High-energy neutrino astronomy

... and astrophysics

https://multimessenger.desy.de/

Winter, Walter
DESY, Zeuthen, Germany

CCEPP summer school, CAS
Beijing, China
Aug. 20-21, 2021

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

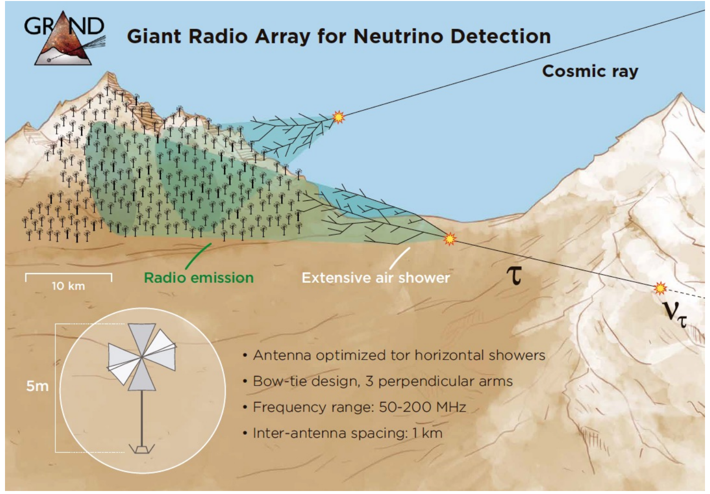
Contents

- Observations (overview of selected results)
- Physics of neutrino production (theory)
- Neutrinos from AGN blazars (overview)
- Multi-messenger interpretation of TXS 0506+056
- Diffuse neutrino flux from AGN blazars?

Lecture 1

- Neutrinos from Tidal Disruption Events (TDEs)
- Neutrinos and the origin of the Ultra-High Energy Cosmic Rays (UHECRs)
- The future of neutrino astronomy →
- Conclusions

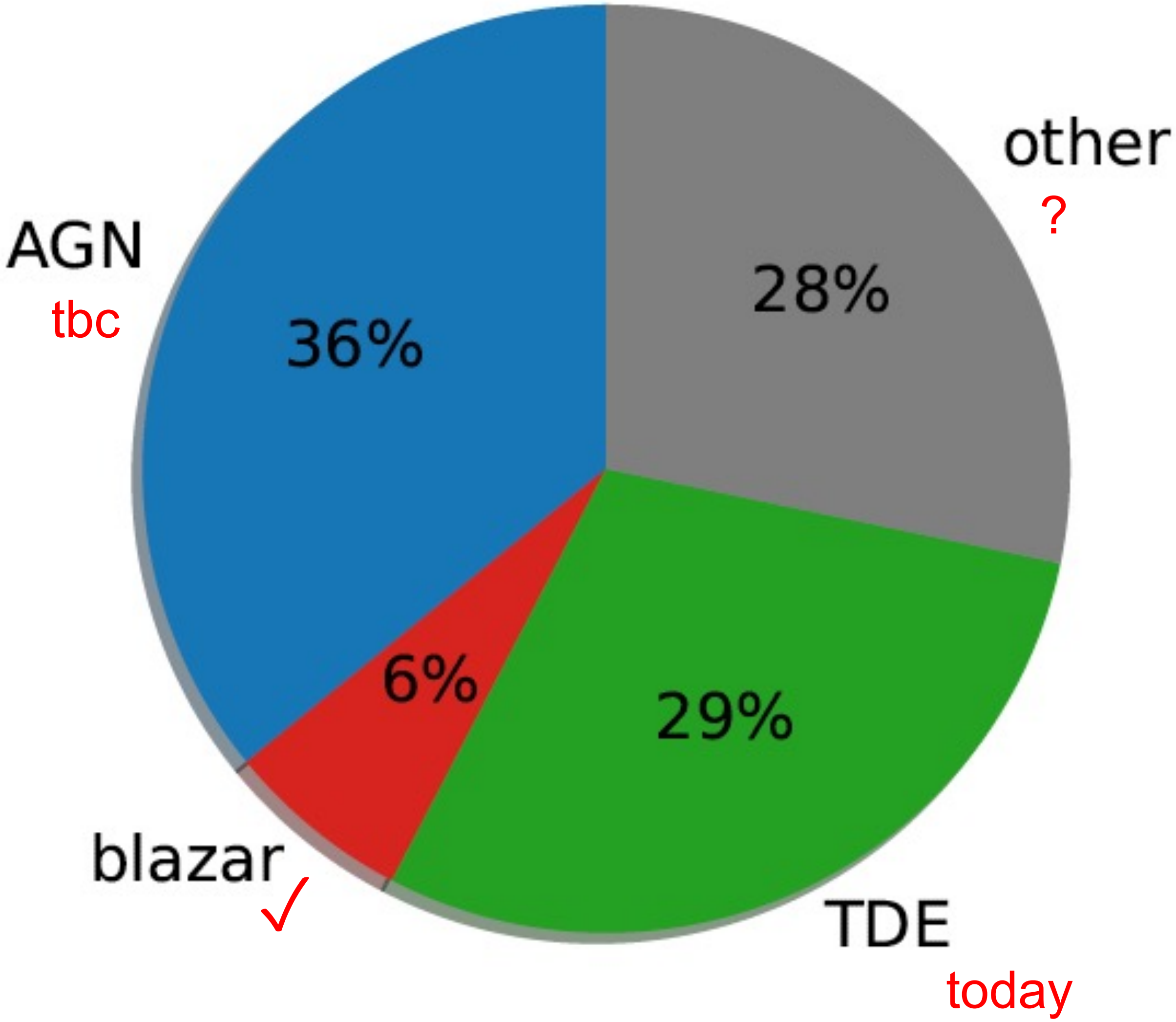
Lecture 2



Recap (yesterday)

Summary (part I)

- Several source associations of neutrinos, and a diffuse flux of astrophysical neutrinos
- AGN blazars established a likely source of neutrinos, but probably not the dominant contribution to the diffuse flux (stacking limit!). Ways out?
- AGN cores, starburst galaxies possible contenders (abundant, less luminous)
- Better statistics needed for firm conclusions
- Open issue: Galactic sources? Probably to be addressed by KM3NeT/ANTARES in future.



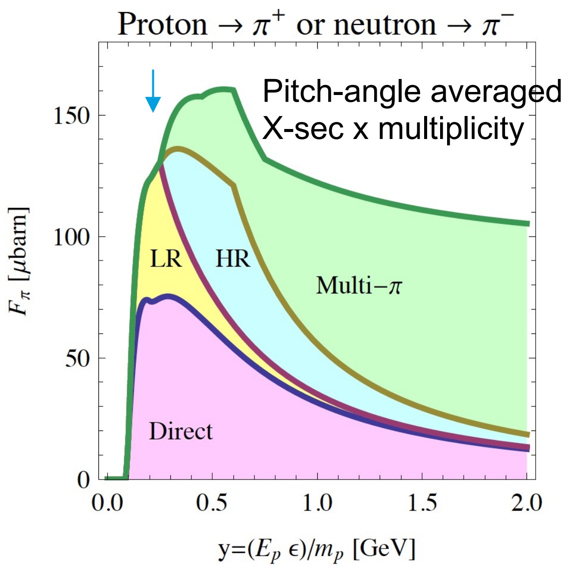
Bartos et al, arXiv:2105.03792

Multiple messengers from photo-pion production

- Neutrino peak determined by maximal cosmic ray energy
  [conditions apply: for target photons steeper (softer) than ε^{-1} (and low enough ε_{min})] →
- Interaction with target photons
  (Δ-resonance approximation for C.O.M. energy):

$$p + \gamma \rightarrow \Delta^+ \rightarrow \begin{cases} n + \pi^+ & \rightarrow \nu \\ p + \pi^0 & \rightarrow \gamma \end{cases}$$

E_γ [keV] ~ 0.01 Γ^2/E_ν [PeV]
keV energies interesting!
(computed for Δ-res, yellow) →

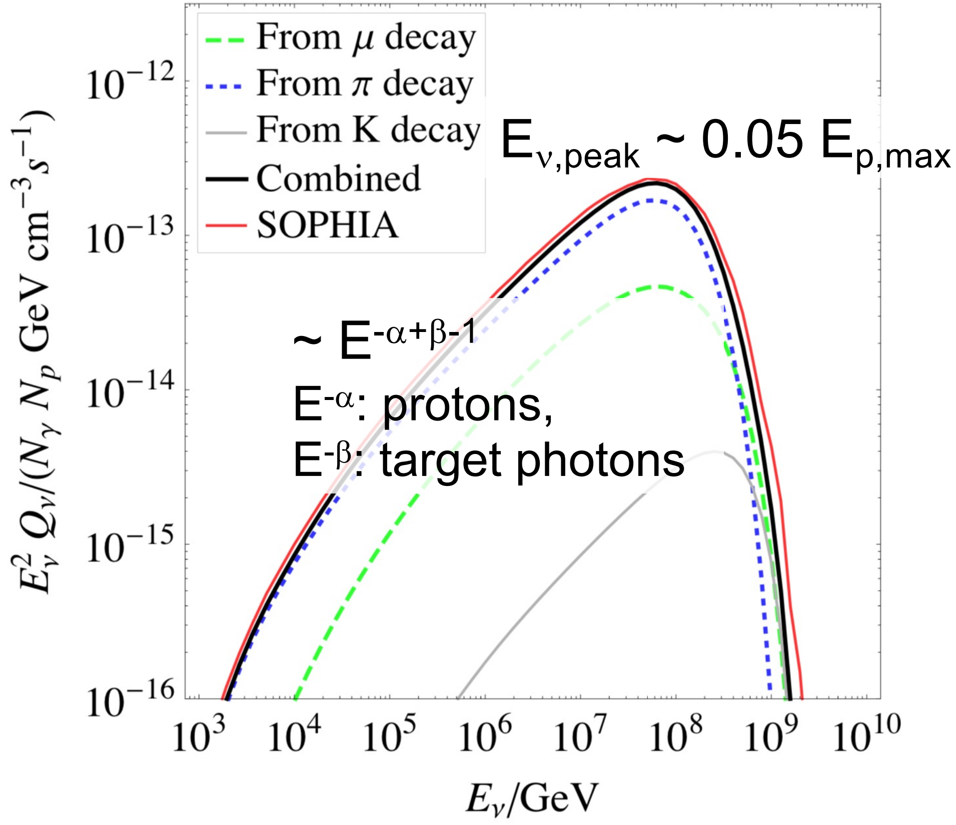


- Photons from pion decay:

$$\pi^0 \rightarrow \gamma + \gamma$$

Injected at $E_{\gamma,peak}$ ~ 0.1 $E_{p,max}$
TeV–PeV energies interesting!
(but: electromagnetic cascade in source!)

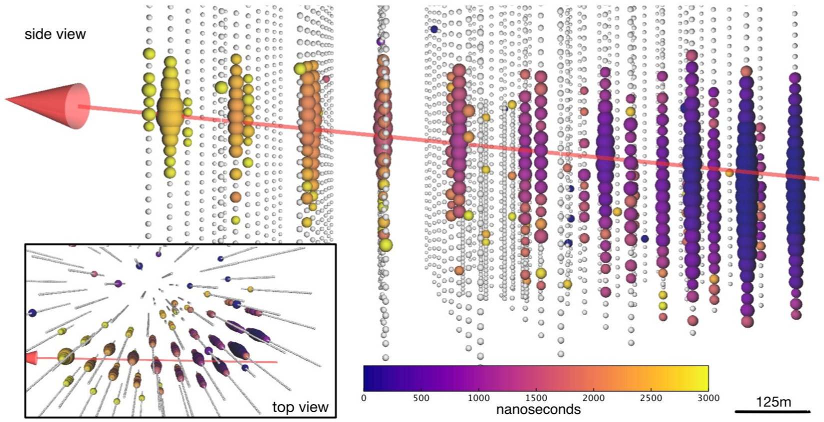
AGN neutrino spectrum (example)

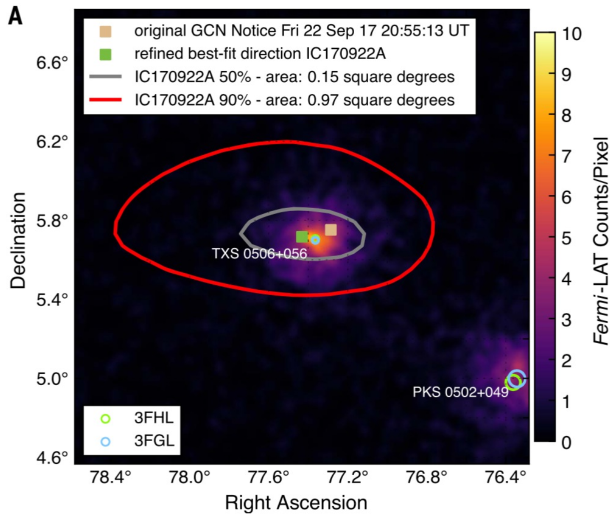


From: Hümmer et al, Astrophys. J. 721 (2010) 630; for a more complete view of possible cases, see Fiorillo et al, JCAP 07 (2021) 028

A neutrino from the flaring AGN blazar TXS 0506+056

Sept. 22, 2017:
A neutrino in coincidence with a blazar flare





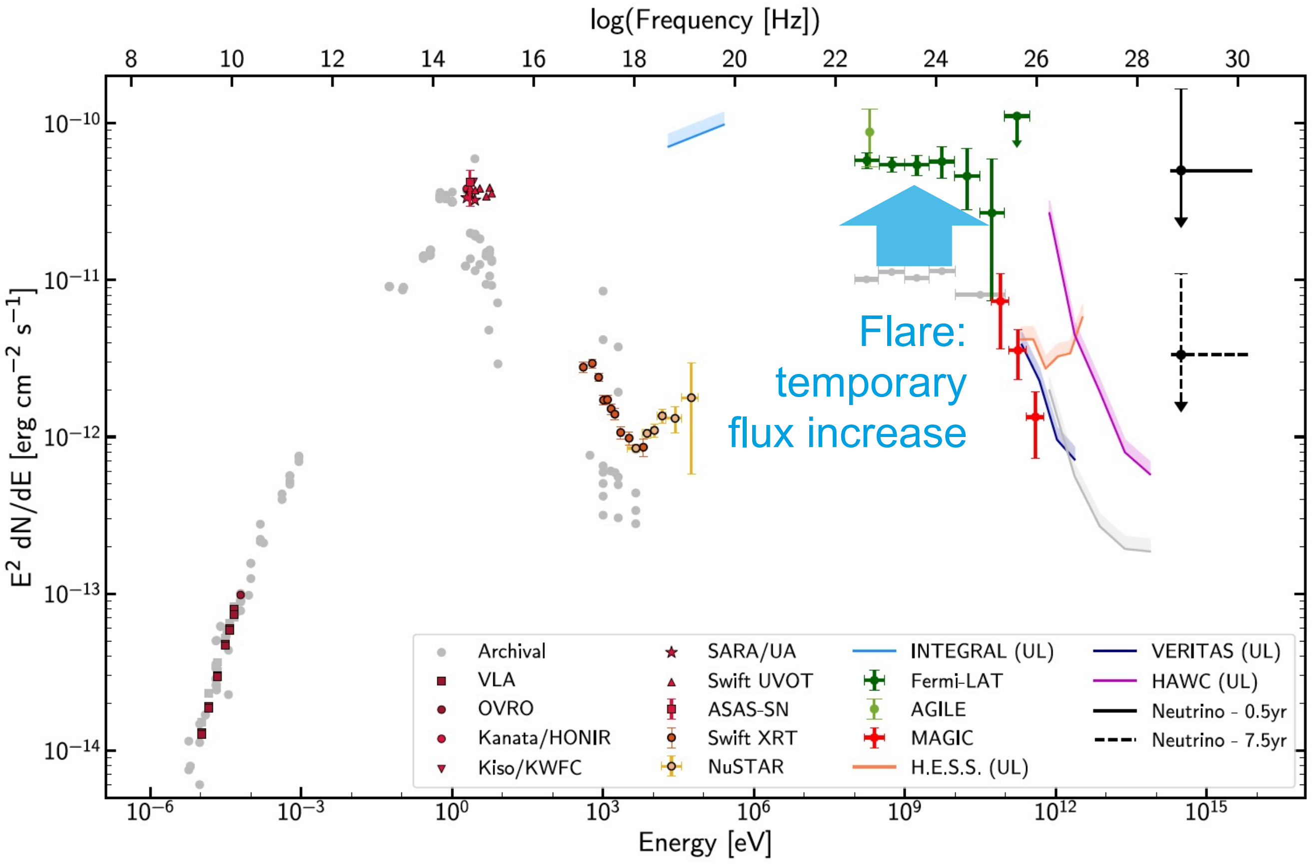
Observed by Fermi-*LAT* and MAGIC (blazar flare)

Significance for correlation: 3σ

z = 0.3365 ± 0.0010

Paiano et al, 2018

SED from a multi-wavelength campaign



Color: coincident with neutrino; gray: archival data

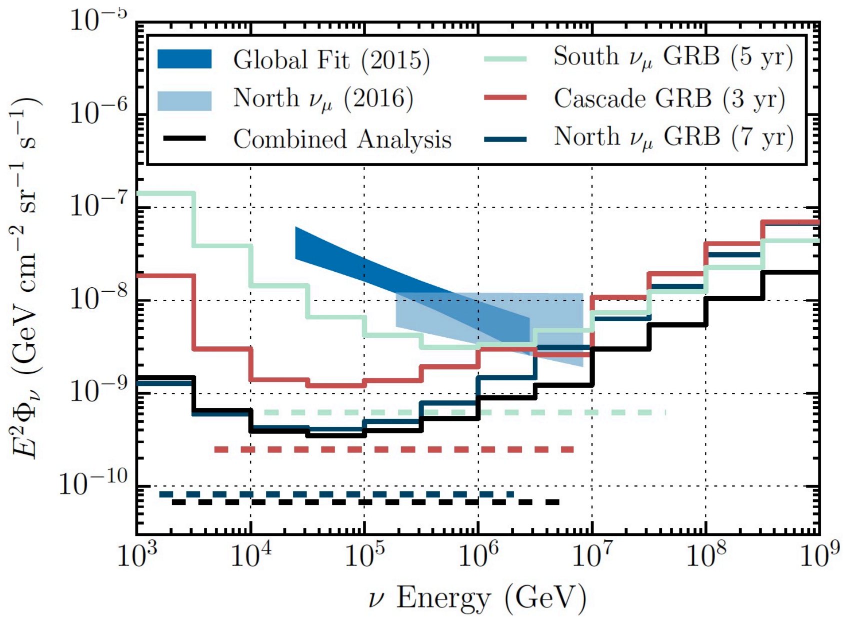
Science 361 (2018) no. 6398, eaat1378

Stacking limits ...

... for the most energetic sources classes

Gamma-Ray Bursts (GRBs)

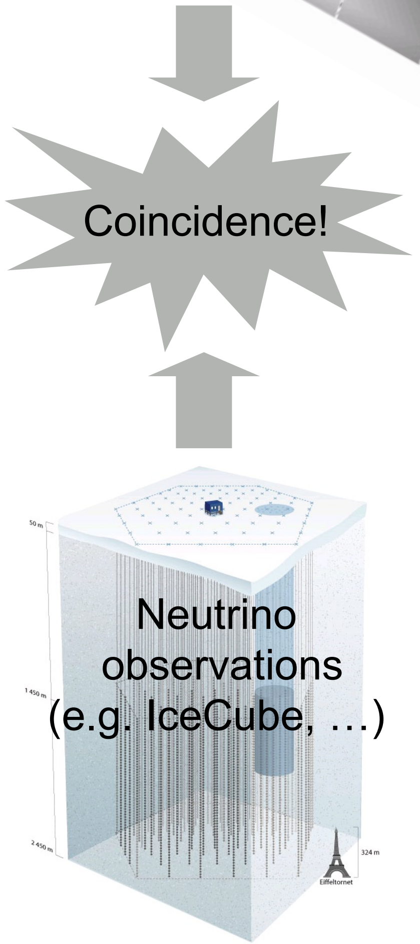
- Transients, time variability
- High luminosity over short time



- Less than ~1% of observed ν flux

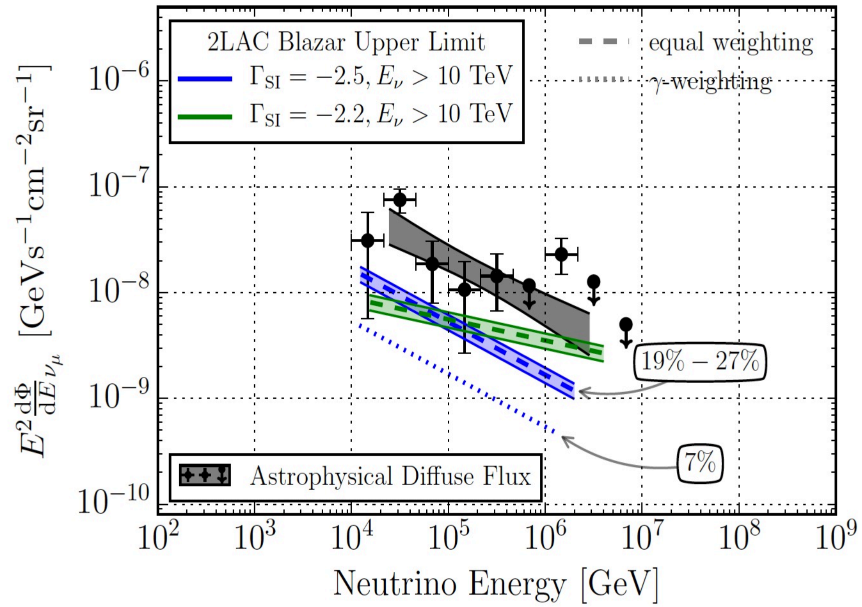
IceCube, Nature 484 (2012) 351;
Newer version: arXiv:1702.06868

(Source: NASA)



Active Galactic Nuclei (AGNs)

- Steady emission with flares
- Lower luminosity, longer duration



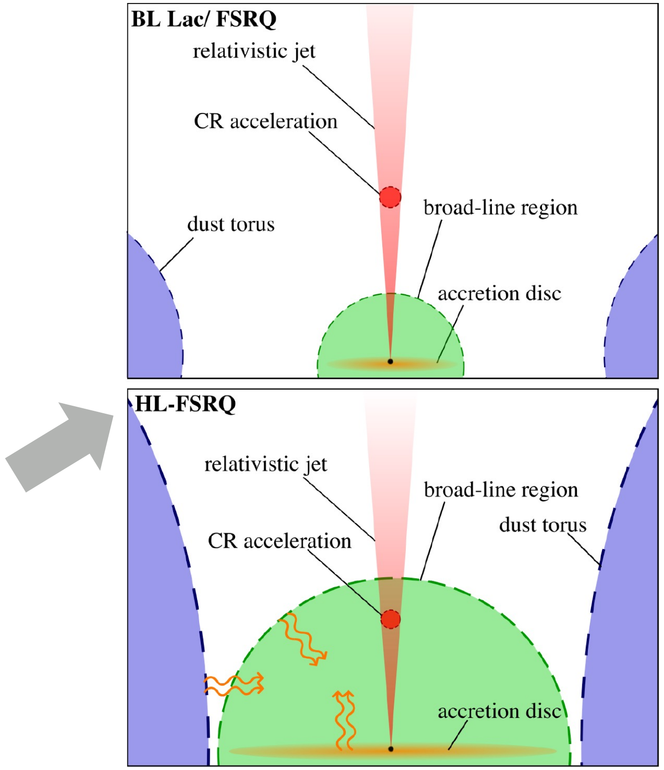
- Less than ~25% of observed ν flux?

IceCube, Astrophys. J. 835 (2017) 45

Diffuse neutrino flux from AGN blazars?

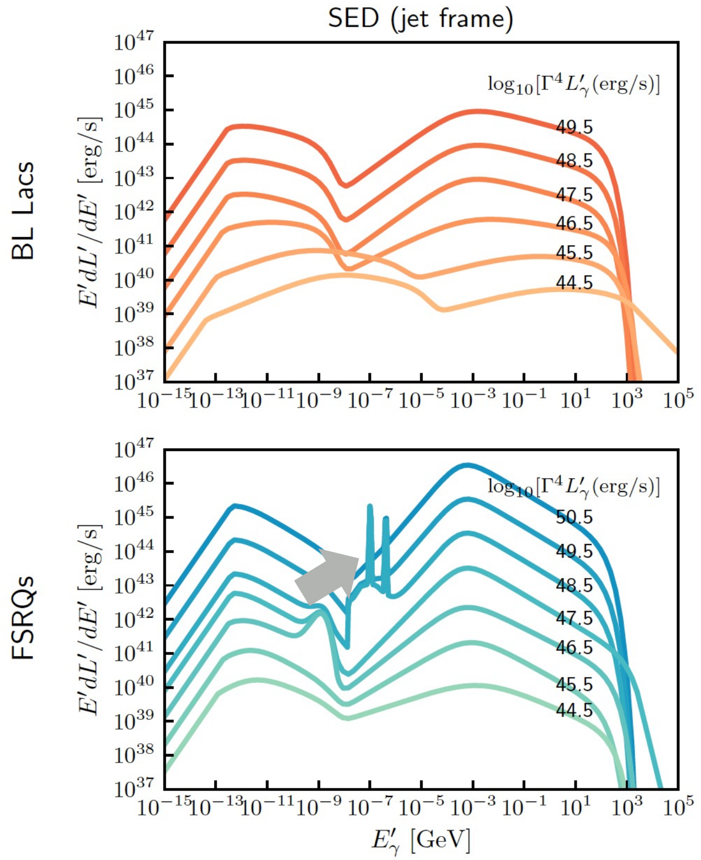
Ingredients: Neutrino production and population models

- Geometry determined by disk luminosity:



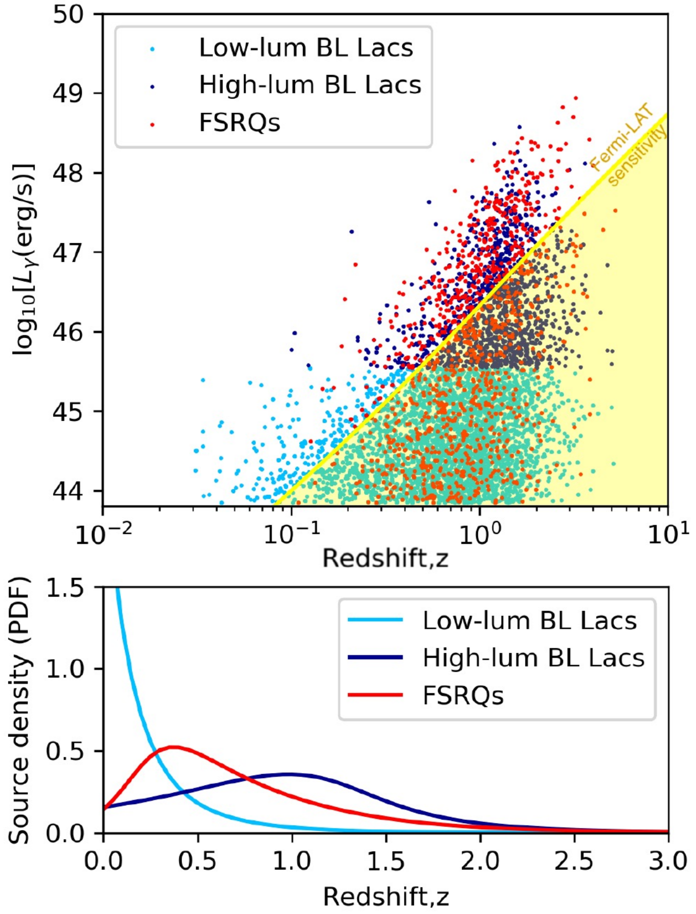
- For HL-FSRQs, the blob is exposed to boosted external fields

- SED follows "blazar sequence":



Rodrigues, Fedynitch, Gao, Boncioli, WW, ApJ 854 (2018) 54; Murase, Inoue, Dermer, PRD 90 (2014) 023007; Palladino, Rodrigues, Gao, WW, ApJ 871 (2019) 41; Rodrigues, Heinze, Palladino, van Vliet, WW, PRL 126 (2021) 191101

- Population model: LL-BL Lacs, HL-BL Lacs, FSRQs



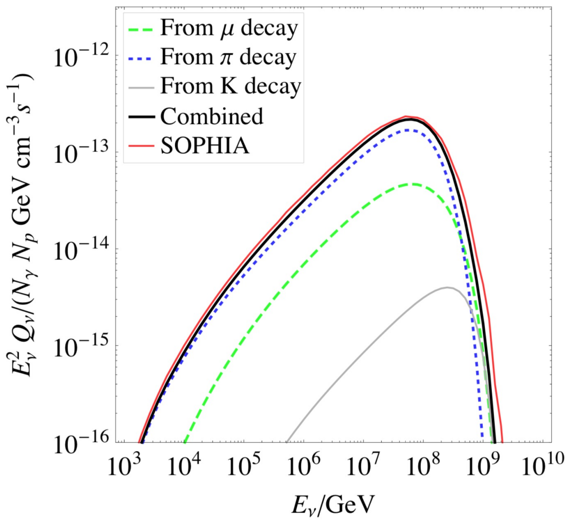
Population model by Ajello et al, 2012+2014; sources from Fermi's 3LAC catalogue

Describes diffuse γ-ray BG by construction!

