

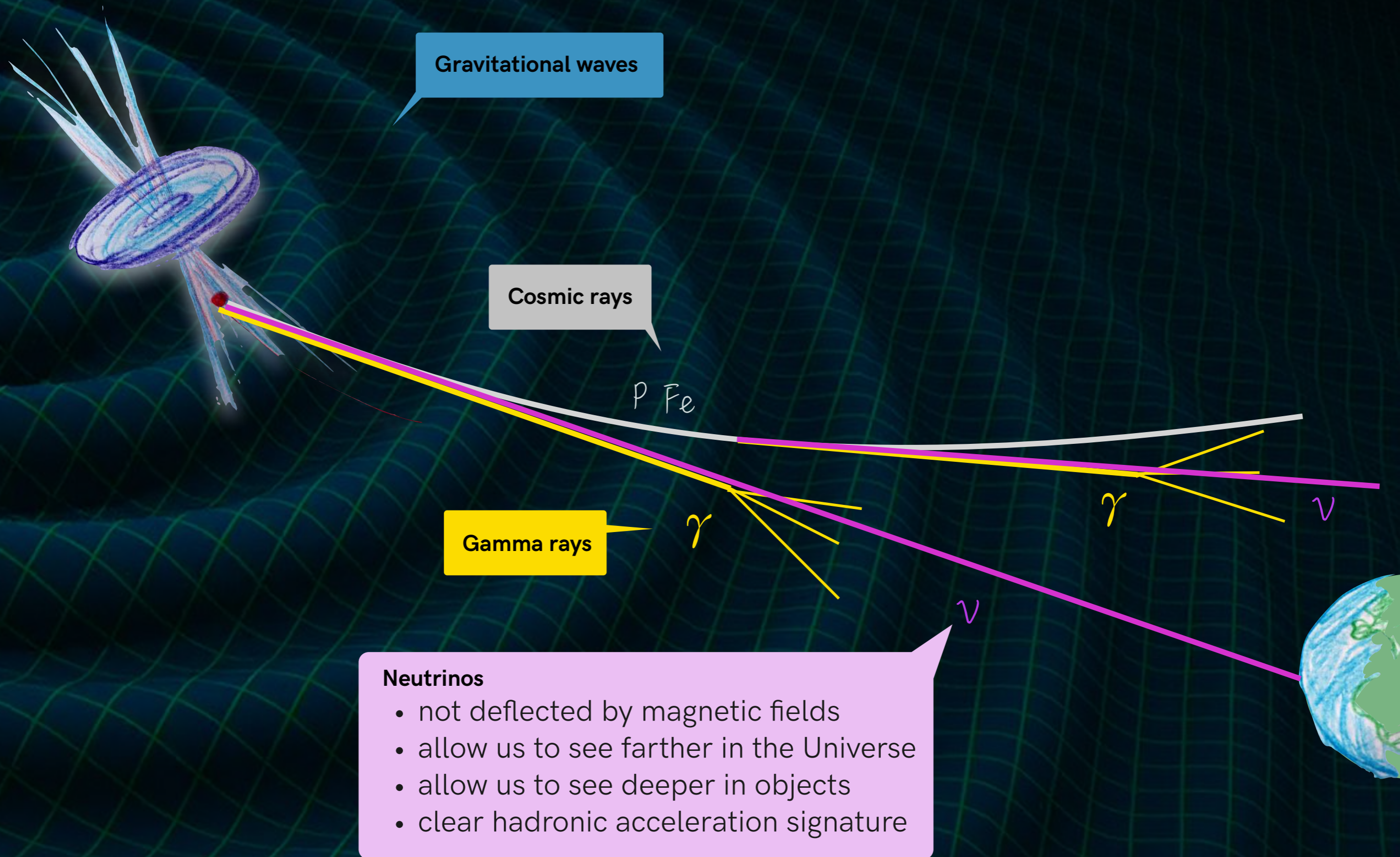


# EeV Neutrino Astronomy

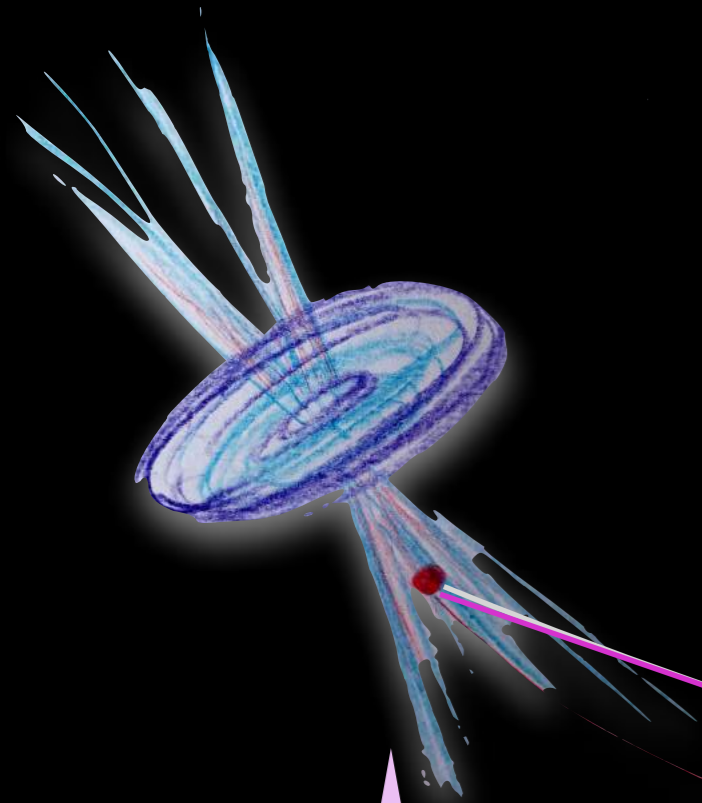
Kumiko Kotera - *Institut d'Astrophysique de Paris*

Cosmic Rays and Neutrinos in the Multi-Messenger Era - 07/12/2020

# UHECRs and friends



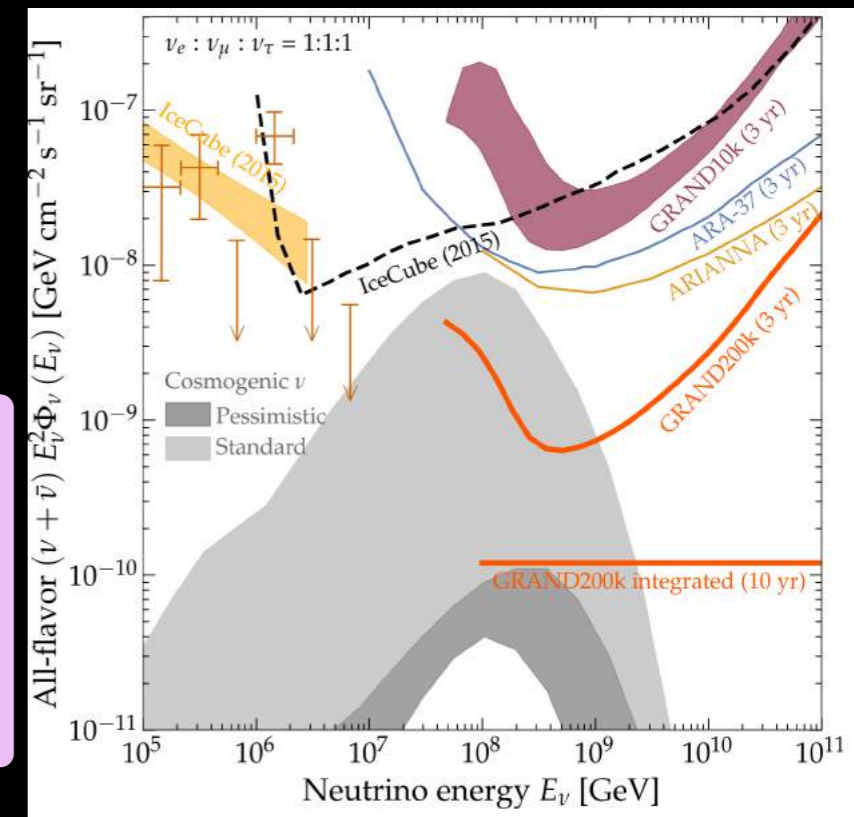
# Cosmogenic and astrophysical neutrinos



