Institute for Theoretical Particle Physics and Cosmology | RWTH AACHEN UNIVERSITY

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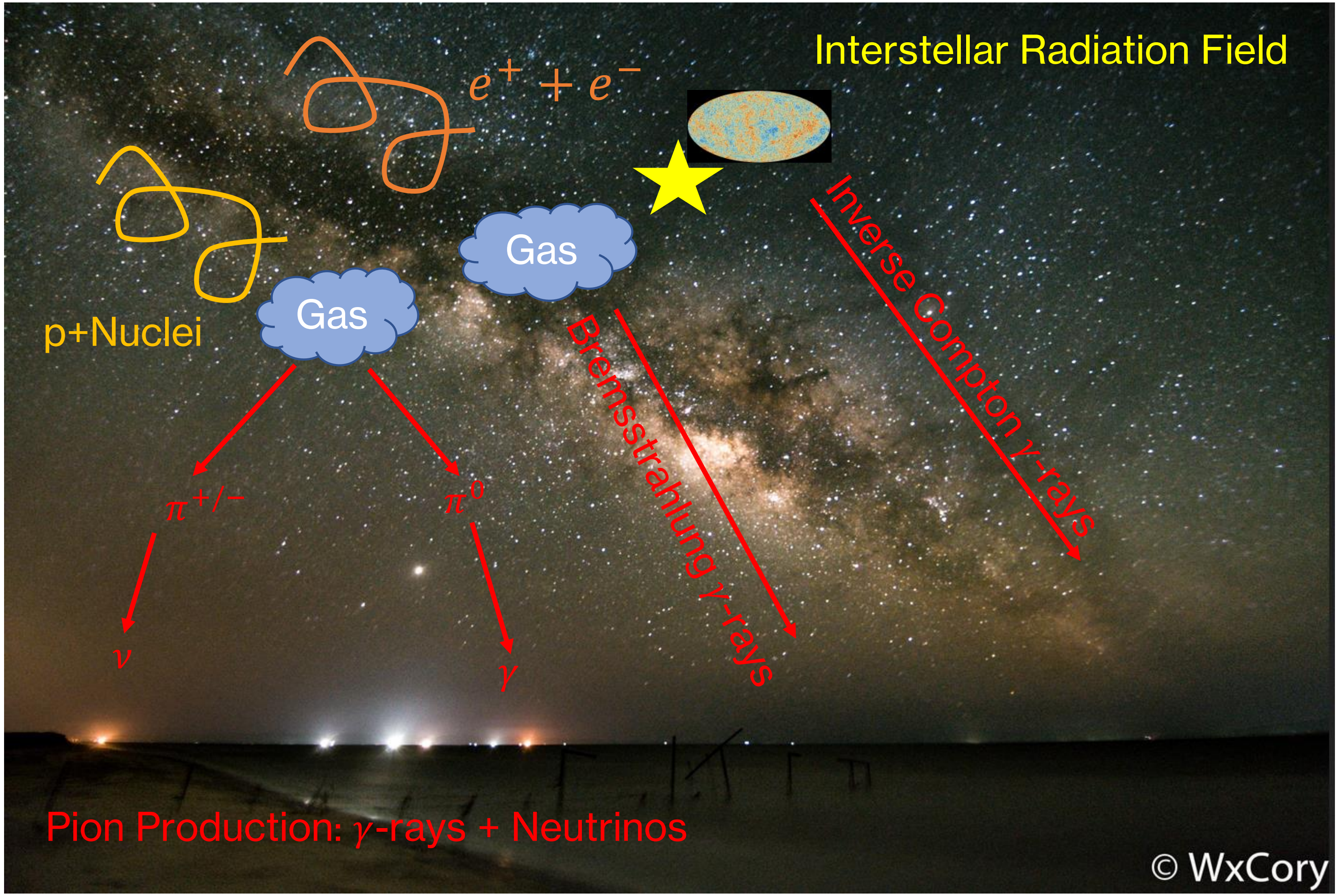
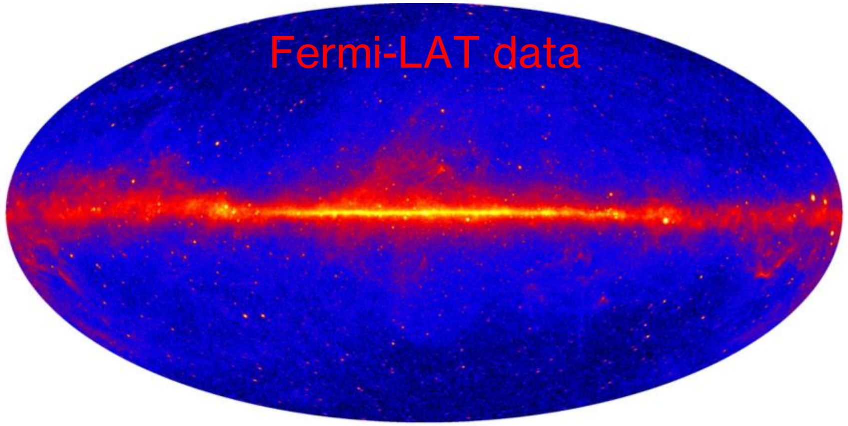
Updating Models of Galactic Diffuse Neutrinos

10/2022 | ECAP AT School | Georg Schwefer

Galactic Diffuse Emission



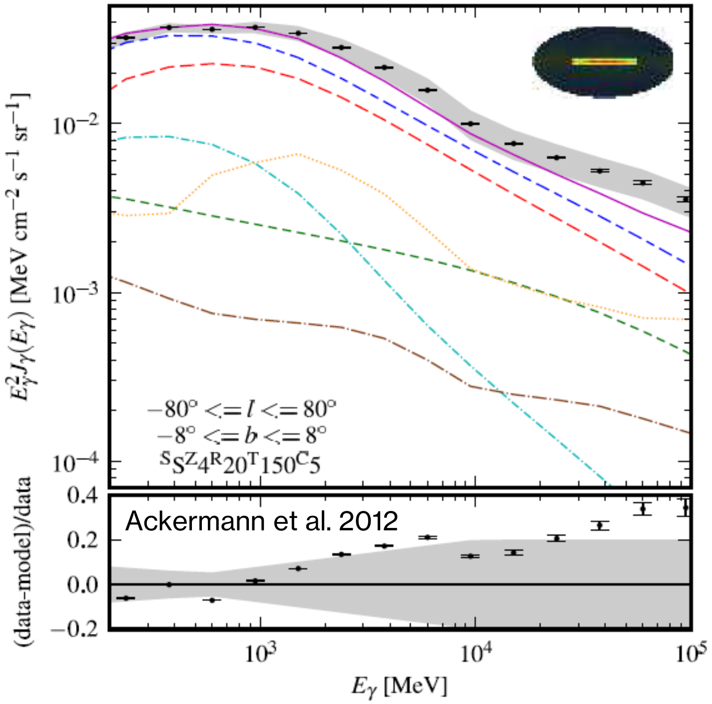


- Radiation produced by „sea“ of cosmic rays in the Milky Way
- Neutrinos isolate hadronic component
- Guaranteed Signal for IceCube
  - ➢ Discovery could be within reach within near future
  - ➢ Searches need model templates
- Learn about propagation and sources of hadronic galactic cosmic rays

Existing Models

Fermi-π^0: Ackermann et al. 2012

- Goal: Fit Fermi-LAT data at GeV energies
- CR model: Homogeneous Diffusion, powerlaw spectra
- Extrapolated to IceCube energies as single powerlaw
- Conservative neutrino prediction
- Large residuals with Fermi-LAT data in galactic center



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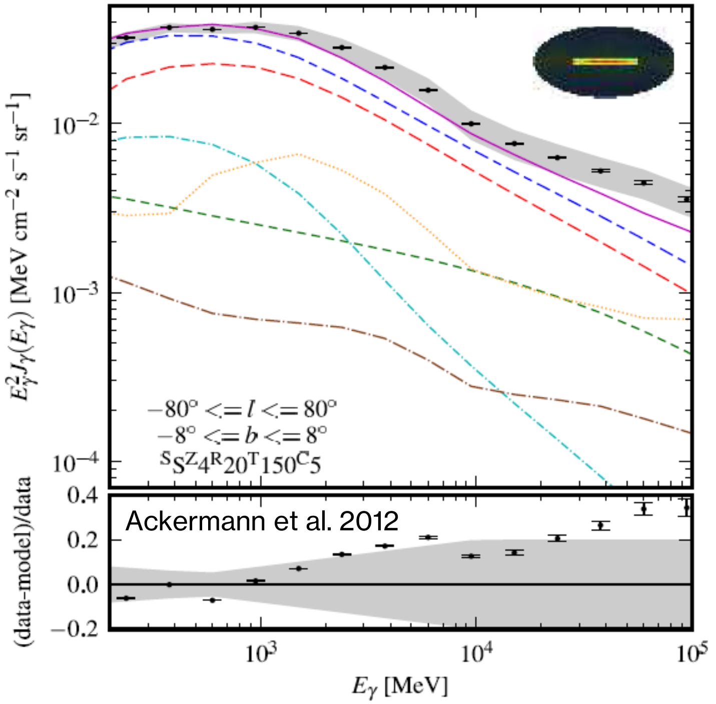
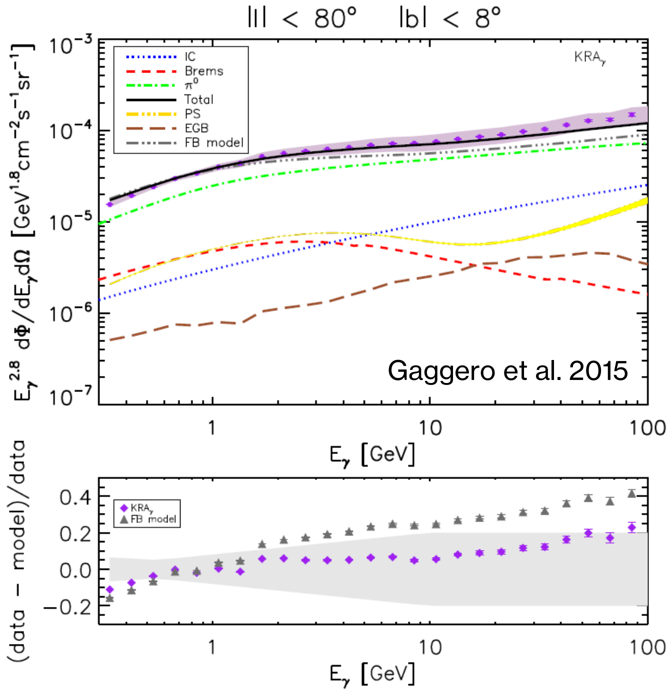
KRAγ: Gaggero et al. 2015

- Radius-dependent diffusion: Spectral hardening towards galactic center
- Two different cutoff energies: 5 PeV & 50 PeV
- Optimistic neutrino prediction





Updating those models

Why are updates necessary?

- Old models anchored and optimized at GeV energies
- Based on old data & inputs
- Consideration and quantification of uncertainties on all inputs

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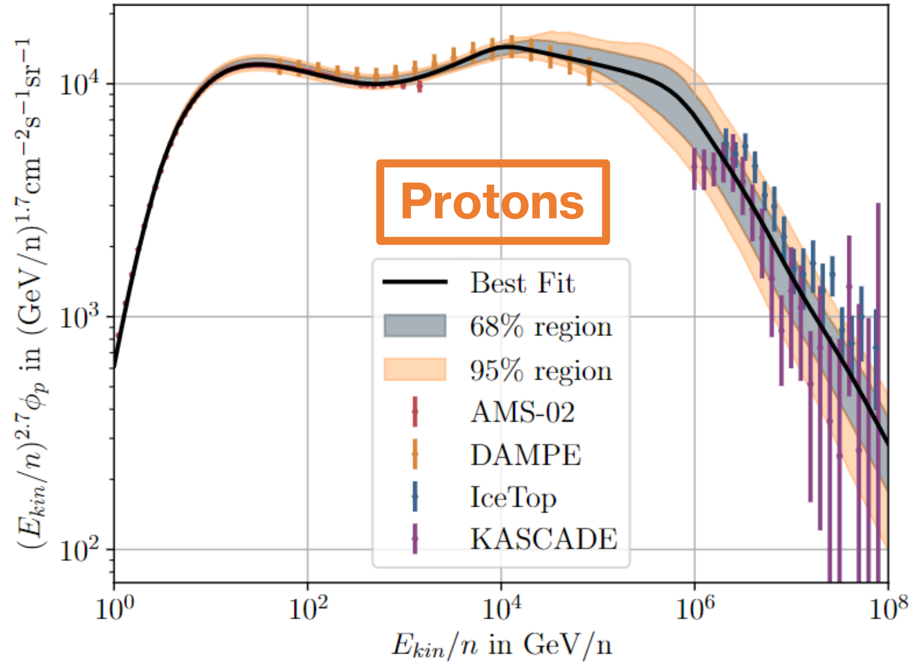
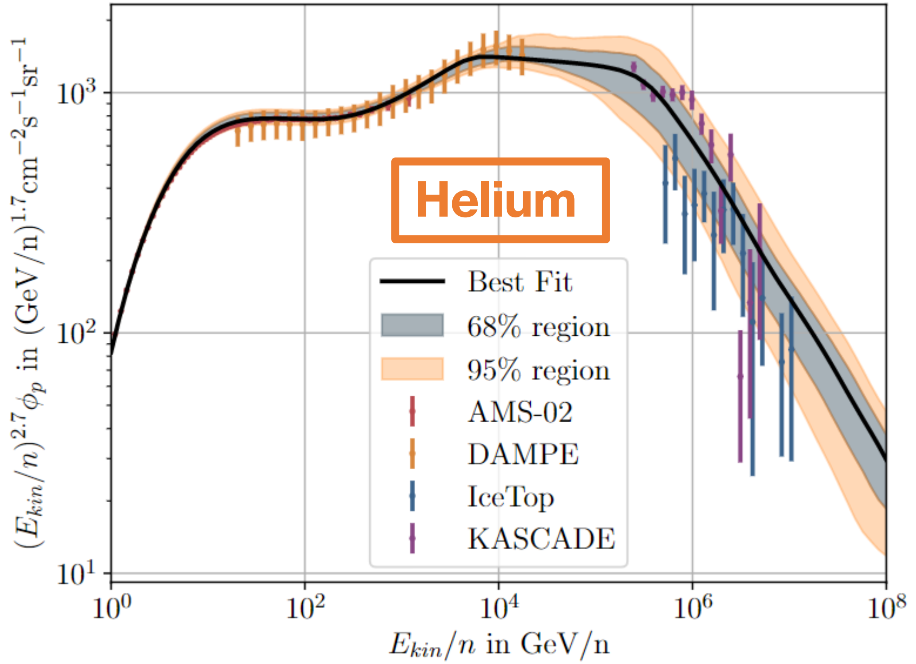
  - From MCMC fit to local cosmic ray data
  - Free energy scale shifts to combine datasets





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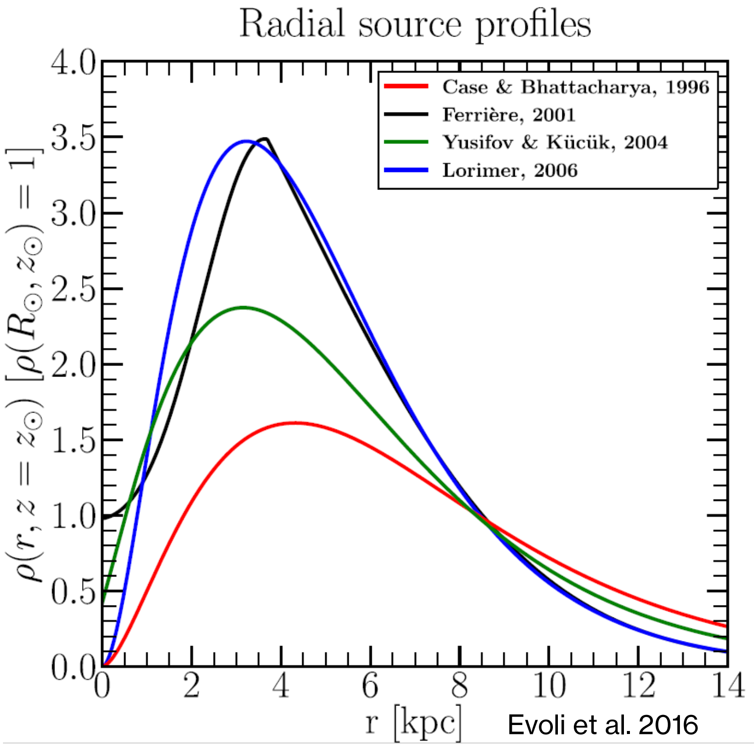
  - Different analytical parametrizations



Evoli et al. 2016

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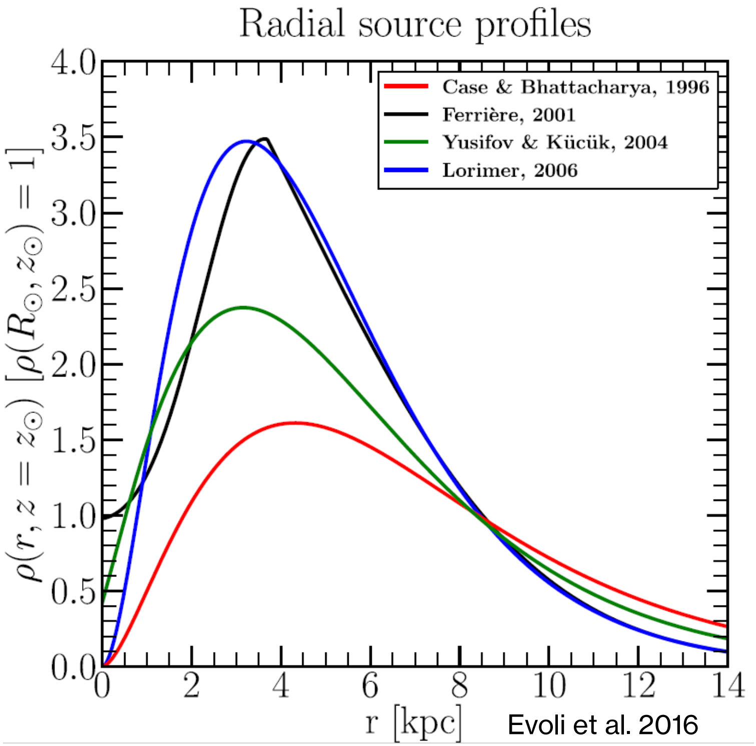

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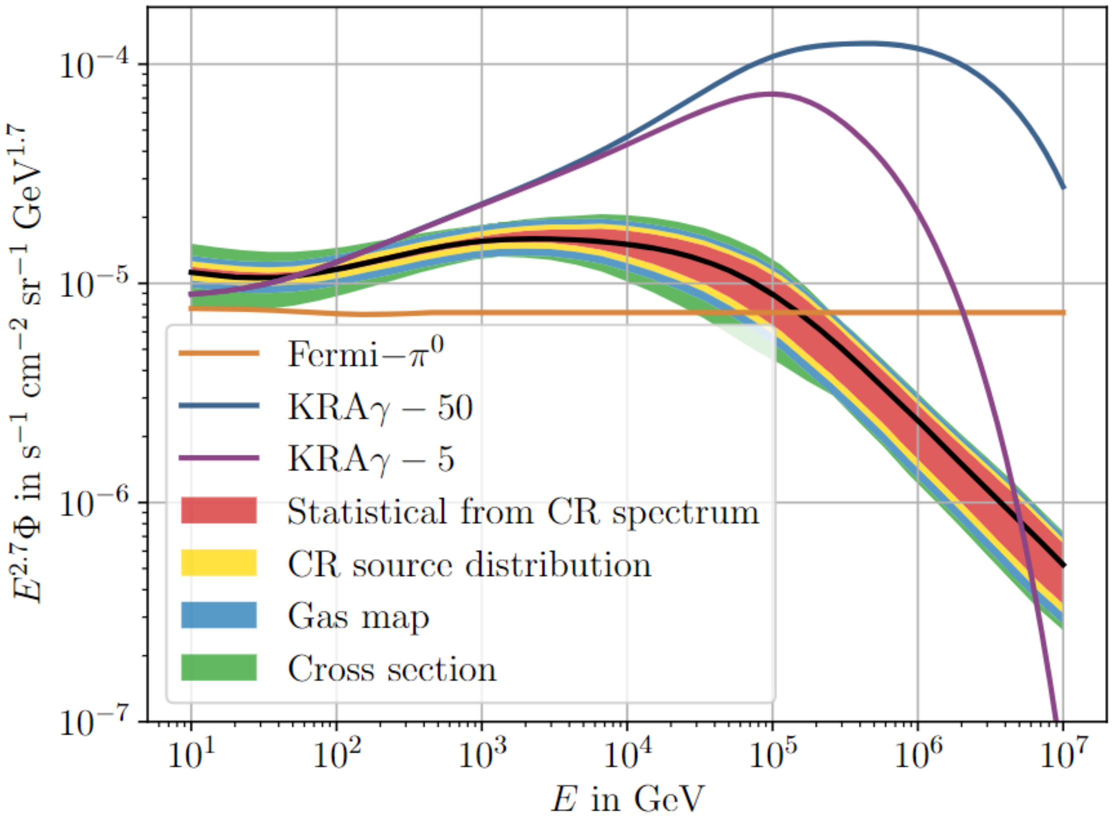
- ➢ **Gas map**
  - Radio Survey
  - 3D Reconsutruction
  - Spin Temperature/Optical Depth
- ➢ **Cross Section**
  - Hadronic interaction model

Resulting models and uncertainties

Inner Galaxy: |b|<8°, |l|<80°



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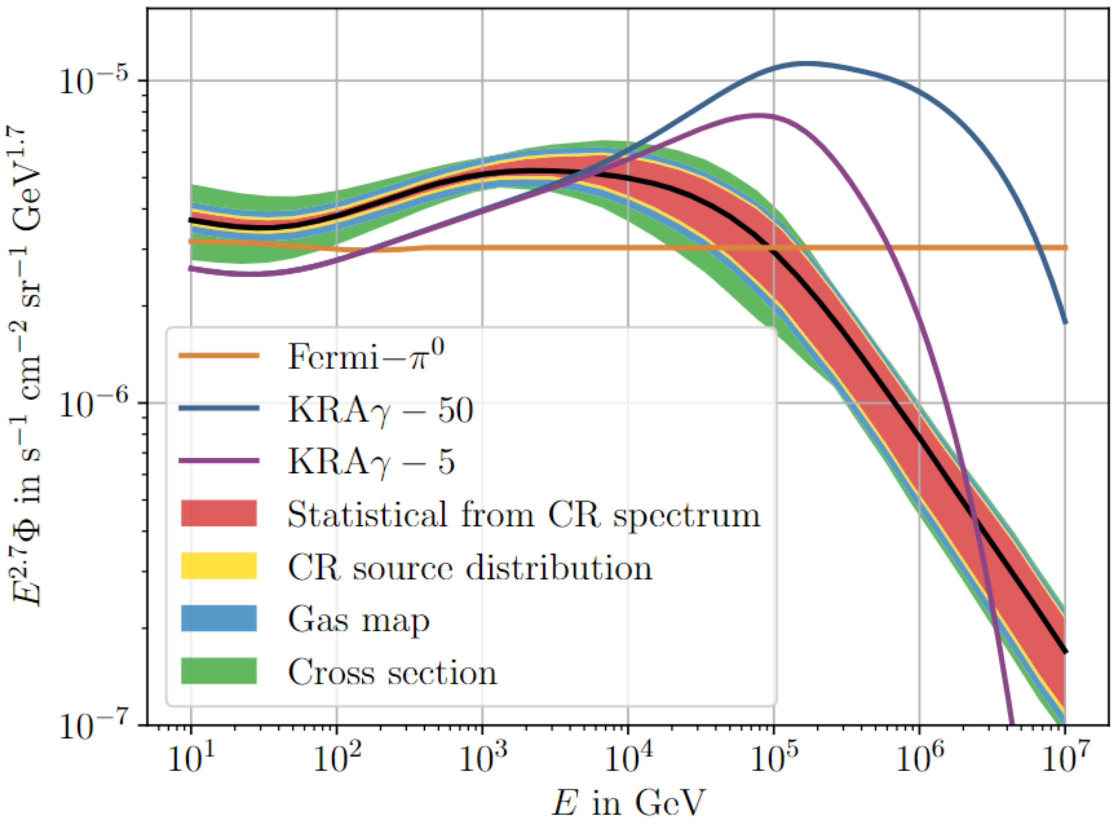


Summary

Updating models of galactic diffuse neutrino emission

- Required for IceCube searches and understanding results
- Motivated by new data & inputs
- Goal: Quantify uncertainties
- Anchor point: Local cosmic ray data
  - Systematic fit with MCMC
- Systematic uncertainties considered
  - Cosmic ray source distribution
  - Gas map: Survey, Spin Temperature, Reconstruction
  - Cross Section: Hadronic Interaction Model

Next: Use in upcoming IceCube analyses

Fit to local CR data

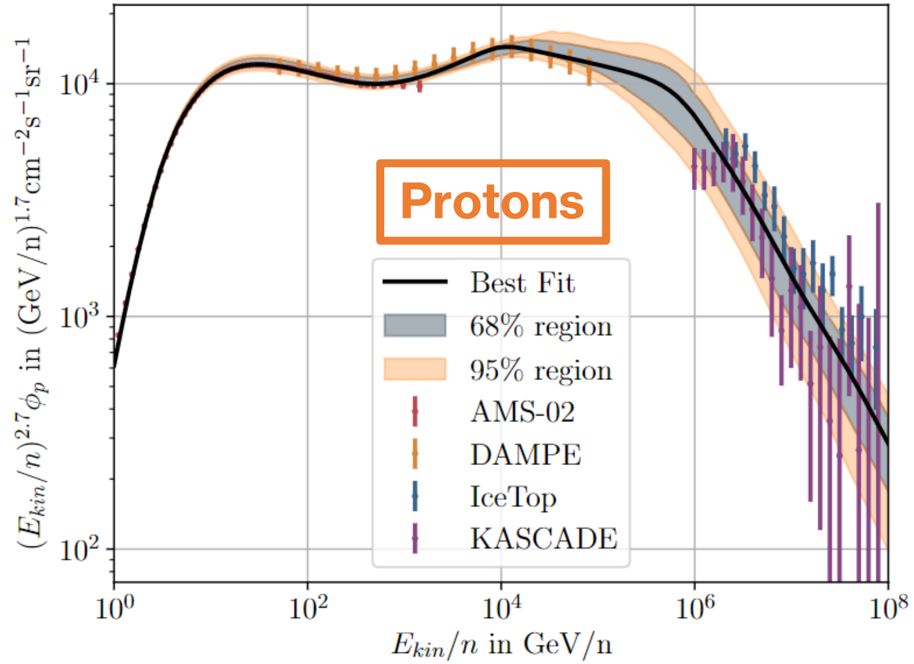
Combined fit to

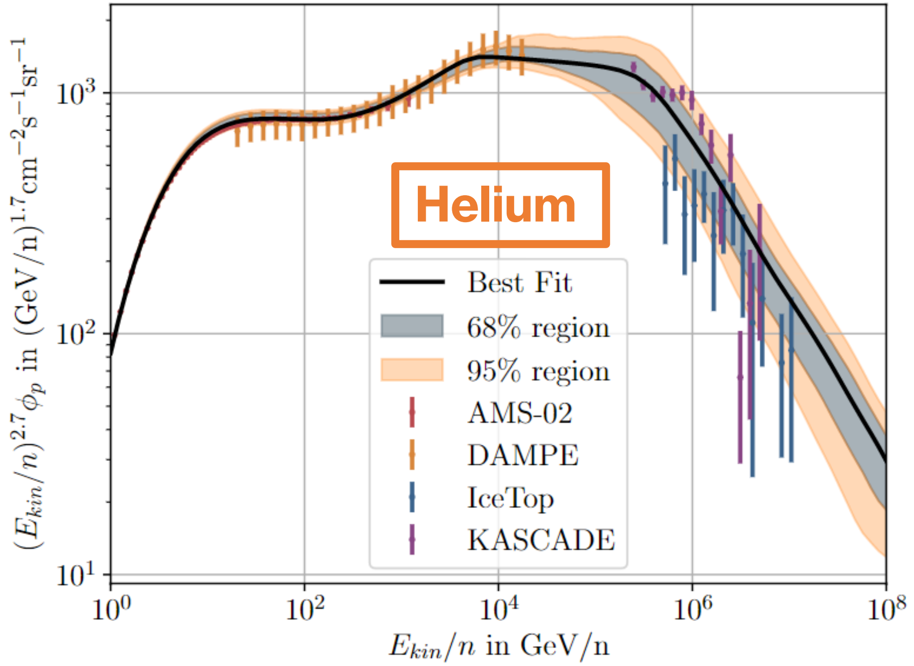
- AMS-02, DAMPE, IceTop KASCADE Proton + Helium
  - ➢ Responsible fur bulk of diffuse emission
- AMS-02 Carbon + B/C
  - ➢ Fix CR diffusion coefficient
- AMS-02 $e^- + e^+$
  - ➢ IC gamma rays

- Datasets incompatible: Energy scale shifts as fit parameters

- DRAGON cosmic ray propagation code

- Large parameter space (26) & uncertainties matter
  - ➢ MCMC scan





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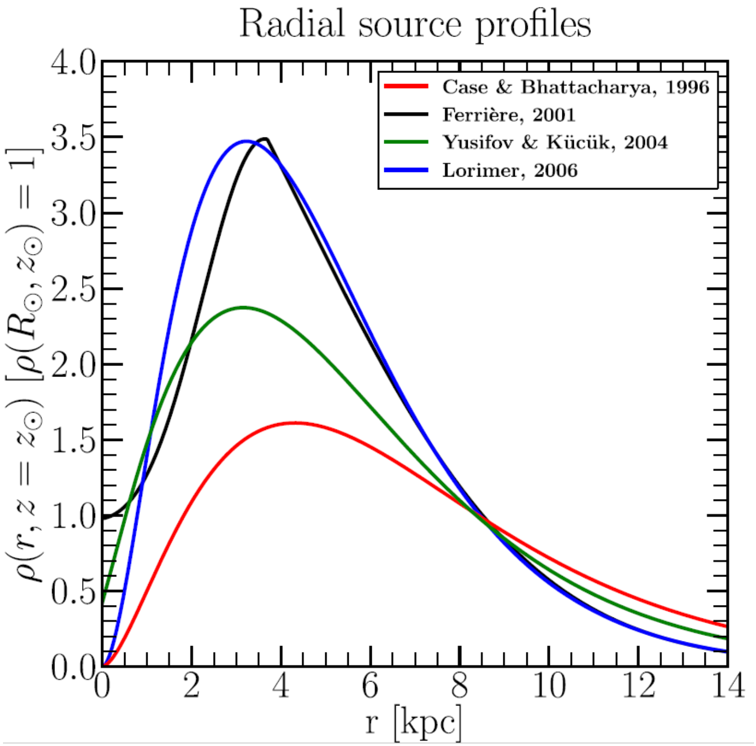

