Diffuse Galactic gamma-ray emission: entering the era of the TeV/PeV frontier

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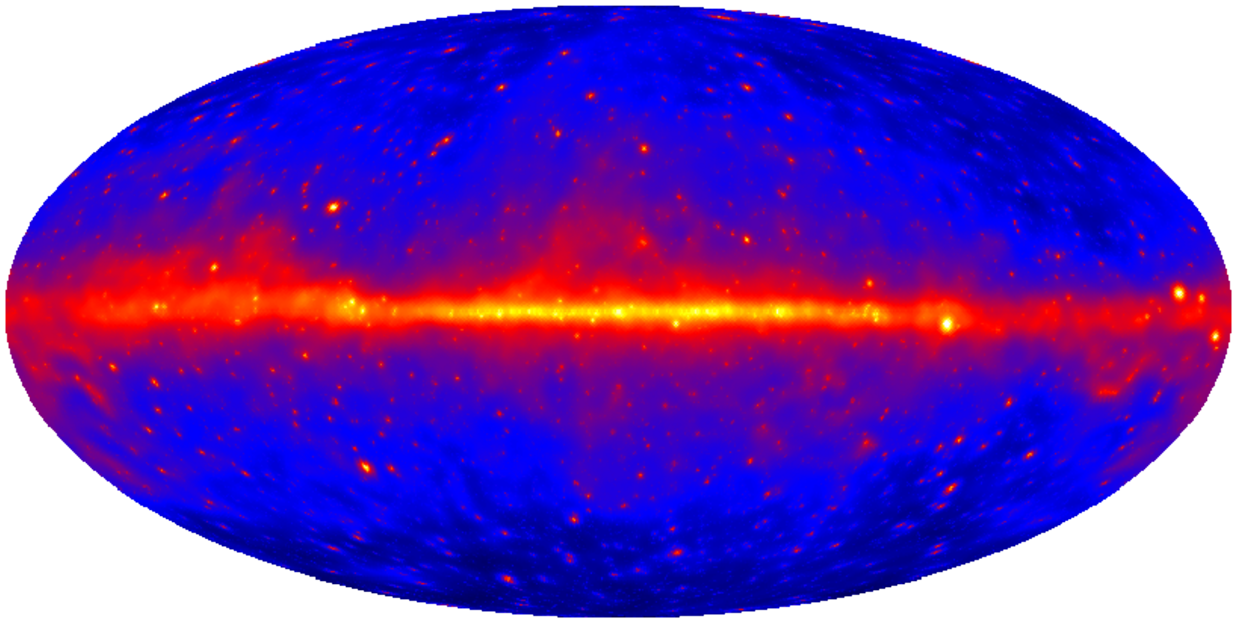
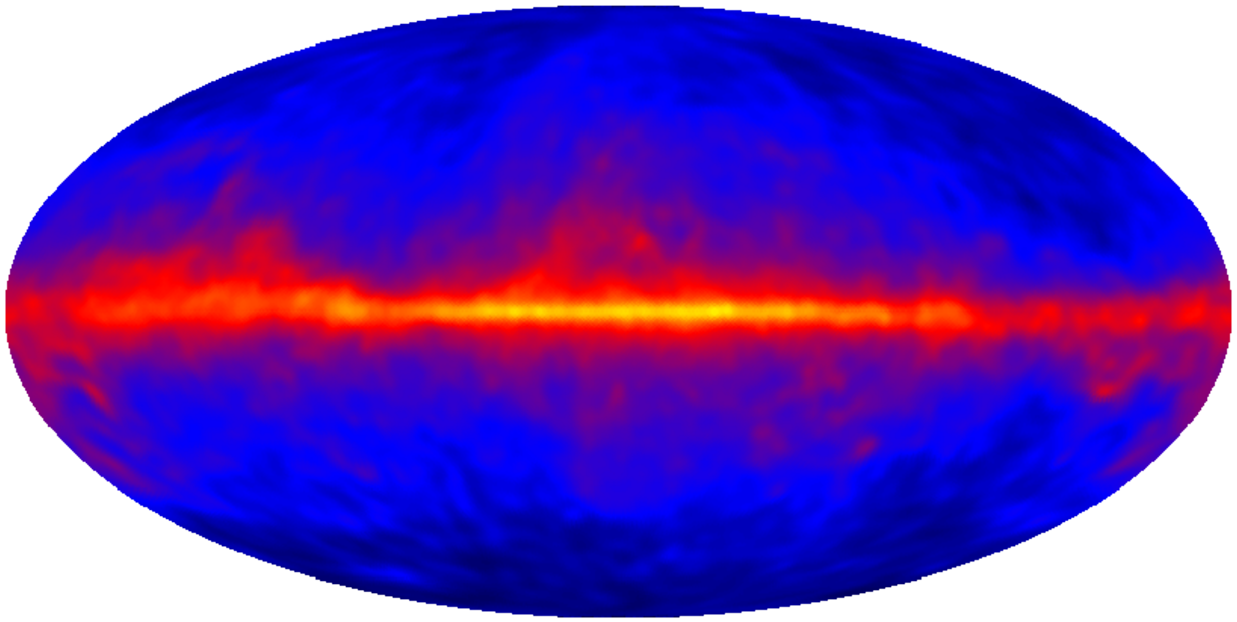
- Generalities
- The diffuse GeV sky: lessons from *Fermi*
- Entering the era of the TeV/PeV frontier
- Prospects for CTAO
- Final remarks

Diffuse and interstellar emission

Fermi LAT
gamma rays > 600 MeV

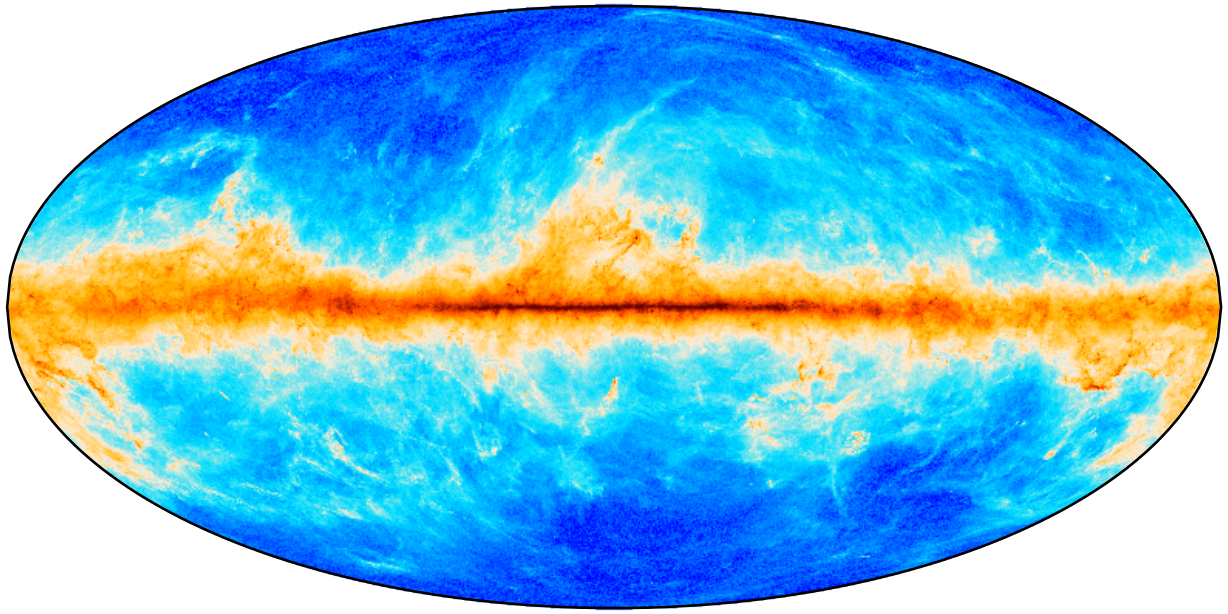


Fermi LAT
gamma rays > 600 MeV
sources removed
DIFFUSE EMISSION



Selig et al. (2015) A&A 581 A126

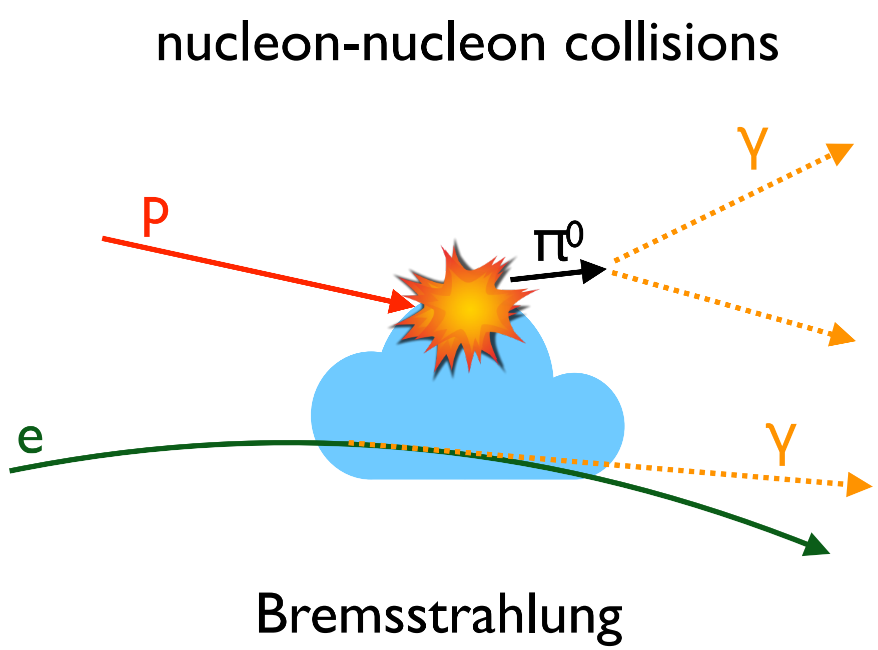
Planck+IRAS
model of dust thermal emission

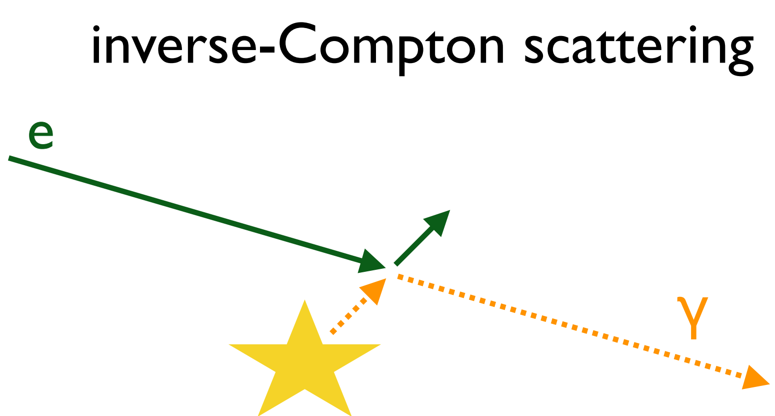


Planck collaboration (2014) A&A 571 A11

- Diffuse emission = not related to individual sources
- GeV: good correlation gamma rays /interstellar matter → CR interactions
- Diffuse emission = interstellar emission + unresolved sources