## Cosmogenic neutrinos

**Cosmic backgrounds**  
interactions on CMB, UV/  
opt/IR photons

*cosmogenic neutrino and  
gamma-ray production*

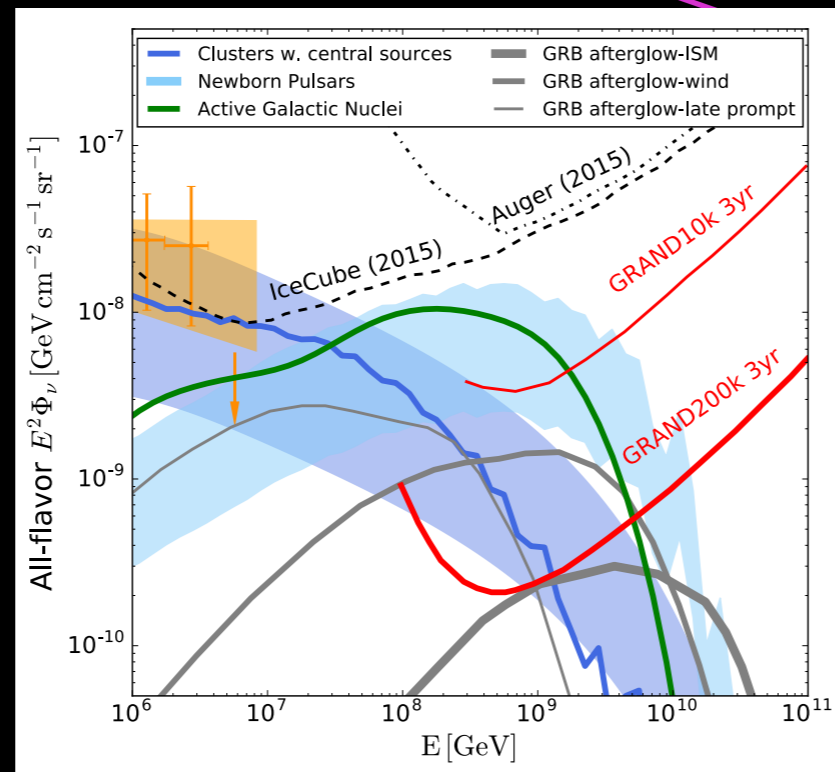


## Backgrounds

- radiative? baryonic?
- evolution, density?
- magnetic field: deflections?

*associated neutrino and  
gamma-ray production*

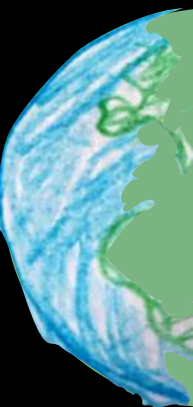
## Astrophysical neutrinos



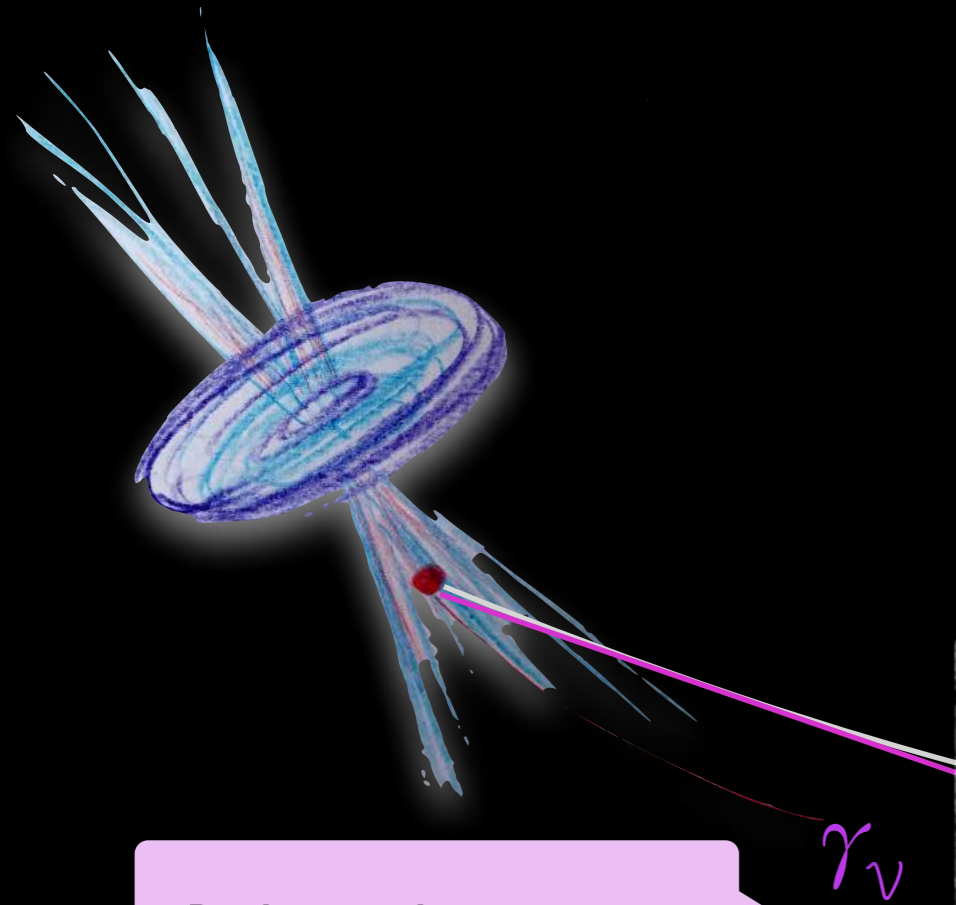
$p \bar{p}$

$\gamma \nu$

$\gamma \nu$



# Current multi-messenger data: useful to understand UHECRs?



## Backgrounds

- radiative? baryonic?
- evolution, density?
- magnetic field: deflections?

*associated neutrino and gamma-ray production*

## Cosmic backgrounds

interactions on CMB, UV/opt/IR photons

*cosmogenic neutrino and gamma-ray production*

Secondaries take up 5-10% of parent cosmic-ray energy

$$E_\nu \sim 5\% E_{\text{CR}}$$

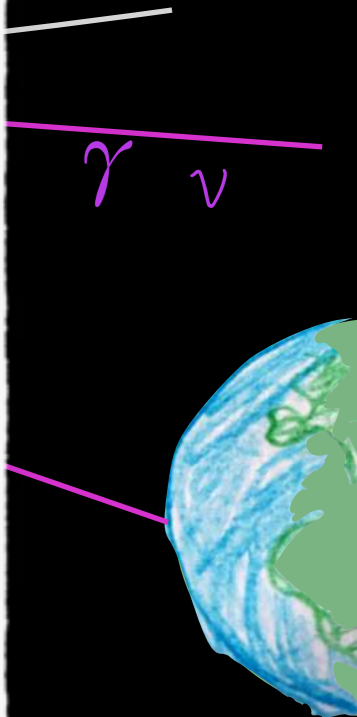
$$E_\gamma \sim 10\% E_{\text{CR}}$$

$$E_{\text{CR}} > 10^{18} \text{ eV}$$

$$E_\nu > 10^{16} \text{ eV}$$

**IceCube neutrinos do not directly probe UHECRs**

Actually, none of the current multi-messenger data  
(except UHECR data) can directly probe UHECRs  
... but they help :-)

