

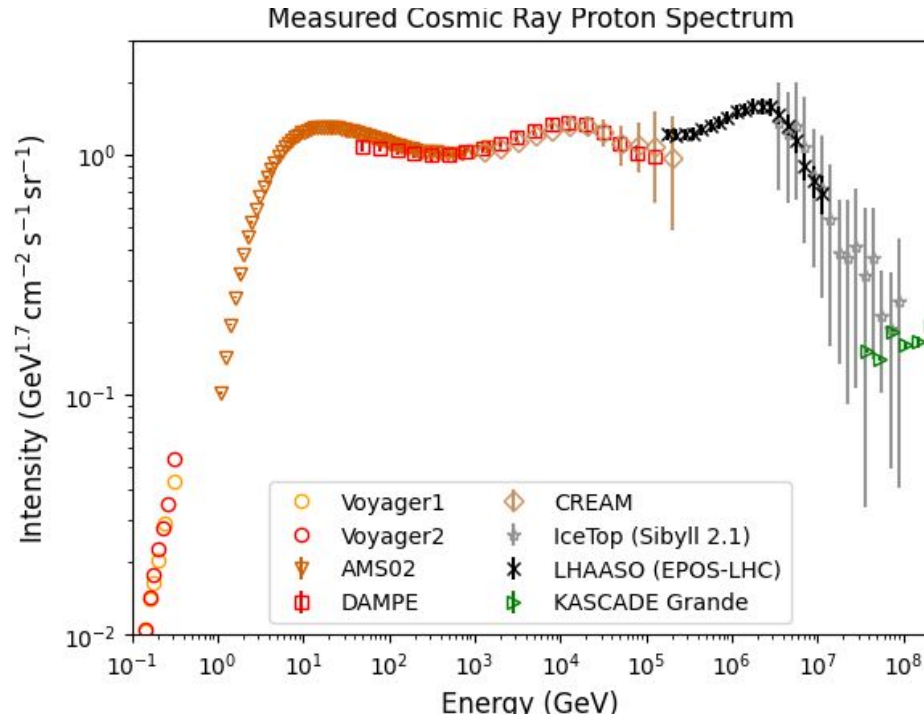
A Case for Microquasars as Galactic PeVatrons

Passage of the Year 2026 - 14/10/2026

Speaker/Candidate:
Loo Chun Khai

Supervisor:
Prof. Pasquale Blasi

Cosmic Ray Protons 'Knee'



LHAASO shows a “**knee**” in pure proton spectrum

Search for galactic PeVatron is still on

Hardening ~ 300 TeV could suggest a **second class** of source

Microquasars (μ QS)

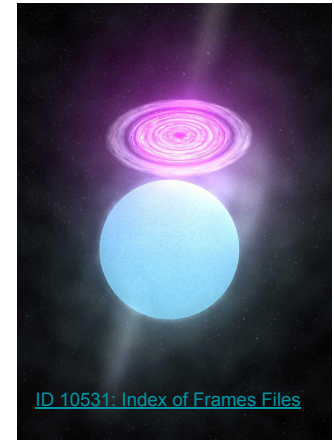
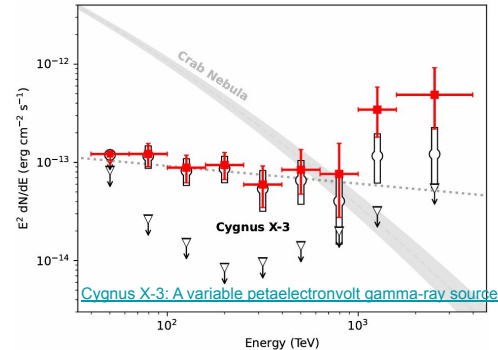
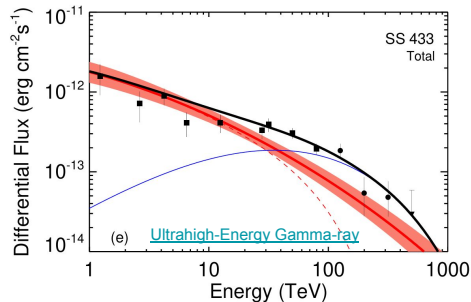
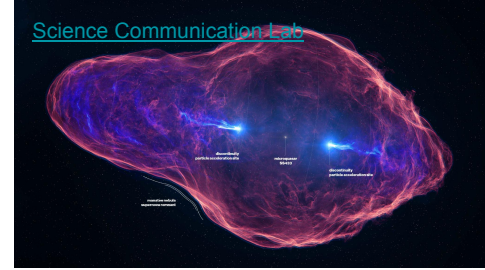
Binary systems with a compact object accreting material from its companion star

Luminosities $> 10^{39}$ erg/s in X-rays, very powerful sources

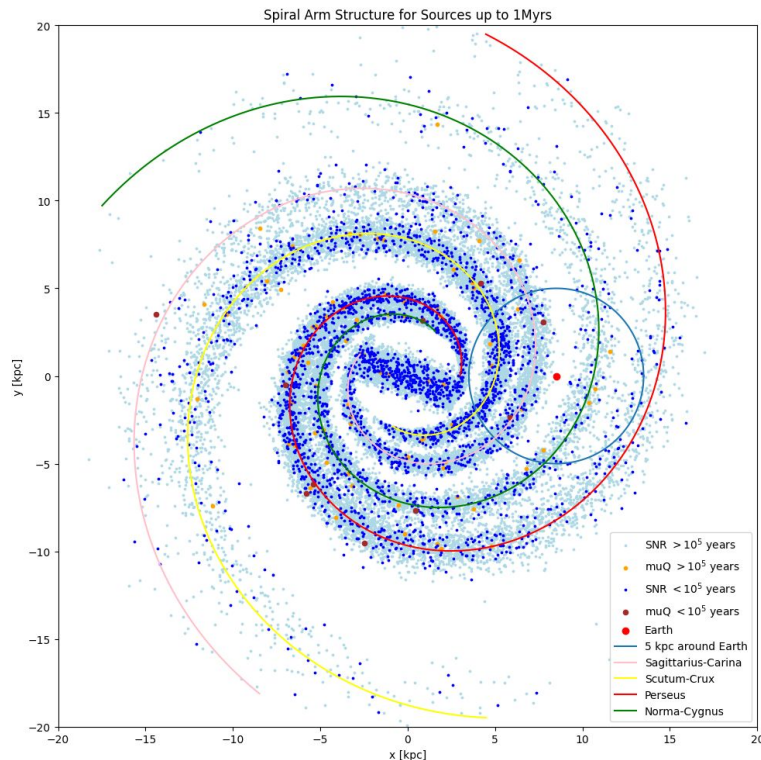
Hillas criterion $E_{\text{max}} \approx 57 \text{ PeV} \sqrt{(L/1 \times 10^{39} \text{ erg/s})}$

100 TeV γ -rays of SS433, Cygnus X-3, V4641 Sgr. suggest PeV protons in μ QS

Likely active period 10^5 years, formation rate 1 in 10^4 years



The Sources



We don't know all sources $\Rightarrow$ 2 approaches

- **Smooth** source approximation, classic but misses stochasticity
- **Monte Carlo** simulations

SNRs dominate below ~ 50 TeV and μ QS above that

Different source properties and lifetime, but **same spatial distribution**

Included **spiral arms** for more accurate approximation of galaxy

Propagation - Diffusion and Causality

$$\frac{\partial n}{\partial t} - D \vec{\nabla}^2 n = Q$$

Valid at long times

Acausal tails

Limiting Propagation Speed

$$\tau \frac{\partial^2 n}{\partial t^2} + \frac{\partial n}{\partial t} - D \vec{\nabla}^2 n = Q$$

Bookkeeping variables

$$\tau = \frac{D}{v^2} = \frac{1}{3} \frac{\lambda}{v} \quad a = \frac{1}{2\tau}$$

$$G(r, t) = \frac{\theta(t - r/v)}{(4\pi Dt)^{3/2}} \exp\left(-\frac{r^2}{4Dt}\right)$$

