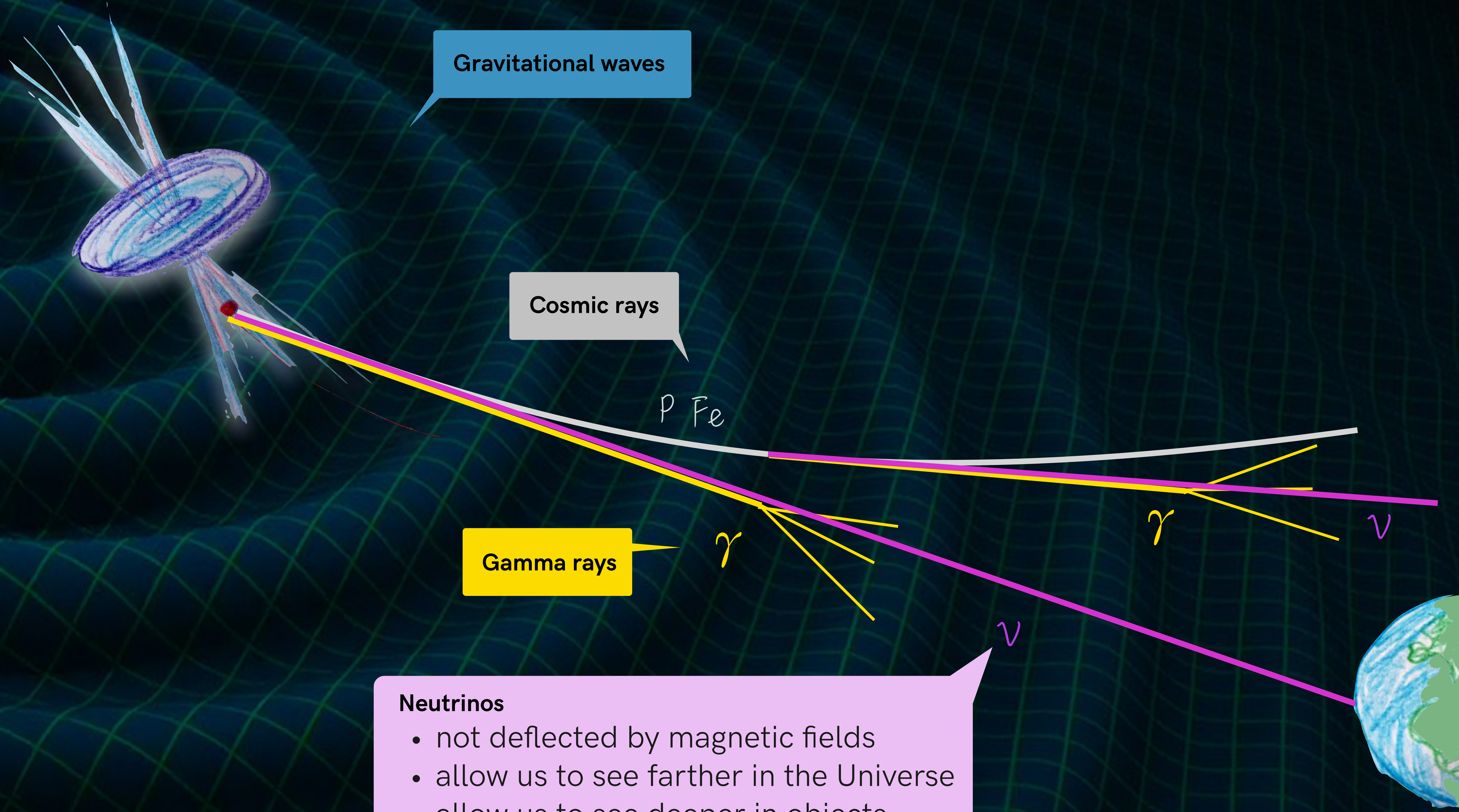
EeV Neutrino Astronomy

Kumiko Kotera - *Institut d'Astrophysique de Paris*

IIHE - 26/11/2020

UHECRs and friends



Gravitational waves

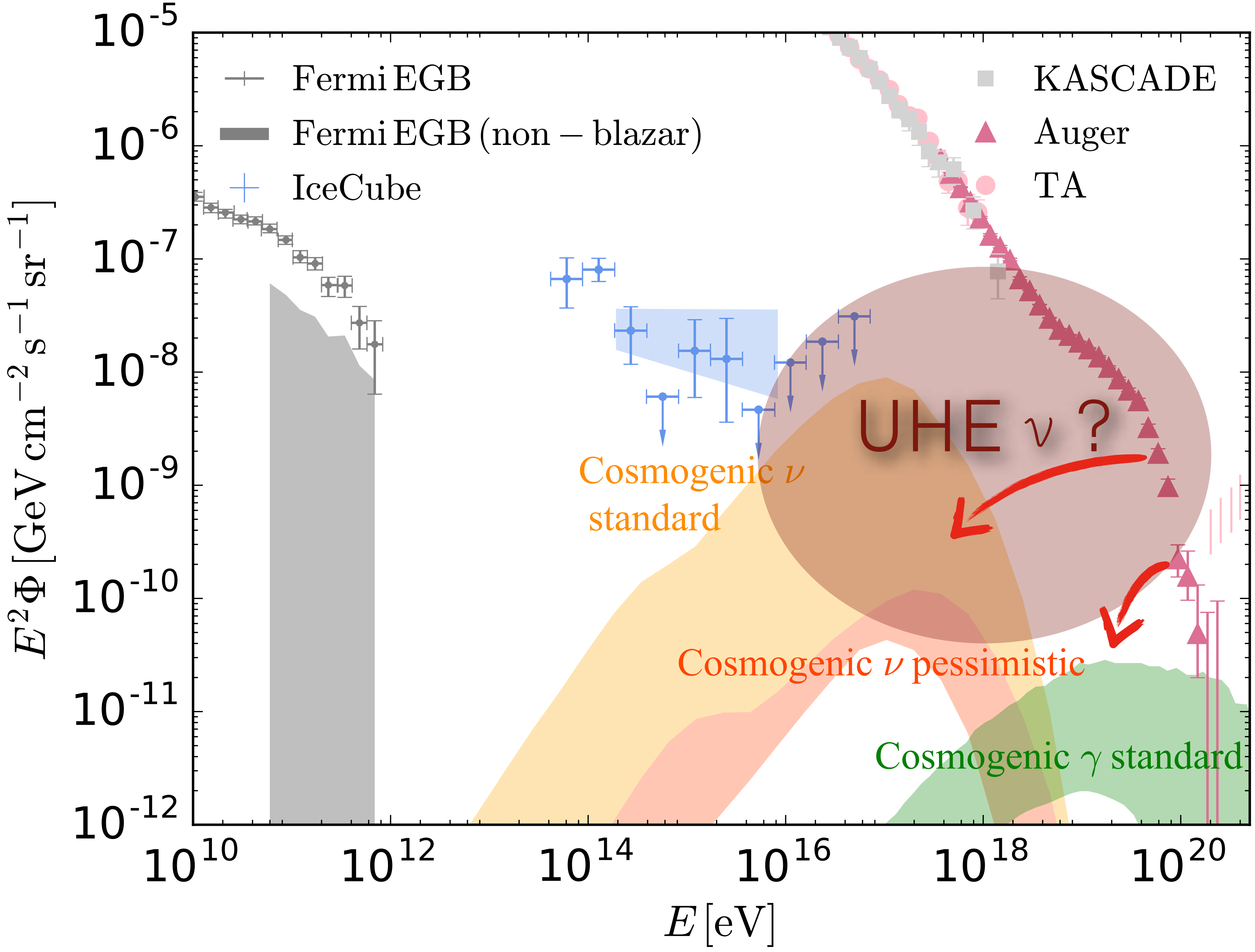
Cosmic rays

Gamma rays

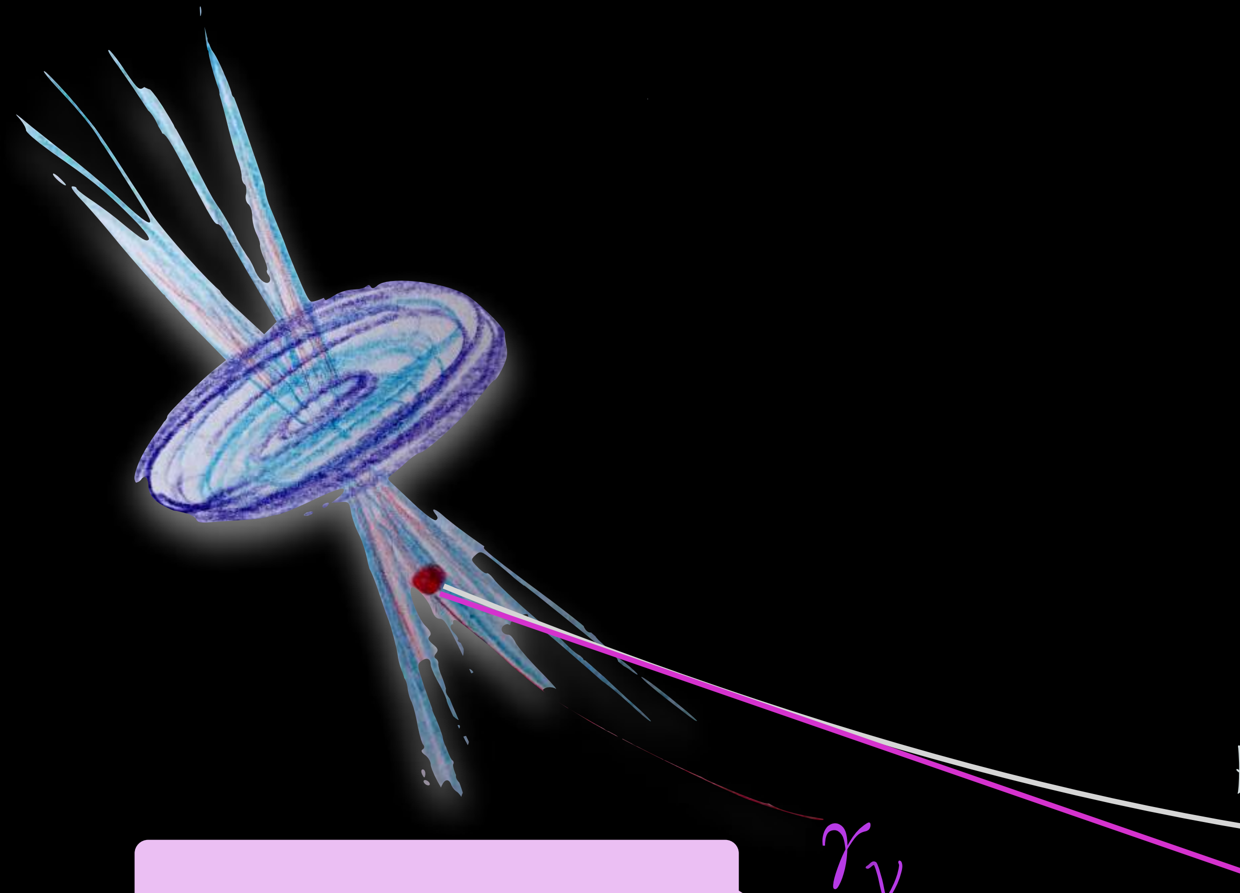
Neutrinos
- not deflected by magnetic fields
- allow us to see farther in the Universe
- allow us to see deeper in objects
- clear hadronic acceleration signature

UHE neutrinos: a challenging no-man's land

Alves Batista, de Almeida, Lago, KK, 2018
GRAND Science & Design, 2018
KK, Allard, Olinto 2010



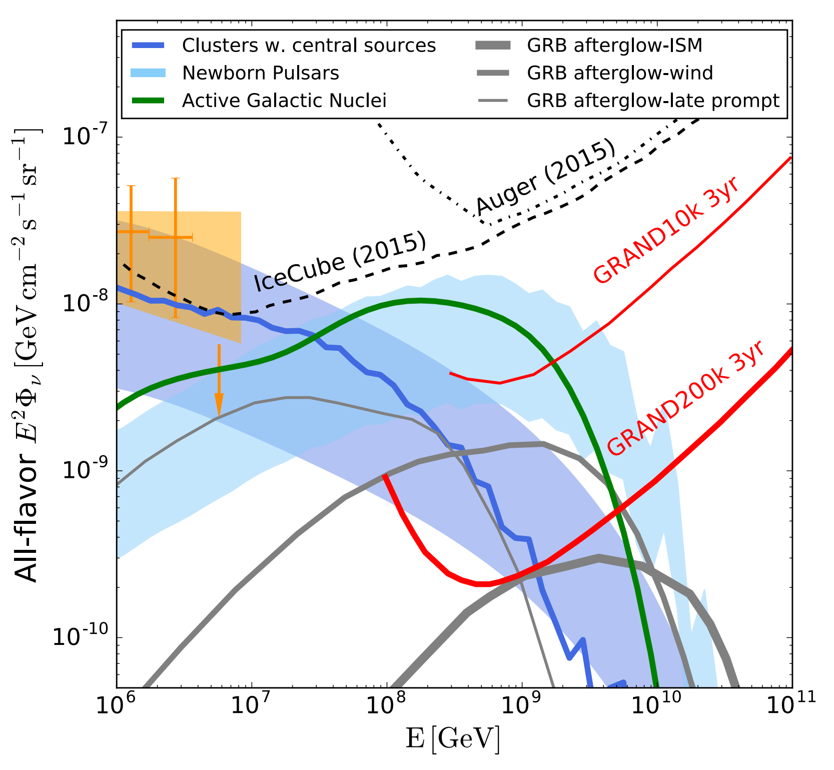
Current multi-messenger data: useful to understand UHECRs?