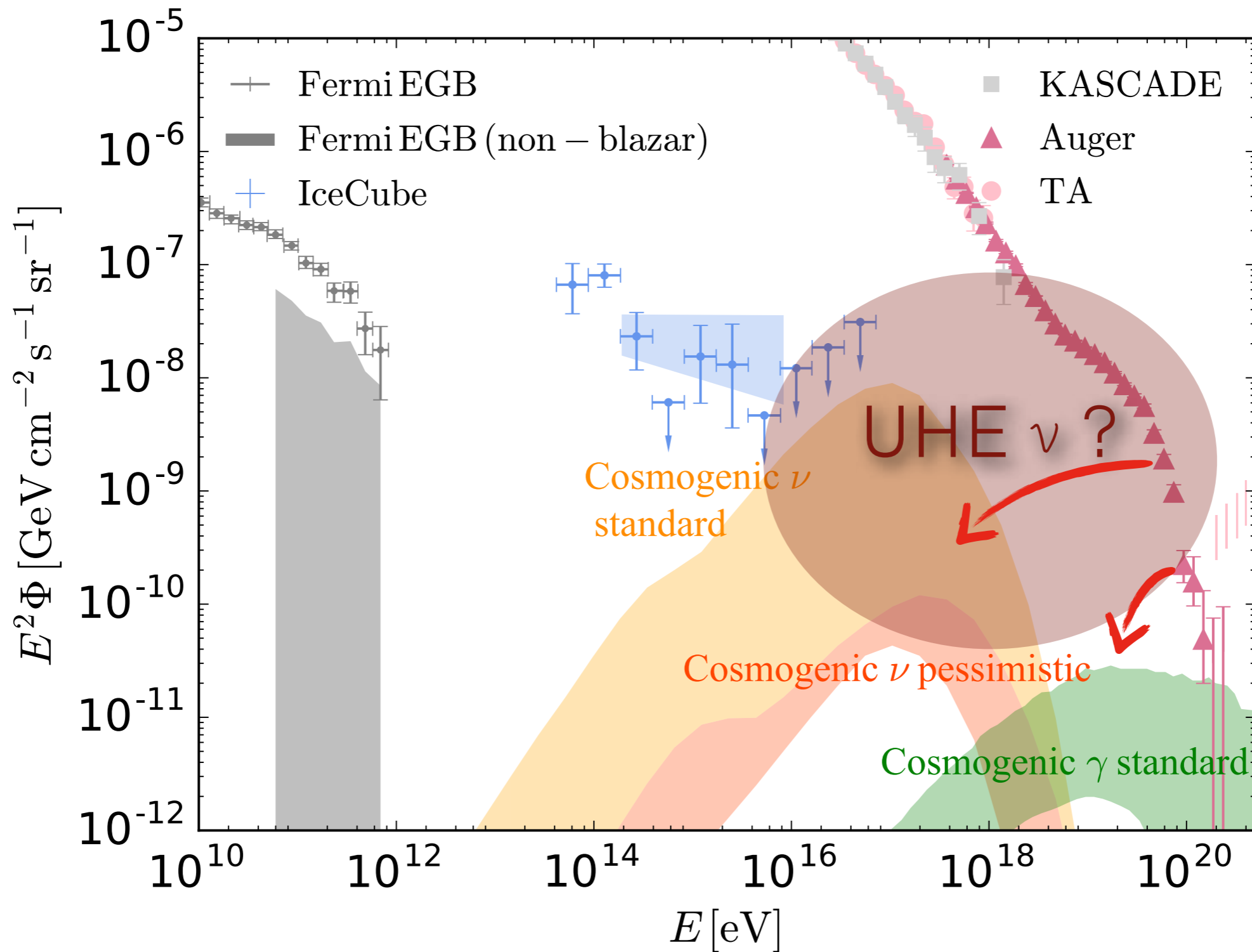


# ✳ UHE neutrinos: a challenging no-man's land

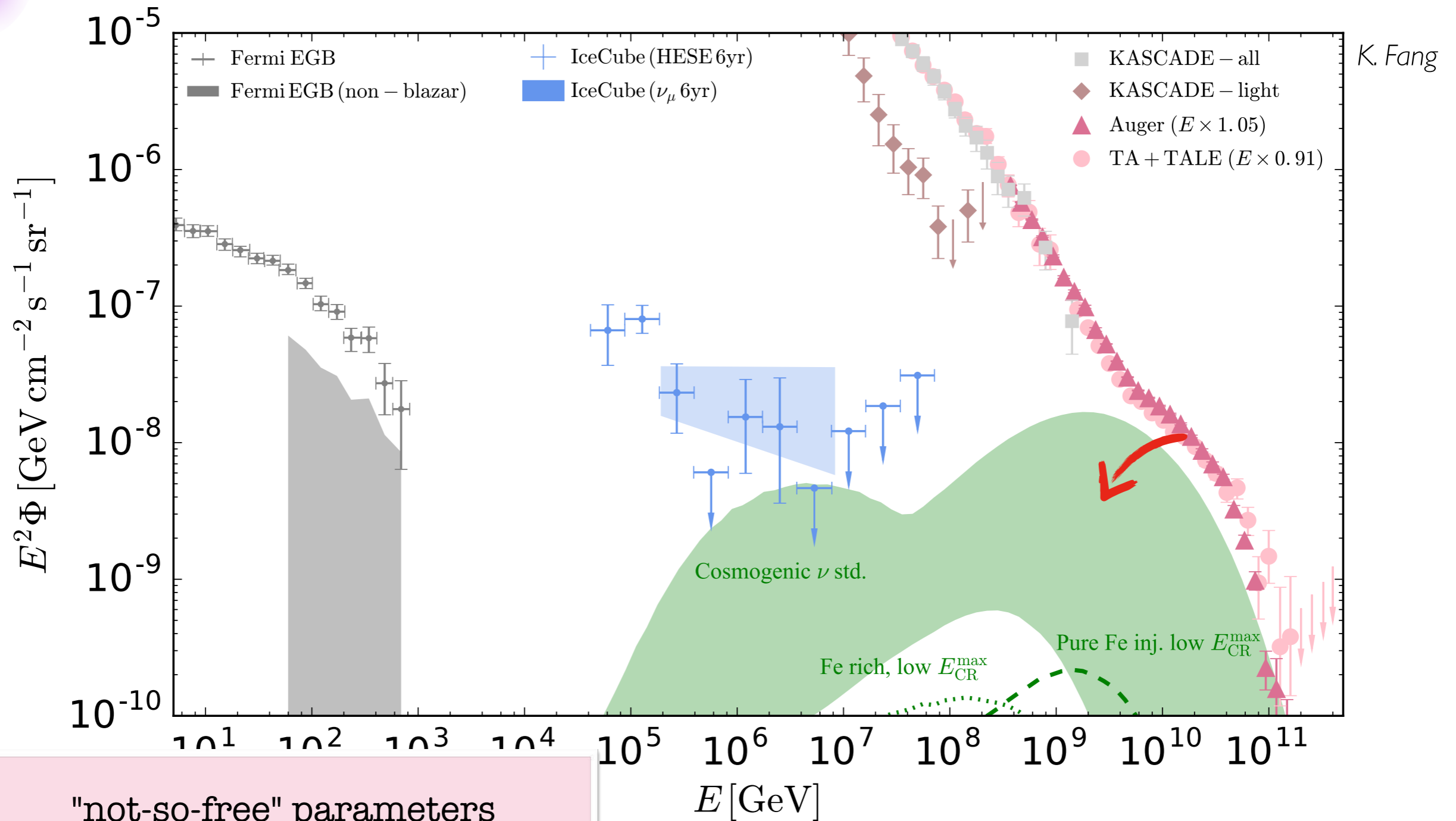
*Alves Batista, de Almeida, Lago, KK, 2018*

*GRAND Science & Design, 2018*

*KK, Allard, Olinto 2010*



# The guaranteed cosmogenic neutrinos



## "not-so-free" parameters

- $A$  flux normalisation
- $\gamma$  injection spectral index
- $R_{\text{max}}$  (max. rigidity  $\sim$  max. proton energy)
- composition
- source evolution history

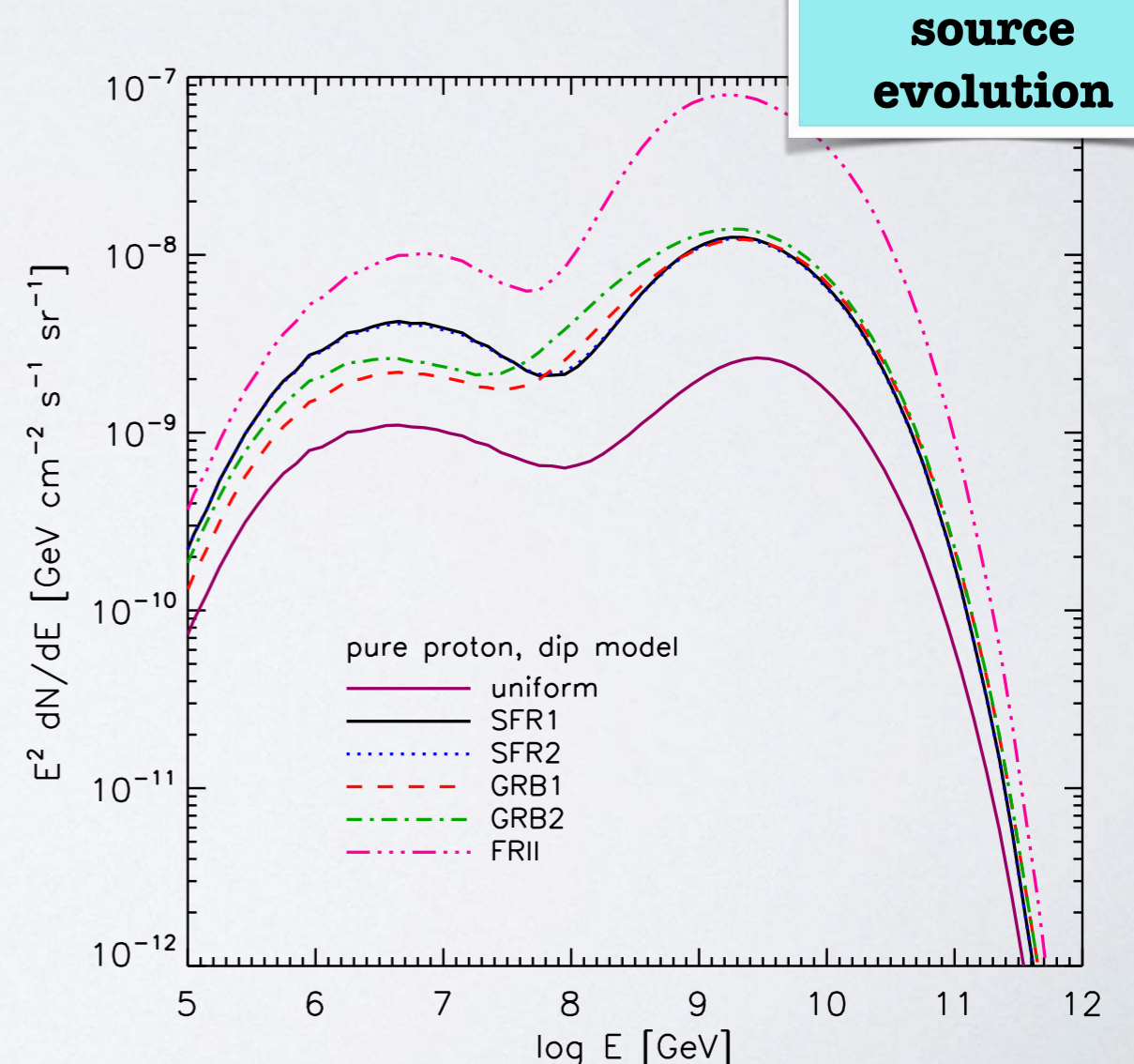
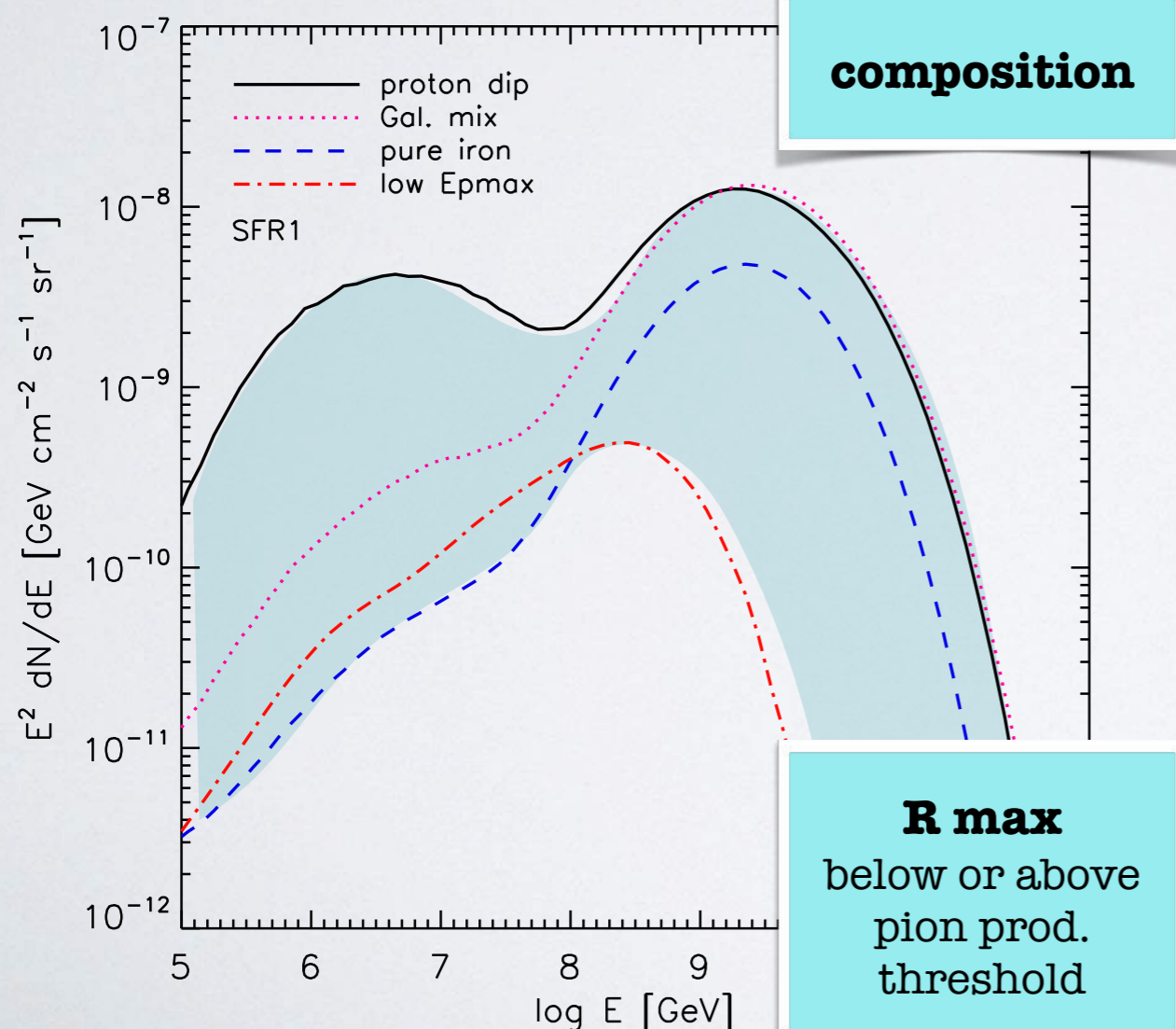
cosmogenic neutrinos guaranteed  
if sources of UHECRs  
@cosmological distances

