arxiv.2202.00694

High-energy neutrino astronomy: A new window to the Universe

Julia Tjus | 03.06.2022
Ruhr-Universität Bochum, Germany
& RAPP Center

CIM @SFB1491 · 30. Mai

Congratulations to Prof. Francis Halzen who is awarded with the honorary doctorate 🎓
and Prof. Wolfgang Rhode who received the honorary professorship from @ruhrunibochum 👏
#SFB1491 #neutrino #astroparticlephysics

Contents

- Observations of high-energy neutrinos with IceCube
- Modeling of high-energy neutrino production
- Interpretation in the multimessenger context

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- Observations of high-energy neutrinos with IceCube
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Entering the age of neutrino astronomy

See talk by Tom Stuttard

See talk by Nahee Park

- 2013: first detection of diffuse, astrophysical flux
- 2018: first evidence for a correlation between gamma-ray emission from TXS0506+056 and a high-energy neutrino
- Realtime analysis: regular alerts of „golden“ and „bronze“ event alerts

What have we learned from IceCube?

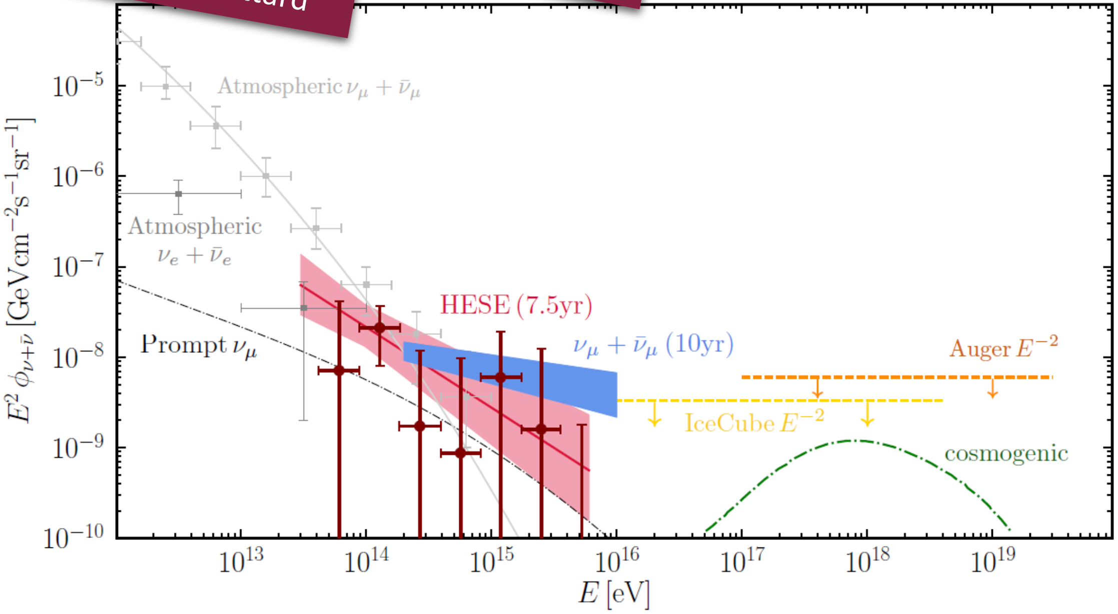
- Diffuse flux @ level

$E^2 dN/dE \sim 1e\text{-}8$ GeV/(s sr cm^2)

- Diffuse spectral index ~ $E^{-2.5}$
- Diffuse flux **not** dominated by Galactic emission
- Composition (ν_μ, ν_e,ν_τ) compatible with pionic production (but still very uncertain
- Evidence for sources (~3σ level): **blazars & Seyferts**

See talk by Tom Stuttard

See talk by Nahee Park



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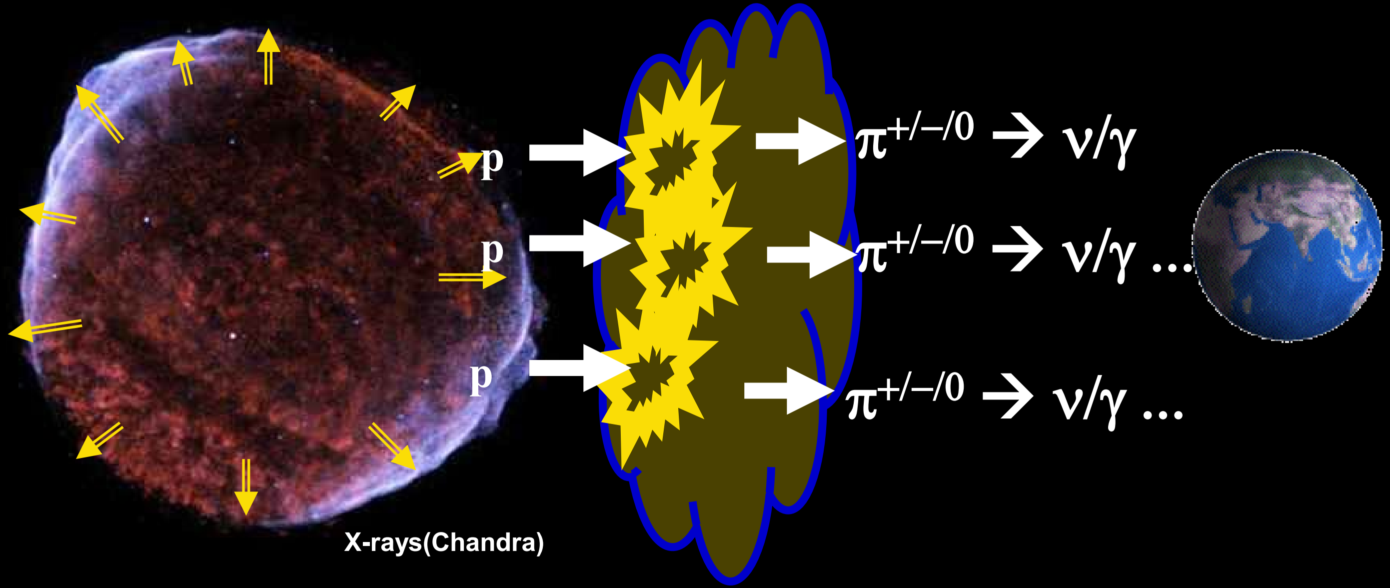
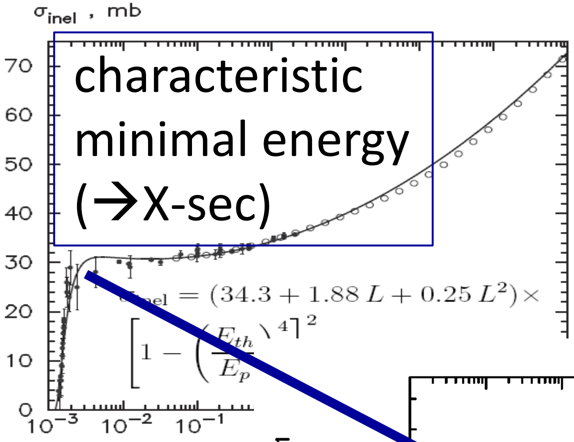
1.) CR acceleration 2.) CR interaction 3.) Detection

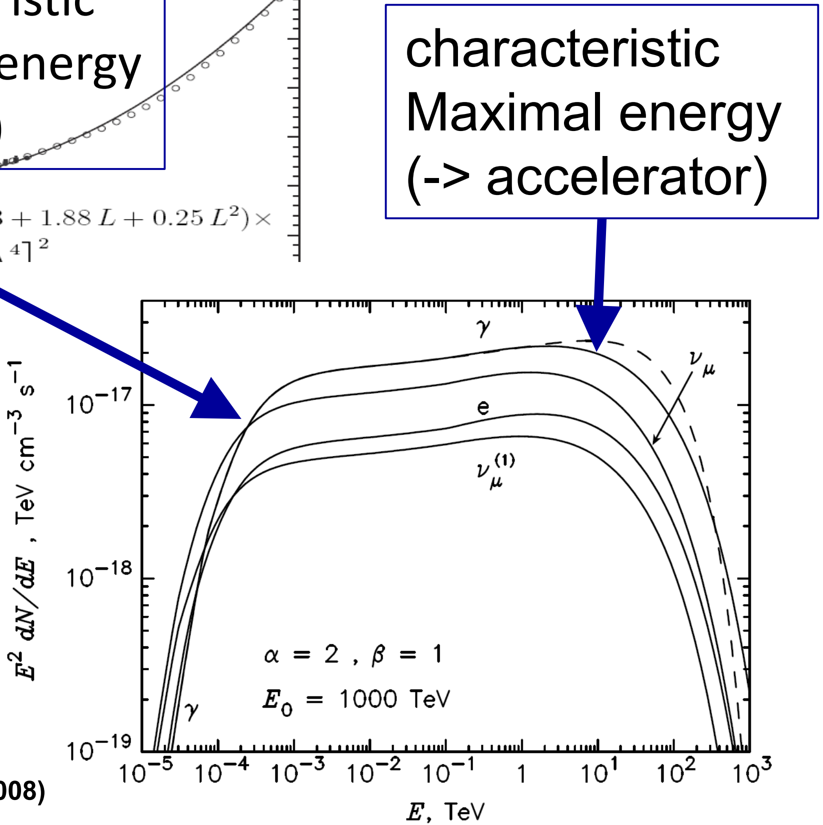


$dN_{CR}/dE_{CR} \sim E_{CR}^{-2}$ $dN_{\nu/\gamma}/dE_{\nu/\gamma} \sim E_{\nu/\gamma}^{-2}$

E_{max} E_{max} /20 (ν)

Hadronic interactions





Figs: Kelner et al, PRD (2008)

- $p_{CR}\ p_{target} \rightarrow \#(\pi^{+/-/0})$
- $\pi^+ \rightarrow \mu^+\nu_\mu \rightarrow e^+\ \nu_e\ \overline{\nu}_\mu\ \nu_\mu$
- $\pi^- \rightarrow \mu^-\overline{\nu}_\mu \rightarrow e^-\ \nu_e\ \nu_\mu\ \overline{\nu}_\mu$
- $\pi^0 \rightarrow \gamma\gamma$ (E~TeV)

