arXiv:2202.00694

Theory and Interpretation of Multimessenger Astrophysics

Julia Tjus | 04.01.2023

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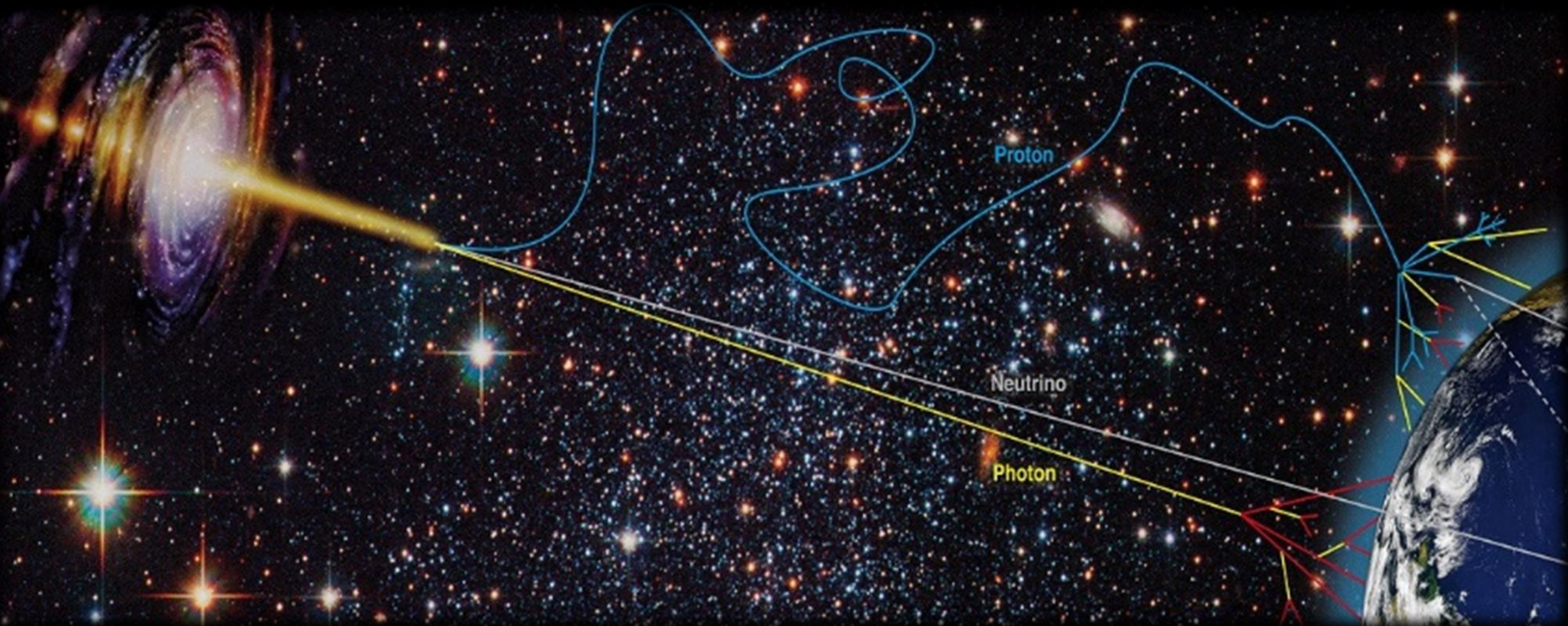
Multimessenger astrophysics:
combination of astrophysics with fundamental aspects of matter



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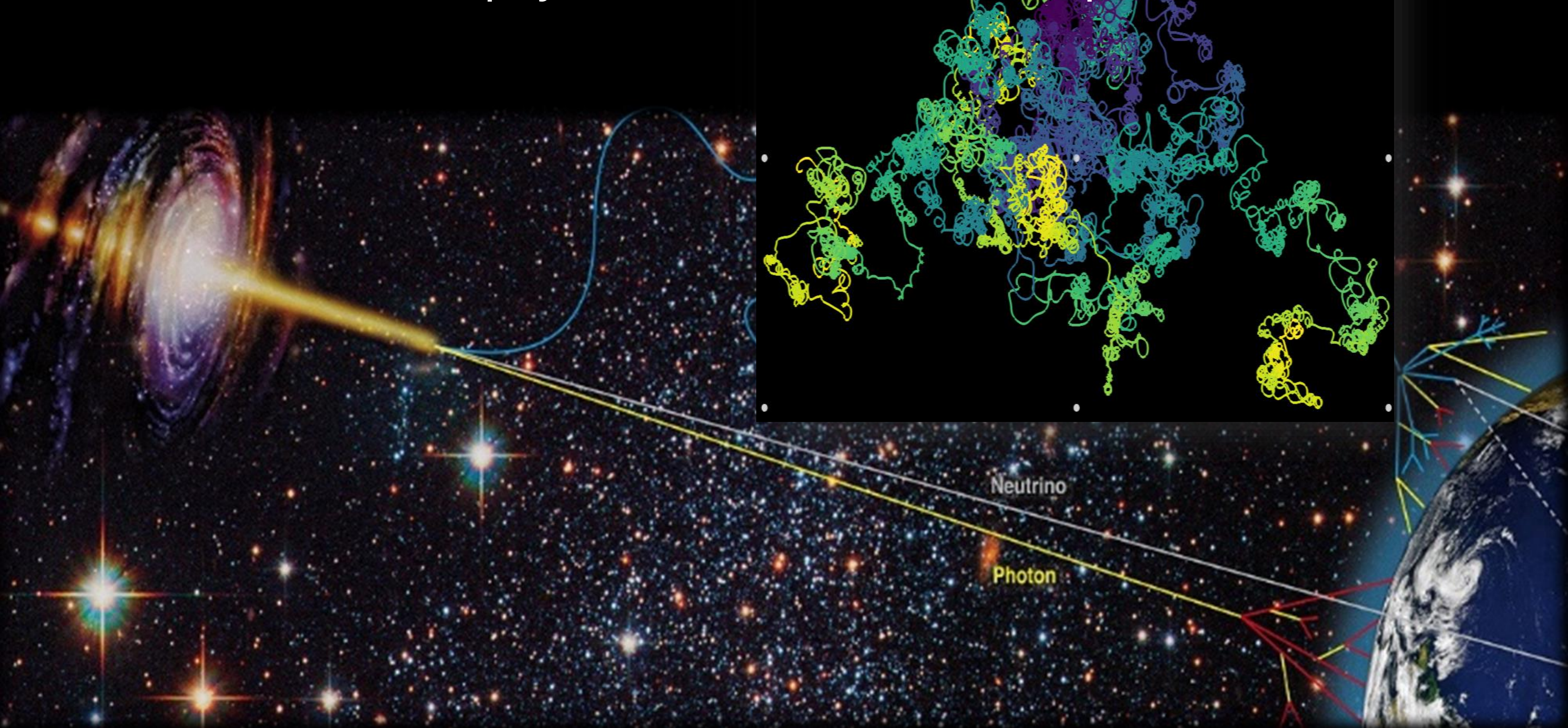

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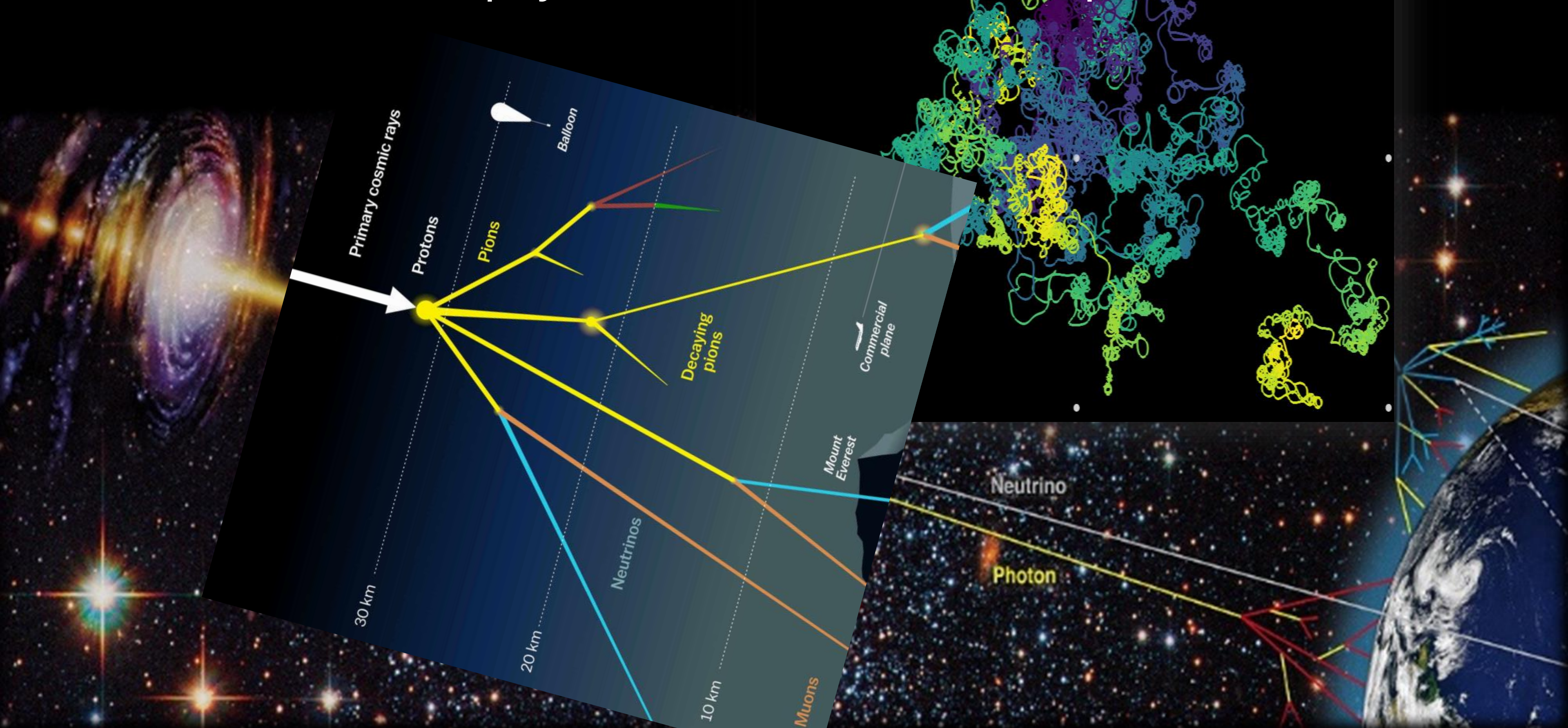
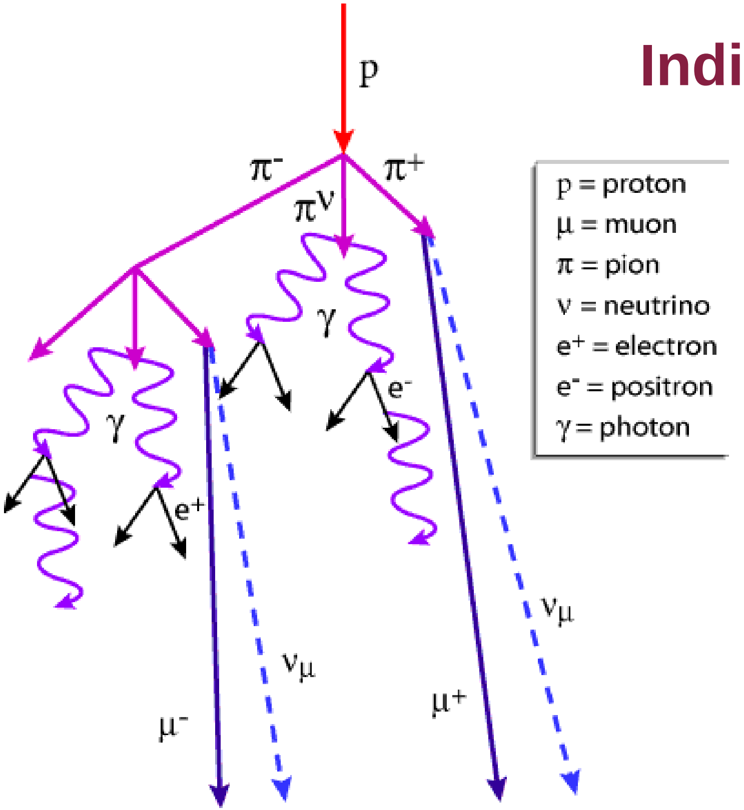


Information available today to investigate origin

Direct: cosmic rays

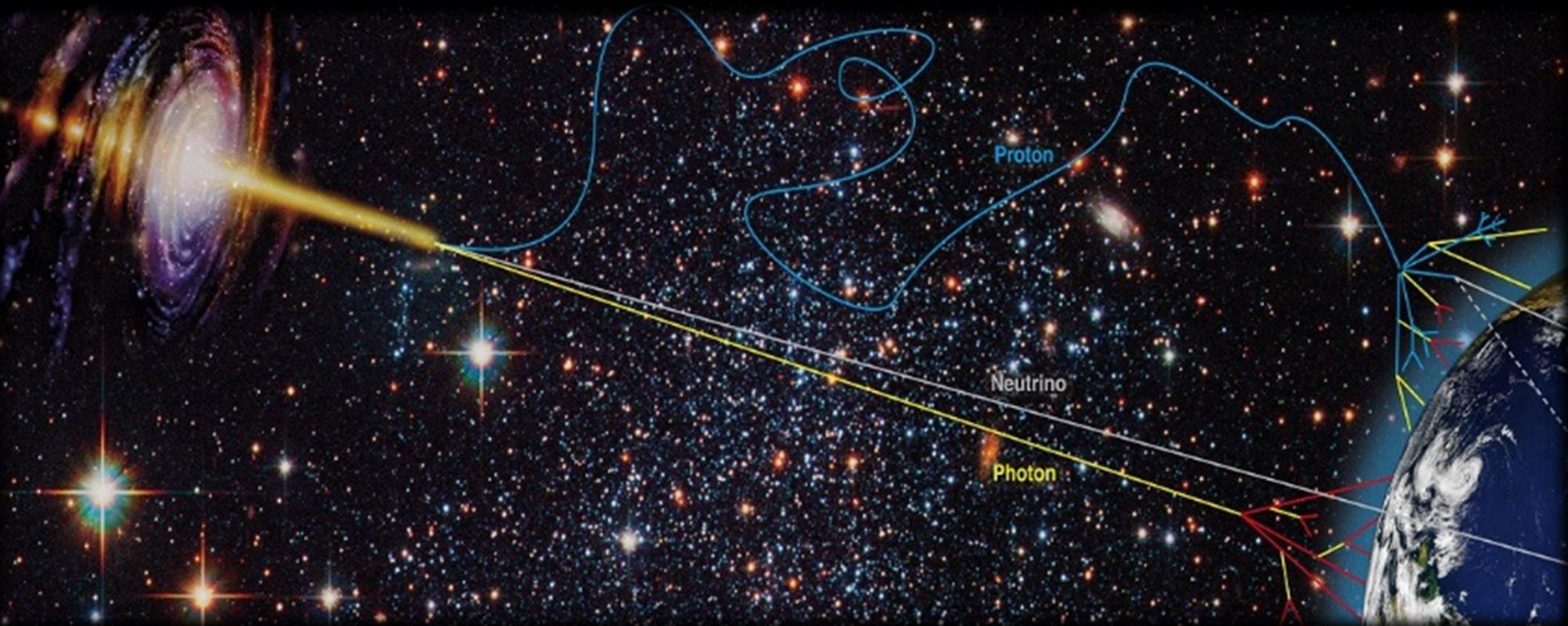
- Hadrons: Spectral behavior (all-particle and chemical composition) **MeV – ZeV**
- Electrons: primary spectrum (local) **MeV – 20 TeV**
- Anisotropy level **TeV – 10 PeV, EeV**



Indirect: e, ν, γ, ...

- Positronspectrum/ -fraction **MeV - TeV**
- Gammas: Sources, diffuse emission **MeV – 10(0) TeV**
- Neutrinos: first detection **TeV – PeV**

Multimessenger astrophysics:
a puzzle from low to high-energy and including γ, ν, and GWs



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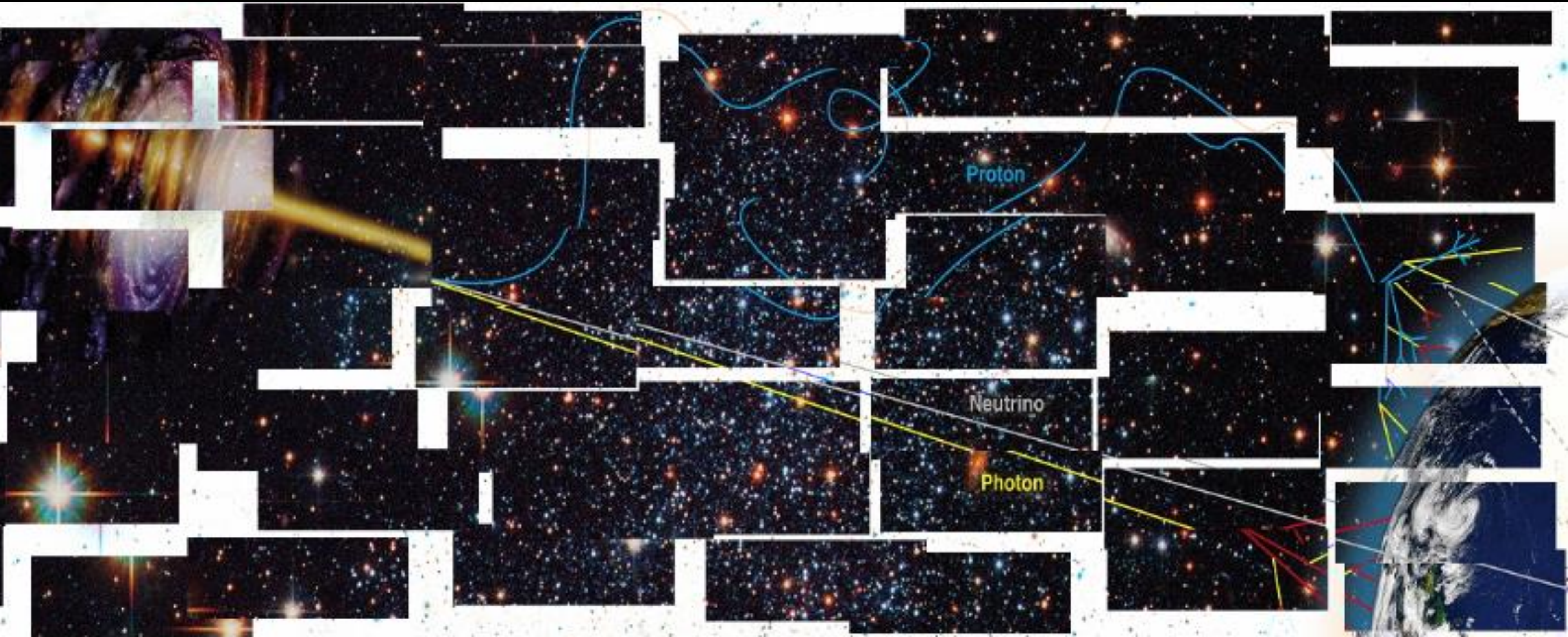
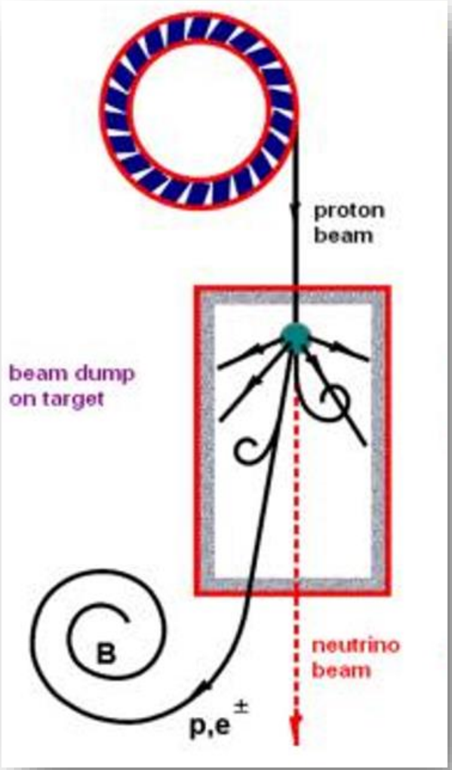
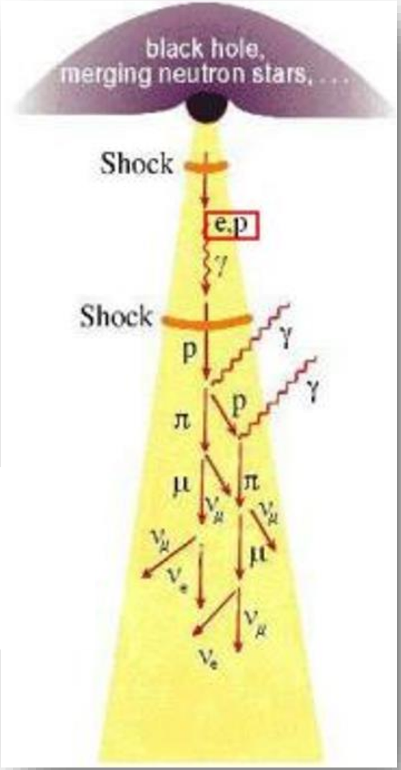


