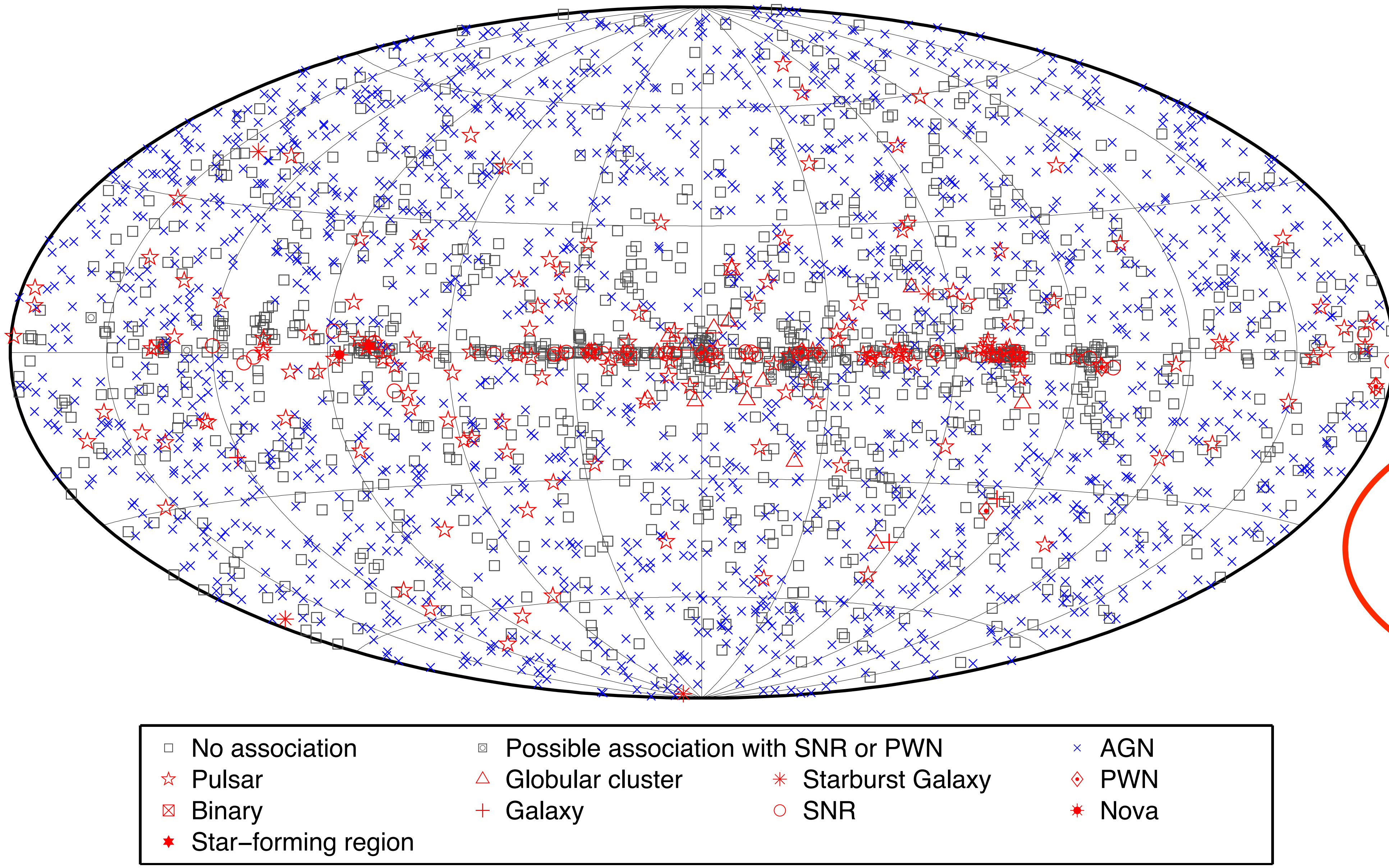
1FLE
0.03 – 0.1 GeV
198 sources
arXiv:1806.10865

3FGL
0.1 – 300 GeV
3033 sources
arXiv:1501.02003

3FHL
1556 sources
10 GeV – 2000 GeV
arXiv:1702.00664

courtesy of W. Hoffmann, TeVPa 2018

GeV-TeV Gamma-ray point sources



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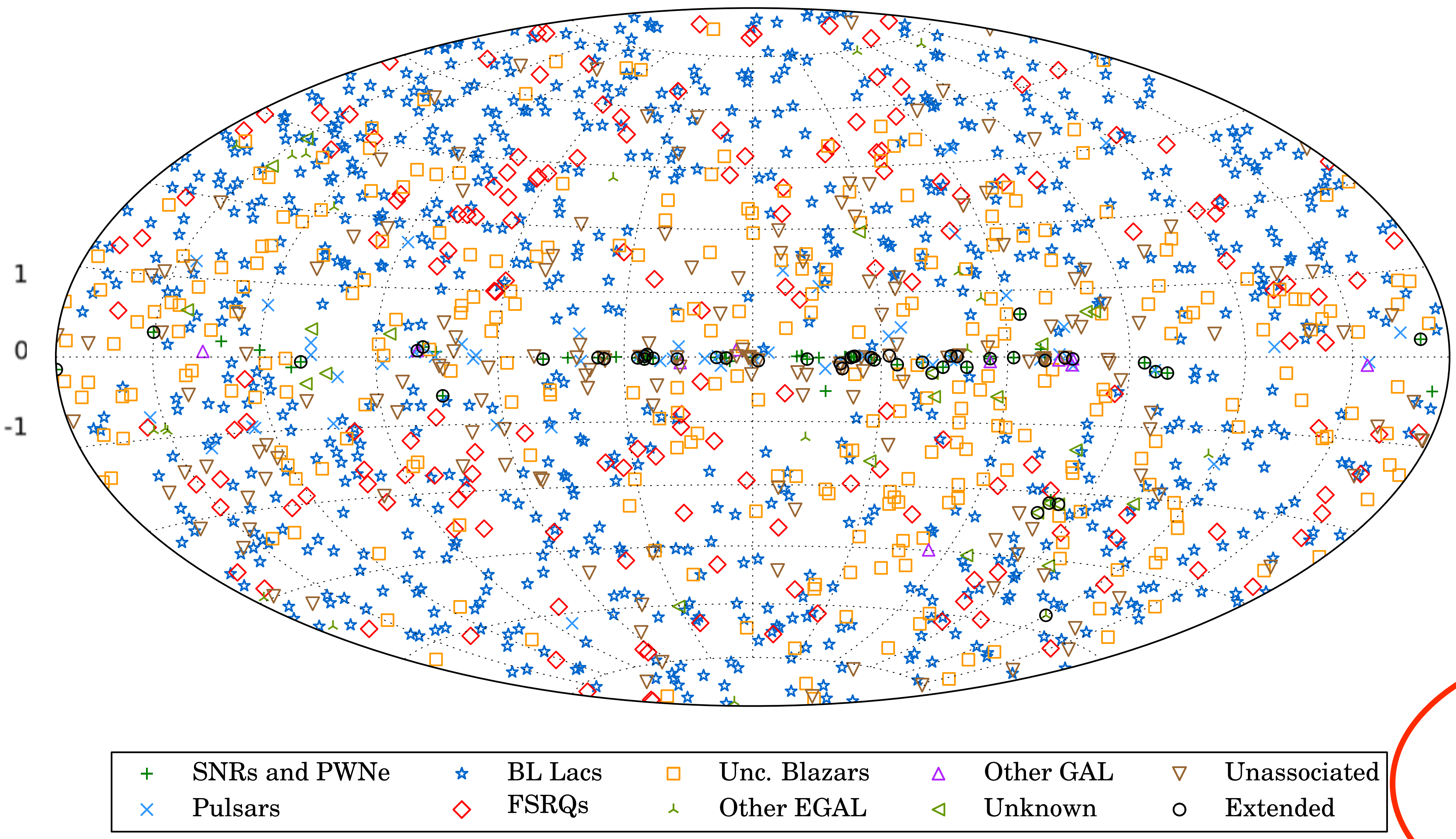
GeV-TeV Gamma-ray point sources



urces in grey

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3FGL
0.1 – 300 GeV
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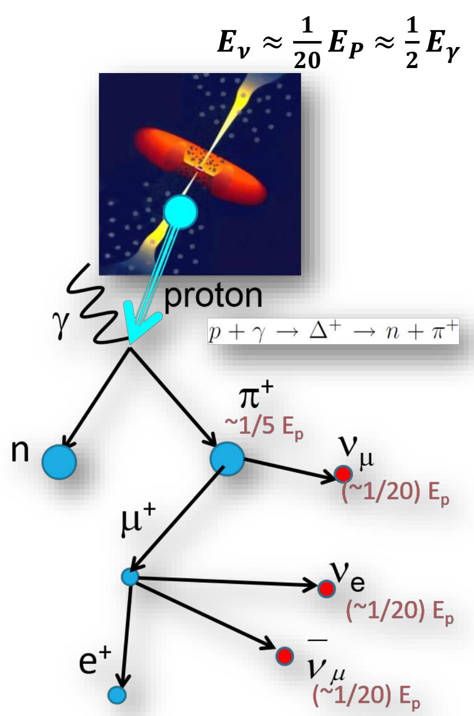
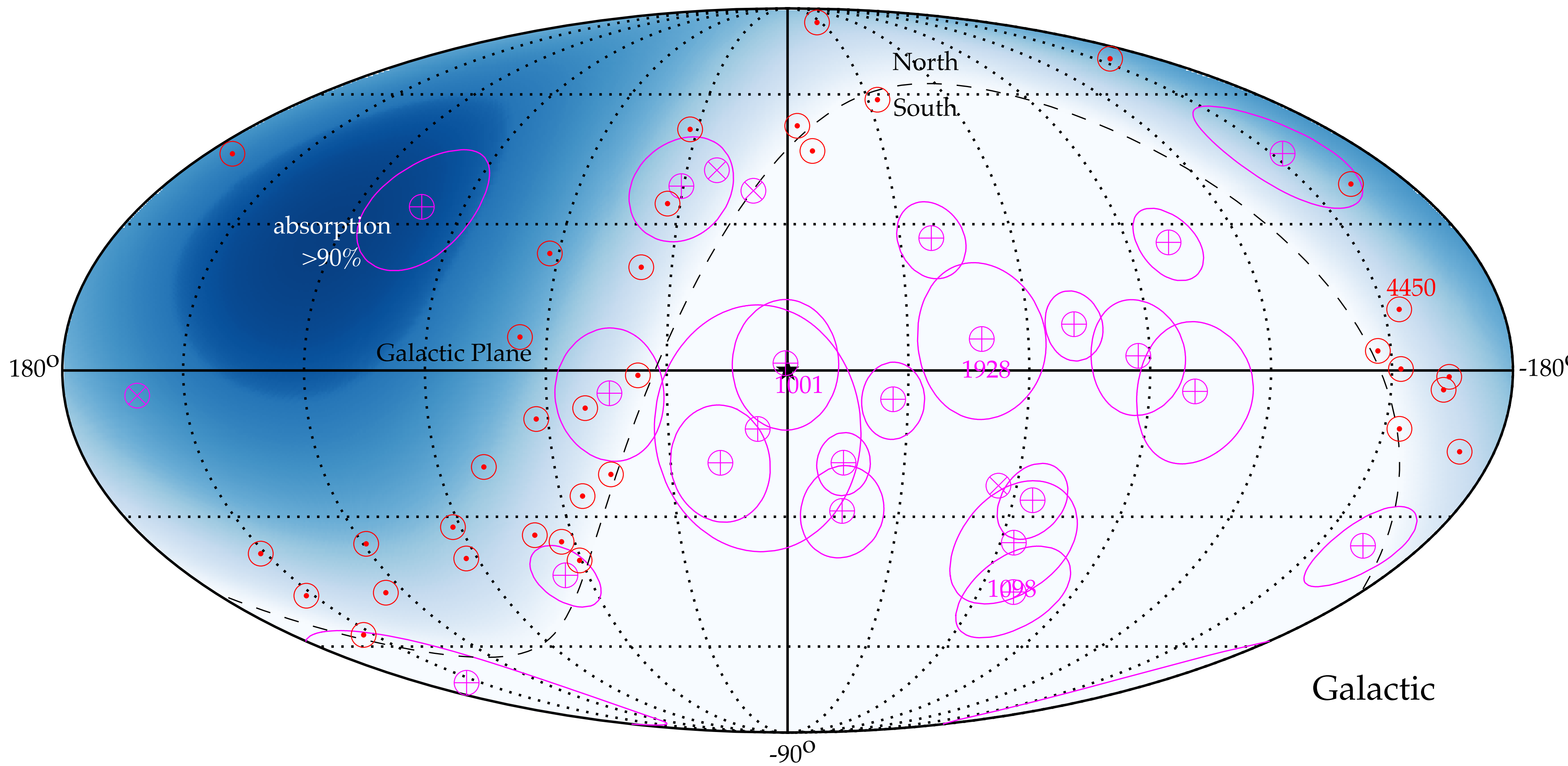
3FHL
1556 sources
10 GeV – 2000 GeV
arXiv:1702.00664

A tribute to the data: Neutrinos



Arrival directions of most energetic neutrino events (HESE 6yr (magenta) & $\nu_\mu + \overline{\nu}_\mu$ 8yr (red))

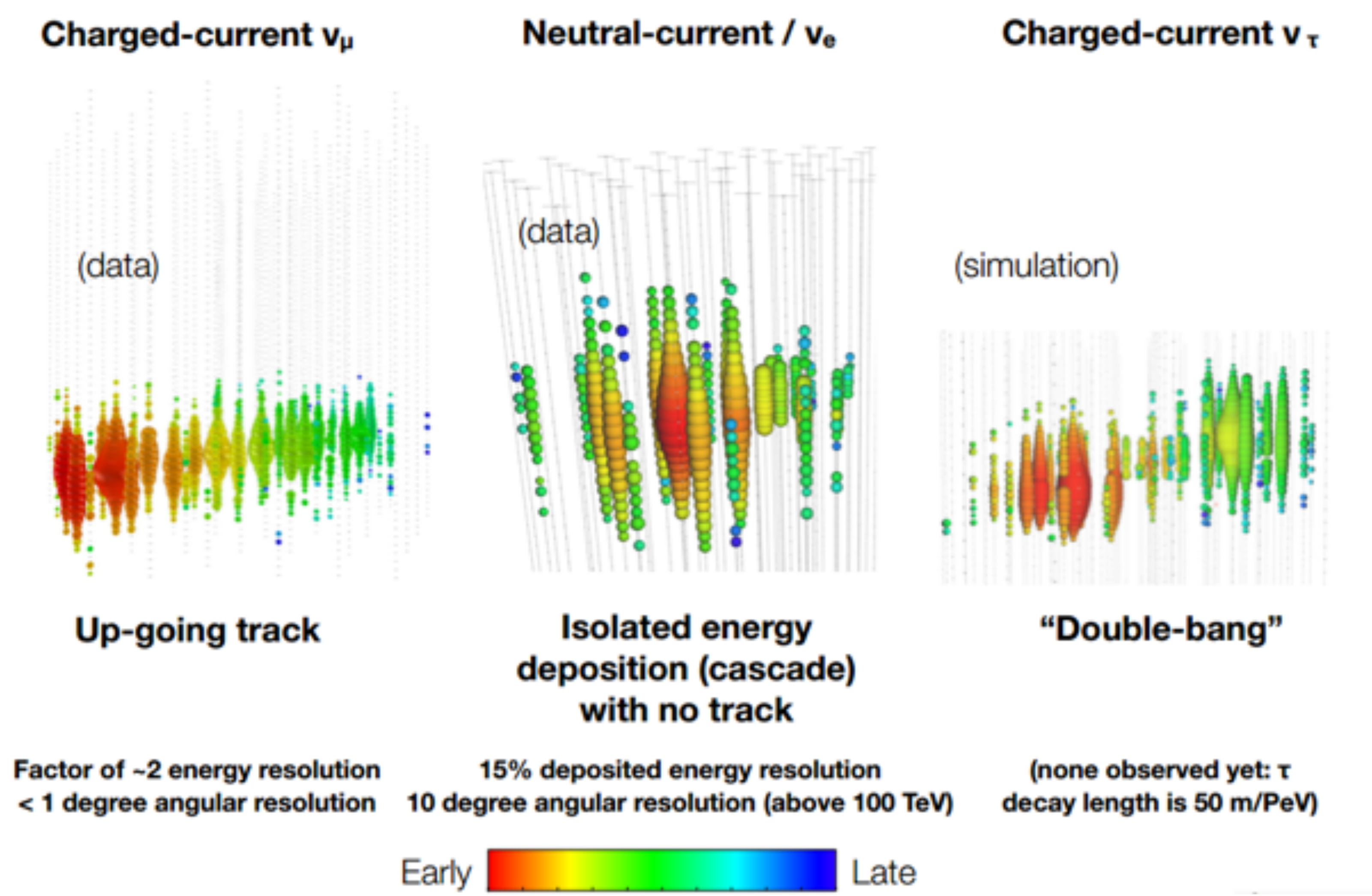


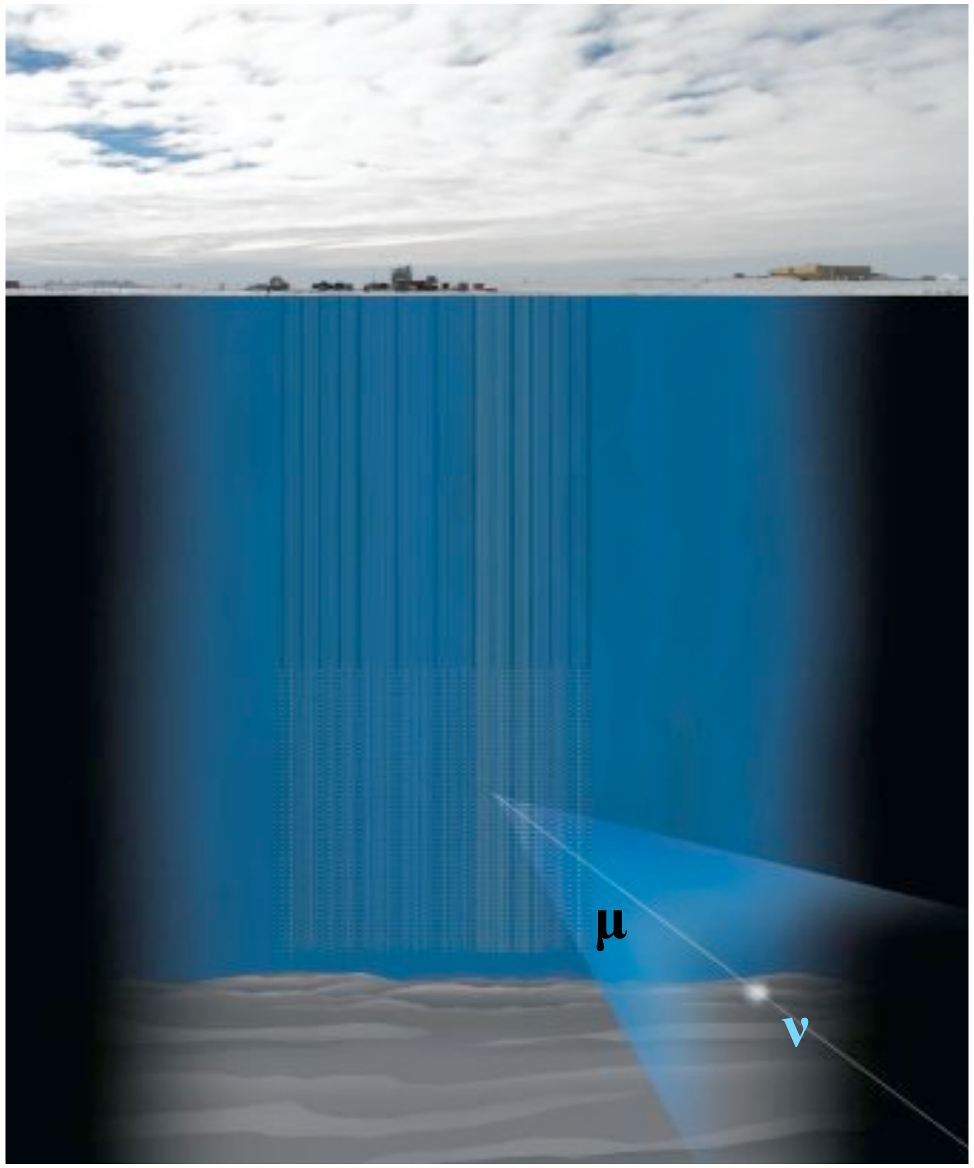
- New window on the high-energy Universe opened in 2013 [IceCube collab., Science 342 (2013)]

- Two classes of events:
  - ☆ HESE: High-energy starting events [6 years] [IceCube collab., Science 342 (2013); ICRC 2017]
  - ☆ Up-going muon tracks [8 years] [IceCube collab, ApJ 833 (2016); ICRC 2017]

A tribute to the data: Neutrinos

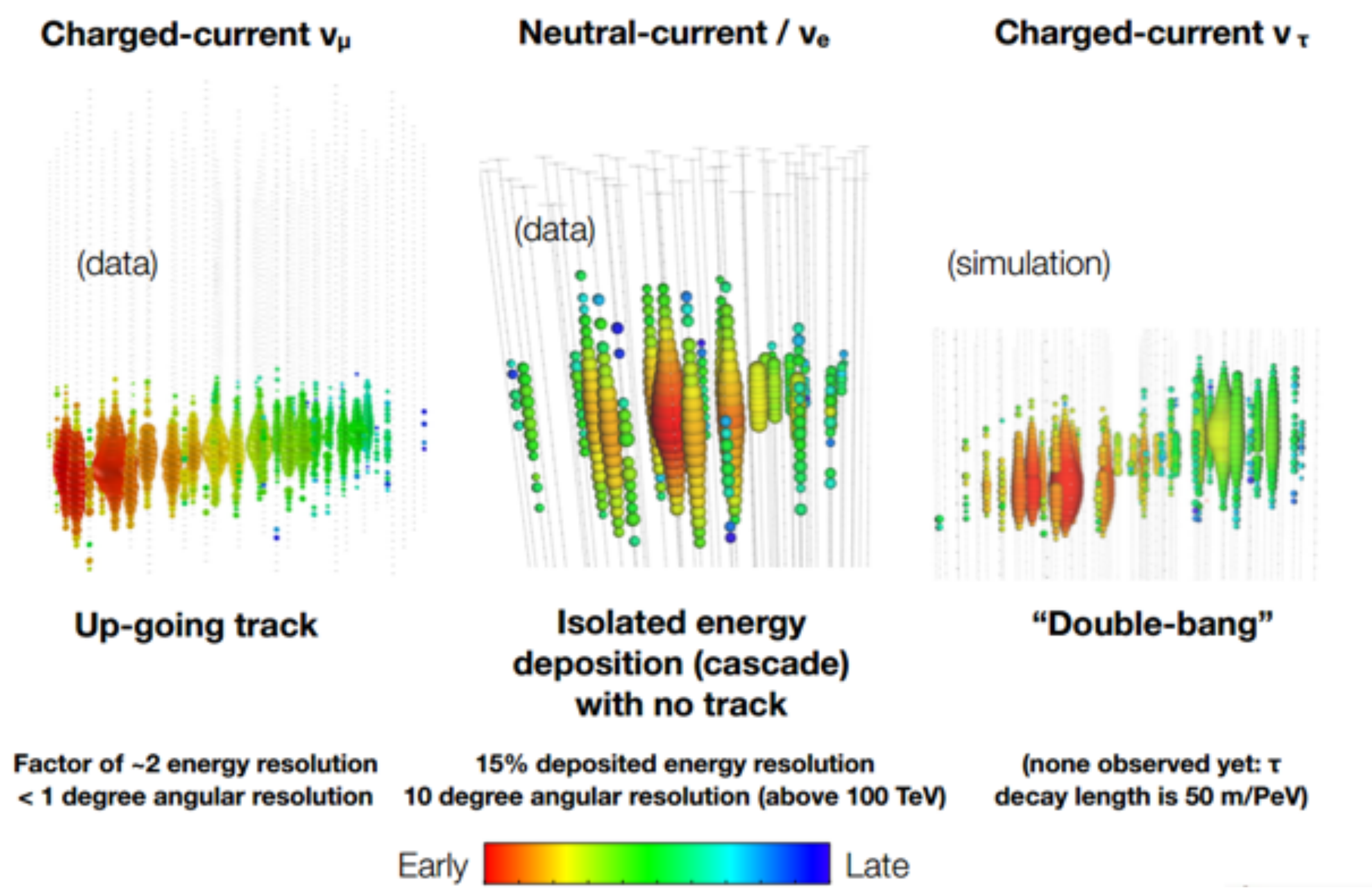
- **HESE**: interaction inside the detector
- **Through-going muons**: interaction outside the detector

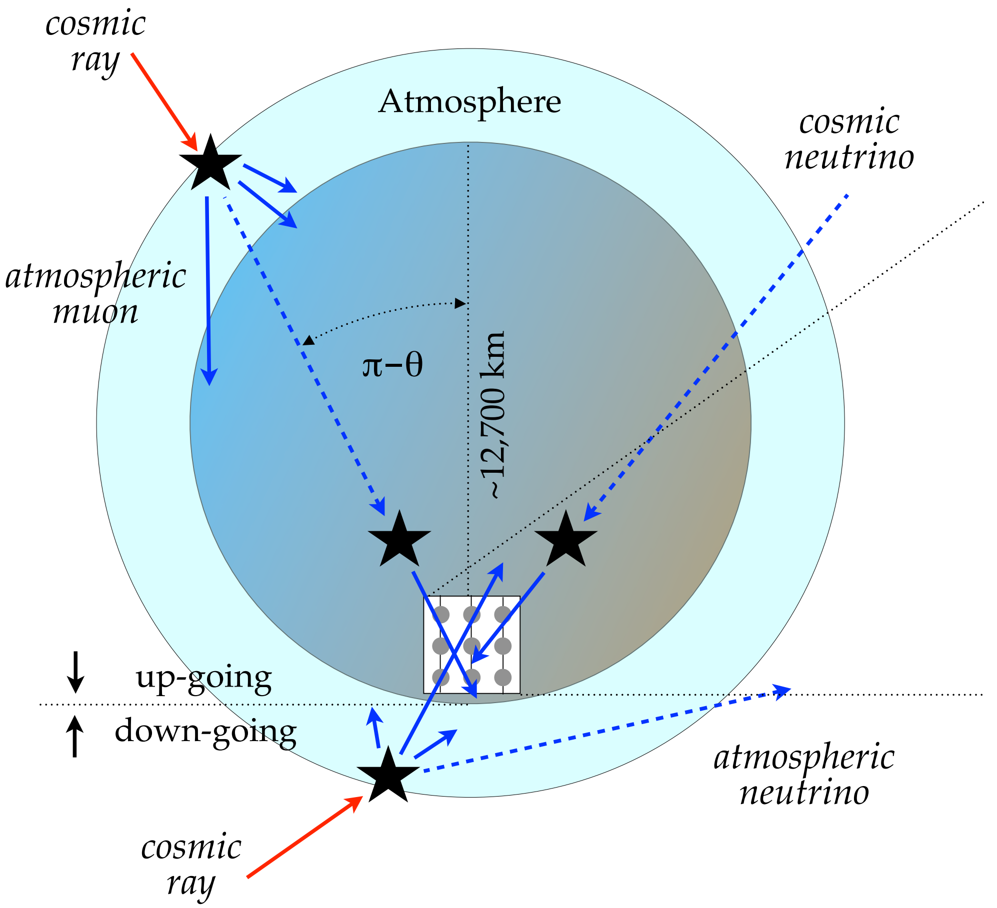




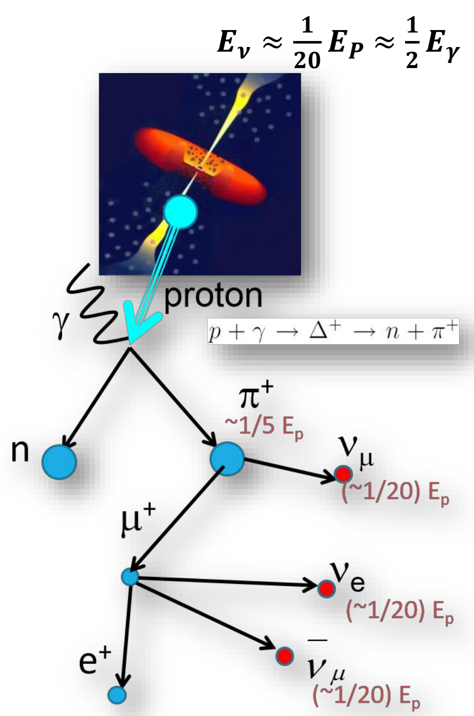
A tribute to the data: Neutrinos

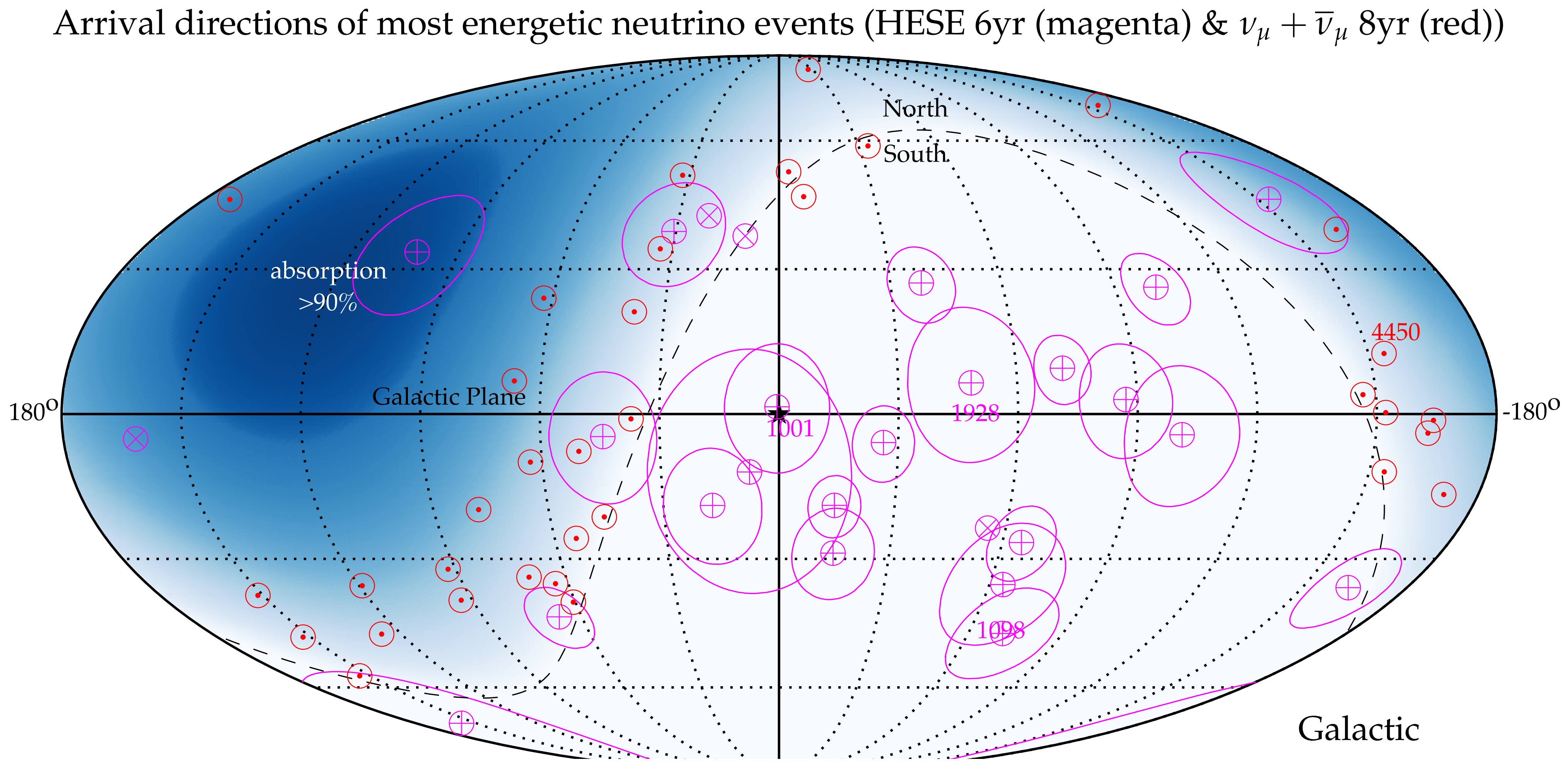
- **HESE**: interaction inside the detector
- **Through-going muons**: interaction outside the detector