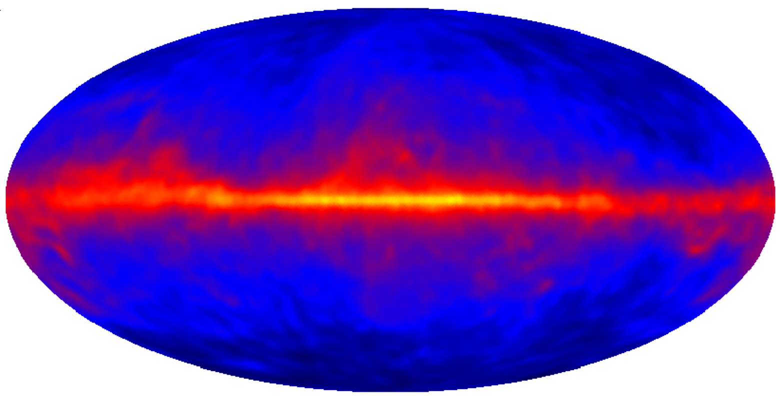
Interstellar emission: what and why





- Probe of cosmic rays and interstellar matter&radiation fields
- Background to study individual sources, dark matter …

Modelling interstellar emission



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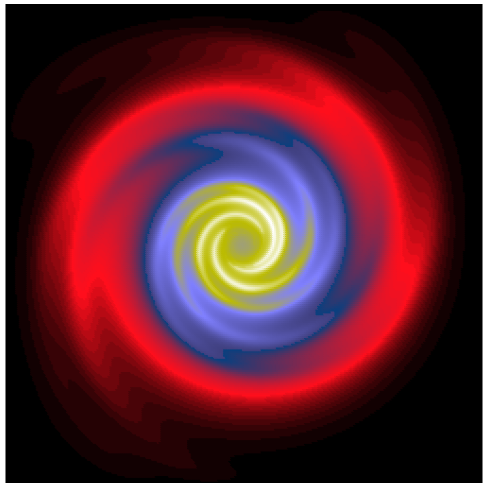
COSMIC RAYS



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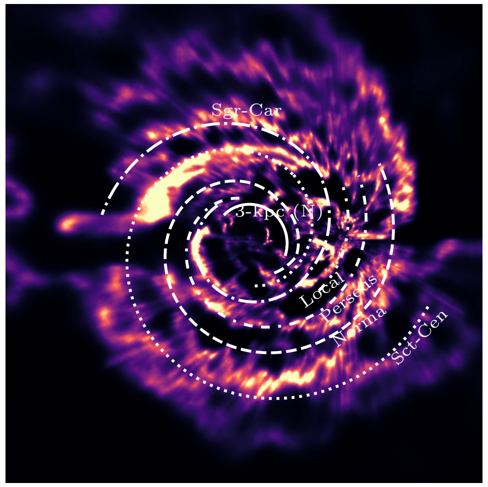
INTERSTELLAR
GAS
&PHOTONS



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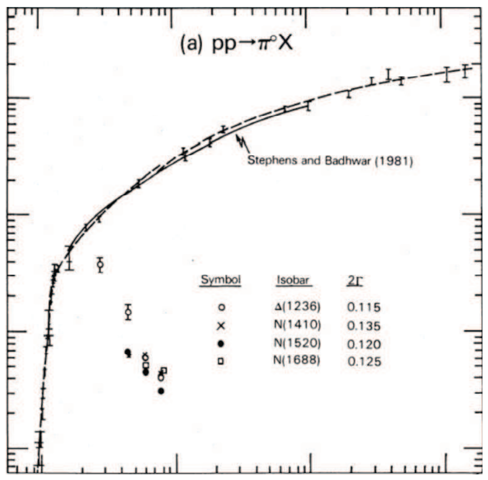
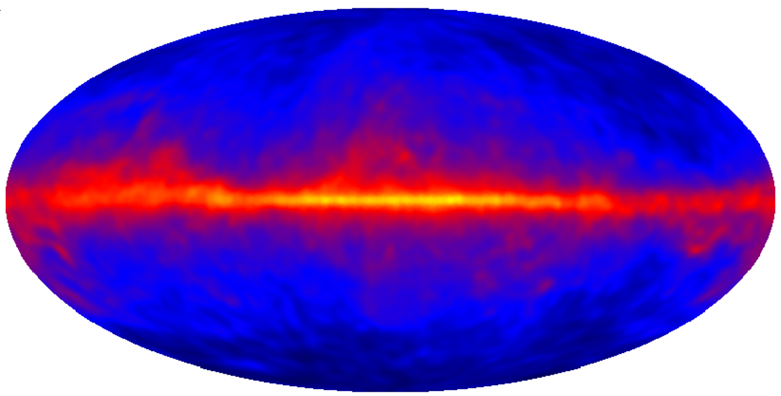
CROSS SECTIONS



Modelling interstellar emission



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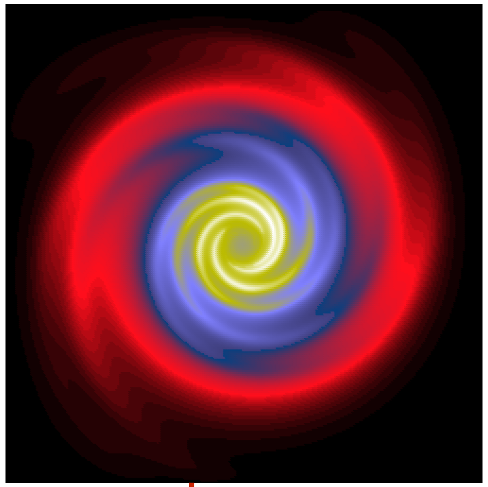

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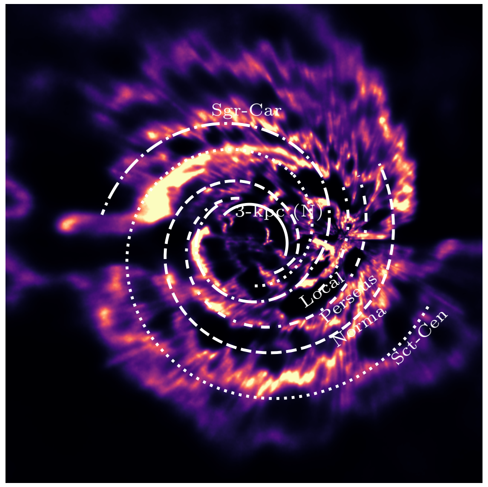
INTERSTELLAR GAS &PHOTONS



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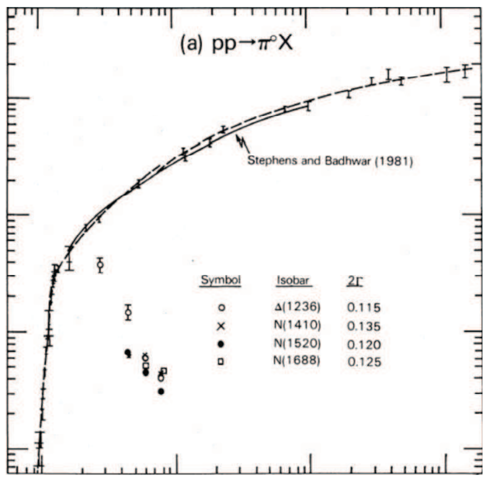
CROSS SECTIONS

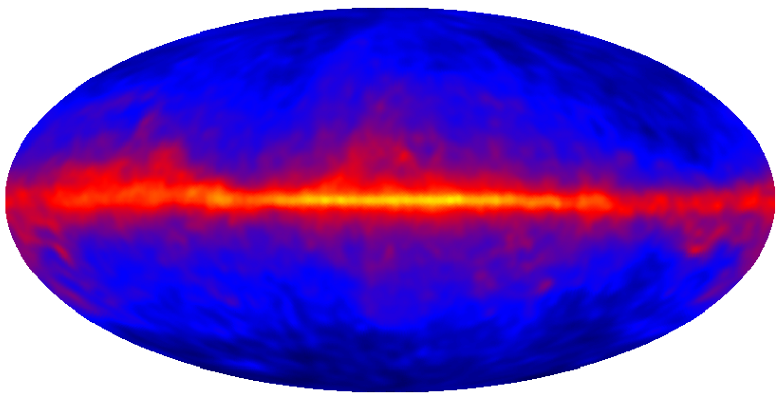


- Empirical models fitted to gamma-ray data
- Solutions of CR propagation equation*
  (e.g., GALPROP, DRAGON, PICARD)
- Particle Tracking
- Simulations based on coupled CR+MHD equations

*Standard implementations based on

- steady-state solutions
- smoothly-distributed sources
- isotropic, homogeneous diffusion with scalar diffusion coefficient

Modelling interstellar emission



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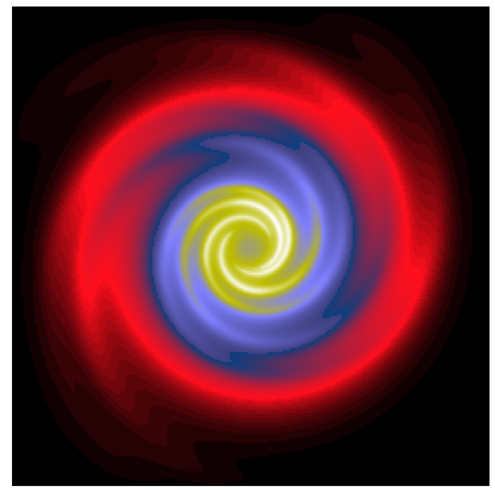

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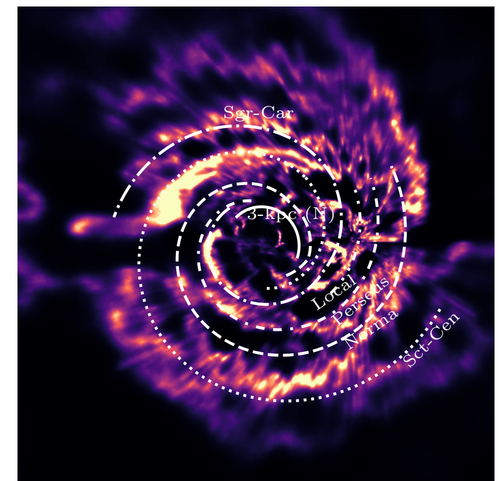
INTERSTELLAR
GAS
&PHOTONS



