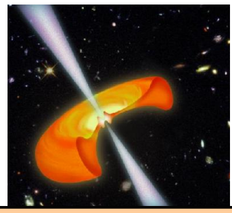
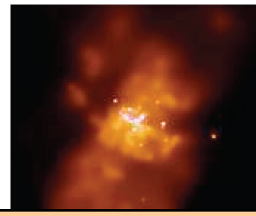
GRAND Science Case:
high-energy neutrino astronomy for real

Kumiko Kotera - *Institut d'Astrophysique de Paris*

Probing the working of the most violent phenomena in the Universe





Most violent sources

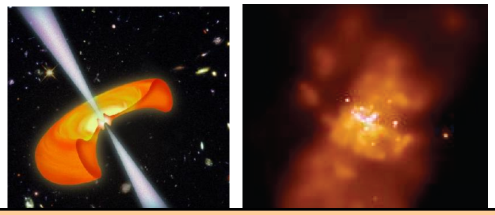
Physics of the sources?

gamma-ray bursts,
pulsars, magnetars,
AGN...

acceleration

UHECR

Probing the working of the most violent phenomena in the Universe



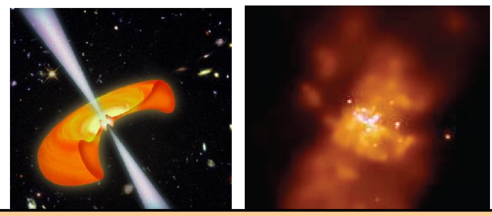
Physics of the sources?

gamma-ray bursts,
pulsars, magnetars,
AGN...

Most violent sources

acceleration

UHECR



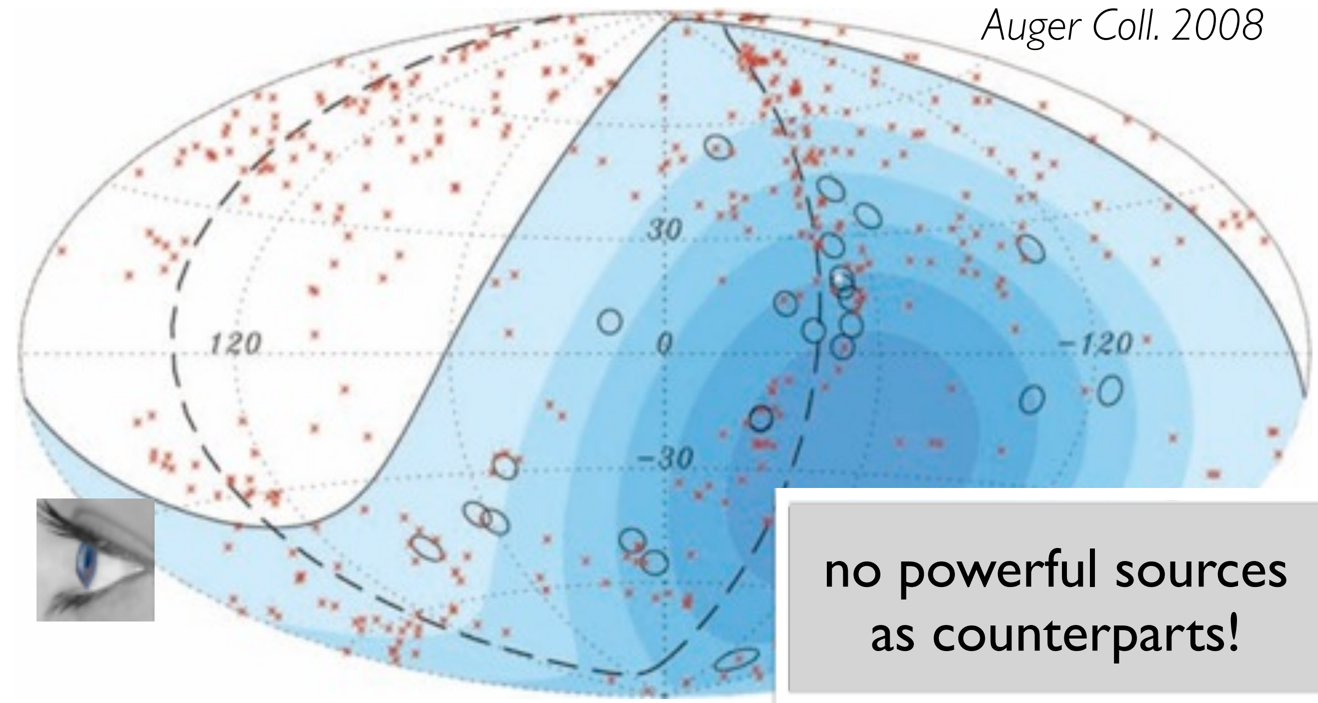
Most violent sources

Physics of the sources?

gamma-ray bursts,
pulsars, magnetars,
AGN...

acceleration

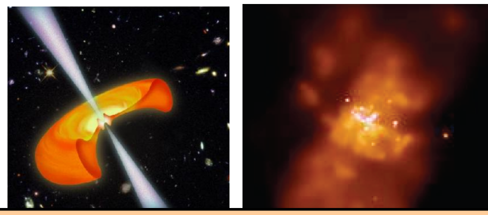
UHECR



Auger Coll. 2008

no powerful sources
as counterparts!

Probing the working of the most violent phenomena in the Universe



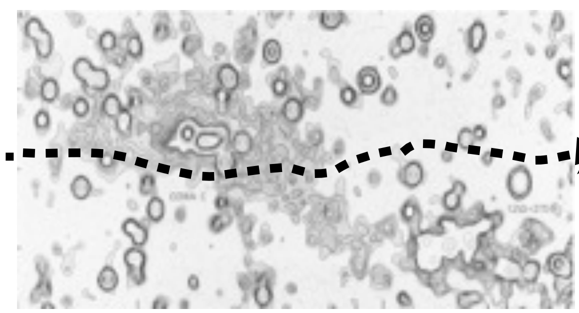
Most violent sources

Physics of the sources?

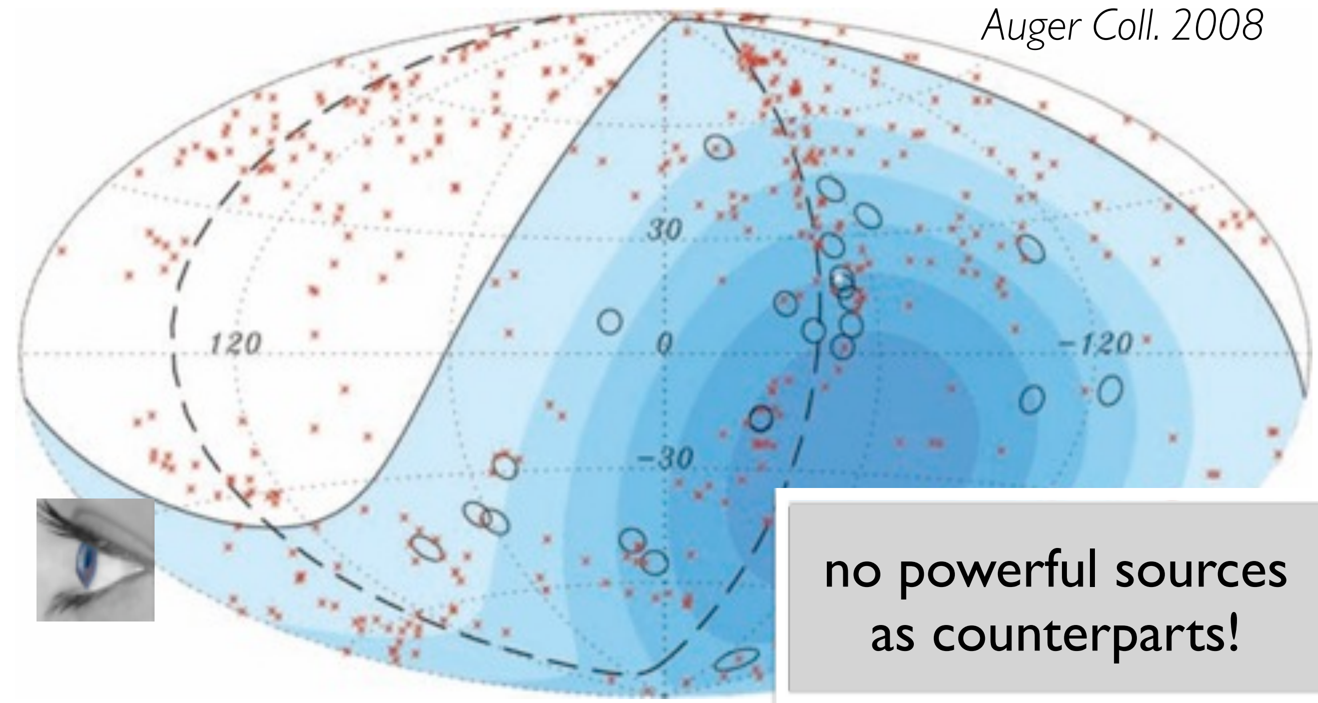
gamma-ray bursts,
pulsars, magnetars,
AGN...

acceleration

UHECR



Auger Coll. 2008

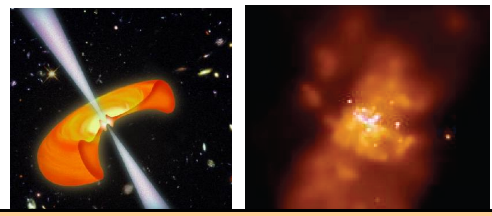


no powerful sources
as counterparts!

Extragalactic magnetic fields?

deflection : spatial decorrelation
time delay : temporal decorrelation if transient source

Probing the working of the most violent phenomena in the Universe



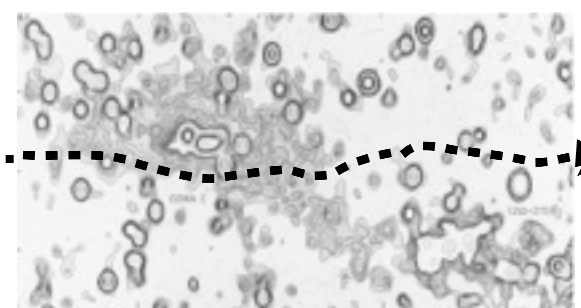
Most violent sources

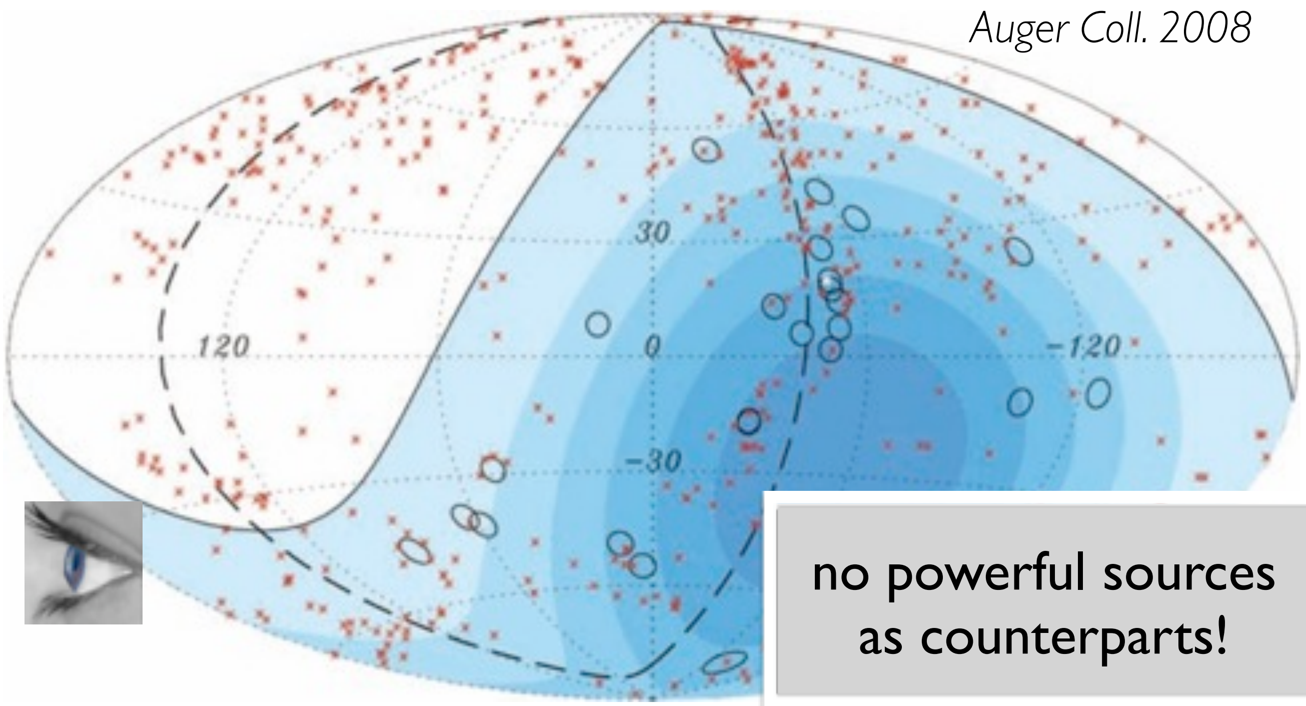
Physics of the sources?

gamma-ray bursts,
pulsars, magnetars,
AGN...

acceleration

UHECR





no powerful sources
as counterparts!

interactions on baryonic and
photonic backgrounds

Extragalactic magnetic fields?

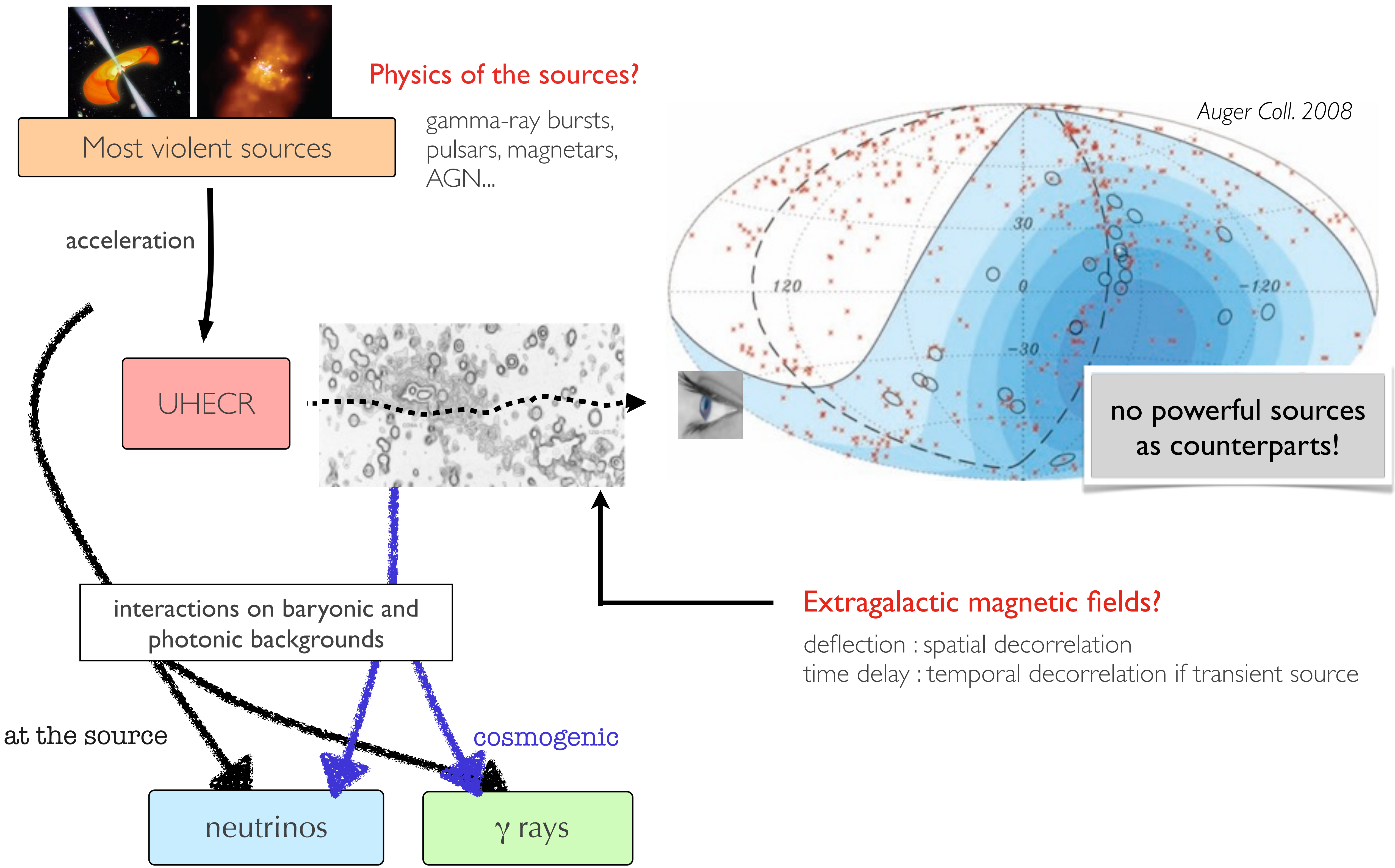
deflection : spatial decorrelation
time delay : temporal decorrelation if transient source

cosmogenic

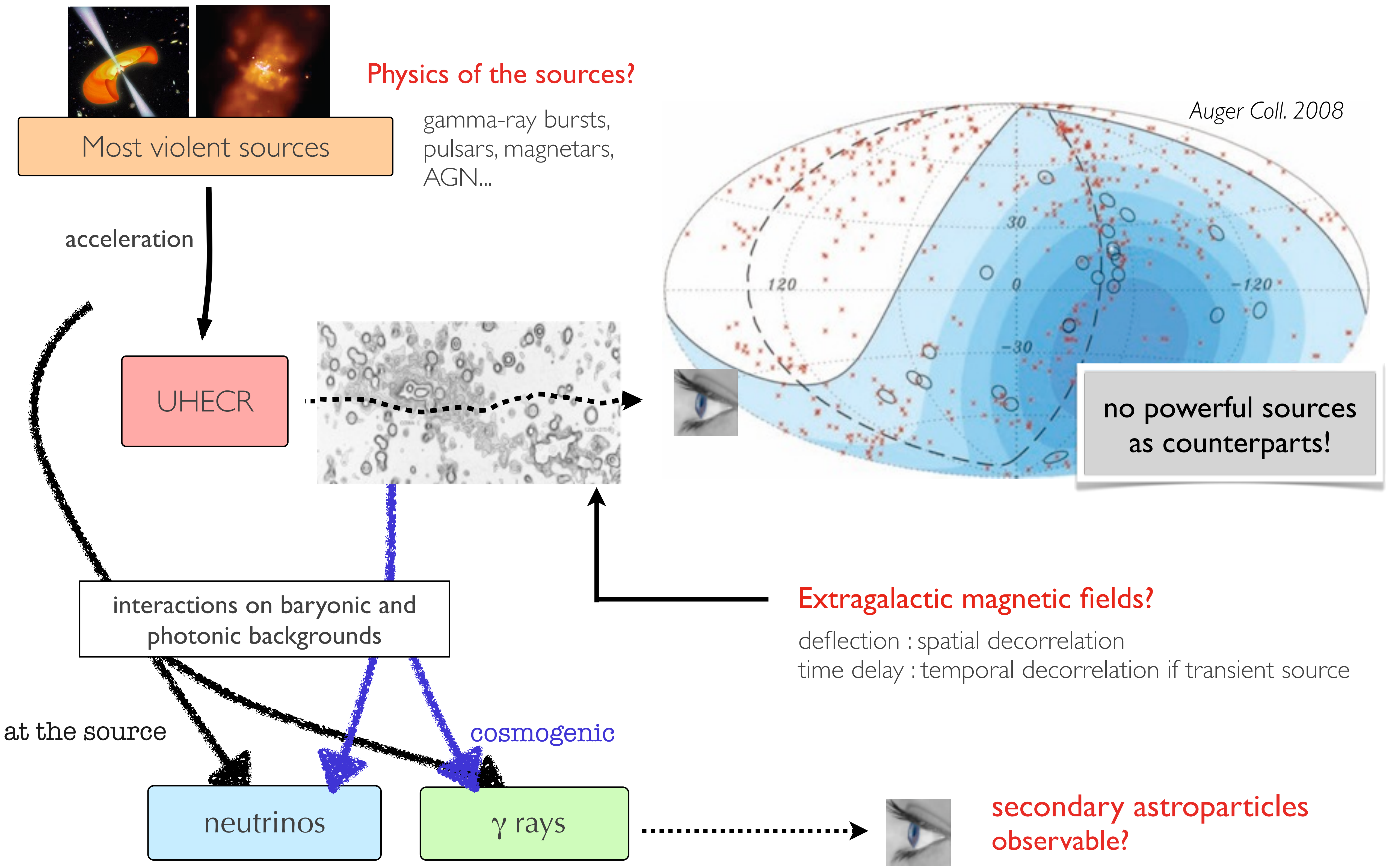
neutrinos

γ rays

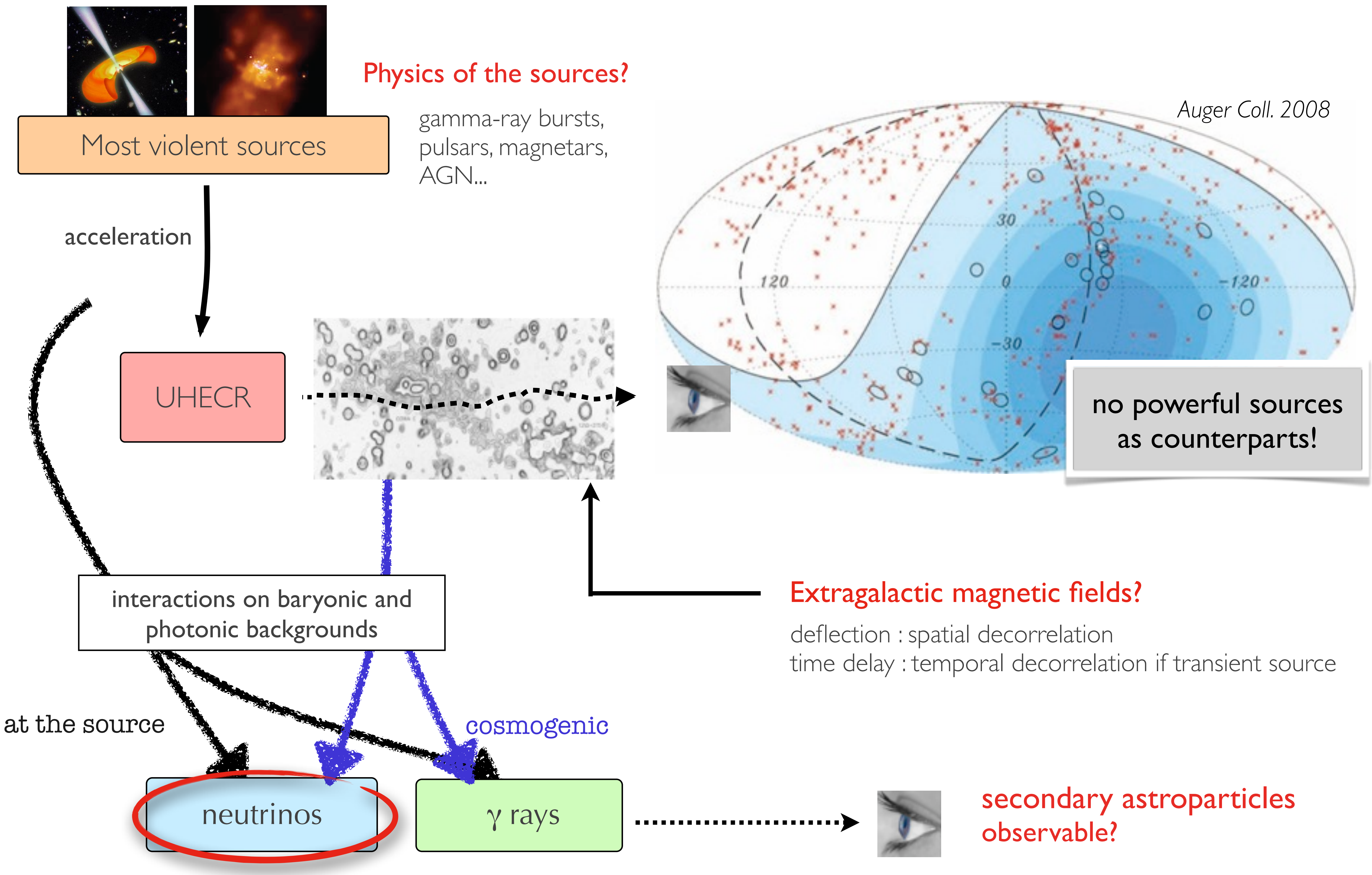
Probing the working of the most violent phenomena in the Universe



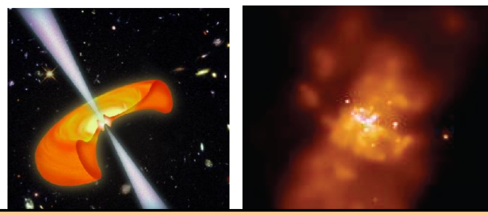
Probing the working of the most violent phenomena in the Universe



Probing the working of the most violent phenomena in the Universe



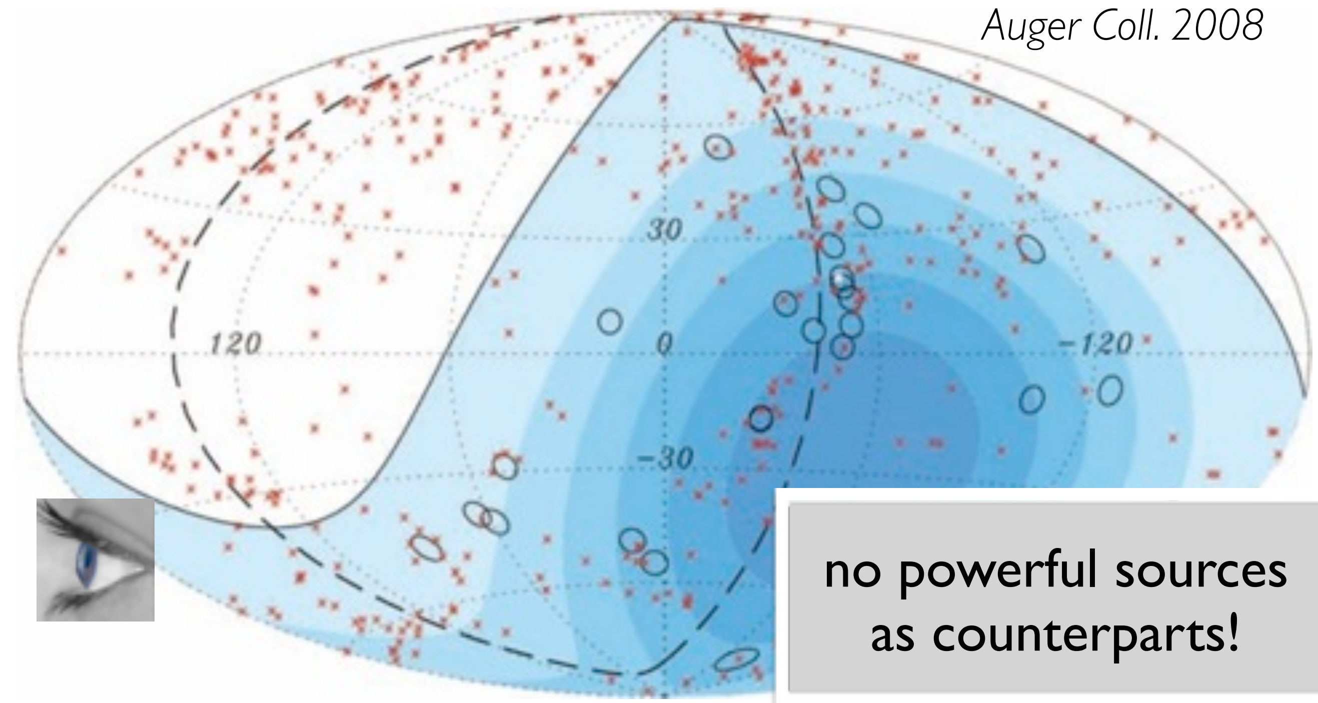
Probing the working of the most violent phenomena in the Universe



Physics of the sources?