Particle Physics: Heavens and Earth

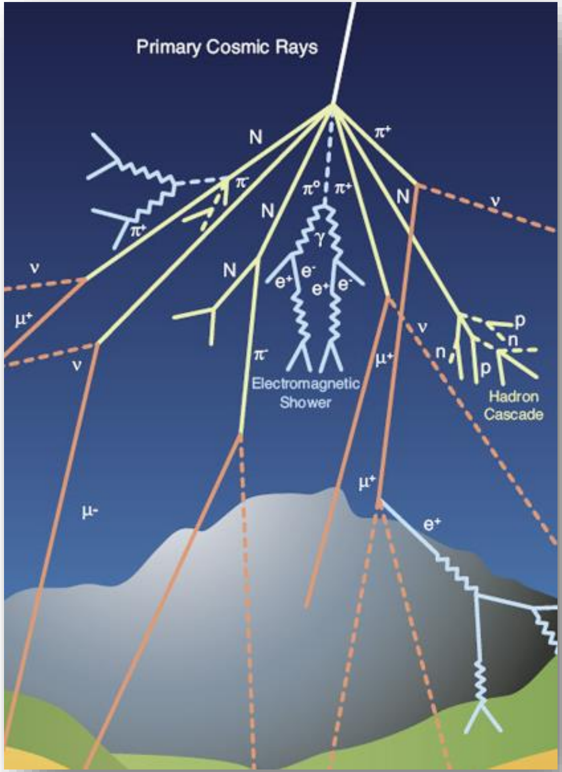
Particle Accelerator



Astrophysical Jet

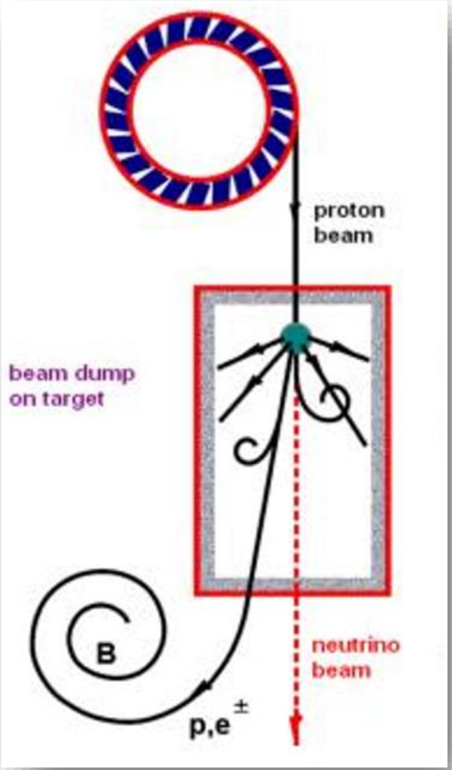


Earth Atmosphere



Part I Accelerator and Earth Atmosphere

Particle Accelerator



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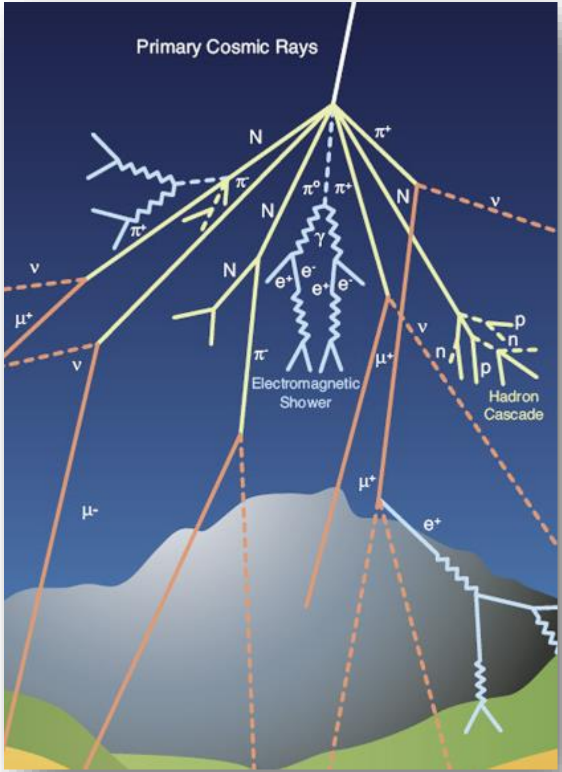
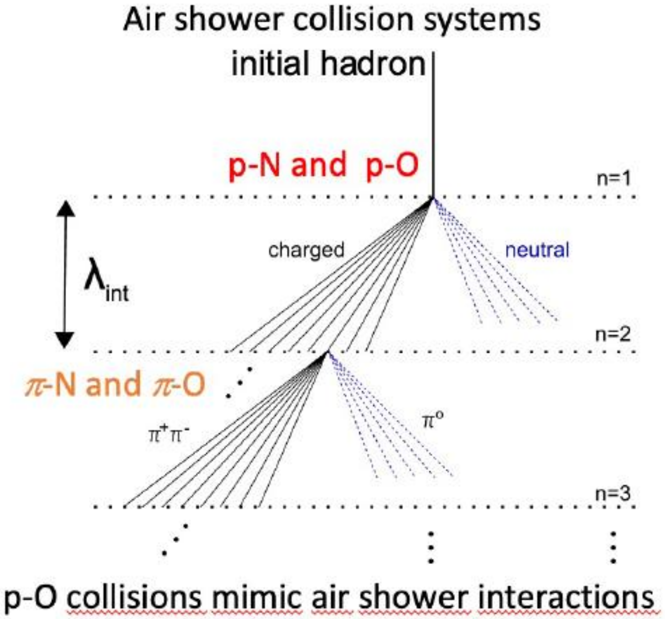


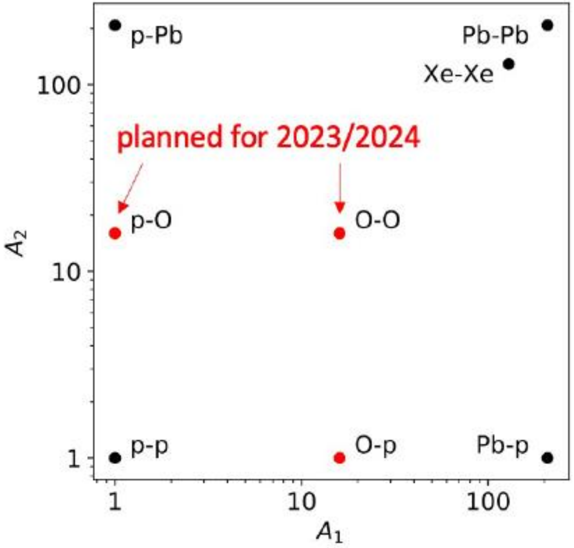
Forward cross-section measurements at heavens and Earth



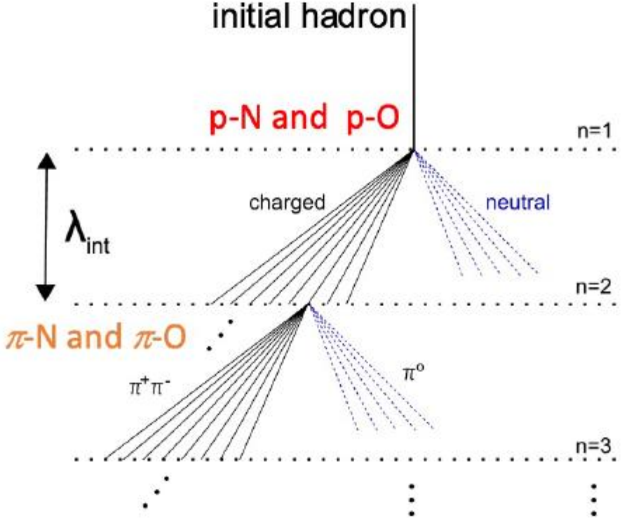
Forward cross-section measurements at heavens and Earth

Collision systems at the LHC

Run 3: p-p @ 14 TeV, p-O @ 10 TeV



Air shower collision systems



p-O collisions mimic air shower interactions

Fixed target data at sub-TeV (LHCb only)

- p+(p,...,O,N,...) @ 0.11 TeV
- Pb+(p,...,O,N,...) @ 0.07 TeV
- O+O, O+p @ 0.08 TeV (in Run 3)

Forward cross-section measurements at heavens and Earth

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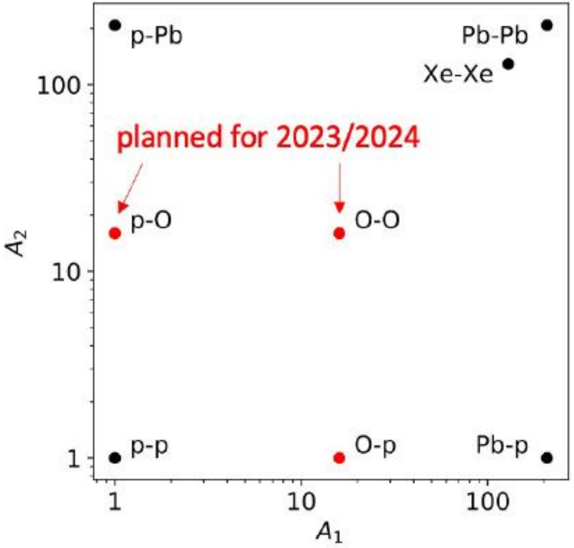

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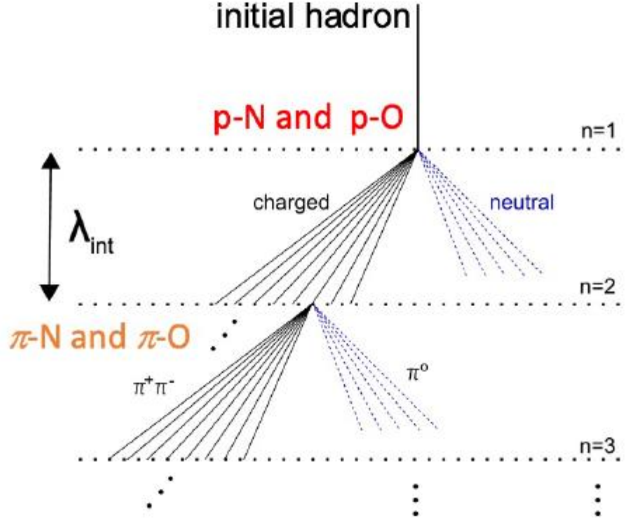

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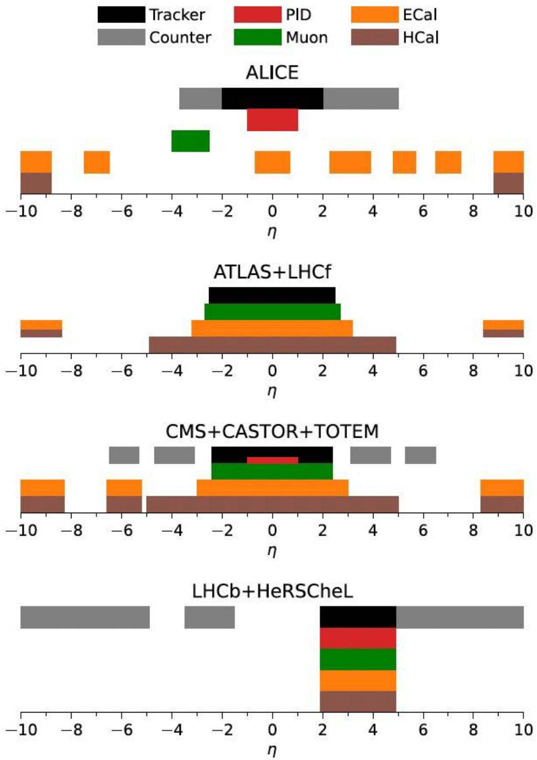

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Atmospheric muons and neutrinos

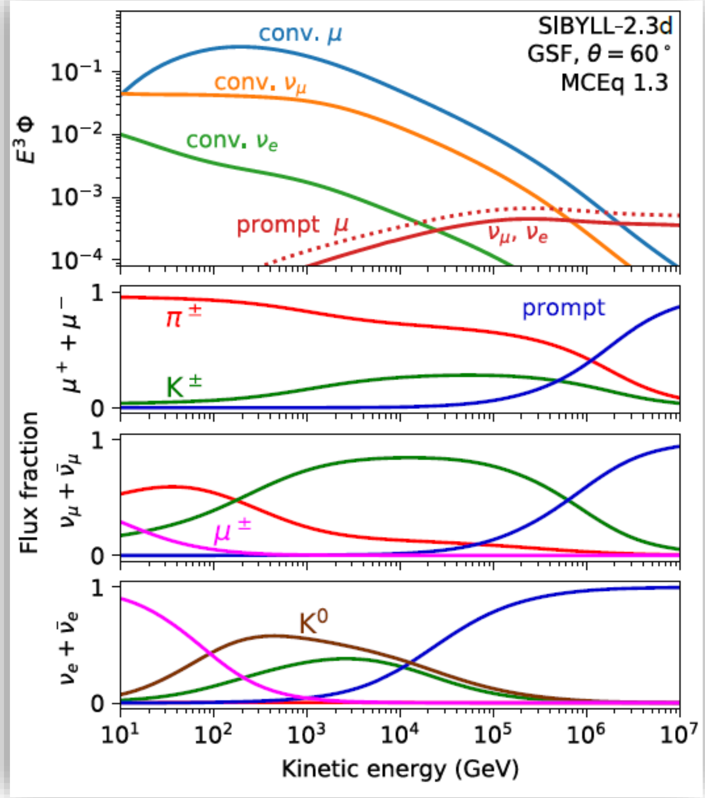
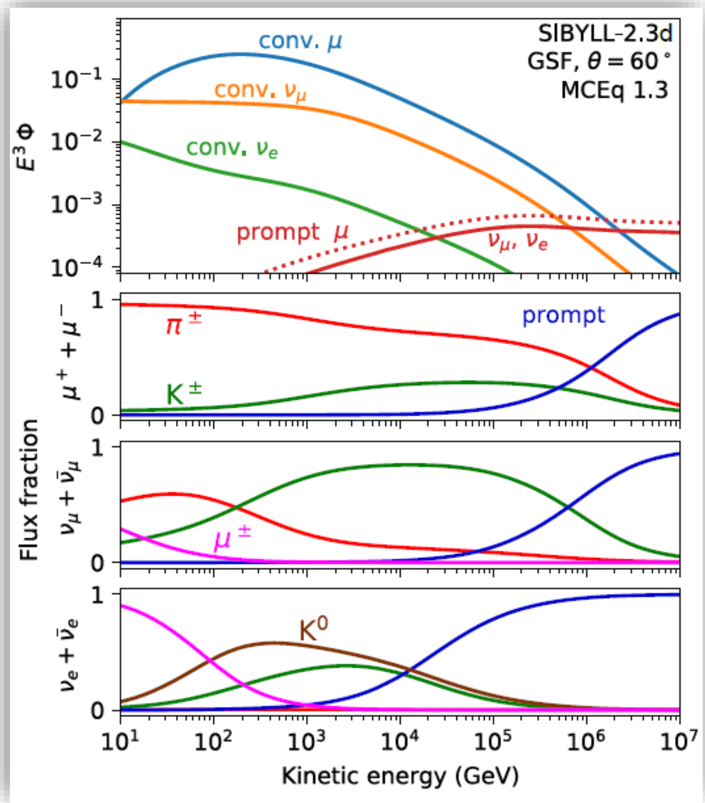
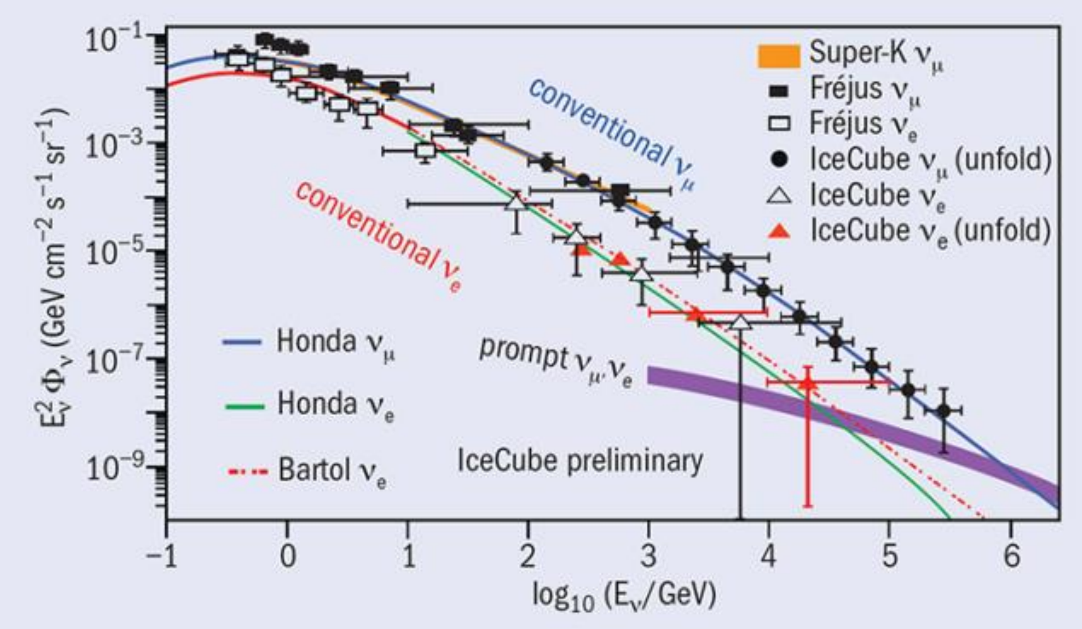


Fig: A. Fedynitch, JKB & Desiati, PRD (2012)

Atmospheric muons and neutrinos

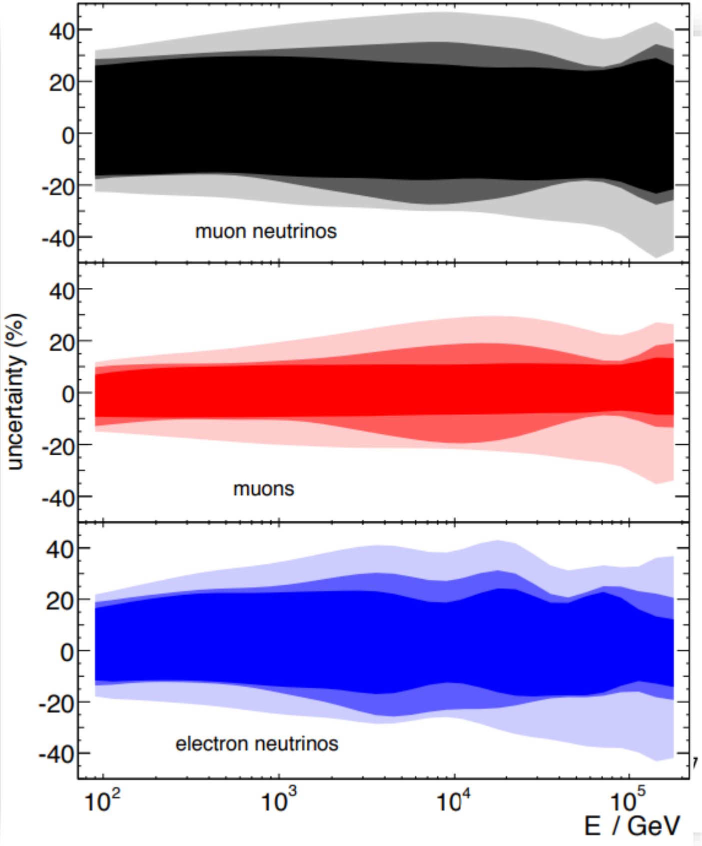




Measurements up to ~PeV energies

Fig: A. Fedynitch, JKB & Desiati, PRD (2012)