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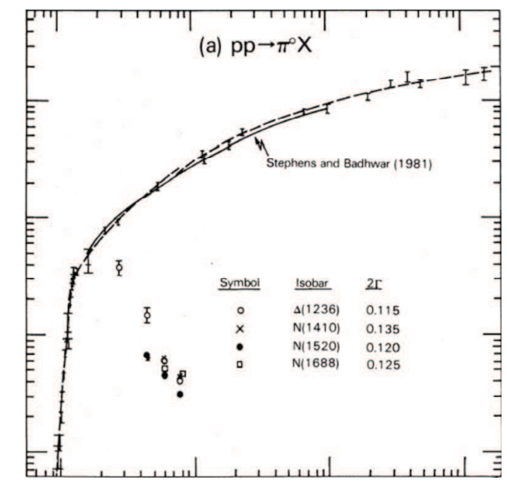
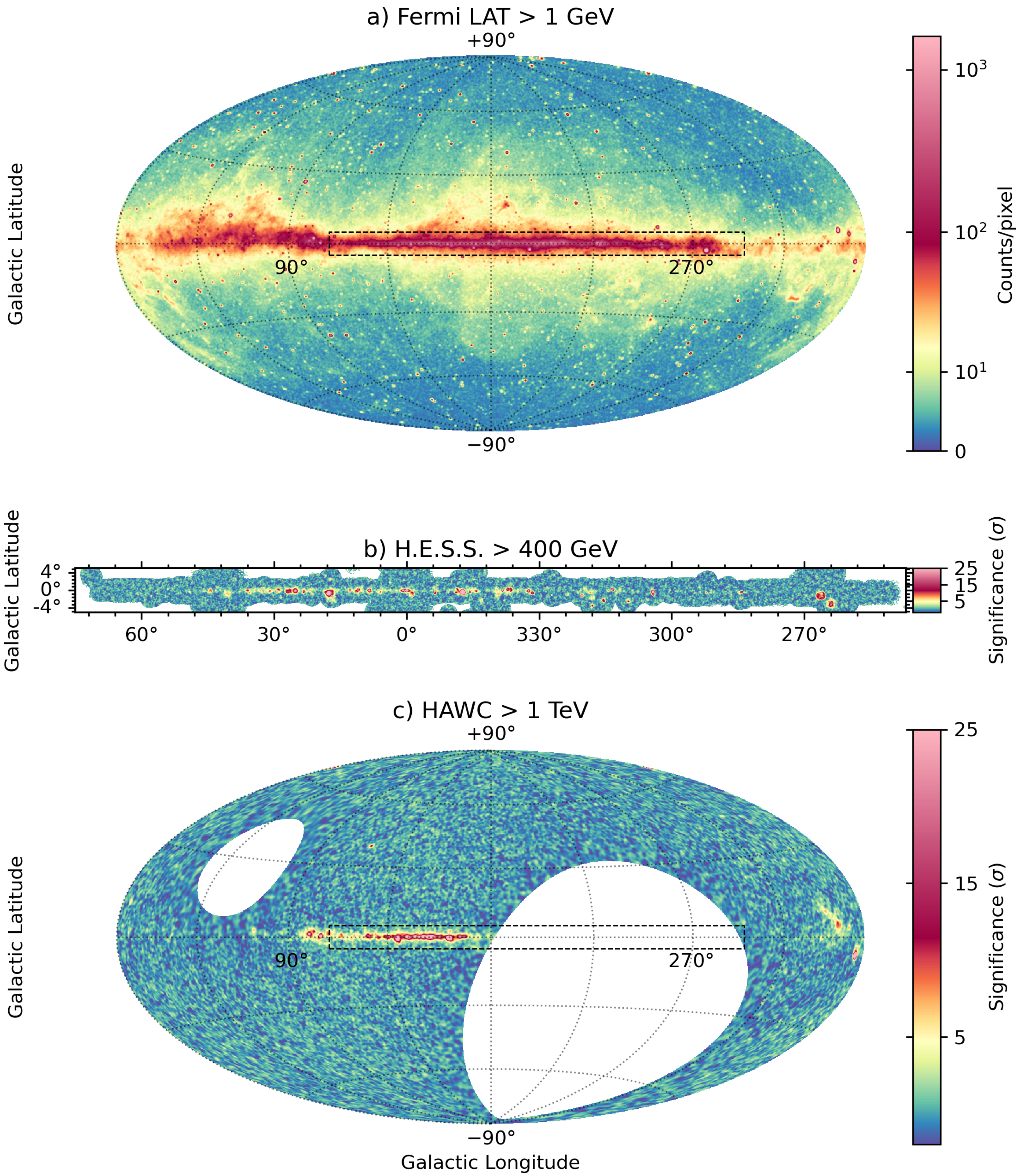


- Lines from atomic (H I) and molecular (CO, CS, ...) transitions → Doppler shift gives quasi-3D information
- Emission from ionised gas (Hα, free-free, radio-recombination lines, …)
- Dust thermal emission and extinction ~ total gas tracer
- Stellar population models, Galactic rotation curves, radiative transfer, …

Observations



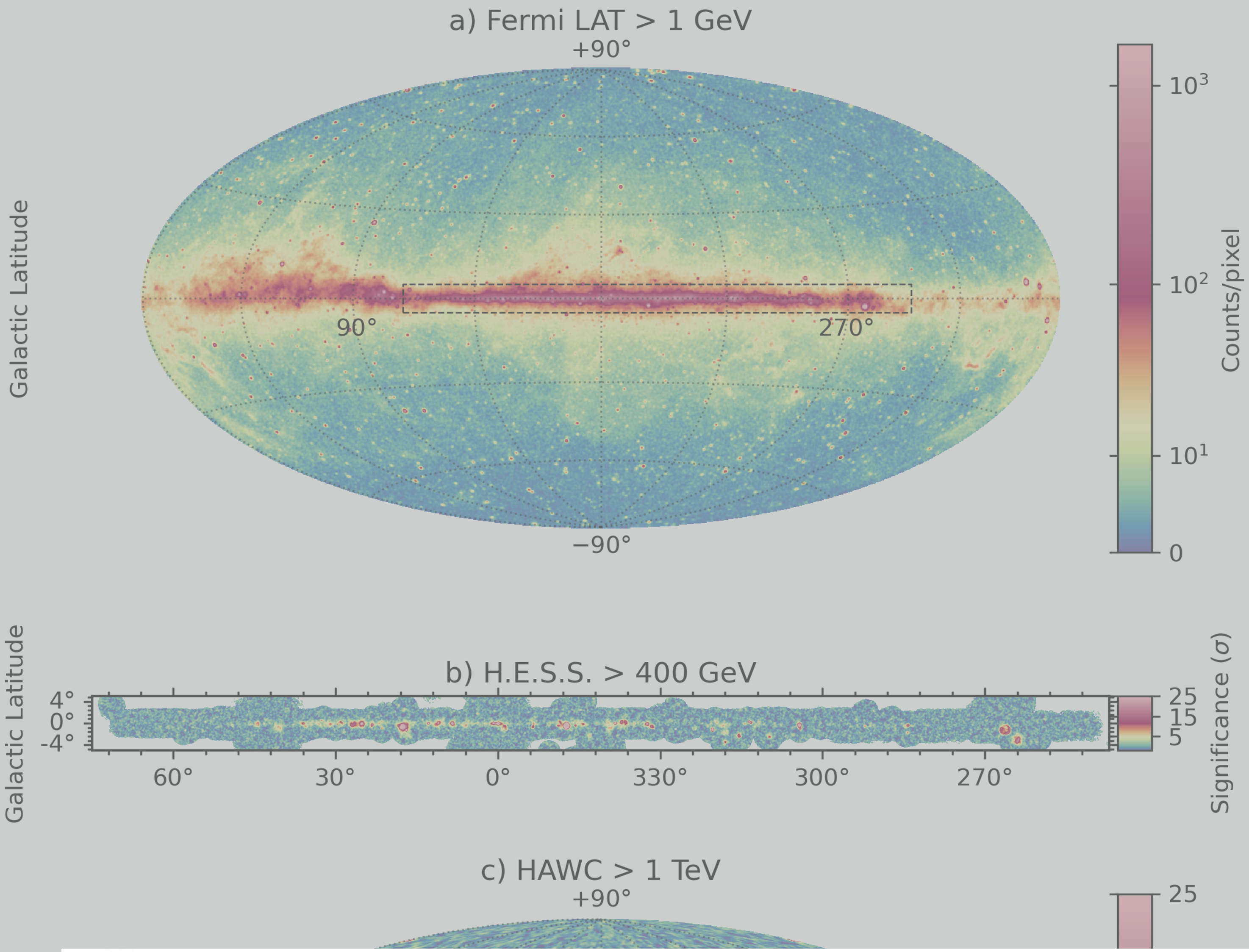
LT, Gaggero and Martin (2021) Universe 7 5 141

Pair-tracking space telescopes
- low background, large field of view
- pic of emission from CR interactions
- diffuse emission dominates over individual sources

Imaging atmospheric Cherenkov Telescopes
- modest field of view, good angular resolution
- background subtraction → challenging to study diffuse emission
- discrete sources prevail

Air-shower arrays
- large field of view, reach PeV energies
- explore knee region
- good energy overlap with neutrino measurements

Observations



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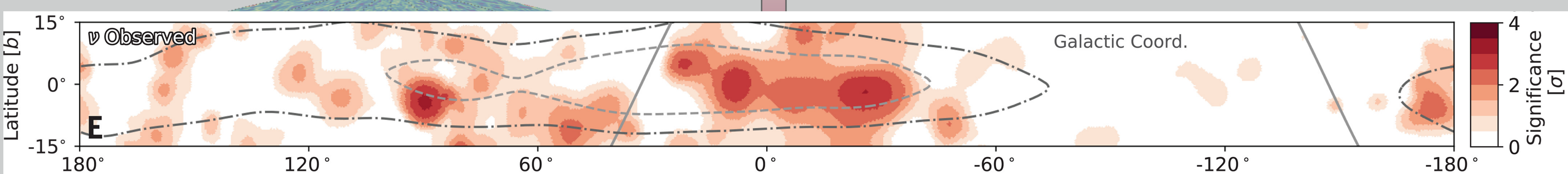

Icecube collaboration (2023) Science 380 6652 1338

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- Generalities
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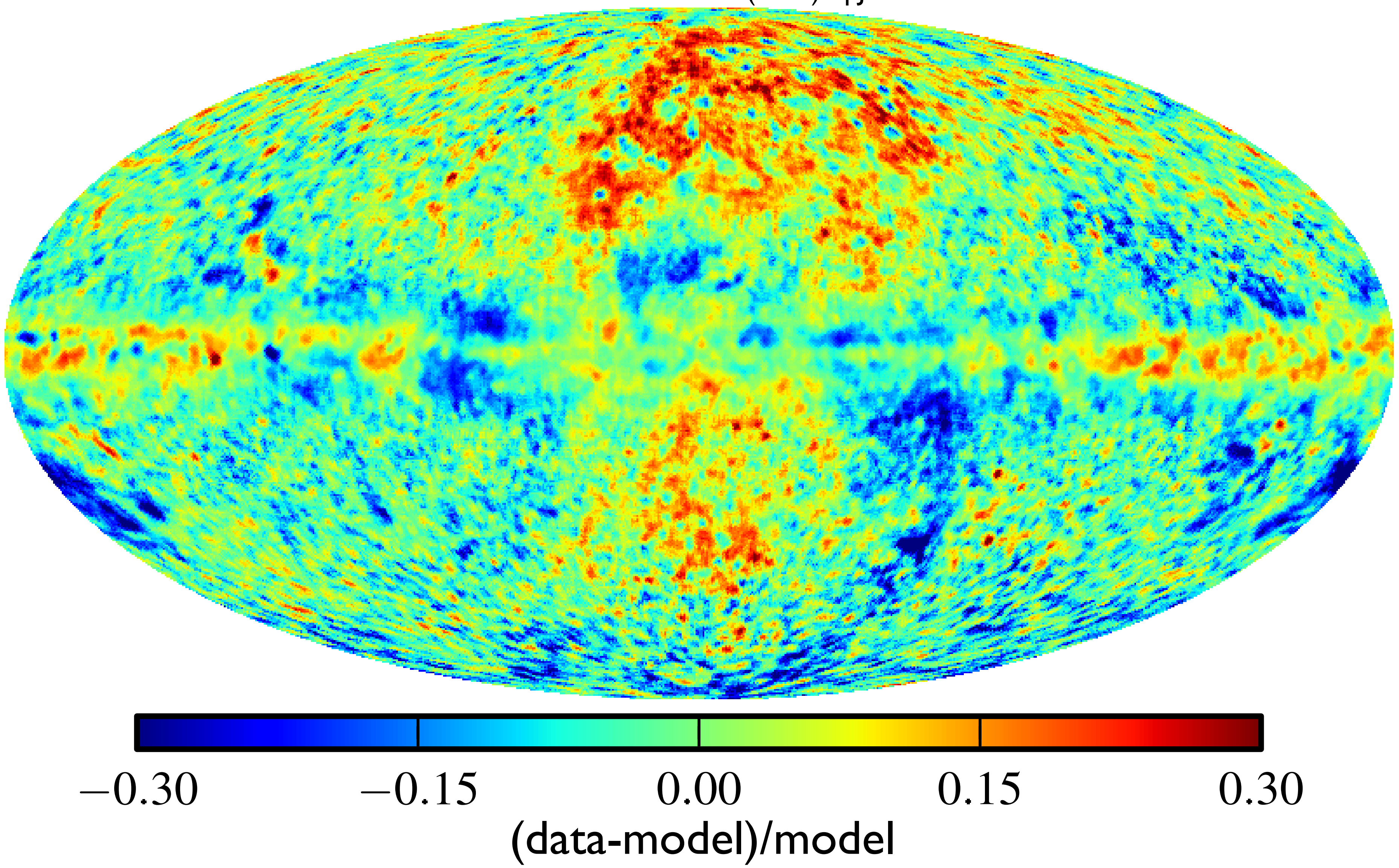
- Prospects for CTAO
- Final remarks