The key questions





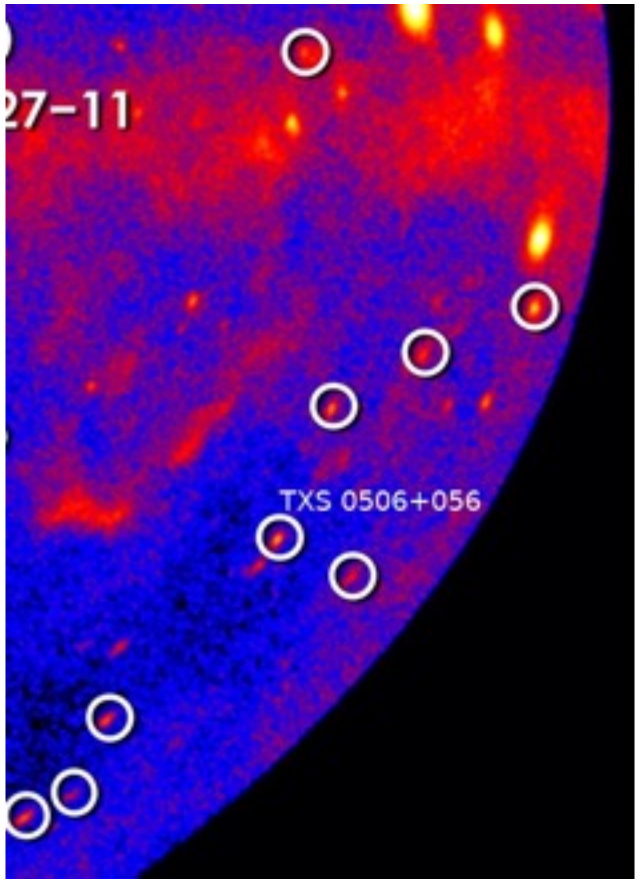
- **Consistent with isotropy** —> Most likely extra-Galactic origin.
- What about a possible Galactic component? How can these data, together with gamma-ray data, constrain CR propagation models [first part]
- Which class of sources contribute the most? How can we identify them using multi-messenger data? [second part]

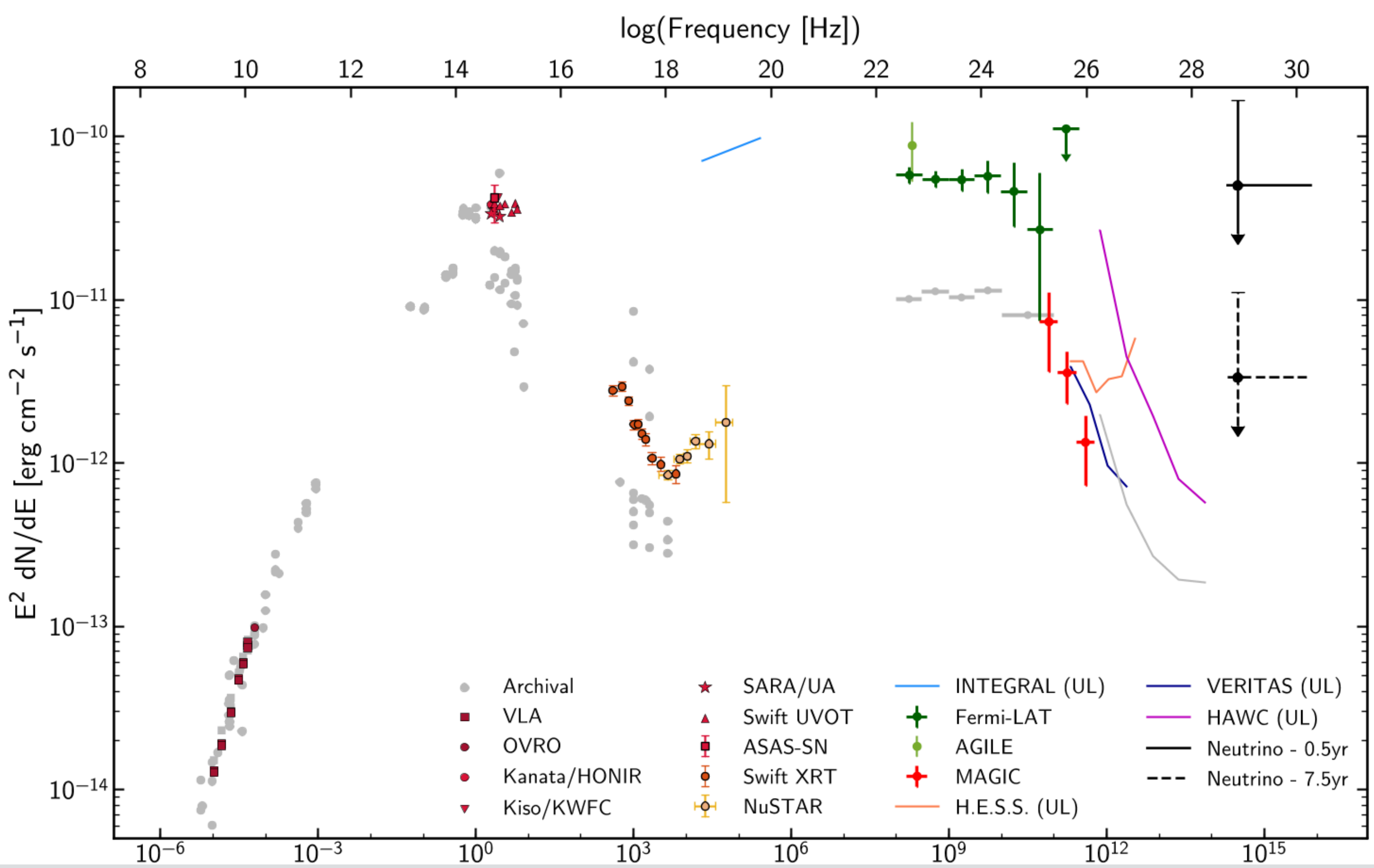
A spectacular complementarity between γ-rays and neutrinos

- 22/09/2017: Icecube detects a ~290 TeV muon neutrino, dubbed **`IceCube-170922A`**, selected by the Extremely High Energy (EHE) online event filter, and reported as a **public alert** (EHE alerts are based on well-reconstructed, HE muon-track events)

- Most likely source: **`TXS 0506+056`**, a distant (~1.7 Gpc) **blazar** with high intrinsic γ-ray luminosity
- This source was found to be in a **flaring state** by the Fermi-LAT experiment

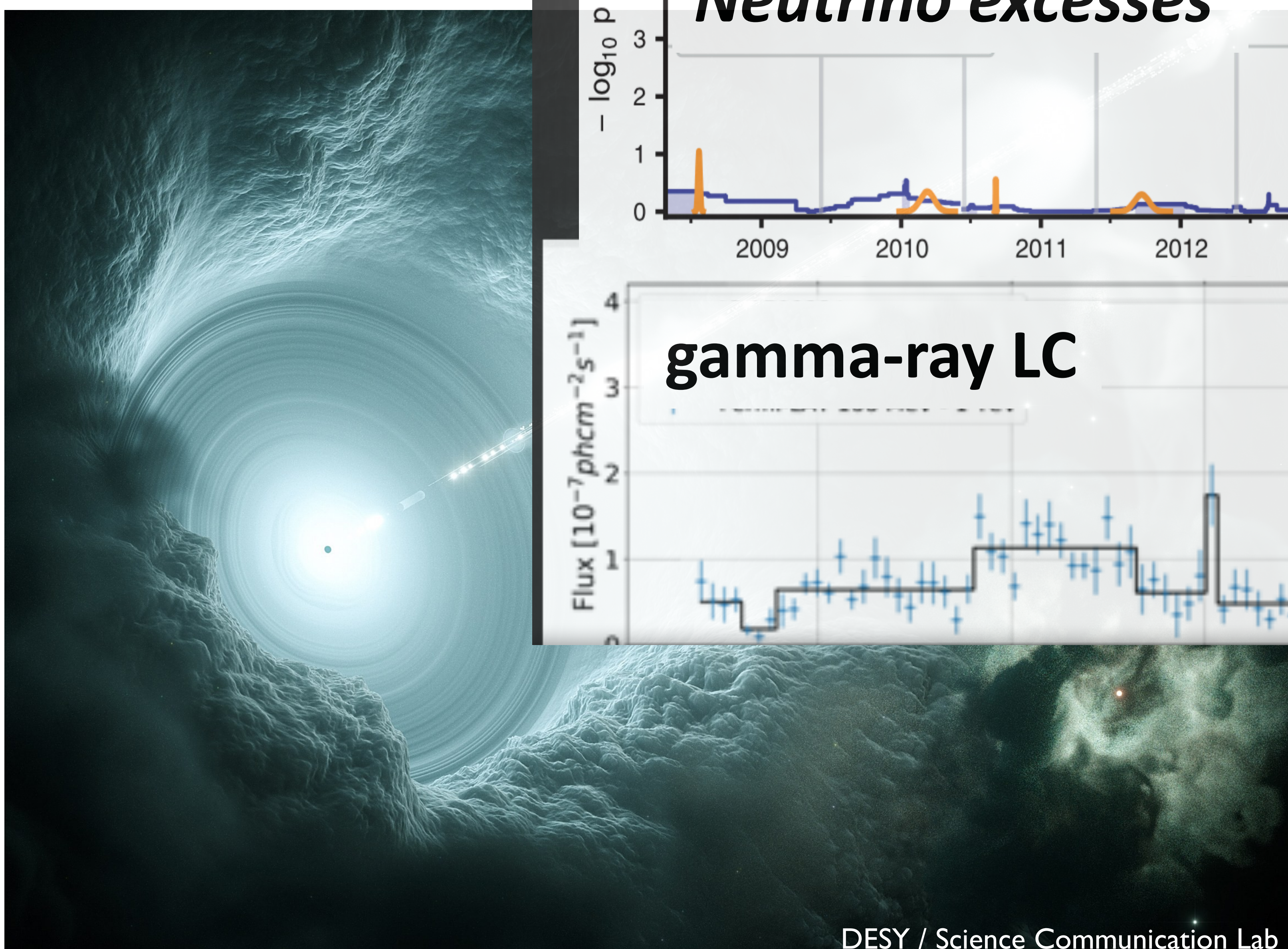
- Further observed in many wavelength including radio, infrared, optical, X-rays and gamma-rays: **Spectacular multi-messanger and multi-wavelength spectrum!**

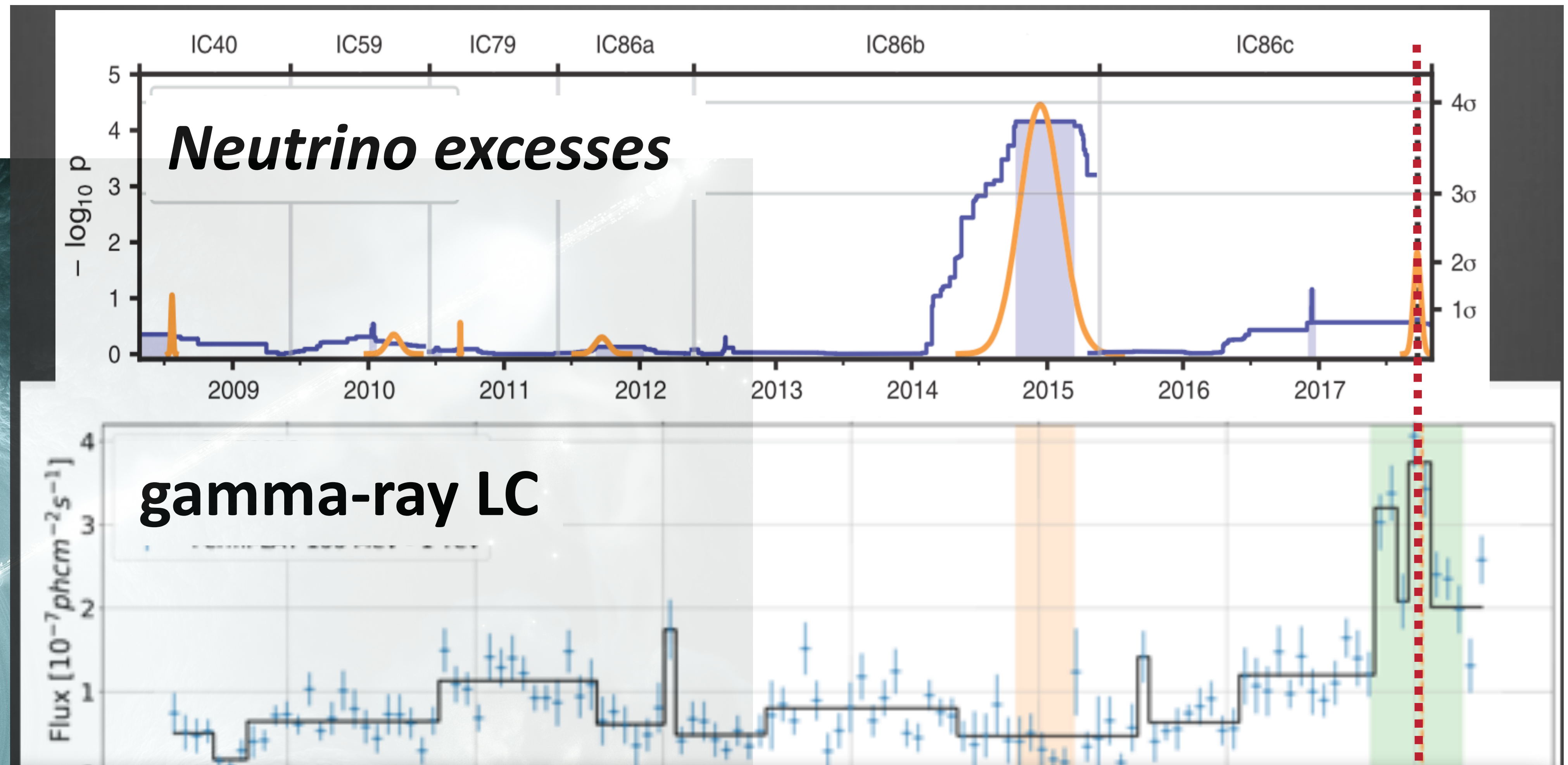




A spectacular complementarity between γ-rays and neutrinos

- Further evidence for an **earlier flare** of lower-energy neutrinos in 2014-2015 (identified in the complete, unprocessed sample of events detected by IceCube), which supports the identification of that blazar as the source of **`IceCube-170922A`**
- However, **no gamma rays from the earlier flare**



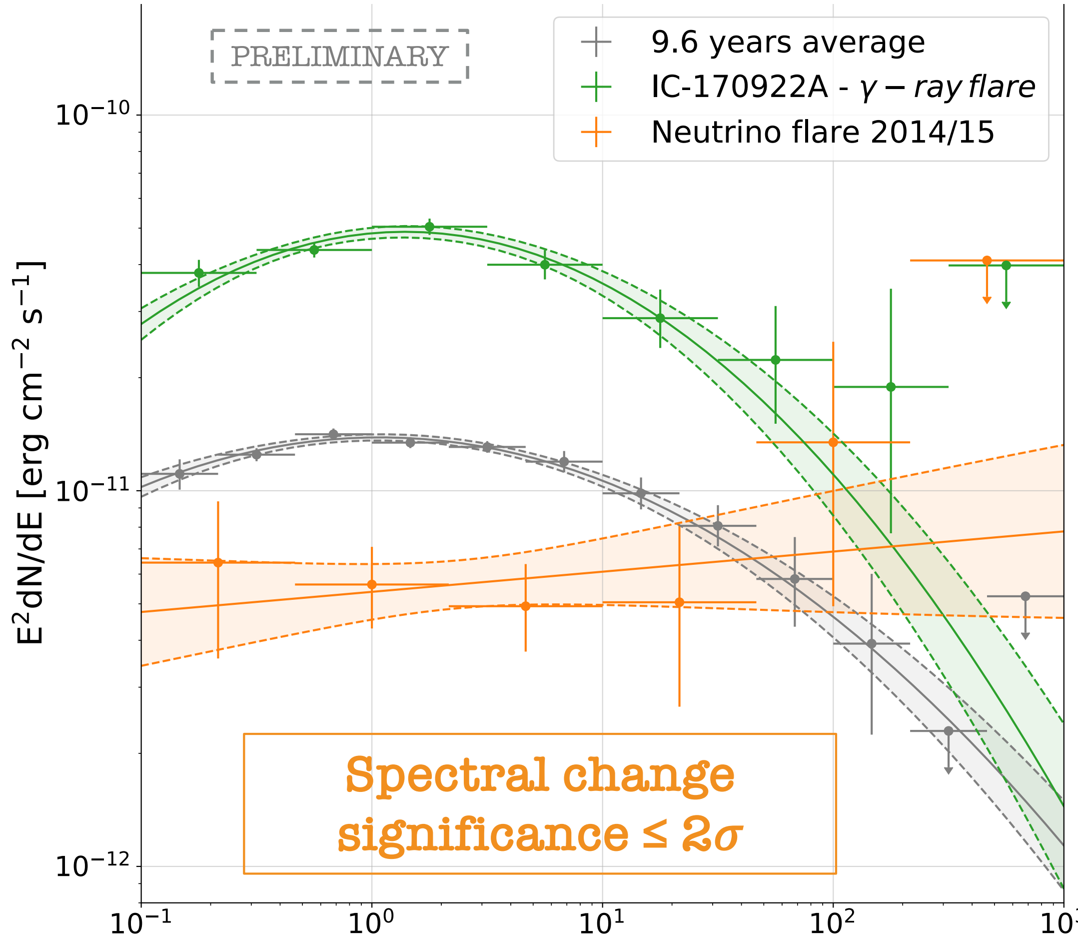


Lessons learned

- The AGN **TXS0506+056** can be the source of the HE neutrino detected in 2017
  - The HE event in 2017 and the excess in 2014/2015 are signatures of *different states:*

☆ The **2014/15 flare** seems to be characterized by **low flux/ hard spectrum.**

☆ The **2017 flare** was characterized by **large flux/ soft spectrum.**

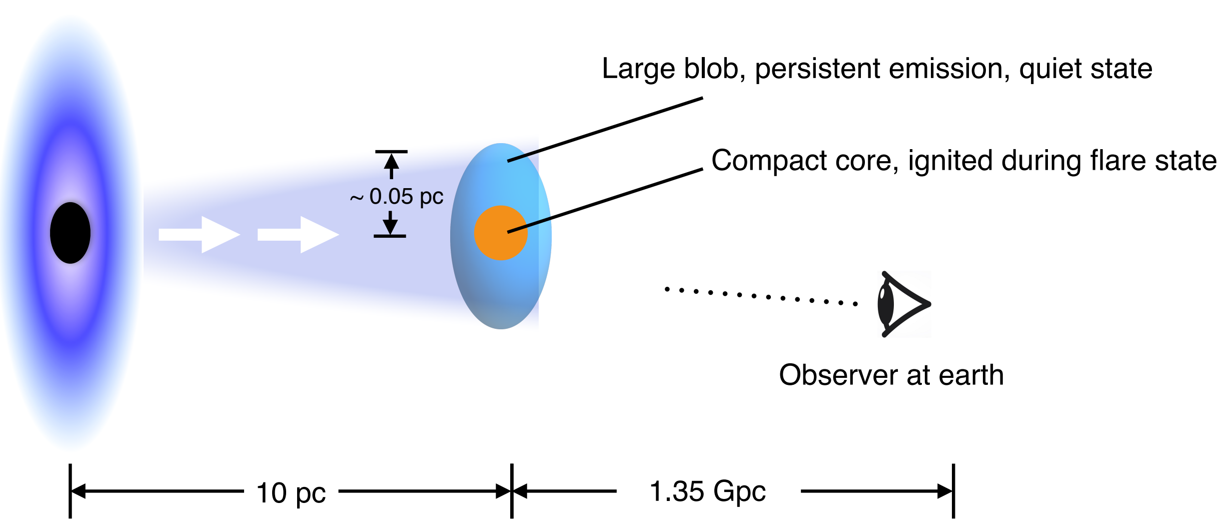


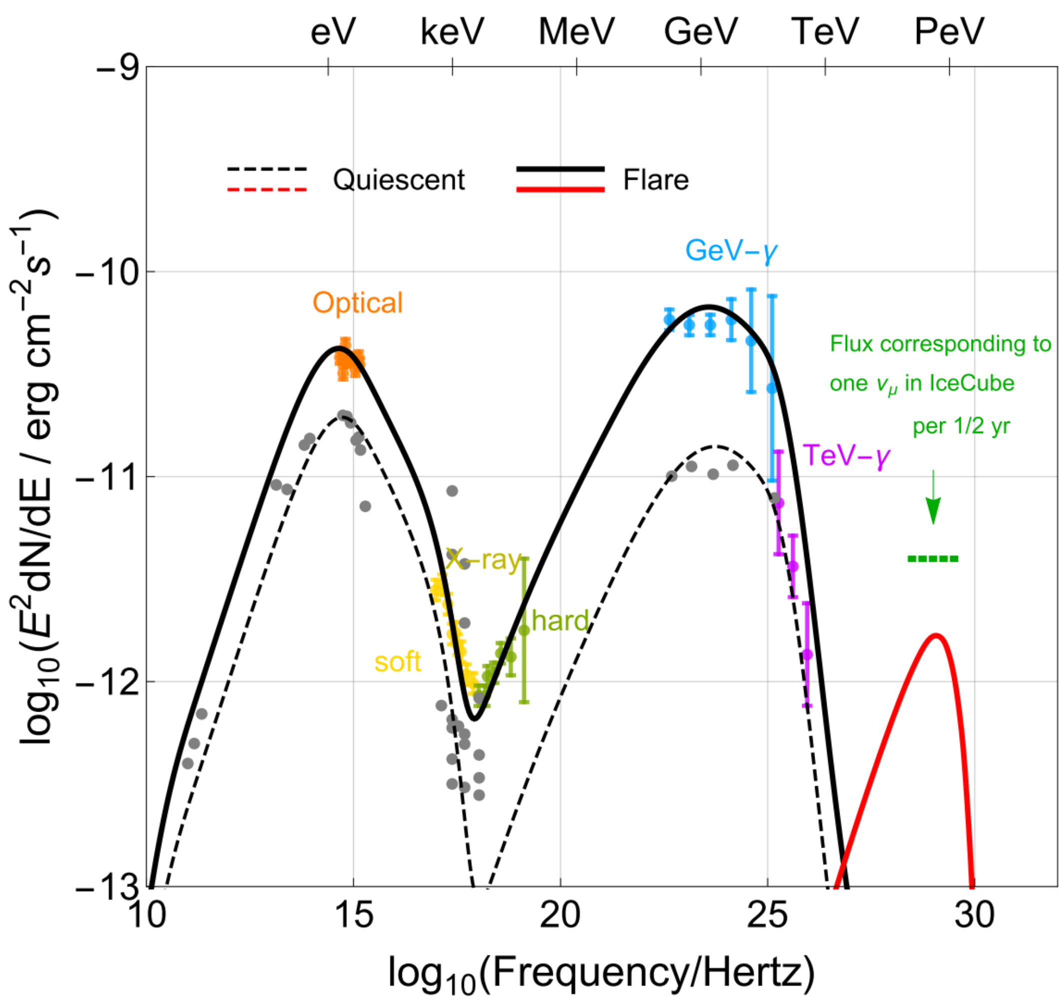
courtesy of S. Garrappa, TevPa 2018

A spectacular complementarity between γ-rays and neutrinos

Model building is complicated!

- **One zone lepto-hadronic models** [e.g. Murase+ 2018 1807.04537]
  - ☆ A **leptonic scenario with a radiatively-subdominant hadronic component** provides a physically-consistent single-zone picture
  - ☆ The SED exhibits its greatest sensitivity to hadronic processes across its **0.1–100 keV** "dip": Flux variations over this energy range are likely to reflect the source's high-energy neutrino emissions: **Regular X-ray monitoring will provide a critical test**
- **Two-zone models** [e.g. Gao+ 2018]





Point sources: Other associations?

GB6 J1040+0617

Counterpart for HESE 63

Preview from TeVPa 2018

IC-141209A

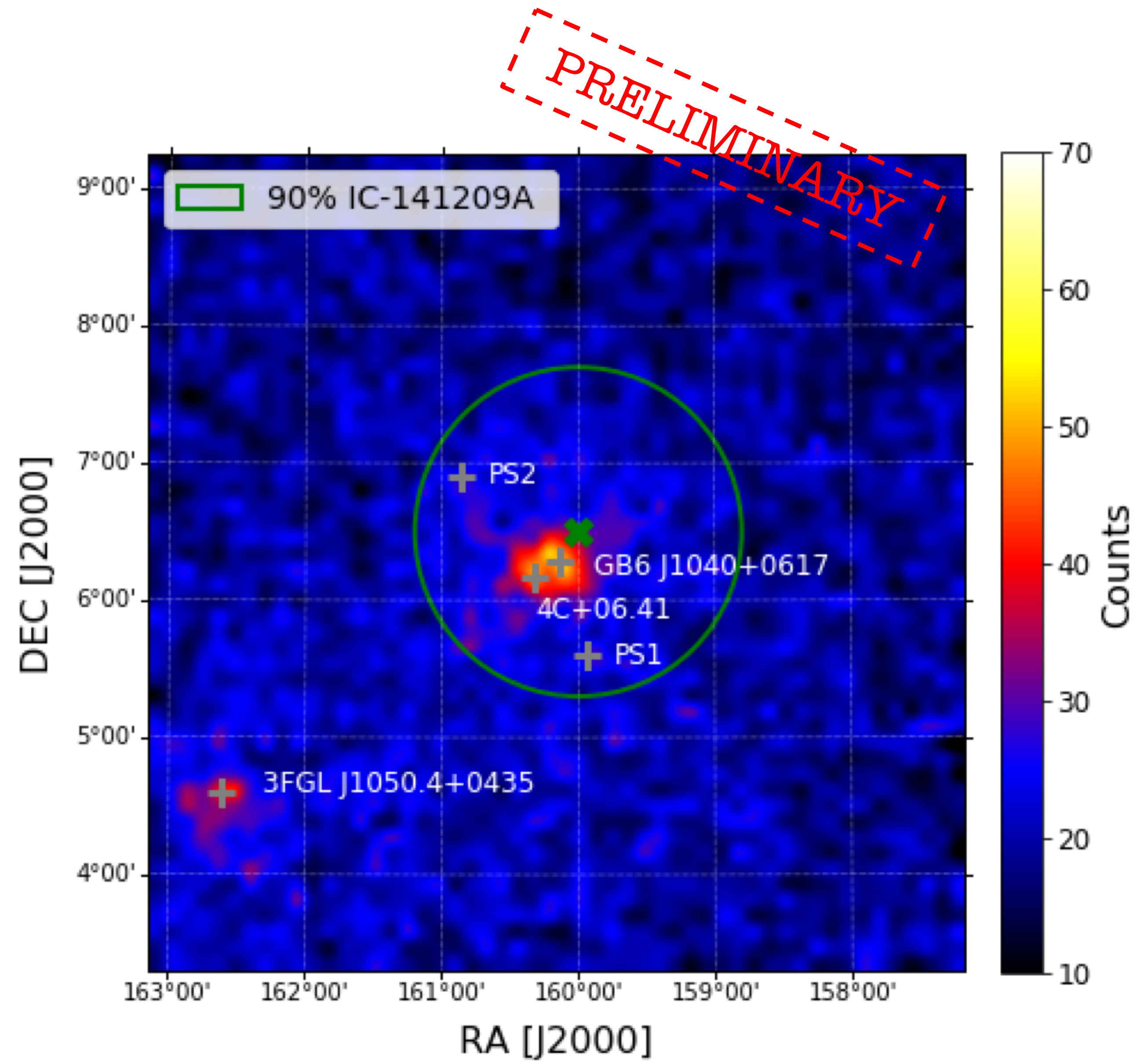
- MJD 57000.14
- (Ra , Dec) = (160.0°, 6.5°)
- Ang. Err. (90%) : 1.2°

GB6 J1040+0617

- BL Lac, LSP
- 3FGL J1040.4+0615
- z = 0.7351± 0.0045 *
- Dist. from IC-141209A: 0.27°

ROI

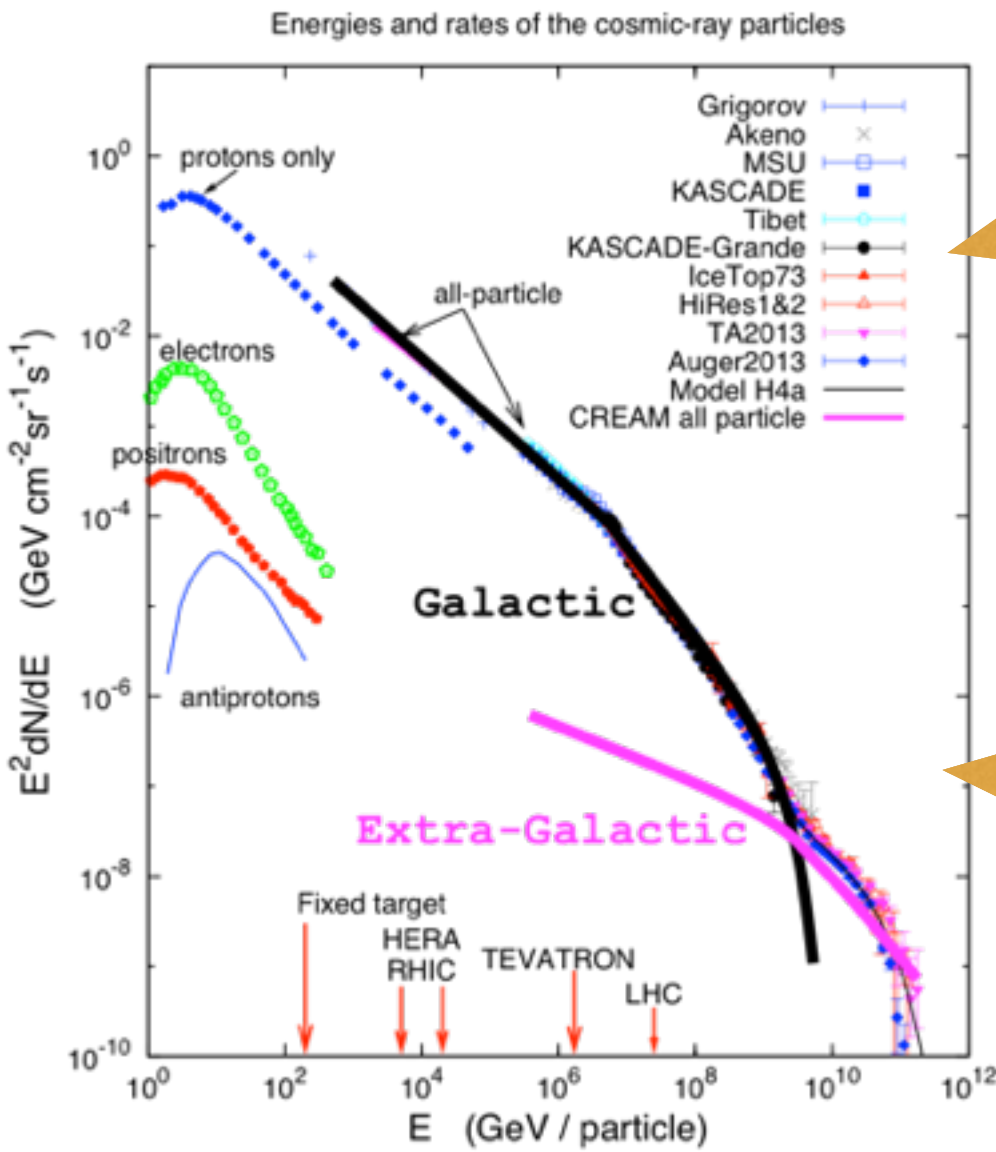
- 4C+06.41 (QSO)
- Two additional sources (PS1 and PS2) found using 9.6 years of data
- PS2 also included in FL8Y as FL8Y J1043.3+0651
- Very dim, can be excluded as possible counterparts.