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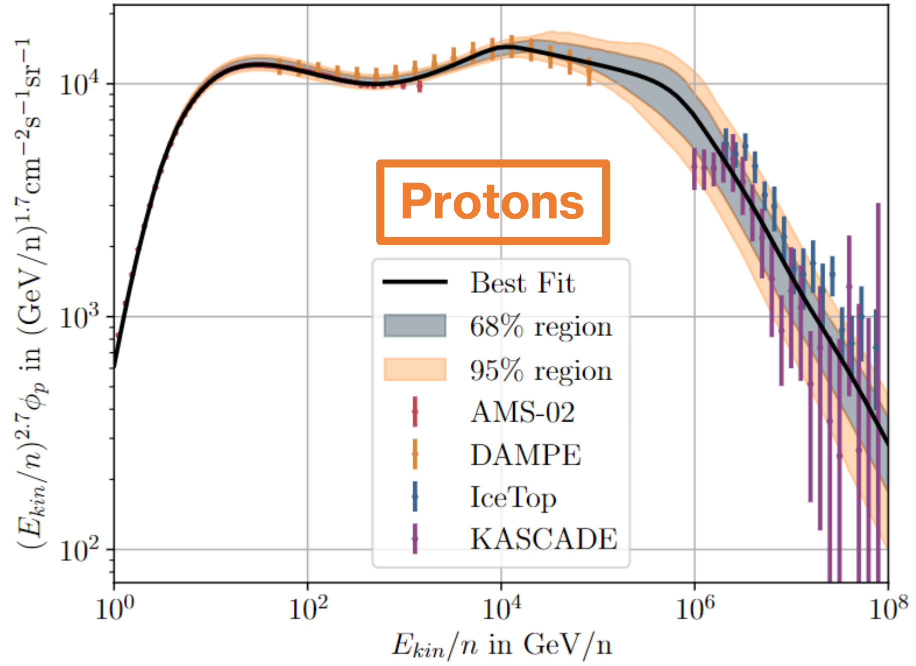

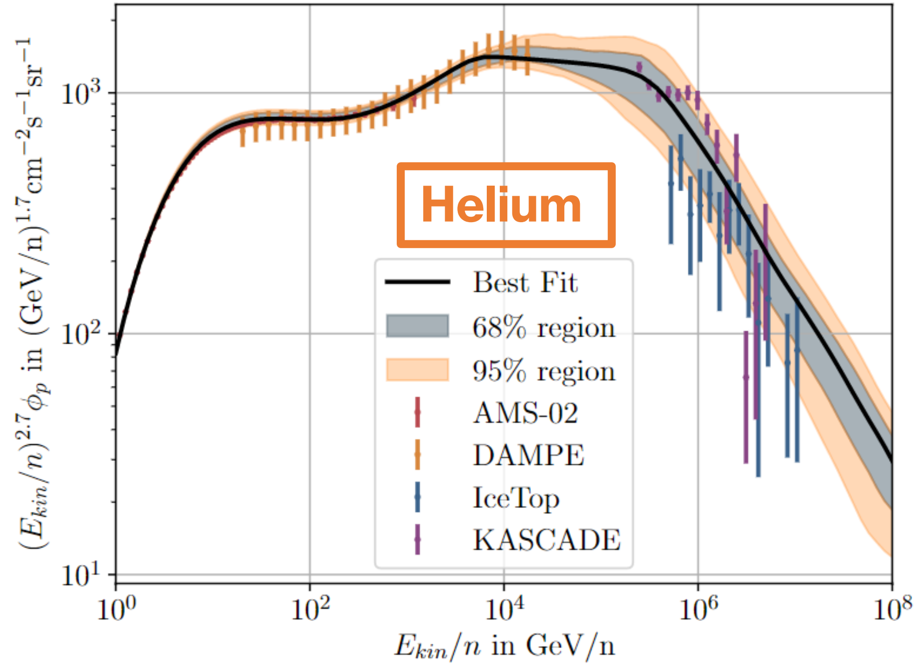

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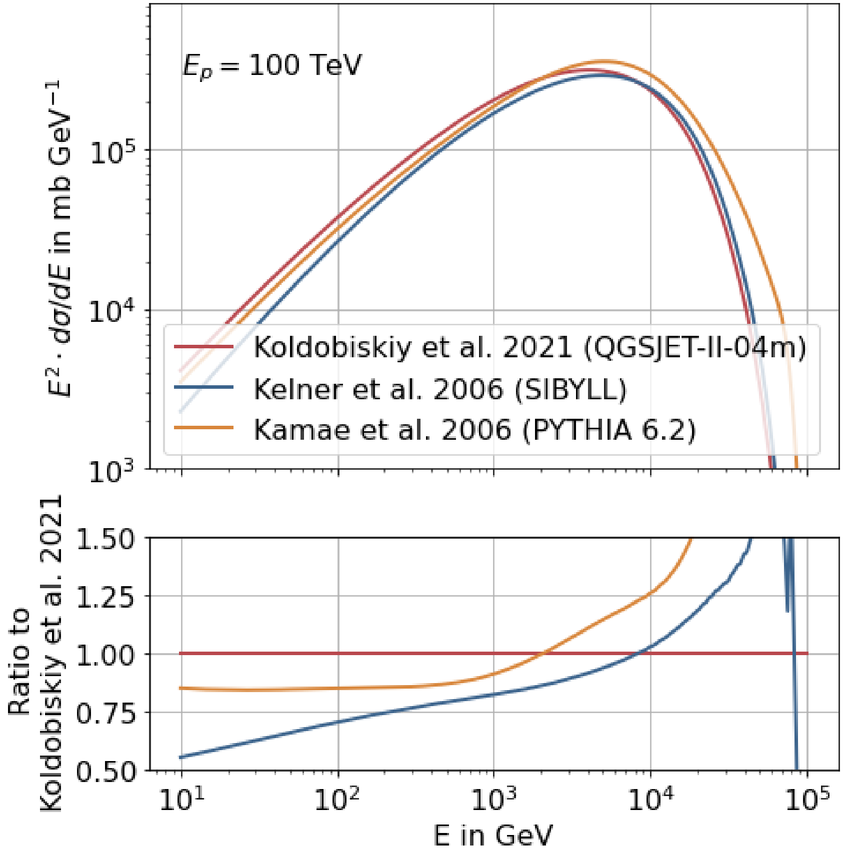

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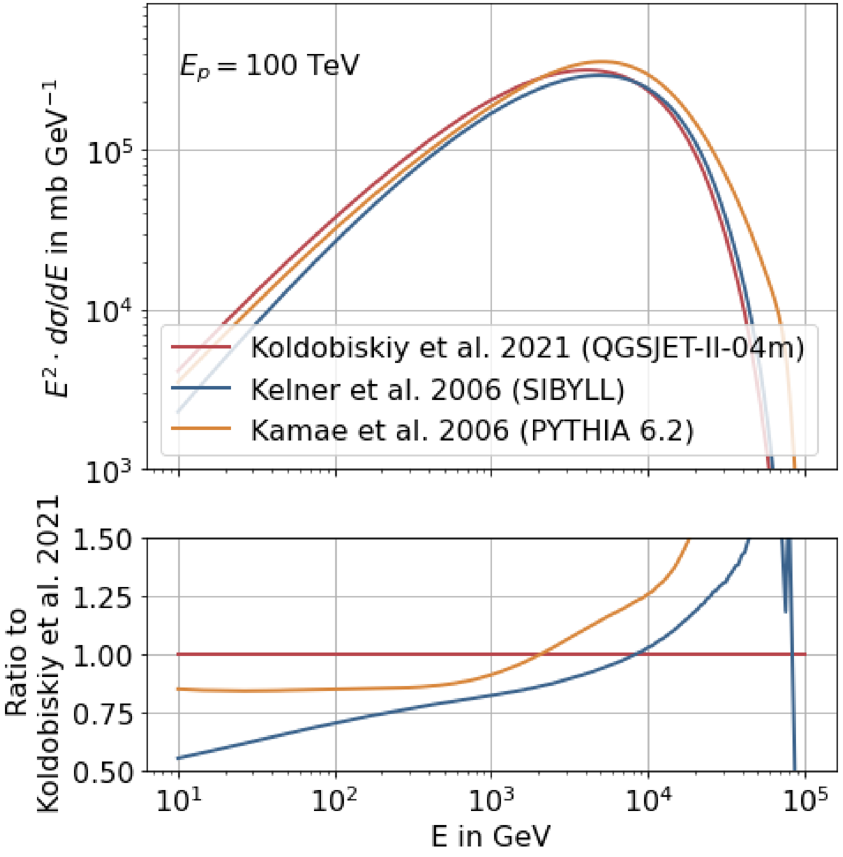

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Conventional approach

- Anchored on local cosmic ray data
- No attempt to explain e.g. Fermi-LAT anomalies
- Cosmic Ray Model
  - ➢ Homogeneous diffusion
  - ➢ Spectral features as breaks in diffusion coefficients

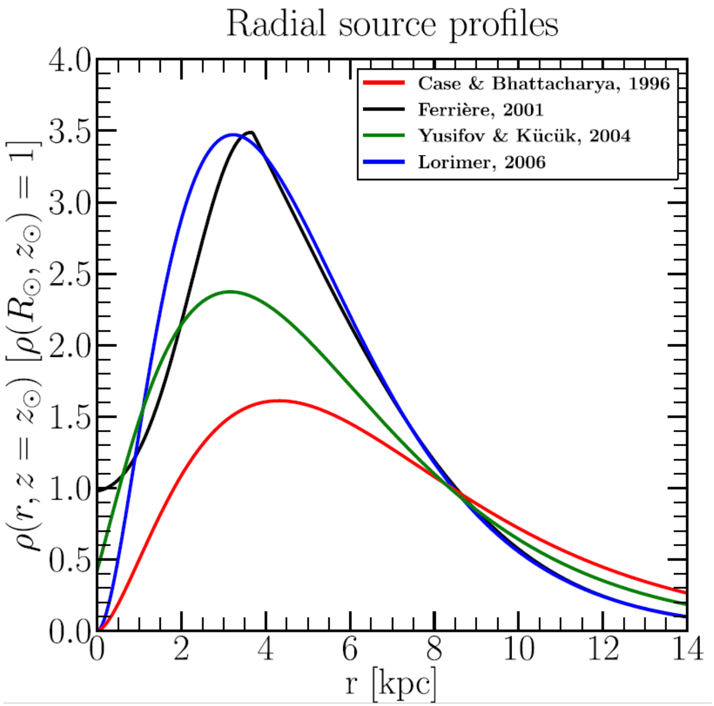
$$D(R) = D_0 \beta \left(\frac{R}{R_1}\right)^{\delta_1} \prod_{i=1}^{4} \left(1 + \left(\frac{R}{R_i}\right)^{1/s_i}\right)^{s_i(\delta_{i+1}-\delta_i)}$$

  - ➢ Smooth source distribution up to PeV

Systematic uncertainties

Gas Map

- SNR distribution in Milky Way uncertain
- Fits to population measurements of progenitors and remnants

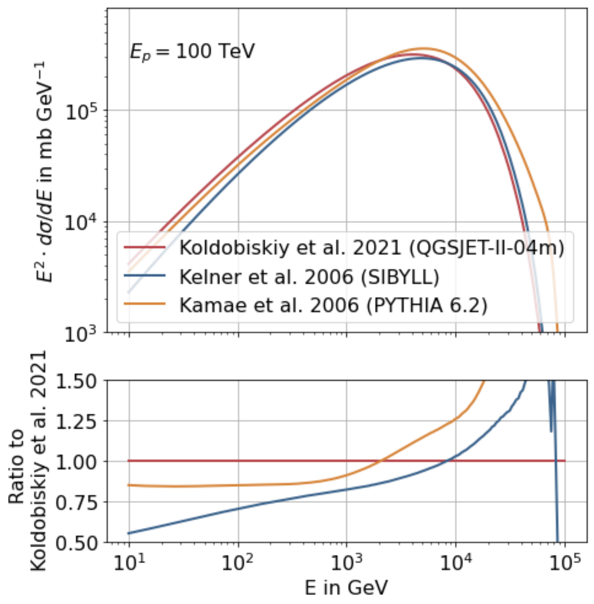


Cross Section

2 older default parametrizations (2006)

- Kelner et al. (SIBYLL)
- Kamae et al. (PYTHIA 6.2)

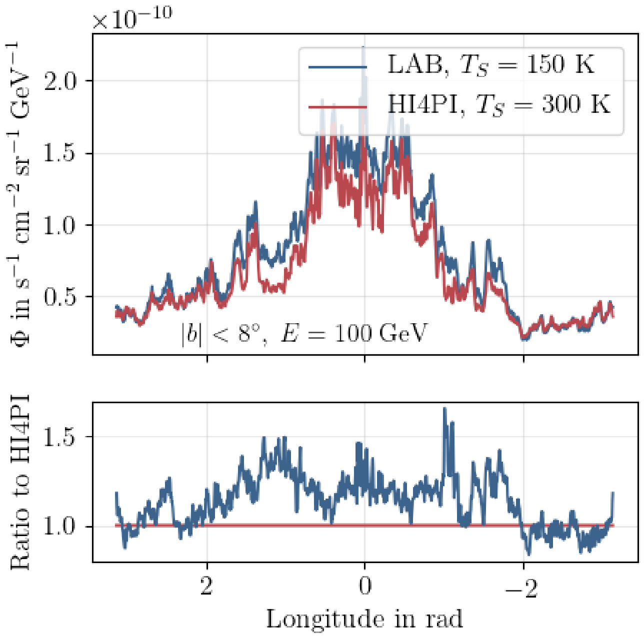
From 2021: AAfrag (QGSJET-II-04m)



Source distribution

Uncertainties from:

- Survey
- Reconstruction
- Spin Temperature



The Basic Ingredients

$$\underbrace{I_{\nu/\gamma}(E_{\nu/\gamma}, l, b)}_{\text{Flux in a given direction}} = \underbrace{\frac{c}{4\pi}\int_{l,b} ds}_{\text{Line-of-Sight Integral}}\, \underbrace{n_{gas}(\vec{x})}_{\text{Gas density maps}} \int dE_p\, \underbrace{n_{CR}(E_p, \vec{x})}_{\text{Galactic Cosmic Ray Distribution}}\, \underbrace{\frac{d\sigma(E_p, E_{\gamma/\nu})}{dE_{\nu/\gamma}}}_{\text{Production Cross Section}}$$

3 Main Inputs

Gas Density Maps:
- Radio surveys
- Analytical Parametrizations

Galactic Cosmic Ray Distribution:
- Spatial and Spectral distributions
- Numerically solve cosmic ray propagation equation
- Alternative: Analytical parametrization

Inelastic Production Cross Section:
- Parametrizations & Interpolations based on hadronic interaction models

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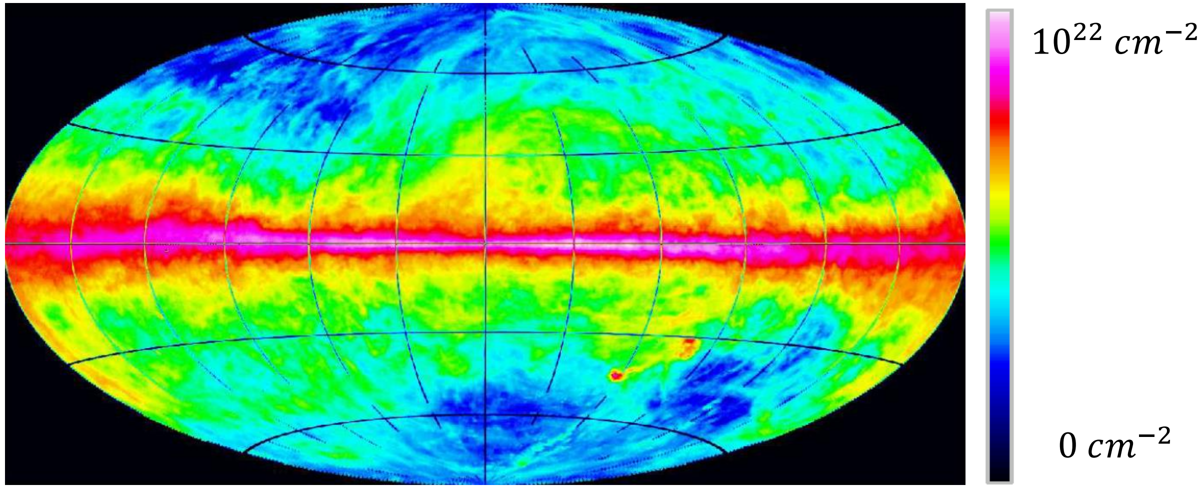

HI column densities

Kalberla et al. 2005

From radio surveys:
- Atomic Hydrogen: 21 cm line
- Molecular Hydrogen: CO lines

Uncertainties:
- Spin Temperature
- $CO - H_2$ conversion
- 3D-deconvolution

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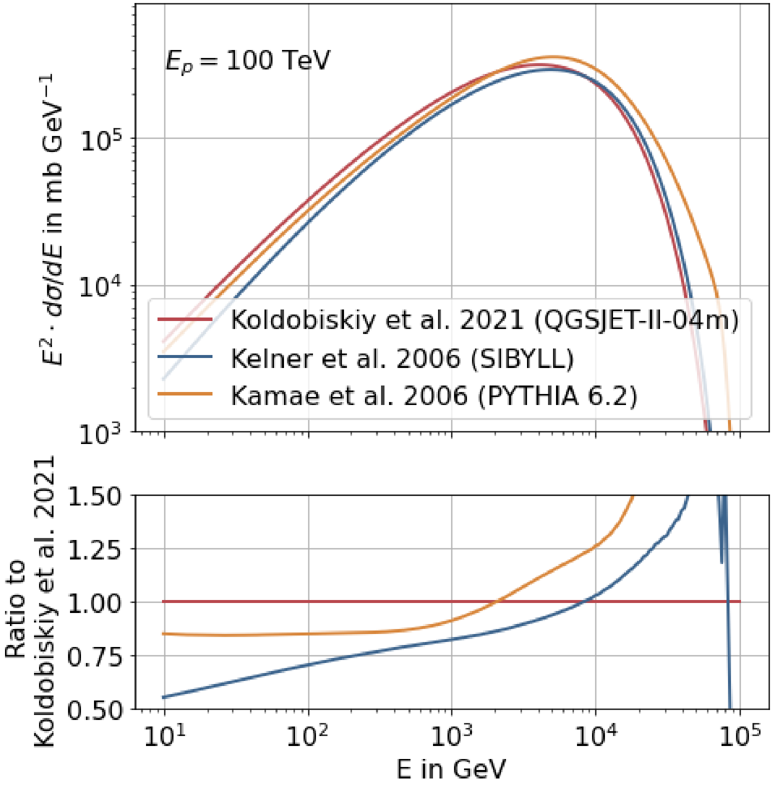
Parametrizations & Interpolations based on hadronic interaction models

Standard:

- Kelner et al. 2006: SIBYLL 2.1
- Kamae et al. 2006: PYTHIA 6.2

New:

- Koldobiskiy et al. 2021: QGSJET-II-04m



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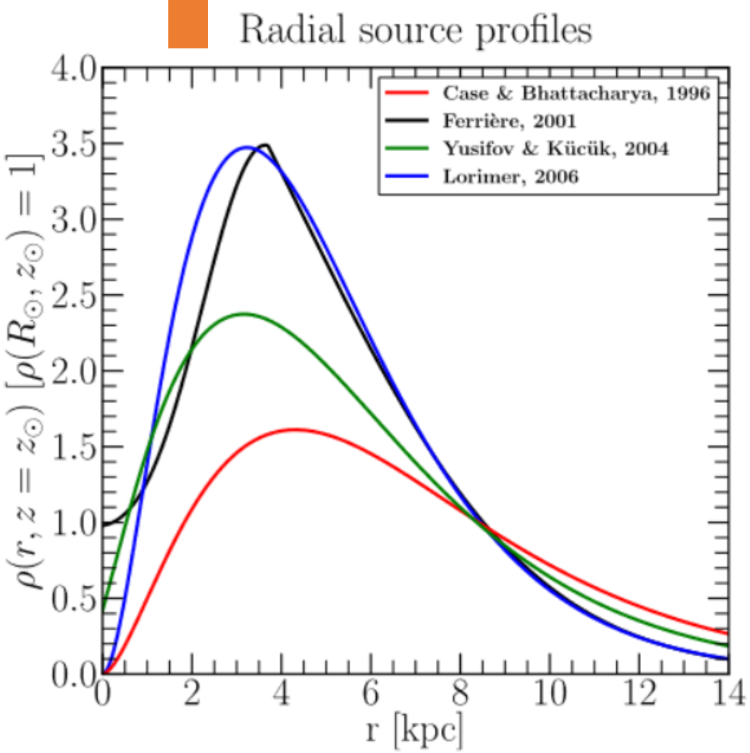
→ Solve cosmic ray propagation equation

Modifying Diffusion:
- Anisotropy
- Spatial variation
- Spectral breaks

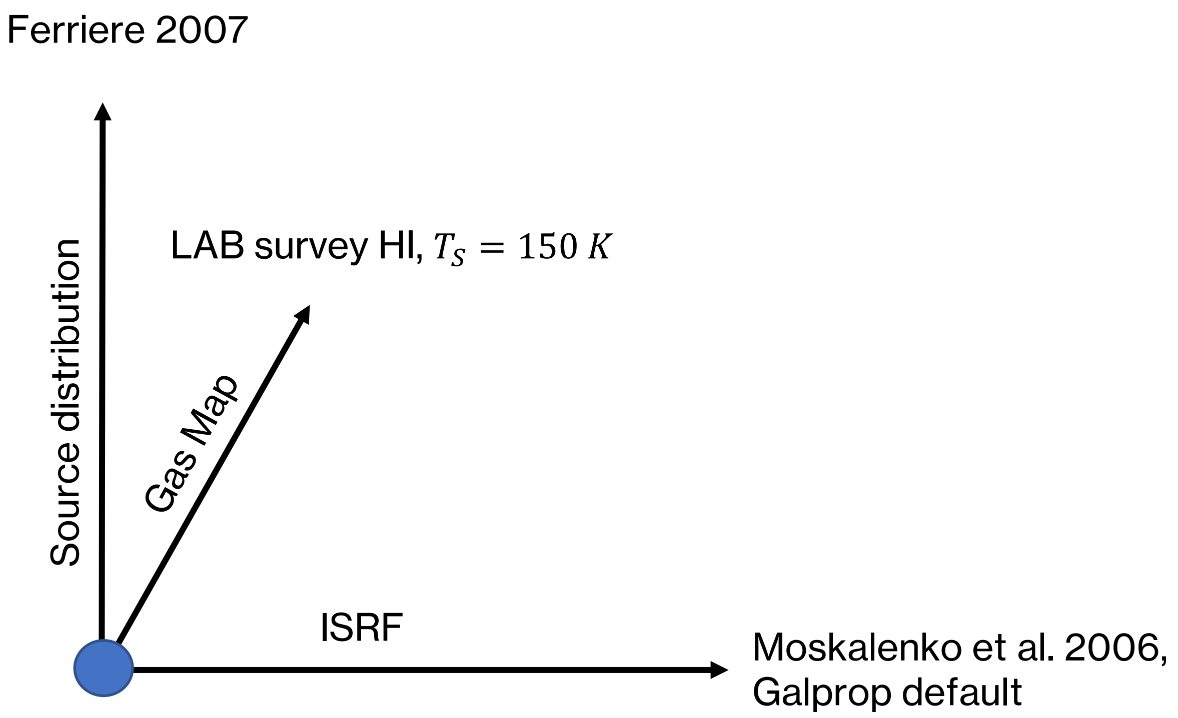
Modifying Sources:
- Spatial distribution
- Multiple source classes
- Individual sources

Tools: GALPROP, DRAGON, etc.



Fermi-LAT Compatibility

- Fermi-π^0 like model: No hardening towards galactic center



Ferriere 2007

Source distribution

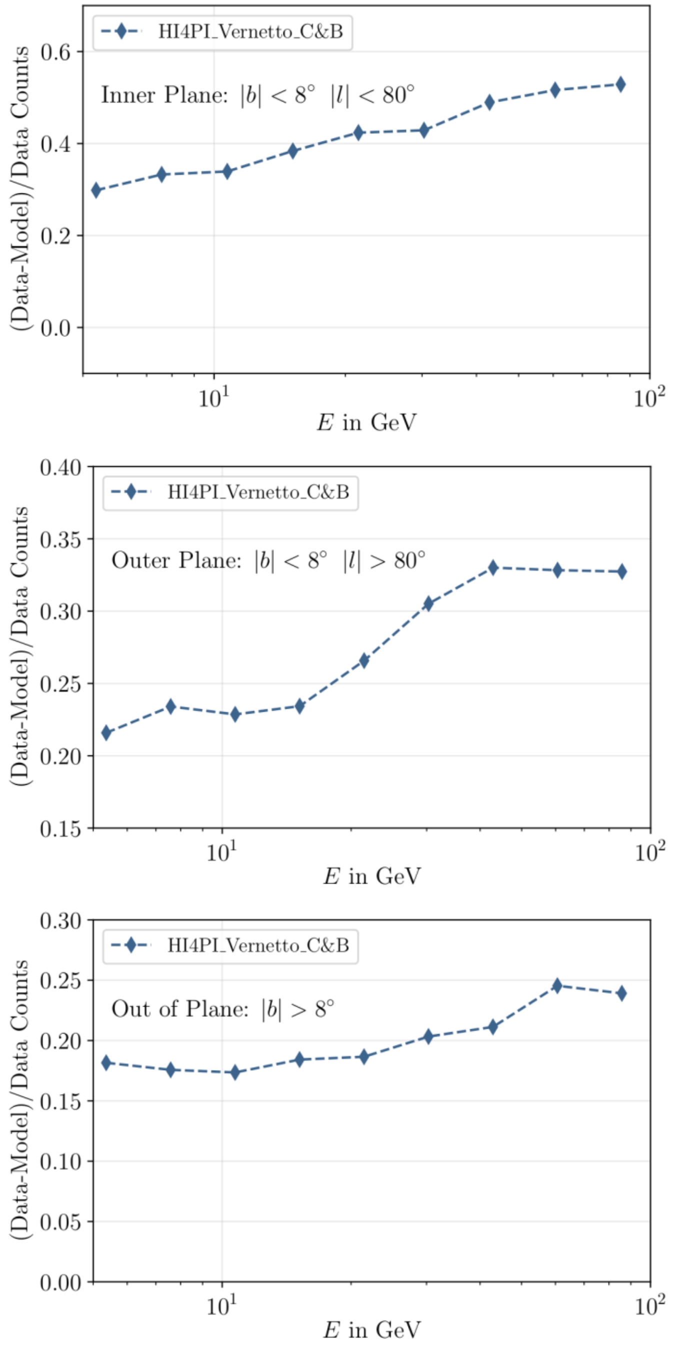
LAB survey HI, $T_S = 150\ K$

Gas Map

ISRF

Moskalenko et al. 2006,
Galprop default

Gas: HI4PI survey HI, $T_S = 300\ K$
ISRF: Vernetto et al. 2016
Sources: Case & Bhattacharya 1996



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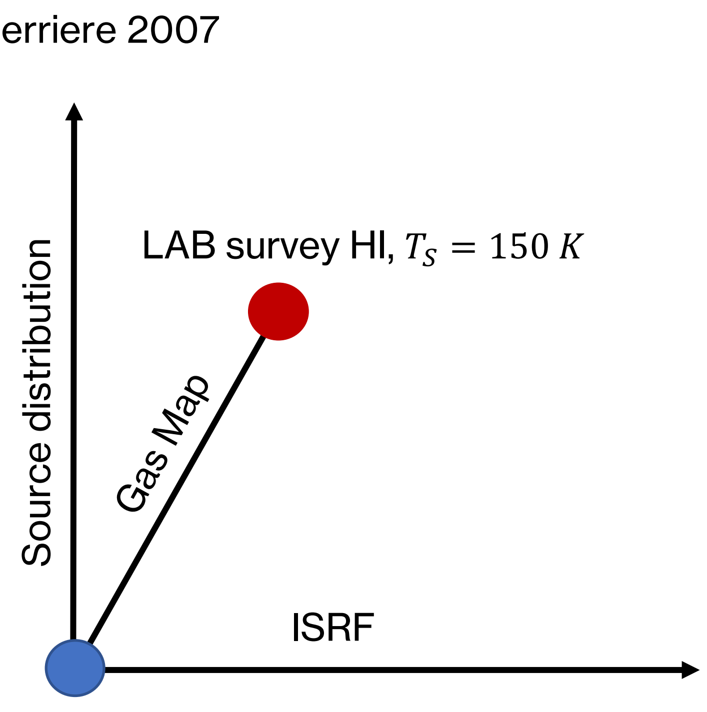

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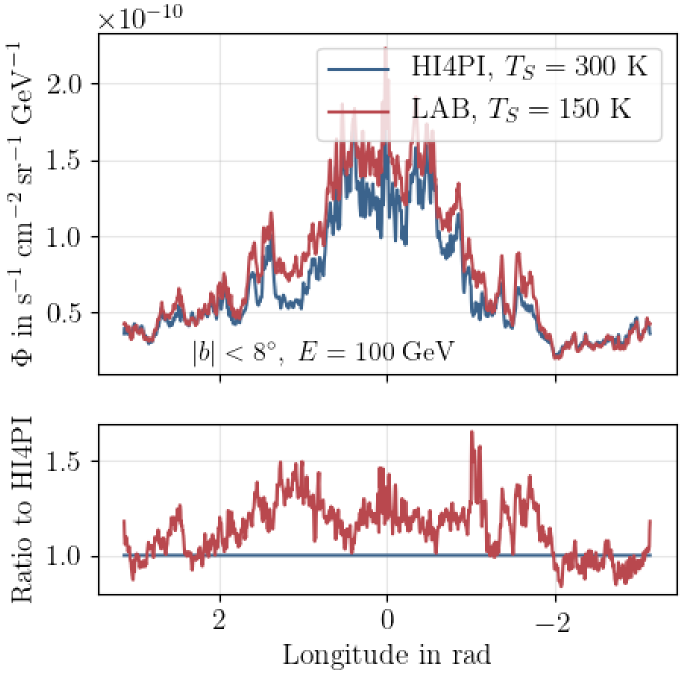