Atmospheric muons and neutrinos



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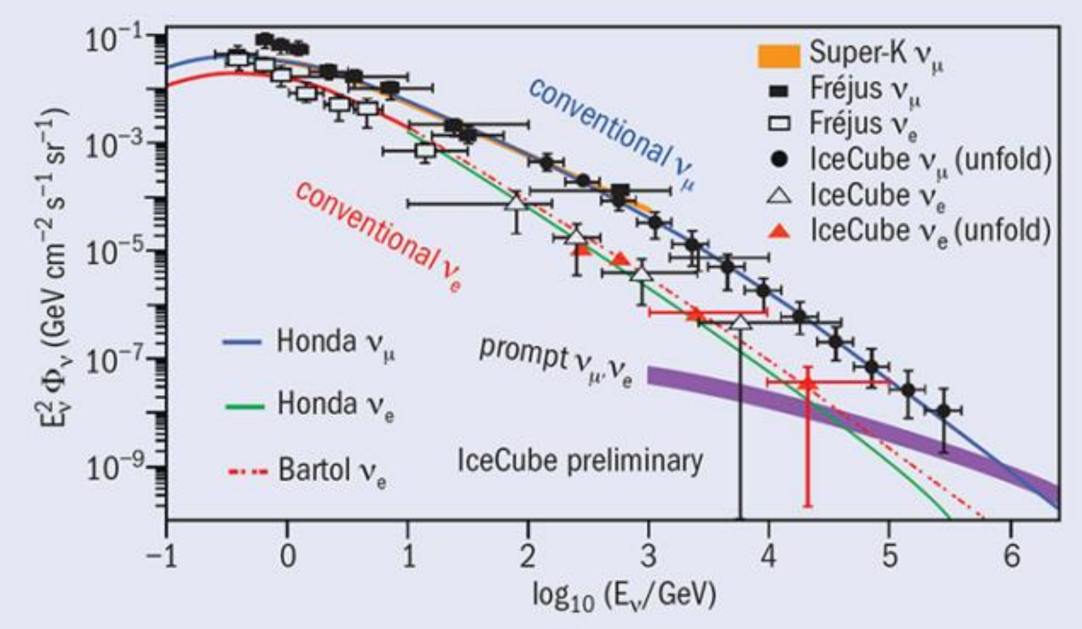


Measurements up to ~PeV energies

Predictions depending largely depending on first interaction model

Large uncertainties from unknown part of parameter space

- Forward scattering (η → ∞)
- Relevance of parameterspace at
  - large Q^2
  - small Bjorken x relevant

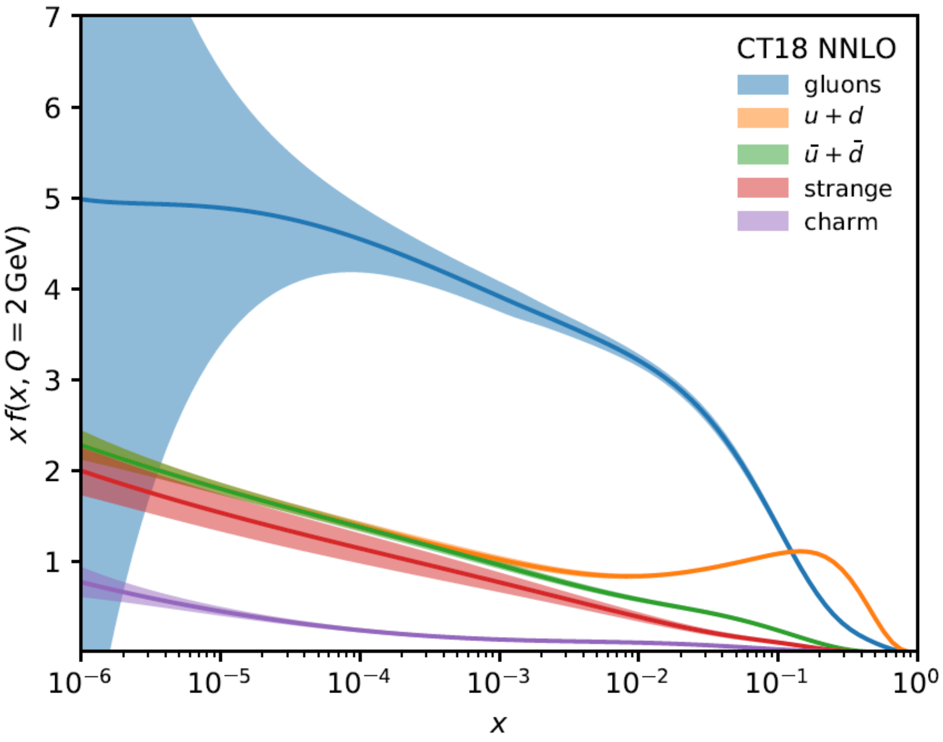
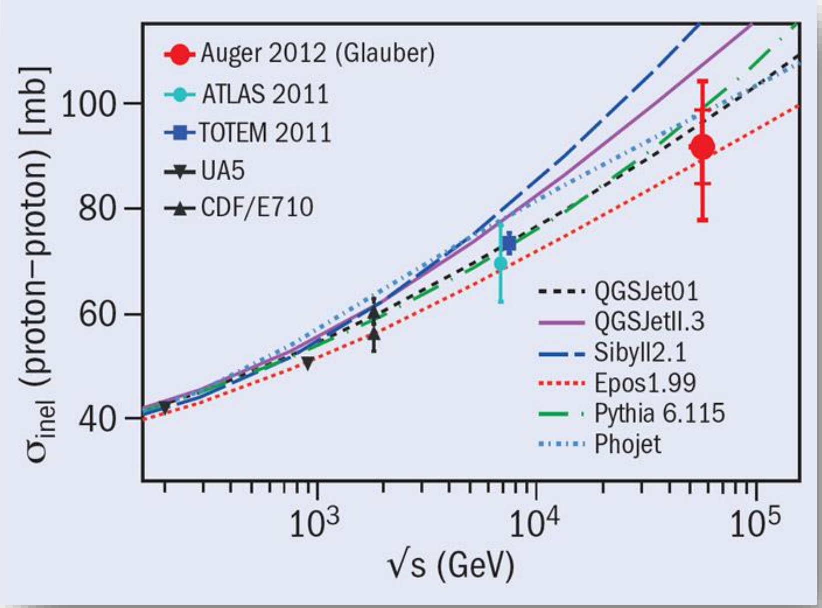


Fig: J. Albrecht et al., Review, Astroph. & Space Science (2022)

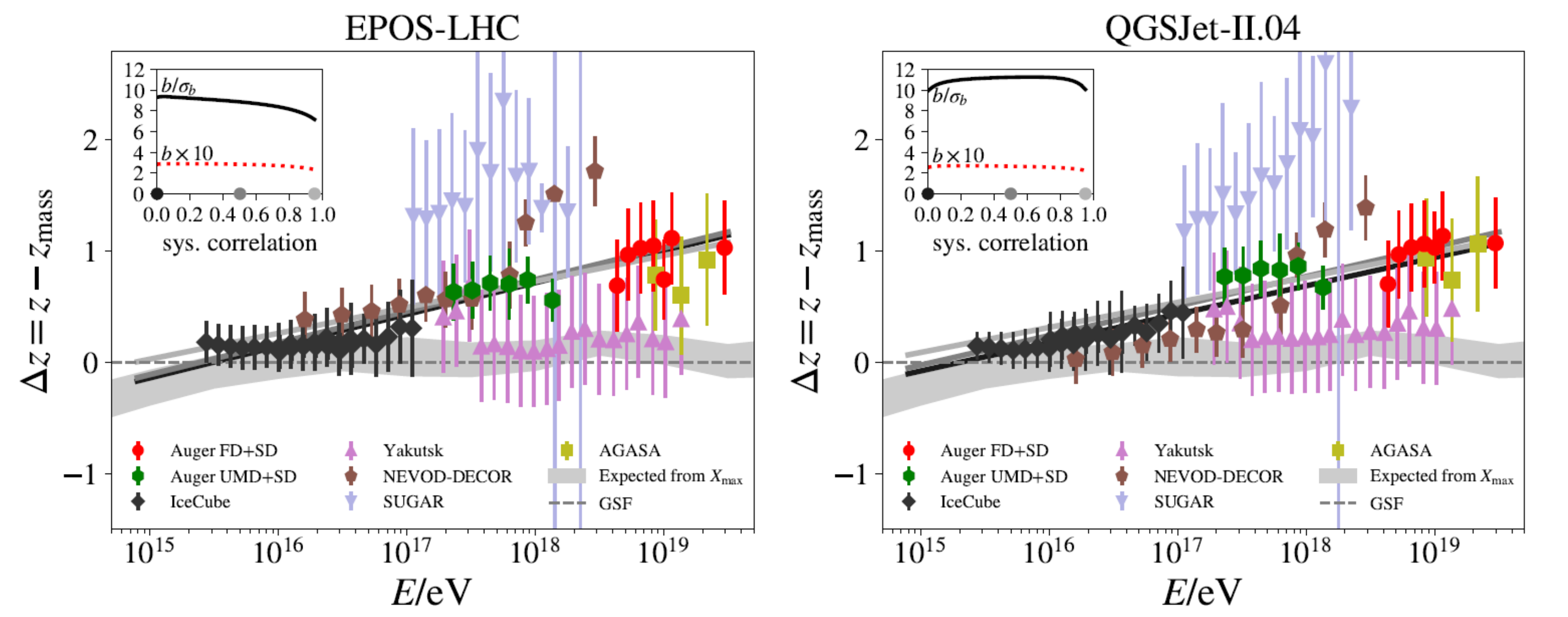
Cross section at the highest energies – comparison with Monte Carlo

- Auger measurements of cross section at $\sqrt{s} = 6 \cdot 10^4 \text{GeV}$
- Constrains validity of different interaction models
- ➔ constraint of physics of hadronic interactions at the highest energies
- Astroparticle physics measurements can be used to constrain models at the highest energies



P Abreu *et al.*, *Phys. Rev. Lett.* (2012)

The Muon Puzzle

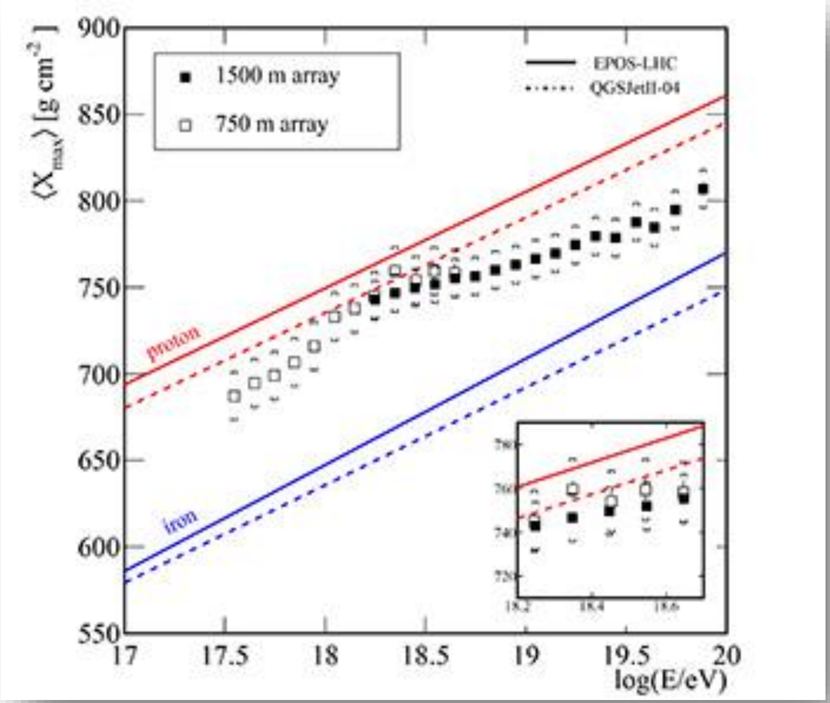


Excess of muons in the data with respect to the simulations ($\Delta z > 0$)

Need to understand first interaction vertex in atmosphere to solve puzzle

Affects accelerator data as well

Observables of air showers dependent on first interaction models



The Pierre Auger Collaboration, Phys. Rev. D 96, 122003 (2017)

Important to understand first interaction models to disentangle cosmic-ray composition (p to Fe) and this way to identify cosmic-ray sources

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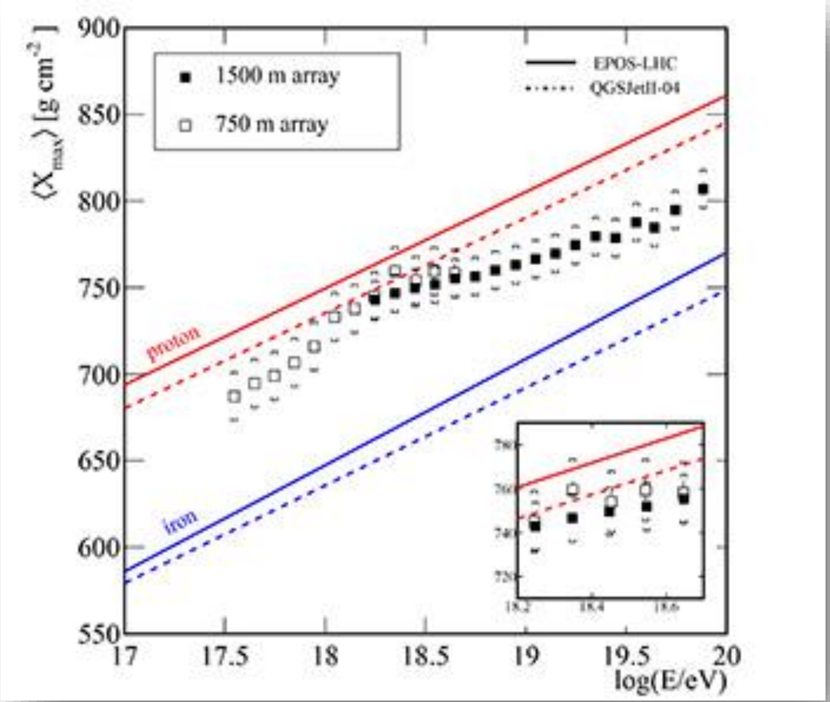

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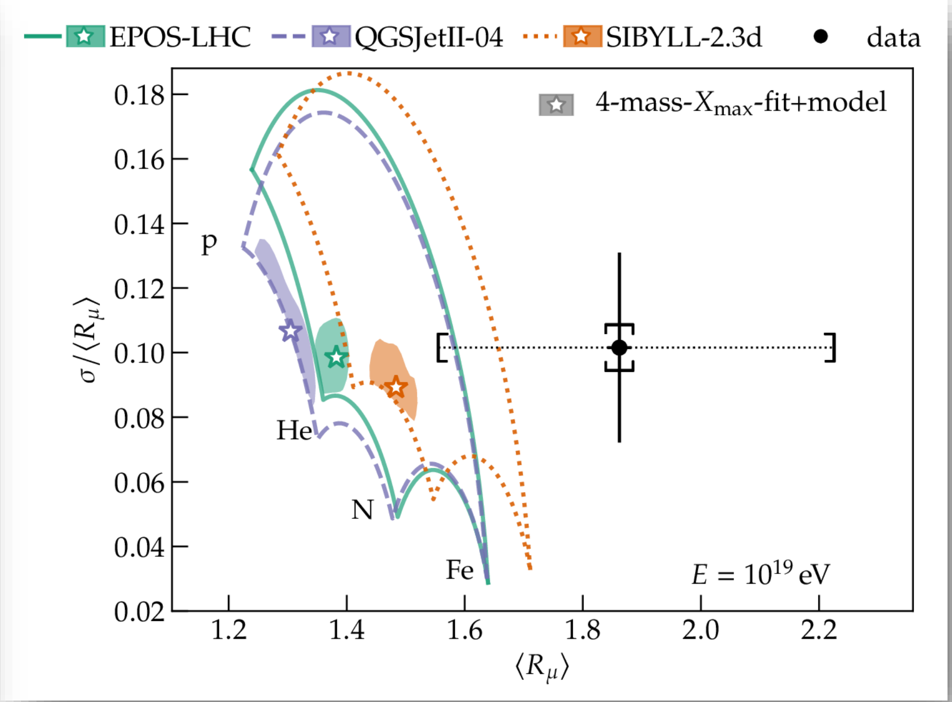
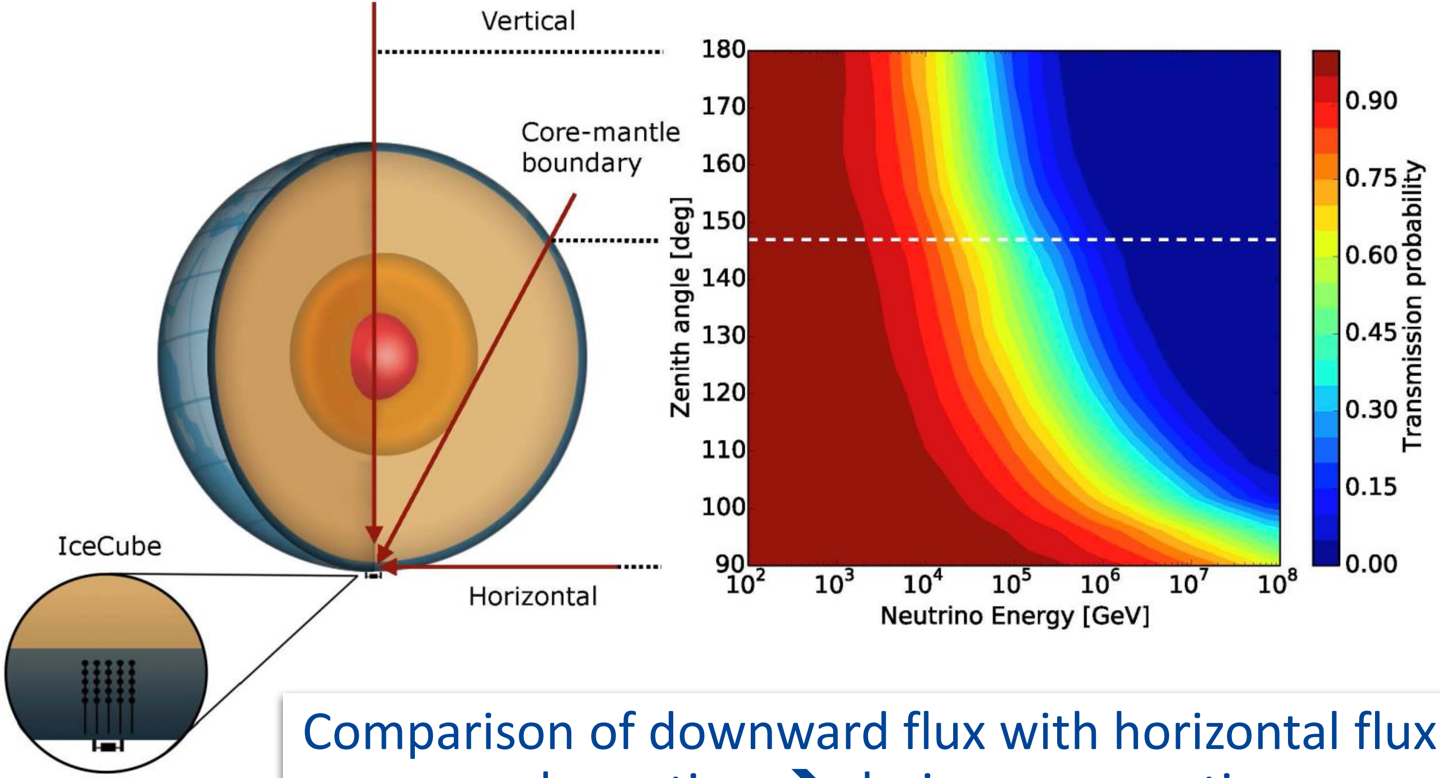