## "not-so-free" parameters

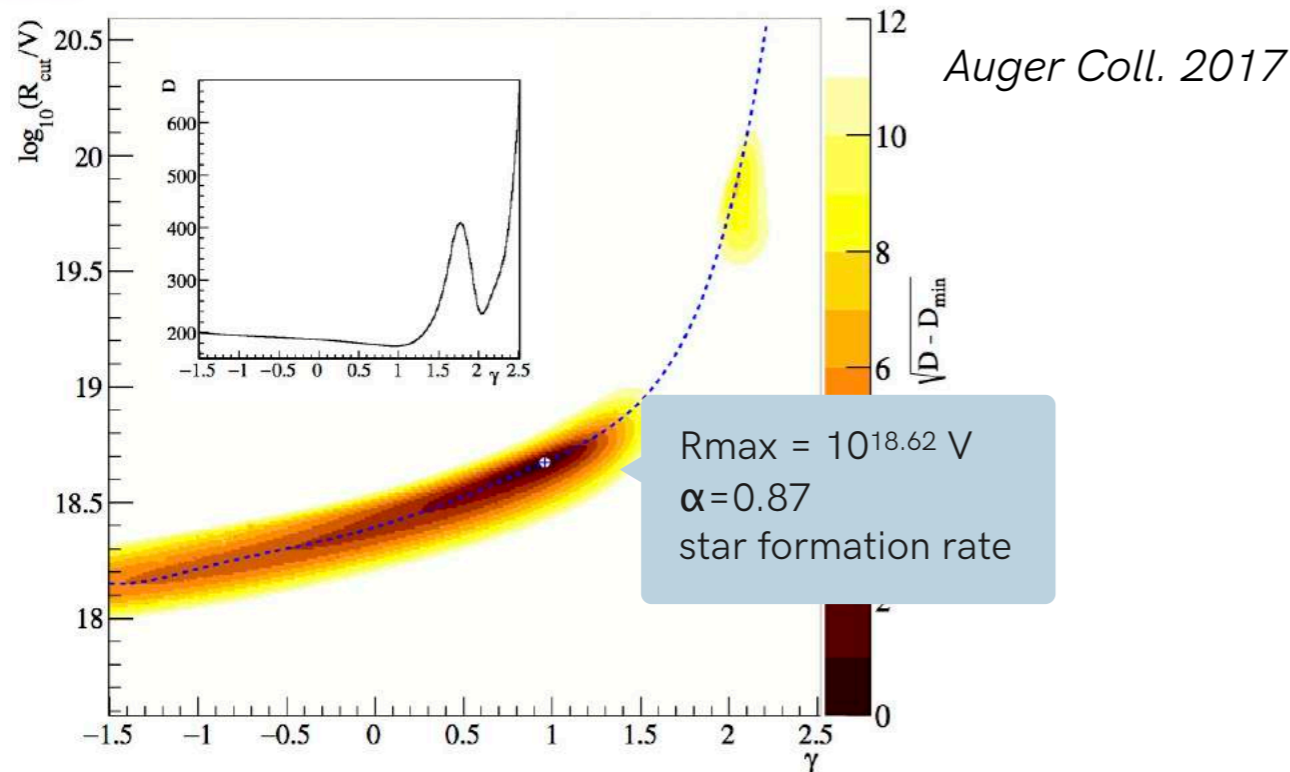
- $A$  flux normalisation
- $\gamma$  injection spectral index
- $R_{\max}$  (max. rigidity  $\sim$  max. proton energy)
- composition
- source evolution history

► depend strongly on observations of UHECRs

► less dependent but affects injection spectrum



# Information from UHECR spectra and composition



## UHECR parameters

- A flux normalisation
- $\alpha$  injection spectral index in  $E^{-\alpha}$
- $R_{\max}$  (max. rigidity  $\sim$  max. proton energy)
- composition
- source evolution e.g., SFR/AGN or in  $(1+z)^m$

Alves Batista, de Almeida, Lago, KK, 2018

- if emissivity evolution free parameter  $\rightarrow$  best fit  $m = -1.5$
- Negative source evolution:
  - e.g., tidal disruption events
  - cosmic variance local dominant of sources
- very hard spectral indices difficult to reconcile with most particle acceleration models.  $\alpha > \sim 1$  favored in theory.

