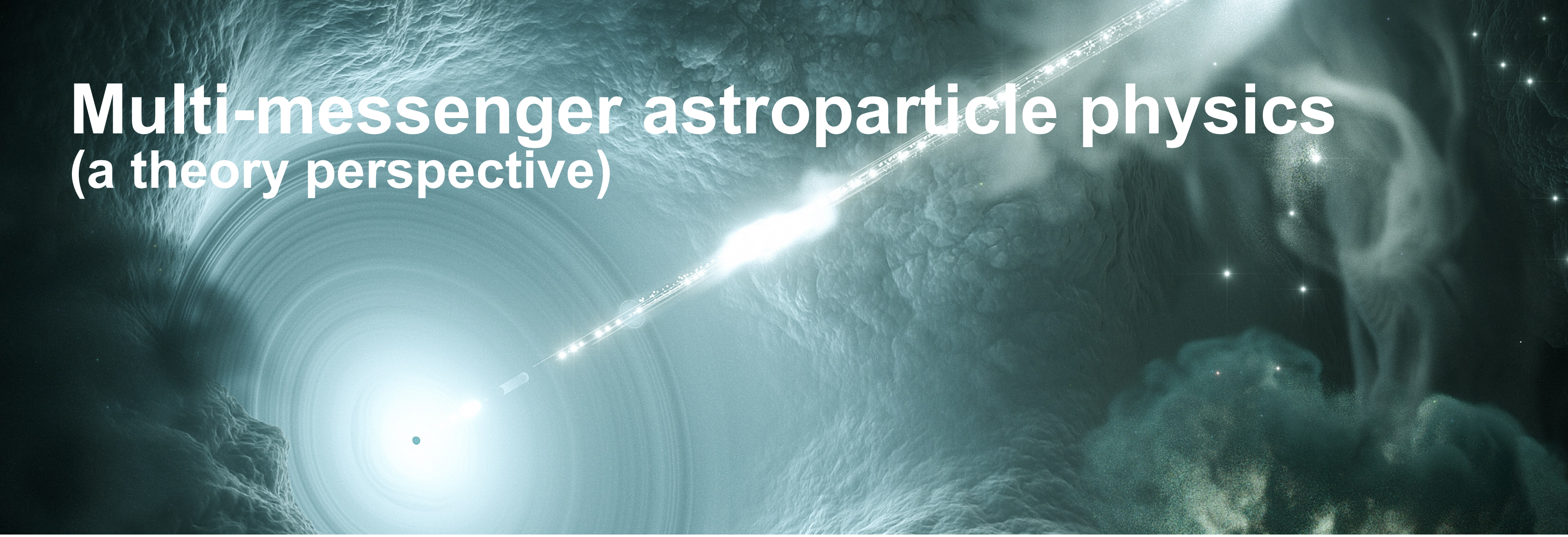


Multi-messenger astroparticle physics
(a theory perspective)

Walter Winter
DESY, Zeuthen, Germany

Astroparticle Physics in Germany –
Status and Perspektives (Zeuthen meetings)

Mainz university
September 17-19, 2018

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

erc NeuCos DESY

Contents

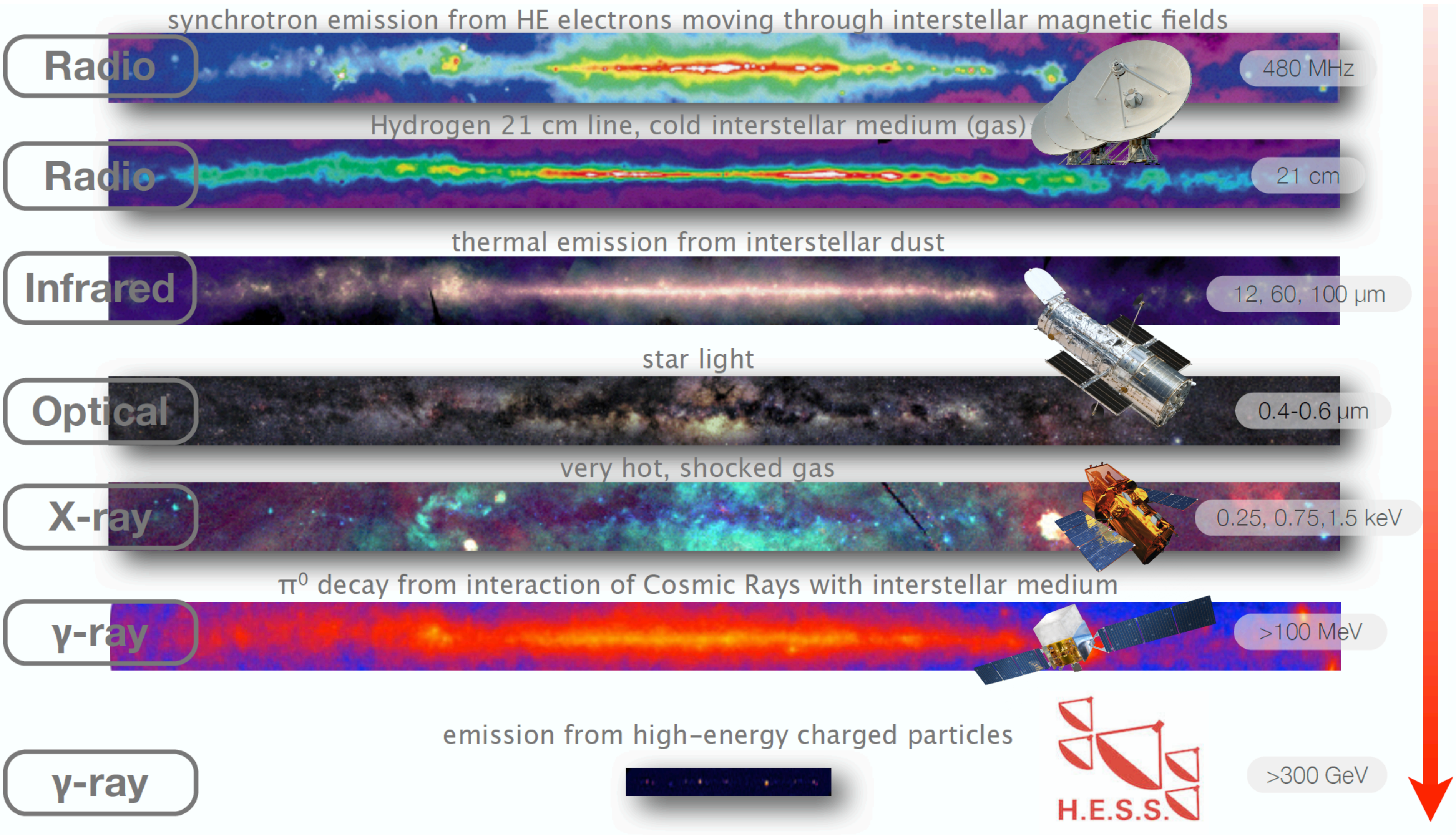
- Introduction
- Testing UHECR paradigms with cosmogenic neutrinos
  Multi-messenger propagation/transport models
  (will not talk about 3D models, CRPropa ...)
- Common origin of cosmic diffuse neutrinos and UHECRs?
  Multi-messenger source-propagation models
  (include nuclei)
- AGN flares – indicative for the origin of cosmic rays?
  Multi-messenger-multi-wavelength source models
  (protons only)
- Summary and conclusions

Physics level

Theory level

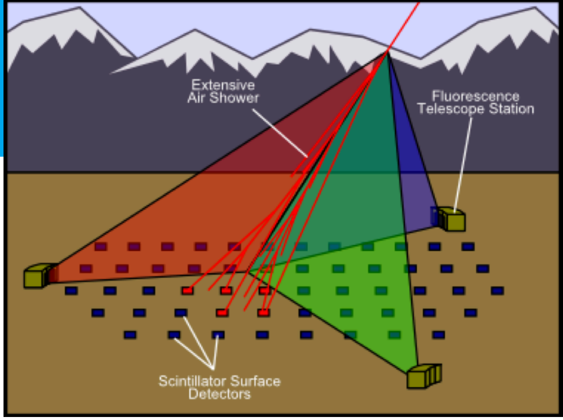
Current State-of-the-art

EM radiation: The Milky Way at *multiple wavelengths*

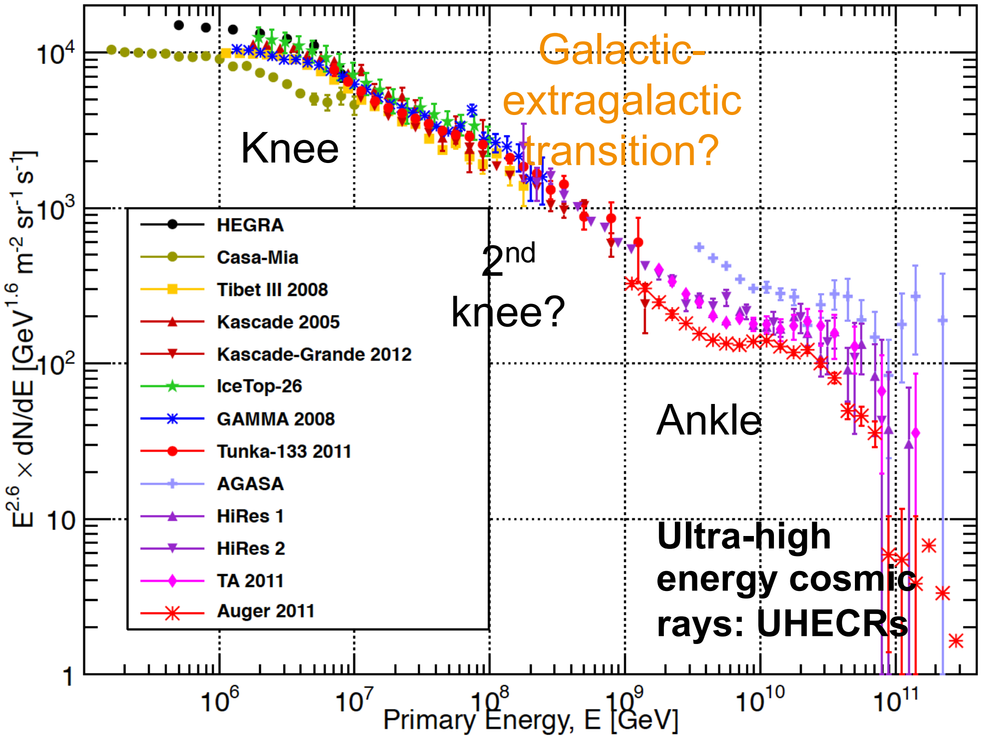


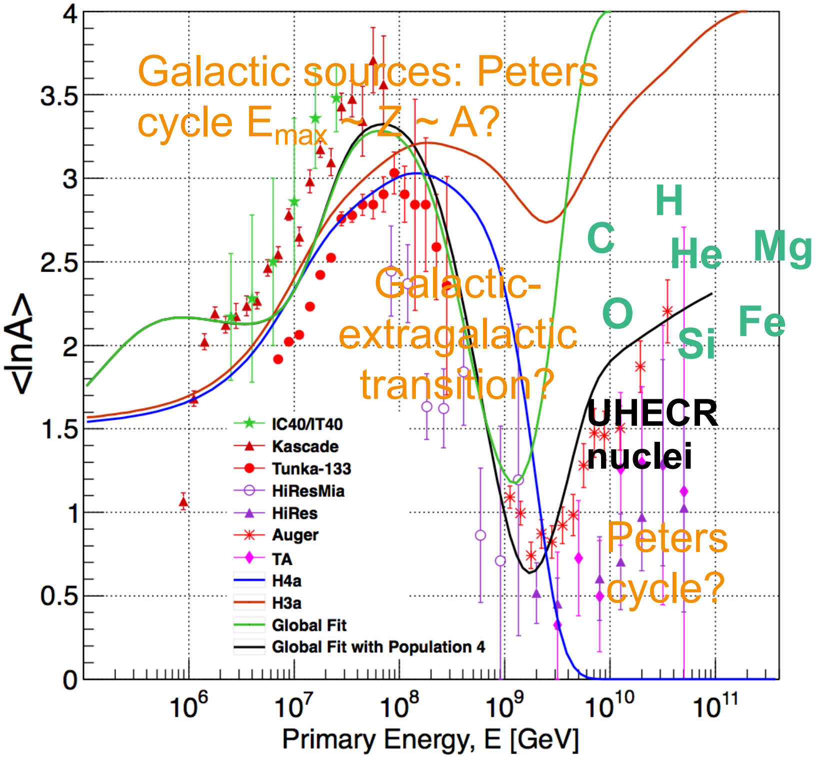
Adopted from G. Maier

Cosmic rays: Spectrum and composition



- Charged particles, proton or heavier nuclei
- Spectrum with breaks (knee, 2nd knee, ankle)
- Composition non-trivial function of energy