The Pierre Auger Collaboration, Phys. Rev. Lett. 126, 152002 (2021)

Important to understand first interaction models to disentangle cosmic-ray composition (p to Fe) and this way to identify cosmic-ray sources

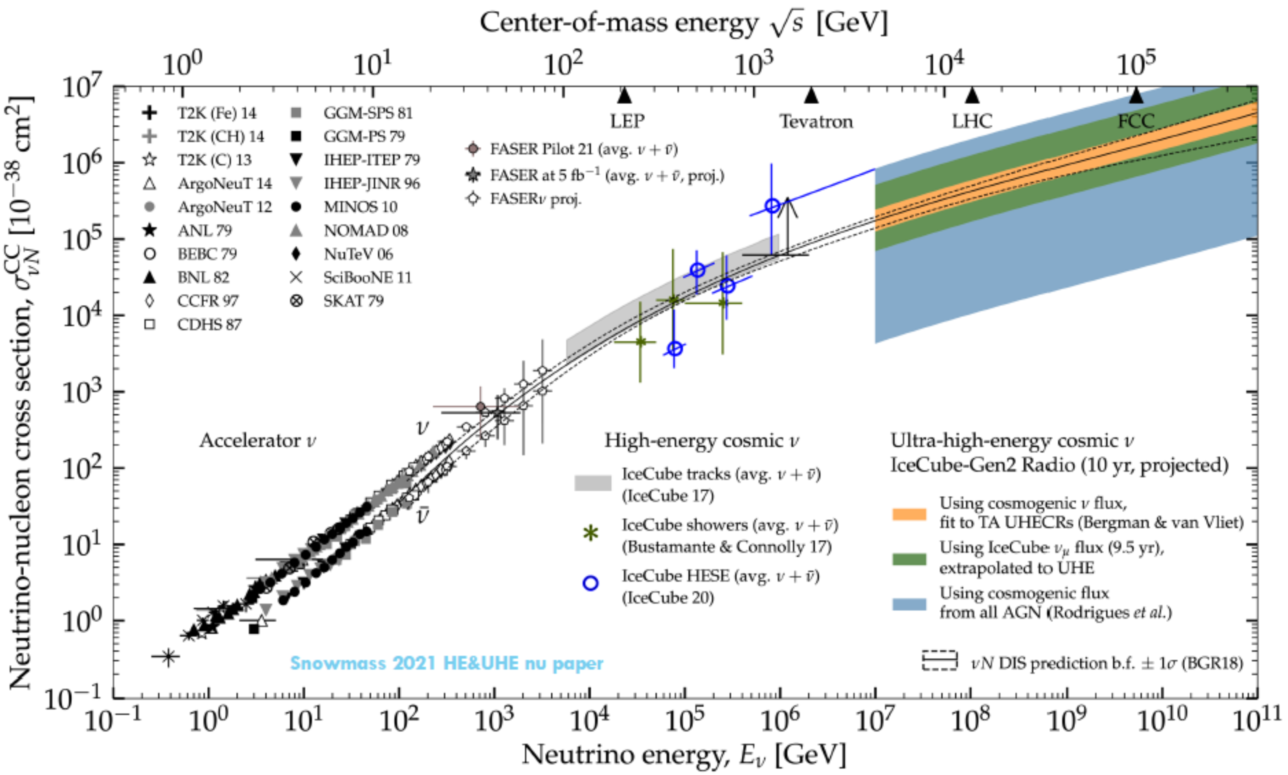
νN cross section at 10^5 GeV with IceCube



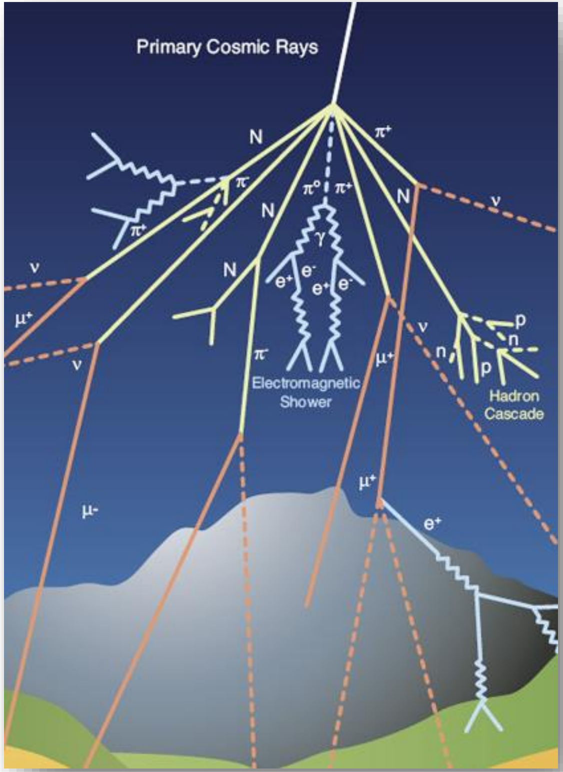
Comparison of downward flux with horizontal flux ➔ measure absorption ➔ derive cross section

Neutrino cross section measurements

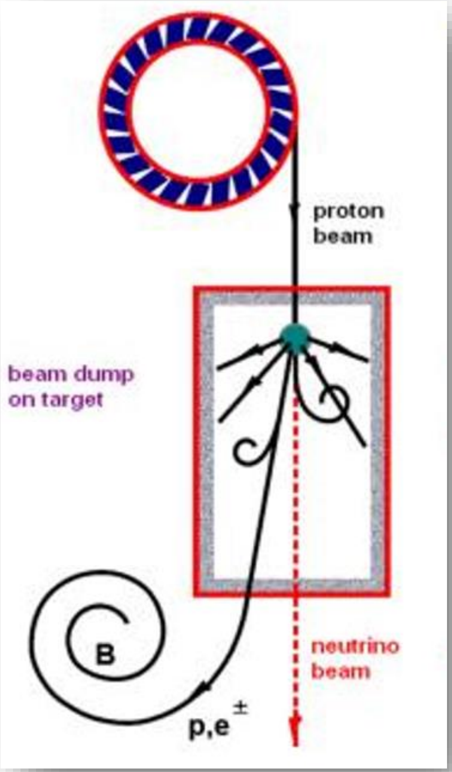
DIS to probe inner structure of proton – IceCube contributes to constrain pdfs by constraining the neutrino cross section at the highest energies



Summary Atmosphere + Accelerator

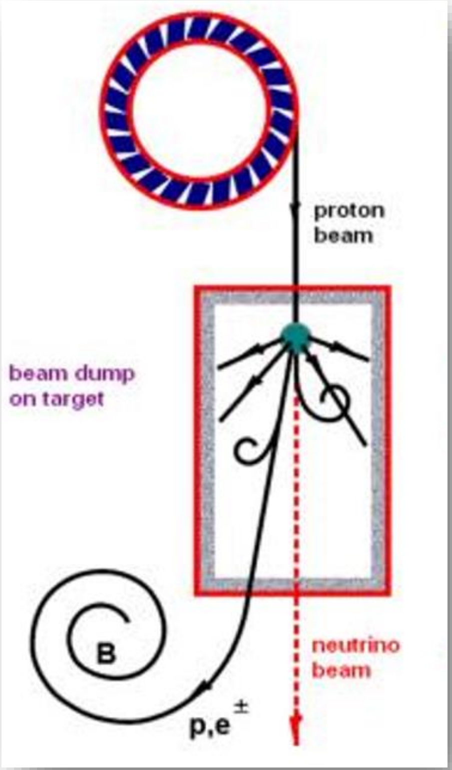


- Cross-section measurements start to constrain models at the highest energies & reveal problems (Auger/IceCube)
- Observables can be used to tune MC and to improve theory
- Observations might reveal BSM physics in the future



Part II Accelerator and Astrophysics

Particle Accelerator



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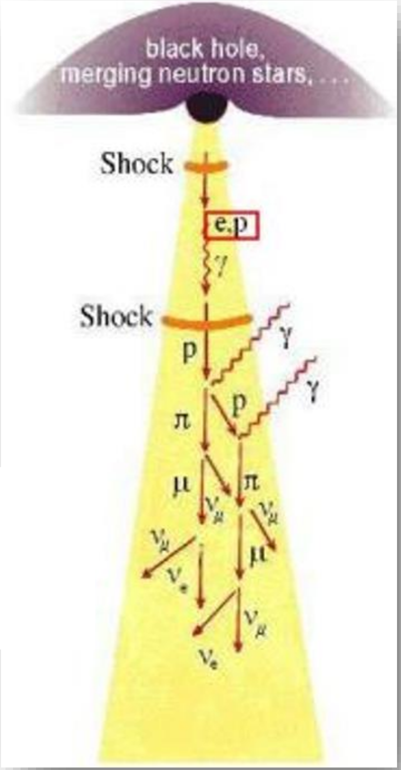
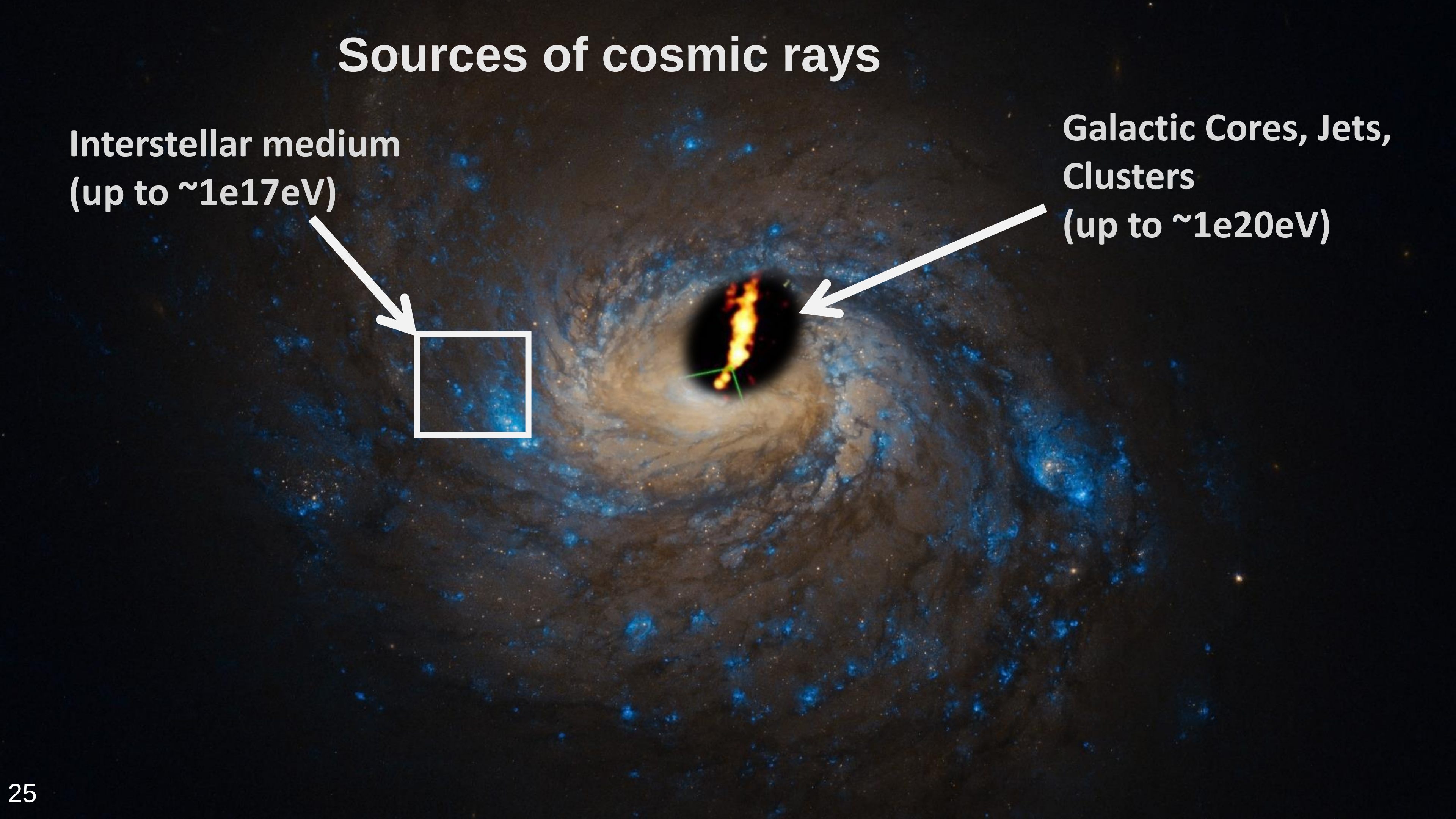
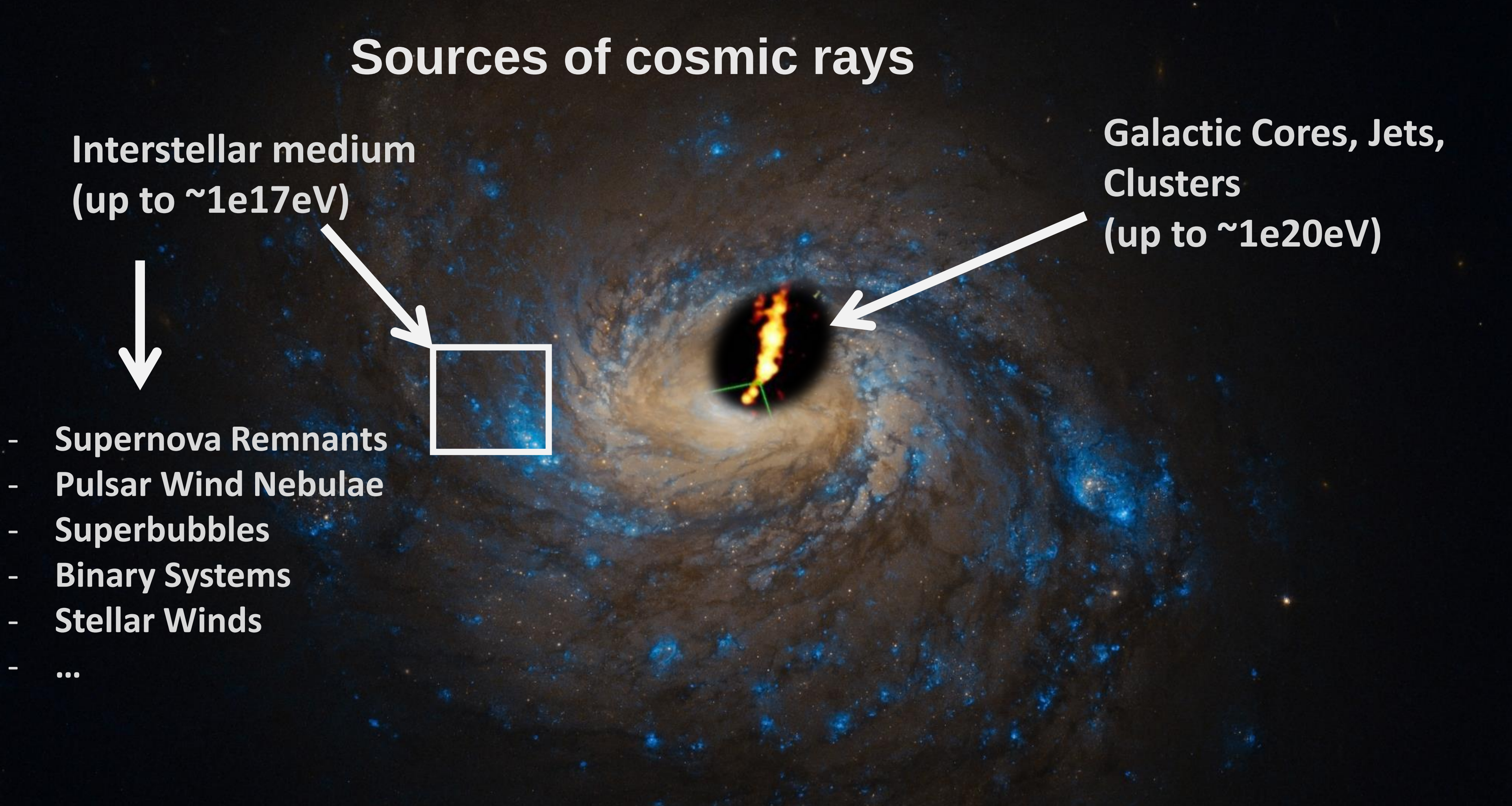


Sources of cosmic rays




Sources of cosmic rays
Interstellar medium
(up to ~1e17eV)
- Supernova Remnants
- Pulsar Wind Nebulae
- Superbubbles
- Binary Systems
- Stellar Winds
- …
Galactic Cores, Jets,
Clusters
(up to ~1e20eV)

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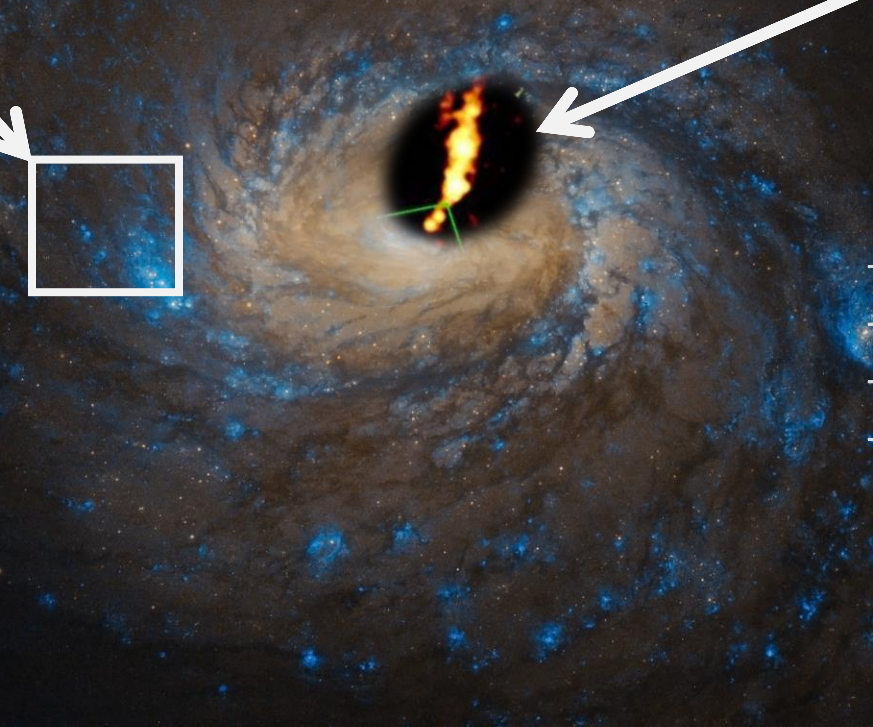

Galactic Cores, Jets, Clusters (up to ~1e20eV)

- Jets in active Galaxies
- Core of active Galaxy
- Gamma-ray bursts
- Galaxy Clusters