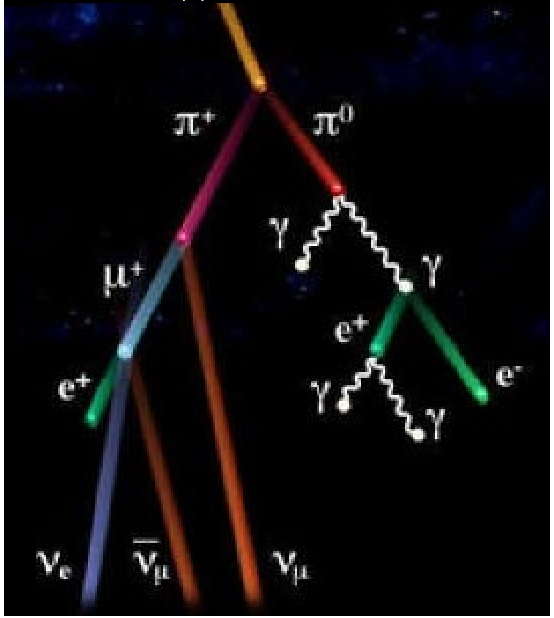


Photo-Hadronic interactions

characteristic
minimal energy
$E_p * E_\gamma > (m_\Delta^2 - m_p^2)/4$

characteristic
Maximal energy
(-> accelerator/muon loss)

- $p_{CR}\ \gamma_{target} \rightarrow (\Delta) \rightarrow \#(\pi^{+/-/0})$
- $\pi^+ \rightarrow \mu^+ \nu_\mu \rightarrow e^+ \nu_e \bar{\nu}_\mu \nu_\mu$
- $\pi^- \rightarrow \mu \bar{\nu}_\mu \rightarrow e^- \nu_e \nu_\mu \bar{\nu}_\mu$
- $\pi^0 \rightarrow \gamma\gamma$ (E~TeV)

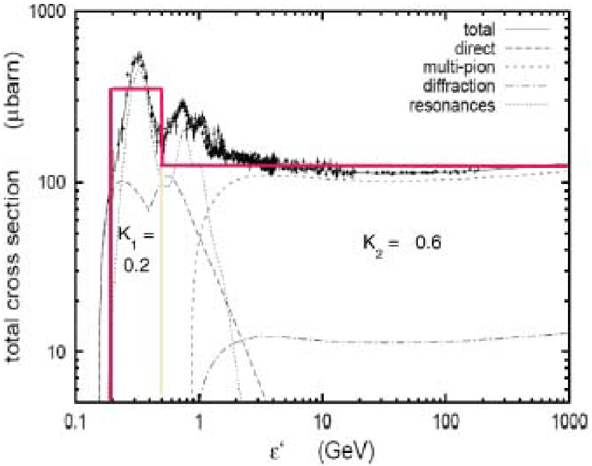


Fig: Dermer&Atoyan, New J Phys (2006)

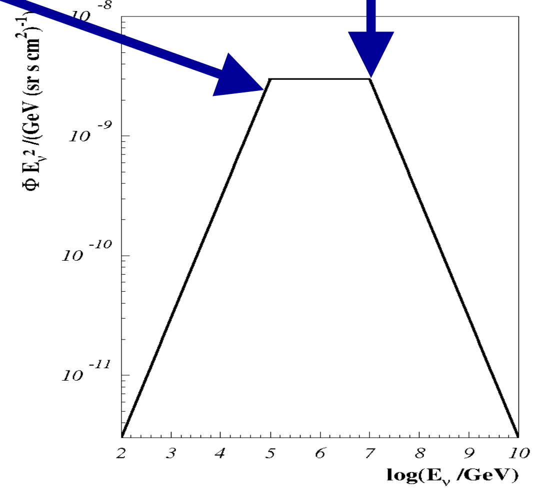
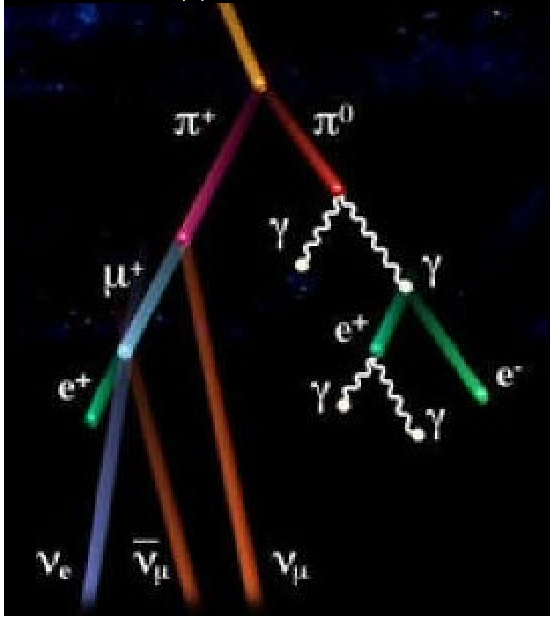
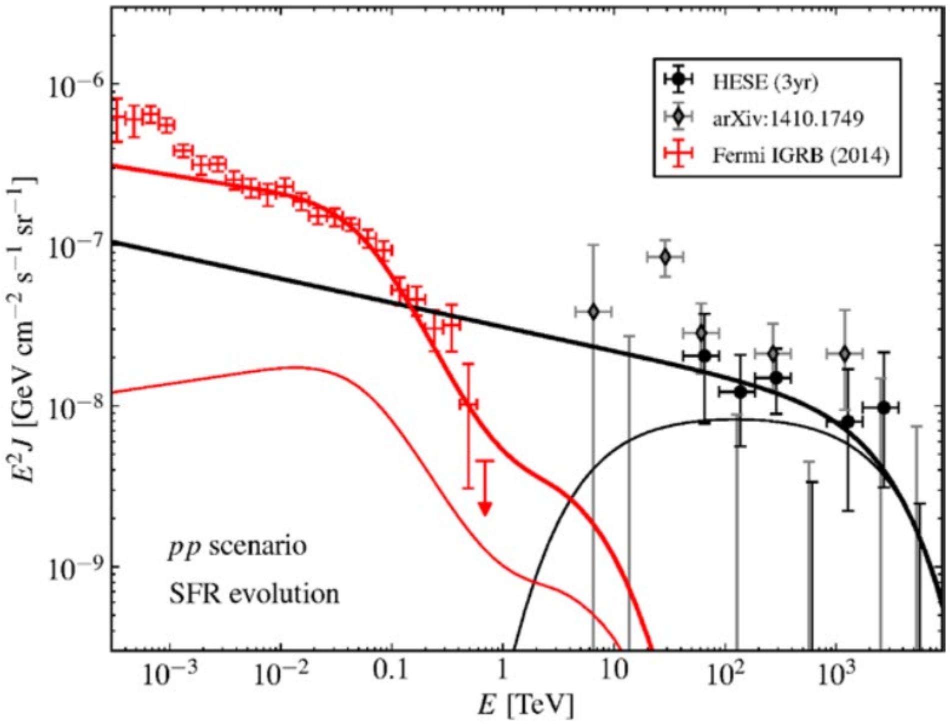


Fig: JKB, Phys.Rep. 2008



Co-production of gamma-rays and neutrinos

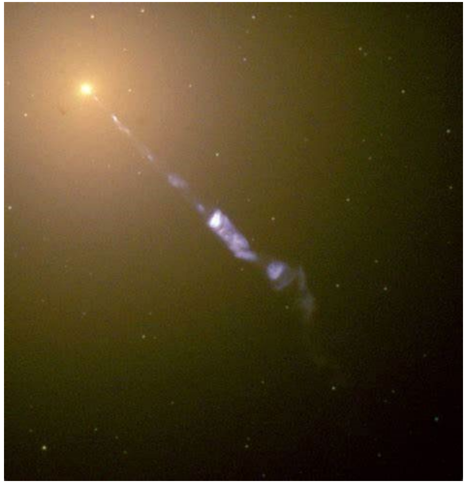
- Gamma-ray measurements as upper limits to neutrino production
- Spectra steeper than E^{-2} quickly overproduce gamma-ray measurements (Fermi) when only considering intergalactic γ–γ
- Intrinsic γ–γ or γ-gas component needed?

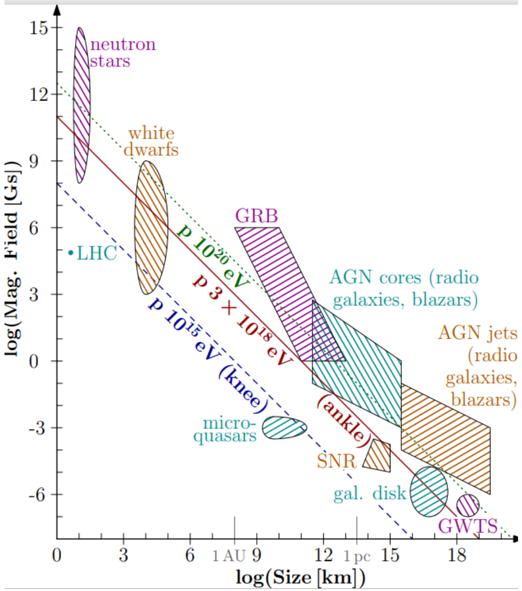


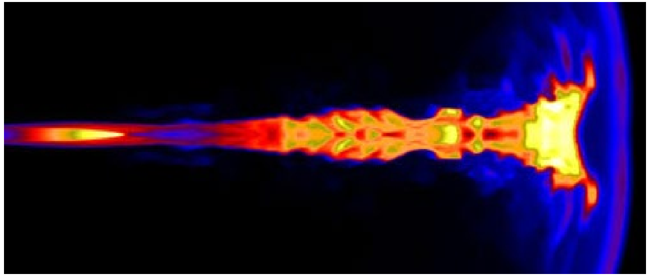
Ahlers & Halzen, Rep. Prog. Phys. 78:126901 (2015)