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

associated neutrino and gamma-ray production

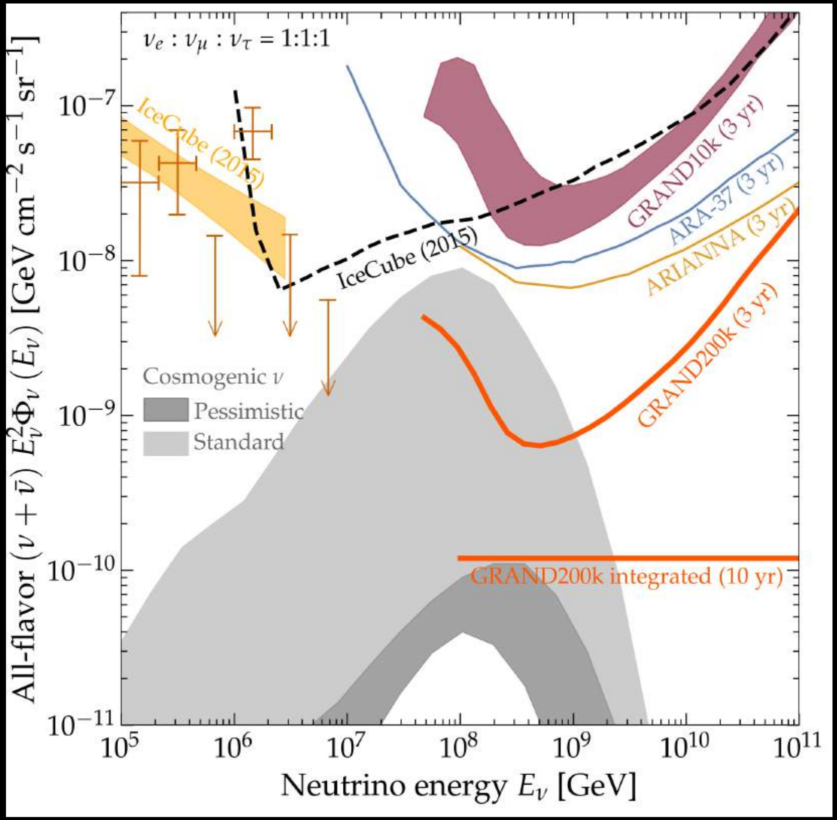
Astrophysical neutrinos

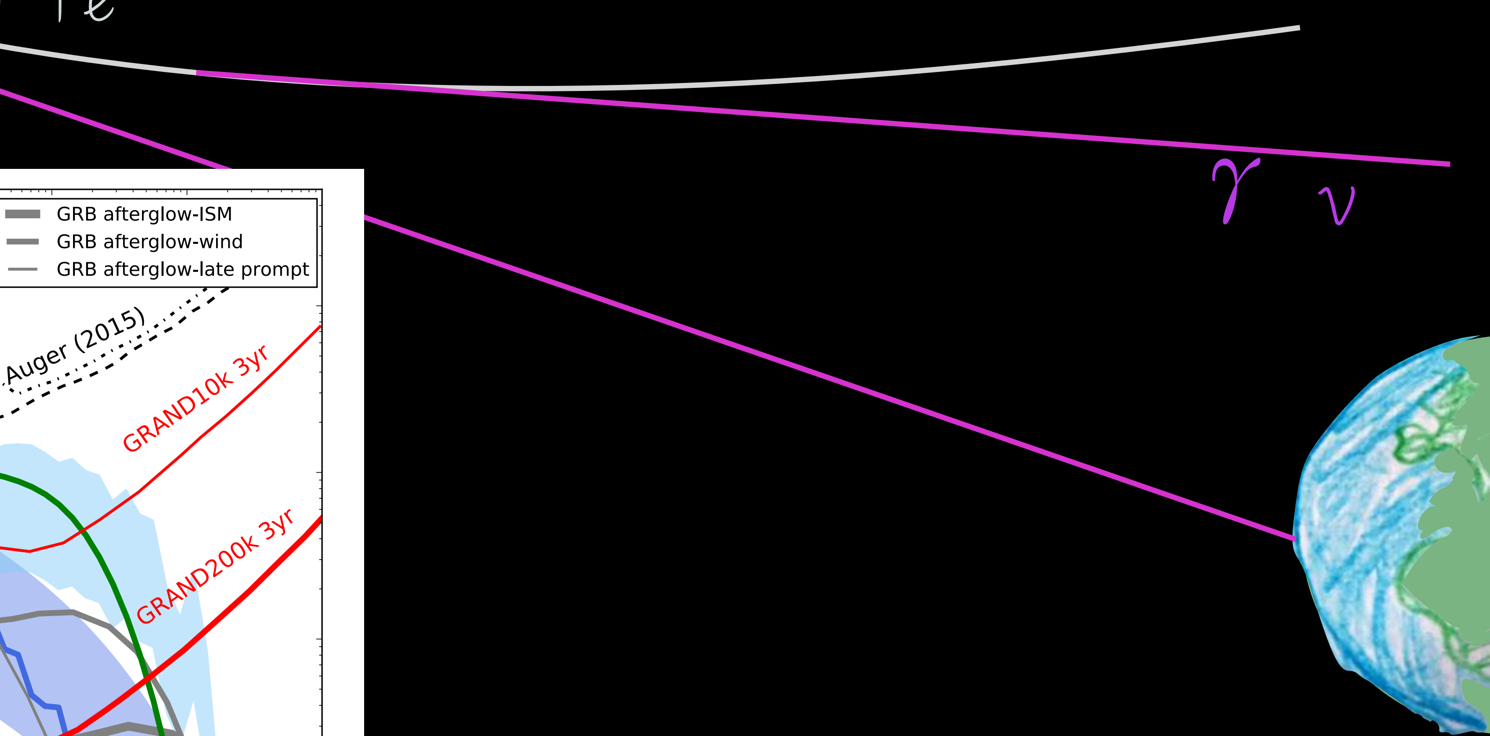


Cosmogenic neutrinos

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

cosmogenic neutrino and gamma-ray production





Current multi-messenger data: useful to understand UHECRs?

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

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

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

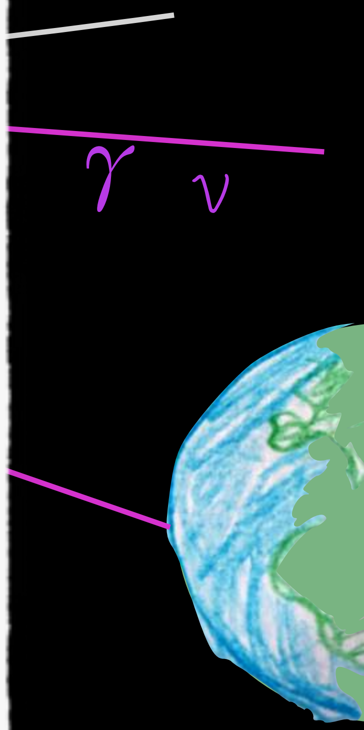
$E_\gamma \sim 10\% \, E_{CR}$

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

$E_\nu > 10^{16}$ 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 :-)



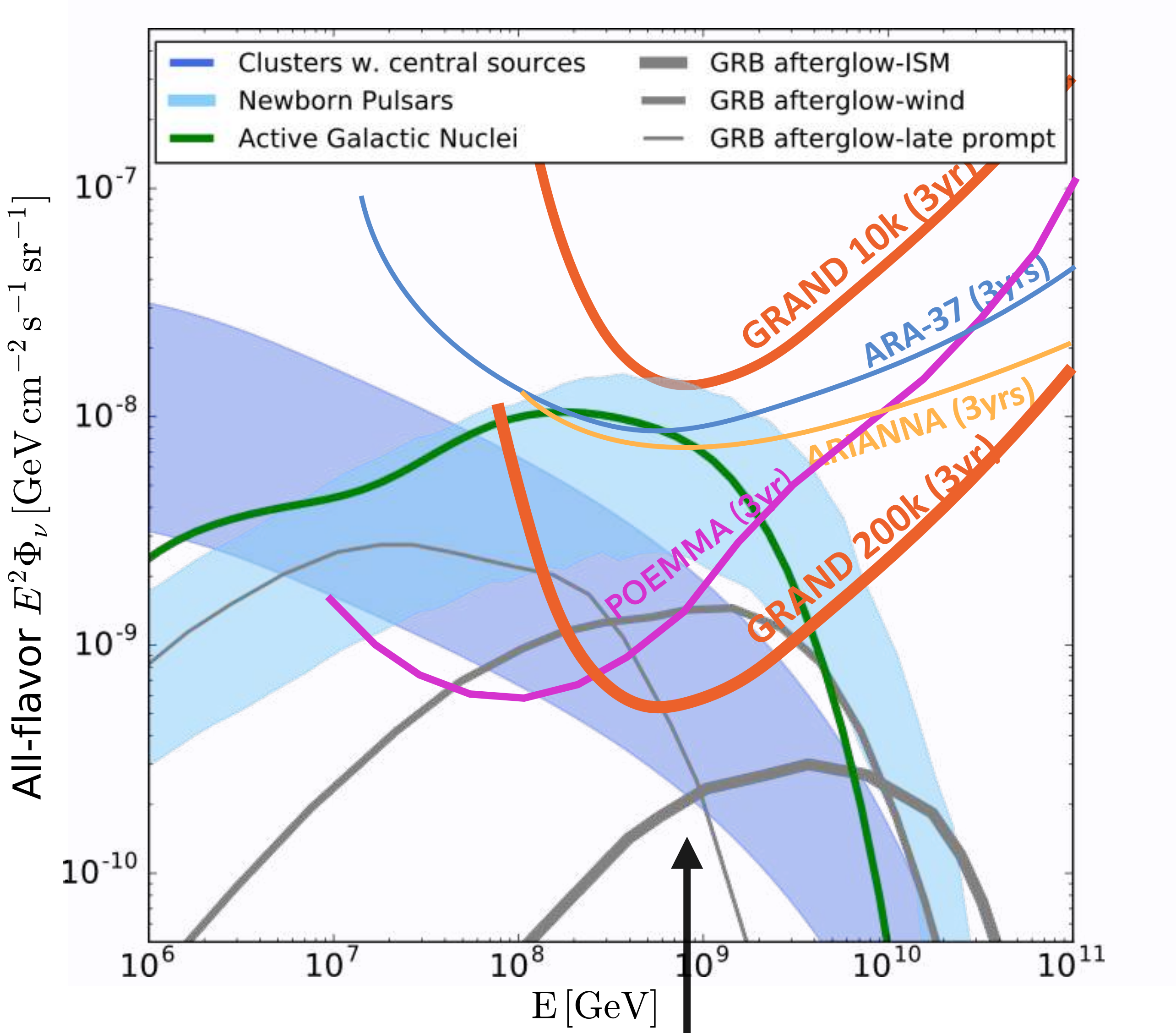
What we can aim to do with future observatories

cosmogenic:
guaranteed

direct from source:
likely more abundant

pessimistic scenarios
of cosmogenic neutrinos = good!