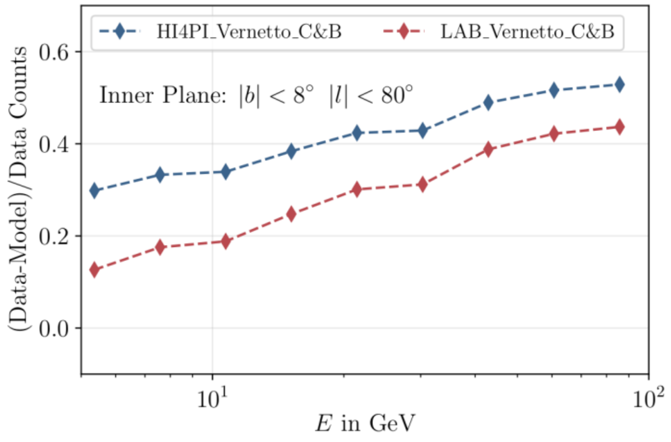

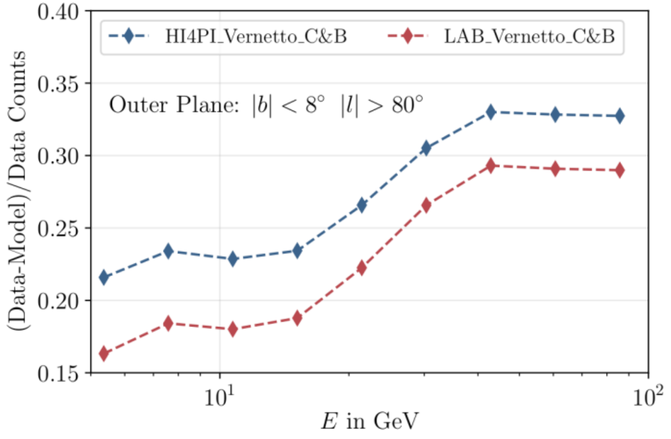

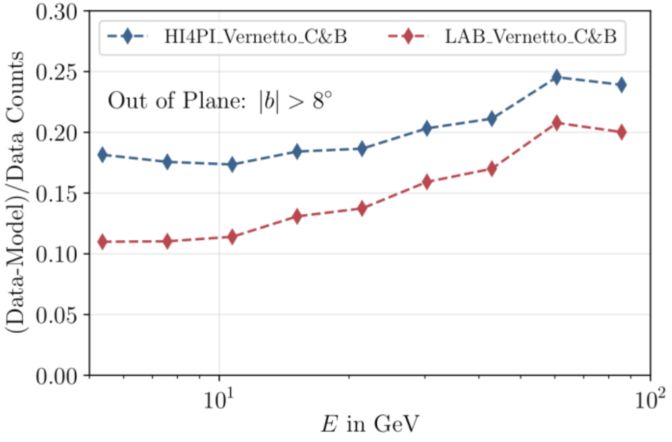

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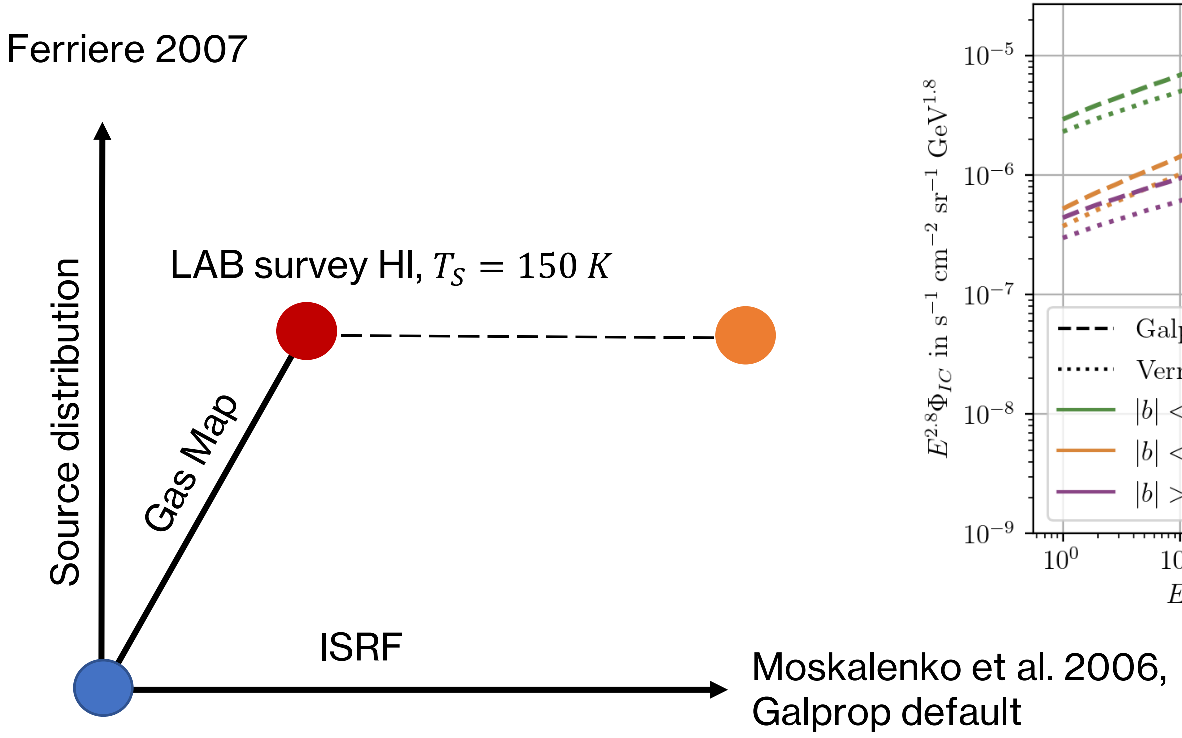

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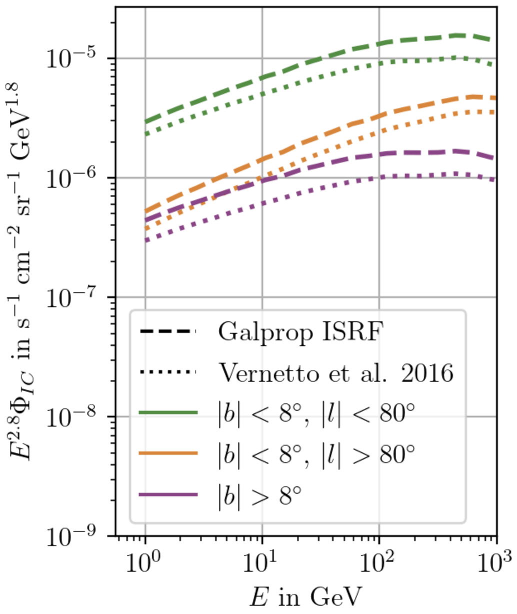

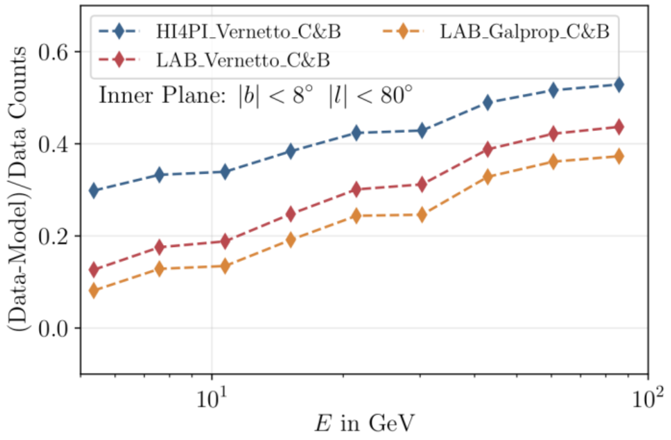

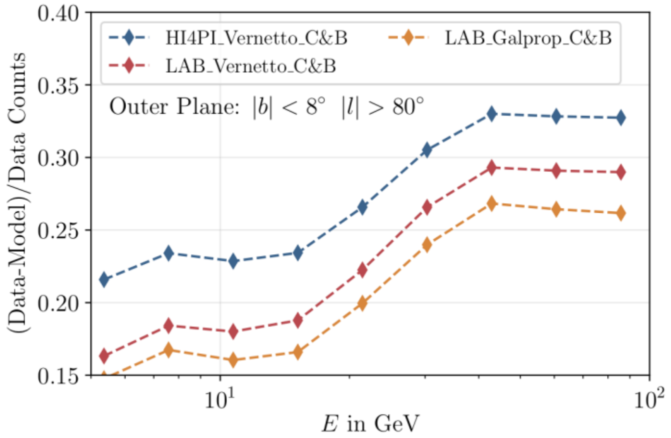

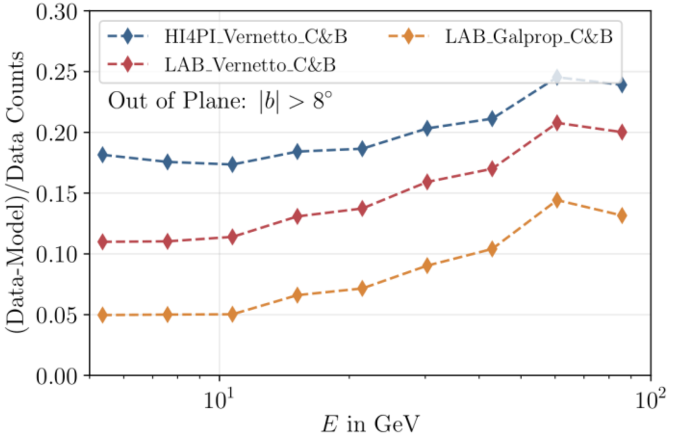

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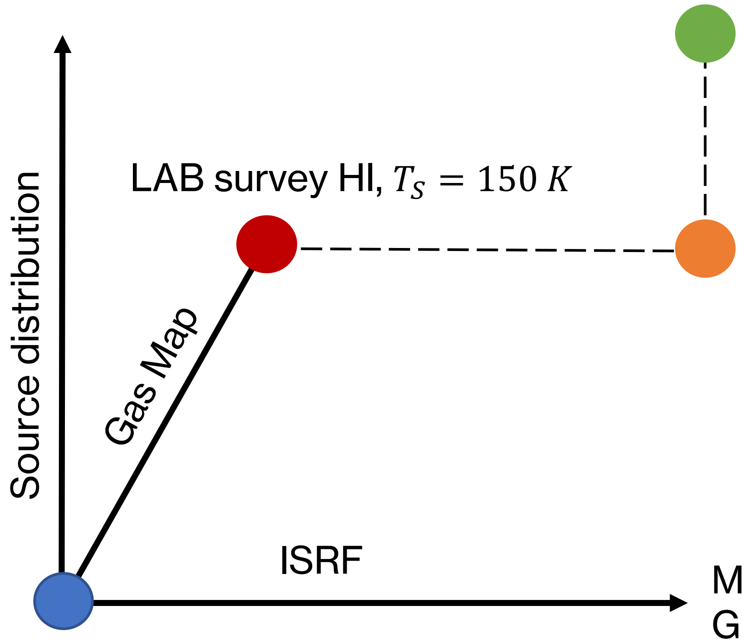

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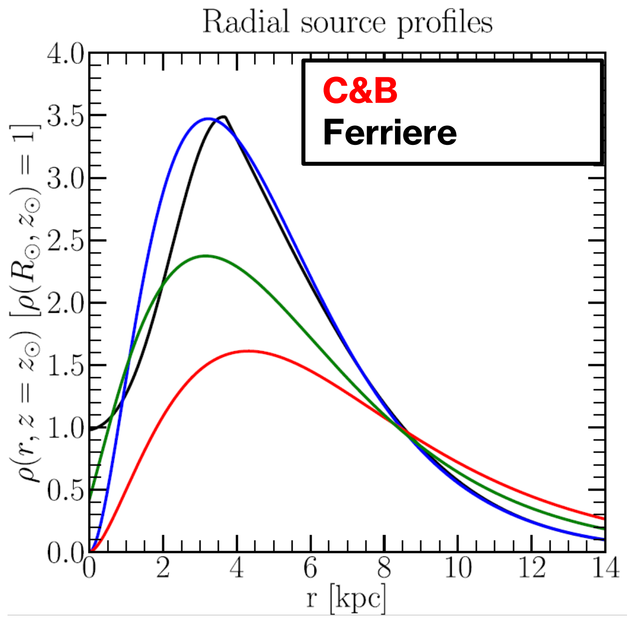
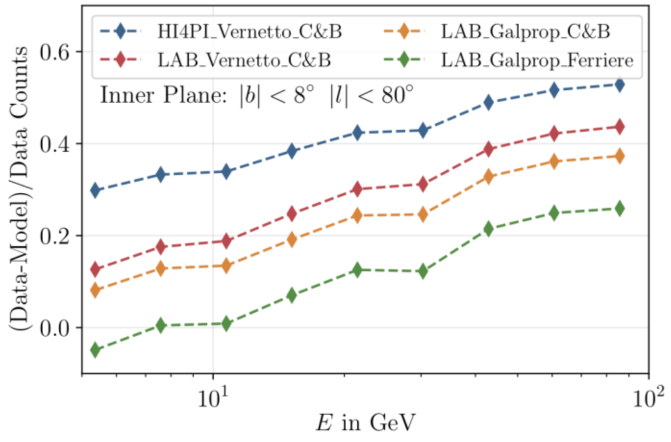
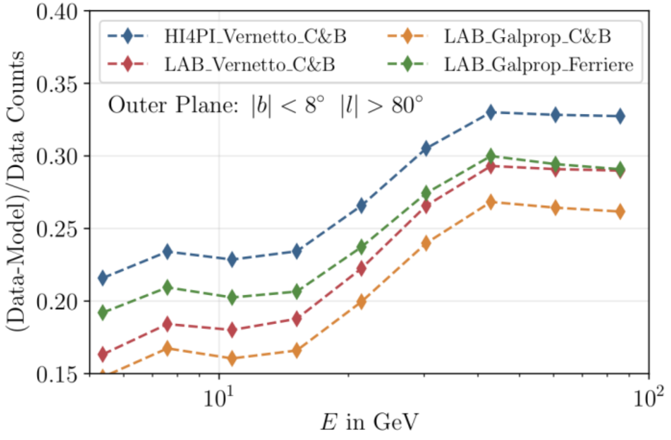
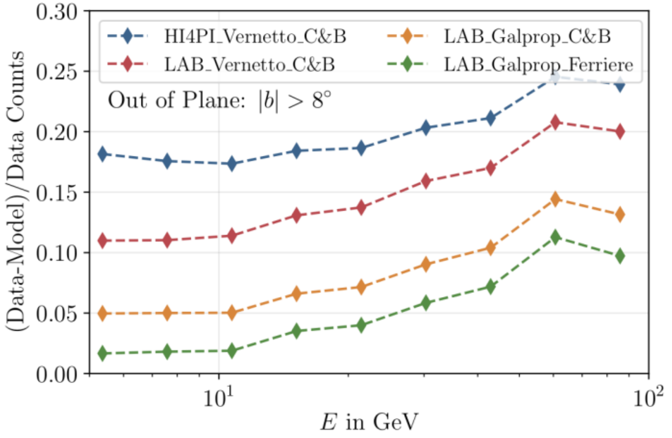




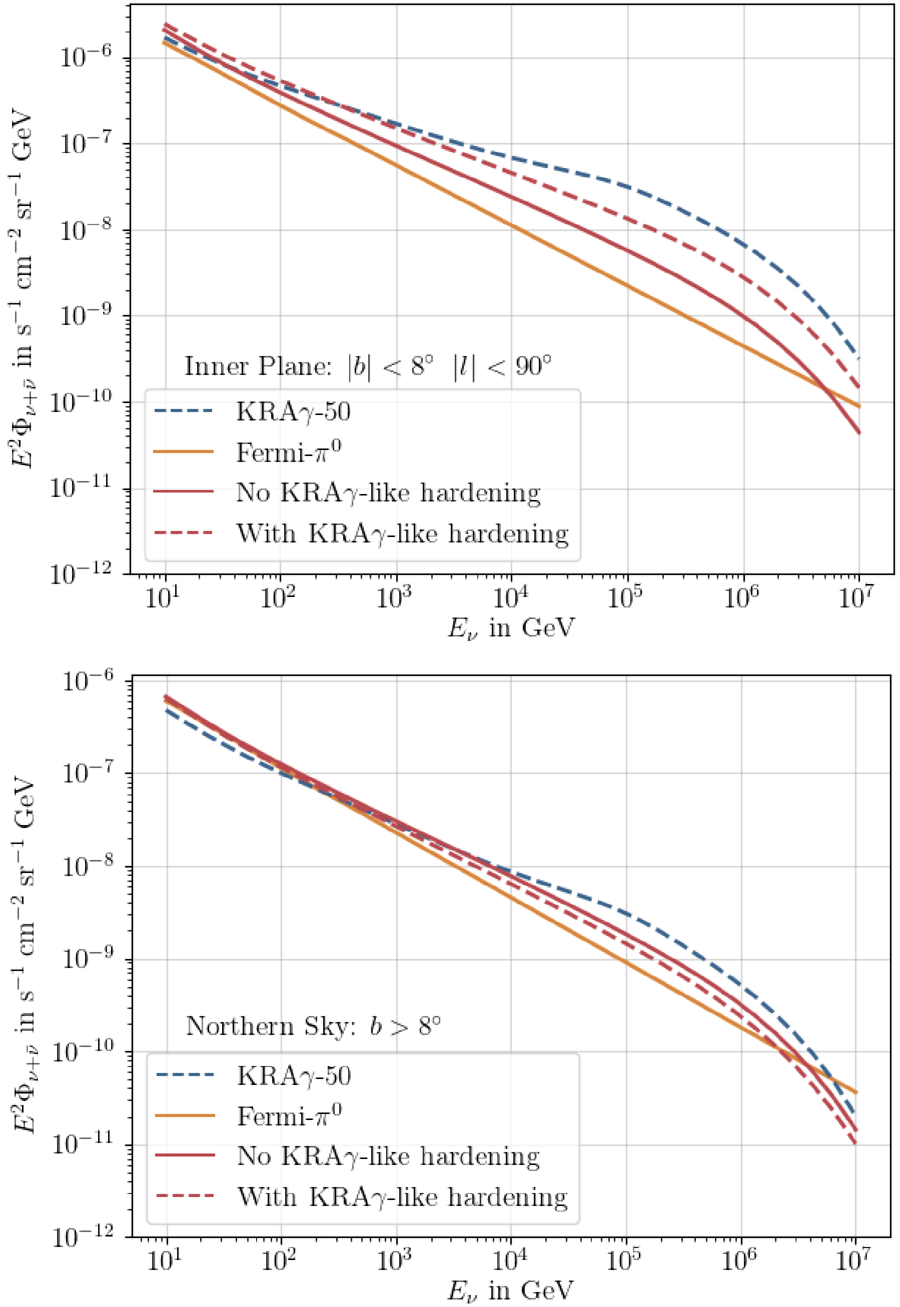




Extension to IceCube Energies

- ➢ Hadronic component: powerlaw with cutoff at 50 PeV
- ➢ 2 Models: With and without KRAγ-like hardening
- ➢ In between Fermi-π^0 and KRAγ models at IceCube energies
- ➢ In future:
  - Explicit treatment of CR composition
  - Fit to indirect CR data
  - Test compatibility with VHE & UHE gamma ray measurements

Single-Flavor Neutrino Spectra



Summary and Outlook

- Update models of galactic diffuse emission

- Cosmic ray model based on fit to AMS-02

- Fermi-LAT compatibility: Fluxes generally underpredicted
  - Increased flux in data
  - Well-known galactic center hardening→KRAγ-like models
  - Anticenter excess requires different solution → Halo height?
  - Best fitting models: Systematics set to maximum values

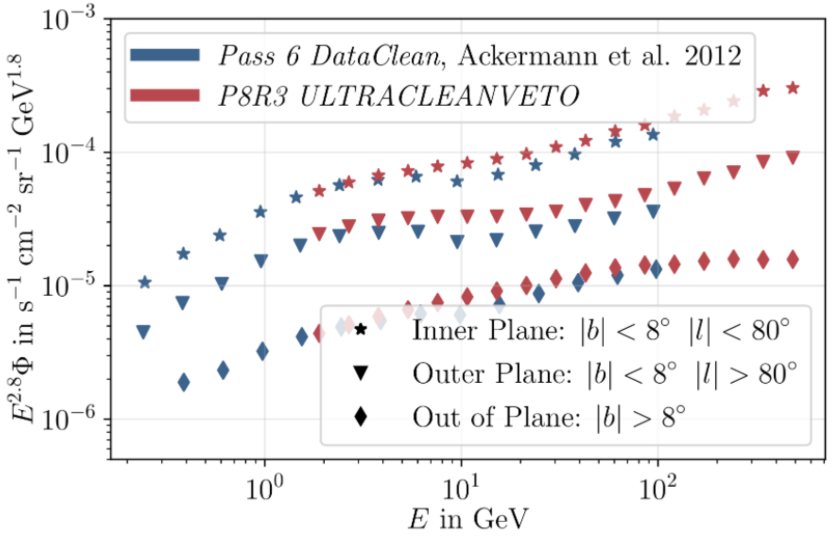
- Future work:
  - Test additional dependencies: Halo height, unresolved sources, different CR diffusion models,...
  - Extend cosmic ray fit to higher energies

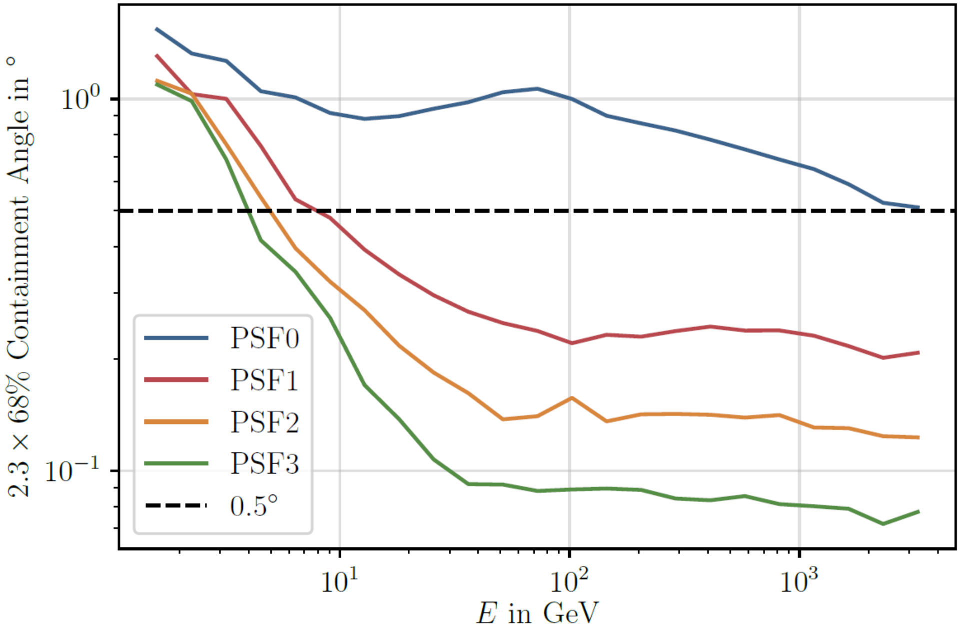
- Test neutrino models in future IceCube searches

Investigating Fermi-LAT compatibility

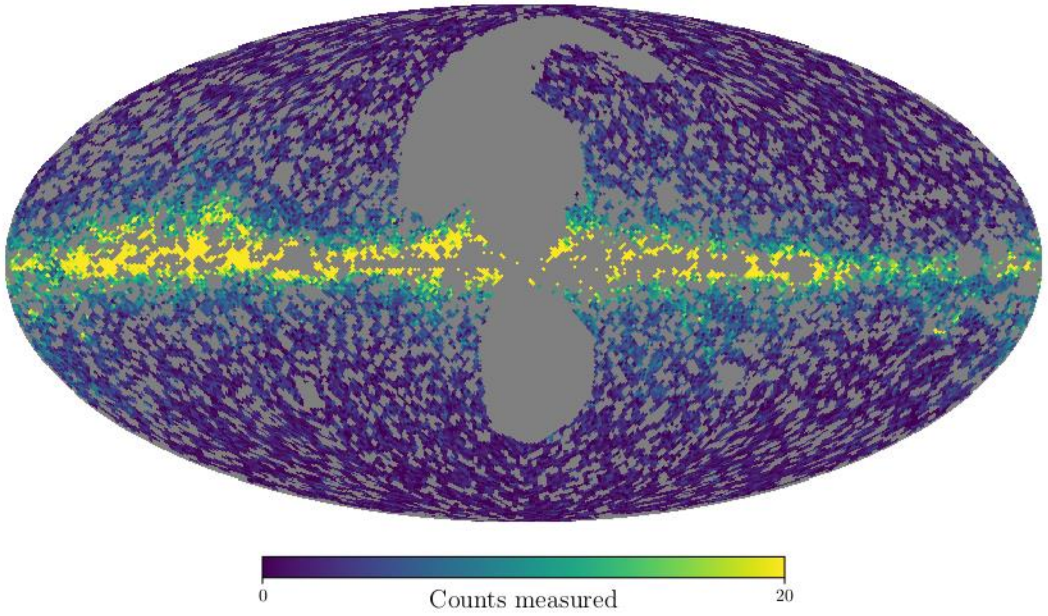
- Increased flux with respect to Pass 6

- Sources: Masked out
  - 4FGL Point & extended sources
  - Fermi Bubbles
  - North Polar Spur





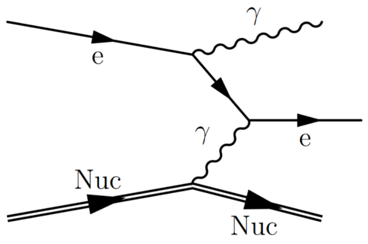
Fermi-LAT measured counts at 5 GeV



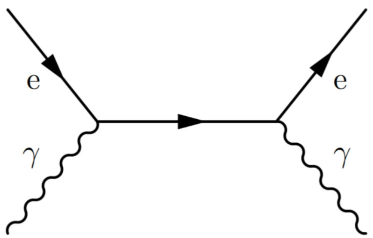
Galactic Diffuse Emission

- Radiation produced by „Sea“ of galactic cosmic rays in the Milky Way

- **Bremsstrahlung**



- **Inverse Compton Scattering**



- **Pion Production**

$$p_{CR} + p_{gas} \rightarrow X + \pi^0/\pi^+/\pi^-$$

$$\pi^0 \rightarrow 2\gamma$$

$$\pi^+/\pi^- \rightarrow \mu^+/\mu^- + \nu_\mu/\bar{\nu}_\mu$$

$$\mu^+/\mu^- \rightarrow e^+/e^- + \nu_e/\bar{\nu}_e + \bar{\nu}_\mu/\nu_\mu$$

Gamma Rays Only

Gamma Rays and Neutrinos

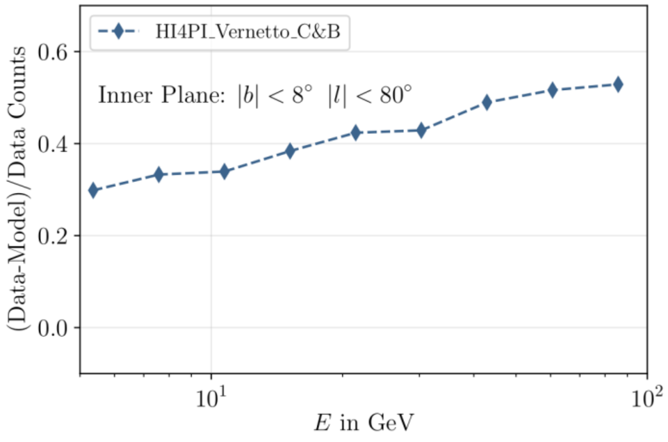
- Guaranteed Signal for IceCube
  - Discovery could be within reach within near future
  - Searches need model templates

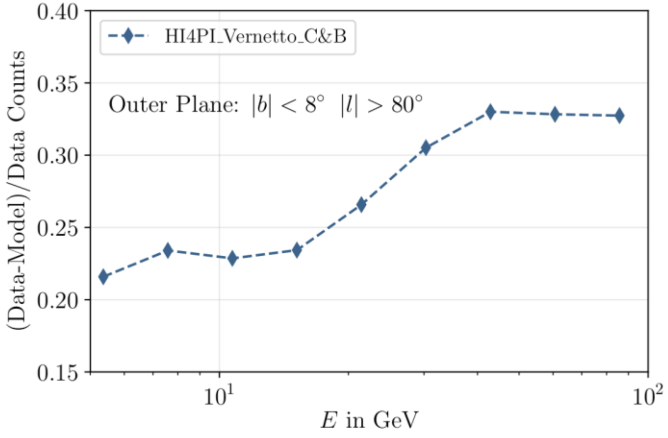
- Learn about propagation and sources of hadronic galactic cosmic rays

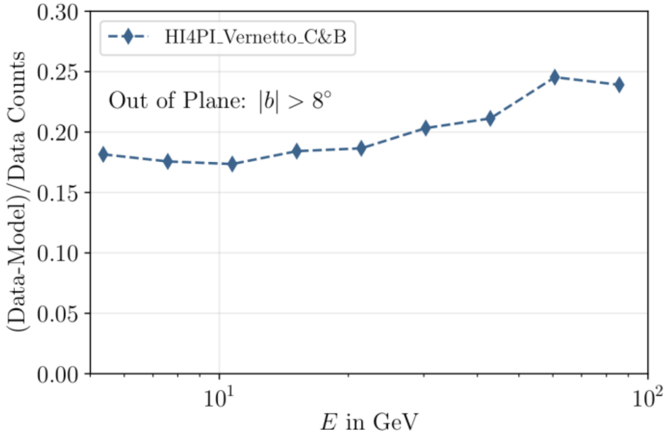
Some systematic dependencies

- Fermi-π^0 like model: No hardening towards galactic center

Gas Map	ISRF	Source distribution
HI4PI survey HI, $T_S = 300\ K$	Vernetto et al. 2016	Case & Bhattacharya 1996