Recap: AGN neutrino spectrum ...and two hypotheses

There is no unified (ν, γ-ray, UHECR) one zone model!

$E_{\nu,peak}$ ~ 0.05 $E_{p,max}$



$E_{p,max}$ ~1-10 PeV

Moderately efficient CR acclerators

1) AGN blazars describe neutrino data

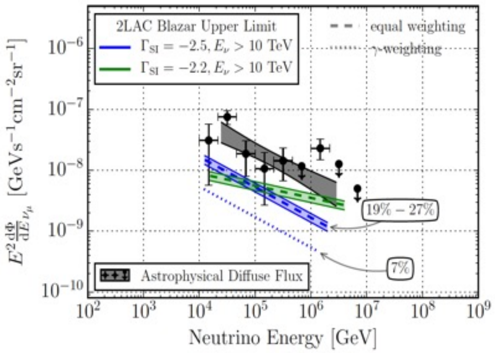
$E_{p,max}$ ~ 1-10 EeV (R_{max} ~ 1-10 EV)

Very efficiency CR accelerators

2) AGN jets describe UHECR data

Postulate that:

1. The diffuse neutrino flux is dominated by AGN blazars (such as the extragalactic γ-ray flux!)
2. The blazar stacking limit is obeyed →
   IceCube, Astrophys. J. 835 (2017) 45



3. The baryonic loading evolves over the blazar sequence (depends on L_γ); the one of TXS 0506+056 is in the ballpark of self-consistent SED models

Postulate that:

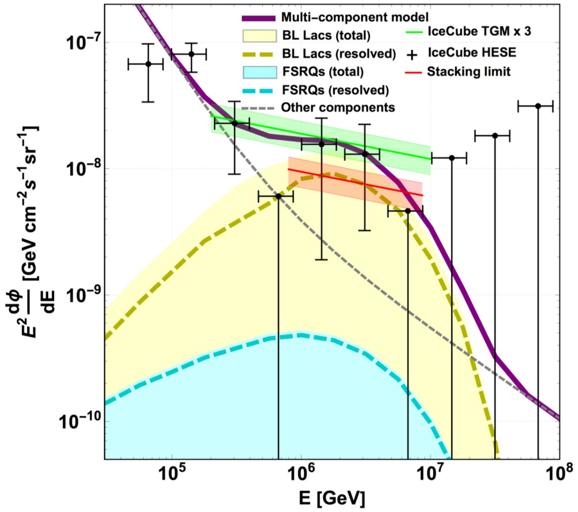
1. AGN jets (can be misaligned!) describe Auger data across the ankle
   (spectrum very well, composition observables roughly)
2. The injection compositon is roughly Galactic
3. Different classes (LL-BL Lacs, HL-BL Lacs, FSRQs) can have a different baryonic loading

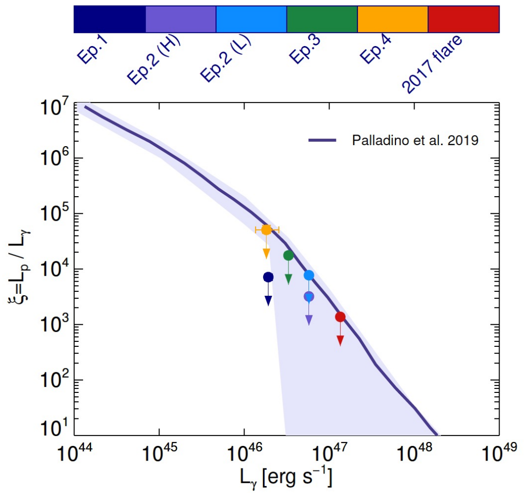
Conclusions for different hypotheses

More later!

1) AGN blazars describe neutrino data

1. Unresolved BL Lacs must dominate the diffuse neutrino flux
2. The baryonic loading must evolve, as otherwise efficient neutrino emitters (esp. FSRQs) stick out

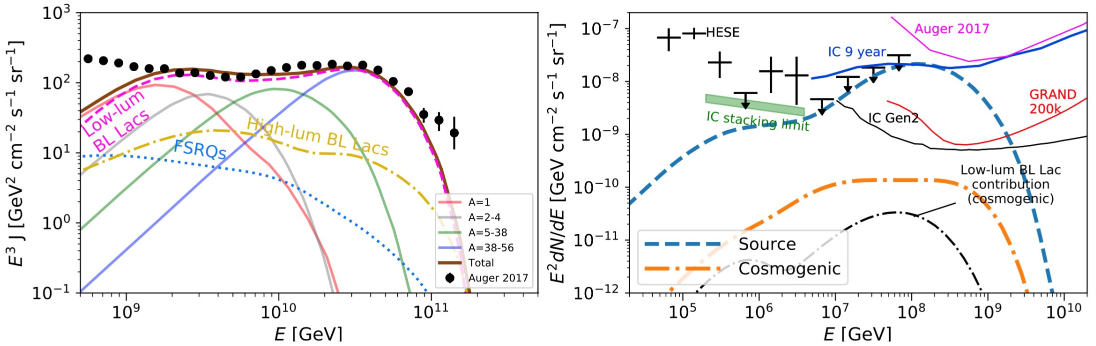




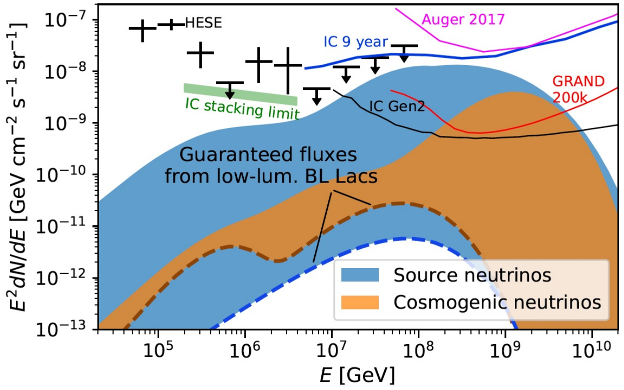
Palladino, Rodrigues, Gao, Winter, ApJ 871 (2019) 41;
Right Fig. from Petropoulou et al, arXiv:1911.04010: same behavior also found in multi-epoch description of TXS 0506+056

2) AGN jets describe UHECR data

1. UHECR description driven by LL-BL Lacs because of
   - Low luminosity → rigidity-dependent max. energy
   - Negative source evolution

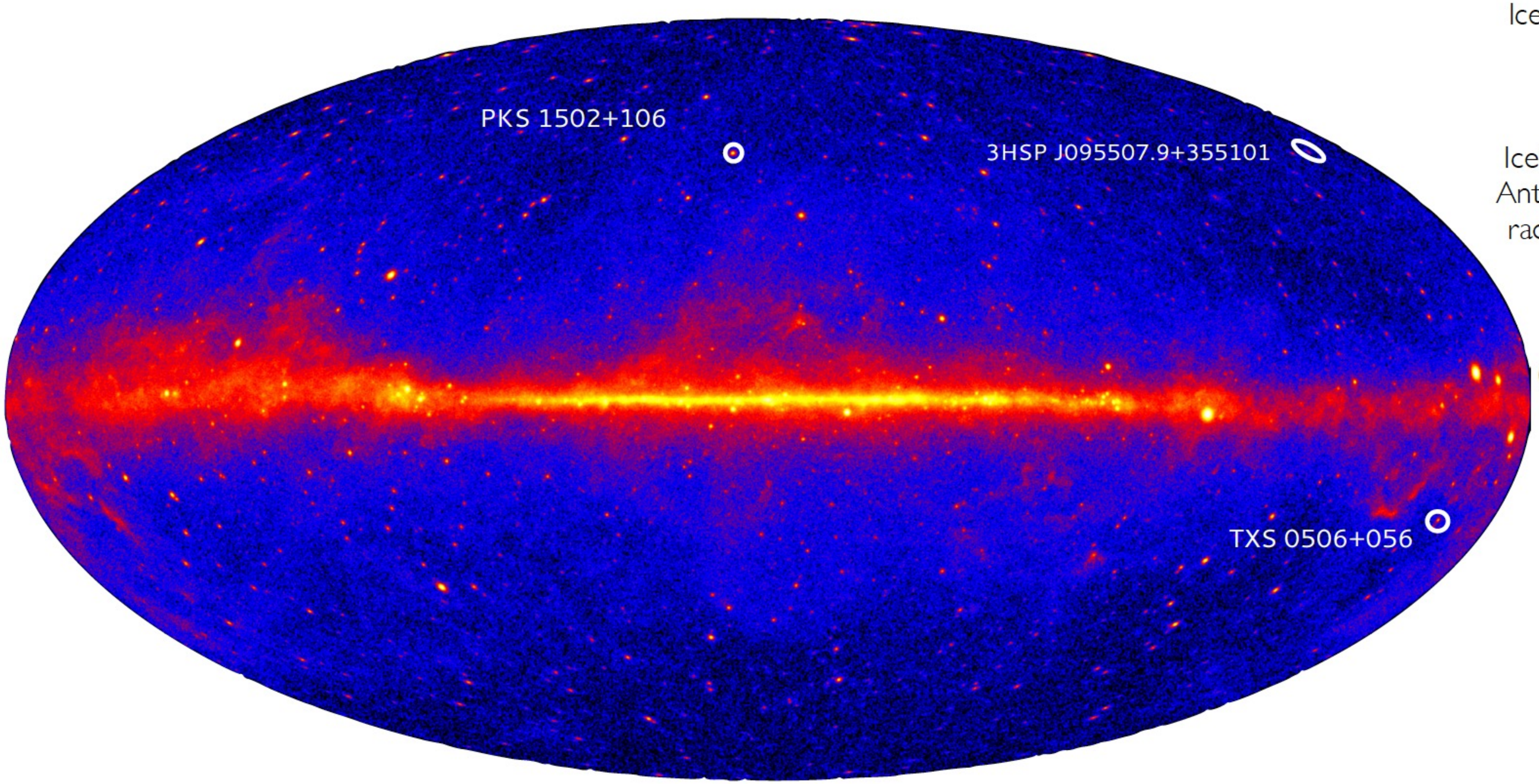


2. Neutrinos mostly come from FSRQs, peak at high energies, and may even outshine the cosmogenic flux there



Rodrigues, Heinze, Palladino, van Vliet, Winter, PRL 126 (2021) 191101

Blazars coincident with high-energy neutrinos



Several dozen associations so far:

IceCube sends public alerts since 2016
Fermi-LAT follow up: 6 blazars in 23 follow-ups (S. Garrappa #812)
Telamon (M. Sadler #1320)
IceCube flares - X-rays (Sharma #299)
Antares flares - radio (Illuminati #1137)
radio blazars + Antares (Aublin #1240
IACTs: (Satalecka #907)

4FGL J0658.6+0636+IC201114A: (de Menezes #296, Rosales de Leon #308)

3.3σ IceCube Coll 10yr Point-Source Analysis (3 blazars)
Franckowiak et al ApJ 893 (2020)
Giommi et al MNRAS 497 (2020)
Hovatta et al A&A 650 (2021)
Plavin et al ApJ 908 (2021)

Evaluating the significance of coincidences: Capel #1346

11 PKS B1424-418+IC35 Kadler, Nat Phys 12 (2016), Gao, Pohl, Winter, ApJ 843 (2017)

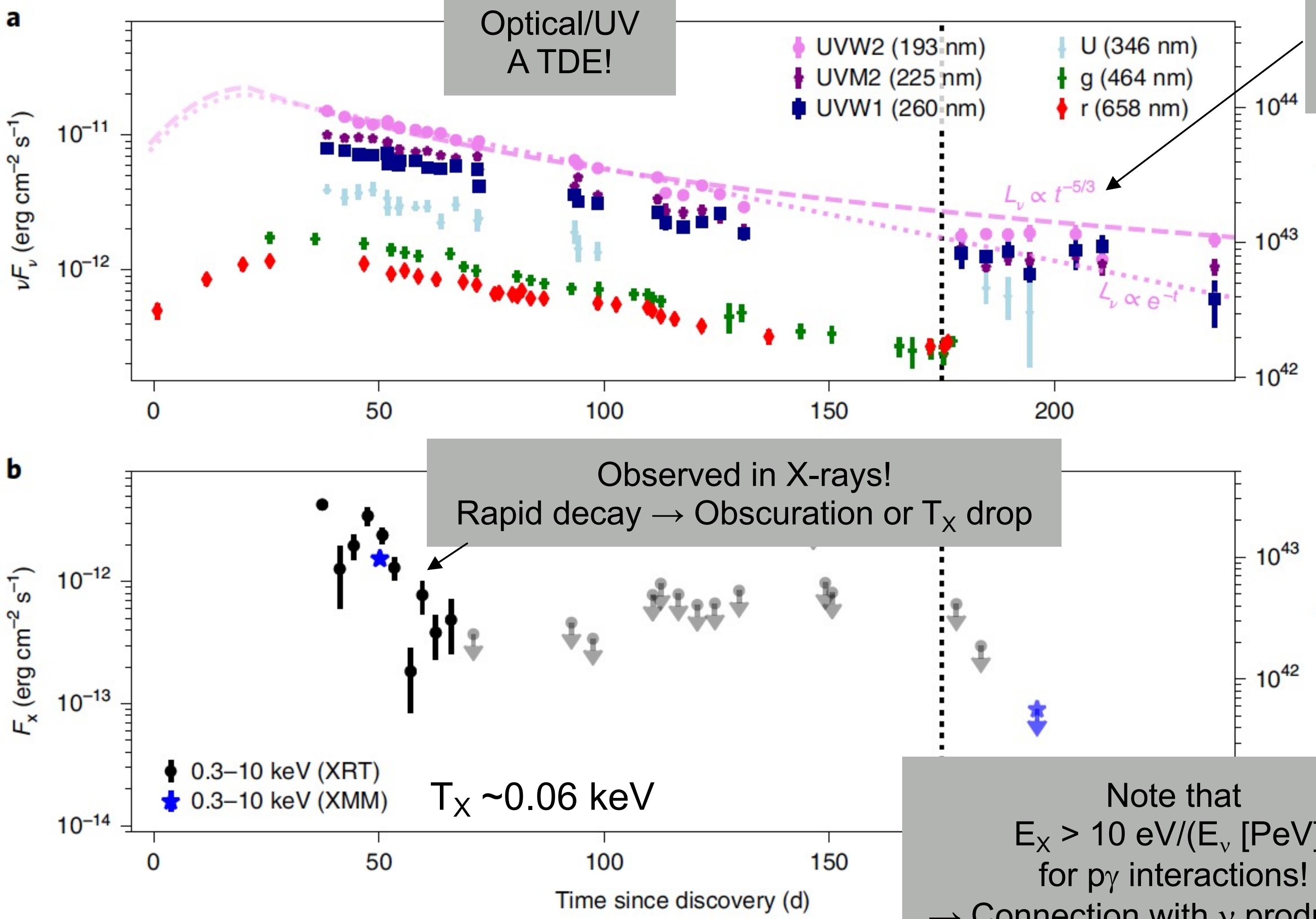
F. Oikonomou @ ICRC 2021

Neutrinos from TDEs

Tidal Disruption Events

MOVIE

Observation of a neutrino from AT2019dsg



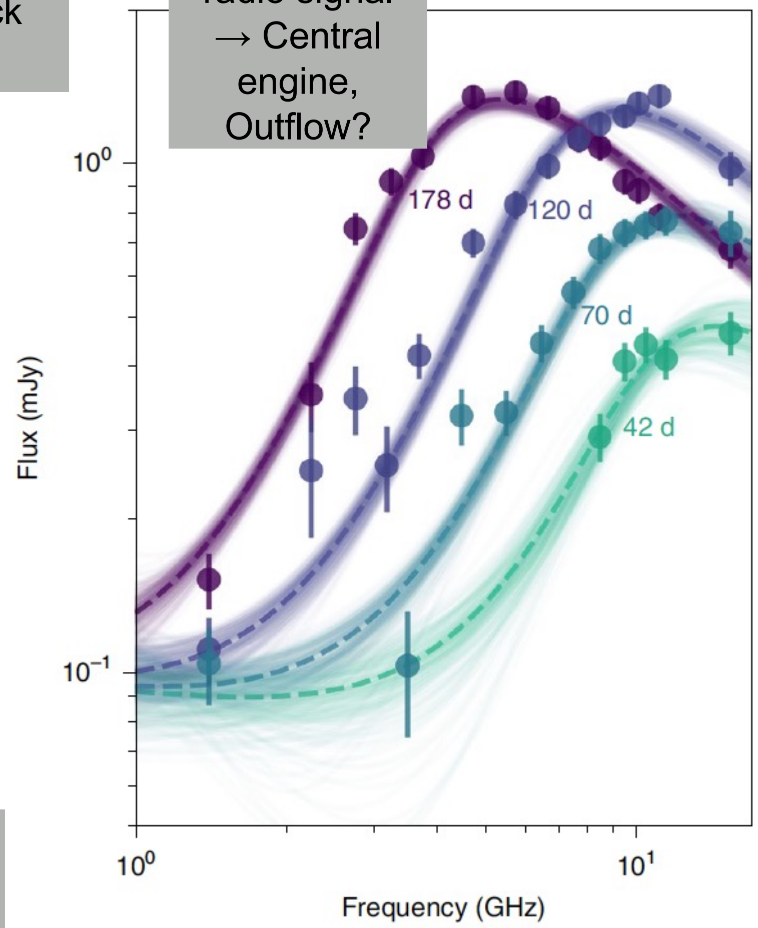
Optical/UV
A TDE!

Typical mass fallback rate

Observed in X-rays!
Rapid decay → Obscuration or T_X drop

T_X ~0.06 keV

Note that
E_X > 10 eV/(E_ν [PeV])
for pγ interactions!
→ Connection with ν production?



Evolving radio signal
→ Central engine, Outflow?

Stein et al, Nature Astronomy 5 (2021) 510

How to disrupt a star 101

- Force on a mass element in the star (by gravitation) ~ force exerted by the SMBH at distance

$$r_t = \left(\frac{2M}{m}\right)^{1/3} R \simeq 8.8 \times 10^{12}\,\mathrm{cm} \left(\frac{M}{10^6\ M_\odot}\right)^{1/3} \frac{R}{R_\odot} \left(\frac{m}{M_\odot}\right)^{-1/3}$$

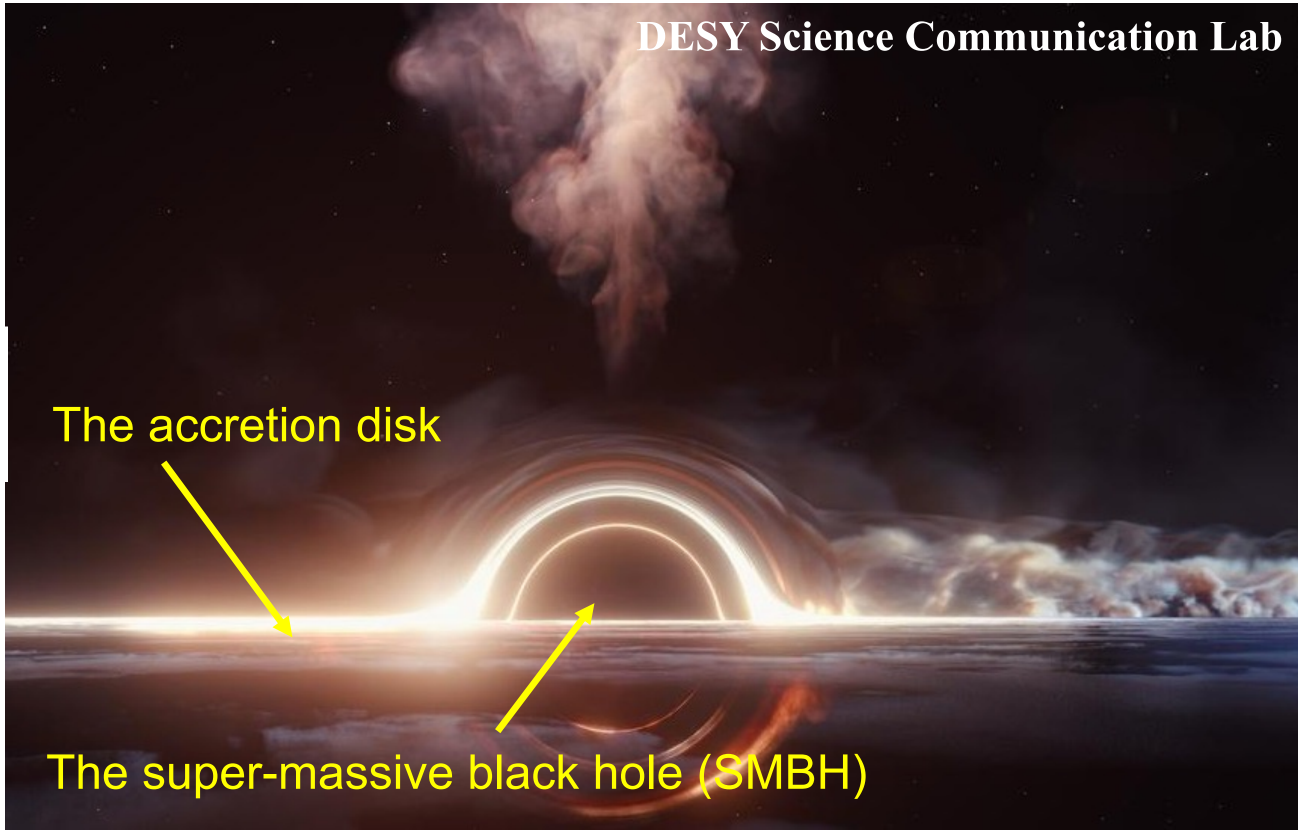
- Has to be beyond Schwarzschild radius

$$R_s = \frac{2MG}{c^2} \simeq 3 \times 10^{11}\,\mathrm{cm} \left(\frac{M}{10^6\ M_\odot}\right)$$

- From the comparison ($r_t > R_s$) and TDE demographics, one obtains M <~ 10^8 $M_\odot$
  Hills, 1975; Kochanek, 2016; van Velzen 2017
- Schwarzschild time indicator for time variability of an engine?

$$\tau_s \sim 2\pi R_s/c \simeq 63\,\mathrm{s} \left(\frac{M}{10^6\ M_\odot}\right)$$

→ Fastest time variability ~ 100s



- Measure for the luminosity which can be re-processed from accretion through the SMBH: Eddington luminosity

$$L_{\mathrm{Edd}} \simeq 1.3\ 10^{44}\ \mathrm{erg/s}\,(M/(10^6\ M_\odot))$$

(TDEs are often Super-Eddington at peak)

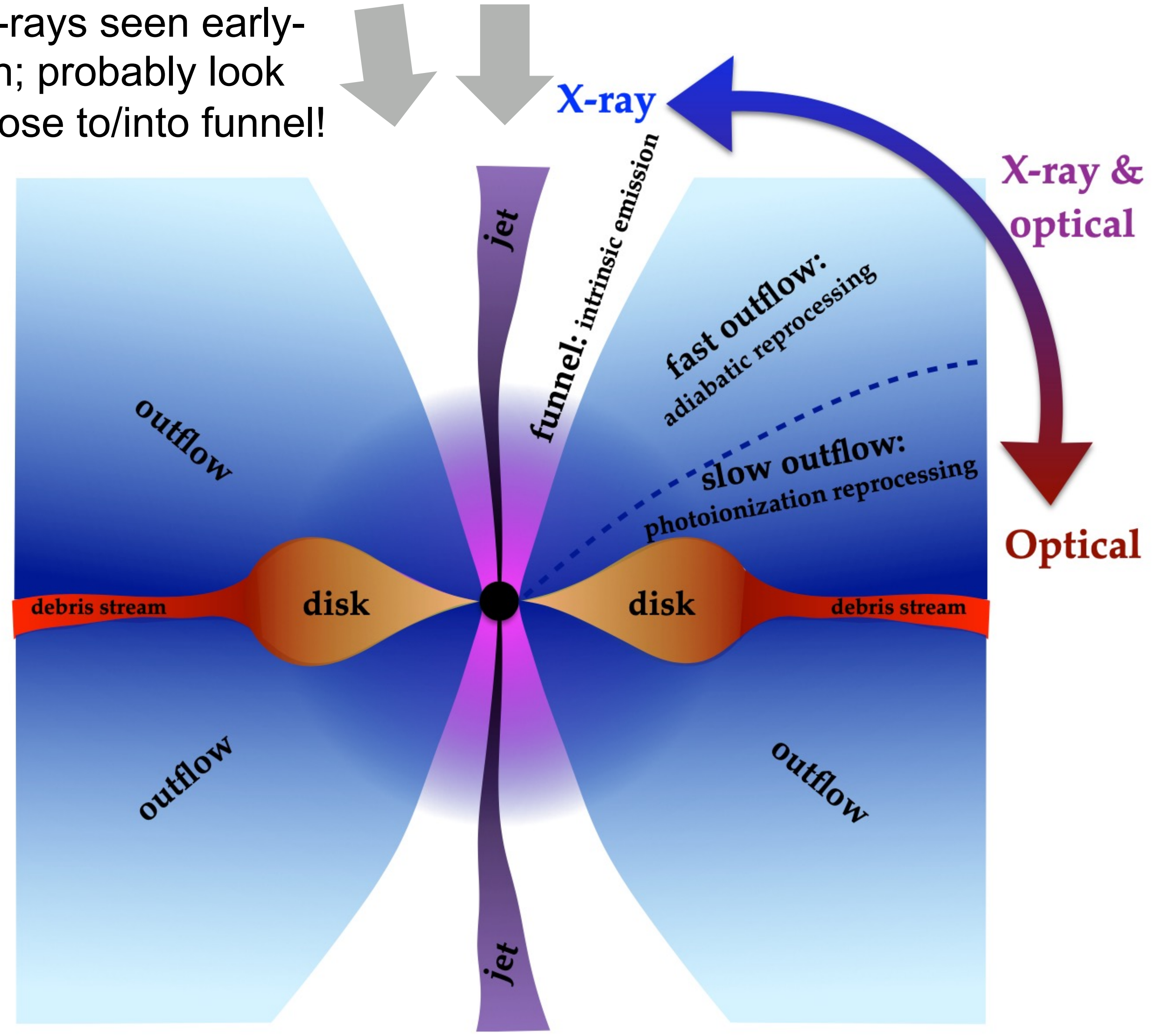
- Measure for the maximally available energy: E_{max} ~ 10^{54} erg (half a solar mass)

A TDE unified model

... used to motivate a concordance model

- Matches several aspects of AT2019dsg very well (L_{bol}, R_{BB}, X-rays/obscuration?)
- Supported by MHD sims; $M_{SMBH} = 5\ 10^6\ M_\odot$ used; we use **conservatively $M_{SMBH} = 10^6\ M_\odot$**
- A jet is optional in that model, depending on the SMBH spin
- Observations from model:
  - Average mass accretion rate $\dot{M} \sim 10^2 L_{\rm Edd}$
  - ~ 20% of that into jet
  - ~ 3% into bolometric luminosity
  - ~ 20% into outflow
  - Outflow with
    v ~ 0.1 c (towards disk) to
    v ~ 0.5 c (towards jet)

X-rays seen early-on; probably look close to/into funnel!