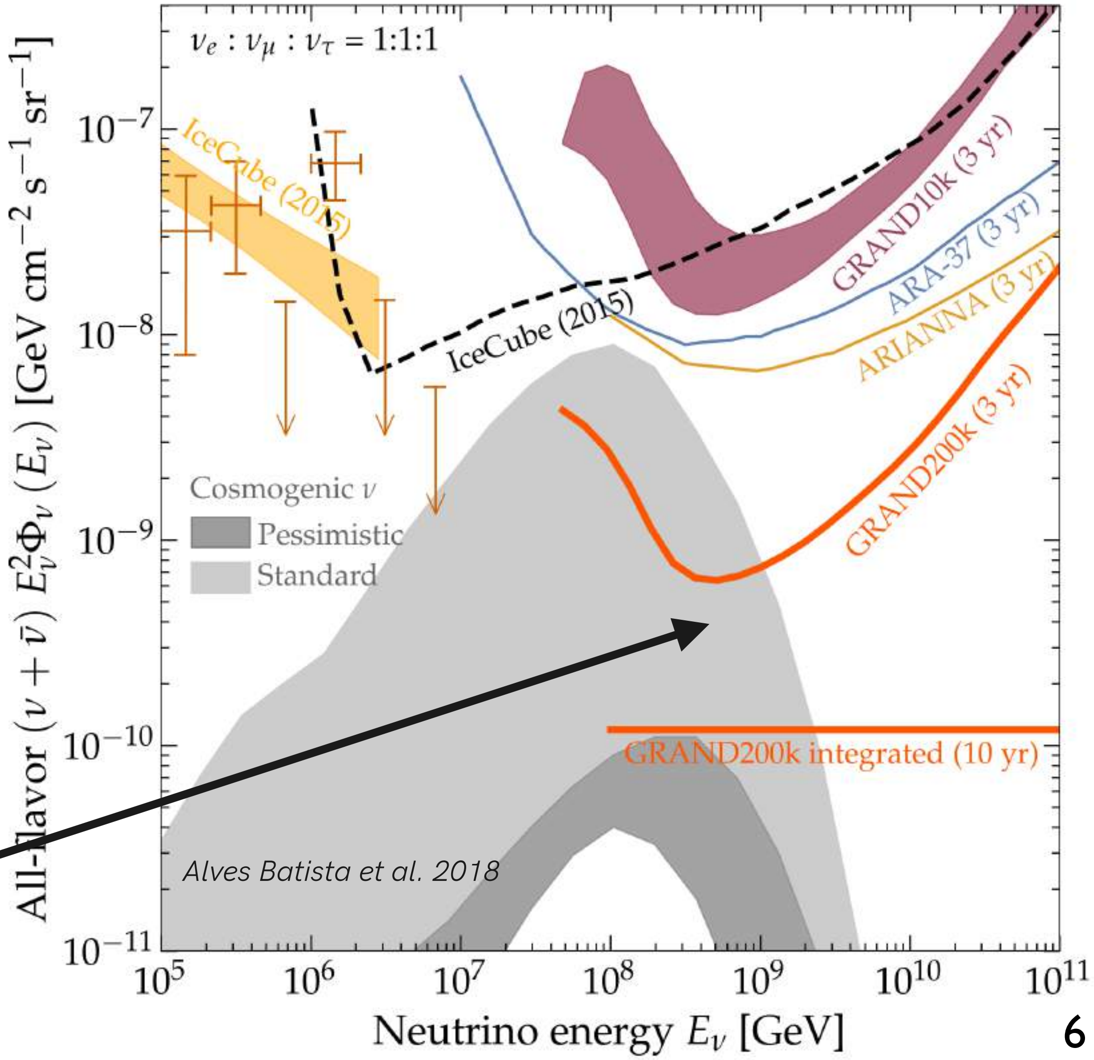
low background for source neutrinos



detect EeV neutrino **point sources**

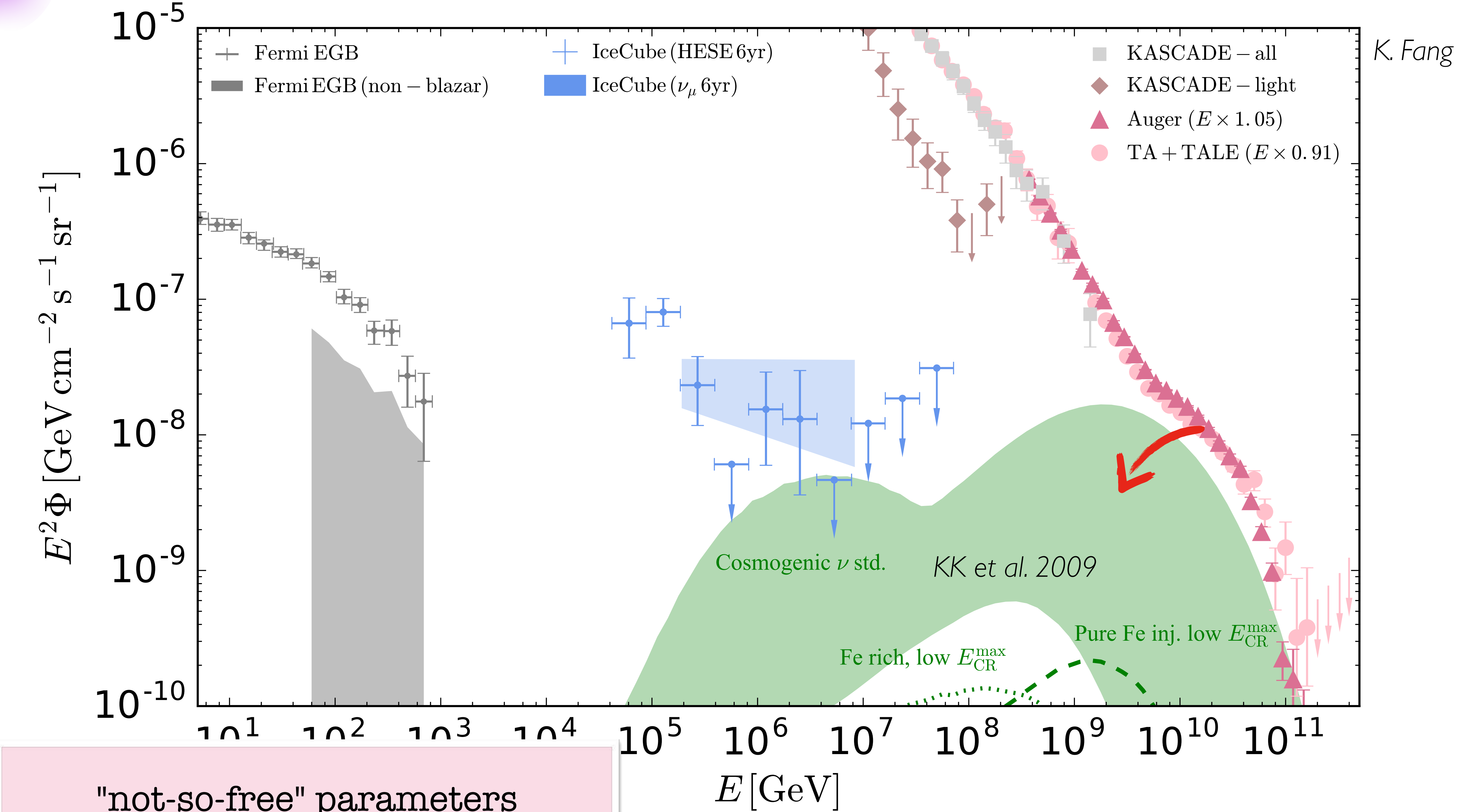
100s of events
<1° angular resolution

detect **cosmogenic** neutrinos



Alves Batista et al. 2018

The guaranteed cosmogenic neutrinos



K. Fang

KK et al. 2009

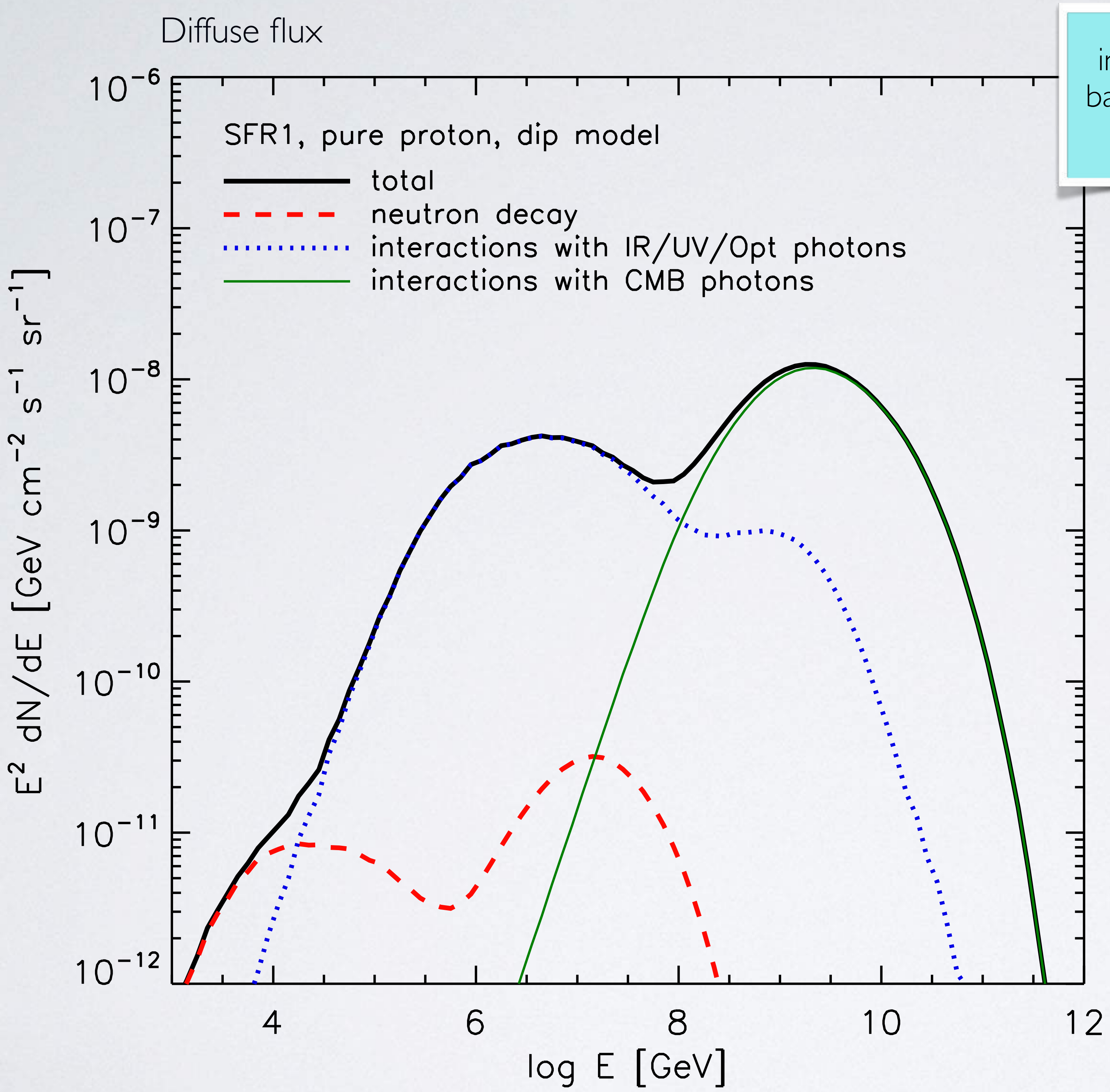
"not-so-free" parameters

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

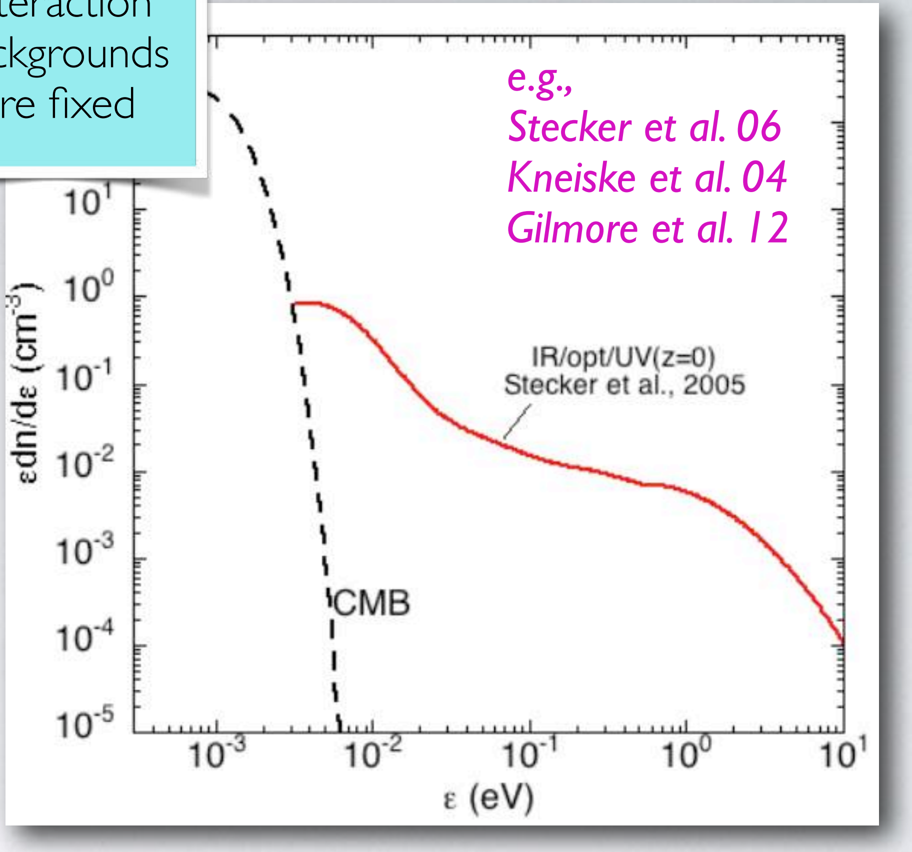
cosmogenic neutrinos guaranteed
if sources of UHECRs
@cosmological distances