Possible extragalactic neutrino sources

See also talk by I. Bartos







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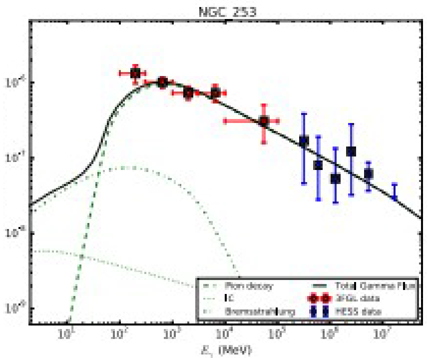
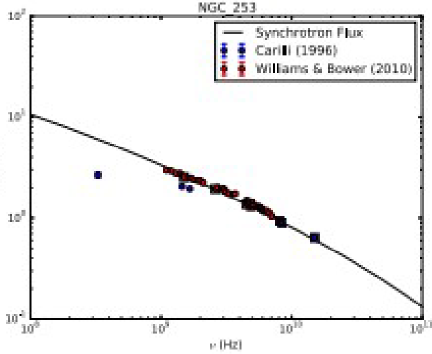
Spiral galaxies – the starburst part

Gamma

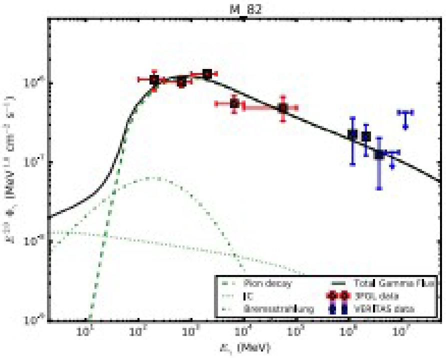
Radio

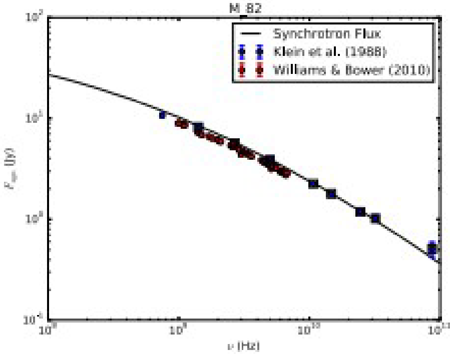
NGC253



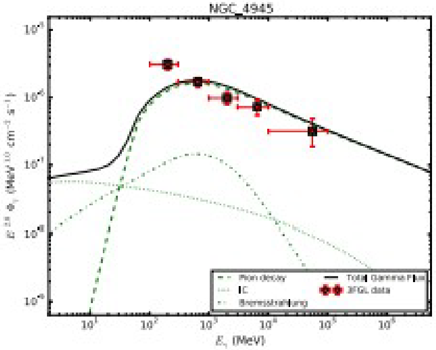


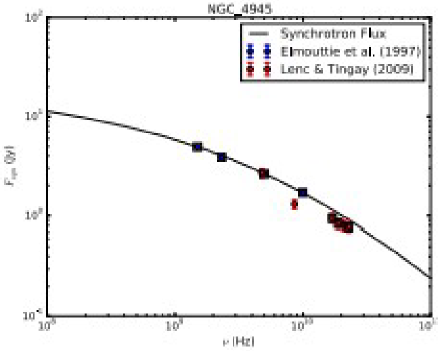
M82



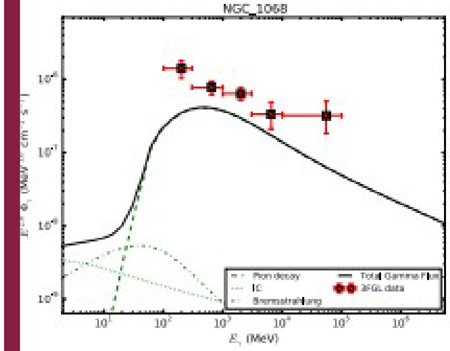


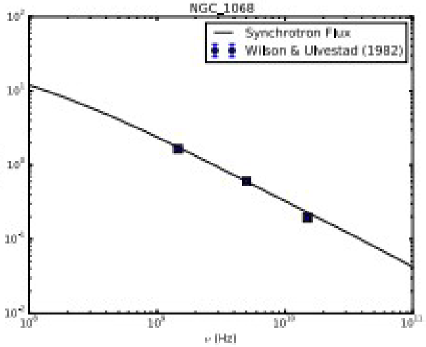
NGC4945





??? NGC1068

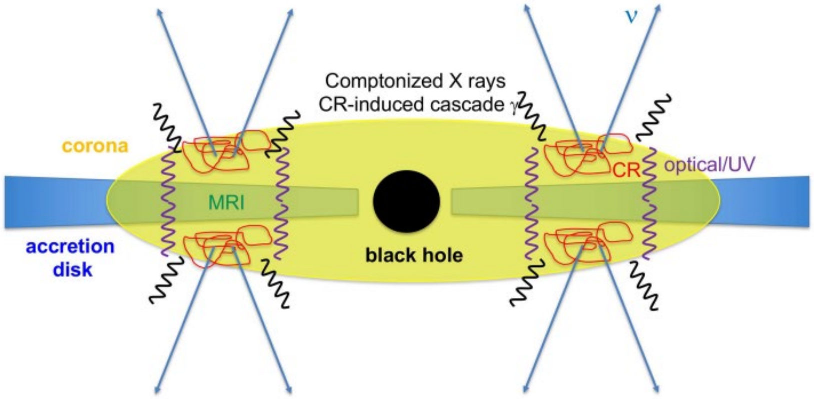


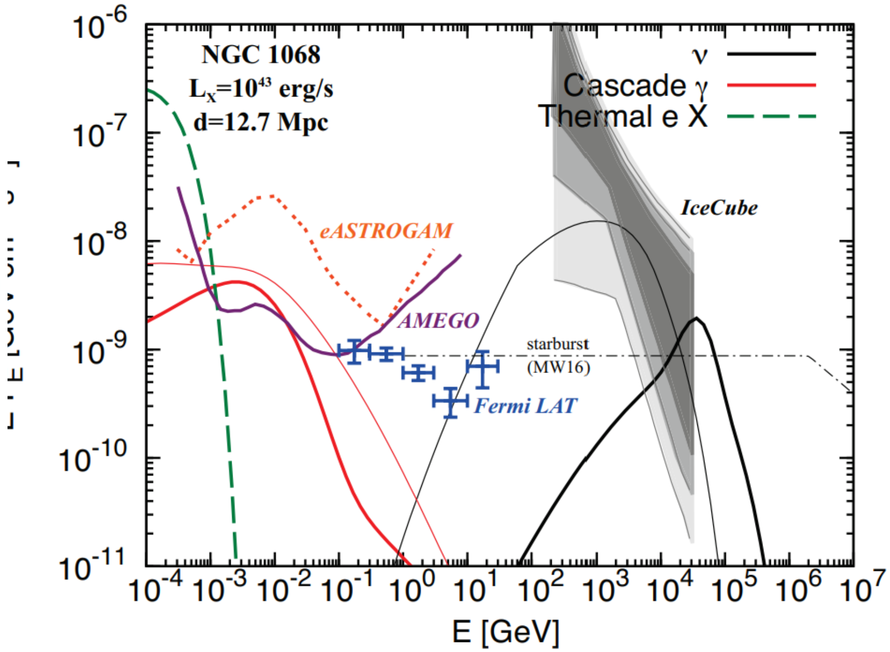


Eichmann & JBT, ApJ (2016)

Core-dominated
The case of NGC1068

NGC1068:
Contribution from interactions with the disk Corona

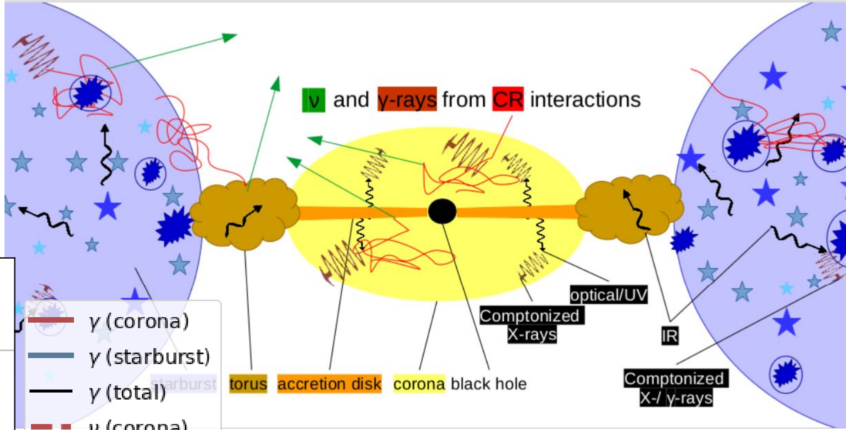


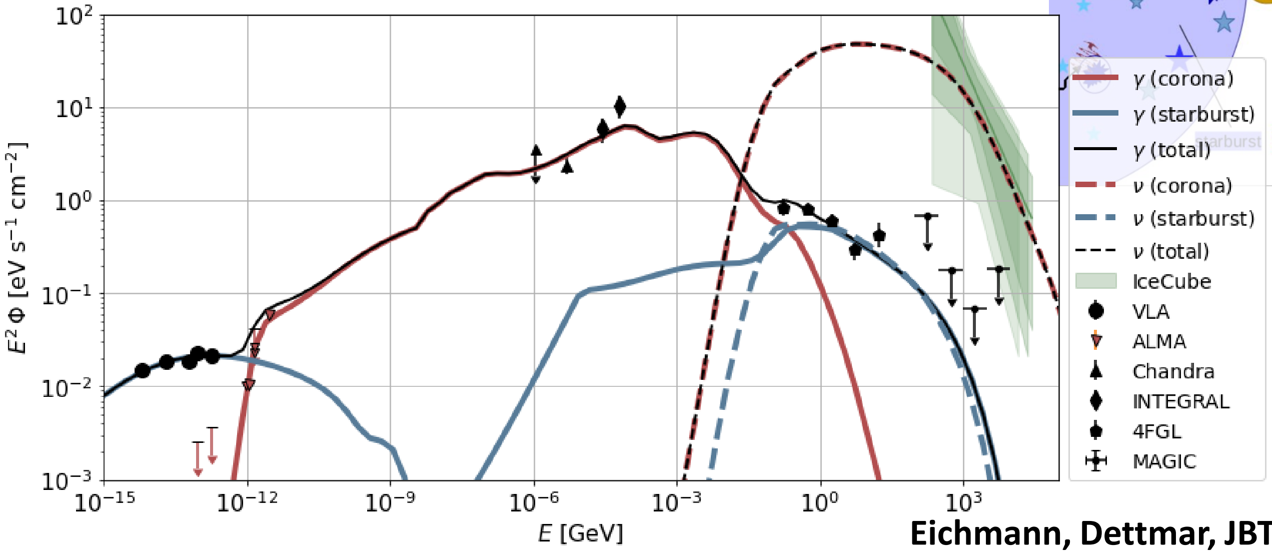


Murase, Kimora & Mészárosz, PRL 125:011101 (2020)
See also further work by Kheirandish, Murase & Kimura, ApJ 922 (2021)