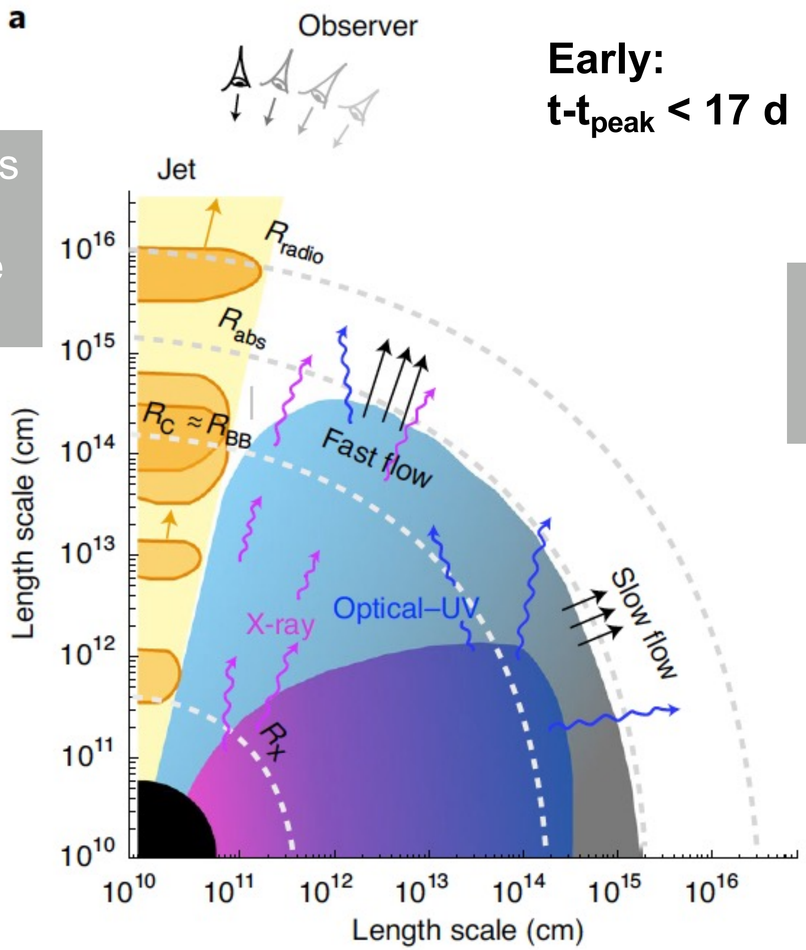
Dai, McKinney, Roth, Ramirez-Ruiz, Coleman Miller, 2018

A jetted concordance scenario

See BACKUP slides for more details

... based on TDE unified model

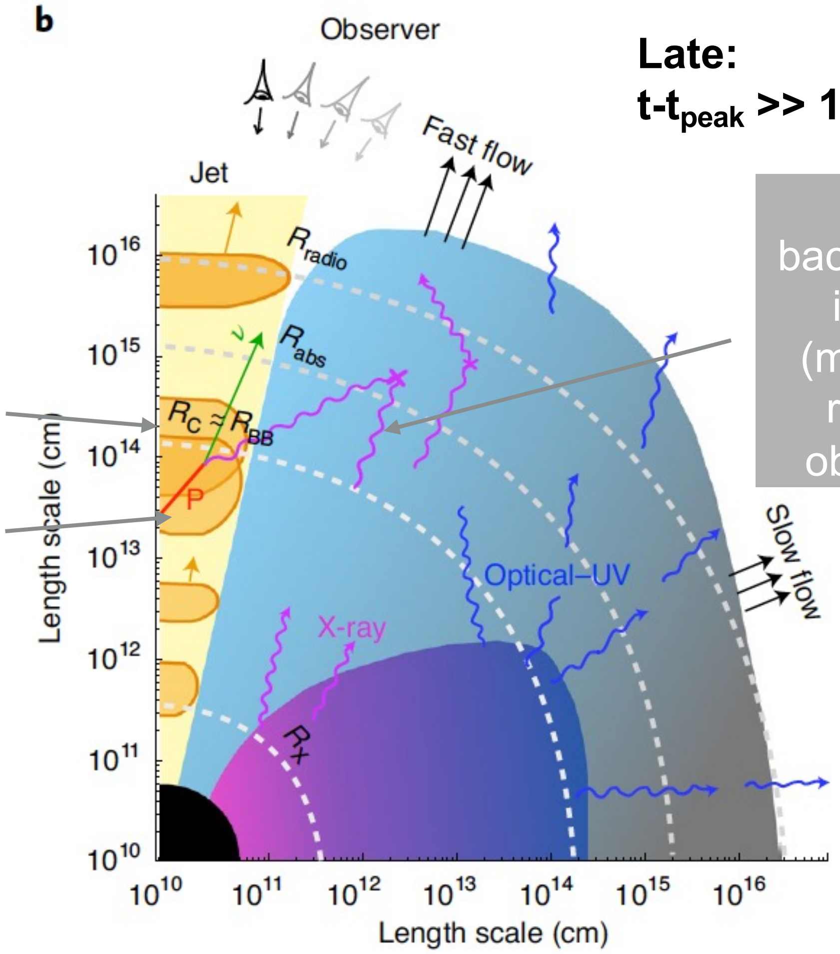
No neutrinos at t_{peak} (no intense target)



Early:
$t-t_{peak}$ < 17 d

Production radius decreases with R_{BB} (observed)

Particle acceleration in internal shocks



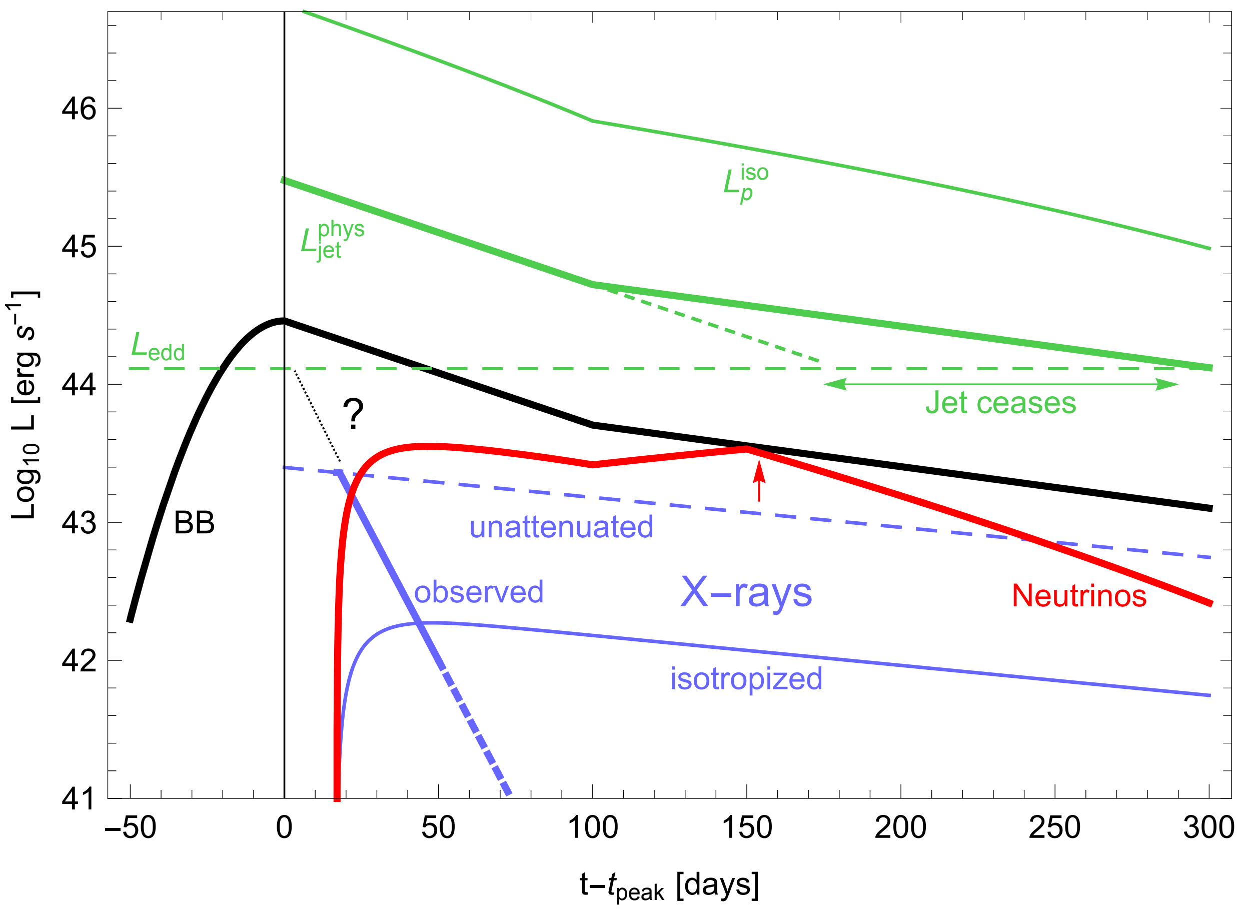
Late:
$t-t_{peak}$ >> 17 d

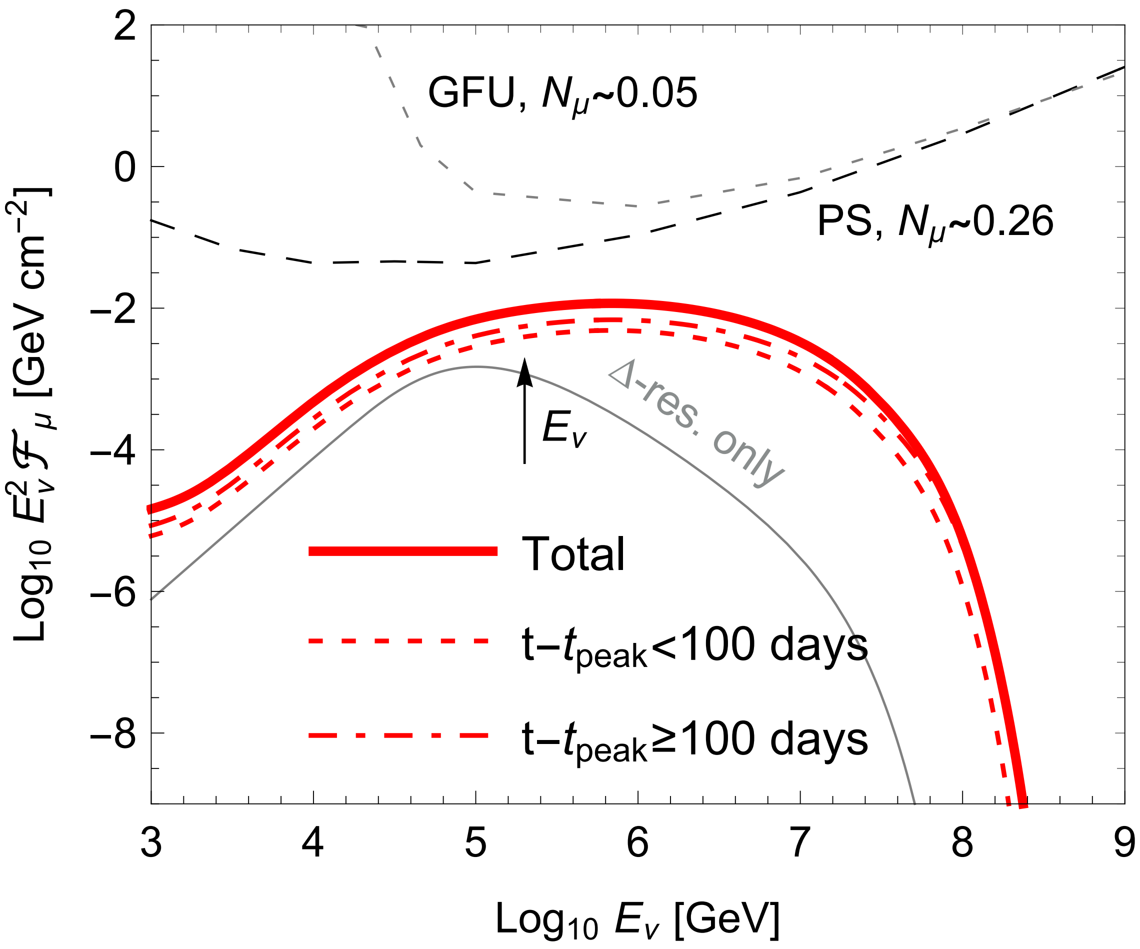
X-ray back-scattering in outflow (may also be reason for obscuration)

Winter, Lunardini, Nature Astronomy 5 (2021) 472;
see also Liu, Xi, Wang, 2020 for an off-axis jet

Results for neutrino luminosity lightcurve and spectrum

(black/thick purple: follow data; red curve: computational result; others: model ingredients)

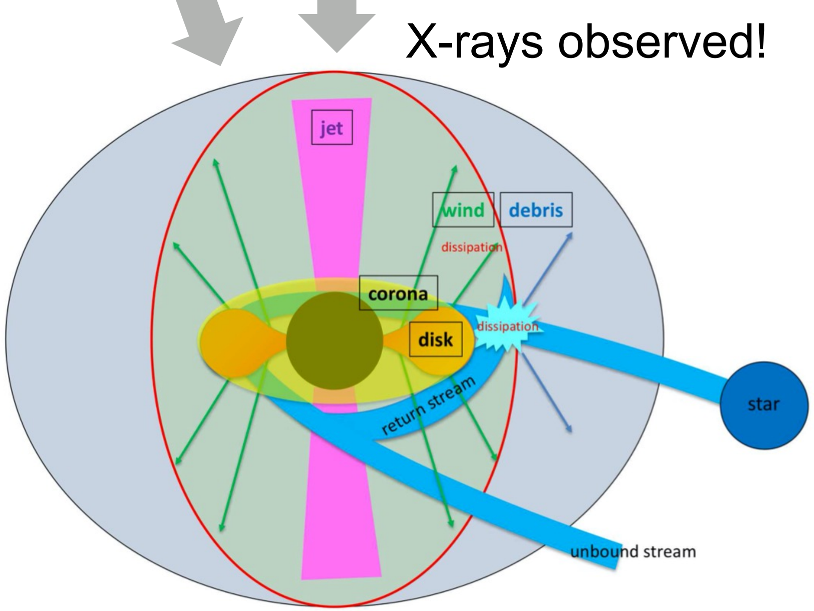


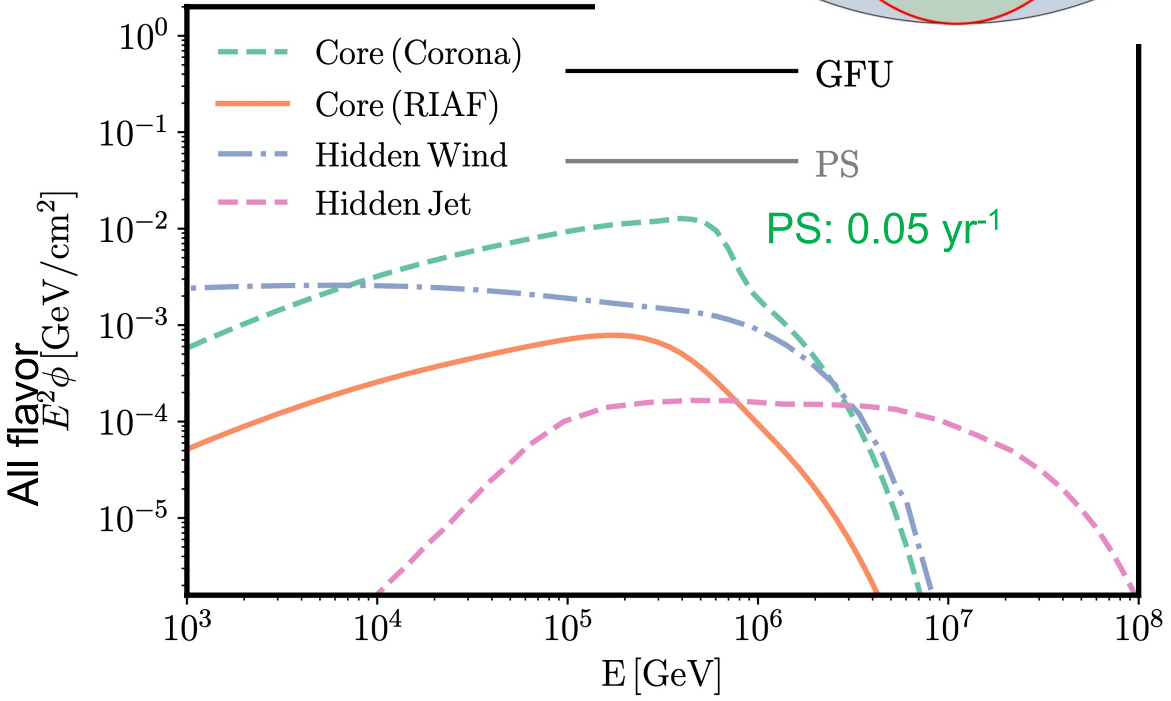


Winter, Lunardini, Nature Astronomy 5 (2021) 472
(slightly modified figure)

Challenges and comparison to alternatives

X-rays observed!





Murase et al, arXiv:2005.08937; see also Hayasaki, Yamazaki, 2019

Jetted models

- Choked jet: probably too low luminosity
- **Jet breakout model: where are other non-thermal signatures?** (see backup)

Core models

- Corona model: parameters guesstimated from AGNs (where large assumed B for efficient stochastic acceleration is potentially in conflict with radio data ... **Inoue, Khangulyan, Doi, arXiv:2105.08948)**
- RIAF phase:
  typically many years after peak

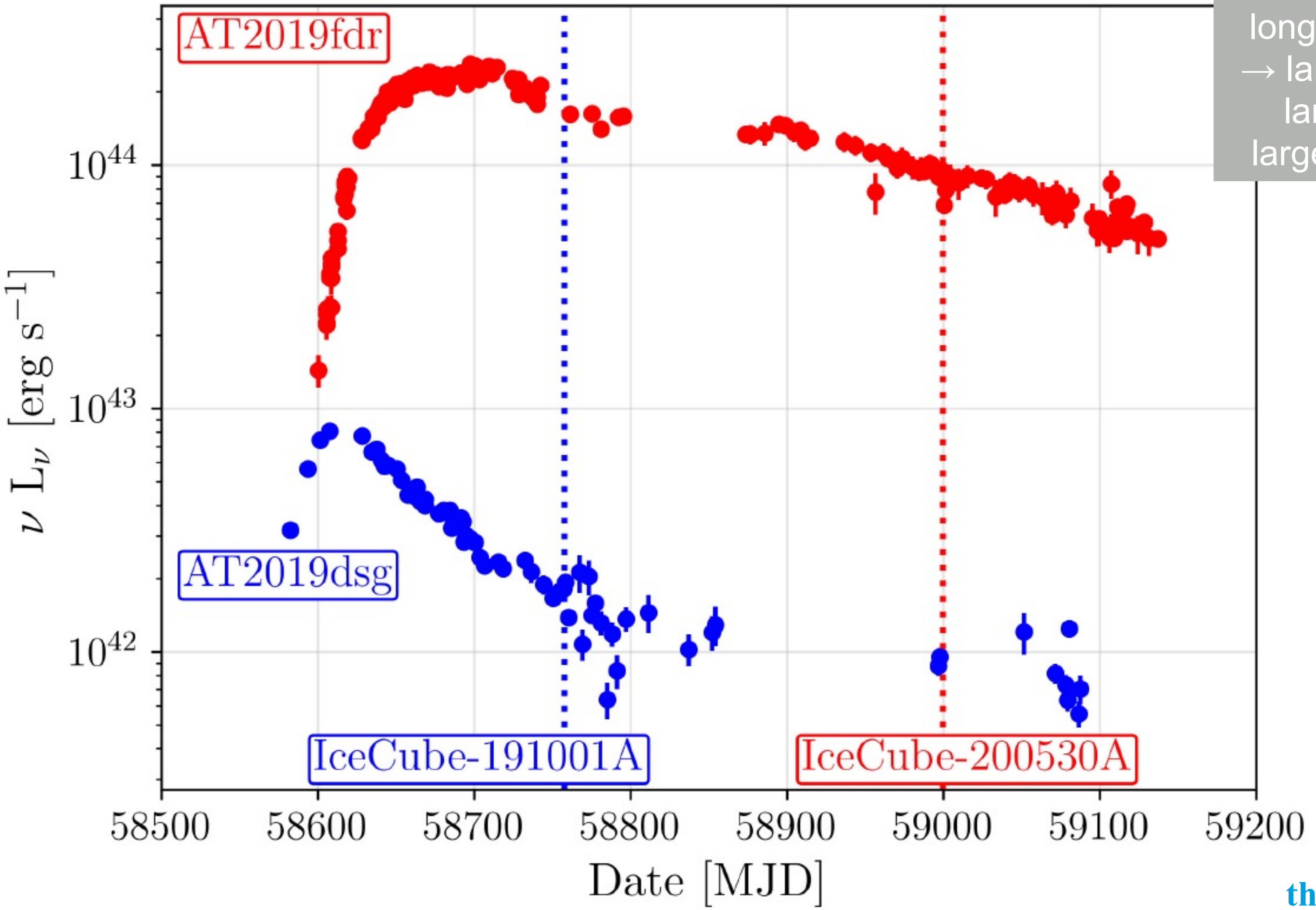
Hidden wind model:

- Large uncertainties from geometry

Alternatives to jetted models have in common:

- Lower neutrino event rate
- No late-arrival prediction for neutrino
- Require large SMBH mass > $10^7\ M_\odot$ (→ energetics problem on page 6)
- Do not explain why X-rays seen

Outlook/expectations



More luminous, longer duration → larger M_{SMBH}, larger star, larger system?

