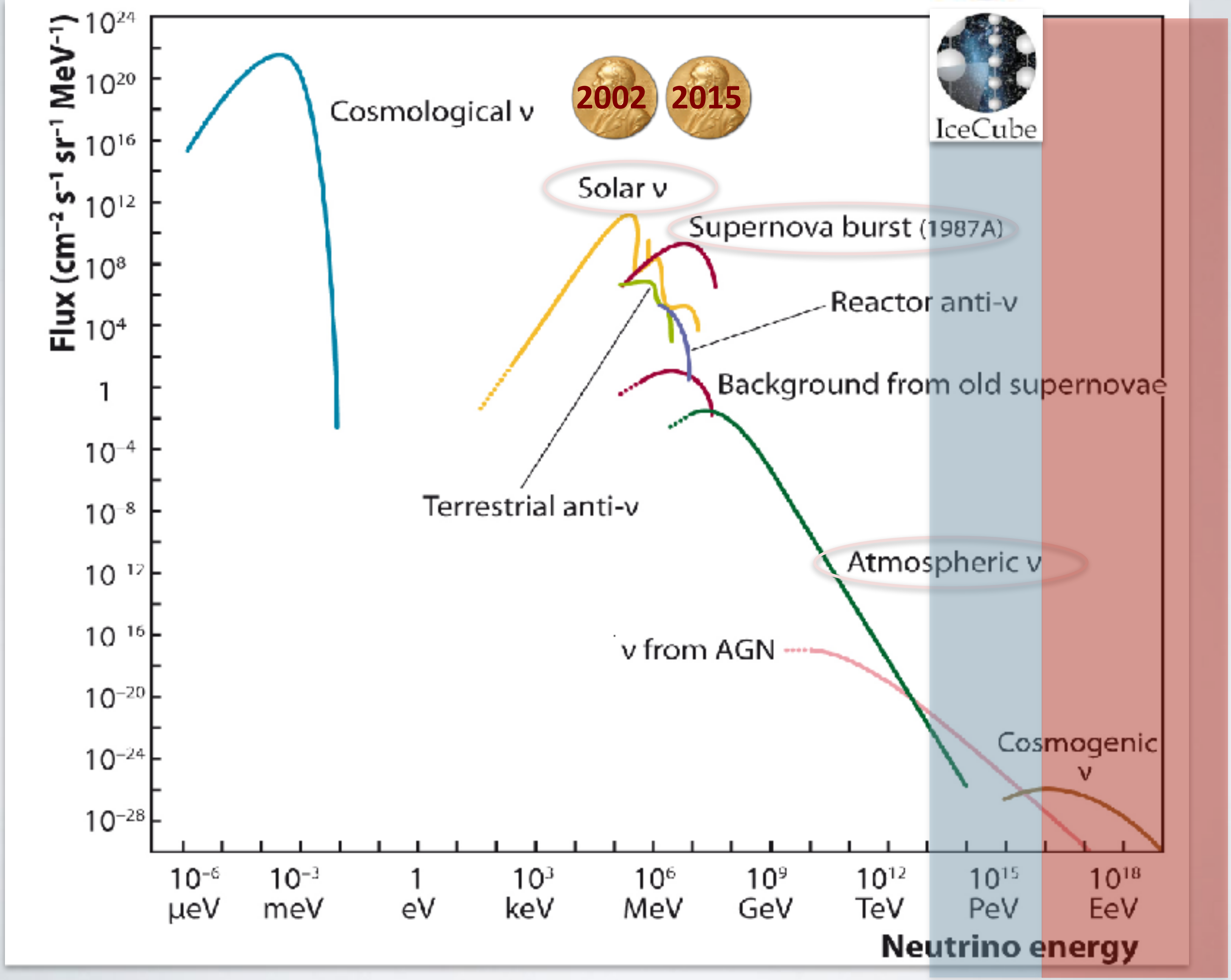
EeV Neutrino Astronomy

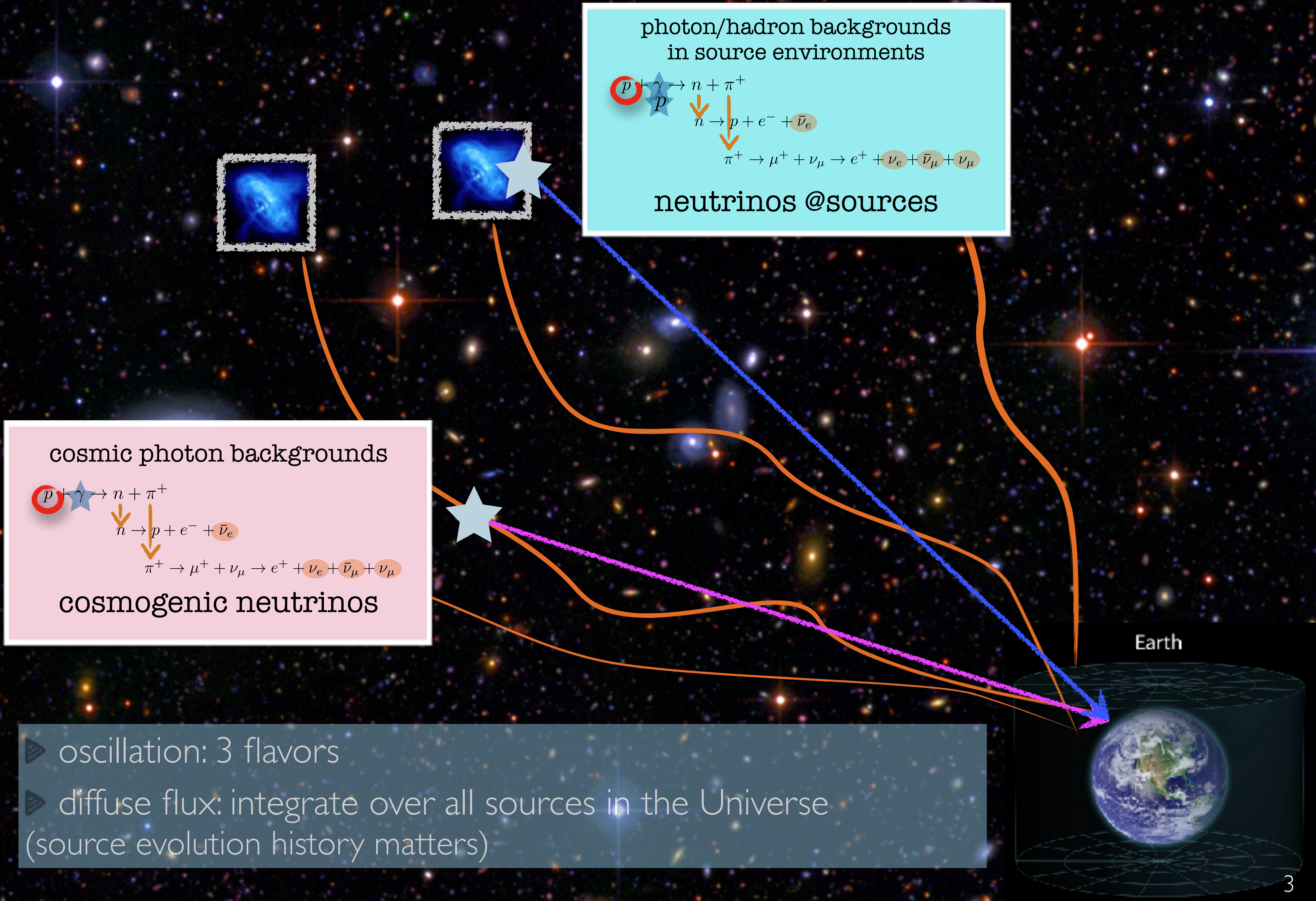
Kumiko Kotera - *Institut d'Astrophysique de Paris*

SuGAR 2018 - 24/01/2018

Neutrinos!


Flux (cm⁻² s⁻¹ sr⁻¹ MeV⁻¹)
10²⁴
10²⁰
10¹⁶
10¹²
10⁸
10⁴
1
10⁻⁴
10⁻⁸
10⁻¹²
10⁻¹⁶
10⁻²⁰
10⁻²⁴
10⁻²⁸
Cosmological ν
2002
2015
Solar ν
Supernova burst (1987A)
Reactor anti-ν
Background from old supernovae
Terrestrial anti-ν
Atmospheric ν
ν from AGN
Cosmogenic ν
10⁻⁶ μeV
10⁻³ meV
1 eV
10³ keV
10⁶ MeV
10⁹ GeV
10¹² TeV
10¹⁵ PeV
10¹⁸ EeV
Neutrino energy
KM3NeT
IceCube

Producing EeV neutrinos



photon/hadron backgrounds in source environments

$p + \gamma \rightarrow n + \pi^+$

p

$n \rightarrow p + e^- + \bar{\nu}_e$

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

neutrinos @sources

cosmic photon backgrounds

$p + \gamma \rightarrow n + \pi^+$

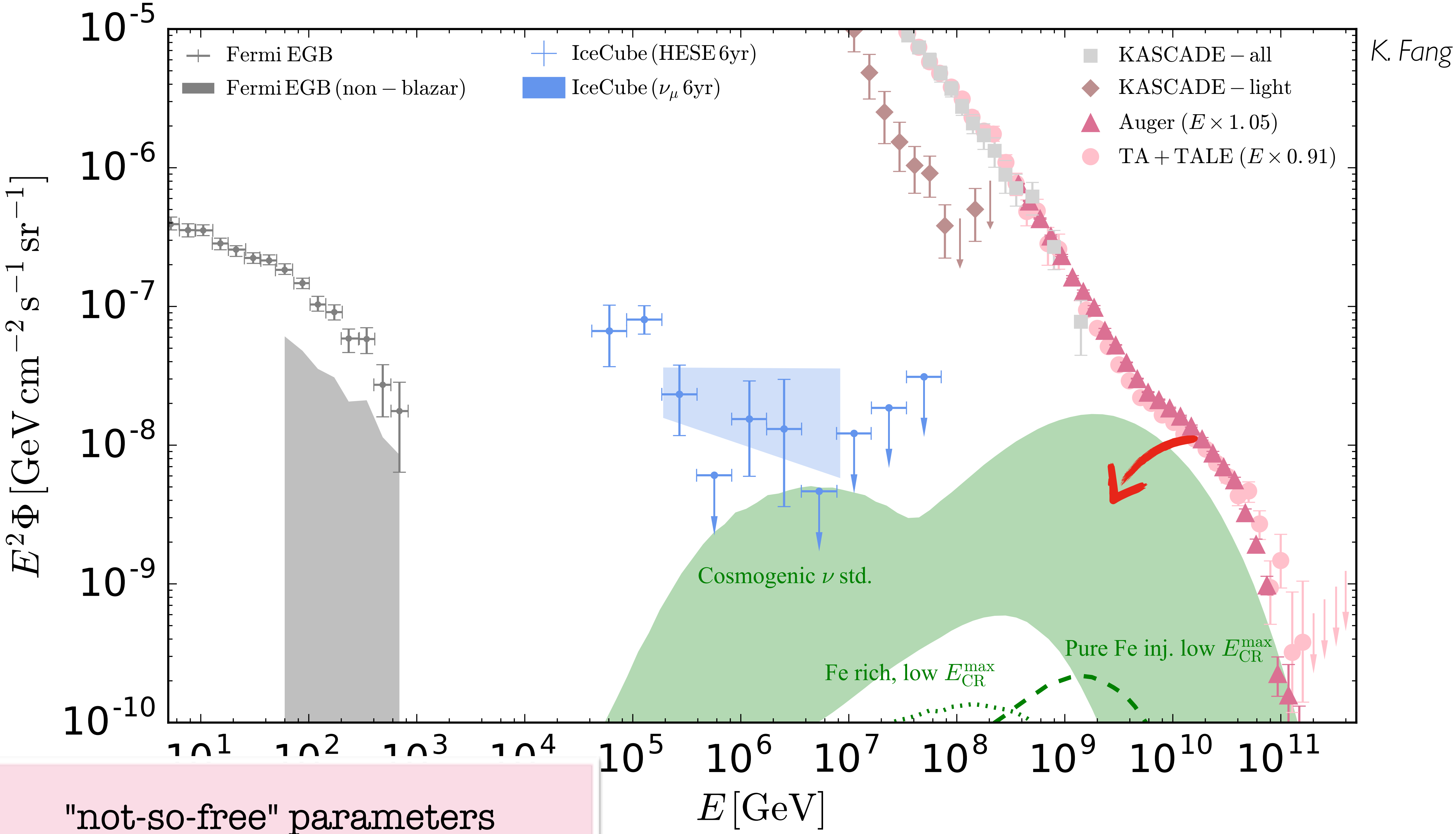
$n \rightarrow p + e^- + \bar{\nu}_e$

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

cosmogenic neutrinos

- oscillation: 3 flavors
- diffuse flux: integrate over all sources in the Universe (source evolution history matters)