When models meet data

Fermi LAT collaboration (2012) ApJ 750 3

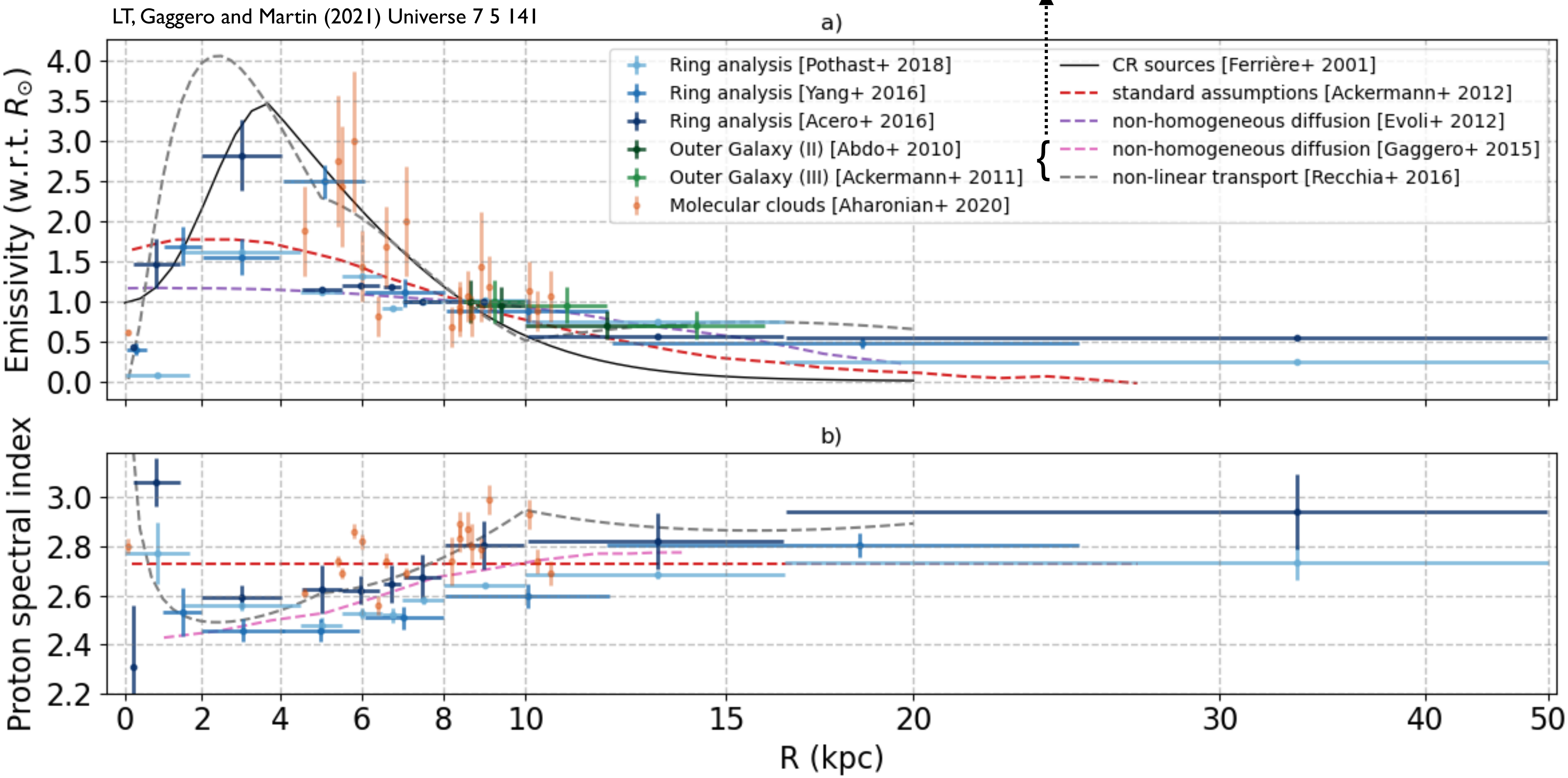


- extended residual emission at ~30% level
- excesses → features not included in models (*Fermi* bubbles, GC excess, Cygnus cocoon, …)
- solutions: unresolved sources, unmodeled gas/radiation fields, localised particle injection (+ peculiar transport conditions?), exotic processes

Cosmic rays throughout the Galactic disk

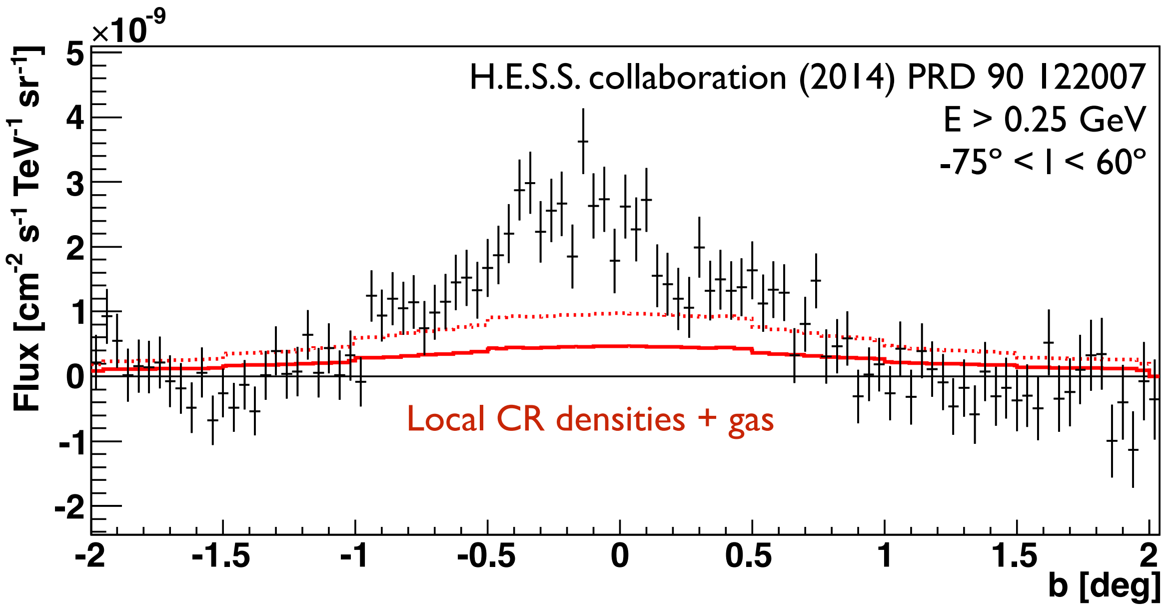
different extrapolations to TeV/PeV domain

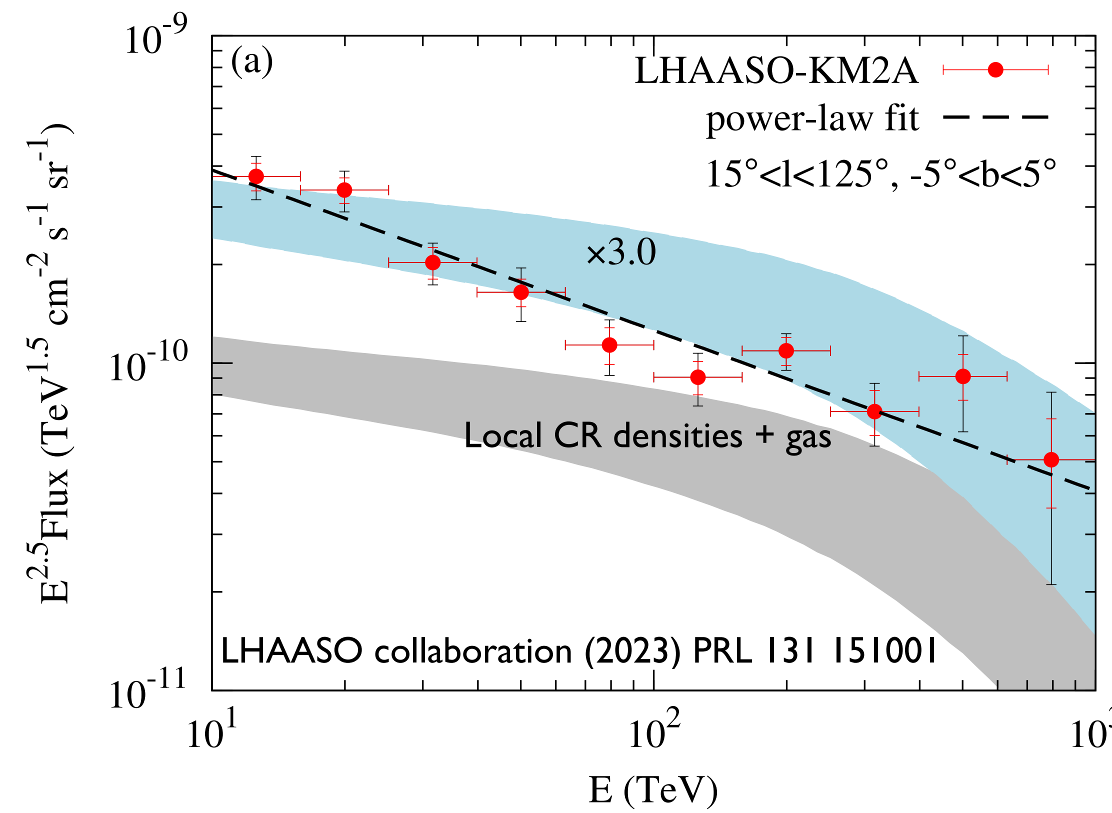
LT, Gaggero and Martin (2021) Universe 7 5 141