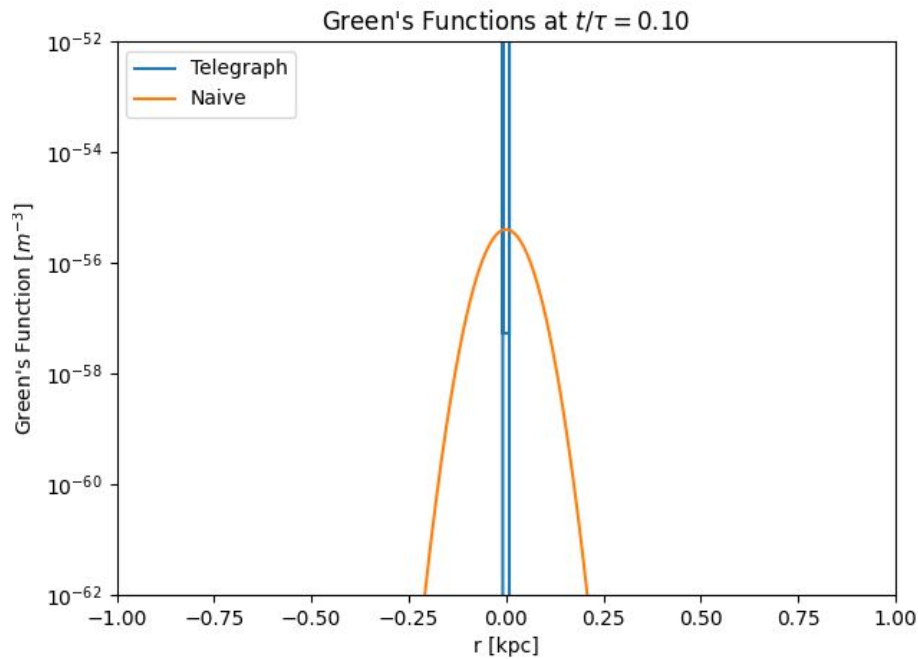
$$G(r, t) = \frac{e^{-at}}{\tau} \left(\frac{\delta(t - r/v)}{4\pi v^2 r} + \theta(t - r/v) \frac{a}{4\pi v^2} \frac{I_1(a\sqrt{t^2 - r^2/v^2})}{\sqrt{t^2 - r^2/v^2}} \right)$$

[1610Tautz_2834_2015-0109.dvi](#)

Free escape boundary $n(z=\pm H) = 0$, use mirror charge method

$$G_{esc} = \sum_{n=-\infty}^{\infty} (-1)^n G(r, x, y, z, t_s, x_s, y_s, (-1)^n z_s - 2nH)$$

Green's Function in Action



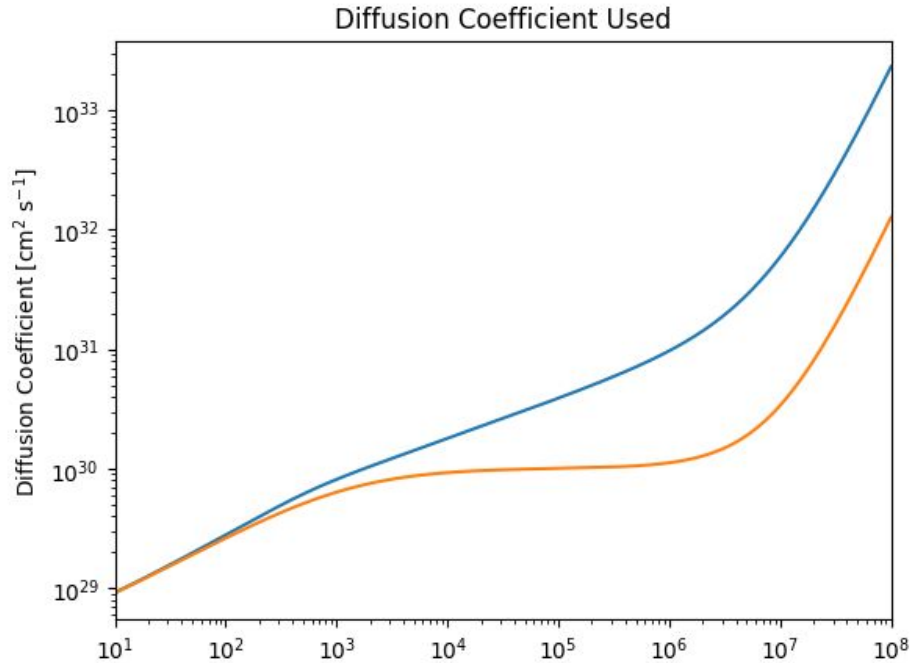
Pure diffusion **violates causality**

If most sources lie in diffusive regime $\Rightarrow$ safe

Huge difference at small times
(could be **long** for **large E**)

Ballistic domination $\Rightarrow$ feature?

Diffusion Coefficient



< 1 TeV fitted from B/C and ^{10}Be data

> 1 TeV **poor constraints**, choice:

- Kolmogorov (classical)
- Flat / Energy independent (no parallel modes)

[Origin of the spectral features observed in the cosmic-ray spectrum](#)

Above ~ 10 PeV, $r_g \approx l_c$, we get E^2 diffusion

$$D_{\text{gal}}(E) = 2v_A H + D_0 \left(\frac{E}{\text{GeV}} \right)^\delta \left[1 + \left(\frac{E}{E_b} \right)^{\Delta\delta/s} \right]^{-s}$$

Flux Calculation

Source term $Q(E) = \frac{\eta(\beta - 2)L}{E_0^2 \left[1 - \left(\frac{E_{\max}}{E_0} \right)^{-\beta+2} \right]} E^{-\beta}$

10^{51} ergs for SNR

Flux calculation $\phi = Q \cdot G \cdot c / 4\pi$

Monte Carlo: draw position from ϱ , age uniformly, for muQs draw Luminosity

$$P(L) \propto L_{39}^{-1.6} \exp \frac{-L_{39}}{15.2}, L_{39} = \frac{L}{10^{39} \text{ erg/s}}$$

$$\phi_{\mu Q} = \frac{n}{4\pi} \int_{\min(0, t_{\text{source}} - t_{\text{age}})}^{t_{\text{age}}} dt G(\vec{r}, t, E)$$

$$\phi_{\text{tot}} = \sum_i \phi_i \quad \phi_{\text{smooth}} = \int_0^\infty dt \int d^3r \rho(\vec{r}) \phi(\vec{r}, t, E)$$

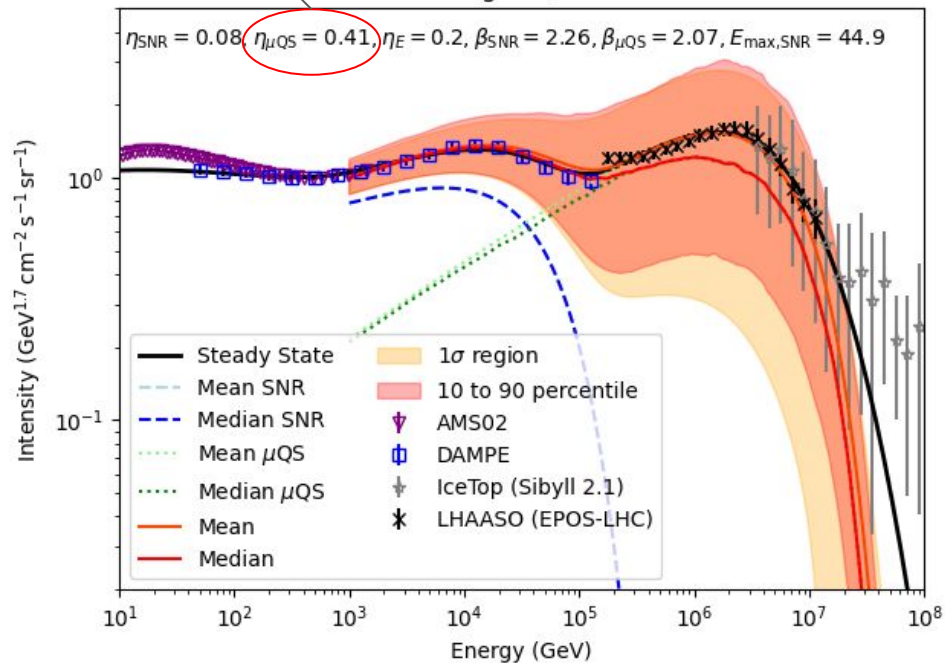
Parameters: $\eta_{\text{SNR}}, \eta_{\mu\text{QS}}, \beta_{\text{SNR}}, \beta_{\mu\text{QS}}, E_{\max, \text{SNR}}, \eta_E \Rightarrow$ Fit to DAMPE, LHAASO

Fraction of Hillas Criterion $E_{\max, \mu\text{QS}} \approx \eta_E 57 \text{ PeV} \sqrt{L_{39}}$