The guaranteed cosmogenic neutrinos



"not-so-free" parameters

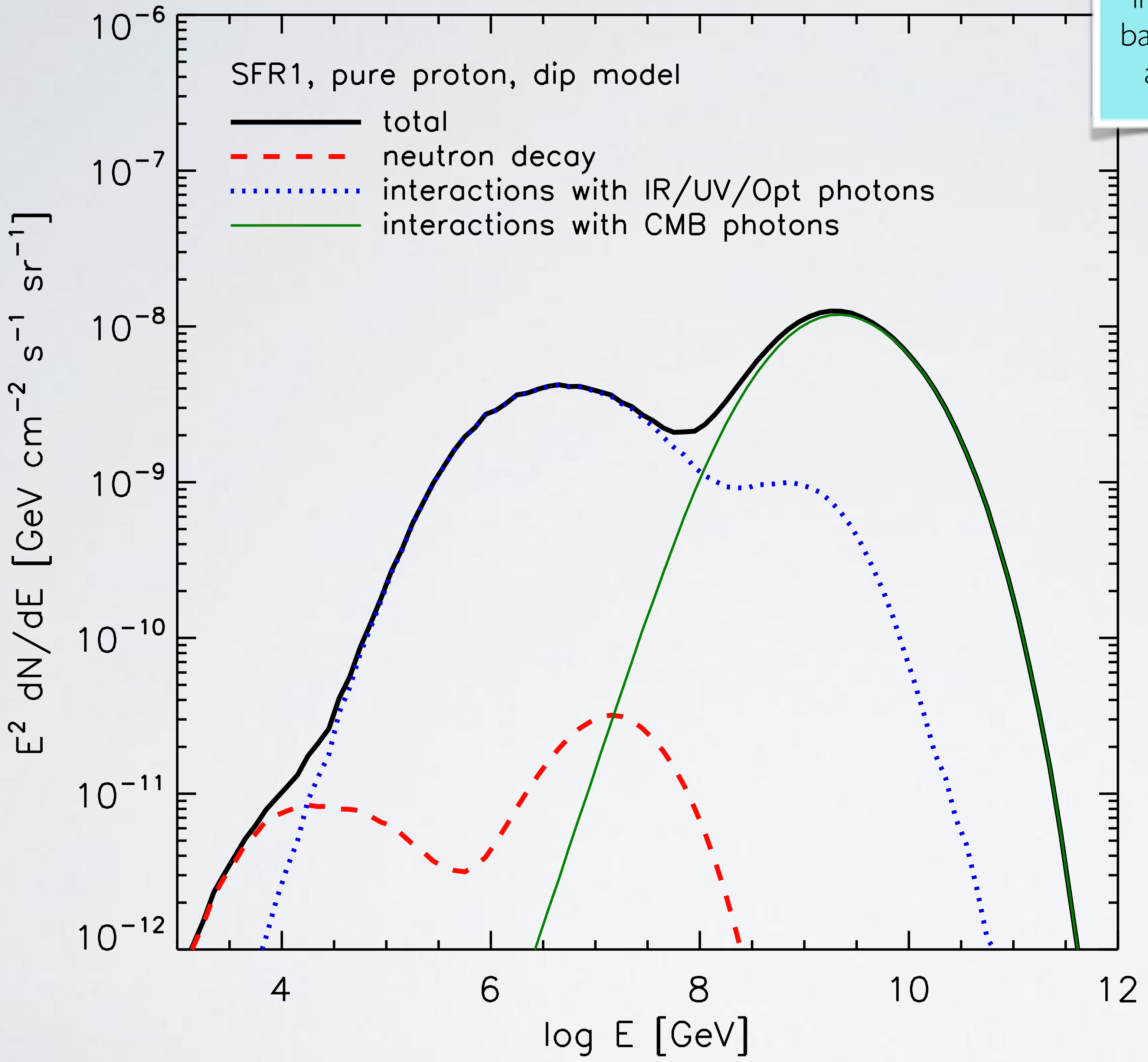
- A flux normalisation
- ɣ injection spectral index
- R_{max} (max. rigidity ~ max. proton energy)
- composition
- source evolution history

cosmogenic neutrinos guaranteed
if sources of UHECRs
@cosmological distances

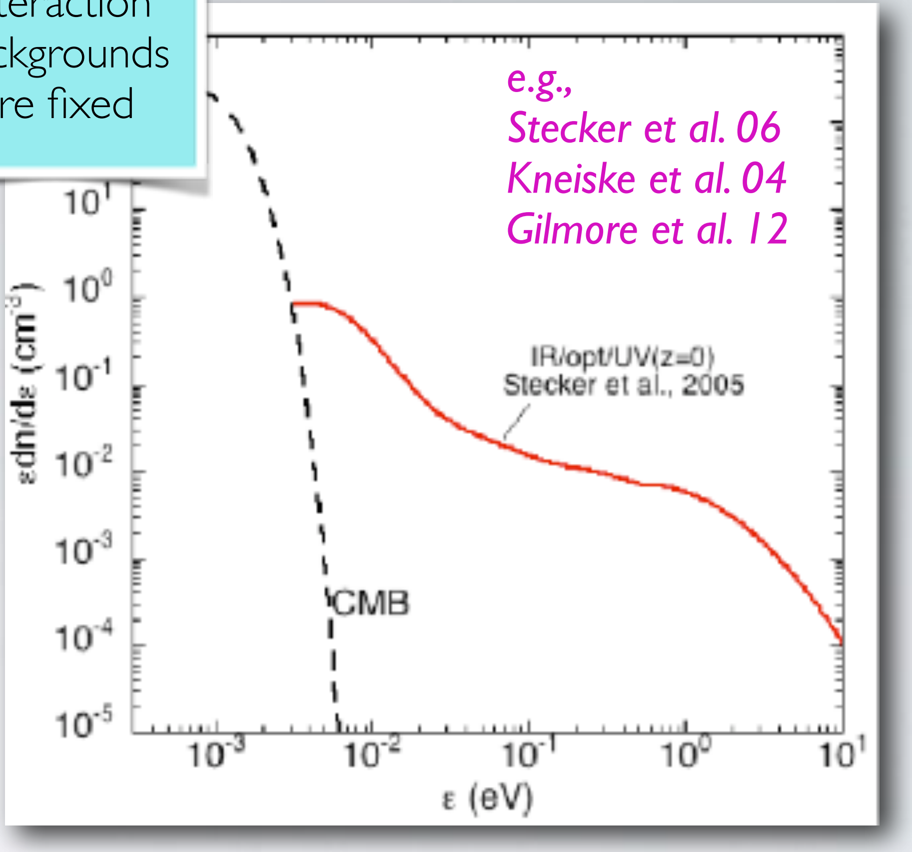
Cosmogenic neutrinos: production channels

KK, Allard, Olinto 2010

Diffuse flux



interaction backgrounds are fixed



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

Principal ingredients

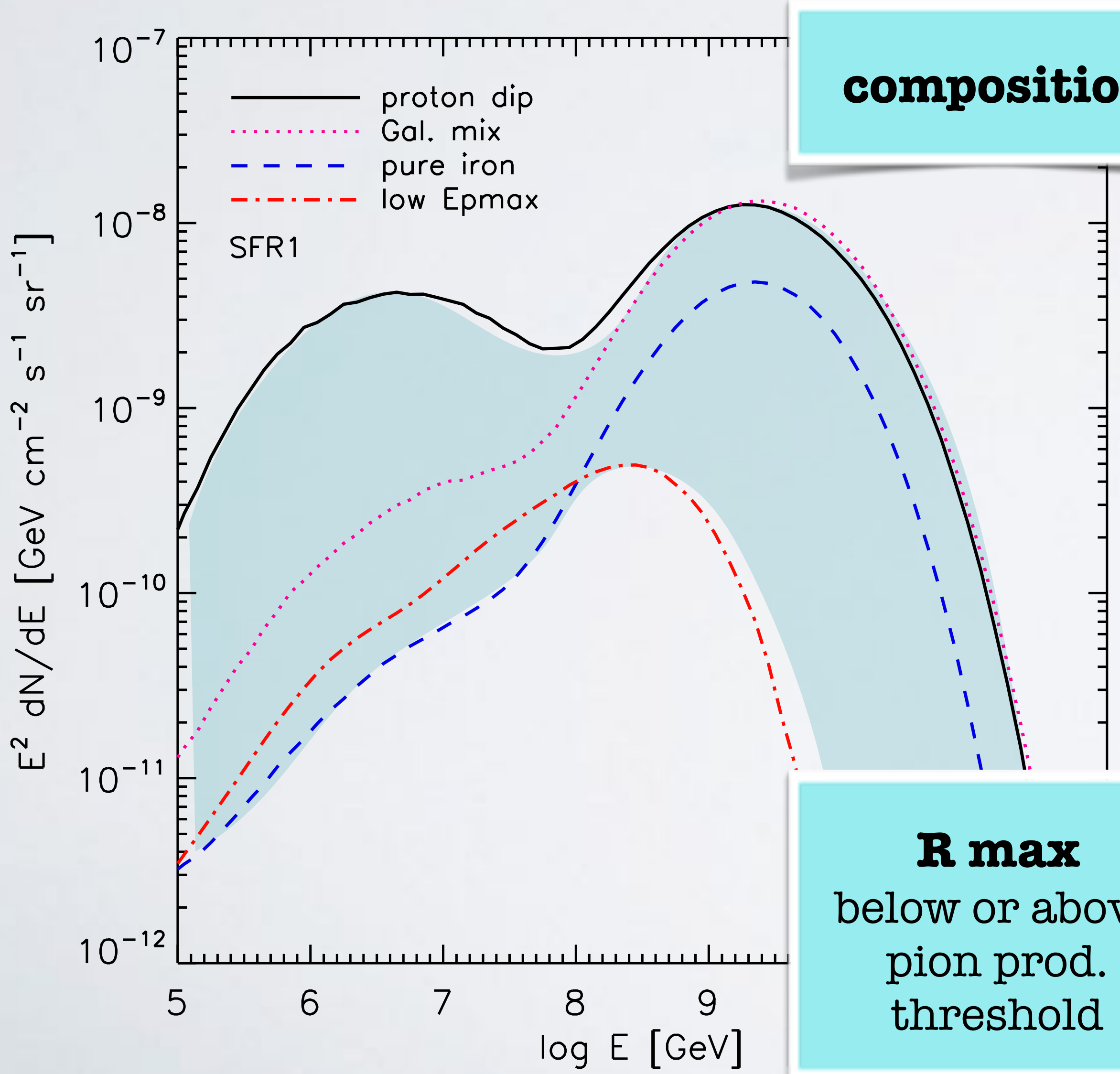
KK, Allard, Olinto 2010

"not-so-free" parameters

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

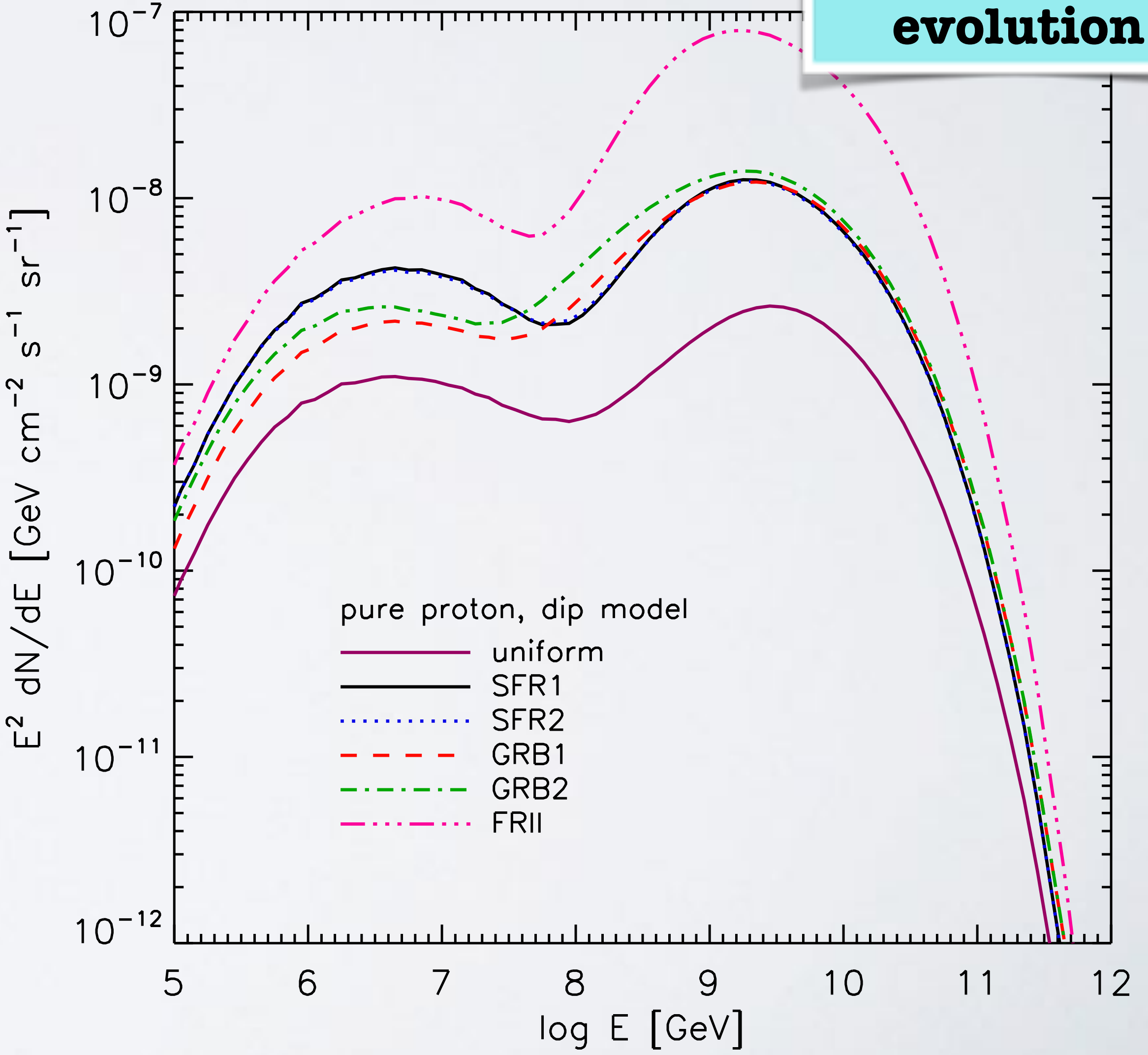
▶ depend strongly on observations of UHECRs