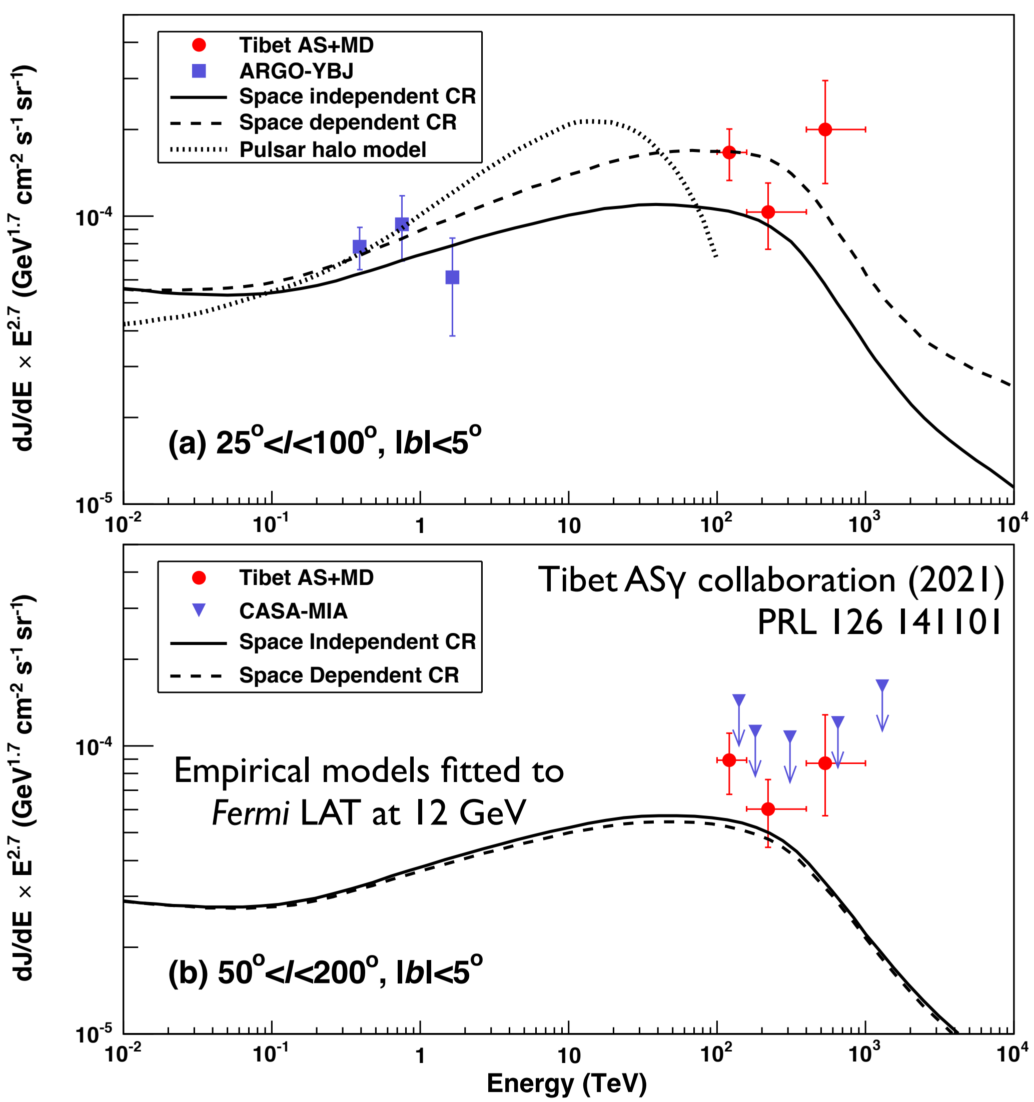


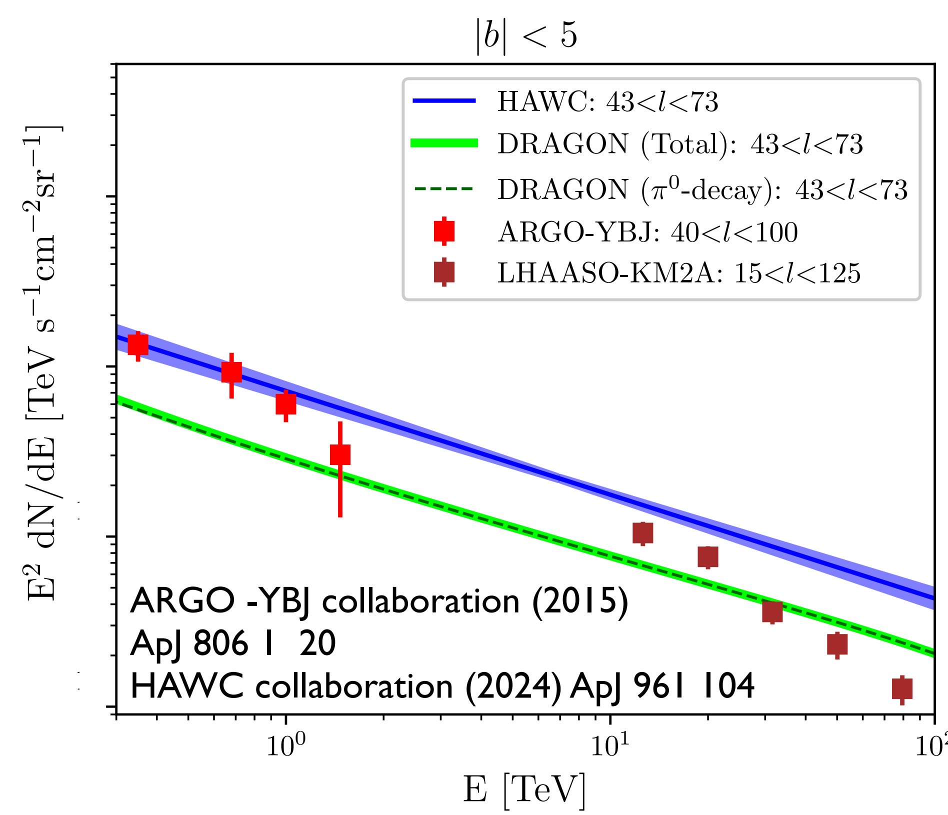
- Generalities
- The diffuse GeV sky: lessons from *Fermi*
- Entering the era of the TeV/PeV frontier
- The next generation of TeV/PeV instruments
- Final remarks