From: Robert Stein & Simeon Reusch @ Cosmic Rays and Neutrinos in the Multi-Messenger Era, Paris, Dec. 7-11, 2020; Reusch,..., WW, et al, in preparation

Neutrinos and the origin of the UHECRs

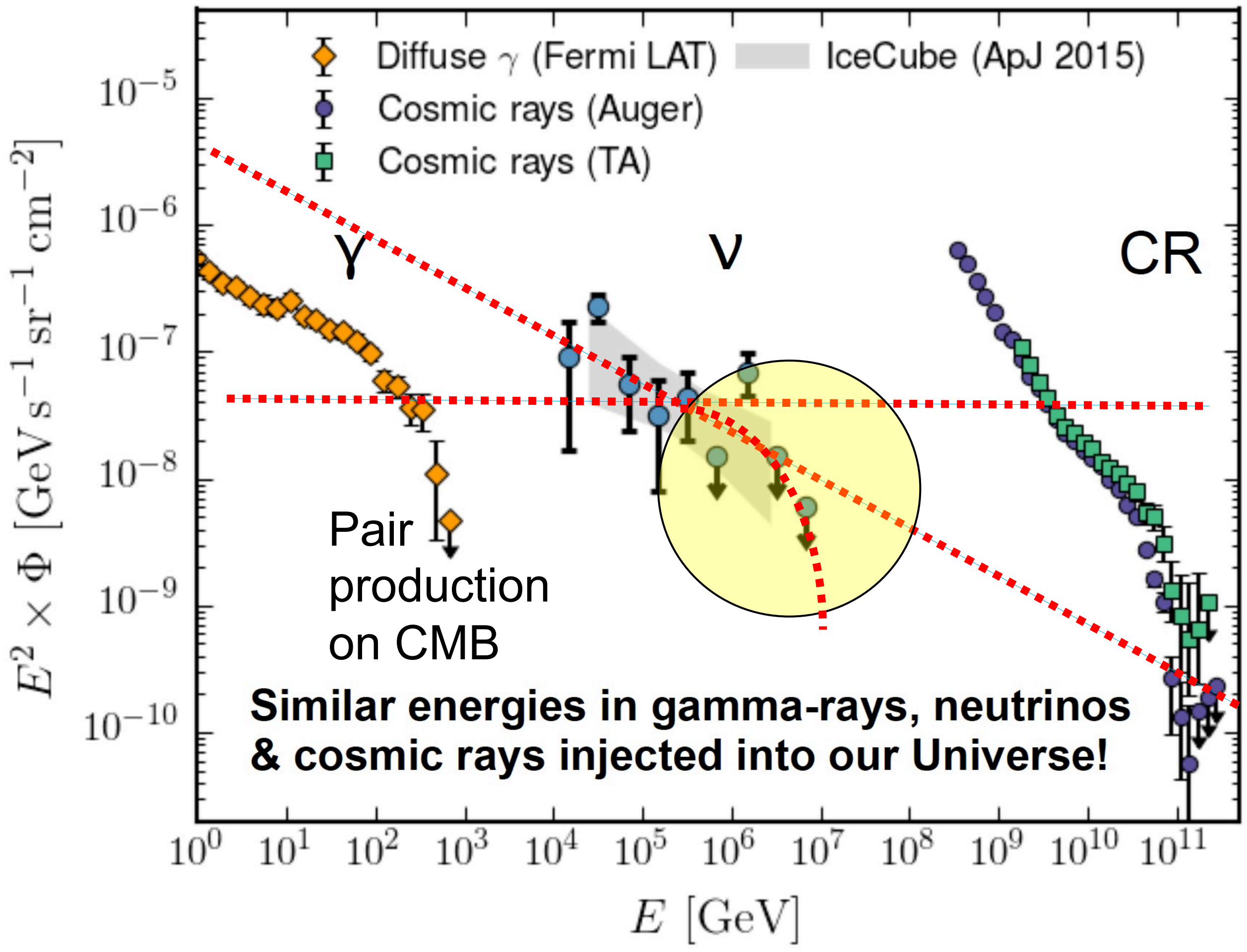
Focus on transients

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}

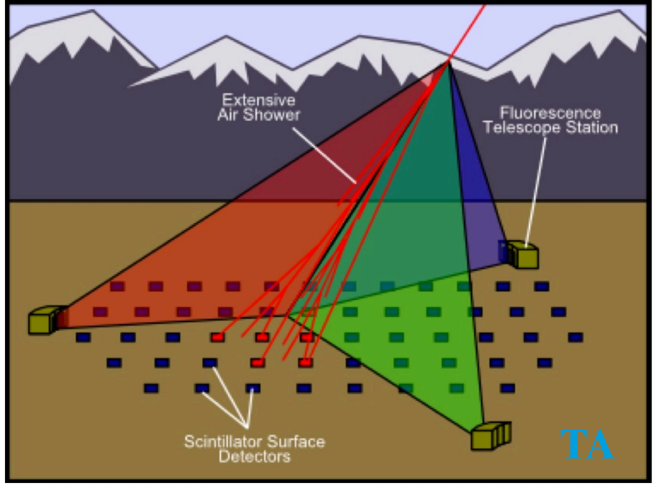


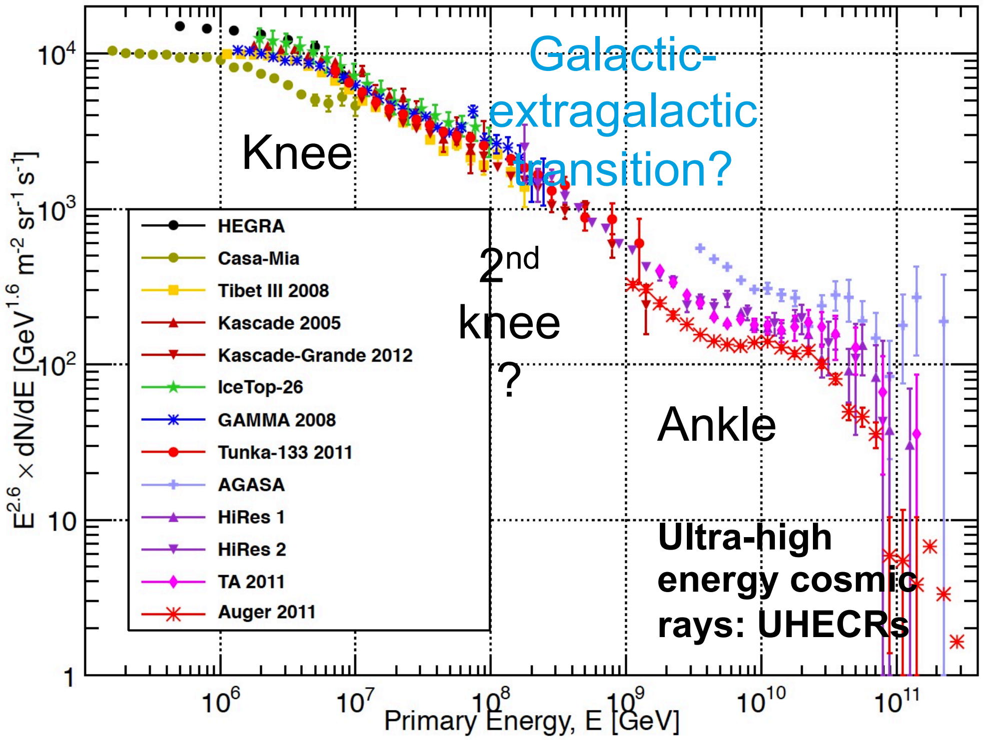
Mohrmann, Kowalski

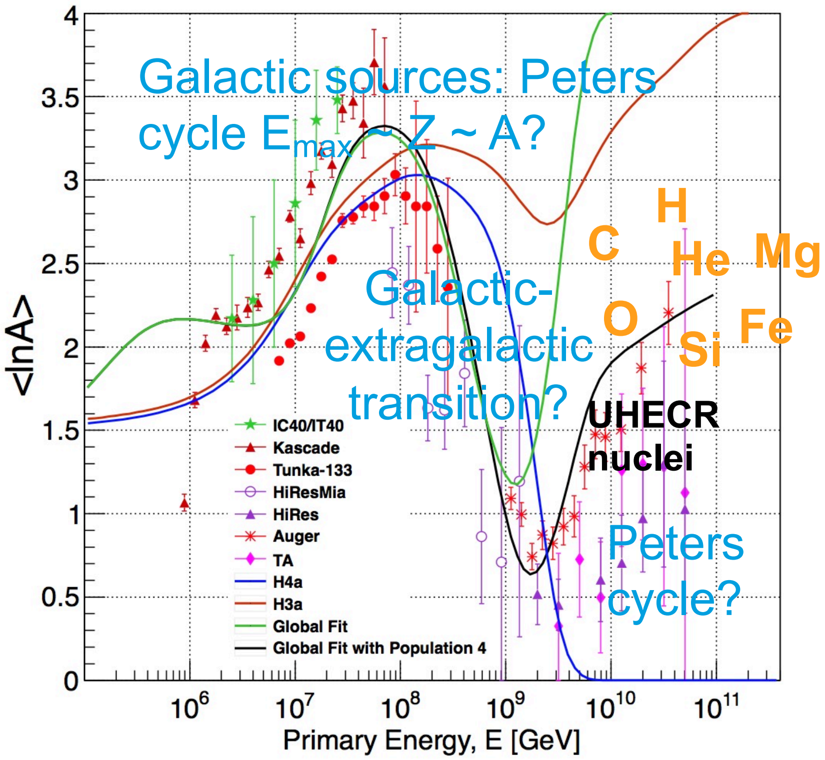
UHECRs: Spectrum and composition

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

Observables:
1) Spectrum
2) Composition: $\langle X_{max} \rangle$
3) Composition: $\sigma(X_{max})$



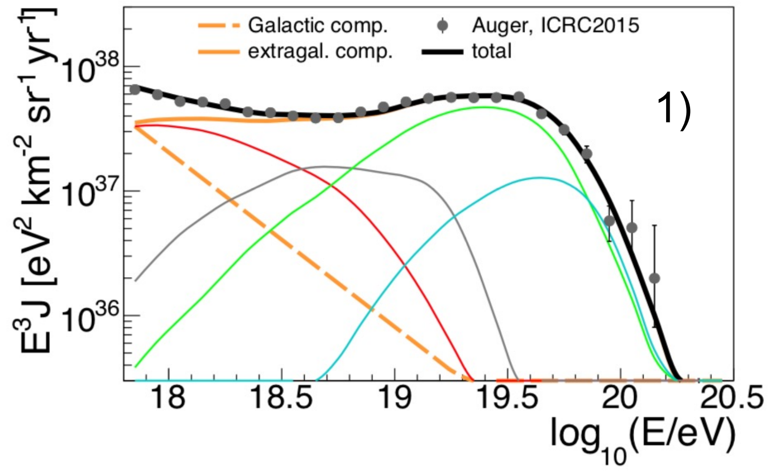


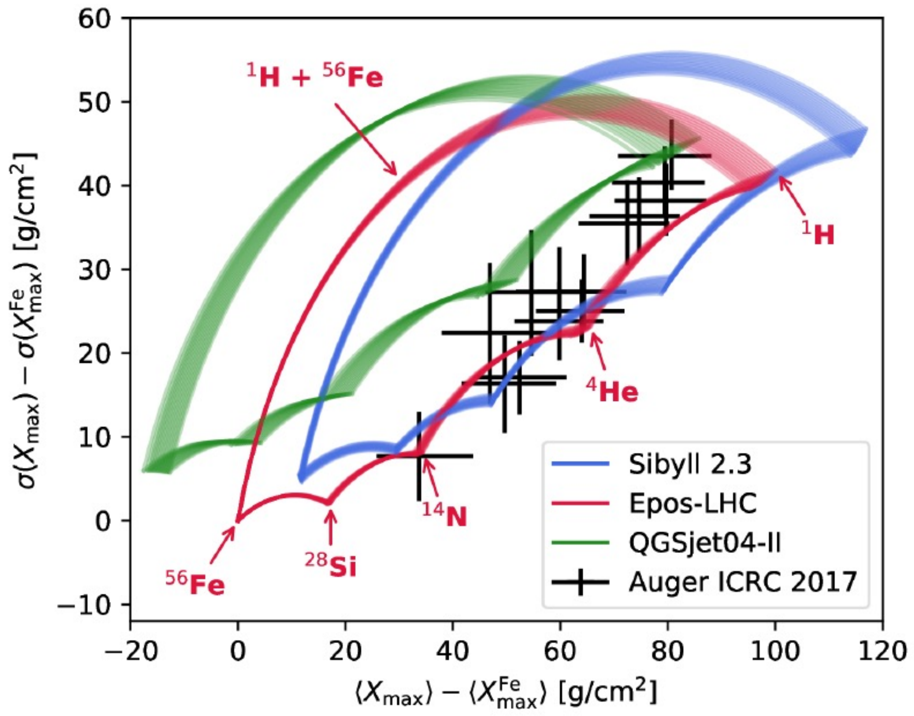


Lorentz force = centrifugal force ➔ $E_{max} \sim Z\, c\, B\, R \sim Z$ (Peters cycle)

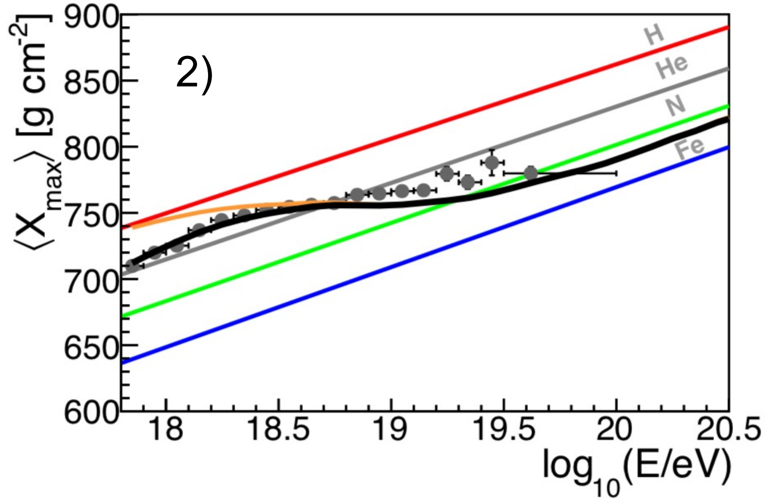
Gaisser, Stanev, Tilav, 2013

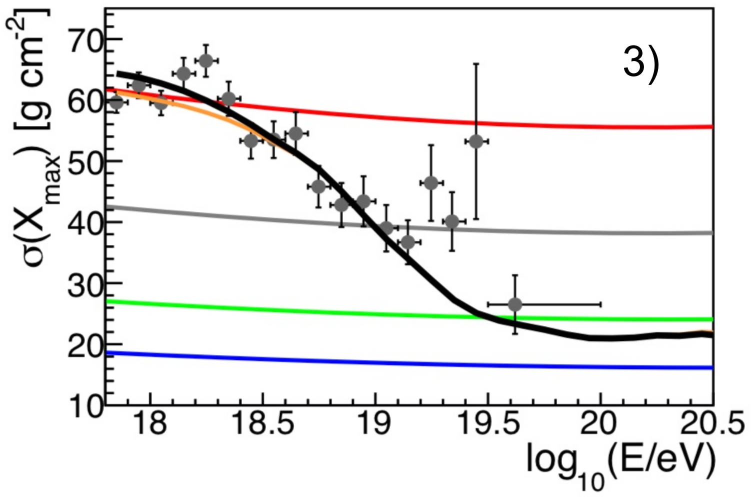
Description of observables (a typical example)





Data favor pure composition!



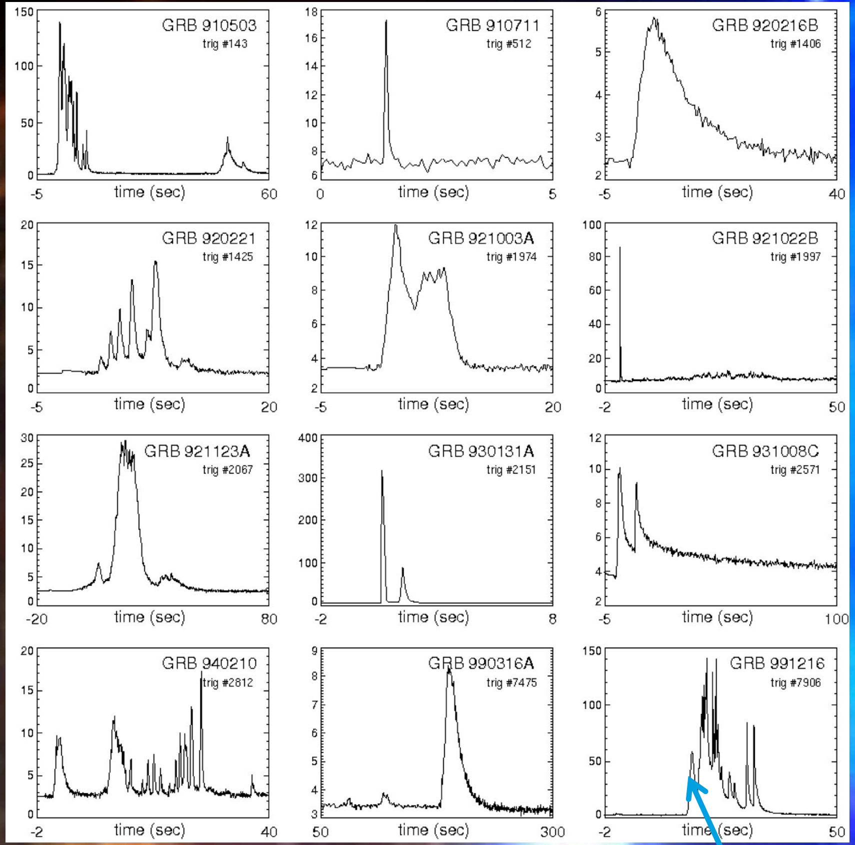


Observables:
1) Spectrum
2) Composition: <X_{max}>
3) Composition: $\sigma(X_{max})$

LL-GRBs in Biehl, Boncioli, Lunardini, WW, Sci. Rep. 8 (2018) 1; Upper right plot from PhD thesis Jonas Heinze, https://edoc.hu-berlin.de/handle/18452/22177

Gamma-ray bursts (GRBs)

Daniel Perley

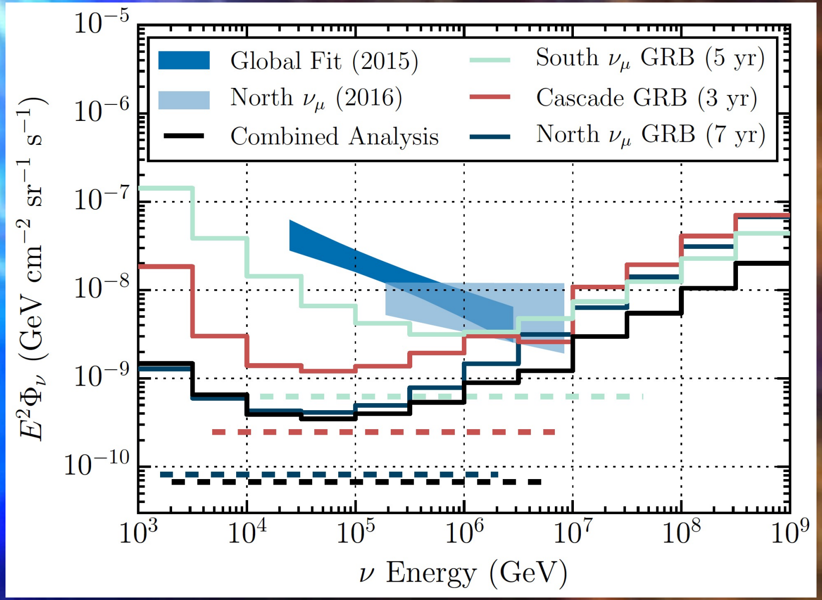


t_v: variability timescale

Several populations, such as

- **Long-duration bursts** (~10 – 100s), from collapses of massive stars? **HL-GRBs**
- Short-duration bursts (~ 0.1 – 1 s), from neutron star mergers. Low total energy output!
- Low-luminosity GRBs from intrinsically weaker engines, or shock breakout? **LL-GRBs** Potentially high rate, longer duration (but only locally observed)

- Neutrino stacking searches: <~1% of diffuse neutrino flux



IceCube, Nature 484 (2012) 351;
Newest update: arXiv:1702.06868

Source: NASA

Transients which may power the UHECRs

- Required energy per transient event to power UHECRs:

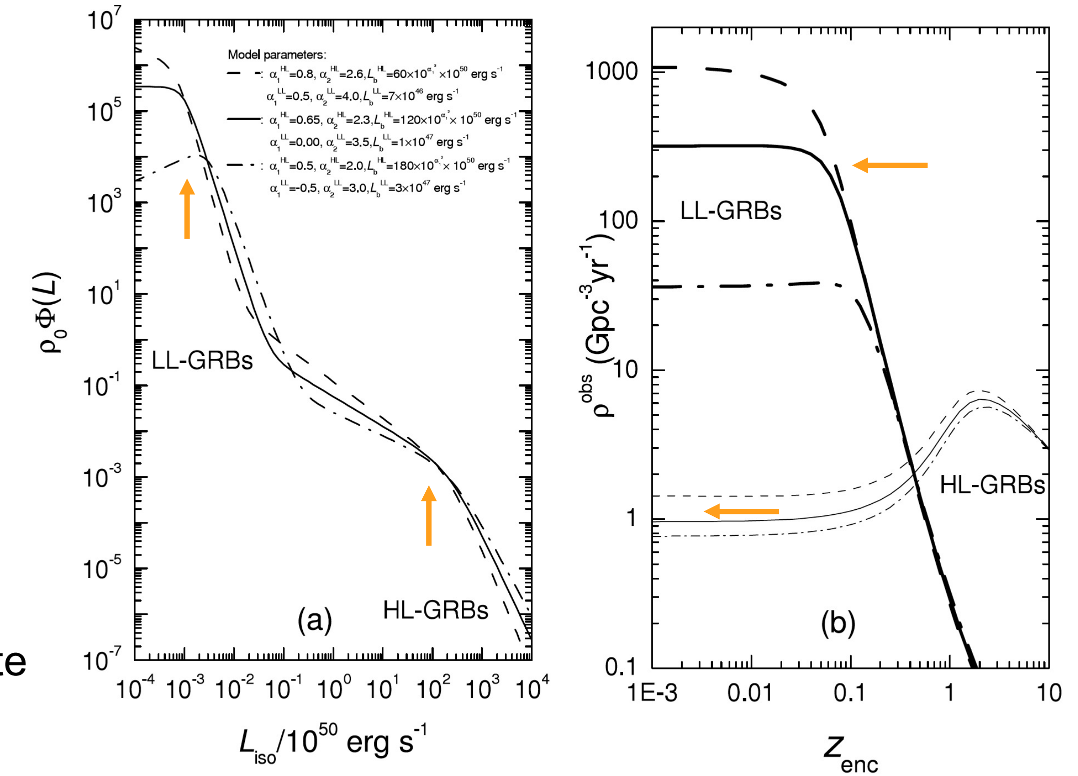
$$E_{\rm CR}^{[10^{10},10^{12}]} = 10^{53}\,{\rm erg} \cdot \frac{\dot{\varepsilon}_{\rm CR}^{[10^{10},10^{12}]}}{10^{44}\,{\rm erg\,Mpc^{-3}\,yr^{-1}}} \frac{\rm Gpc^{-3}\,yr^{-1}}{\dot{n}_{\rm GRB}\big|_{z=0}}$$

Required energy output per source | Fit to UHECR data | Source density

from Baerwald, Bustamante, Winter, Astropart. Phys. 62 (2015) 66; Fit energetics: Jiang, Zhang, Murase, arXiv:2012.03122; early args: Waxman, Bahcall, ...

- Connection with gamma-rays: $E_{\rm CR}^{[10^{10},10^{12}]} \sim 0.2\, f_e^{-1} E_\gamma$ if all UHECRs can escape, and 20% of the CR energy is in UHECRs (typical for E^{-2} spectrum).
  f_e^{-1}: **baryonic loading** $(L_{CR}/L_\gamma)_{inj}$
- Examples in this talk: can all sustain this energy (roughly)
  - **HL-GRBs**: $E_\gamma \sim 10^{52}$ erg s^{-1} x 10 s ~ 10^{53} erg, rate ~ 1 Gpc^{-3} yr^{-1}
    ☞ Ok for $f_e^{-1} > 10$. *Seems widely accepted mainstream ...*
  - **LL-GRBs**: $L_\gamma \sim 10^{47}$ erg s^{-1}, rate ~ 300 Gpc^{-3} yr^{-1}
    ☞ Ok for Duration [s] x $f_e^{-1} > 10^5$;
    duration disputed (closer to typical GRBs, rather than 10^4 s?)
  - **Jetted TDEs**: $E_\gamma \sim 10^{47}$ erg s^{-1} x 10^6 s ~ 10^{53} erg (Sw J1644+57), rate 0.1 Gpc^{-3} yr^{-1} ☞ Ok for f_e^{-1} >~ 100; *local rate + L_γ disputed*

Liang, Zhang, Virgili, Dai, 2007; see also: Sun, Zhang, Li, 2015



Neutrino production efficiency in GRBs (as example)

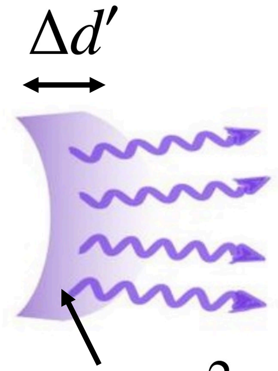
$$\lambda'_{\mathrm{mfp}} = \frac{1}{n'_\gamma \, \sigma_{p\gamma}}$$

... from geometry estimators; production volume determines efficiency!