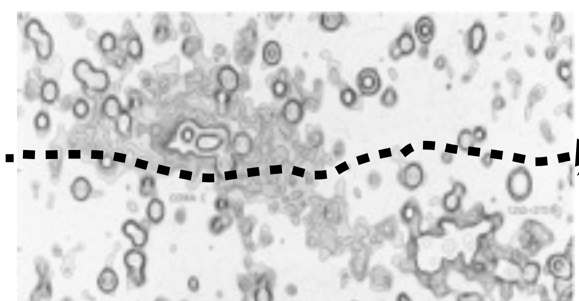
Most violent sources

gamma-ray bursts,
pulsars, magnetars,
AGN...



acceleration

UHECR



no powerful sources
as counterparts!

interactions on baryonic and
photonic backgrounds

Extragalactic magnetic fields?

deflection : spatial decorrelation
time delay : temporal decorrelation if transient source

at the source

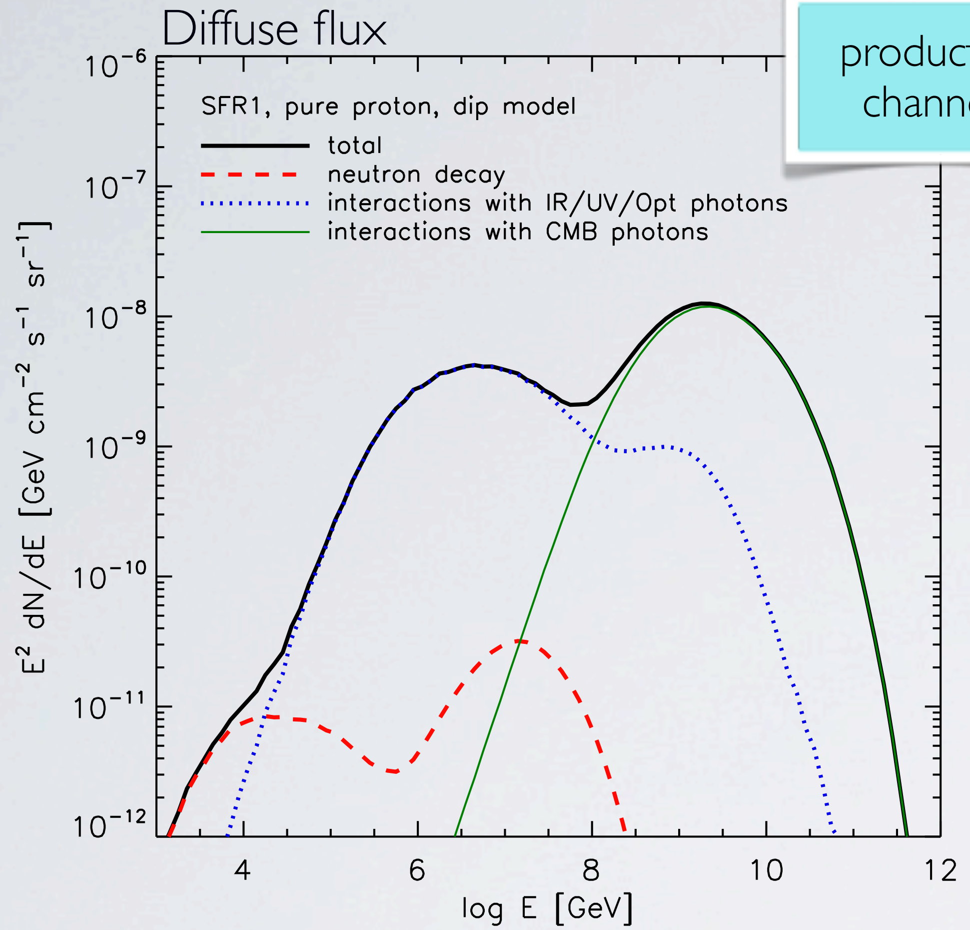
cosmogenic

neutrinos

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

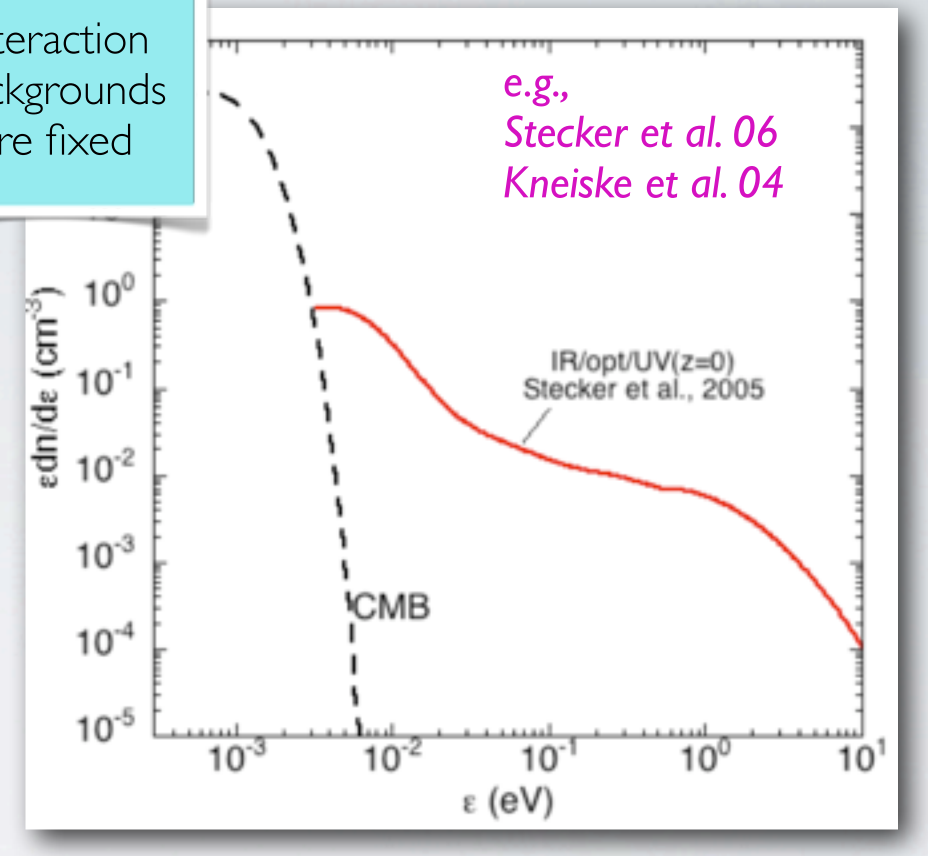
les

The guaranteed cosmogenic neutrinos

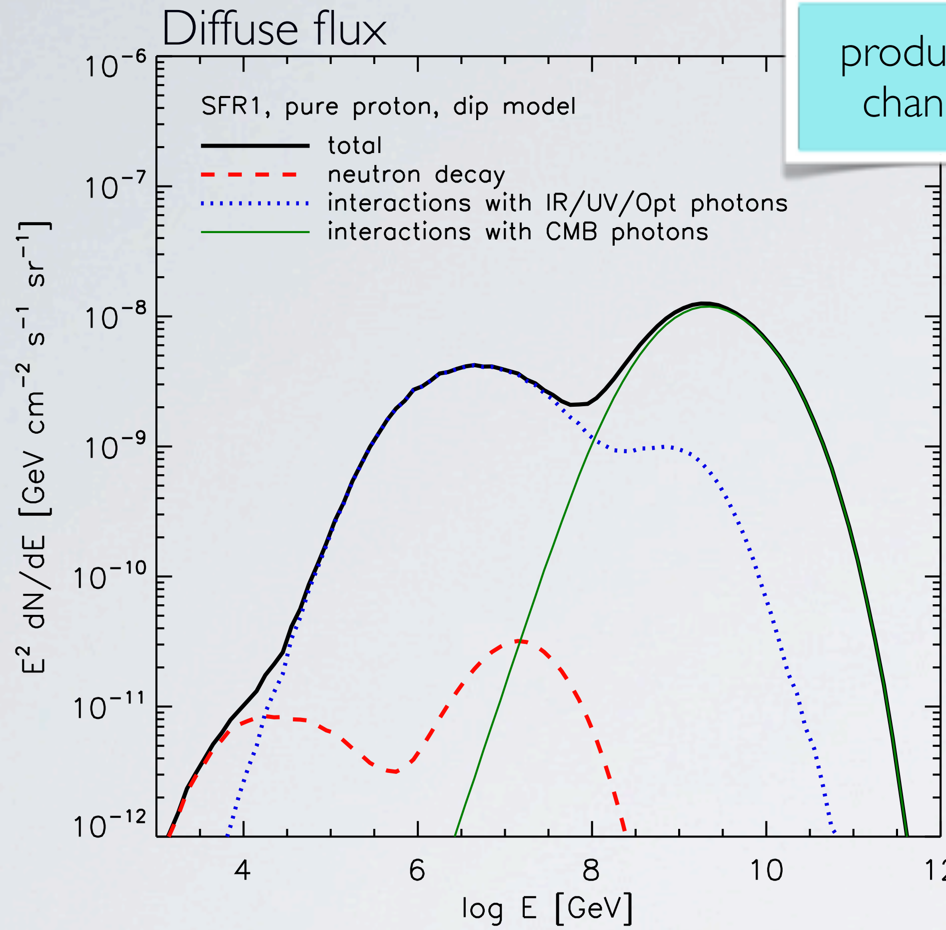


production channels

interaction backgrounds are fixed

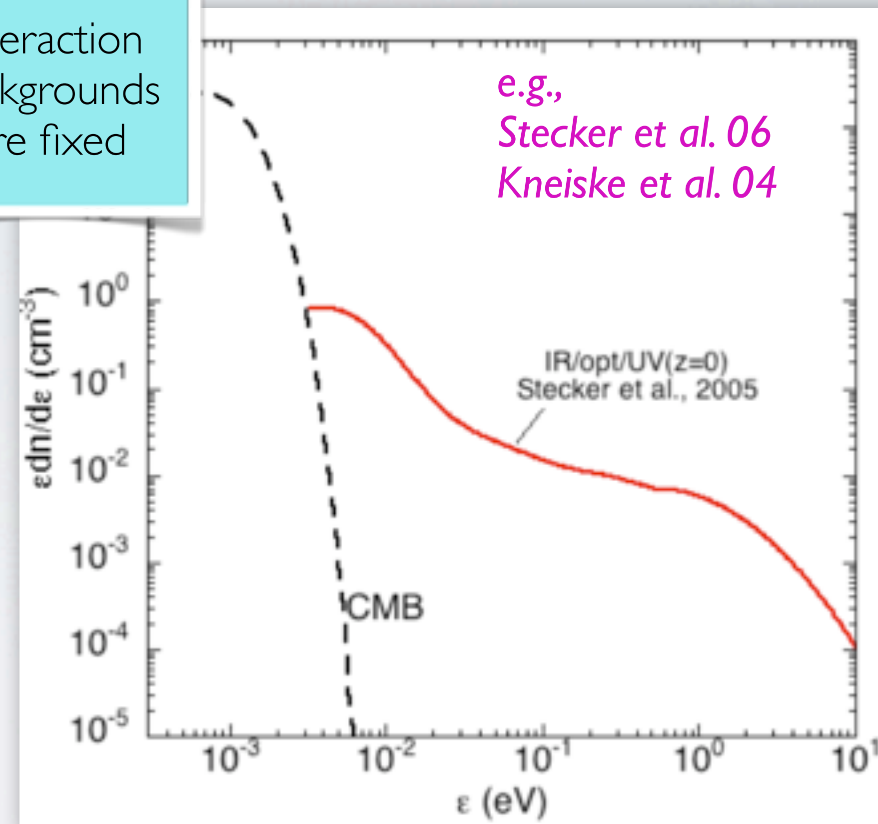


The guaranteed cosmogenic neutrinos



production channels

interaction backgrounds are fixed



What UHECR source(s)?

some associated issues:

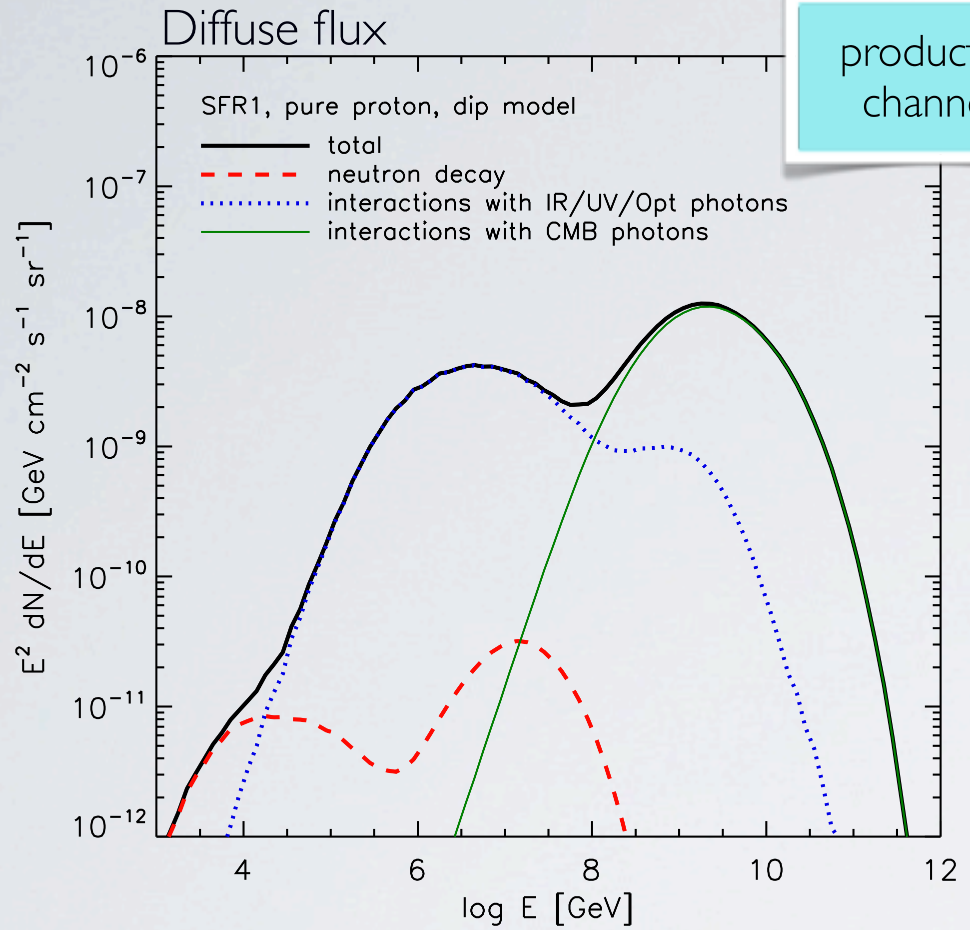
⟶ injected chemical composition?

⟶ cosmological evolution of source?

⟶ Galactic/extragalac transition?

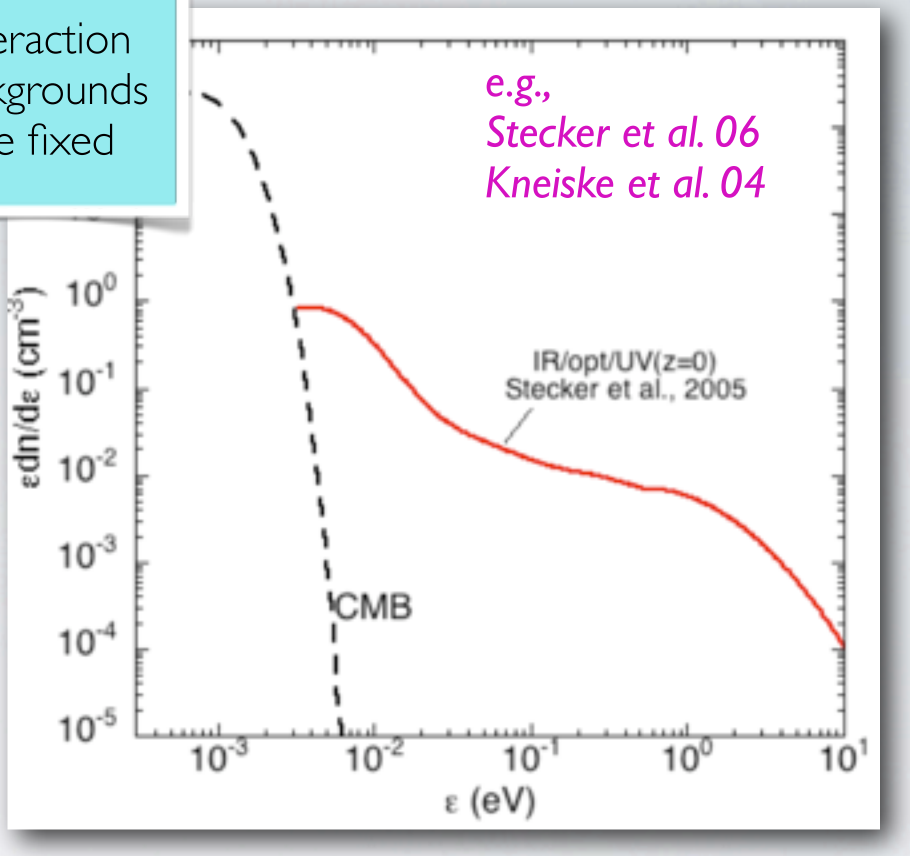
⟶ maximum injected energy?

The guaranteed cosmogenic neutrinos



production channels

interaction backgrounds are fixed



What UHECR source(s)?

some associated issues:

→ injected chemical composition?

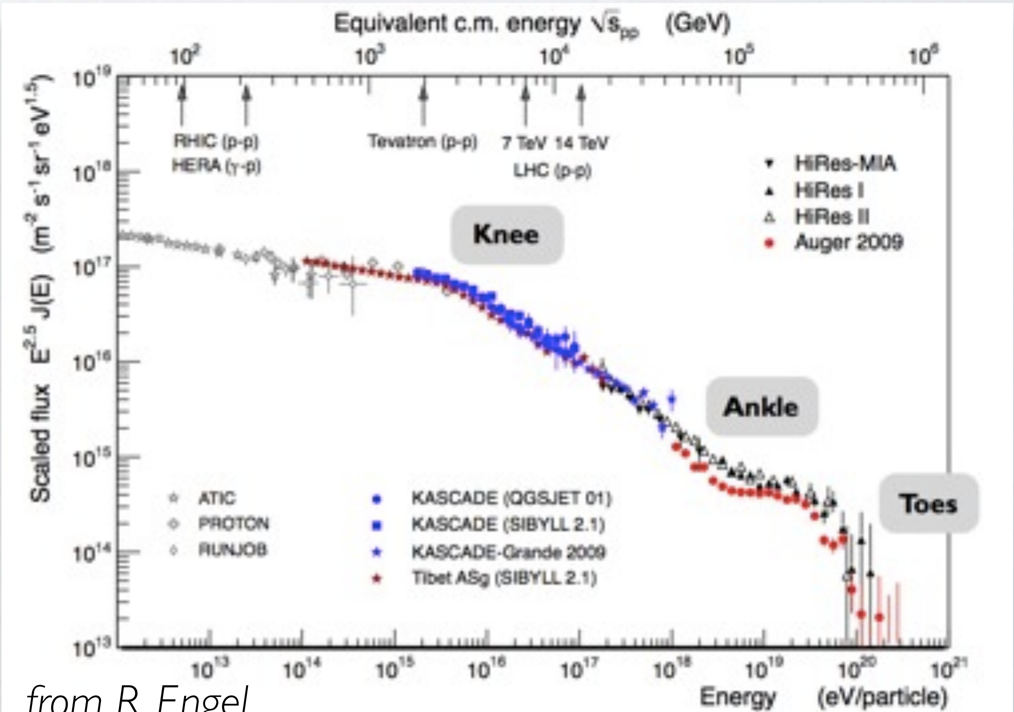
→ cosmological evolution of source?

→ Galactic/extragalac transition?

→ maximum injected energy?

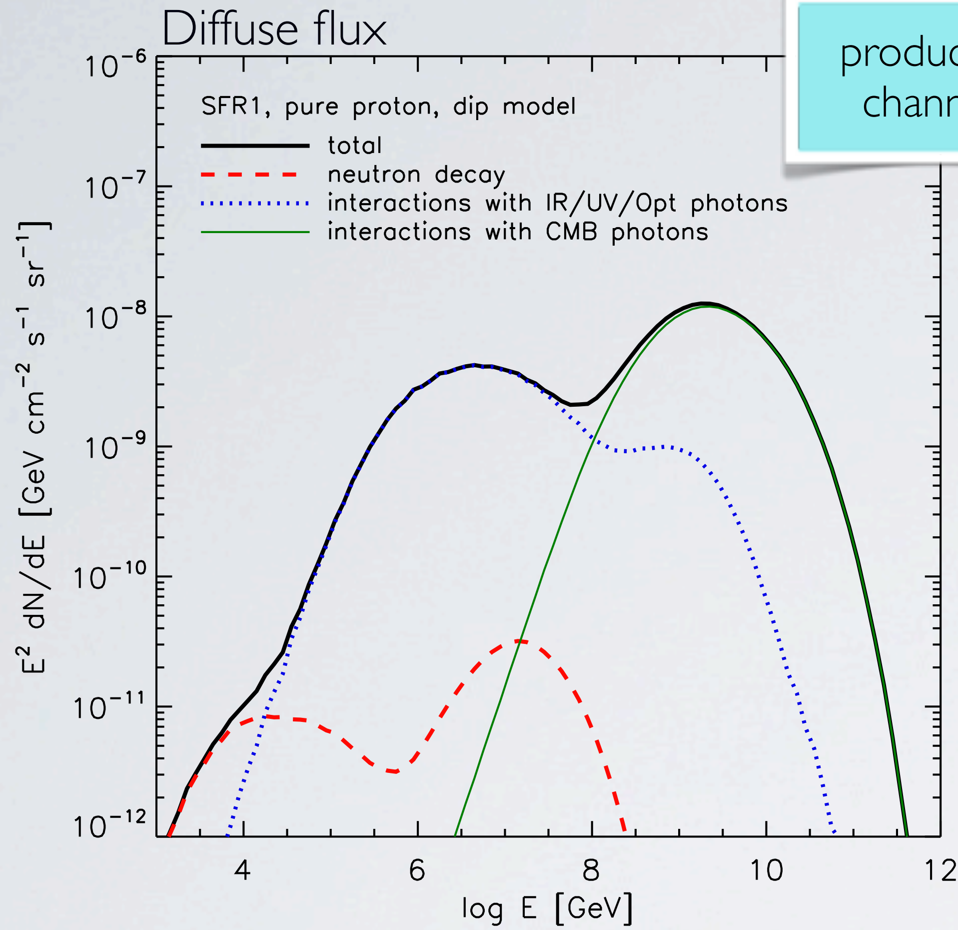
+

fit to observed spectrum of UHECRs



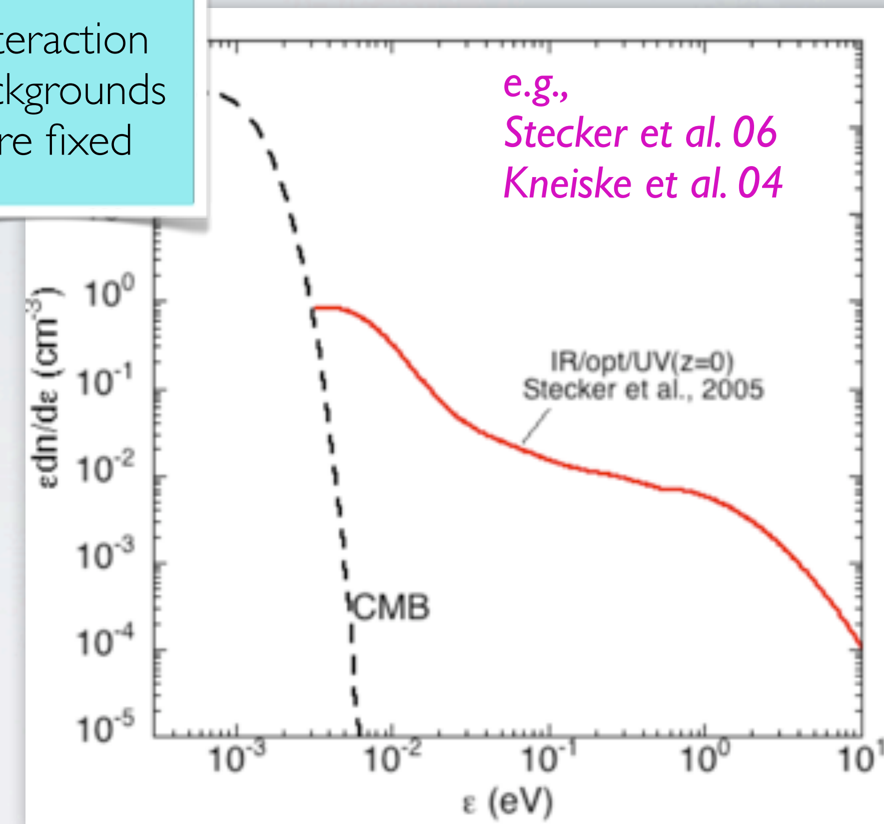
from R. Engel

The guaranteed cosmogenic neutrinos



production channels

interaction backgrounds are fixed



fit to observed spectrum of UHECRs

What UHECR source(s)?

some associated issues:

⟶ injected chemical compo

⟶ cosmological evolution of

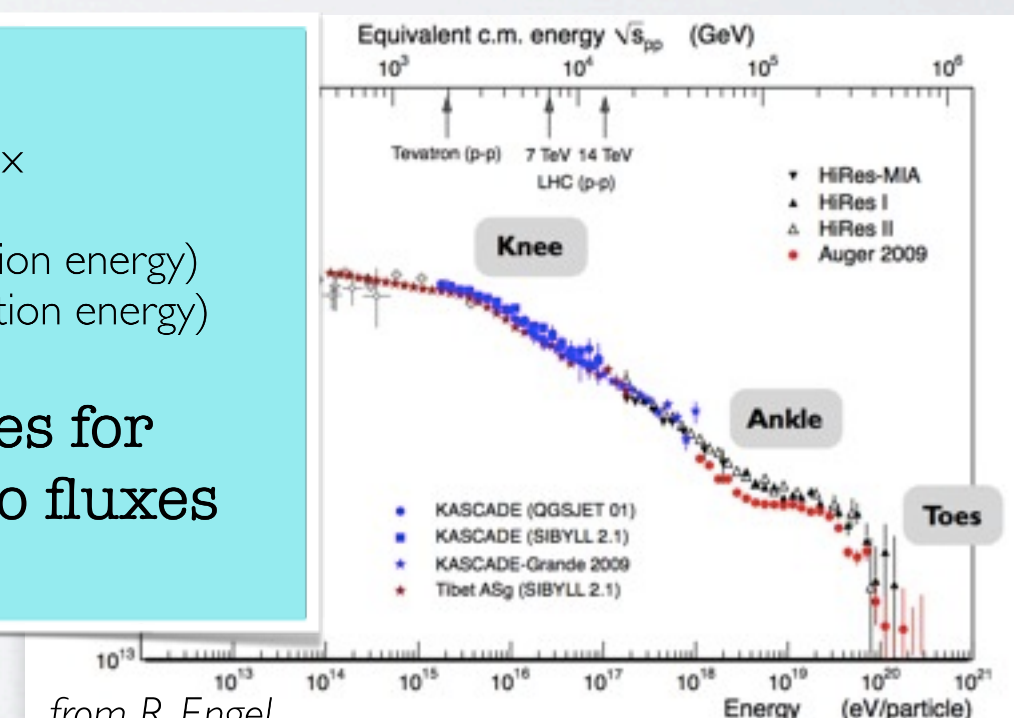
⟶ Galactic/extragalac transit

⟶ maximum injected energ

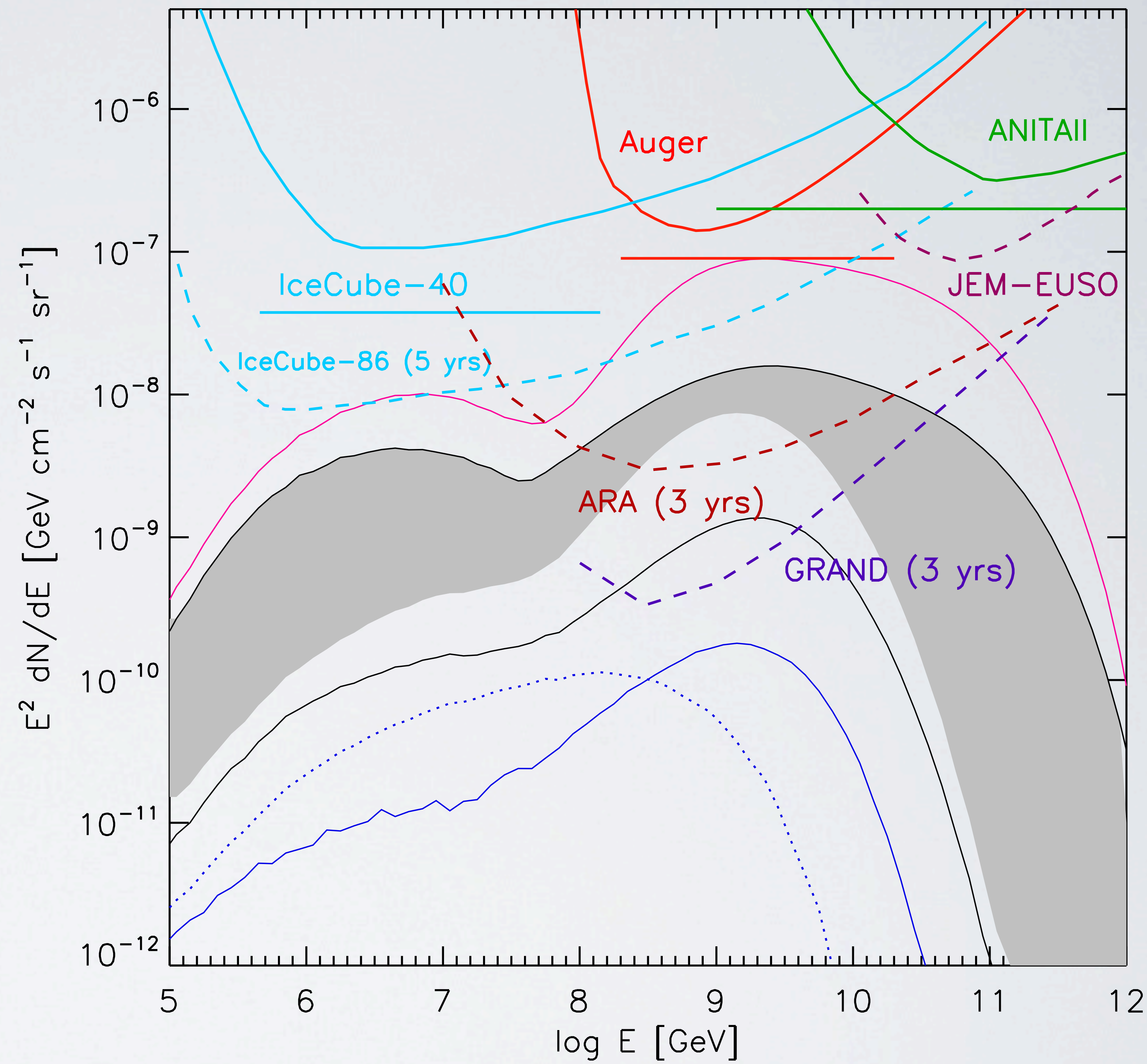
fixes:

injection spectral index
flux normalisation
Ep min (minimum proton injection energy)
Ep max (maximum proton injection energy)

limited possibilities for cosmogenic neutrino fluxes



K.K., Allard & Olinto, 2010



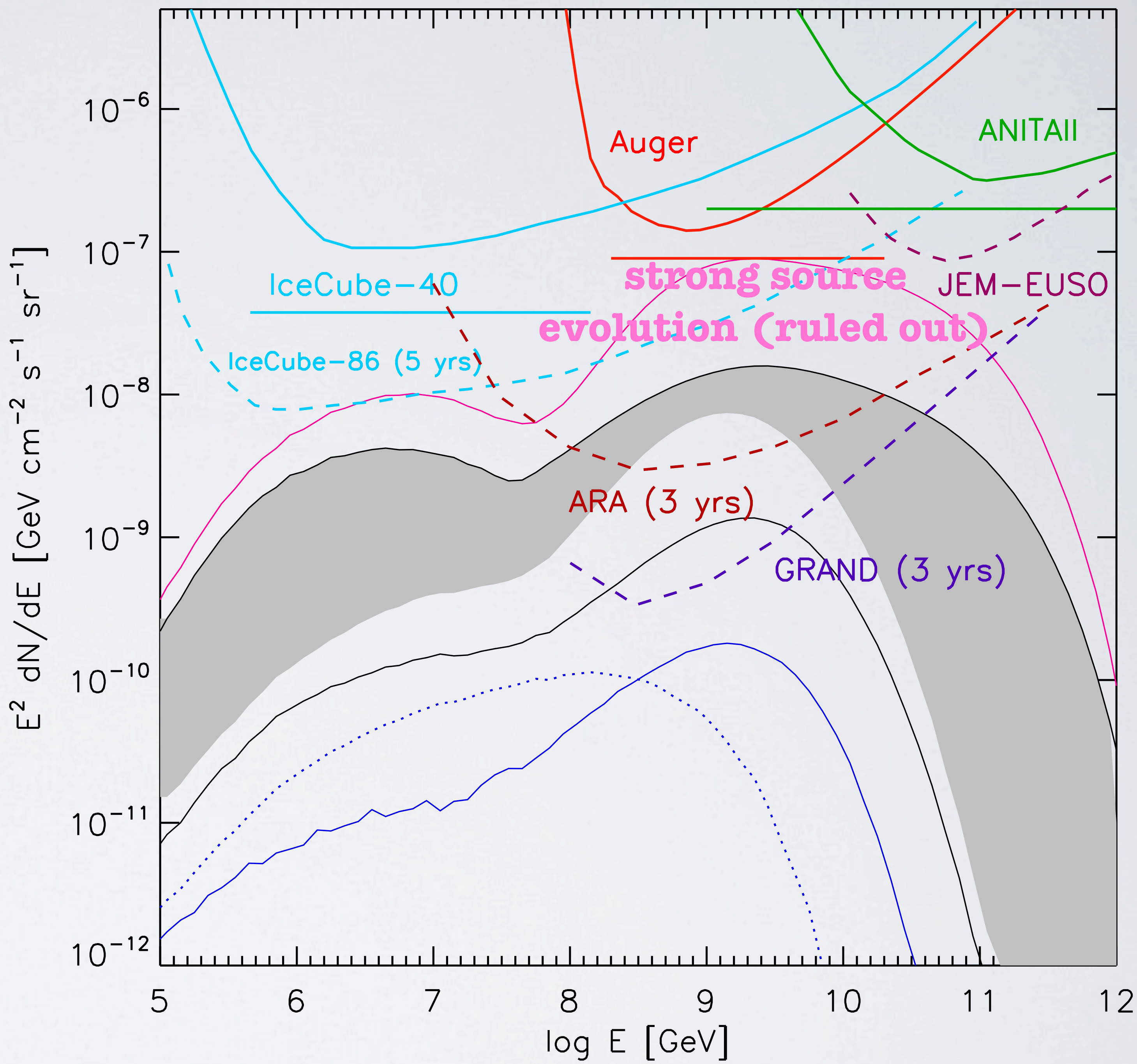
"reasonable"

proton to Galactic mixed composition

$E_{Z,max} > Z \times 10^{19}$ eV

cosmological source evolution ~ star formation rate

K.K., Allard & Olinto, 2010



“reasonable”

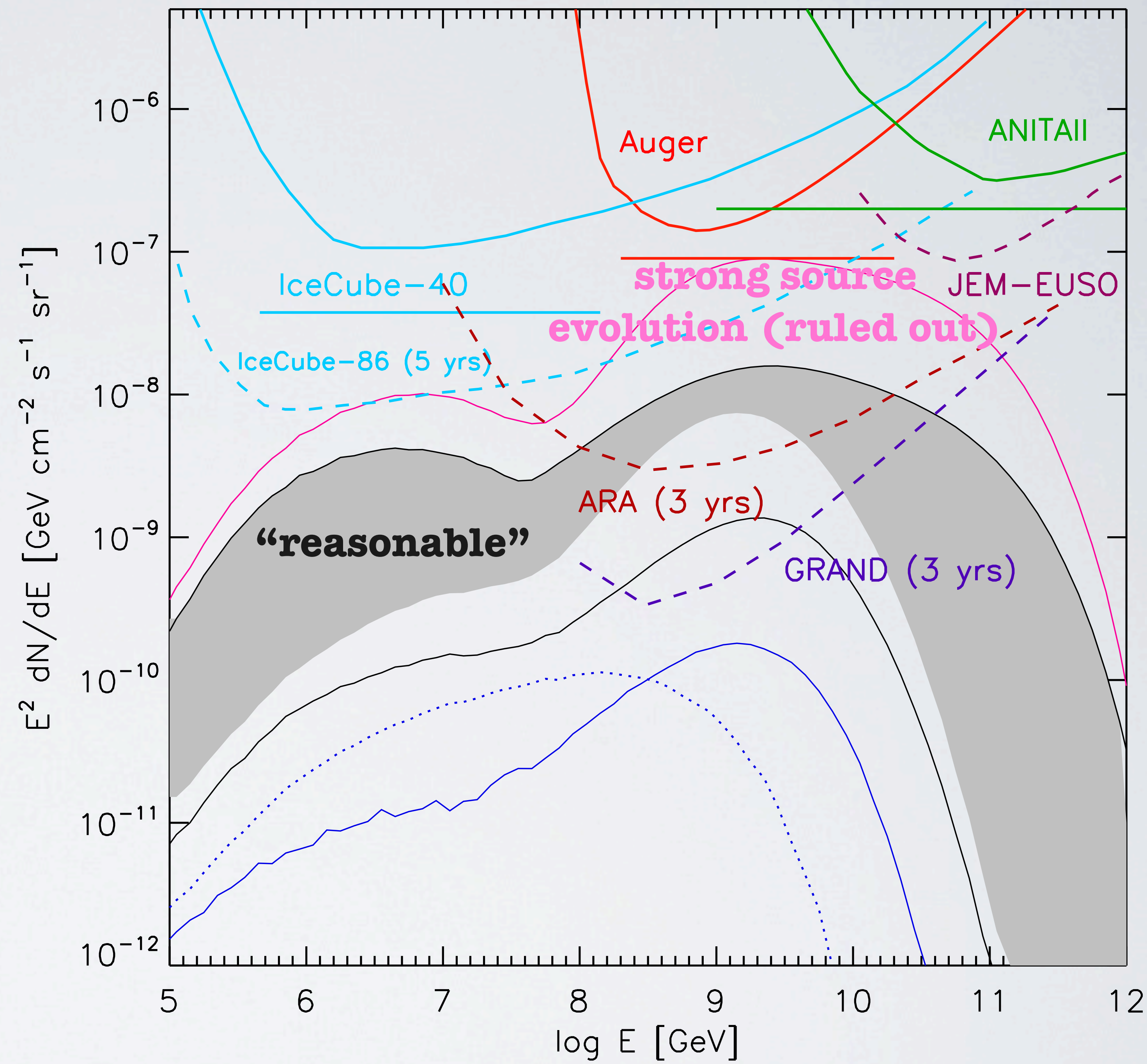
proton to Galactic mixed composition

$E_{Z,max} > Z\times10^{19}$ eV

cosmological source evolution ~ star formation rate

The guaranteed cosmogenic neutrinos

K.K., Allard & Olinto, 2010



"reasonable"

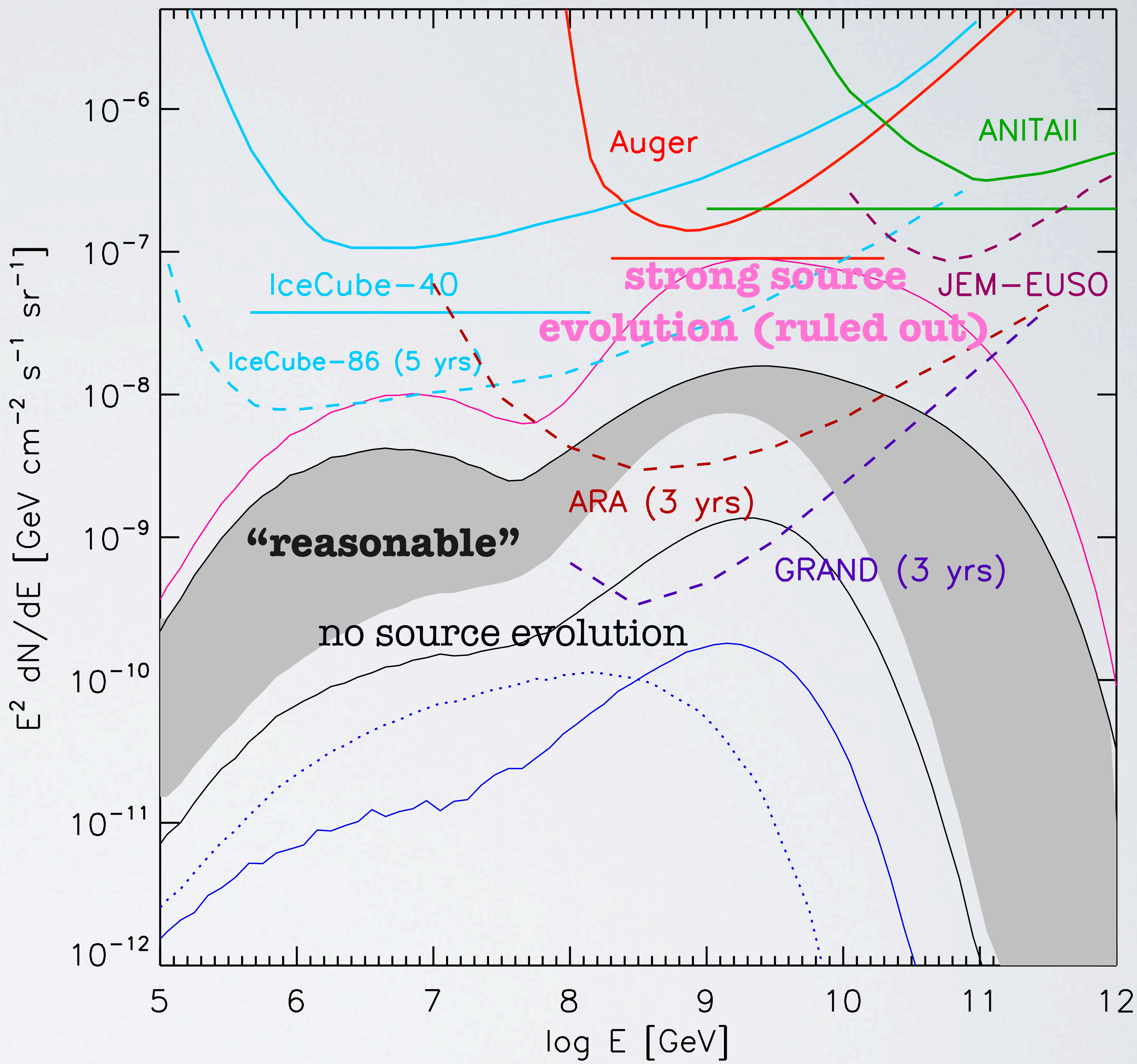
proton to Galactic mixed composition

$E_{Z,max} > Z \times 10^{19}$ eV

cosmological source evolution ~ star formation rate

The guaranteed cosmogenic neutrinos

K.K., Allard & Olinto, 2010



"reasonable"

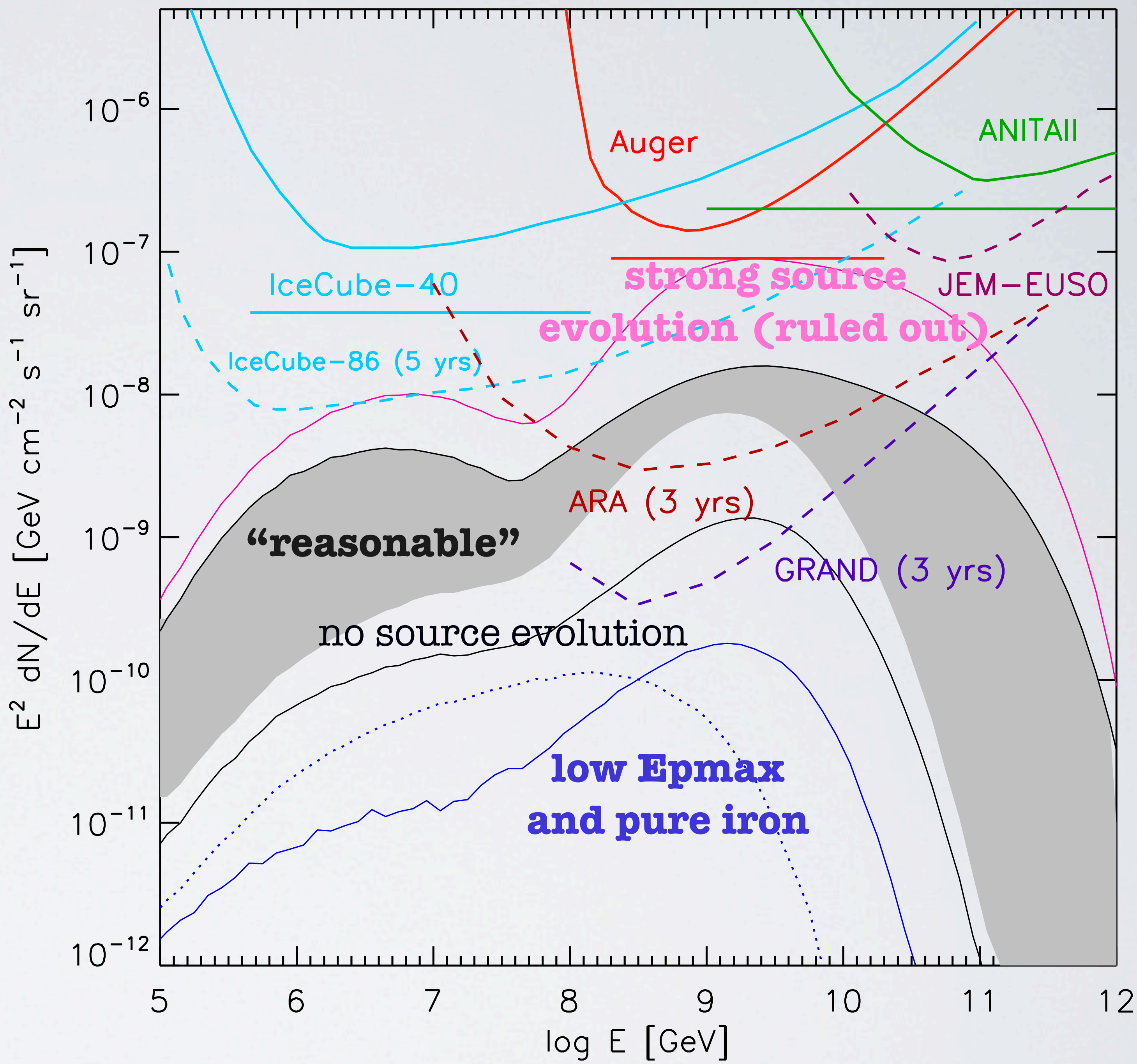
proton to Galactic mixed composition

$E_{Z,max} > Z \times 10^{19}$ eV

cosmological source evolution ~ star formation rate

The guaranteed cosmogenic neutrinos

K.K., Allard & Olinto, 2010



"reasonable"

proton to Galactic mixed composition

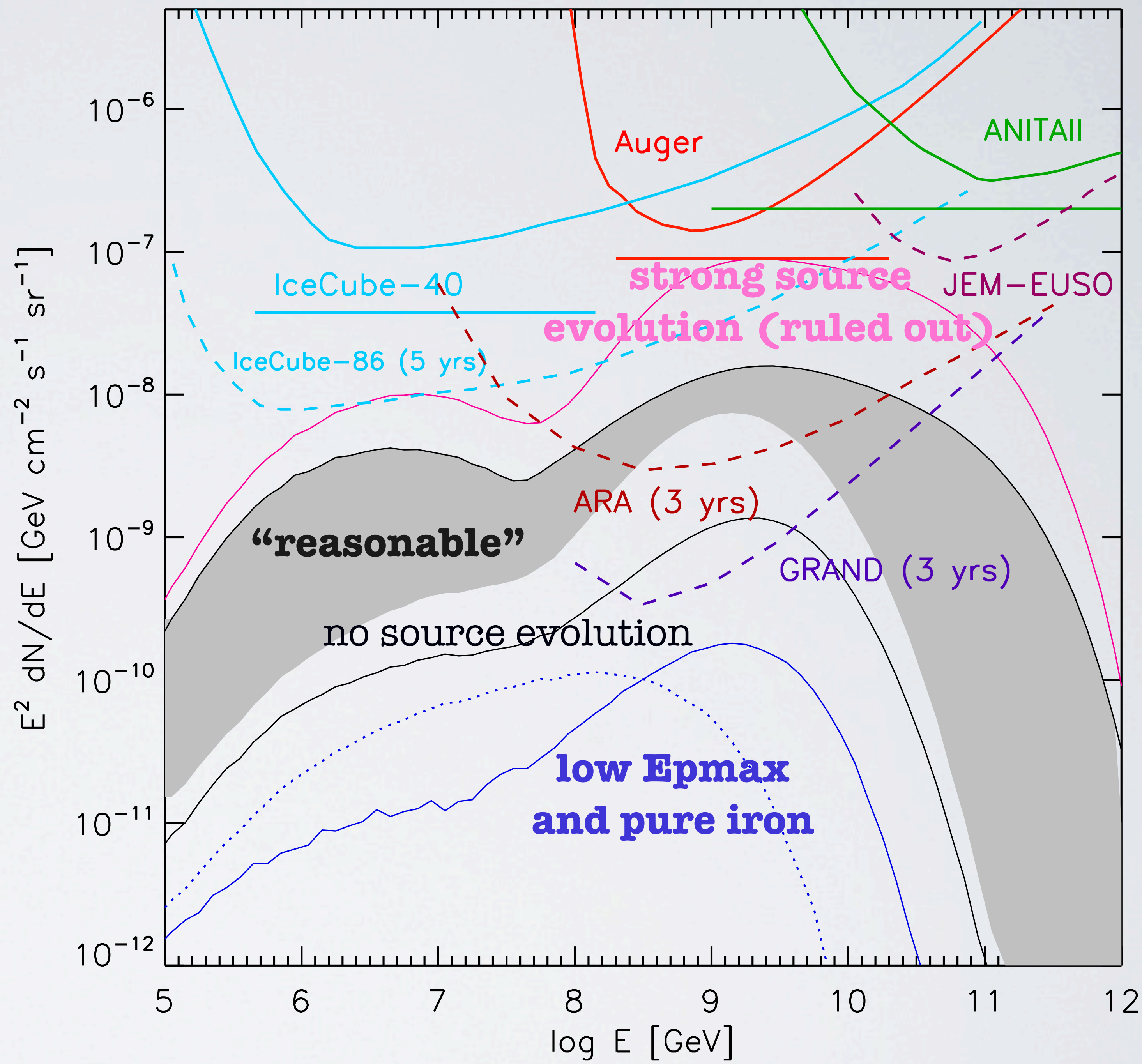
$E_{Z,max} > Z \times 10^{19}$ eV

cosmological source evolution ~ star formation rate

in terms of neutrino detection:
in "reasonable" param. range, EeV region is safe

in terms of getting info on sources:
once EeV region has been observed, PeV region can help discriminate composition and Galactic/extraGal. transition models

sad cases for neutrino detection:
iron and/or no source evolution



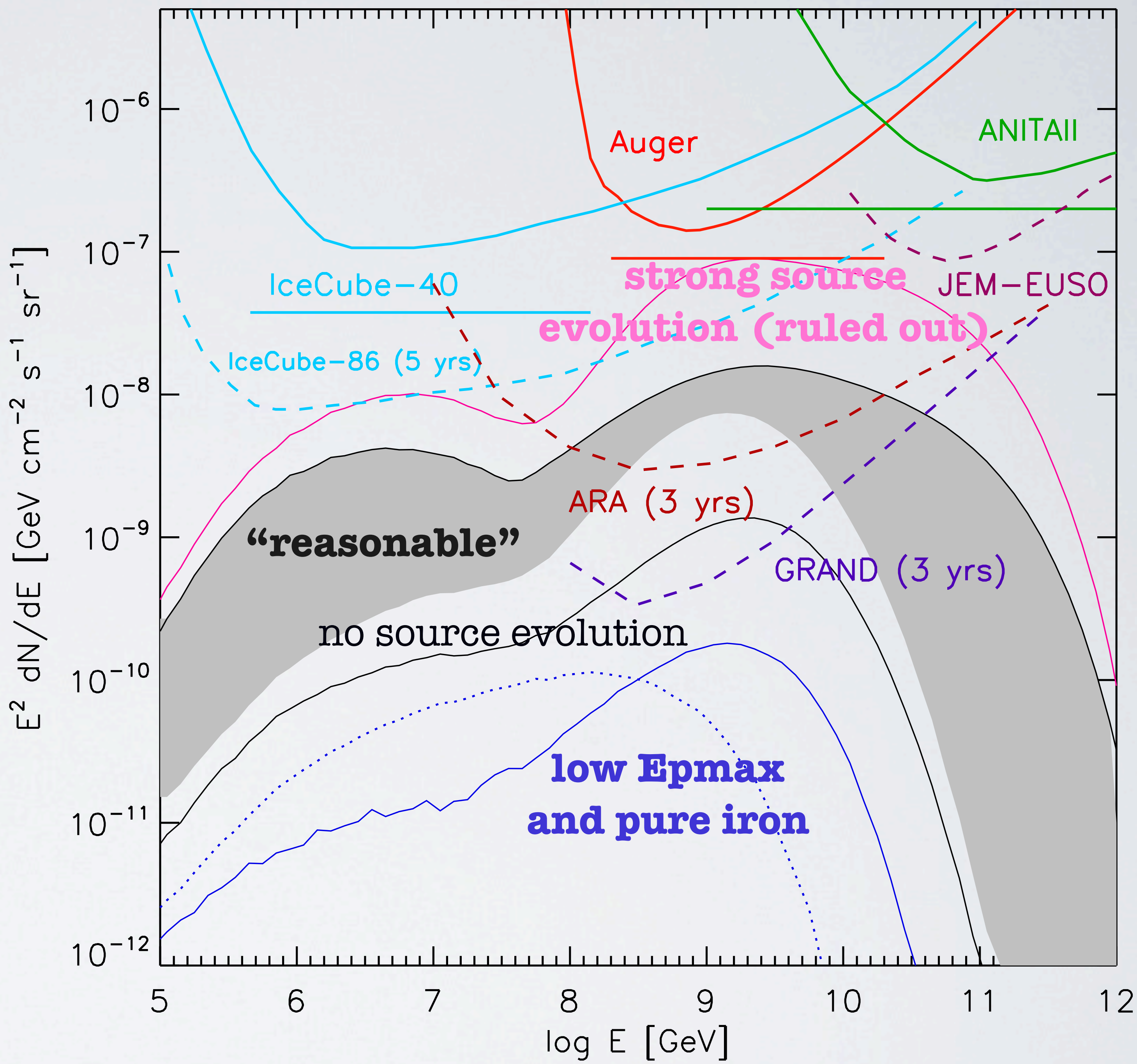
"reasonable"
proton to Galactic mixed composition
$E_{Z,max} > Z\times10^{19}$ eV
cosmological source evolution ~ star formation rate