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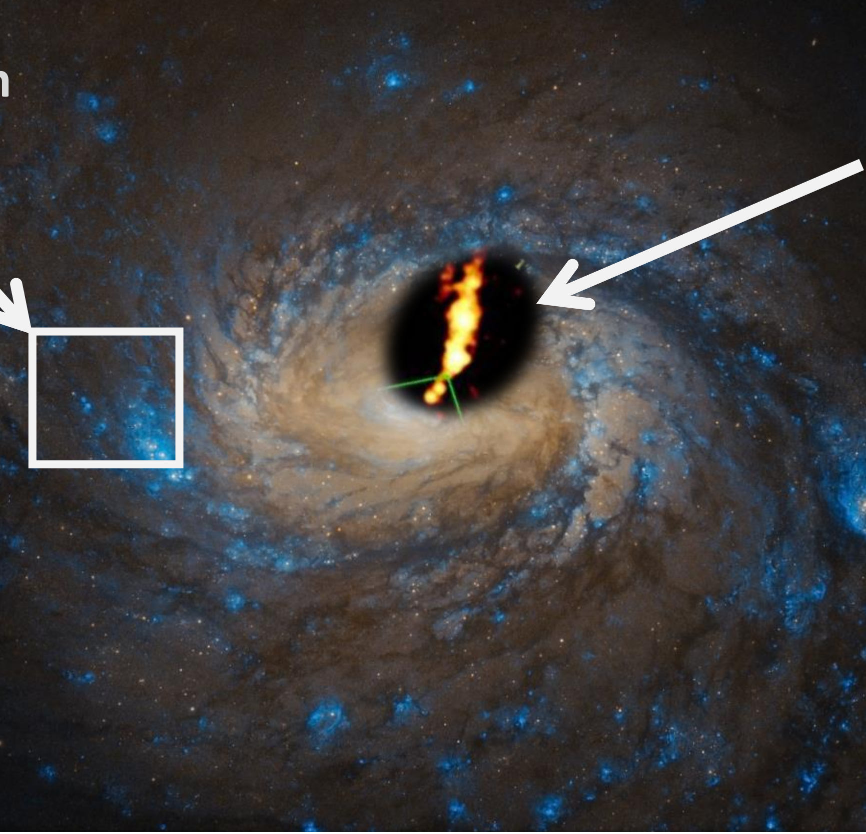

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(up to ~1e20eV)

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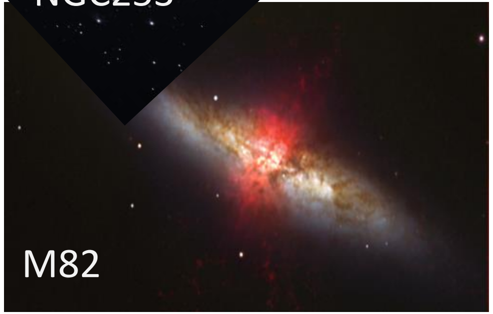
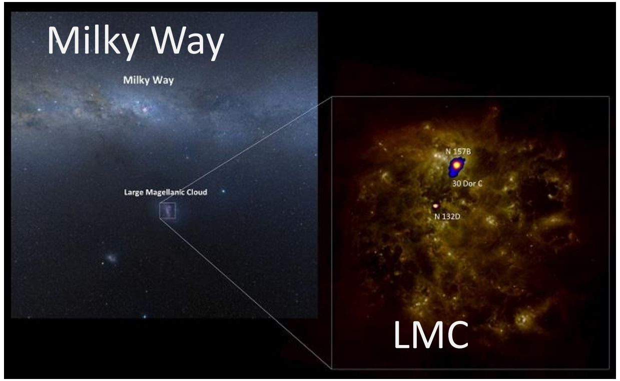
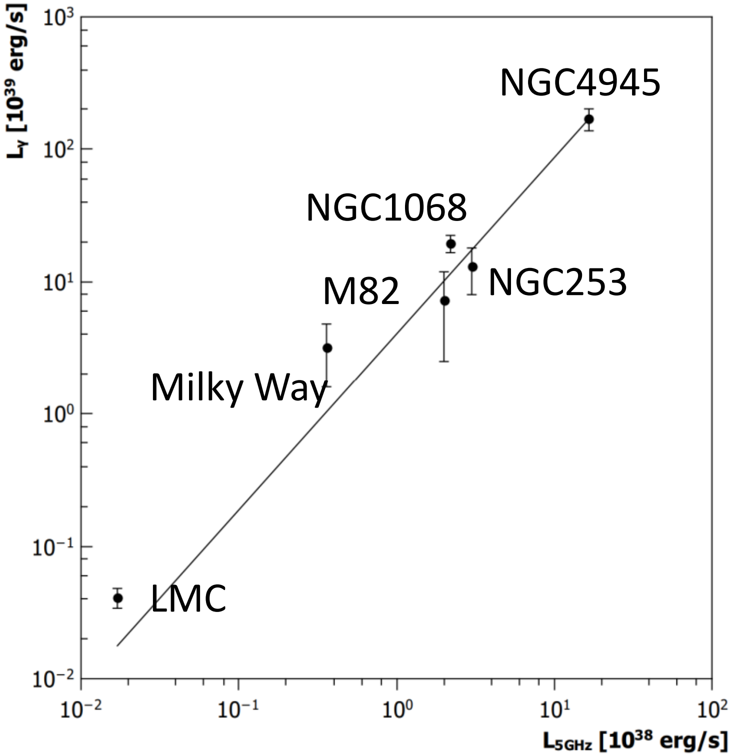
Here: test of CRs from ISM and AGN cores/jets by multimessenger detection

Cosmic-ray secondaries from ISM: starburst galaxies







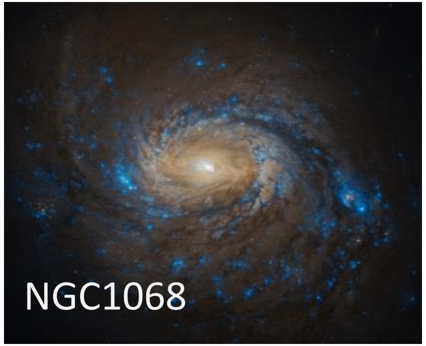


Fig: JKB, Multifrequency view of starburst galaxies, Vulcano Conference 2011

Cosmic-ray secondaries from ISM: The Milky Way

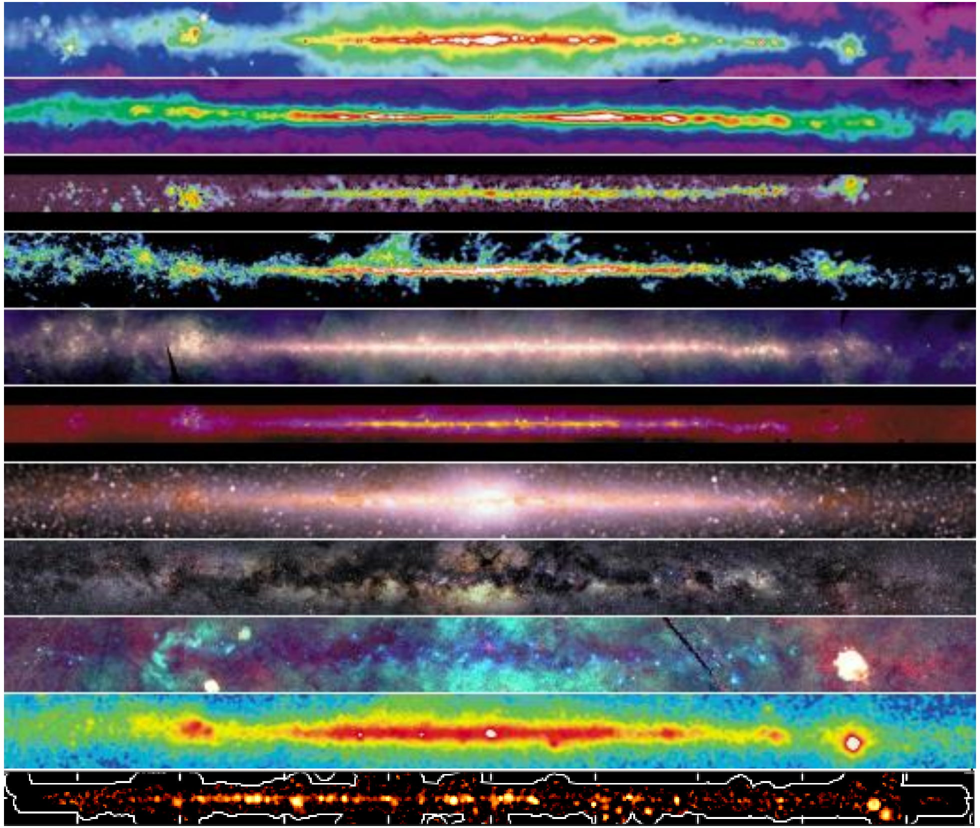


Fig: NASA & H.E.S.S. Galactic Plane Survey

Cosmic-ray secondaries from ISM: The Milky Way

- Diffuse emission from CRs relatively well-described (p, IC, brems)
- BUT:
  - Central region still mismatch (astrophysics VS Dark Matter)
  - Many details that are in need of explanation (Fermi Bubbles, GC PeVatron, CR Gradient, …)
- Problem with Milky Way: sitting in the middle of the system makes observations (& interpretation) somewhat difficult

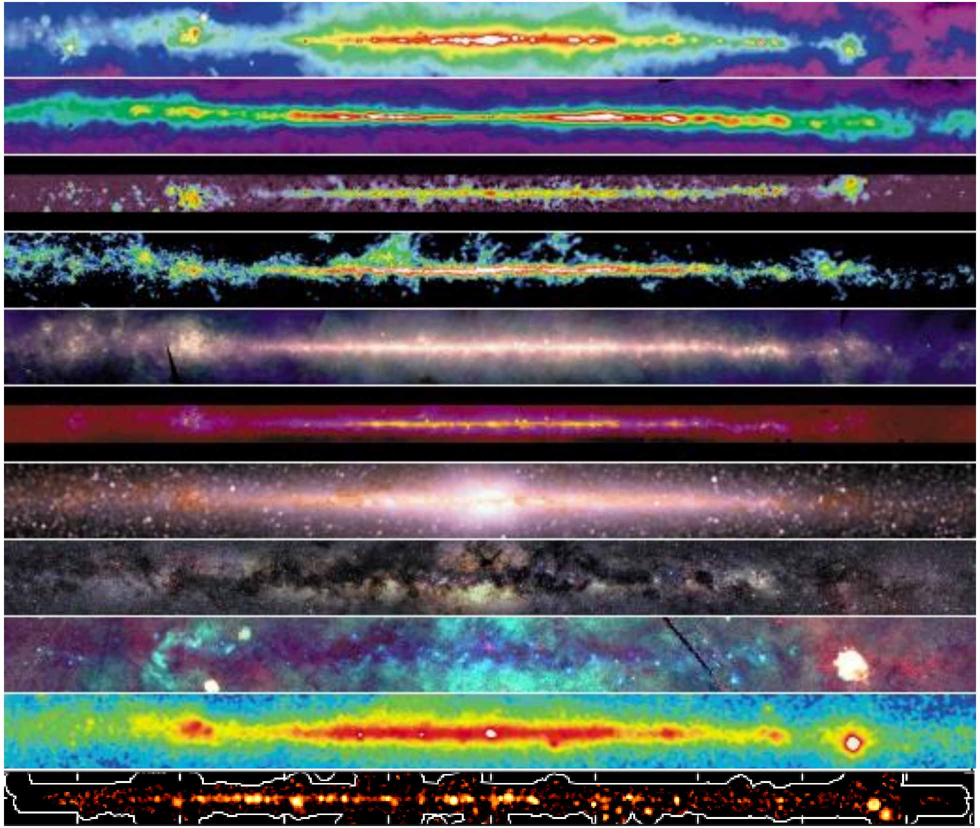


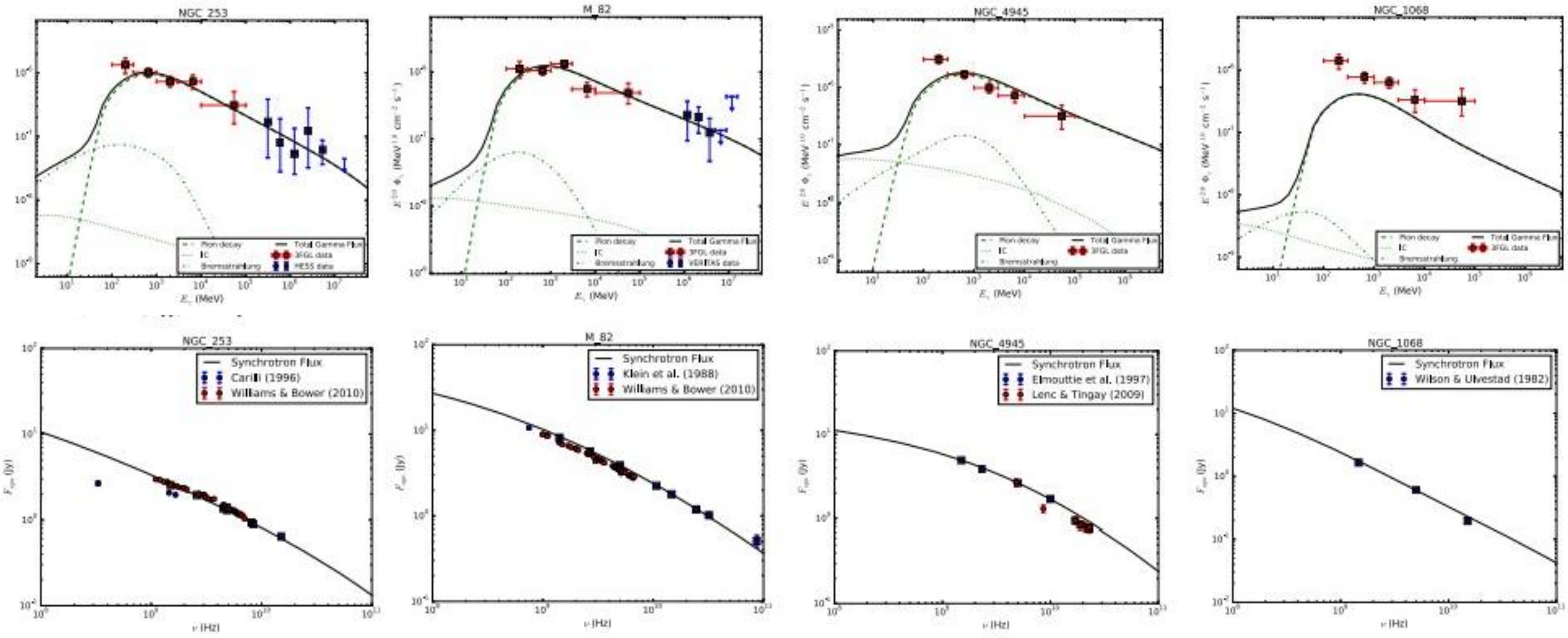
Fig: NASA & H.E.S.S. Galactic Plane Survey

Spiral galaxies – the starburst part

NGC253 | M82 | NGC4945 | NGC1068

Gamma

Radio



Eichmann & JBT, ApJ (2016)

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???

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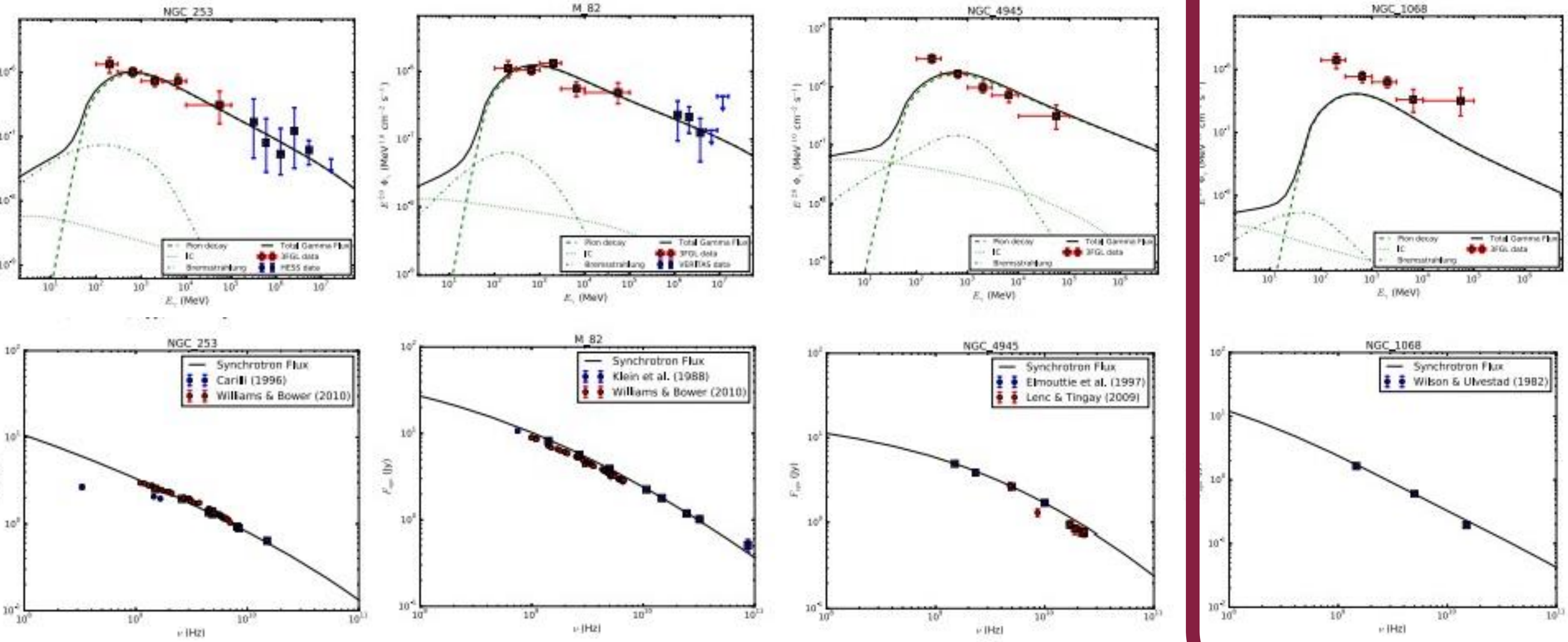
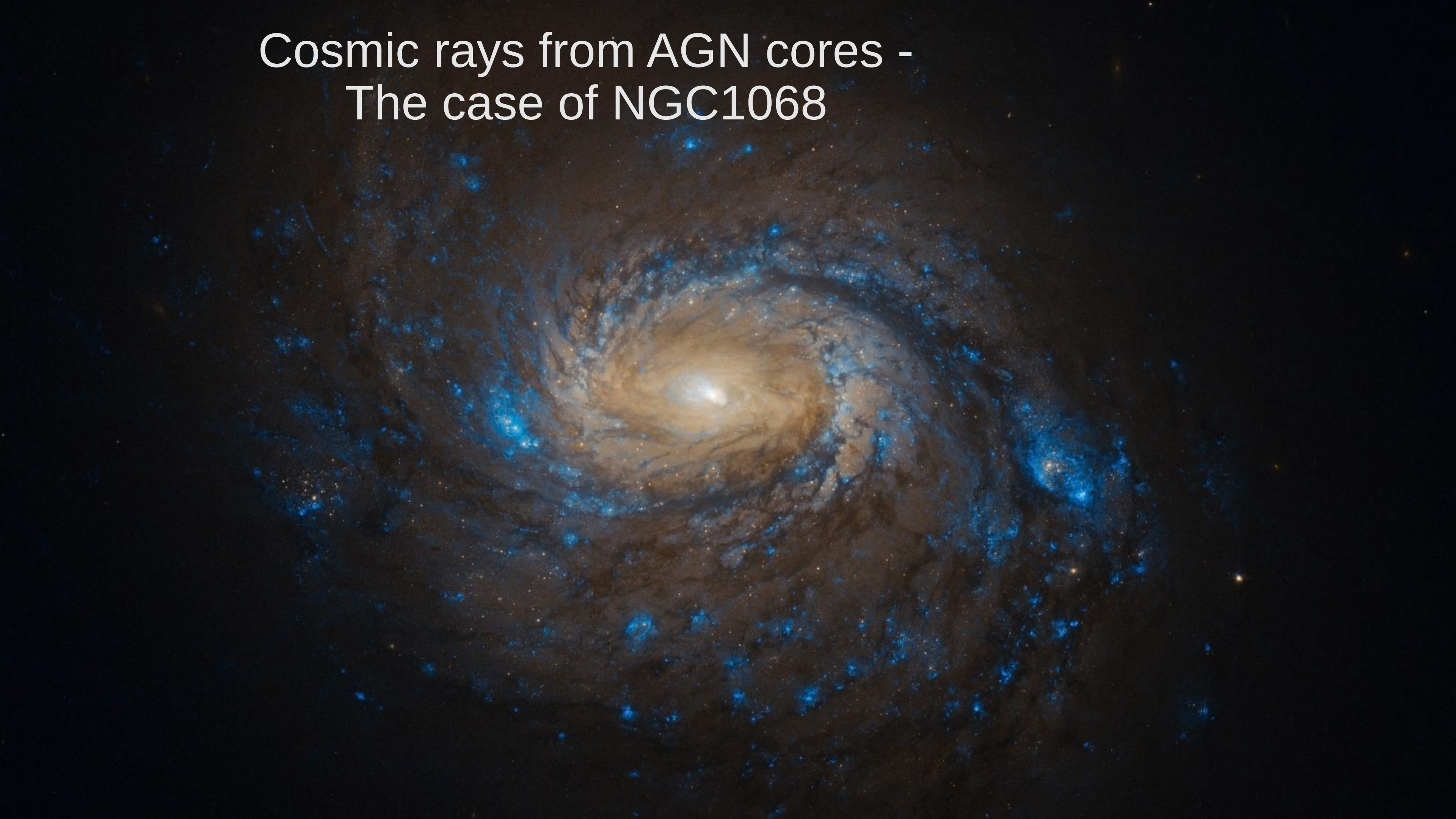