- Need photon density, which can be obtained from energy density; generically:

$$u'_\gamma \equiv \int \varepsilon' \, N'_\gamma(\varepsilon') \mathrm{d}\varepsilon' = \frac{L_\gamma \, \Delta d'/c}{\Gamma^2 \, V'_{\mathrm{iso}}} = \frac{L_\gamma}{4\pi c \Gamma^2 R^2}$$

L'_γ



$$V'_{\mathrm{iso}} = 4\pi R^2 \cdot \Delta d'$$

- Scales ~1/R^2 from simple geometry arguments
- *Internal shock scenario*: e.g. Guetta et al, 2004

$$R \simeq 2\Gamma^2 \frac{c \, t_v}{1+z} \qquad \Delta d' \simeq \Gamma \frac{c t_v}{1+z} \quad \Rightarrow \quad f_{p\gamma} \propto L_\gamma / (\Gamma^4 t_v \epsilon_{\gamma,\mathrm{br}})$$

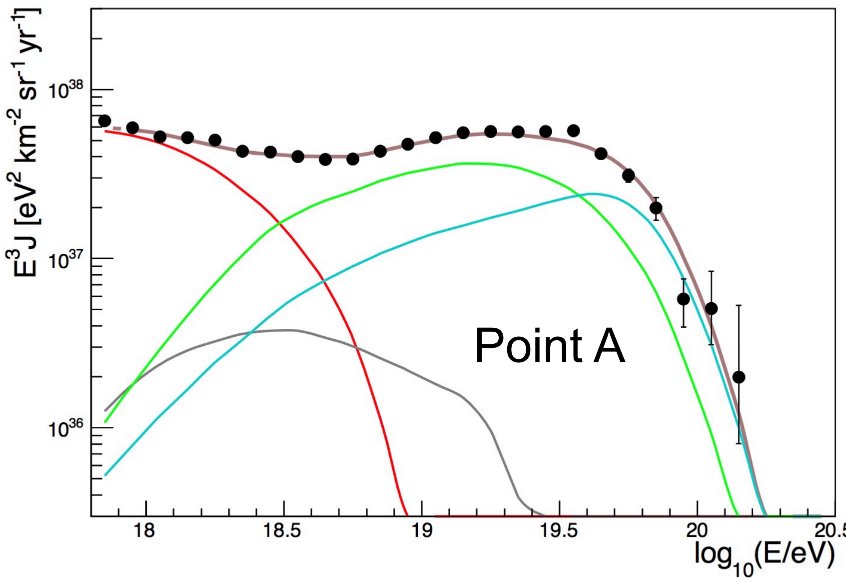
$$(f_{p\gamma} \propto \Delta d' / \lambda'_{\mathrm{mfp}} \sim \Delta d' \, \sigma_{p\gamma} u'_\gamma / (\epsilon_{\gamma,\mathrm{br}}/\Gamma))$$

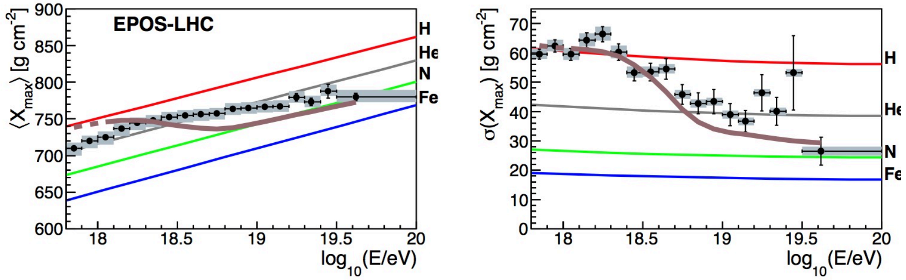
- *Magnetic re-connection models*: est. for *R* from pulse timescale (larger)
- *Photospheric emission*: *R* corresponds to photospheric radius
- *Multi-zone models*: *R* and Δd' individually calculated for each collision
- **Production radius R and luminosity Lγ are the main control parameters for the neutrino production**
  [t_v does not vary as much as L_γ]
  e.g. He et al, 2012; Zhang, Kumar, 2013; Biehl et al, arXiv:1705.08909 (Sec. 2.5) for details

The vanilla one-zone prompt model

Neutrino and cosmic ray emission at same collision radius R

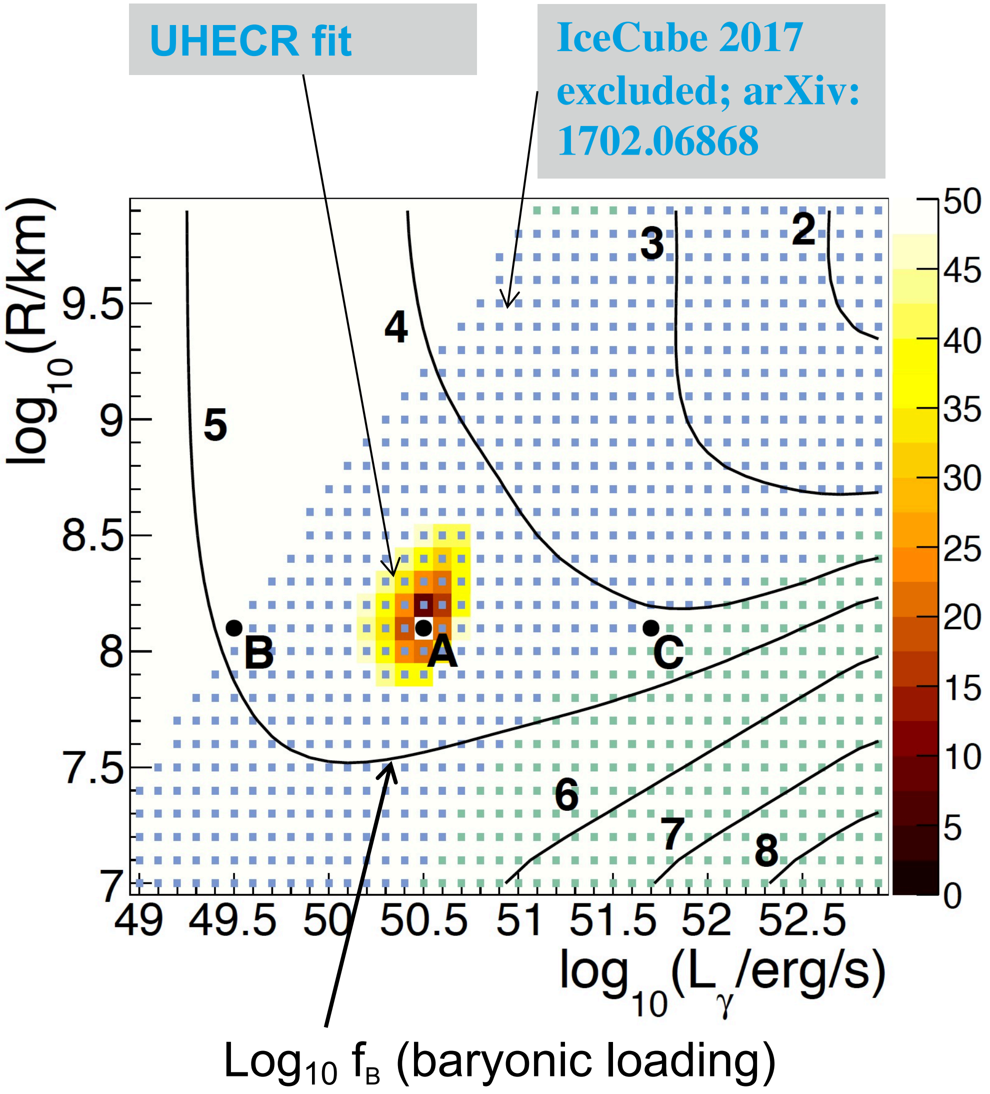
- Can describe UHECR data, roughly
- Scenario is constrained by neutrino non-observatons





Recipe:

- Fit UHECR data, then compute predicted neutrino fluxes
- Here only one example; extensive parameter space studies have been performed
- Conclusion relatively robust for parameters typically expected for HL-GRBs



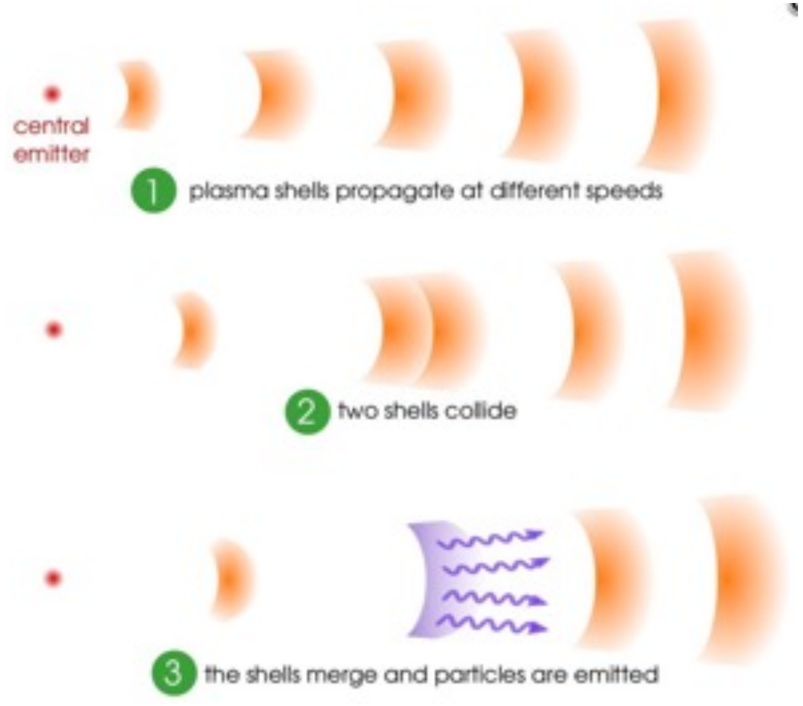
Biehl, Boncioli, Fedynitch, Winter, arXiv:1705.08909
Astron. Astrophys. 611 (2018) A101;
Baerwald, Bustamante, Winter, Astropart. Phys. 62 (2015) 66

Back to the roots:
Multi-collision models

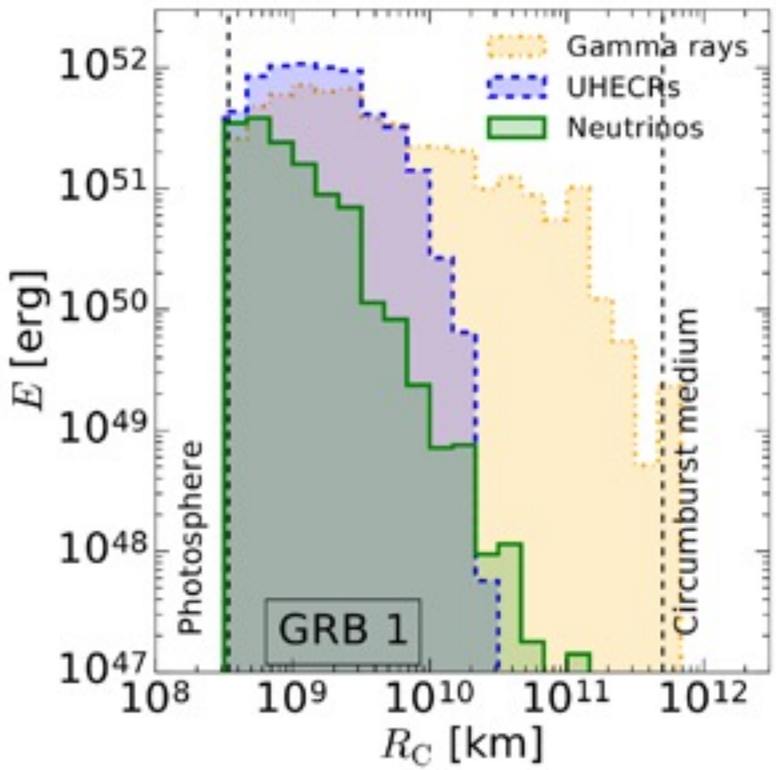
The GRB prompt emission comes from multiple zones

Bustamante, Baerwald, Murase, Winter, Nature Commun. 6, 6783 (2015);
Bustamante, Heinze, Murase, Winter, ApJ 837 (2017) 33;
Rudolph, Heinze, Fedynitch, Winter, ApJ 893 (2020) 72
see also Globus et al, 2014+2015;
earlier works e.g. Guetta, Spada, Waxman, 2001 x 2

Collision model, illustrated



Multi-messenger emission



Bustamante, Baerwald, Murase, Winter, Nature Commun. 6, 6783 (2015)

Observations

- The neutrino emission is lower (comes from a few collisions close to the photosphere)
- UHECRs and γ-rays are produced further out, where the radiation densities are lower
  - ➢ Releases tension with neutrino data
- The **engine properties** determine the nature of the (multi-messenger) light curves
- Many aspects studied, such as impact of collision dynamics, interplay engine properties and light curves, dissipation efficiency etc.

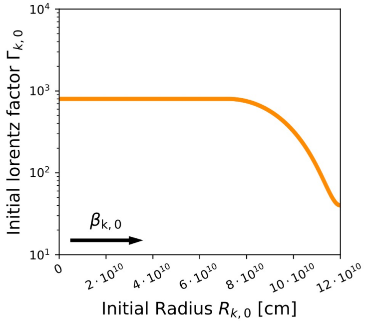
A new (unified) model with free injection compositions

Systematic parameter space study requires model which can capture stochastic and deterministic engine properties

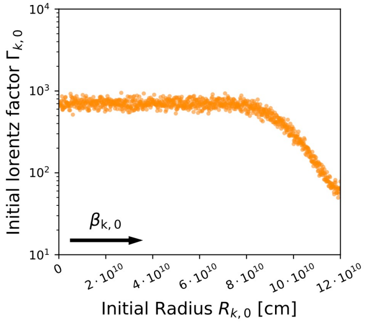
Model description

- Lorentz factor ramp-up from Γ_{min} to Γ_{max}, stochasticity (A_Γ) on top

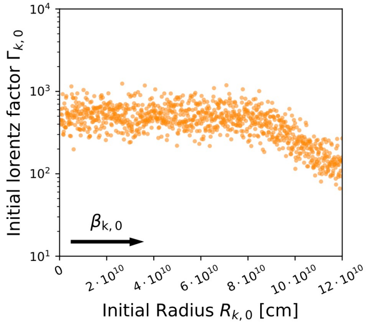
SR-0S
Strong (engine) ramp-up, no stochasticity



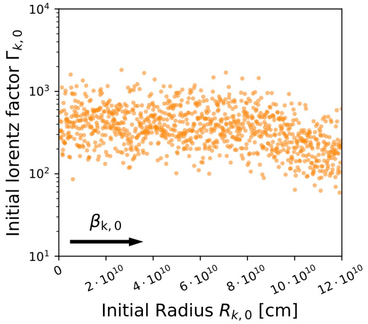
SR-LS
Strong (engine) ramp-up, low stochasticity



WR-MS
Weak (engine) ramp-up, medium stochasticity



WR-HS
Weak (engine) ramp-up, high stochasticity

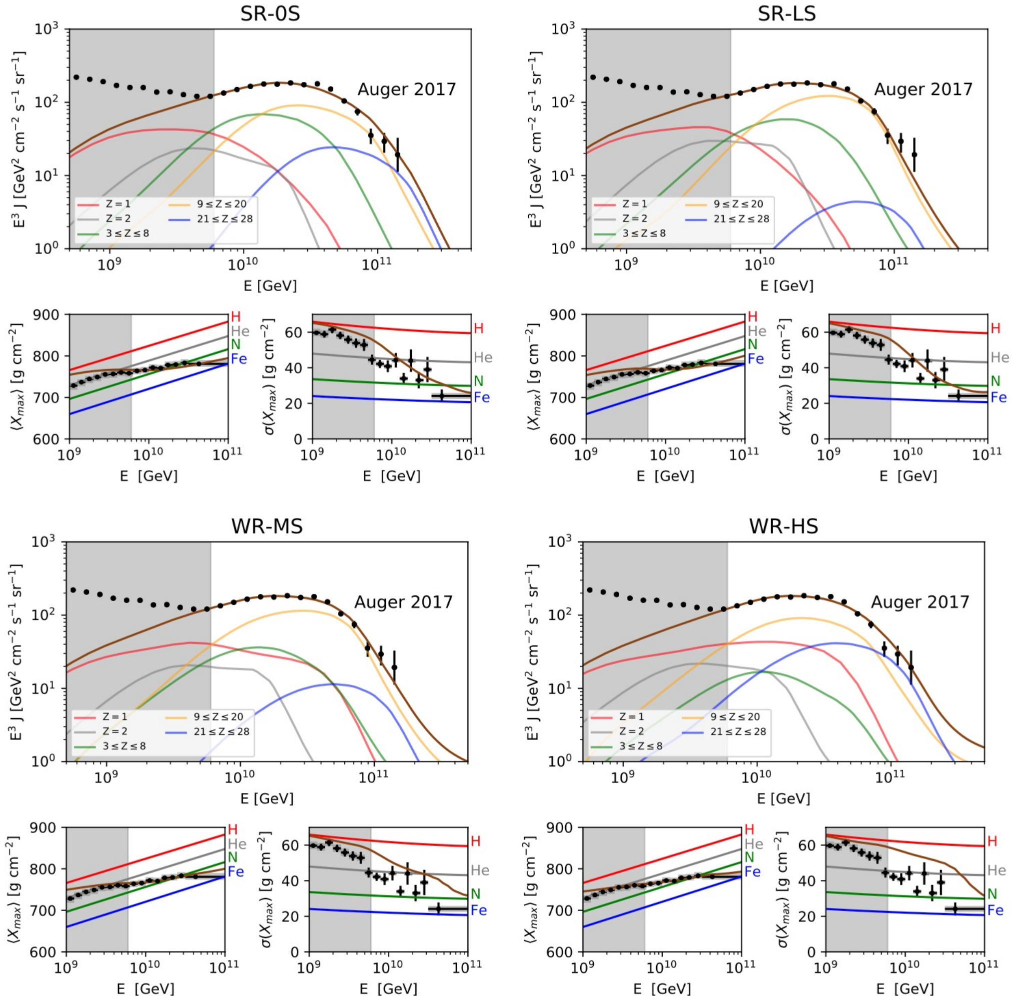


Describes UHECR data over a large range of parameters!

(systematically studied)

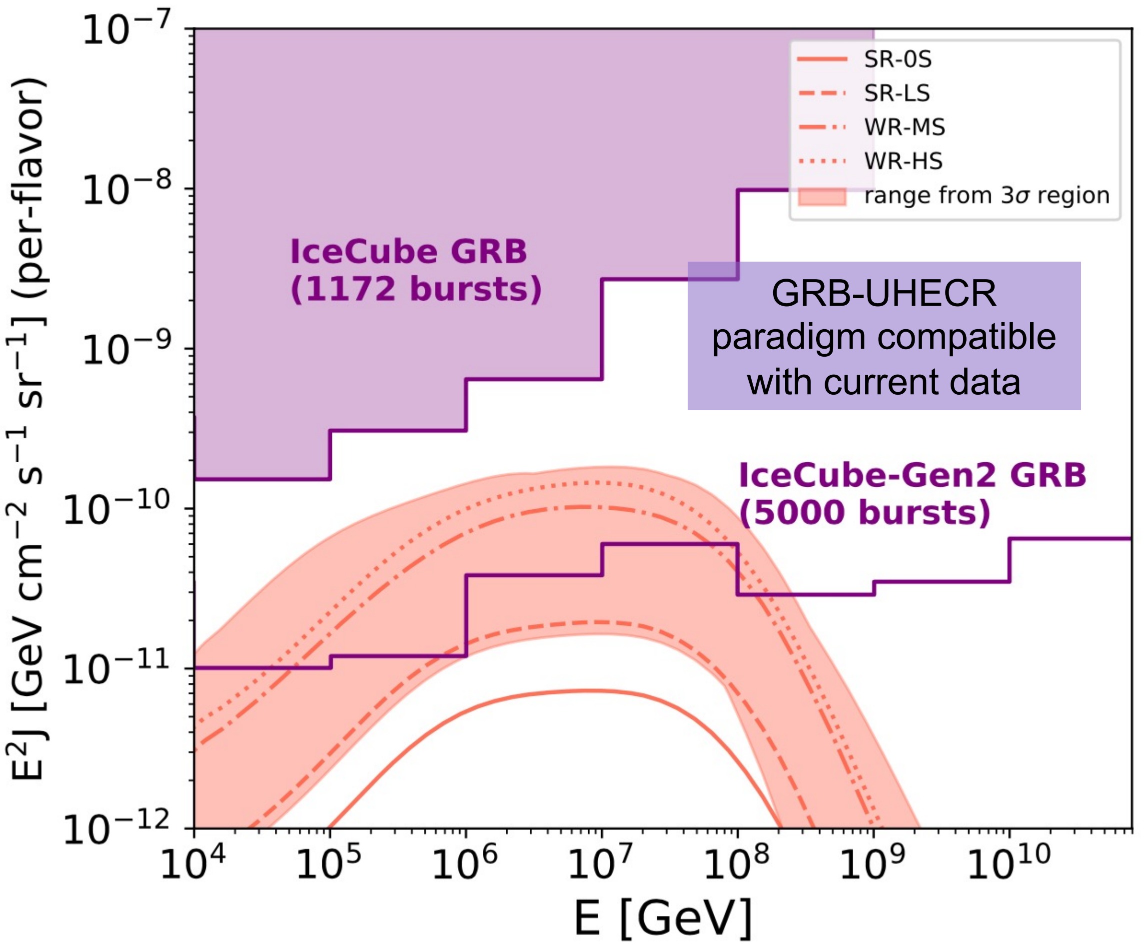
Heinze, Biehl, Fedynitch, Boncioli, Rudolph, Winter, MNRAS 498 (2020) 4, 5990, arXiv:2006.14301

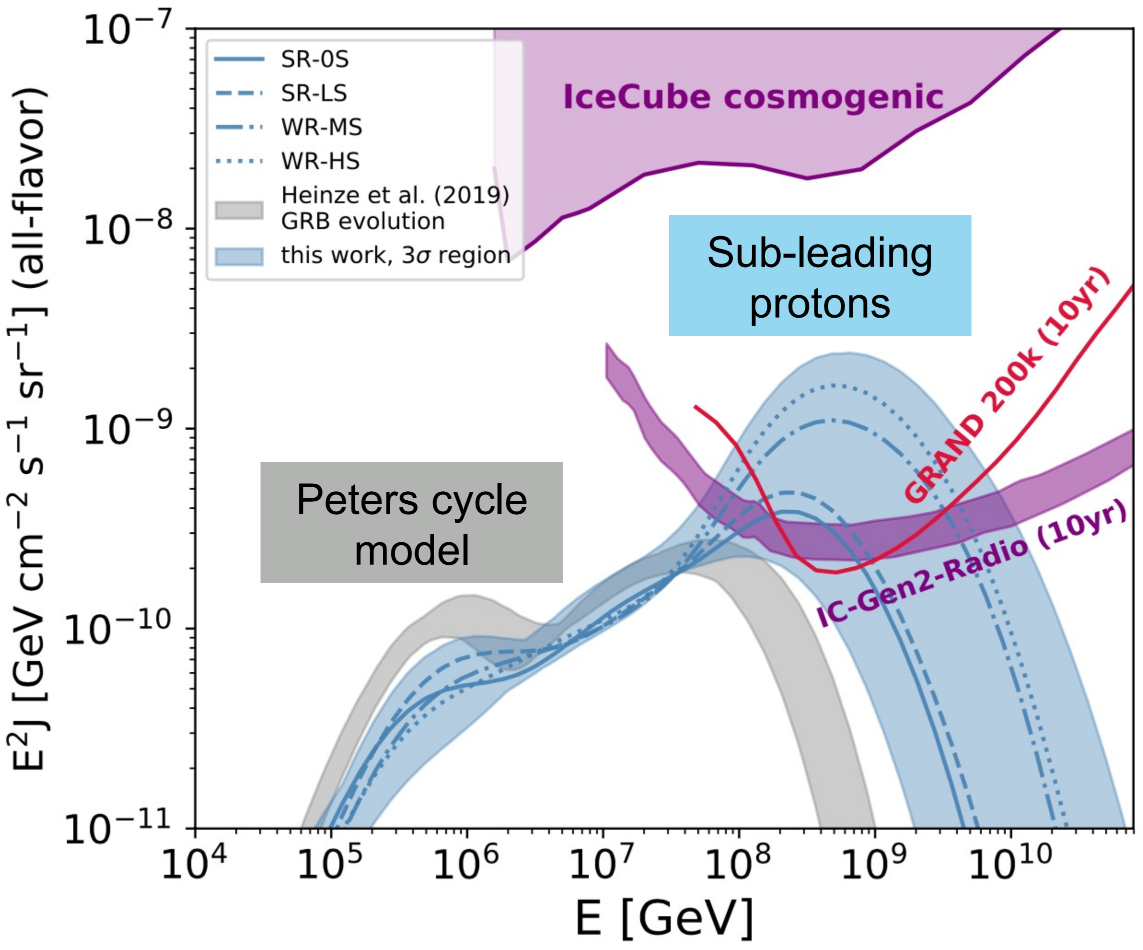
Description of UHECR data



Inferred neutrino fluxes from the parameter space scan

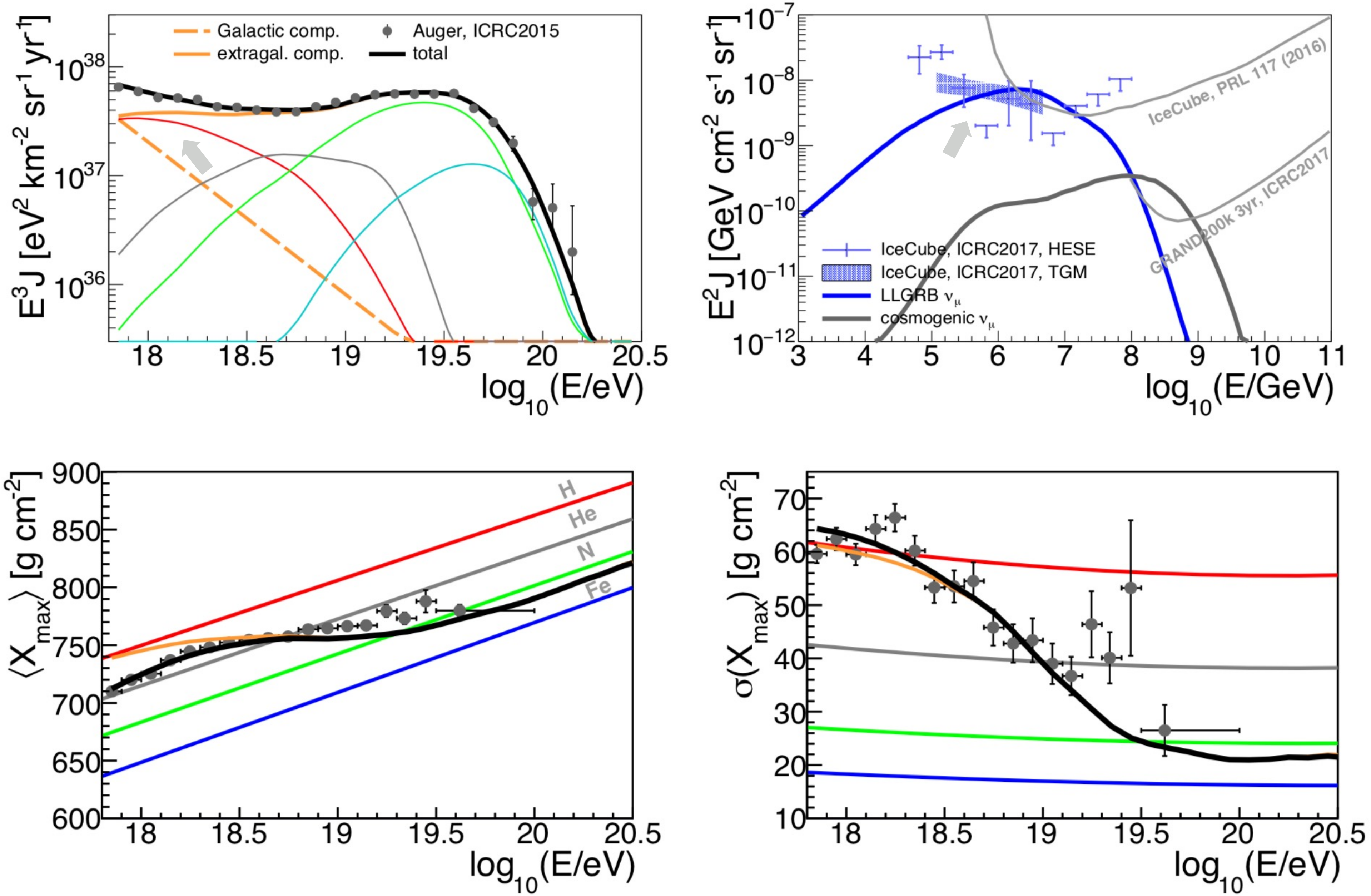
Prompt neutrino flux possibly testable with IceCube-Gen2, cosmogenic one in future radio instruments





Heinze, Biehl, Fedynitch, Boncioli, Rudolph, Winter, MNRAS 498 (2020) 4, 5990, arXiv:2006.14301