phenomenologically  
reasonable models with  
good deviances

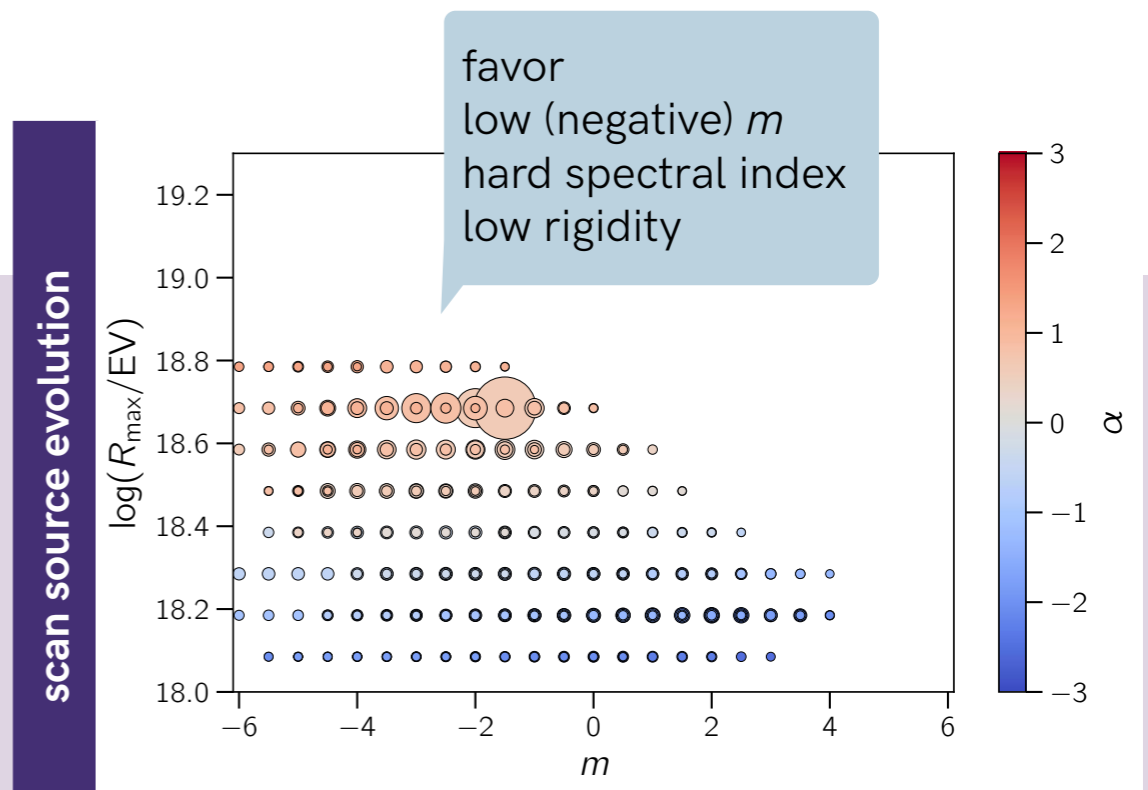
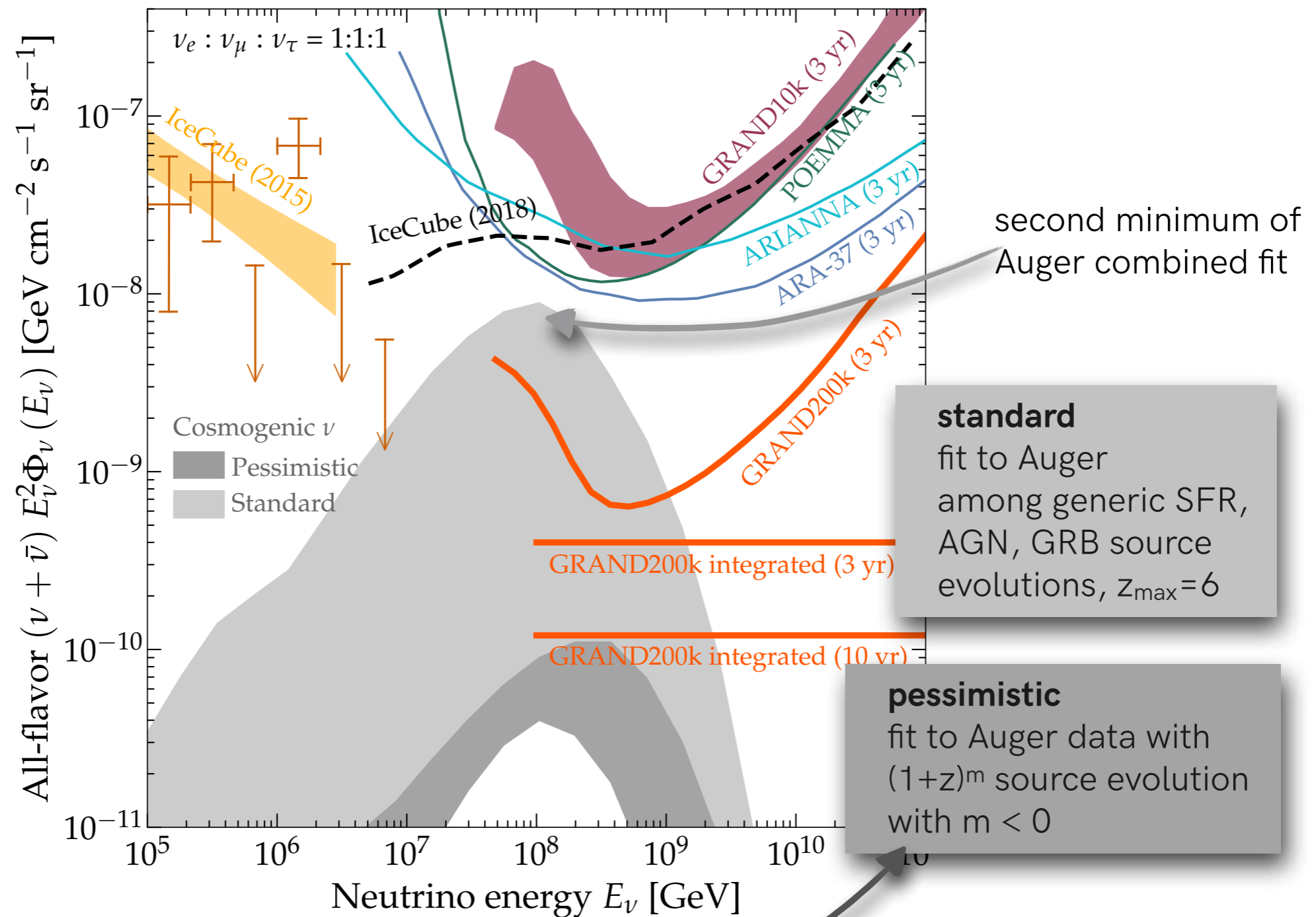


Table 1. Best-fit parameters for specific spectral indices.

$m$	$\alpha$	$\log(R_{\max}/V)$	$f_p$	$f_{\text{He}}$	$f_N$	$f_{\text{Si}}$	$f_{\text{Fe}}$	D
-1.5	+1.00	18.7	0.0003	0.0002	0.8867	0.1128	0.0000	1.46
SFR	+0.80	18.6	0.0764	0.1802	0.6652	0.0781	0.0001	1.63
AGN	+0.80	18.6	0.1687	0.1488	0.6116	0.0709	0.0000	1.59
GRB	+0.80	18.6	0.1362	0.1842	0.6059	0.0738	0.0000	1.60

# Learning from secondary neutrinos?

Alves Batista, de Almeida, Lago, KK, 2018  
 GRAND Science & Design, 2018  
 KK, Allard, Olinto 2010  
 Van Vliet et al. arXiv:1707.04511



**most pessimistic!**

adding IGMF  $\rightarrow$  harder  $\alpha \rightarrow$  increases neutrino flux  
 alleviating simplifying assumption  $\rightarrow$  increases neutrino flux

# Computing astrophysical neutrino fluxes

## mechanisms:

shock acceleration  
magnetic reconnection...

## at various locations:

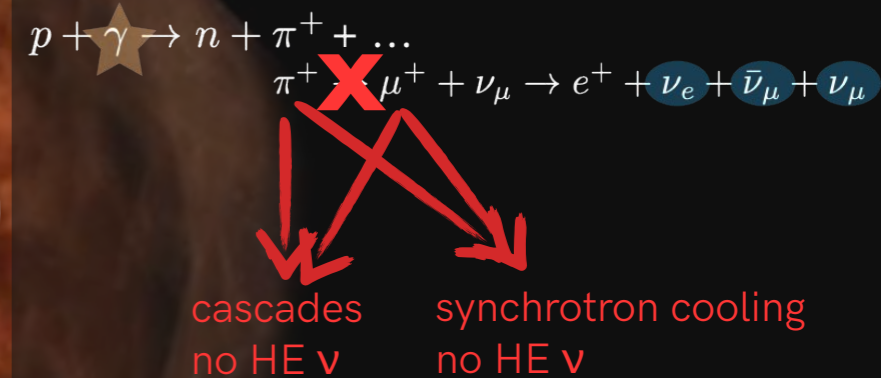
inner/external/side jet  
wind  
accretion disk...