Results - Diffusion

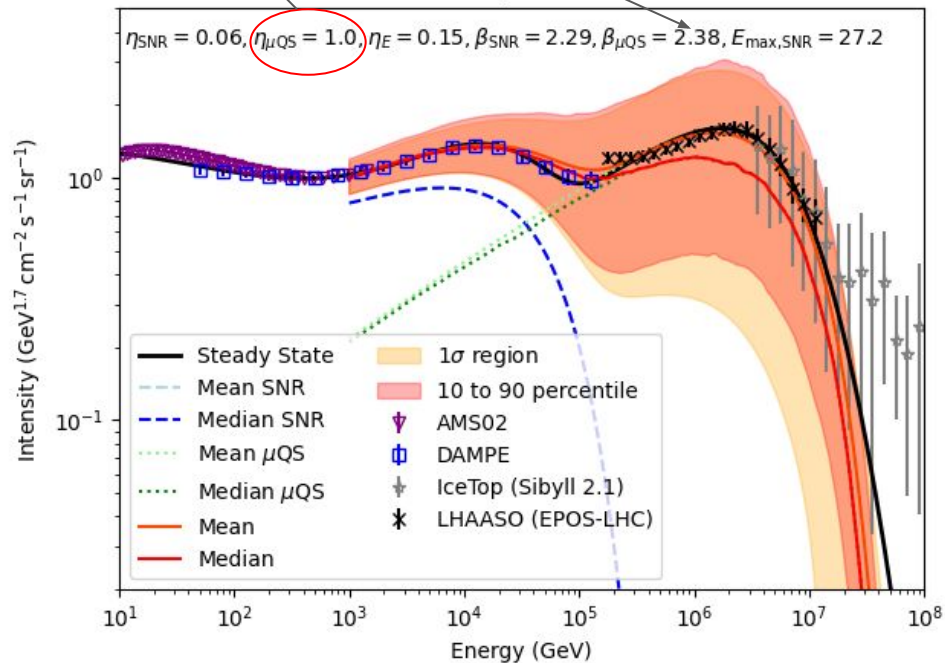
Large, fast escape

Kolmogorov, Naive

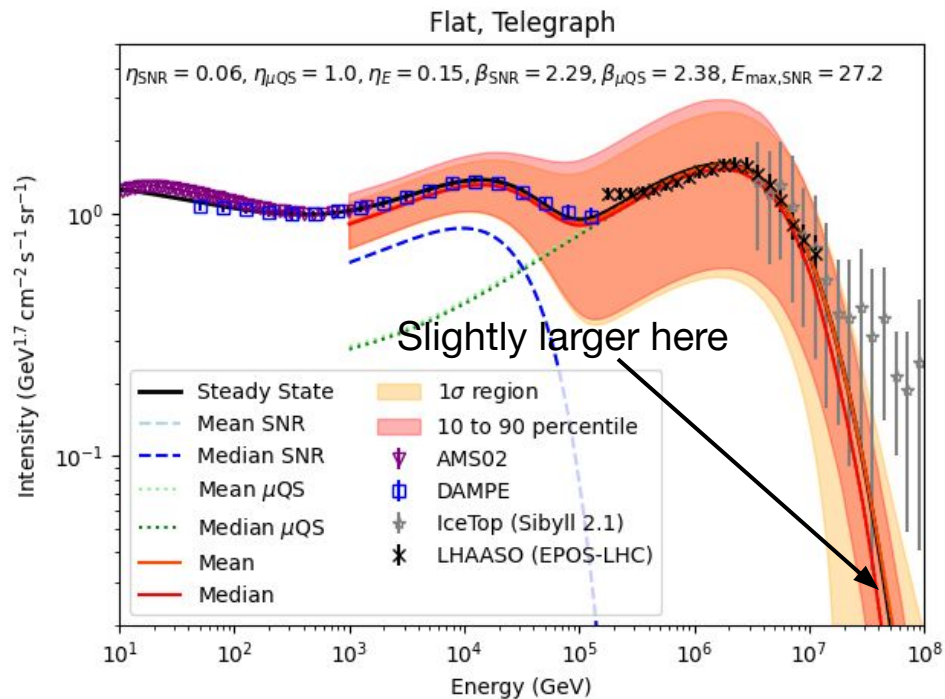
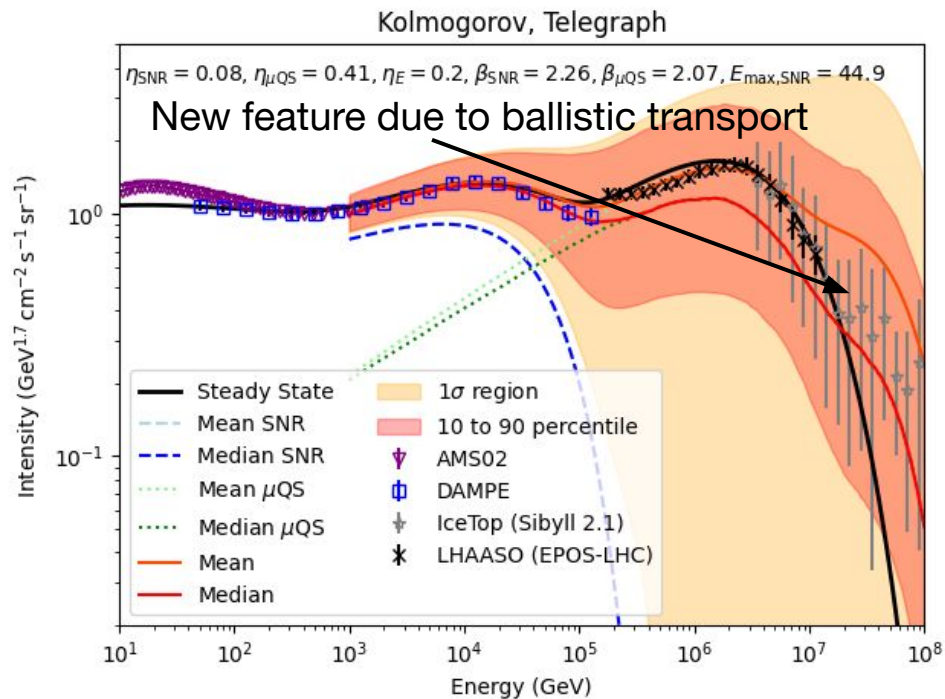


Large, soft injection

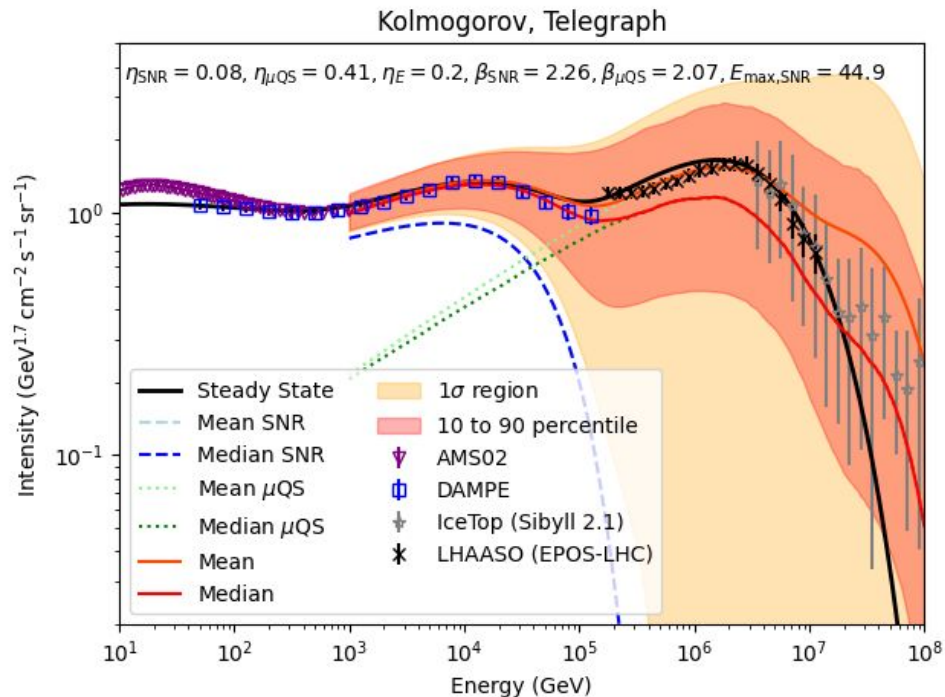
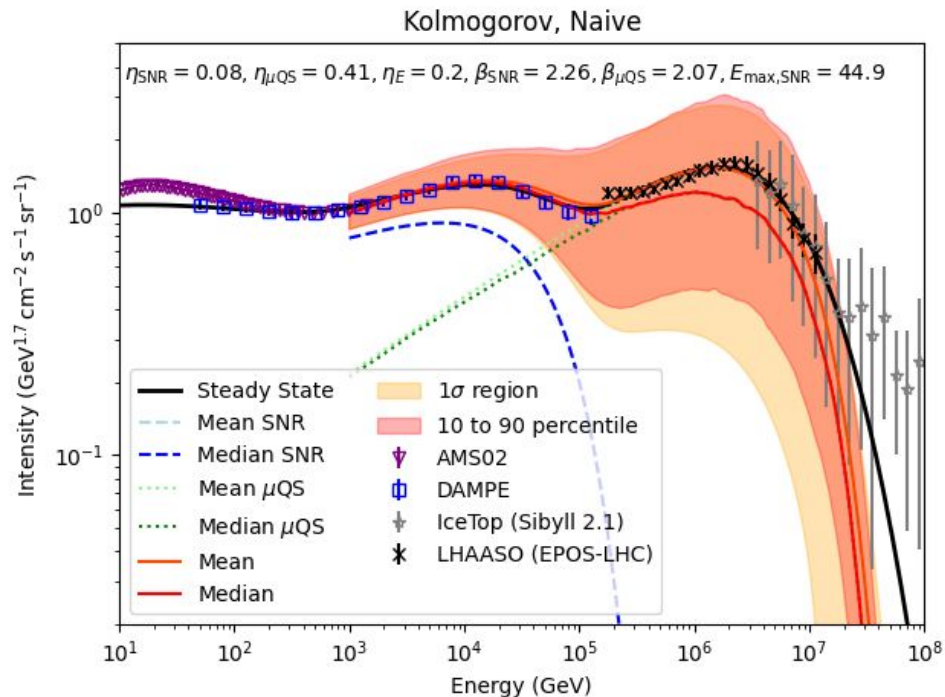
Flat, Naive