K.K., Allard & Olinto, 2010

in terms of neutrino detection:
in "reasonable" param. range, EeV region is safe

in terms of getting info on sources:
once EeV region has been observed, PeV region can help discriminate composition and Galactic/extraGal. transition models

sad cases for neutrino detection:
iron and/or no source evolution



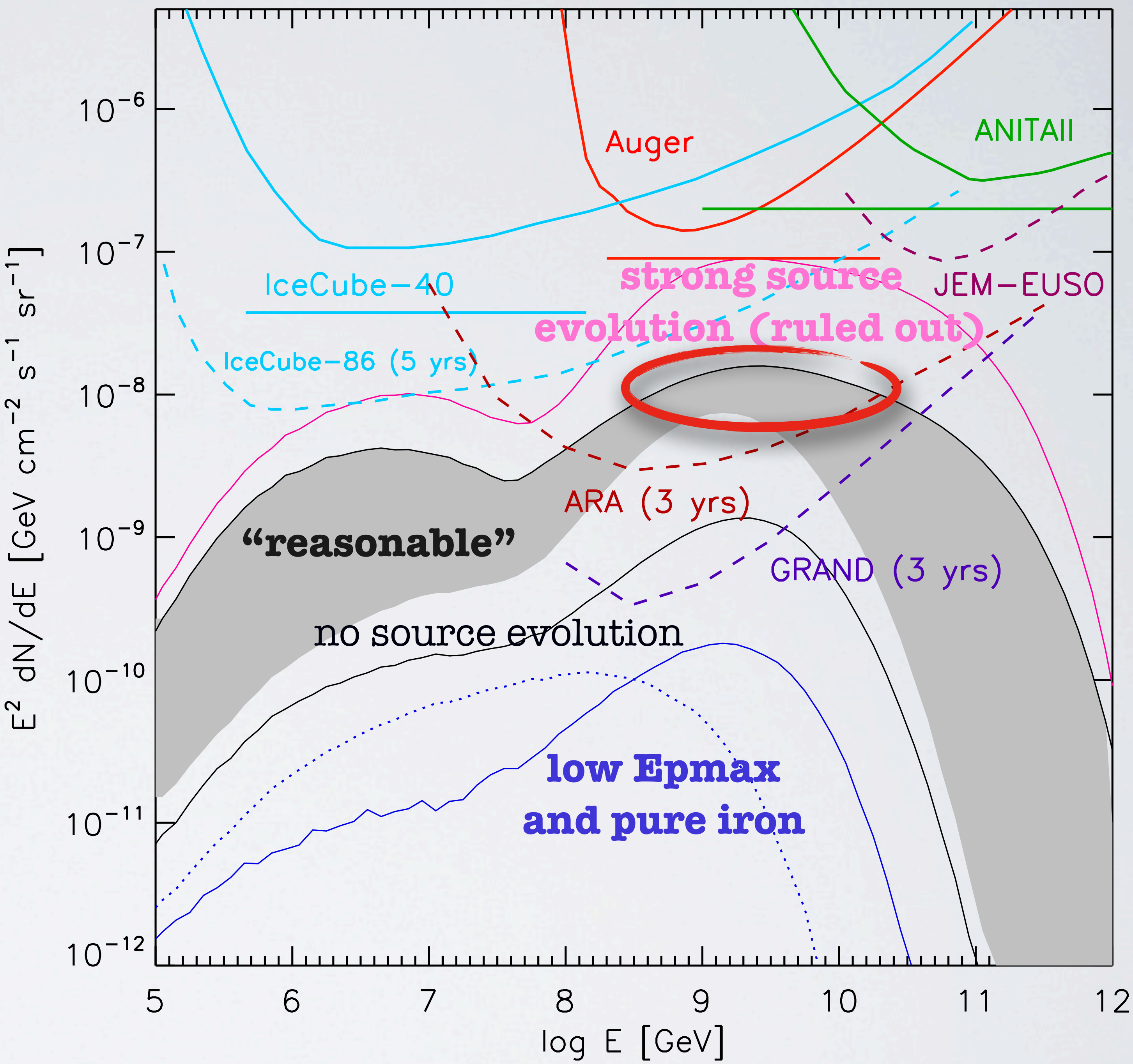
"reasonable"
proton to Galactic mixed composition
$E_{Z,max} > Z \times 10^{19}$ eV
cosmological source evolution ~ star formation rate

K.K., Allard & Olinto, 2010

in terms of neutrino detection:
in "reasonable" param. range, EeV region is safe

in terms of getting info on sources:
once EeV region has been observed, PeV region can help discriminate composition and Galactic/extraGal. transition models

sad cases for neutrino detection:
iron and/or no source evolution



"reasonable"
proton to Galactic mixed composition
$E_{Z,max} > Z \times 10^{19}$ eV
cosmological source evolution ~ star formation rate

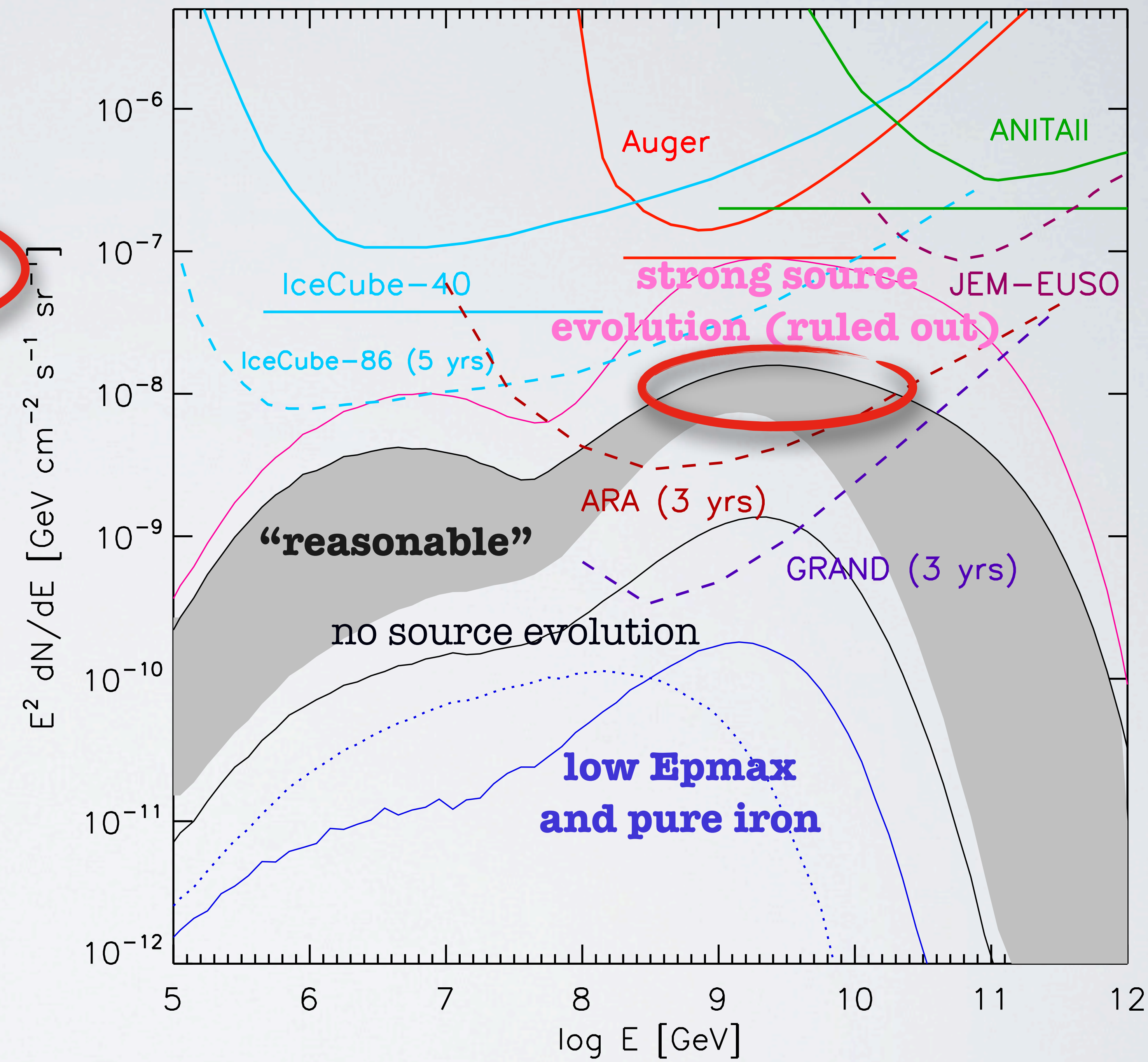
The guaranteed cosmogenic neutrinos

K.K., Allard & Olinto, 2010

in terms of neutrino detection:
in "reasonable" param. range, EeV region is safe

in terms of getting info on sources:
once EeV region has been observed, PeV region can help discriminate composition and Galactic/extraGal. transition models

sad cases for neutrino detection:
iron and/or no source evolution



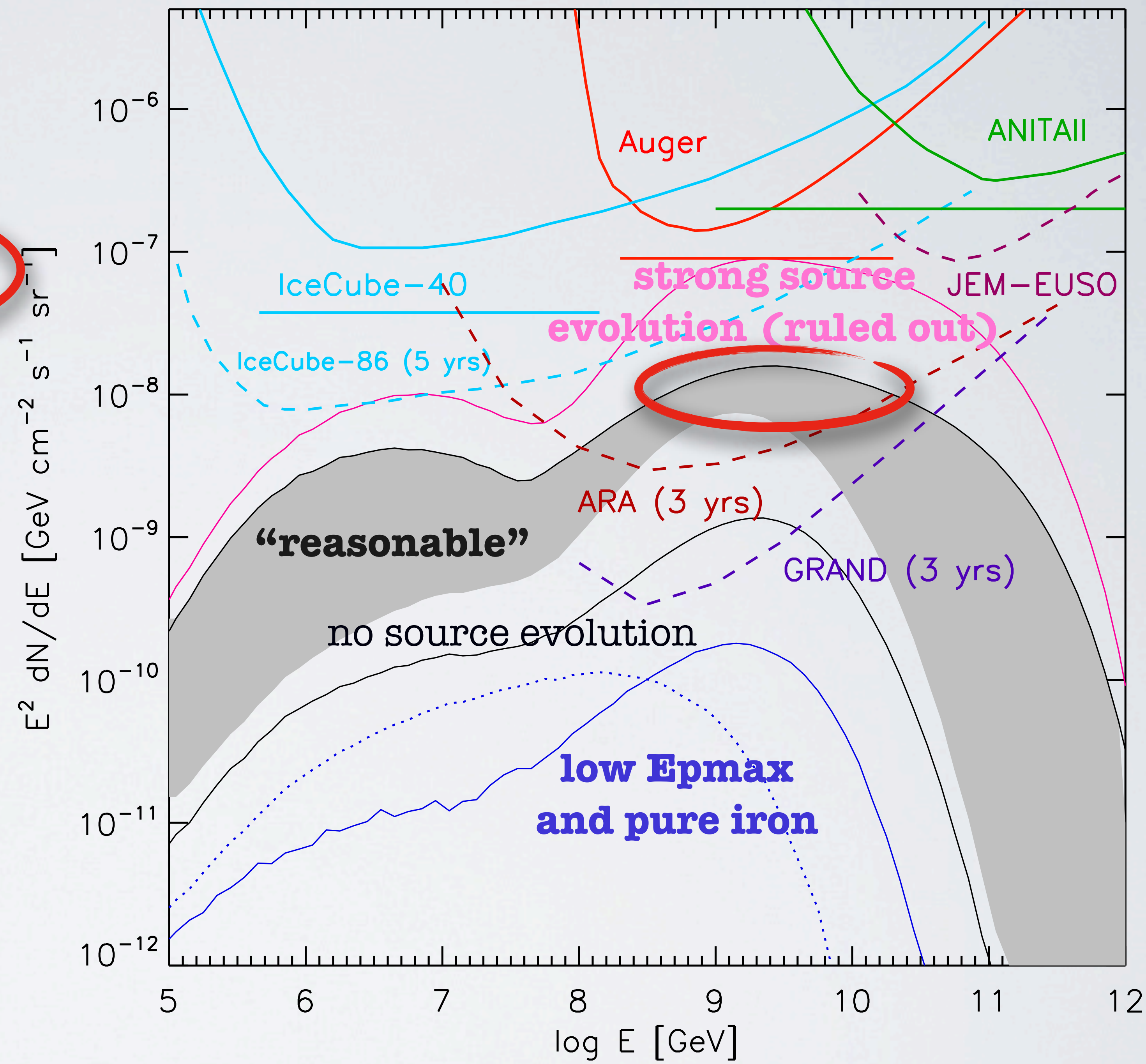
"reasonable"
proton to Galactic mixed composition
$E_{Z,max} > Z\times10^{19}$ eV
cosmological source evolution ~ star formation rate

K.K., Allard & Olinto, 2010

in terms of neutrino detection:
in "reasonable" param. range, EeV region is safe

in terms of getting info on sources:
once EeV region has been observed, PeV region can help discriminate composition and Galactic/extraGal. transition models

sad cases for neutrino detection:
iron and/or no source evolution



observation of diffuse cosmogenic neutrino spectra:
serious information on

⟶ injected UHECR chemical composition

⟶ cosmological evolution of UHECR source

⟶ Galactic/extragalac transition of cosmic rays

⟶ maximum injected energy at UHECR sources

"reasonable"
proton to Galactic mixed composition
$E_{Z,max} > Z \times 10^{19}$ eV
cosmological source evolution ~ star formation rate

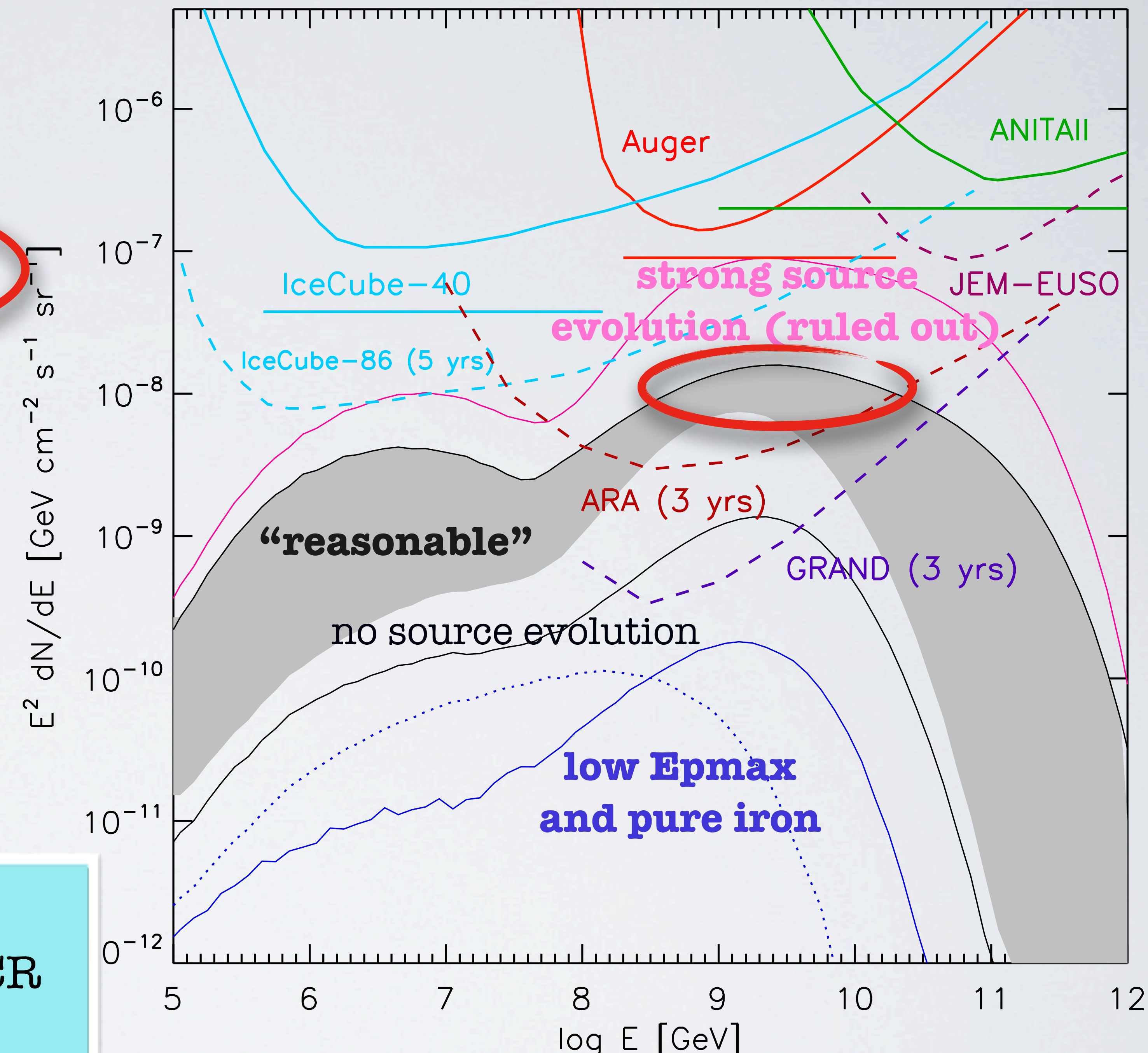
The guaranteed cosmogenic neutrinos

K.K., Allard & Olinto, 2010

in terms of neutrino detection:
in "reasonable" param. range, EeV region is safe

in terms of getting info on sources:
once EeV region has been observed, PeV region can help discriminate composition and Galactic/extraGal. transition models

sad cases for neutrino detection:
iron and/or no source evolution



observation of diffuse cosmogenic neutrino spectra:

serious i

—

—

—

—

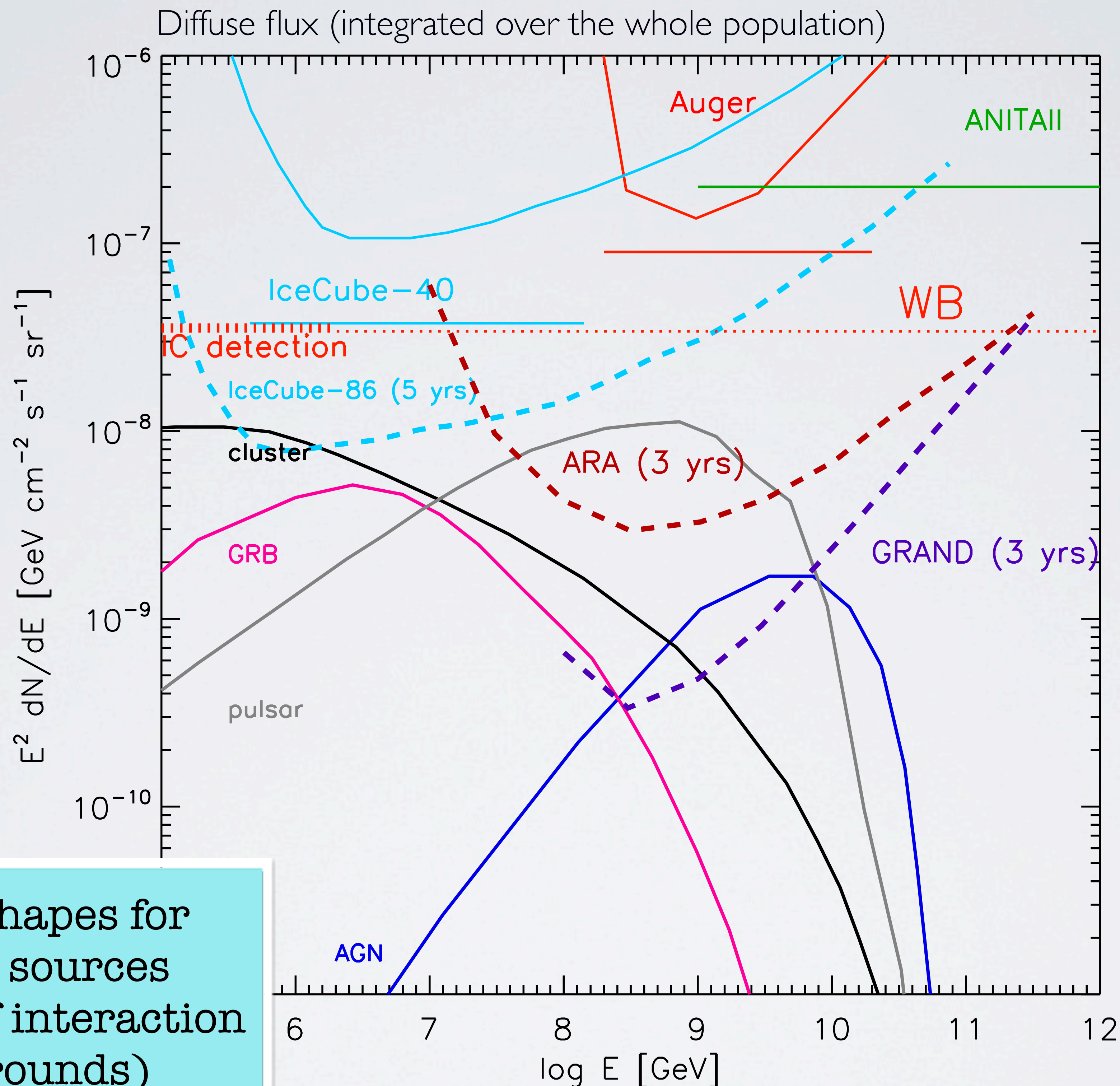
we converge on the characteristics of the UHECR source population :-)

(we don't necessarily identify sources - and don't necessarily start doing neutrino astronomy) :-(

btw, it might not be the first thing we see!

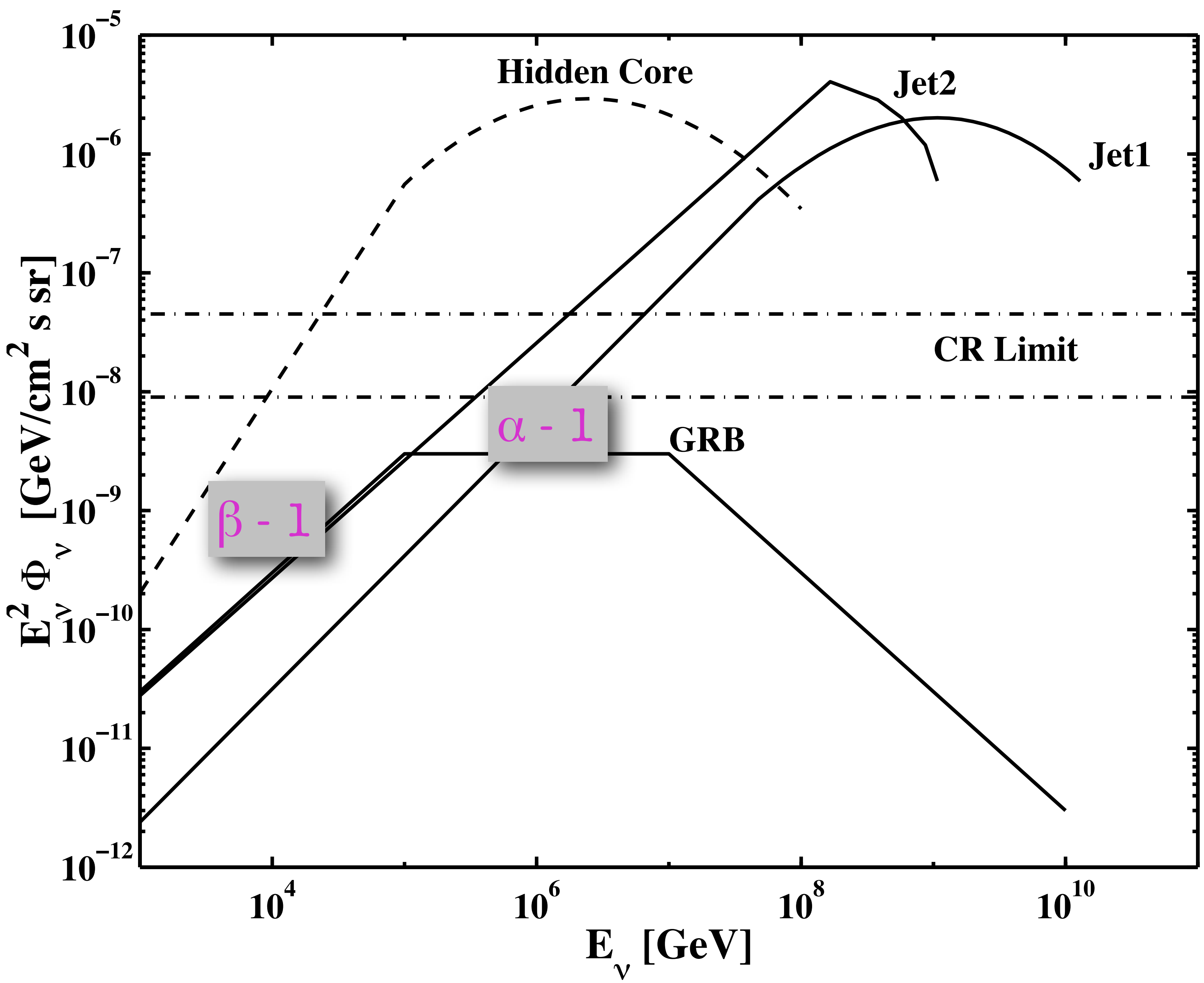
"reasonable"
proton to Galactic mixed composition
$E_{Z,max} > Z\times10^{19}$ eV
cosmological source evolution ~ star formation rate

Neutrinos produced at the source (diffuse flux)



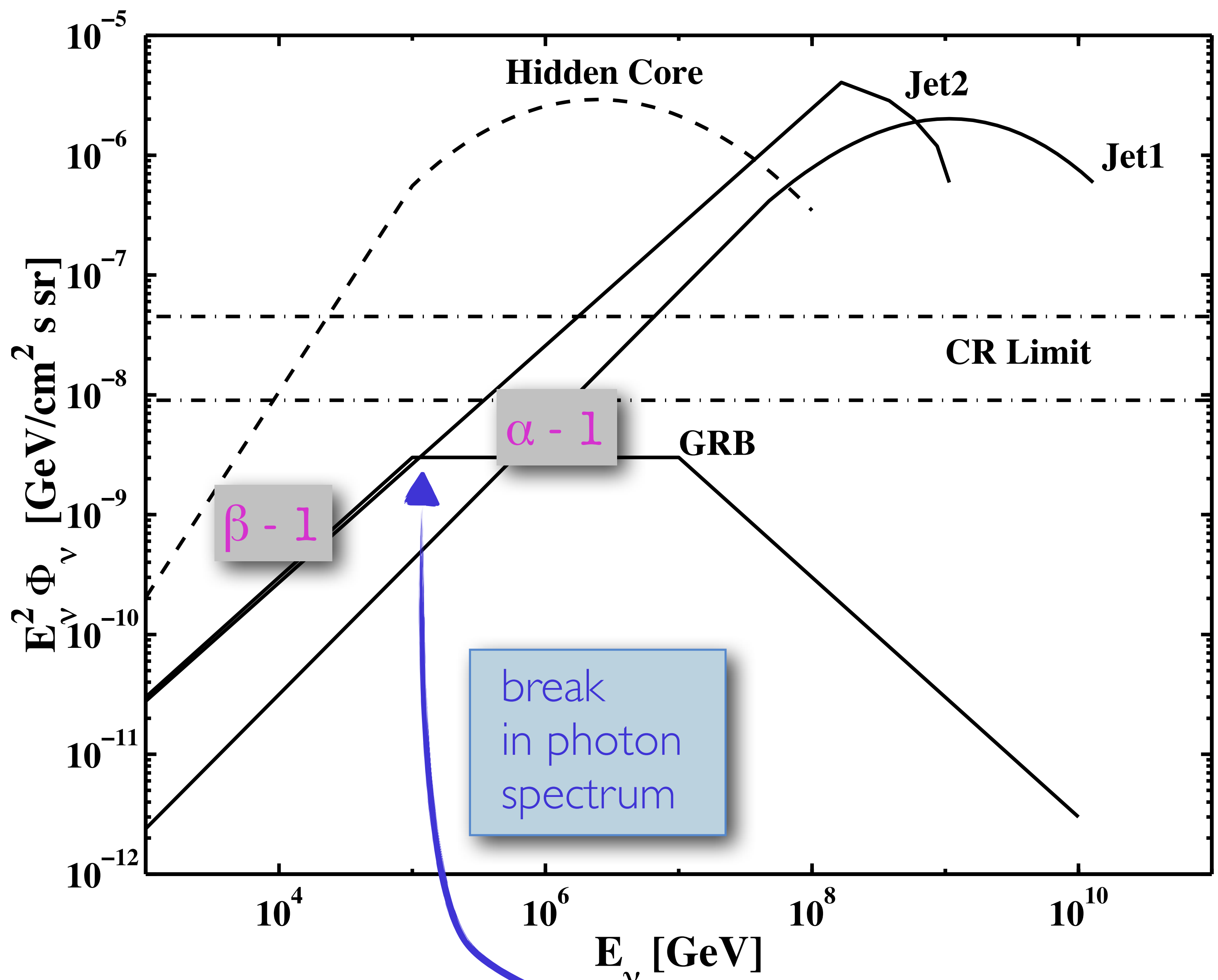
unique shapes for various sources (because of interaction backgrounds)