▶ less dependent but affects injection spectrum



composition

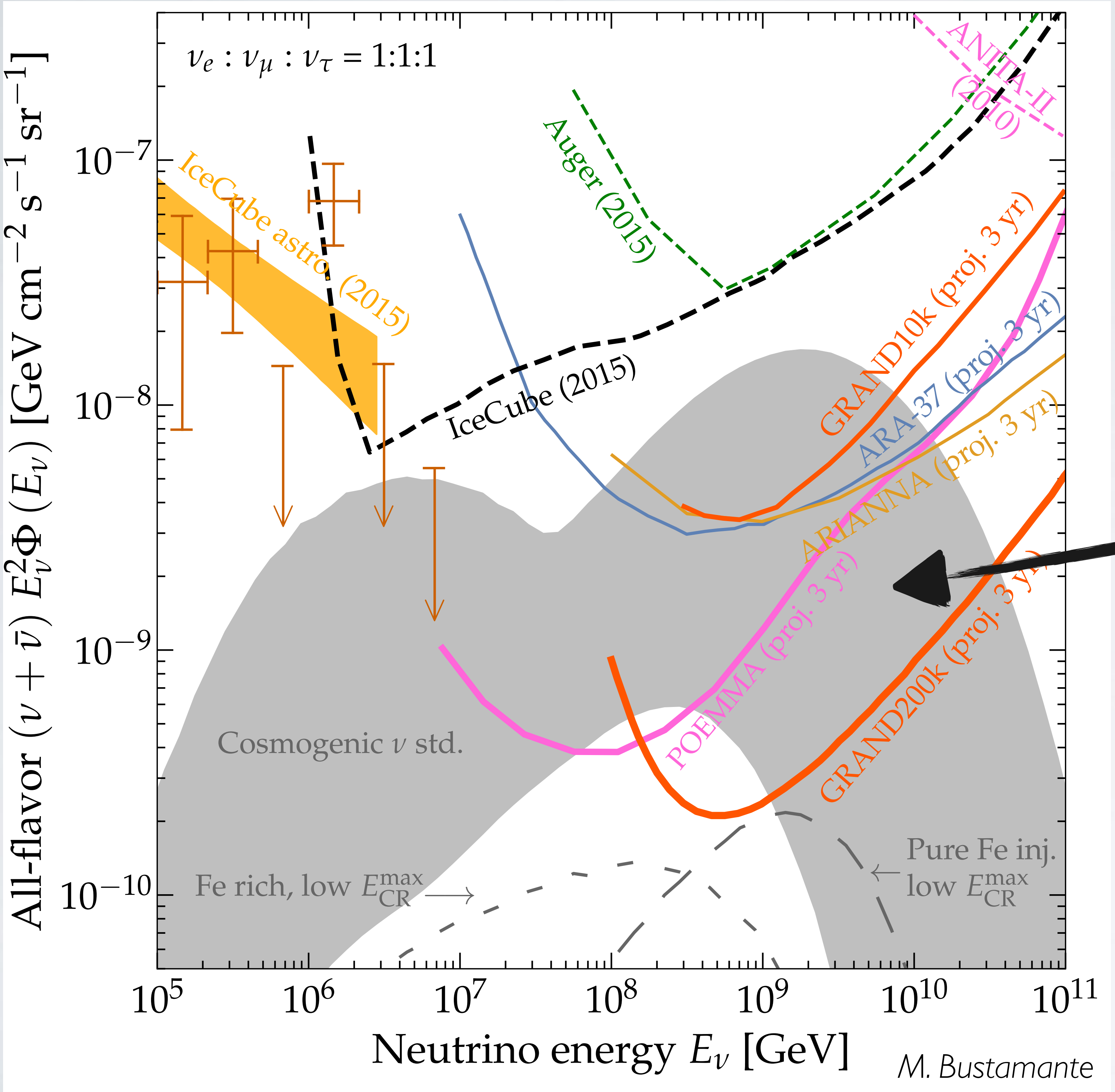
R max
below or above pion prod. threshold