Results - Telegraph



Results - Ballistic Transport Effects



Ballistic transport, becomes important when $H^2/D \sim H/c$, at high energies
 Not present in flat diffusion case since D is still small

Dipole Anisotropy

Anisotropy Definition

Define as $\vec{\delta} = \frac{3\vec{J}}{cn}$. Up to normalisations n and flux are the same.

Look at $\frac{\partial n}{\partial t} - D\vec{\nabla}^2 n = Q$, identify $\vec{J} = D\vec{\nabla} n$

For telegraph equation $\tau \frac{\partial^2 n}{\partial t^2} + \frac{\partial n}{\partial t} - D\vec{\nabla}^2 n = Q$, finite speed is included as well

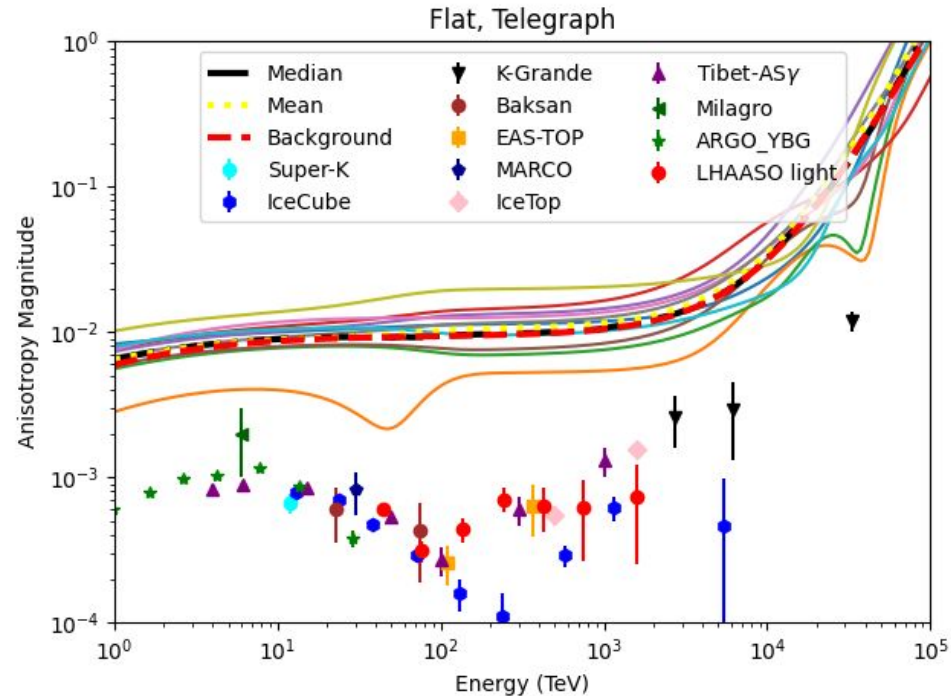
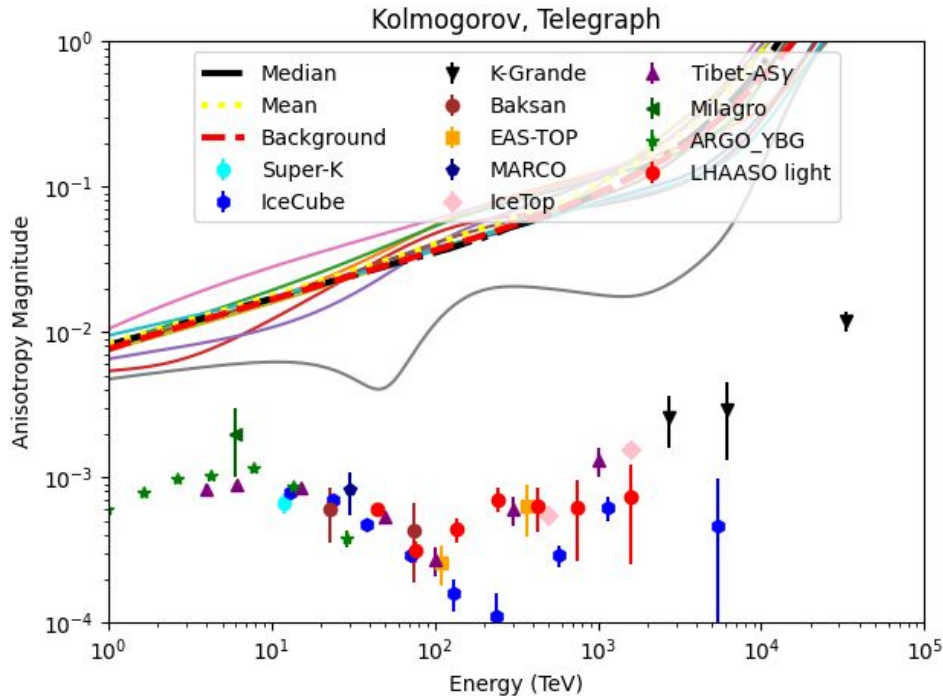
$$\vec{J} = -\frac{D}{\tau} \int_0^t dt' \exp\left(-\frac{t-t'}{\tau}\right) \vec{\nabla} n(\vec{r}, t')$$

Unused, computationally expensive and effect is $\sim 1\%$

$$\vec{\delta} = \frac{3 \sum_i \vec{J}}{c \sum_i n}$$

Generally: more sources towards galactic centre $\Rightarrow$ dipole points towards GC