Cosmogenic neutrinos: production channels

KK, Allard, Olinto 2010



interaction backgrounds are fixed



e.g.,
Stecker et al. 06
Kneiske et al. 04
Gilmore et al. 12

Cosmogenic neutrinos: principal ingredients

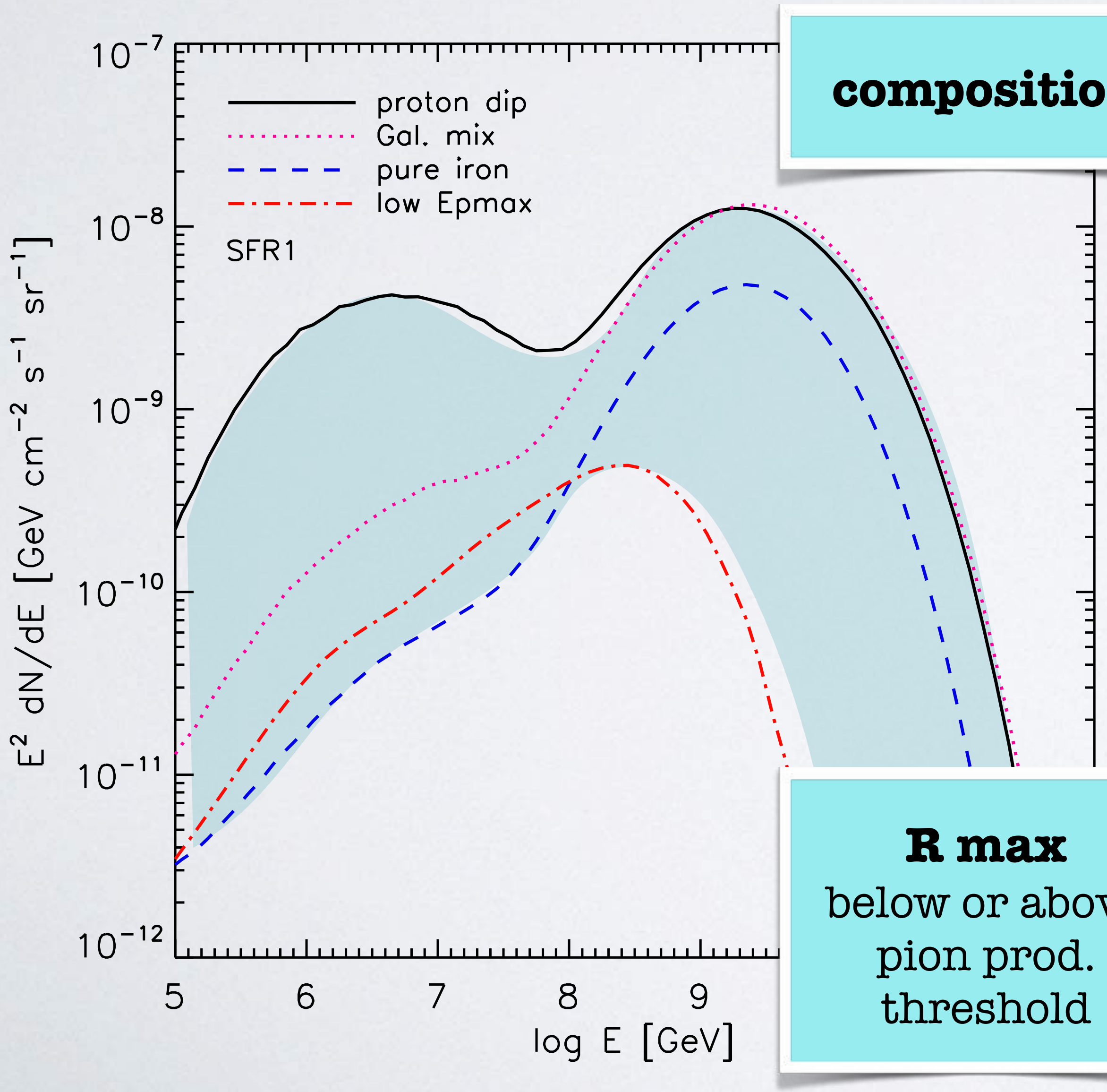
KK, Allard, Olinto 2010

"not-so-free" parameters

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

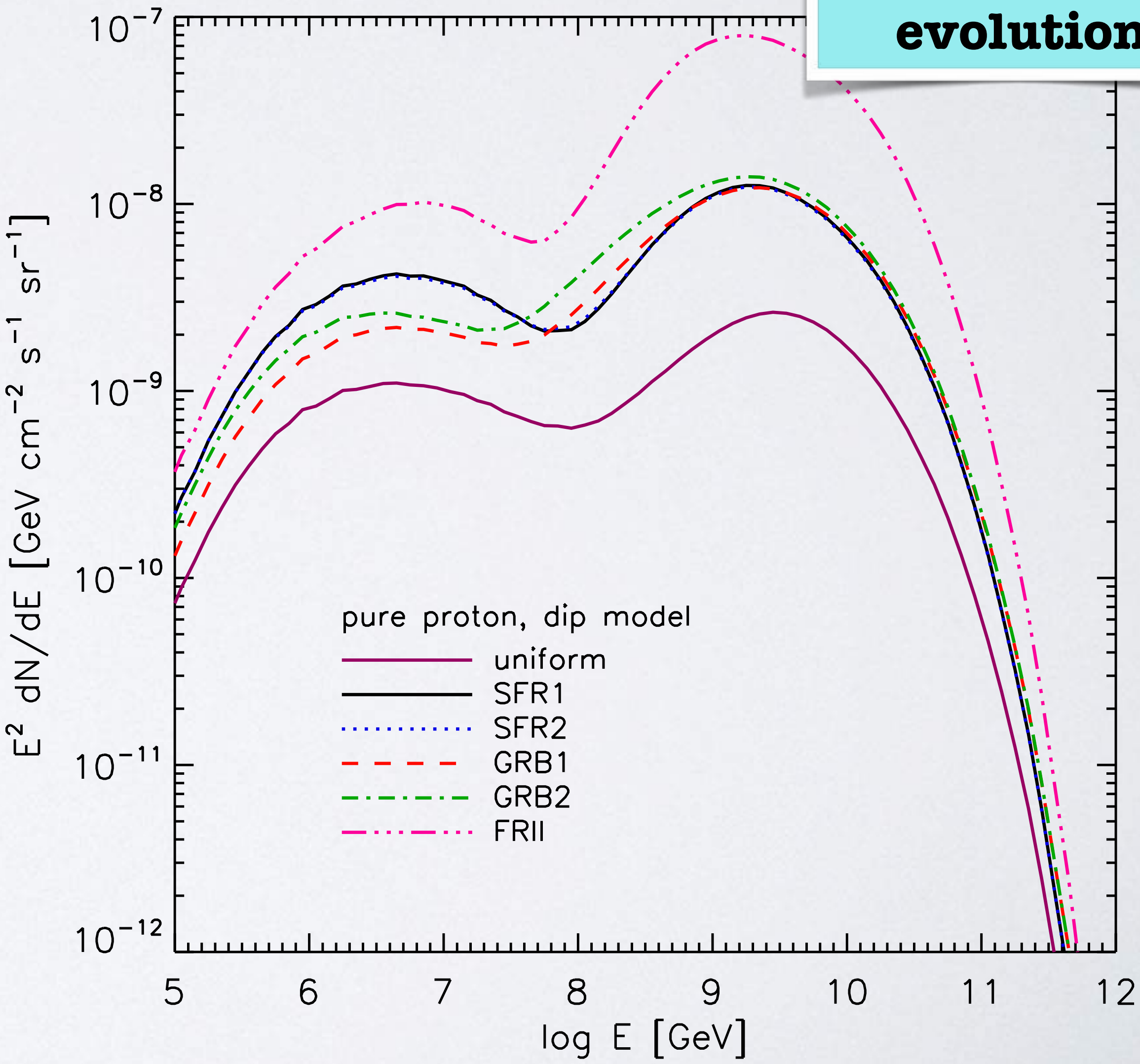
▶ depend strongly on observations of UHECRs

▶ less dependent but affects injection spectrum



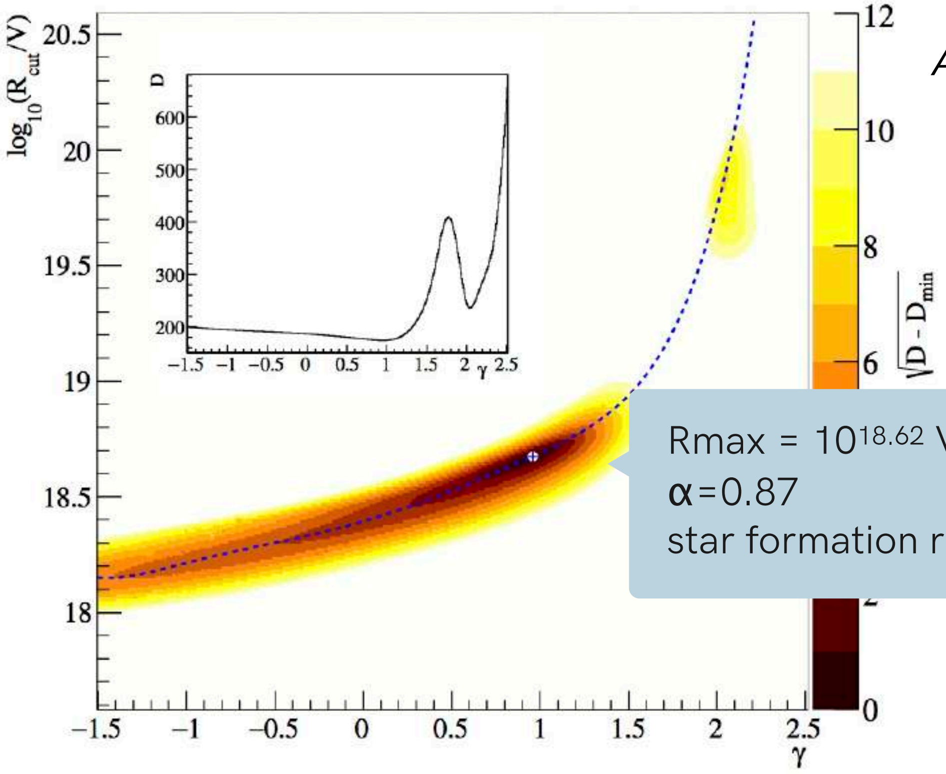
composition

R max
below or above pion prod. threshold



source evolution

Information from UHECR spectra and composition



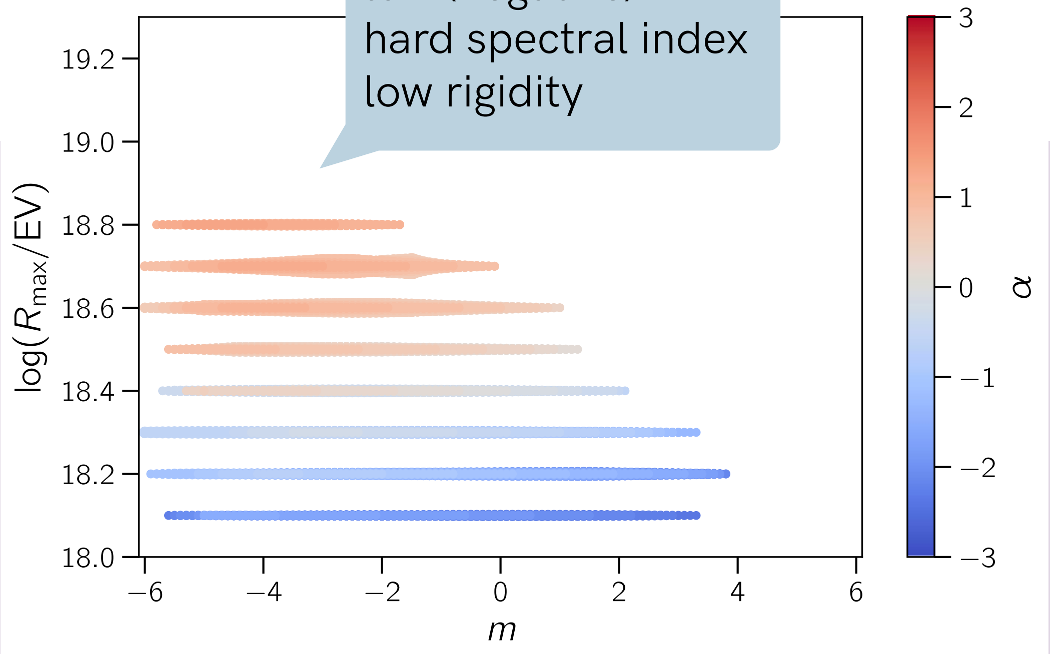
Auger Coll. 2017

Rmax = $10^{18.62}$ V
α=0.87
star formation rate

UHECR parameters

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

scan source evolution



favor
low (negative) *m*
hard spectral index
low rigidity

Alves Batista, de Almeida, Lago, KK, 2018

- if emissivity evolution free parameter —> 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. α>~1 favored in theory.