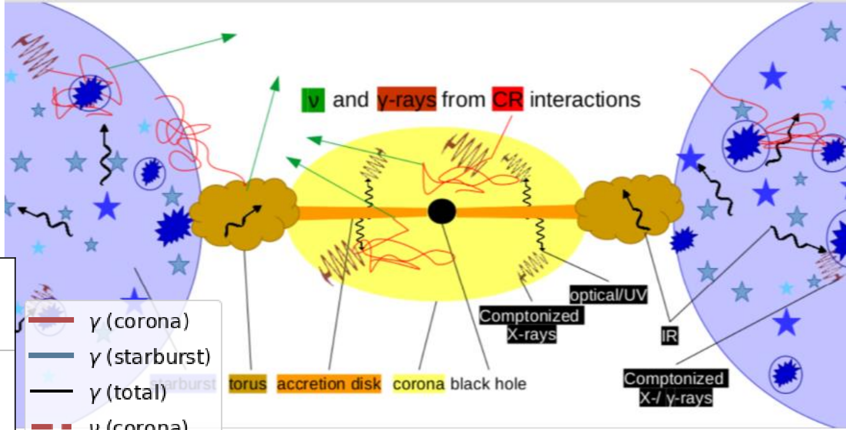
Eichmann & JBT, ApJ (2016)

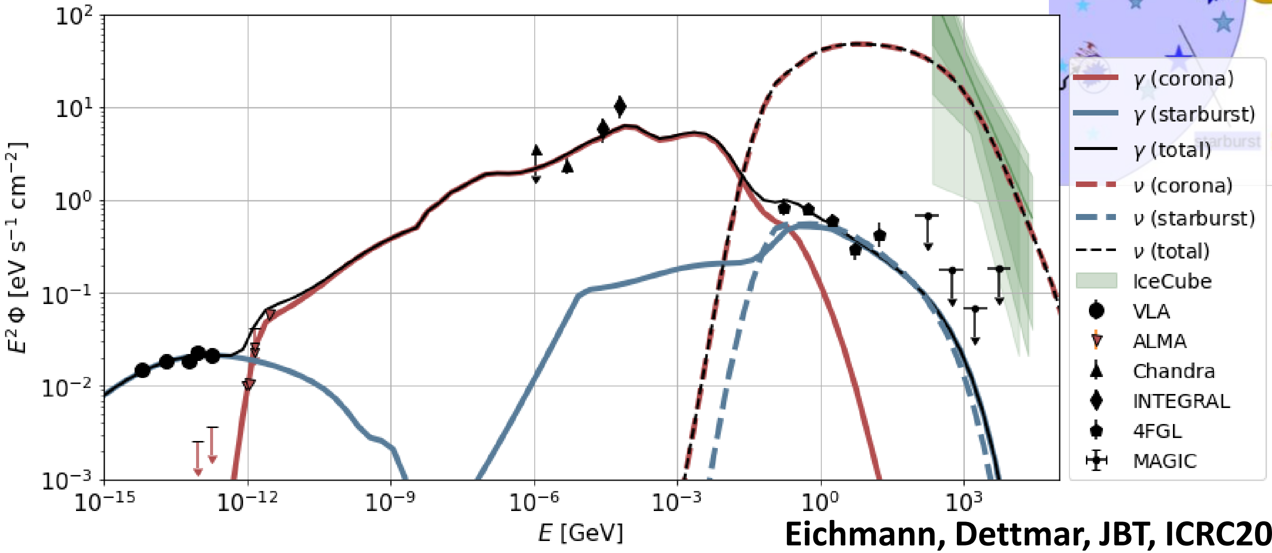
Cosmic rays from AGN cores -
The case of NGC1068



NGC1068: neutrinos in the multimessenger picture

- Multimessenger fit: combination of starburst + corona contribution

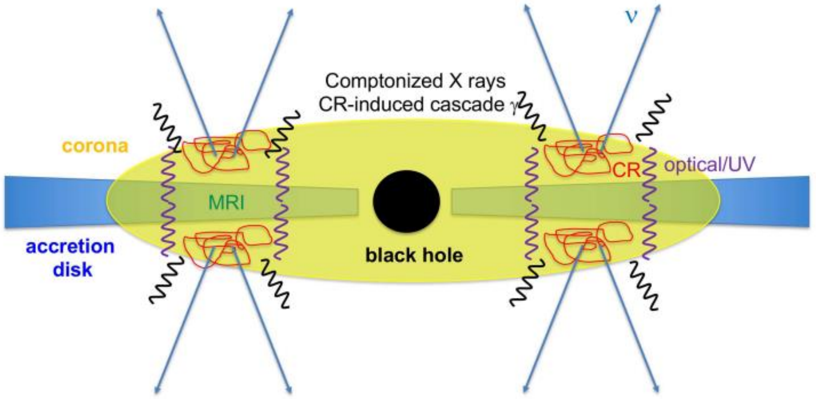




Eichmann, Dettmar, JBT, ICRC2021, 2108.06990

Eichmann, Oikonomou, Salvatore, Dettmar, JBT, A&A (Nov 2022)

NGC1068: Contribution from interactions with the disk Corona



Murase, Kimora & Mészárosz, PRL 125:011101 (2020)
See also further work by Kheirandish, Murase & Kimura, ApJ 922 (2021)

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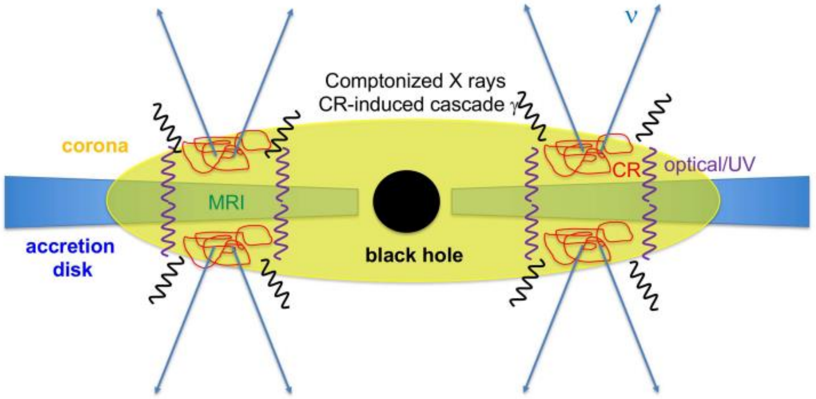

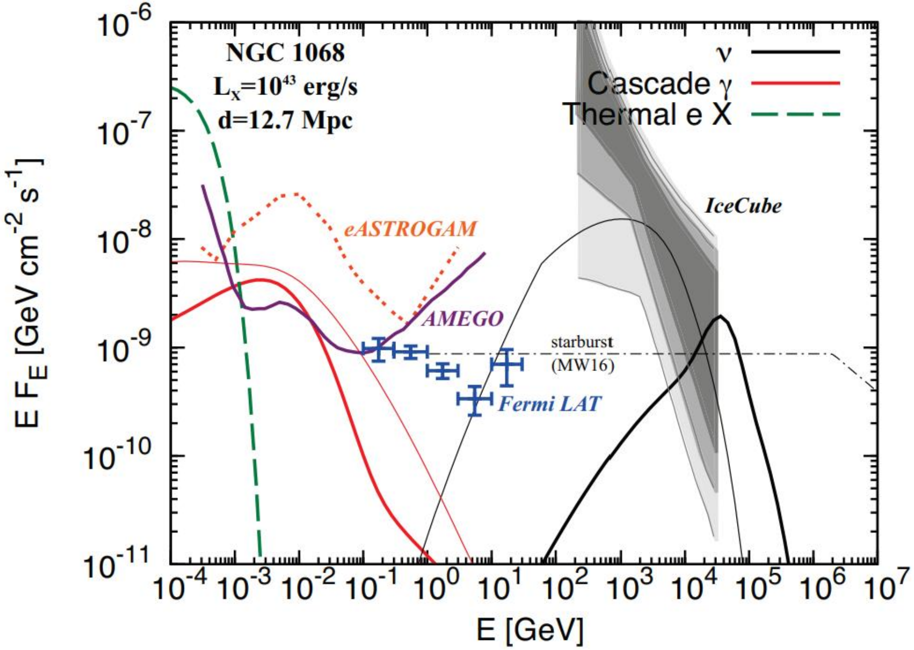

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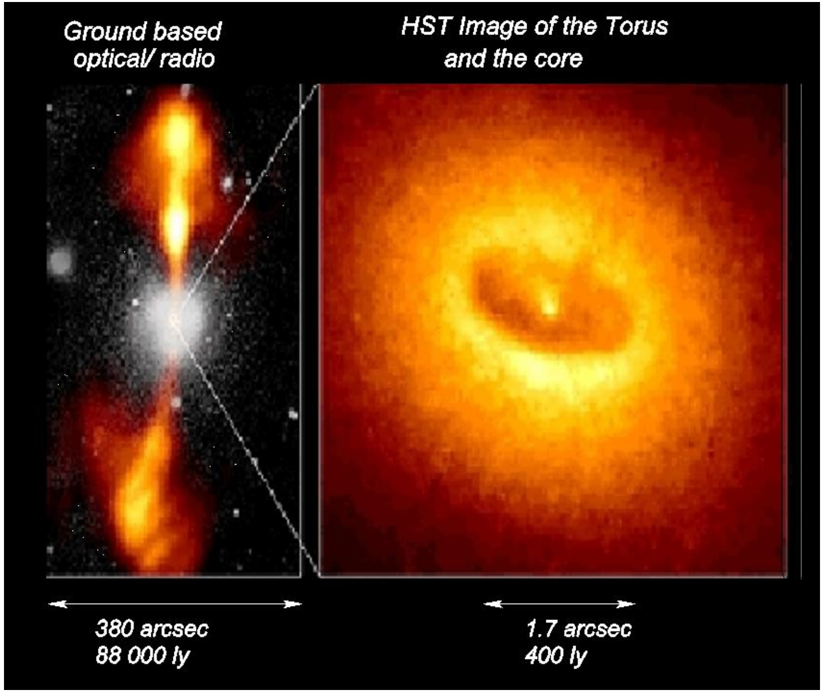
Cosmic rays from Jets of active Galaxies



NGC4042, Credit: Hubble

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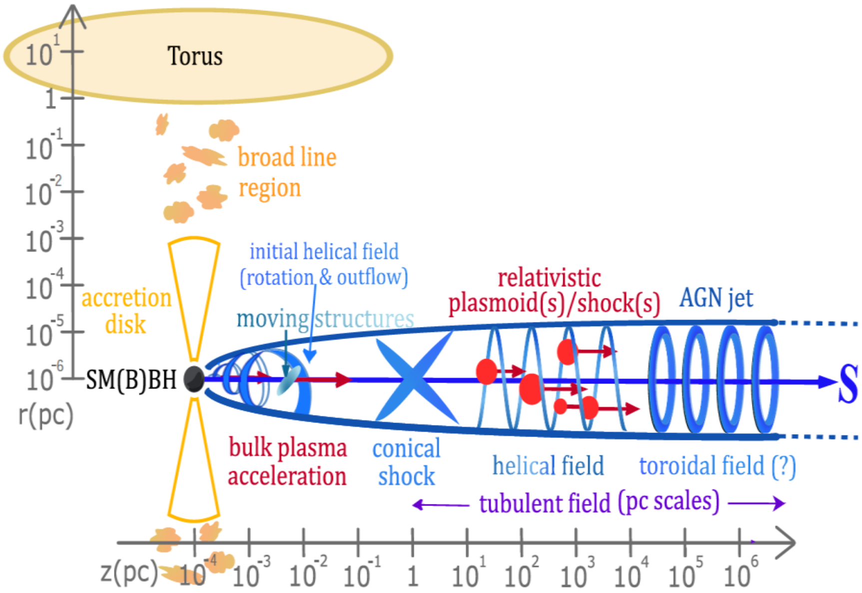
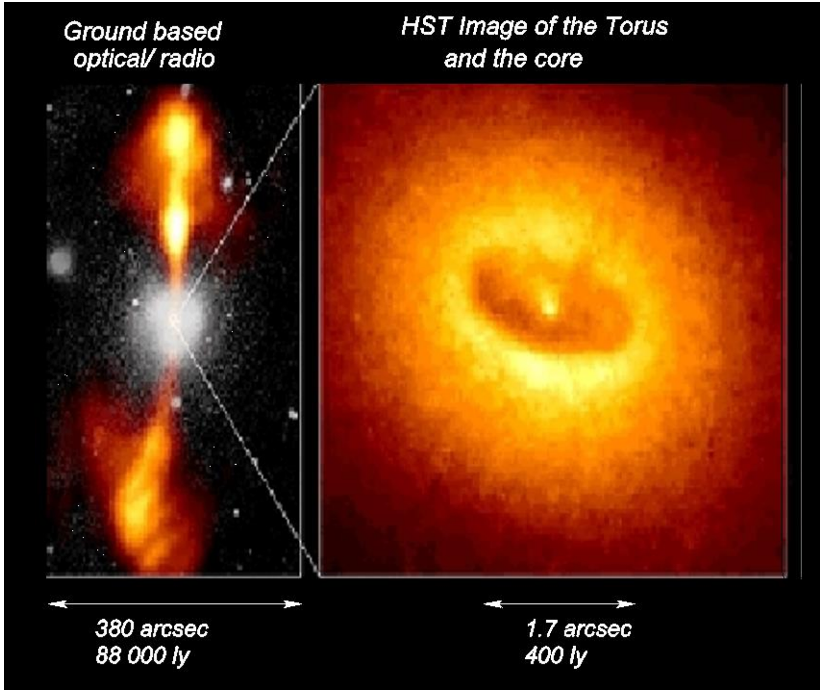


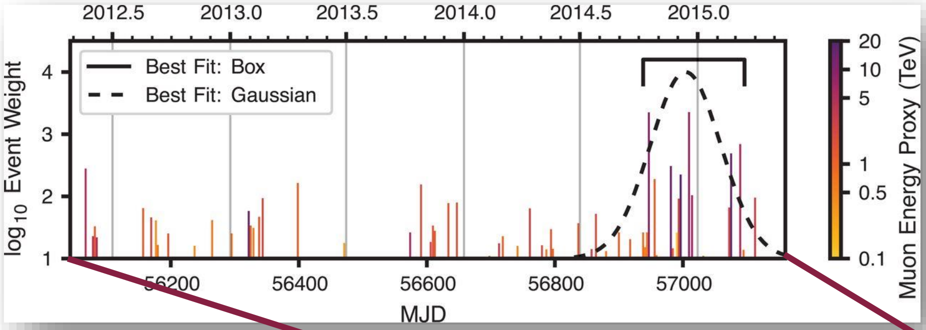
JBT et al, MDPI Physics (2022)



NGC4042, Credit: Hubble

Multimessenger emission with TXS0506+056

Neutrino excess @ ~3σ in 2014/2015



Aartsen et al (IceCube Coll), Science (2018)

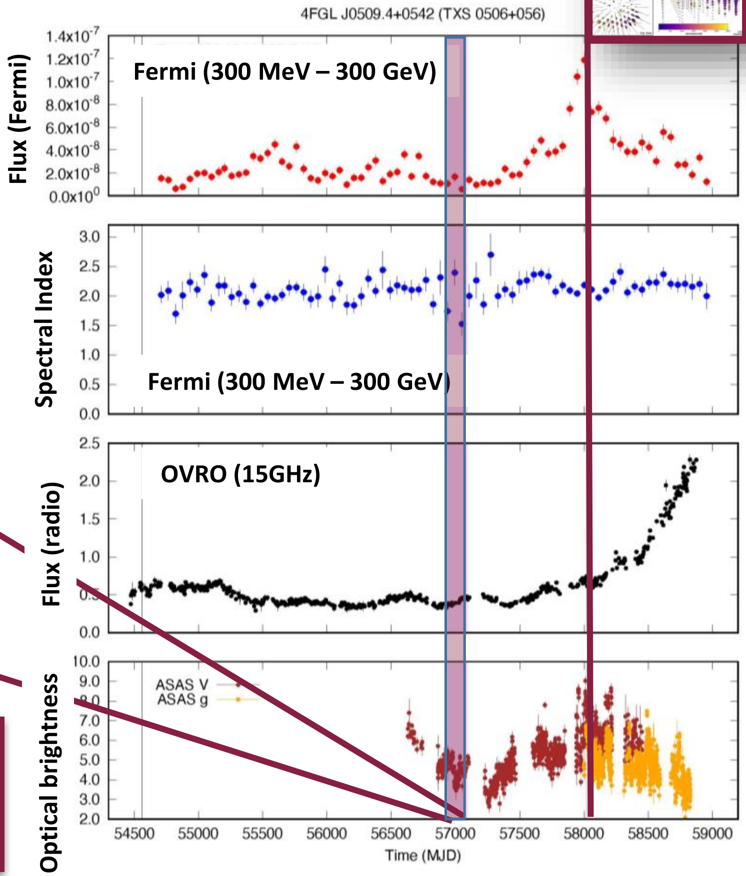
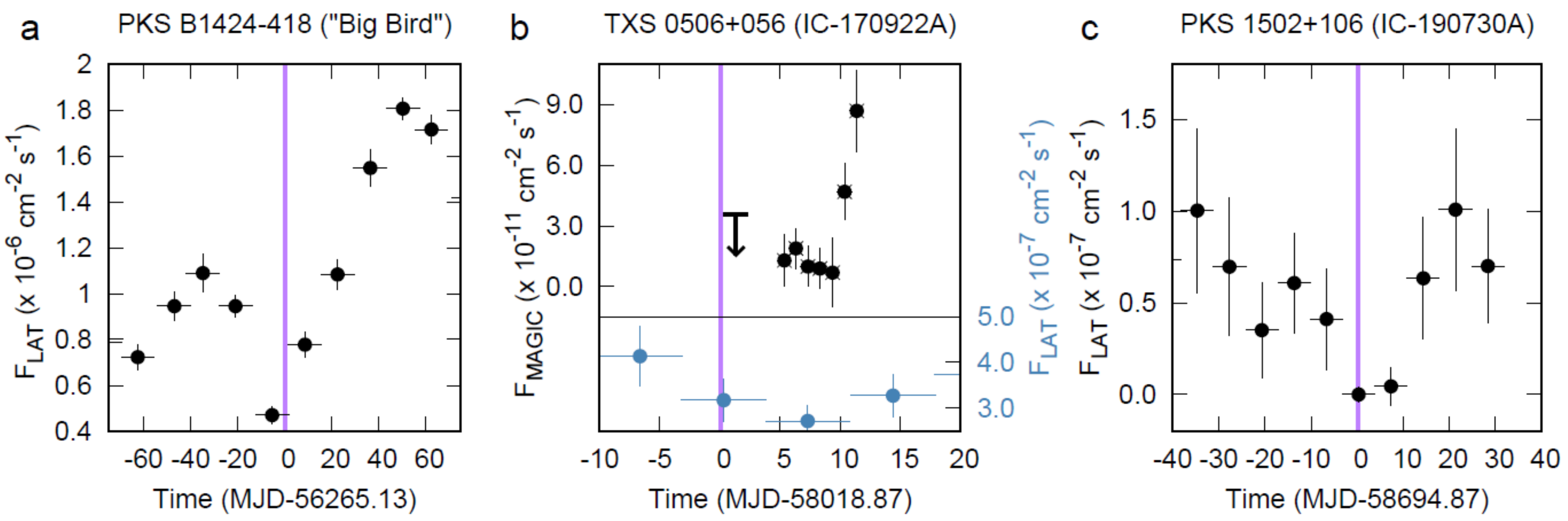