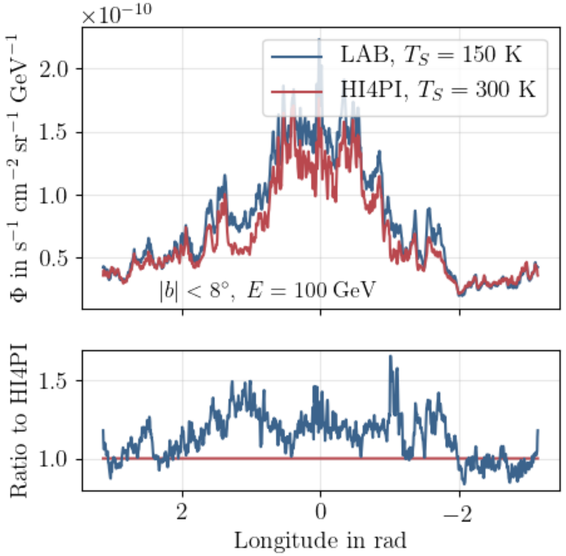


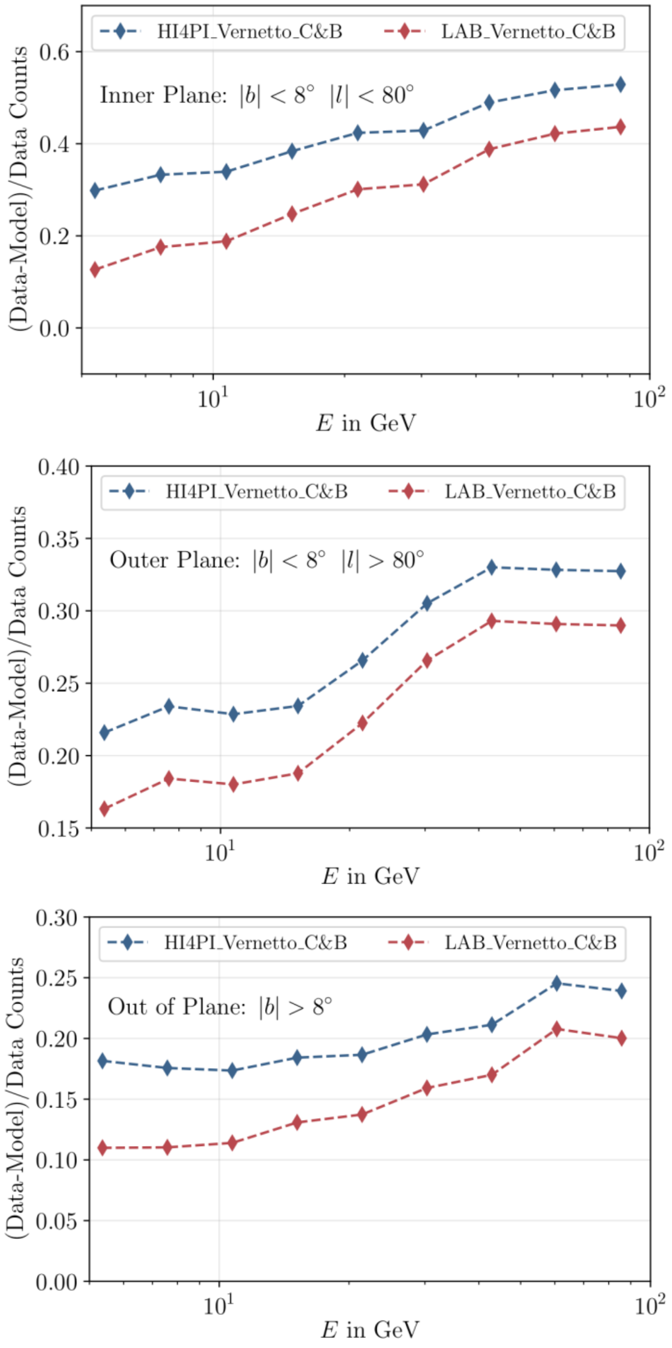


Some systematic dependencies

- ➢ Fermi-π^0 like model: No hardening towards galactic center

Gas Map	ISRF	Source distribution
HI4PI survey HI, $T_S = 300\ K$	Vernetto et al. 2016	Case & Bhattacharya 1996
LAB survey HI, $T_S = 150\ K$		**C&B** **Ferriere**





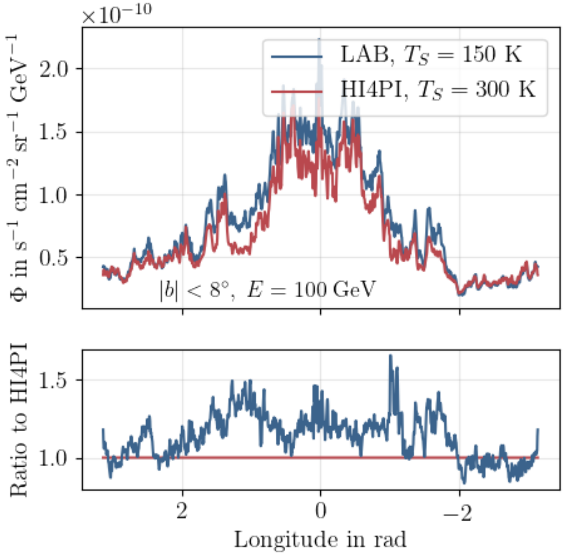
Some systematic dependencies

- Fermi-π^0 like model: No hardening towards galactic center

Gas Map

HI4PI survey HI, $T_S = 300\ K$

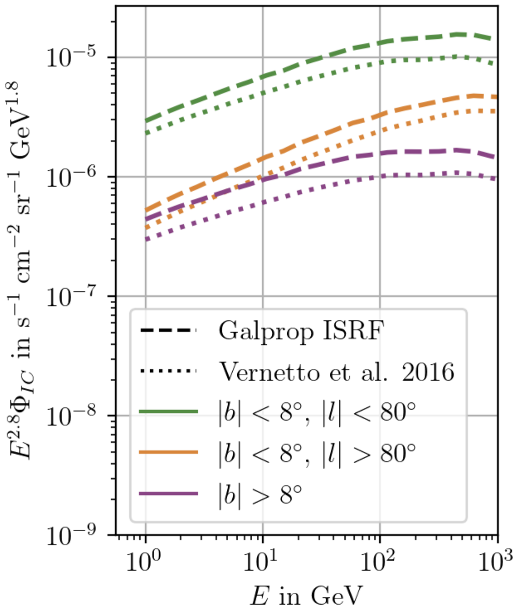
LAB survey HI, $T_S = 150\ K$



ISRF

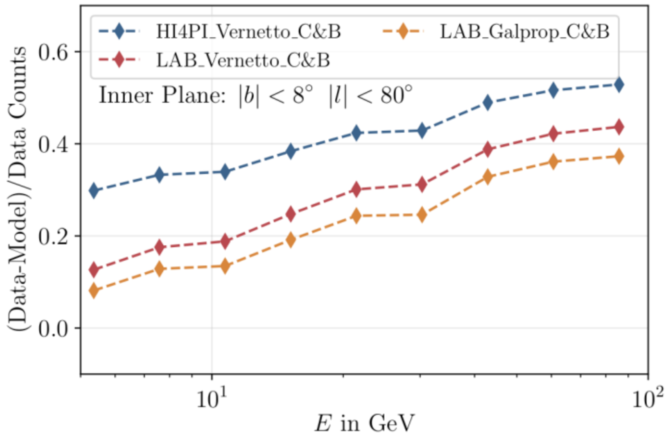
Vernetto et al. 2016

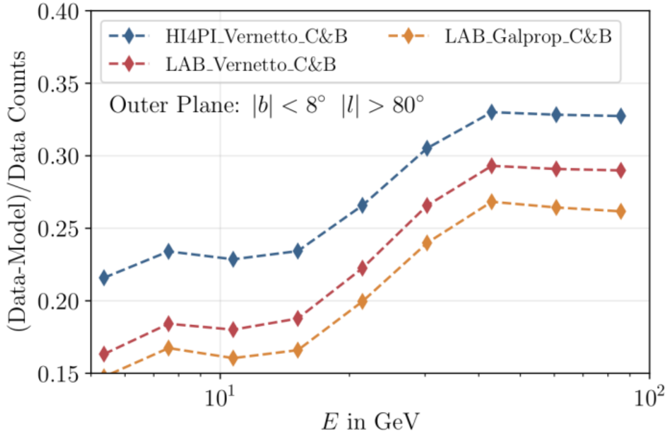
Moskalenko et al. 2006,
Galprop default

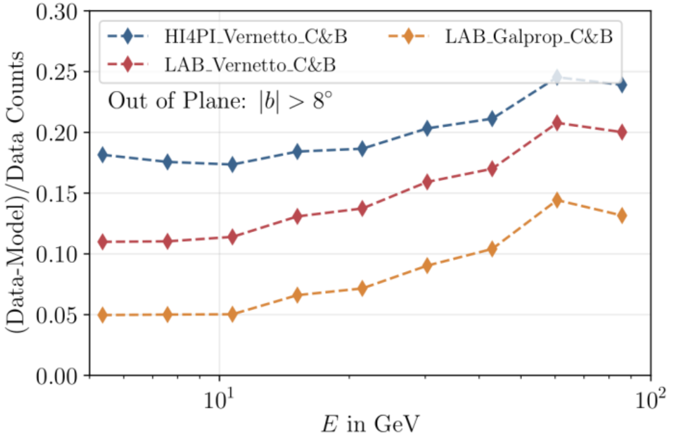


Source distribution

Case & Bhattacharya 1996







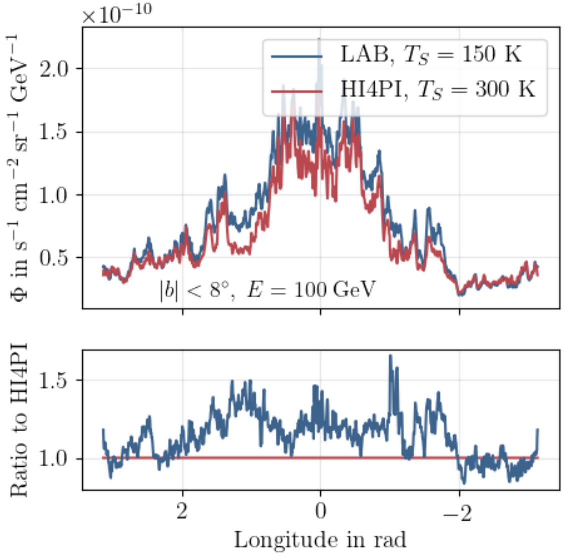
Some systematic dependencies

- Fermi-π^0 like model: No hardening towards galactic center

Gas Map

HI4PI survey HI, $T_S = 300\ K$

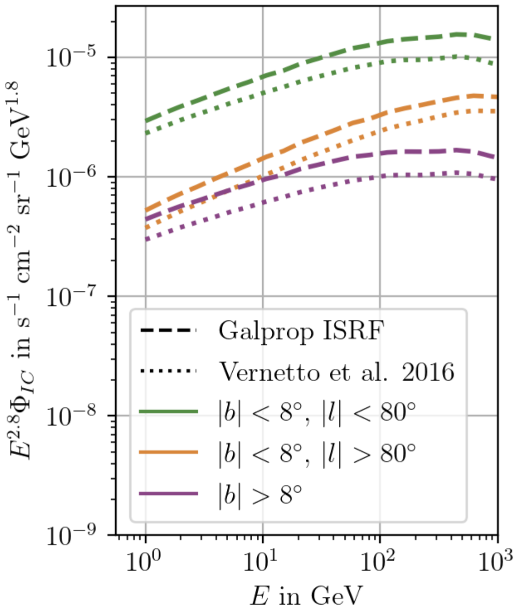
LAB survey HI, $T_S = 150\ K$



ISRF

Vernetto et al. 2016

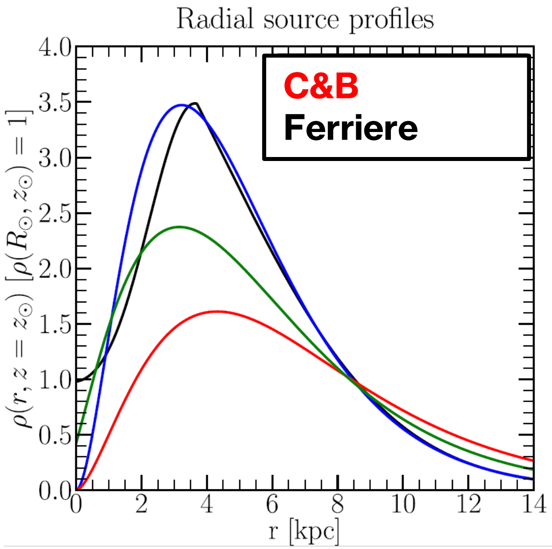
Moskalenko et al. 2006,
Galprop default

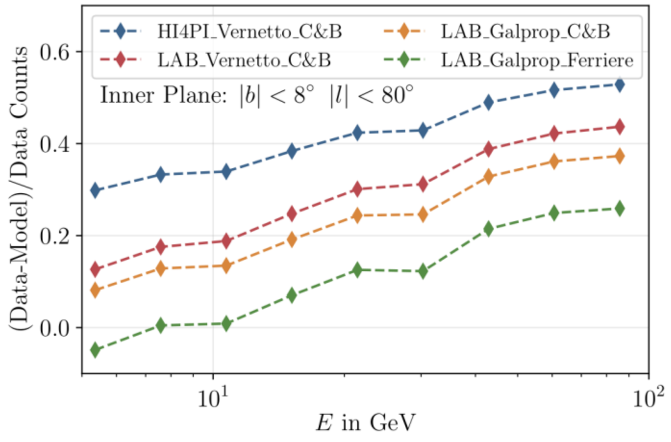


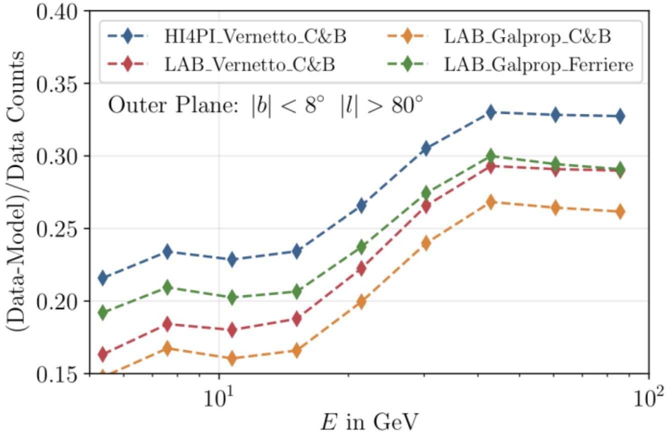
Source distribution

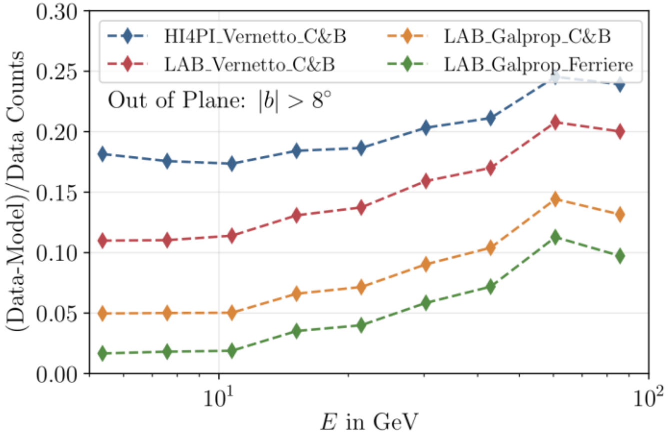
Case & Bhattacharya 1996

Ferriere 2007









Fit to AMS-02

- ➢ **Pure Diffusion Model**
- ➢ **Fit to p, He, C, B/C, e^+, e^-**

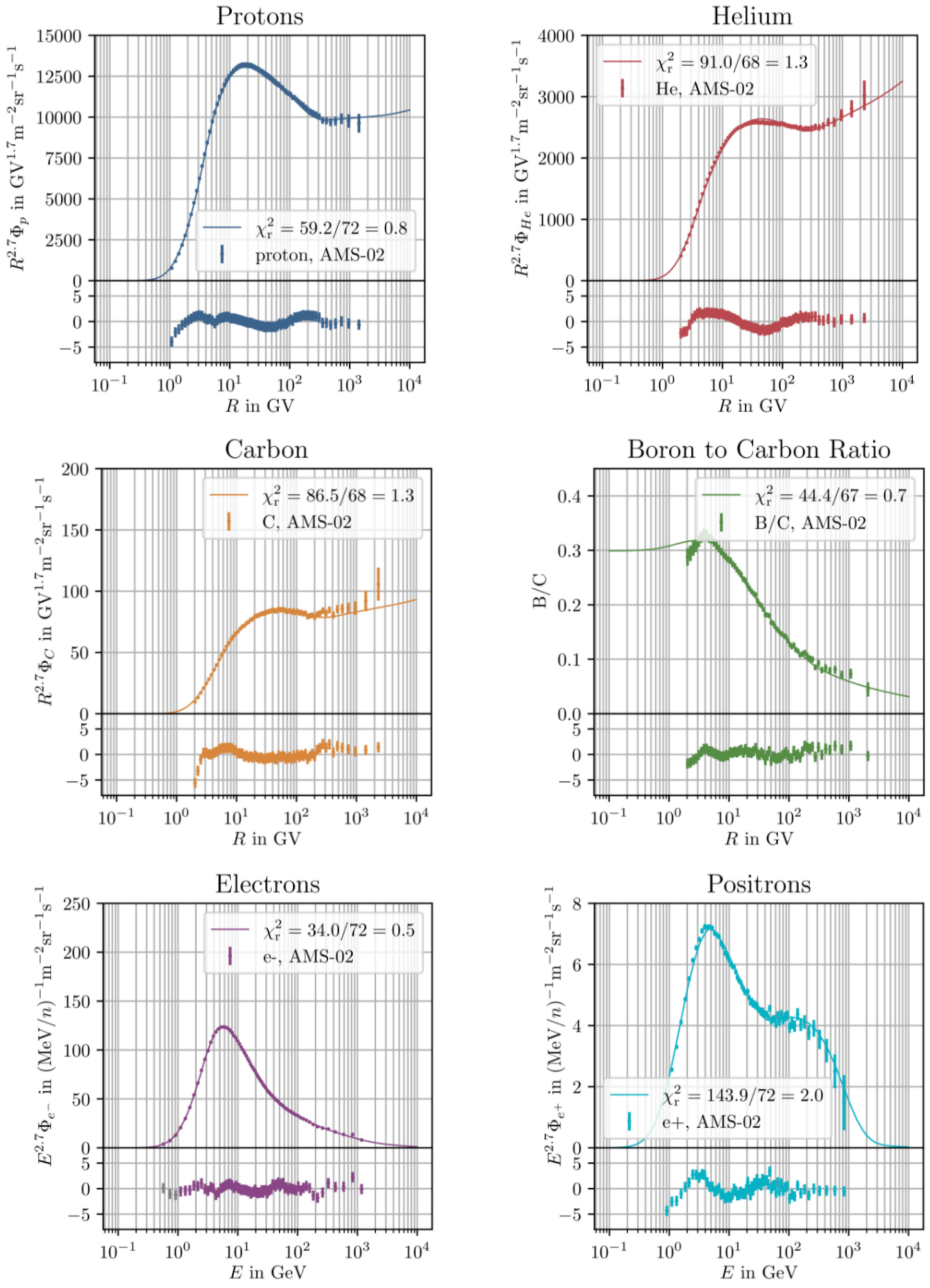
Free parameters:

- Diffusion Coefficient $D(R) = D_0 \beta \left(\frac{R}{R_1}\right)^{\delta_1} \prod_{i=1}^{2} \left(1 + \left(\frac{R}{R_i}\right)^{1/s_i}\right)^{s_i(\delta_{i+1}-\delta_i)}$

- Nuclear Injection Spectrum
  - Single powerlaw
  - Different spectral index for p, He, C

- Leptons
  - Broken powerlaw for electrons
  - Extra component for Positrons

➢ $\frac{\chi^2}{\mathrm{ndf}} \approx 1$ for all species except positrons



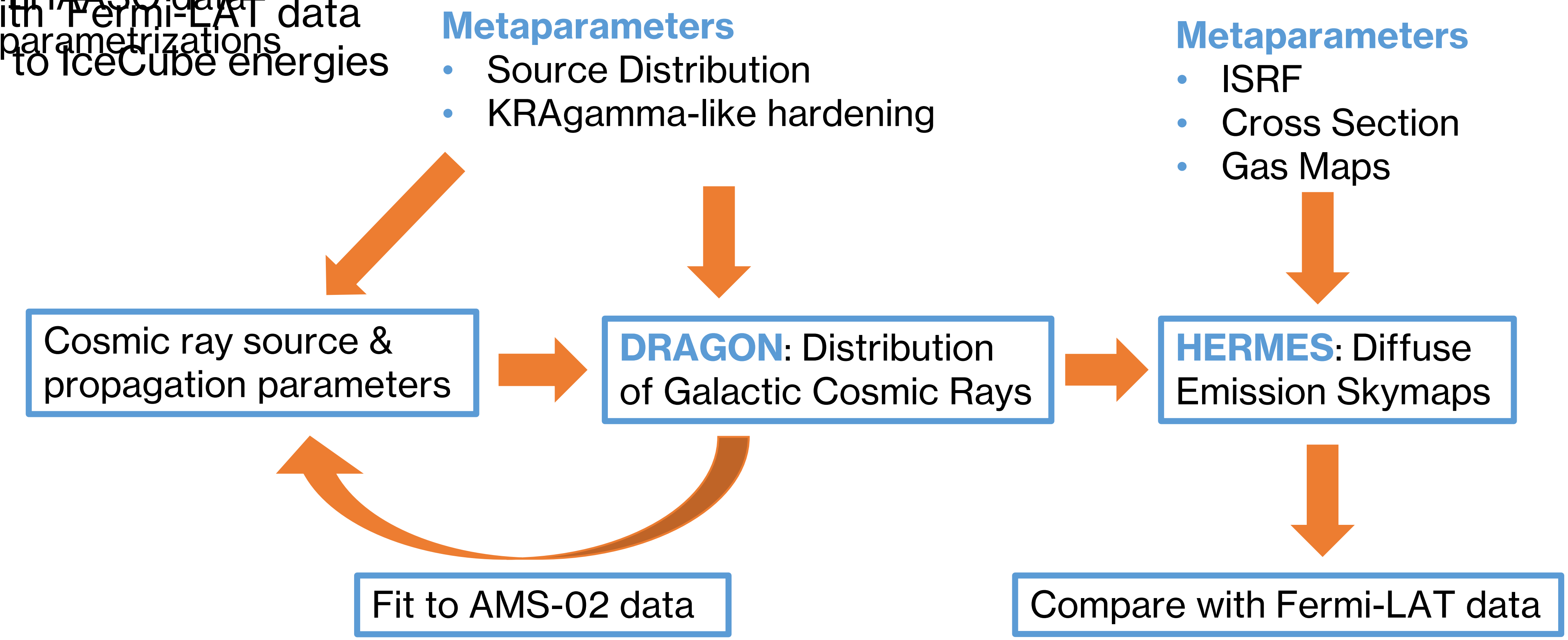
Updating the models

The approach:

1. Fit local Cosmic Rays to AMS-02
2. Compare with Fermi-LAT data
3. Extrapolate to IceCube energies

New since 2012/2015:

- Updated direct cosmic ray data
- Release of Fermi-LAT data
- Tibet-ASγ and LHAASO data
- Cross section parametrizations
- HI gas maps
- ISRF models



Metaparameters

- Source Distribution
- KRAgamma-like hardening

Metaparameters

- ISRF
- Cross Section
- Gas Maps

Cosmic ray source & propagation parameters

DRAGON: Distribution of Galactic Cosmic Rays

HERMES: Diffuse Emission Skymaps

Fit to AMS-02 data

Compare with Fermi-LAT data

Existing Baselines II: KRAgamma

Gaggero et al. 2015

- Spectral hardening towards galactic center

$$\kappa(p) = \kappa_0 \left(\frac{p}{p_0}\right)^{\delta}$$

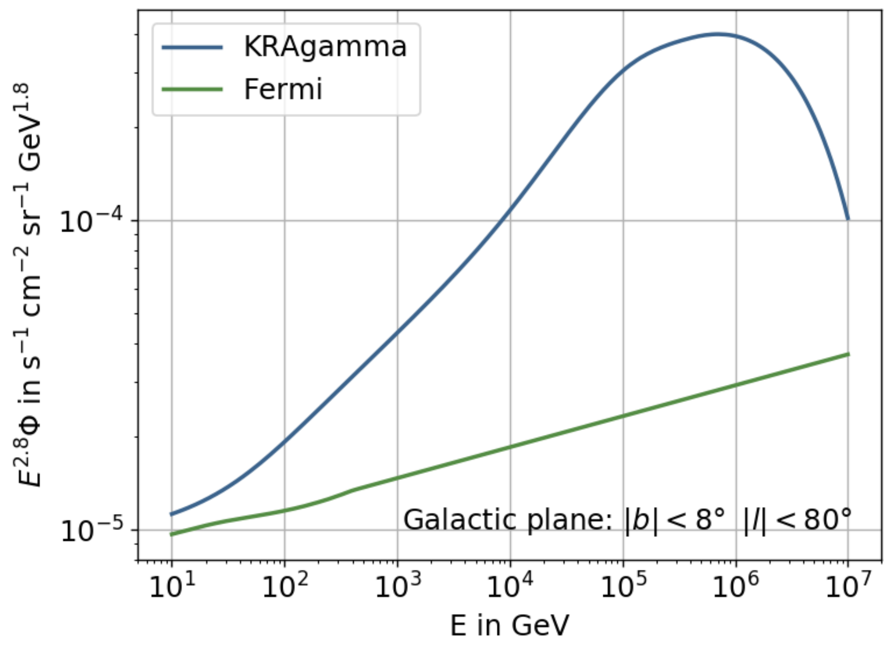
$$\delta(R) = A\,R + B \Longrightarrow \gamma(R) \approx \gamma_0 + \delta(R)$$

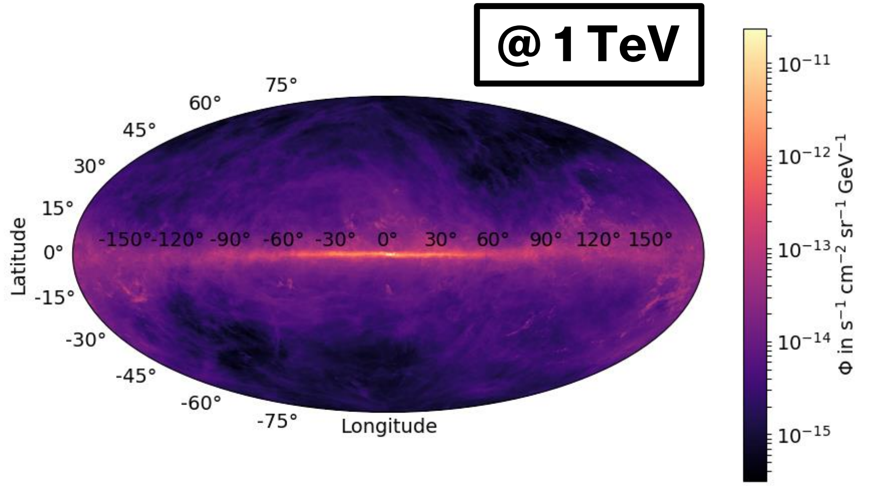
- Very optimistic

However:

- Hard to reproduce
  →Spectral break at 20 TeV
  →Longitudinal profile
- Already constrained by neutrino measurements
  - 90% U.L.: 0.9 * model baseline

Muon-Neutrino Spectra





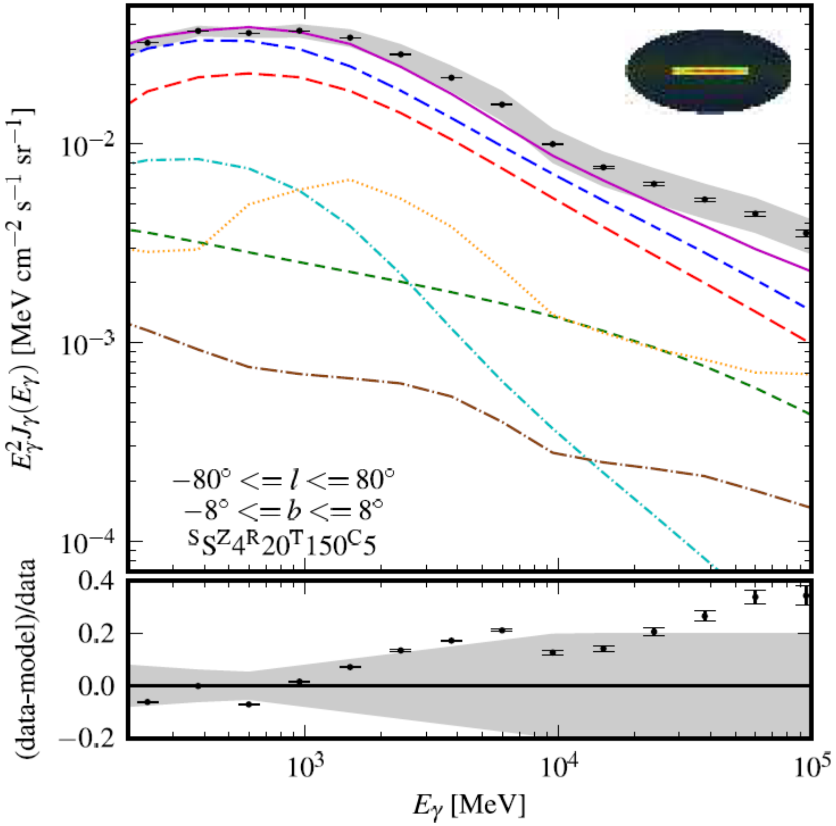
Existing Baselines I: Fermi-π_0

Ackermann et al. 2012

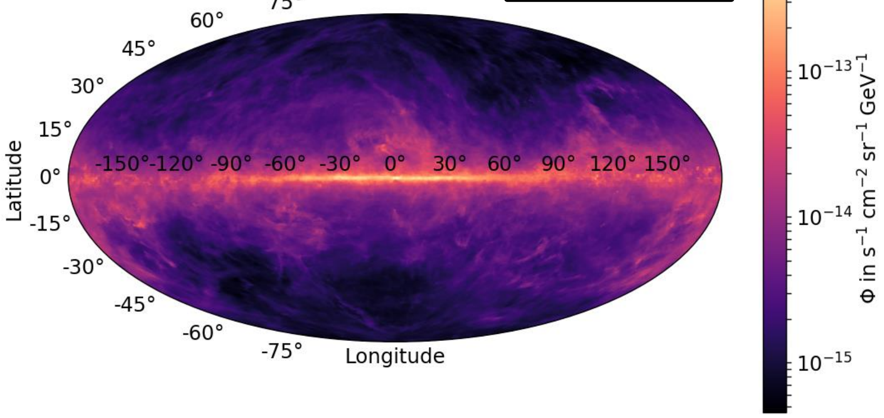
- Developed to fit Fermi-LAT data
- Idea: local CR properties apply throughout entire galaxy
- Single powerlaw spectrum with $\gamma = 2.72$
- Conservative
- 90% U.L. constraint: 7.5 * model baseline

However:

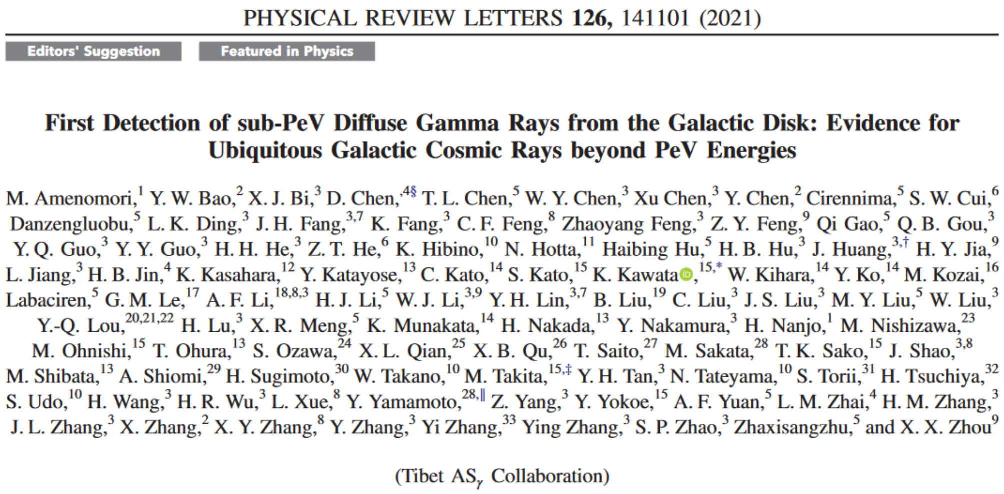
- Often misused in Neutrino Analyses
- Fails to explain Fermi-LAT
  →At high energies
  →In the galactic center



@ 1 TeV



Recently...