—> max. acceleration energy  
spectrum

## Cosmic-ray acceleration

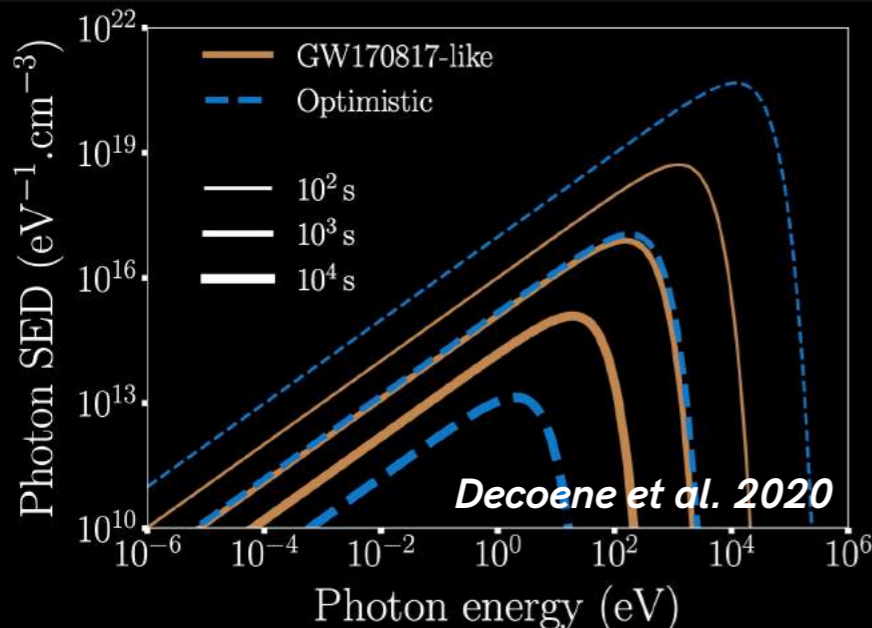
ejecta

## Cosmic-ray interactions + cooling Neutrino production



## Radiative + hadronic backgrounds

density, spectra, time evolution  
in acceleration region and beyond



## Ex: red kilonova ejecta

### Thermodynamical equilibrium

Metzger et al. 2011

$$\frac{d\mathcal{E}}{dt} = -\frac{\mathcal{E}}{R} \frac{dR}{dt} - \frac{\mathcal{E}}{t_{\text{esc}}} + \dot{Q}_r + \dot{Q}_{\text{fb}}$$

energy evolution      mechanical losses      radiative losses

$$t_{\text{esc}} \approx \left( \frac{3M\kappa}{4\pi R^2} + 1 \right) \frac{R}{c}$$

opacity (lanthanides)