Fig: Emma Kun, Budapest

➔ Two potential neutrino flares of very different nature:
- ➔ 2014/2015: ~100 days long, ~10TeV in energy, no MM activity
- ➔ 2018: 1 neutrino with ~300TeV energy, coincident γ-ray flare

Time-domain of AGN

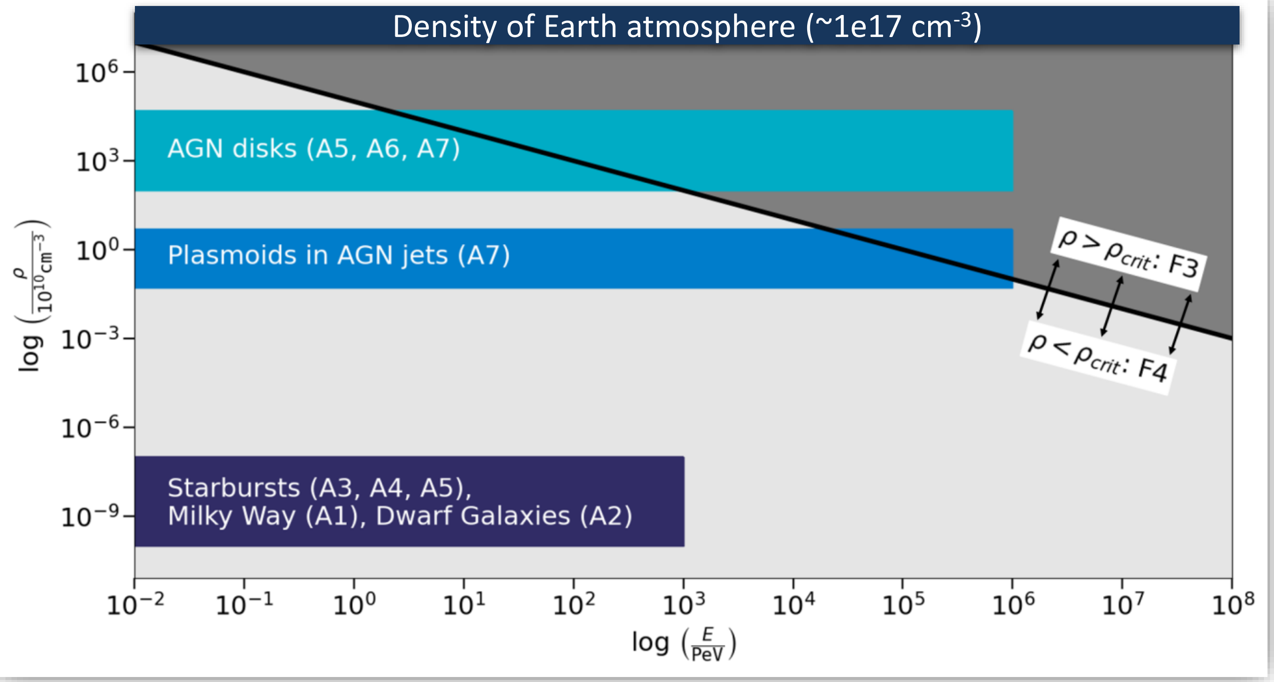


Neutrinos arrive in gamma-minima? Possible if gas density extreme: photon absorption

Kun, Bartos, JBT, Biermann, Halzen, Mez´´o ApJL (2021)

Charm-quark physics in astrophysics?

Precision measurements of hadronic interactions at the highest energies needed to understand particle fluxes from dense environment in the Universe



Charm-quark physics in astrophysics?

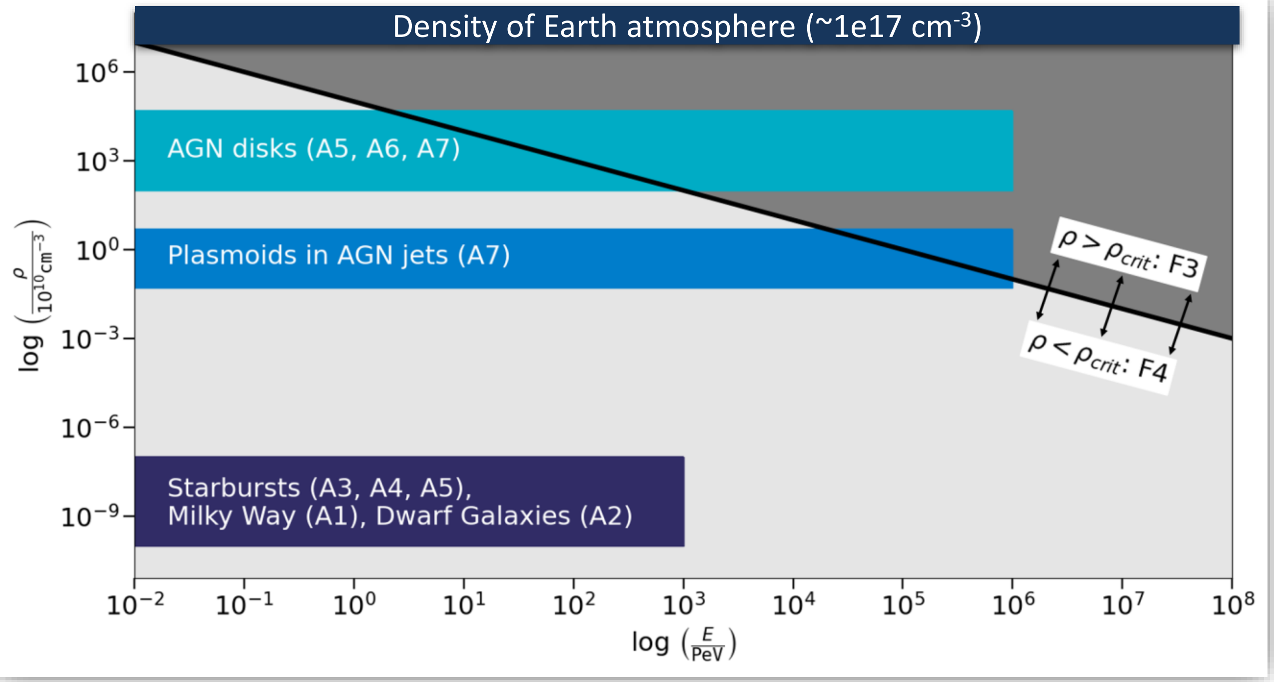
Precision measurements of hadronic interactions at the highest energies needed to understand particle fluxes from dense environment in the Universe

Critical density:

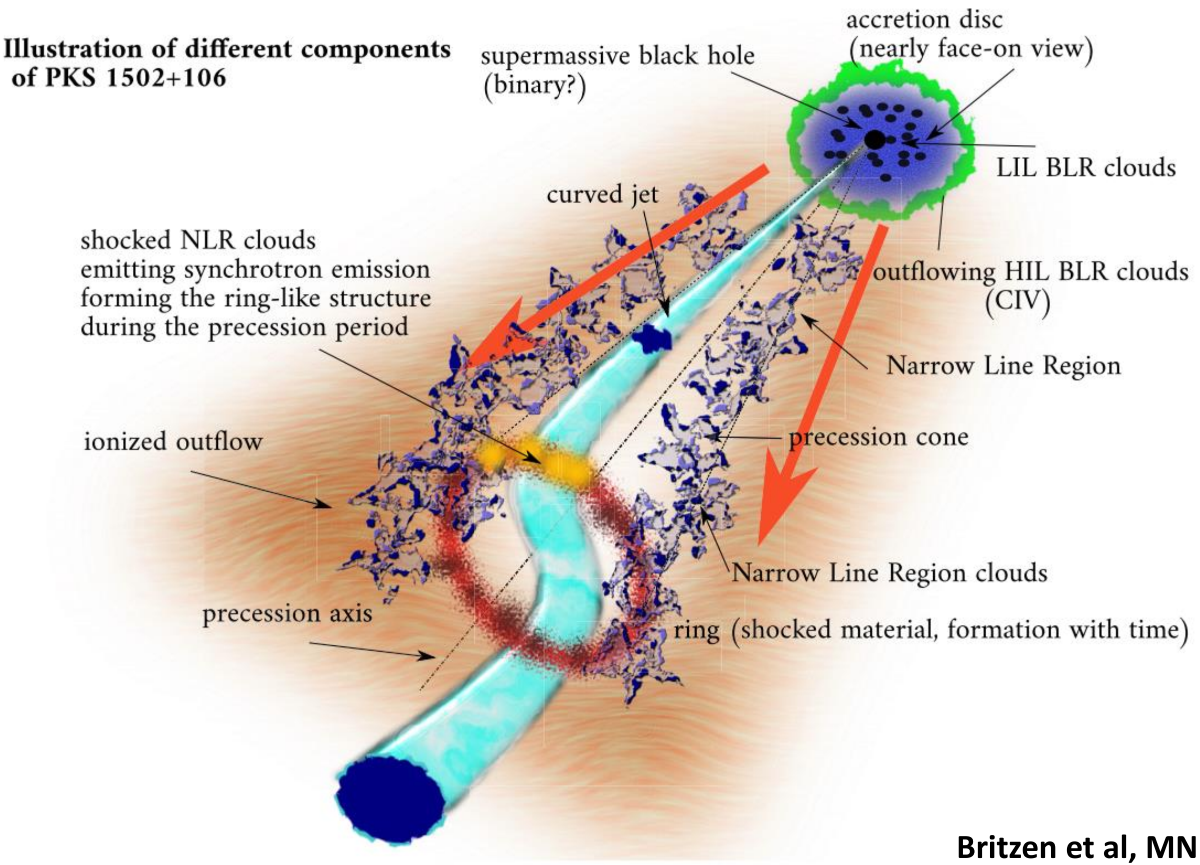
$$c \cdot \gamma \cdot \tau_{\pi^{\pm}} > \lambda_{mfp} = \frac{1}{\sigma \cdot \rho}$$

$\Rightarrow \pi$ absorption

➔ charm-flux revealed (as in Earth atmosphere)

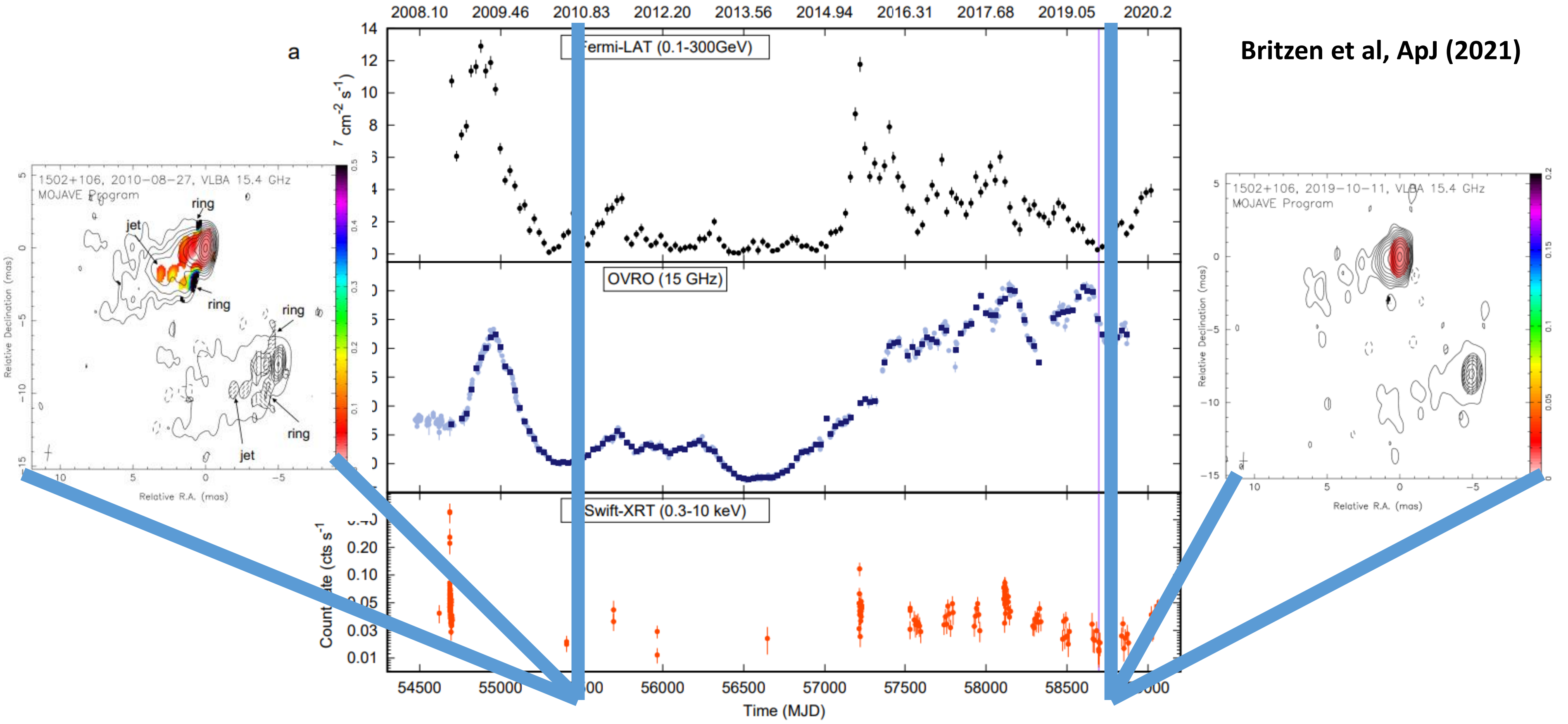


Example PSK1502+106: a curved, precessing jet?



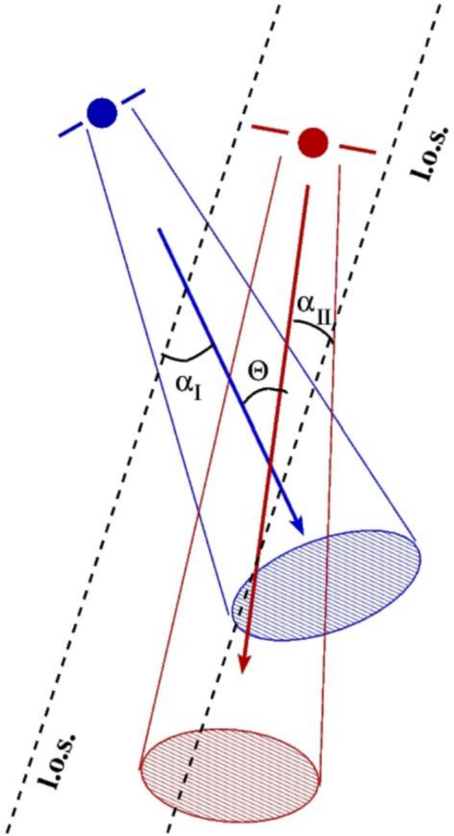
Britzen et al, MNRAS 503 (3): 3145 (2021)

PKS1502+106 – ν, γ, radio, polarization

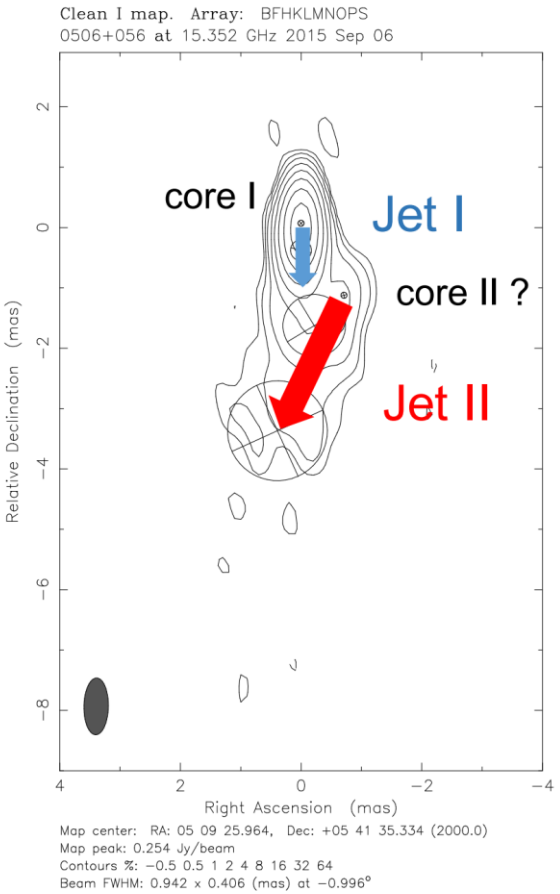


Britzen et al, ApJ (2021)

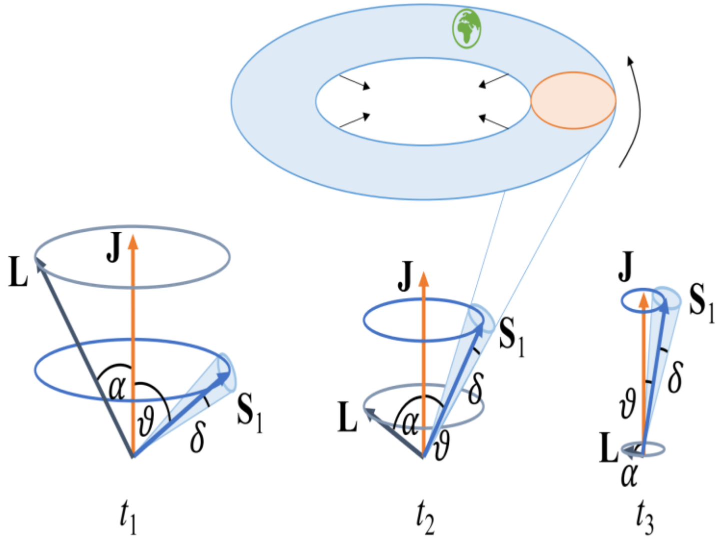
Example TXS0506+056: another precessing jet system?



Britzen et al, A&A (2019)



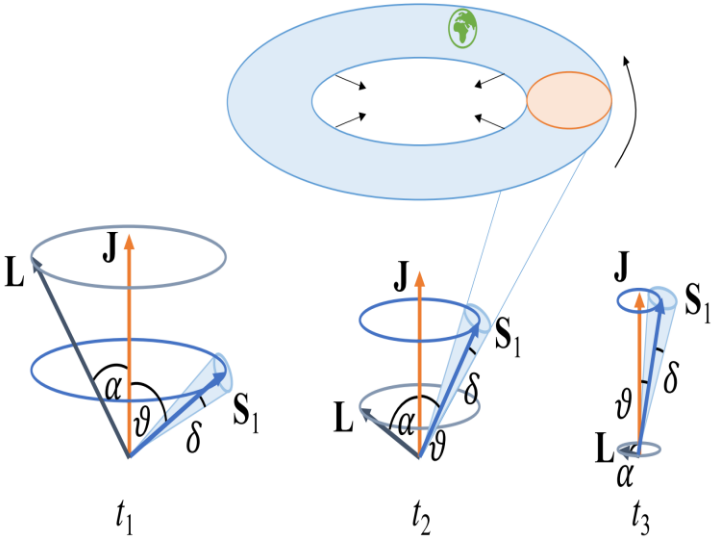
TXS0506+056 – a precessing jet?