NGC1068: neutrinos in the multimessenger picture

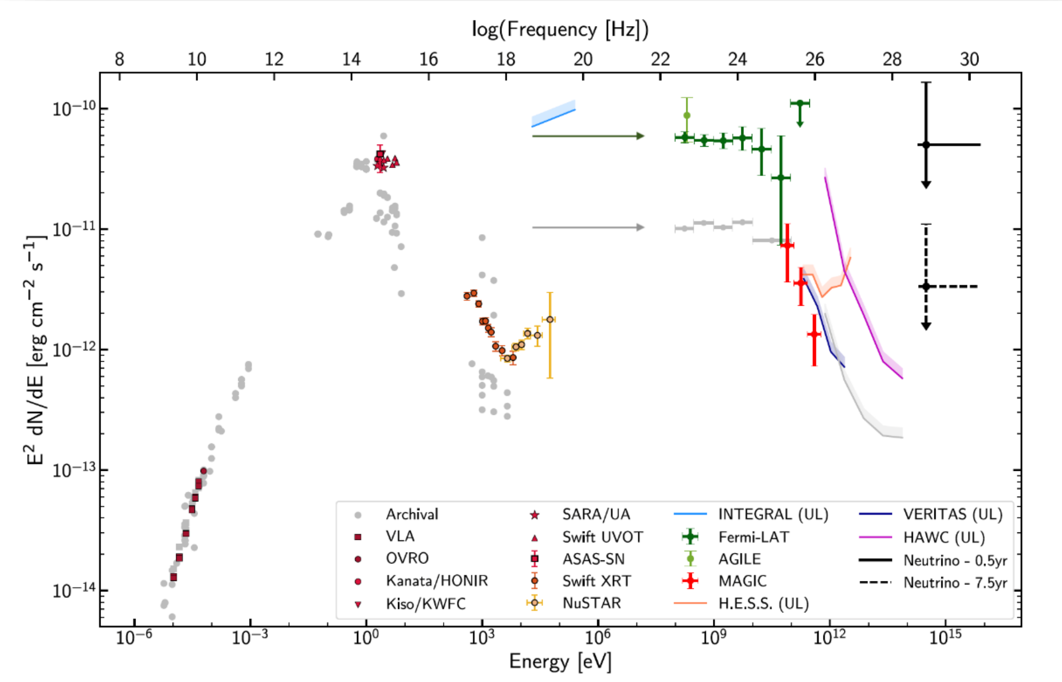
- Multimessenger fit: combination of starburst + corona contribution

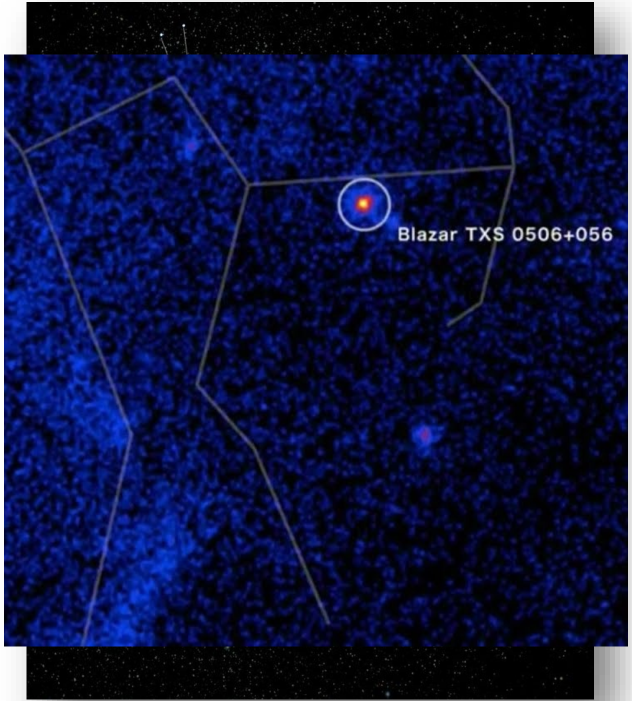




Eichmann, Dettmar, JBT, ICRC2021, 2108.06990
Eichmann, Oikonomou, Salvatore, Dettmar, JBT, in prep (2022)

Jet-dominated Active Galaxy: The case of TXS0506+056

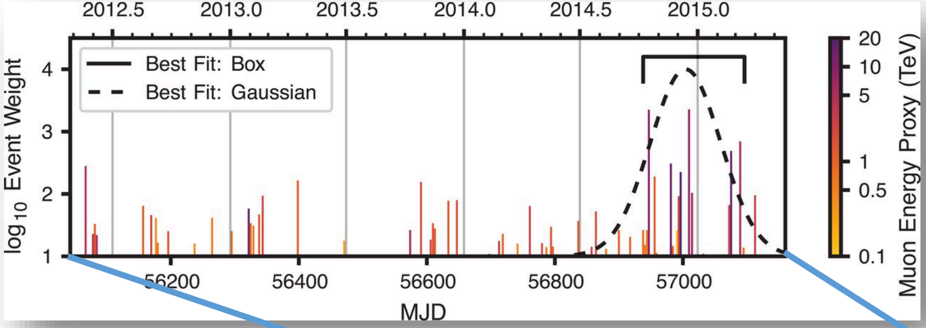




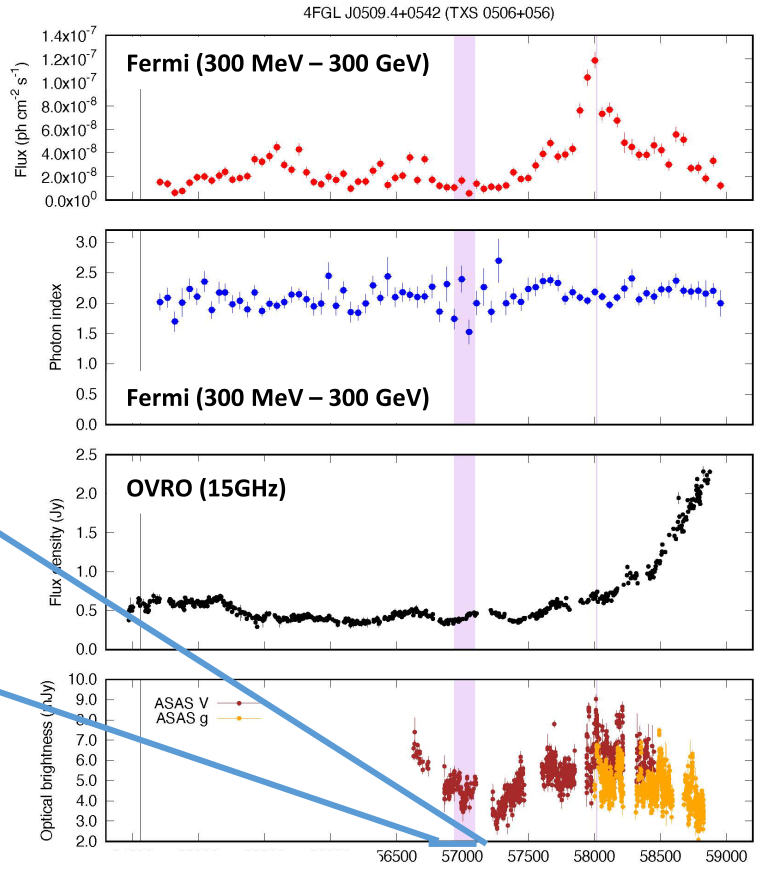
Aartsen, ..., JBT, ... et al (IceCube/Fermi/MAGIC Coll), Science (2018)