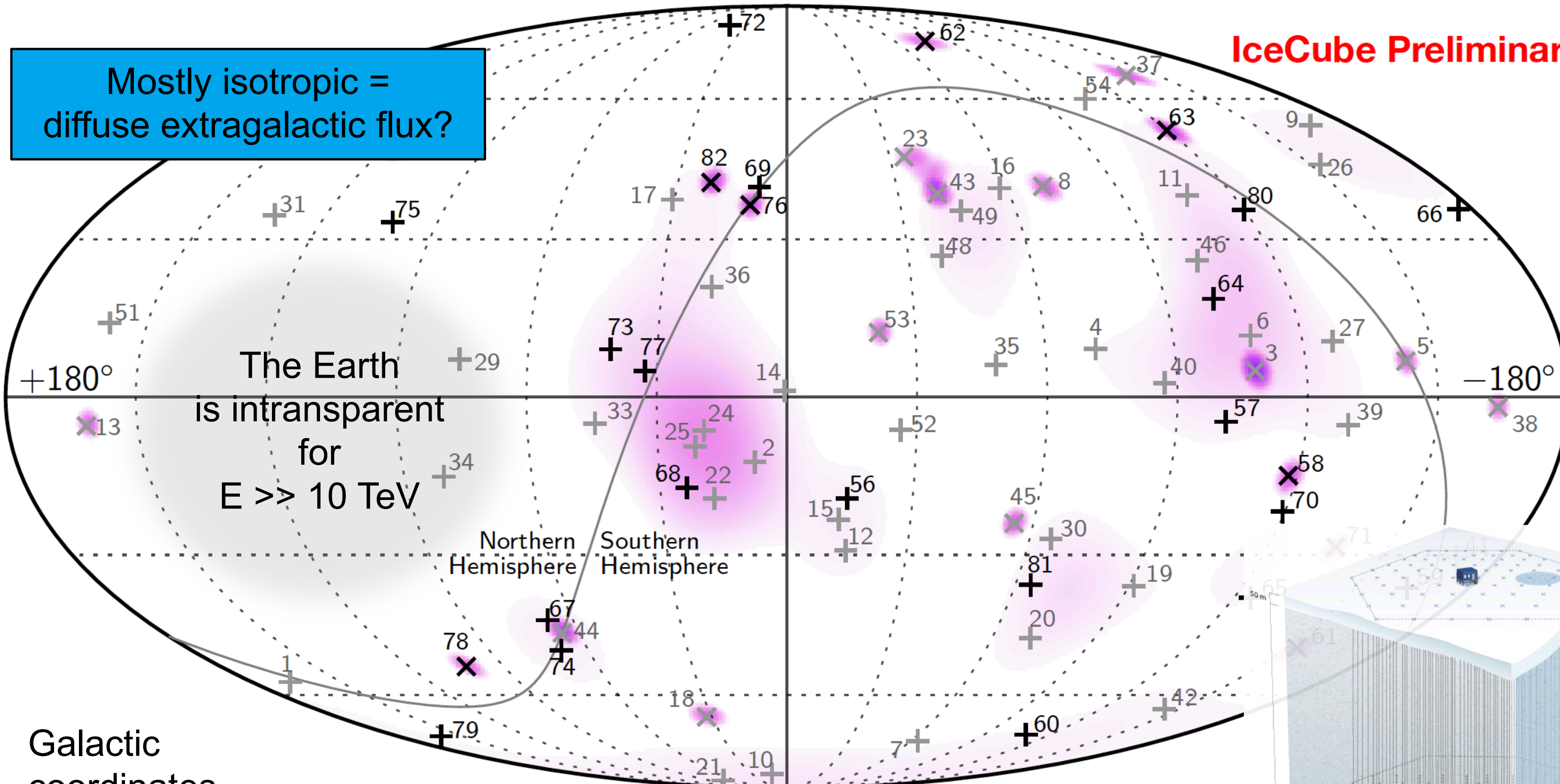


Lorentz force = centrifugal force ➔ E_{max} ~ Z c B R ~ Z (Peters cycle)

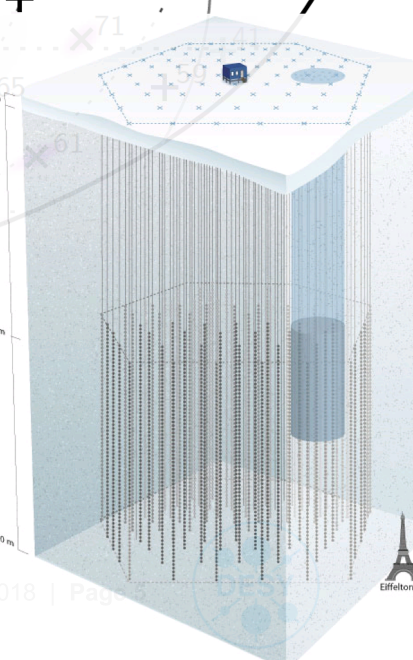
Gaisser, Stanev, Tilav, 2013

A flux of high energy cosmic neutrinos

Mostly isotropic = diffuse extragalactic flux?



The Earth is intransparent for E >> 10 TeV



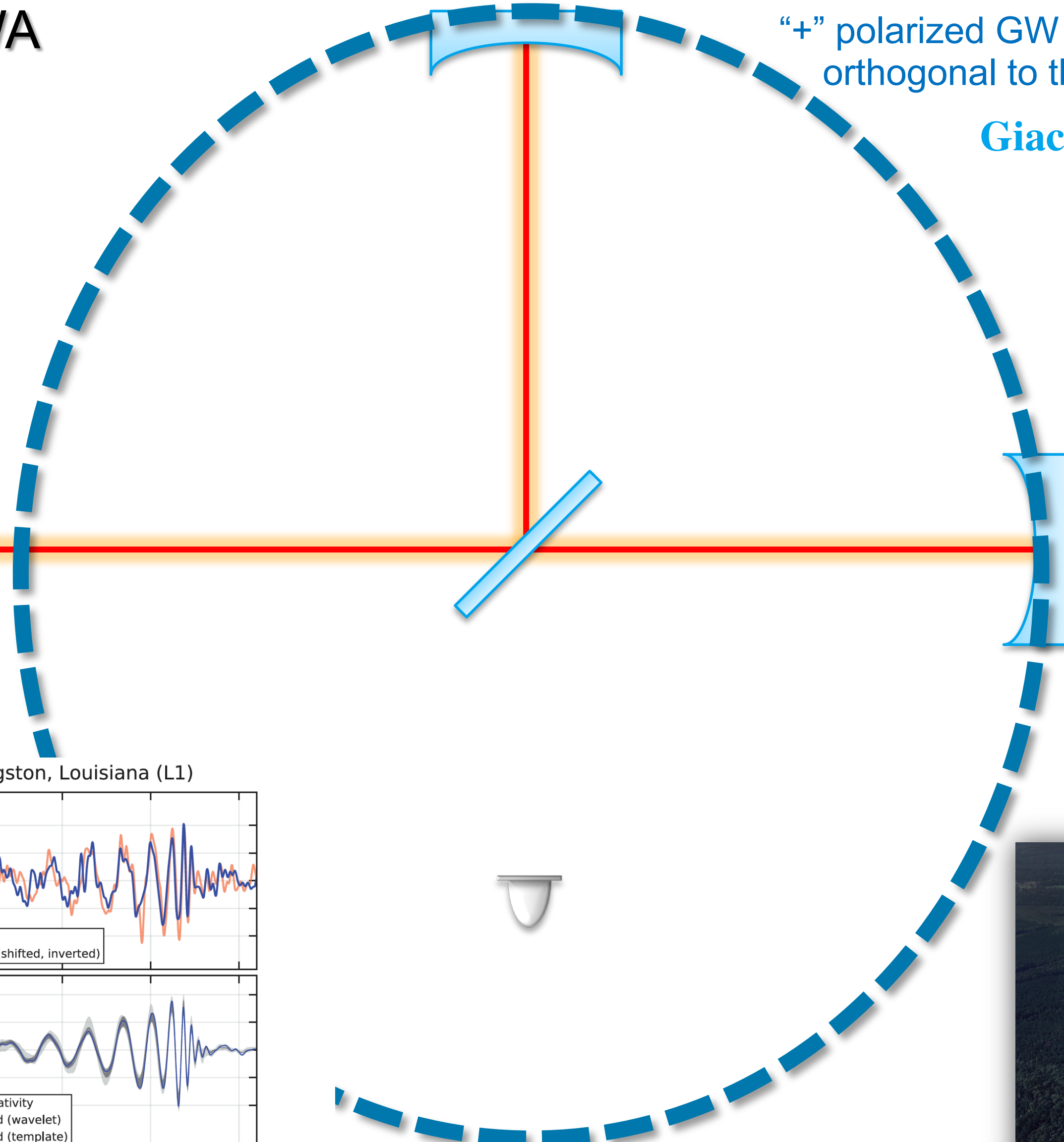
IceCube: Science 342 (2013) 1242856; Phys. Rev. Lett. 113, 101101 (2014); update from Kopper at ICRC 2017

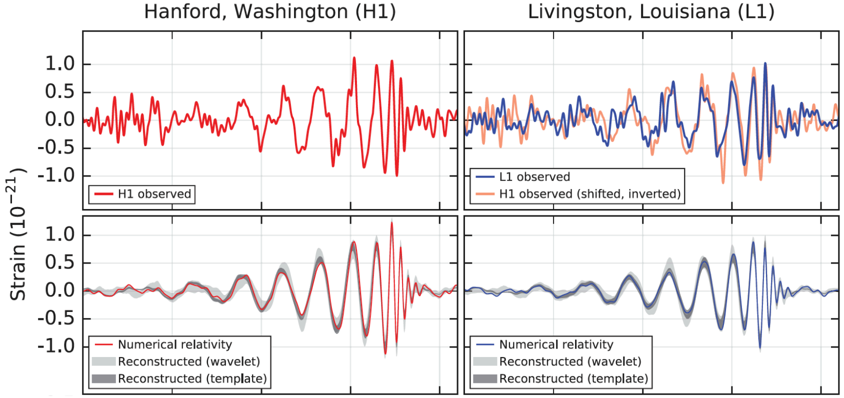
Gravitational waves

Hanford, WA

“+” polarized GW propagating orthogonal to the screen

Giacomo Ciani





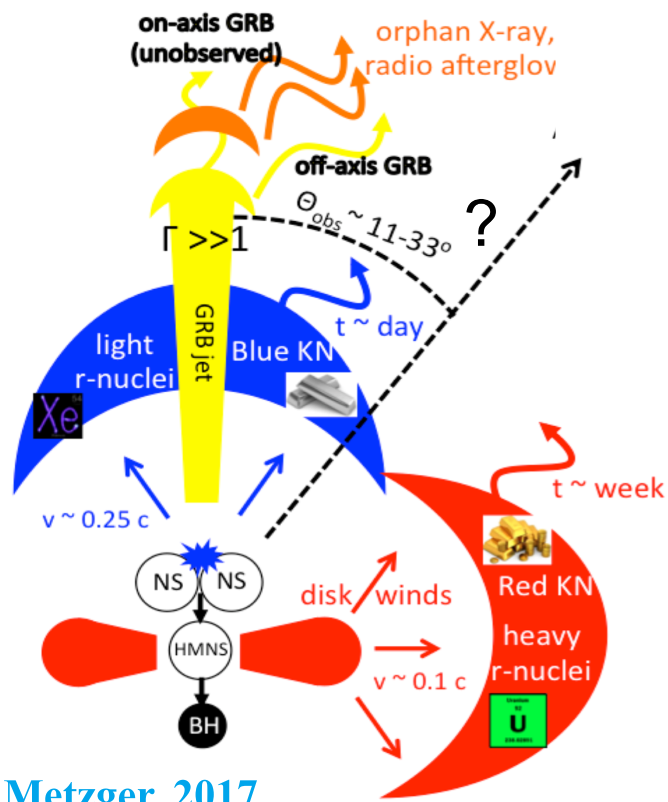
Ligo/Virgo, PRL 2016 x 2, Figure: GW 150914

Livingston, LA

Multi-messenger signals: where do we stand?

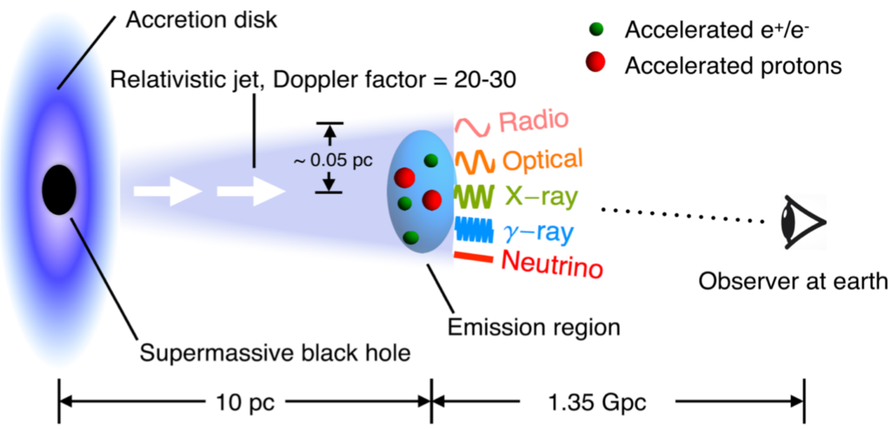
- The birth of extragalactic multi-messenger astronomy: **Feb. 23, 1987**.
  Detection of ~25 neutrinos from supernova explosion →

- Observation of a NS-NS merger in gravitational waves on **Aug. 17, 2017**, associated with
  - A short gamma-ray burst
  - A kilonova, indicating the formation of heavy elements by r-processes