Waxman & Bahcall 99



Simplified example: neutrino flux from GRBs

Waxman & Bahcall 99

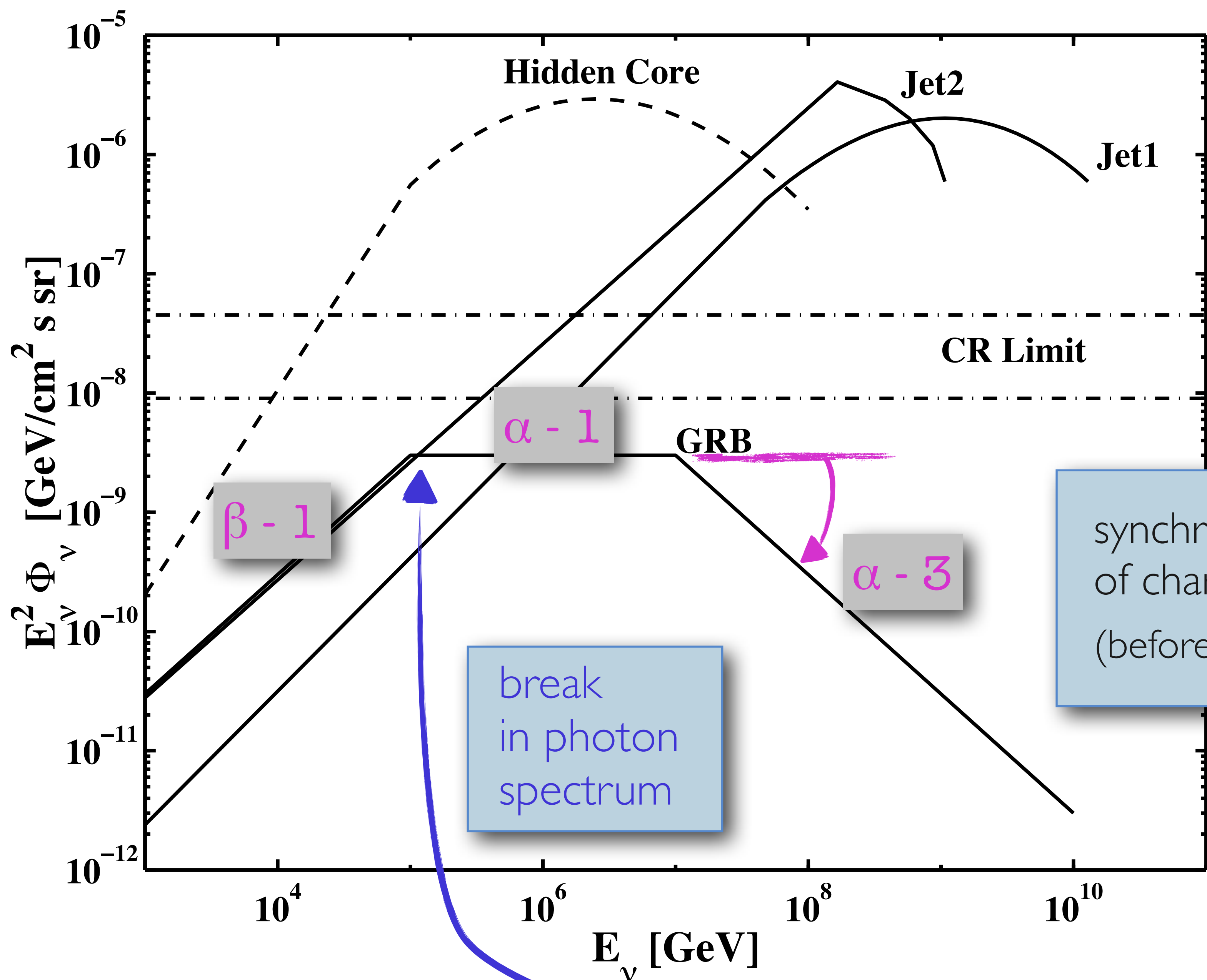


GRB gamma-ray spectrum:

$$\frac{dn}{d\varepsilon} = \frac{L_b e^{-(\varepsilon/\varepsilon^{\max})}}{4\pi r^2 \Gamma^2 c(\varepsilon^b)^2} \begin{cases} (\varepsilon/\varepsilon^b)^{-\alpha} & (\text{for } \varepsilon^{\min} \le \varepsilon < \varepsilon^b) \\ (\varepsilon/\varepsilon^b)^{-\beta} & (\text{for } \varepsilon^b \le \varepsilon \le \varepsilon^{\max}) \end{cases}$$

Simplified example: neutrino flux from GRBs

Waxman & Bahcall 99

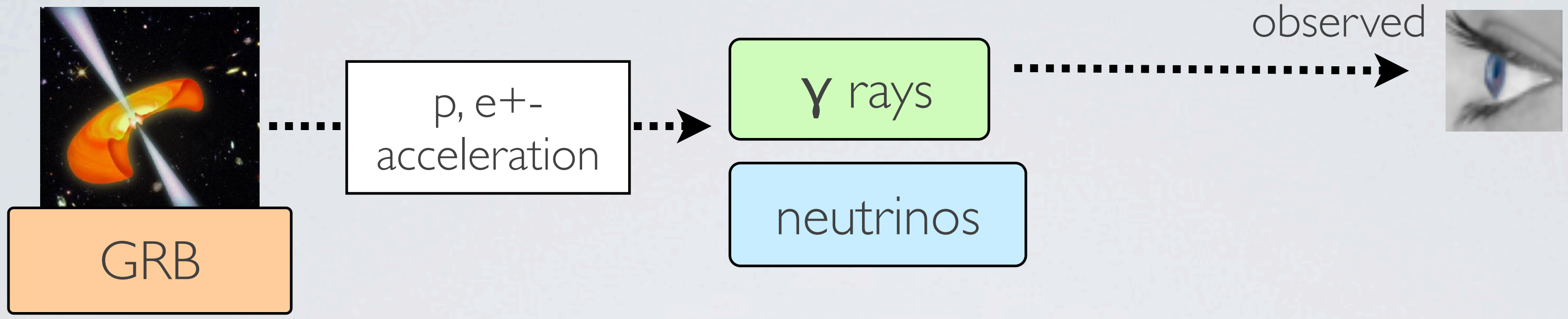


synchrotron cooling
of charged mesons
(before decay and production of ν)

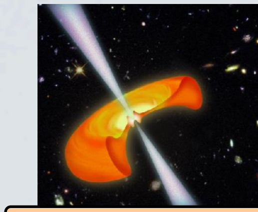
GRB gamma-ray spectrum:

$$\frac{dn}{d\varepsilon} = \frac{L_b e^{-(\varepsilon/\varepsilon^{\max})}}{4\pi r^2 \Gamma^2 c (\varepsilon^b)^2} \begin{cases} (\varepsilon/\varepsilon^b)^{-\alpha} & (\text{for } \varepsilon^{\min} \le \varepsilon < \varepsilon^b) \\ (\varepsilon/\varepsilon^b)^{-\beta} & (\text{for } \varepsilon^b \le \varepsilon \le \varepsilon^{\max}) \end{cases}$$

Multi-messenger connections



Multi-messenger connections



GRB

p, e+-
acceleration

γ rays

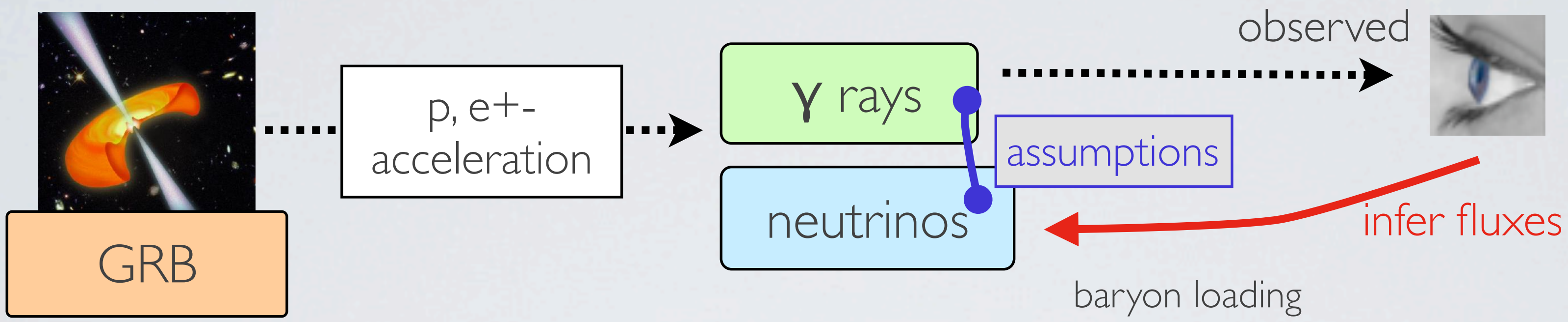
neutrinos

assumptions

observed

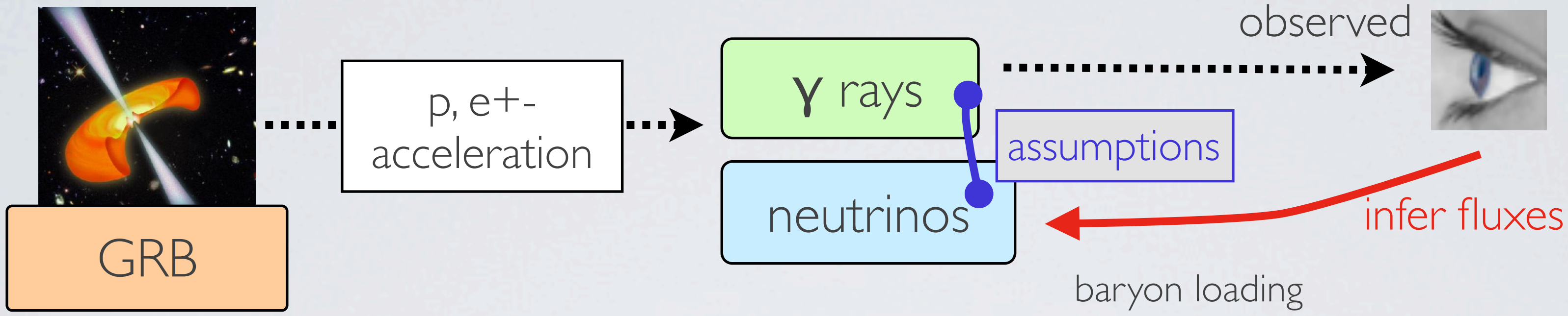
baryon loading
burst Lorentz factor
Emin, Emax of cosmic rays
acceleration region (internal/external/reverse shock?)
cosmic ray composition ...

Multi-messenger connections

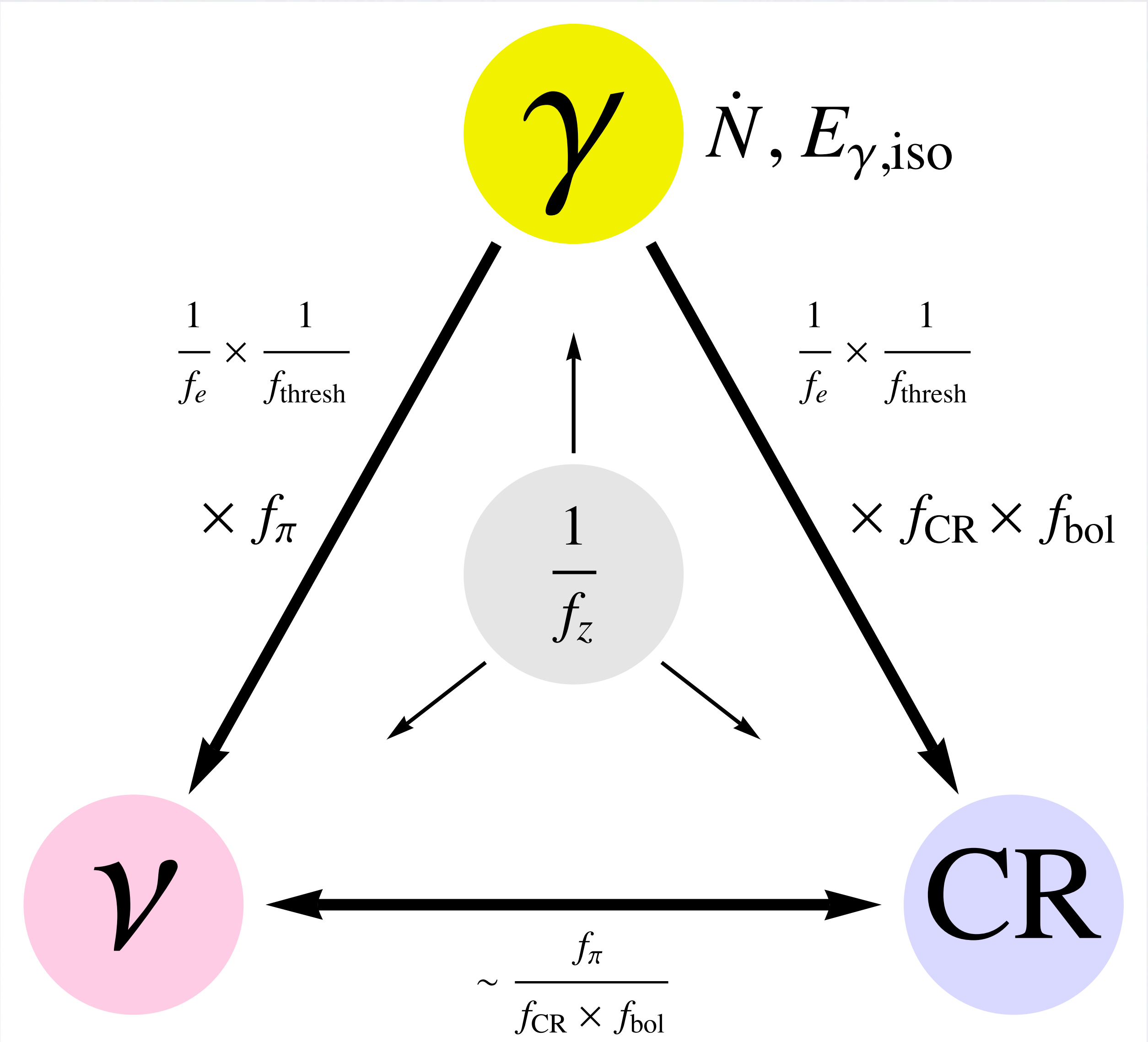


baryon loading
burst Lorentz factor
Emin, Emax of cosmic rays
acceleration region (internal/external/reverse shock?)
cosmic ray composition ...

Multi-messenger connections



baryon loading
burst Lorentz factor
Emin, Emax of cosmic rays
acceleration region (internal/external/reverse shock?)
cosmic ray composition ...



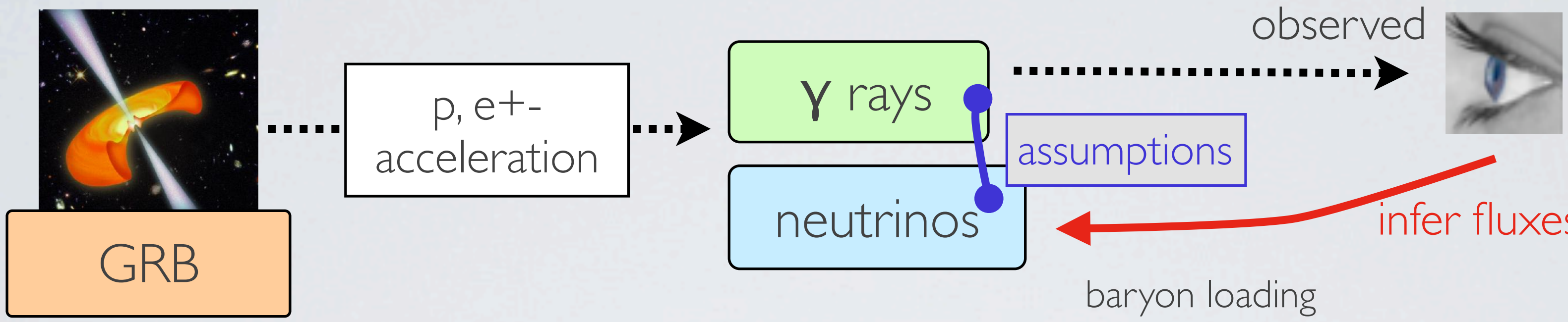
$\dot{N}$ number of observable GRBs per year

$E_{\gamma,iso}$ isotropic equivalent energy in gamma-rays

$E_{CR} = 10^{19-20}$ eV

Baerwald et al. 14

Multi-messenger connections

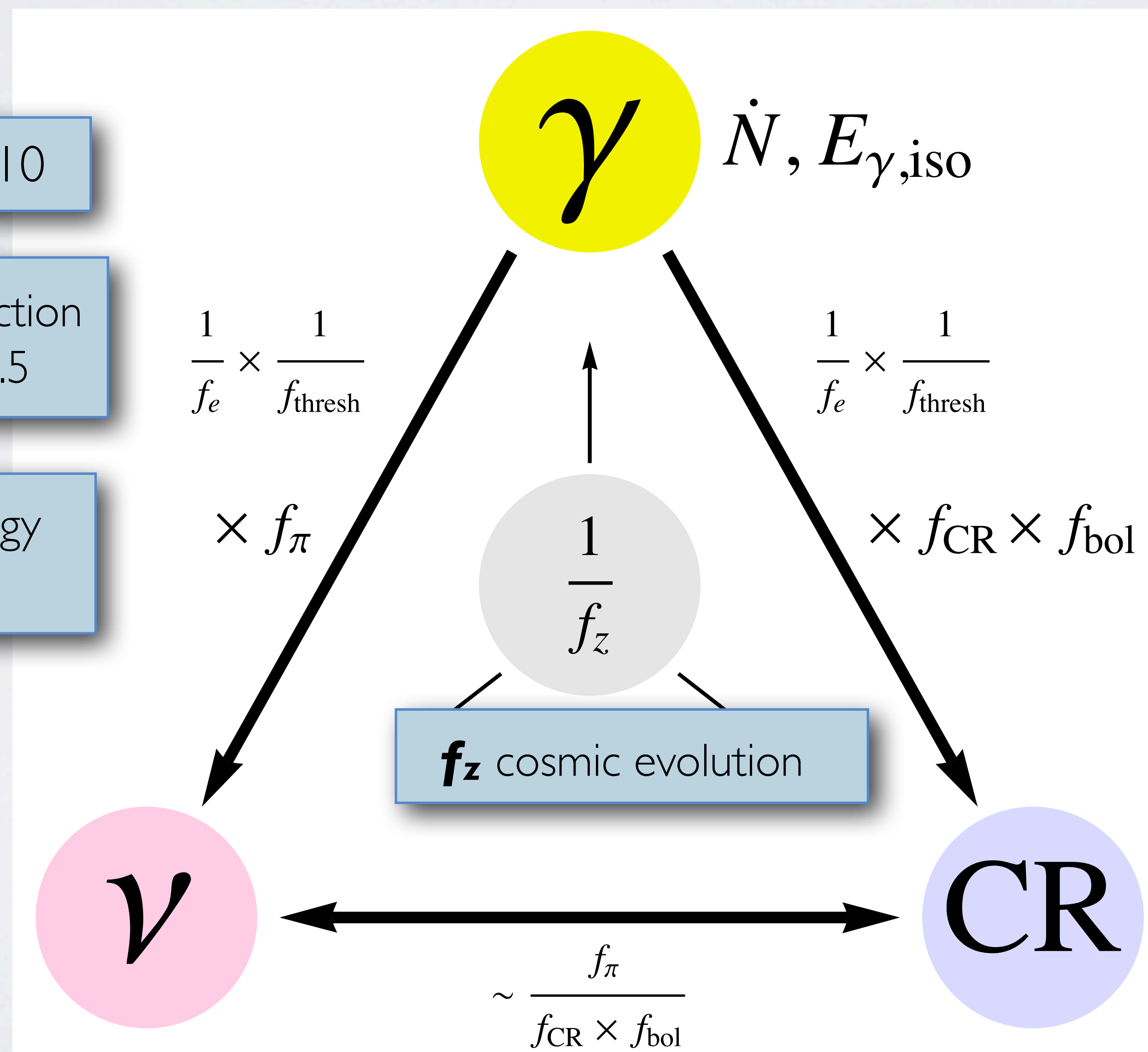


baryon loading
burst Lorentz factor
Emin, Emax of cosmic rays
acceleration region (internal/external/reverse shock?)
cosmic ray composition ...

f_e^{-1} baryonic loading >10

f_{thres} instrument thresh. correction for GRBs not observed ~ 0.2-0.5

f_π fraction of baryonic energy going into pion production



Baerwald et al. 14

$\dot{N}$ number of observable GRBs per year

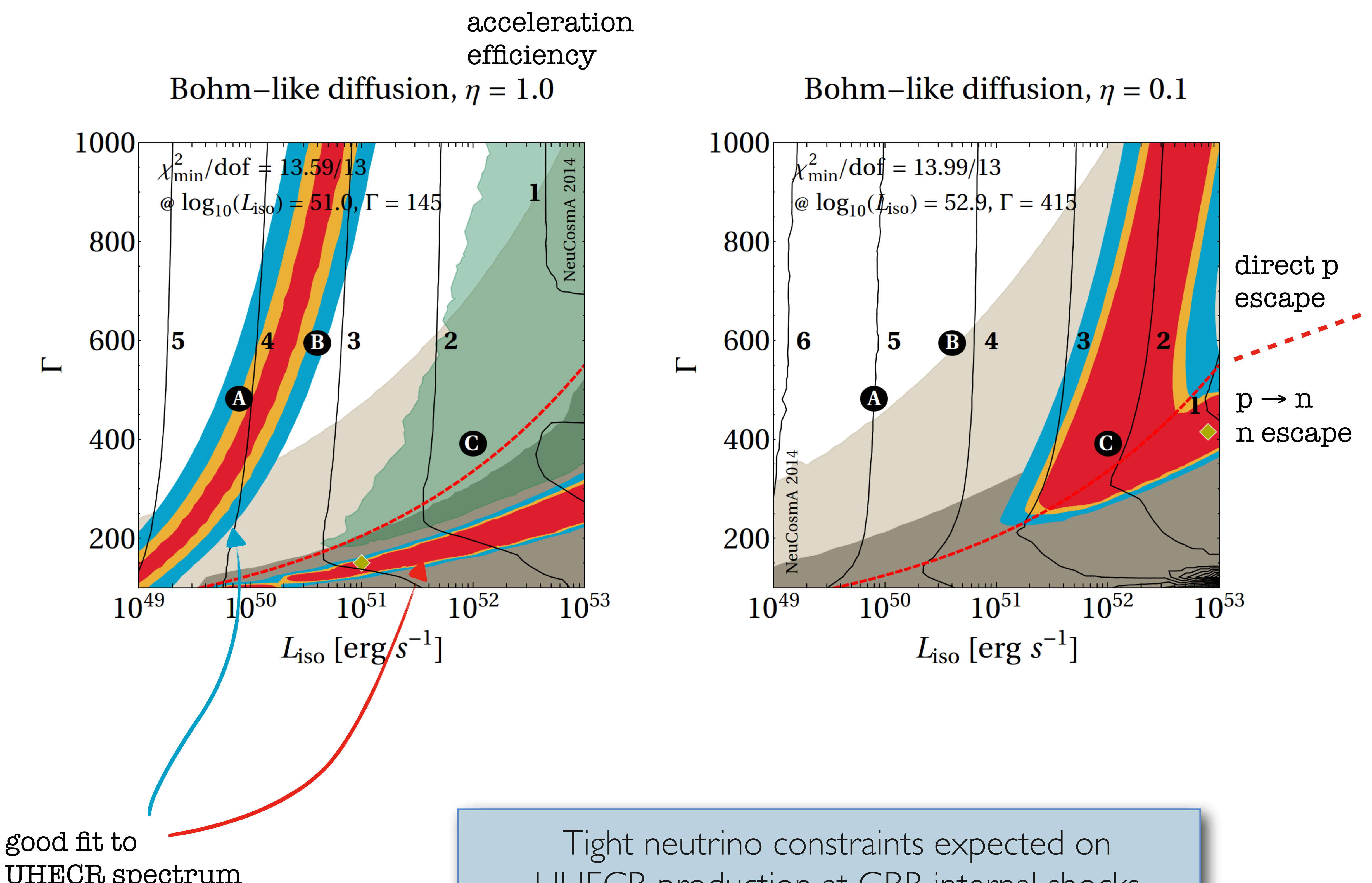
$E_{\gamma,iso}$ isotropic equivalent energy in gamma-rays

f_{CR} fraction of baryonic energy going into CR prod.

f_{bol} fraction of total CR energy going into UHE << 1

$E_{CR} = 10^{19-20}$ eV

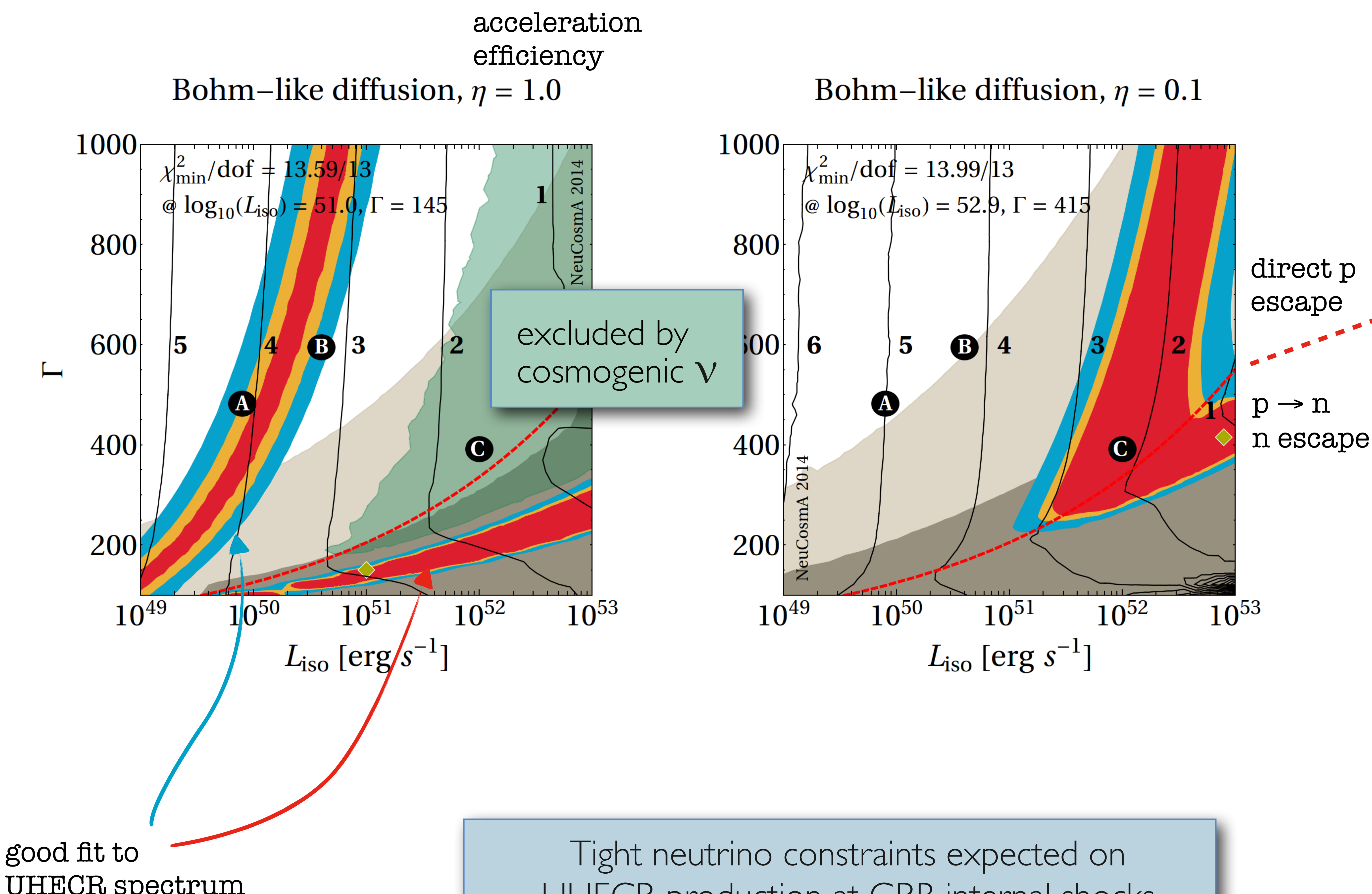
Baerwald et al. (2014)