TXS0506+056 – time domain

Neutrino excess @ ~3σ in 2014/2015



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



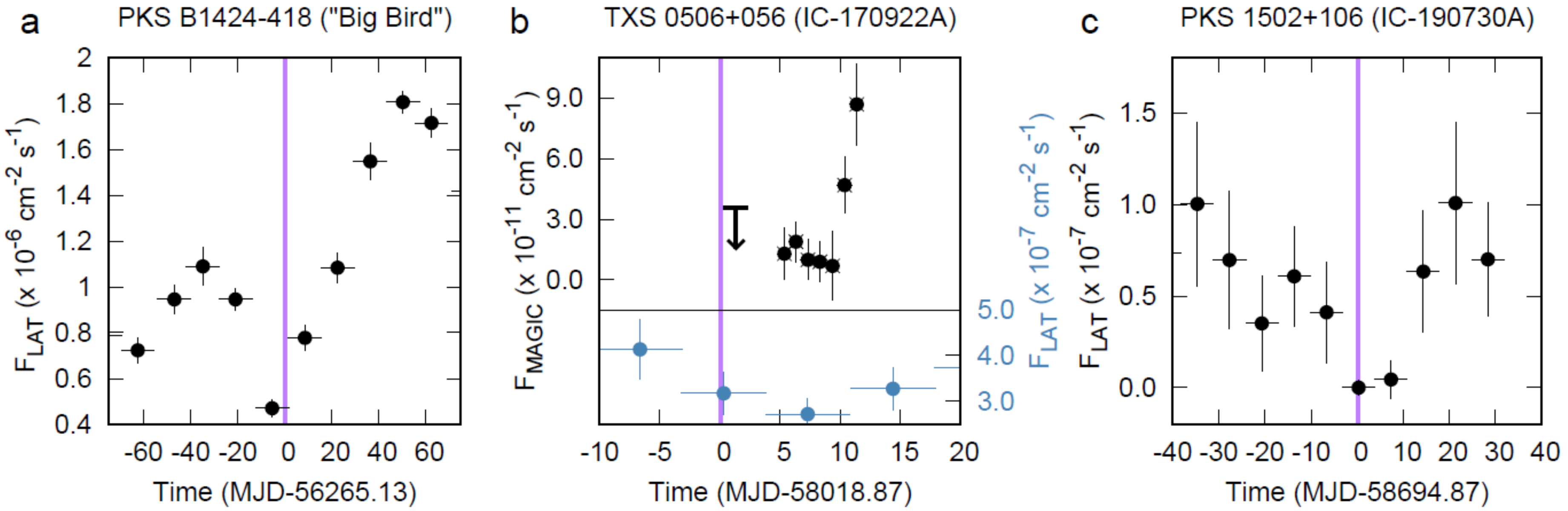
➔ Two potential neutrino flares of very different nature:

- ➔ 2014/2015: ~100 days long, ~10TeV in energy, no MM activity
- ➔ 2018: 1 neutrino with ~300TeV energy, coincident γ-ray flare

Difficult to model 2014/2015 flare, see e.g.
Rodrigues et al, ApJL 874 (2019); Reimer, Bötter & Buson, ApJ (2019)

Figure: Emma Kun (Budapest)

Time-domain of AGN



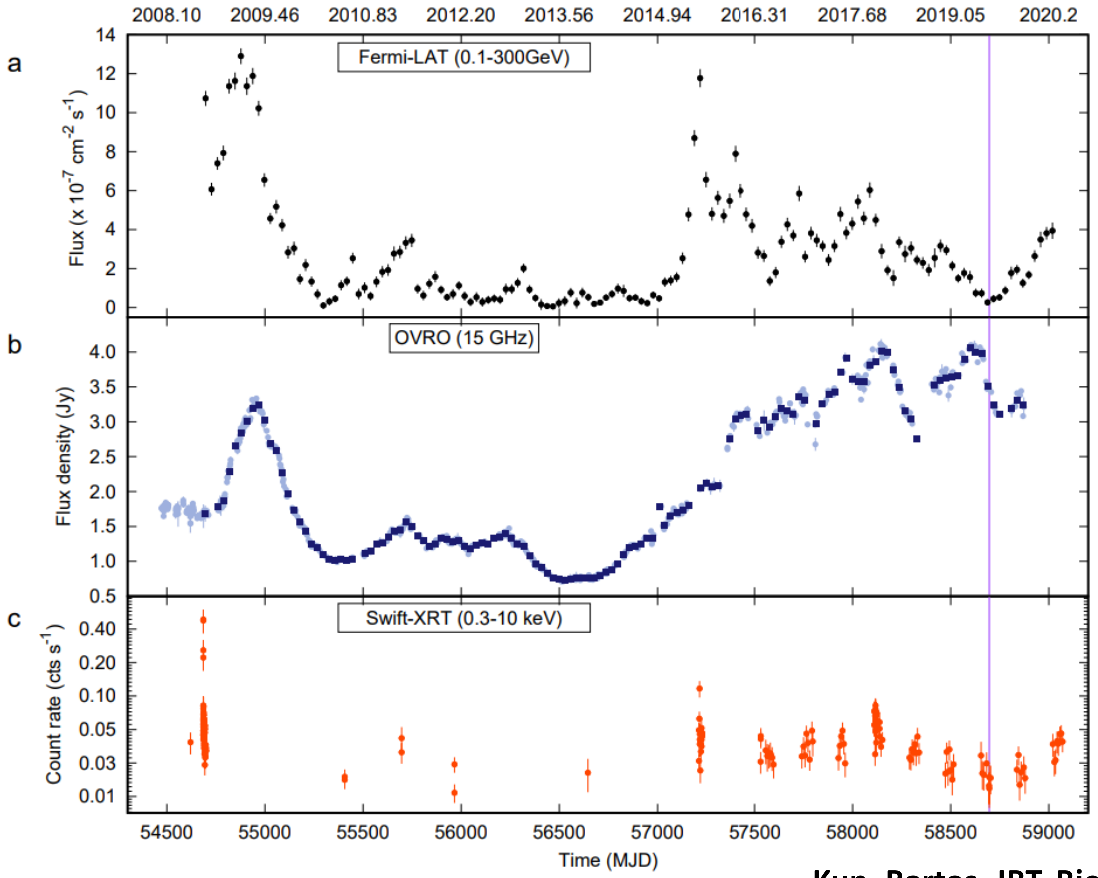
Kun, Bartos, JBT, Biermann, Halzen, Mez´´o ApJL (2021)

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

Future propagation models: test this hypothesis with 3-dim gas & B-field distribution

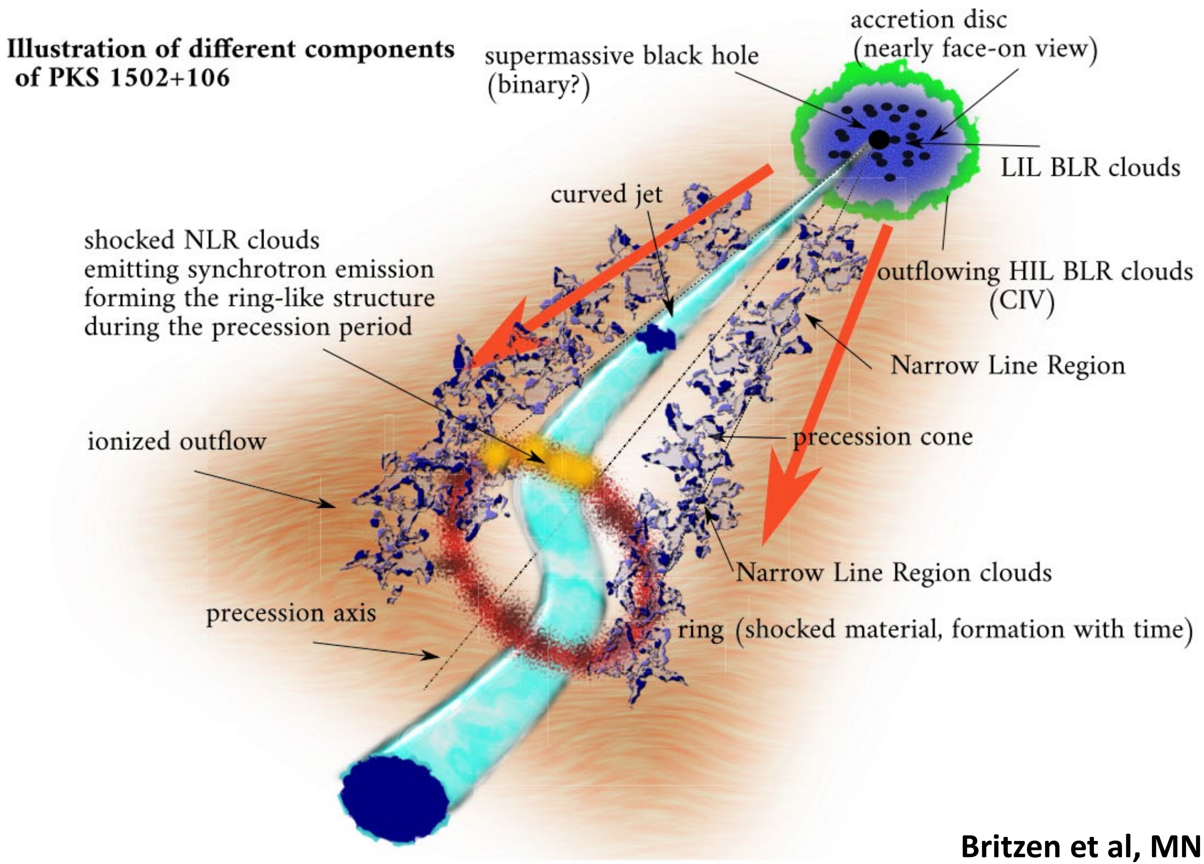
Physics constraints from simultaneous time- and energy-domain modeling