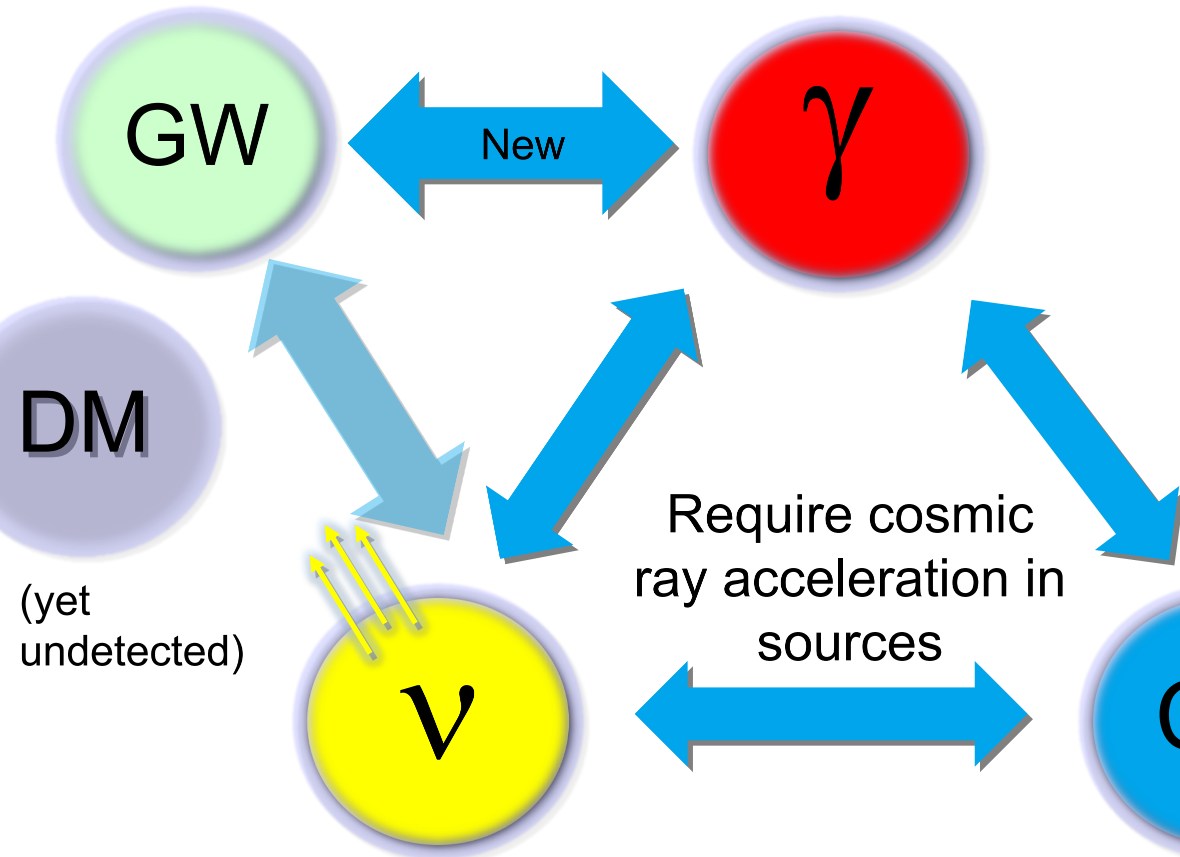
Metzger, 2017

- Coincidence of a neutrino event with a blazar flare of TXS 0506+056 on **Sept. 22, 2017**



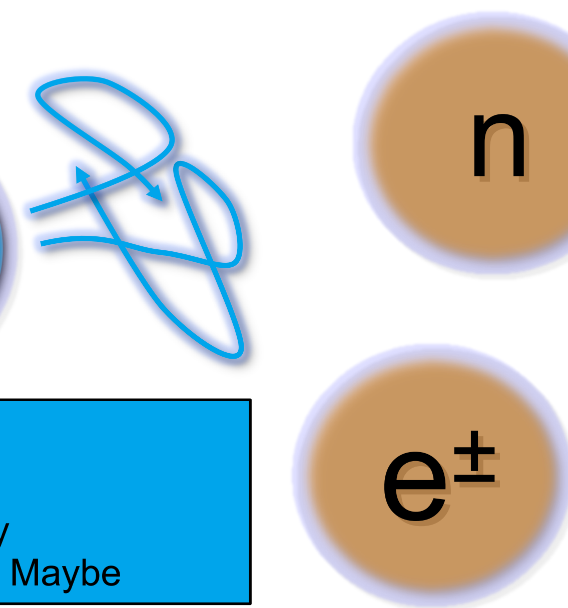
Gao et al, 2018

Multi-messenger astrophysics: Focus of this talk



Photon observations can be often described without cosmic rays (see example p.22)

Multi-messenger relationships including a **baryonic loading**



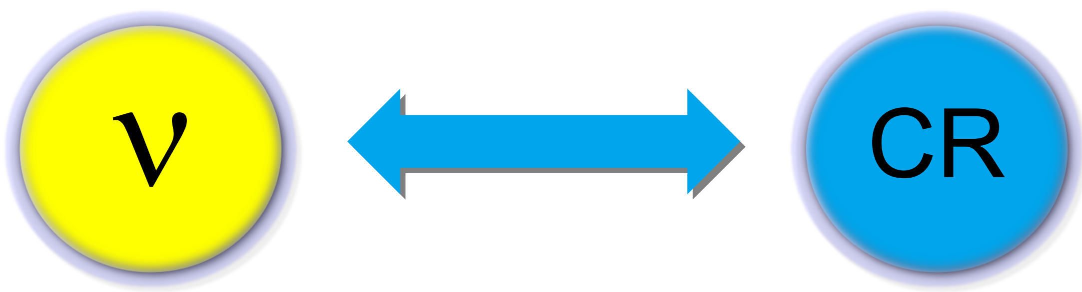
Most of these of extragalactic origin

Extragalactic origin?
- Beyond ankle: Yes
- Beyond 10^{18} eV: Probably
- Between knee and ankle: Maybe

Focus on extragalactic, baryonically loaded sources at highest energies

Testing UHECR paradigms with cosmogenic neutrinos

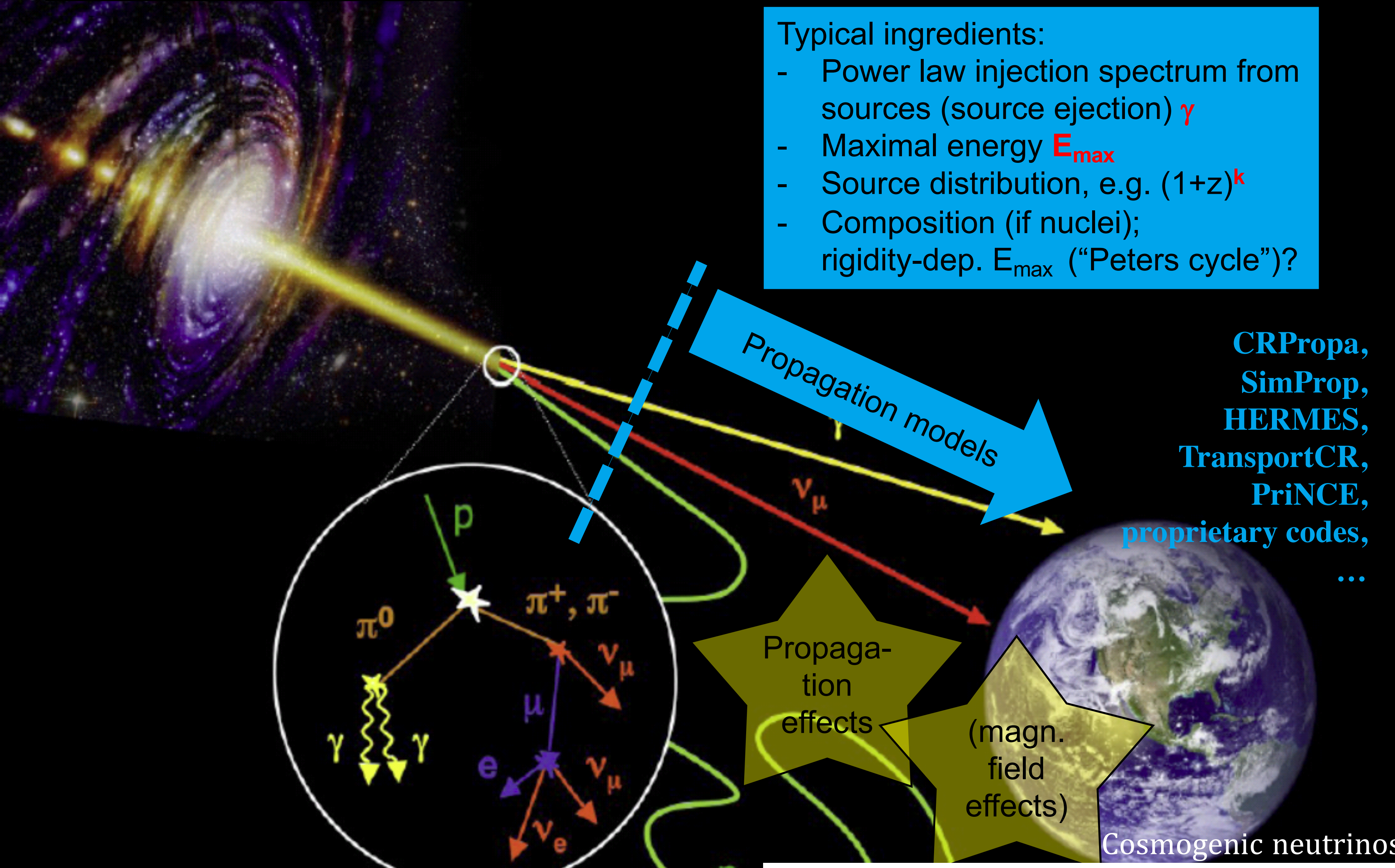
(Multi-messenger propagation/transport models)



UHECR propagation models

Typical ingredients:

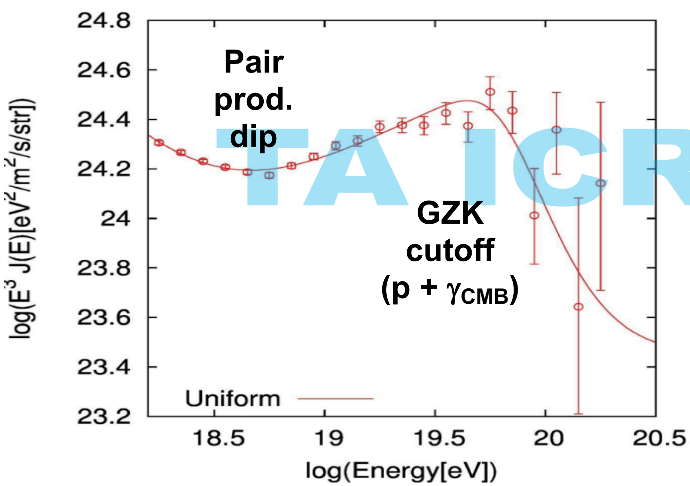
- Power law injection spectrum from sources (source ejection) γ
- Maximal energy E_{max}
- Source distribution, e.g. $(1+z)^k$
- Composition (if nuclei); rigidity-dep. E_{max} (“Peters cycle”)?

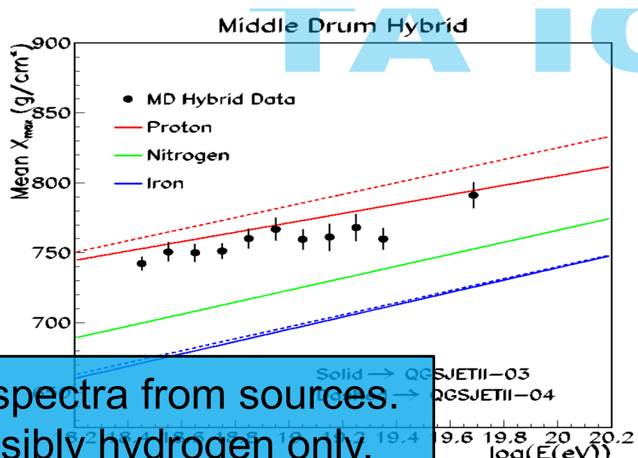


$$p+\gamma_{\text{CMB}} \rightarrow \Delta^{+} \rightarrow \begin{cases} n+\pi^{+} & 1/3 \text{ of all cases} \\ p+\pi^{0} & 2/3 \text{ of all cases} \end{cases}$$

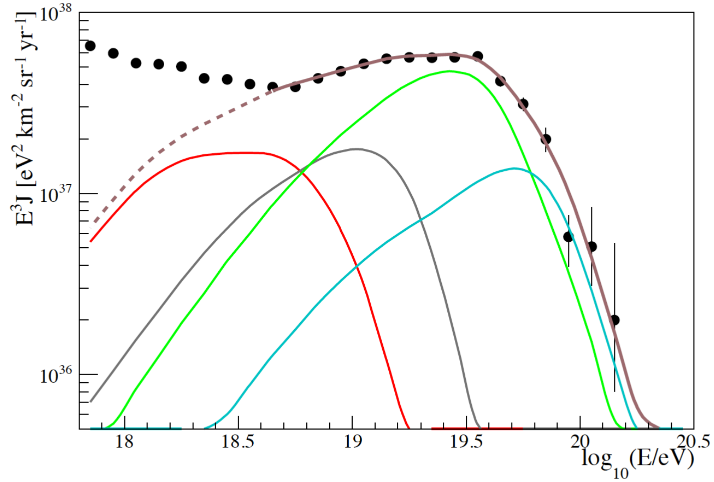
Current theoretical paradigms (from propagation models)