source evolution

The guaranteed cosmogenic neutrinos

KK, Allard, Olinto 2010



M. Bustamante

R max
below or above pion prod. threshold

- Rmax = $10^{19-21.5}$ eV

spectral index
flux of secondary protons

- s=1.8-2.6

source evolution history

- ~SFR

composition

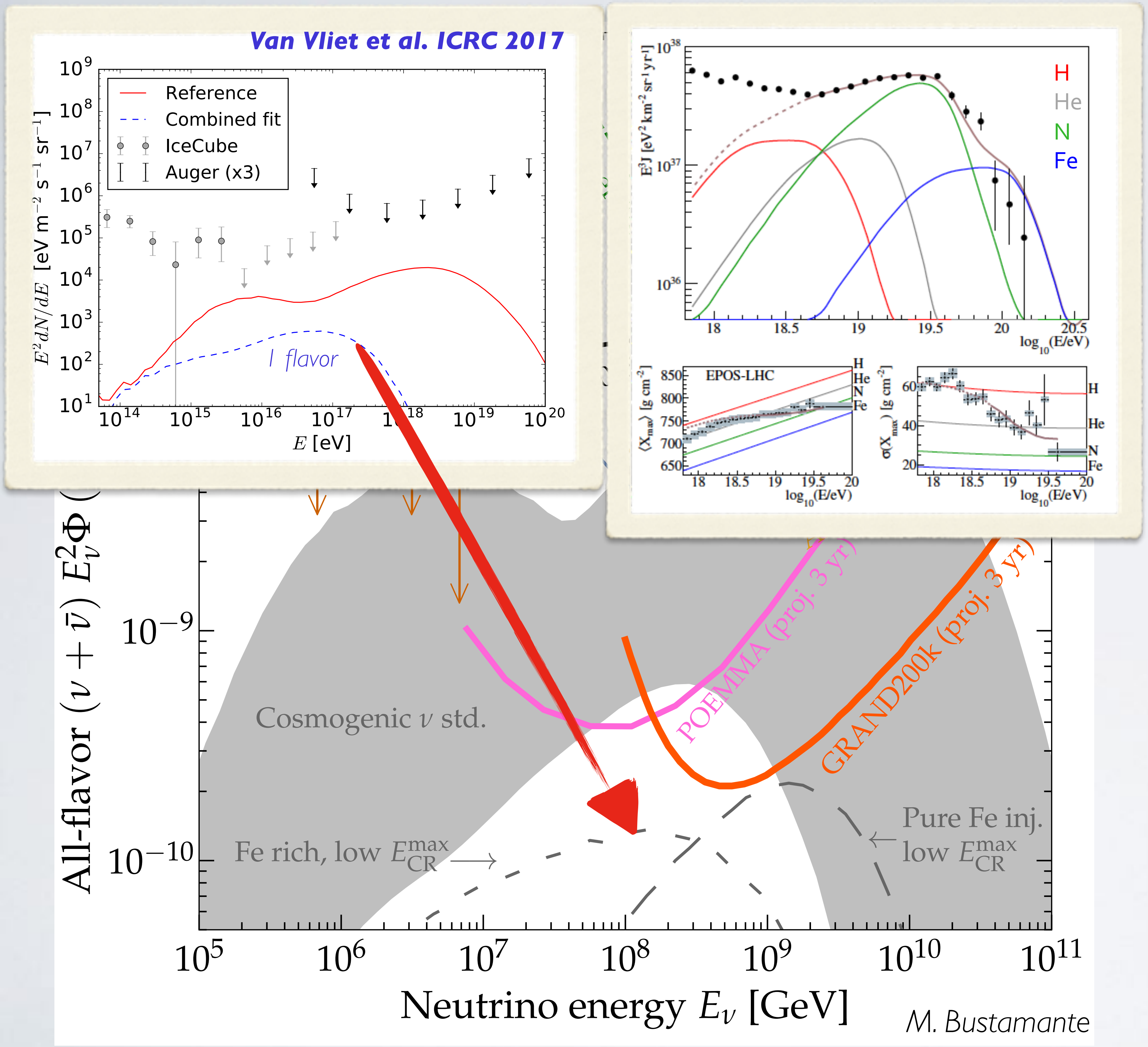
- 30% Fe
- Galactic mix
- 100% p

UHECR flux normalisation

The guaranteed cosmogenic neutrinos - Auger best fit

Auger Coll. ICRC 2017

Van Vliet et al. ICRC 2017



R max
below or above
pion prod.
threshold

- $R_{max} = 10^{18.62}$ eV

spectral index
flux of secondary
protons

- s=0.87

source evolution
histor

- uniform

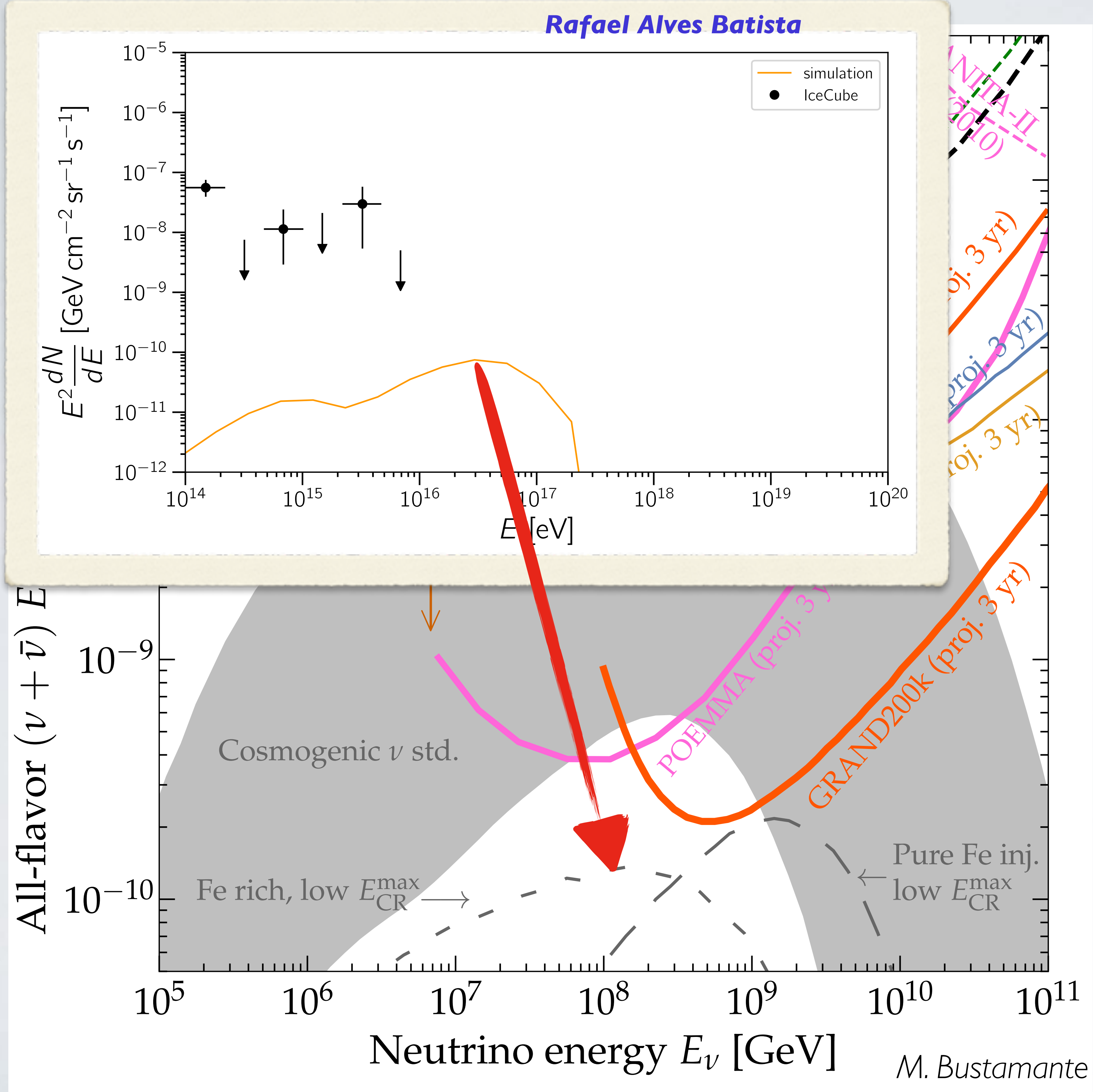
composi

- 88% Ni,
12% Si

UHECR flux
normalisation

New Auger best fit - relaxing source evolution

R. Alves Batista



R max
below or above pion prod. threshold

- Rmax = $10^{20.1}$ eV

spectral index
flux of secondary protons

- s=1

source evolution histor

- m=-1.5

composi

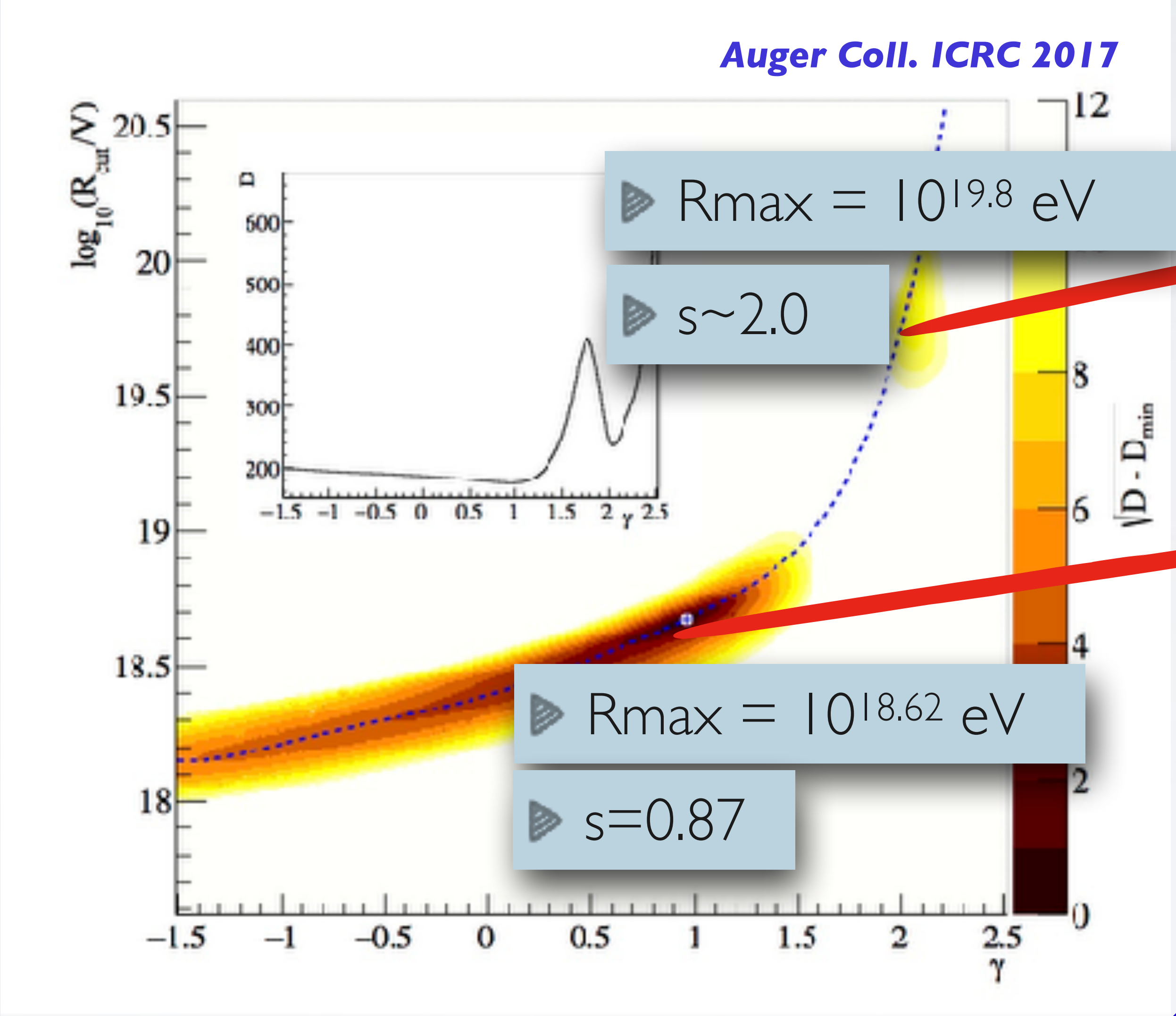
- 88% Ni, 12% Si

UHECR flux normalisation

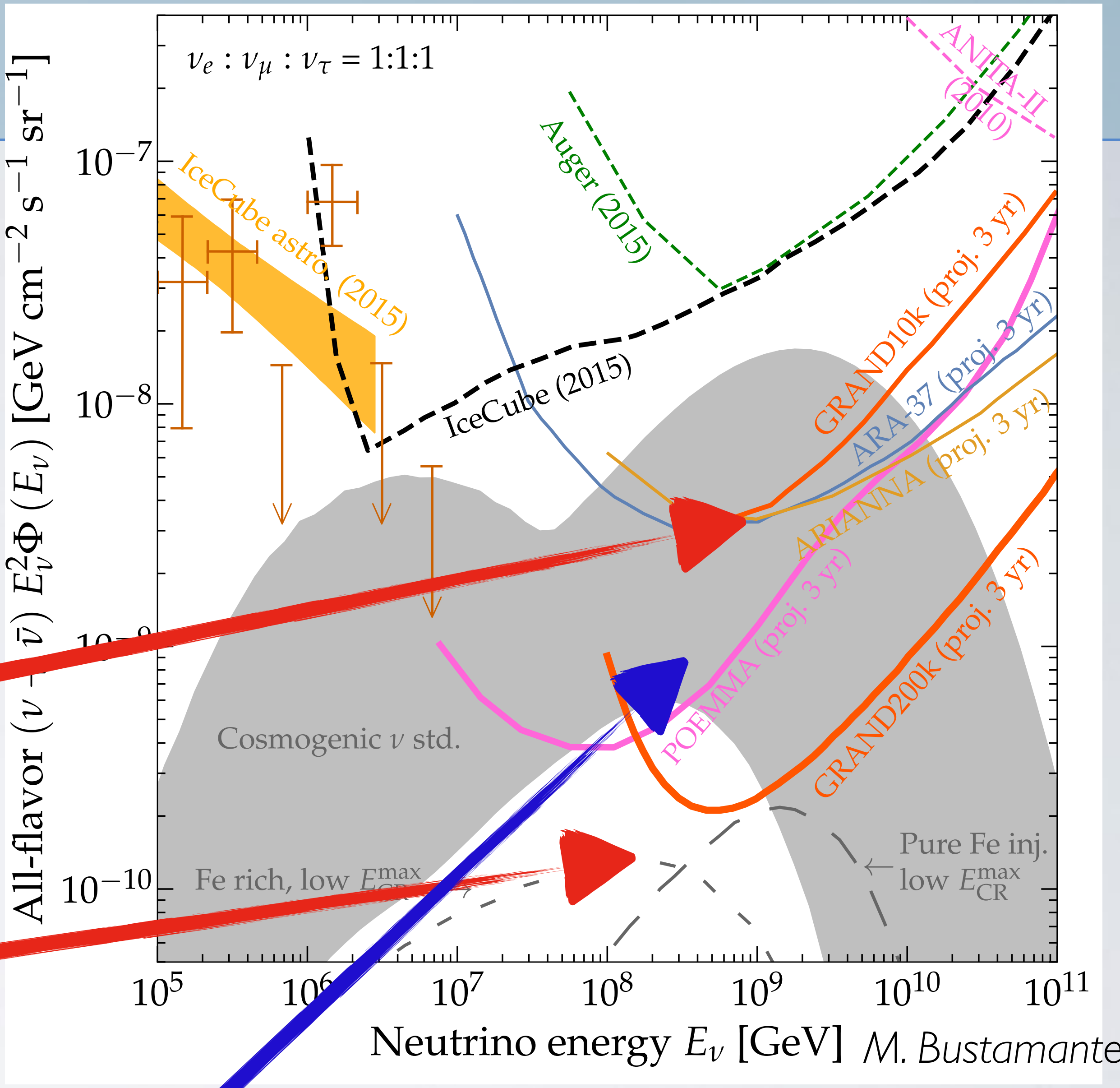
The Auger best fits

FIG. 8. Two-dimensional projection of the parameter space illustrating the goodness of data description. Contributions from five mass groups are considered: ^{1}H, ^{2}He, ^{14}N, ^{28}Si, and ^{56}Fe. The minimized χ^2 is shown as function of the cosmic-ray injection index γ and the maximum rigidity $R_{\rm cut}$ above which an exponential suppression of the source flux is assumed. Figure

Auger Coll. ICRC 2017



- Rmax = $10^{19.8}$ eV
- s~2.0
- Rmax = $10^{18.62}$ eV
- s=0.87



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Wittkowski & Auger Coll. ICRC 2017

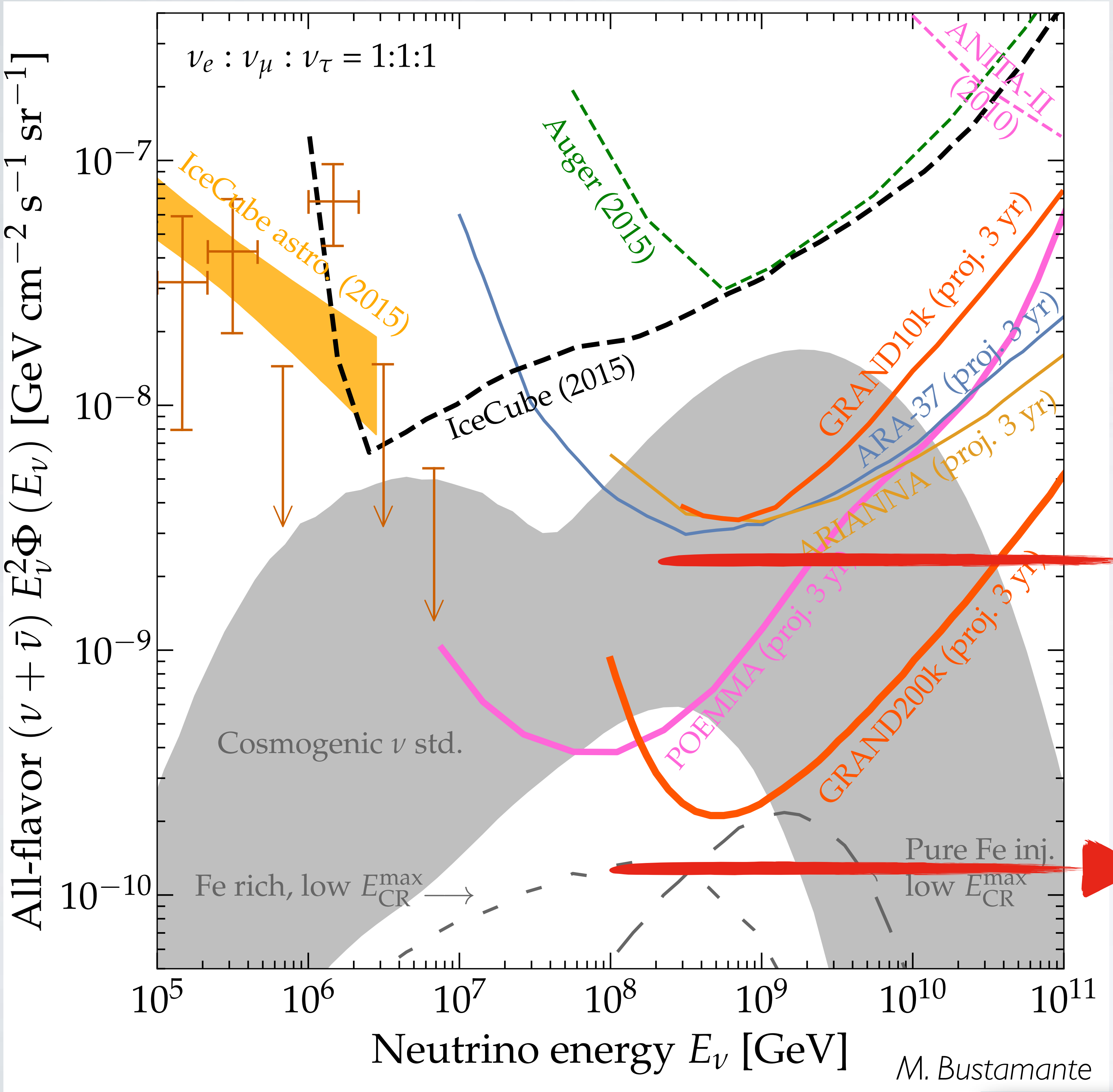
- influence of EGMF

Model	γ	$\log_{10}(\frac{R_{\rm cut}}{\rm eV})$	$f_{\rm H}/\%$	$f_{\rm He}/\%$	$f_{\rm N}/\%$	$f_{\rm Si}/\%$	$f_{\rm Fe}/\%$	$D_{\rm min} = D^J_{\rm min} + D^{X_{\rm max}}_{\rm min}$
I	$1.61^{+0.08}_{-0.07}$	$18.88^{+0.03}_{-0.07}$	3.0	2.1	73.5	21.0	0.4	$191.9 = 37.3 + 154.6$
II	$0.61^{+0.05}_{-0.06}$	$18.48^{+0.01}_{-0.02}$	11.0	13.8	67.9	7.2	0.1	$221.3 = 48.7 + 172.6$
see [3]	$0.87^{+0.08}_{-0.06}$	$18.62^{+0.02}_{-0.02}$	0	0	88	12	0	$191.9 = 29.2 + 162.7$

Table 1: Best-fit parameter values of γ, $R_{\rm cut}$, and f_α with $\alpha \in \{\rm H, He, N, Si, Fe\}$ obtained by minimizing the deviance D as well as the minimal deviance $D_{\rm min}$ and the contributions $D^J_{\rm min}$ and $D^{X_{\rm max}}_{\rm min}$ for our models I (with EGMF) and II (without EGMF). For comparison, the results of the 1D simulations from [3] are also shown.