Tight neutrino constraints expected on UHECR production at GRB internal shocks

Constraints on GRBs with IceCube in the coming years

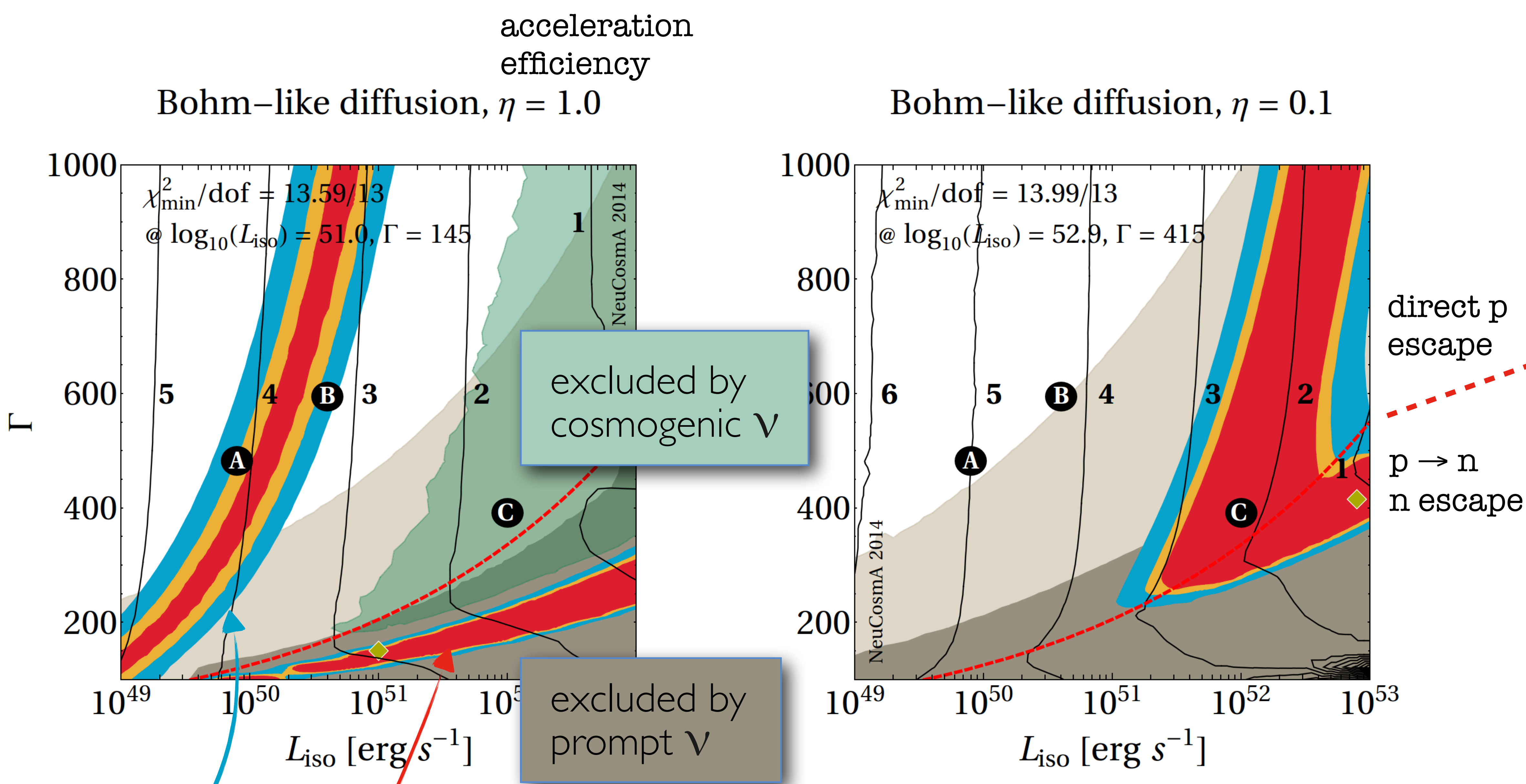
Baerwald et al. (2014)



Tight neutrino constraints expected on UHECR production at GRB internal shocks

Constraints on GRBs with IceCube in the coming years

Baerwald et al. (2014)

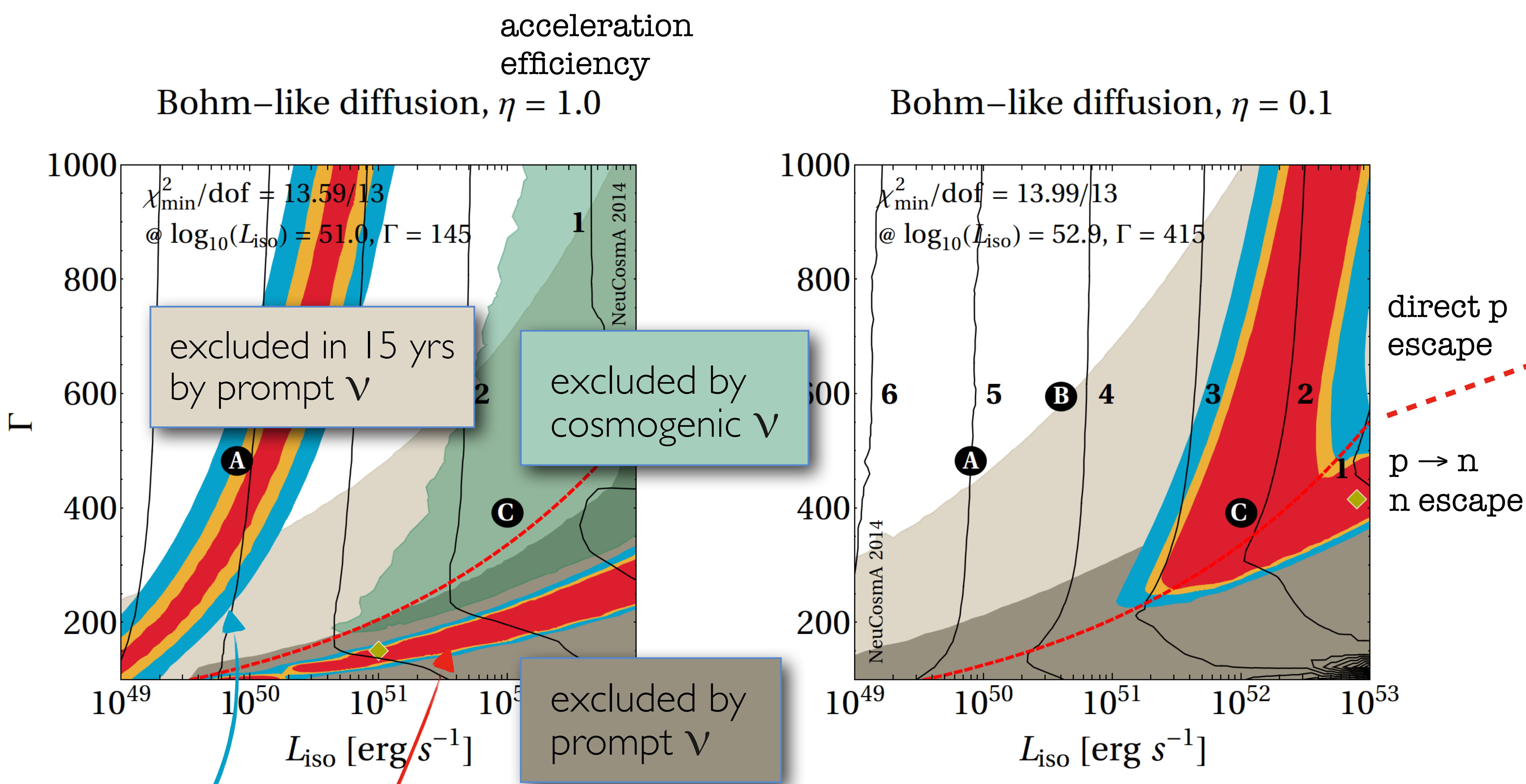


good fit to
UHECR spectrum

Tight neutrino constraints expected on
UHECR production at GRB internal shocks

Constraints on GRBs with IceCube in the coming years

Baerwald et al. (2014)

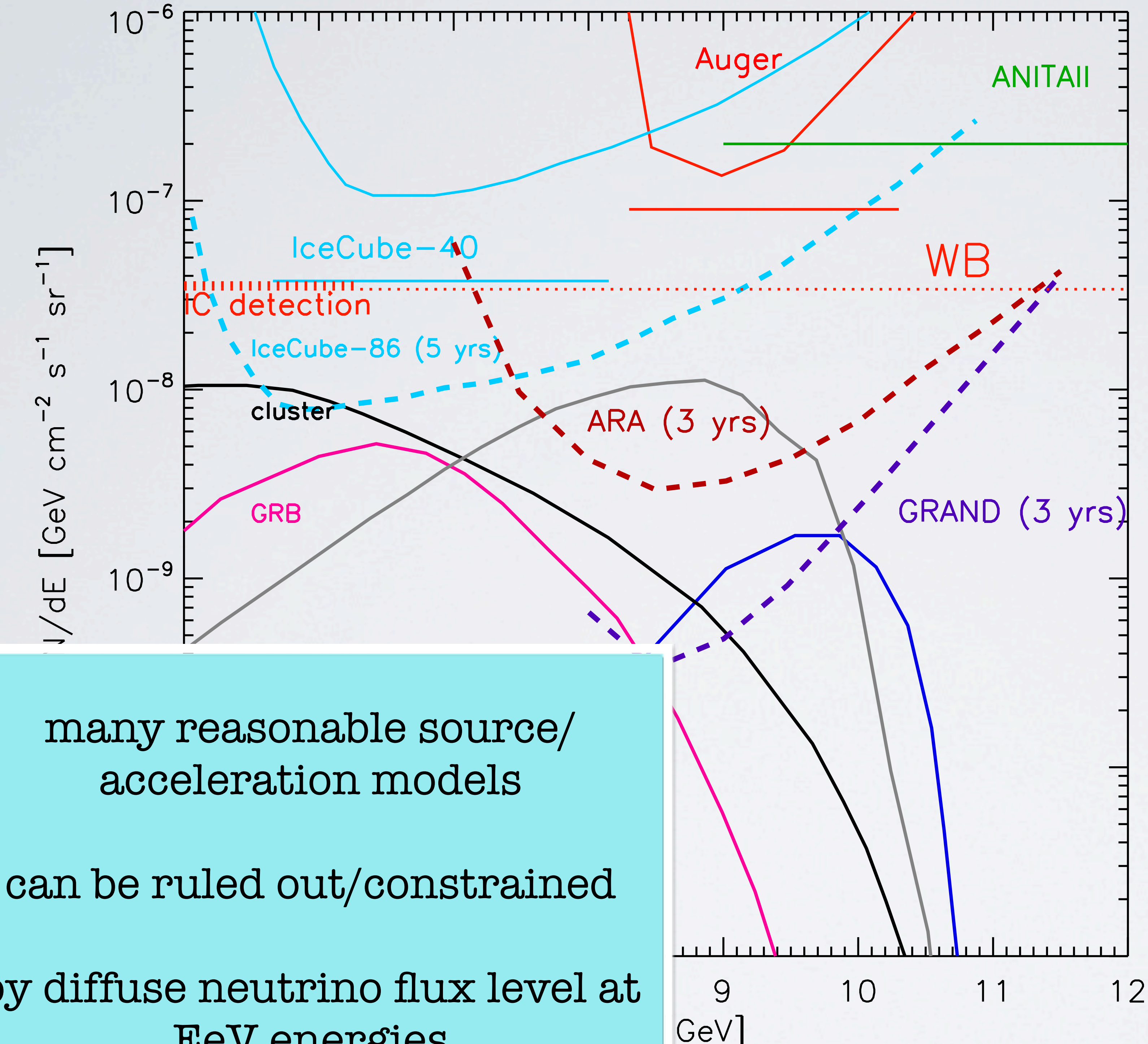


good fit to
UHECR spectrum

Tight neutrino constraints expected on
UHECR production at GRB internal shocks

Neutrinos produced at the source (diffuse flux)

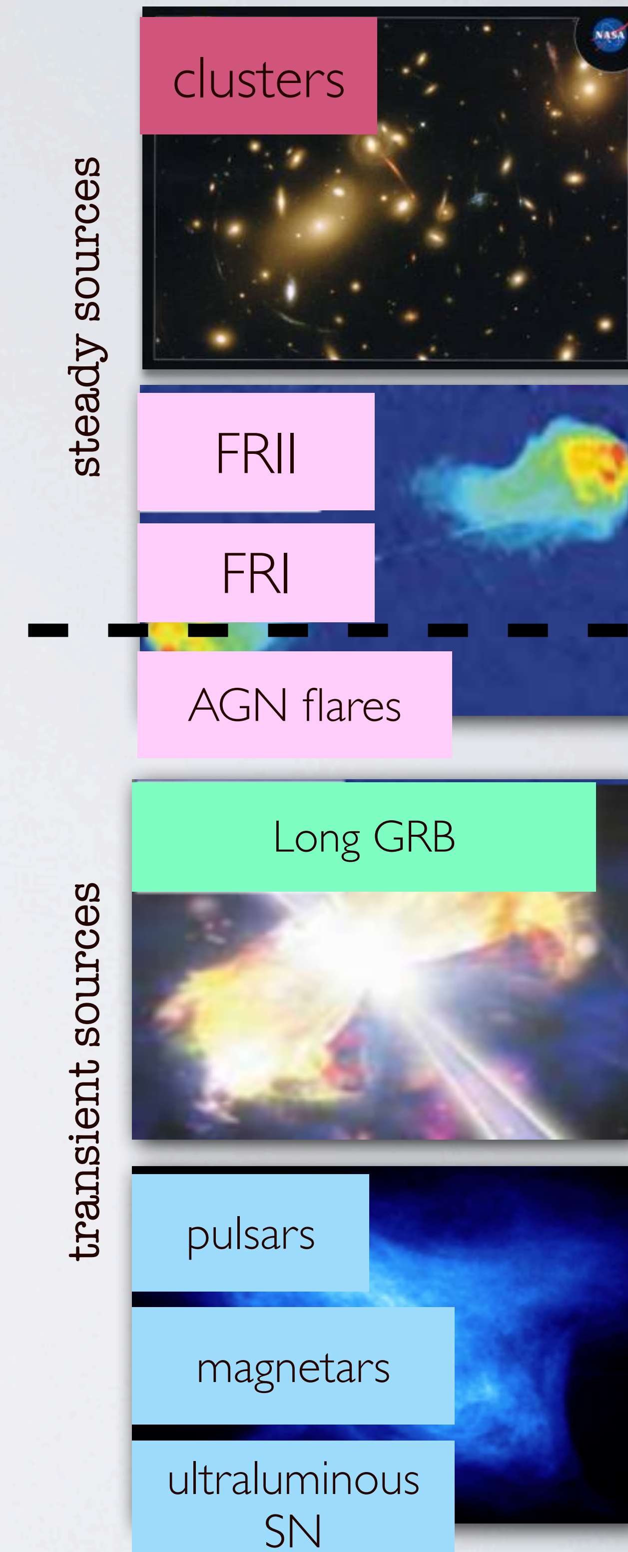
Diffuse flux (integrated over the whole population)



many reasonable source/
acceleration models

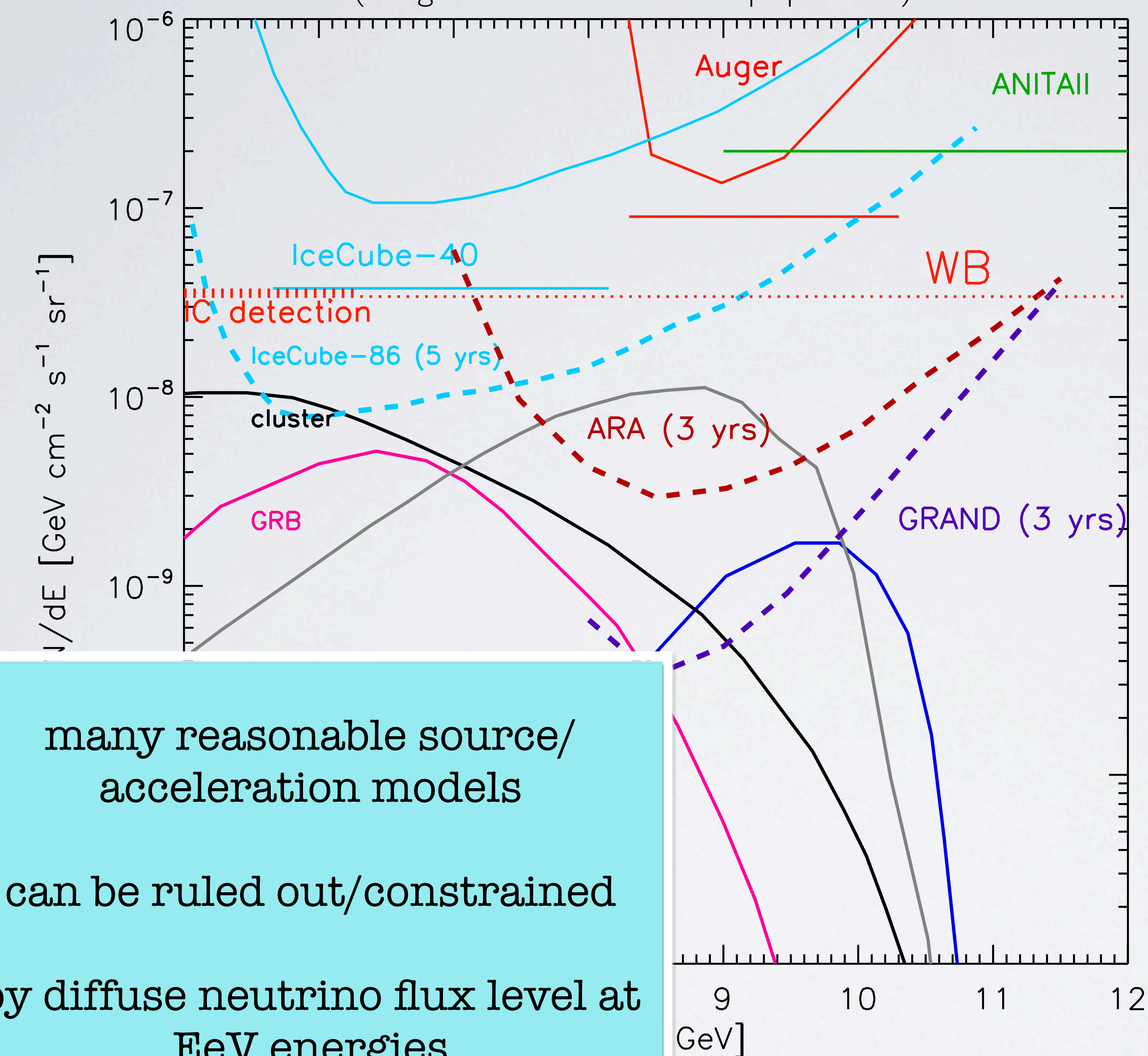
can be ruled out/constrained

by diffuse neutrino flux level at
EeV energies



Neutrinos produced at the source (diffuse flux)

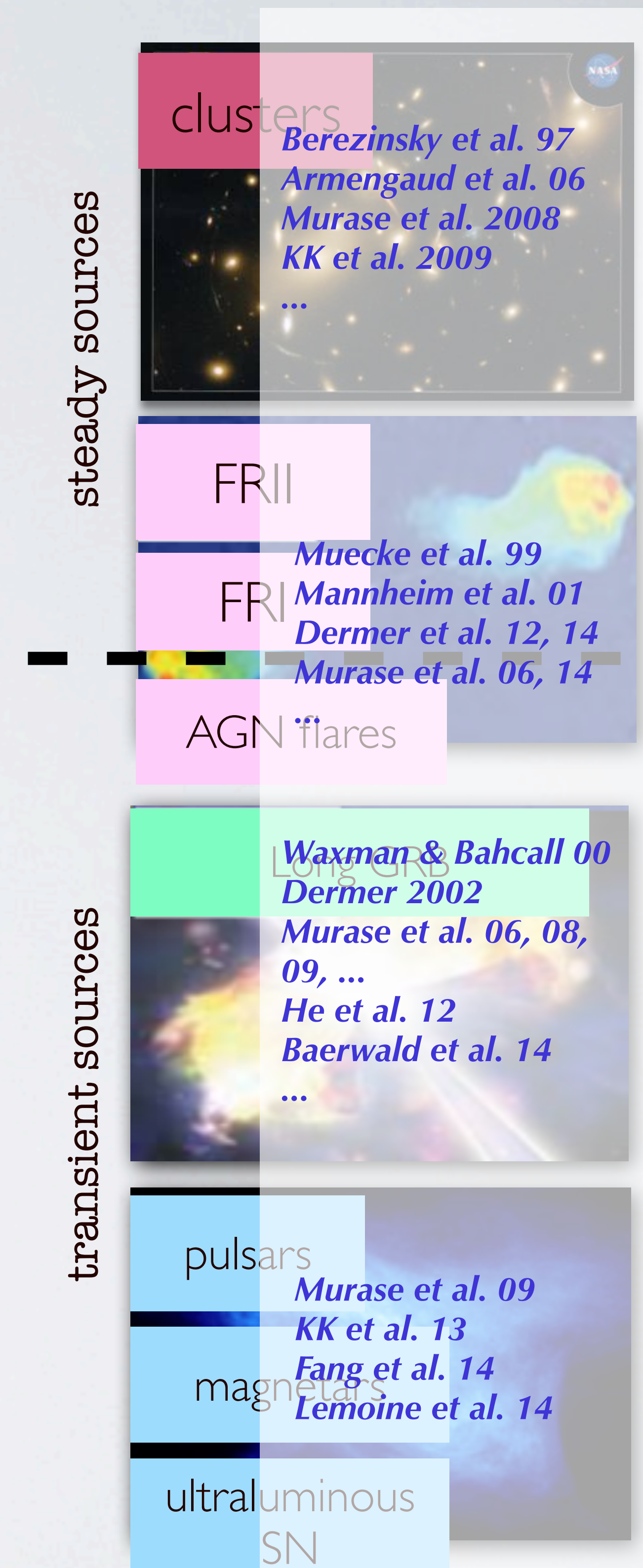
Diffuse flux (integrated over the whole population)



many reasonable source/ acceleration models

can be ruled out/constrained

by diffuse neutrino flux level at EeV energies



What one could do with many very high energy neutrinos

- constrain source populations by stacking analysis

@ position of ultraluminous SN, blazars (flares), GRBs...

- understand the origin of IceCube neutrinos

Ultimate goal: neutrino astronomy

- observe neutrinos in coincidence with e-m signal
- neutrinos astronomy of one object
- time-variability of neutrino signal

What one could do with many very high energy neutrinos

- constrain source populations by stacking analysis

@ position of ultraluminous SN, blazars (flares), GRBs...

- understand the origin of IceCube neutrinos

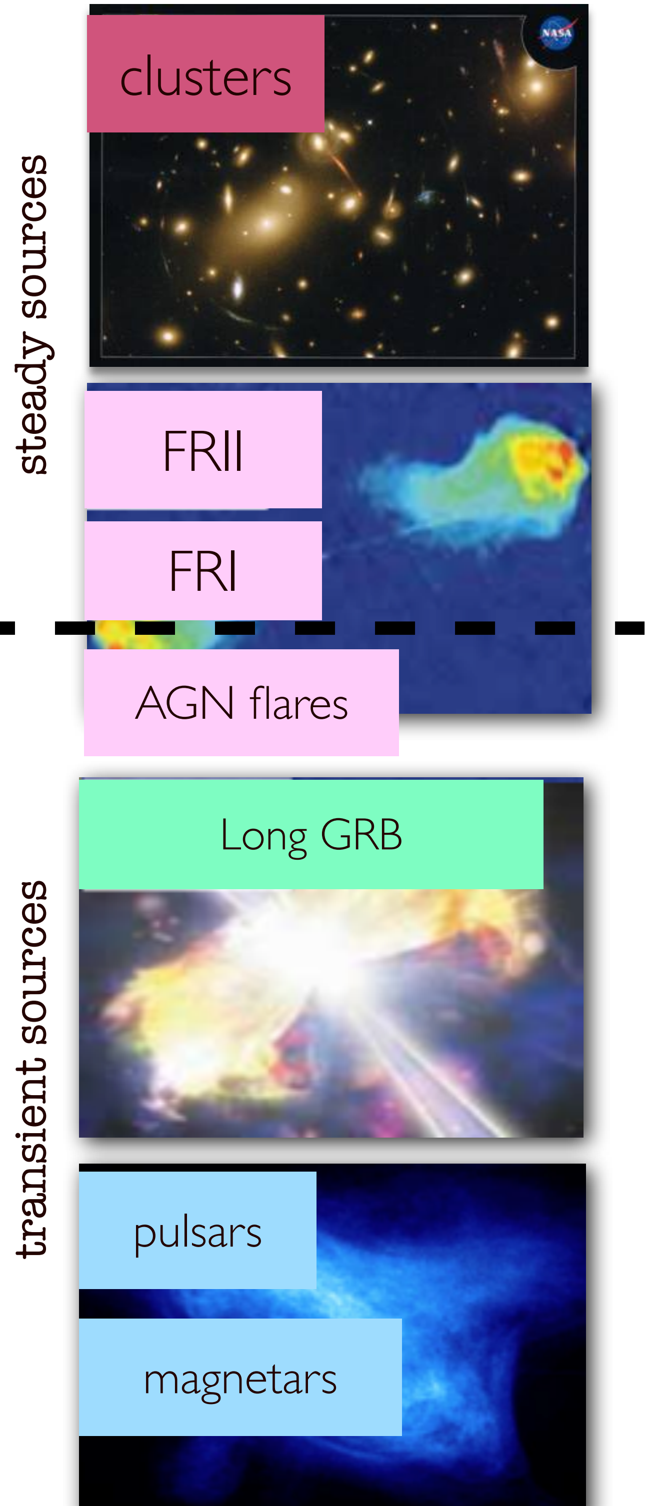
Ultimate goal: neutrino astronomy

- observe neutrinos in coincidence with e-m signal
- neutrinos astronomy of one object
- time-variability of neutrino signal

best with transient objects

- powerful
- not so rare for many types (ultraluminous SN, blazar flares...)
- best candidate to produce UHECRs

Total energy budget and number density of sources



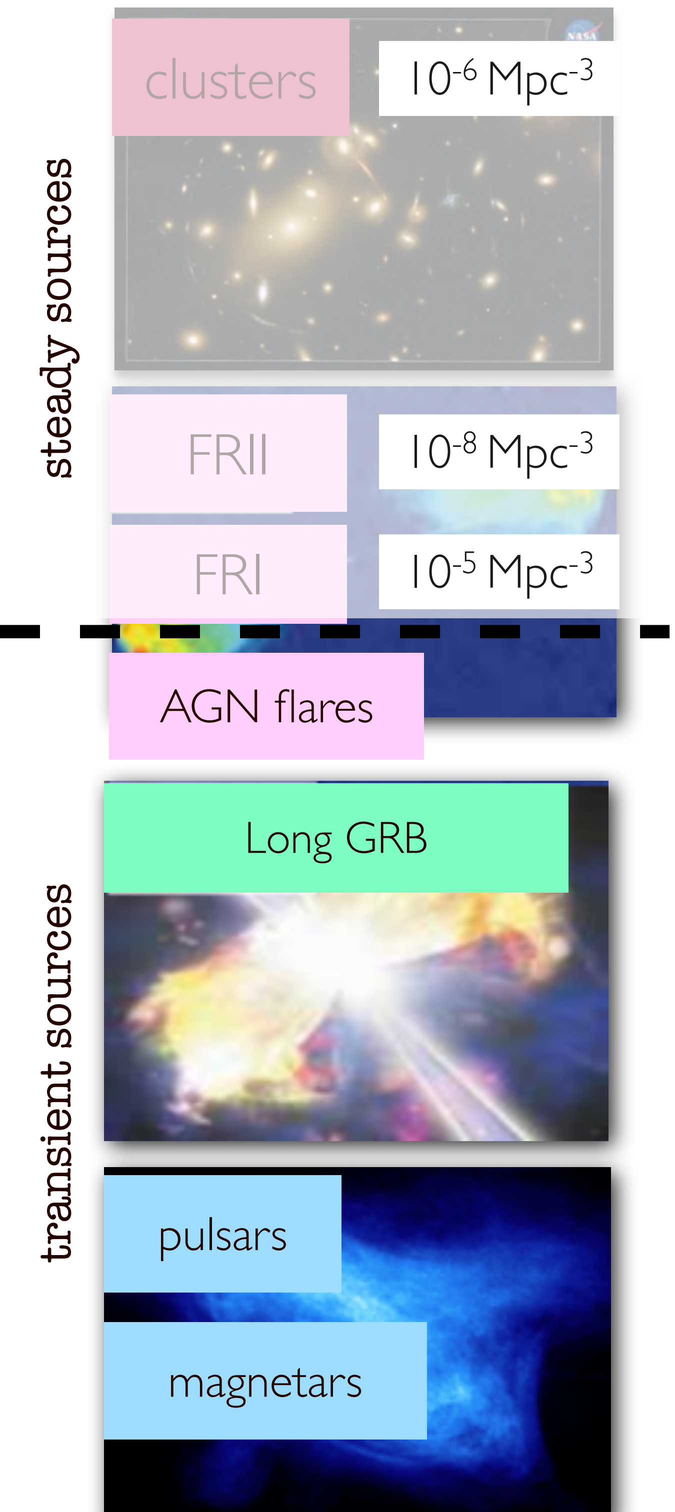
lack of multiplets in the sky (many events from small angular spot)