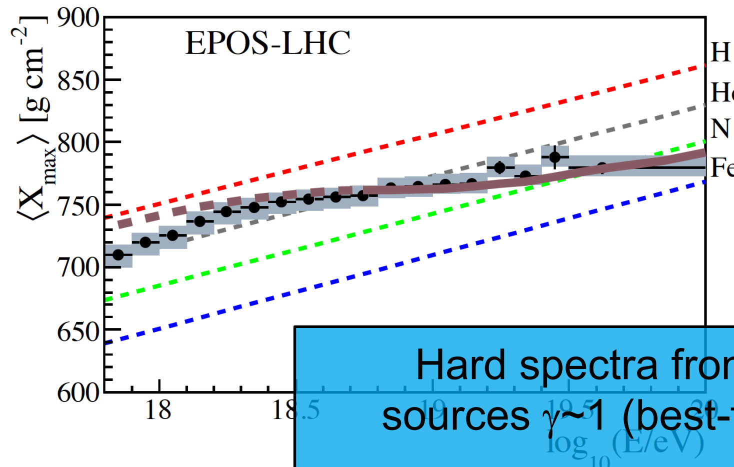
TA (Telescope Array) vs. Auger





Jui @ ICRC 2015; update: arXiv:1808.03680





Auger global fit, 1612.07155

Soft spectra from sources. Possibly hydrogen only. Proton dip model?
Berezinsky, Gazizov, Grigorieva, 2005

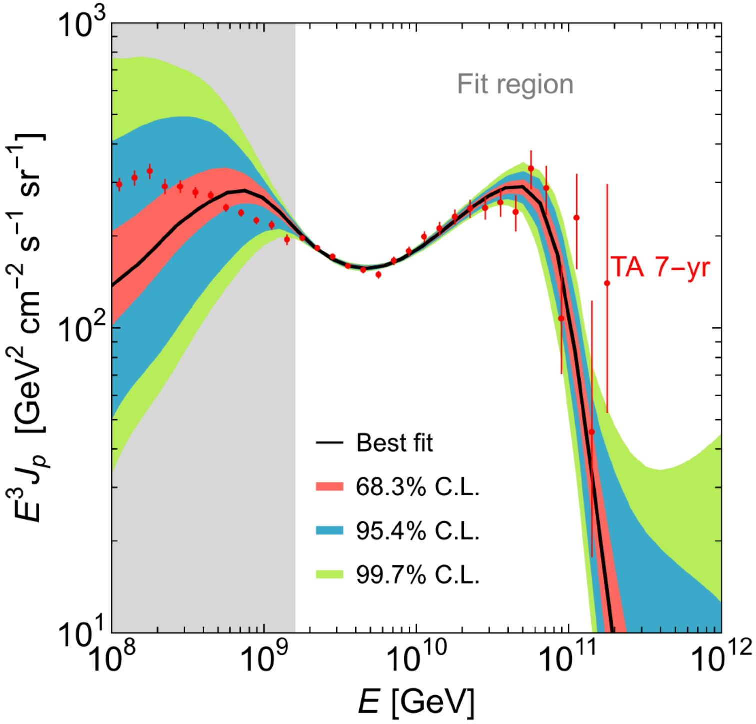
What can neutrinos and γ-rays tell us?

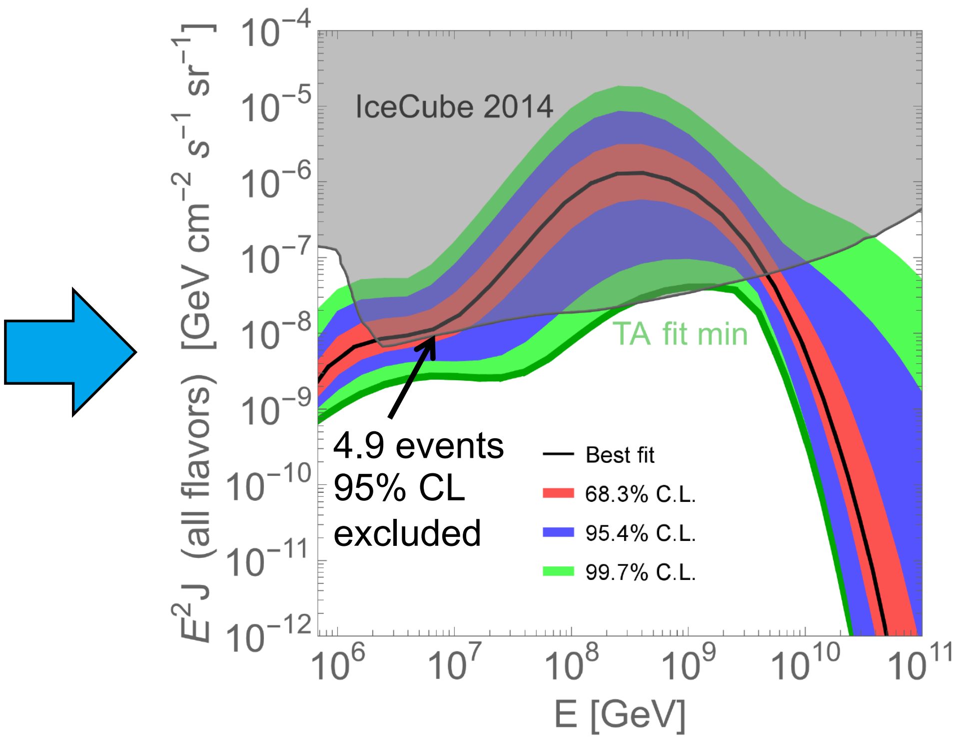
Hard spectra from sources γ~1 (best-fit).

Elements up to silicon (?) from sources

Cosmogenic neutrinos challenge the proton dip model

- Model (γ, E_{max}, k) with fully marginalized parameters (3D): TA 7-year meets IceCube 2014 data
  Heinze, Boncioli, Bustamante, Winter, ApJ 825 (2016) 122





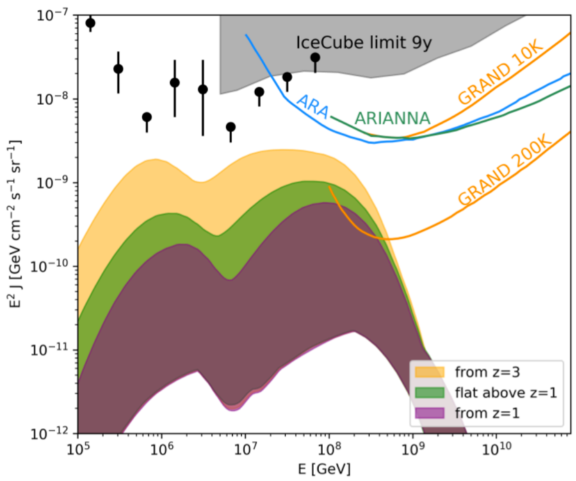
- Possible (likely?) interpretation: **The composition is not dominated by protons at the highest energies;**
  similar arguments can be obtained from γ-rays **e. g. Supanitsky, 2016**

Cosmogenic neutrinos: Post-diction from Auger data?

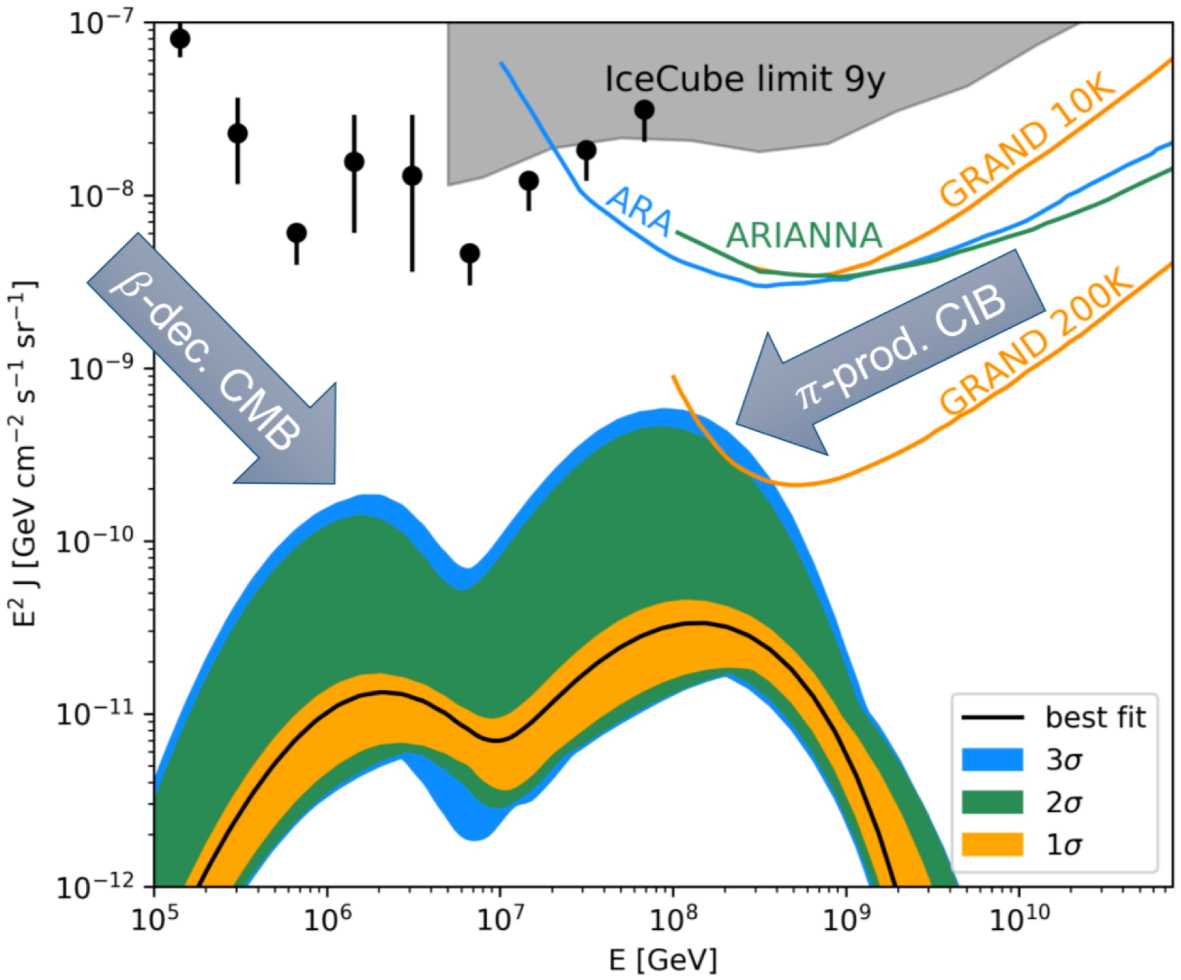
Assumption: rigidity-dependent maximal energy

- Contribution from sources up to z~1
- Can be a factor of a few higher if CR injection at higher z:

$$n_{\rm evol}(z) = \begin{cases} (1+z)^m & , z \le 1 \\ ? & , z > 1 \end{cases}$$



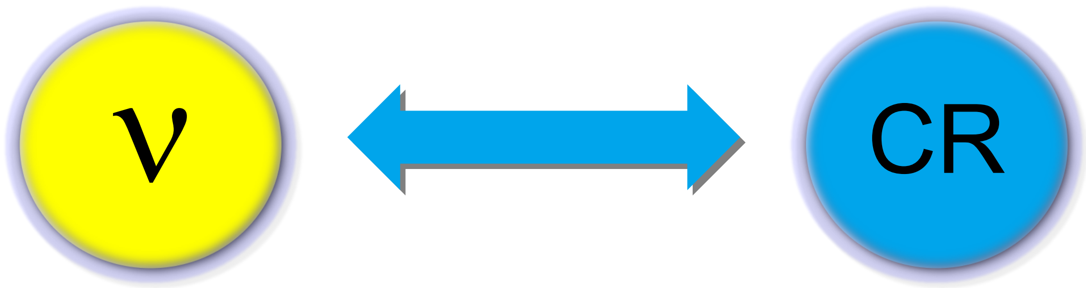
- Hardly depends on disintegration and shower models (CR fit does!)