PHYSICAL REVIEW LETTERS **126,** 141101 (2021)

Editors' Suggestion **Featured in Physics**

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

M. Amenomori,[1] Y. W. Bao,[2] X. J. Bi,[3] D. Chen,[4§] T. L. Chen,[5] W. Y. Chen,[3] Xu Chen,[3] Y. Chen,[2] Cirennima,[5] S. W. Cui,[6] Danzengluobu,[5] L. K. Ding,[3] J. H. Fang,[3,7] K. Fang,[3] C. F. Feng,[8] Zhaoyang Feng,[3] Z. Y. Feng,[9] Qi Gao,[5] Q. B. Gou,[3] Y. Q. Guo,[3] Y. Y. Guo,[3] H. H. He,[3] Z. T. He,[6] K. Hibino,[10] N. Hotta,[11] Haibing Hu,[5] H. B. Hu,[3] J. Huang,[3,†] H. Y. Jia,[9] L. Jiang,[3] H. B. Jin,[4] K. Kasahara,[12] Y. Katayose,[13] C. Kato,[14] S. Kato,[15] K. Kawata,[15,*] W. Kihara,[14] Y. Ko,[14] M. Kozai,[16] Labaciren,[5] G. M. Le,[17] A. F. Li,[18,8,3] H. J. Li,[5] W. J. Li,[3,9] Y. H. Lin,[3,7] B. Liu,[19] C. Liu,[3] J. S. Liu,[3] M. Y. Liu,[5] W. Liu,[3] Y.-Q. Lou,[20,21,22] H. Lu,[3] X. R. Meng,[5] K. Munakata,[14] H. Nakada,[13] Y. Nakamura,[3] H. Nanjo,[1] M. Nishizawa,[23] M. Ohnishi,[15] T. Ohura,[13] S. Ozawa,[24] X. L. Qian,[25] X. B. Qu,[26] T. Saito,[27] M. Sakata,[28] T. K. Sako,[15] J. Shao,[3,8] M. Shibata,[13] A. Shiomi,[29] H. Sugimoto,[30] W. Takano,[10] M. Takita,[15,‡] Y. H. Tan,[3] N. Tateyama,[10] S. Torii,[31] H. Tsuchiya,[32] S. Udo,[10] H. Wang,[3] H. R. Wu,[3] L. Xue,[8] Y. Yamamoto,[28,‖] Z. Yang,[3] Y. Yokoe,[15] A. F. Yuan,[5] L. M. Zhai,[4] H. M. Zhang,[3] J. L. Zhang,[3] X. Zhang,[2] X. Y. Zhang,[8] Y. Zhang,[3] Yi Zhang,[33] Ying Zhang,[3] S. P. Zhao,[3] Zhaxisangzhu,[5] and X. X. Zhou[9]

(Tibet AS$_\gamma$ Collaboration)

PoS PROCEEDINGS OF SCIENCE

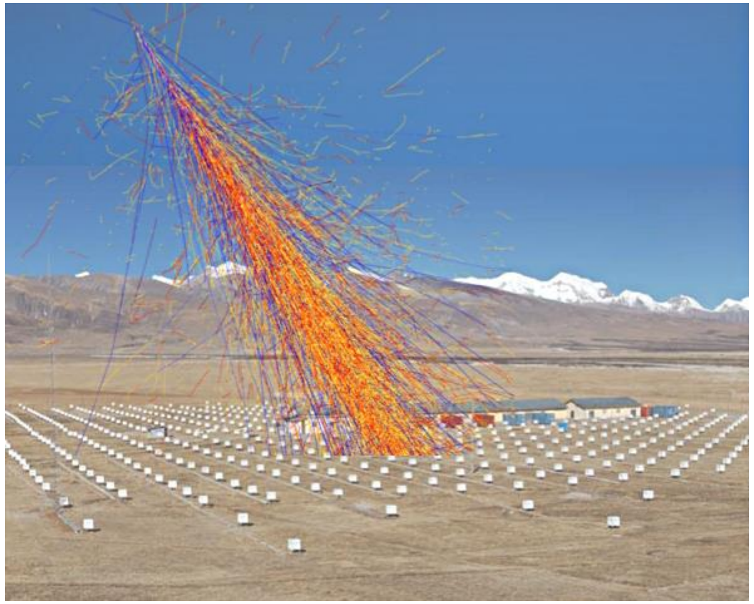
ONLINE ICRC 2021

Measurement of very-high-energy diffuse gamma-ray emission from Galactic plane with LHAASO-KM2A

Rui Zhang,[a,b,*] **Shiping Zhao,**[a,c,*] **Yi Zhang**[a] **and Qiang Yuan**[a] **on behalf of the LHAASO Collaboration**

(a complete list of authors can be found at the end of the proceedings)

- **First measurements of diffuse gamma rays above 100 TeV by Tibet-ASγ & LHAASO**



What do diffuse measurements tell us?

Fundamental question of Astroparticle Physics: Origin and propagation of cosmic rays

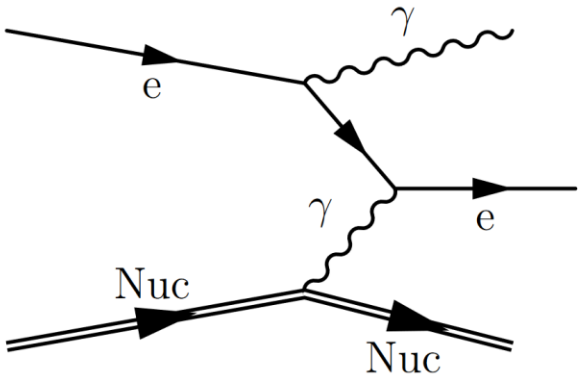
Problem: Charged cosmic ray measurements probe only local environment

→ How to probe the entire galactic volume?

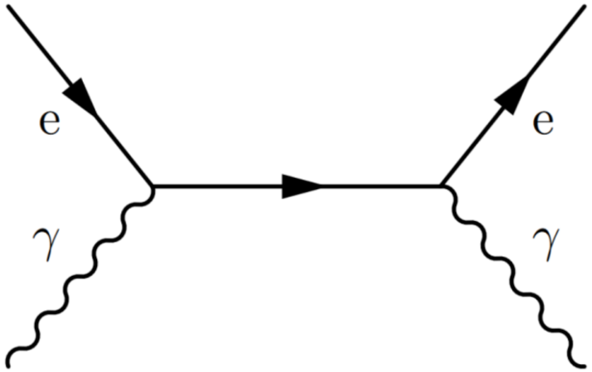
→ Measure radiation produced by interactions of cosmic rays in interstellar space

Diffuse Emission Processes

- **Bremsstrahlung**



- **Inverse Compton Scattering**



- **Pion Production**

$$p_{CR} + p_{gas} \to X + \pi^0/\pi^+/\pi^-$$

$$\pi^0 \to 2\gamma$$

$$\pi^+/\pi^- \to \mu^+/\mu^- + \nu_\mu/\bar{\nu}_\mu$$

$$\mu^+/\mu^- \to e^+/e^- + \nu_e/\bar{\nu}_e + \bar{\nu}_\mu/\nu_\mu$$

$$\underbrace{\hspace{6cm}}_{\text{Leptonic}} \qquad \underbrace{\hspace{4cm}}_{\text{Hadronic}}$$

Leptonic

- Gamma rays only
- Electron energy losses: Less important at higher energies

Hadronic

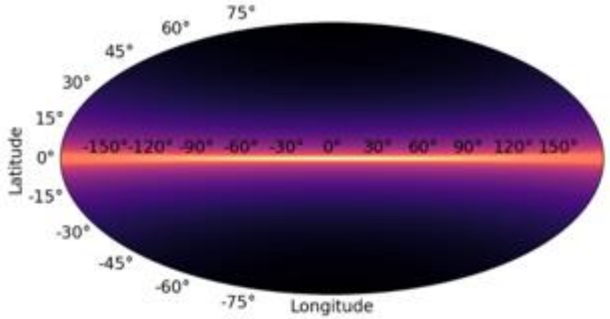
- Gamma rays and neutrinos

Analytic Models for Tibet ASγ

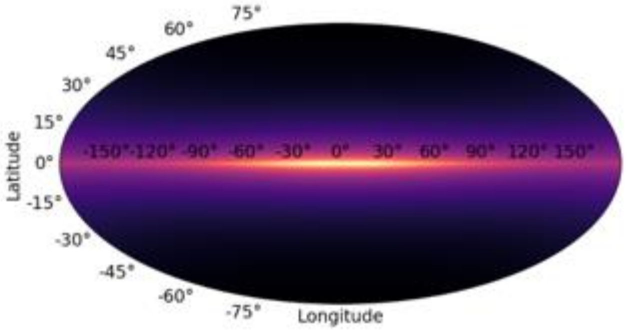
Fang & Murase 2021

$$I_{\nu/\gamma}(E_{\nu/\gamma}, l, b) = \frac{c}{4\pi}\int_{l,b} ds\, n_{gas}(\vec{x}) \int dE_p\, n_{CR}(E_p,\vec{x}) \frac{d\sigma(E_p,E_{\gamma/\nu})}{dE_{\nu/\gamma}} \propto n_{CR} n_H(r,z)\cdot \frac{dN_\nu}{dE_\nu}(E)$$

$$n_{\rm CR} n_N(r,z) \propto \begin{cases} 1 & r < R_{\rm disk} \text{ and } |z| < z_{\rm disk} \\ 0 & \text{otherwise}\end{cases}$$



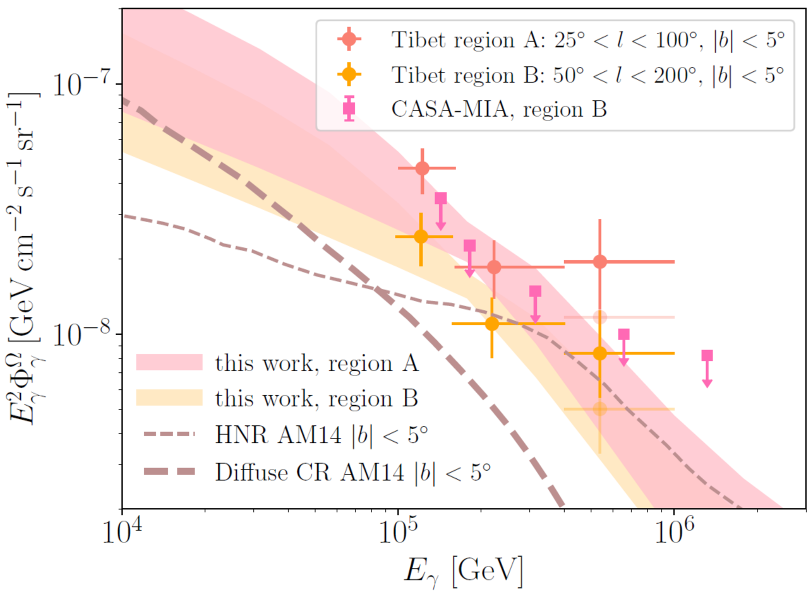
$$n_{\rm CR} n_N(r,z) \propto \left(\frac{r}{R_\odot}\right)^\zeta \exp\left[-\eta\left(\frac{r-R_\odot}{R_\odot}\right) - \frac{|z|}{z_g}\right]$$



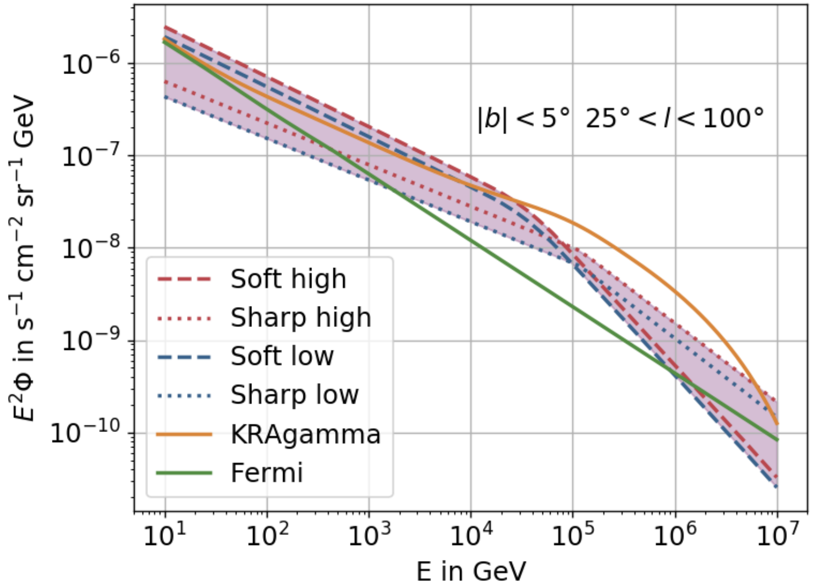
$$\frac{dN}{dE_n} \propto \begin{cases} E_\nu^{-\alpha_{\nu 1}} & E_\nu < E_{\nu,\rm bk} \\ E_\nu^{-\alpha_{\nu 2}} & E_\nu > E_{\nu,\rm bk}\end{cases}$$

$$\frac{dN}{dE_\nu} \propto E_\nu^{-\alpha_\nu}\left[1+\left(\frac{E_\nu}{E^*}\right)^w\right]^{-\delta/w}$$

Gamma Rays



Neutrinos



Work in Progress: New Benchmark model

New model should accomodate:

➢ **Diffuse Measurements**
- Fermi-LAT
- Tibet-ASγ & LHAASO

➢ **Cosmic Ray Measurements (AMS/CALET/DAMPE)**
- Proton
- Helium
- B/C

➢ **Latest gas maps & cross sections**

Our method: MCMC scan

- Choose set of model parameters
- Estimate of the width of the parameter space
- Propagate to IceCube sensitivity estimates

Searches for Galactic Diffuse Neutrinos

➢ Different Experiments

IceCube

- O(1 km^3) volume
- South Pole

Antares

- O(0.01 km^3) volume
- Mediterranean Sea

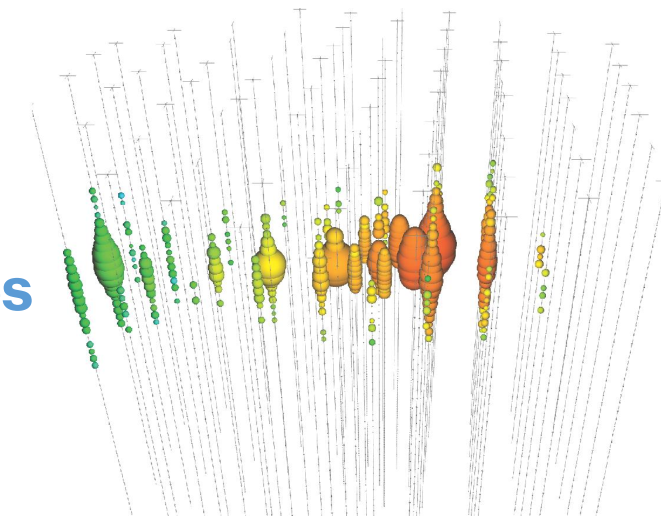
➢ Different Channels

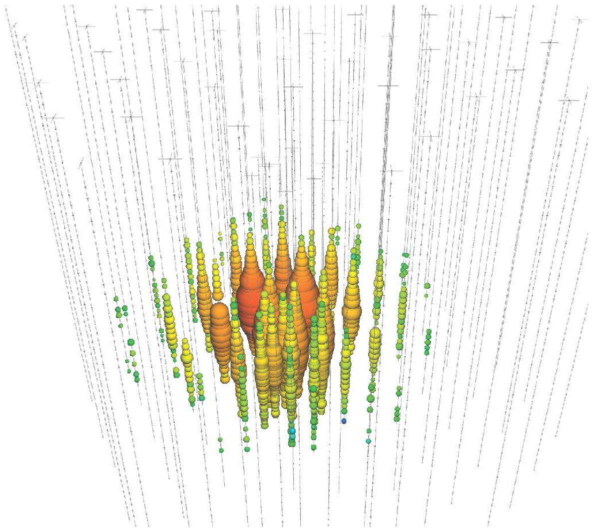
Tracks

- Only for $z \geq 90^\circ$
- Good pointing
- Bad energy resolution

Cascades

- Full Sky
- Bad Pointing
- Good energy resolution





So Far: Upper Limits only

Goal: Calculate Sensitivity of future analyses

- Potential in combining analyses?
- Model dependence?

Getting Rate Predictions

Poisson Likelihood: $\ln\mathcal{L}(\mathcal{D}|C_{\text{gal}},C_{\text{diff}},C_{\text{atmo}},\vec{\xi}) = \sum_{i}^{n_{Ebins}}\sum_{j}^{n_{zbins}}\sum_{k}^{n_{rabins}} \mathcal{D}_{ijk}\cdot\ln N^{\text{tot}}_{ijk}(C_{\text{gal}},C_{\text{diff}},C_{\text{atmo}},\vec{\xi}) - N^{\text{tot}}_{ijk}(C_{\text{gal}},C_{\text{diff}},C_{\text{atmo}},\vec{\xi})$

Flux Predictions:
- Atm. Conventional & Prompt
- Isotropic Astrophysical
- Galactic

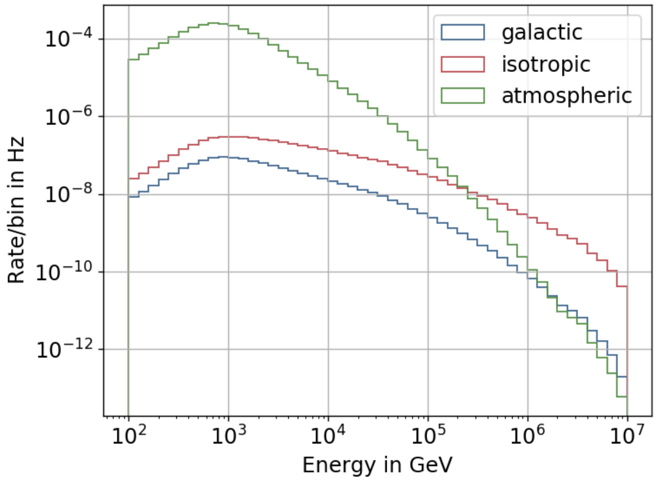
×

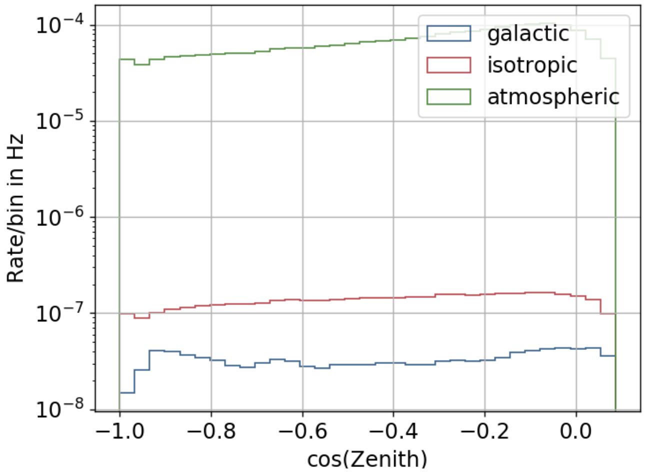
Effective area(s)
- Self-veto effect for cascades

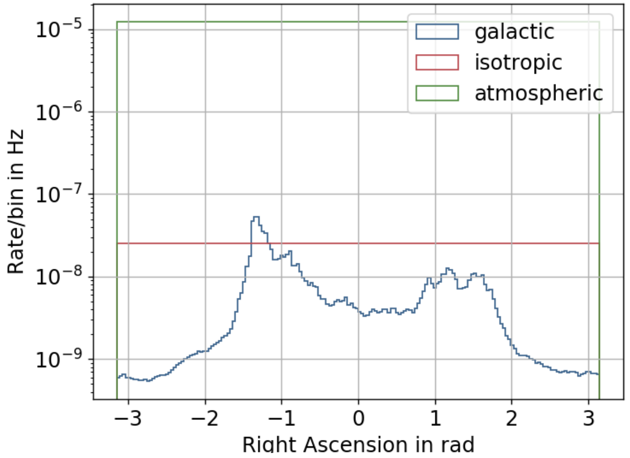
+

- Binning
- Energy & angular resolution

Tracks







Fisher Forecasting Paper: https://arxiv.org/abs/1704.05458

Fisher Forecasting: Basic Formalism

Cramèr-Rao bound: $\mathrm{cov}\left[\hat{\theta}_i, \hat{\theta}_j\right] \equiv \langle (\hat{\theta}_i - \theta_i)(\hat{\theta}_j - \theta_j) \rangle_{\mathcal{D}(\boldsymbol{\theta})} \geq (\mathcal{I}(\hat{\boldsymbol{\theta}})^{-1})_{ij}$

Fisher Information Matrix: $\mathcal{I}_{ij}(\boldsymbol{\theta}) \equiv \left\langle \left(\frac{\partial \ln \mathcal{L}(\mathcal{D}|\boldsymbol{\theta})}{\partial \theta_i} \right) \left(\frac{\partial \ln \mathcal{L}(\mathcal{D}|\boldsymbol{\theta})}{\partial \theta_j} \right) \right\rangle_{\mathcal{D}(\boldsymbol{\theta})} = - \left\langle \frac{\partial^2 \ln \mathcal{L}(\mathcal{D}|\boldsymbol{\theta})}{\partial \theta_i \partial \theta_j} \right\rangle_{\mathcal{D}(\boldsymbol{\theta})}$

Poisson Likelihood: $\ln \mathcal{L}(\mathcal{D}|C_{\mathrm{gal}}, C_{\mathrm{diff}}, C_{\mathrm{atmo}}, \vec{\xi}) = \sum_i^{n_{Ebins}} \sum_j^{n_{zbins}} \sum_k^{n_{rabins}} \mathcal{D}_{ijk} \cdot \ln N_{ijk}^{\mathrm{tot}}(C_{\mathrm{gal}}, C_{\mathrm{diff}}, C_{\mathrm{atmo}}, \vec{\xi}) - N_{ijk}^{\mathrm{tot}}(C_{\mathrm{gal}}, C_{\mathrm{diff}}, C_{\mathrm{atmo}}, \vec{\xi})$

→ Linear in data → Replace data with Asimov set

→ $\mathcal{I}_{\alpha\beta}(\vec{\theta}) = \sum_i^{n_{Ebins}} \sum_j^{n_{zbins}} \sum_k^{n_{rabins}} \frac{\partial N_{ijk}^{\mathrm{tot}}(\vec{\theta})}{\partial \theta_\alpha} \frac{1}{N_{ijk}^{\mathrm{tot}}(\vec{\theta})} \frac{\partial N_{ijk}^{\mathrm{tot}}(\vec{\theta})}{\partial \theta_\beta}$

From here: **Equivalent counts method**

- Expected upper limits & Discovery reaches
- Relies on solving implicit equations
- No Pseudoexperiments, No Fits
- Computationally Cheap

Sensitivity Results

Sensitivity: Median expected 90% upper limit in units of baseline model expectation

Analysis	Lifetime	KRAgamma	Fermi-π_0	Analytic
IceCube Cascades	10 years	0.132	1.12	0.21-0.70
IceCube Tracks	10 years	0.61	2.92	0.64-1.97
Antares Tracks+Cascades	10 years	1.04	10.6	2.4-7.6
Combined	10 years	0.127	1.03	0.20-0.63

- Combining datasets: $\mathcal{L}_{tot} = \prod_i \mathcal{L}_i \Longrightarrow \mathcal{I}_{tot} = \sum_i \mathcal{I}_i$
- IceCube Cascades clearly most sensitive
- View of galactic center crucial for KRAgamma sensitivity
- IceCube Tracks + Antares contribute 8%-17% to combined sensitivity

Summary

- Galactic Diffuse Emission can help reveal galactic cosmic ray properties
- Neutrinos not detected yet, but discovery not too far away
- Range of models available, none without deficiencies
- Fisher Forecasting is lightweight method to get IceCube & Antares sensitivities
- IceCube Cascades are most sensitive channel
- Combination of analyses important for model differentiation
- Future work:
  - New benchmark model
  - Systematic parameter study

Thank you for your Attention!

Backup Slides

Combining Datasets

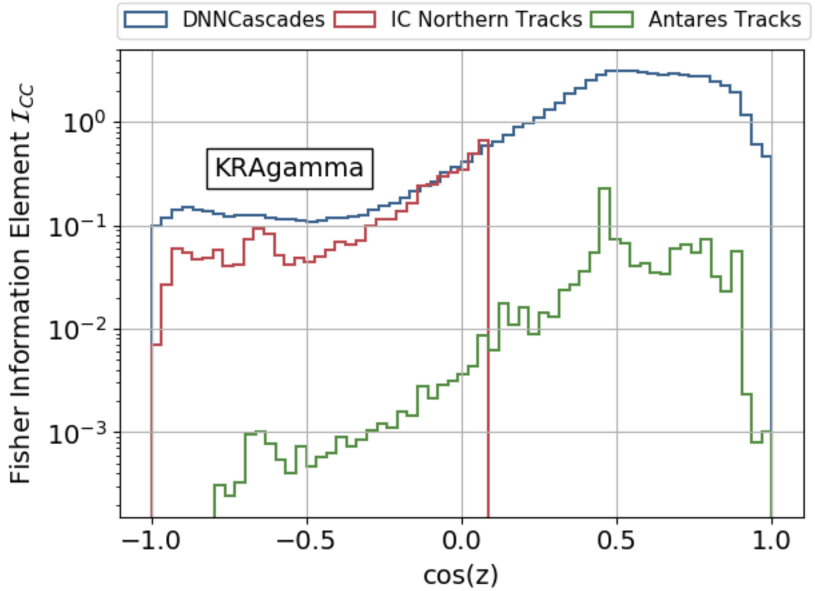
$$\mathcal{I}_{\alpha\beta}(\vec{\theta}) = \sum_{i}^{n_{Ebins}} \sum_{j}^{n_{zbins}} \sum_{k}^{n_{rabins}} \frac{\partial N_{ijk}^{\mathrm{tot}}(\vec{\theta})}{\partial \theta_\alpha} \frac{1}{N_{ijk}^{\mathrm{tot}}(\vec{\theta})} \frac{\partial N_{ijk}^{\mathrm{tot}}(\vec{\theta})}{\partial \theta_\beta}$$

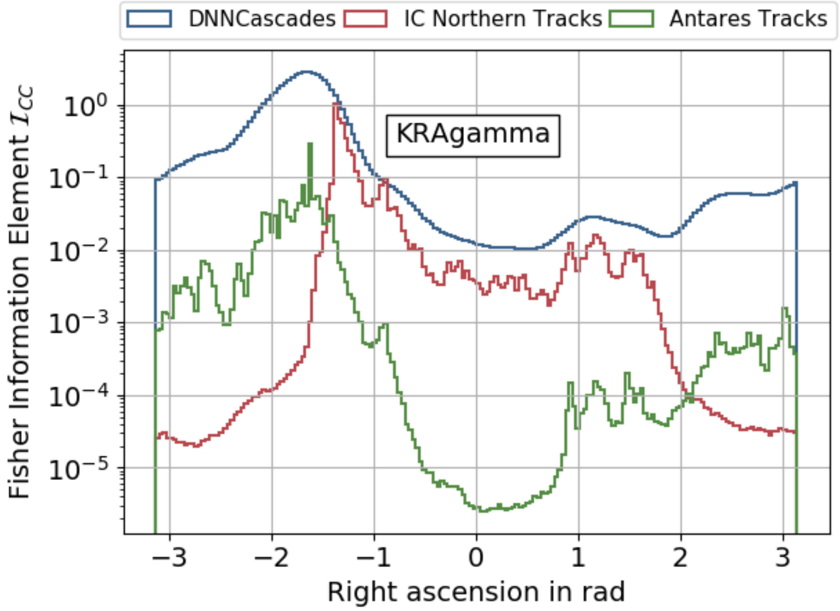
- Independent Analyses: $\mathcal{L}_{tot} = \prod_i \mathcal{L}_i$
- If parameters are the same: $\mathcal{I}_{tot} = \sum_i \mathcal{I}_i$

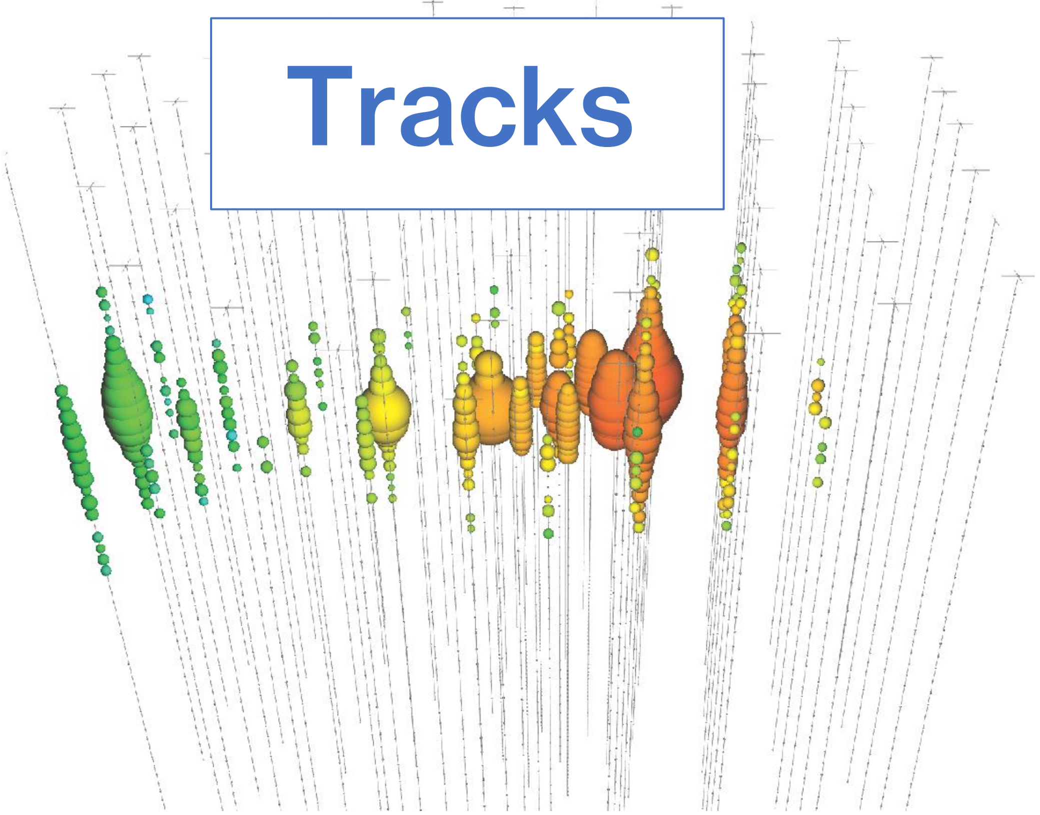
→ Very easy in Fisher Forecasting

→ **10 year IC Tracks + IC Cascades + Antares Tracks & Cascades**

Model	**10yr IC Cascade only**	**10yr All**	**Information Contribution**		
			IC Ccd.	IC Tracks	Antares
KRAgamma	0.132	0.127	92%	6%	2%
Fermi-π^0	1.12	1.03	87%	12%	1%
Analytic	0.21-0.70	0.20-0.63	82%-92%	6%-16%	1%-2%