PKS1502+106



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

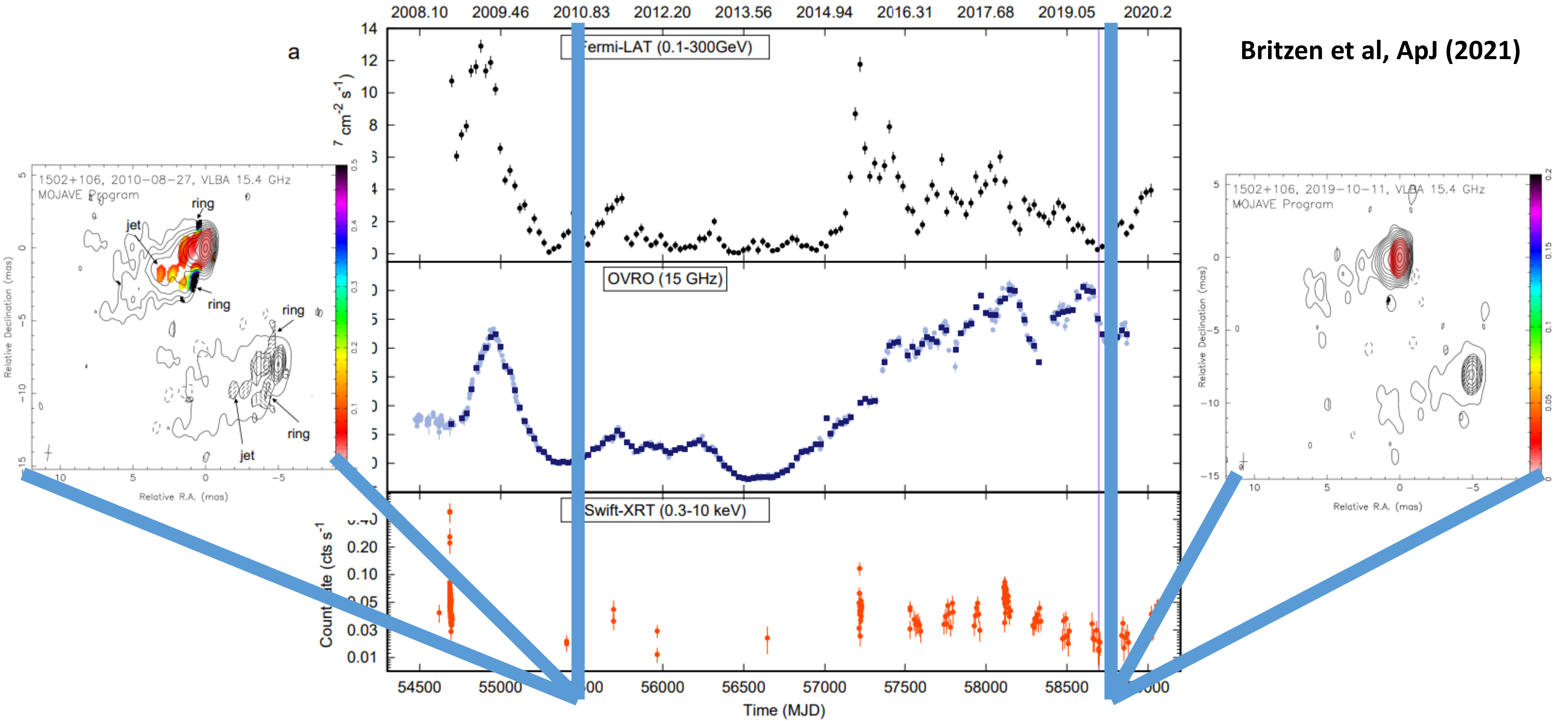
PSK1502+106: a curved, precessing jet?



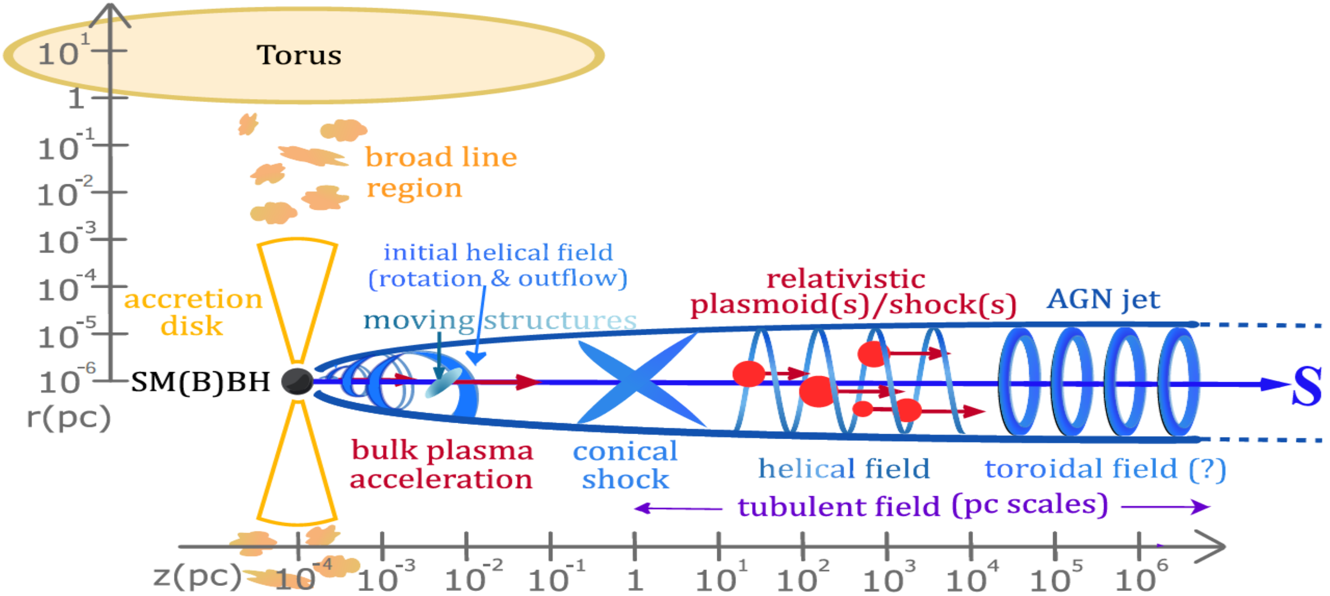
Britzen et al, MNRAS 503 (3): 3145 (2021)

PKS1502+106 – ν, γ, radio, polarization

Britzen et al, ApJ (2021)



Quantative AGN cosmic-ray modeling



- **B-field structure** (blue/red): acceleration (shocks/plasmoids), propagation dominantly along fieldlines, diffusion and energy dependence sensitive to $\delta B/B$
- Gas structure/Photon fields (yellow/red): interactions, relevant for γ-ray & neutrino production, gamma absorption

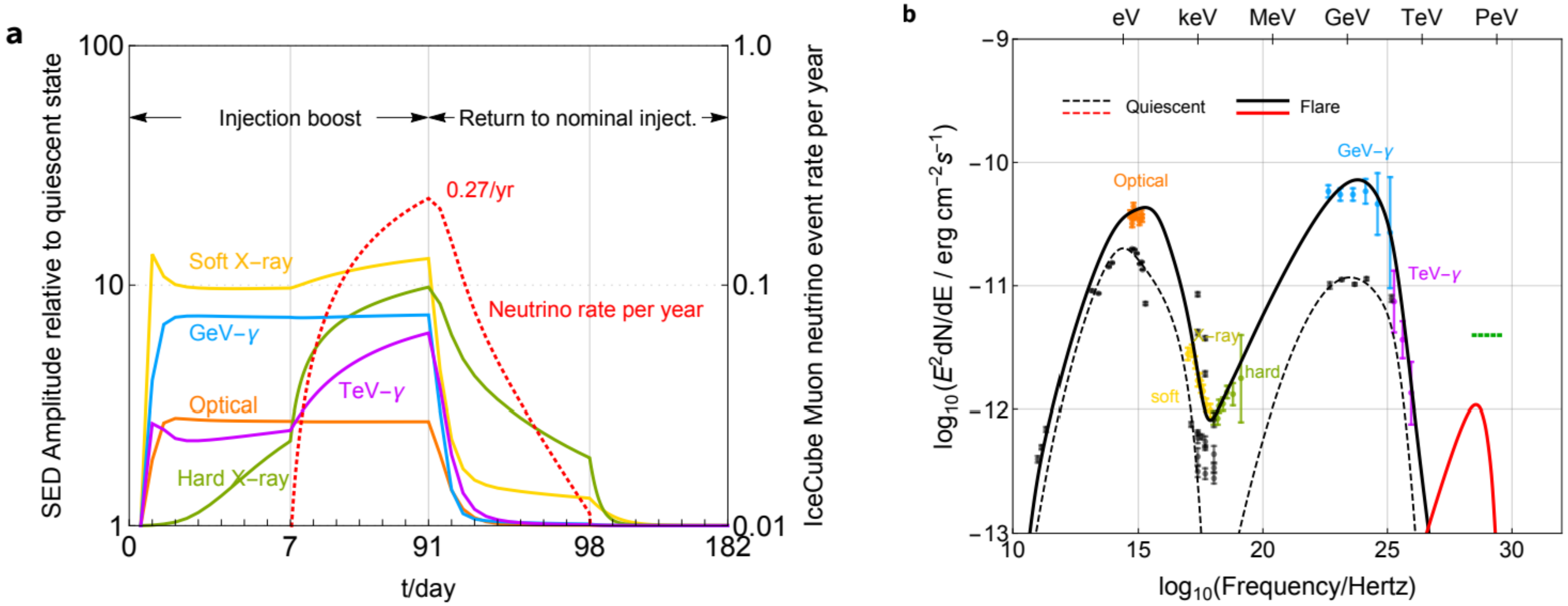
Fig: JBT et al, MDPI Physics (2022)

Blazar propagation tools

- **Basic features:**
  - Solution of the transport equation, including important radiation processes (e/p-Synchrotron, IC, photohadronic interactions, [hadron-hadron])
  - Transport properties summarized in escape term $\frac{n}{\tau}$
    - $\tau \sim E^1$ (Bohm diffusion)
    - $\tau \sim E^{1/3}$ (Kolmogorov diffusion)
    - $\tau \sim const$ (Ballistic propagation)