The guaranteed cosmogenic neutrinos

KK, Allard, Olinto 2010



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GRAND **10k**

ARIANNA

ASKARYAN RADIO ARRAY

if lucky: a few EeV cosmogenic neutrinos

POEMMA

GRAND

EeV neutrinos guaranteed
if lucky: hundreds of events

GRAND talk by S. de Jong this afternoon

Producing EeV neutrinos

photon/hadron backgrounds
in source environments

$p + \gamma \to n + \pi^+$

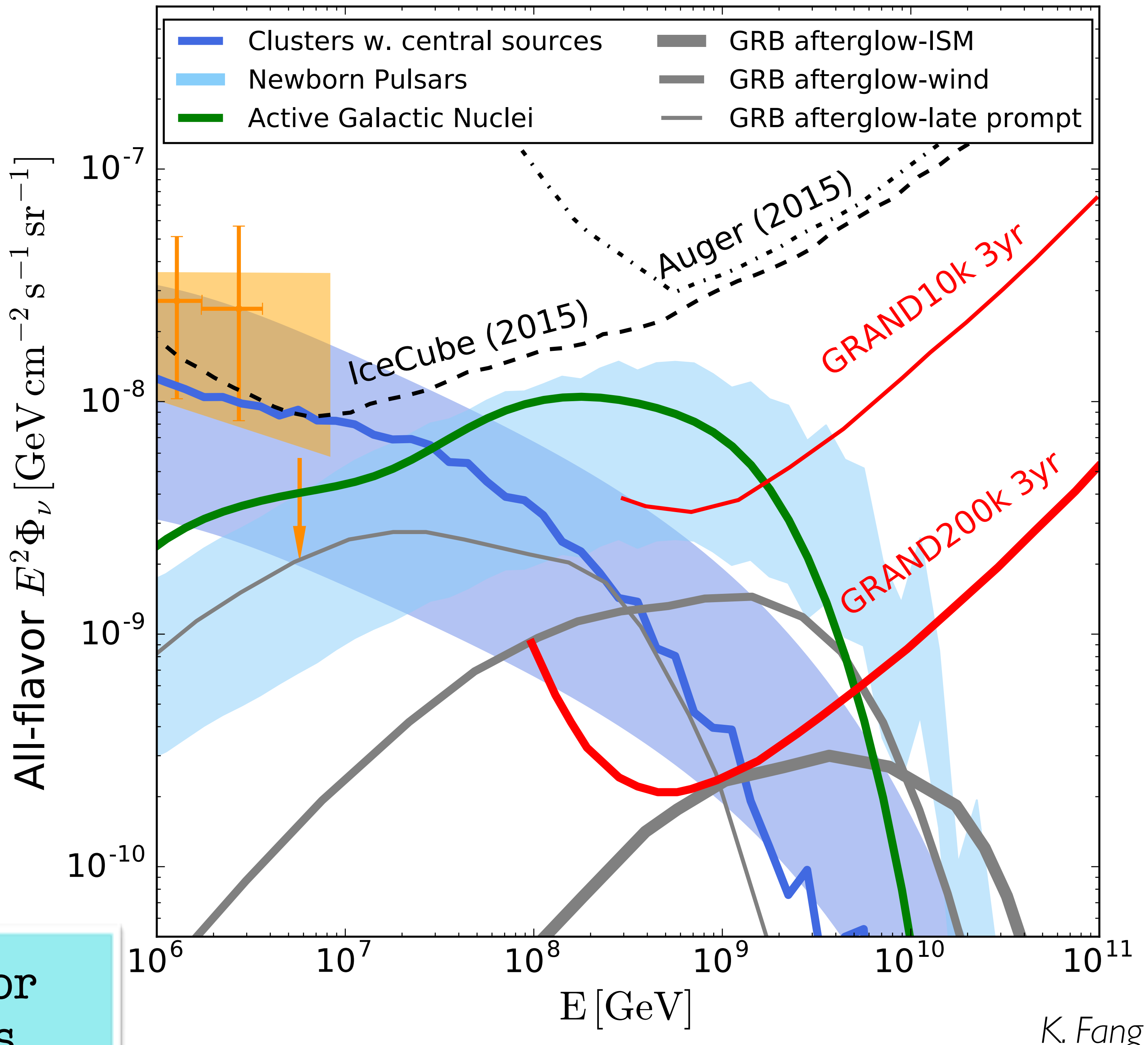
$n \to p + e^- + \bar{\nu}_e$

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

neutrinos @sources

Neutrinos produced at the source (diffuse flux)

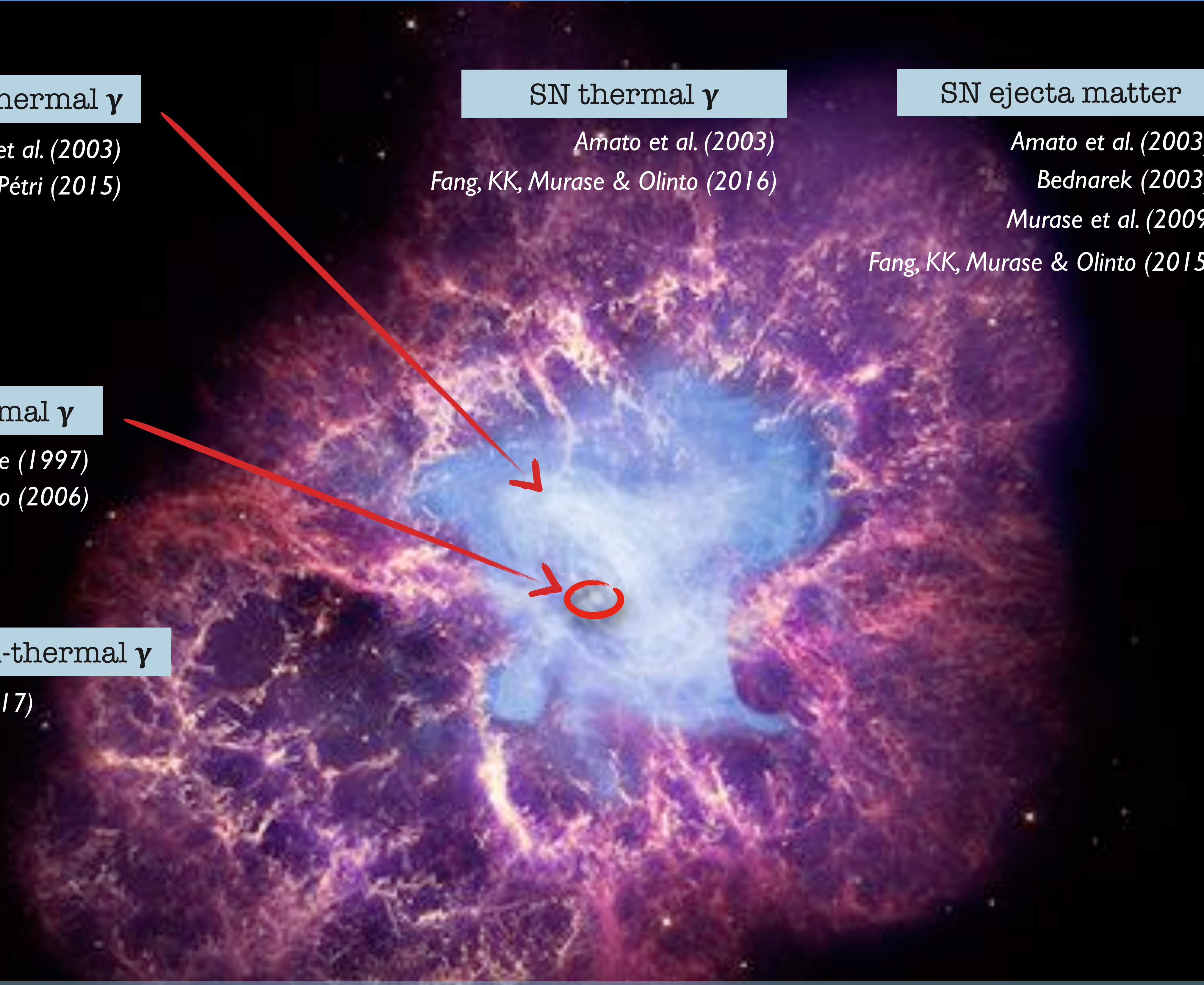
Diffuse flux (integrated over the whole population)



K. Fang

unique shapes for various sources (because of interaction backgrounds)

Interaction backgrounds for neutrino production



nebula non-thermal γ

Amato et al. (2003)
Lemoine, KK, Pétri (2015)

SN thermal γ

Amato et al. (2003)
Fang, KK, Murase & Olinto (2016)

SN ejecta matter

Amato et al. (2003)
Bednarek (2003)
Murase et al. (2009)
Fang, KK, Murase & Olinto (2015, 2016)

star's thermal γ

Bednarek & Protheroe (1997)
Link & Burgio (2006)

Crab flares non-thermal γ

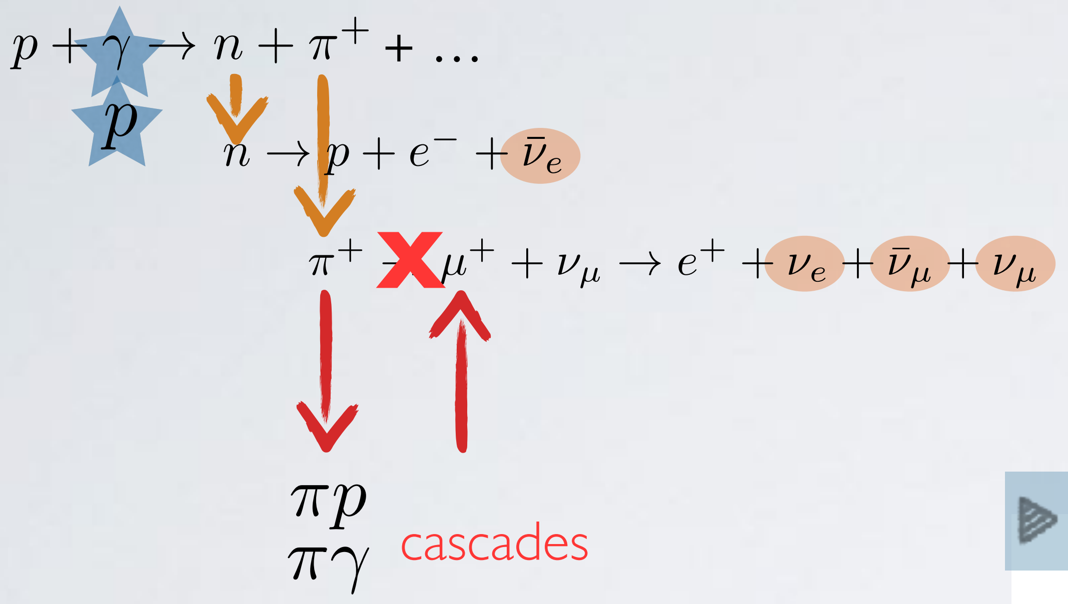
Guépin & Kotera (2017)

- Most promising for > PeV neutrinos: interactions in SN

Understanding the neutrino spectra from SN region

Murase et al. (2009)
Fang, KK, Murase, Olinto 2013, 2016

Most promising & robust way to produce observable > PeV neutrinos from pulsars/magnetars