phenomenologically reasonable models with good deviances

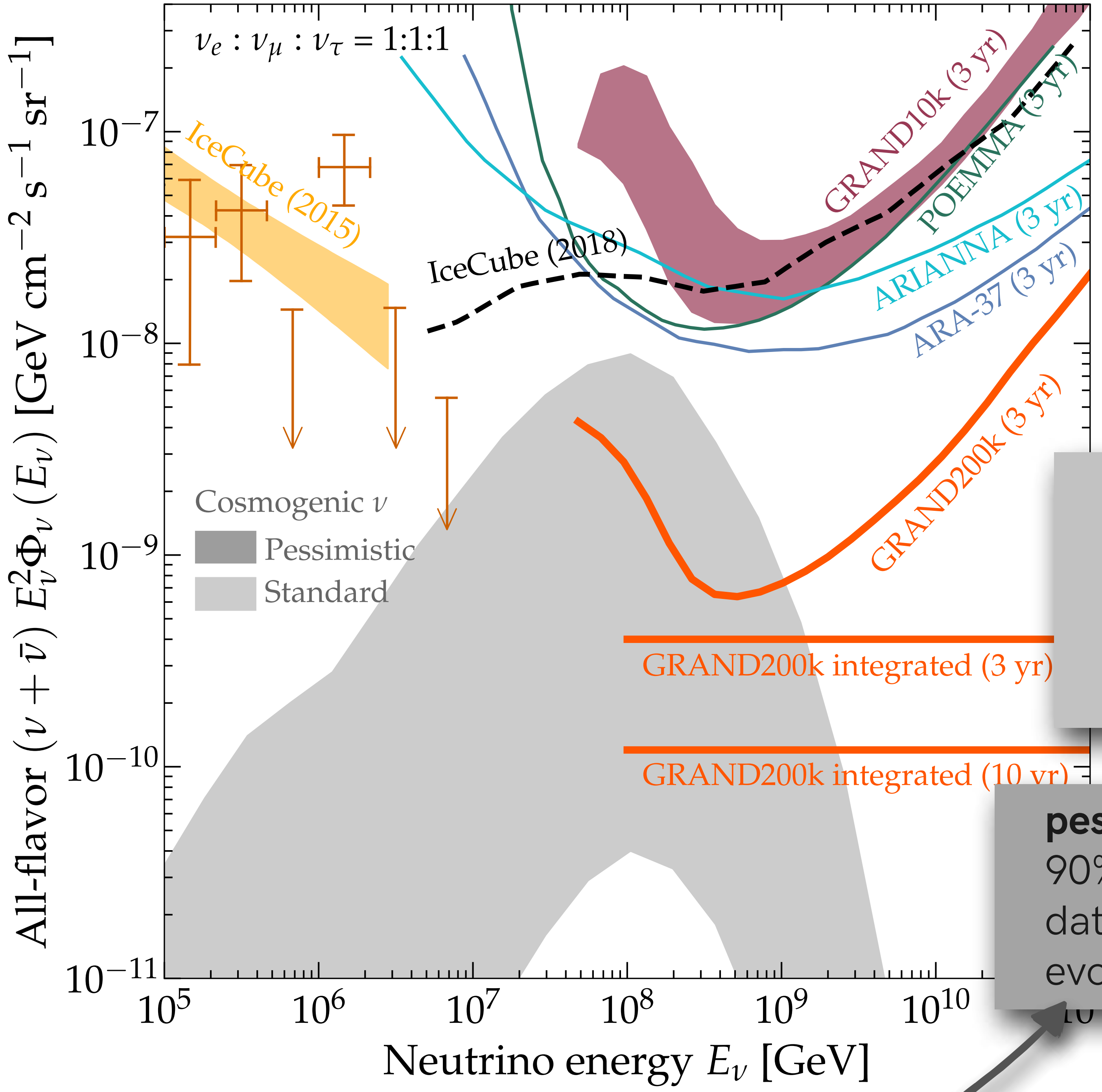
Table 1. Best-fit parameters for specific spectral indices.

m	α	$\log(R_{max}/V)$	f_p	f_{He}	f_N	f_{Si}	f_{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, submitted
GRAND Science & Design, in prep

KK, Allard, Olinto 2010
Van Vliet et al. arXiv:1707.04511



standard
99% C.L. fit to Auger among generic SFR, AGN, GRB source evolutions

pessimistic
90% C.L. fit to Auger data with $(1+z)^m$ source evolution with $m < 0$

most pessimistic!
adding IGMF —> harder α —> increases neutrino flux
alleviating simplifying assumption —> increases neutrino flux