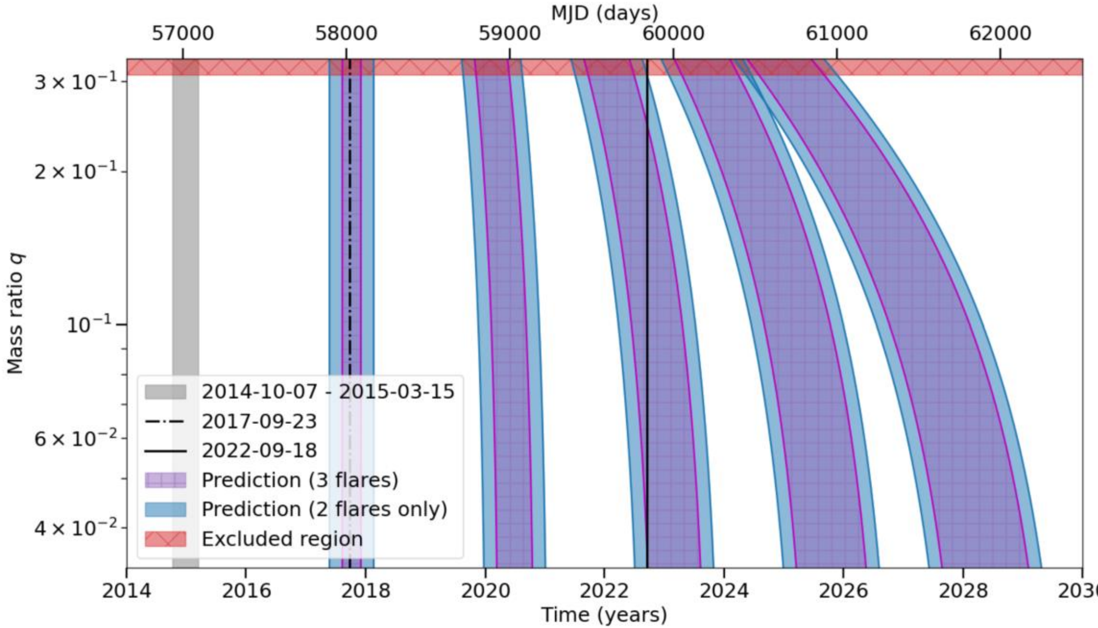


Gergely & Biermann, ApJ (2009)

deBrujin, Bartos, JBT, Biermann, ApJL (2020)

TXS0506+056 – a precessing jet?



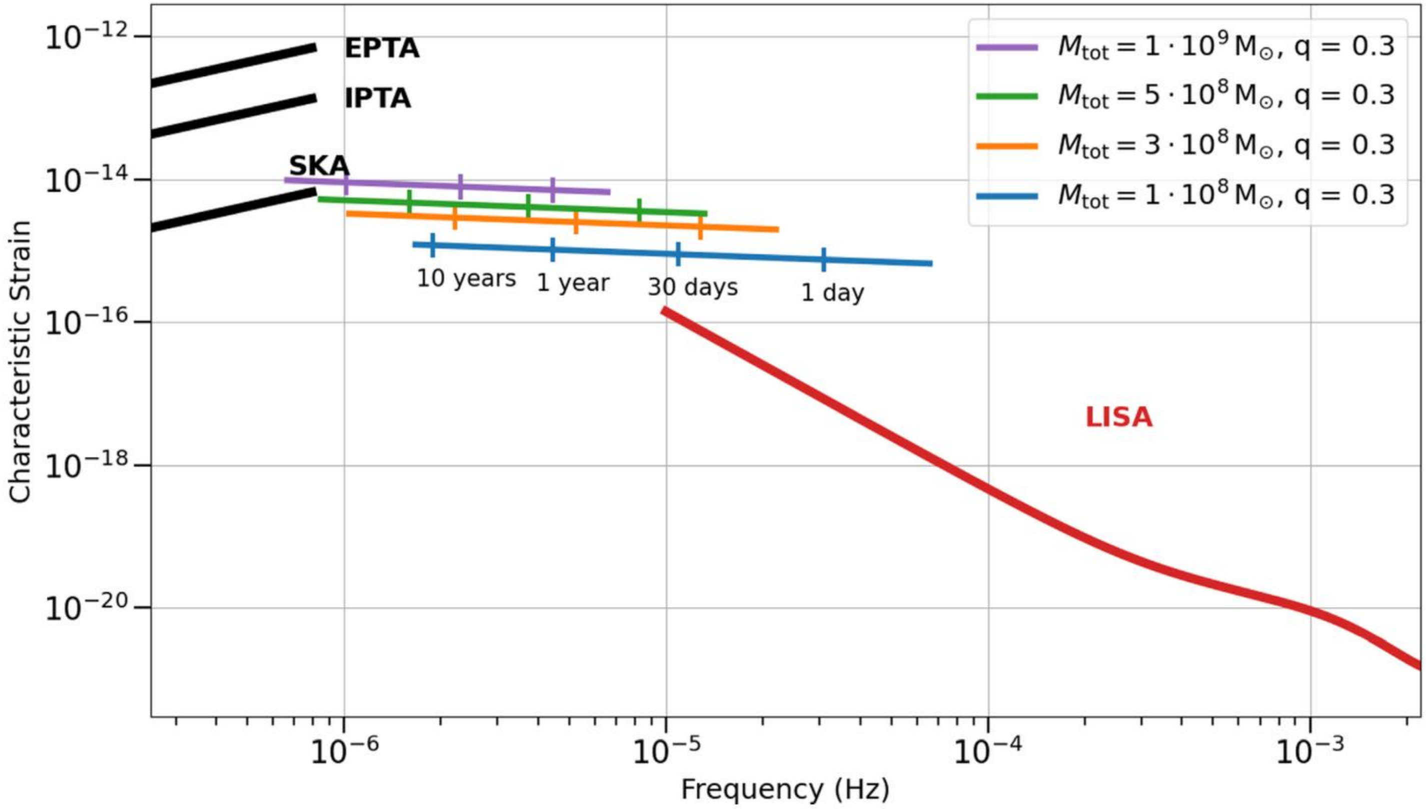


Gergely & Biermann, ApJ (2009)

deBrujin, Bartos, JBT, Biermann, ApJL (2020)

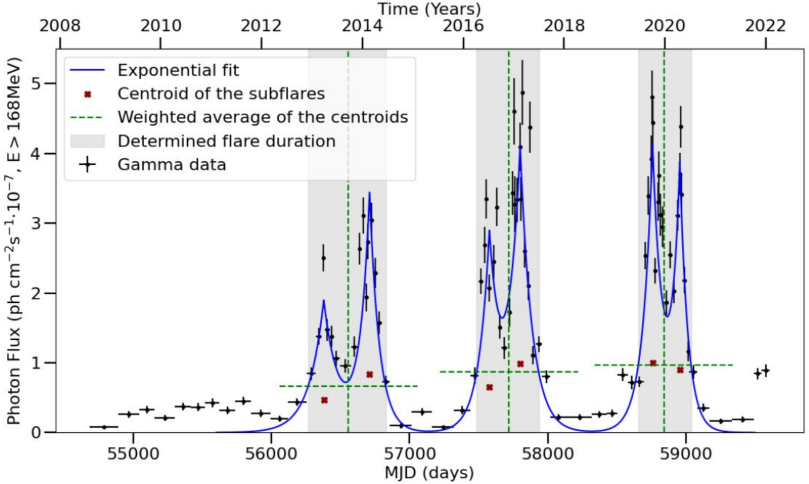
JBT, Jaroschewski, Ghorbanietemad, Bartos, Kun, Biermann (ApJL, Dec 2022)

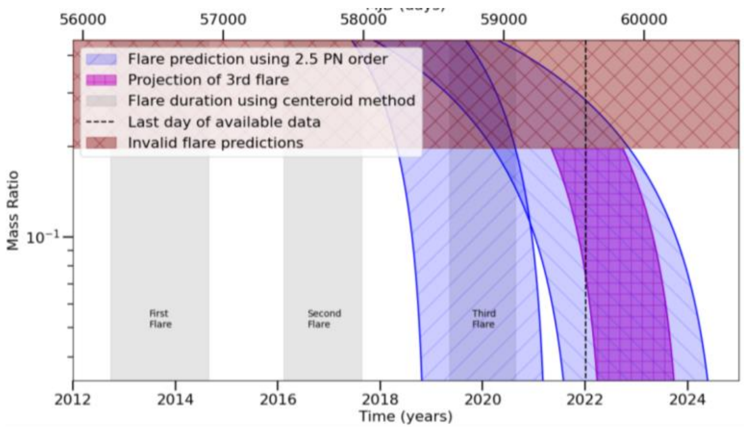
What if? – Gravitational Waves from TXS

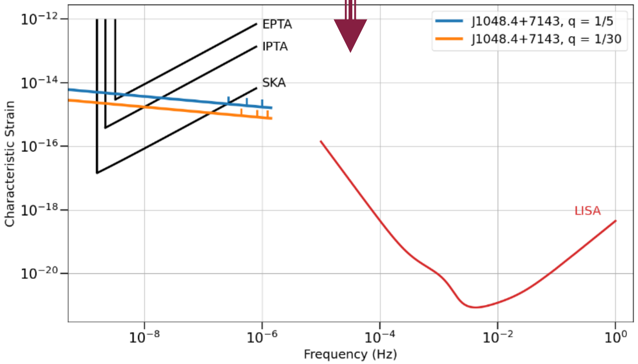


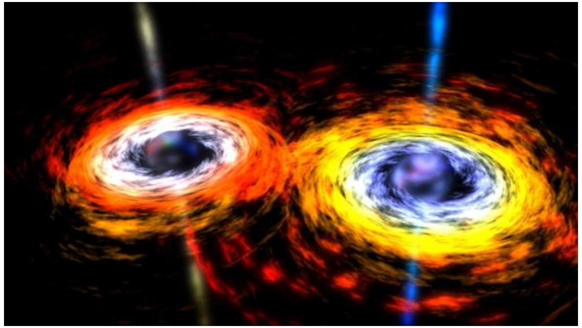
JBT, Jaroschewski, Ghorbanietemad, Bartos, Kun, Biermann (ApJL, Dec 2022)

ν/γ-GW-connection for more SMBBHs – a future perspective



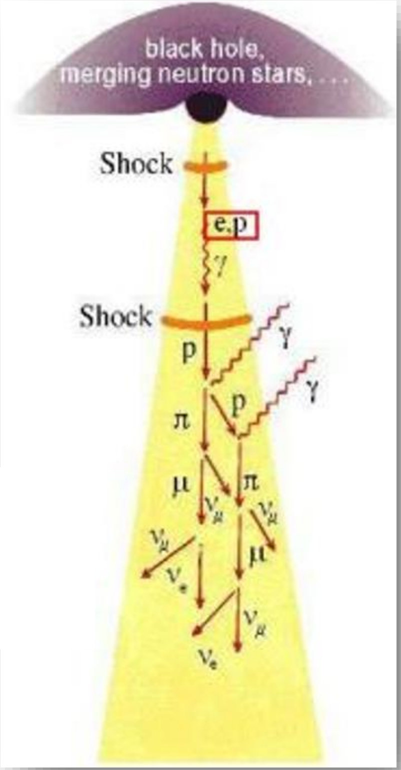






Kun, **…**, **JBT**, et al, ApJ (Dec 2022)

Summary Astro + Accelerator

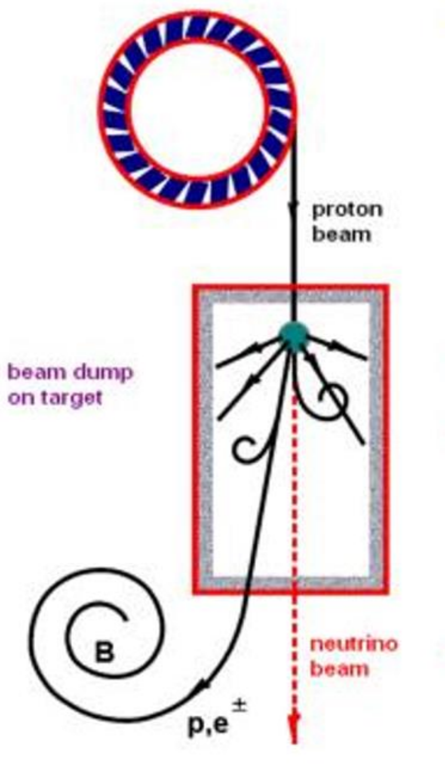


Consistent picture: astrophysical neutrinos >> astrophysical γ-rays

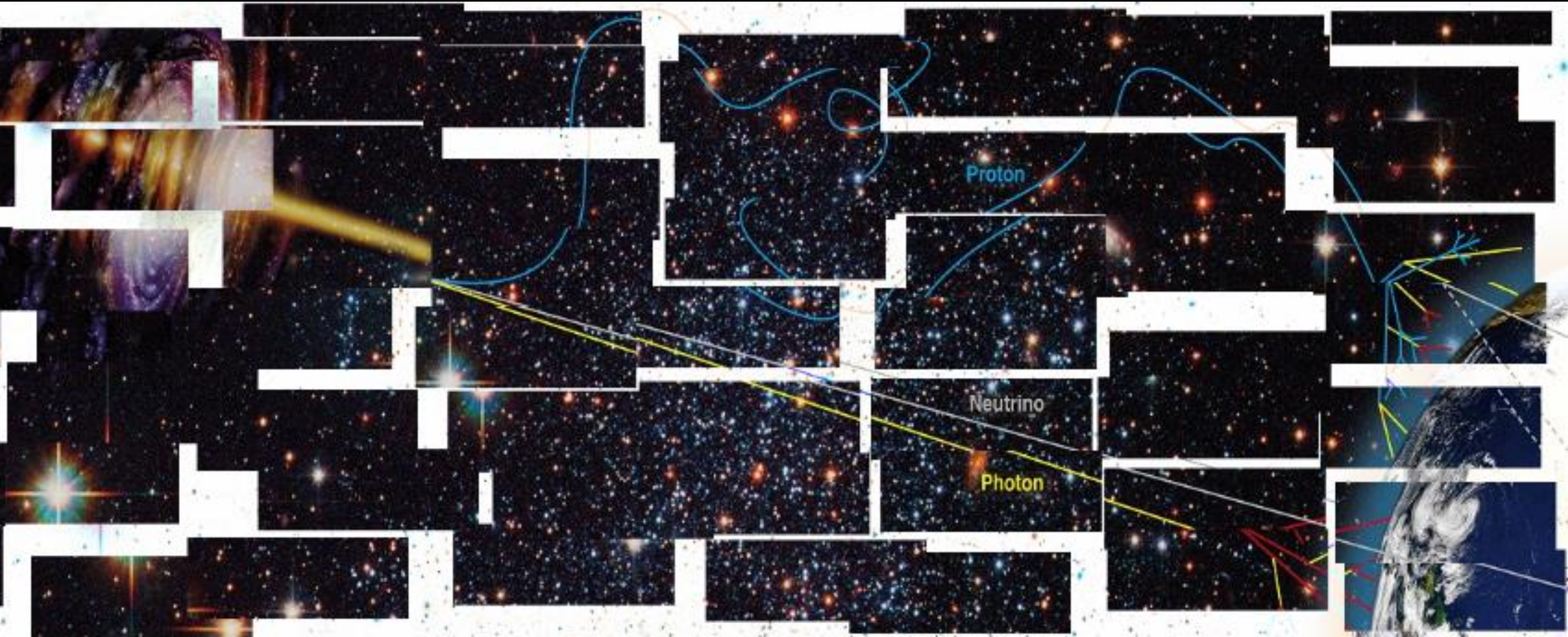
➔ Requires environments of γ-ray absorption ➔ extreme densities

➔ Particle fluxes with short decay timescales become relevant

➔ Future opens up for particle physics with cosmic accelerators



Multimessenger astrophysics:
a puzzle for physicists



Multimessenger astrophysics:
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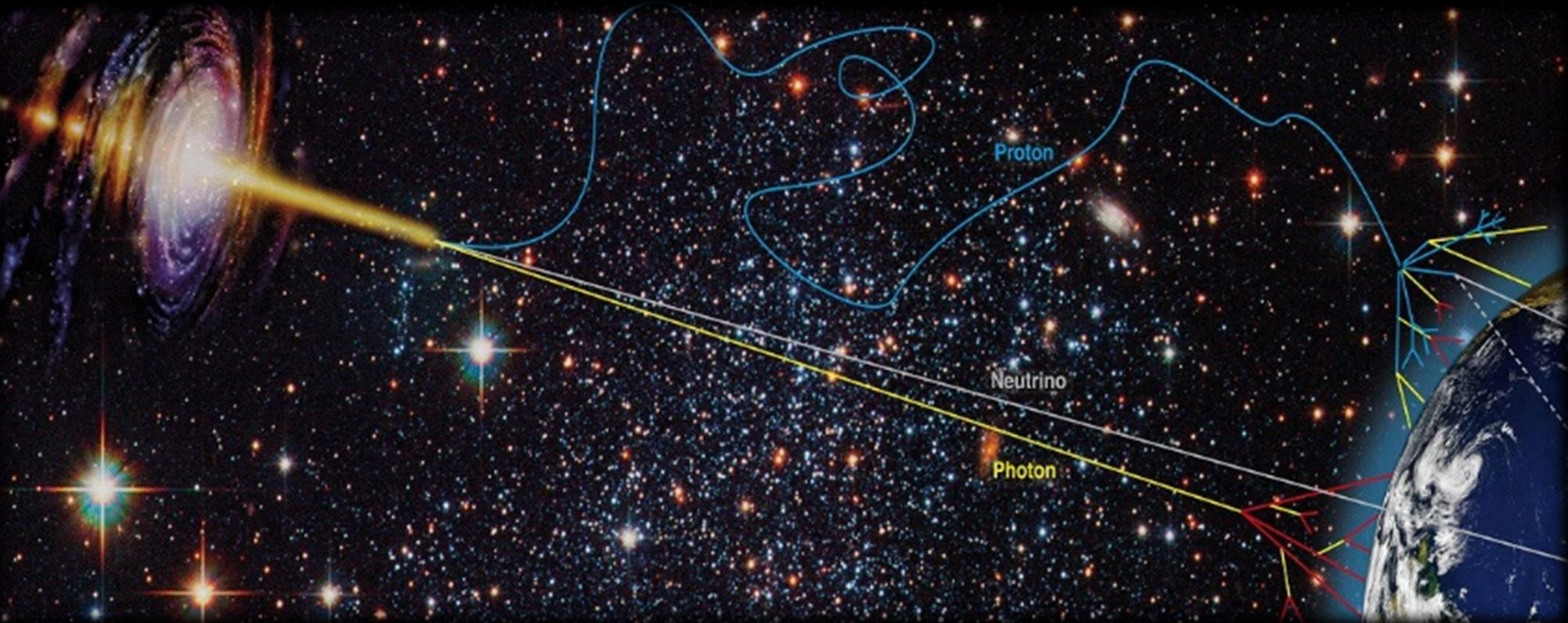
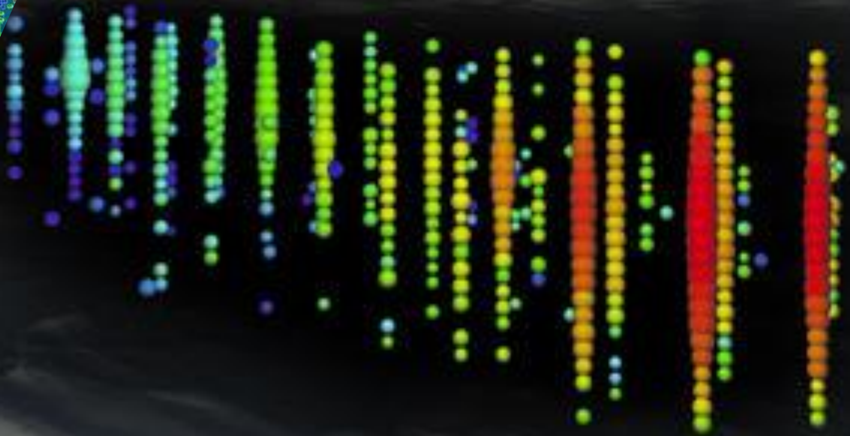


Thank you for listening – time for questions ☺



Julia Tjus | 04.01.2023

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