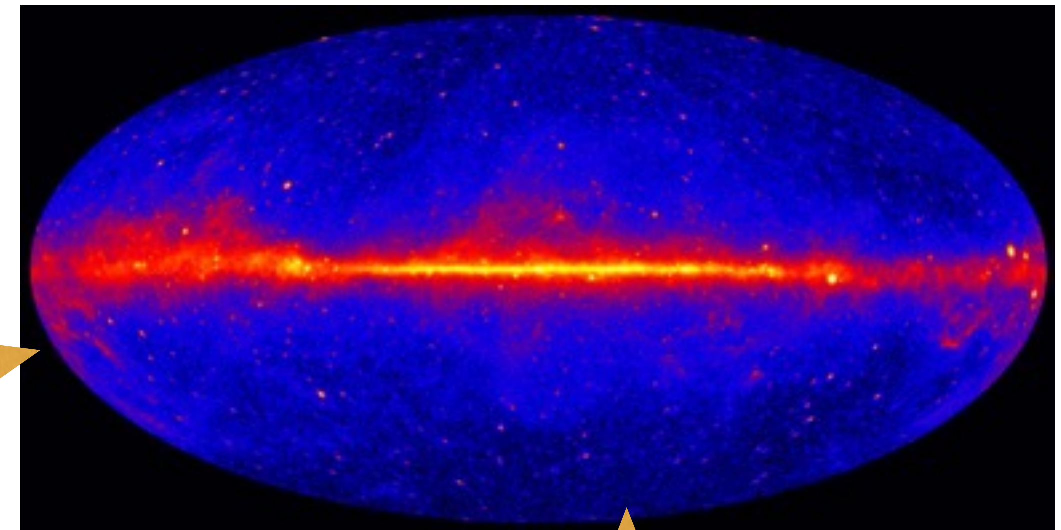


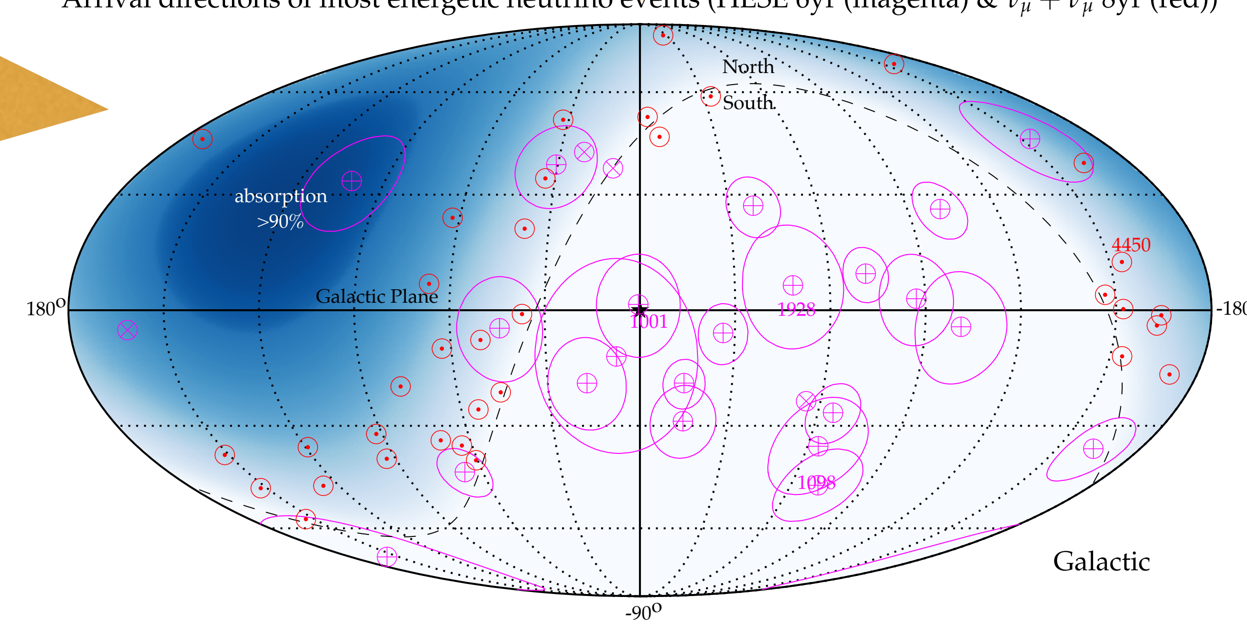
Garrappa+ (in preparation)


Part 1: Gamma-Neutrino connections in our Galaxy

The CR-gamma-neutrino connection



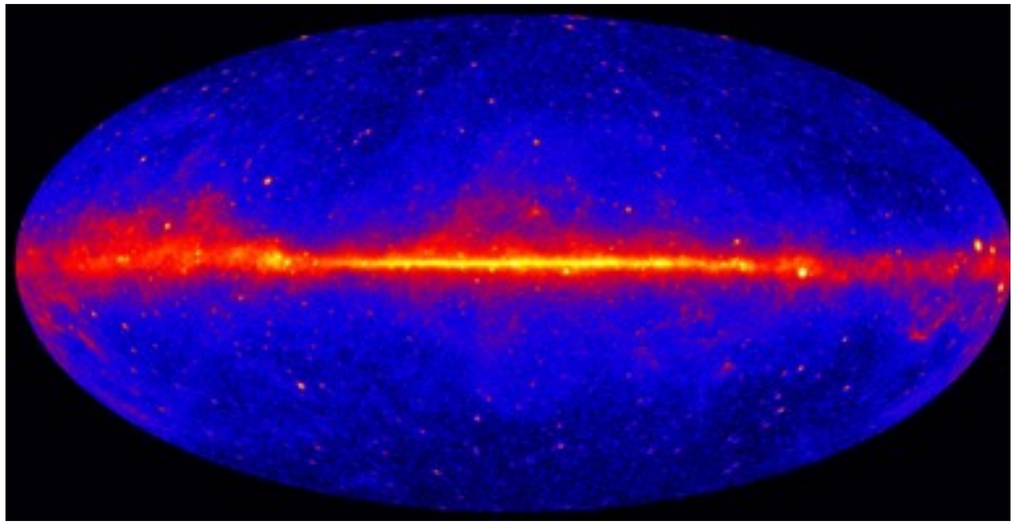


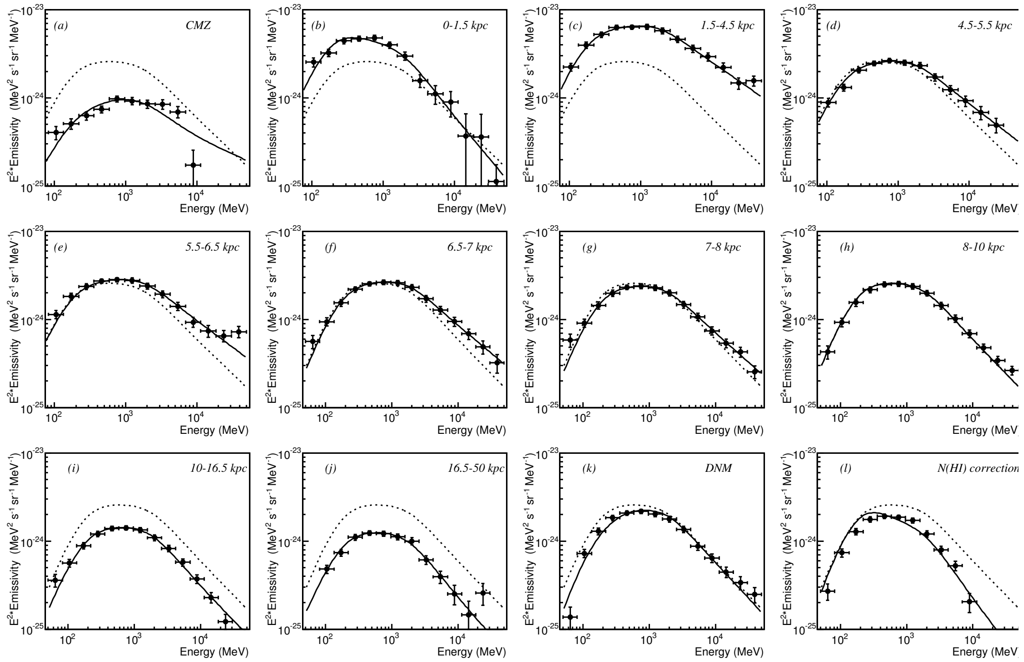


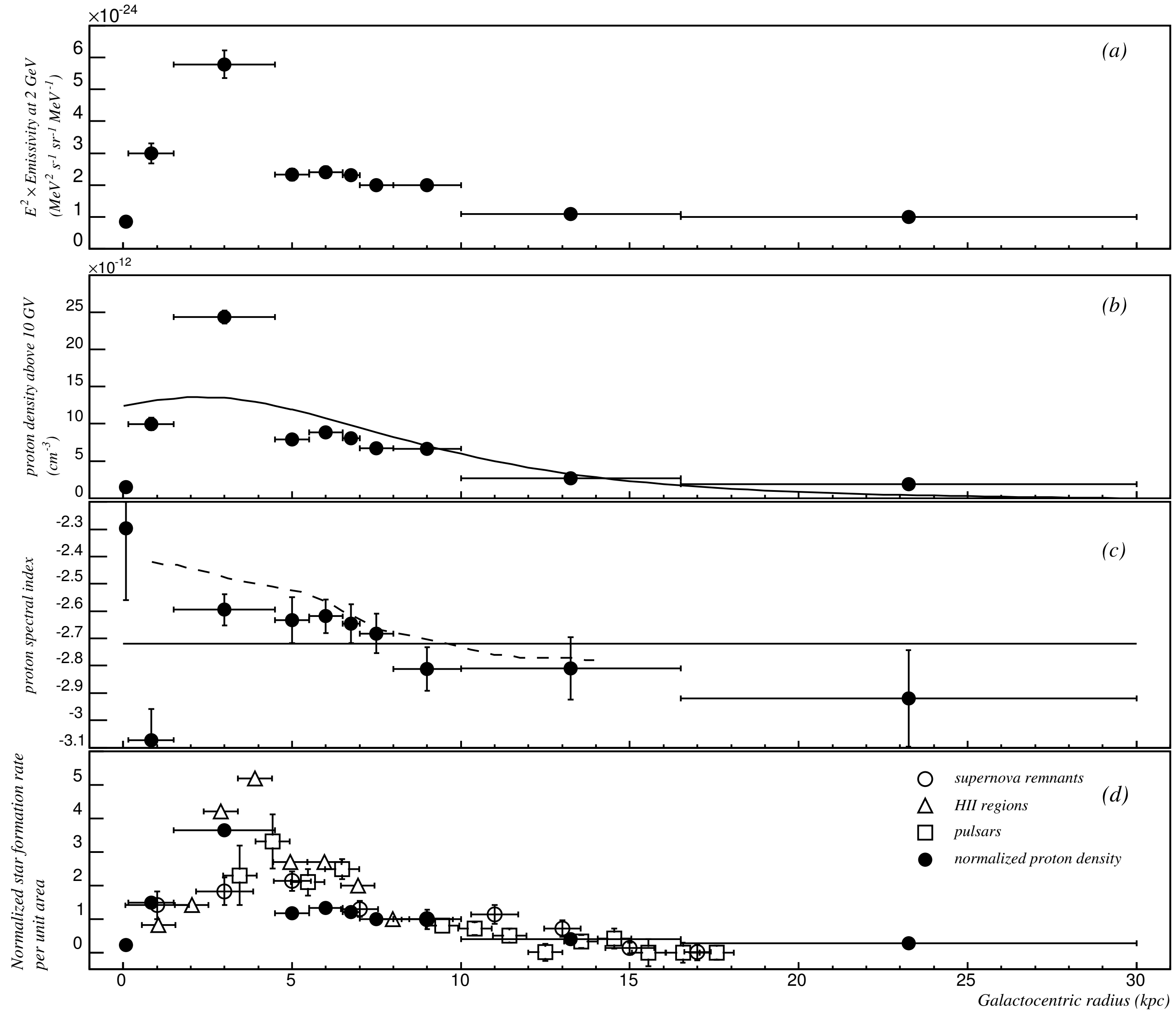
Two key questions

- Which fraction of the neutrinos detected by IceCube is Galactic?

- **What can gamma-ray and neutrino data teach us about the physics of CR transport and the mechanisms of CR confinement?**







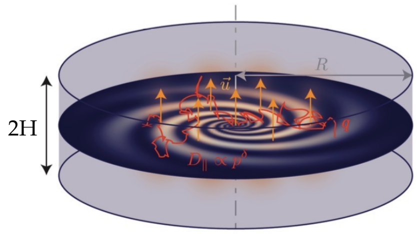
The “orthodoxy” of CR physics

The three pillars

- 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

The numerical approach to model the problem

All the **physical processes** that can affect CR transport in the Galaxy and shape the diffuse CR sea are modeled *within a large diffusion box,* in a framework inspired by the “pillars” discussed before
[Morrison, Olbert, Rossi 1954; Ginzburg&Syrovatskii 1964; Berezinskii et al. 1990]



- **Primary CR production**
- **Secondary CR production** via spallation
- ***Rigidity-dependent* diffusion**. Usually parametrized in a simple way, guided from QLT results. Usually modeled as an isotropic and homogeneous rigidity-dependent coefficient (*simpler than the prediction of the simplest theory we have*) with relevant exceptions!
- *Rigidity-independent* **advection**
- Possibly, stochastic **II order Fermi acceleration** (*reacceleration*)
- **Energy losses**

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

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

$$J_i = -D_{ij} \nabla_j N$$

The numerical approach to model the problem

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[Morrison, Olbert, Rossi 1954; Ginzburg&Syrovatskii 1964; Berezinskii et al. 1990]

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- *Rigidity-independent* **advection**
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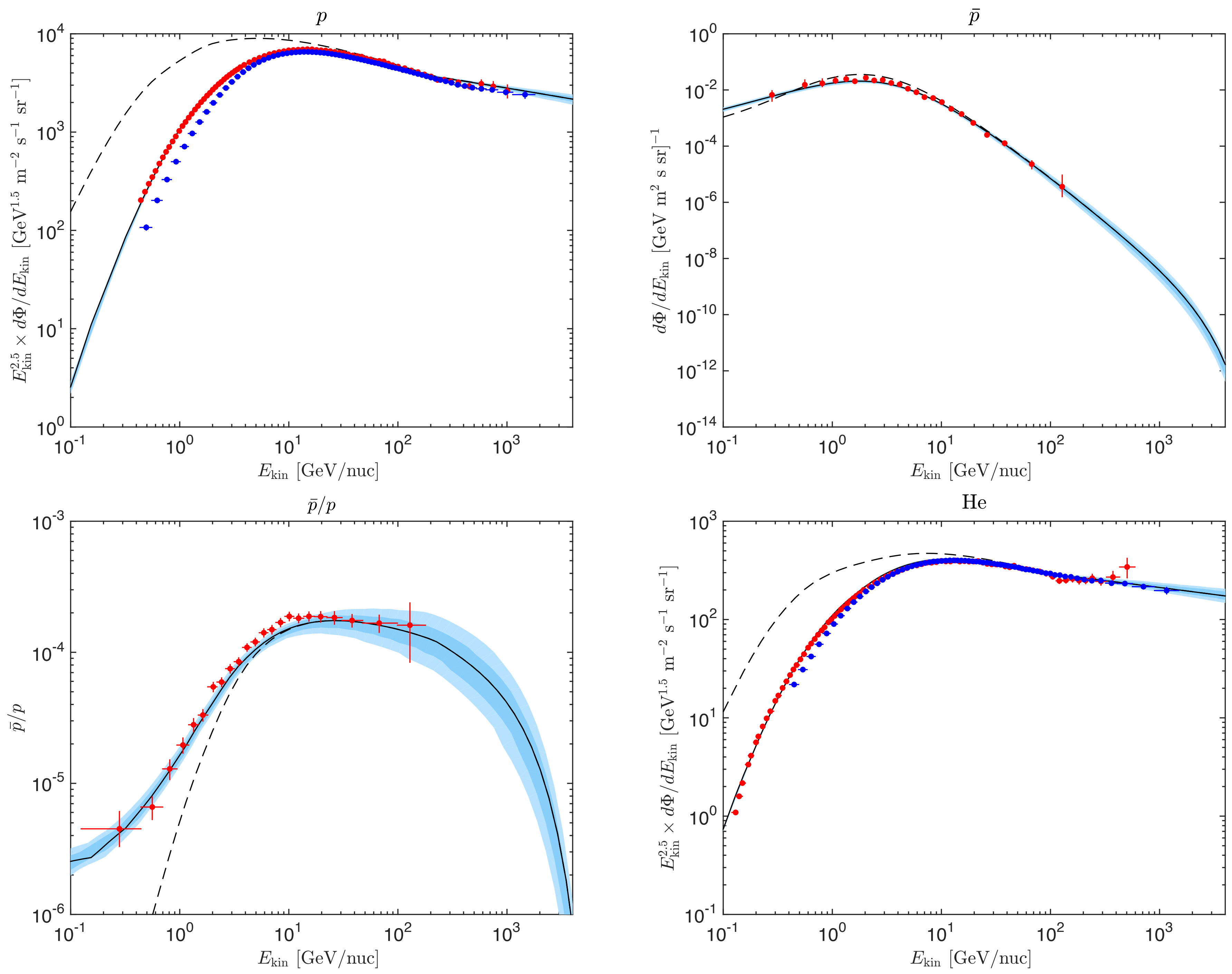
The good news

The power of multi-channel phenomenological analyses:
The "conventional scenarios" seem to work for many channels



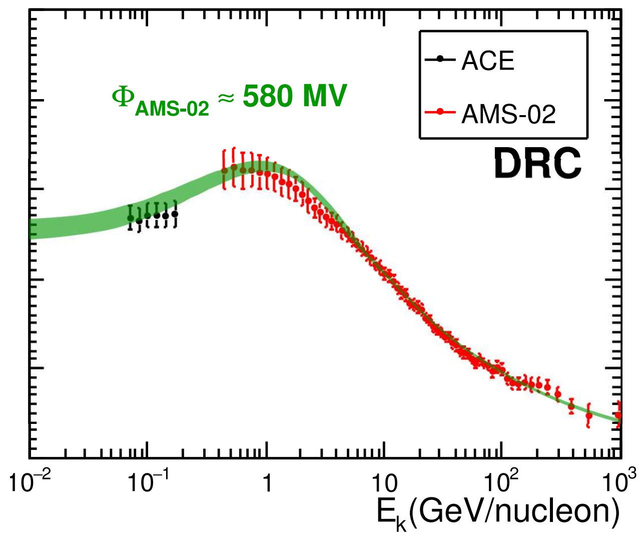
[Johanneson+, 2016]

The good news

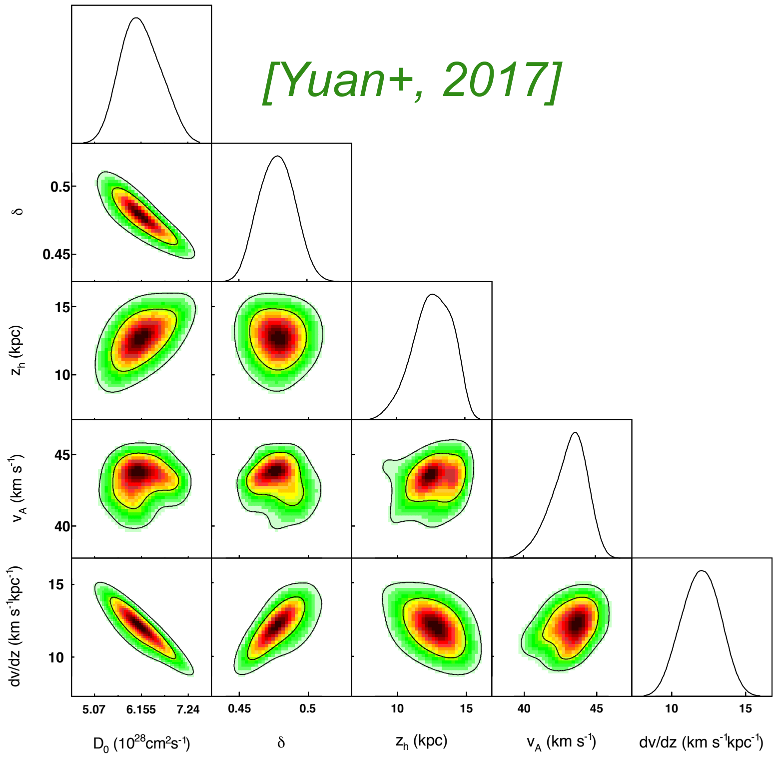
The "conventional scenarios" seem to work for many channels…

TABLE II: Posterior mean and 68% credible uncertainties of the model parameters

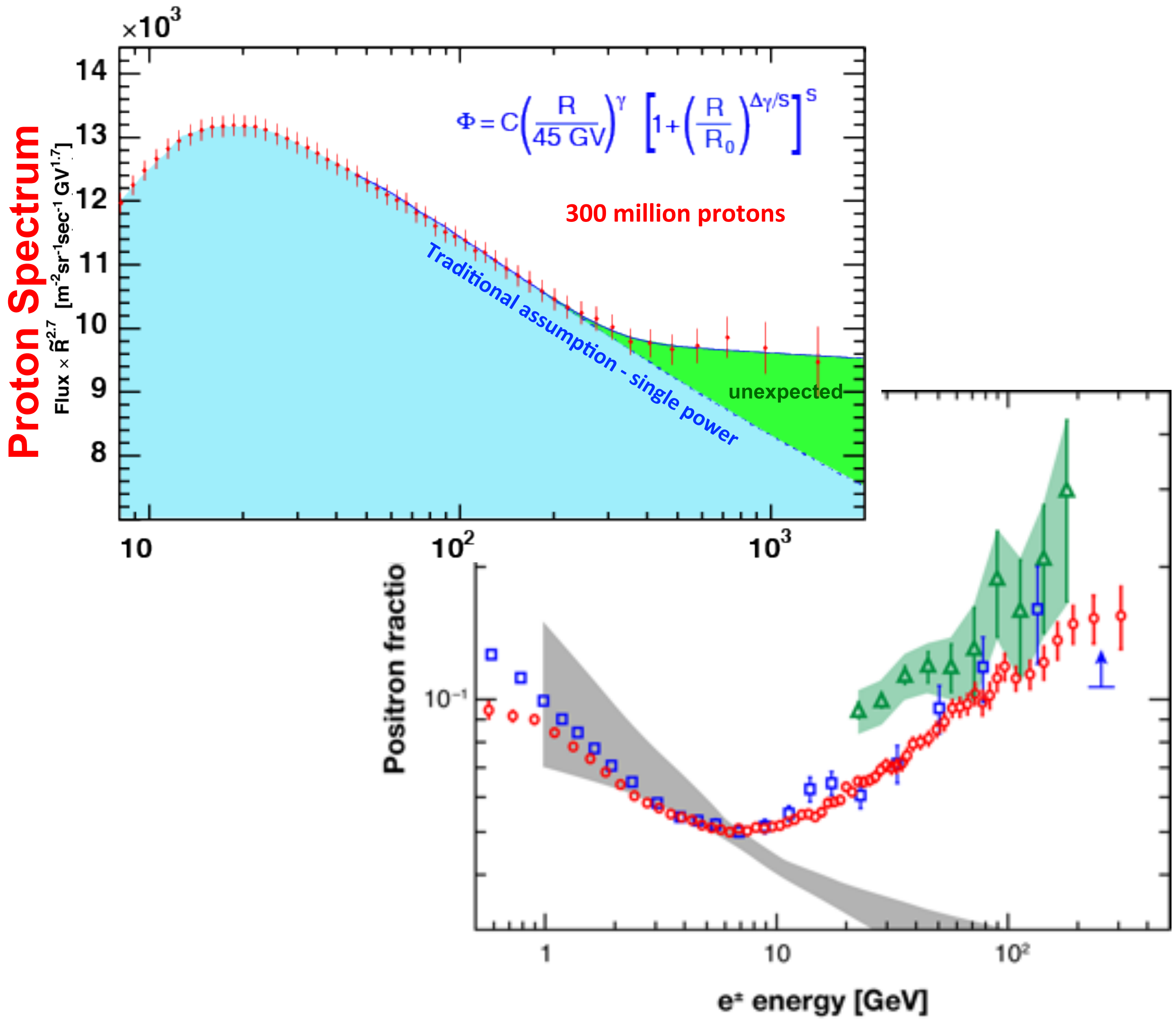
	Unit	PD	DC	DC2	DR	DR2	DRC
D_0	$(10^{28}\text{cm}^2\text{s}^{-1})$	5.29 ± 0.51	4.20 ± 0.30	4.95 ± 0.35	7.24 ± 0.97	4.16 ± 0.57	6.14 ± 0.45
δ		0.471 ± 0.006	0.588 ± 0.013	0.591 ± 0.011	0.380 ± 0.007	0.500 ± 0.012	0.478 ± 0.013
z_h	(kpc)	6.61 ± 0.98	10.90 ± 1.60	10.80 ± 1.30	5.93 ± 1.13	5.02 ± 0.86	12.70 ± 1.40
v_A	(km s^{-1})	—	—	—	38.5 ± 1.3	18.4 ± 2.0	43.2 ± 1.2
dV_c/dz	$(\text{km s}^{-1}\text{ kpc}^{-1})$	—	5.36 ± 0.64	5.02 ± 0.55	—	—	11.99 ± 1.26
R_0	(GV)	—	—	5.29 ± 0.23	—	—	—
η		—	—	—	—	-1.28 ± 0.22	—
$\log(A_p)^a$		-8.334 ± 0.003	-8.334 ± 0.003	-8.336 ± 0.003	-8.347 ± 0.002	-8.334 ± 0.002	-8.345 ± 0.002
ν_1		2.44 ± 0.01	2.45 ± 0.01	2.43 ± 0.01	1.69 ± 0.02	2.04 ± 0.03	1.82 ± 0.02
ν_2		2.34 ± 0.03	2.30 ± 0.01	2.30 ± 0.01	2.37 ± 0.01	2.33 ± 0.01	2.37 ± 0.01
$\log(R_{br})^b$		5.06 ± 0.13	4.82 ± 0.05	4.78 ± 0.06	4.11 ± 0.02	4.03 ± 0.03	4.22 ± 0.03
Φ_0	(GV)	0.595 ± 0.005	0.537 ± 0.006	0.419 ± 0.005	0.180 ± 0.008	0.290 ± 0.014	0.220 ± 0.008
Φ_1	(GV)	0.495 ± 0.011	0.485 ± 0.011	0.472 ± 0.012	0.487 ± 0.011	0.485 ± 0.011	0.482 ± 0.013
χ^2/dof		748.6/463	591.0/462	494.6/461	438.8/462	341.0/461	380.5/461

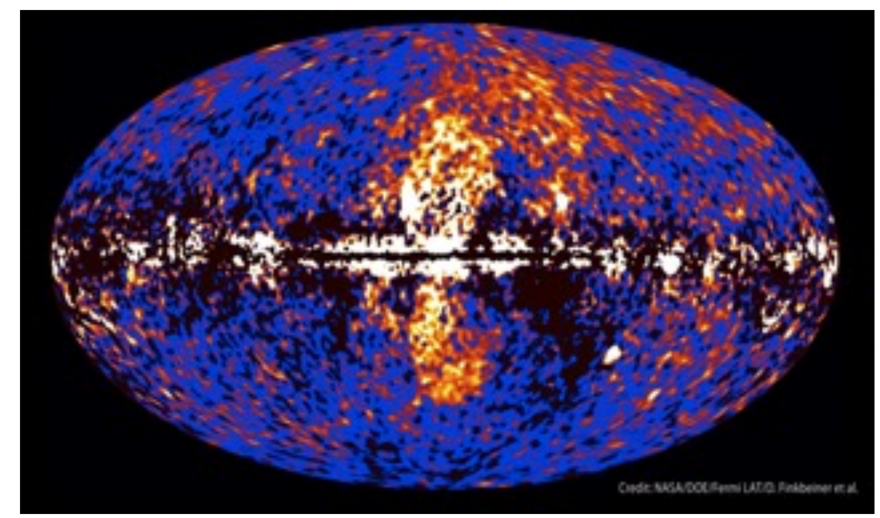


[Yuan+, 2017]

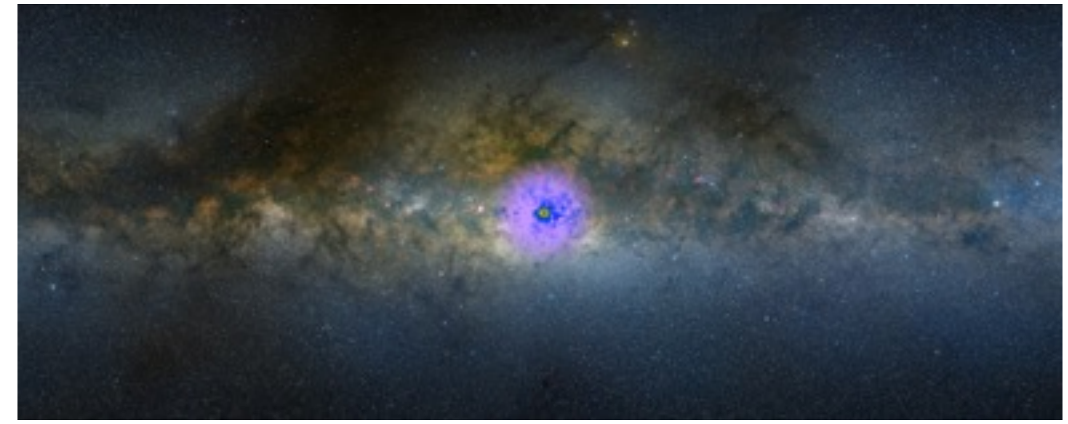


… however, there are also **relevant anomalies** to be explained, both in direct measurements and in gamma-ray data! **Those anomalies can teach a lot about the physics of transport**

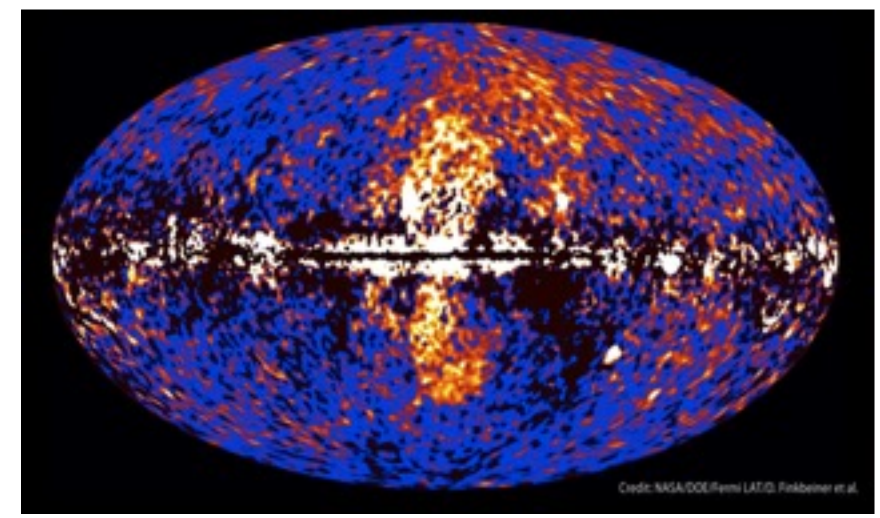




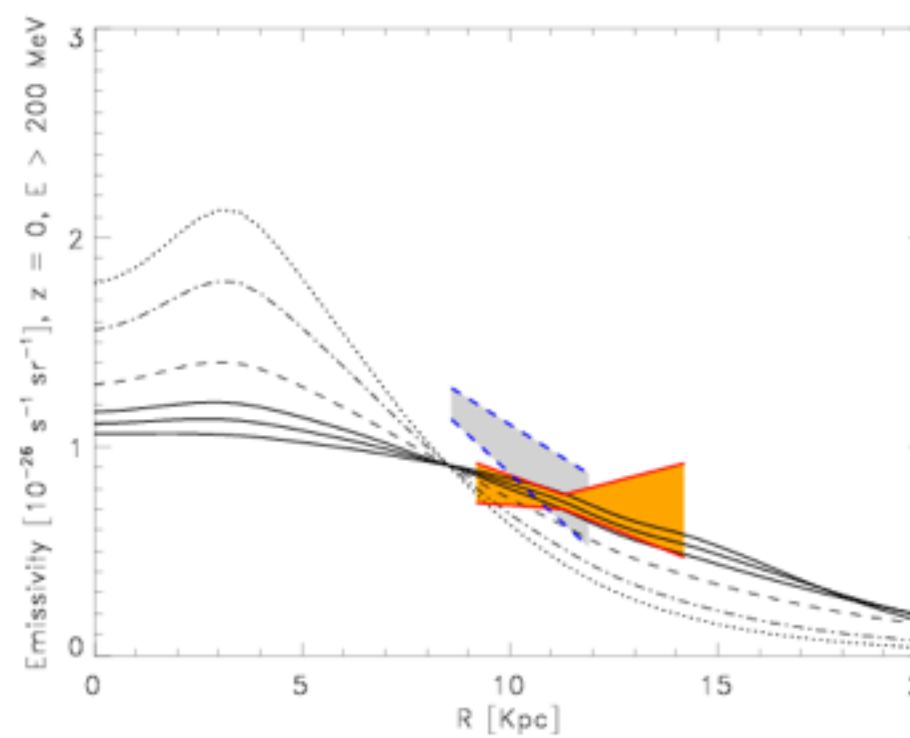
List of anomalies inferred from gamma rays



- **“GeV extended emission from the inner Galaxy”**
  - ☆ *millisecond pulsars?* [Lee+ 2016, Bartels+ 2016]
  - ☆ *molecular clouds?* [De Boer+ 2017]
  - ☆ *dark matter?* [Hooper&Goodenough 2011, Daylan+ PDU 2016, many others…]



- **Fermi Bubbles**



- **Spectral variations** of the proton spectrum towards the inner Galaxy

- **Gradient problem**

List of anomalies inferred from gamma rays

- **"GeV extended emission from the inner Galaxy"**
  - ☆ *millisecond pulsars?* [Lee+ 2016, Bartels+ 2016]
  - ☆ *molecular clouds?* [De Boer+ 2017]
  - ☆ *dark matter?* [Hooper&Goodenough 2011, Daylan+ PDU 2016, many others…]

- **Fermi Bubbles**

This anomaly is particularly interesting in the context of gamma-ray and neutrino connections!