TeV/PeV measurements



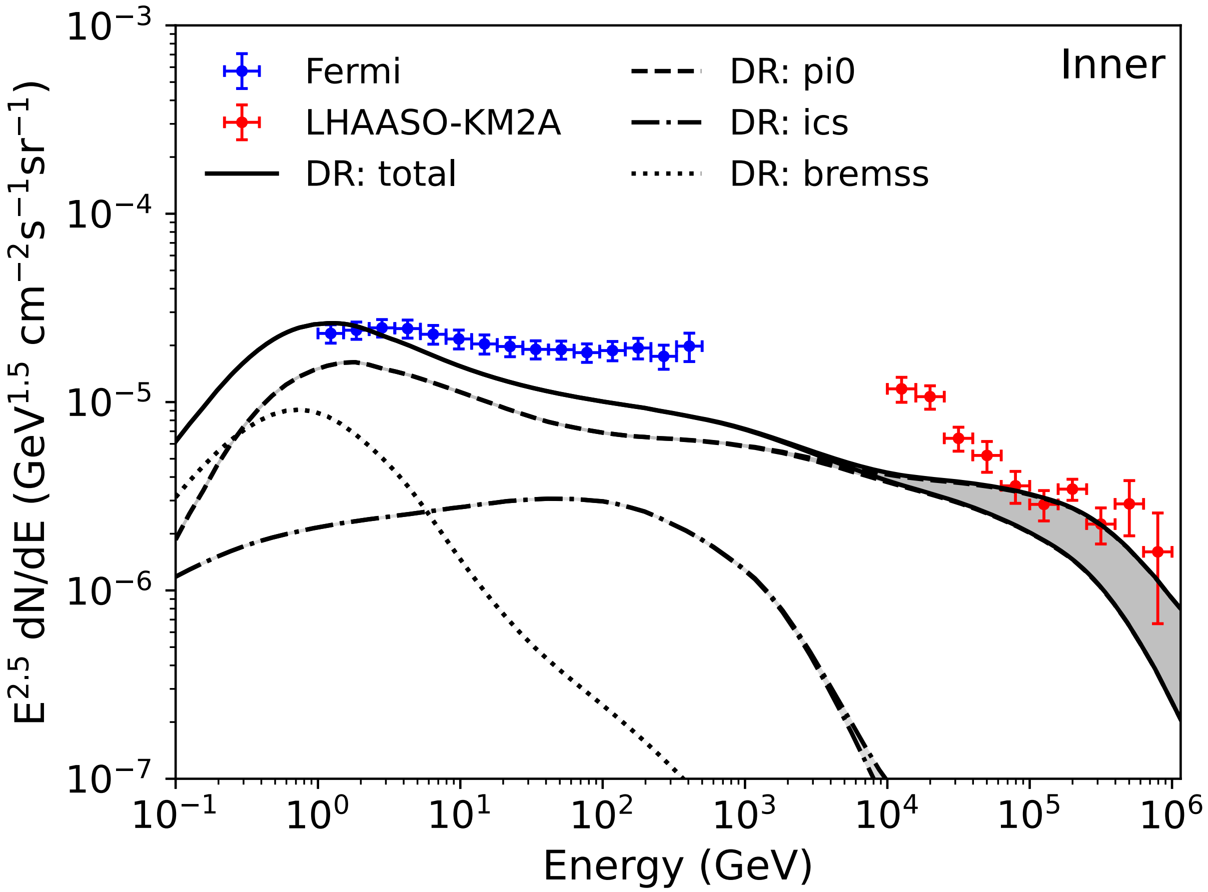




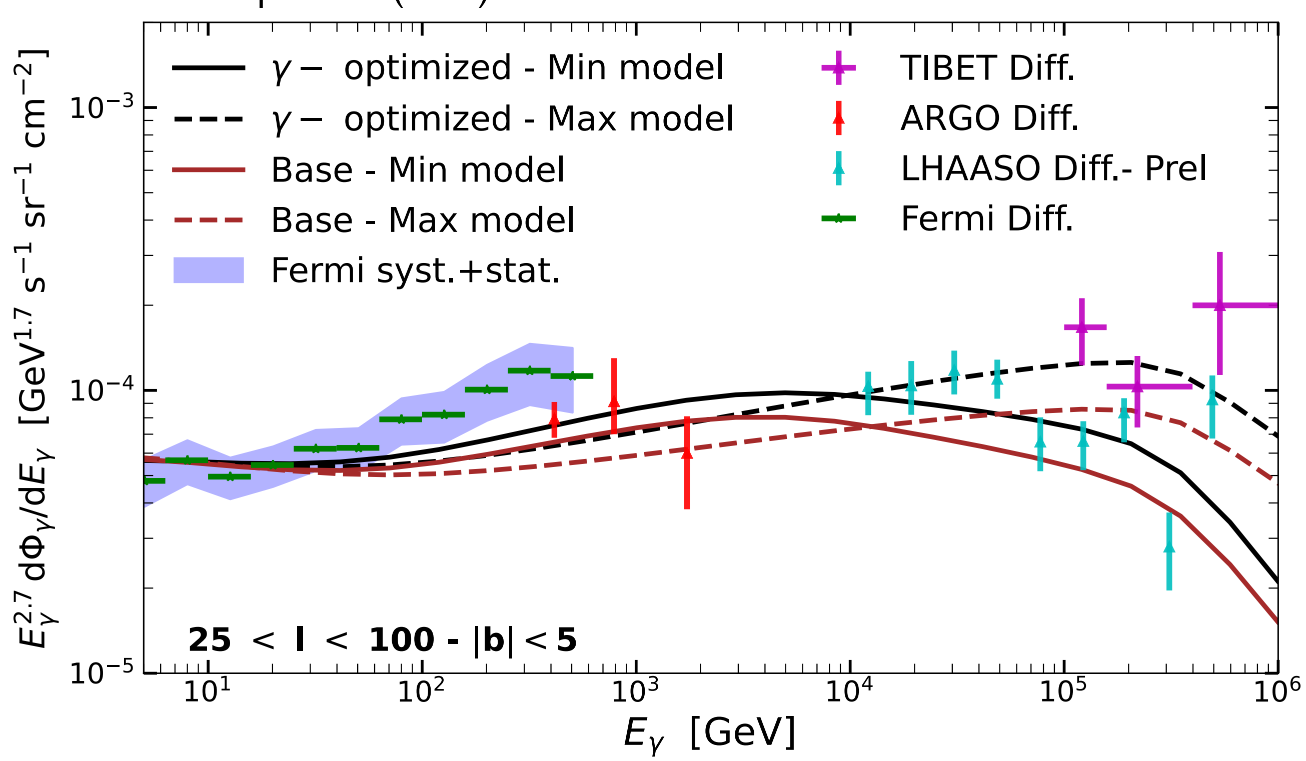


Measurements versus interstellar models

Zhang et al. (2023) ApJ 957 43



De La Torre Luque et al. (2023) A&A 672 A58



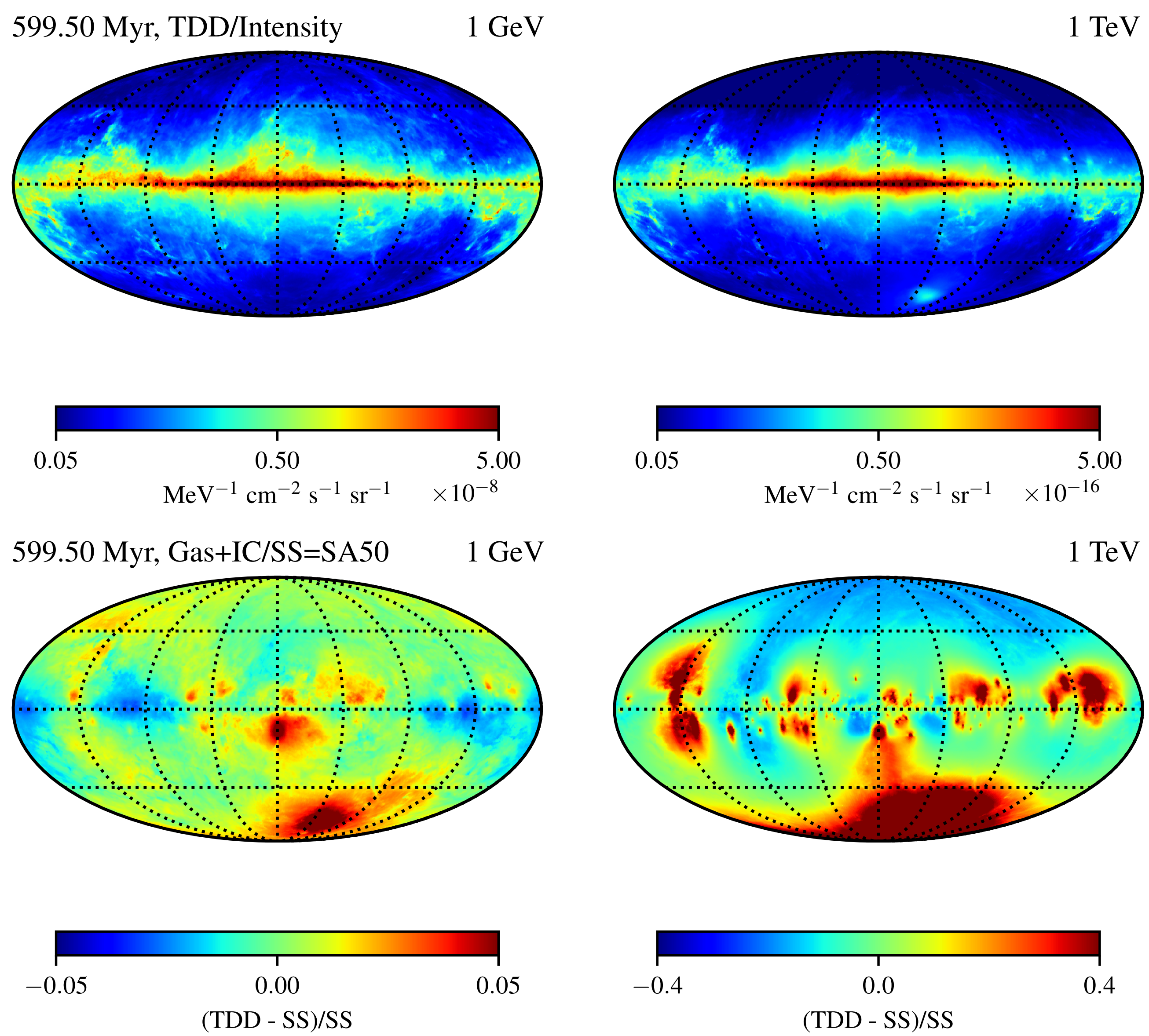
- Consistency unclear, depends on model details
  - local CR spectra
  - homogeneity of diffusion
  - masses of interstellar gas
  - …
- Do neutrinos and diffuse gamma rays have the same interstellar origin?
  - Controversial (e.g., Fang et al. 2024 versus Kai et al 2024)
  - Depends on unresolved sources' contributions for the two messengers

Modelling challenges

Are standard implementations of CR propagation models OK for TeV/PeV emission?

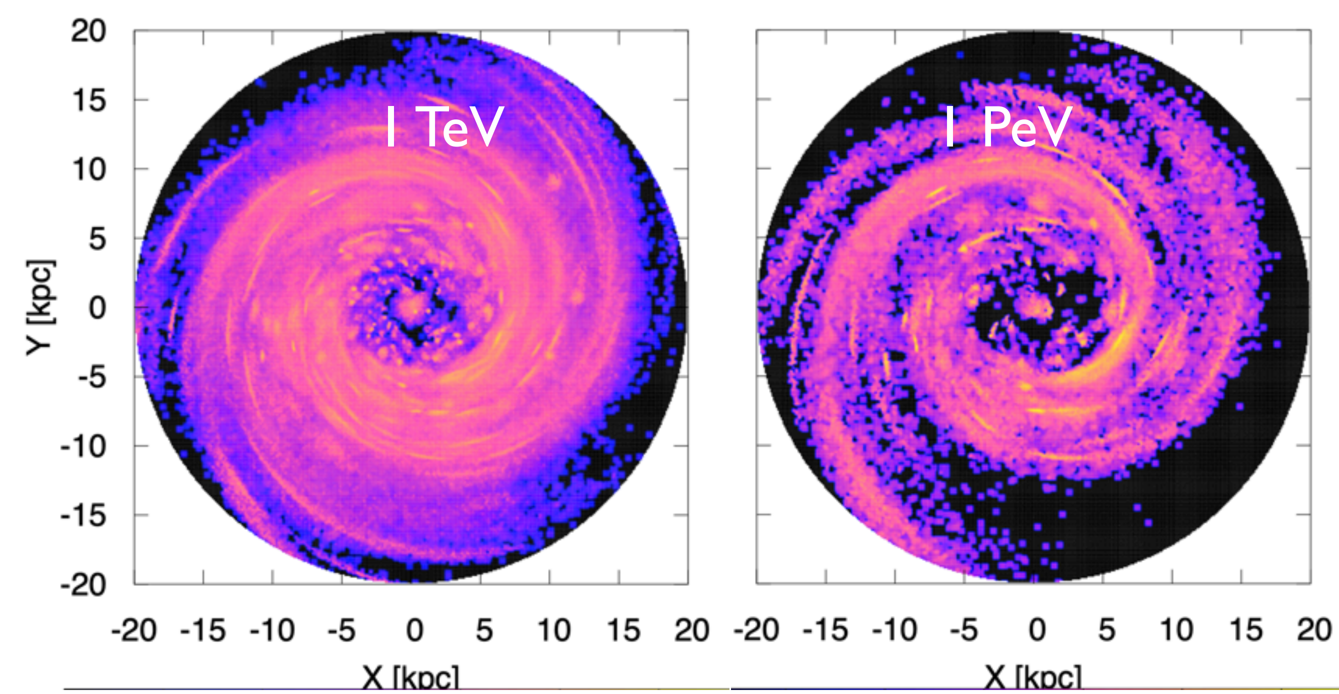
Discretised sources

Porter et al. (2019) ApJ 887 2 250



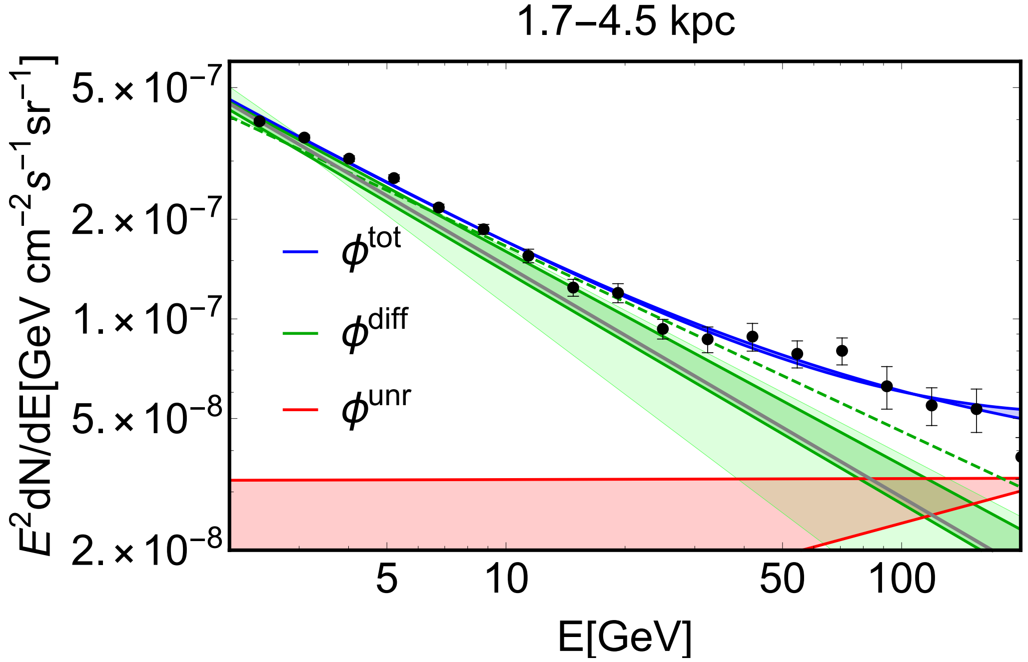
Discretised sources
+ anisotropic diffusion