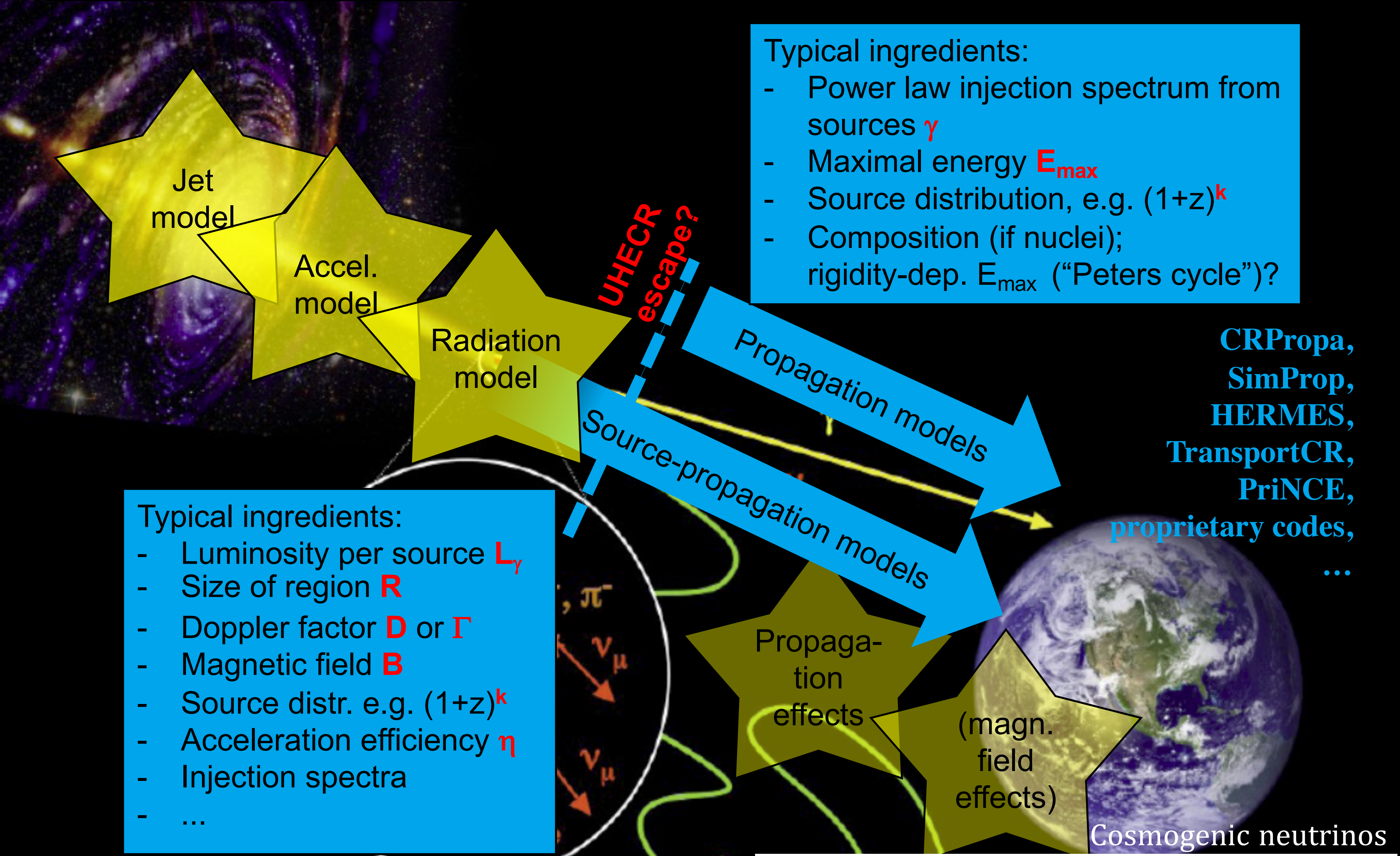
Jonas Heinze @ TeVPA 2018; Heinze, Fedynitch, Boncioli, WW, in prep; see also: Alves Batista et al, arXiv: 1806.10879; Moller, Denton, Tamborra, arXiv:1809.04866; Das, Razzaque, Gupta, 1809.05321

Common origin of diffuse neutrinos and UHECRs?

(Multi-messenger source-propagation models)



From propagation to source-propagation models



Typical ingredients:

- Power law injection spectrum from sources γ
- Maximal energy E_{max}
- Source distribution, e.g. $(1+z)^k$
- Composition (if nuclei); rigidity-dep. E_{max} ("Peters cycle")?

Typical ingredients:

- Luminosity per source L_γ
- Size of region **R**
- Doppler factor **D** or Γ
- Magnetic field **B**
- Source distr. e.g. $(1+z)^k$
- Acceleration efficiency η
- Injection spectra
- ...

CRPropa,
SimProp,
HERMES,
TransportCR,
PriNCE,
proprietary codes,
...

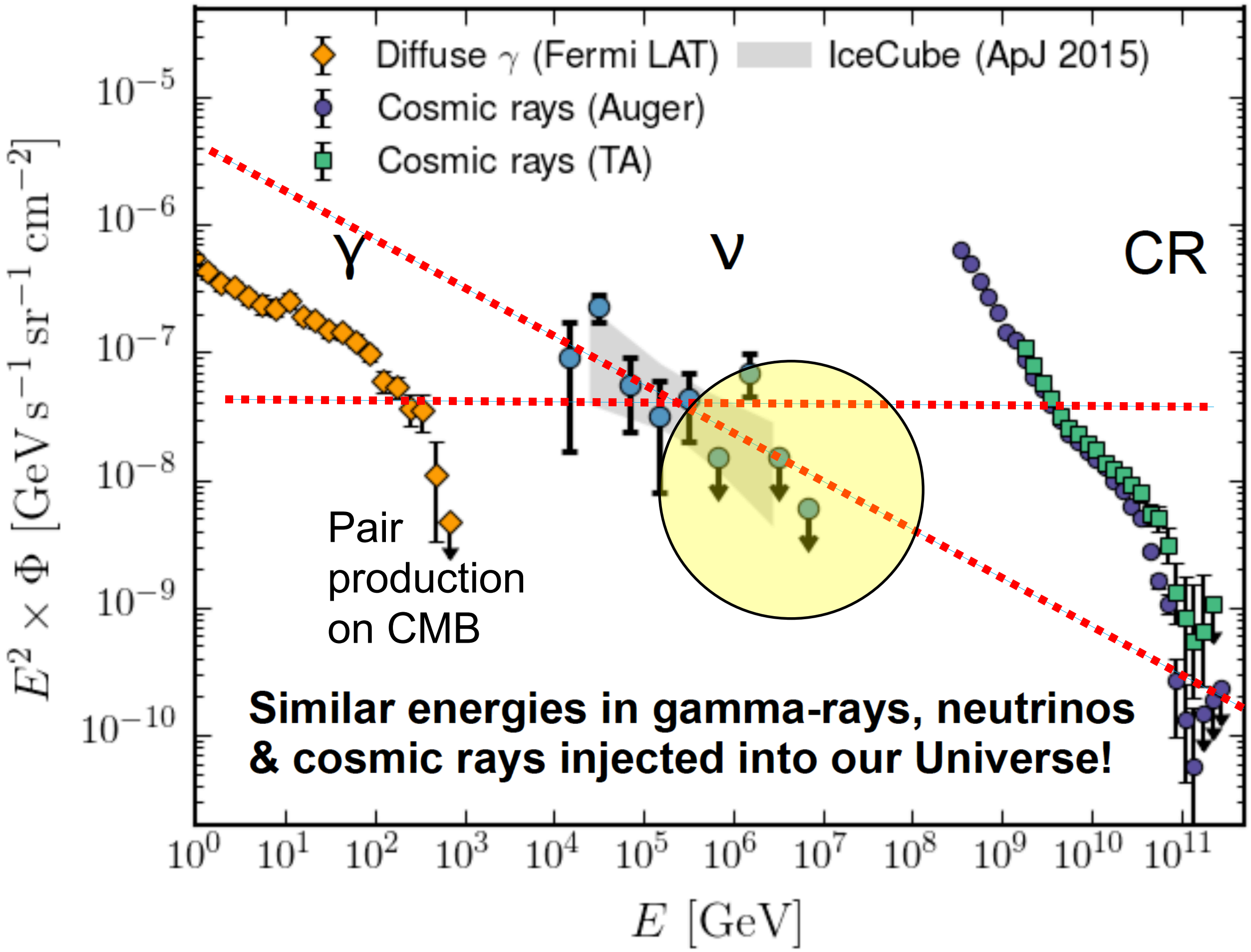
Cosmogenic neutrinos

$$p + \gamma_{\text{CMB}} \rightarrow \Delta^+ \rightarrow \begin{cases} n + \pi^+ & 1/3 \text{ of all cases} \\ p + \pi^0 & 2/3 \text{ of all cases} \end{cases}$$

Energetics: The Waxman-Bahcall argument

- Neutrino flux matches UHECR injection
  Waxman, Bahcall, Phys. Rev. D59 (1999) 023002
  ... and diffuse γ-rays
  see Fermi-LAT, Astrophys. J. 799 (2015) 86

- Caveats:
  - Extrapolation over many order of E
  - Energy imbalance if softer than E^{-2}
  - **Neutrino-UHECR connection if cutoff ... how can this be avoided?**



Mohrmann, Kowalski

Neutrino-UHECR-γ-ray connection in photohadronic models

- Neutrino peak determined by maximal cosmic ray energy
- UHECR connection typically implies high neutrino energy peak
- Interaction with target photons (Δ-resonance approximation):

$$p + \gamma \longrightarrow \Delta^+ \longrightarrow \begin{cases} n + \pi^+ \\ p + \pi^0 \end{cases}$$

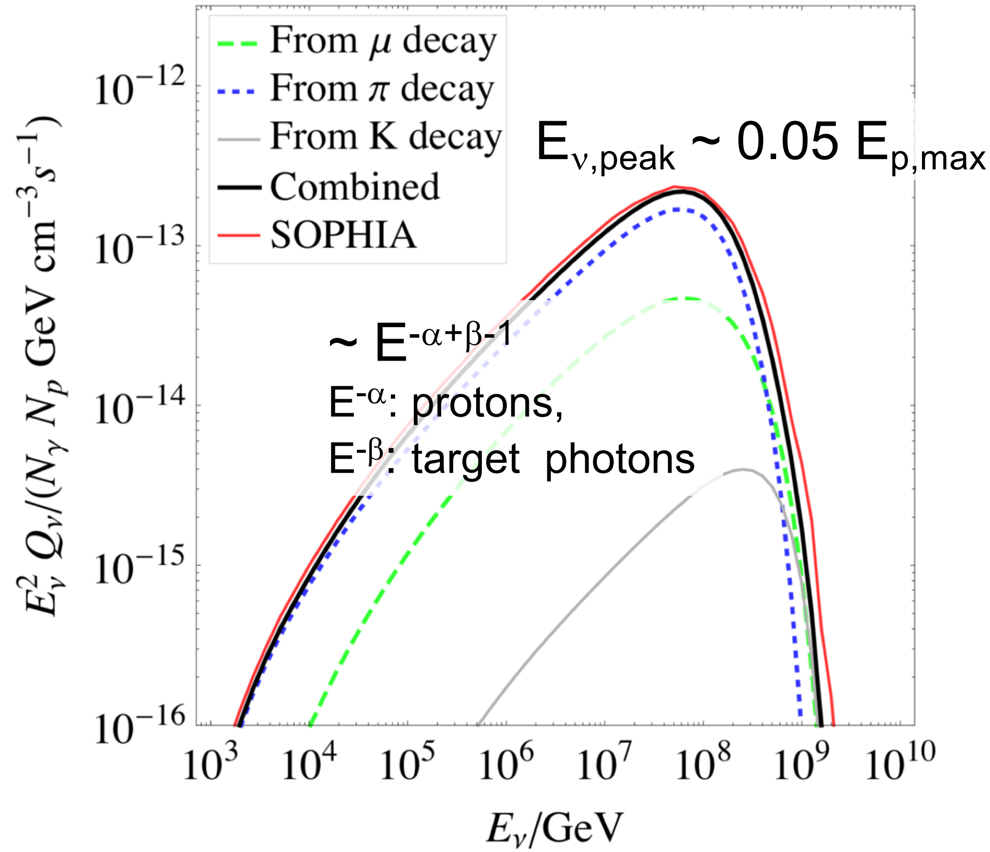
E_γ [keV] ~ $0.01\ \Gamma^2/E_\nu$ [PeV]
keV energies interesting!

- Photons from pion decay:

$$\pi^0 \longrightarrow \gamma + \gamma$$

Injected at $E_{\gamma,peak}$ ~ $0.1\ E_{p,max}$
TeV–PeV energies interesting!
(EM cascade!)

AGN neutrino spectrum (example)



From: Hümmer et al, Astrophys. J. 721 (2010) 630

Decouple the maximal UHECR and neutrino energies?

- Synchrotron cooling of secondaries in neutrino production chain:

$$\pi^+ \rightarrow \mu^+ + \nu_\mu \,,$$
$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

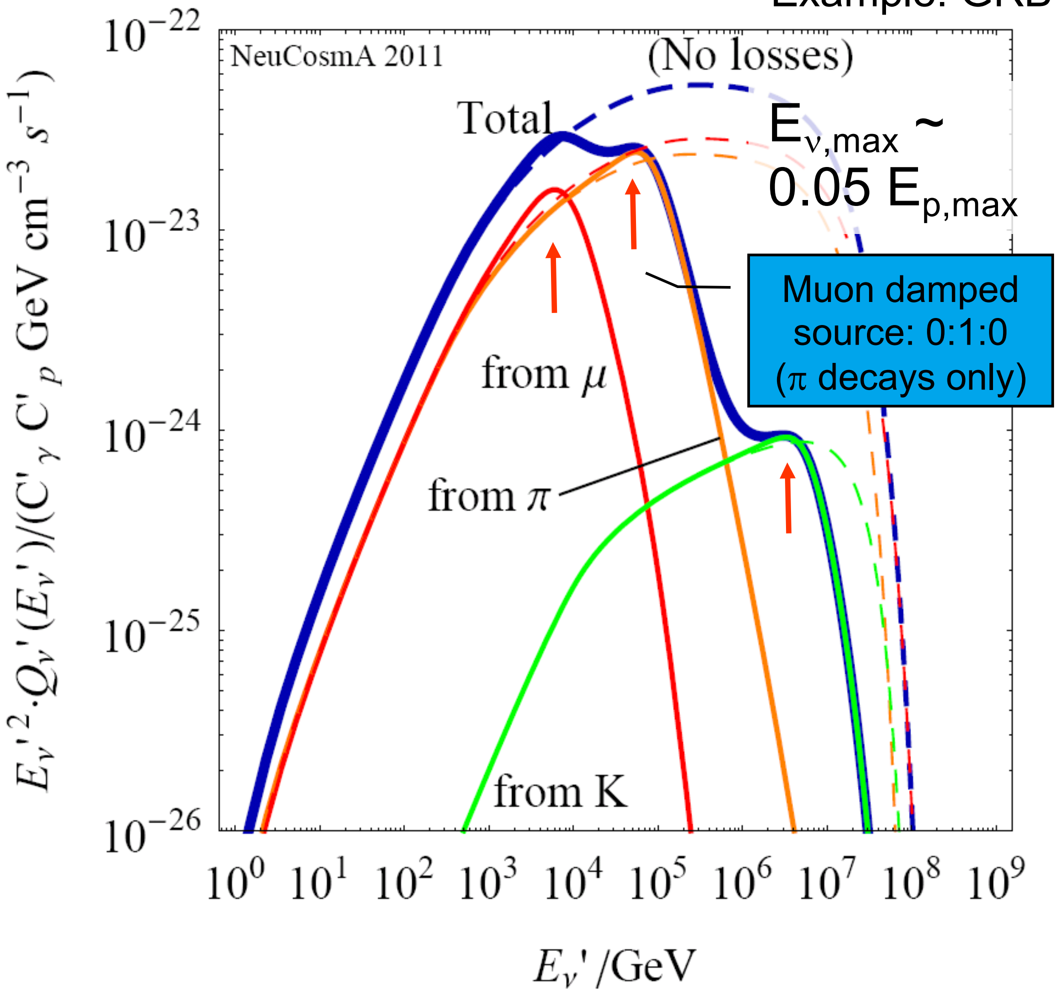
- Spectra (μ, π, K) energy loss-steepend above critical energy

$$E'_c = \sqrt{\frac{9\pi\epsilon_0 m^5 c^7}{\tau_0 e^4 B'^2}}$$

Depends on particle physics only (m, τ_0), and **B‘**

- Points towards sources with strong enough B‘: Gamma-Ray Bursts, Tidal Disruption Events, ...