### Fall-back

$$\dot{Q}_{\text{fb}} = \epsilon_{\text{fb}} \dot{M}_{\text{fb}} c^2$$

mass accretion rate

### Nuclear reaction

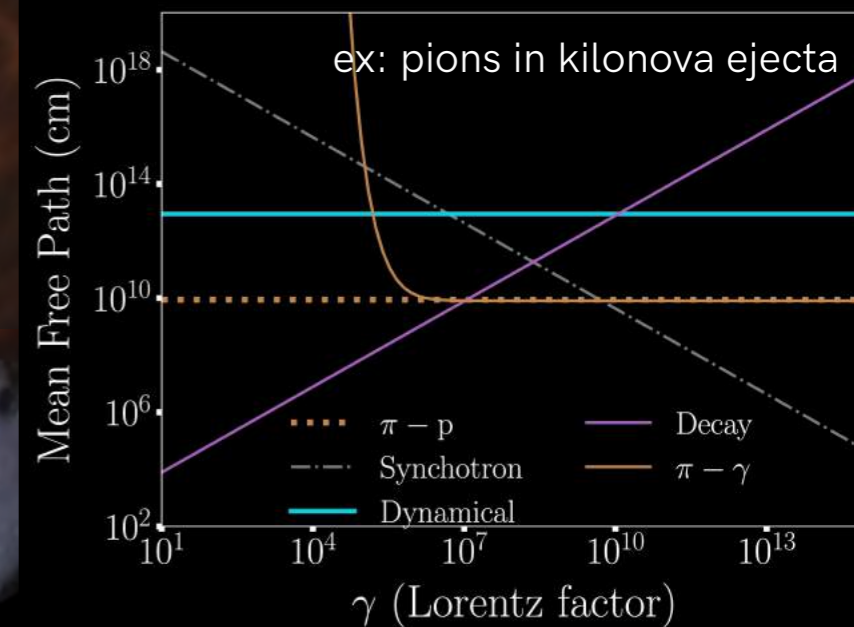
Barnes et al. 2016

$$\dot{Q}_r = M X_r \dot{\epsilon}_r(t)$$

M. R. Drout et al, 2017

nuclear mass energy  
lanthanides mass fraction

V. Decoene PhD



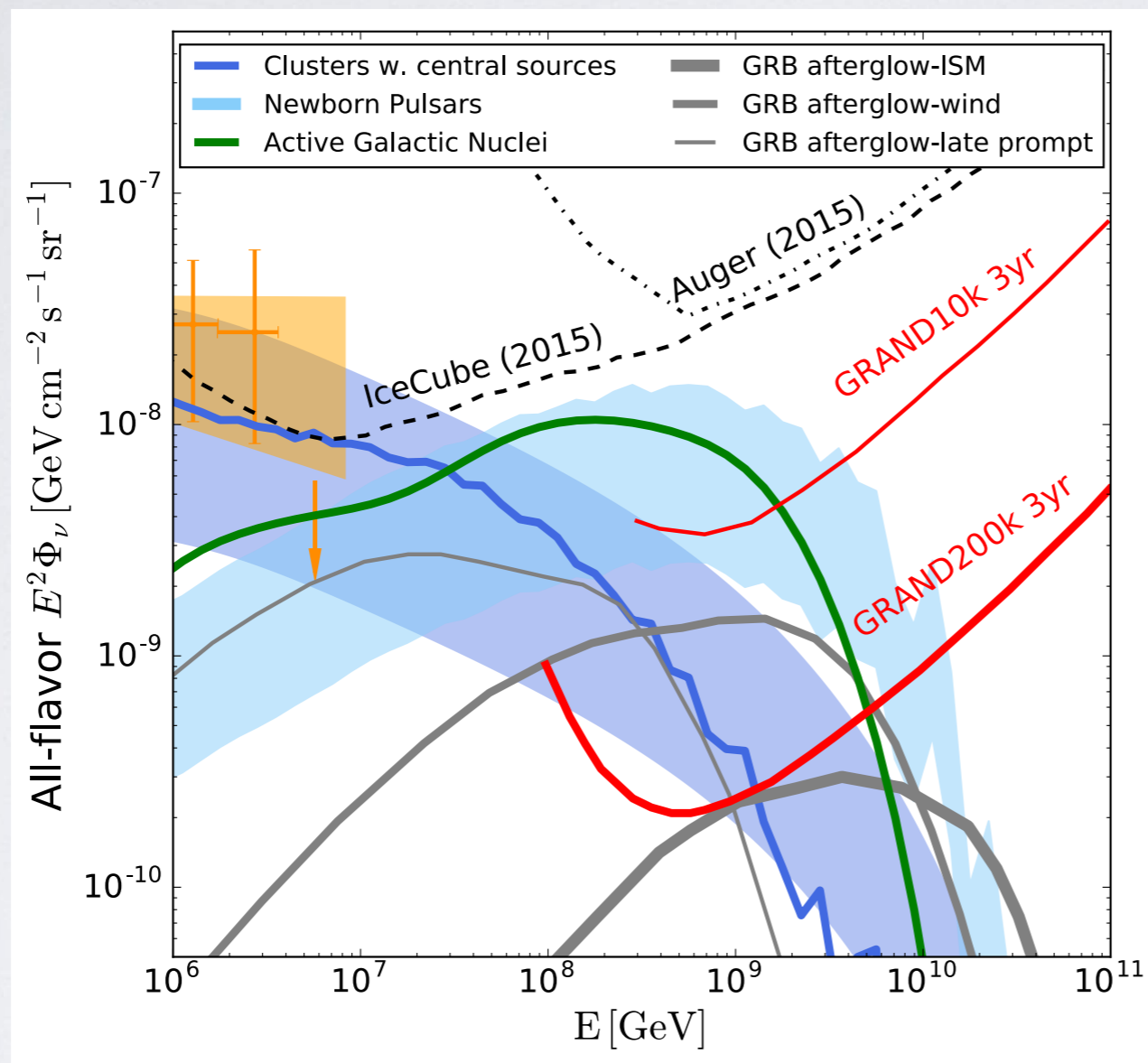
Decoene et al. 2020

# Astrophysical UHE neutrinos: produced at the source

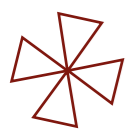
GRAND Science & Design, 2018

## Diffuse flux

integrated over the whole population



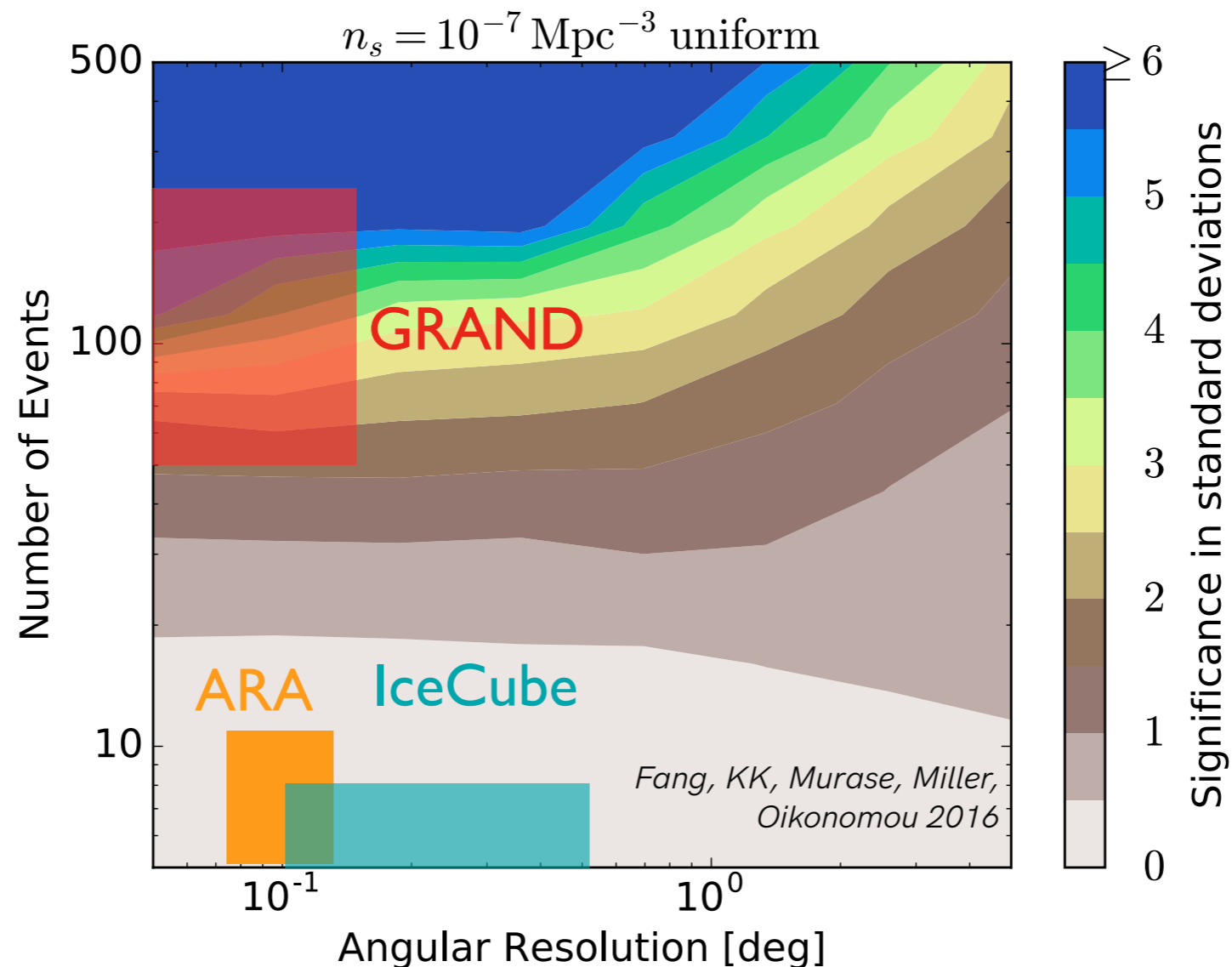
unique shapes for  
various sources  
(because of interaction  
backgrounds)



# Can we hope to detect very high-energy neutrino sources?

Neutrinos don't have a horizon: won't we be polluted by background neutrinos?

*Fang, KK, Miller, Murase, Oikonomou JCAP 2016*



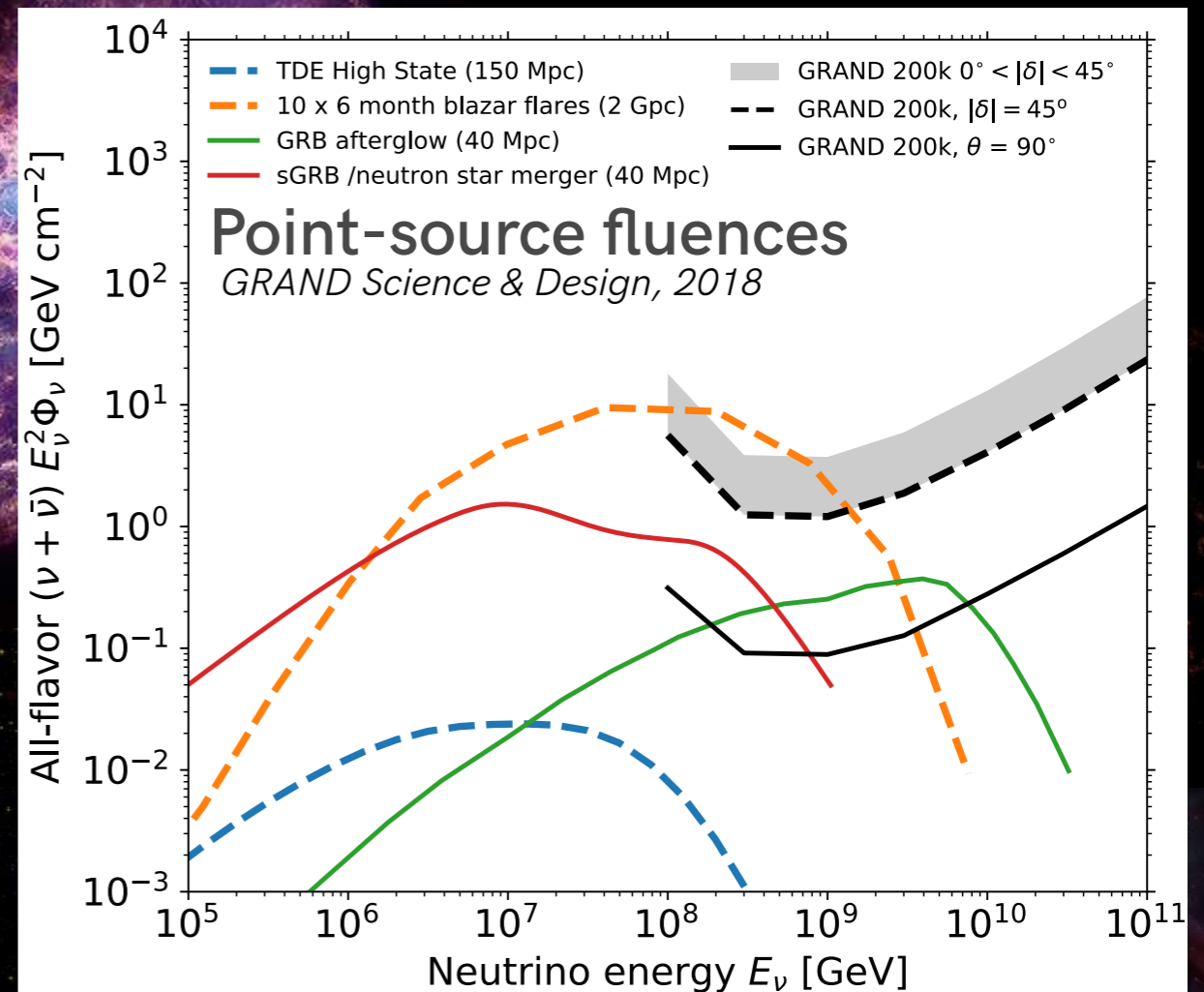
boxes for experiments assuming neutrino flux:  $10^{-8} \text{ GeV cm}^{-2} \text{ s}^{-1}$

**YES if**

- ▶ good angular resolution ( $<$  fraction of degree)
- ▶ number of detected events  $> 100$ s