Describing UHECRs and neutrinos with LL-GRBs

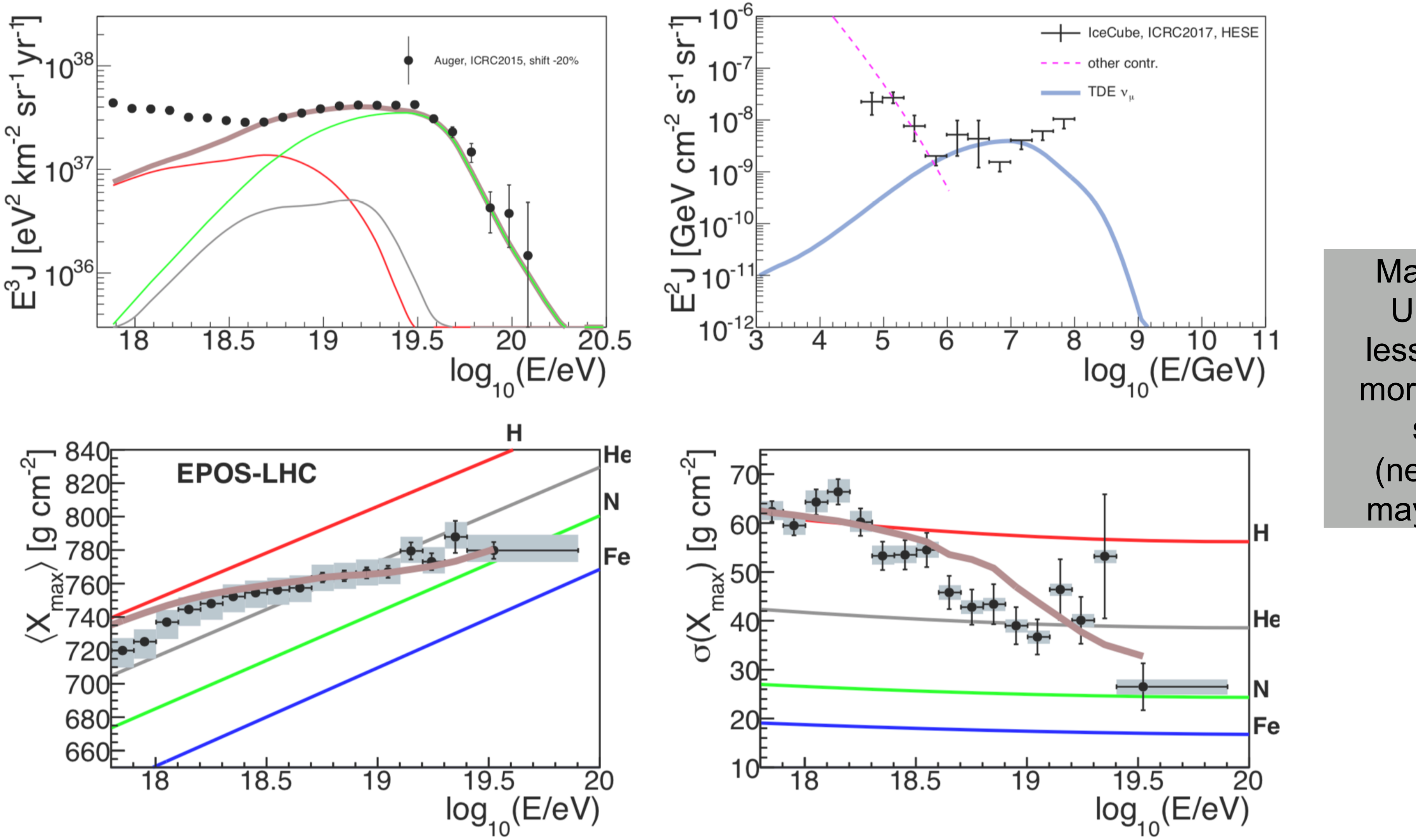


- Can be simultaneously described
- The radiation density controls the neutrino production and sub-ankle production of nucleons
- Subankle fit and neutrino flux require similar parameters

Boncioli, Biehl, Winter, ApJ 872 (2019) 110; arXiv:1808.07481

Injection composition and escape from **Zhang et al., PRD 97 (2018) 083010;**

Another example: jetted Tidal Disruption Events (TDE)



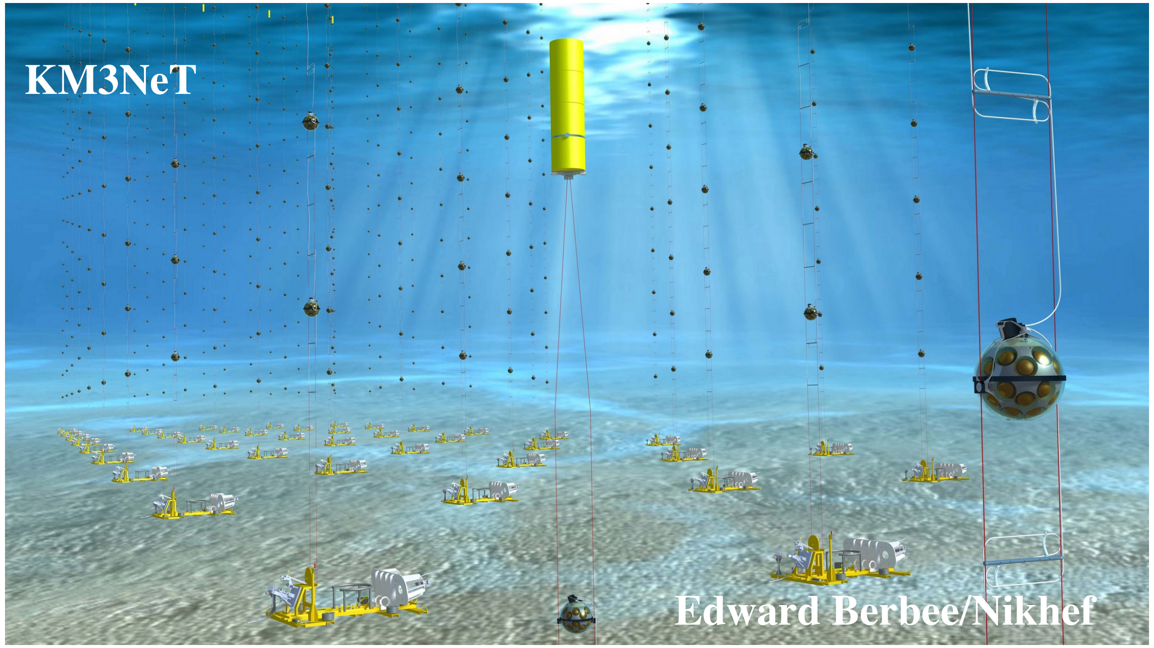
May work for UHECRs if less luminous, more abundant sources (neutrino flux may be lower)

Biehl, Boncioli, Lunardini, WW, Sci. Rep. 8 (2018) 1; arXiv:1711.03555

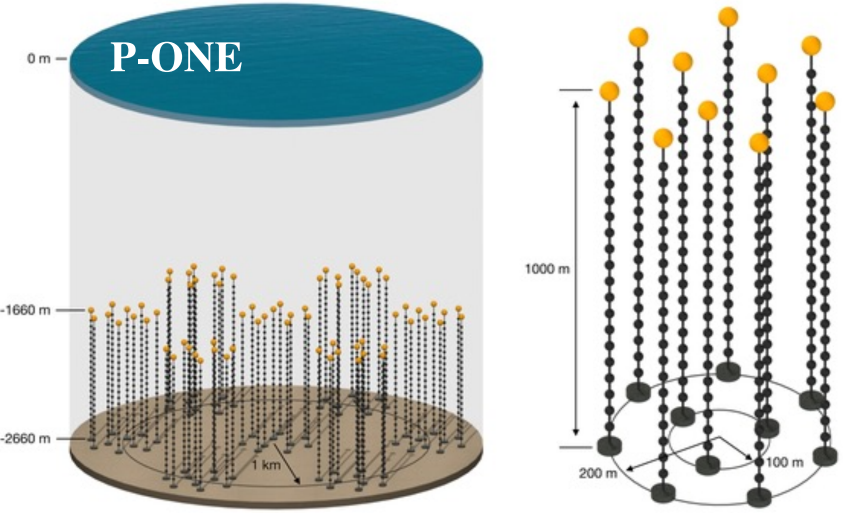
The future of high-energy neutrino astronomy

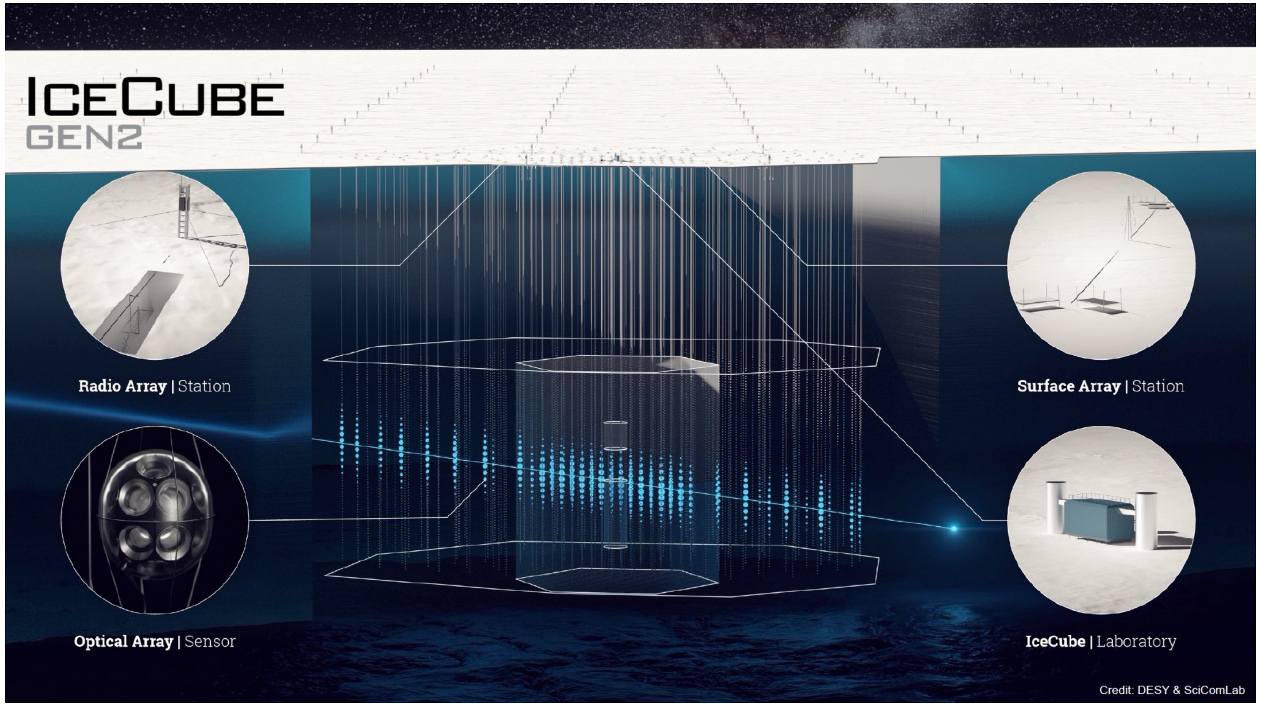
Future neutrino telescopes: PeV neutrinos

... towards a global neutrino observatory?



Elisa Resconi/TUM

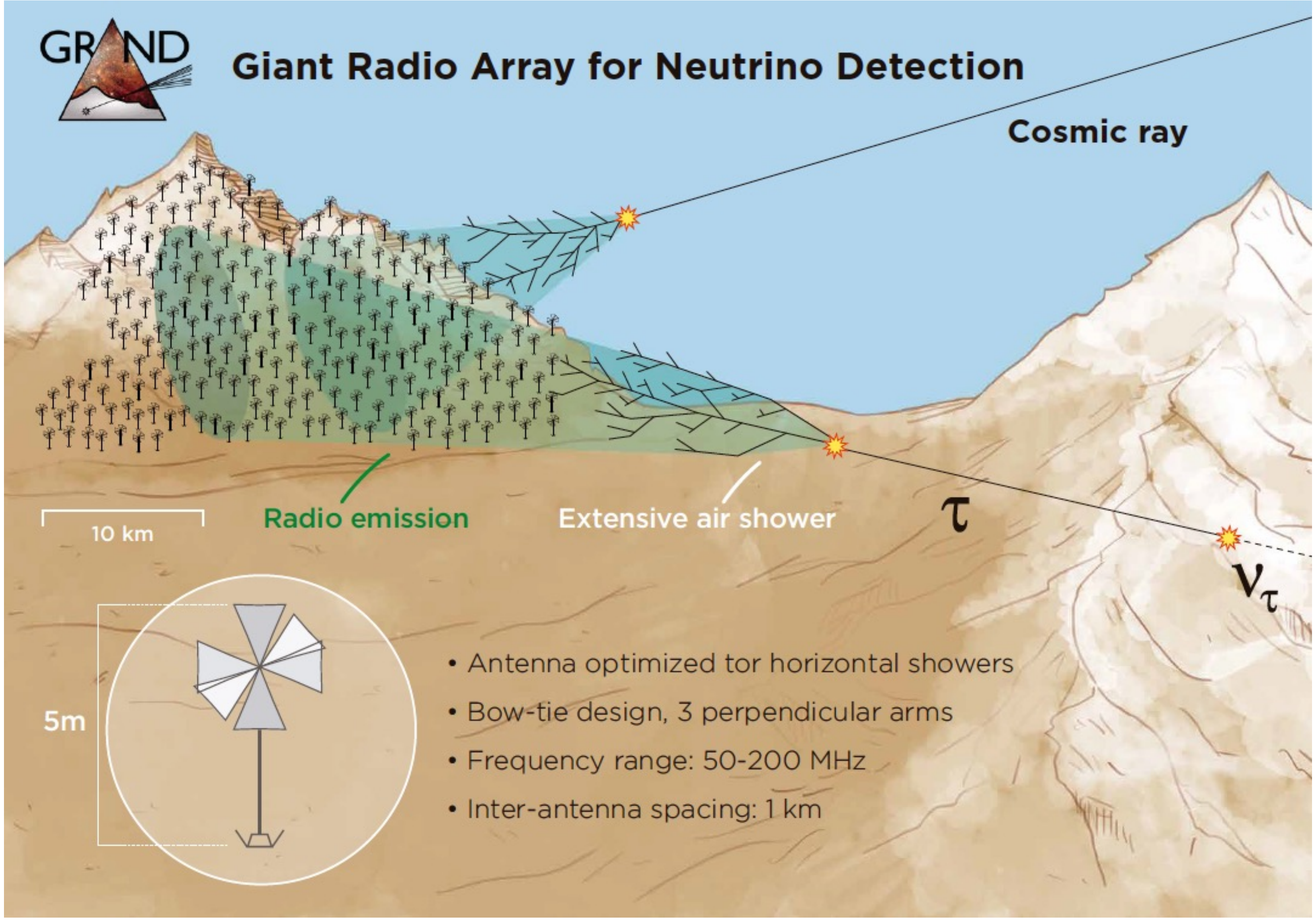




Radio detection of neutrinos

Example: GRAND

Others:
RNO-G
ARA/ARIANNA
IceCube-Gen2
...



Sci. China Phys.Mech.Astron. 63 (2020) 1, 219501

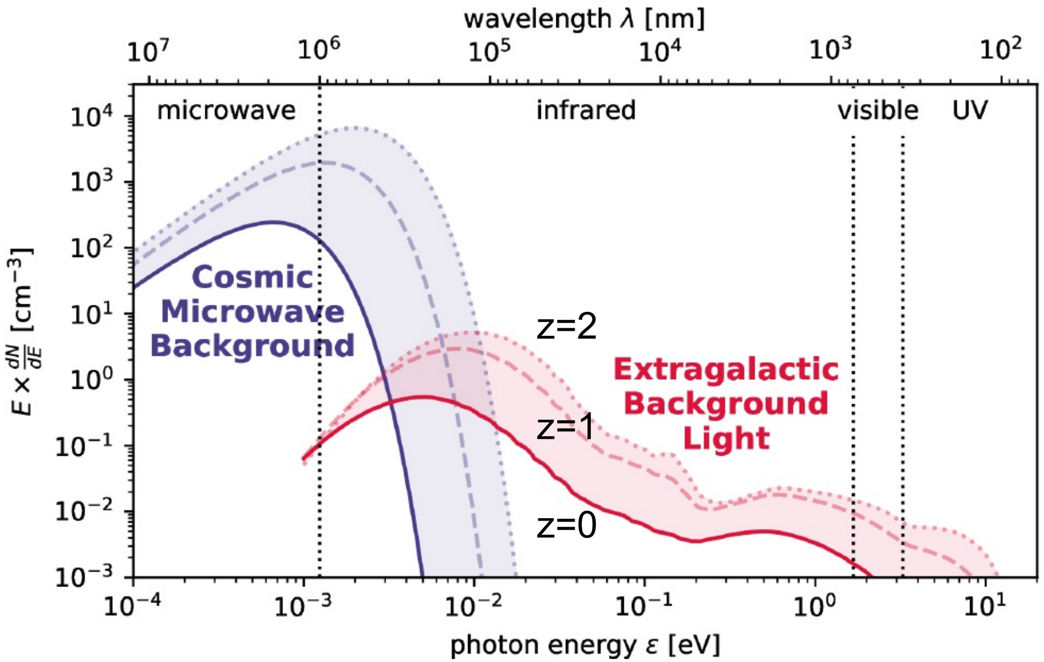
Main physics case: cosmogenic neutrinos

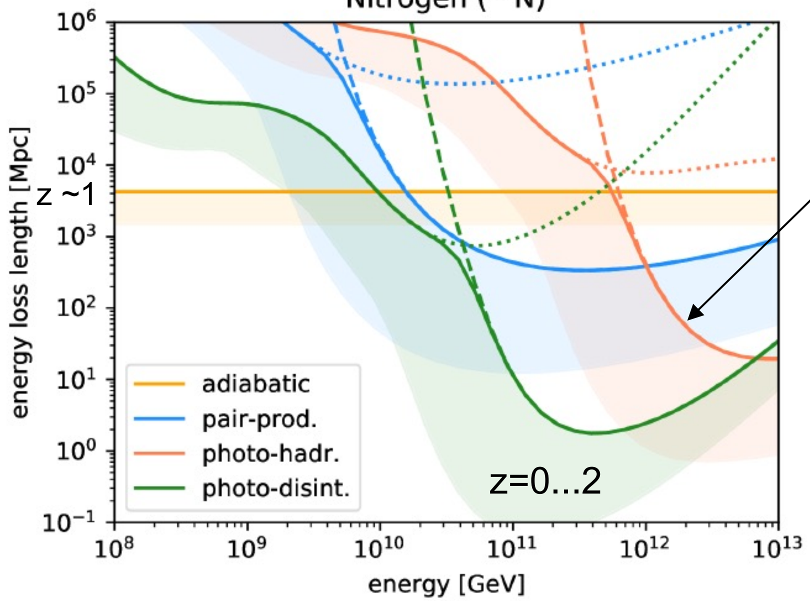
Transport equation similar to radiation models (solved in co-moving density Y), for species *i*:

$$\partial_t Y_i = -\partial_E(b_{\text{ad}} Y_i) - \partial_E\left(b_{e^+e^-} Y_i\right) - \Gamma_i Y_i + \sum_j Q_{j\to i}(Y_j) + J_i$$

Adiabatic losses (expansion of Universe)	Pair production losses	Interactions (escape term)	Injection (interactions)	Injection (sources)

Nuclei subject to disintegration. A nuclear cascade develops!





Neutrino production: photohadronic interactions

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

NB: UHECRs cannot travel further than z ~ 1

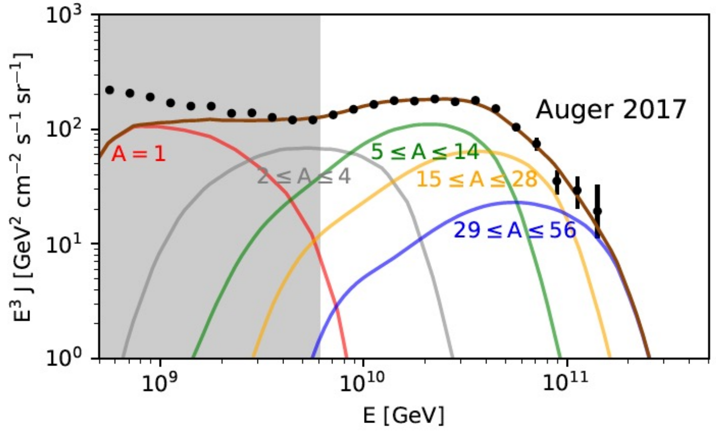
From PhD thesis Jonas Heinze, https://edoc.hu-berlin.de/handle/18452/22177

Baseline UHECR fit model (Peters cycle model)

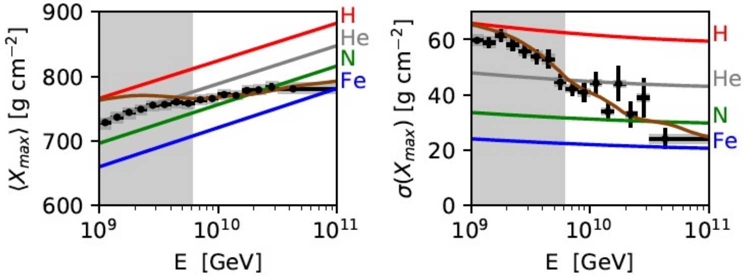
Three parameters:

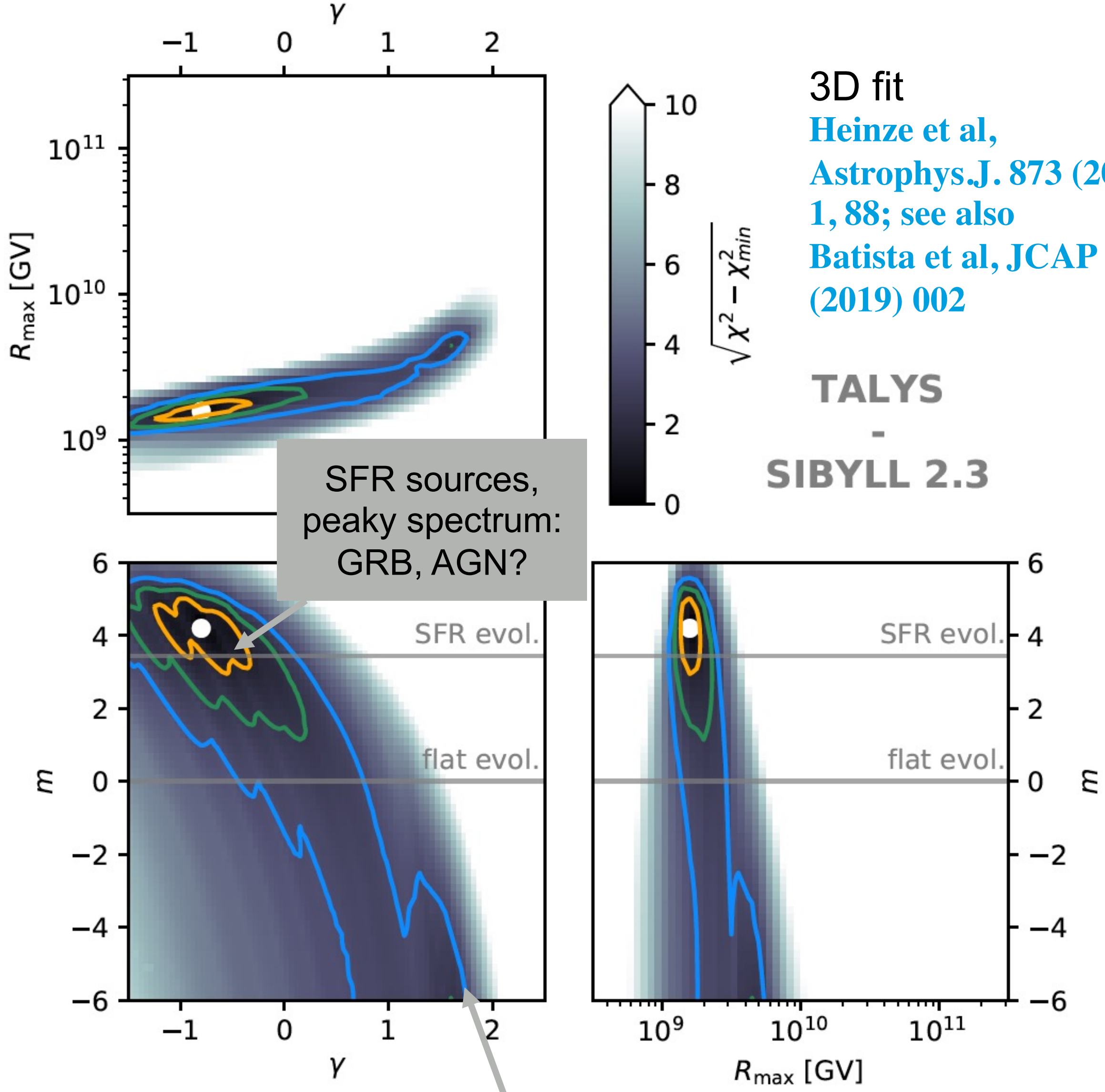
- γ: $E^{-\gamma}$ is the injection spectrum from sources
- R_{max}: Sources have $E_{max}=Z \times R_{max}$ (Peters cycle)
- m: Sources evolve $(1+z)^m$
  (NB I: SFR evolution: m ~ 3.4 for z < 1)
  (NB II: UHECRs do not travel from farther)

Best-fit spectrum



Best-fit compositon





3D fit
Heinze et al, Astrophys.J. 873 (2019) 1, 88; see also Batista et al, JCAP 01 (2019) 002

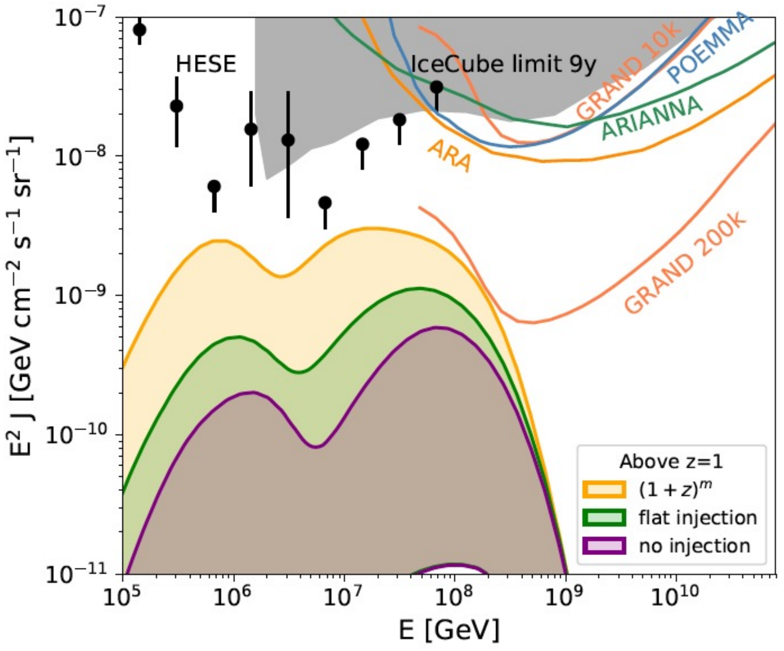
TALYS - SIBYLL 2.3

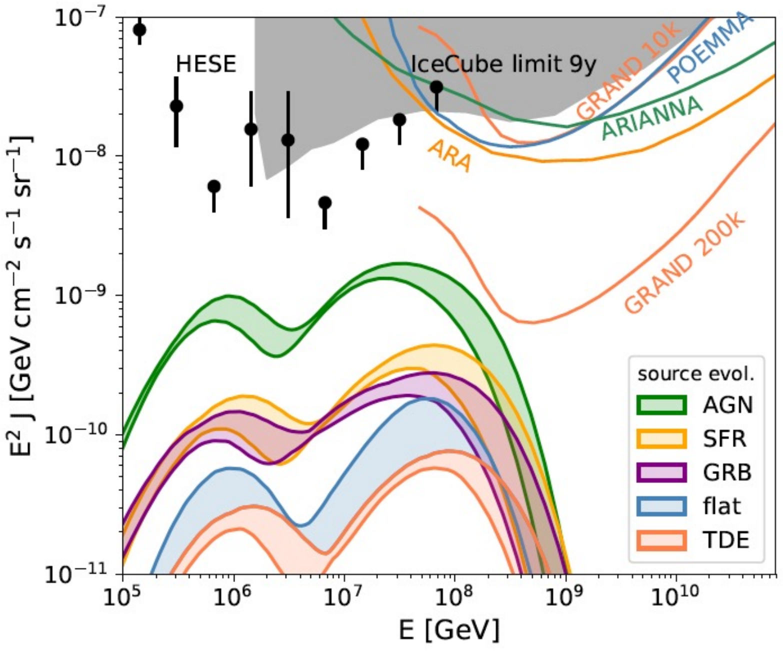
SFR sources, peaky spectrum: GRB, AGN?