Results - Magnitude

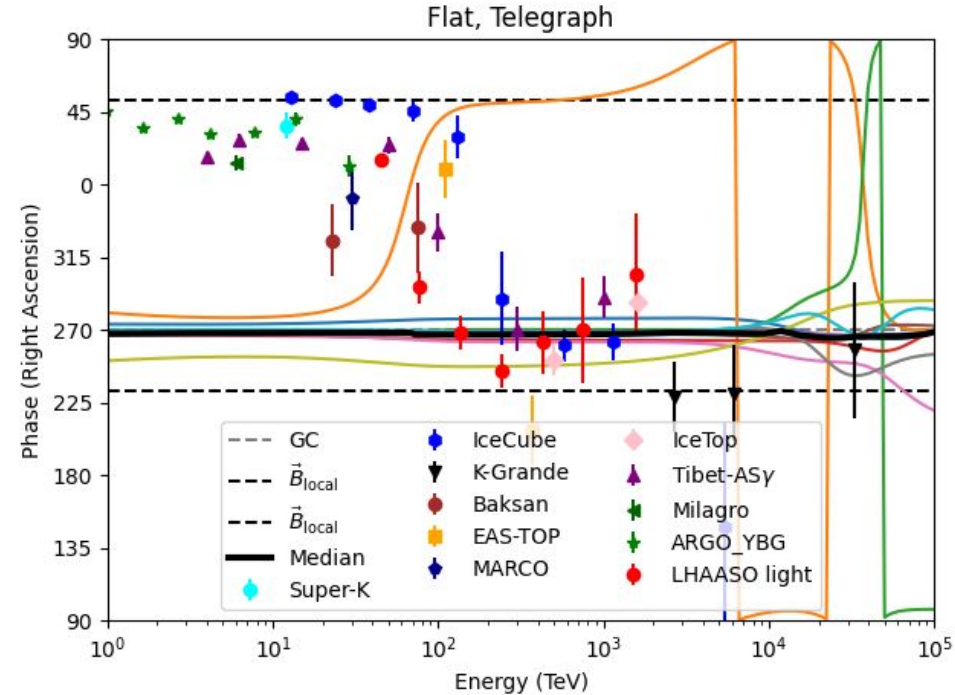
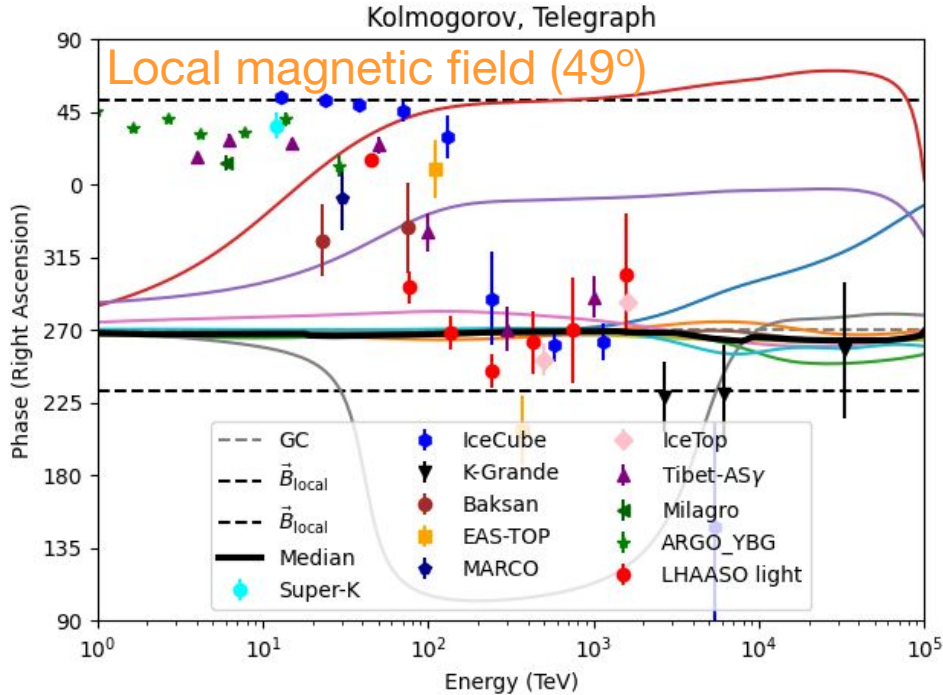


Sum of background and fluctuations (very important)

Way too large compared to observations - even background is too much

Dip at ~ 100 TeV not reliably reproduced, but possible

Results - Phase (Right Ascension)

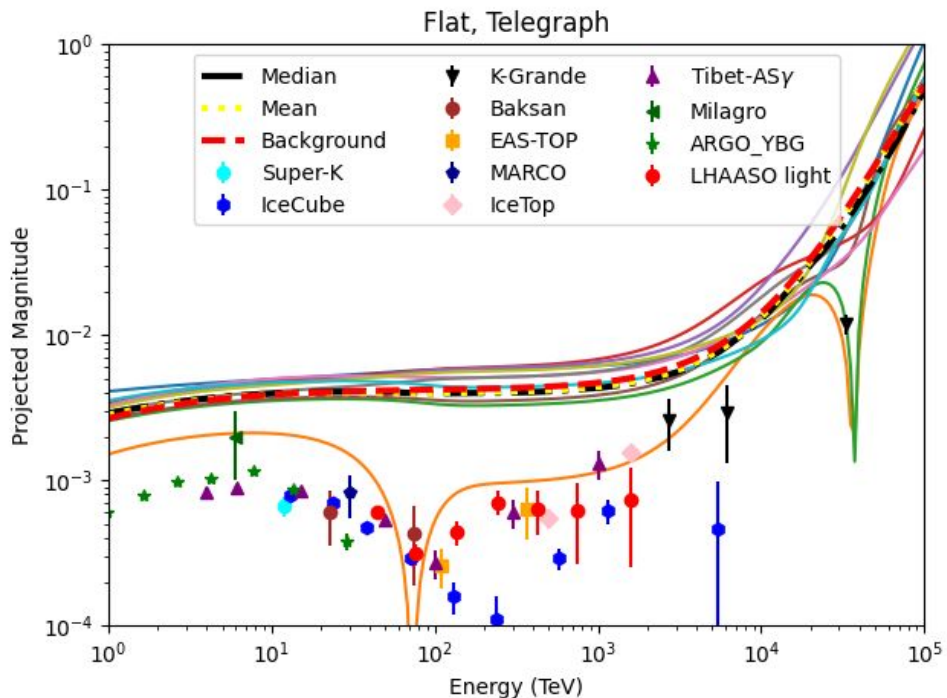
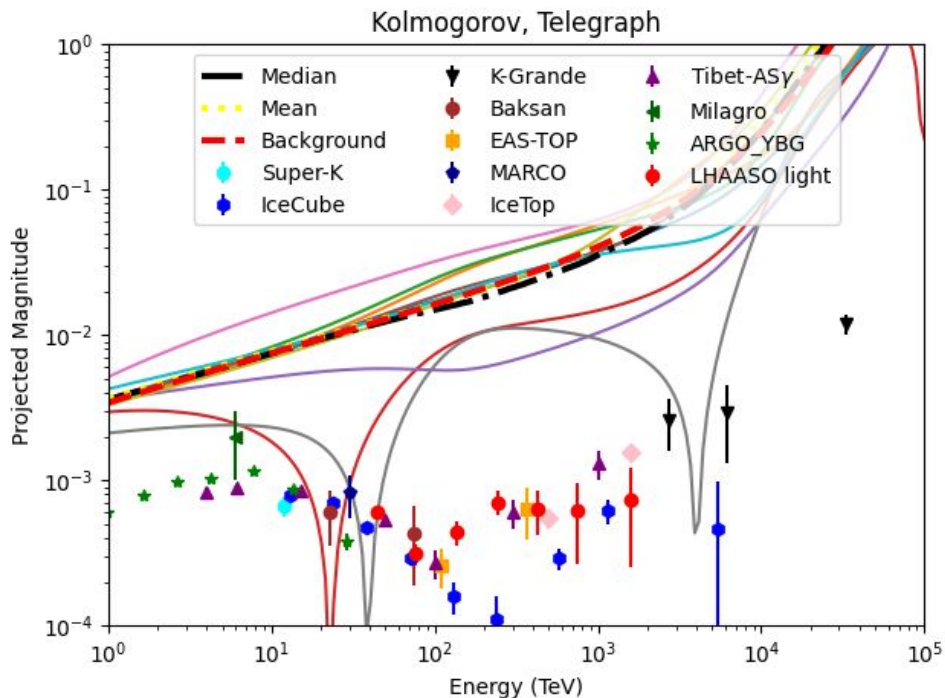


Generally point toward centre, as expected, but don't match observations

Large fluctuations due to nearby young source

Dip in magnitude correspond to phase reversal

Projection onto Local Magnetic Field

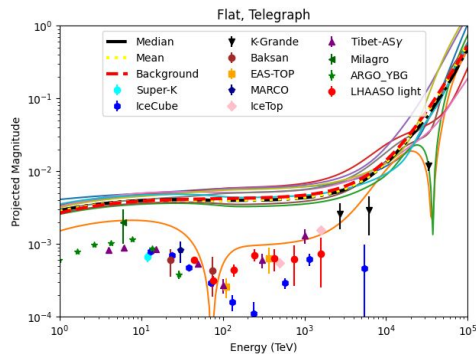
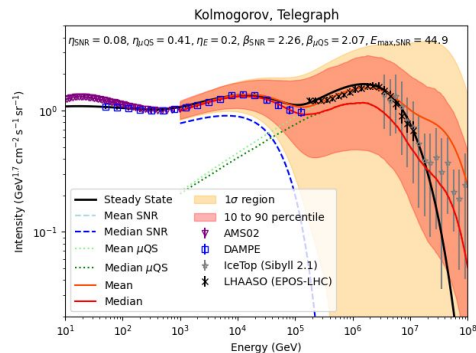


Extremely anisotropic D (only parallel to B)

More dips since phase reversal (49°) easier to come by

Magnitude still too large - maybe suppressed D locally?