low rigidities
$R_{max} \sim 10^{18.1\text{-}18.8}$ V

R_{max}
below or above pion prod. threshold

very hard
$-1.5 < \alpha < +1.2$

spectral index
flux of secondary protons
$E^{-\alpha}$

source evolution history

composition

intermediate dominated
p 8%, He 18%, N 67%, Fe 0.01%

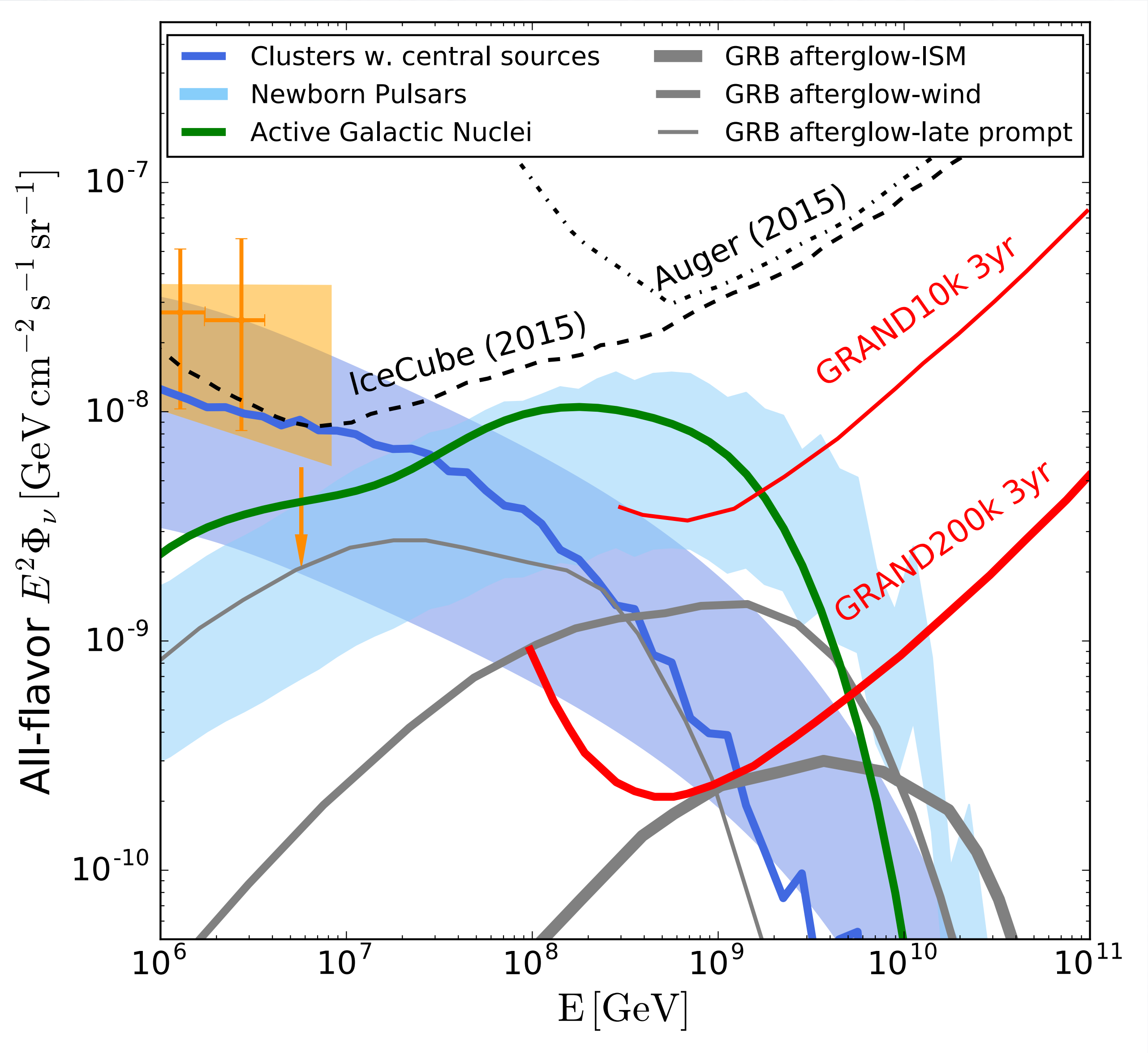
UHECR flux normalisation

Astrophysical UHE neutrinos: produced at the source

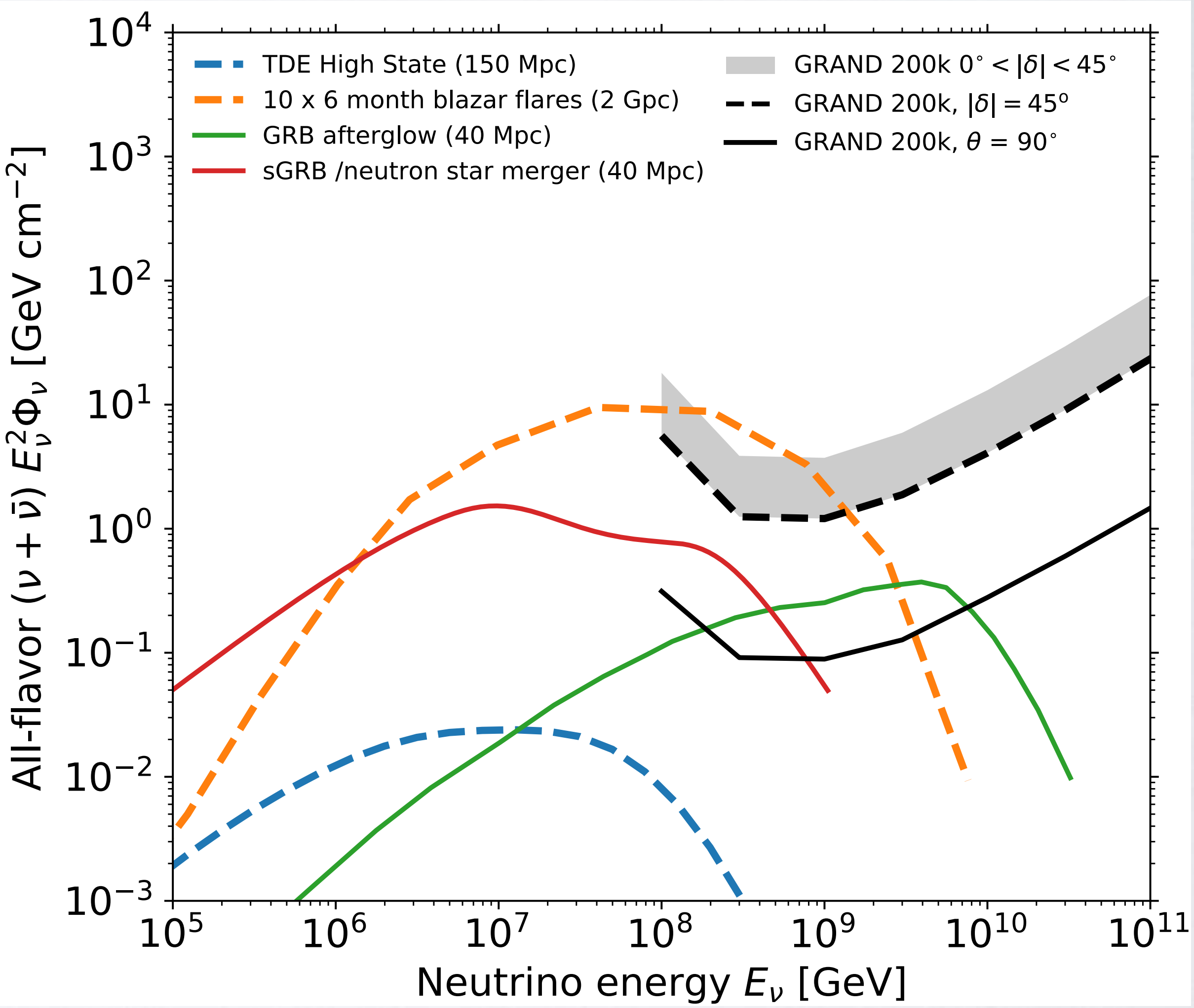
GRAND Science & Design, 2018

Diffuse flux

integrated over the whole population



Point-source fluences



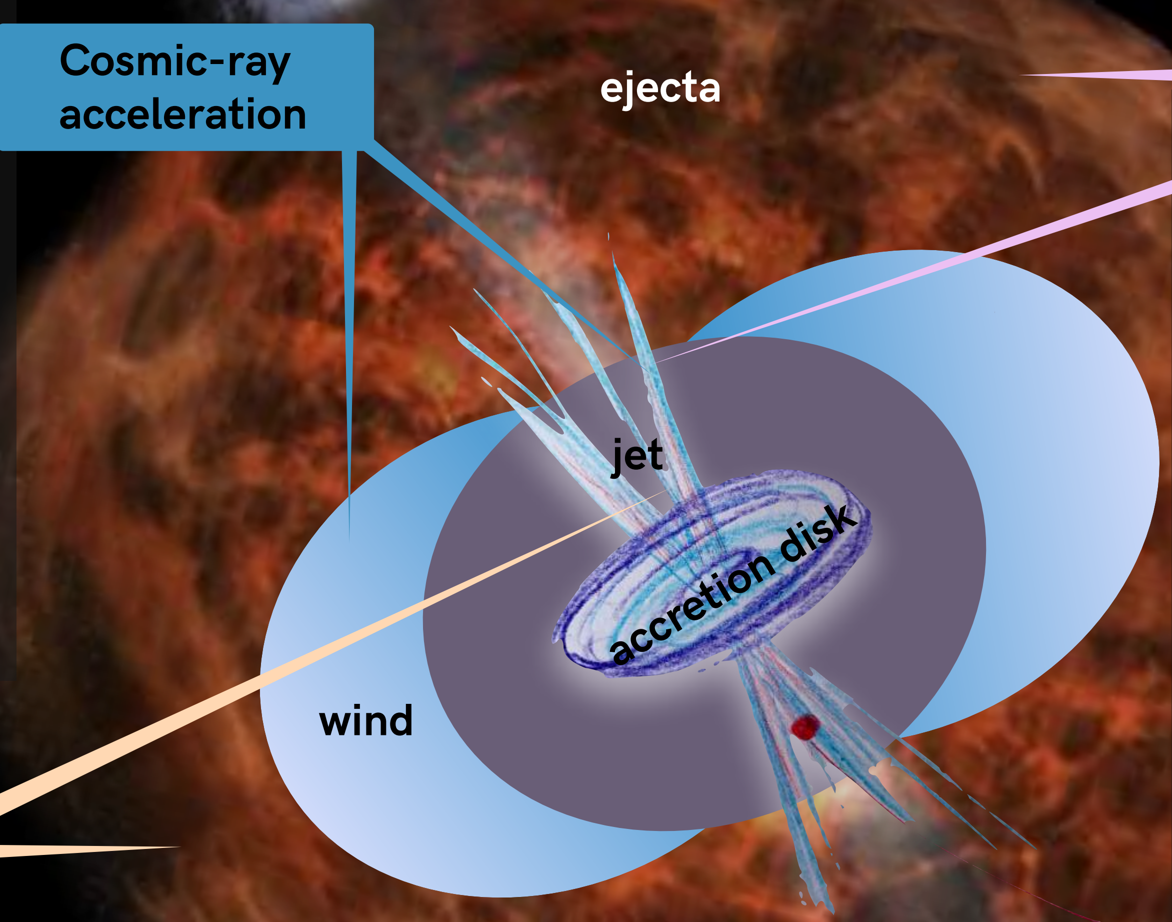
unique shapes for
various sources
(because of interaction
backgrounds)

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

Cosmic-ray interactions + cooling
Neutrino production

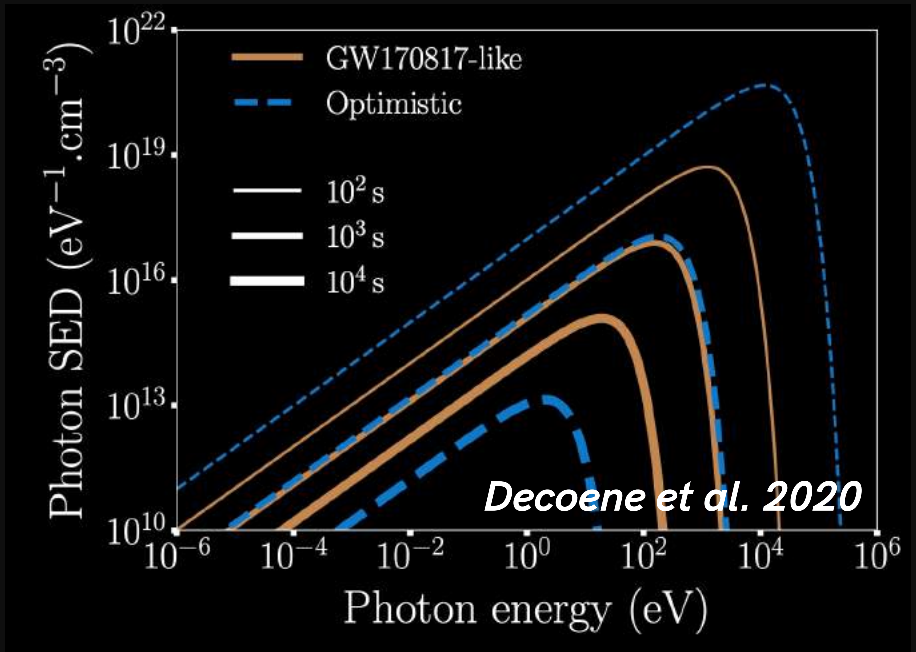
$$p + \gamma \rightarrow n + \pi^+ + \ldots$$
$$\pi^+ \rightarrow \mu^+ + \nu_\mu \rightarrow e^+ + \nu_e + \bar{\nu}_\mu + \nu_\mu$$

cascades
no HE ν

synchrotron cooling
no HE ν

Radiative + hadronic backgrounds

density, spectra, time evolution
in acceleration region and beyond



Decoene et al. 2020

Ex: red kilonova ejecta

- **Thermodynamical equilibrium**

Metzger et al. 2011

$$\underbrace{\frac{d\mathcal{E}}{dt}}_{\text{energy evolution}} = \underbrace{-\frac{\mathcal{E}}{R}\frac{dR}{dt}}_{\text{mechanical losses}} \underbrace{- \frac{\mathcal{E}}{t_{\mathrm{esc}}}}_{\text{radiative losses}} + \dot{Q}_{\mathrm{r}} + \dot{Q}_{\mathrm{fb}}$$

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

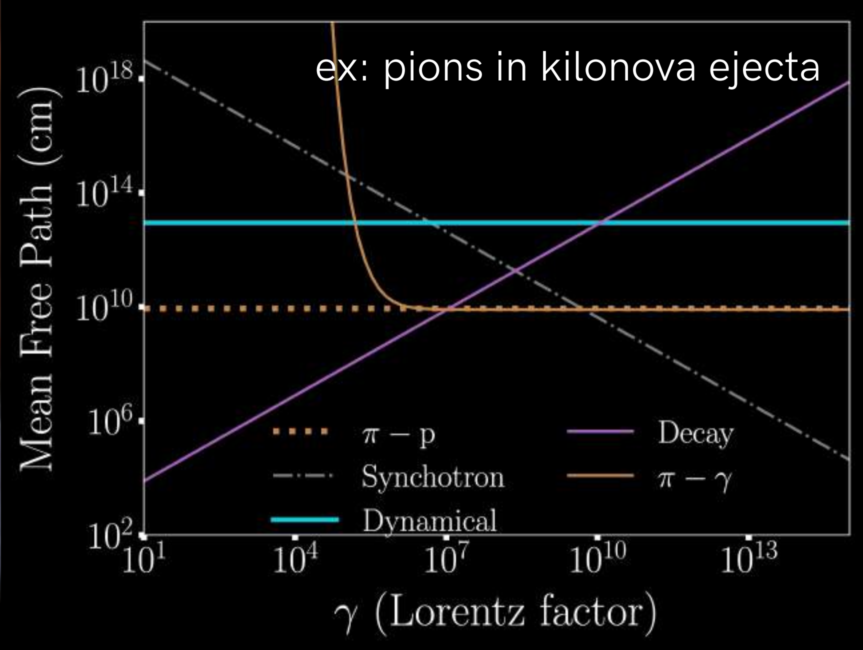
- **Fall-back**

$$\dot{Q}_{\mathrm{fb}} = \epsilon_{\mathrm{fb}}\dot{M}_{\mathrm{fb}}c^2 \quad \text{mass accretion rate}$$

- **Nuclear reaction** Barnes et al. 2016
M. R. Drout et al, 2017

$$\dot{Q}_{\mathrm{r}} = M\,\underbrace{X_{\mathrm{r}}}_{\text{lanthanides mass fraction}}\,\underbrace{\dot{e}_{\mathrm{r}}(t)}_{\text{nuclear mass energy}}$$