More typical acceleration spectrum, negative source evolution. TDEs?

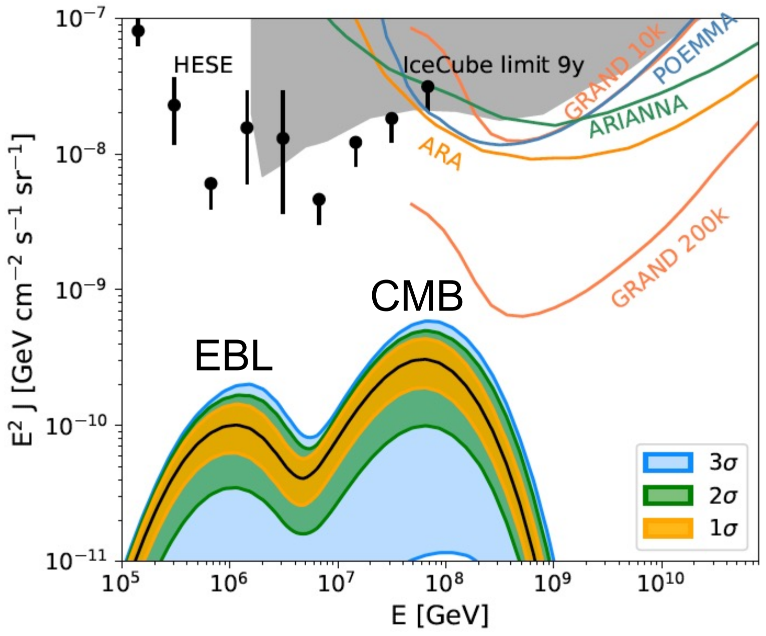
Cosmogenic neutrino flux post-dicted from UHECR fit

- Cosmogenic neutrino prediction from fit to UHECR flux
- Depends on extrapolation for z>1 (UHECRs do not care!)
- Conclusion: No cosmogenic neutrinos in baseline model!





Heinze et al, Astrophys. J. 873 (2019) 1, 88



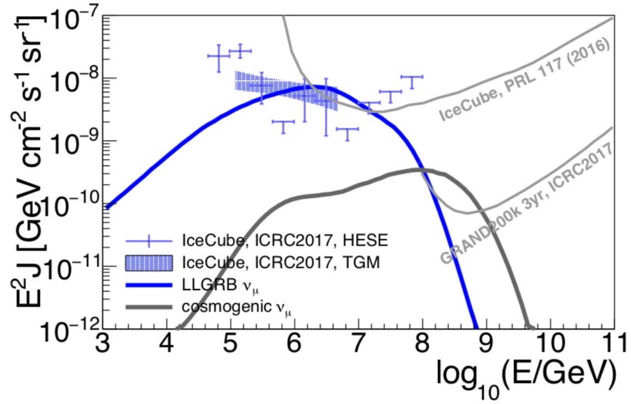
<u>However:</u>

- UHECR data allow for a sub-dominant light component
- That potentially produces cosmogenic neutrinos efficiently

van Vliet et al, Phys. Rev. D 100 (2019) 2

Real-life examples from this presentation

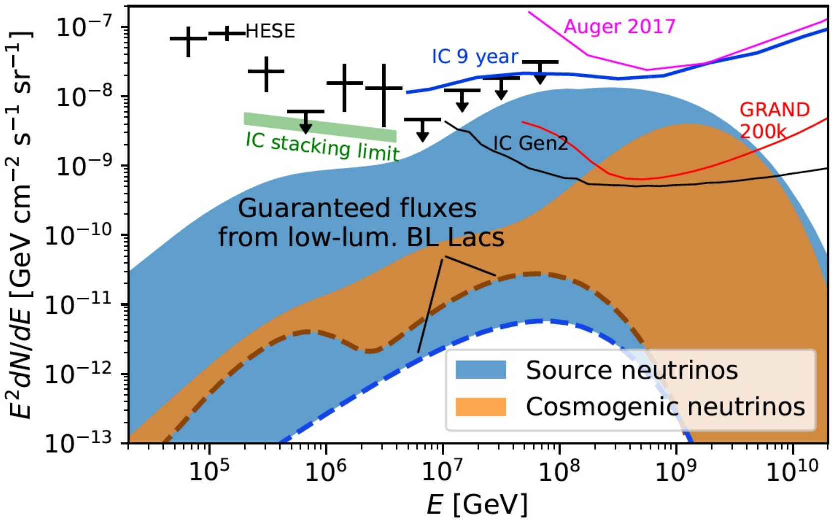
- Low-luminosity GRBs:



Boncioli, Biehl, Winter, ApJ 872 (2019) 110

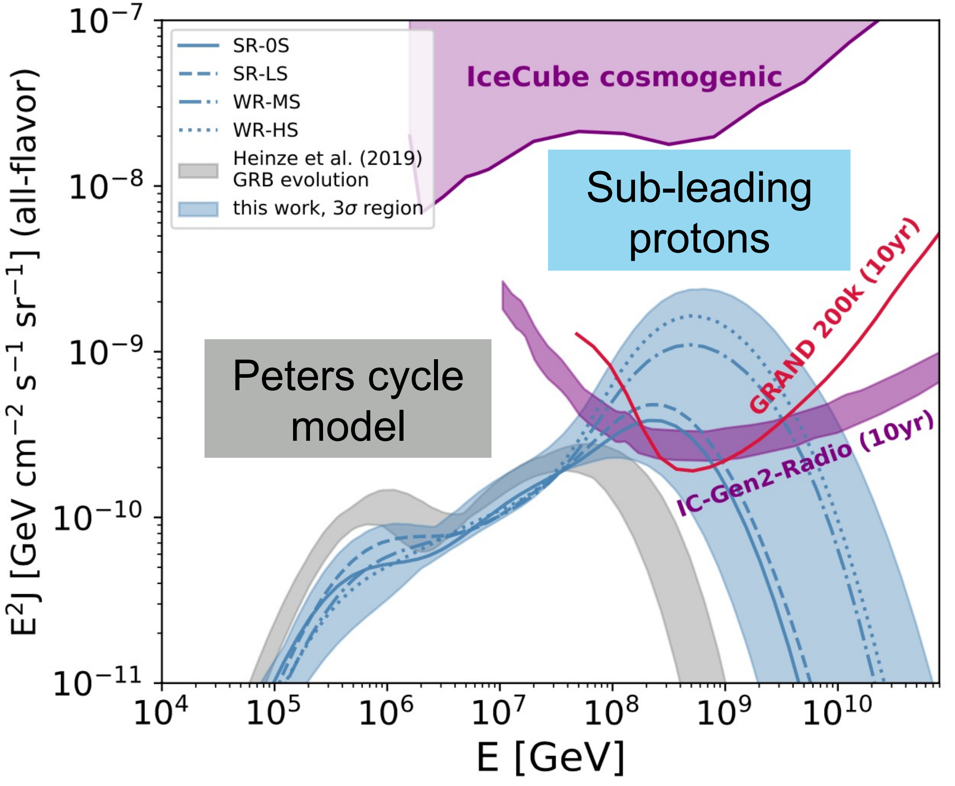
Here the UHECR spectrum and composition fit, together with the source model, determine the cosmogenic flux

- AGN jets:



Rodrigues et al PRL 126 (2021) 191101

- Standard GRBs:

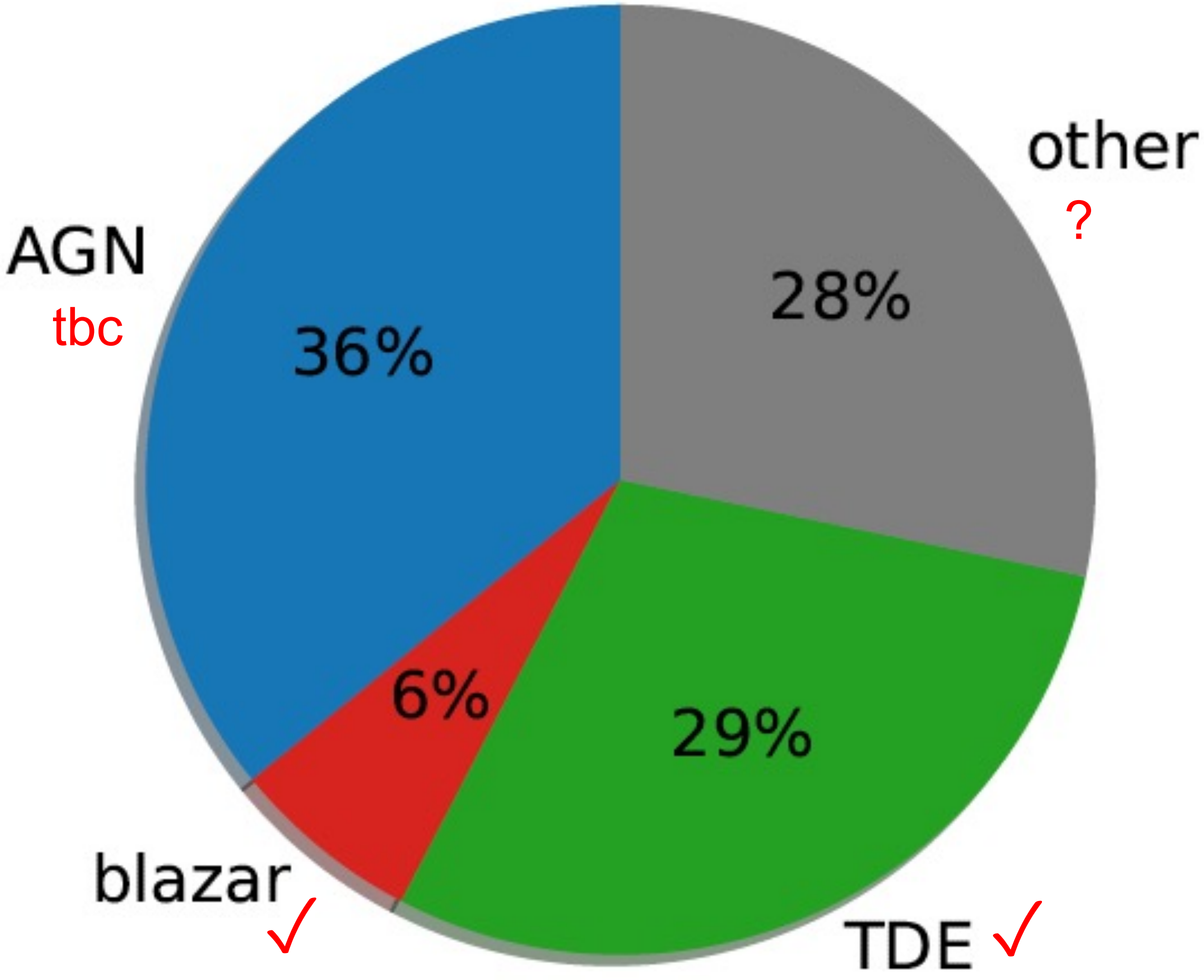


Heinze et al MNRAS 498 (2020) 4, 5990

Foreground-background issue:
Is the cosmogenic neutrino flux really dominant at the highest energies, or is it outshined by sources?

Summary

- Several source associations of neutrinos, and a diffuse flux of astrophysical neutrinos
- Future neutrino astronomy requires much better statistics
- Radio detection of neutrinos interesting to find neutrinos at the highest energies
- Origin of UHECRs yet unclear. New arguments from neutrino astronomy? →



Bartos et al, arXiv:2105.03792

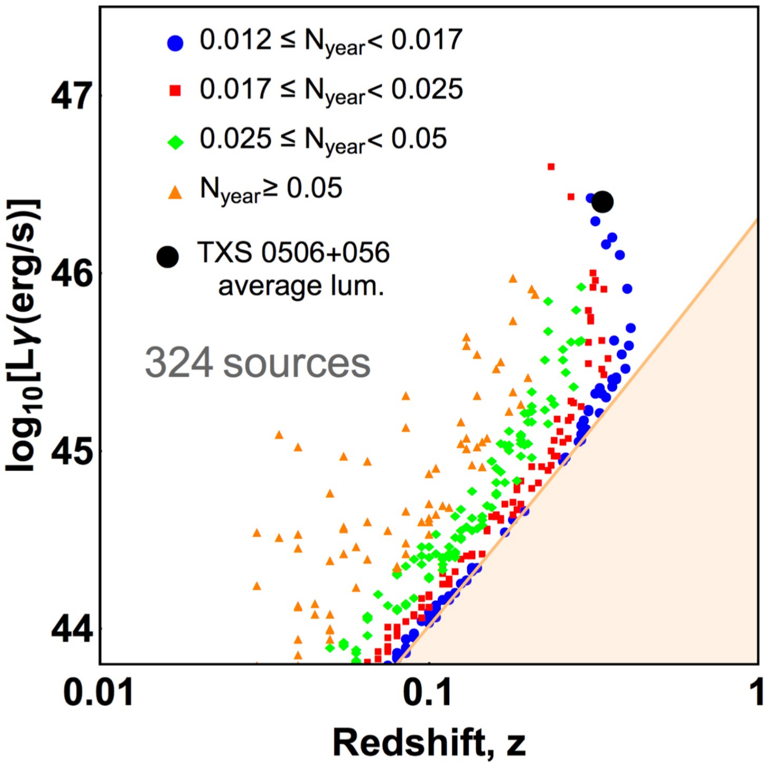
BACKUP

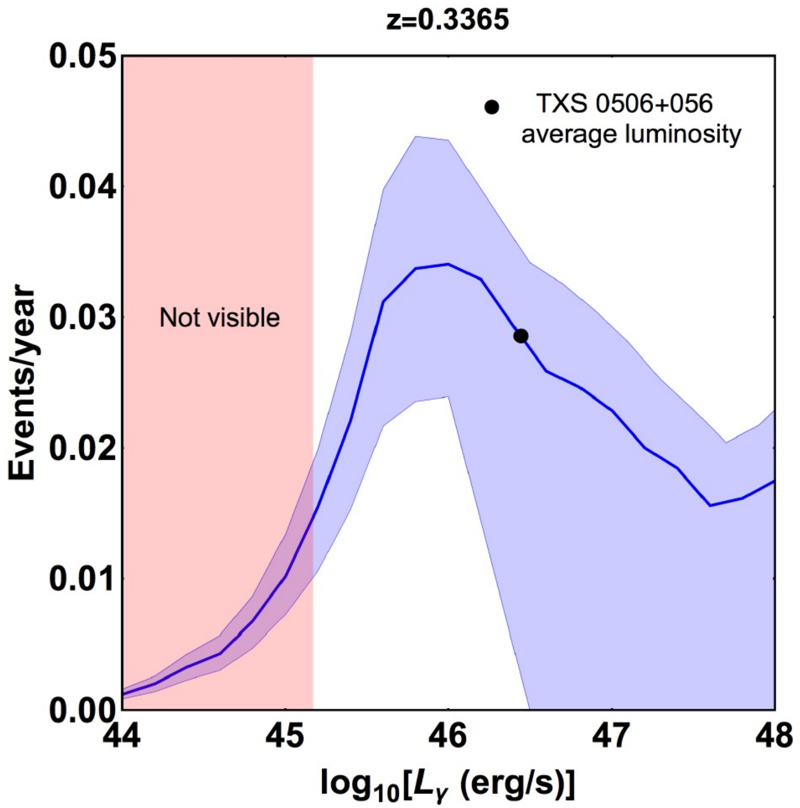
Interpretation: Consequences for TXS 0506+056

$E_{p,max}$ ~1-10 PeV

- Many similar sources, each producing << 1 ν event/year
- Consistent with expect. from Eddington bias
- About 0.3 flare associations/year expected if blazars 10% of time in flaring state (duty cycle)

- TXS 0506+056 is, in that picture, not a special source, is close to the "sweet spot" (by construction)
- Archival 2014-15 flare cannot be explained (a special event?)





Palladino, Rodrigues, Gao, WW, ApJ 871 (2019) 41

Neutrino energetics (TDEs)

... an upper model-independent limit

- Upper limit for average neutrino luminosity (4π solid angle emission, for pp similar):
  $L_\nu \sim 25\ L_{edd}\ \times\ f_{comp}\ \times\ \varepsilon_{acc}\ \times\ \tau_{p\gamma}\ \times\ 1/8\ \ll$ **$0.1\ L_{edd}$**

  - Average mass accretion rate
  - Fraction in outflow, BB, jet, ... (0.03-0.2?)
  - Accelerated fraction into non-thermal PeV (!) energy protons (<< 0.2?)
  - Optical thickness <= 1, but typically << 1
  - Per flavor

- Yields $E_\nu \sim 200$ days x $0.1\ L_{edd} \sim\ 2\ 10^{50}$ erg $(M_{SMBH}/10^6\ M_\odot)$
  $\rightarrow$ 0.2 events for $M_{SMBH} \sim 10^6\ M_\odot$ →

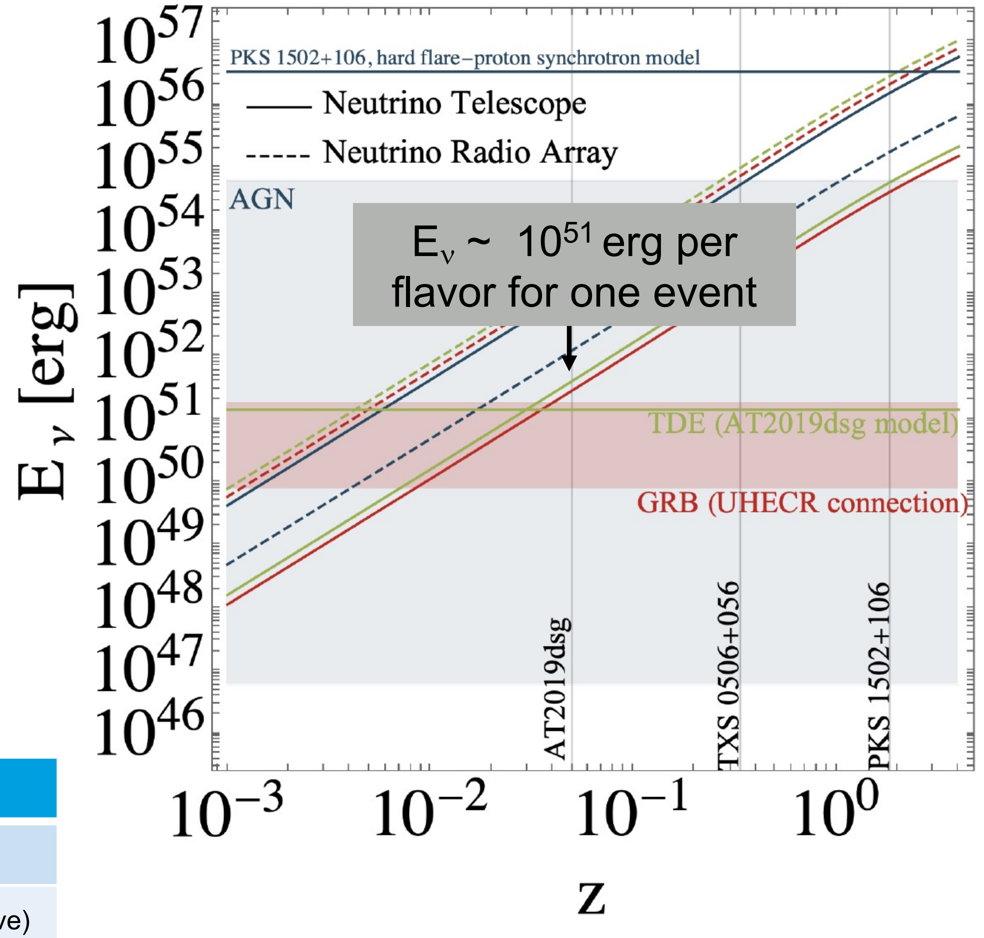
- **Conclusion:**
  either $M_{SMBH} > 10^7\ M_\odot$ and super-efficient energy conversion,
  or the outflow must be collimated with $\theta \ll 1$ such that $L_\nu \rightarrow L_\nu / \theta^2$

Estimates for SMBH mass

$M_{SMBH}/M_\odot$	Reference
$\sim 2\ 10^7$	McConnel, Ma, 2012
$3\ 10^5\ ...\ 10^7$	Wevers et al, 2019 (conservative)
1.2-1.4 10^6	Ryu, Krolik, Piran, 2020
2.2-8.6 10^6	Cannizzaro et al, 2021

- For a relativistic jet: second option with $\theta \sim 1/\Gamma$

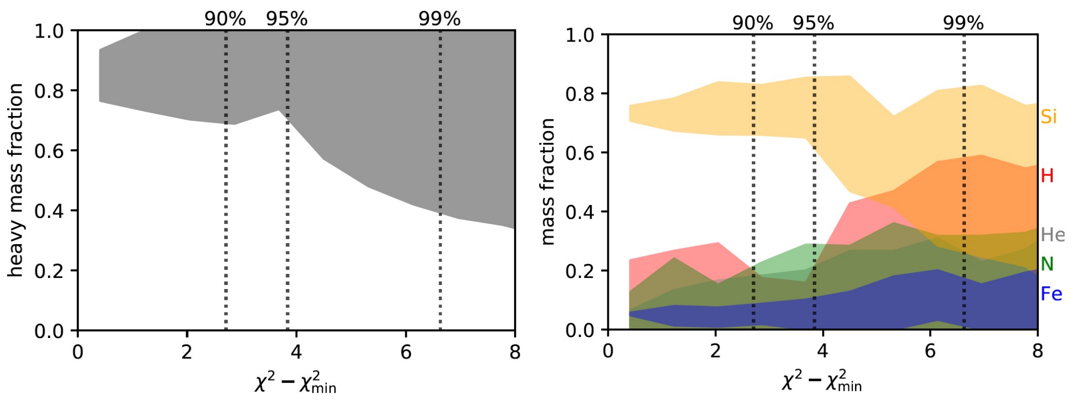
(figure for all flavors, typical spectral shapes)



Fiorillo, van Vliet, Morisi, Winter, arXiv:2103.16577

Interpretation of the results (GRB multi-collision model)

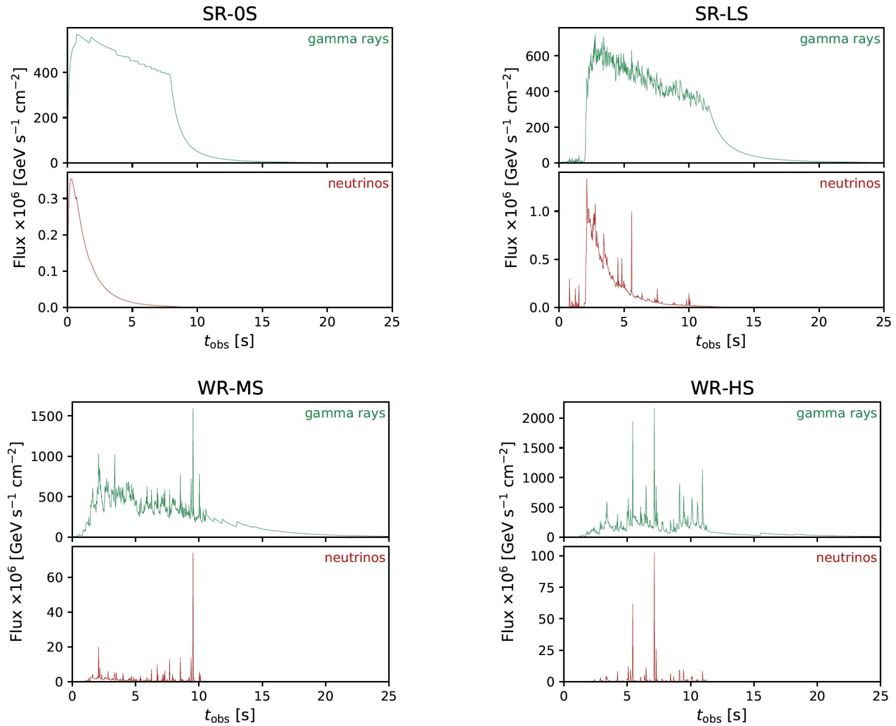
- The required injection compositon is derived: more that 70% heavy (N+Si+Fe) at the 95% CL



- Self-consistent energy budget requires kinetic energies larger than 10^{55} erg – **probably biggest challenge for UHECR paradigm**