Conclusion



Proton Flux:

- Microquasars together with SNR can reasonably reproduce the observed proton flux
- Causality and corresponding ballistic transport need to be accounted for; telegraph equation shows a feature at ~ 10 PeV
- The “knee” is mainly due to propagation effects: transition to E^2 diffusion

Dipole Anisotropy:

- Dipole anisotropy consists of background and fluctuations
- Background already exceeds observations; fluctuations may reduce magnitude, but rarely seen
- Projection onto local magnetic field explains dipole phase and makes dips in magnitude more common, but background points to the “wrong” side

Grazie, Thank you
Danke, Merci
Gracias, Xièxiè



Publication and Participations

Publication

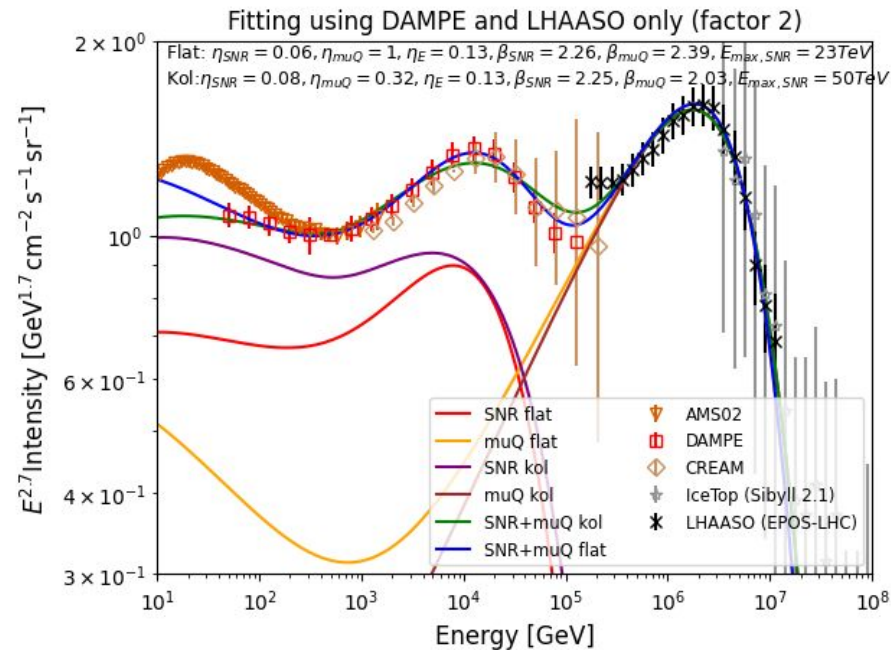
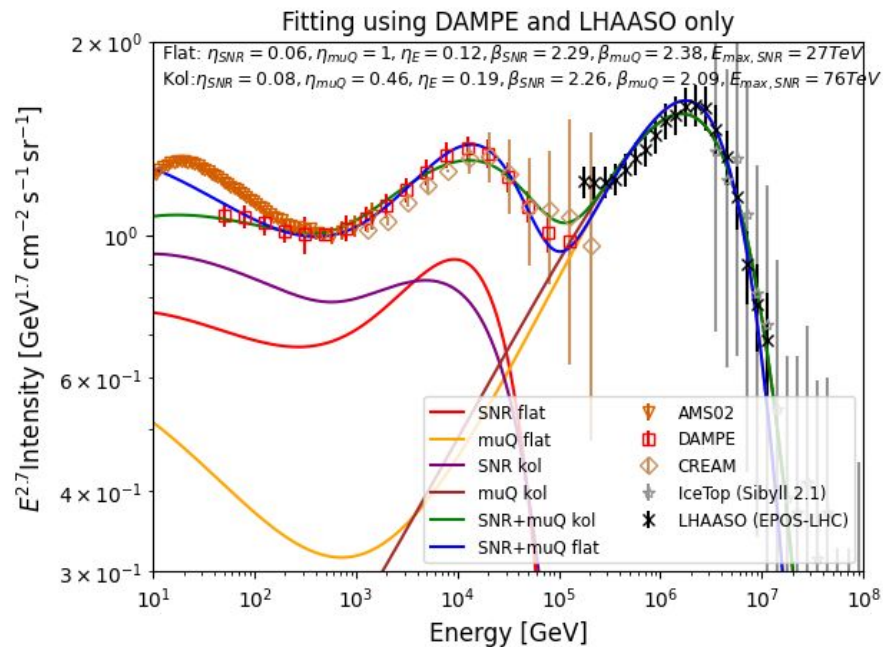
- Contribution of μ QS to Galactic cosmic rays - in preparation

Participation

- School
 - Advances in Modeling High-Energy Astrophysical Sources: Insights from recent multimessenger discoveries” - Oral Presentation
 - 5th Graduate School on Astro-Particle Physics” - Poster
- Conference
 - 29th European Cosmic Ray Symposium (ECRS2026) - Oral Presentation
 - 9th Heidelberg International Symposium on High-Energy Gamma-Ray Astronomy - Poster

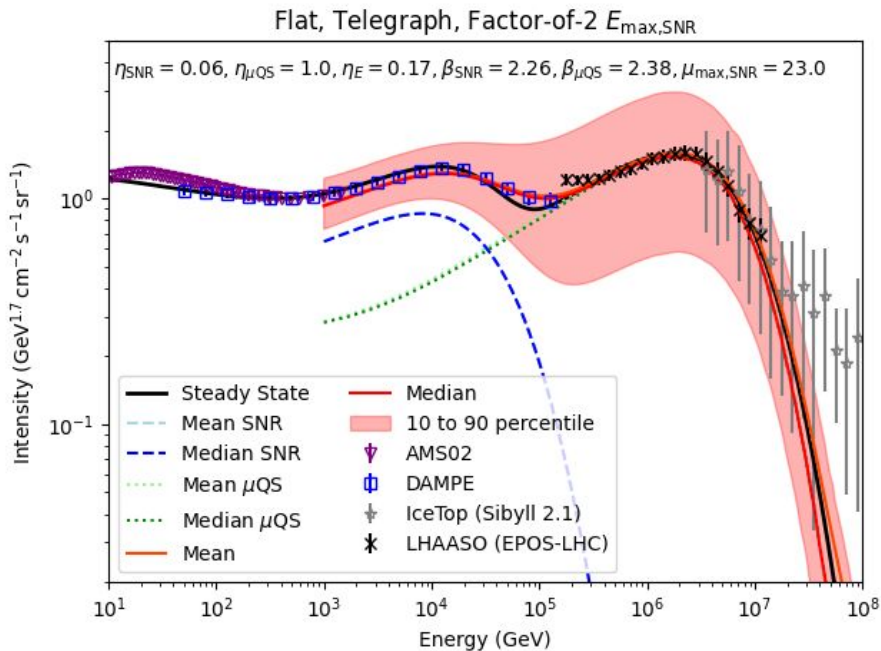
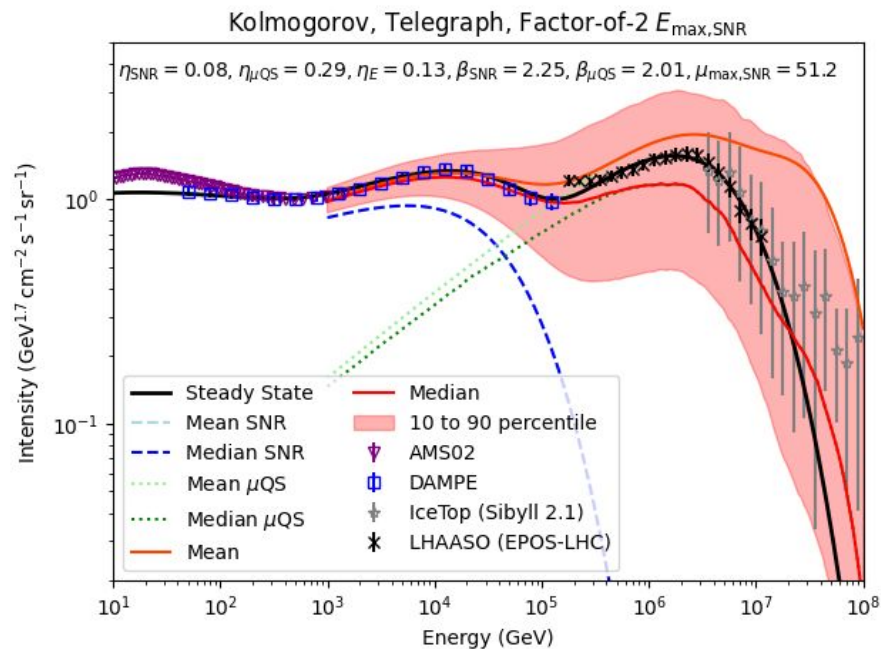
Backup Slides