- **Spectral variations** in the proton spectrum towards the inner Galaxy

- **Gradient problem**

Spectral hardening from gamma-ray data

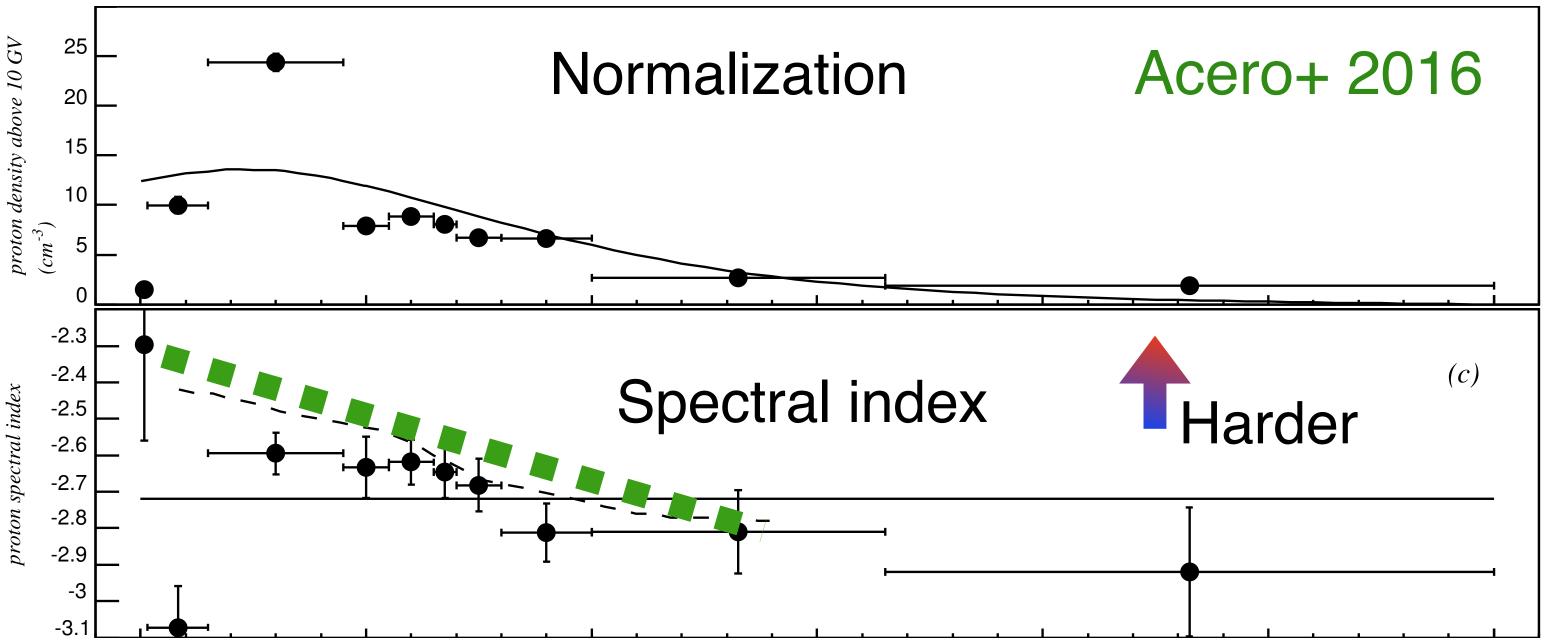
- A progressive **CR hardening in the inner Galaxy** inferred from gamma-ray data was first noticed in [Gaggero et al., PRD 2015, arXiv: 1411.7623]

- Confirmed by the Fermi-LAT collaboration via a **template-fitting procedure** based on:

☆ Ring decomposition for the gas distribution
☆ Model for the IC emission,
☆ Catalogs of point and extended sources

sky window ($\|b\| < 5°$)	α ($\Phi \sim E_\gamma^{-\alpha}$)	sky window ($\|b\| < 5°$)	α ($\Phi \sim E_\gamma^{-\alpha}$)
$0° < \|l\| < 10°$	2.55 ± 0.09	$40° < \|l\| < 50°$	2.57 ± 0.09
$10° < \|l\| < 20°$	2.49 ± 0.09	$50° < \|l\| < 60°$	2.56 ± 0.09
$20° < \|l\| < 30°$	2.47 ± 0.08	$60° < \|l\| < 70°$	2.60 ± 0.09
$30° < \|l\| < 40°$	2.57 ± 0.08	$70° < \|l\| < 80°$	2.52 ± 0.09

TABLE I. *Energy slope of* Fermi-LAT *γ-ray data on the Galactic disk. The power-law index has been obtained by fitting the data in the energy window $E_\gamma = [5 - 50]$ GeV. We average in latitude over the interval $|b| < 5°$.*



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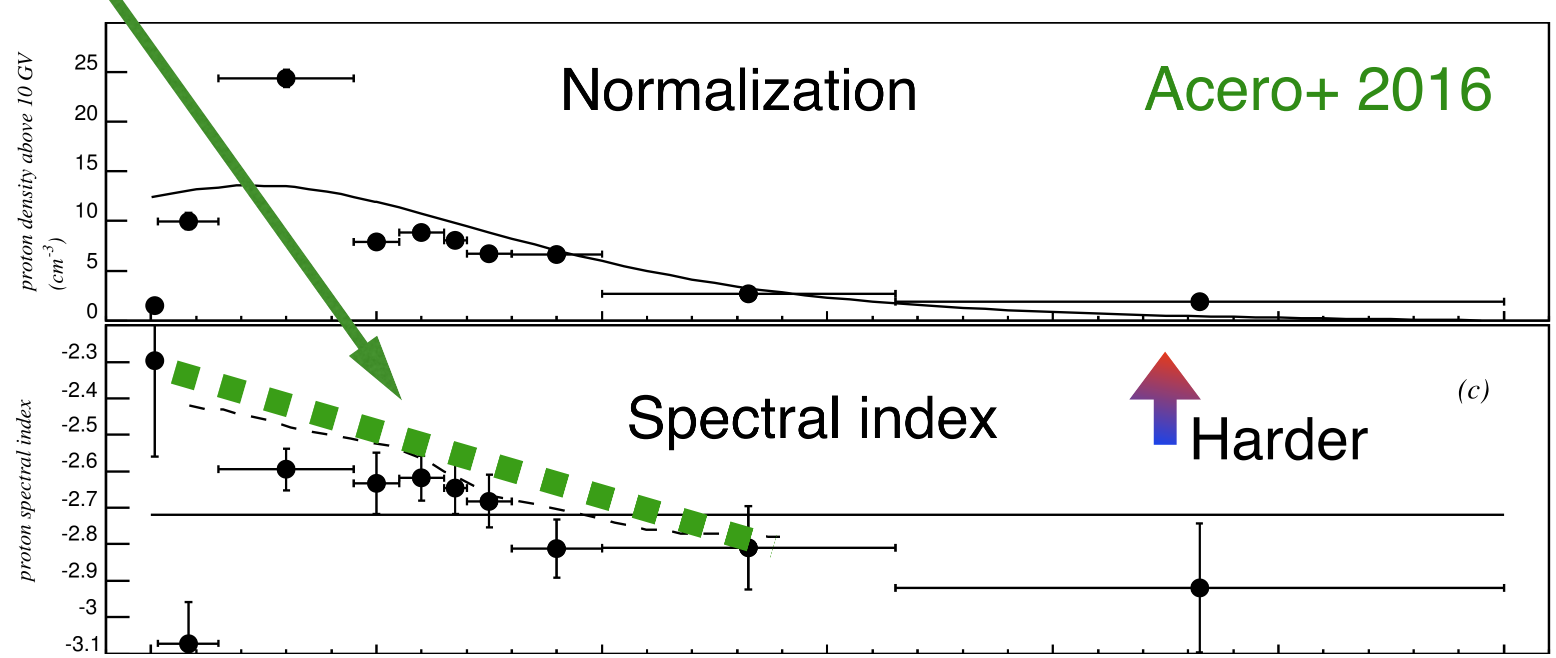
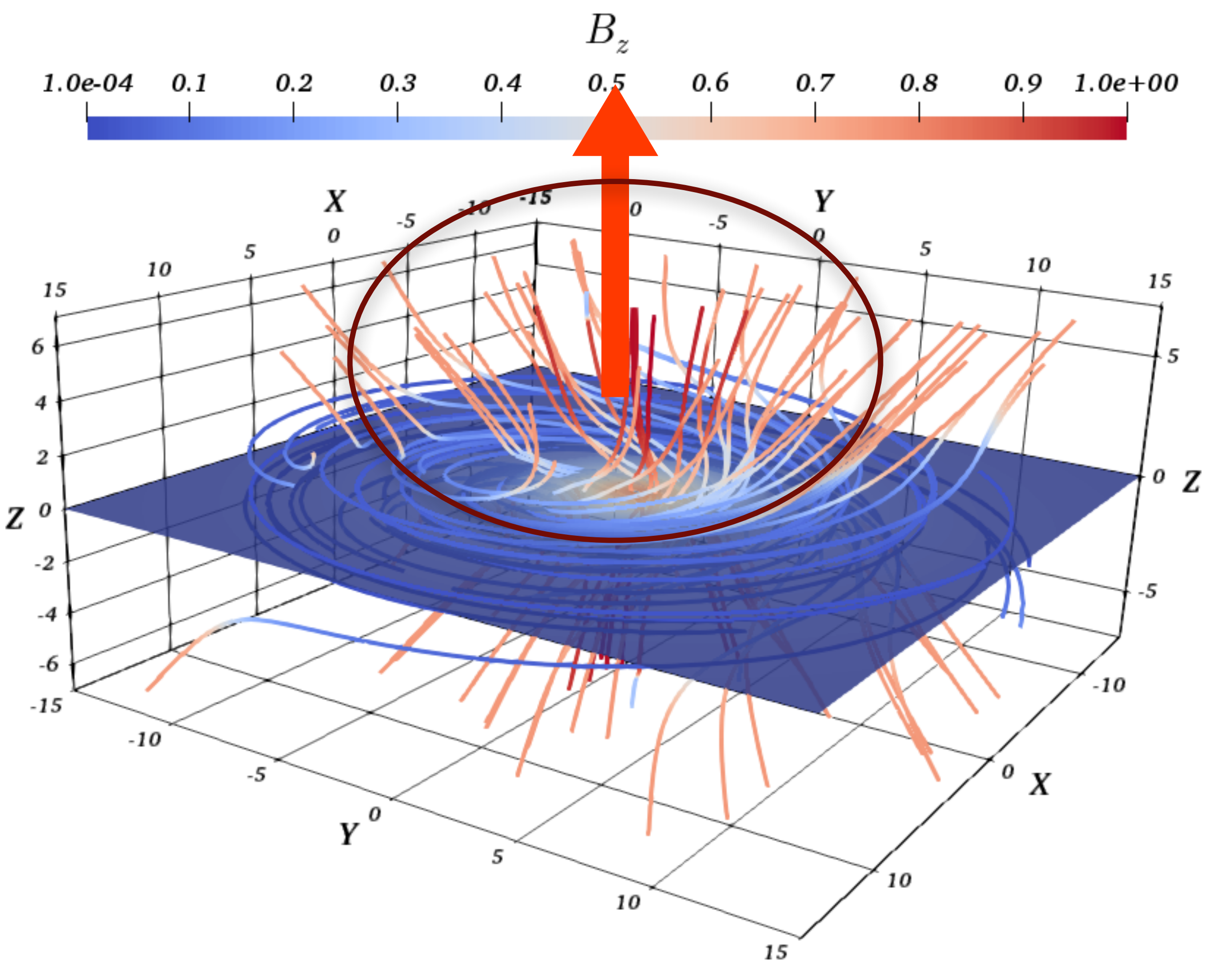


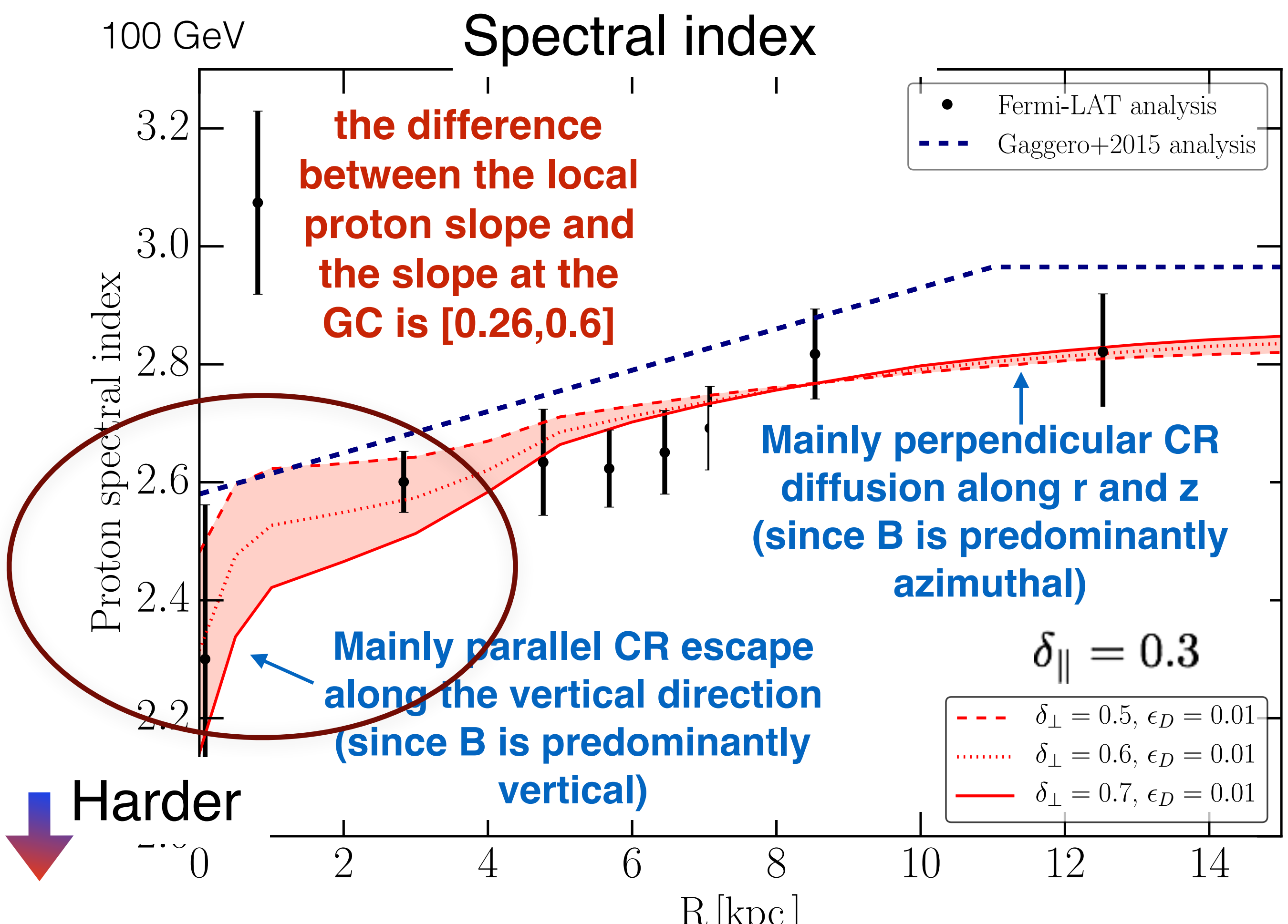
Is this a potential **signature of anisotropic CR transport?**

$$D_{ij} \equiv D_\perp \delta_{ij} + (D_\parallel - D_\perp) b_i b_j \,, \qquad b_i \equiv \frac{B_i}{|\mathbf{B}|} \,,$$

Improved modeling of large-scale topology of the Galactic magnetic field: poloidal component in the inner Galaxy

Enhanced parallel escape in the vertical direction in the inner Galaxy





S.S. Cerri, **DG**, et al., JCAP 2017

Physical interpretations (II)

Alternative explanation for the progressive hardening based on CR self confinement

Growth-damping balance of self-generated magnetic turbulence

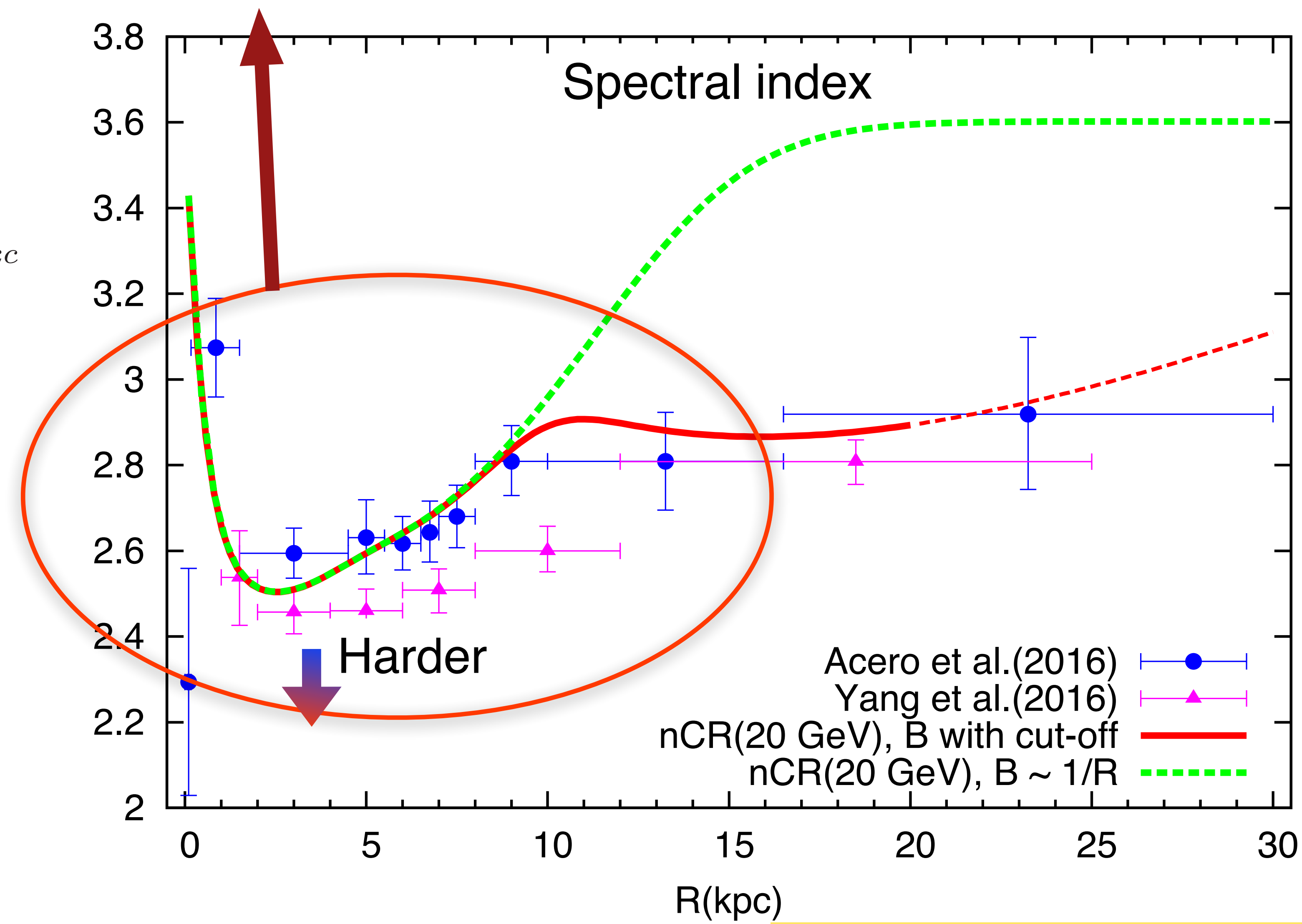
$$\frac{\partial}{\partial k}\left[D_{kk}\frac{\partial W}{\partial k}\right]+\Gamma_{\rm CR}W=q_W(k).$$

$$\Gamma_{\rm cr}(k)=\frac{16\pi^2}{3}\frac{v_{\rm A}}{k\,W(k)B_0^2}\left[p^4v(p)\frac{\partial f}{\partial z}\right]_{p=qB_0/kc}$$

$$D_{kk}=C_{\rm K}v_{\rm A}k^{7/2}W(k)^{1/2}$$

Stronger CR gradients
—> more effective self-confinement
—> low diffusion coefficient
—> advection takes over at larger energies
—> propagated spectrum closer to the inj. one

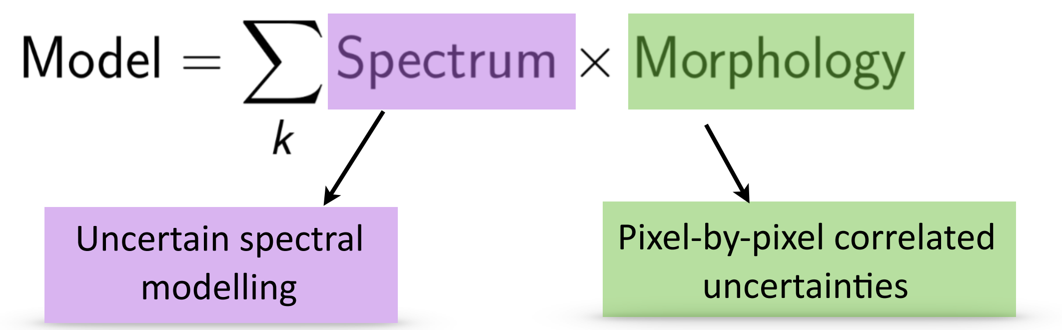
this effect only holds for E < ~50 GeV!



Recchia, Blasi, Morlino 2016

Latest characterization with SkyFACT

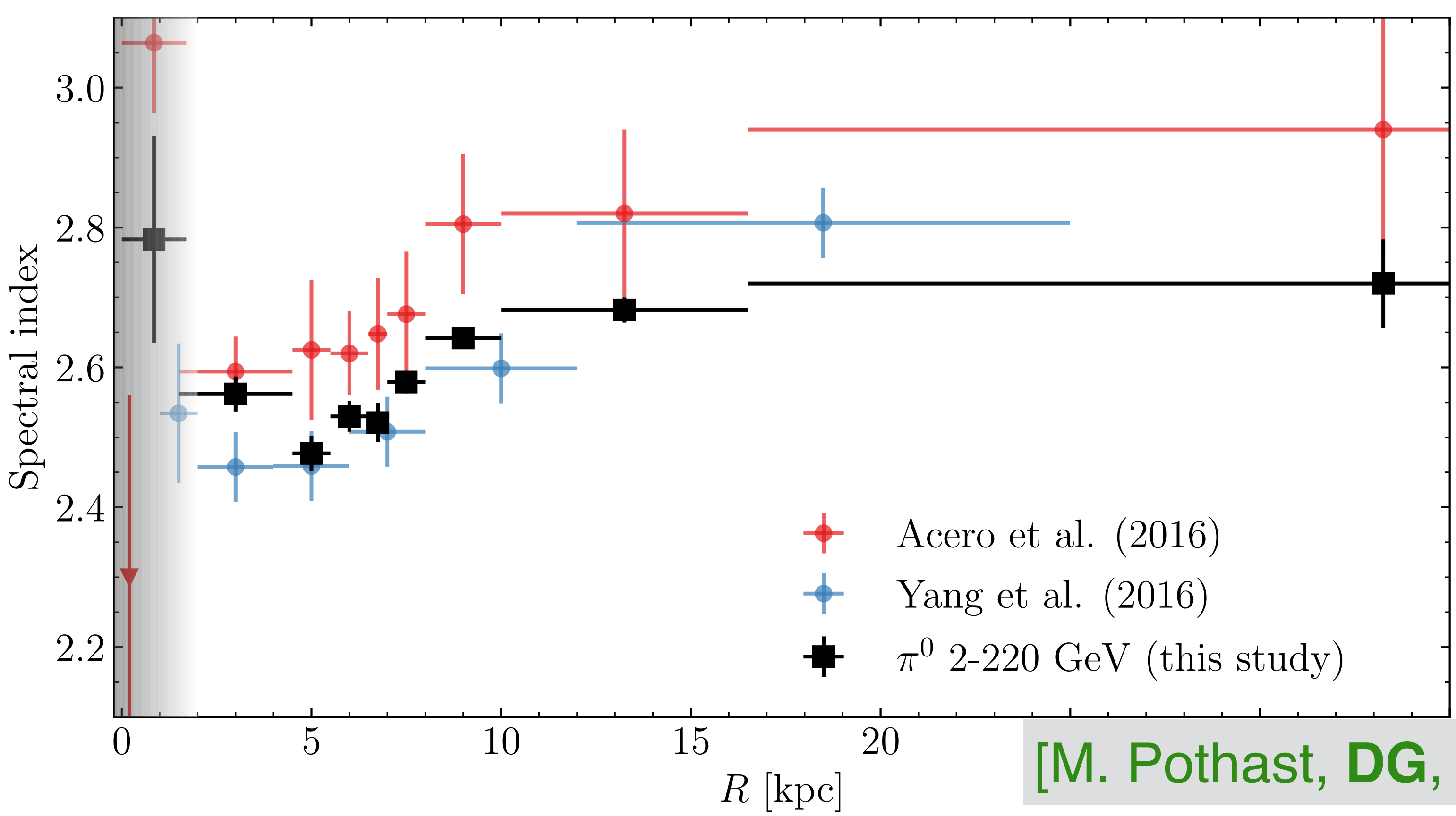
- Adaptive template-fitting analysis
- **Spectral trend confirmed outside the Galactic bulge**
- Unclear behavior at very low radii!
- High-energy fits show same trend!



$$\phi_{pb} = \sum_k T_p^{(k)} \tau_p^{(k)} \cdot S_b^{(k)} \sigma_b^{(k)} \cdot \nu^{(k)}$$

$$\ln \mathcal{L} = \ln \mathcal{L}_{\mathrm{P}} + \ln \mathcal{L}_{\mathrm{R}}(\lambda, \lambda', \lambda'', \eta, \eta')$$

Penalized Poisson likelihood with regularisation conditions



Components	Notes
IGRB	Fixed isotropic template, 25% spectral freedom.
3FGL PSC	Fixed positions, 5% spectral freedom, 30% freedom on normalizations.
Extended Sources	Free spectra and templates, mild spatial smoothing.
Fermi bubbles	Fixed template, 1% spectral freedom
ICS	Factor of 3 spatial freedom, 25% spectral freedom, strong spatial smoothing.
Gas rings	30% spatial freedom, 25% spectral freeom, mild spatial smoothing.

[M. Pothast, **DG**, E. Storm, C. Weniger, arXiv:1807.04554]

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Model $= \sum_k$ Spectrum × Morphology

Spectrum → Uncertain spectral modelling

Morphology → Pixel-by-pixel correlated uncertainties

$$\phi_{pb} = \sum_k T_p^{(k)} \tau_p^{(k)} \cdot S_b^{(k)} \sigma_b^{(k)} \cdot \nu^{(k)}$$

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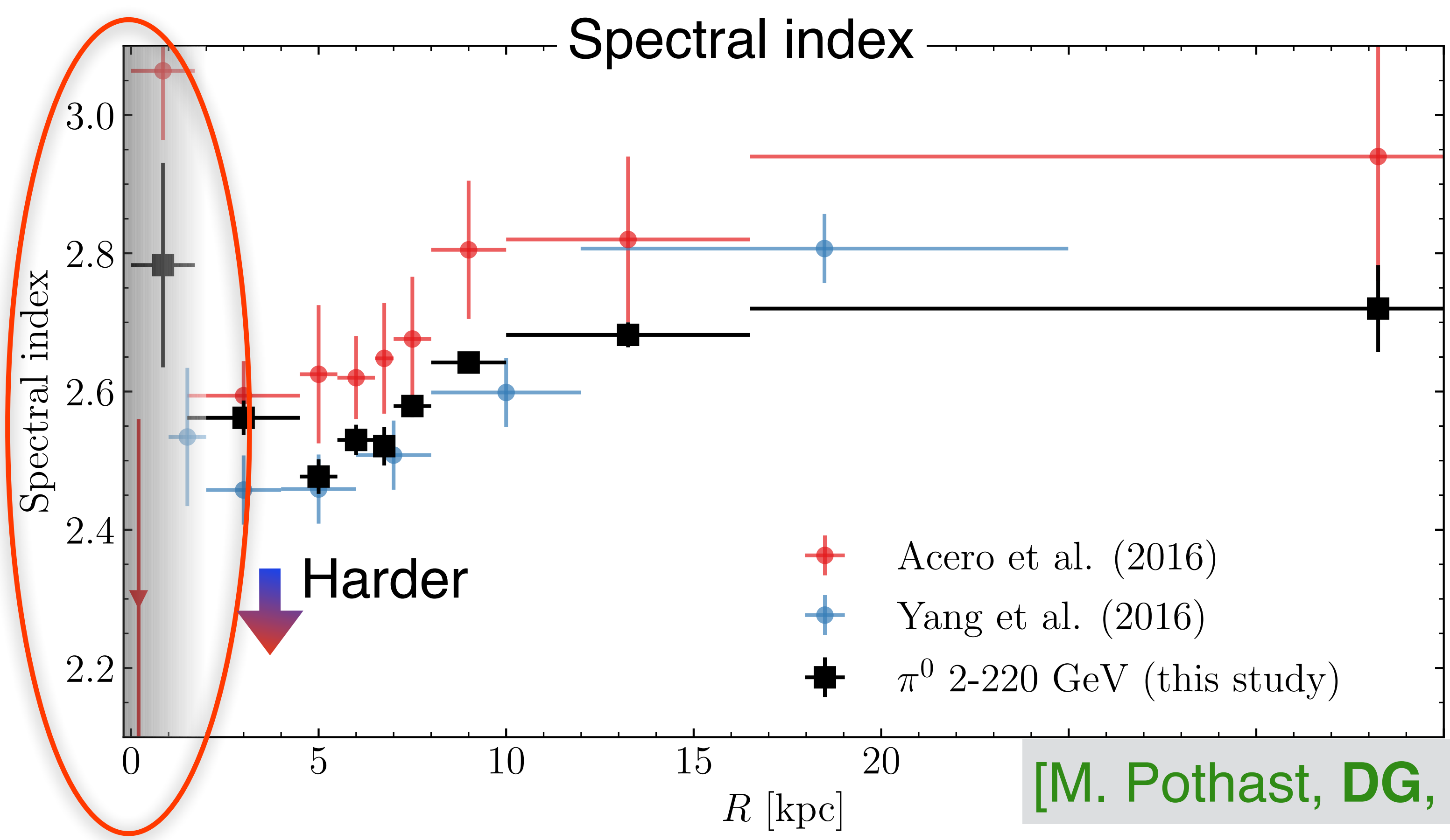

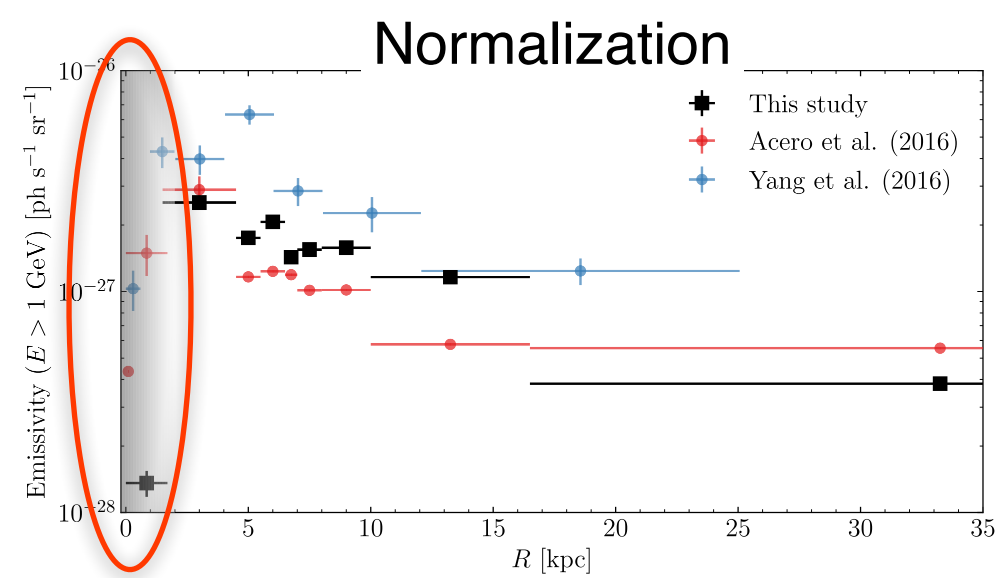

[M. Pothast, **DG**, E. Storm, C. Weniger, arXiv:1807.04554]

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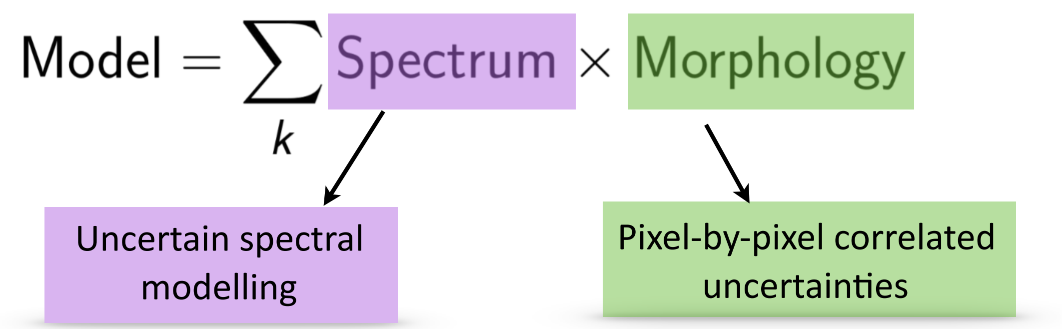