$p + \gamma \to n + \pi^+ + \ldots$

p

$n \to p + e^- + \bar{\nu}_e$

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

πp

$\pi\gamma$ cascades

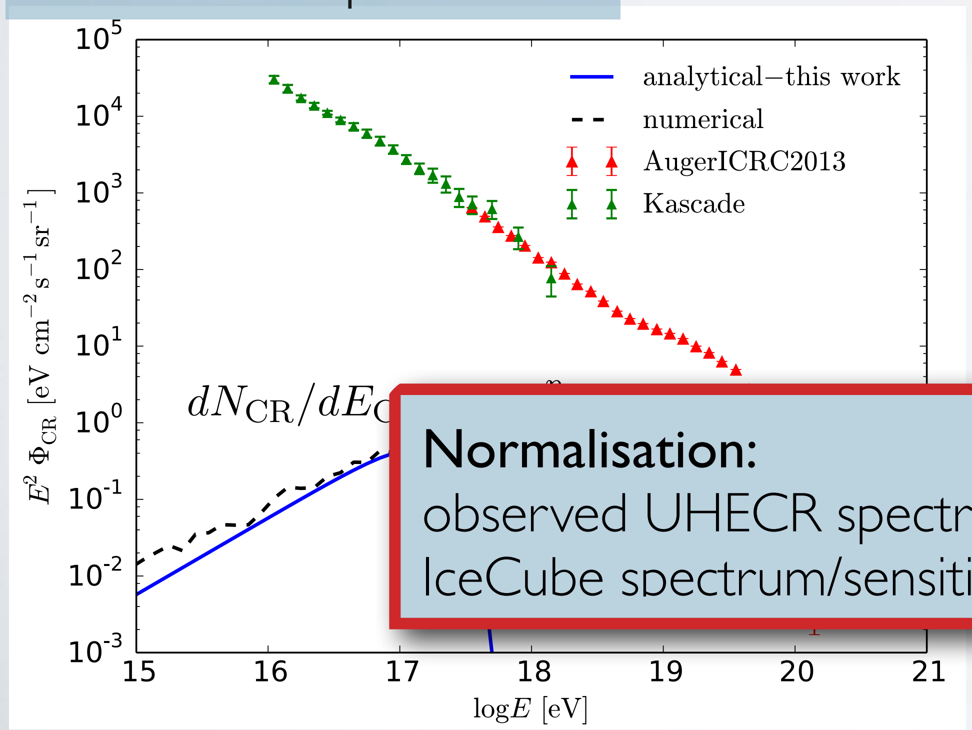
meson production efficiency

$$f_{\rm mes} = \min\left(\tau_{pp} + \tau_{p\gamma}, 1\right)$$

neutrino suppression factor

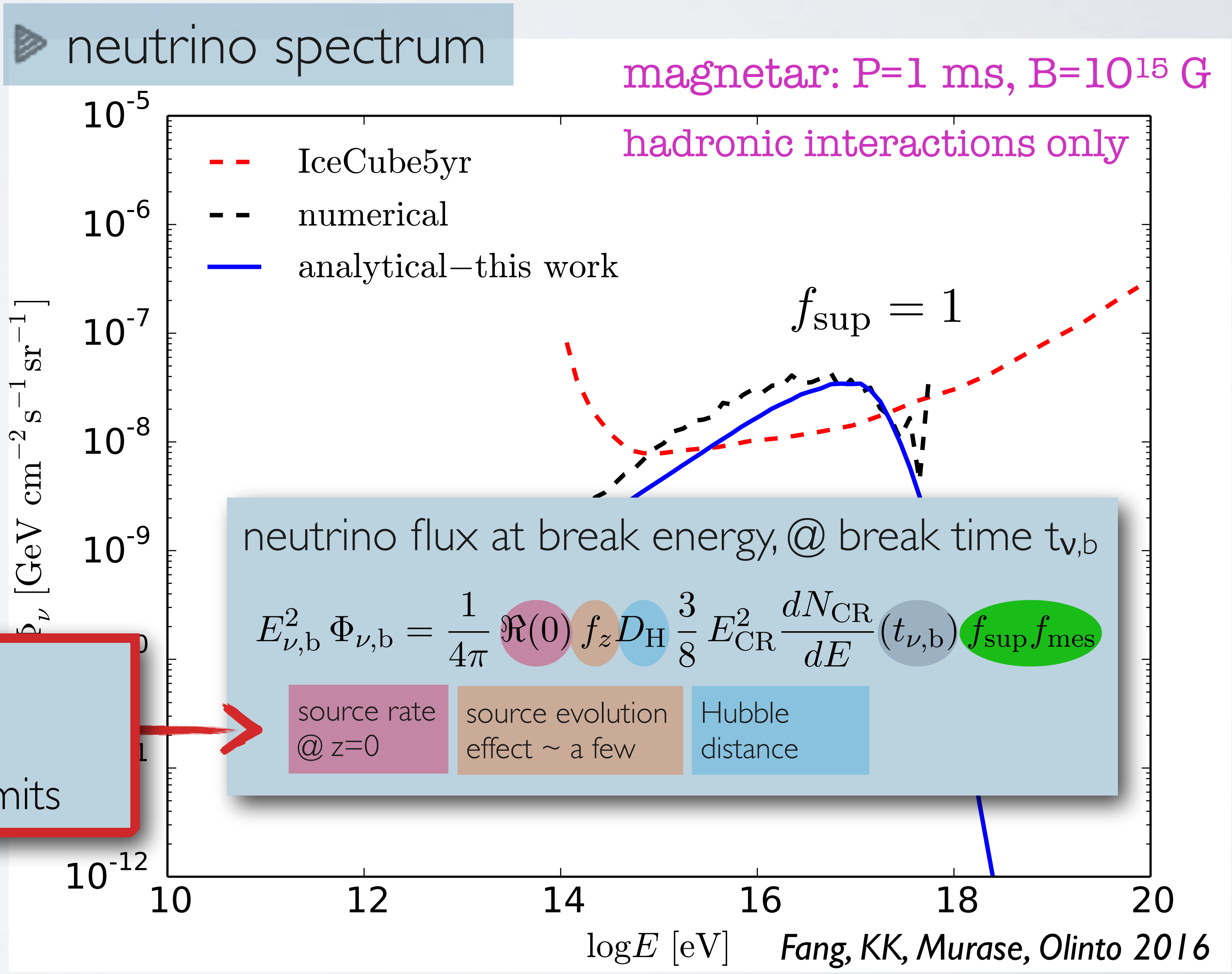
$$f_{\rm sup} = \min\left[1, \left(\left(\frac{t_{\pi p}}{\gamma_\pi\, \tau_\pi}\right)^{-1} + \left(\frac{t_{\pi\gamma}}{\gamma_\pi\, \tau_\pi}\right)^{-1}\right)^{-1}\right]$$

UHECR spectrum



Normalisation:
observed UHECR spectrum
IceCube spectrum/sensitivity limits

neutrino spectrum



neutrino flux at break energy, @ break time $t_{\nu,b}$

$$E^2_{\nu,b}\,\Phi_{\nu,b} = \frac{1}{4\pi}\,\Re(0)\,f_z D_{\rm H}\,\frac{3}{8}\,E^2_{\rm CR}\,\frac{dN_{\rm CR}}{dE}(t_{\nu,b})\,f_{\rm sup} f_{\rm mes}$$

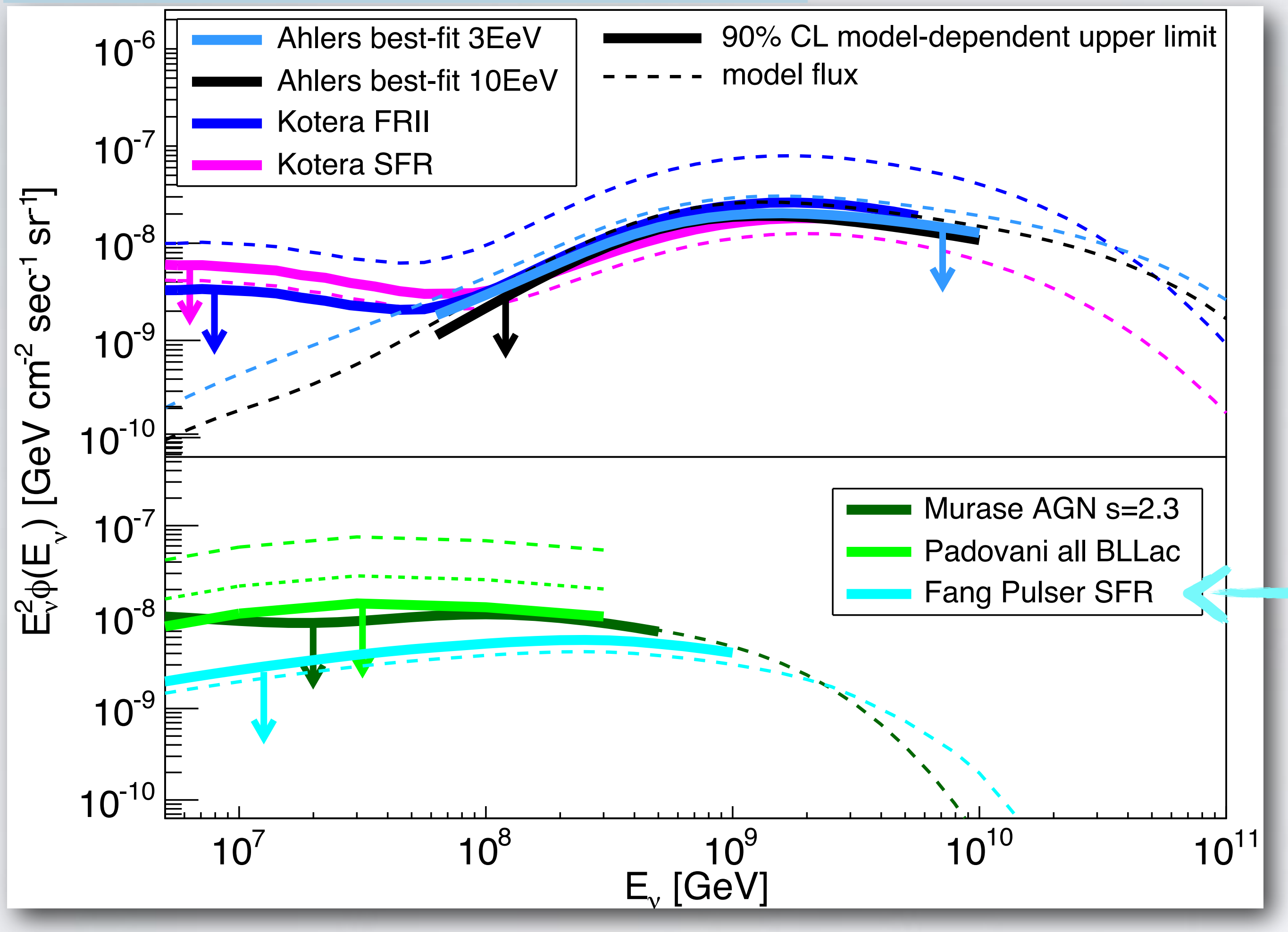
source rate @ z=0	source evolution effect ~ a few	Hubble distance

Fang, KK, Murase, Olinto 2016

IceCube constraints on newborn pulsars as sources of UHECRs

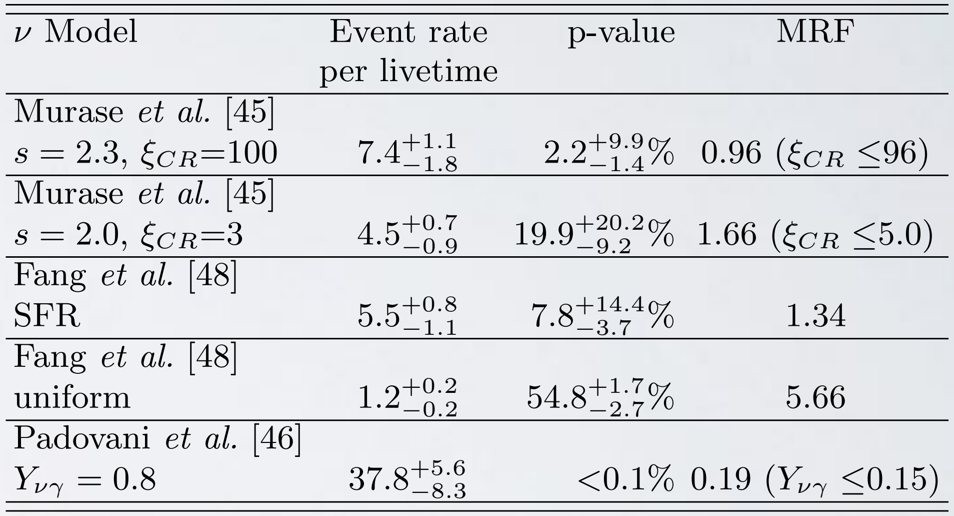
Aartsen et al. 2016

model dependent 90% C.L. limits



Expected number of events in 2426 days of effective livetime

Model Rejection Factor



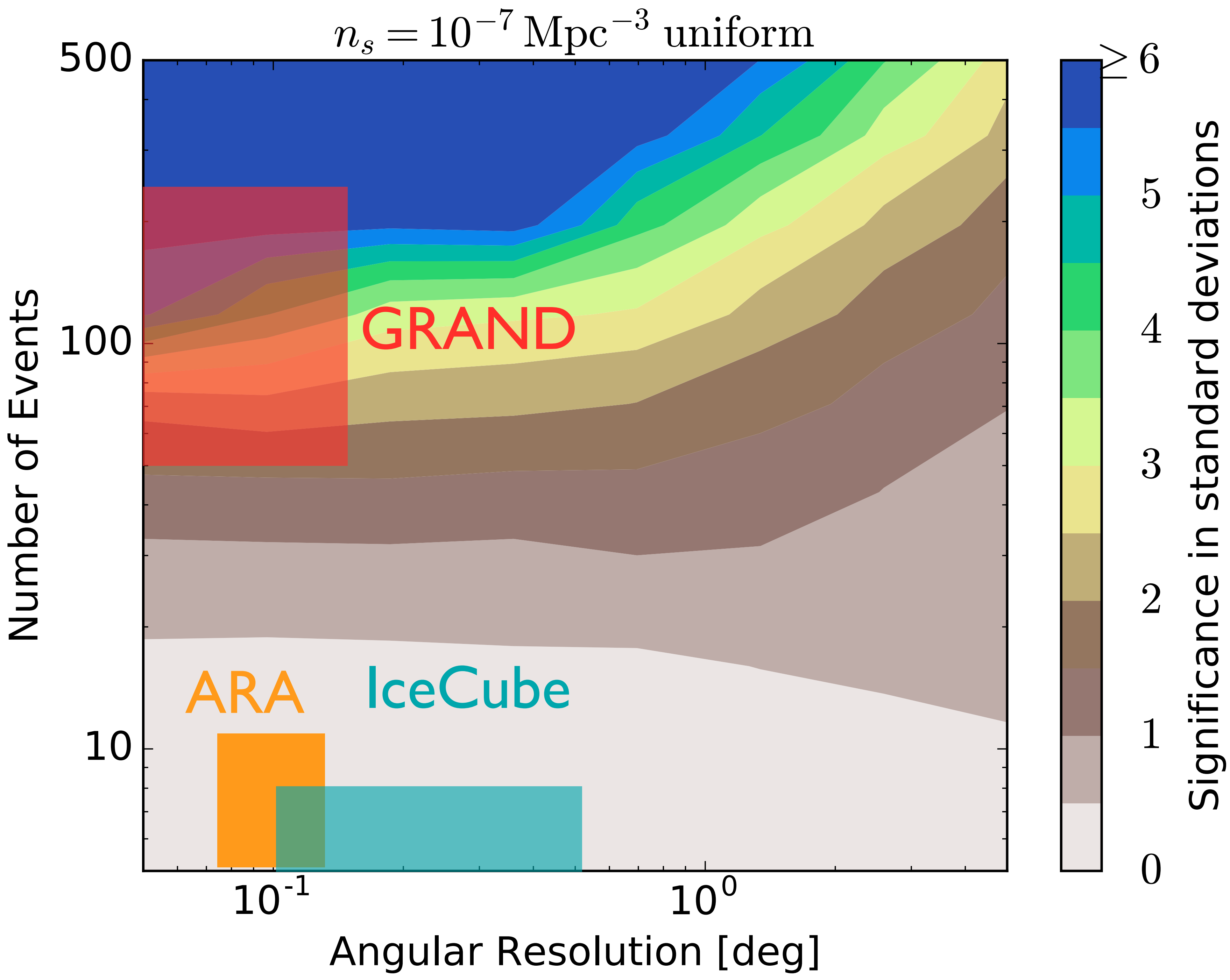
ν Model	Event rate per livetime	p-value	MRF
Murase *et al.* [45] $s = 2.3$, ξ_{CR}=100	$7.4^{+1.1}_{-1.8}$	$2.2^{+9.9}_{-1.4}\%$	0.96 ($\xi_{CR} \leq 96$)
Murase *et al.* [45] $s = 2.0$, ξ_{CR}=3	$4.5^{+0.7}_{-0.9}$	$19.9^{+20.2}_{-9.2}\%$	1.66 ($\xi_{CR} \leq 5.0$)
Fang *et al.* [48] SFR	$5.5^{+0.8}_{-1.1}$	$7.8^{+14.4}_{-3.7}\%$	1.34
Fang *et al.* [48] uniform	$1.2^{+0.2}_{-0.2}$	$54.8^{+1.7}_{-2.7}\%$	5.66
Padovani *et al.* [46] $Y_{\nu\gamma} = 0.8$	$37.8^{+5.6}_{-8.3}$	<0.1%	0.19 ($Y_{\nu\gamma} \leq 0.15$)