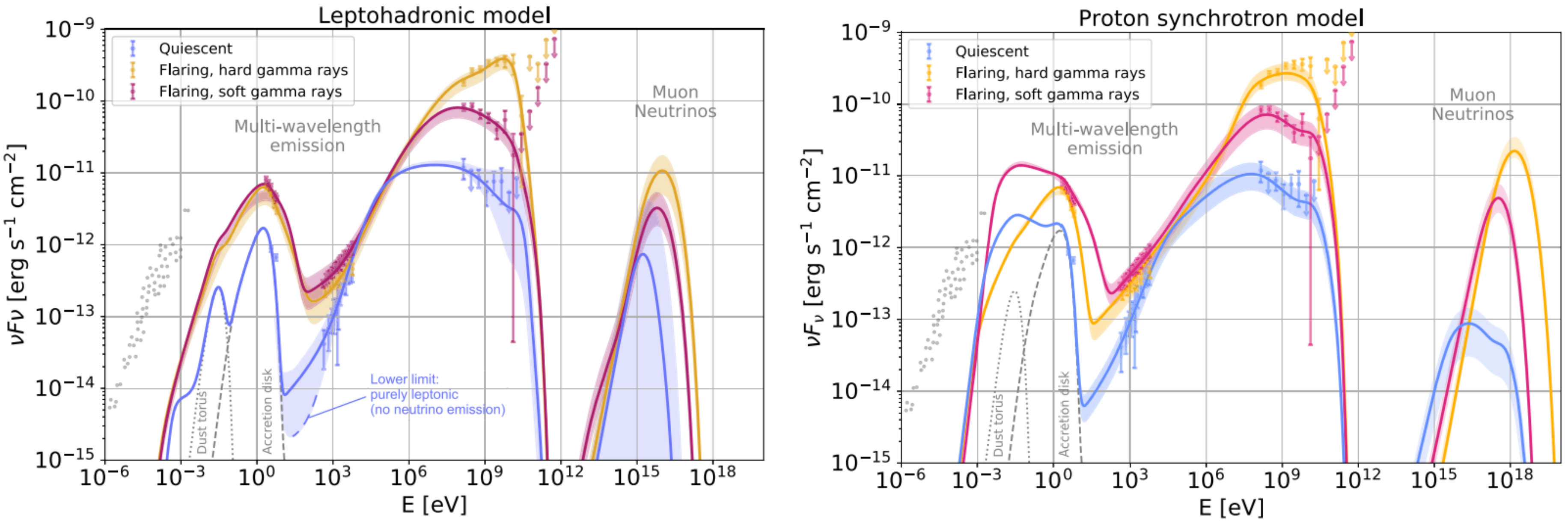
- AM3 (Gao et al, 2017)
- PARIS (Cerutti et al, 2015)
- ATHEνA (Dimitrakoudis et al, 2012)
- Böttcher et al (2013)

Example Multimessenger emission for TXS, 2017-flare



Gao et al, Nat.Phys. 3:88 (2019)

Example SED of PKS1502 in different states

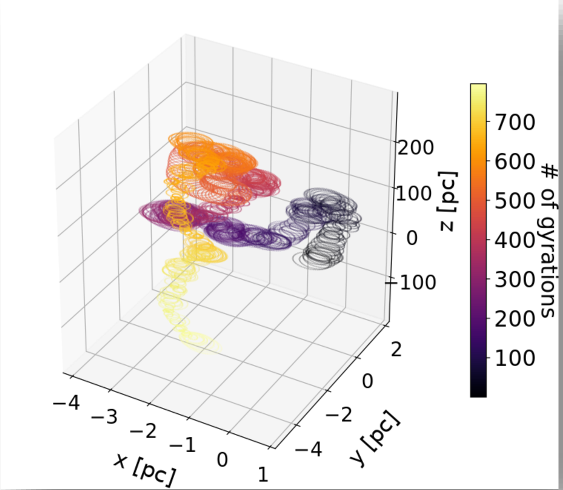


Rodrigues et al, ApJ 912:54 (2021)

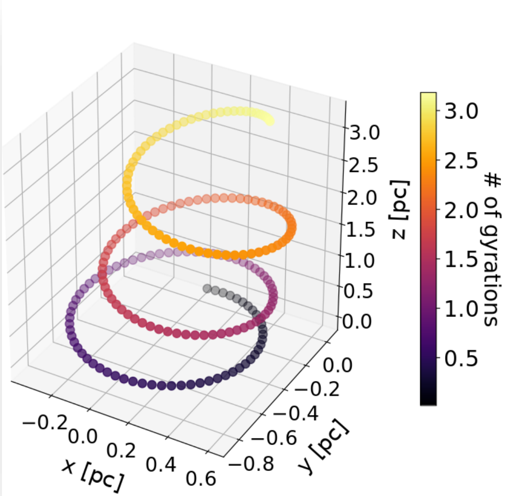
The new kid on the block: AGNPropa
A test-particle approach

$$\frac{\delta n}{\delta t} = \nabla \cdot \left(\hat{D} \cdot \nabla n\right) - \vec{u} \cdot \nabla n + Q$$

$$\frac{d\boldsymbol{p}}{dt} = q(\boldsymbol{v} \times \boldsymbol{B})$$



B = B$_0$+ δB



conversion into Stochastic Differential Equation (SDE):

$$dr_\nu = A_\nu dt + D_{\nu\mu} d\omega^\mu$$

➔ treatment as quasi-particles

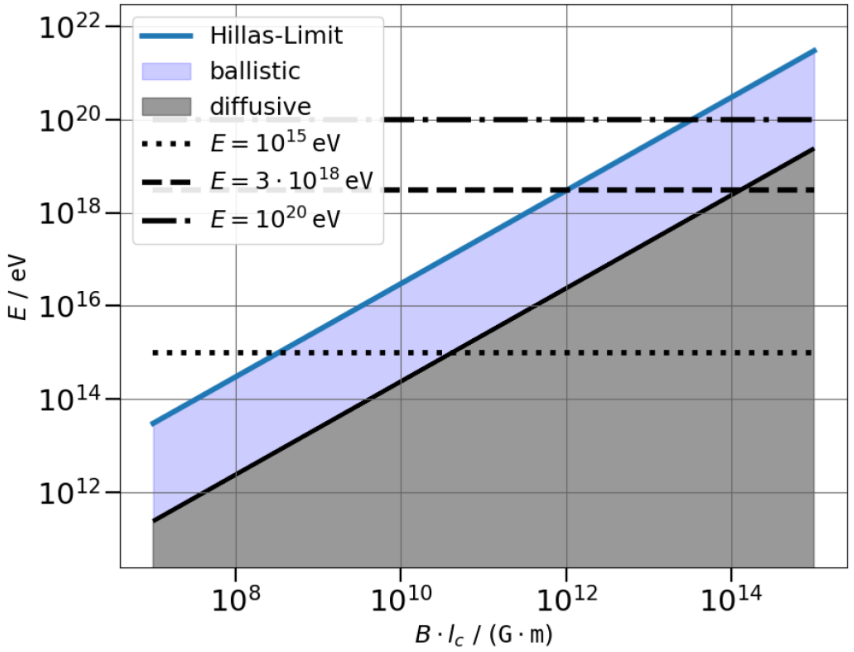
Merten, JBT, Fichtner, Sigl, JCAP (2017)

Numerical solution via Cash-Karb or Boris-Push

Treatment in one framework
➔ 3-dim treatment of diffusion or ballistic propagation in most exact way

Hörbe, Morris, Cotter, JBT, MNRAS (2020)

AGNPropa: Propagation effects on spectra



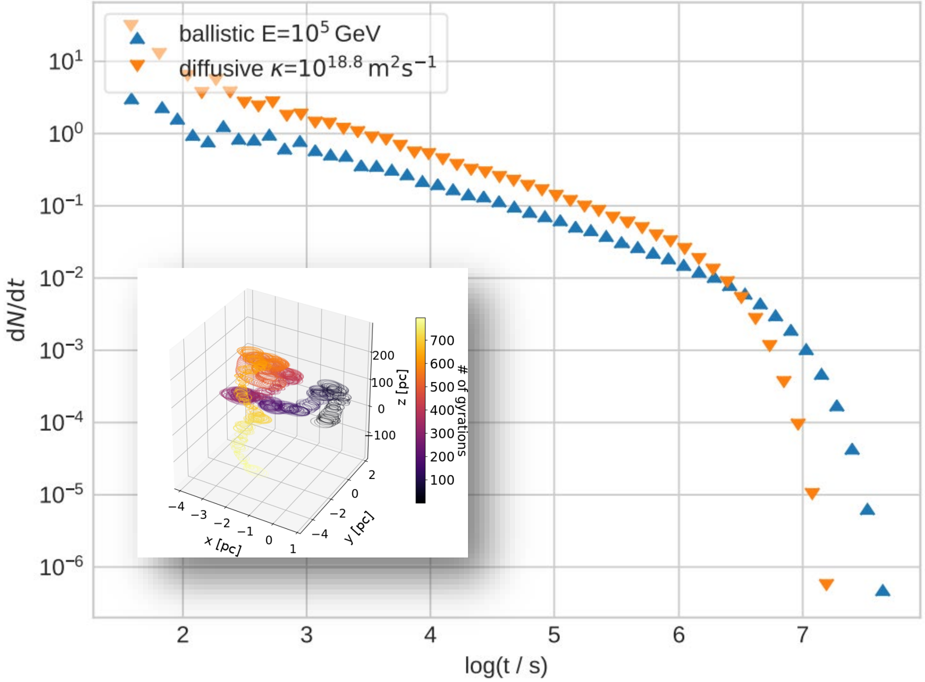
$$E \gtrsim Z \cdot \left(\frac{l_c}{10^{11}\,\mathrm{m}} \right) \cdot \left(\frac{B}{0.42\,\mathrm{G}} \right) \cdot 10^{15}\,\mathrm{eV}$$

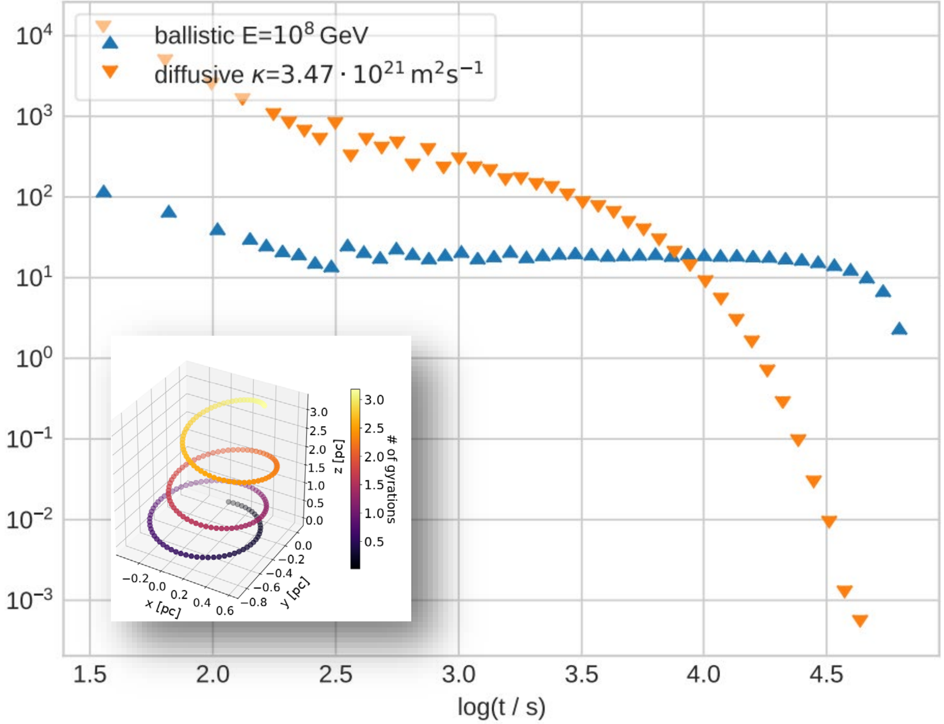
➔ Time scales change from diffusive to ballistic at neutrino energies of around 10-100 TeV ➔ change in neutrino spectrum from steep to flat!