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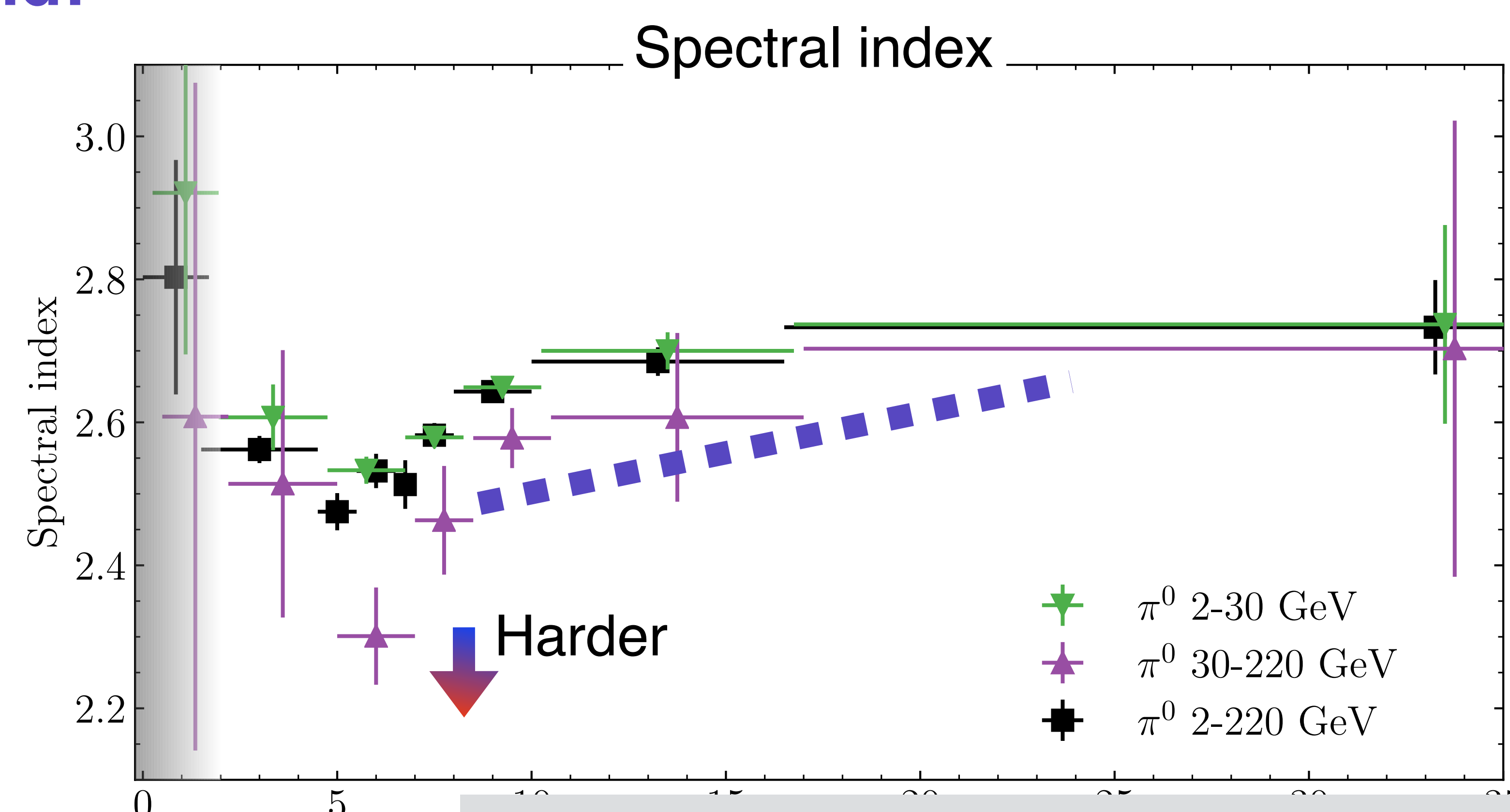


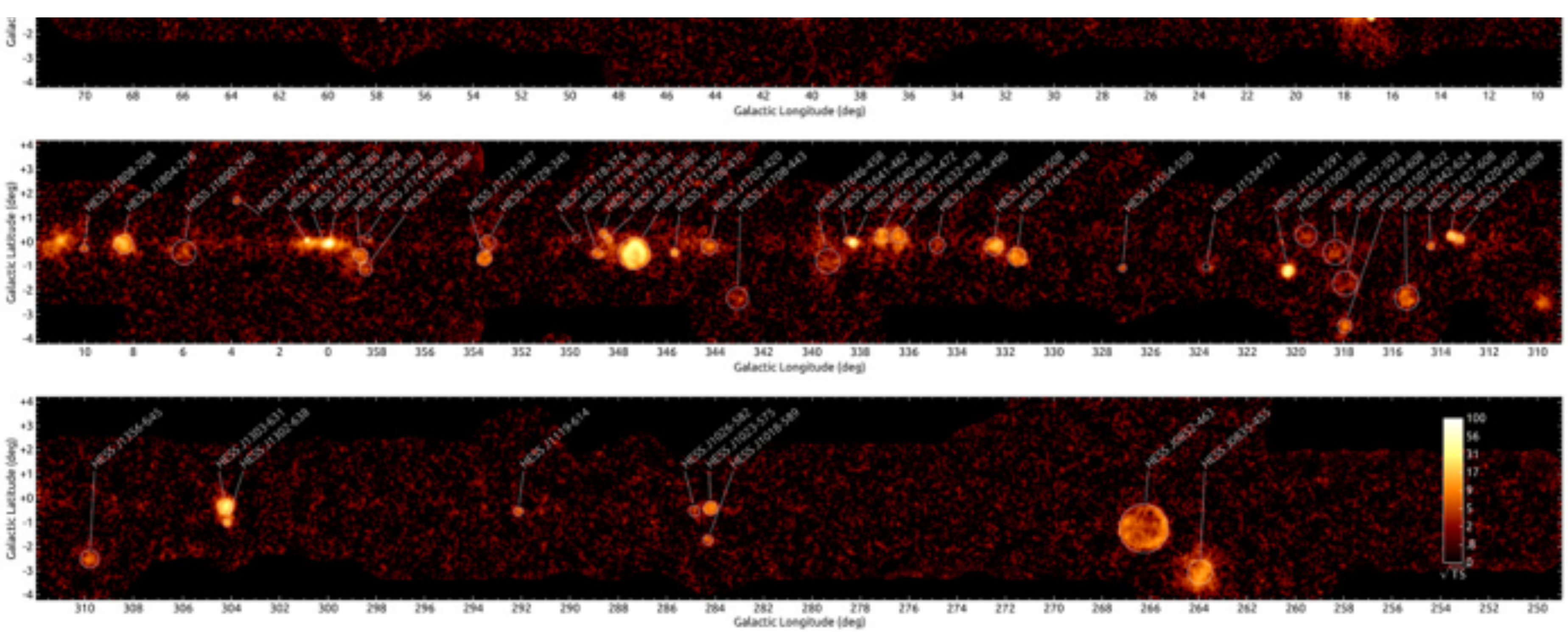
[M. Pothast, **DG**, E. Storm, C. Weniger, arXiv:1807.04554]

Gamma rays: GeV - TeV connections

GeV-TeV connections — moving towards The TeV sky

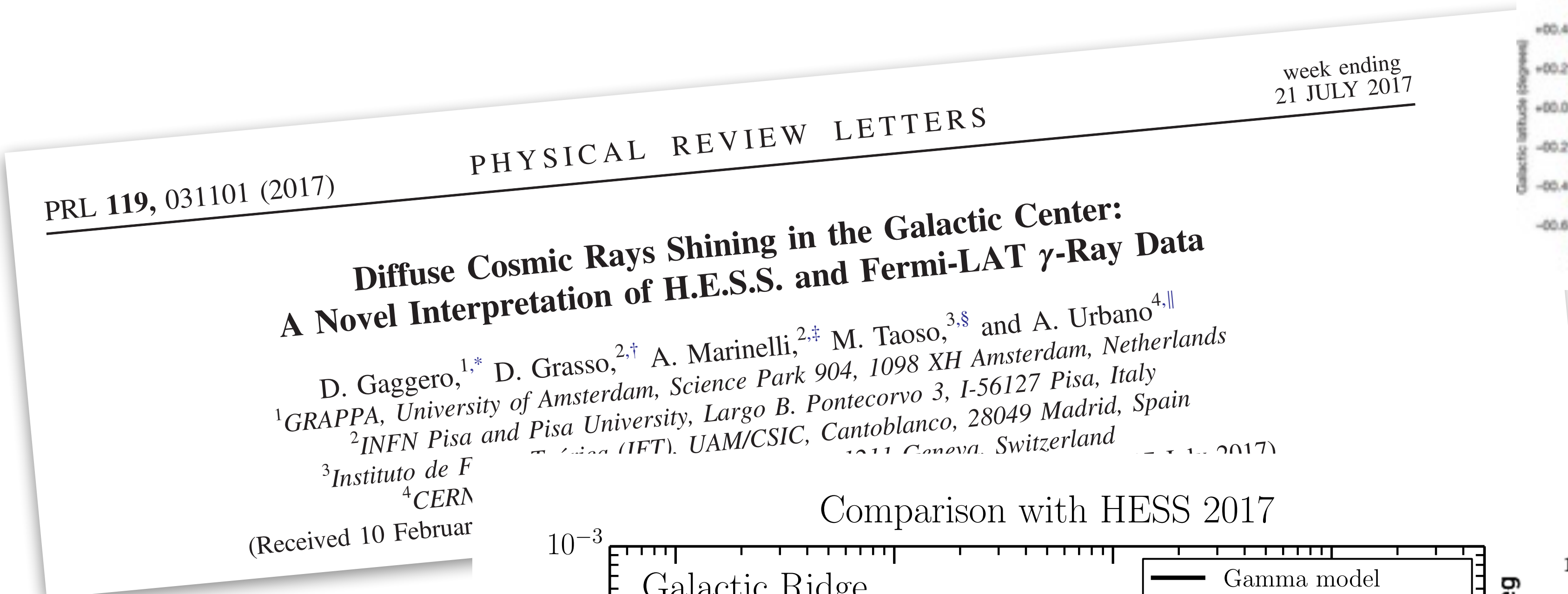
- Does the multi-TeV diffuse emission (still to be detected) show the same behavior? is the CR diffuse sea above the TeV progressively harder towards the Galactic bulge?

- If this is the case, the interpretations based on non-linear physics would be disfavored



Gamma rays: GeV - TeV connections

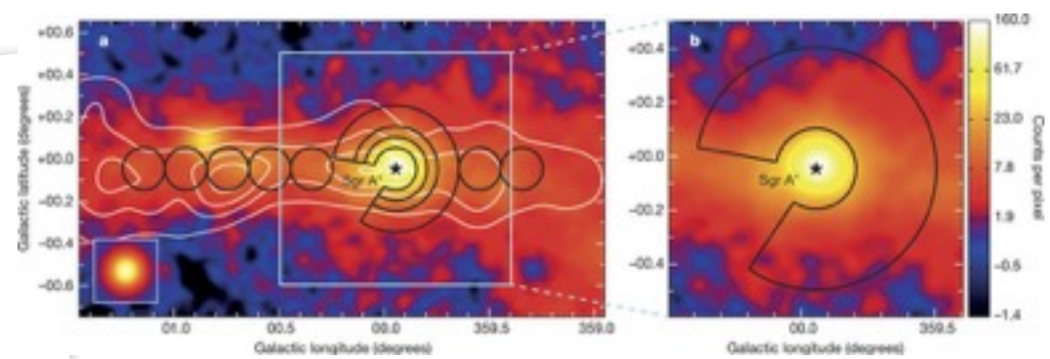
- A “Hard CR sea” in the inner Galaxy can naturally **explain the TeV emission** from the Galactic ridge measured by **H.E.S.S.**


PRL 119, 031101 (2017) PHYSICAL REVIEW LETTERS week ending 21 JULY 2017

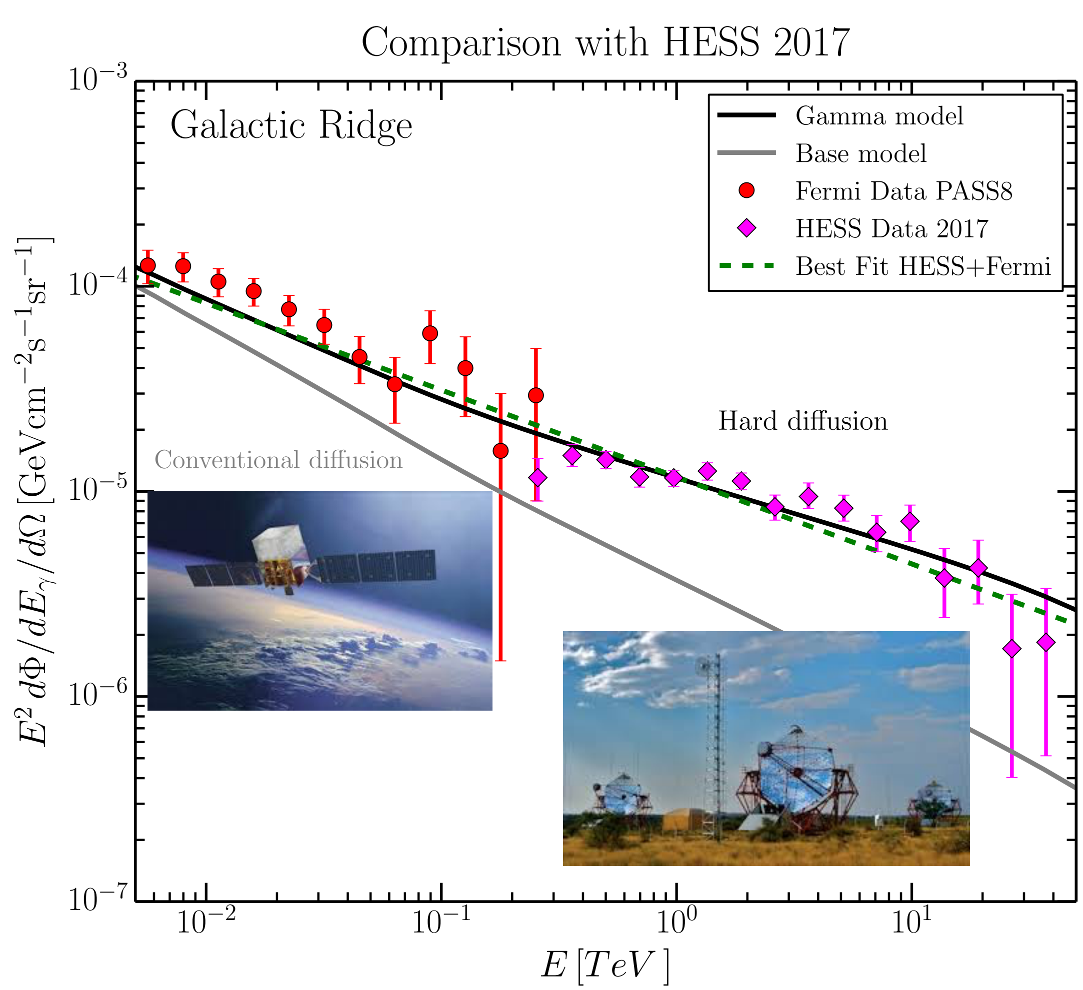
Diffuse Cosmic Rays Shining in the Galactic Center: A Novel Interpretation of H.E.S.S. and Fermi-LAT γ-Ray Data

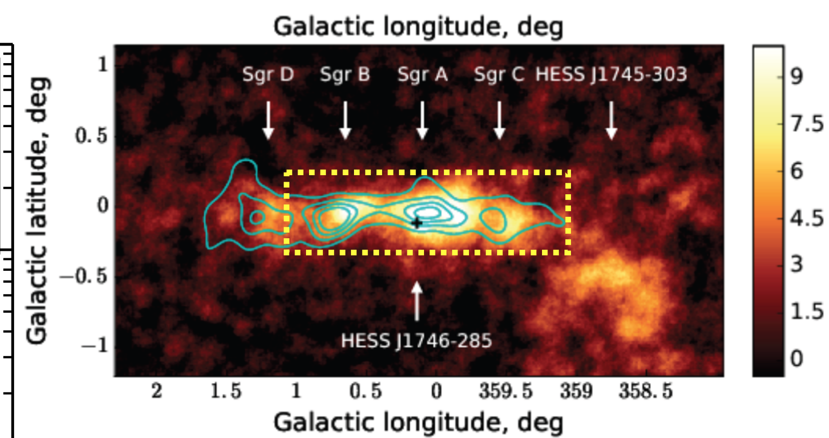
D. Gaggero,[1,*] D. Grasso,[2,†] A. Marinelli,[2,‡] M. Taoso,[3,§] and A. Urbano[4,‖]
[1]*GRAPPA, University of Amsterdam, Science Park 904, 1098 XH Amsterdam, Netherlands*
[2]*INFN Pisa and Pisa University, Largo B. Pontecorvo 3, I-56127 Pisa, Italy*
[3]*Instituto de F... UAM/CSIC, Cantoblanco, 28049 Madrid, Spain*
[4]*CERN ... Geneva, Switzerland*

(Received 10 Februar...



DG, D. Grasso *et al.*, **PRL** 2017

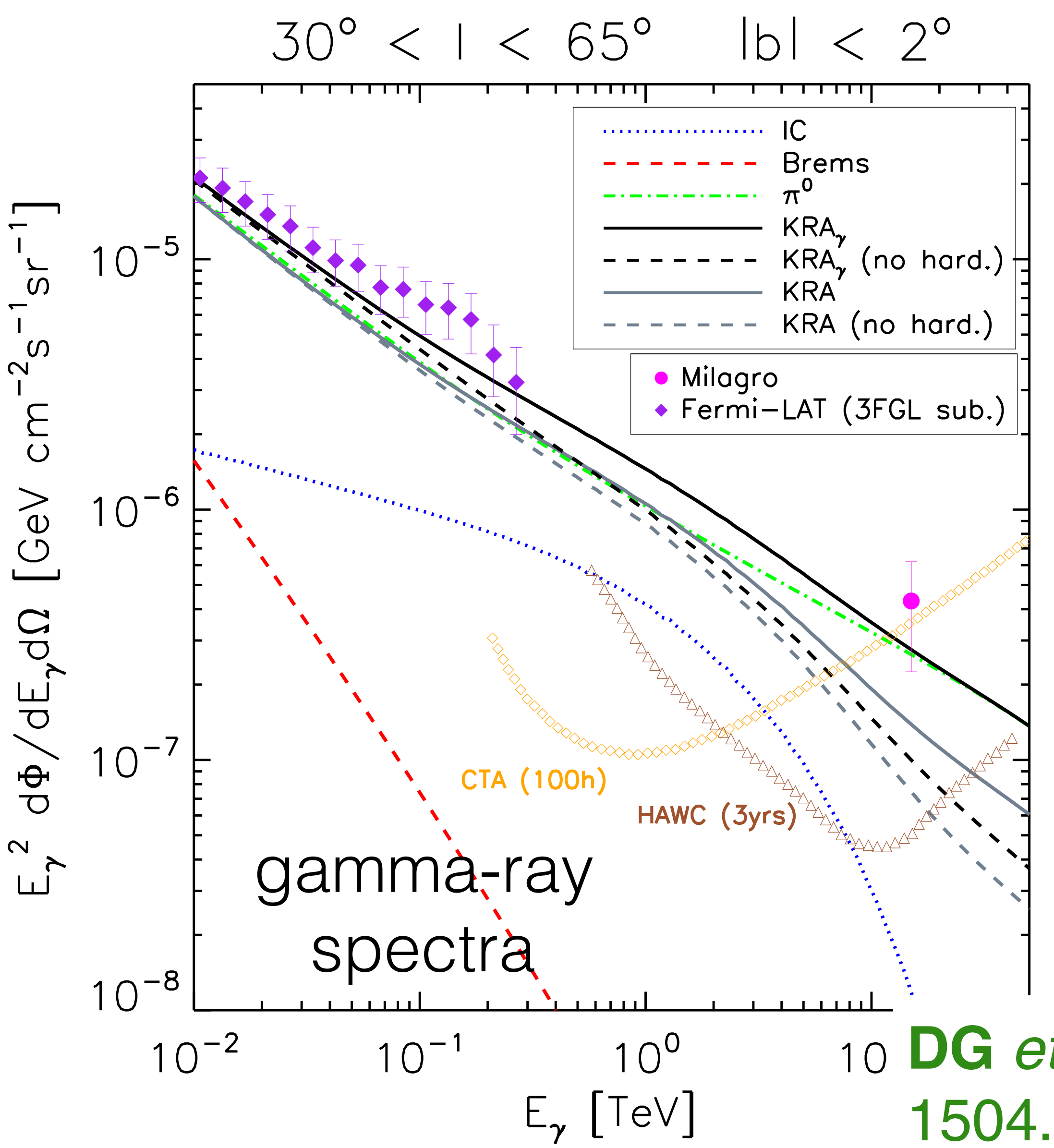


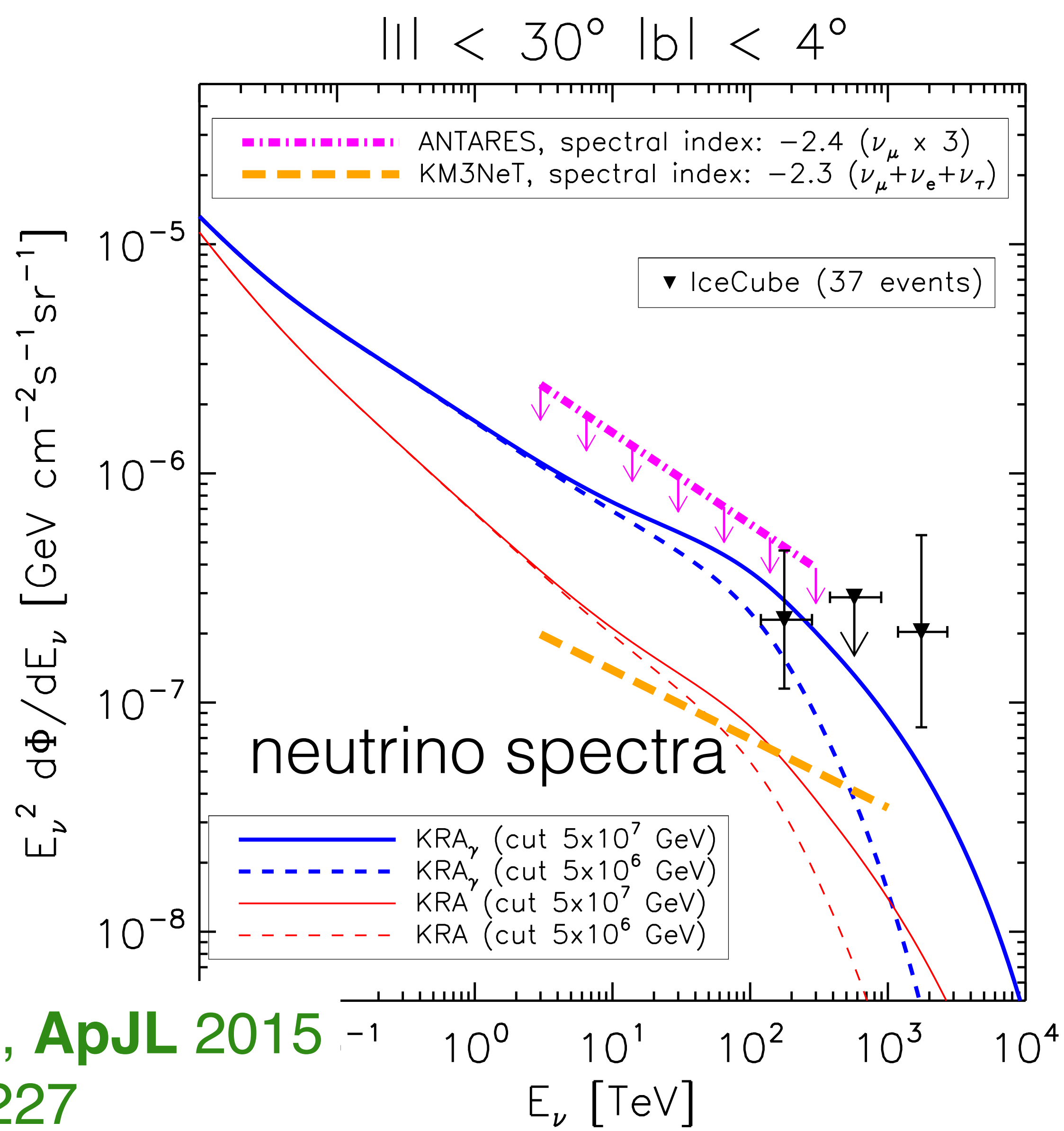


PASS8 Fermi-LAT 470 weeks of data extracted with the v10r0p5 Fermi tool. Point sources from the 3FGL catalogue subtracted.

TeV γ-ray and neutrinos from hard CR spectra

- Models characterized by a hard CR sea in the inner Galaxy, compatible with the trend inferred by Fermi-LAT data, are compatible with the anomalous emission measured by MILAGRO
- The same models predict a relevant neutrino flux from the inner Galaxy
- The 2015 analysis was compatible with the upper limits from ANTARES



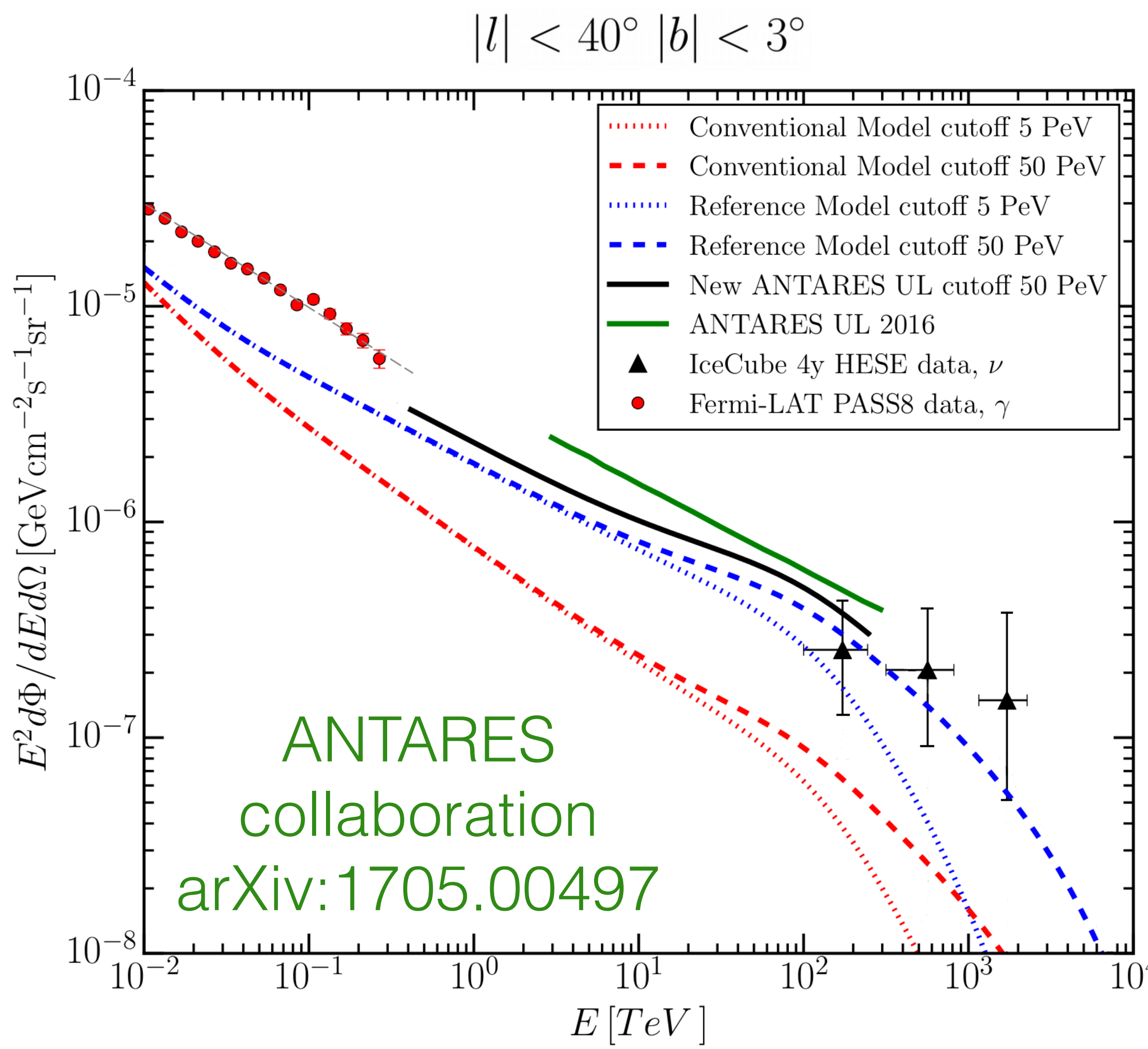


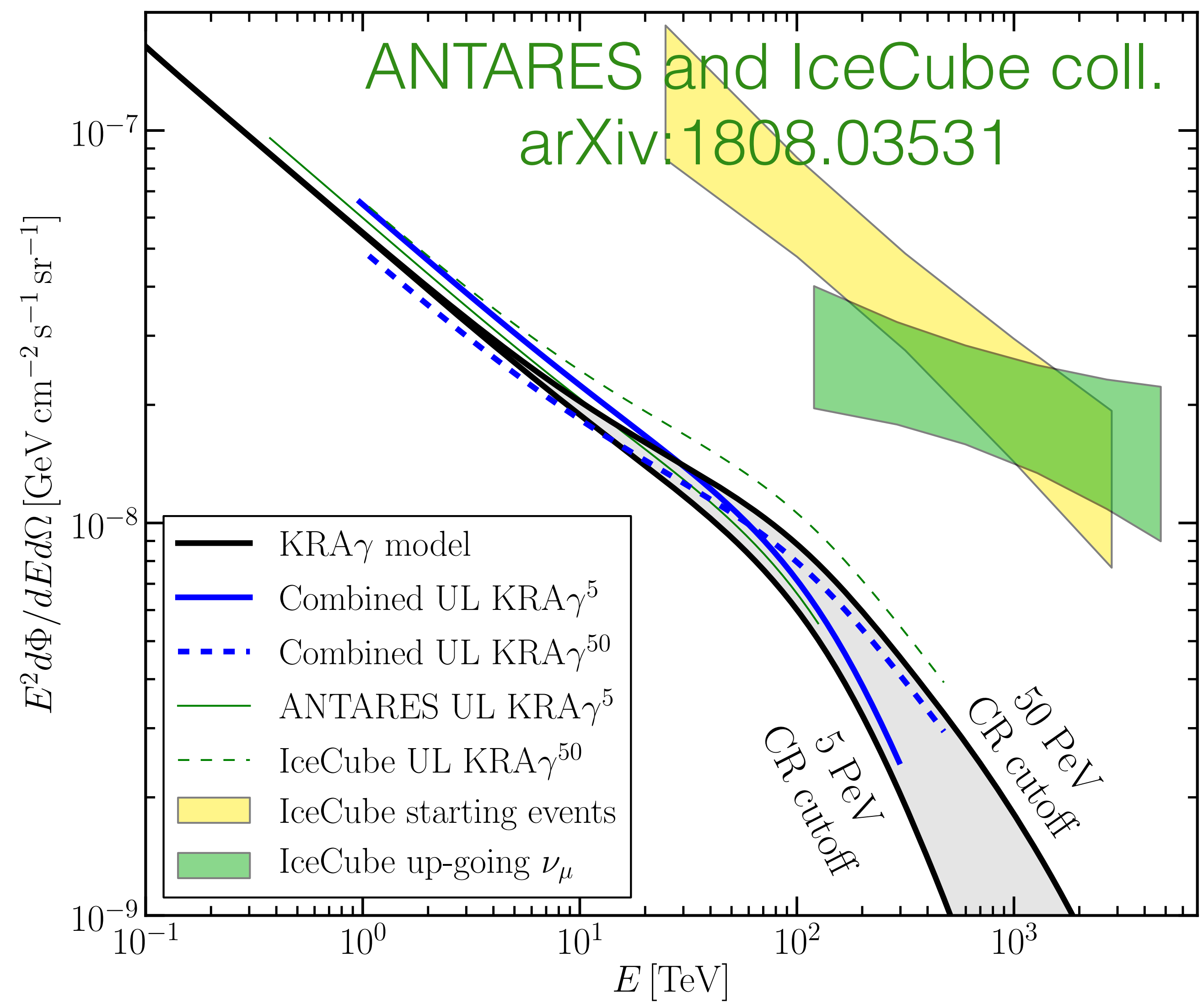
DG *et al.*, ApJL 2015
1504.00227

Latest results

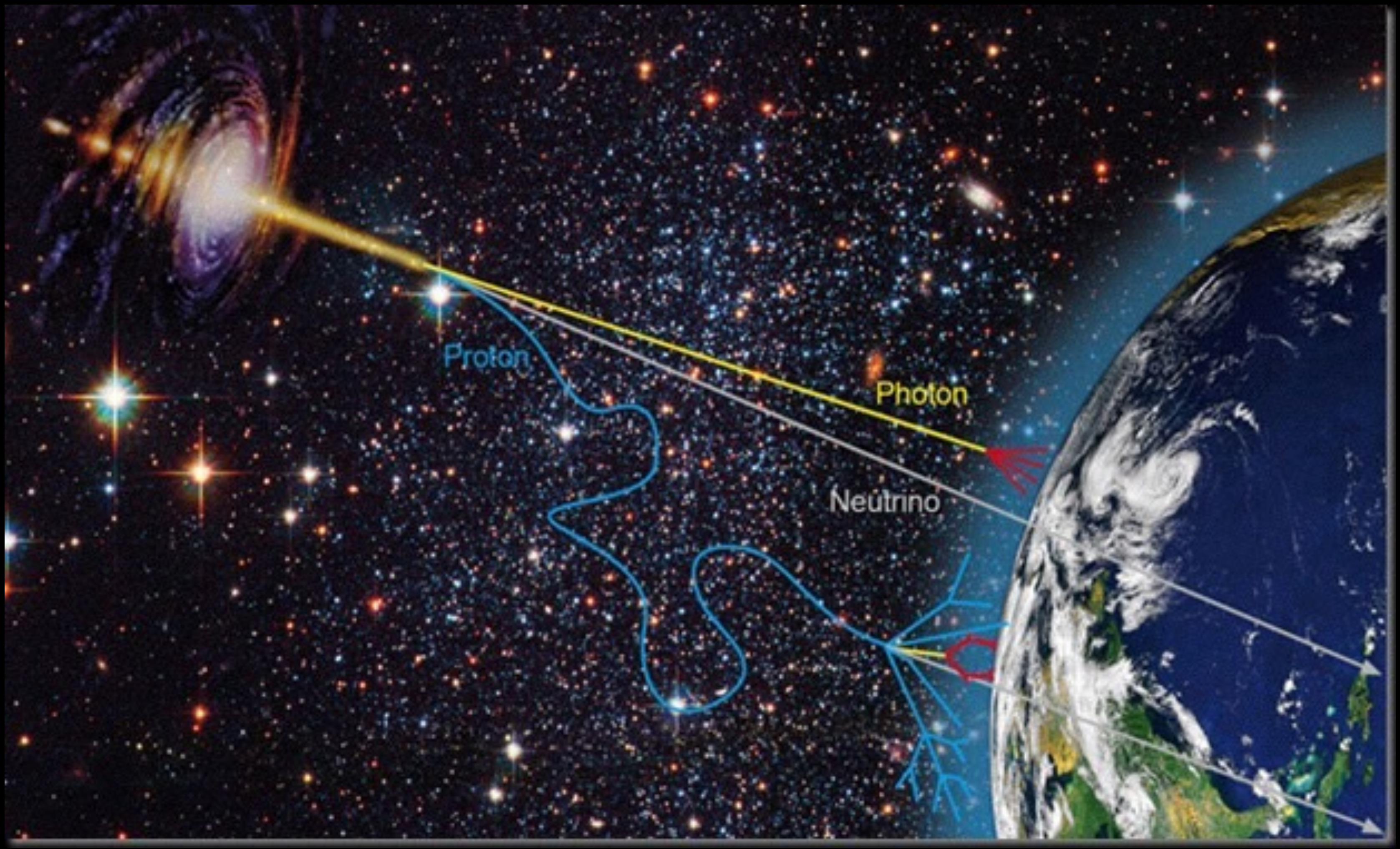
- 2017, ANTARES collaboration: A search for Galactic component using 9 years of ANTARES data (both showers and tracks)