MRF = ratio of expected average upper limit to expected signal

- Population of newborn pulsars as sources of UHECRs **following star formation rate** excluded at 99.9% C.L.

Can we detect very high-energy neutrino sources?

Fang, KK, Murase, Miller, Oikonomou 2016

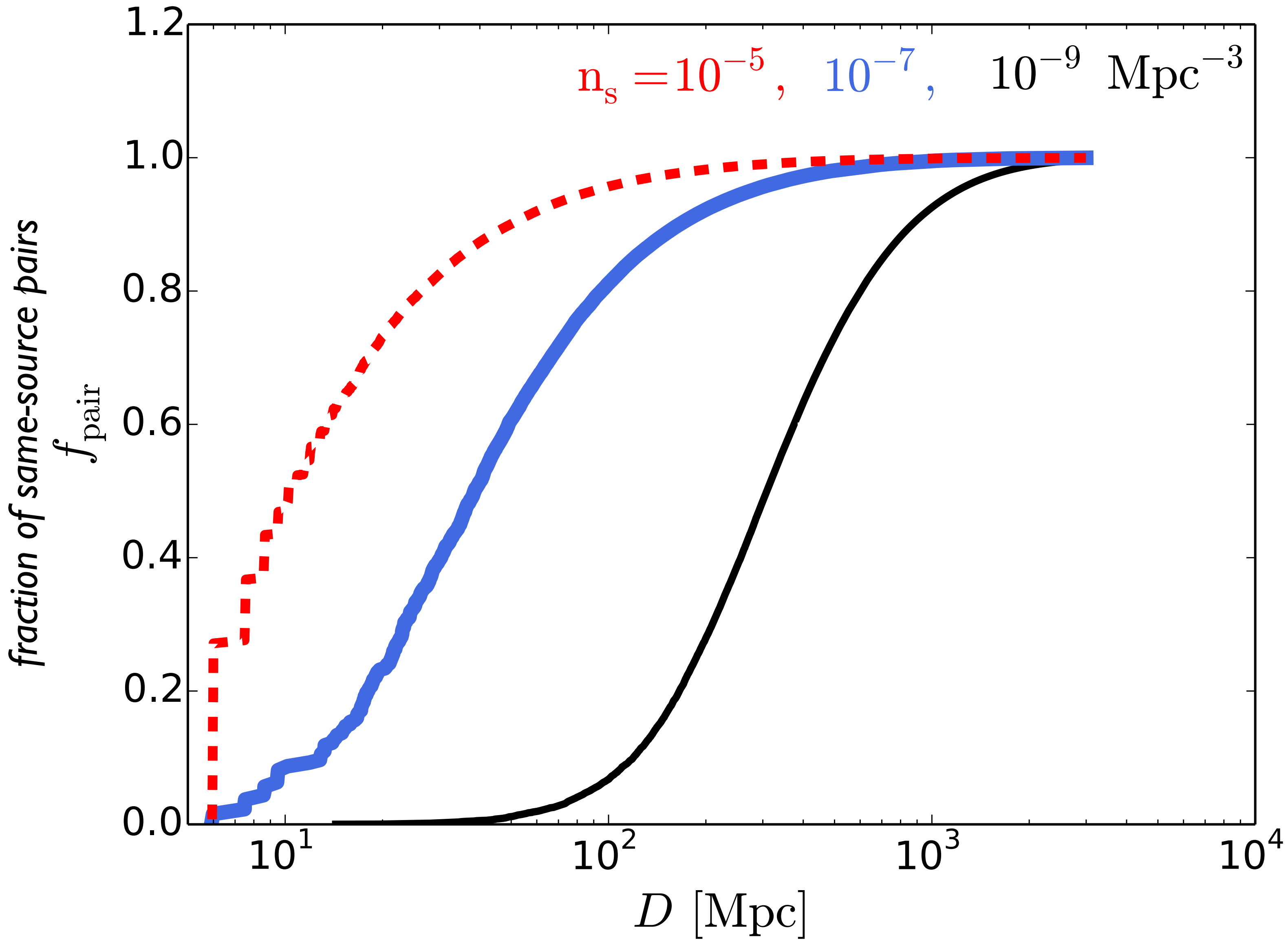


YES if

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

Can we detect very high-energy neutrino sources?

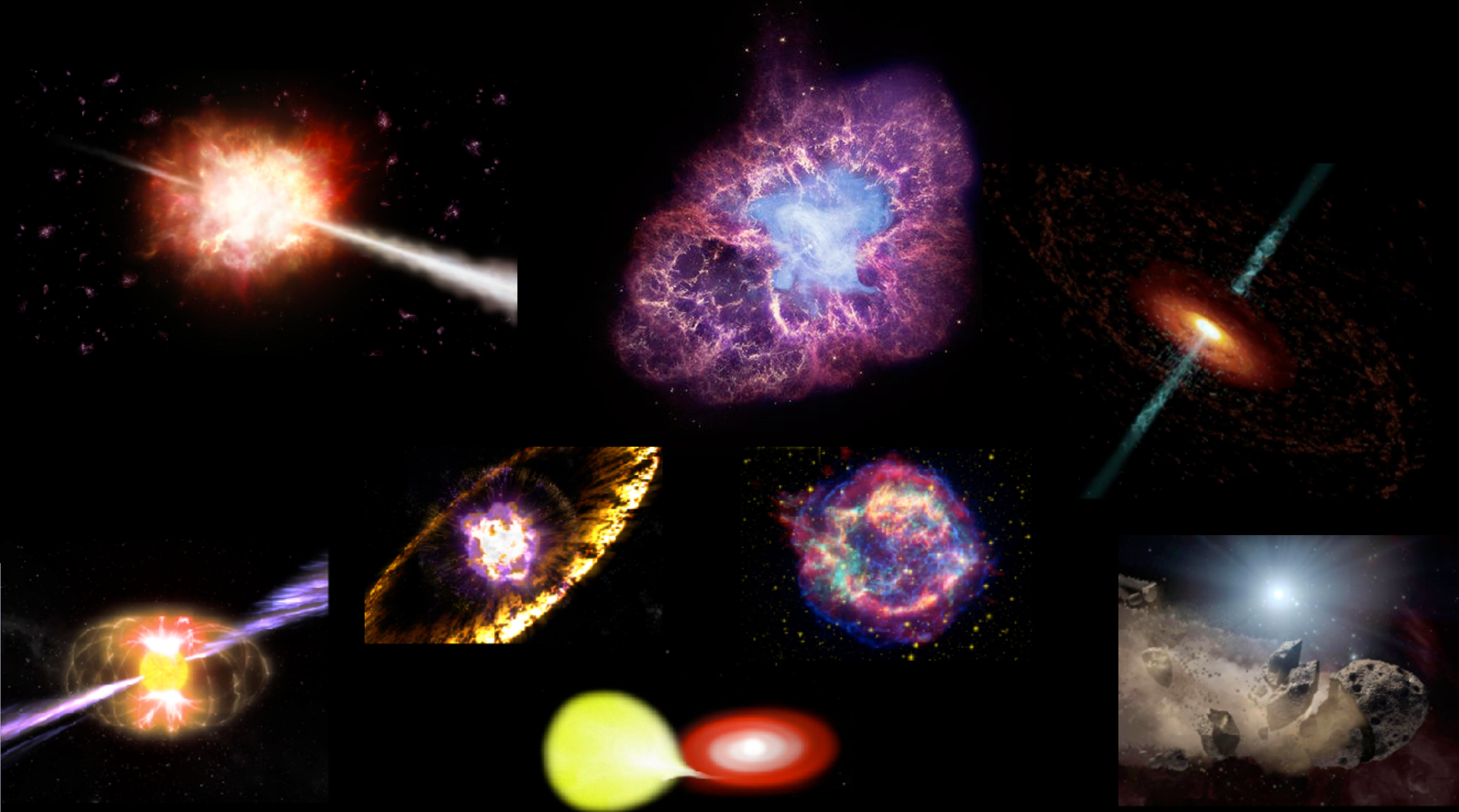
Fang, KK, Murase, Miller, Oikonomou 2016



- if source density > 10^{-9} Mpc^{-3}

almost guaranteed that sources of multiplets are within 200 Mpc (GZK horizon)

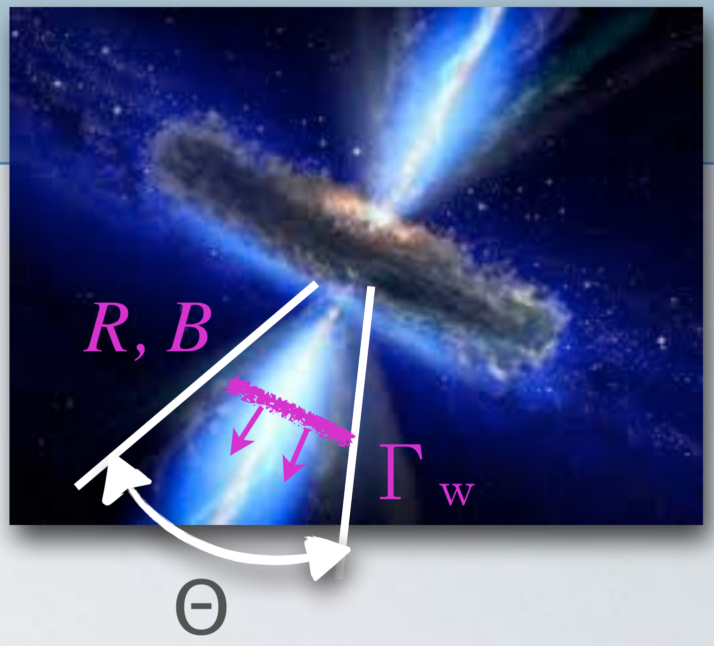
Going for transients



clear signatures to do neutrino astronomy

A luminosity bound

Lemoine & Waxman 09



condition for acceleration

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

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

depends on acc. mechanism and environment

$\mathcal{A} \gg 1$

$\mathcal{A} \sim 1$ at best

Larmor time

$$t_{\rm dyn} \sim R/\beta_{\rm W}\Gamma_{\rm W}c$$

outflow magnetic luminosity

$$L_B \equiv \Gamma_{\rm W} R^2 B^2/2$$

$$> 10^{45}\ Z^{-2} E_{20}^2\ \ {\rm erg\ \ s}^{-1}$$

lower bound of the bolometric luminosity of source

Lemoine & Waxman 09

Lovelace 76, Norman et al. 95, Waxman 05, Aharonian et al. 02, Lyutikov & Ouyed 05, Farrar & Gruzinov 09