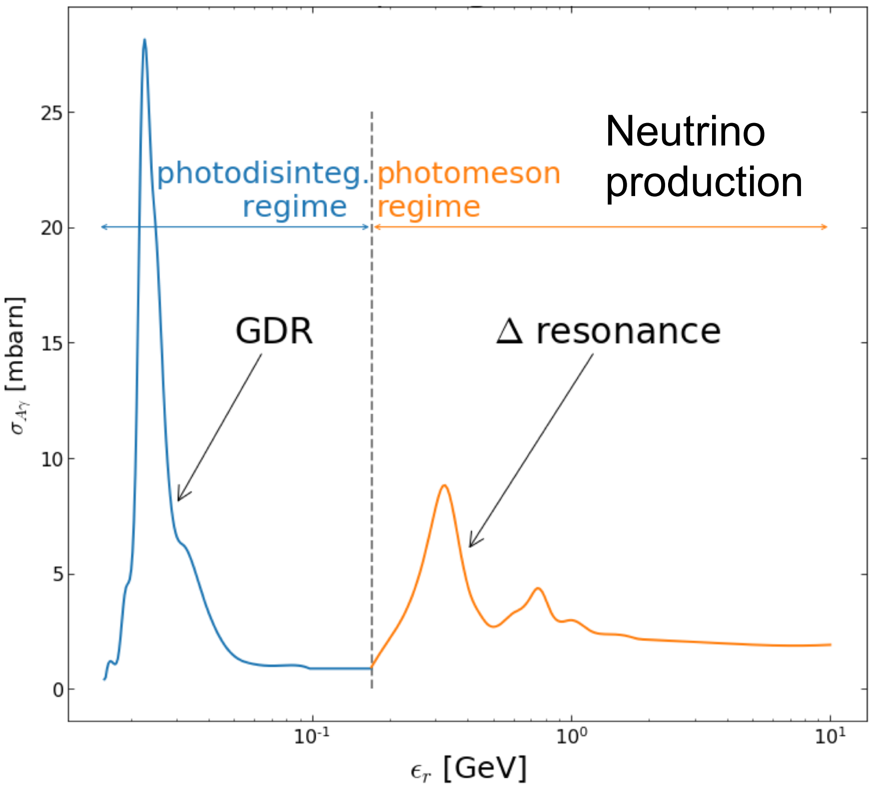
Example: GRB



Baerwald, Hümmer, Winter, Astropart. Phys. 35 (2012) 508; also: Kashti, Waxman, 2005; Lipari et al, 2007; ...

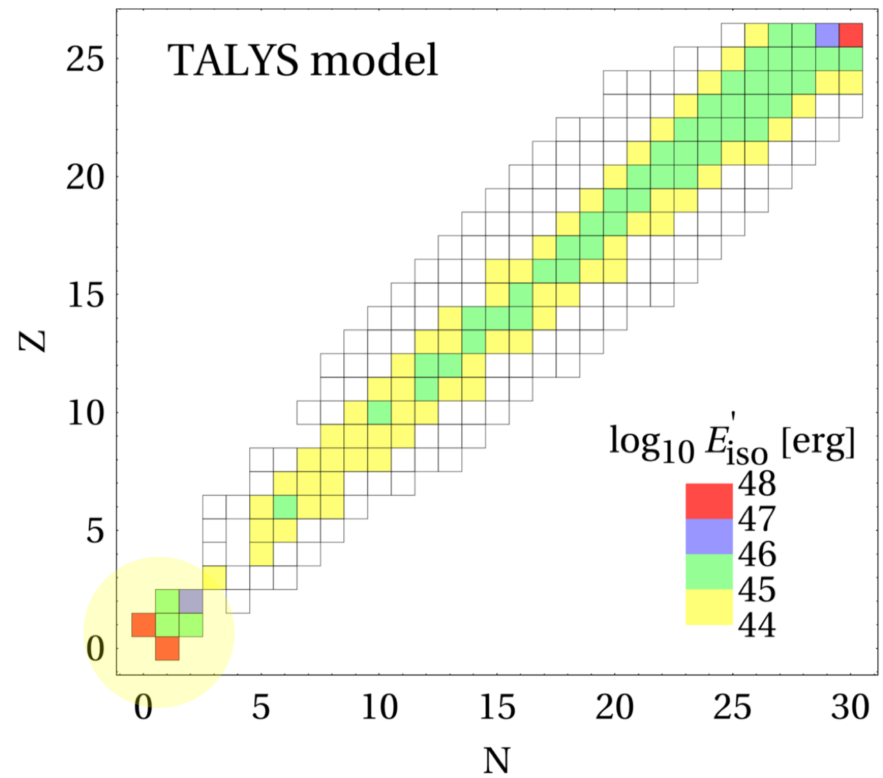
Sources with high radiation densities ... and nuclei

- Efficient neutrino production implies efficient nuclear disintegration
- The nuclear cascade in the source will develop (Example: GRB)



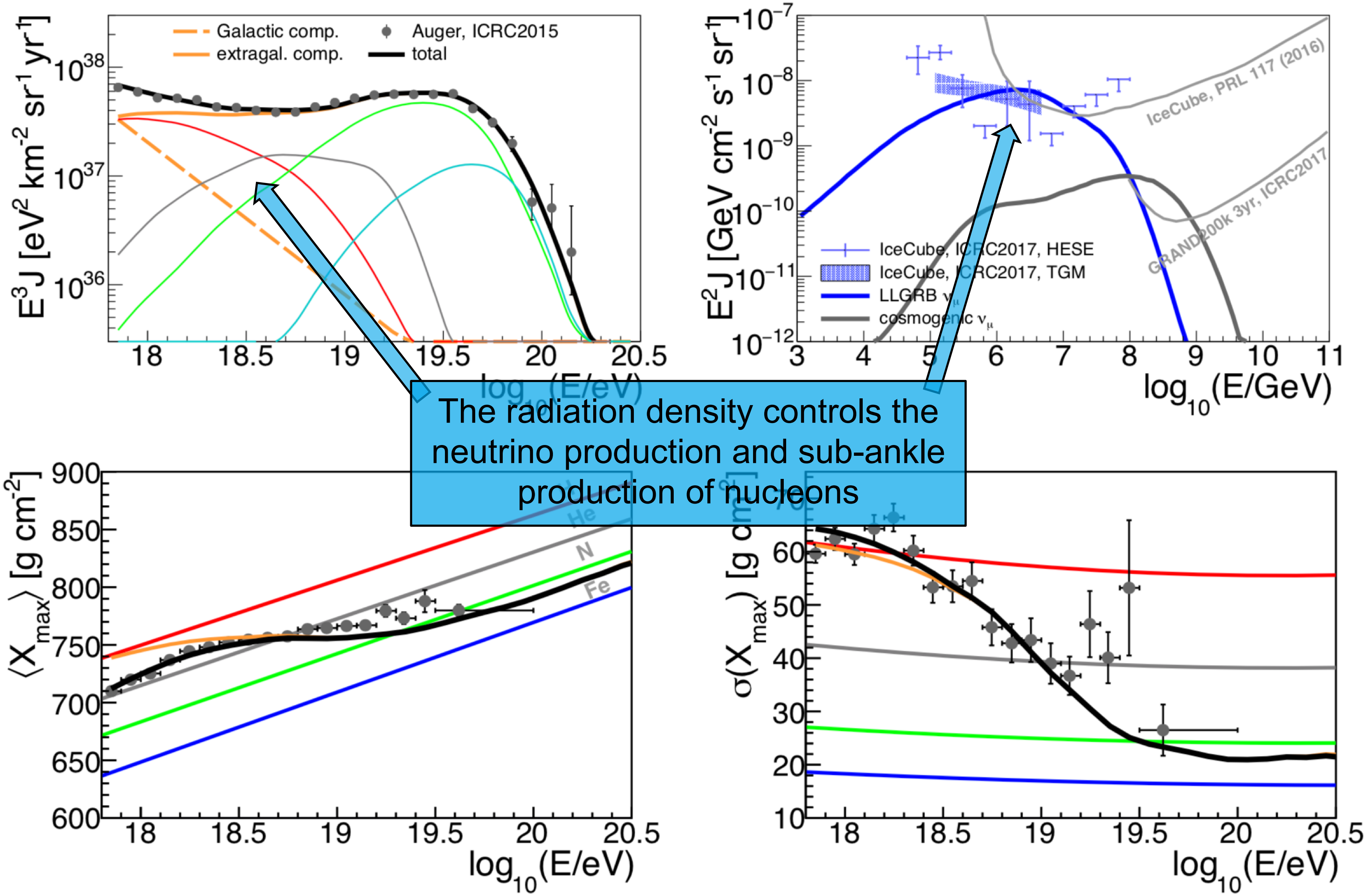
(photon energy in nucleon rest frame)

L. Morejon et al, in prep.



Boncioli, Fedynitch, Winter, Scientific Reports 7 (2017) 4882

Example: low-luminosity Gamma-Ray Bursts



Boncioli, Biehl, Winter, arXiv:1808.07481; injection composition/escape from Zhang et al., 2018; similar example: Tidal Disruption Events in Biehl et al, Sci. Rep. 8 (2018) 10828, see Poster D. Biehl

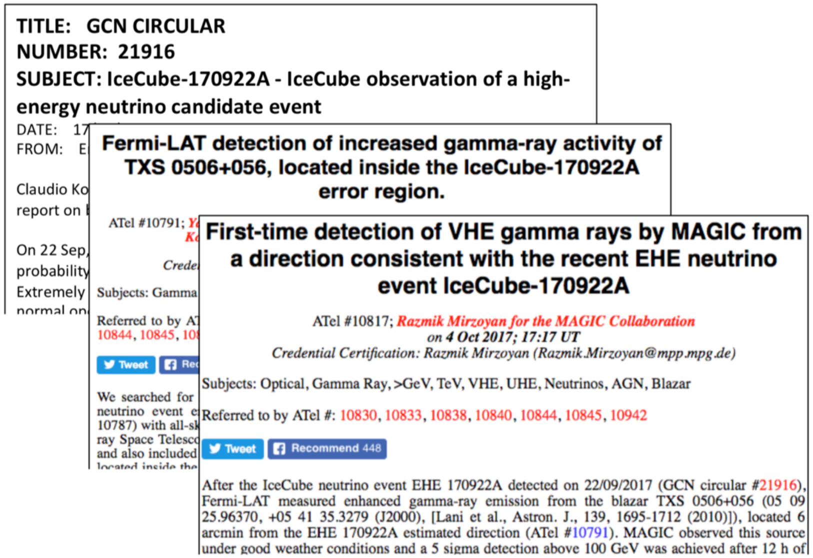
AGN blazar

Active Galactic Nuclei (AGN) blazar flares ... indicative for the origin of cosmic rays?

(Multi-messenger-multi-wavelength source models)

Science 361 (2018) no. 6398, eaat1378; see talk Anna Franckowiak

IceCube-170922A & TXS 0506+056



TITLE: GCN CIRCULAR
NUMBER: 21916
SUBJECT: IceCube-170922A - IceCube observation of a high-energy neutrino candidate event

DATE: 17
FROM: E

Claudio Ko
report on

On 22 Sep,
probability
Extremely

Fermi-LAT detection of increased gamma-ray activity of TXS 0506+056, located inside the IceCube-170922A error region.