- 2018, ANTARES and IceCube collaboration: A search for Galactic component using 10 years of ANTARES track and shower data, as well as 7 years of IceCube track data





Part 2: Gamma-Neutrino connections — Extragalactic

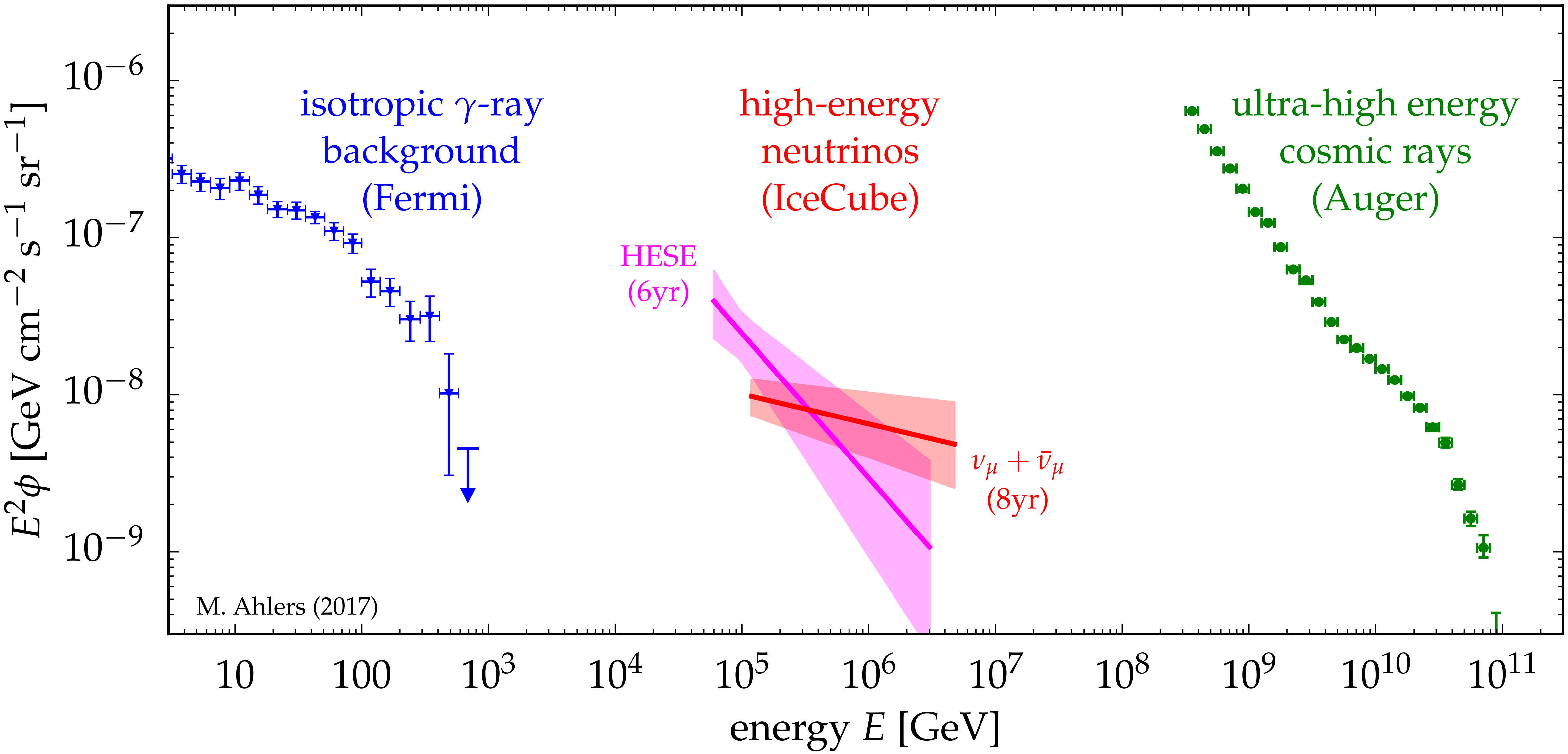


Extra-Galactic sources of IceCube neutrinos?

- association with sources of UHE CRs [Kistler, Stanev & Yuksel'13]
  [Katz, Waxman, Thompson & Loeb'13; Fang, Fujii, Linden & Olinto'14;Moharana & Razzaque'15]
- association with diffuse γ-ray background [Murase, MA & Lacki'13]
  [Chang & Wang'14; Ando, Tamborra & Zandanel'15]
- active galactic nuclei (AGN) [Stecker'13;Kalashev, Kusenko & Essey'13]
  [Murase, Inoue & Dermer'14; Kimura, Murase & Toma'14; Kalashev, Semikoz & Tkachev'14]
  [Padovani & Resconi'14; Petropoulou *et al.*'15; Padovani *et al.*'16; Kadler *et al.*'16; Wang & Loeb'16]
- gamma-ray bursts (GRB) [Murase & Ioka'13; Dado & Dar'14; Tamborra & Ando'15]
  [Senno, Murase & Meszaros'16; Denton & Tamborra'18; Boncioli, Biehl & Winter'18]
- galaxies with intense star-formation (*e.g.* starbursts)
  [He, Wang, Fan, Liu & Wei'13; Yoast-Hull, Gallagher, Zweibel & Everett'13; Murase, MA & Lacki'13]
  [Anchordoqui, Paul, da Silva, Torres& Vlcek'14; Tamborra, Ando & Murase'14; Chang & Wang'14]
  [Liu, Wang, Inoue, Crocker & Aharonian'14; Senno, Meszaros, Murase, Baerwald & Rees'15]
  [Chakraborty & Izaguirre'15; Emig, Lunardini & Windhorst'15; Bechtol *et al.*'15]
- galaxy clusters/groups [Murase, MA & Lacki'13; Zandanel, Tamborra, Gabici & Ando'14]
- tidal disruption events (TDE) [Wang, Liu, Dai & Cheng'11; Senno, Murase & Més'aros'17]
  [Guépin, Kotera, Barausse, Fang & Murase'17; Biehl, Boncioli, Lunardini & Winter'17]

courtesy of M. Ahlers

Diffuse flux: Complementarity between γ-rays and neutrinos



- Different energy ranges, similar energy budget

- Gamma-ray background can constrain models for the neutrino flux
[see e.g. Ando+ 1509.02444, Murase+ 1509.00805 and 1607.01601, many others…]

- Unclear origin of the different spectrum associated to HESE and TGMs

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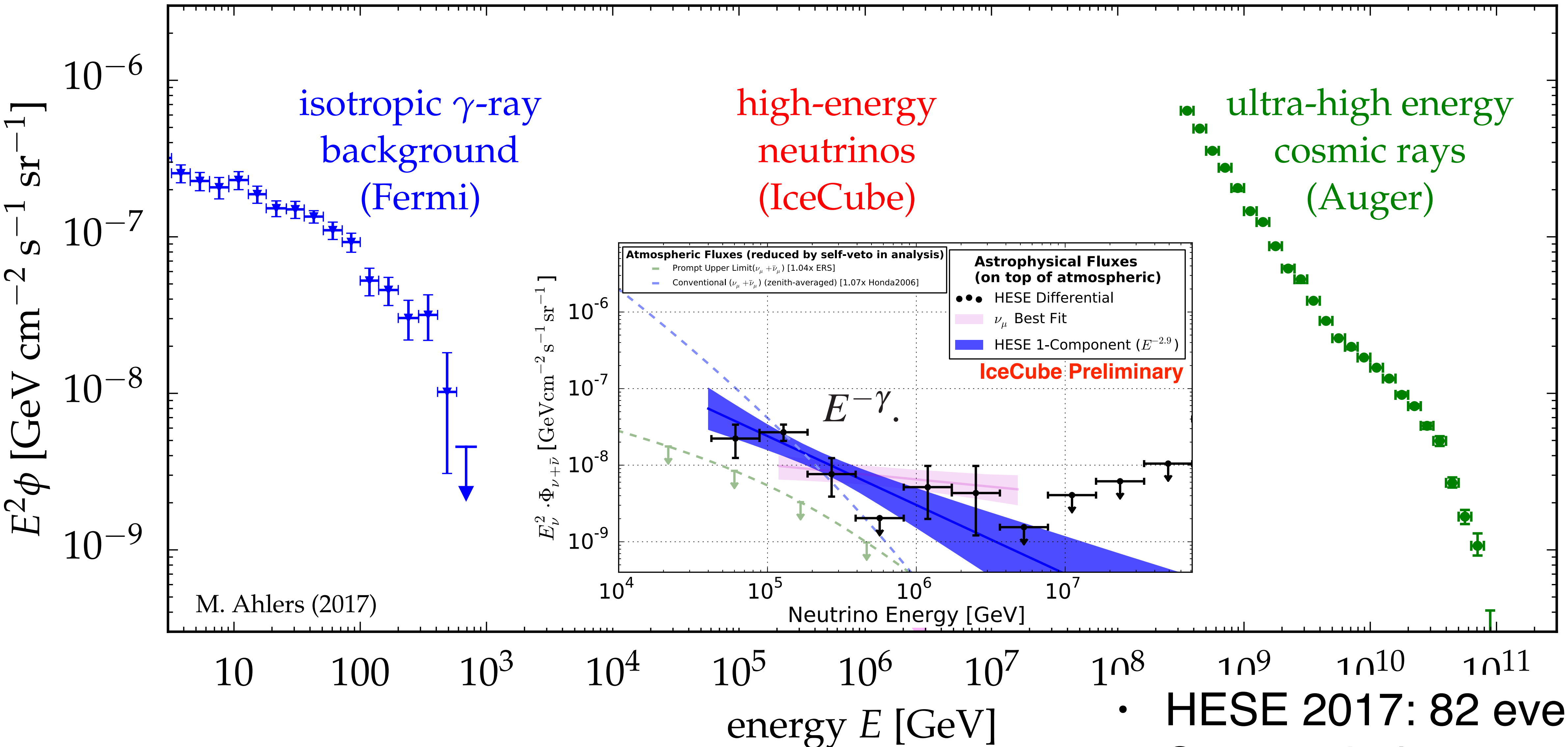

- HESE 2017: 82 events
- Spectral index: $-2.92^{+0.33}_{-0.29}$

- Different energy ranges, similar energy budget

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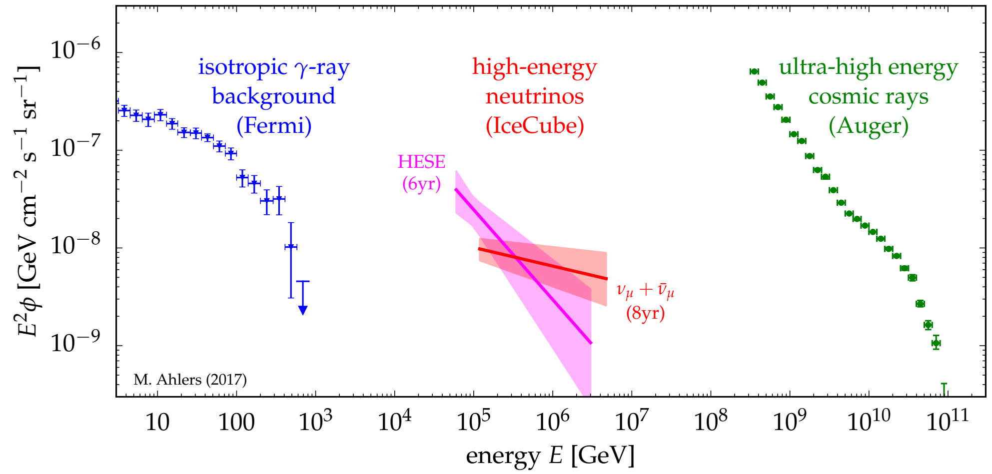
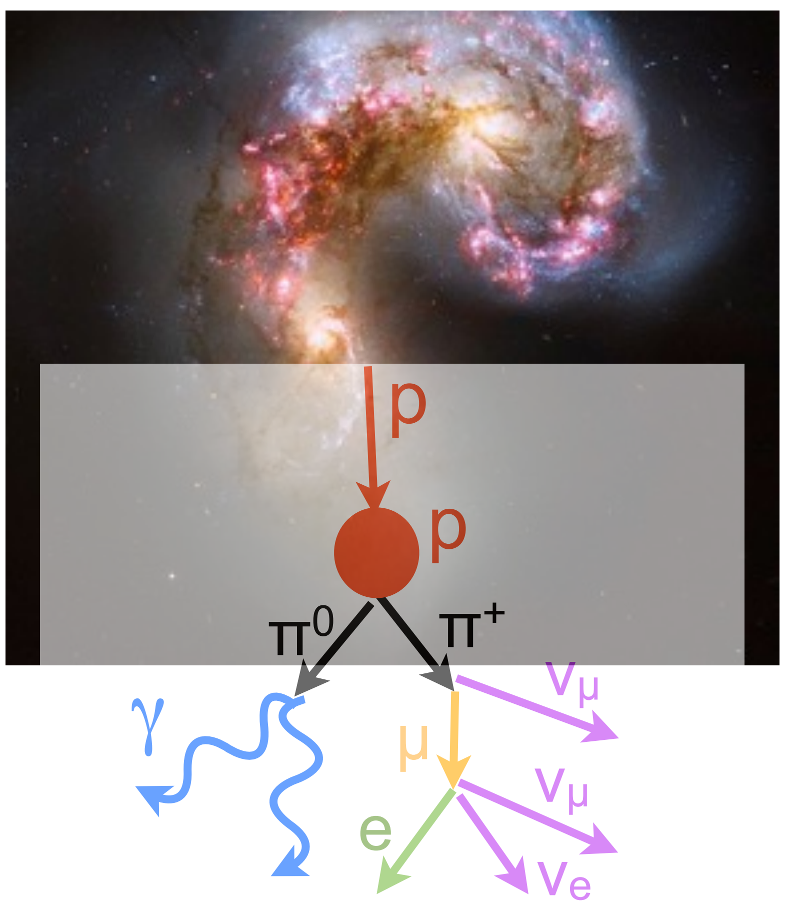
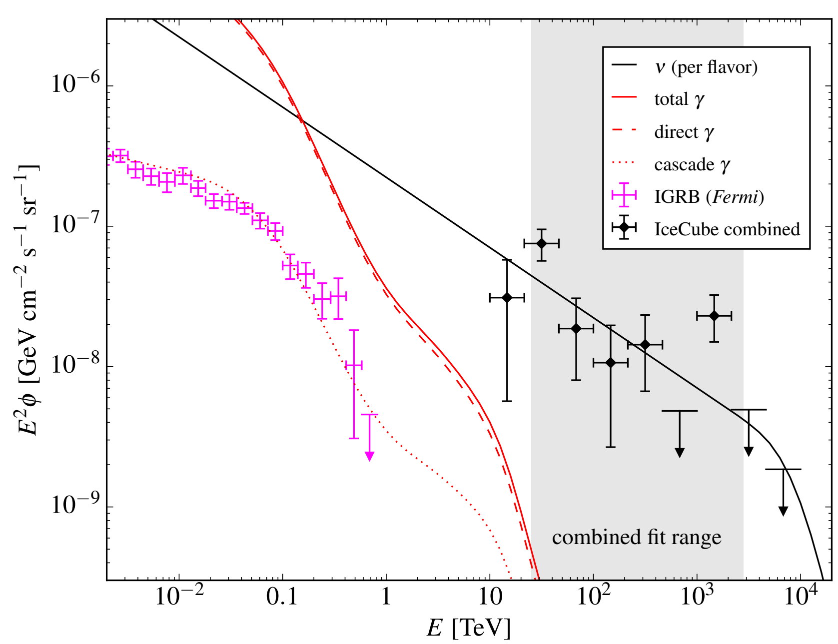


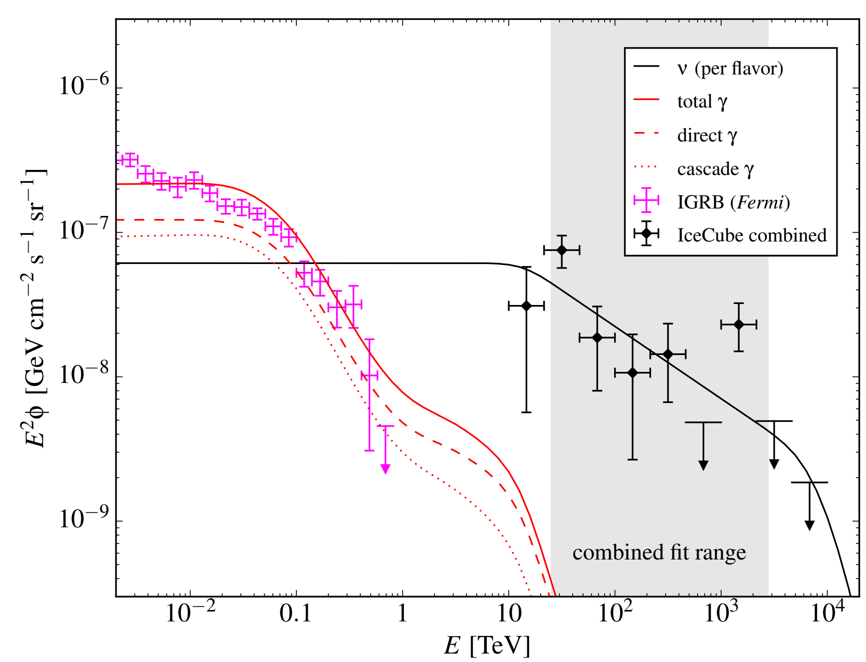
- The constraints change depending on the assumption on the undergoing process



Proton-Proton Interactions

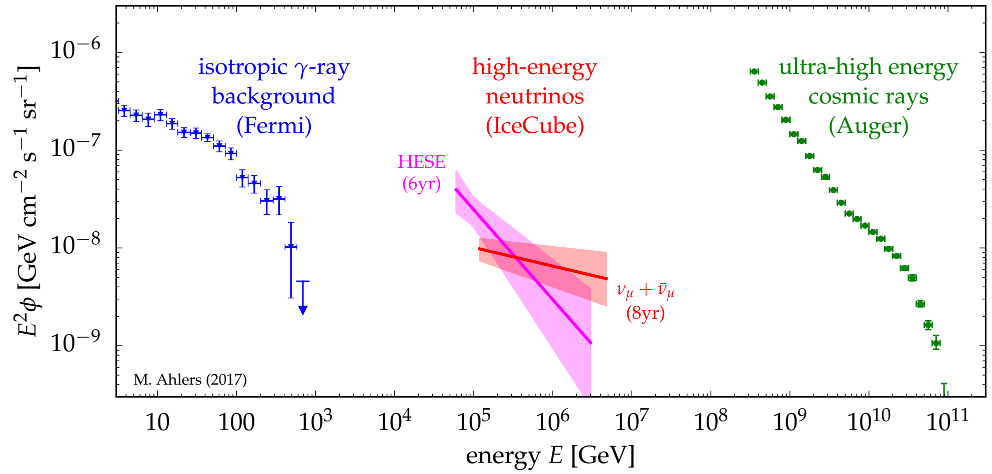
- **pp processes** or "CR reservoir models": neutrinos are produced in the vicinity of the source via inelastic hadronuclear collisions, e.g. in **star-forming galaxies**





- **Upper limits** on the neutrino spectral index, **lower limits** on the IGRB contribution.

Diffuse flux: Complementarity between γ-rays and neutrinos



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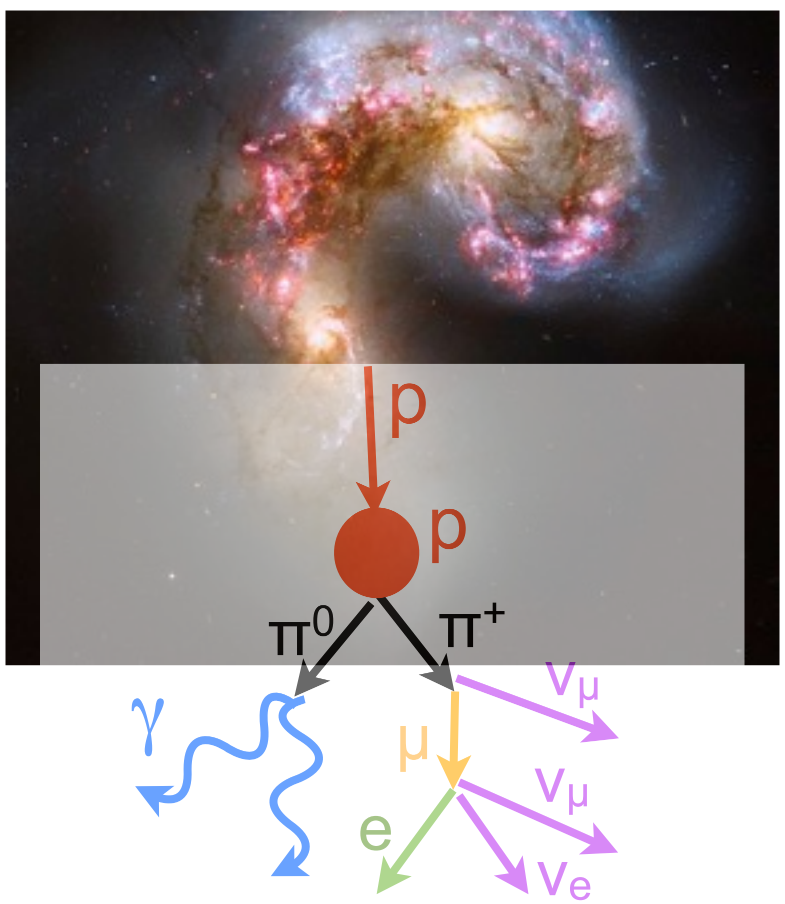

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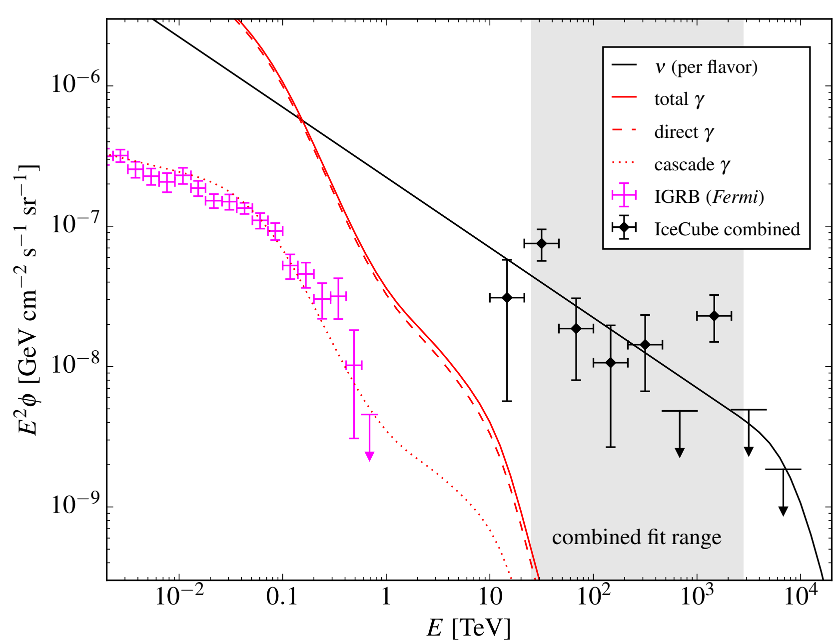
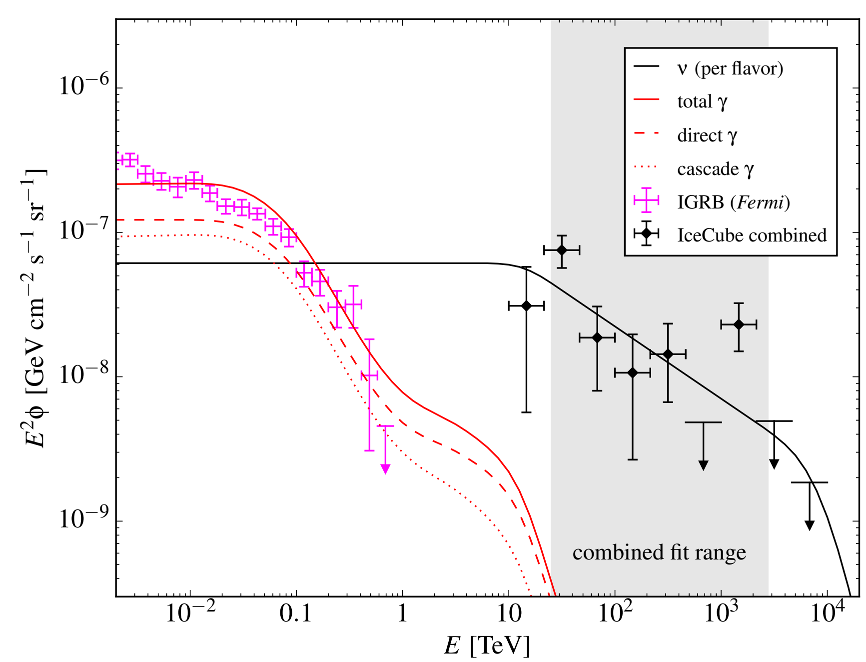
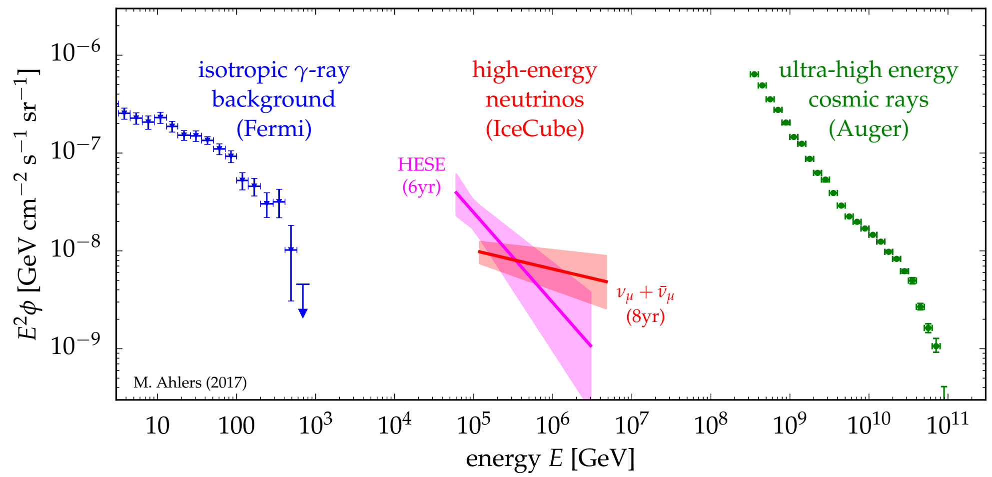




- CRs in SFGs are **unlikely to produce >PeV neutrinos**, while highest reconstructed energy in the HESE is 4.5 PeV —> requires a CR with more than 10-100 PeV

Diffuse flux: Complementarity between γ-rays and neutrinos



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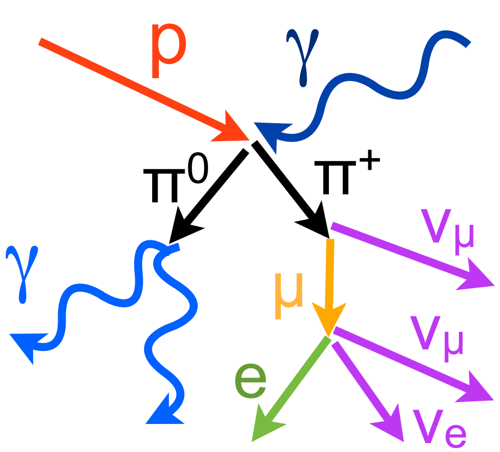
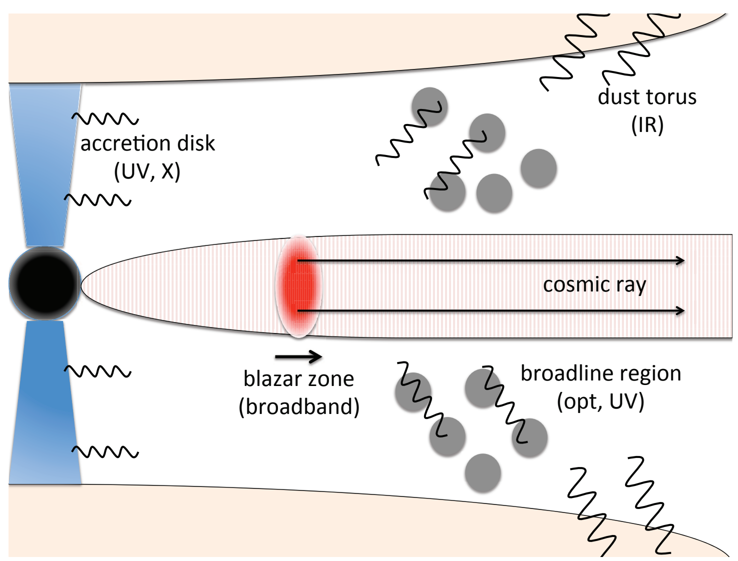
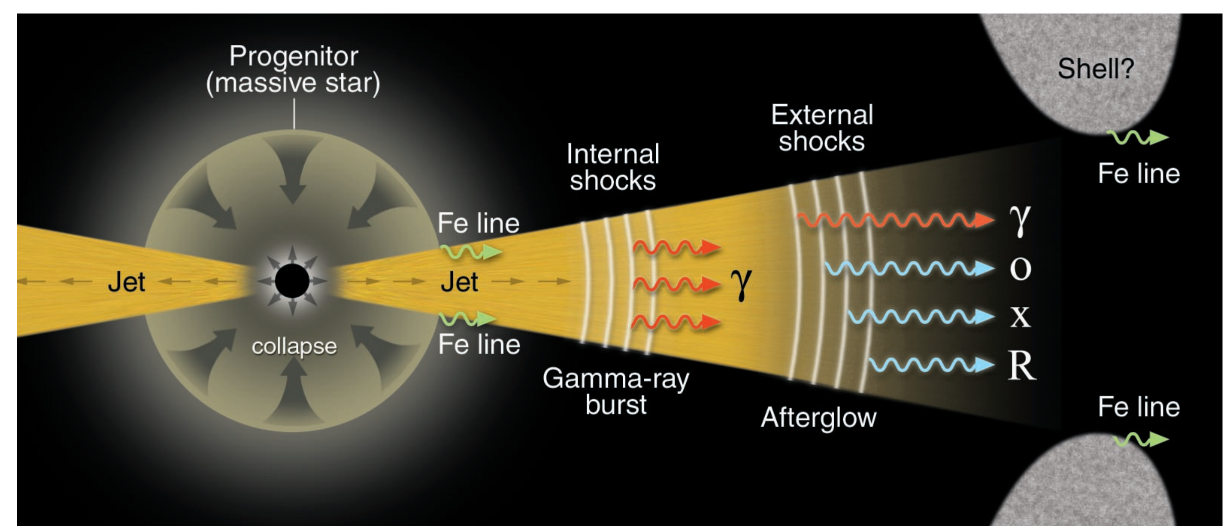