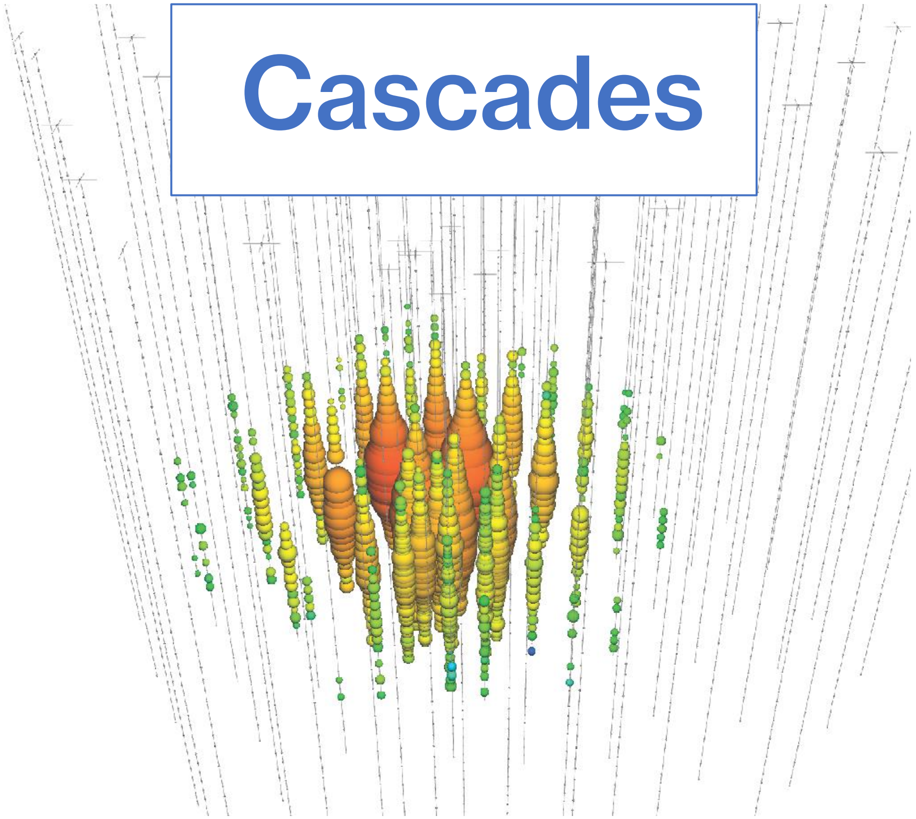






Tracks

- Charged-current $\nu_\mu/\bar{\nu}_\mu$ interactions
- Large statistics, high background
- Only for $z \geq 90°$
- Poor energy resolution
- Good angular resolution < 1°



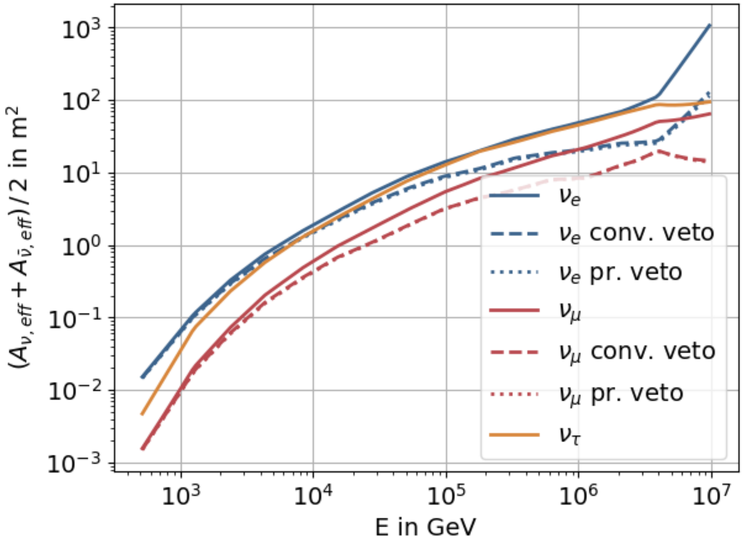
Cascades

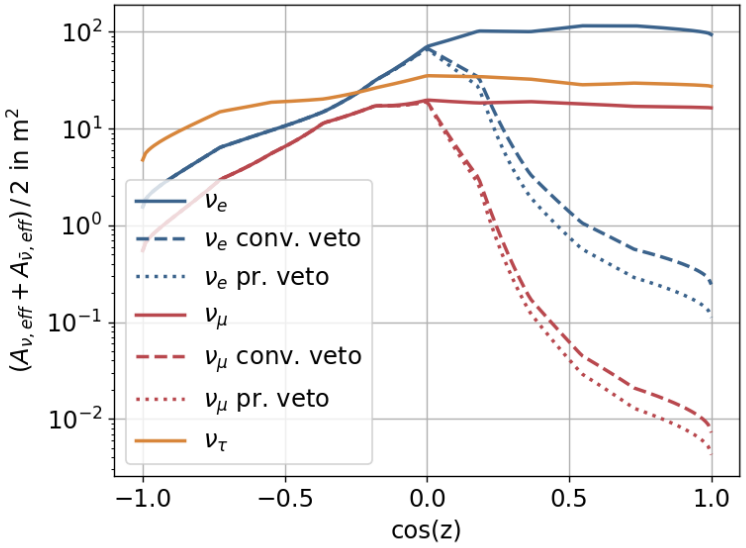
- Interactions of all flavours
- Fewer events, lower background
- All-sky
- Good energy resolution
- Poor angular resolution O(10°)

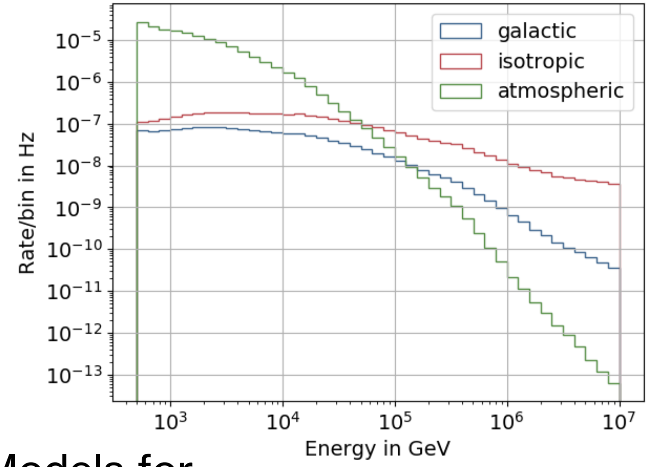
Getting Rate Predictions: Cascades

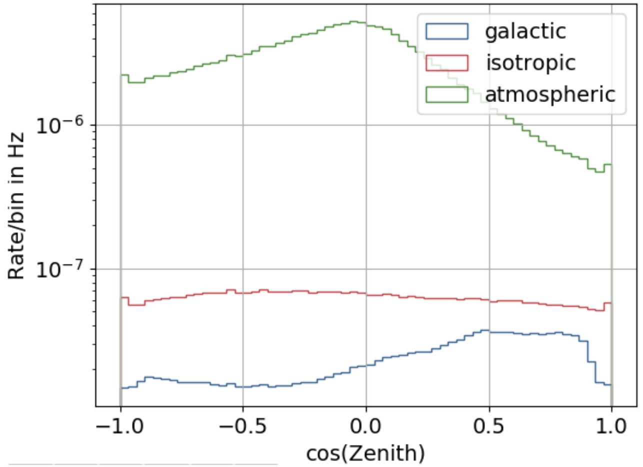
Same principle, but…

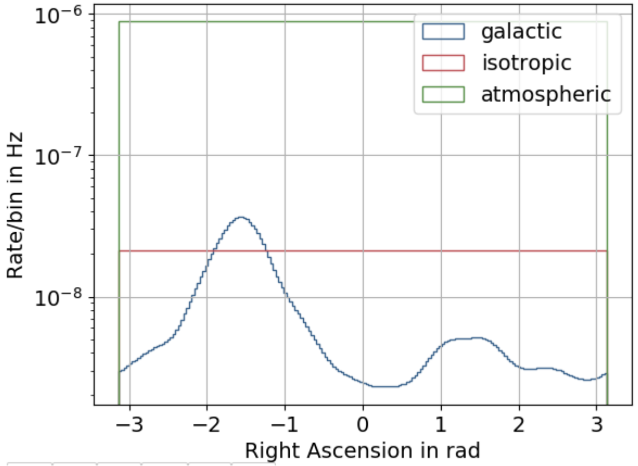
- 3 flavours
- Atmospheric self-veto:
  Atm. neutrinos not selected
  when coincident muon is present







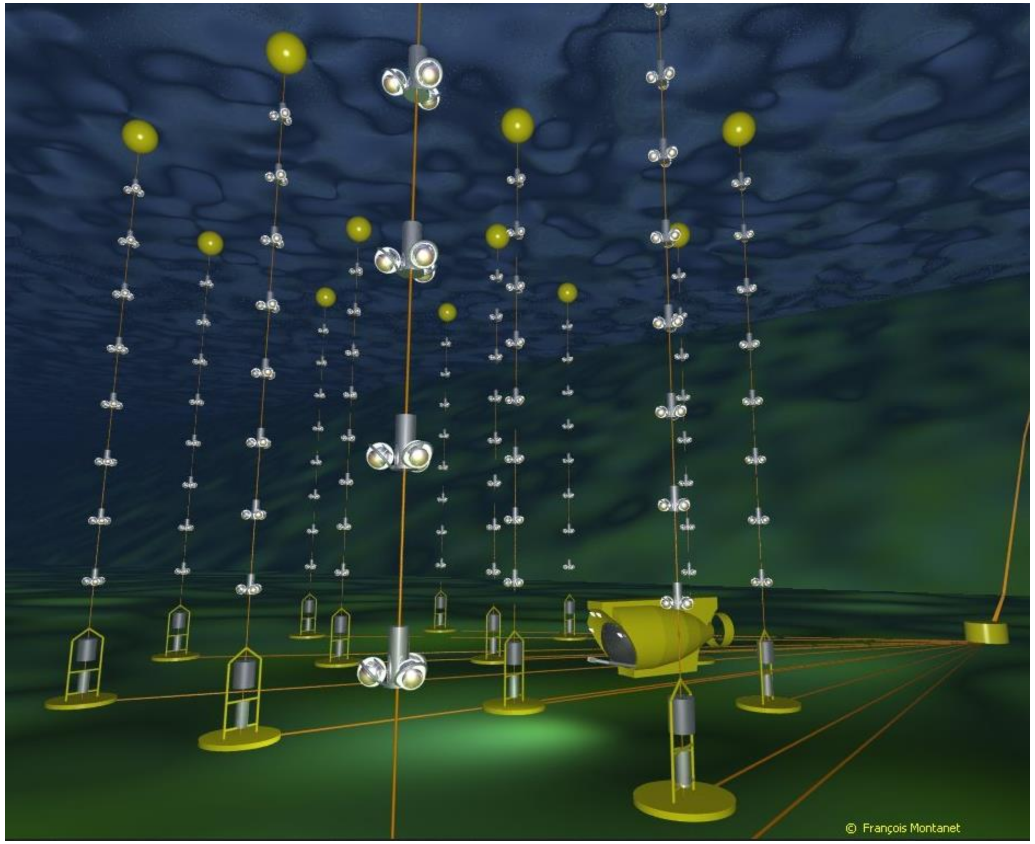


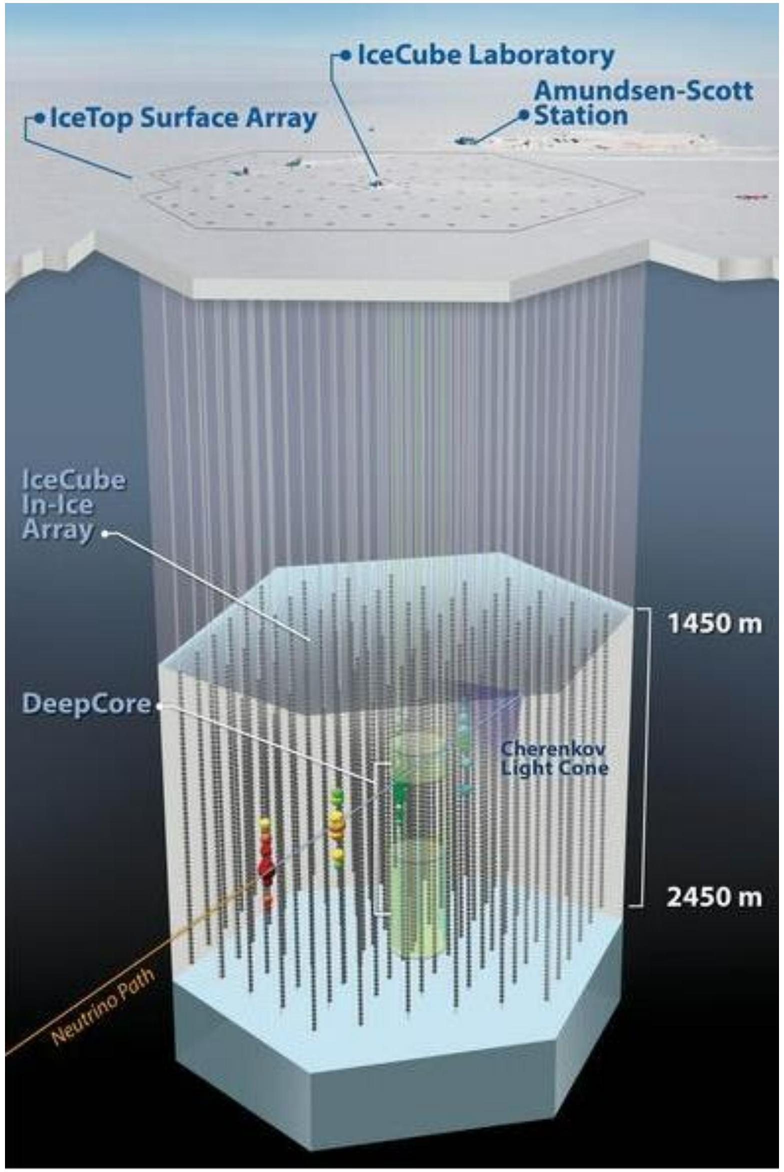


IceCube & Antares

Location: South Pole
Instrumented Volume: O($1\ km^2$)

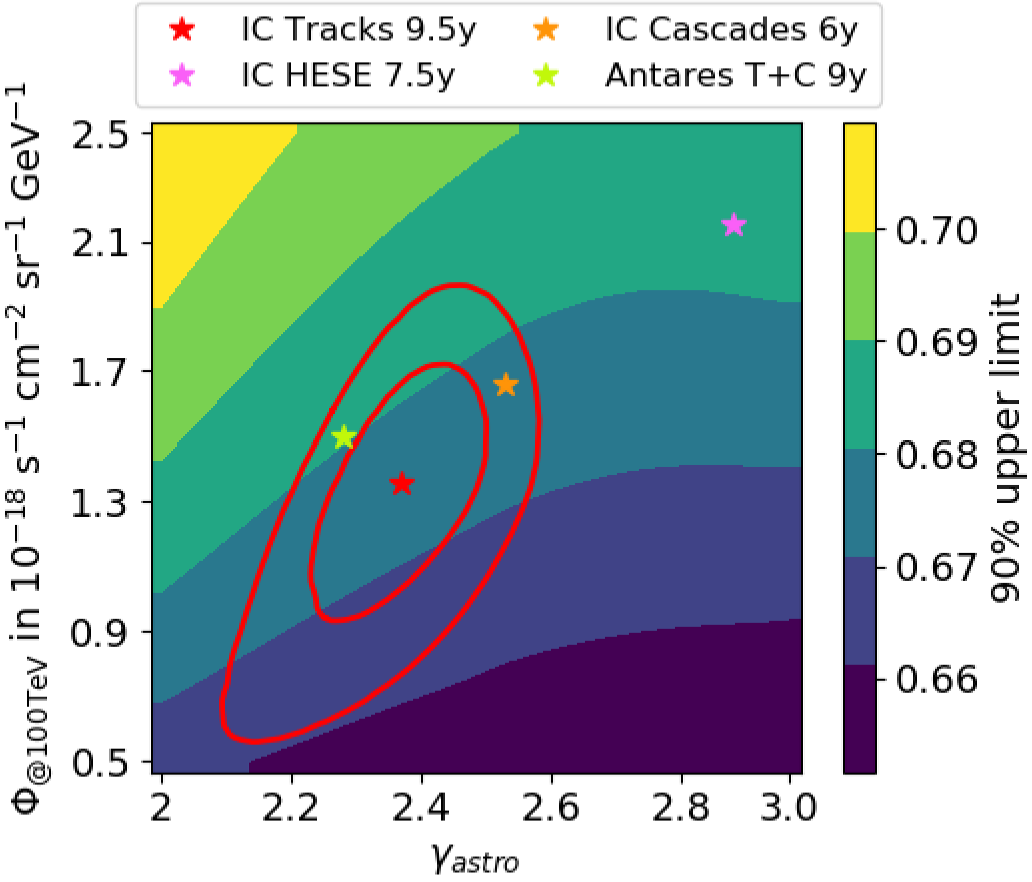
Location: Mediterranean, of the coast of Toulon
Instrumented Volume: O($0.03\ km^2$)



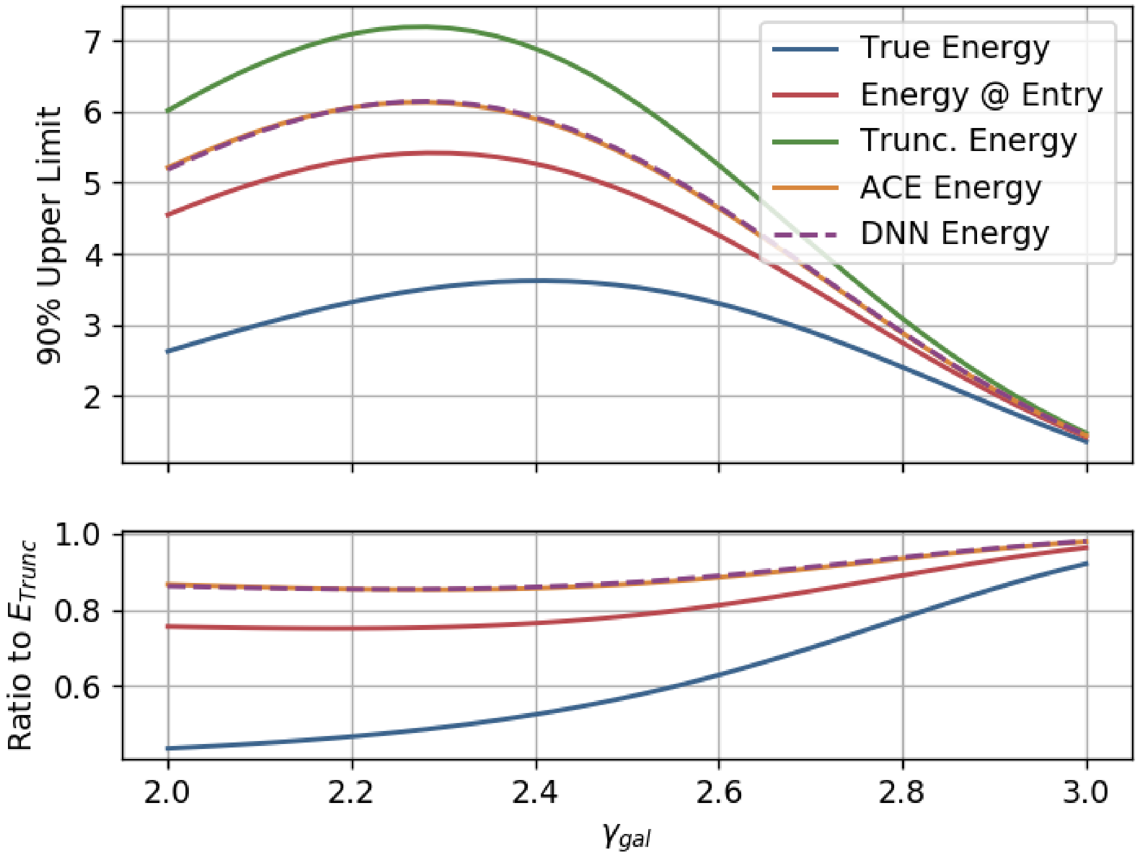


Fisher Forecasting Parameter Study

Uncertainty of isotropic flux



Fermi-pi0: Different energy estimators



Diffusion scenarios

Modelled through diffusion tensor κ

$$\frac{\partial \psi}{\partial t} = \nabla \cdot \left(\kappa \cdot \nabla \psi \right)$$

Basic Scenario:

- Isotropic: $\kappa_{ij}(\vec{r}, p) = \kappa(\vec{r}, p)\delta_{ij}$
- Spatially constant: $\kappa(\vec{r}, p) = \kappa(p)$
- Single Powerlaw: $\kappa(p) = \kappa_0 \left(\frac{p}{p_0} \right)^{\delta}$

Possible Extensions:

- Anisotropy:
  → Diffusion ⊥B different from ∥B
  → Complex magnetic field structure
- Spectral breaks:
  → Breaks in nuclear spectra
  → Different turbulence regimes
- Spatial variation
  → Different turbulence regimes
  → Disk vs. Halo

➢ **Connection to Cosmic Ray Theory: Probe Fundamental Physics**

Covariance matrix

Directly from inverting Fisher Matrix

$$\mathrm{cov}\left[\hat{\theta}_i, \hat{\theta}_j\right] \equiv \langle (\hat{\theta}_i - \theta_i)(\hat{\theta}_j - \theta_j) \rangle_{\mathcal{D}(\boldsymbol{\theta})} \geq (\mathcal{I}(\hat{\boldsymbol{\theta}})^{-1})_{ij}$$

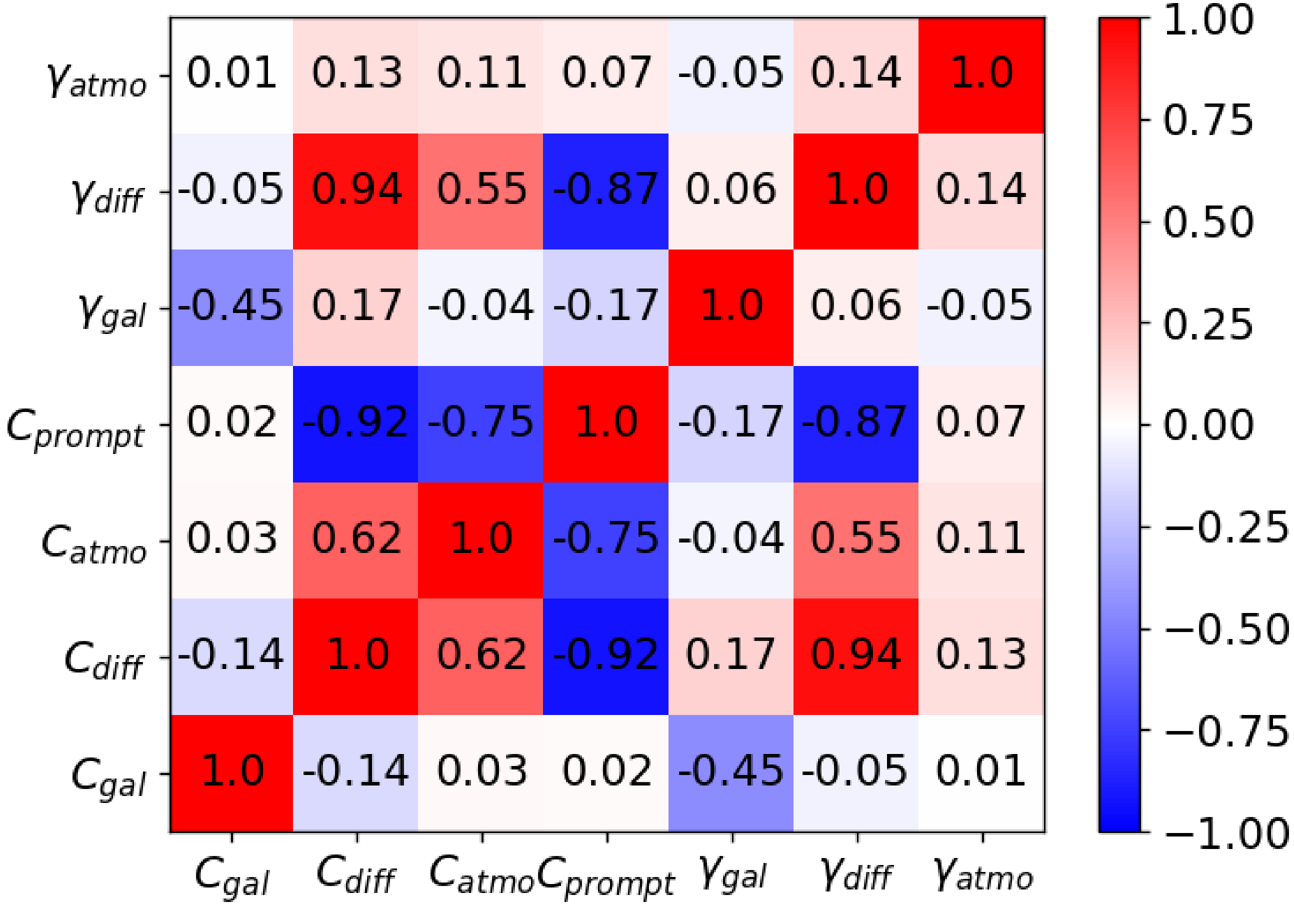
Parameters:

- Component Normalizations
- Spectral index variations

Fixed for each value

True Variable:
Adds dimension to Fisher Matrix

Fermi-π^0 correlations



	C_{gal}	C_{diff}	C_{atmo}	C_{prompt}	γ_{gal}	γ_{diff}	γ_{atmo}
γ_{atmo}	0.01	0.13	0.11	0.07	-0.05	0.14	1.0
γ_{diff}	-0.05	0.94	0.55	-0.87	0.06	1.0	0.14
γ_{gal}	-0.45	0.17	-0.04	-0.17	1.0	0.06	-0.05
C_{prompt}	0.02	-0.92	-0.75	1.0	-0.17	-0.87	0.07
C_{atmo}	0.03	0.62	1.0	-0.75	-0.04	0.55	0.11
C_{diff}	-0.14	1.0	0.62	-0.92	0.17	0.94	0.13
C_{gal}	1.0	-0.14	0.03	0.02	-0.45	-0.05	0.01

$$\mathcal{I}_{\alpha\beta}(\vec{\theta}) = \sum_{i}^{n_{Ebins}} \sum_{j}^{n_{zbins}} \sum_{k}^{n_{rabins}} \frac{\partial N^{\mathrm{tot}}_{ijk}(\vec{\theta})}{\partial \theta_\alpha} \frac{1}{N^{\mathrm{tot}}_{ijk}(\vec{\theta})} \frac{\partial N^{\mathrm{tot}}_{ijk}(\vec{\theta})}{\partial \theta_\beta}$$

The Basic Ingredients

$$\underbrace{I_{\nu/\gamma}(E_{\nu/\gamma}, l, b)}_{\text{Flux in a given direction}} = \underbrace{\frac{c}{4\pi}\int_{l,b} ds}_{\text{Line-of-Sight Integral}} \; \underbrace{n_{gas}(\vec{x})}_{\text{Gas density maps}} \int dE_p \; \underbrace{n_{CR}(E_p, \vec{x})}_{\text{Galactic Cosmic Ray Distribution}} \; \underbrace{\frac{d\sigma(E_p, E_{\gamma/\nu})}{dE_{\nu/\gamma}}}_{\text{Production Cross Section}}$$

3 Main Inputs

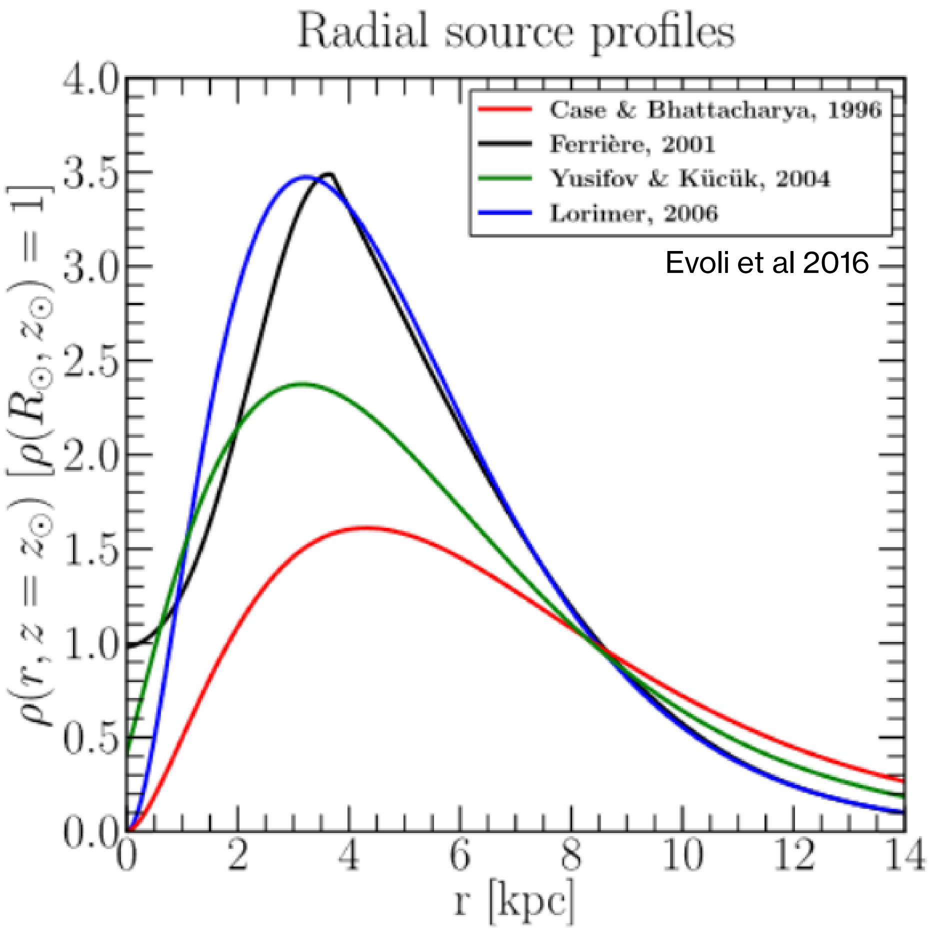
The Basic Ingredients

$$\underbrace{I_{\nu/\gamma}(E_{\nu/\gamma}, l, b)}_{\text{Flux in a given direction}} = \underbrace{\frac{c}{4\pi}\int_{l,b} ds}_{\text{Line-of-Sight Integral}} \; \underbrace{n_{gas}(\vec{x})}_{\text{Gas density maps}} \int dE_p \; \underbrace{n_{CR}(E_p, \vec{x})}_{\text{Galactic Cosmic Ray Distribution}} \; \underbrace{\frac{d\sigma(E_p, E_{\gamma/\nu})}{dE_{\nu/\gamma}}}_{\text{Production Cross Section}}$$