ATel #10791;

Subjects: Gamma

Referred to by AT
10844, 10845, 10

Tweet

We searched for
neutrino event
10787) with all-sk
ray Space Telesc
and also included

First-time detection of VHE gamma rays by MAGIC from a direction consistent with the recent EHE neutrino event IceCube-170922A

ATel #10817; ***Razmik Mirzoyan for the MAGIC Collaboration***
on 4 Oct 2017; 17:17 UT
Credential Certification: Razmik Mirzoyan (Razmik.Mirzoyan@mpp.mpg.de)

Subjects: Optical, Gamma Ray, >GeV, TeV, VHE, UHE, Neutrinos, AGN, Blazar

Referred to by ATel #: 10830, 10833, 10838, 10840, 10844, 10845, 10942

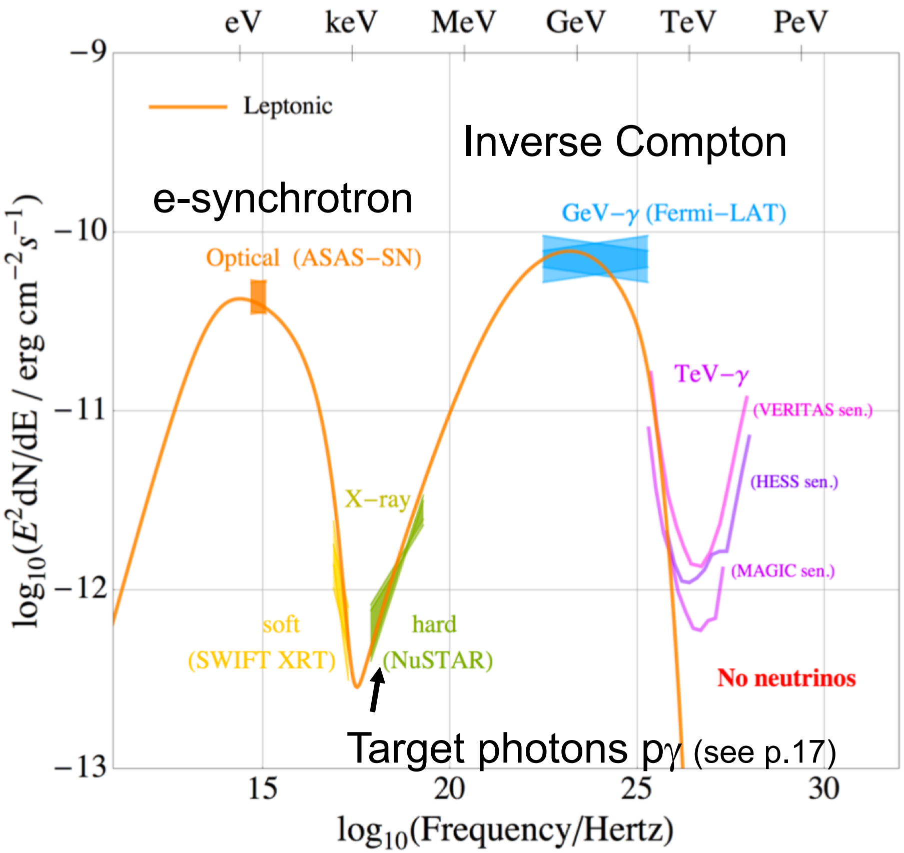
Tweet Recommend 448

After the IceCube neutrino event EHE 170922A detected on 22/09/2017 (GCN circular #21916), Fermi-LAT measured enhanced gamma-ray emission from the blazar TXS 0506+056 (05 09 25.96370, +05 41 35.3279 (J2000), [Lani et al., Astron. J., 139, 1695-1712 (2010)]), located 6 arcmin from the EHE 170922A estimated direction (ATel #10791). MAGIC observed this source under good weather conditions and a 5 sigma detection above 100 GeV was achieved after 12 h of

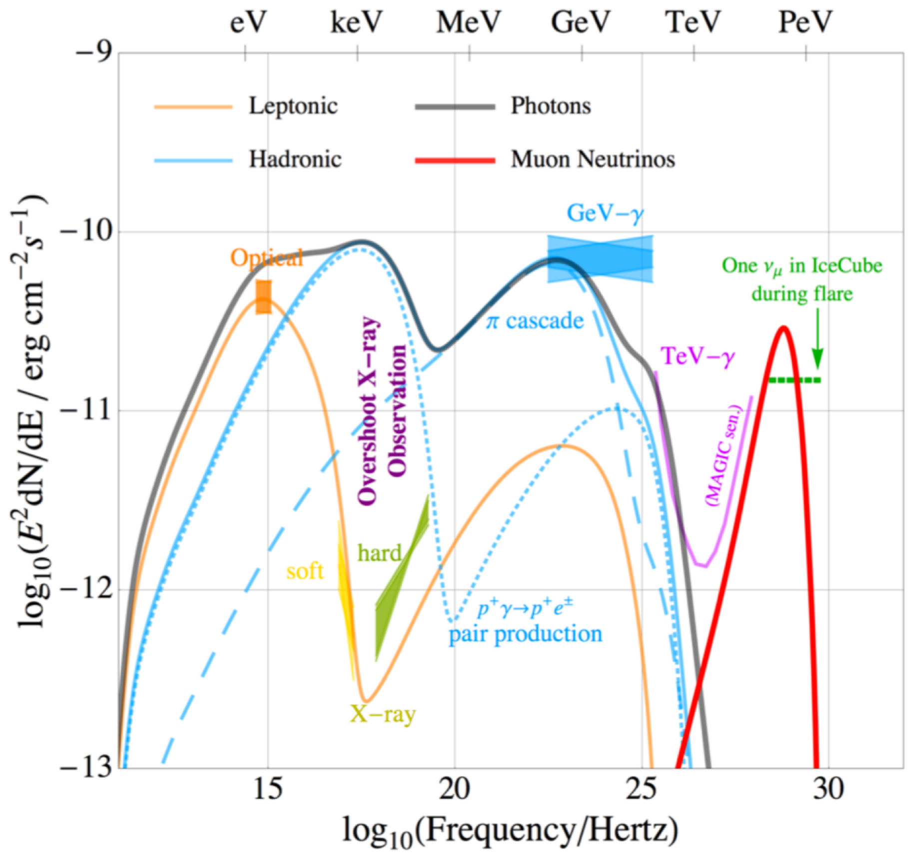
September 22, 2017: a neutrino alert issued by IceCube
Fermi and MAGIC identify a spatially coincident flaring blazar (TXS 0506+056)

A flare model for IceCube 170922A / TXS 0506+56

> Leptonic model



> Hadronic model



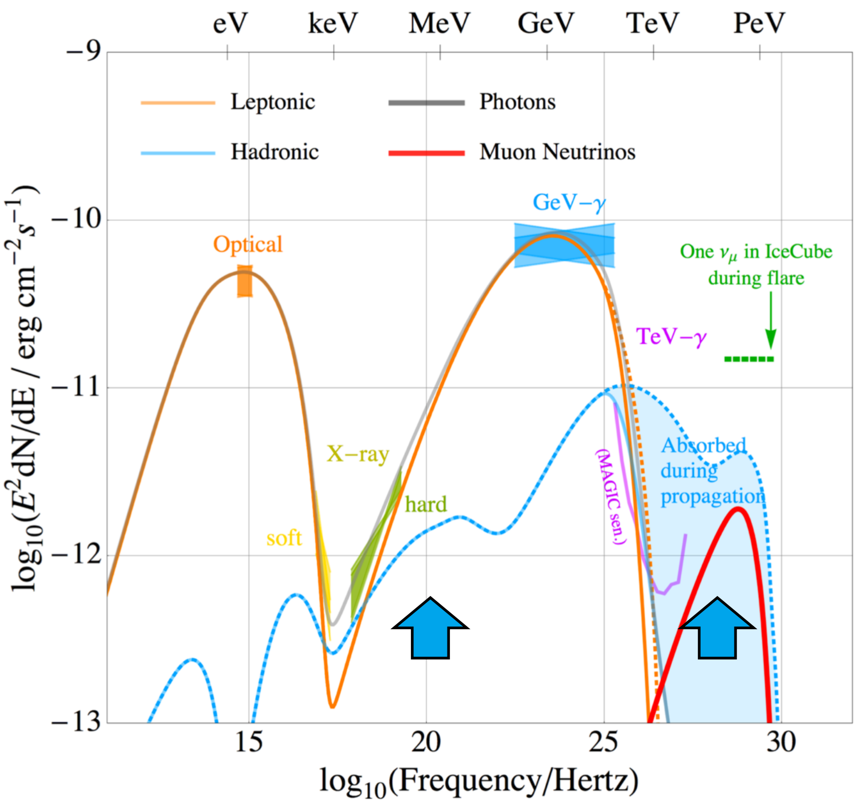
> Fits electromagnetic observations, but no neutrinos

> Describes neutrinos, overhoots X-ray data

Gao, Fedynitch, Winter, Pohl, arXiv:1807.04275;
see also: Gao, Pohl, Winter, ApJ 843 (2017) 109

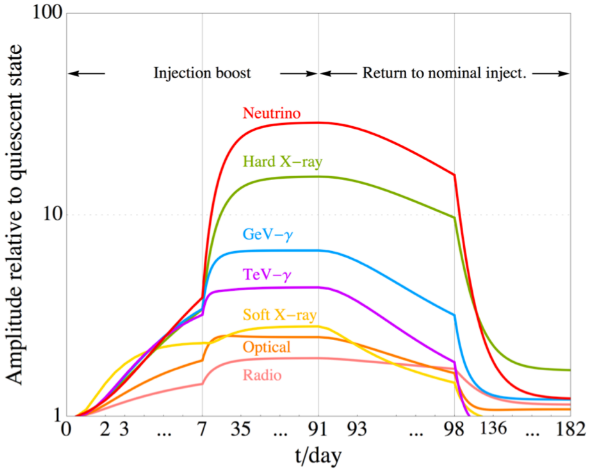
A hybrid model for IceCube 170922A / TXS 0506+56

- **Hybrid one zone model**



Gao, Fedynitch, Winter, Pohl, arXiv:1807.04275

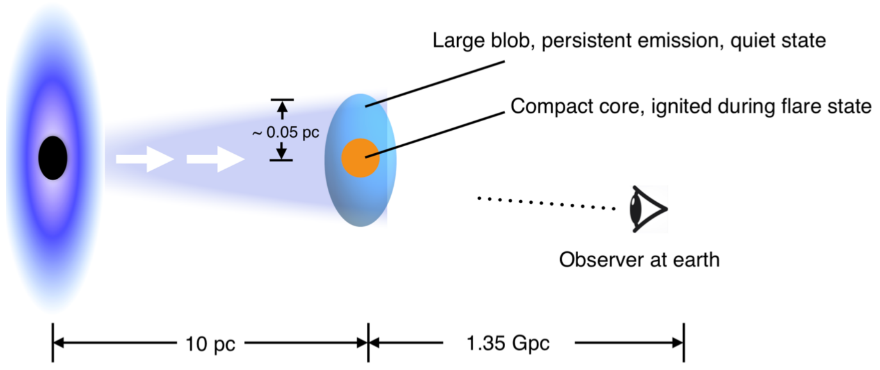
- Flare my simultaneous increase of electron and proton injection: **Evidence for cosmic ray injection**



- X-ray and TeV-data are the EM counterparts for the hadronic loading!
- Flickering in IACT data expected because of EBL attenuation (threshold effect)
- Drawback (this model): L_{edd} exceeded

Lessons learned from TXS 0506+056 - IC170922A (theory)

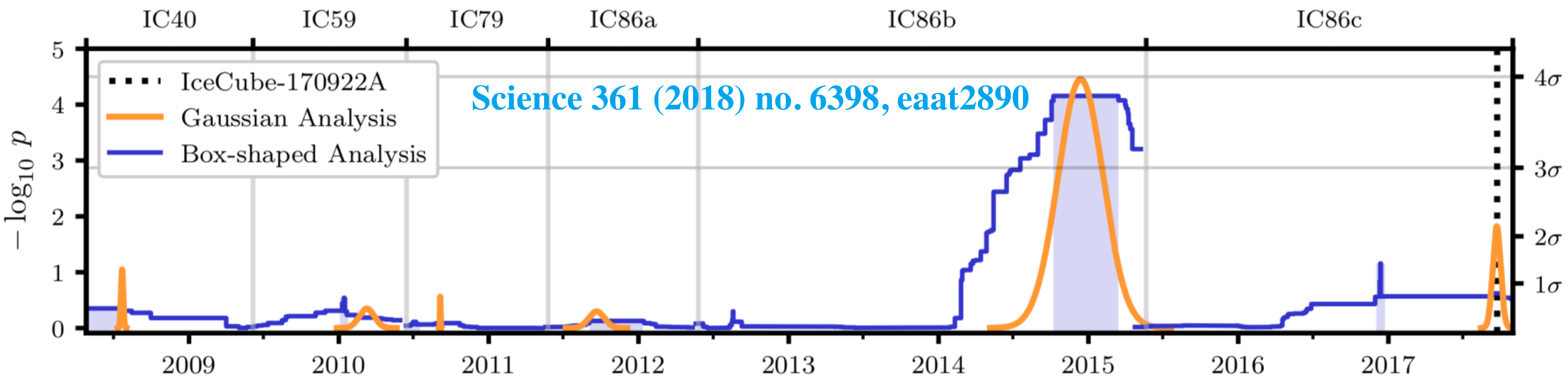
- X-ray and TeV gamma-ray data limit the pion induced cascade; rules out standard hadronic model (second hump from π^0 decay)
- A conventional one zone lepto-hadronic model is feasible, if one accepts one of these two compromises:
  - There has been super-Eddington injection during the flare (by a factor of few hundred)
  - The neutrino spectrum peaks at much higher energies; allows for the connection to UHECRs (works in lepto-hadronic and proton synchrotron models)
- If these are not acceptable, more complicated (multi-zone) models are required:
  - A more compact production region during the flare →
  - Invoke external radiation fields, boosted back into the jet frame
  - Hadro-nuclear interactions with a junk of matter



Shan Gao

Gao et al 2018; Keivani et al, 2018; Sahakyan, 2018; Gokus et at, 2018; MAGIC collaboration, 2018; Cerutti et al, 2018; Padovani et al, 2018; Zhang et al, 2018; Liu et al, 2018; ...