Another possibility even with lower statistics: **Going for transients!**

e.g., TXS 0506+56  
in coincidence with PeV neutrino

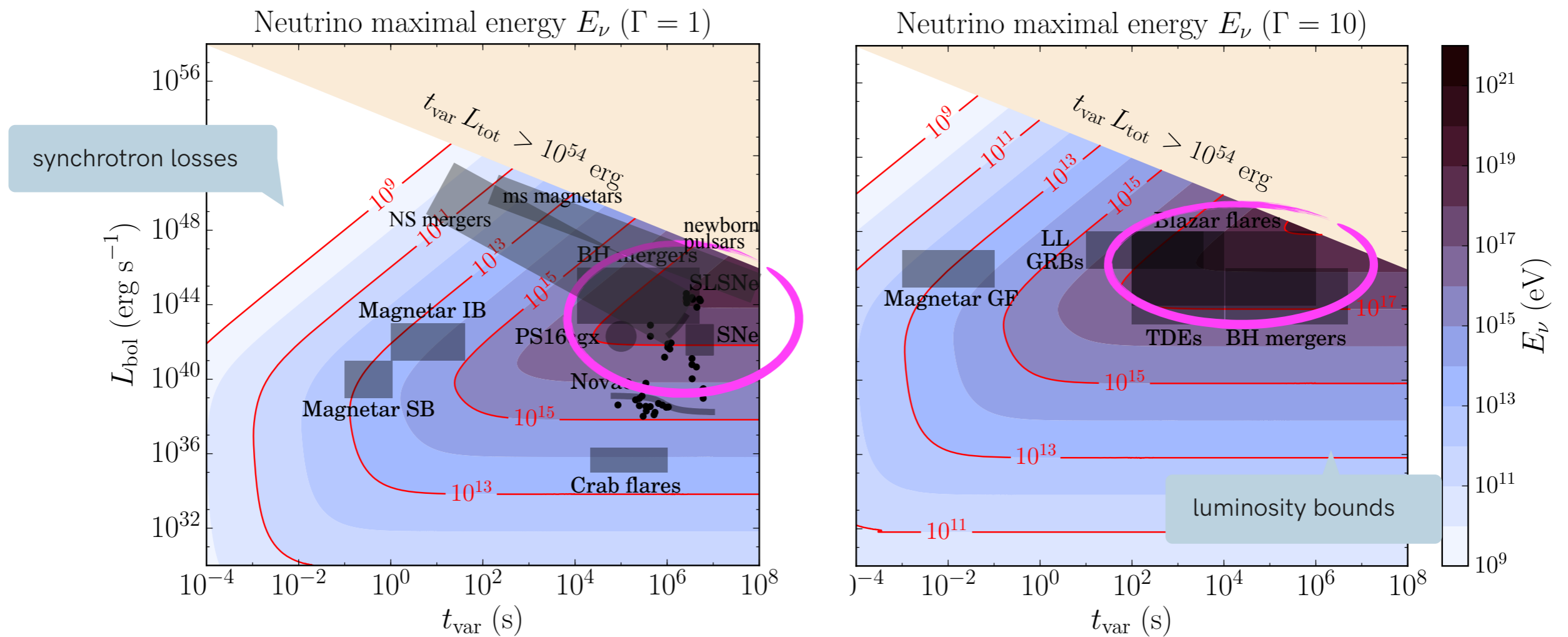


coincident MM+neutrino detection:  
great signatures to do neutrino astronomy

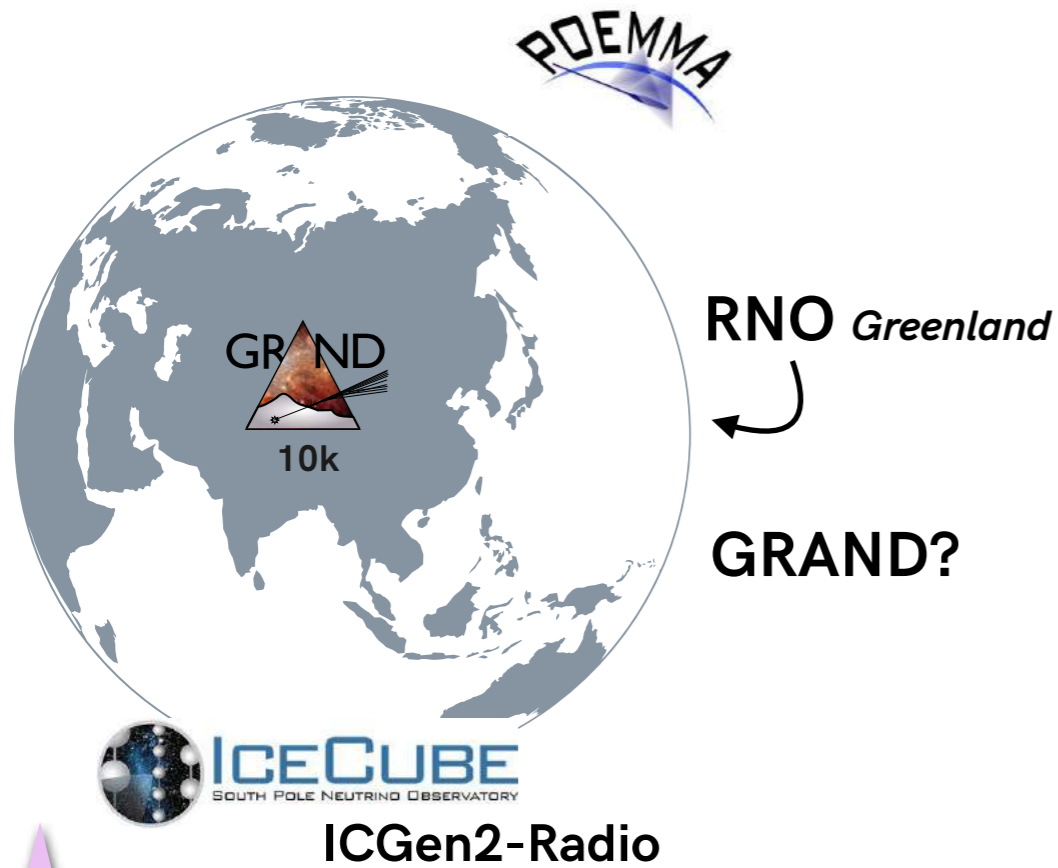
# UHE neutrino production for transients

many transient sources could make it

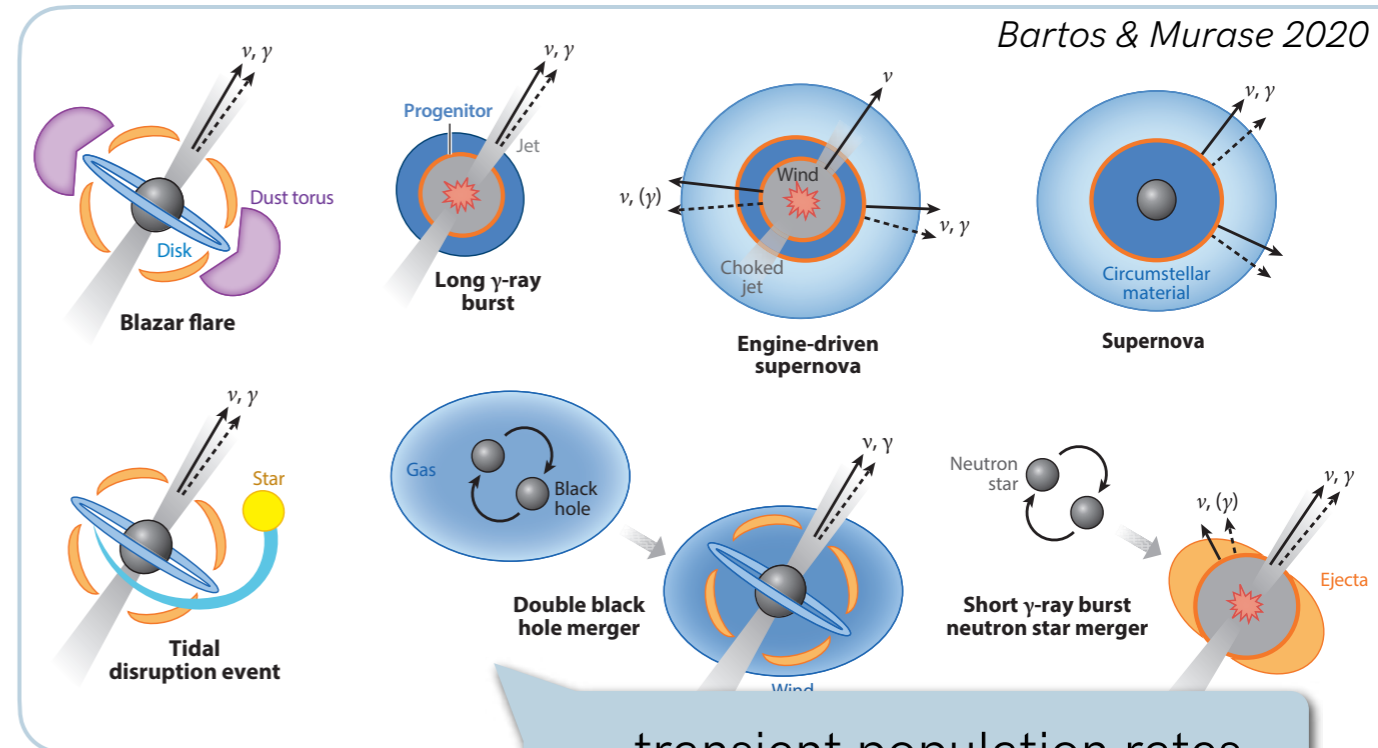
*Guépin & KK 2016*



# Optimizing the detectors locations on Earth to detect transients?



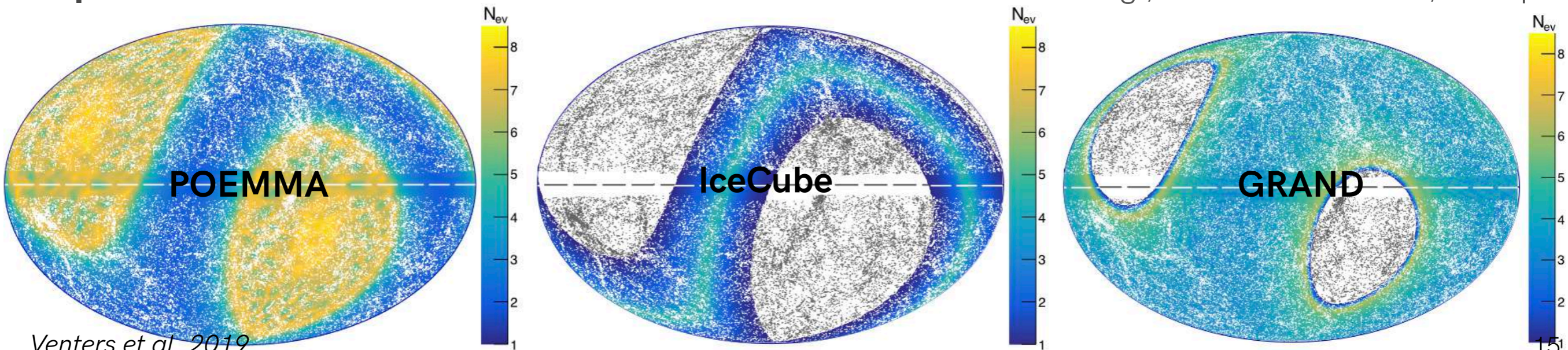
- detector instantaneous field of view
- location on Earth + rotation



- transient population rates
- emission spectra
- duration
- multi-messengers?

## Expected number of neutrino events

short burst model (e.g., Kimura et al. 2017, 40 Mpc)





# EeV Neutrino Astronomy

*May your GRAND dreams come true!*