➢ **apparent number density of sources:**

$n_0 \gtrsim 10^{-5}\ \mathrm{Mpc}^{-3}$

Kashti & Waxman 08, Takami & Sato 09, Abreu et al. 2013

Total energy budget and number density of sources



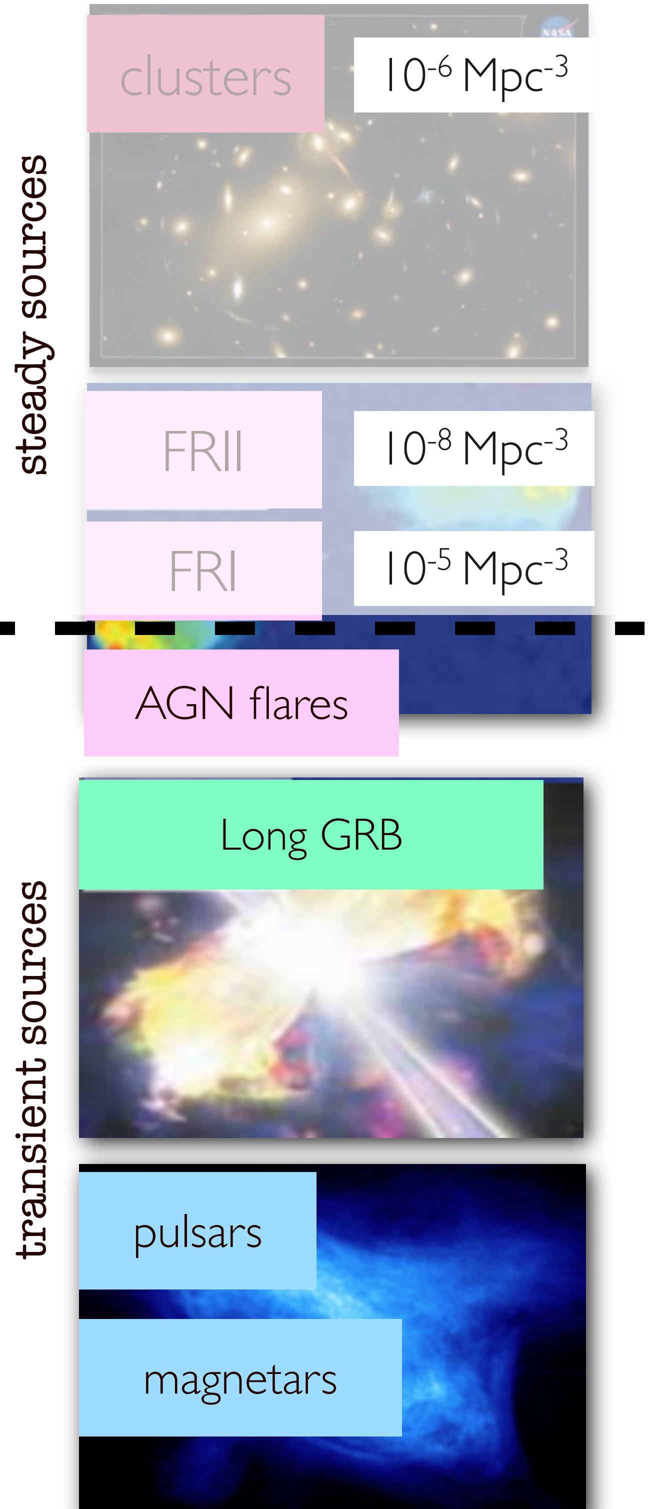
lack of multiplets in the sky (many events from small angular spot)

➢ **apparent number density of sources:**

$n_0 \gtrsim 10^{-5}$ Mpc^{-3}

Kashti & Waxman 08,
Takami & Sato 09,
Abreu et al. 2013

Total energy budget and number density of sources



lack of multiplets in the sky (many events from small angular spot)

➢ **apparent number density of sources:**

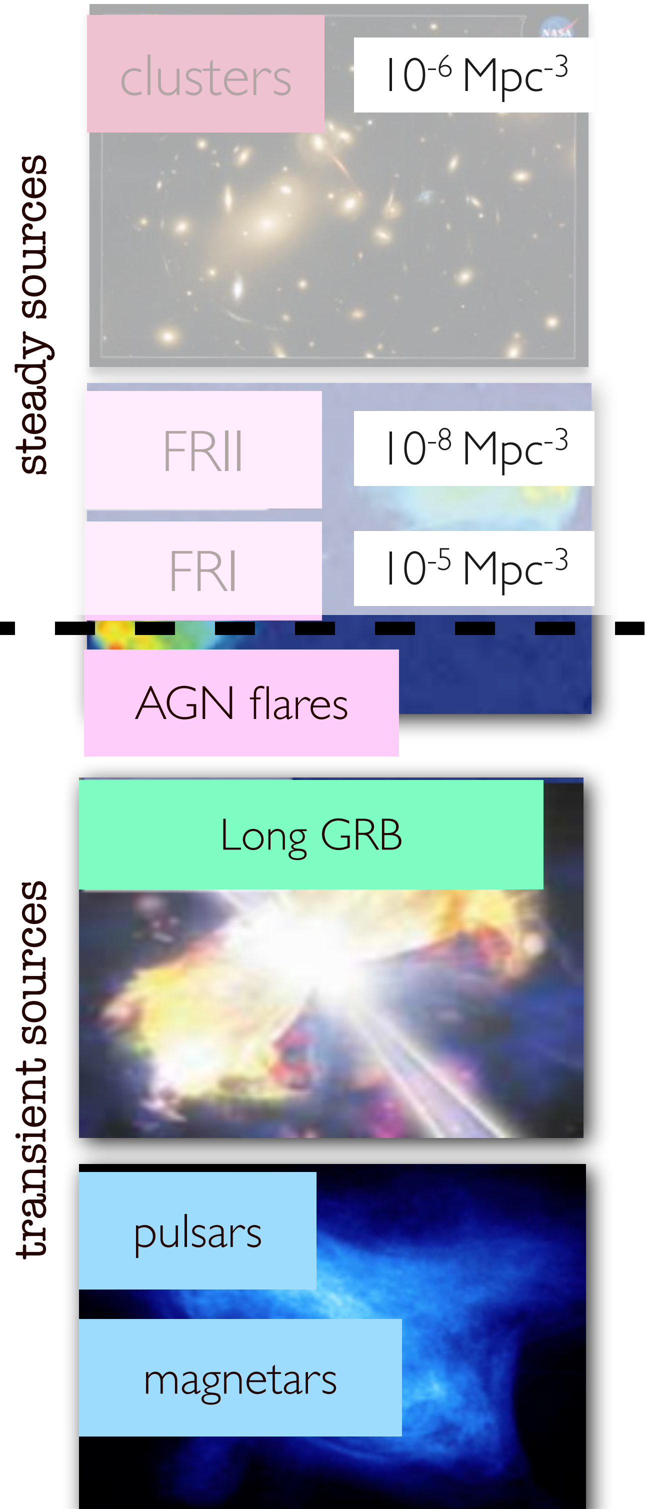
$$n_0 \gtrsim 10^{-5}\ \mathrm{Mpc}^{-3}$$

Kashti & Waxman 08, Takami & Sato 09, Abreu et al. 2013

for transient sources: real number density of UHE proton sources

$\rho_0 \sim n_0$ / (CR time spread τ_d)

τ_d depends on extragalactic + Galactic magnetic fields (not known)



lack of multiplets in the sky (many events from small angular spot)

➢ **apparent number density of sources:**

$n_0 \gtrsim 10^{-5}$ Mpc^{-3}

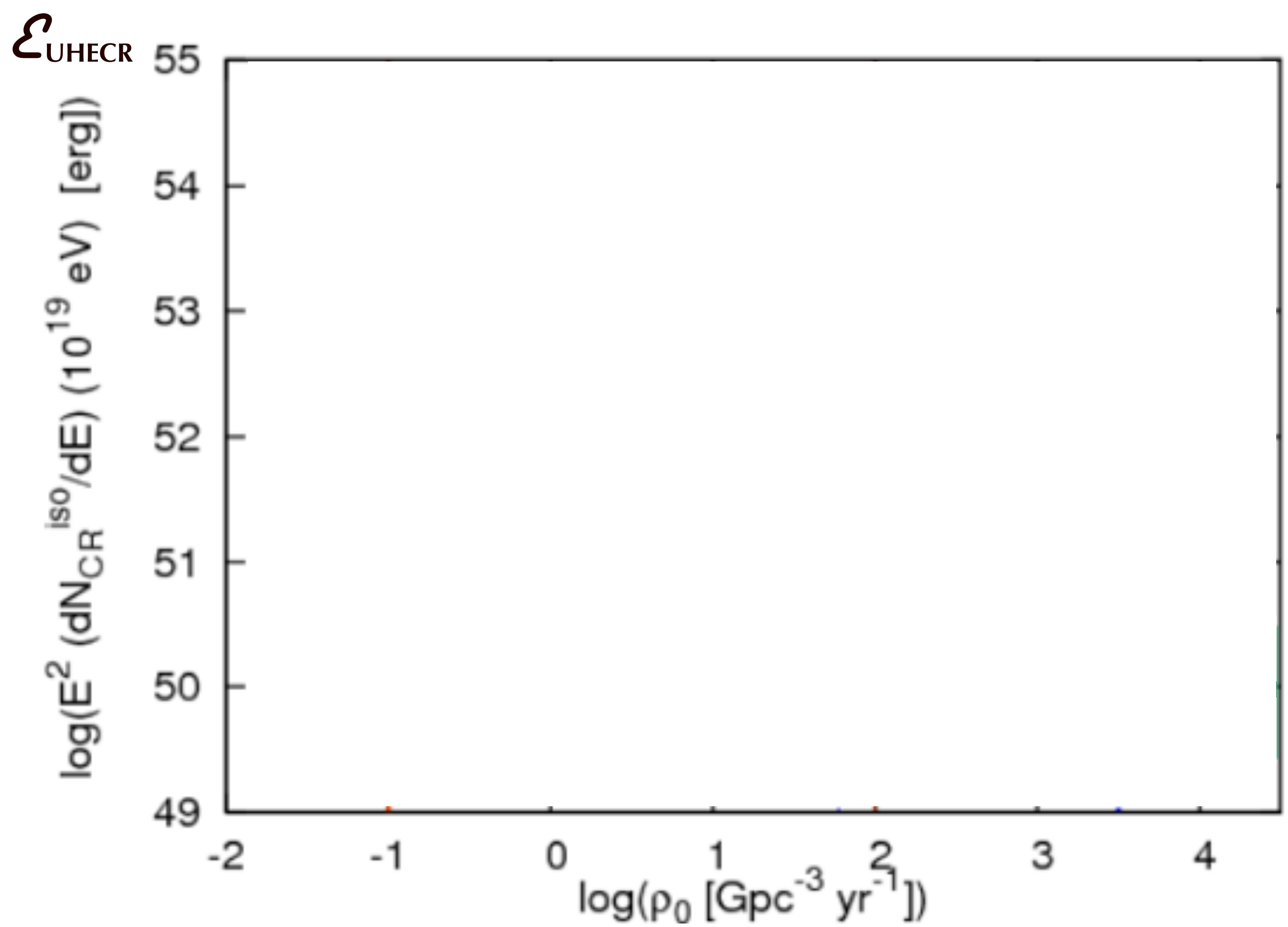
Kashti & Waxman 08, Takami & Sato 09, Abreu et al. 2013

for transient sources: real number density of UHE proton sources

$\rho_0 \sim n_0$ / (CR time spread τ_d)

τ_d depends on extragalactic + Galactic magnetic fields (not known)

Murase & Takami 09



$n_0 = 10^{-4}$ Mpc^{-3}
$s = 2$, protons

from K. Murase

Total energy budget and number density of sources

steady sources

transient sources

lack of multiplets in the sky (many events from small angular spot)

➢ **apparent number density of sources:**

$n_0 \gtrsim 10^{-5}$ Mpc^{-3}

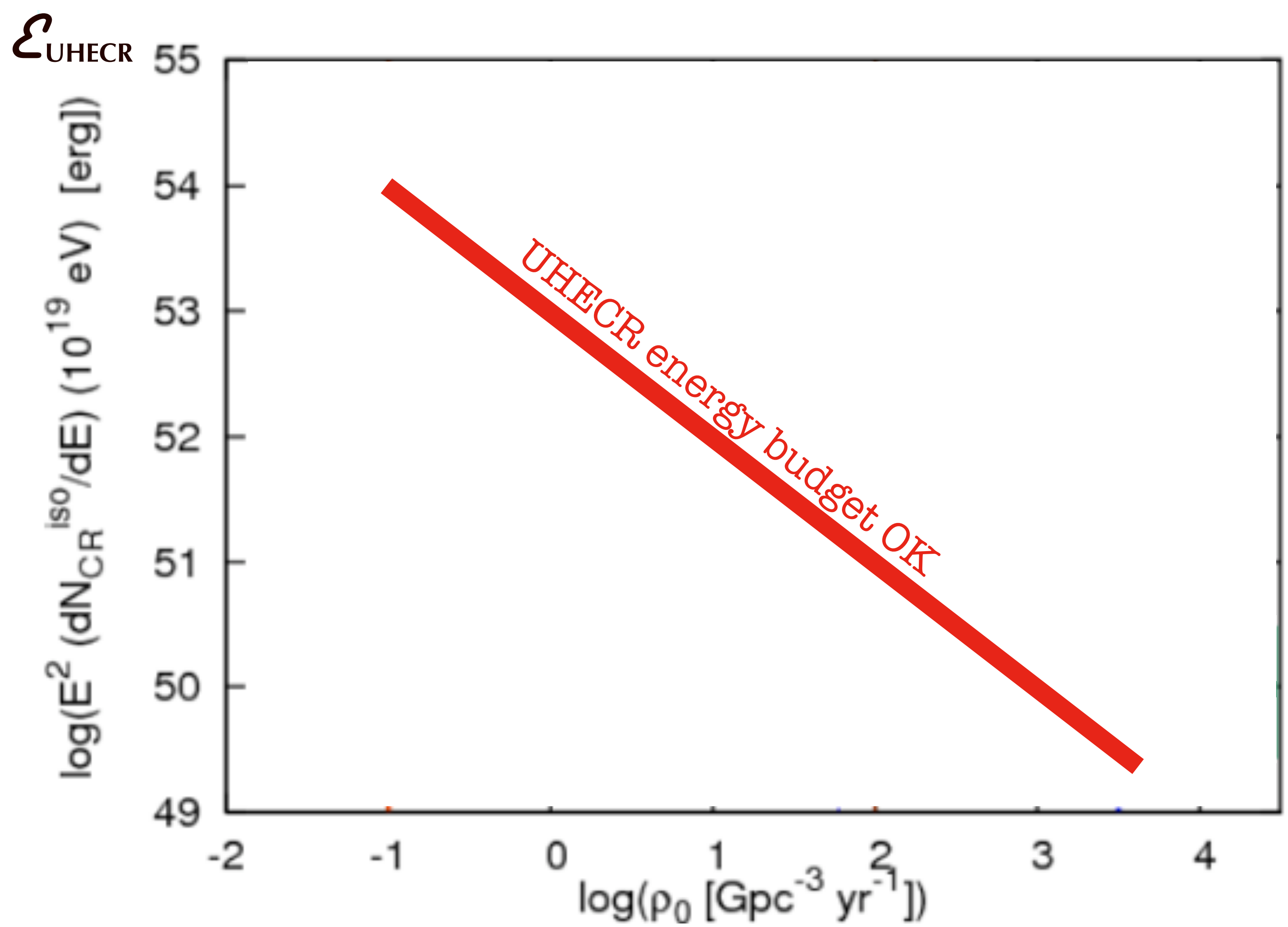
Kashti & Waxman 08, Takami & Sato 09, Abreu et al. 2013

for transient sources: real number density of UHE proton sources

$\rho_0 \sim n_0$ / (CR time spread τ_d)

τ_d depends on extragalactic + Galactic magnetic fields (not known)

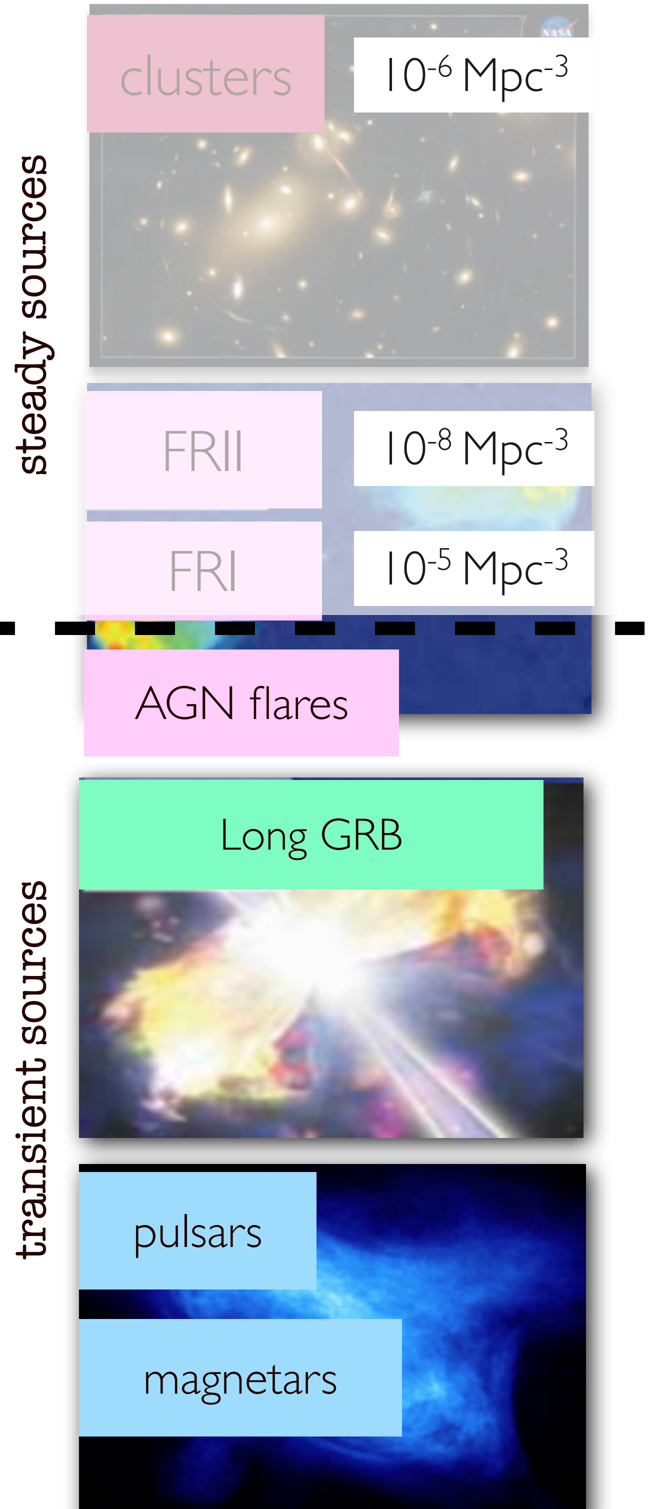
Murase & Takami 09



$n_0 = 10^{-4}$ Mpc^{-3}
s = 2, protons

from K. Murase

Total energy budget and number density of sources



lack of multiplets in the sky (many events from small angular spot)

➢ **apparent number density of sources:**

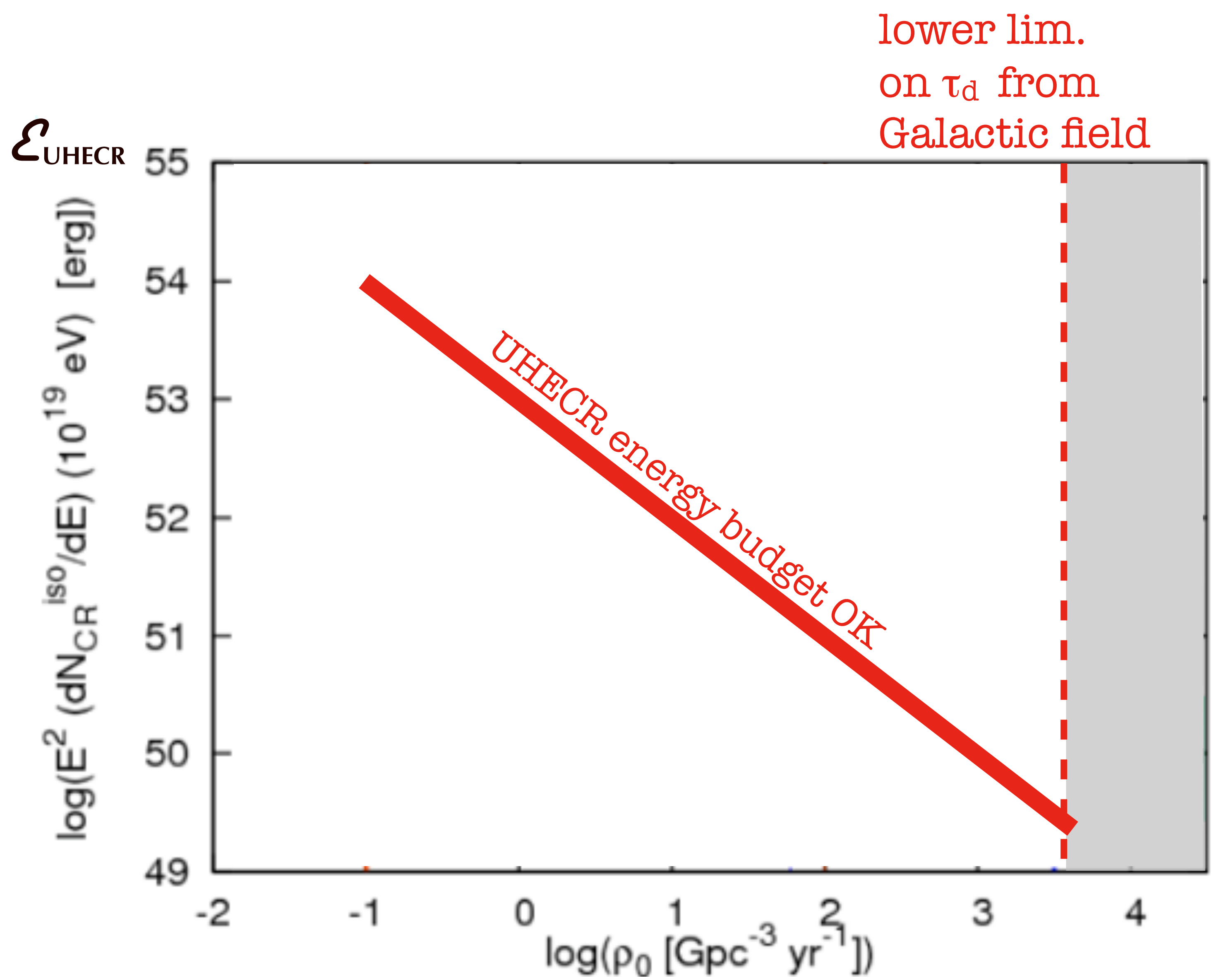
$n_0 \gtrsim 10^{-5}$ Mpc^{-3}

Kashti & Waxman 08, Takami & Sato 09, Abreu et al. 2013

for transient sources: real number density of UHE proton sources

$\rho_0 \sim n_0$ / (CR time spread τ_d)

τ_d depends on extragalactic + Galactic magnetic fields (not known)



Murase & Takami 09

$n_0 = 10^{-4}$ Mpc^{-3}
s = 2, protons

from K. Murase

Total energy budget and number density of sources

steady sources

transient sources

lack of multiplets in the sky (many events from small angular spot)

➢ **apparent number density of sources:**

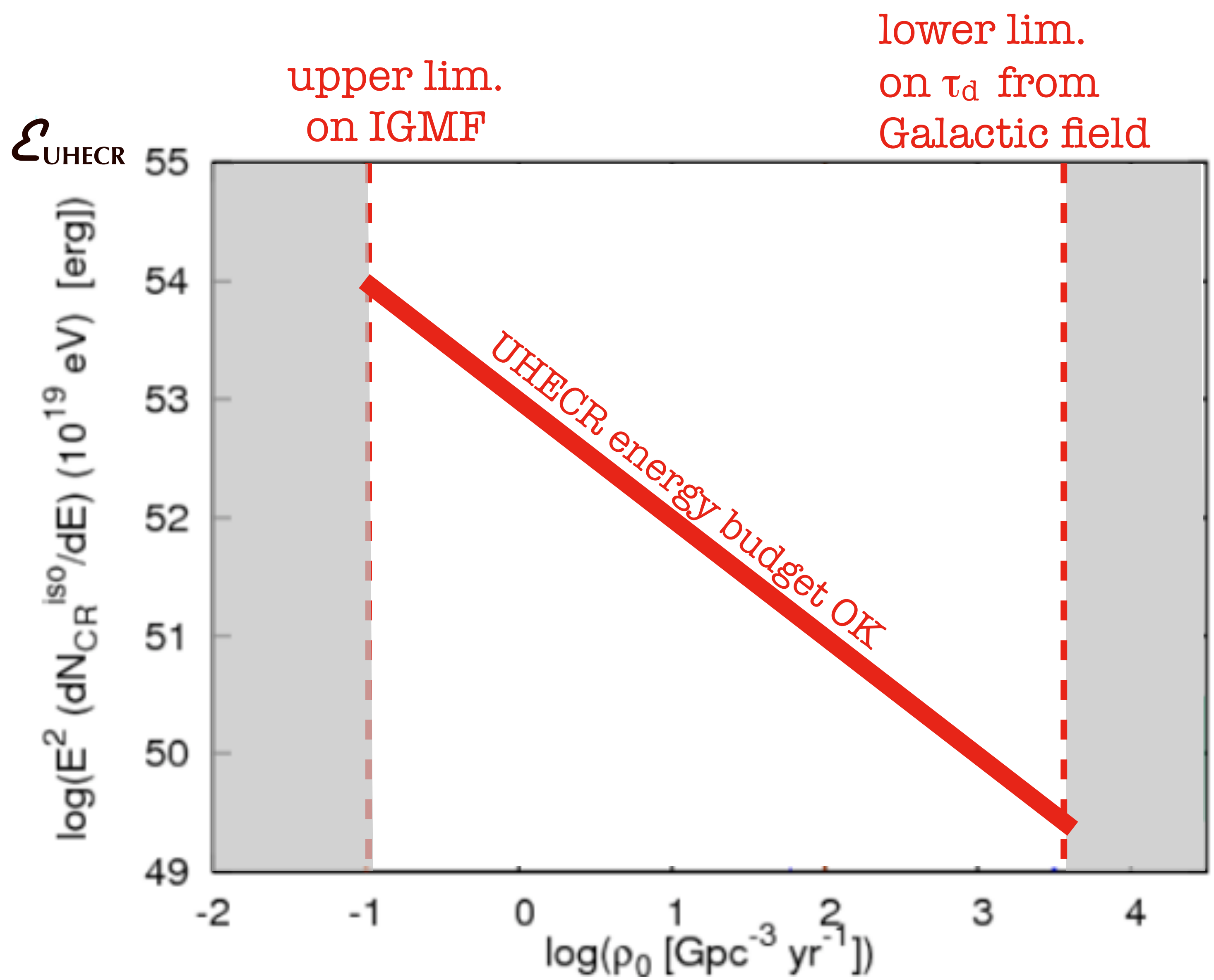
$n_0 \gtrsim 10^{-5}$ Mpc^{-3}

Kashti & Waxman 08, Takami & Sato 09, Abreu et al. 2013

for transient sources: real number density of UHE proton sources

$\rho_0 \sim n_0$ / (CR time spread τ_d)

τ_d depends on extragalactic + Galactic magnetic fields (not known)



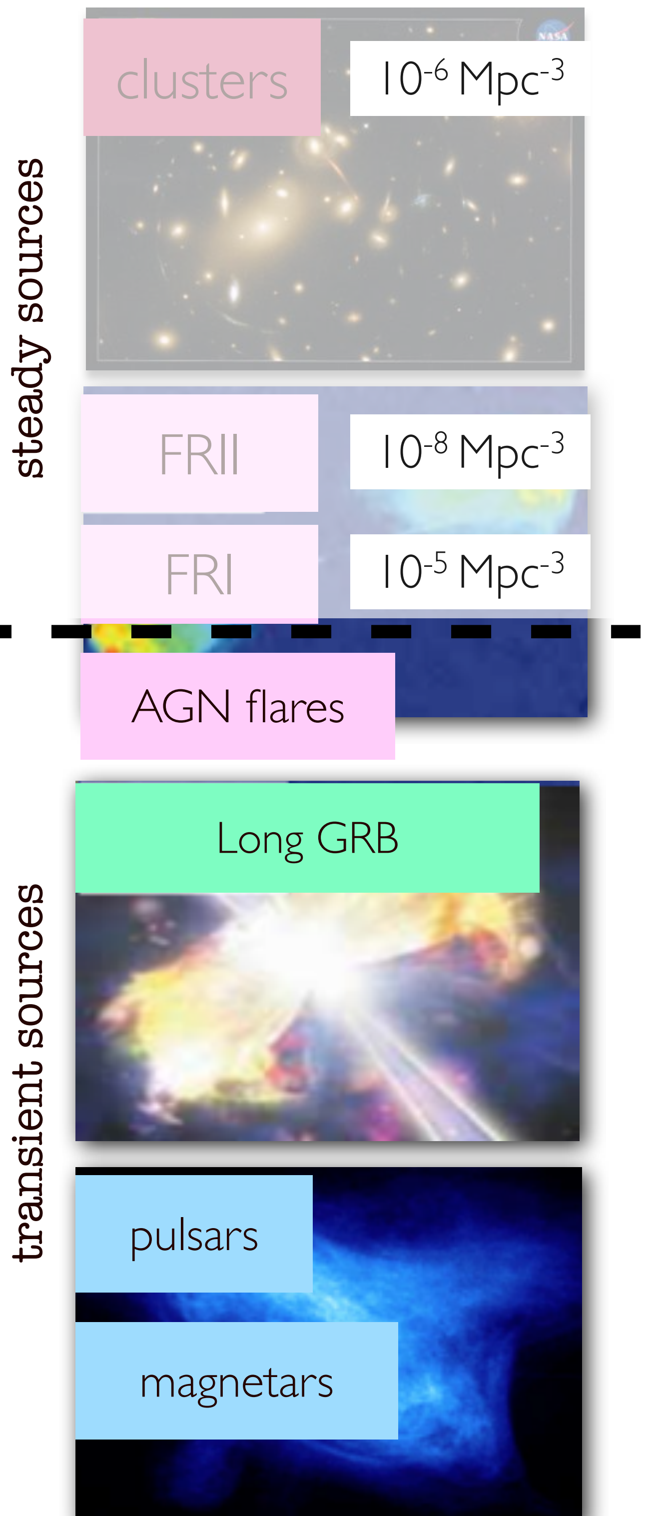
Murase & Takami 09

$n_0 = 10^{-4}$ Mpc^{-3}

s = 2, protons

from K. Murase

Total energy budget and number density of sources



lack of multiplets in the sky (many events from small angular spot)