Photo-Pion Production

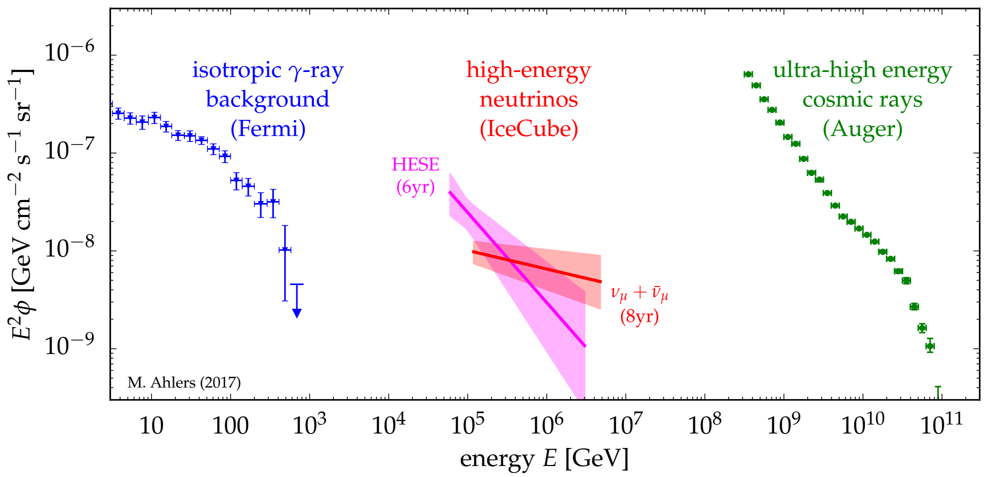
- **pγ processes** or “CR accelerator models”: neutrinos are produced *inside the source*, e.g. in GRBs or blazars [Waxmann&Bahcall ’97 ’00; Meszaros ‘01]





- The radiation field required to produce neutrinos via pγ interactions leads to a large two-photon annihilation optical depth for GeV-TeV gamma rays -> **less constrained by IGRB**

Diffuse flux: Complementarity between γ-rays and neutrinos



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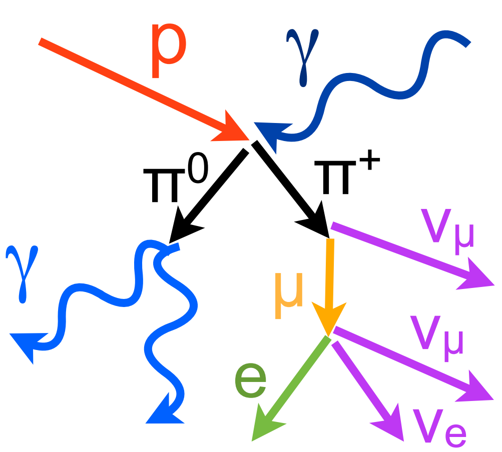

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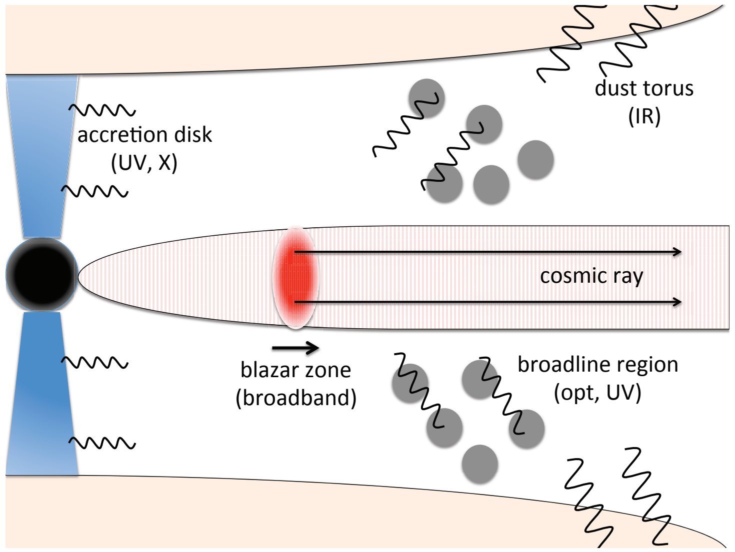
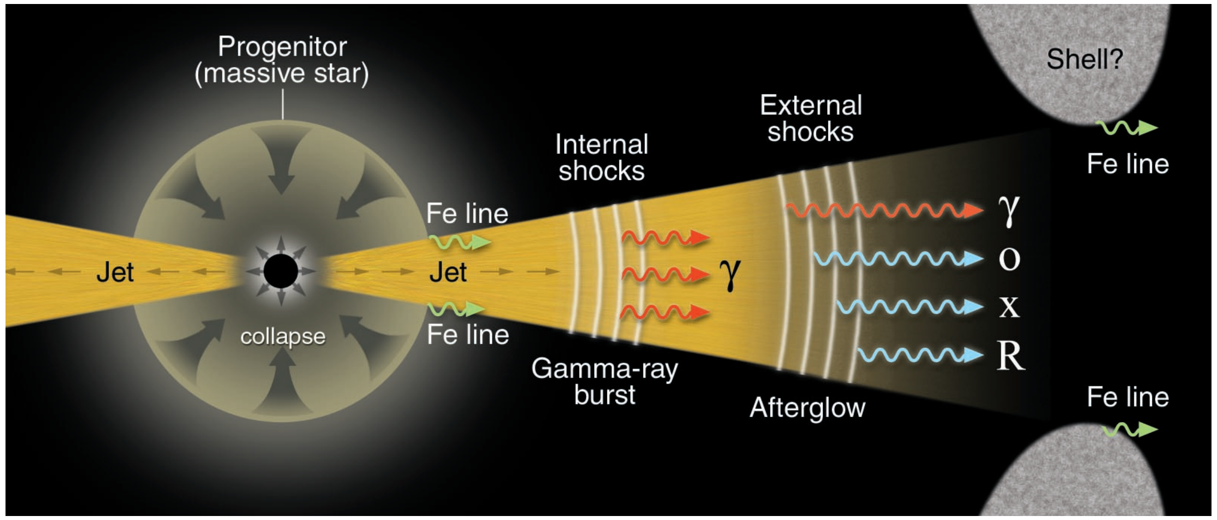




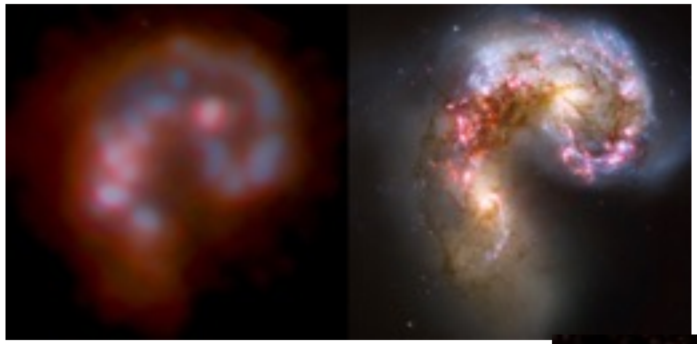
- also, pγ reactions are typically efficient only for sufficiently high-energy CRs, so the resulting γ-rays can contribute to the IGB only via cascades

One-point fluctuation analysis based on e.m. data

- Predicts **pixel-by-pixel neutrino count probability** distribution for a set of source classes based on multi-wavelength data (luminosity function and spectral template)
- **Data:** 6 year HESE data, 58 events (only showers, low veto-passing muon contamination)

Classes of sources under consideration

- **Star-forming galaxies:** The model is based on the infrared luminosity function from the Herschel catalog

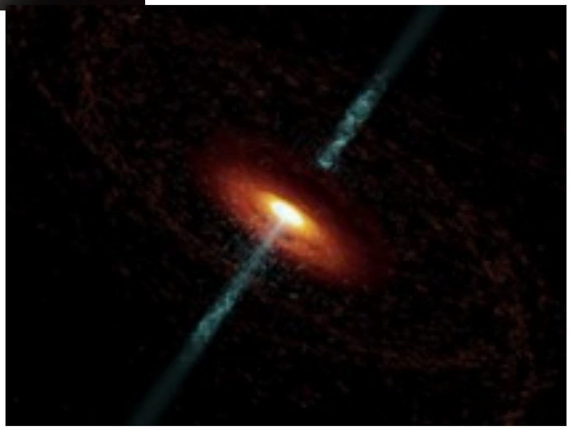


$$L_\gamma(L_{\rm IR}) = 10^\beta \left(\frac{L_{\rm IR}}{10^{10}\,L_\odot}\right)^\alpha \frac{\rm erg}{\rm s}$$

$$\Gamma_{SB} = 2.2$$

Fermi-LAT collaboration, arXiv:1206.1346

- **Blazars:** The model is based on the 2FHL catalog



$$E_\nu^2 F_\nu(E_\nu) = \left[\int_{10\,\rm GeV}^{\infty} E_\gamma F_\gamma dE_\gamma\right] \times \frac{Y}{0.9}\left(\frac{E_\nu}{E_{\nu,\rm peak}}\right)^{1-s} \exp\left(-\frac{E_\nu}{E_{\nu,\rm peak}}\right)$$

$\Gamma_{\rm 2FHL} = 2.5$ Padovani+ arXiv:1506.09135

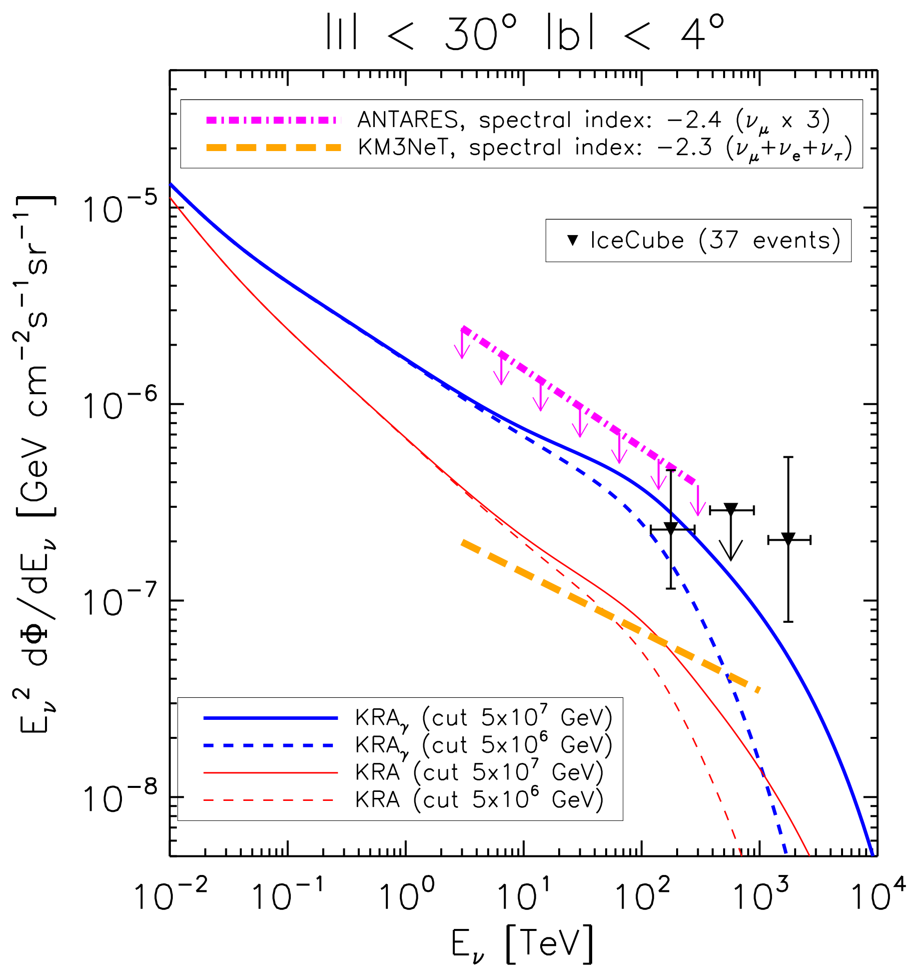
- **Unassociated, isotropic component:** To be fitted to data. Power-law spectrum, normal distribution for the intensity.

One-point fluctuation analysis based on e.m. data

- Predicts **pixel-by-pixel neutrino count probability** distribution for a set of source classes based on multi-wavelength data (luminosity function and spectral template)
- **Data:** 6 year HESE data, 58 events (only showers, low atmospheric contamination)

Classes of sources under consideration

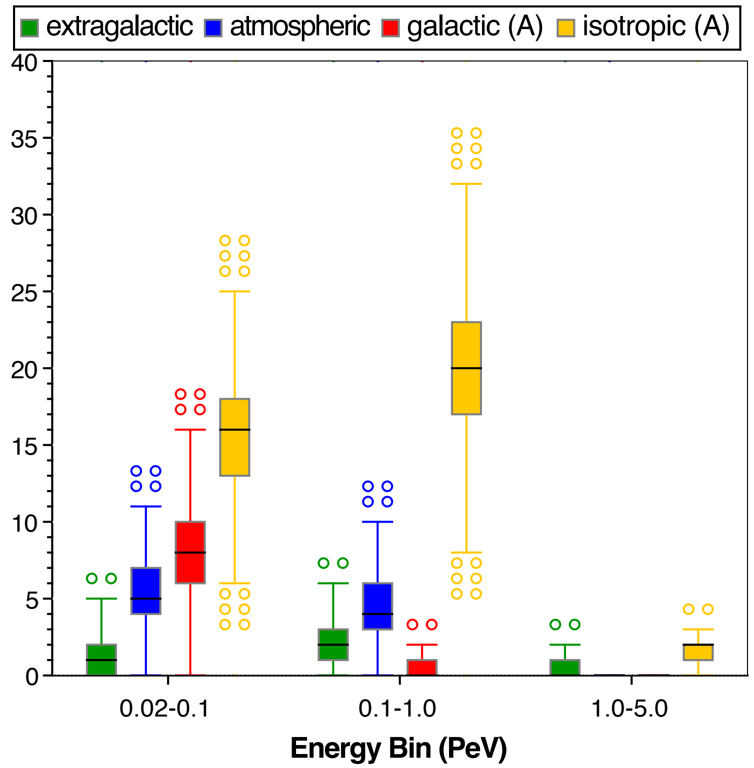
- **Galactic component:** Different models featuring either a constant spectrum or a progressive hardening (see previous part)

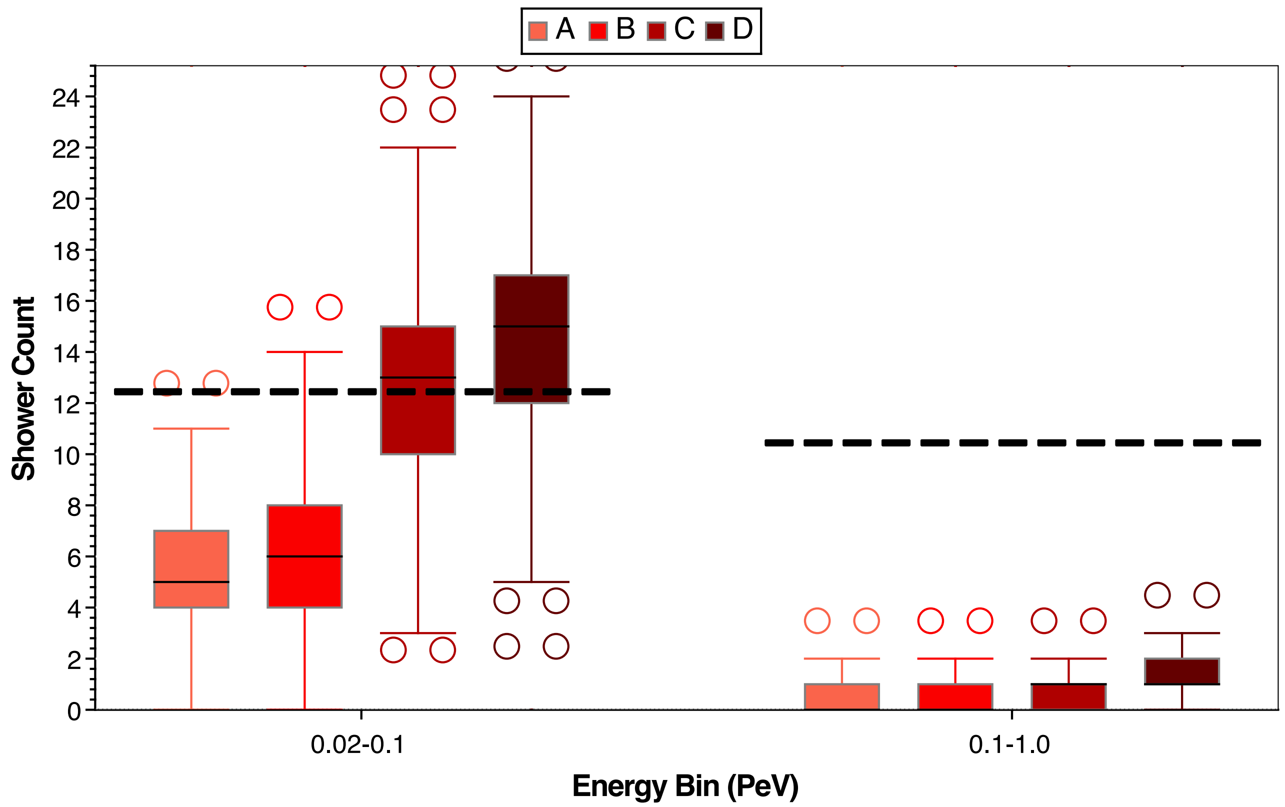


- Models A, B -> "KRA" models from Gaggero+ ApJL 2015, arXiv:1504.00227
  - Featuring **constant CR spectrum** across the Galaxy and tuned on local data. Different high-energy cutoffs.

- Models C, D -> "KRAγ" models
  - Featuring **harder CR spectrum in the inner Galaxy**

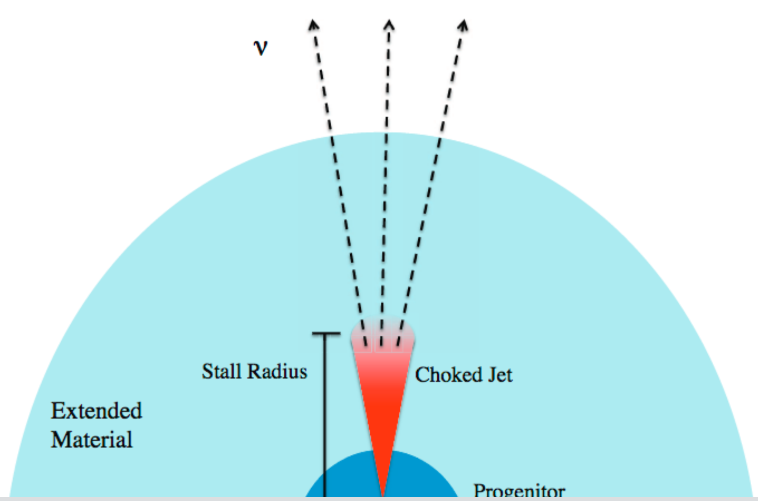
One-point fluctuation analysis: Results



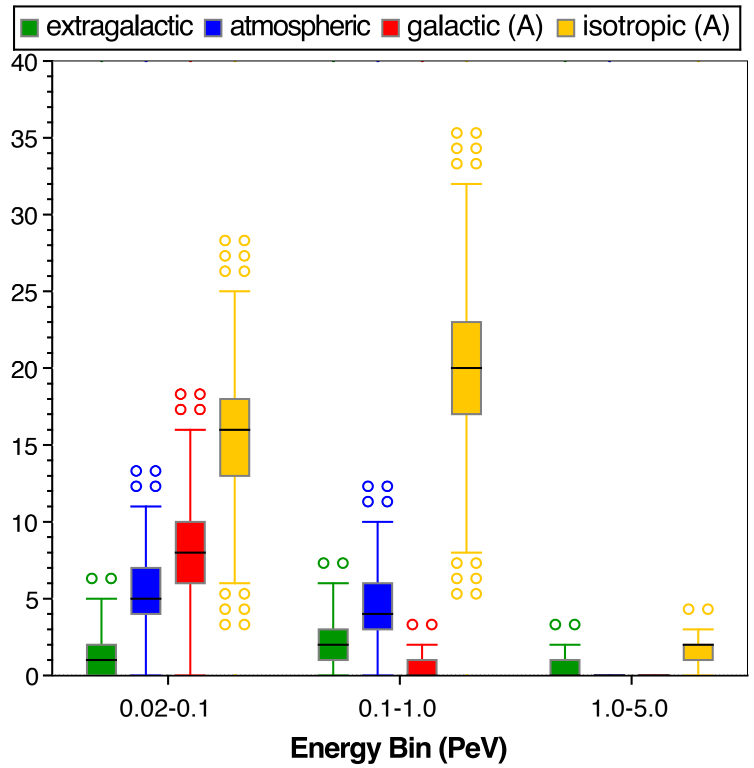


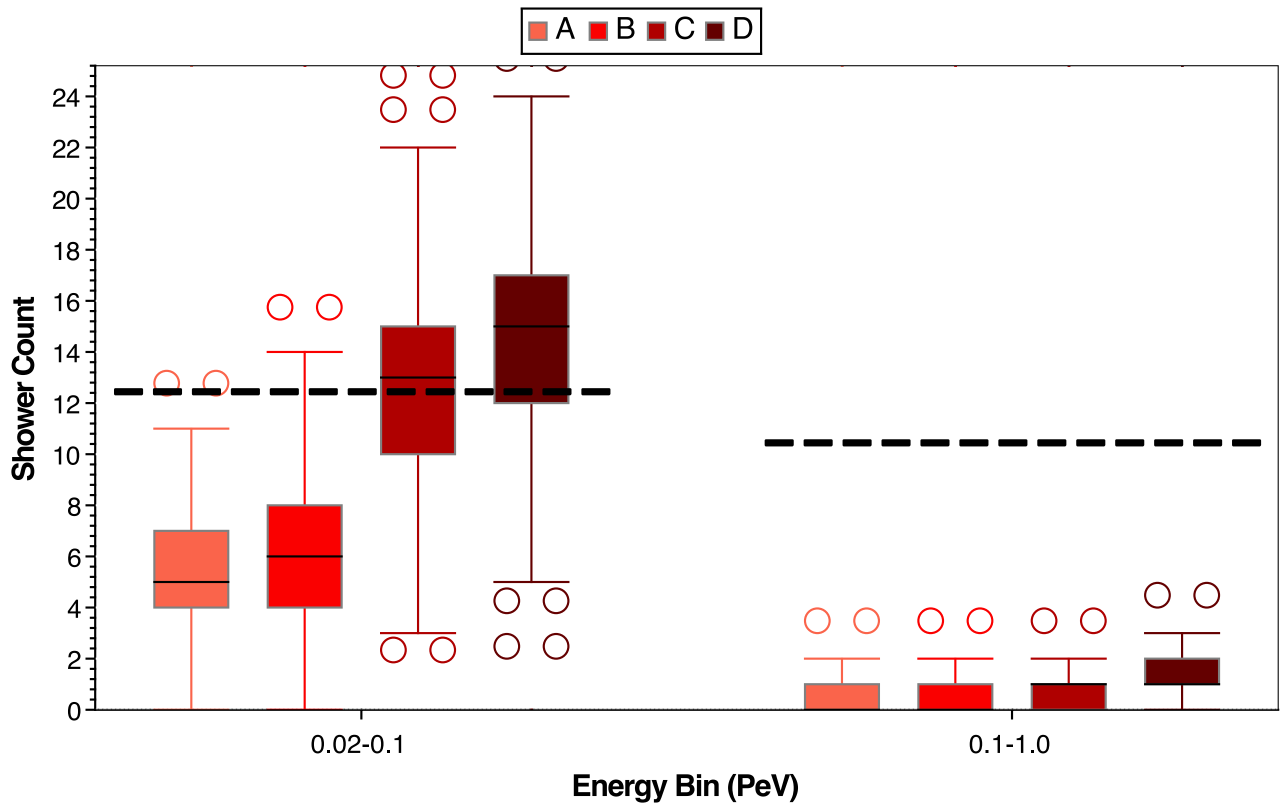
- The additional **isotropic template**, not associated with well-measured point-source classes, actually dominates the fit. Soft spectrum.
- **Hidden source class**, where gamma rays cannot escape? e.g. photohadron processes in choked jets [Meszaros&Waxman 2001, Ando&Beacom 2005, Tamborra + arXiv:1512.01559, Senno+ arXiv:1512.08513, Palladino+ arXiv:1502.02923]
- Possibly connected with a population of **low-luminosity GRBs**

Model	Normalization	Spectrum	(Correlation)
∅	3.42 ± 0.22	2.84 ± 0.63	-0.62
A	2.86 ± 0.22	2.71 ± 0.53	$+0.11$
B	2.81 ± 0.21	2.71 ± 0.54	$+0.18$
C	2.71 ± 0.20	2.69 ± 0.56	$+0.32$
D	2.64 ± 0.19	2.69 ± 0.58	$+0.41$



One-point fluctuation analysis: Results



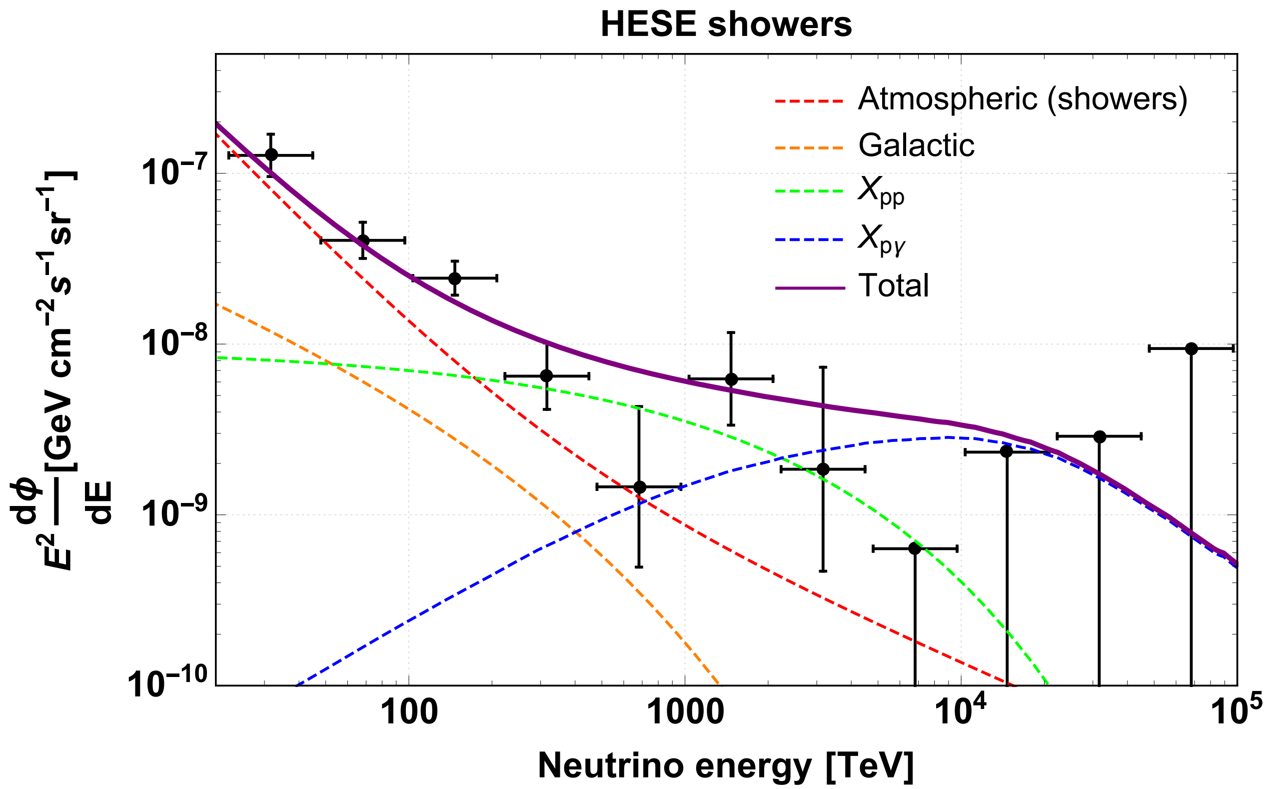


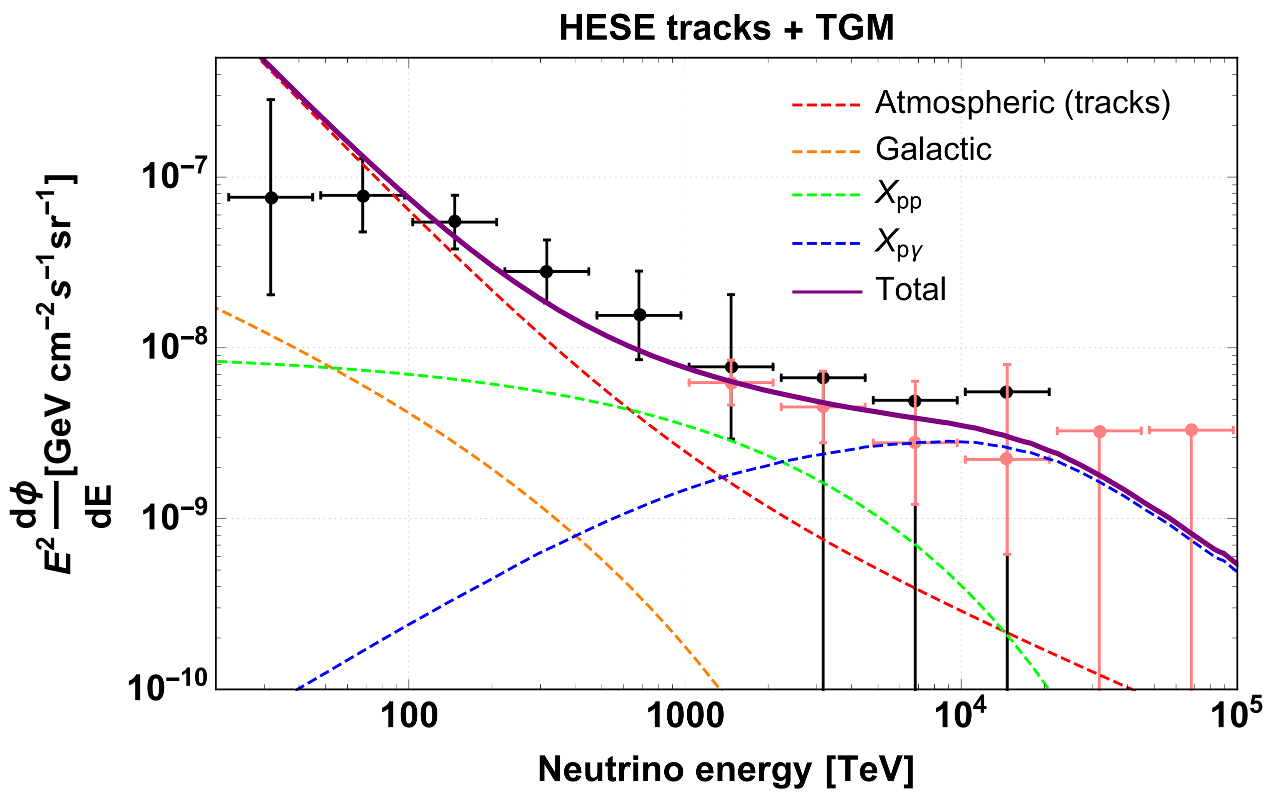
- Models B,C for the **Galactic gamma-ray emission show some tension** with neutrino data (overshoot low-energy bin in the central pixel)
- **Caveat:** Those models are optimized on gamma-ray data in the GeV-TeV domain, while neutrinos probe the multi-TeV domain
- If confirmed, this result may point towards **different spectral trends** in different energy domains, possibly with consequences on the physics of CR transport