Giacinti and Semikoz arXiv:2305.10251



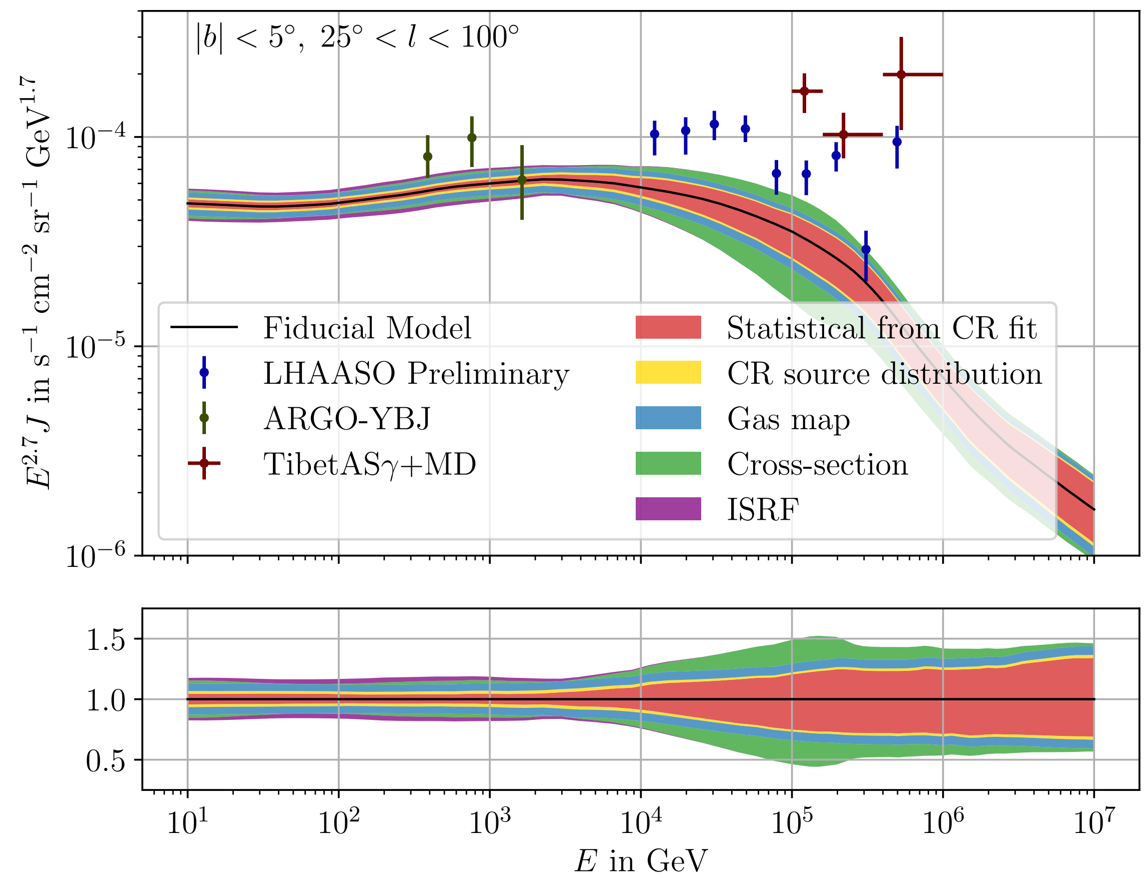
Unresolved sources

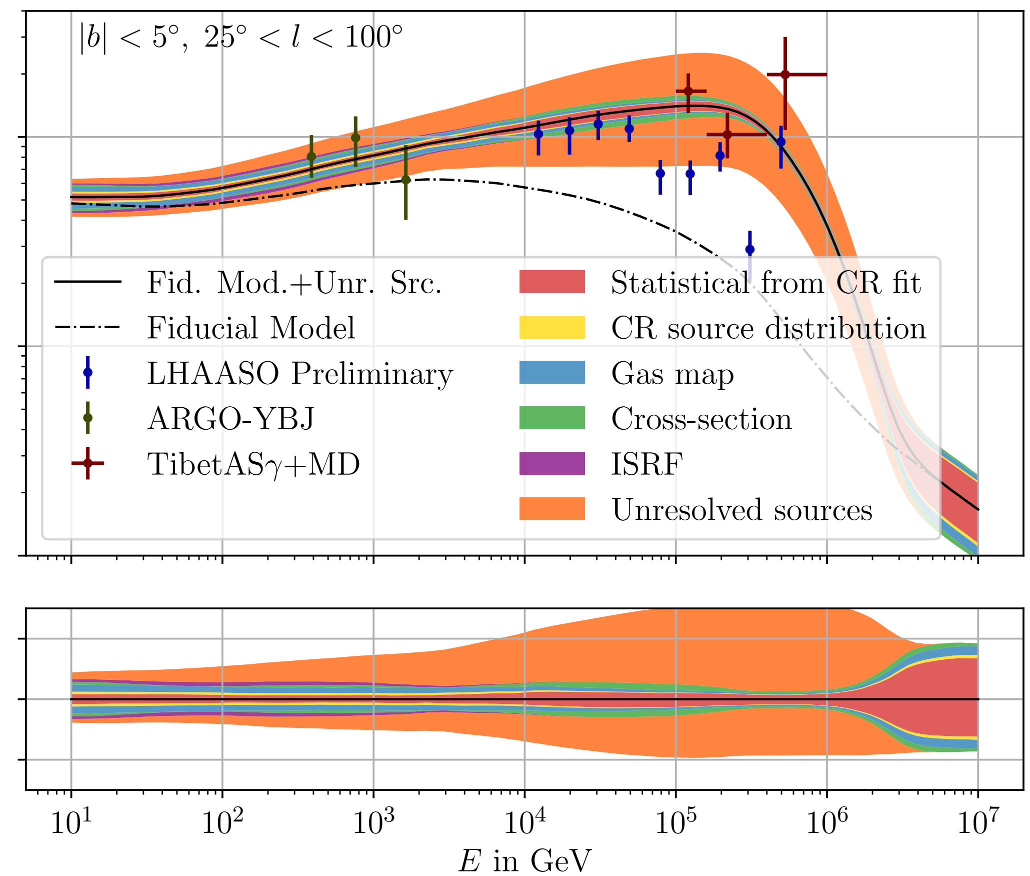
Vecchiotti et al. (2022) Com Phys 5 1



- Estimates based on empirical models fitted to existing source catalogs
- Can explain *Fermi* anomalies and potential excess at TeV/PeV

Schwefer et al. (2023) ApJ 949 1 16

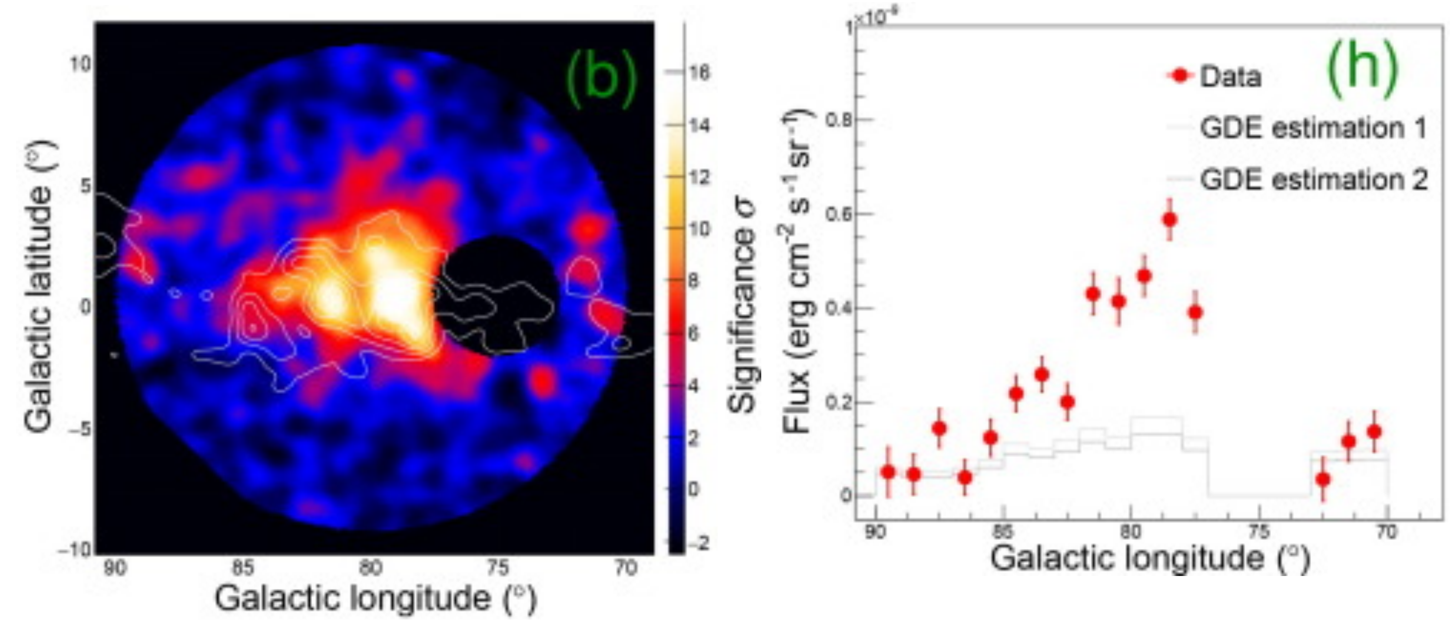




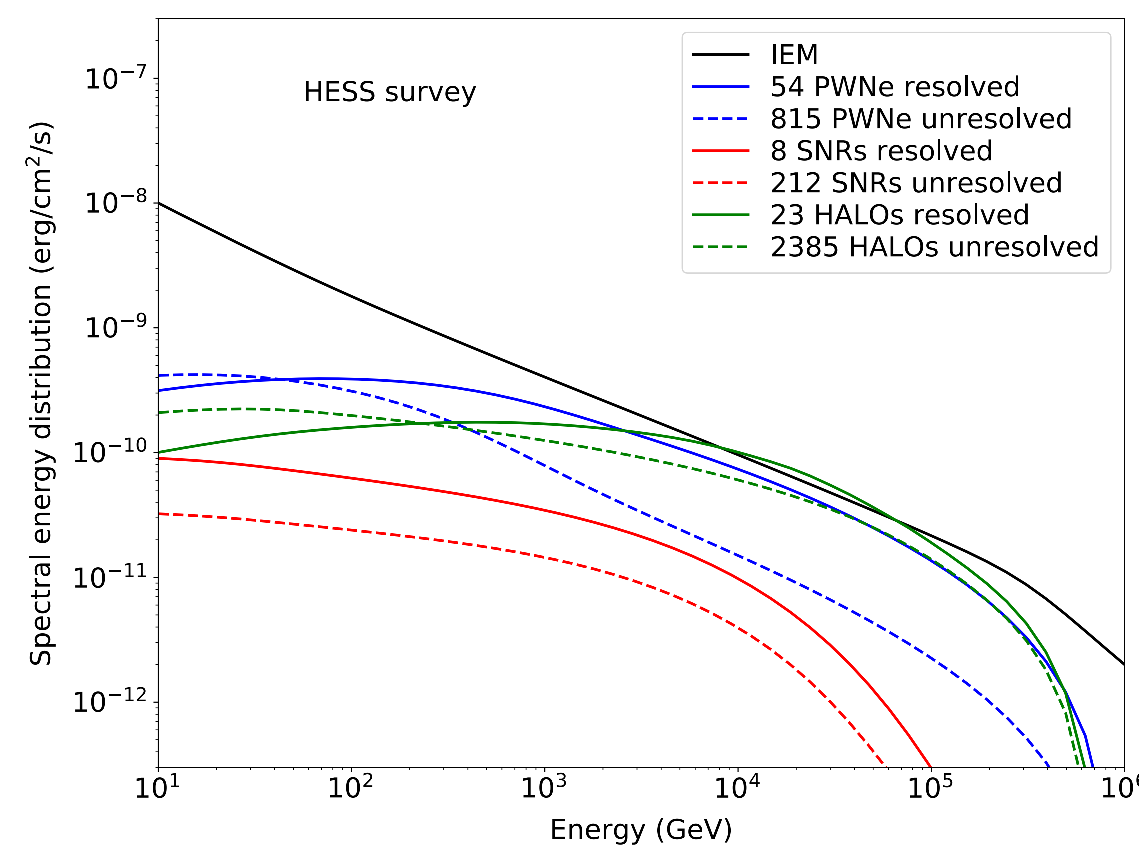
Emission in the vicinity of sources

- Peculiar conditions → impact on transport
  - strong turbulence from winds, explosions …
  - high CR densities (streaming instabilities)
  - high matter and radiation densities (energy losses)
- Confinement/slow diffusion suggested by observations of some supernova remnants and stellar clusters, pulsar halos
- Prevalence of the phenomenon still unclear → contribution to diffuse emission?