	SR-0S	SR-LS	WR-MS	WR-HS
E_γ	$6.67{\cdot}10^{52}$ erg	$8.00{\cdot}10^{52}$ erg	$8.21{\cdot}10^{52}$ erg	$4.27{\cdot}10^{52}$ erg
E^{esc}_{UHECR} (escape)	$2.01{\cdot}10^{53}$ erg	$2.10{\cdot}10^{53}$ erg	$1.85{\cdot}10^{53}$ erg	$1.69{\cdot}10^{53}$ erg
E^{src}_{CR} (in-source)	$5.11{\cdot}10^{54}$ erg	$5.13{\cdot}10^{54}$ erg	$4.62{\cdot}10^{54}$ erg	$4.36{\cdot}10^{54}$ erg
E^{src}_{UHECR} (in-source, UHECR)	$3.70{\cdot}10^{53}$ erg	$4.46{\cdot}10^{53}$ erg	$3.97{\cdot}10^{53}$ erg	$3.57{\cdot}10^{53}$ erg
E_ν	$7.81{\cdot}10^{49}$ erg	$2.18{\cdot}10^{50}$ erg	$1.28{\cdot}10^{51}$ erg	$1.79{\cdot}10^{51}$ erg
$E_{kin,init}$ (isotropic-equivalent)	$2.90{\cdot}10^{55}$ erg	$3.03{\cdot}10^{55}$ erg	$4.50{\cdot}10^{55}$ erg	$7.81{\cdot}10^{55}$ erg

- Light curves may be used as engine discriminator



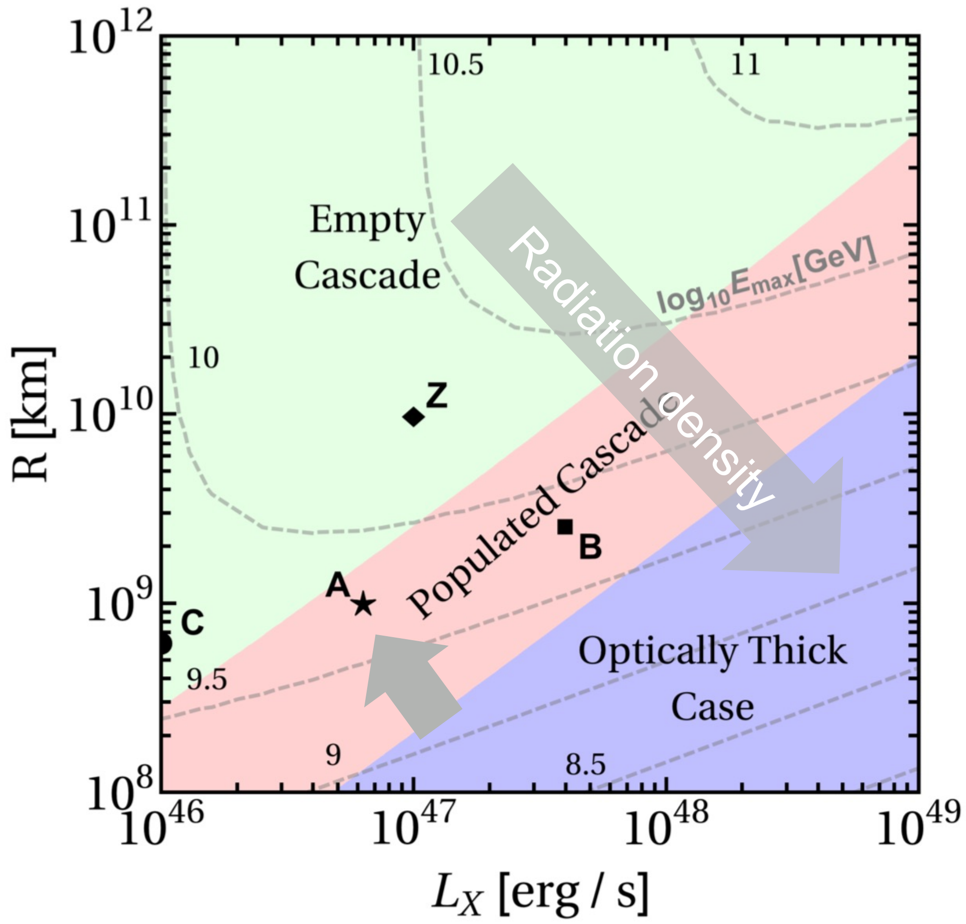
- Description of $\sigma(X_{max})$ is an instrinsic problem (because the data prefer "pure" mass groups, which are hard to obtain in multi-zone or multi-source models)

Heinze, Biehl, Fedynitch, Boncioli, Rudolph, Winter, MNRAS 498 (2020) 4, 5990, arXiv:2006.14301

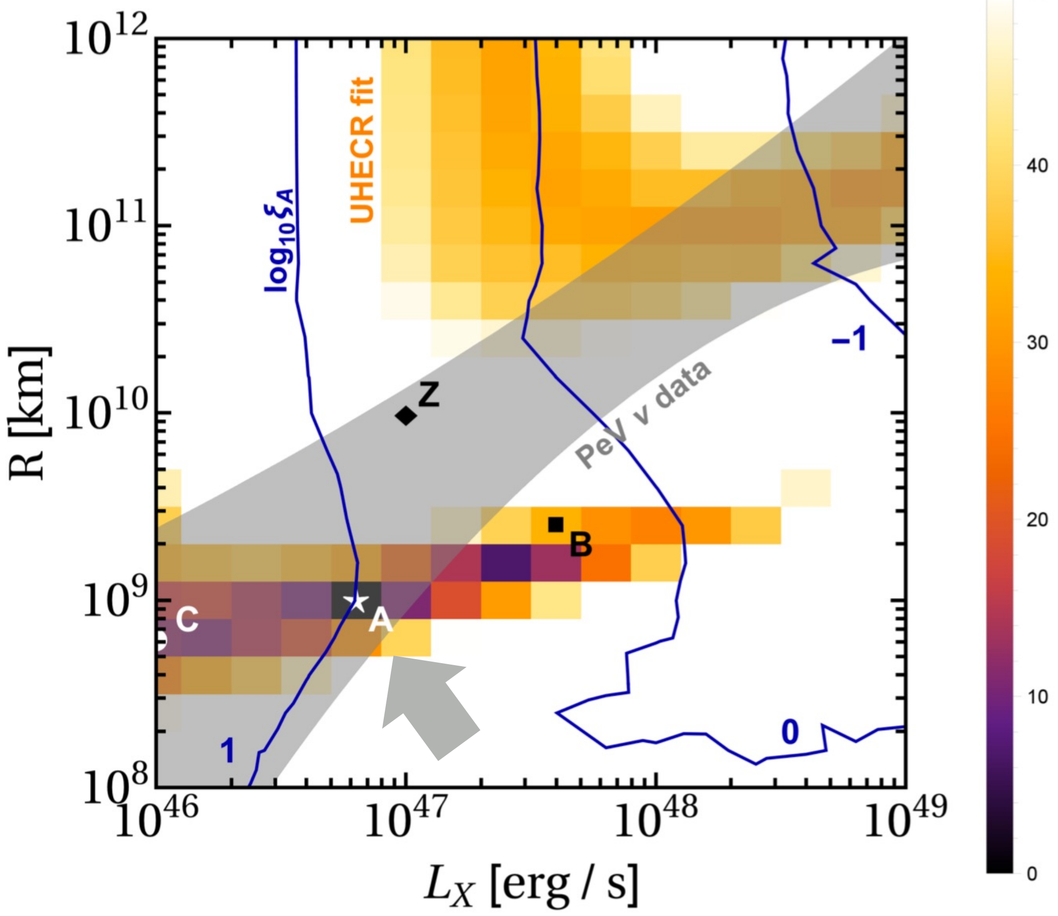
Systematic parameter space studies (LL-GRBs)

What are the model parameter expectations driven by data?

Nuclear cascade and E_{max}



UHECR and neutrino fits

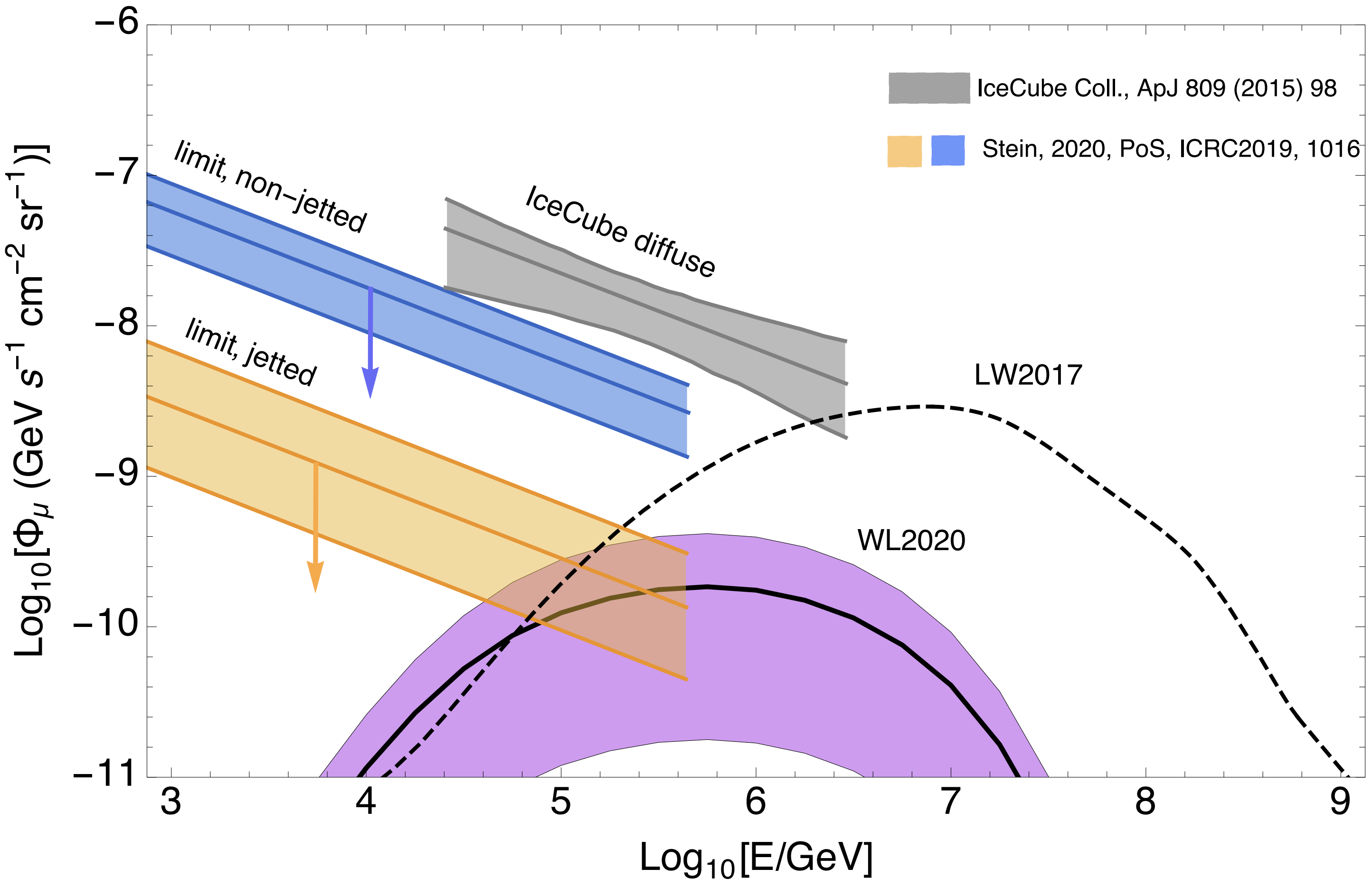


Boncioli, Biehl, Winter, arXiv:1808.07481;
Reference point "Z": Zhang et al., 2018

ξ_A: Baryonic loading ($\log_{10} L_{CR}/L_\gamma$)
(here: T_{90} = 2 10^5 s fixed; **energetics**!)

How about TDEs?

- Diffuse flux from a population of AT2019dsg-like TDE consistent with current bounds
- Expected contribution to the IceCube diffuse neutrino flux at few percent level
- The typical neutrino TDE is probably less luminous than SwJ1644+47
  (used in Lunardini, Winter, Phys. Rev. D 95 (2017) 12, 123001 as prototype)
- Could neutrino-emitting TDE also power the UHECR flux?
  Biehl, Boncioli, Lunardini, Winter, Sci. Rep. 8 (2018) 1; see also Zhang et al., 2017, Guepin et al, 2018
  Note especially recent indications for under-estimated white dwarf TDE rate by factor of 50! (was most critical factor?)
  Tanikawa, Giersz, Sedda, 2021



Winter, Lunardini, PoS ICRC2021 (2021) 997, arXiv:2107.14381

Comparison: transient UHECR and neutrino sources

HL-GRBs

- Well-studied source class
- Can describe UHECR spectrum and composition X_{max}
- Multi-collision models work for a wide range of parameter sets
- Neutrino stacking limits obeyed
- Light curves may be used to further narrow down models
- Cannot describe diffuse neutrinos
- Composition variable $\sigma(X_{max})$ requires some fine-tuning
- Energetics in internal shock scenario is a challenge; more energy in afterglows than previously thought? VHE γ–rays?

LL-GRBs

- Potentially more abundant than HL-GRBs
- Can describe UHECR spectrum and composition even across the ankle
- May at the same time power the diffuse neutrino flux
- Less established/studied source class = more speculative
- Radiation modeling subject to discussions
- Progenitor model disputed
- UHECR+neutrino energetics point require relatively long “standard” LL-GRBs, may be challenged by population studies

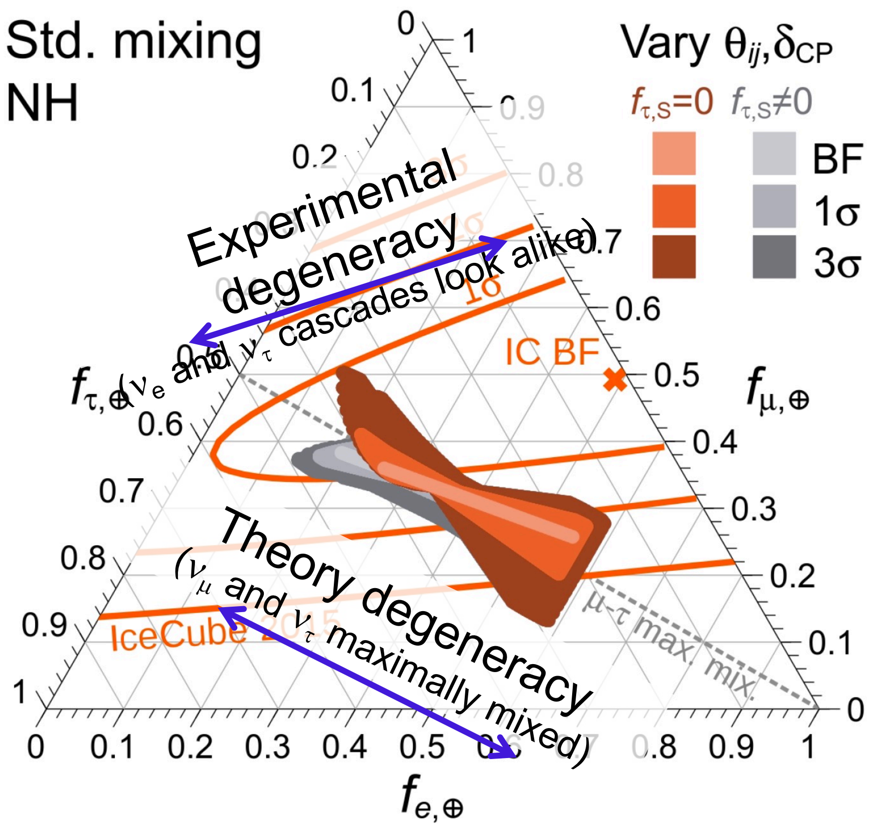
TDEs

- The only transient class from which neutrinos have been observed from → Must accelerate cosmic rays
- Have potentially negative source evolution, which helps UHECRs
- A lot of recent activity in astrophysics; many new discoveries
- Observed TDEs are very diverse
- Models have a lot of freedom
- Local rate and demographics may have to be re-evaluated
- Energetic events, such as the jetted TDE Sw J1644+57, may be rare

Flavor composition in terms of *flavor triangles*

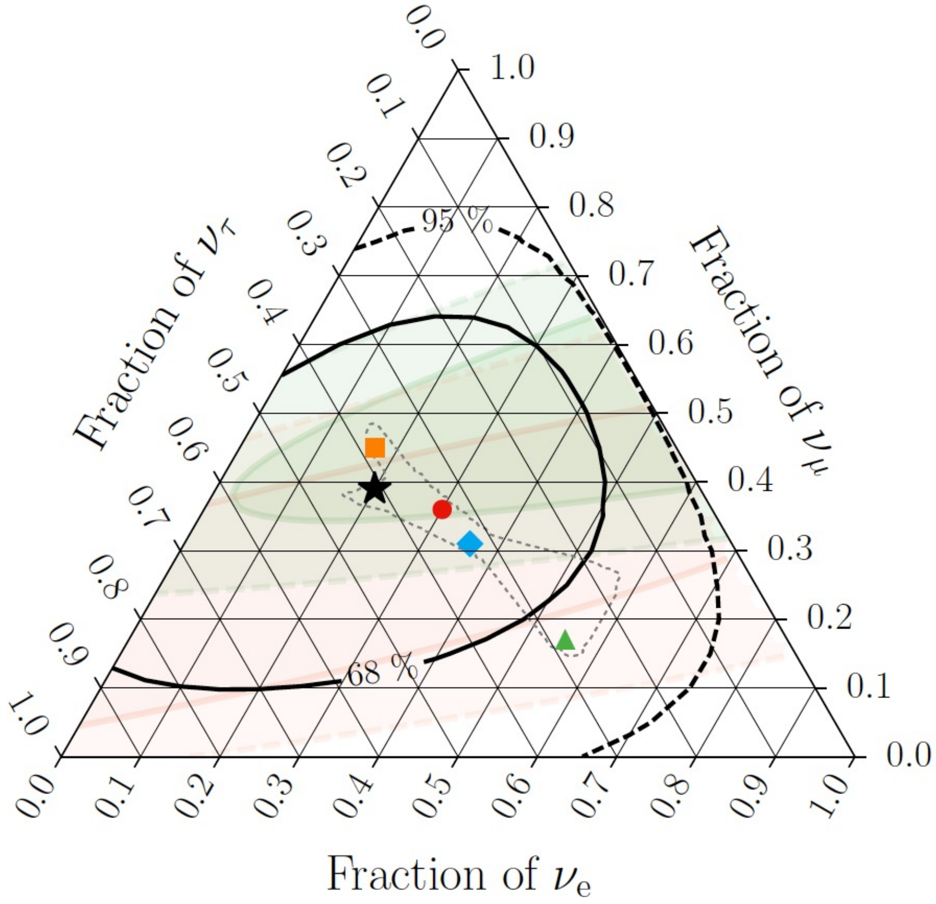
SM expectation

$$P_{\alpha\beta} = \sum_{i=1}^{3} |U_{\alpha i}|^2 |U_{\beta i}|^2$$



Bustamante, Beacom, Winter, PRL 115 (2015) 16, 161302;
Arguelles, Katori, Salvado, PRL 115 (2015) 161303

Measurement (after ν_τ detection)

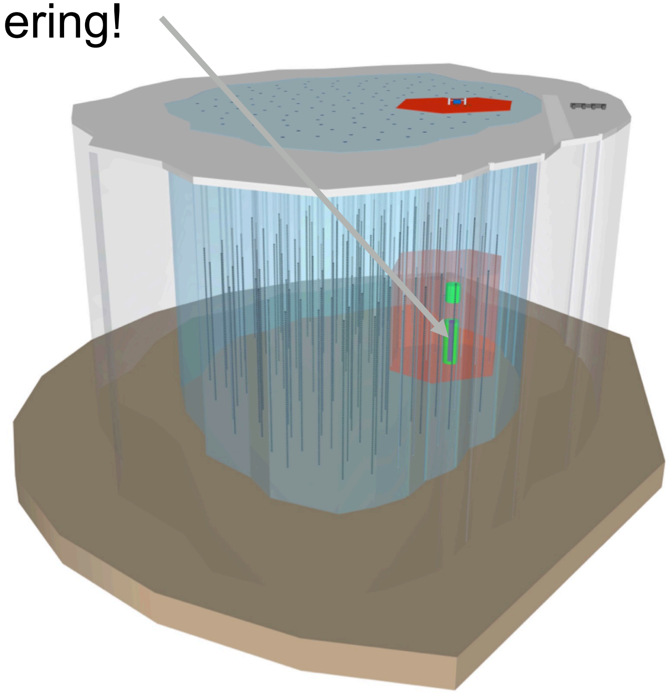


IceCube, arXiv:2011.03561

Future perspectives

IceCube-Gen2

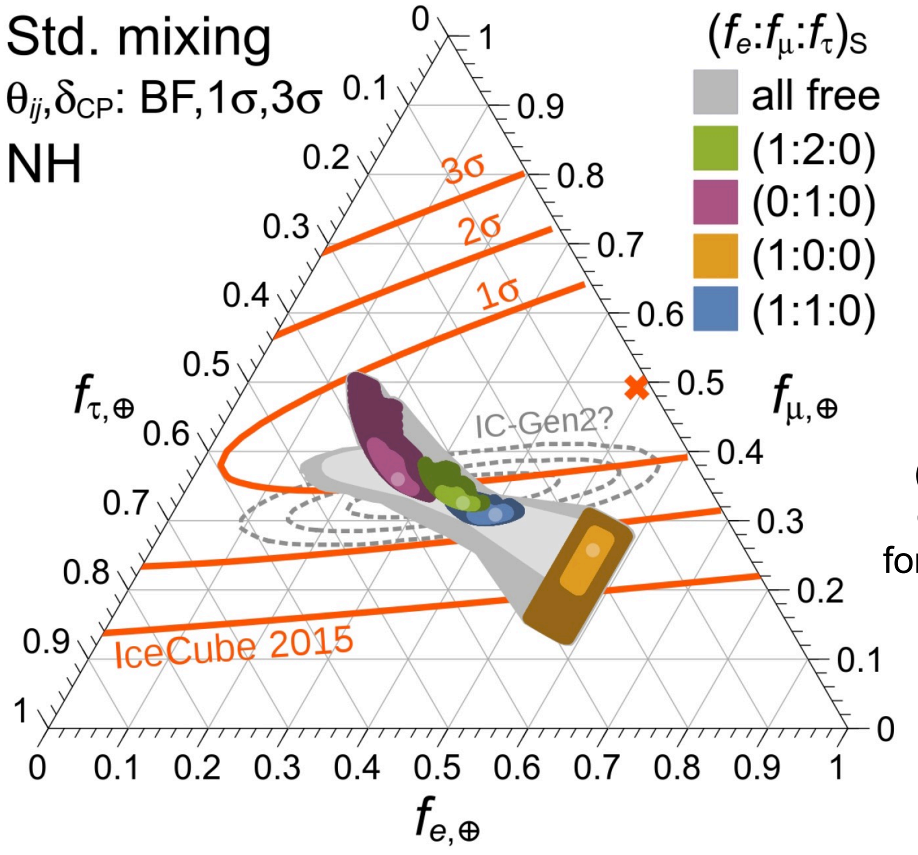
- Instrumented volume O(10) km^3
- Purpose: “deliver substantial increases in the astrophysical neutrino sample for all flavors”
- PINGU-infill for oscillation physics (about 40 strings for lower threshold in DeepCore region). Neutrino mass ordering!
- Similar ideas in sea water (KM3NeT, ARCA/ORCA)



(arXiv:1401.2046, arXiv:1412.5106)

Physics potential

- IceCube-Gen2 could exclude the current best-fit point
- Allowed regions for specific flavor compositions at source even smaller

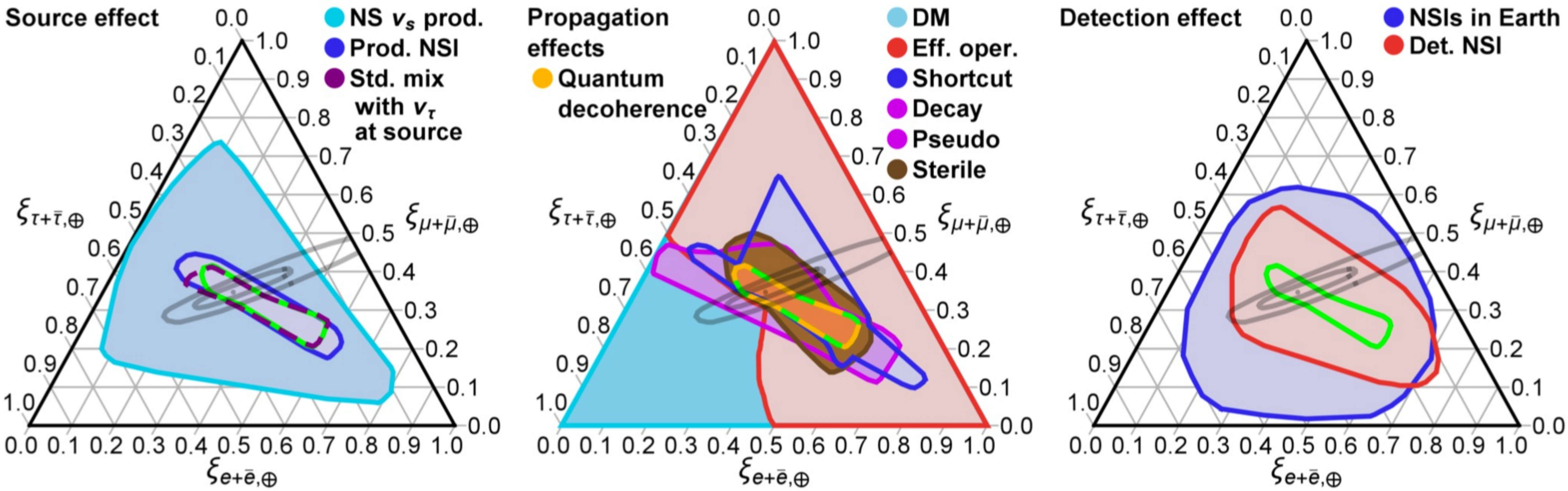


Bustamante, Beacom, Winter, PRL 115 (2015) 16, 161302

(shaded regions: current 3σ range for mixing params)

What ... if there is physics beyond the Standard Model?

Parameter space coverage including oscillation parameters and model parameters



From: Rasmussen et al, Phys. Rev. D96 (2017) 8, 083018;
long list of references therein!

Interesting potential to discover physics BSM