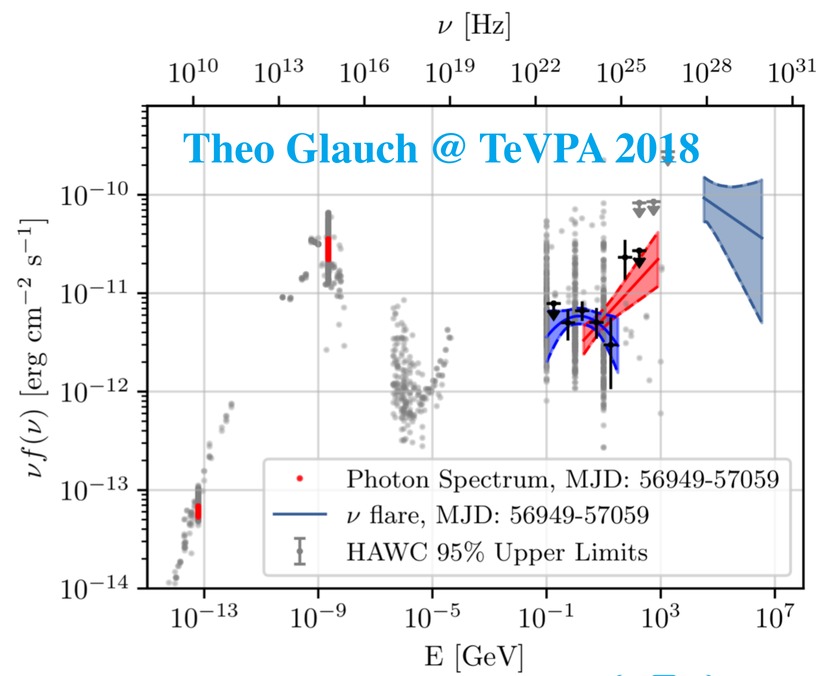
Historical flare: 15+-5 events during 5 months 2014-2015



> More questions than answers:

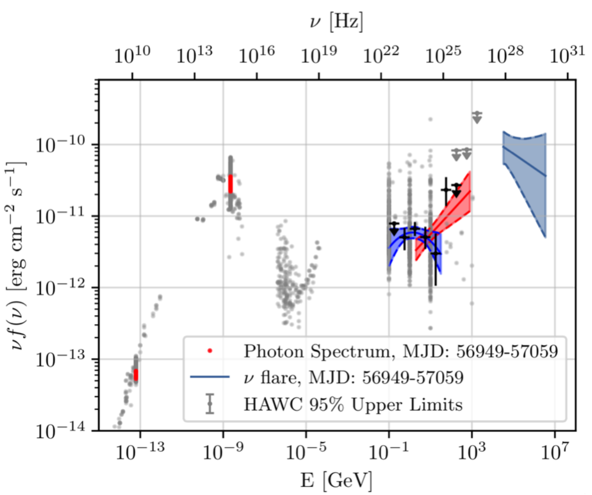
- From same blazar? Or even nearby blazar PKS 0502+049 (which was flaring at the time)
- Situation on data during that period? X-rays?
- Different origin of neutrino signal? Jet-cloud/star interaction?

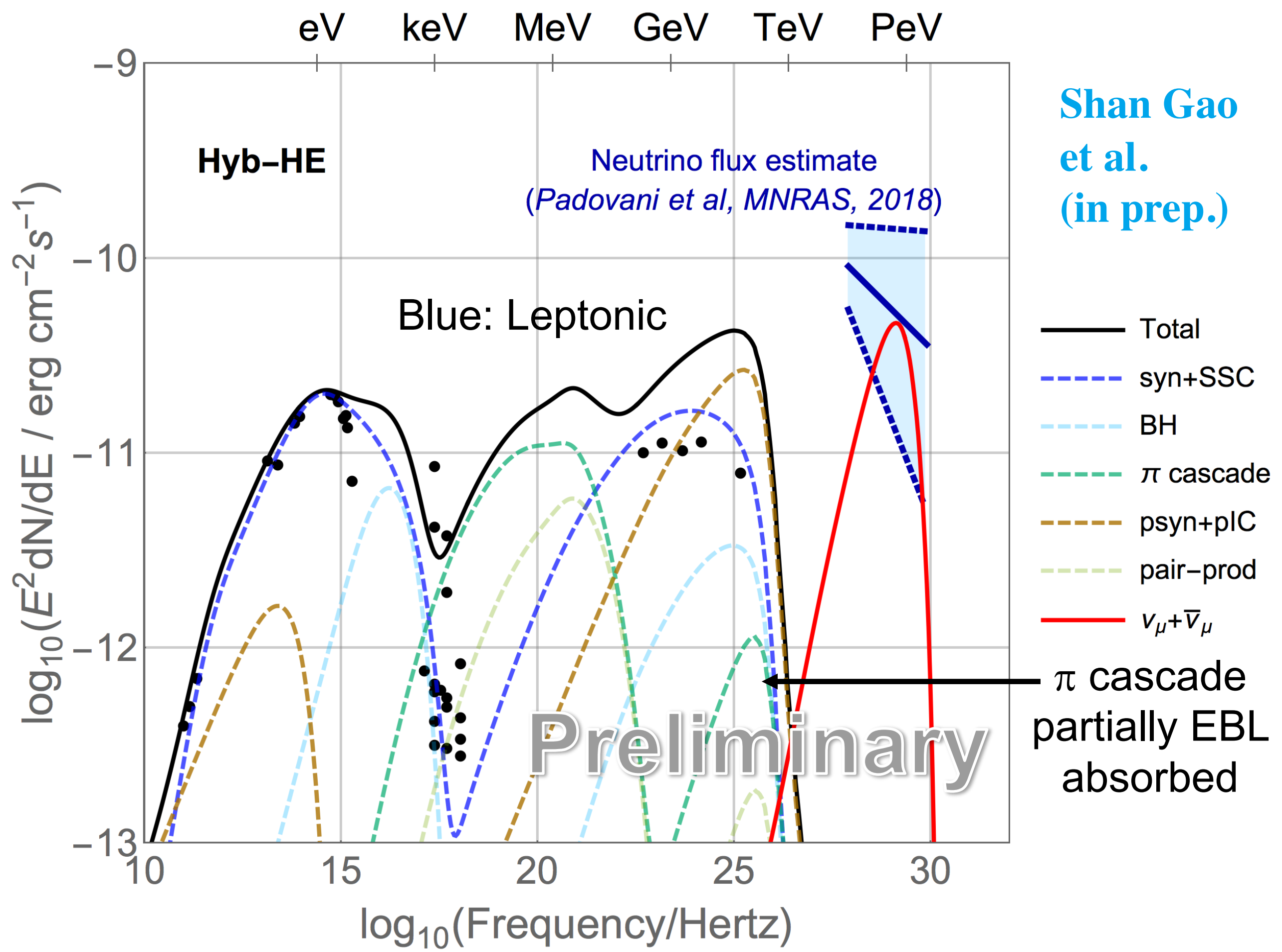
Wang et al, 2018; He et al, 2018; Padovani, Giommi, Resconi, Glauch, Arsioli, Sahakyan, Huber, 2018



Historical flare: One zone example

- Difficult to hide π cascade (X-rays)
- Hardening at GeV energies possible
- Here: excess of L_{edd}



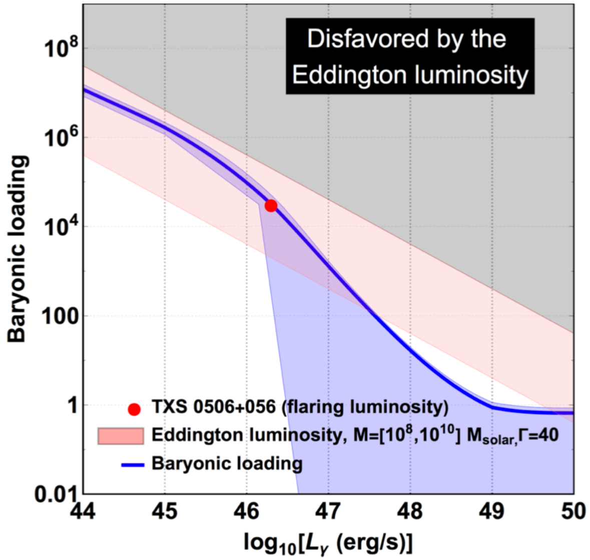


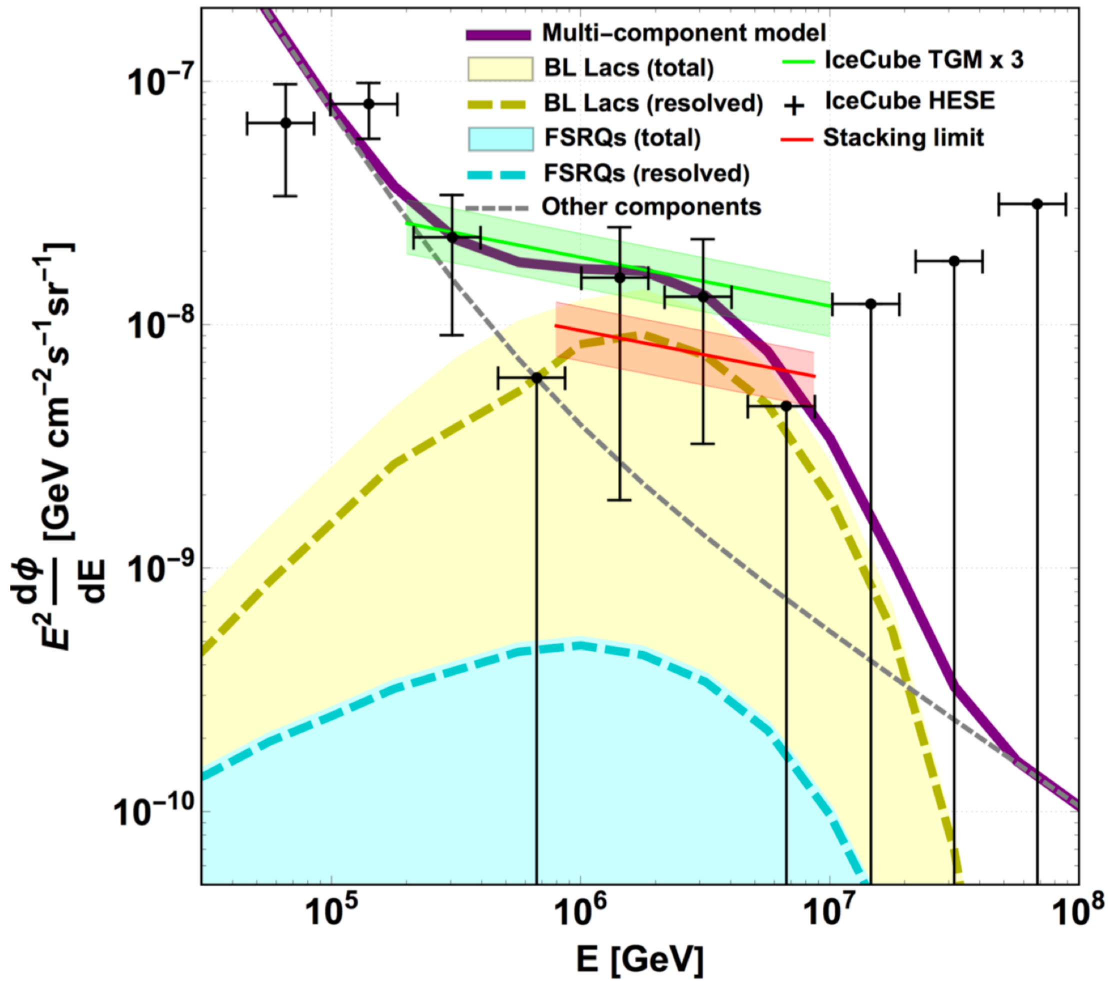
Shan Gao et al. (in prep.)

Model	Features	R/10^15cm (all one-zone)	B′/G	$\delta_{Doppler}$	v_{esc}/c ($e^{\pm}$ and p)	baryonic loading	L_{jet}/L_{Edd}	$E_{\nu,peak}$/PeV	N_ν expected during historical flare
Hyb-HE	hybrid model high $E_{\nu,peak}$ low cascade	100	0.005	70	0.1	$10^{8.0}$	$10^{4.5}$	0.81	8.8

Conclusions for the whole AGN population

- Stacking from Fermi 2LAC-catalogue limits contribution from resolved sources
  IceCube, ApJ 835 (2017) 1, 45
- Self-consistent picture with baryonic loading changing with luminosity:





Palladino, Rodrigues, Gao, Winter, arXiv:1806.04769; based on Ajello et al, 2012/2014

- Predicts ~0.4-1 assoc./year

Summary and conclusions

- Multi-messenger models include different versions, such as
  - Propagation/transport models (cosmogenic neutrinos/γ-rays)
  - Source-propagation models
  - Multi-messenger-multi-wavelength source models
- Cosmogenic neutrinos can test certain composition models; the Auger fit rather points towards cosmogenic neutrinos being background rather than foreground (from sources) at highest energies
- The combined interpretation of diffuse neutrinos and UHECRs requires sources with strong magnetic fields and radiation densities, such as LL-GRBs, TDEs
- Interpretations of multi-messenger-multi-wavelength observations of cosmic-ray accelerators, such as TXS 0506+056, need to rely on theoretical models