V. Decoene PhD

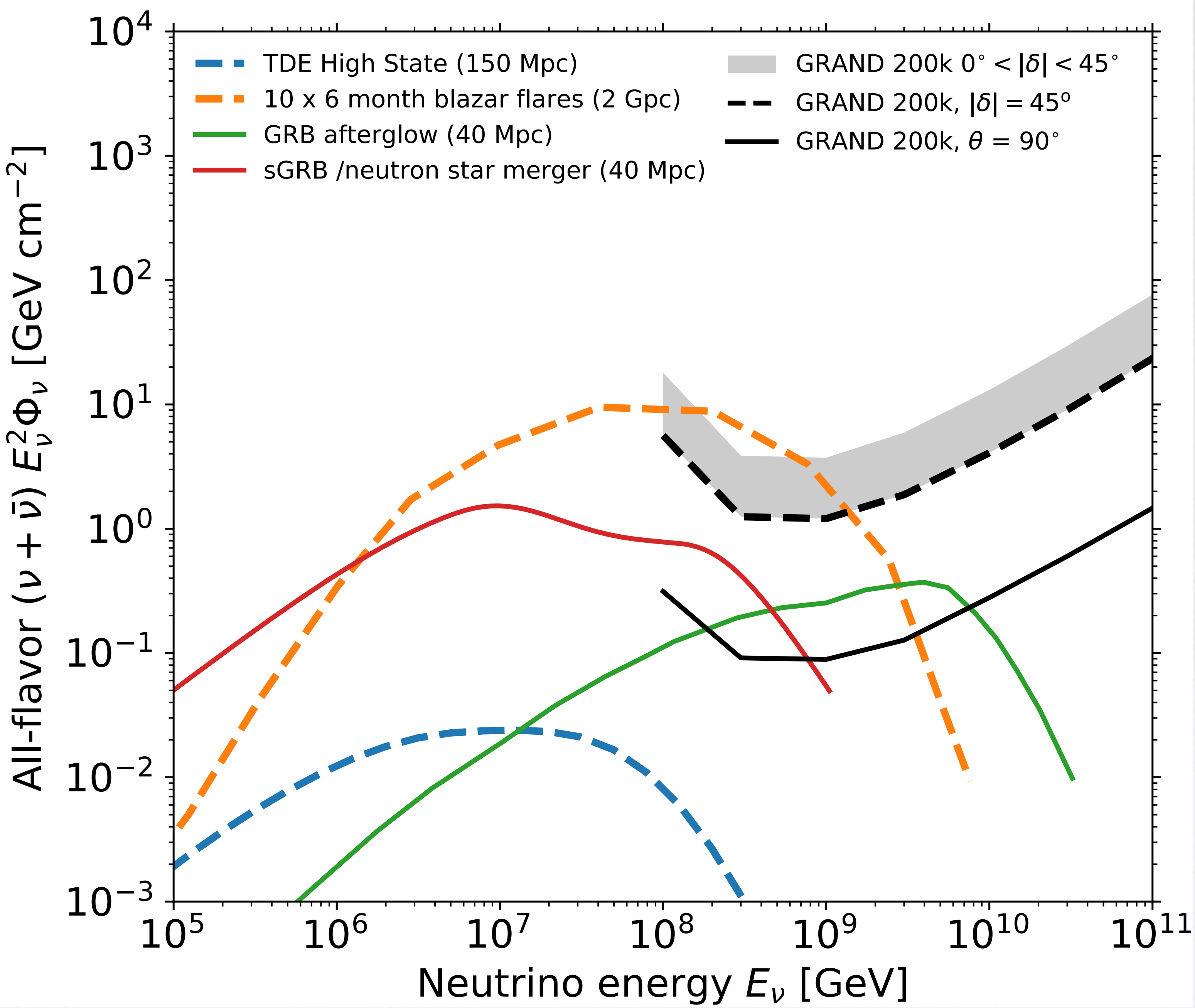


Decoene et al. 2020

Astrophysical UHE neutrinos: produced at the source

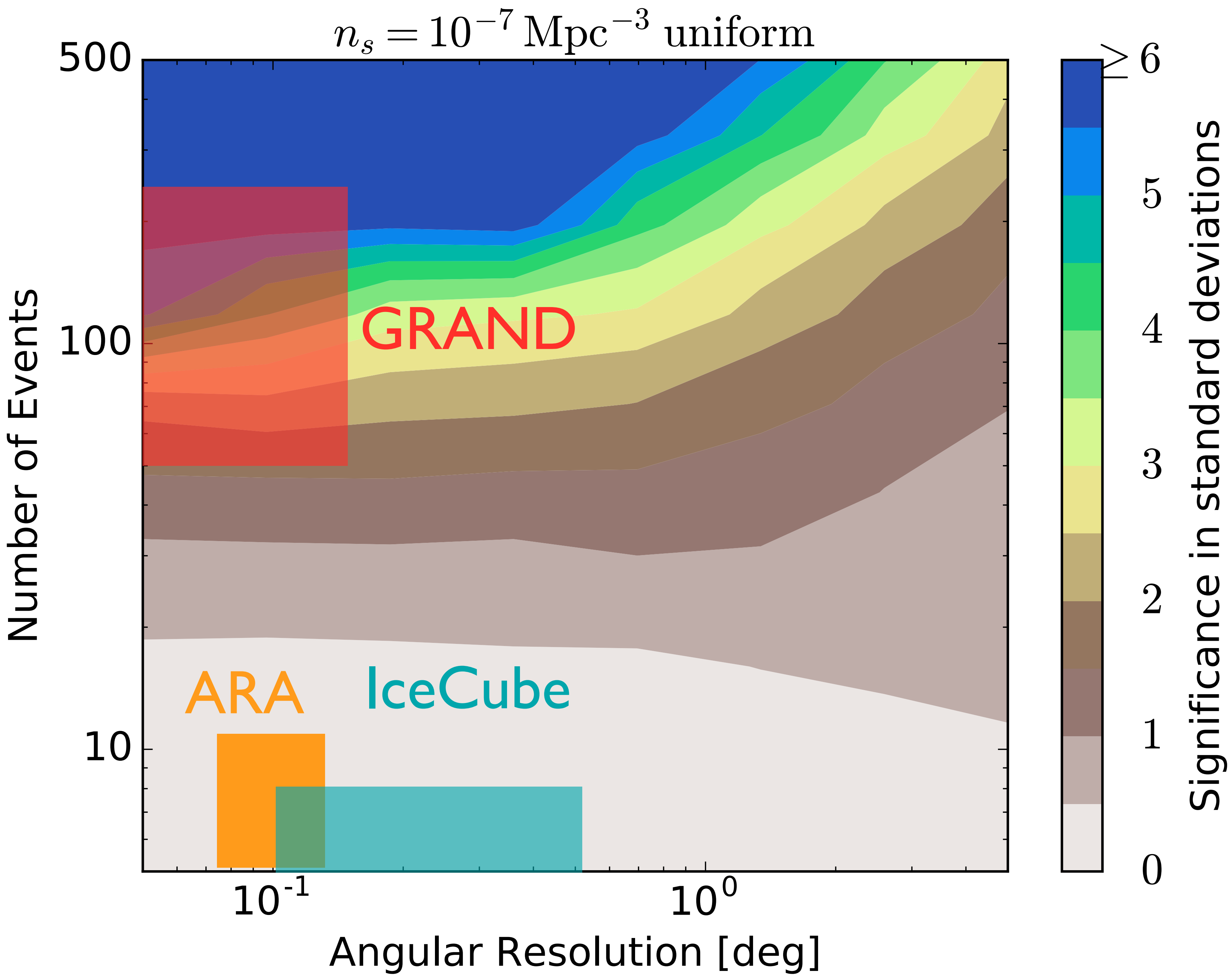
GRAND Science & Design, 2018

Point-source fluences



Can we detect very high-energy neutrino sources?

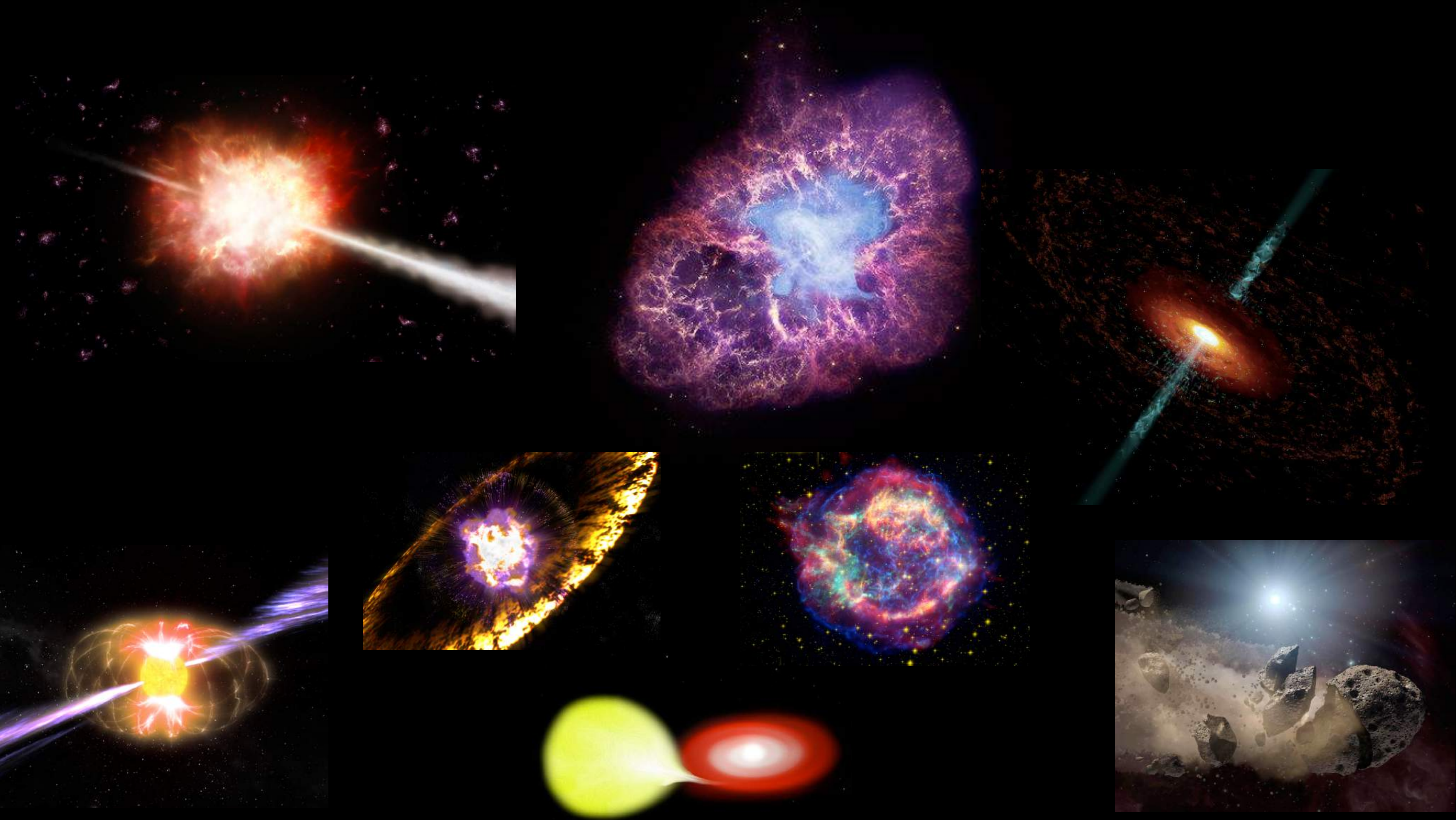
Fang, KK, Murase, Miller, Oikonomou 2016



YES if

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

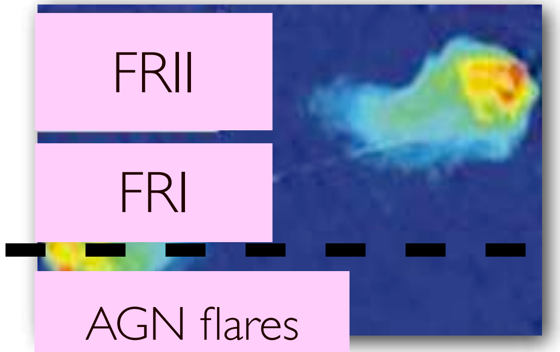
Going for transients

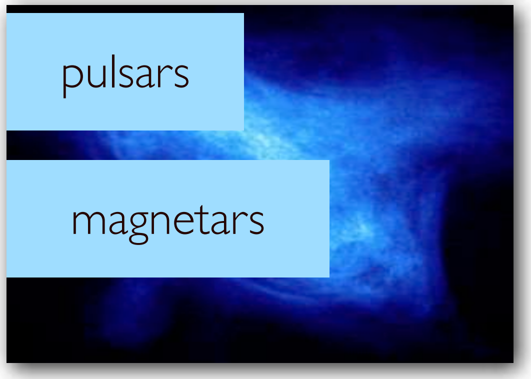


clear signatures to do neutrino astronomy

Condition for acceleration at sources

luminosity budget

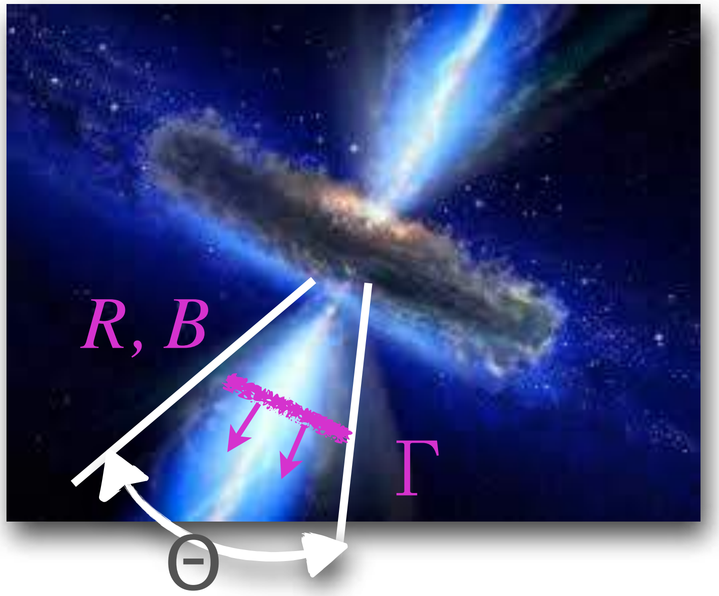





steady sources	clusters	$>10^{45}$ erg/s
	FRII	$10^{46\text{-}48}$ erg/s
	FRI	$<10^{45}$ erg/s
	AGN flares	
transient sources	High luminosity GRB	$10^{51\text{-}52}$ erg/s
	Low luminosity GRB	$10^{50\text{-}51}$ erg/s
	pulsars	$10^{45\text{-}47}$ erg/s
	magnetars	$10^{45\text{-}47}$ erg/s

condition for acceleration

$$t_{\rm acc} \lesssim t_{\rm dyn}$$



$$t_{\rm acc} = \mathcal{A}\, t_{\rm L}$$

depends on acc. mechanism and environment

Larmor time

$\mathcal{A} \gg 1$

$\mathcal{A}$ ~ 1 at best

$$t_{\rm dyn} \sim R/\beta\Gamma c$$

outflow magnetic luminosity

$$L_B \equiv 2\pi R^2 \Theta^2 \frac{B^2}{8\pi} \Gamma^2 \beta c > 10^{45}\ Z^{-2} E_{20}^2\ \ {\rm erg\ \ s}^{-1}$$

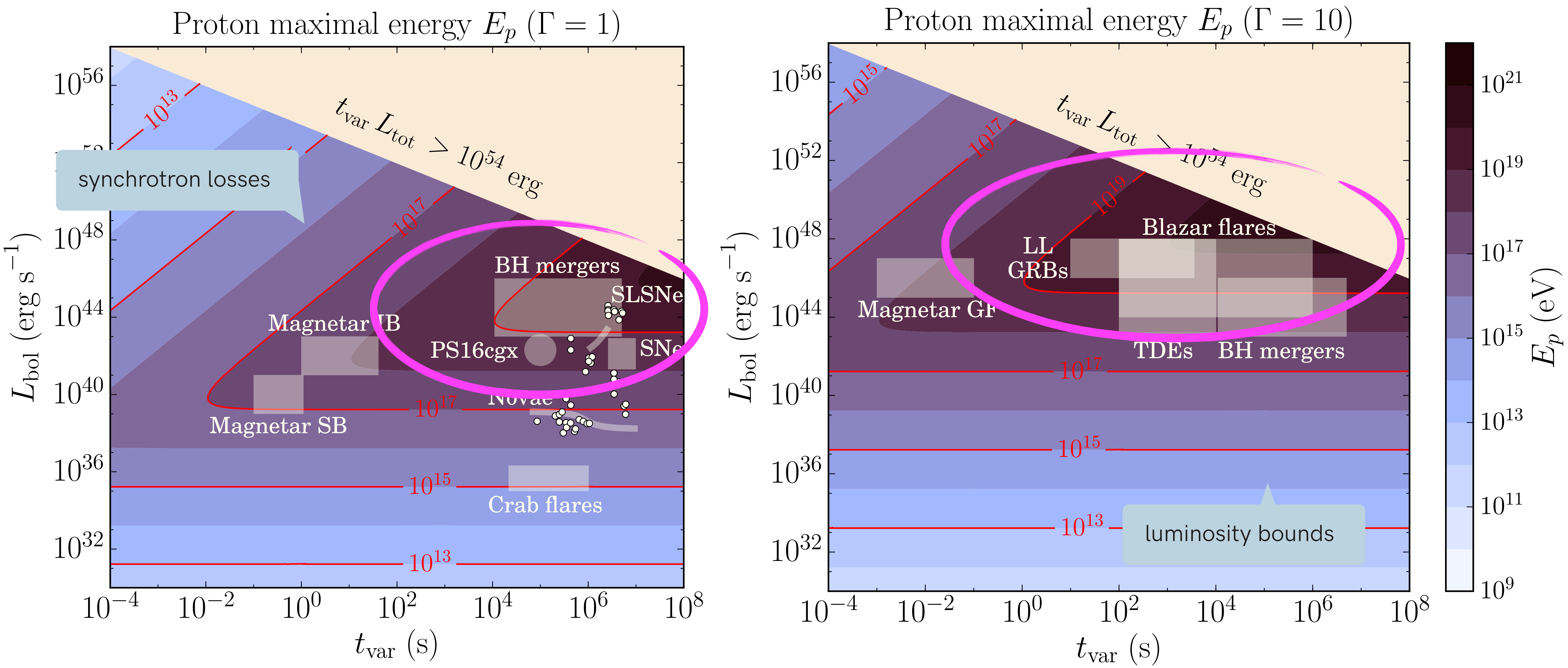
lower bound of the bolometric luminosity of source