Fit Plots



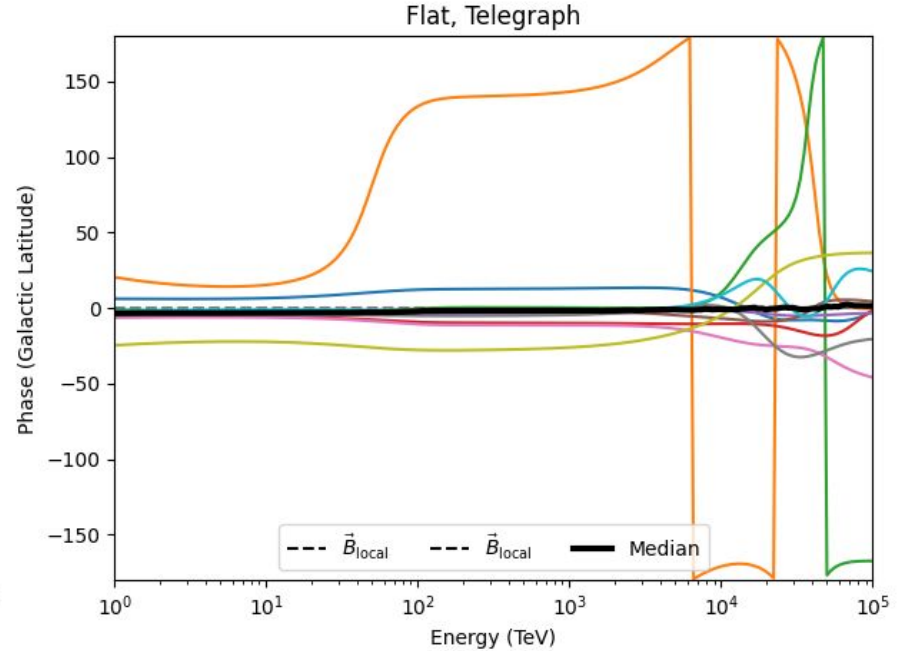
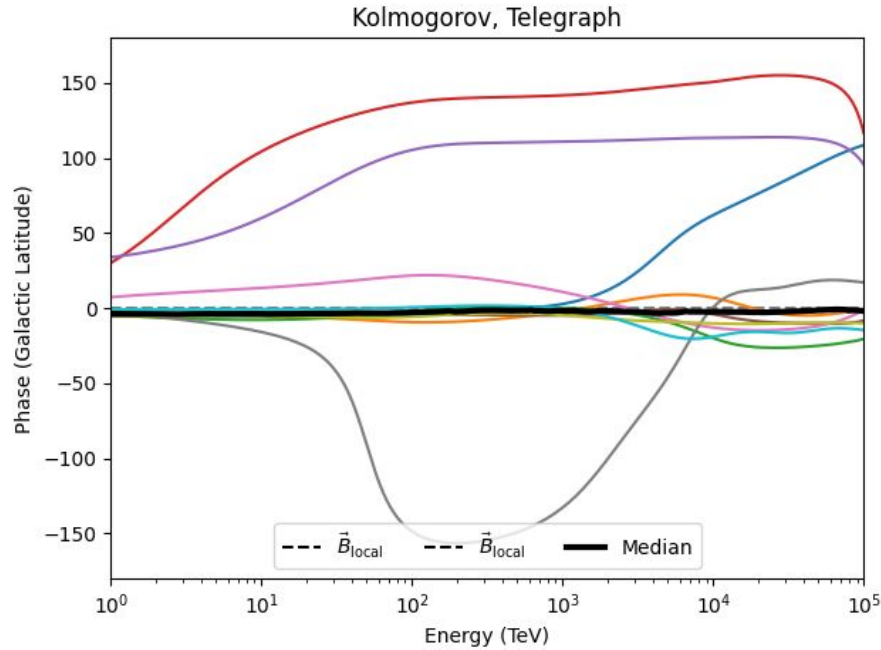
Extended to lower energies and zoomed in
 Included also possibility for $E_{max, SNR}$ to change
 All $\chi^2/\text{d.o.f} < 1$ on total error, reasonable fits

Results - $E_{\text{max,SNR}}$ Vary by Factor 2



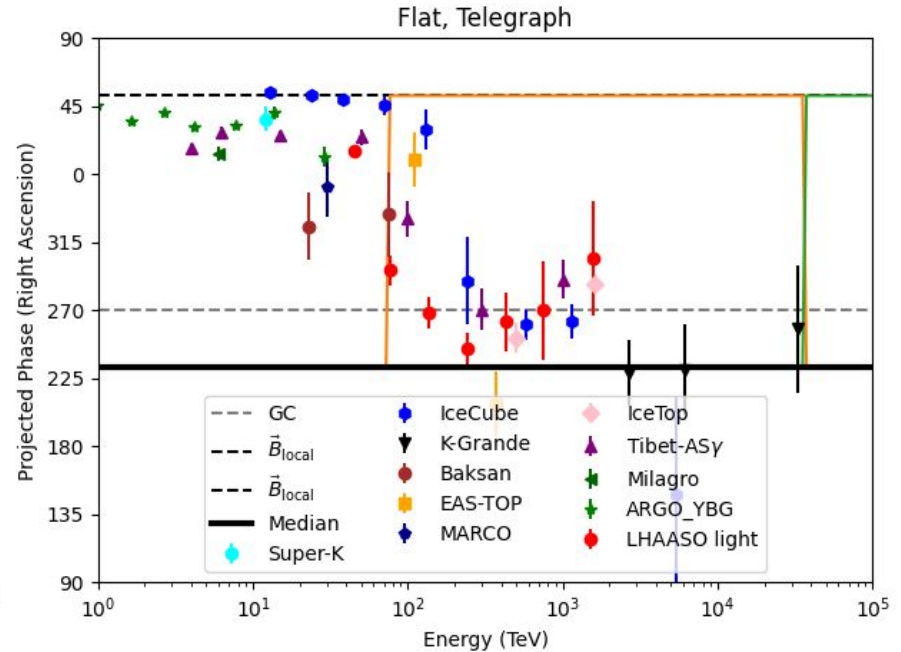
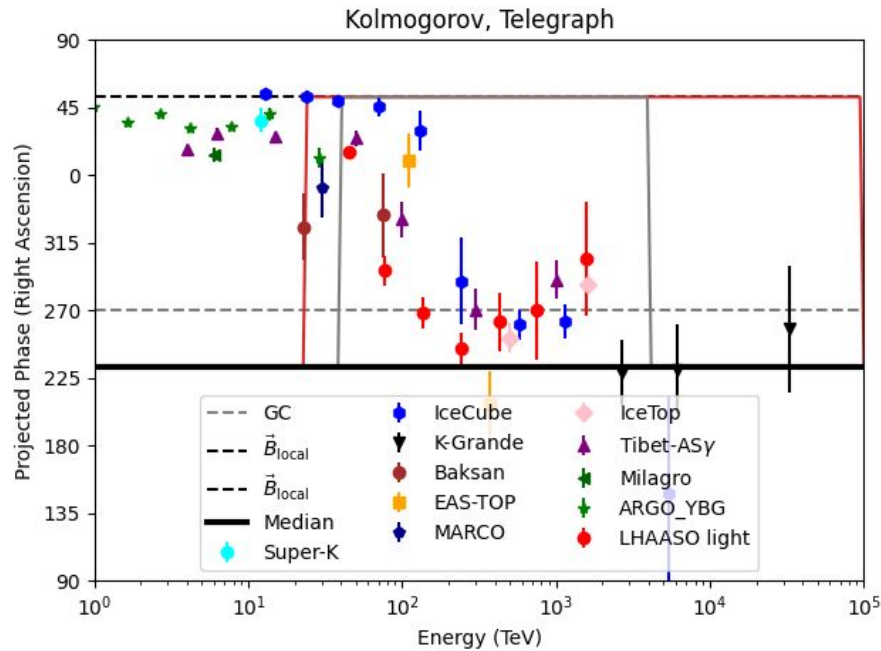
Not much changed, still good fit
Slightly lower μQS efficiency needed, but still high

Results -Phase (Galactic Longitude)



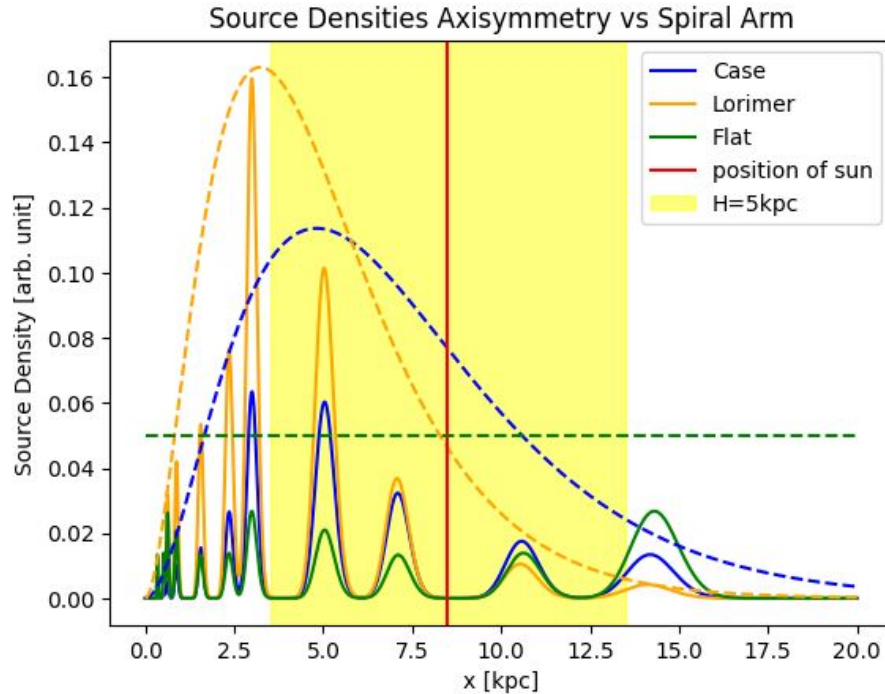
Basically the same as right ascension, but shifted due to tilt