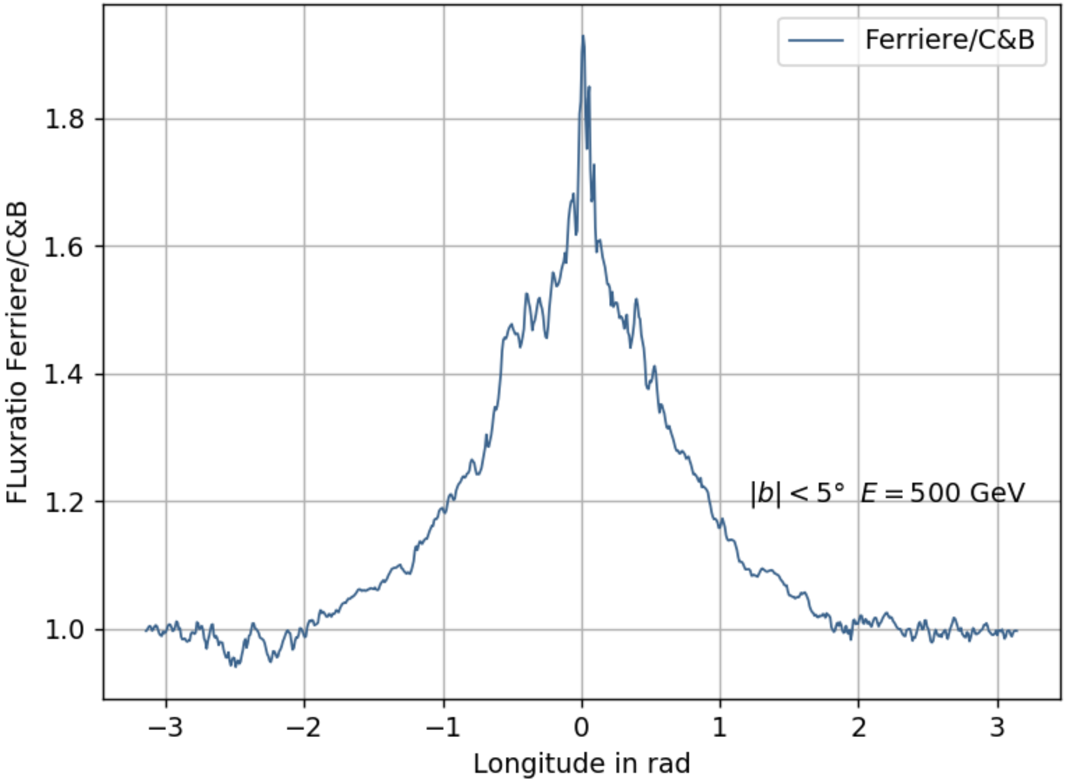
3 Main Inputs

Source distribution and spectra

Assumed sources: Smooth distribution of SNRs



Evoli et al 2016

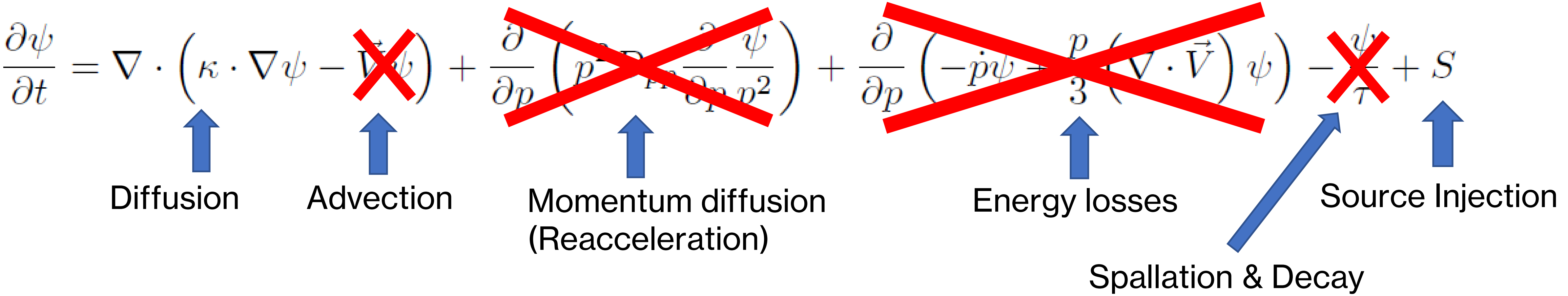


What happens towards the knee?

- Maximum energy of galactic cosmic rays?
- A second poplulation of sources?
- Are individual sources dominant?

Galactic Cosmic Rays

Evolution of Cosmic Ray Spectral density



$$\frac{\partial \psi}{\partial t} = \nabla \cdot \left(\kappa \cdot \nabla \psi - \cancel{\vec{V}\psi}\right) + \frac{\partial}{\partial p}\cancel{\left(p^2 D_{pp} \frac{\partial}{\partial p} \frac{\psi}{p^2}\right)} + \frac{\partial}{\partial p}\cancel{\left(-\dot{p}\psi - \frac{p}{3}\left(\vec{\nabla} \cdot \vec{V}\right)\psi\right)} - \cancel{\frac{\psi}{\tau}} + S$$

Relevant Species for diffuse emission: Proton and Helium

Numerical tools: Finite Difference Codes like GALPROP, DRAGON

Models under Consideration I: Fermi-π^0

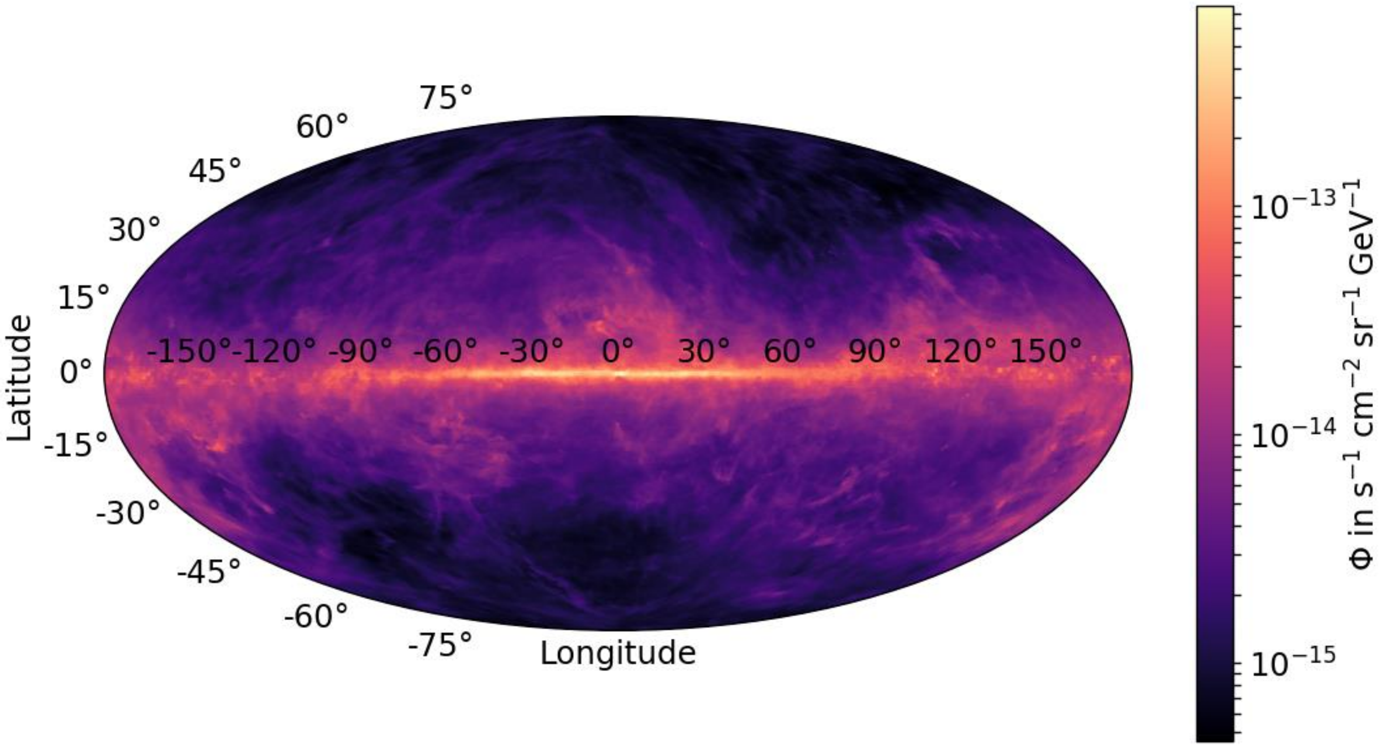
- Same spectrum in entire galaxy
- Conservative

Reproduce from first principles:

Gamma Ray Prediction

- *GALPROP*
- All parameters known

Transform to ν_μ flux prediction

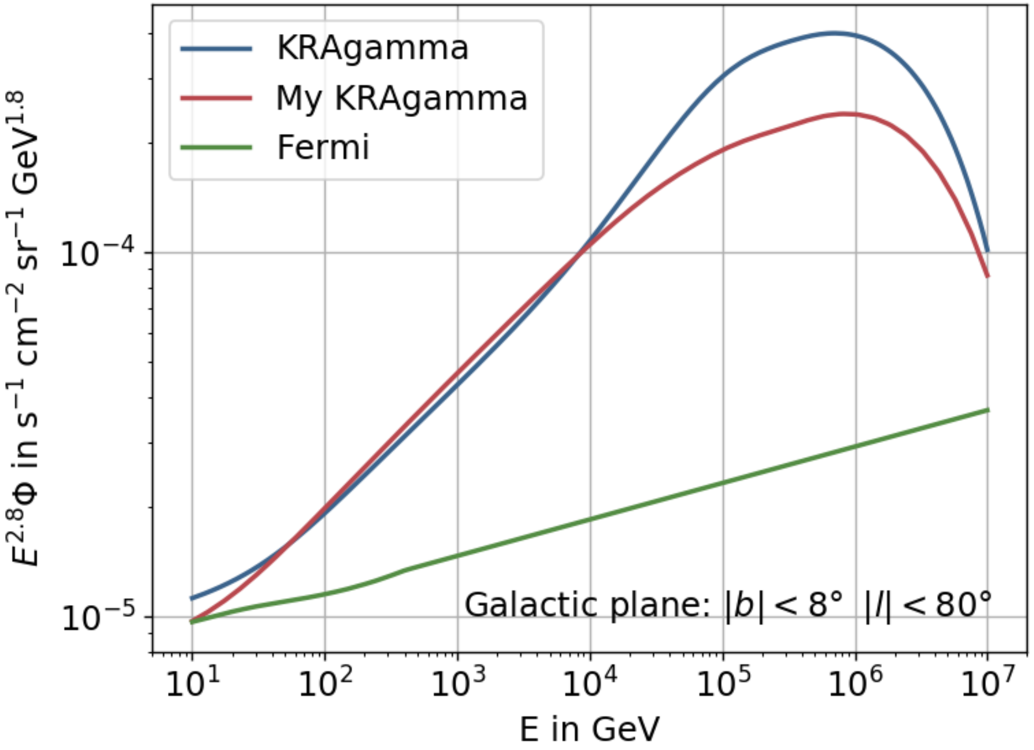


- Flux norm: $\Phi^{\nu_\mu+\bar{\nu}_\mu}_{@100\,\mathrm{TeV}} = 4.5 \cdot 10^{-19}\ \mathrm{GeV}^{-1}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$
- Christian‘s norm: $\Phi^{\nu_\mu+\bar{\nu}_\mu}_{@100\,\mathrm{TeV}} = 31.6 \cdot 10^{-19}\ \mathrm{GeV}^{-1}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ → Arbitrarily chosen norm

Expected **90% upper limit** for **6 years** of **northern tracks** (Christian‘s lifetime): **390%** of prediction

Models under Consideration II: KRAγ

- Spectral hardening towards galactic center
- Optimistic



Reproduce from first principles:

Cosmic Ray Model

- Modified *DRAGON* (radius-dependent diffusion)
- Some unknown parameters

⬇

Line-of-sight integration using *HERMES* tool

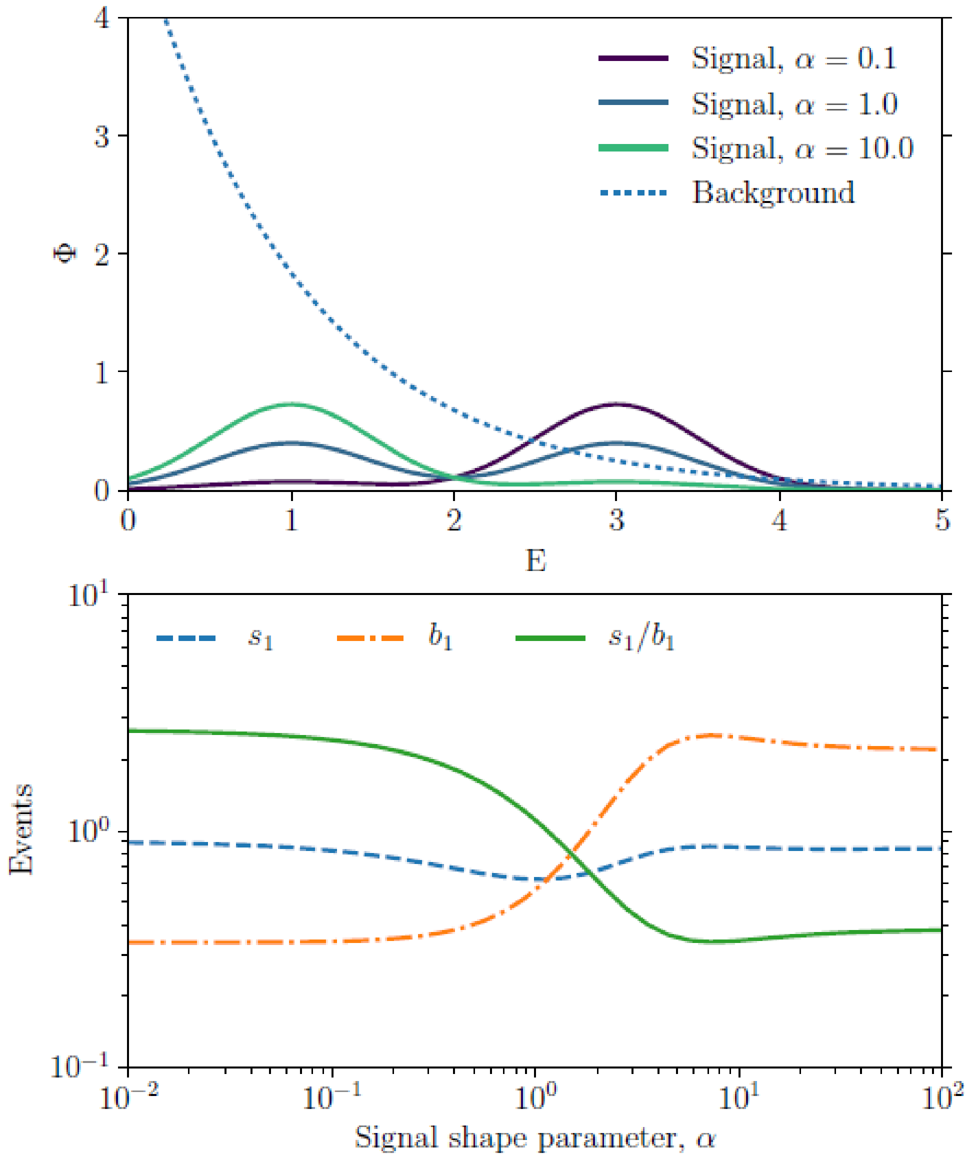
Expected **90% upper limit** for **6 years** of **northern tracks** (Christian's lifetime): **90%** of prediction

Next:

- Modifications of KRAγ scenario
- Explaining Tibet ASγ & LHAASO diffuse flux measurements

Equivalent counts toy example

Taken from Fisher Forecasting Paper:
https://arxiv.org/abs/1704.05458



Diffusion scenarios

Basic Scenario:

- Isotropic: $\kappa_{ij}(\vec{r},p) = \kappa(\vec{r},p)\delta_{ij}$
- Spatially constant: $\kappa(\vec{r},p) = \kappa(p)$
- Single Powerlaw: $\kappa(p) = \kappa_0 \left(\frac{p}{p_0}\right)^{\delta}$

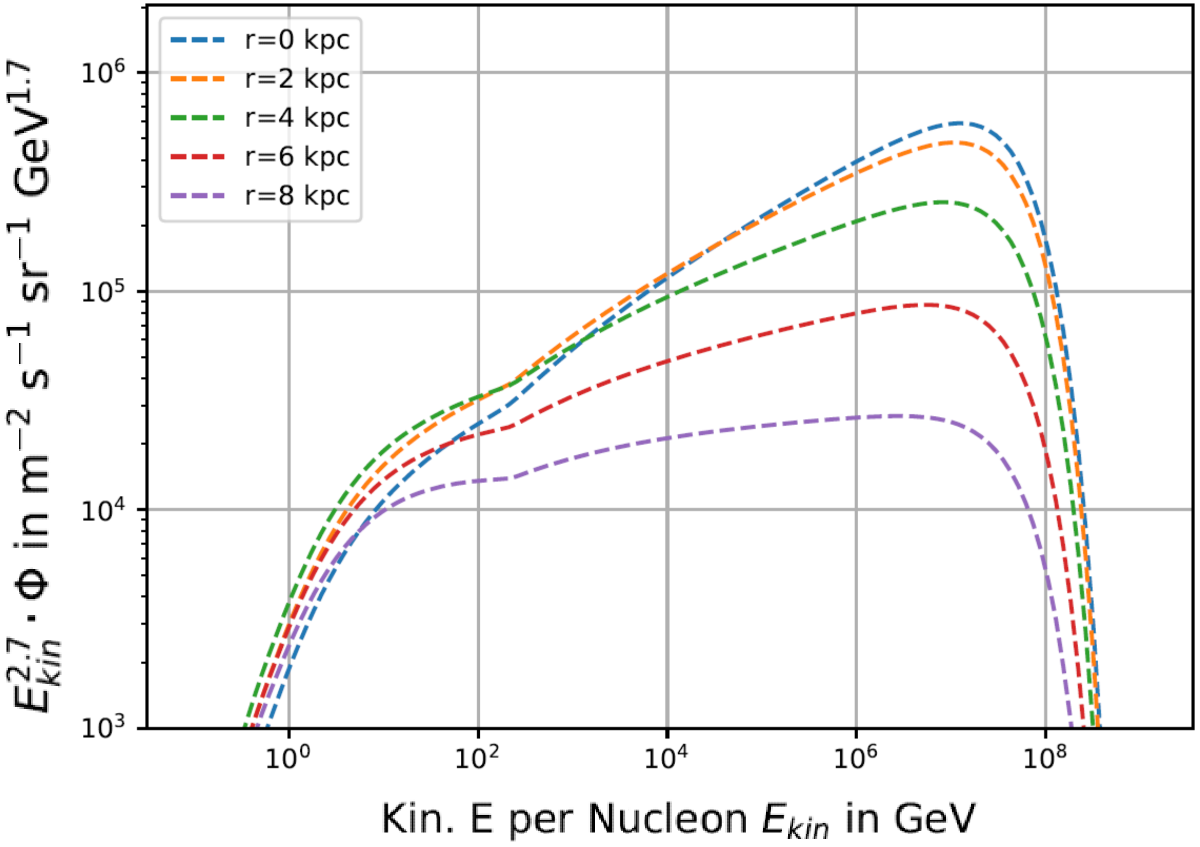
Possible Extensions:

- Anisotropy:
  → Diffusion ⊥B different from ∥B
  → Complex magnetic field structure
- Spectral breaks:
  → Breaks in nuclear spectra
  → Different turbulence regimes
- Spatial variation
  → Different turbulence regimes
  → Disk vs. Halo

Example for extended scenario: KRAgamma (Gaggero et al. 2015)

$$\delta(R) = A\,R + B \Longrightarrow \gamma(R) \approx \gamma_0 + \delta(R)$$

Proton spectra at different galactic radii



The Basic Ingredients II: Line-of-Sight Integration

1. Gamma-ray emissivity
- Cosmic ray distribution
- Production cross section

$$\epsilon_E(E_\gamma, \mathbf{r}) = 4\pi\, n_{\mathrm{H}}(\mathbf{r}) \int \mathrm{d}E \left[\Phi_{\mathrm{H}}(E, \mathbf{r}) \left(\frac{\mathrm{d}\sigma_{\mathrm{p-p}}}{\mathrm{d}E_\gamma} + f_{\mathrm{He}} \frac{\mathrm{d}\sigma_{\mathrm{He-p}}}{\mathrm{d}E} \right) + \Phi_{\mathrm{He}}(E, \mathbf{r}) \left(\frac{\mathrm{d}\sigma_{\mathrm{p-He}}}{\mathrm{d}E_\gamma} + f_{\mathrm{He}} \frac{}{\mathrm{d}E_\gamma} \right) \right] \quad (19)$$

2. Line-of-sight integral
- Multiple galactocentric rings

$$\langle \epsilon_E(\mathbf{r}, E_\gamma) \rangle^i = \frac{\int_0^\infty \mathrm{d}s\, \epsilon_E(E_\gamma, \mathbf{r}) p_{\mathrm{HI}}(\mathbf{r}) \Theta^i_{\mathrm{in}}(\mathbf{r})}{\int_0^\infty \mathrm{d}s\, p_{\mathrm{HI}}(\mathbf{r}) \Theta^i_{\mathrm{in}}(\mathbf{r})}$$

3. Renormalization in every ring
- Galactic gas maps

$$I_\gamma(l, b, E_\gamma) = \frac{1}{4\pi} \sum_i N^i_{\mathrm{H}}(l, b) \langle \epsilon_E(\mathbf{r}, E_\gamma) \rangle^i$$

➢ **Numerical Tools:** GALPROP, HERMES

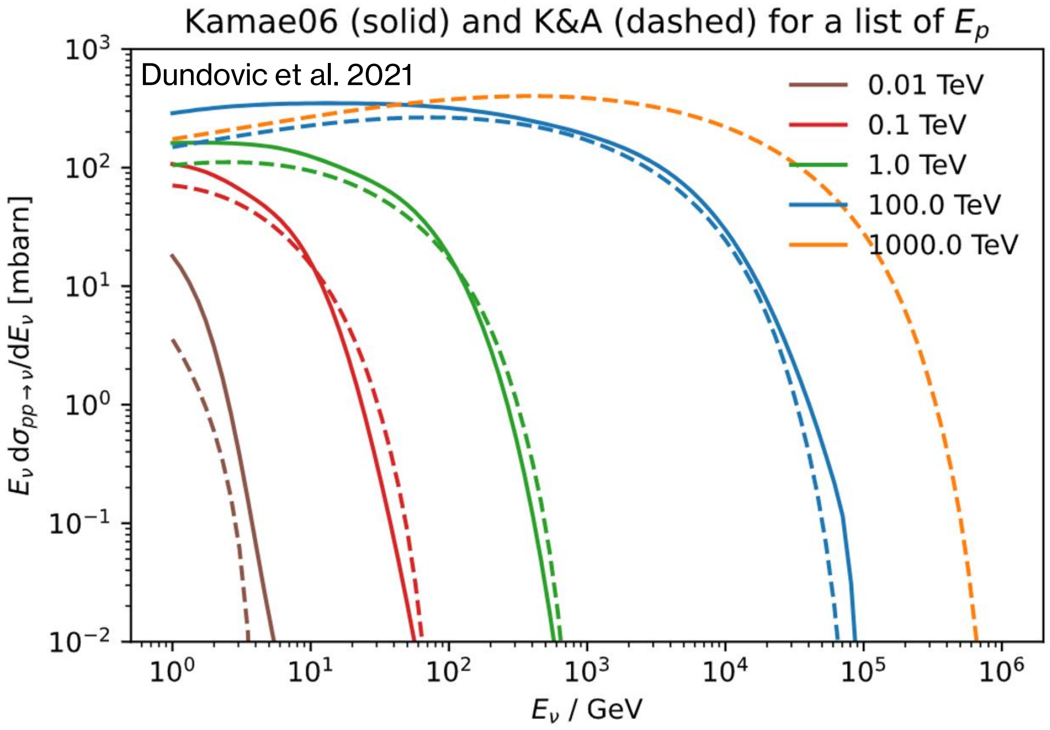
Production Cross Sections

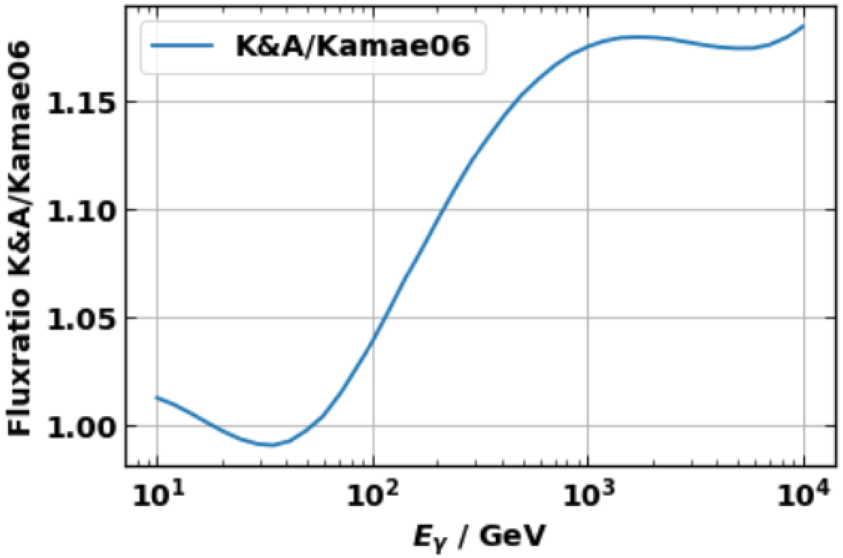
Rules of thumb:

$E_\gamma \approx 0.1\ E_p$
$E_\nu \approx 0.05\ E_p$
$\gamma_{\gamma/\nu} \approx \gamma_{CR}$

More precisely: Analytic parametrizations based on hadronic interaction models

- Kamae et al.: Based on PYTHIA 6.2
- Kelner & Aharonian: Based on SIBYLL





Hydrogen Gas Maps

Atomic Hydrogen HI

- 21 cm hyperfinestructure transition
- For column densities:
  Assumption on spin temperature/optical depth

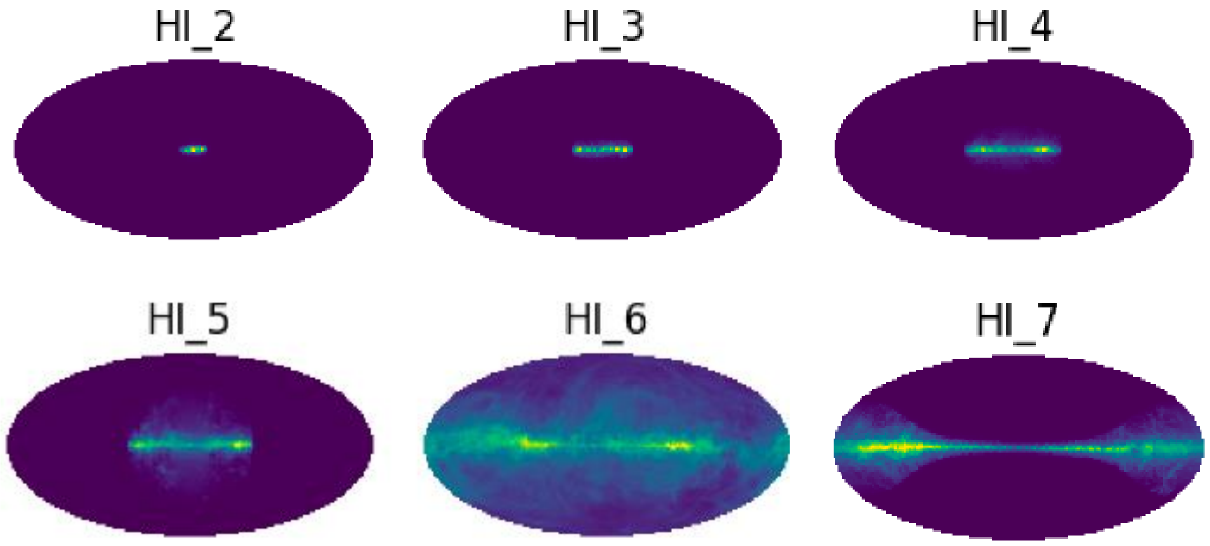
Molecular Hydrogen H_2

- Very relevant in inner galaxy
- H_2 does not emit → Use CO as a tracer
- Poorly constrained (variable) conversion factor X_{CO}

3D Deconvolvement in Galactocentric rings

- Measure Doppler shift of emission
- Assume galactic rotation curve

$$v_{\mathrm{LSR}} = R_\odot \left(\frac{V(R)}{R} - \frac{V_\odot}{R_\odot} \right) \sin(l) \cos(b)$$



Local ring

Fermi-LAT coll. 2019

Existing Baselines

➢ Fermi-π^0

- Developed to fit Fermi-LAT data
- Local properties apply throughout entire galaxy
- Single powerlaw spectrum with $\gamma = 2.72$
- Conservative