Hörbe, Morris, Cotter, JBT, MNRAS (2020)

JBT et al, MPDI Physics (2022)

AGNPropa: Propagation effects on flares

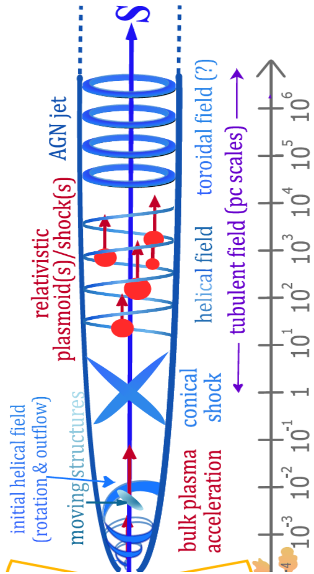


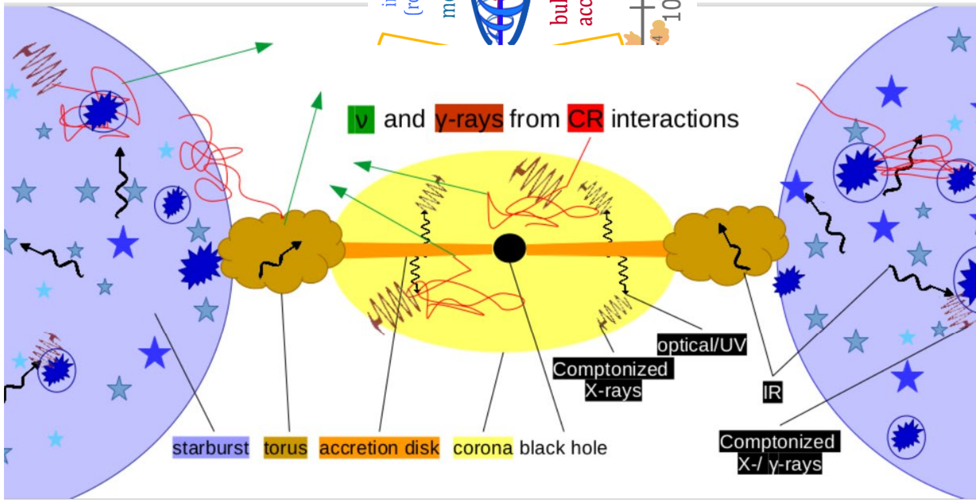


Misinterpretation of flaring behavior when using transport equation approach in the ballistic regime

Summary Theoretical modeling

- Acceleration of particles at foot of AGN jet (reconnection → Fermi-2nd-order → shocks)?
- **Photon targets:** Corona, Broadline Region, Torus, …
- **Gas targets:** plasmoids, BLR, Torus, Disk, Jet-jet interactions, …
- Propagation: 3-dim modeling for proper understanding of flares & spectra
- **Future:** time-dependent modeling to explain **light-curves and SED** at the same time

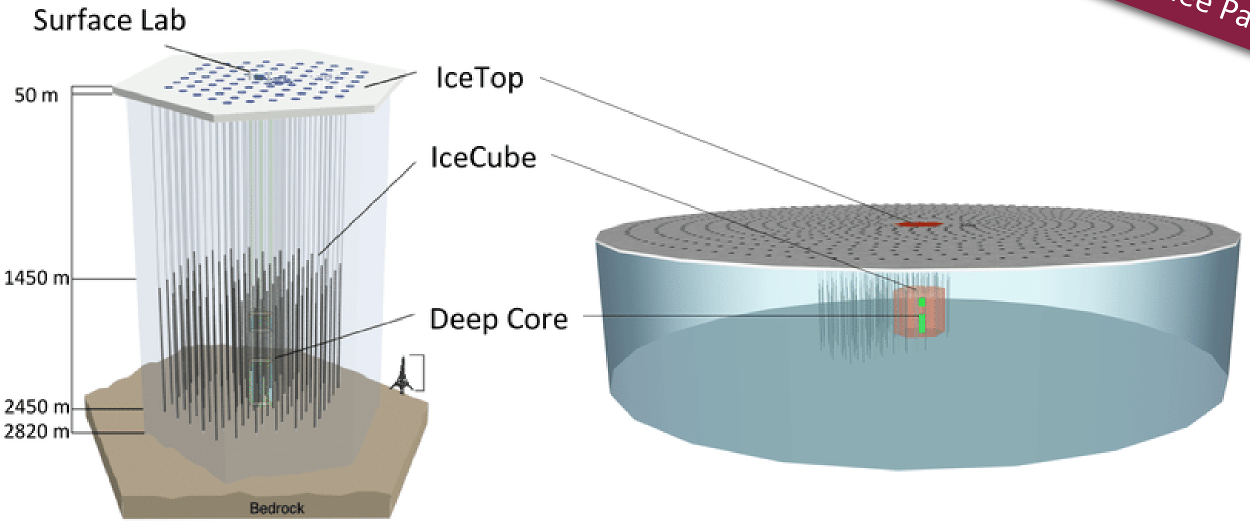


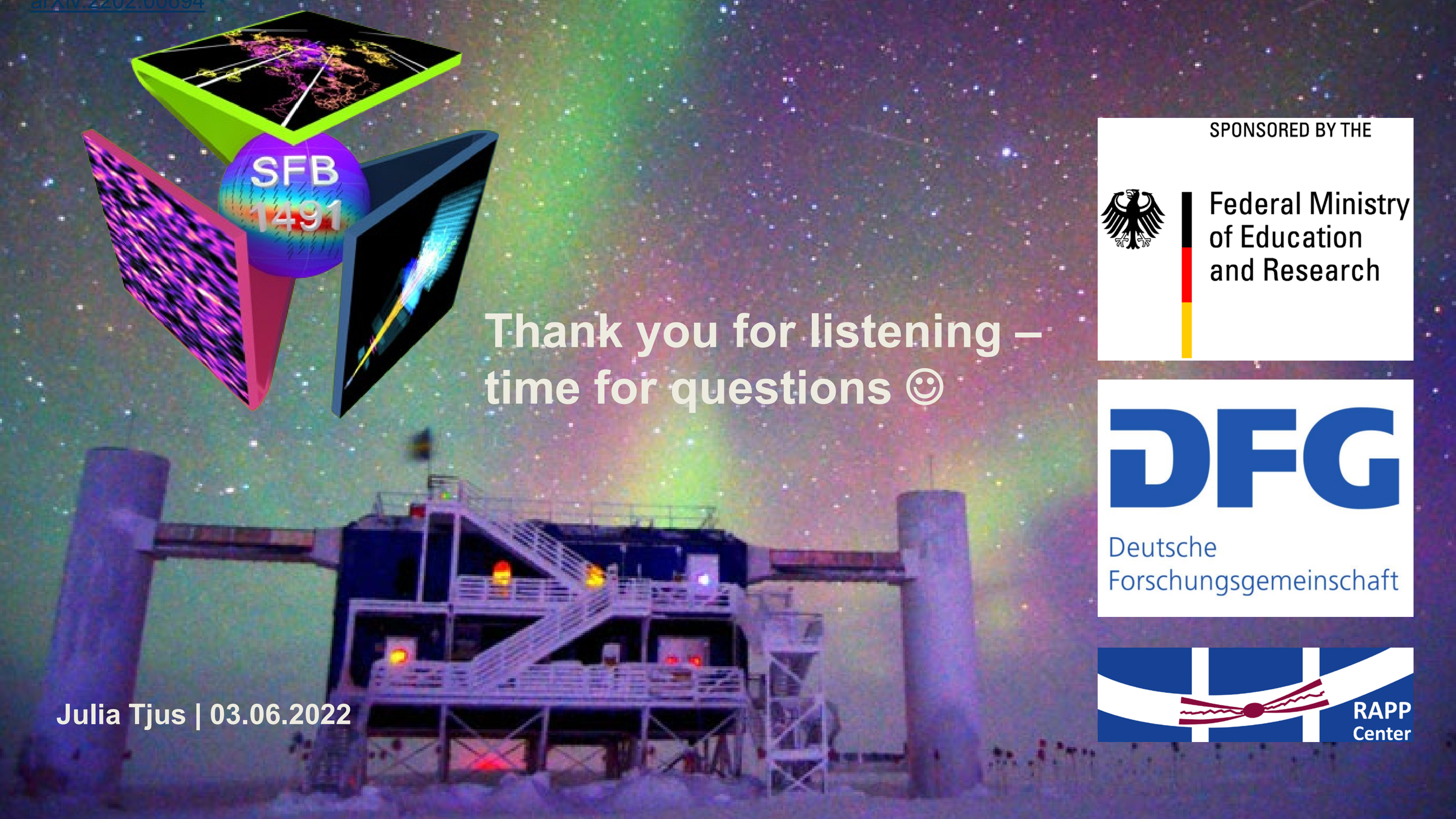


Outlook: Future neutrino astronomy

See talk by Nahee Park

- IceCube-Gen2
- KM3NeT
- Baikal-GVD
- P-ONE
- …
- The future is ν-bright ☺





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Thank you for listening – time for questions ☺

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