LHAASO collaboration Science Bulletin (2024) 69 4

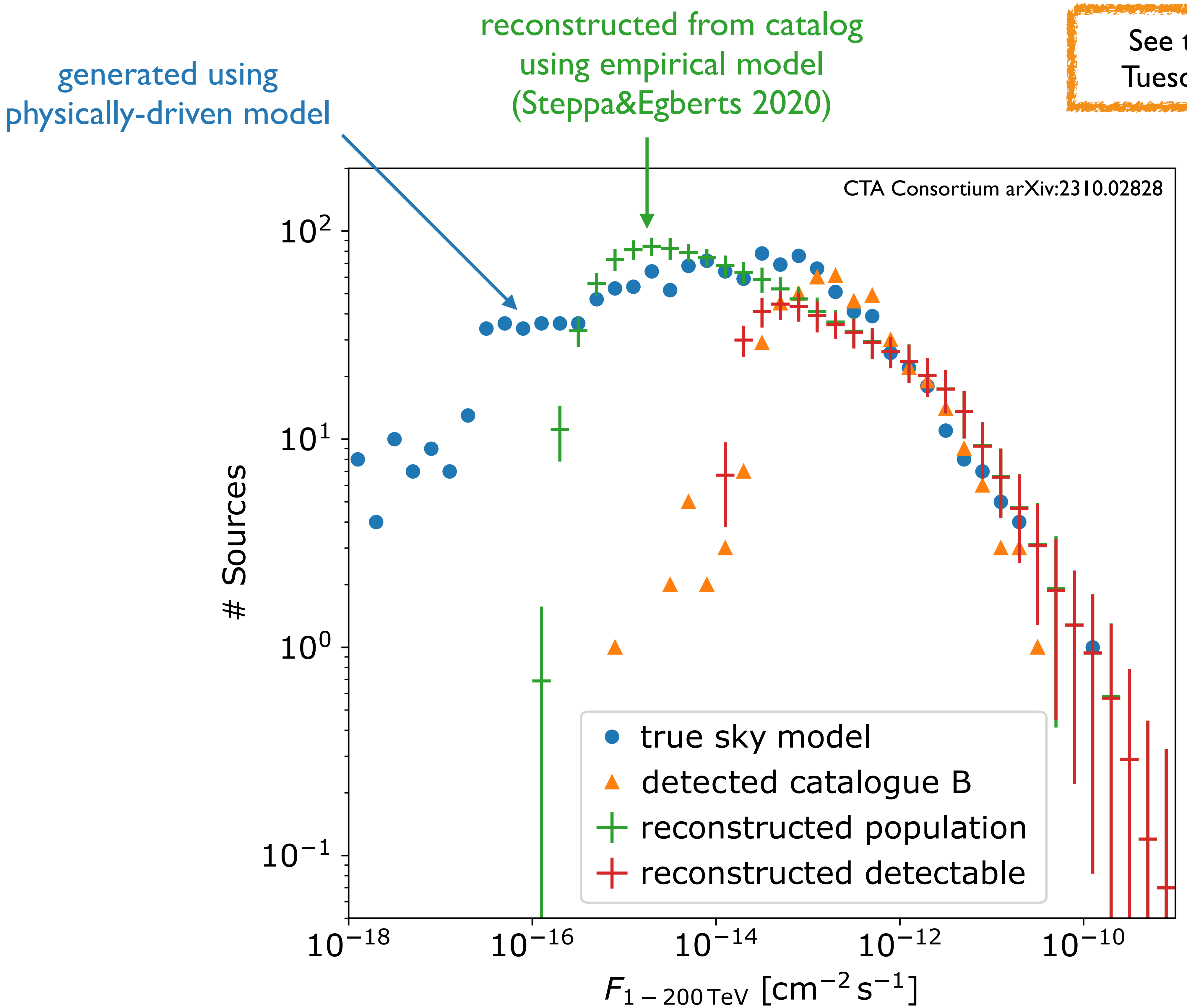


Martin, LT et al. (2022) A&A 666 A7



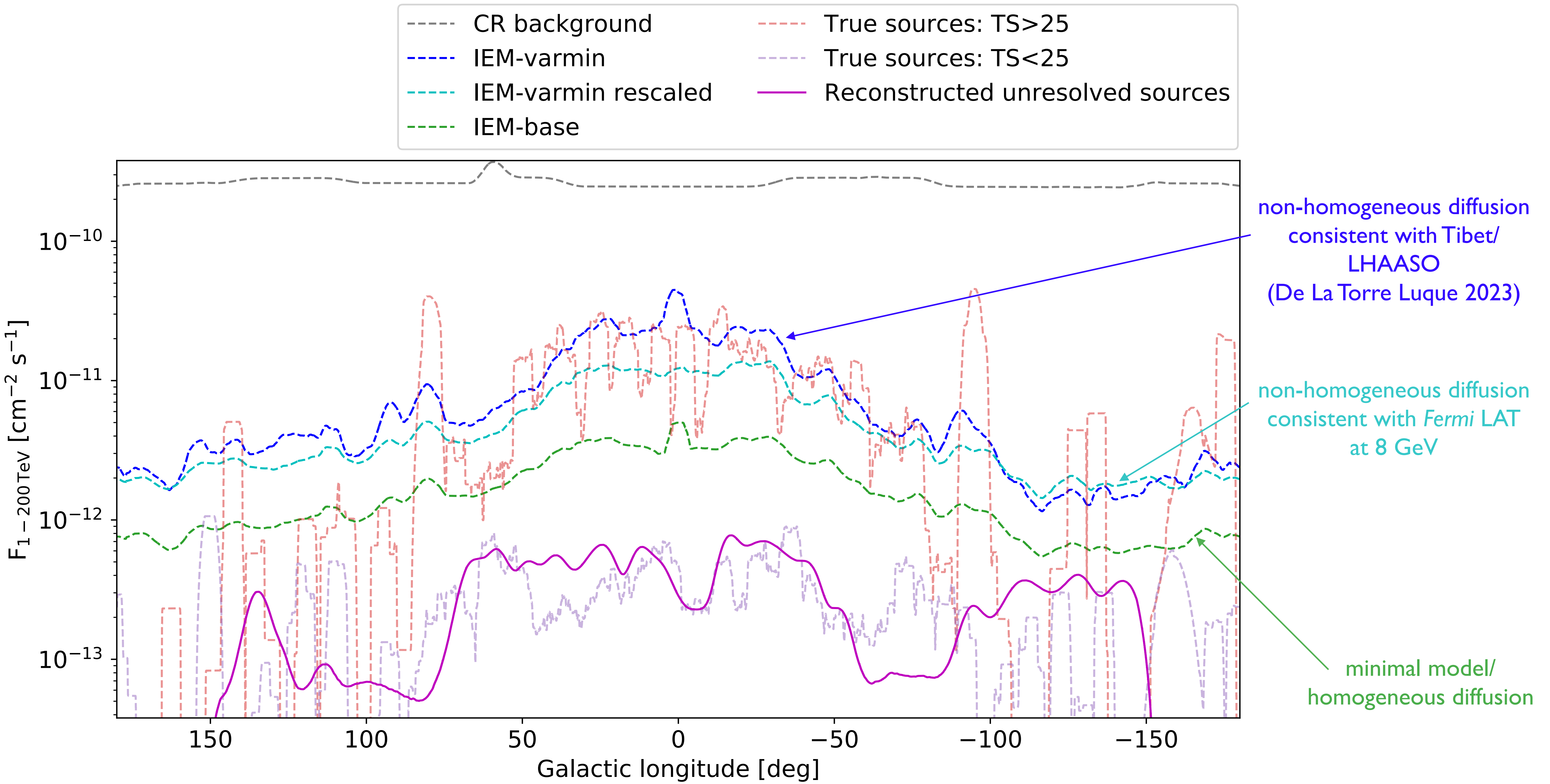
Modelling unresolved sources

See talk by Q. Remy on Tuesday for more details



Diffuse emission and interstellar models

See talk by Q. Remy on Tuesday for more details

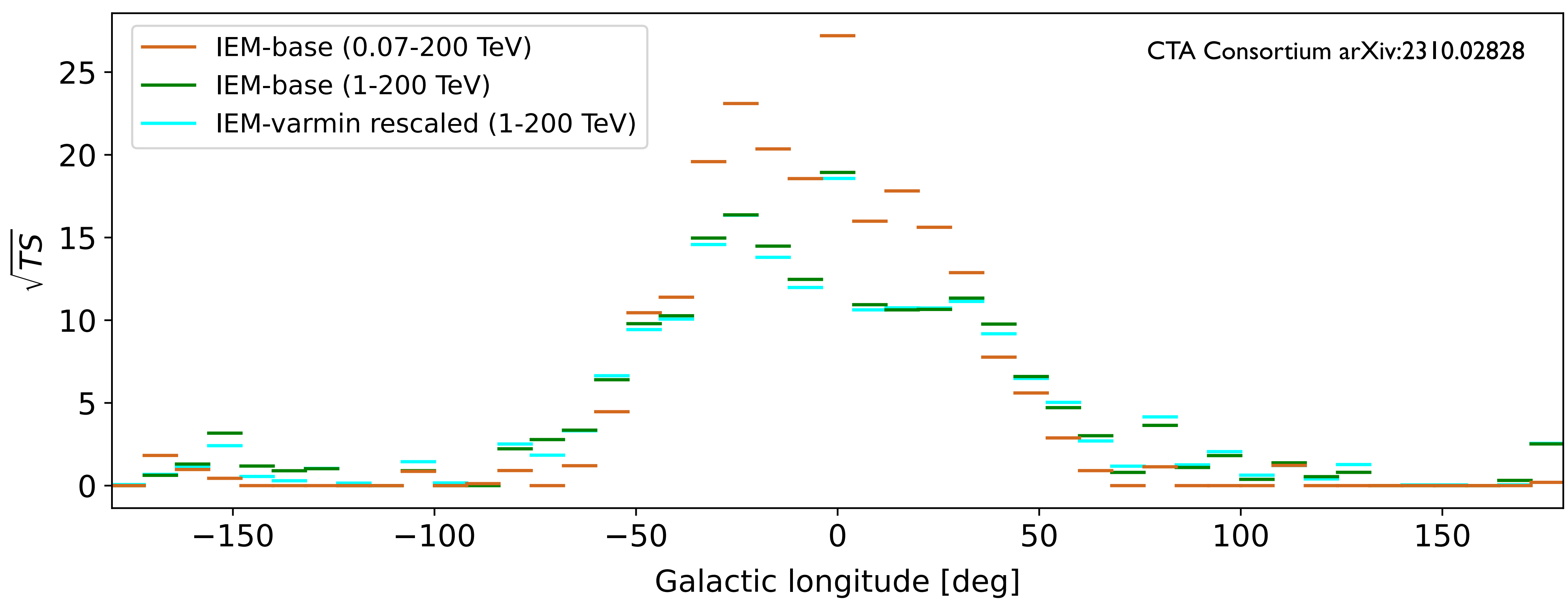


CTA Consortium arXiv:2310.02828

Detectability of diffuse emission

See talk by Q. Remy on Tuesday for more details

- For all models considered significant detection at Galactic longitudes < 60° and energies > 1 TeV
- Different scenarios statistically distinguishable
- Uncertainties in residual CR background and instrument response not taken into account



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Final remarks

- *Fermi* LAT legacy: overall consistency with CR models, but unexplained residuals and anomalies persist
- First measurements at TeV/PeV energies
  - consistency with models and neutrino measurements to be further investigated
  - challenges in modelling, estimating the unresolved source contributions and dealing with extended emission in the vicinity of sources
- Prospects for CTAO
  - standard models: can detect diffuse emission and statistically distinguish different scenarios
  - beyond standard models: key role thanks to unique angular resolution
- Complementary to existing/upcoming air-shower arrays, better data badly needed in the energy range from sub-MeV to several hundred MeV