Alternative approach: Spectral fitting

- **Fixed spectral templates** for different source classes, normalization fitted to the data
- Two different datasets: The **through-going muon** (coming from the Northern hemisphere) and the high-energy starting event (**HESE**) sample
- Aimed at explaining why The observed through-going muon spectrum is harder than the HESE sample
- **Four components**: Residual atmospheric background, standard Galactic contribution, pp source class (SFGs), pγ source class
- The **HESE track dataset seems more sensitive to low energy events**, that are much more affected by atmospheric backgrounds and by the Galactic component, especially for events coming from the Southern hemisphere

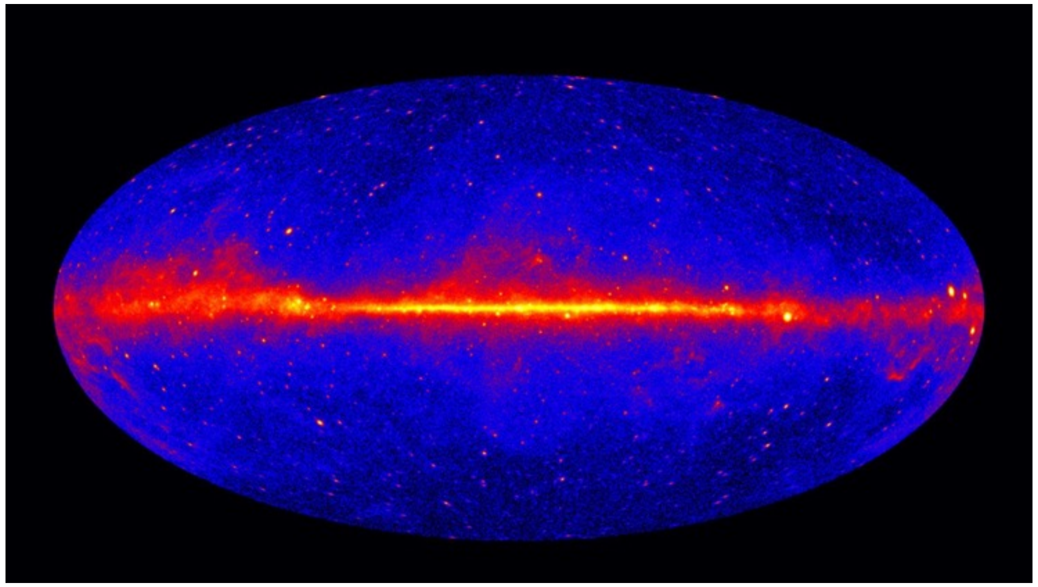
Less affected by veto-passing muons

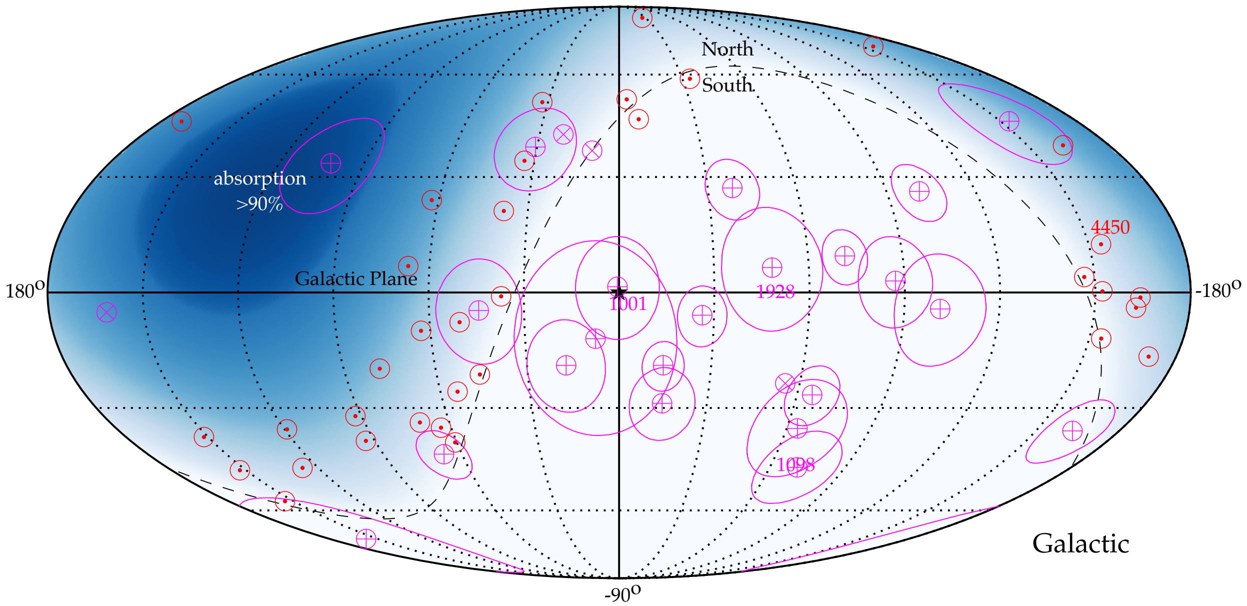




Palladino&Winter, 1801.07277

Conclusions

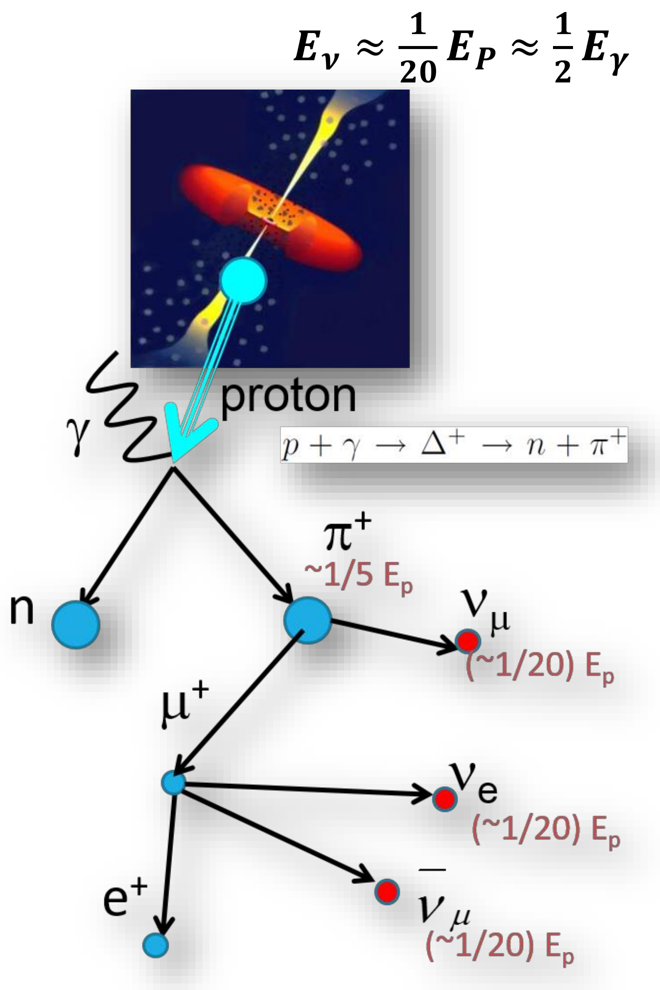


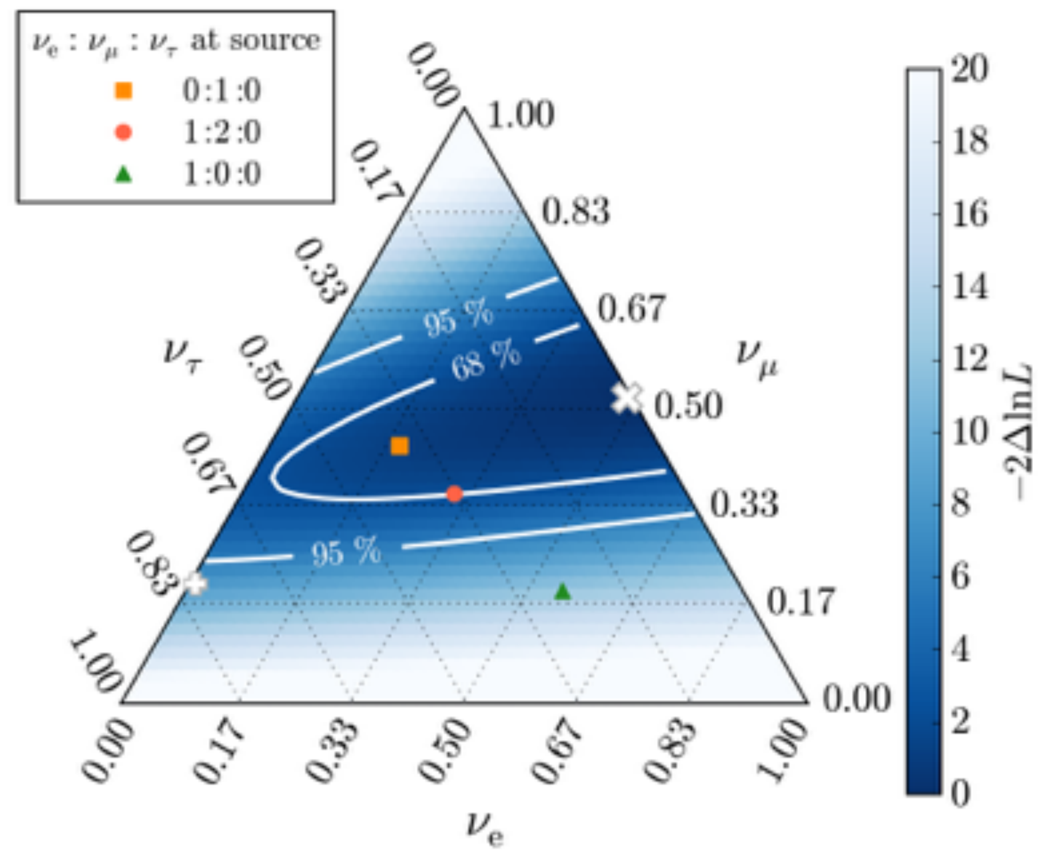


- **We don't know** where the IceCube neutrinos come from. **Different spectra** in different event samples (HESE and TGM) to be understood!
- Large flux (close to WB limit), high level of **isotropy**: Most likely **extra-Galactic** origin, many candidate source classes. Probably **multiple classes of sources** at work, probably numerous faint sources. Different techniques yield different results.
- First identification of a source: **Multi-messenger** astronomy has started!
- Very useful observable to constrain Galactic **CR transport** model, in connection with **gamma-ray** data: Looking forward to a correlation with the **Galactic plane**!

Thank you for your attention!

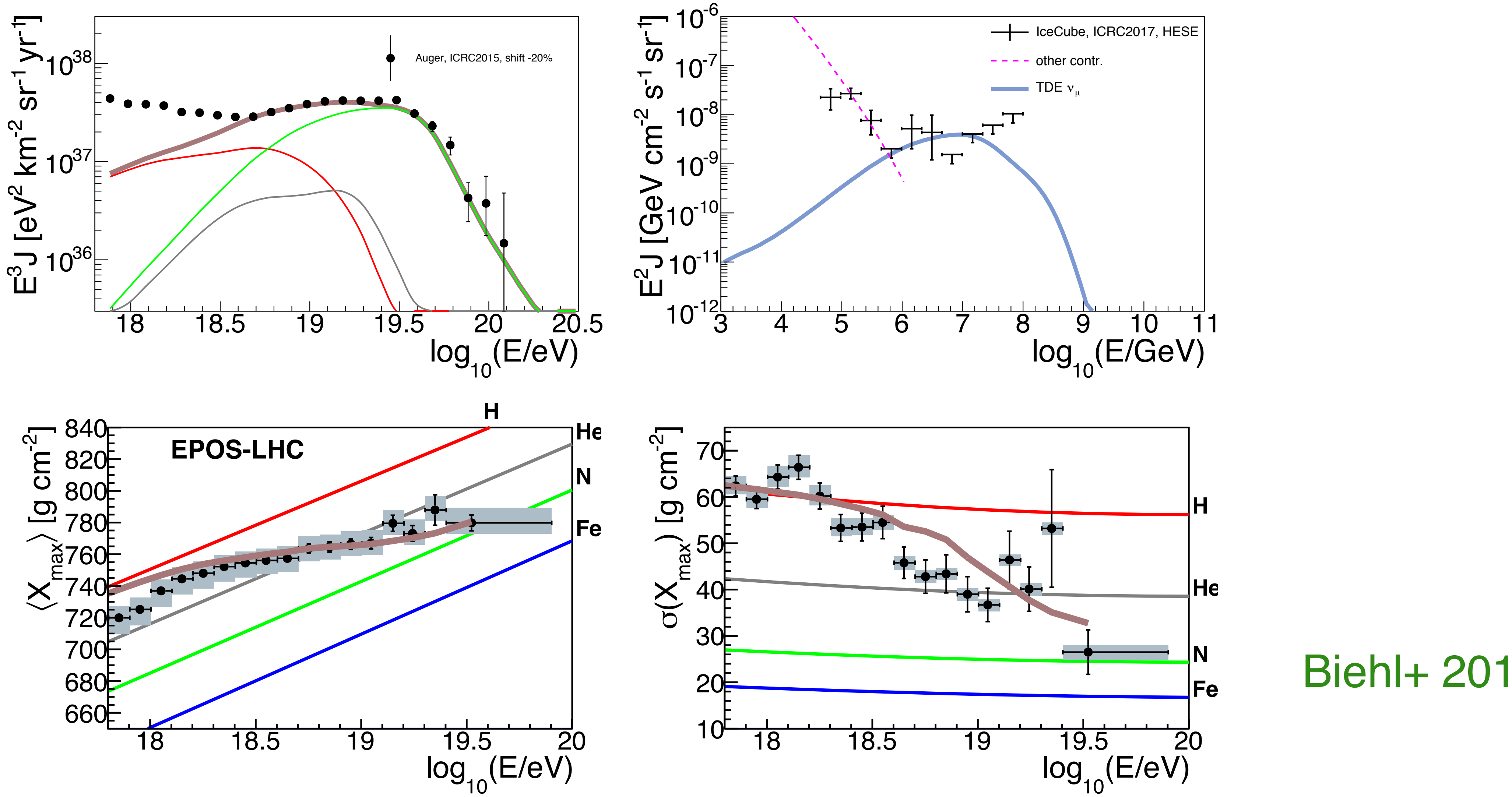
Backup





- IceCube 2017

- In many scenarios, neutrinos are produced in the decay of pions, which create one electron neutrino per every two muon neutrinos and no tau neutrinos (νe : νμ : ντ =1:2:0).
- Because neutrinos switch flavors during their long journey through the universe, the 3-flavor composition at Earth is expected to be approximately even (≈1:1:1).
- The constraints on the flavor composition derived with this study show that the data are compatible with this scenario as well as with the sole production of muon neutrinos (0:1:0).
- Scenarios based on the decay of neutrons whereby only electron neutrinos are produced (1:0:0) are excluded with a significance of 3.6 sigma.



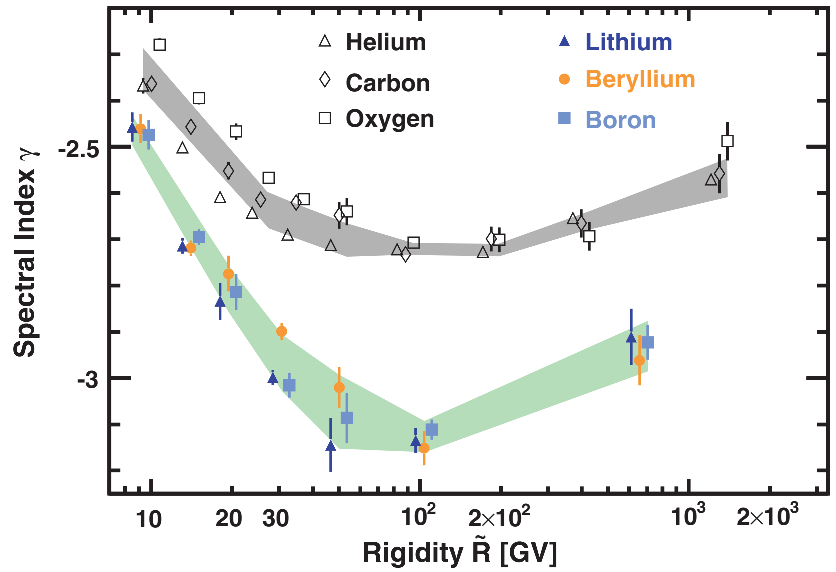
Biehl+ 2017

FIG. 1: Cosmic ray and neutrino observables corresponding to a parameter space point describing both UHECR and neutrino data at the highest energies (point A in Fig. 2, $L_X = 10^{47}$ erg/s, $R = 10^{9.6}$ km, with $G = 540$). *Upper right panel*: predicted muon neutrino spectrum from TDEs, compared to the data from the High Energy Starting Events at IceCube [22]. An additional flux, which might be of atmospheric origin (taken from [22]), is also shown. *Upper left panel*: Simulated energy spectrum of UHECRs (thick curve); and its components from (groups of) different nuclear species (thin, same color coding as in the bottom panels). For comparison, the Auger data are shown [23]. *Lower panels*: Predictions and data [24] on the average (left) and standard deviation (right) of the $X_{\max}$ distributions as a function of the energy. For predictions, EPOS-LHC [25] is assumed as the interaction model for UHECR-air interactions. A shift of -20% is applied to the energy scale of all the UHECR data, see text.

List of anomalies: Charged CRs

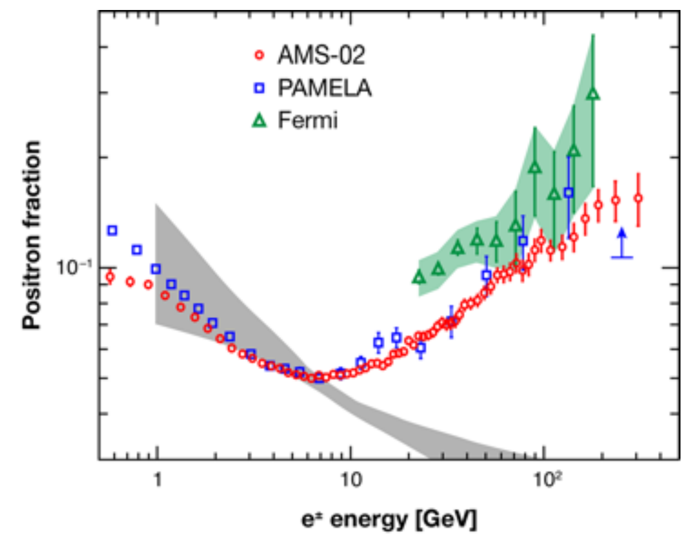
- **Spectral hardening** in primary and secondary species at ~200 GC

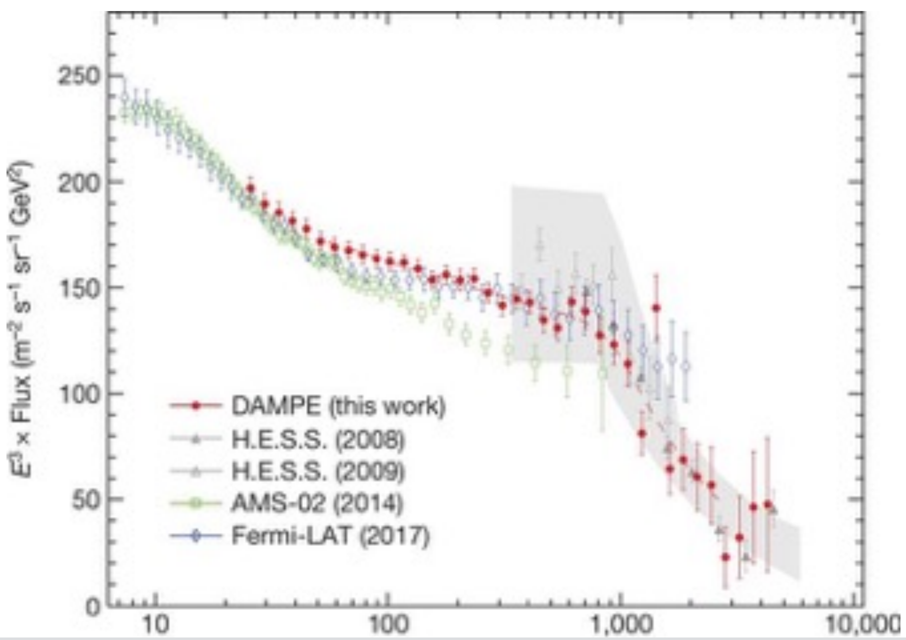
☆ Probably a transport effect.
☆ Different transport properties in the disk and in the halo? [Tomassetti 2015]
☆ Transition from self-generated to pre-existing turbulence? [Blasi, Amato, Serpico, PRL 2012; Aloisio, Blasi, Serpico 2015]



- **Positron excess**

☆ A population of leptonic accelerators (e.g. pulsars?) [Aharonian&Atoyan 1995; Hooper+ 2009, Grasso+ 2009; Yuan+ 2018]
☆ DM interpretation challenged by many constraints (e.g. CMB) [1502.01589]
☆ Anomalous transport properties? Change of paradigm in CR propagation? [P. Lipari arXiv:1707.02504]
☆ [review arXiv:1802.00636]



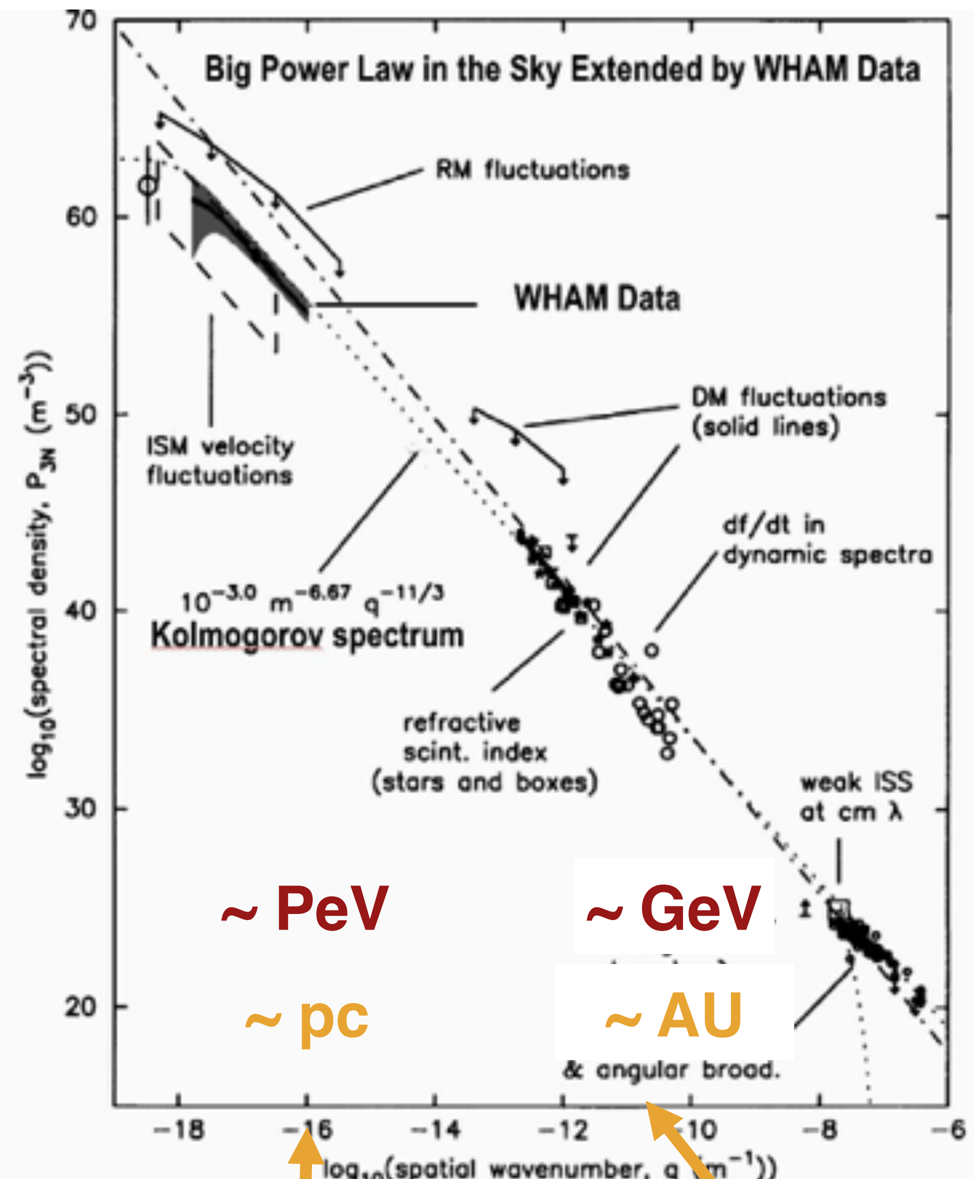


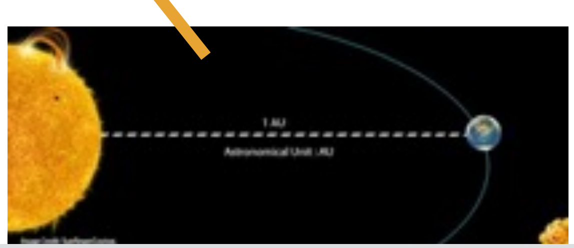
- Low- and high-energy **electrons**?
- Low- and high-energy **antiprotons**?

A bit deeper into the theory…

Guideline: resonant pitch-angle scattering on Alfvénic turbulence

[Morrison 1957; Jokipii ApJ **146** 1966; Jokipii&Parker PRL **21** 1968]

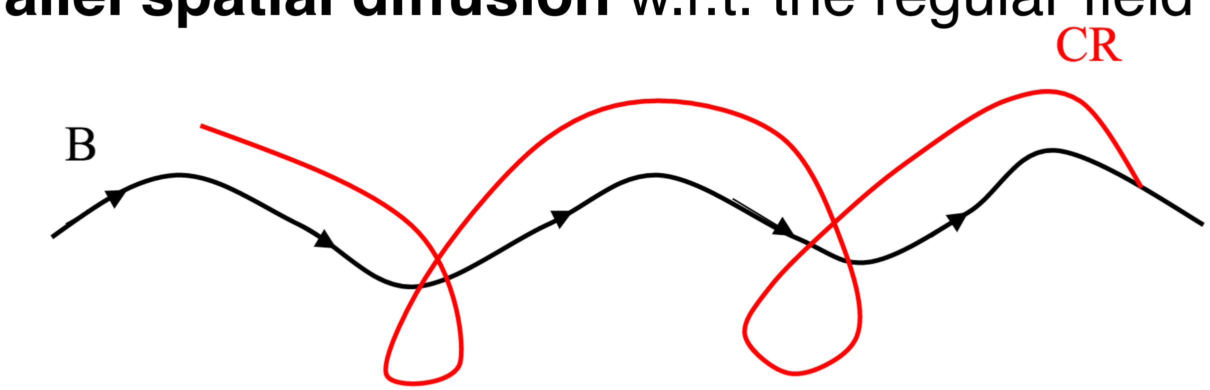




- The ISM is **magnetized** and **turbulent** over a wide inertial range; energy injection at large scales (~100 pc), e.g. by supernova explosions or other mechanisms

- **Pitch-angle scattering:** a resonant interaction between Alfvén waves and charged CRs

- Whenever a CR interacts with an Alfvén wave, if the **resonance condition** is satisfied, changes randomly the pitch angle: This stochastic process eventually results in a mostly **parallel spatial diffusion** w.r.t. the regular field



$$D_{\|} = \frac{1}{3} c^2 \tau_s \approx \frac{1}{3} \frac{c^2}{\Omega_g} \mathcal{F}(k)^{-1} = \frac{1}{3} R_L c \, \mathcal{F}(k)^{-1}$$

$[I(k_{res})\ k_{res}]/B^2$

Bohm diffusion coefficient D_B

A bit deeper into the theory…

Guideline: resonant pitch-angle scattering on Alfvénic turbulence
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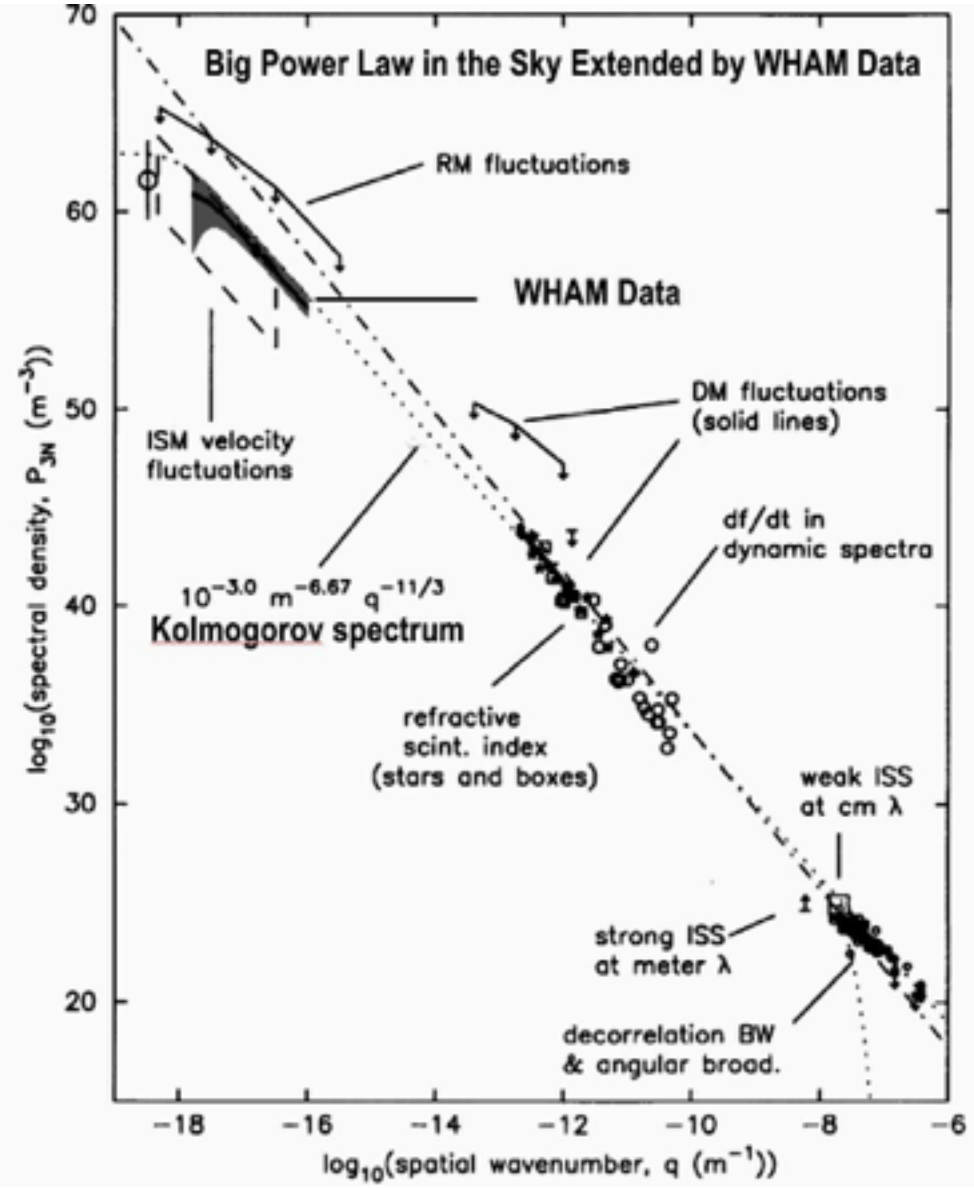

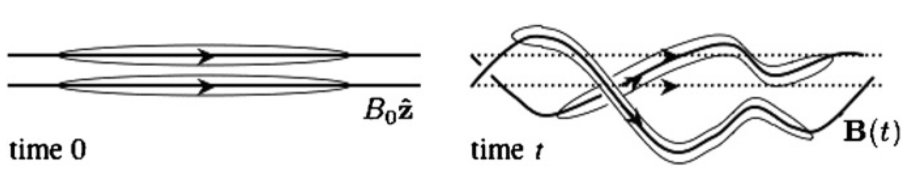

Figure 7. Lagrangian mixing of passive fields: fluctuations develop small scales across, but not along the exact field lines.

The real picture is much more complicated:

- **Non-linear effects at small scales**
  If CRs stream faster than the Alfvén speed, they can amplify waves (naturally of the correct shape for scattering) through the *resonant streaming instability* [Wentzel 1974; Skilling 1975; Cesarsky 1980; Farmer&Goldreich 2003]

- **Pitch-angle scattering is not an efficient confinement mechanism if Alfvénic turbulence is anisotropic.** [Chandran 2000, Yan&Lazarian 2002]