➢ KRAgamma

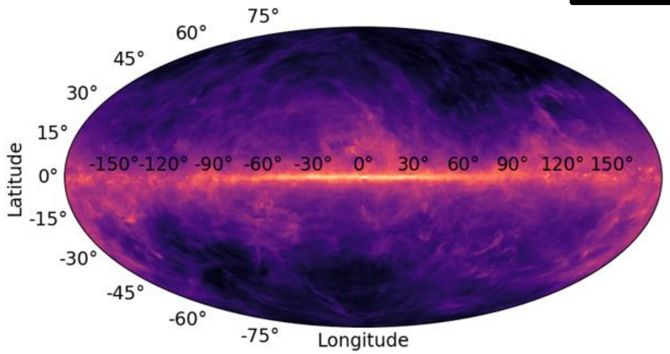
- Spectral hardening towards galactic center

$$\kappa(p) = \kappa_0 \left(\frac{p}{p_0}\right)^{\delta}$$

$$\delta(R) = A\,R + B \Longrightarrow \gamma(R) \approx \gamma_0 + \delta(R)$$

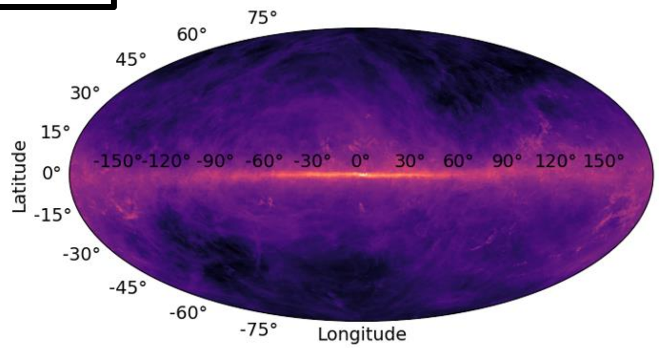
- Very optimistic

Fermi-π^0

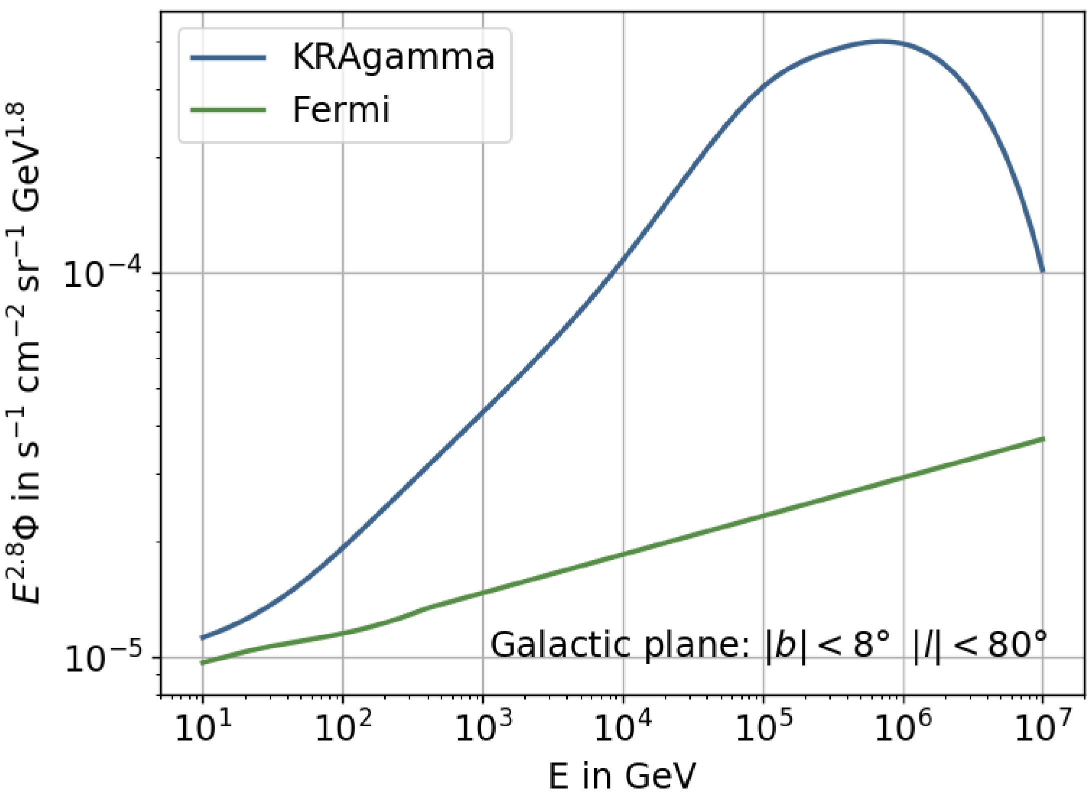


@ 1 TeV

KRAgamma



Muon-Neutrino Spectra from Inner Galaxy



Equivalent Counts Method

$$\boxed{Z(\alpha) = F_{\mathcal{N}}^{-1}(1-\alpha)}$$

Define:

- **Equivalent Signal counts**

$$s_i(\boldsymbol{\theta}) = \frac{\theta_i^2}{\sigma_i^2(\boldsymbol{\theta}) - \sigma_i^2(\boldsymbol{\theta}_0)}$$

- **Equivalent Background counts**

$$b_i(\boldsymbol{\theta}) = \frac{\theta_i^2 \sigma_i^2(\boldsymbol{\theta}_0)}{(\sigma_i^2(\boldsymbol{\theta}) - \sigma_i^2(\boldsymbol{\theta}_0))^2}$$

with $\boldsymbol{\theta}_0 \equiv (\theta_1, \ldots, \theta_{i-1}, 0, \theta_{i+1}, \ldots, \theta_n)^T$

From equivalent counts:

- **Upper limit:** Solution of $s_1(\boldsymbol{\theta}^U) = Z(\alpha) \cdot \sqrt{s_1(\boldsymbol{\theta}^U) + b_1(\boldsymbol{\theta}^U)}$

  with $\boldsymbol{\theta}^U = (\theta_1^U, \theta_2, \ldots, \theta_n)^T$

- **Discovery reach:** Solution of

$$\left(s_1(\boldsymbol{\theta}^D) + b_1(\boldsymbol{\theta}^D)\right) \ln\left(\frac{s_1(\boldsymbol{\theta}^D) + b_1(\boldsymbol{\theta}^D)}{b_1(\boldsymbol{\theta}^D)}\right) - s_1(\boldsymbol{\theta}^D) = \frac{Z(\alpha)^2}{2}$$

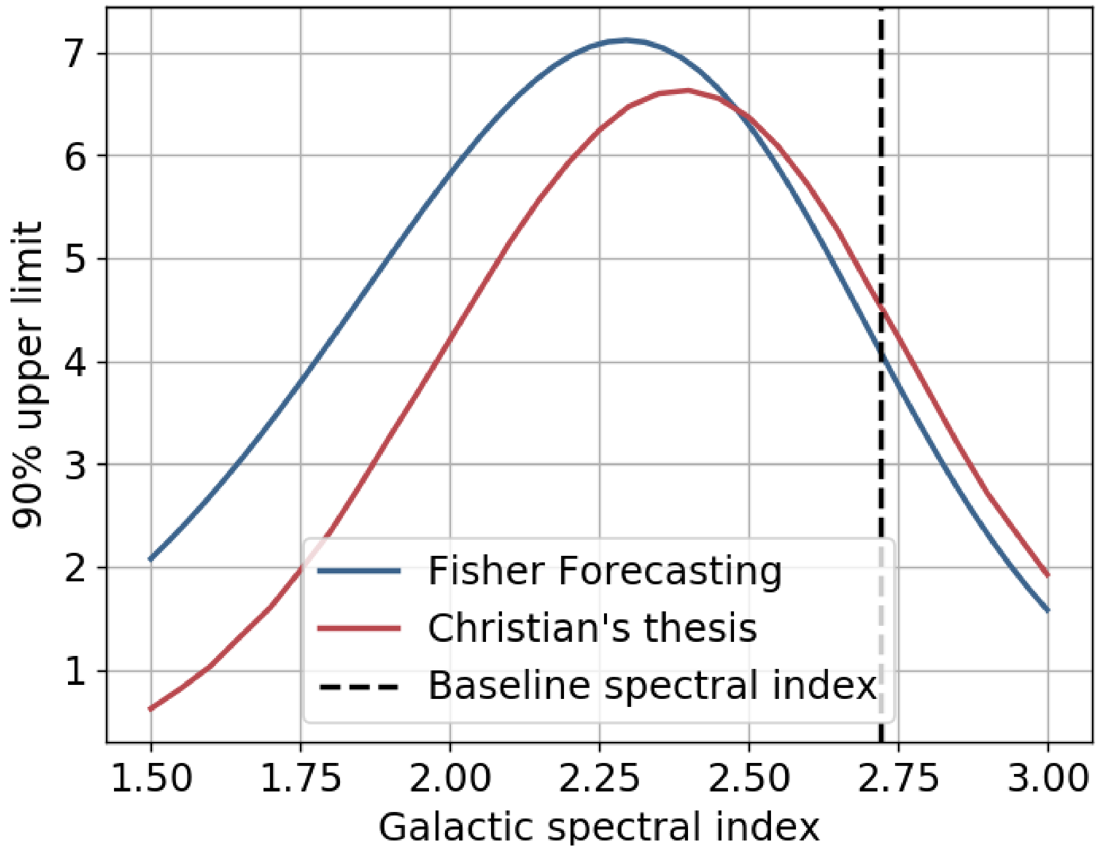
  with $\boldsymbol{\theta}^D = (\theta_1^D, \theta_2, \ldots, \theta_n)^T$

Fisher Forecasting Paper: https://arxiv.org/abs/1704.05458

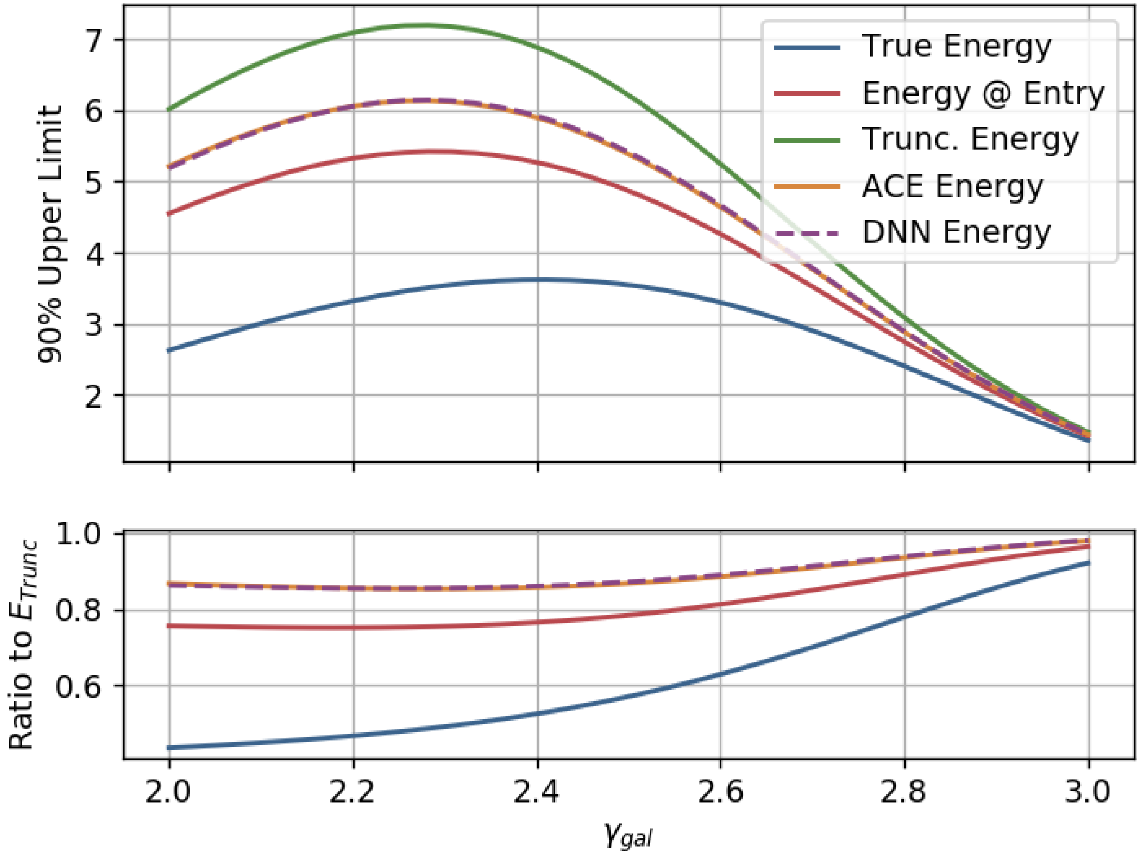
Upper Limits

- Analogous to profile likelihood: Galactic spectral index fixed at each value

Fermi-pi0: Different spectral indices

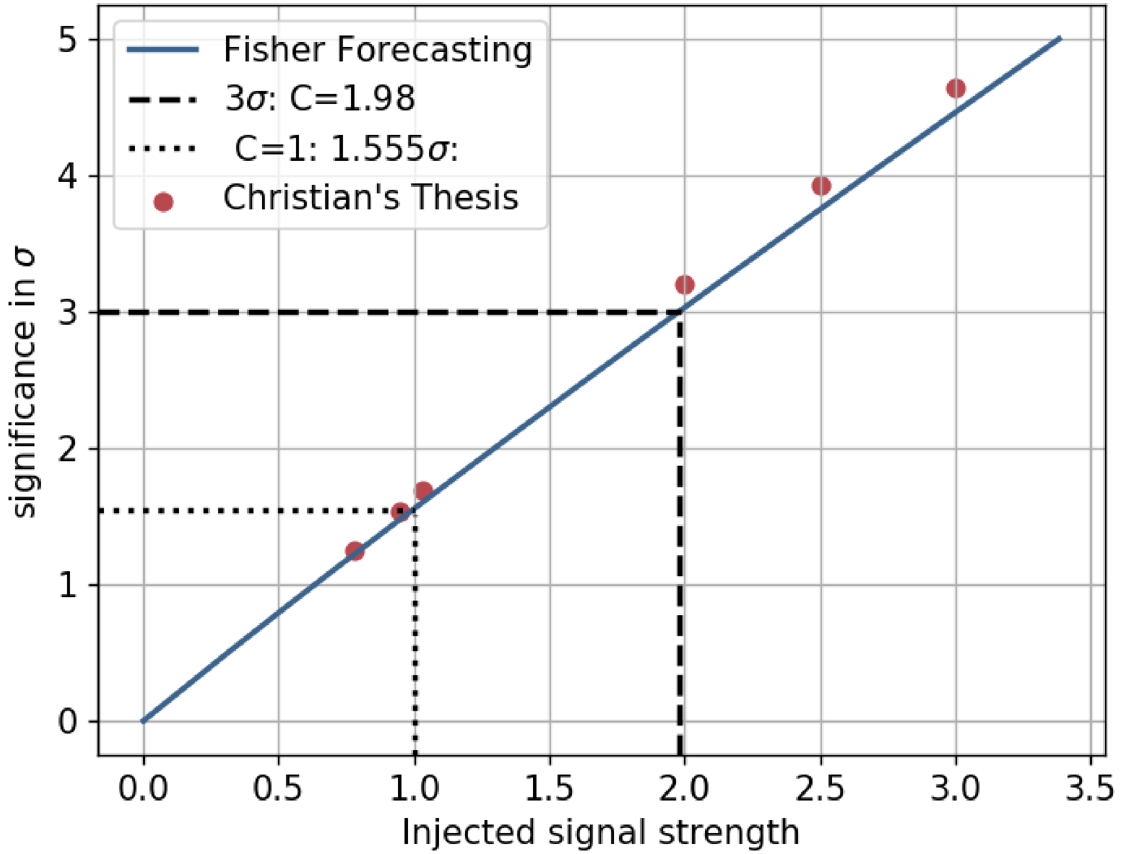


Fermi-pi0: Different energy estimators

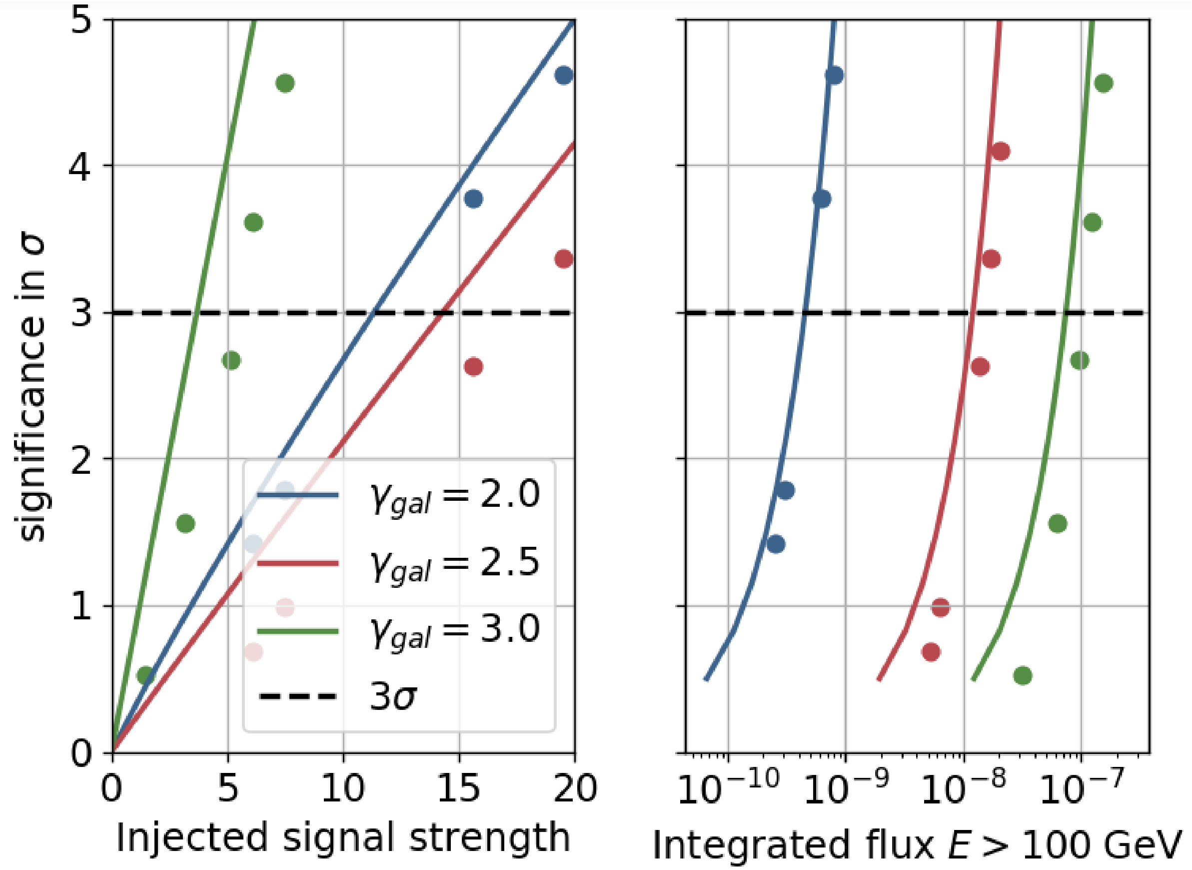


Discovery Reaches

KRAgamma



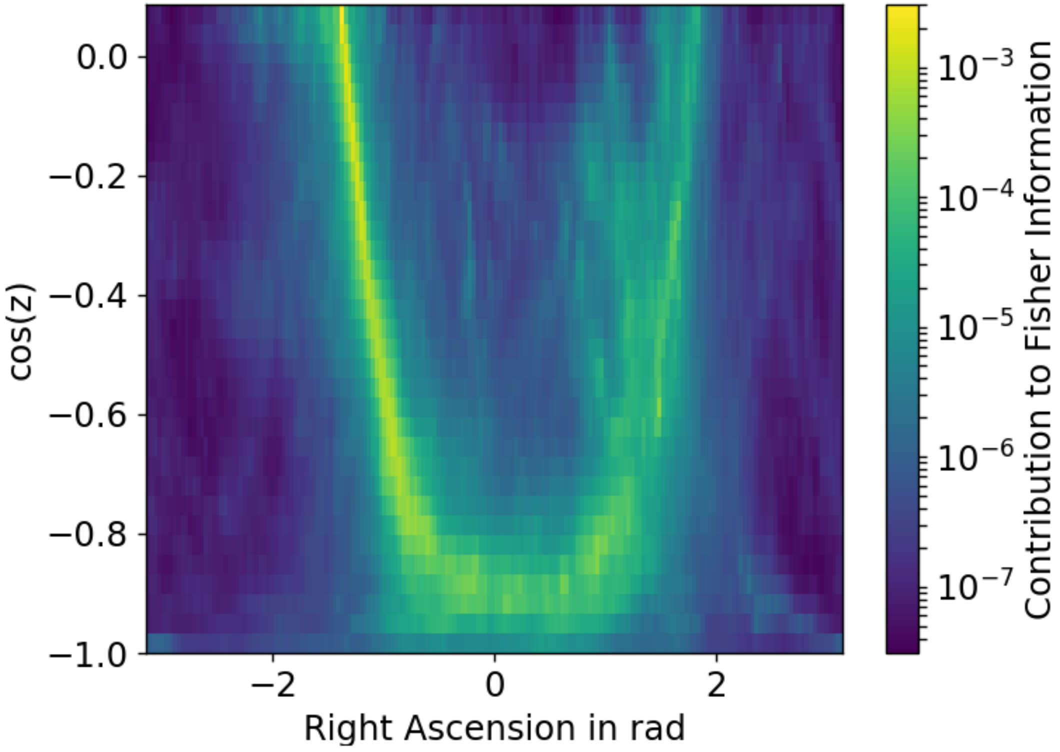
Fermi-pi0



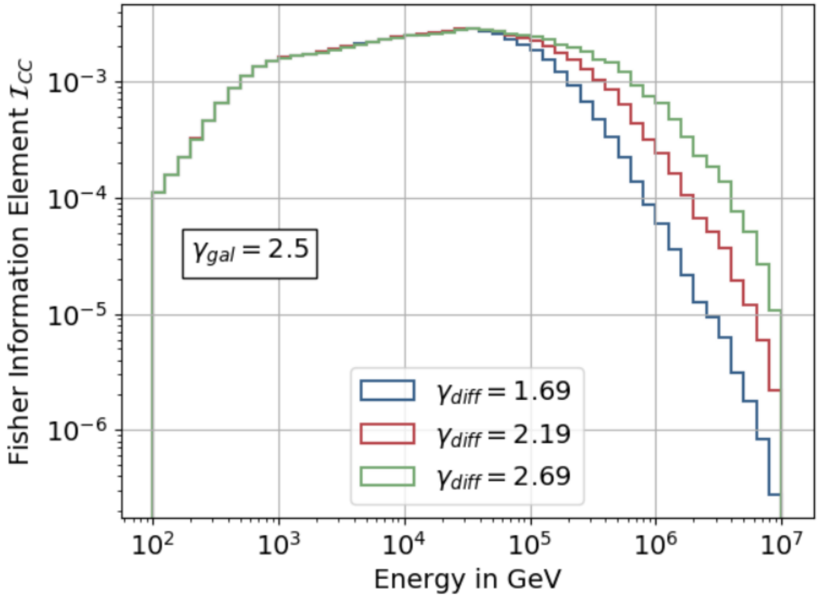
Information maps

$$\mathcal{I}_{\alpha\beta}(\vec{\theta}) = \sum_{i}^{n_{Ebins}} \sum_{j}^{n_{zbins}} \sum_{k}^{n_{rabins}} \frac{\partial N^{\mathrm{tot}}_{ijk}(\vec{\theta})}{\partial \theta_\alpha} \frac{1}{N^{\mathrm{tot}}_{ijk}(\vec{\theta})} \frac{\partial N^{\mathrm{tot}}_{ijk}(\vec{\theta})}{\partial \theta_\beta}$$

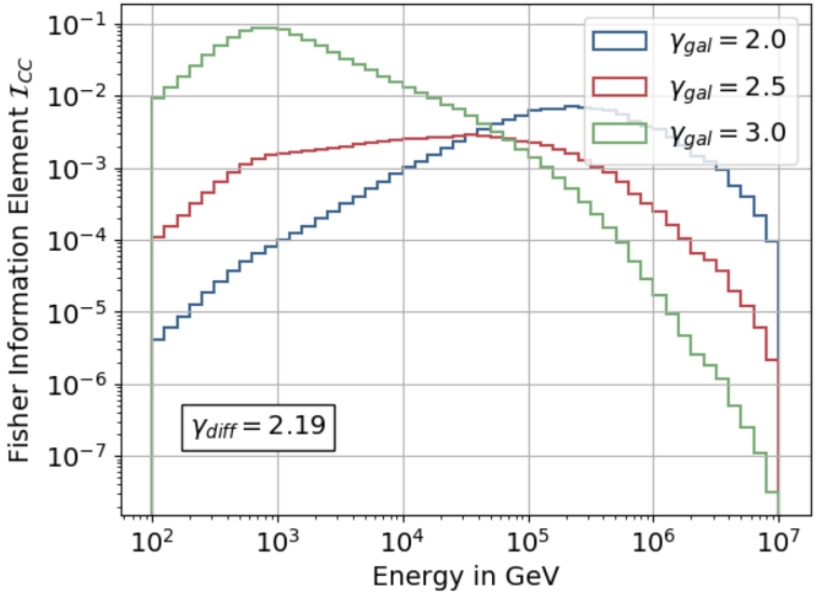
→ Maps of information from each bin



Fixed γ_{gal}, different γ_{diff}



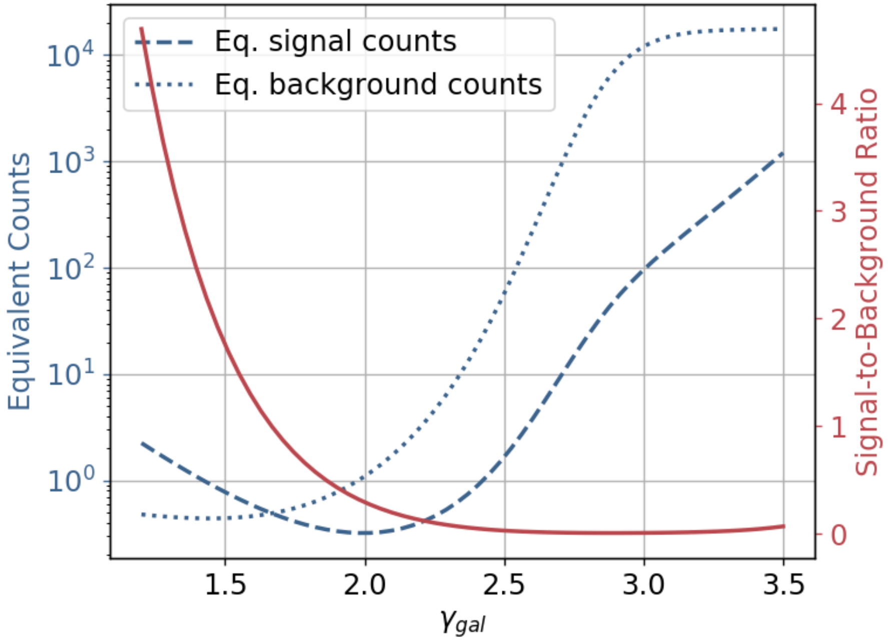
Fixed γ_{diff}, different γ_{gal}



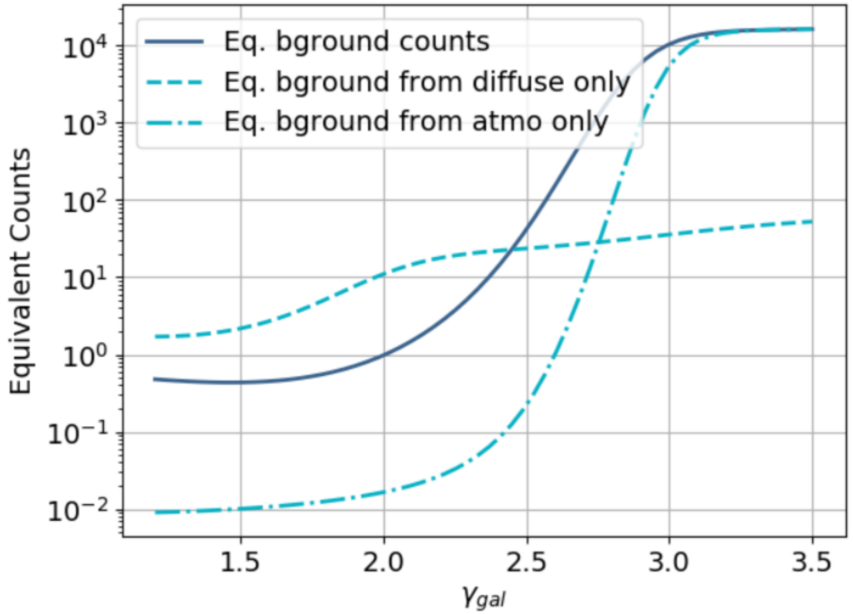
Equivalent Counts

$$s_i(\boldsymbol{\theta}) = \frac{\theta_i^2}{\sigma_i^2(\boldsymbol{\theta}) - \sigma_i^2(\boldsymbol{\theta}_0)}$$

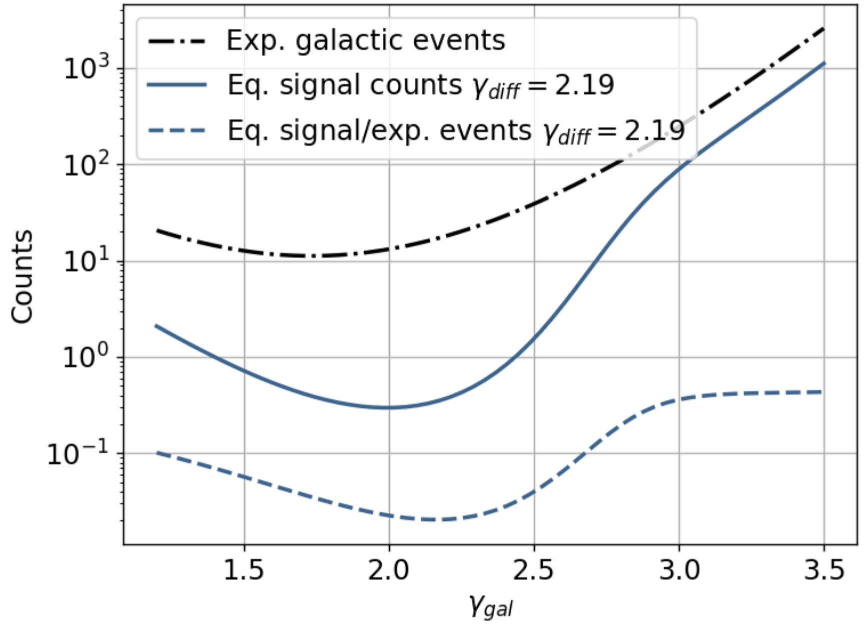
$$b_i(\boldsymbol{\theta}) = \frac{\theta_i^2 \sigma_i^2(\boldsymbol{\theta}_0)}{(\sigma_i^2(\boldsymbol{\theta}) - \sigma_i^2(\boldsymbol{\theta}_0))^2}$$



Fermi-pi0



Single-Component Backgrounds



Eq. Signal/# of events

Interpretation:

- **Background:** Proportional to relevant background
- **Signal:** Fraction of signal carrying the information