Lemoine & Waxman 2009

Condition for acceleration at sources for transients

source bolometric luminosity $> 10^{45}\,Z^{-2}E_{20}^{2}\ \mathrm{erg\ s^{-1}}$ *Lemoine & Waxman 2009*

many transient sources could make it *Guépin & KK 2016*

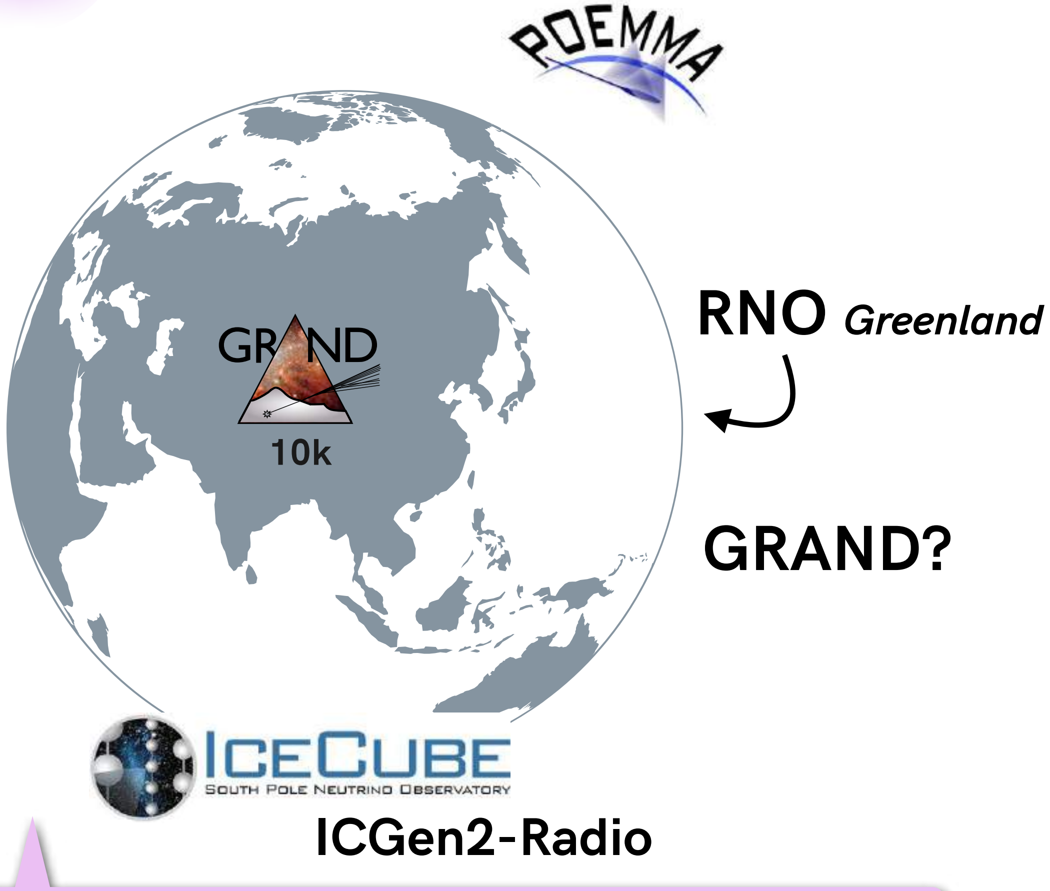


synchrotron losses

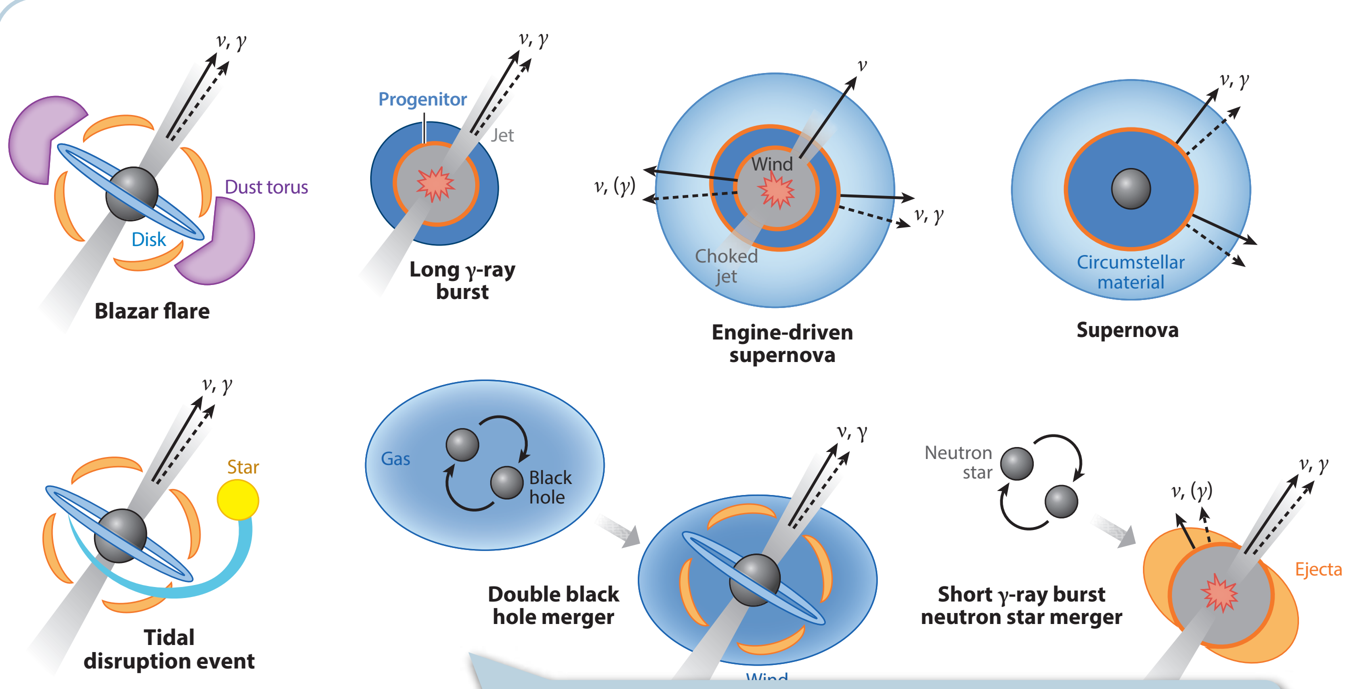
luminosity bounds

"Hillas plot for transients"

Optimizing the detectors locations on Earth to detect transients?



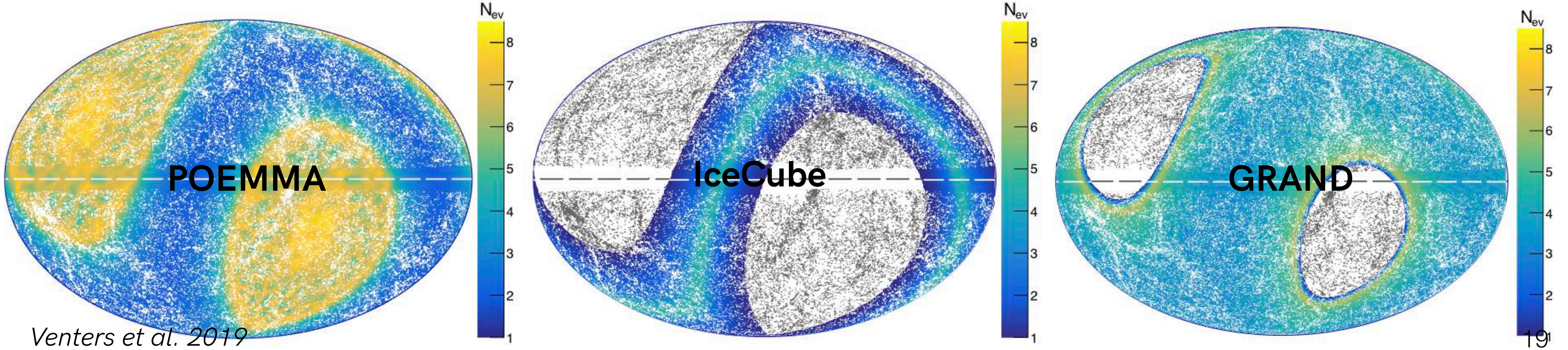
- detector instantaneous field of view
- location on Earth + rotation



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

Expected number of neutrino events

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



Venters et al. 2019

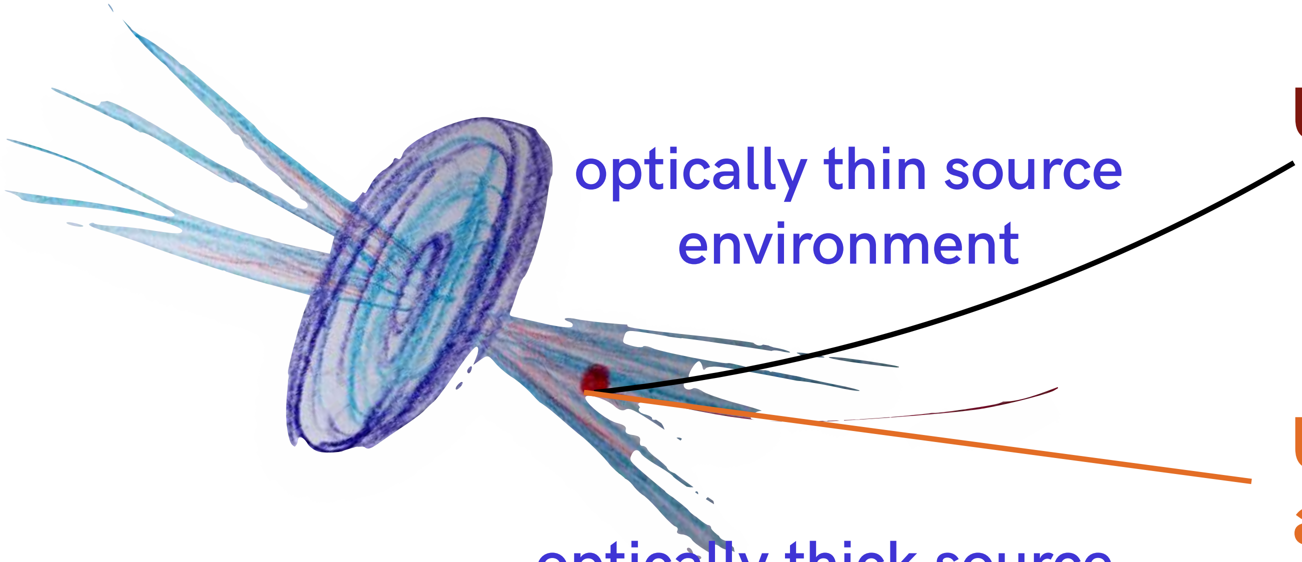
If the **measured** UHECR composition is not protons

it is NOT the end of the world at all!

- sources emitting observable UHECRs and UHE neutrinos **are likely not the same!**
  - a source will be opaque to UHECR protons to produce abundant UHE neutrinos
  - **observable** UHE (>10^{17} eV) neutrino sources are sources of UHECRs
  - **but they are likely NOT observable sources of UHECRs!**

if measured **UHECR composition** heavy
UHE neutrino astronomy completely possible

not really related



optically thin source environment

optically thick source environment

UHECRs escape
less abundant UHE neutrinos

UHECRs interact
abundant UHE neutrinos?

EeV Neutrino Astronomy

May your GRAND dreams come true!

Kumiko Kotera - Institut d'Astrophysique de Paris - IIHE