Results - Projected Phase (Right Ascension)



Uninteresting since its one way or the other
Phase flip $\leftrightarrow$ Dip in dipole
Mostly still wrong direction at lower energies

Source Distributions



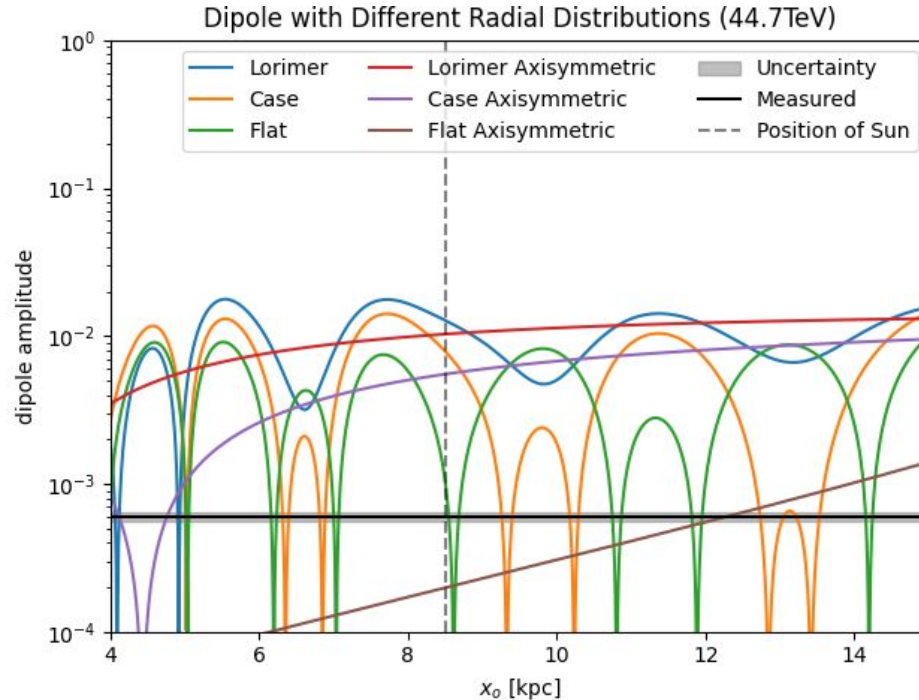
Lorimer used for MC simulations

Solid lines are with spiral arms, dotted lines are axisymmetric case

Imbalance between sources between left and right of the red line within shaded region leads to dipole

Without spiral arms its large, including **spiral arms** further **enhances** the dipole

Position of Observer - Background

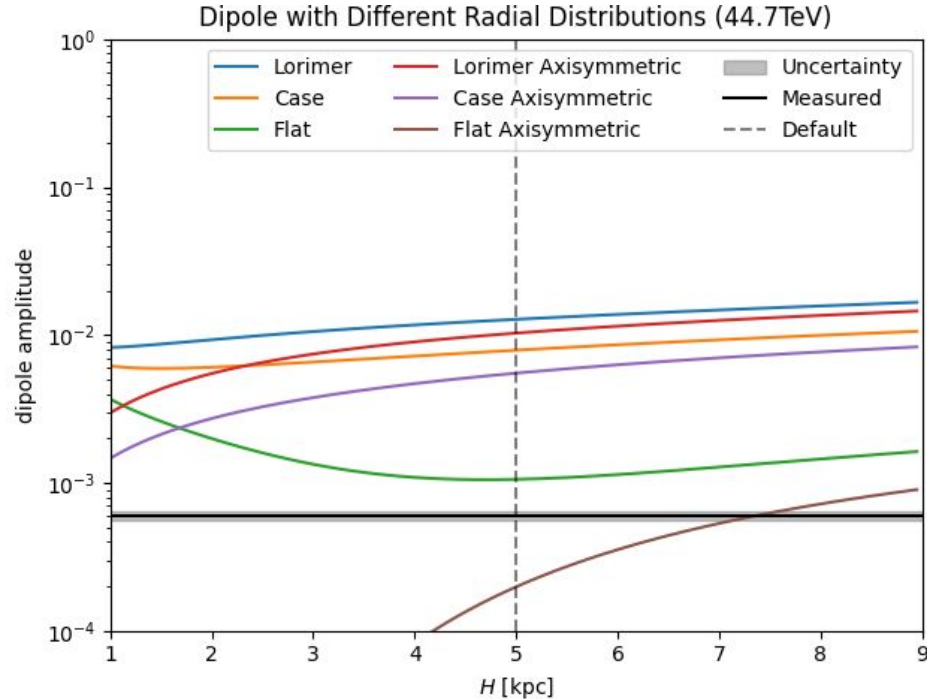


Lorimer the default distribution - no phase flip

Flat and Case - phase flip for tiny dipole - solution for magnitude?

Spiral arms strongly modulate the magnitude but minima non-trivial

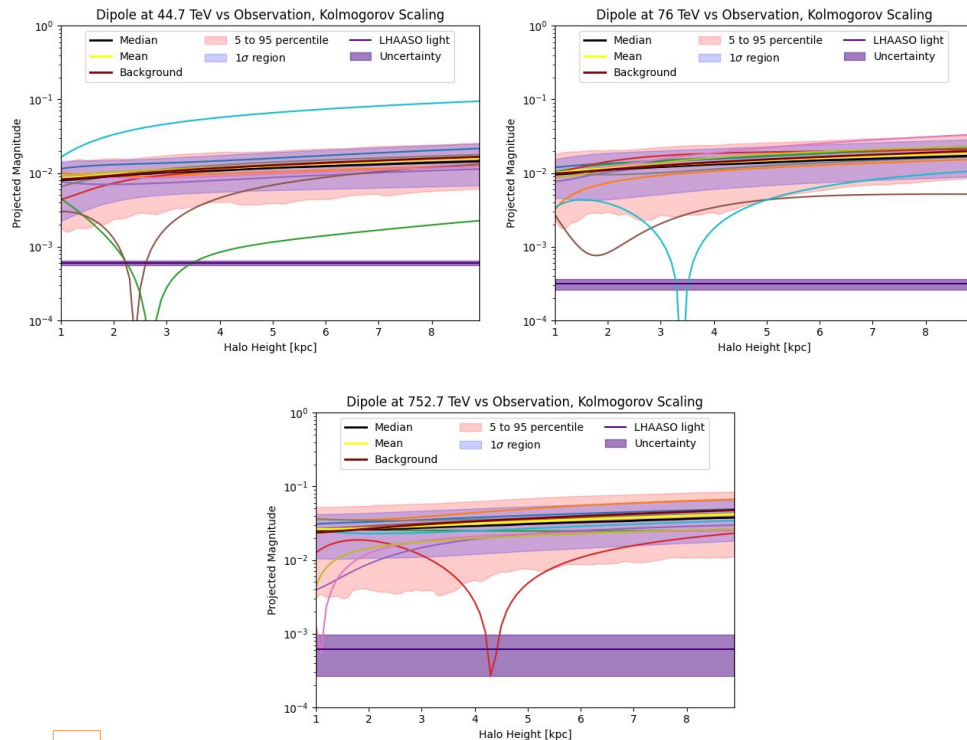
Halo Height - Background



Even with small H dipole exceeds observations (sun position)

Isotropic distribution dipole comes from edge of galaxy effect

Integral vs Monte Carlo



Nearby sources much more important for dipole than for flux

Integral only captures the **background** dipole due to ϱ

Actual dipole is **sum** of background and fluctuations (only seen in MC)

$$\vec{\delta} = \frac{3 \sum_i \vec{J}}{c \sum_i n} \quad \vec{\delta} = \frac{3D\vec{\nabla} \int d^3x dt \rho(\vec{x})G(\vec{x}, t, E)}{c \int d^3x dt \rho(\vec{x})G(\vec{x}, t, E)}$$