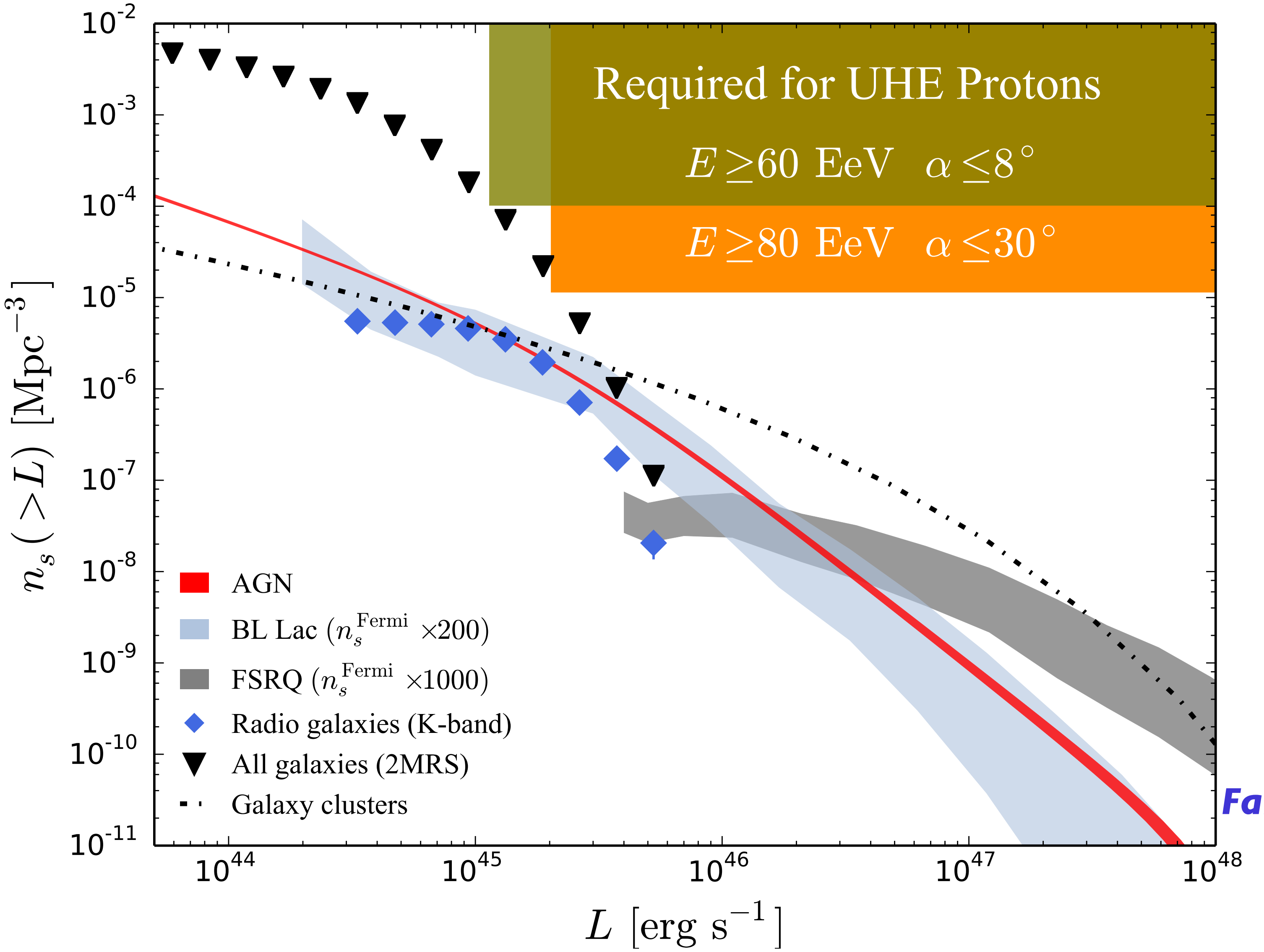
UHECRs cannot be protons from steady sources

➢ **lower bound of the bolometric luminosity of source** ***Lemoine & Waxman 09***

outflow magnetic luminosity $L_B \equiv \Gamma_{\rm W} R^2 B^2/2 > 10^{45}\, Z^{-2} E_{20}^2\ {\rm erg\ s^{-1}}$

level of clustering in the sky in Auger data ***Abreu et al. 2013***

➢ **apparent number density of sources** @ given energy and angular deflection α

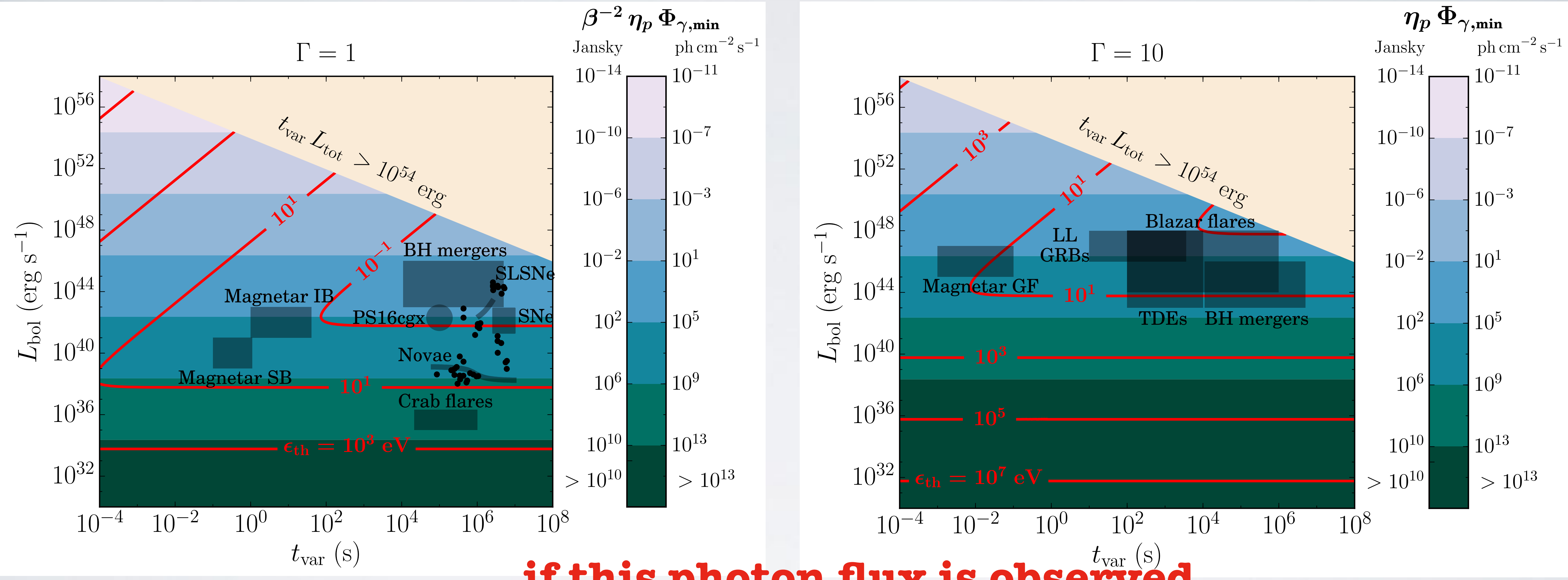


Fang & KK, 2016

- **heavy elements from steady sources**
- **or sources = transient**

Neutrino flares!

Guépin & KK (2017)



if this photon flux is observed, there is a chance to see a neutrino flare from that event

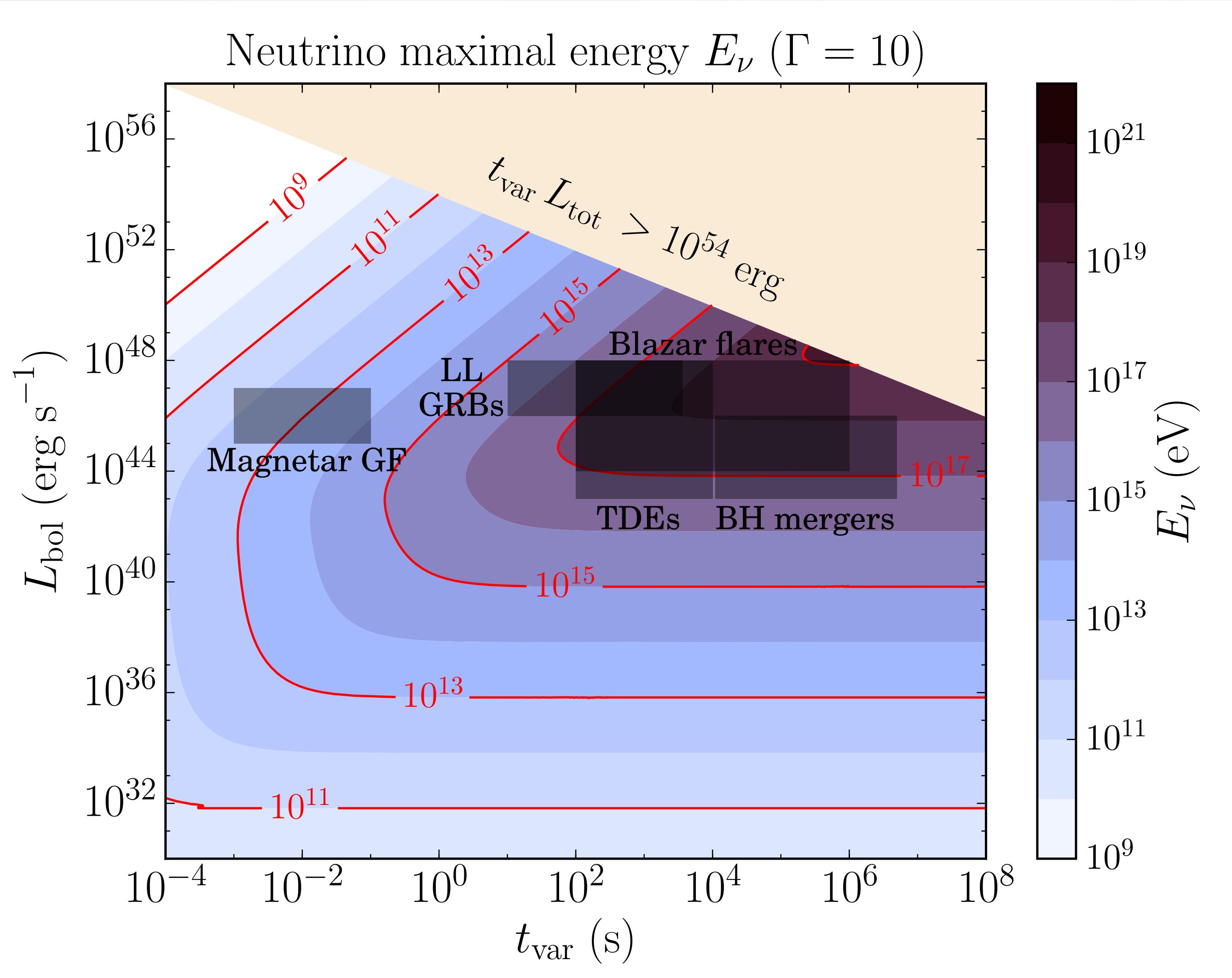
photon flux **needed** for detection with IceCube

photon flux **observed**

Source	Γ	$t_{\rm var}$ (s)	$L_{\rm bol}$ (erg s^{-1})	$E_{p,\max}$ (PeV)	$E_{\nu,\max}$ (PeV)	$\epsilon_{\rm th}$ [$\epsilon_{\rm b}$] (eV)	$\Phi_{\gamma,\min}$ (ph cm^{-2} s^{-1})	$\Phi_{\gamma,\rm obs}$ ph cm^{-2} s^{-1})	$D_{\rm L}$ [z]
GRB 080319B	300	0.01 – 1	10^{53}	10^{5} – 10^{6}	1 – 10^{2}	10 – 10^{2}	10^{4}	10 – 10^{4}	[0.937]
GRB 100316D	10	10^{2} – 10^{3}	10^{47}	10^{4} – 10^{5}	10 – 10^{2}	0.1	10^{4}	10^{-1} – 1	260 Mpc
PKS 1424-418	10	10^{4} – 10^{5}	2 × 10^{48}	10^{5}	10^{3} – 10^{4}	0.1	1.7 × 10^{3}	3 × 10^{2}	[1.522]
SGR 1806-20	10	10^{-3} – 0.01	2 × 10^{47}	10^{2} – 10^{3}	10^{-4} – 10^{-3}	[10^{5}]	10^{4}	[10^{7}]	15 kpc
Swift J1644+57	10	100	4 × 10^{48}	10^{4}	1 – 10	[10^{4}]	10^{3}	[0.6]	1.8 Gpc
PS16cgx	1	10^{5}	10^{42} – 10^{43}	10^{3} – 10^{4}	10^{2}	10^{-2} – 0.1	10^{4} – 10^{5}	8 × 10^{-1}	0.1 – 0.2]
Crab Flares	1	10^{4} – 10^{6}	10^{35} – 10^{36}	1	10^{-2} – 10^{-1}	10^{2}	10^{11} – 10^{12}	< 10^{-2}	1.9 kpc

Neutrino flares in EeV! with GRAND

Guépin & KK (2017)



photon flux **needed**
for detection with GRAND

Class	$E_{\nu,\rm max}$ (GeV)	ϵ_γ (eV)	$\eta_p\,\Phi_{\gamma,\rm min}$ (ph cm^{-2} s^{-1})	$D_{\rm L,max}$ [$z_{\rm max}$]
Blazar flares	10^{10}	0.1	10^3	[1.2]
LL GRBs*	10^9	0.1	10^3	18 Mpc
TDEs	10^9	10^4	10^3	25 Mpc
SLSNe	10^9	10^{-3}	10^2	7.9 Mpc
SNe*	10^9	10^{-2}	10^4	79 kpc

EeV Neutrino Astronomy

May your GRAND dreams come true!*

*Giant Radio Array for Neutrino Detection

Kumiko Kotera - Institut d'Astrophysique de Paris - SuGAR 2018