➢ **apparent number density of sources:**

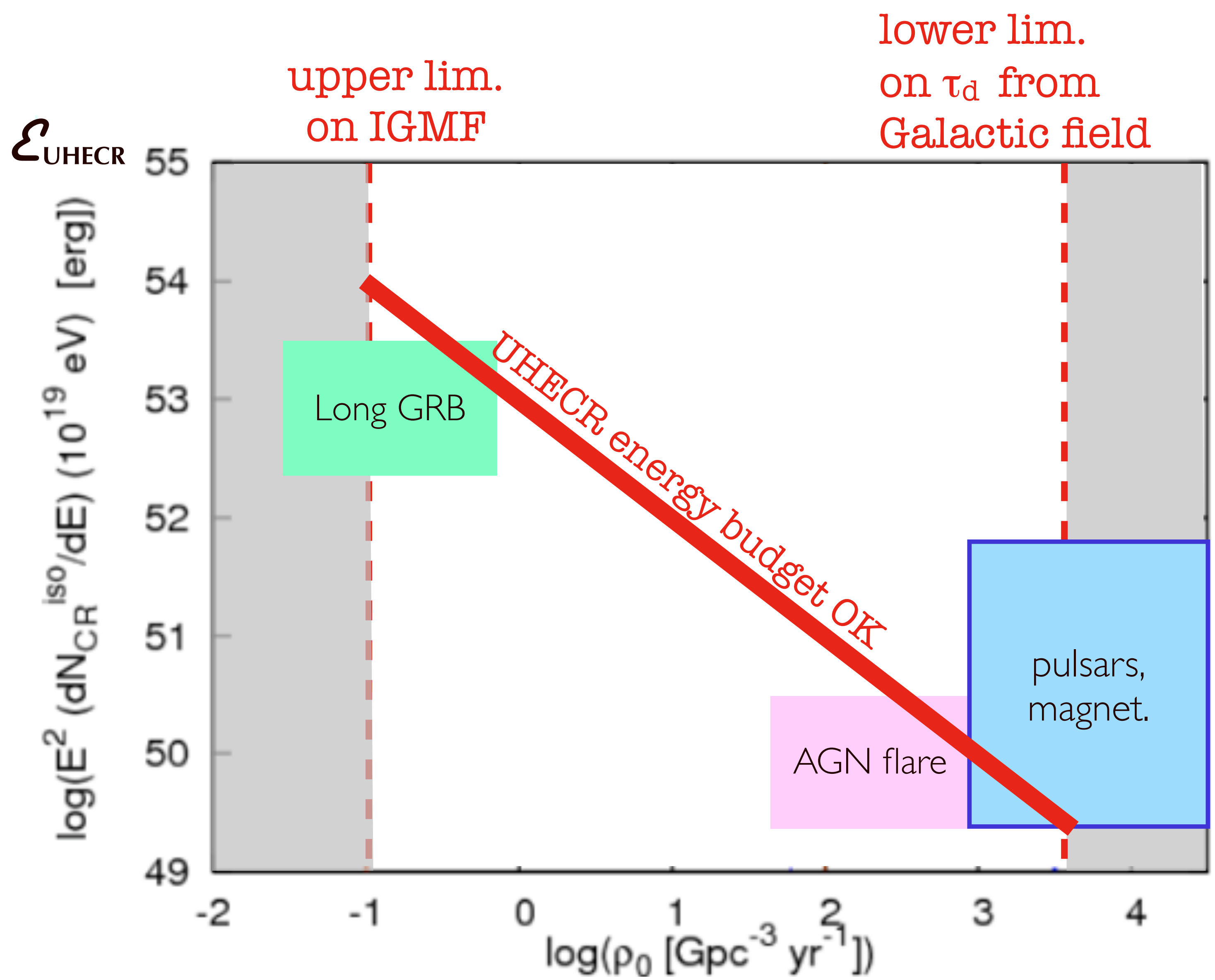
$n_0 \gtrsim 10^{-5}$ Mpc^{-3}

Kashti & Waxman 08, Takami & Sato 09, Abreu et al. 2013

for transient sources: real number density of UHE proton sources

$\rho_0 \sim n_0$ / (CR time spread τ_d)

τ_d depends on extragalactic + Galactic magnetic fields (not known)

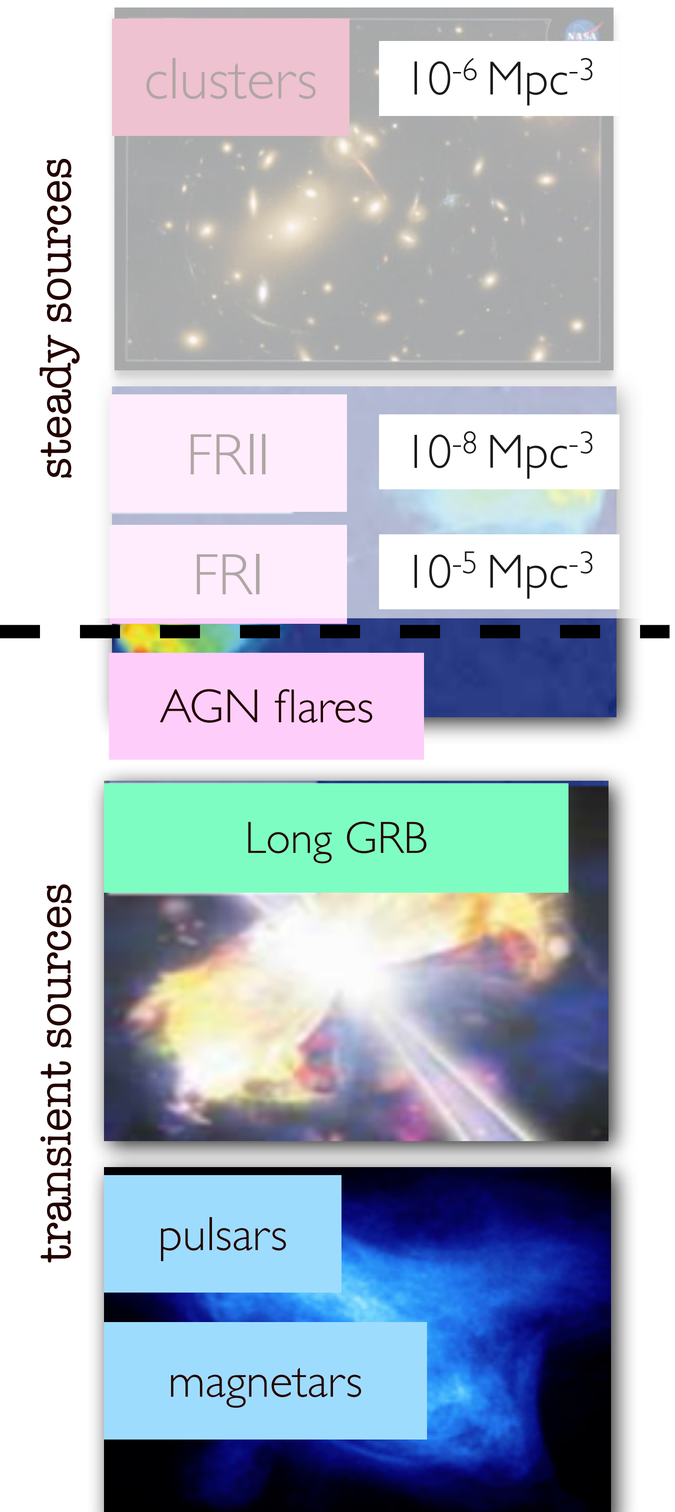


Murase & Takami 09

$n_0 = 10^{-4}$ Mpc^{-3}
s = 2, protons

from K. Murase

Total energy budget and number density of sources



lack of multiplets in the sky (many events from small angular spot)

➢ **apparent number density of sources:**

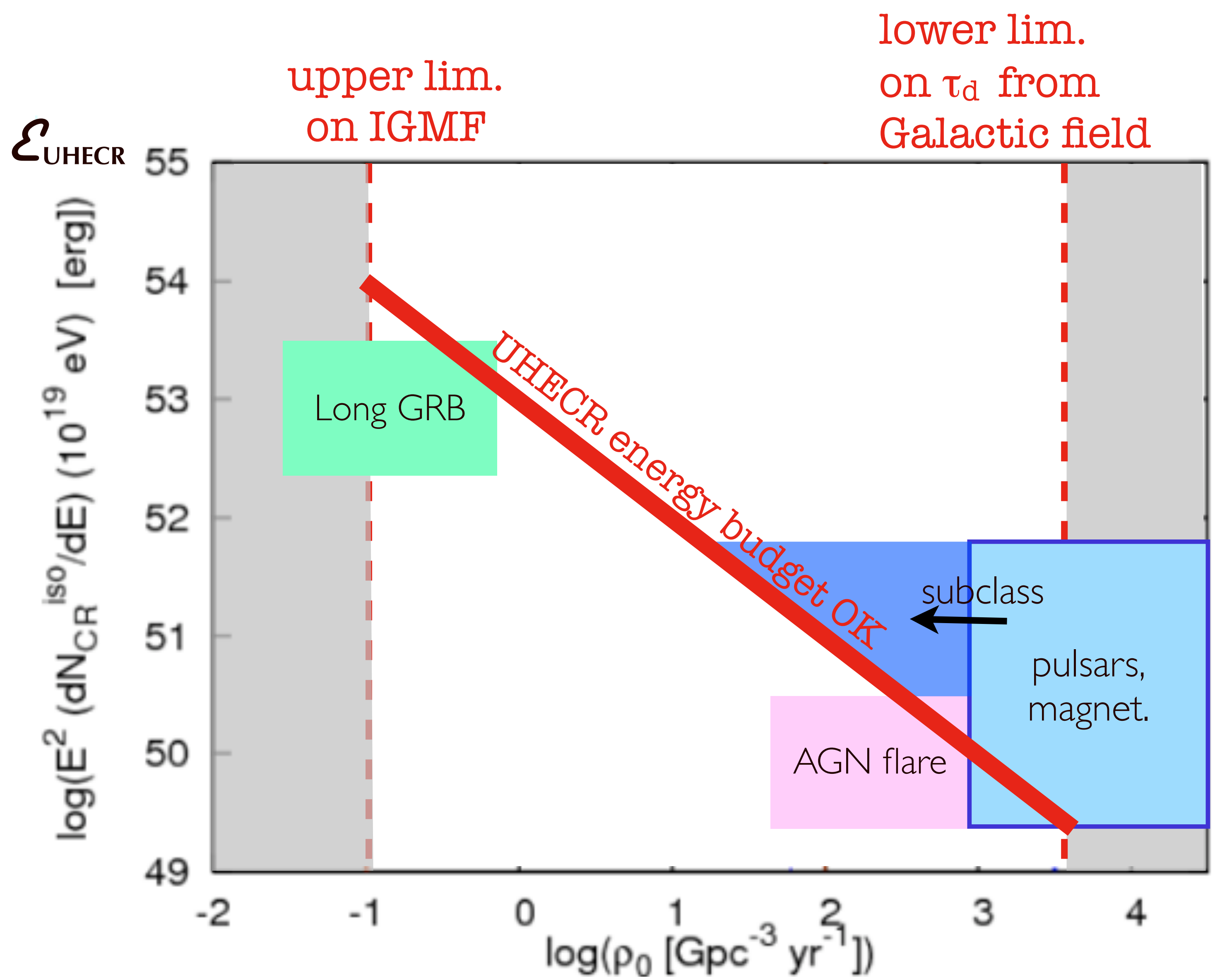
$n_0 \gtrsim 10^{-5}$ Mpc^{-3}

Kashti & Waxman 08, Takami & Sato 09, Abreu et al. 2013

for transient sources: real number density of UHE proton sources

$\rho_0 \sim n_0$ / (CR time spread τ_d)

τ_d depends on extragalactic + Galactic magnetic fields (not known)



Murase & Takami 09

$n_0 = 10^{-4}$ Mpc^{-3}

s = 2, protons

from K. Murase

Total energy budget and number density of sources

steady sources

transient sources

lack of multiplets in the sky (many events from small angular spot)

➢ **apparent number density of sources:**

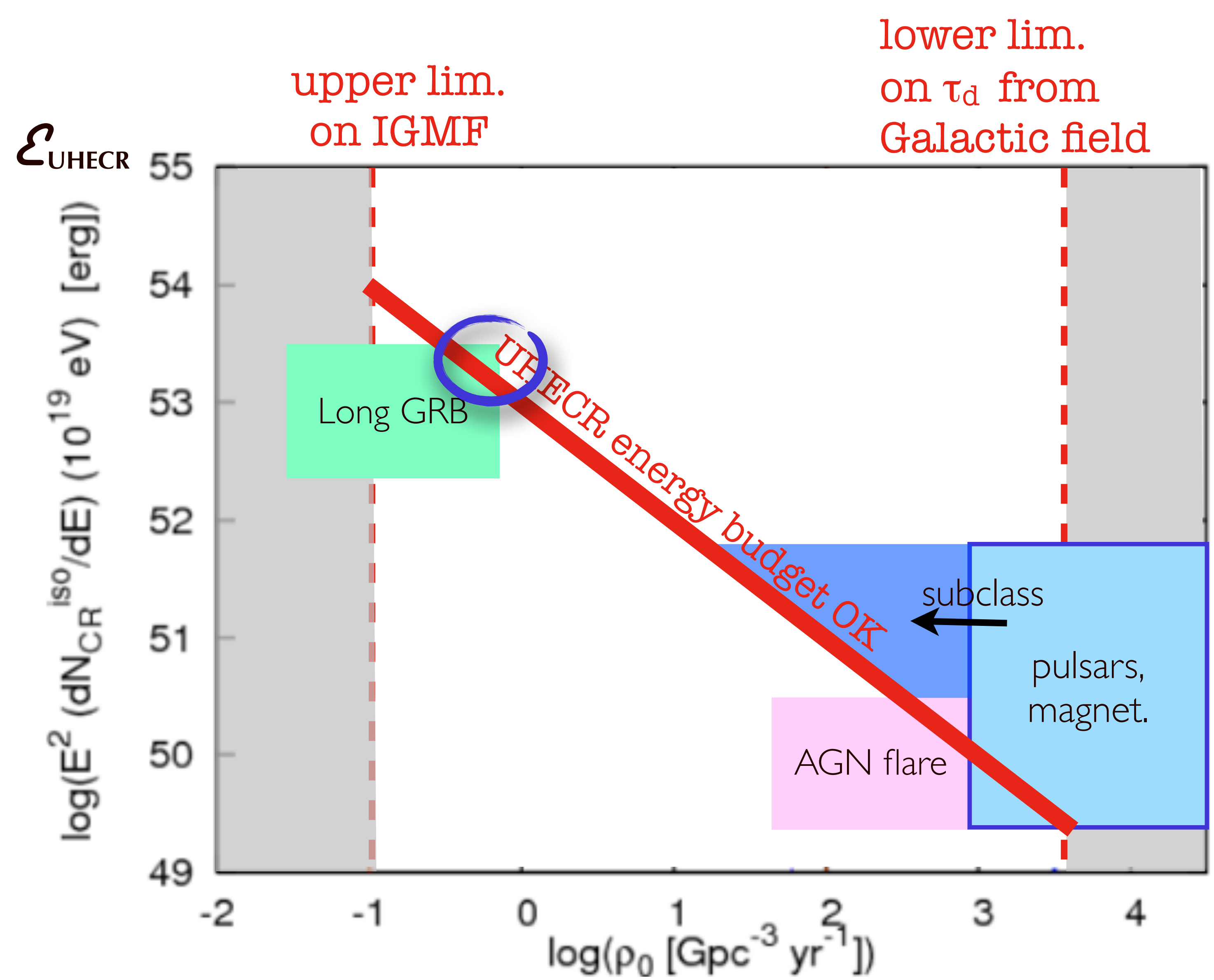
$n_0 \gtrsim 10^{-5}$ Mpc^{-3}

Kashti & Waxman 08, Takami & Sato 09, Abreu et al. 2013

for transient sources: real number density of UHE proton sources

$\rho_0 \sim n_0$ / (CR time spread τ_d)

τ_d depends on extragalactic + Galactic magnetic fields (not known)



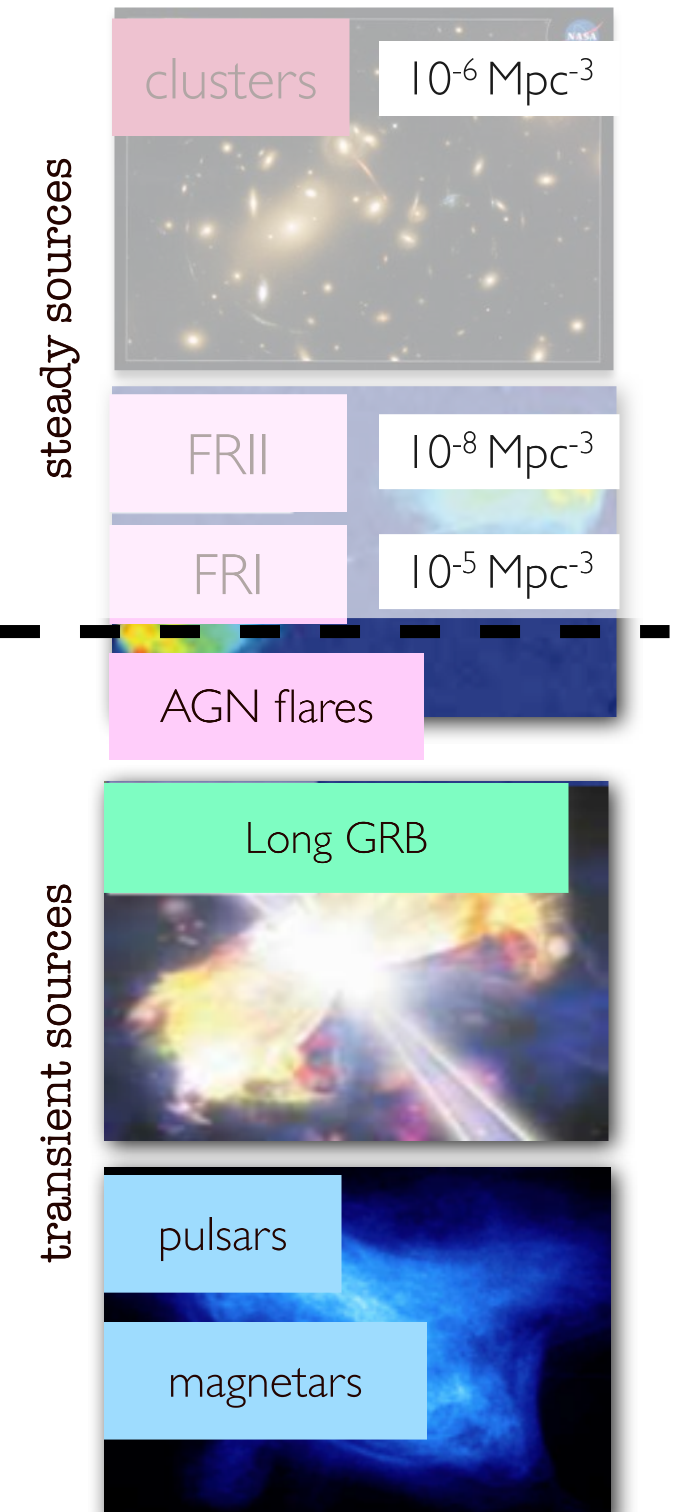
Murase & Takami 09

$n_0 = 10^{-4}$ Mpc^{-3}

s = 2, protons

from K. Murase

Total energy budget and number density of sources



lack of multiplets in the sky (many events from small angular spot)

➢ **apparent number density of sources:**

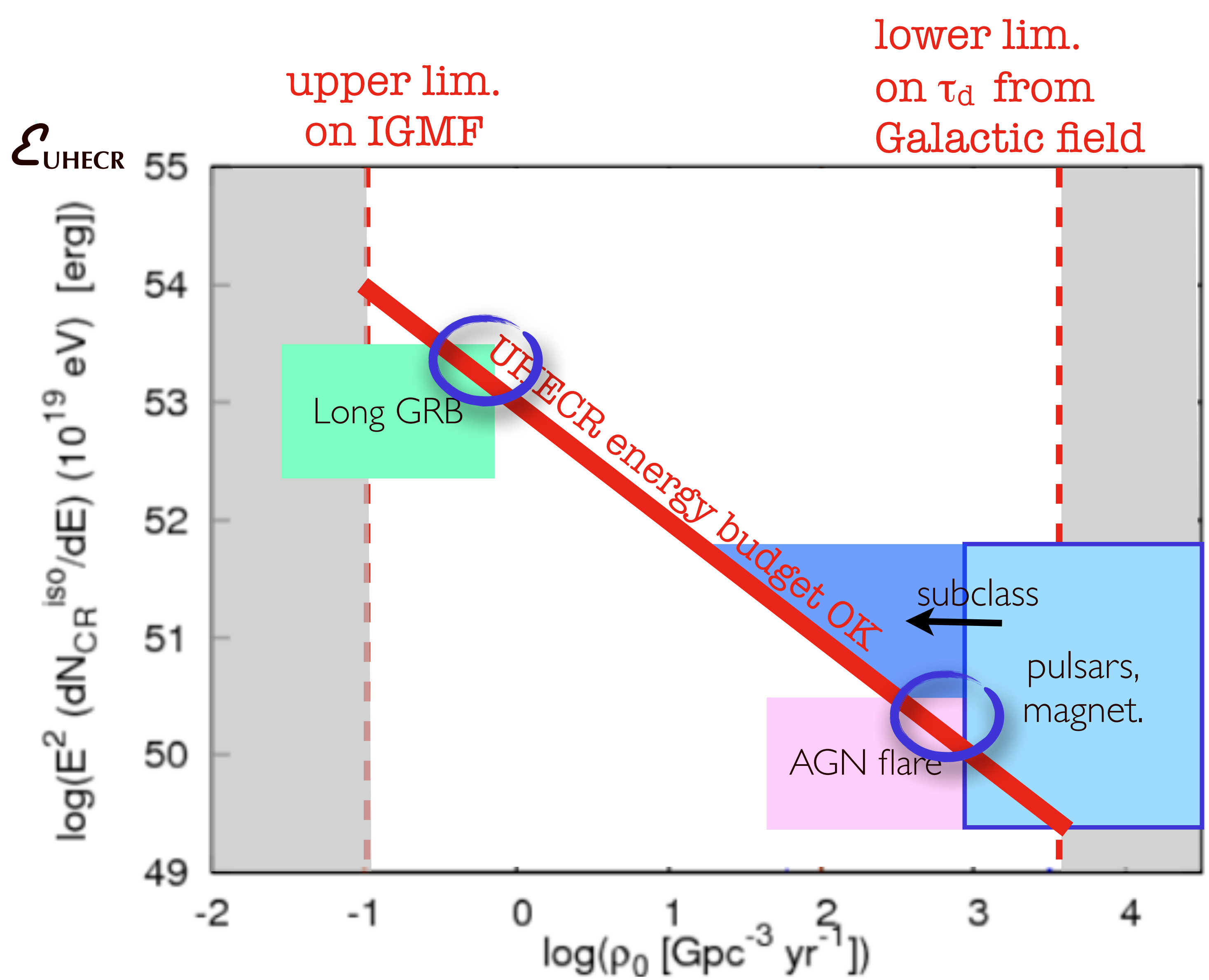
$n_0 \gtrsim 10^{-5}$ Mpc^{-3}

Kashti & Waxman 08, Takami & Sato 09, Abreu et al. 2013

for transient sources: real number density of UHE proton sources

$\rho_0 \sim n_0$ / (CR time spread τ_d)

τ_d depends on extragalactic + Galactic magnetic fields (not known)

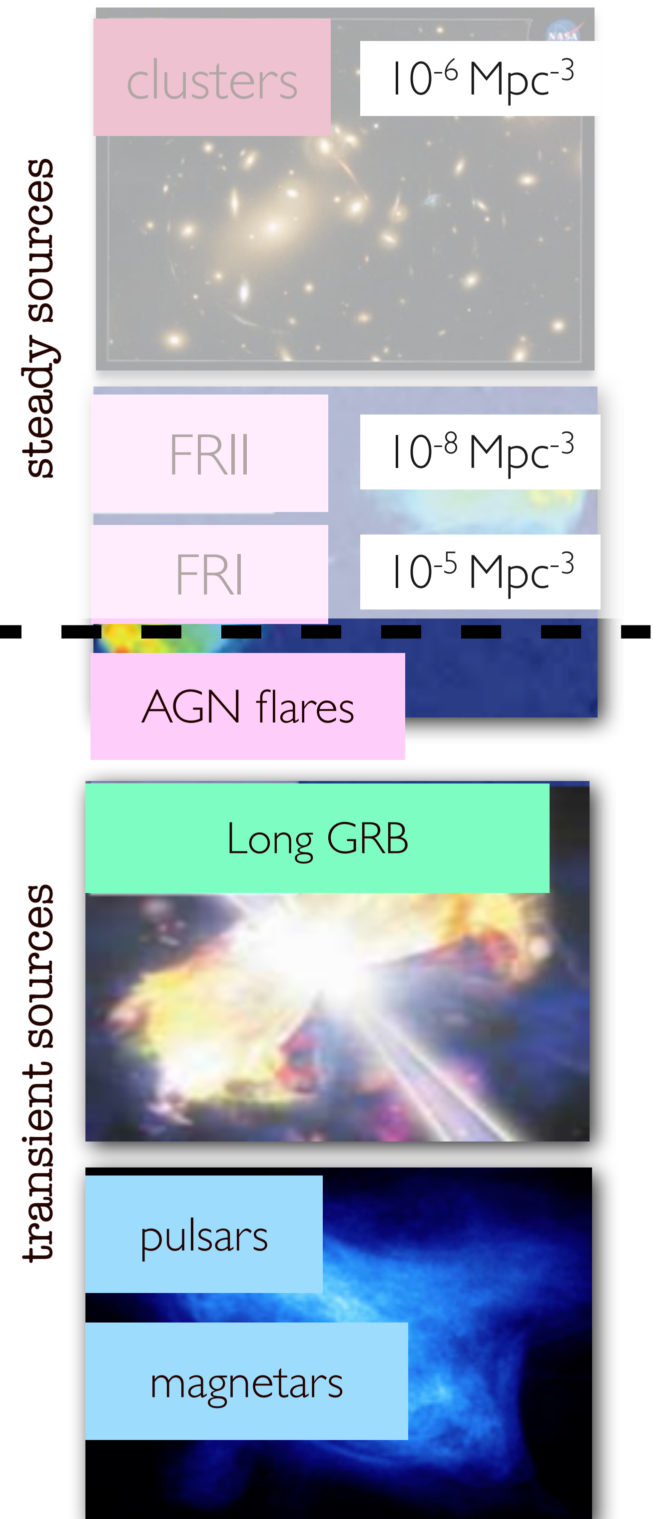


Murase & Takami 09

$n_0 = 10^{-4}$ Mpc^{-3}

s = 2, protons

Total energy budget and number density of sources



lack of multiplets in the sky (many events from small angular spot)

➢ **apparent number density of sources:**

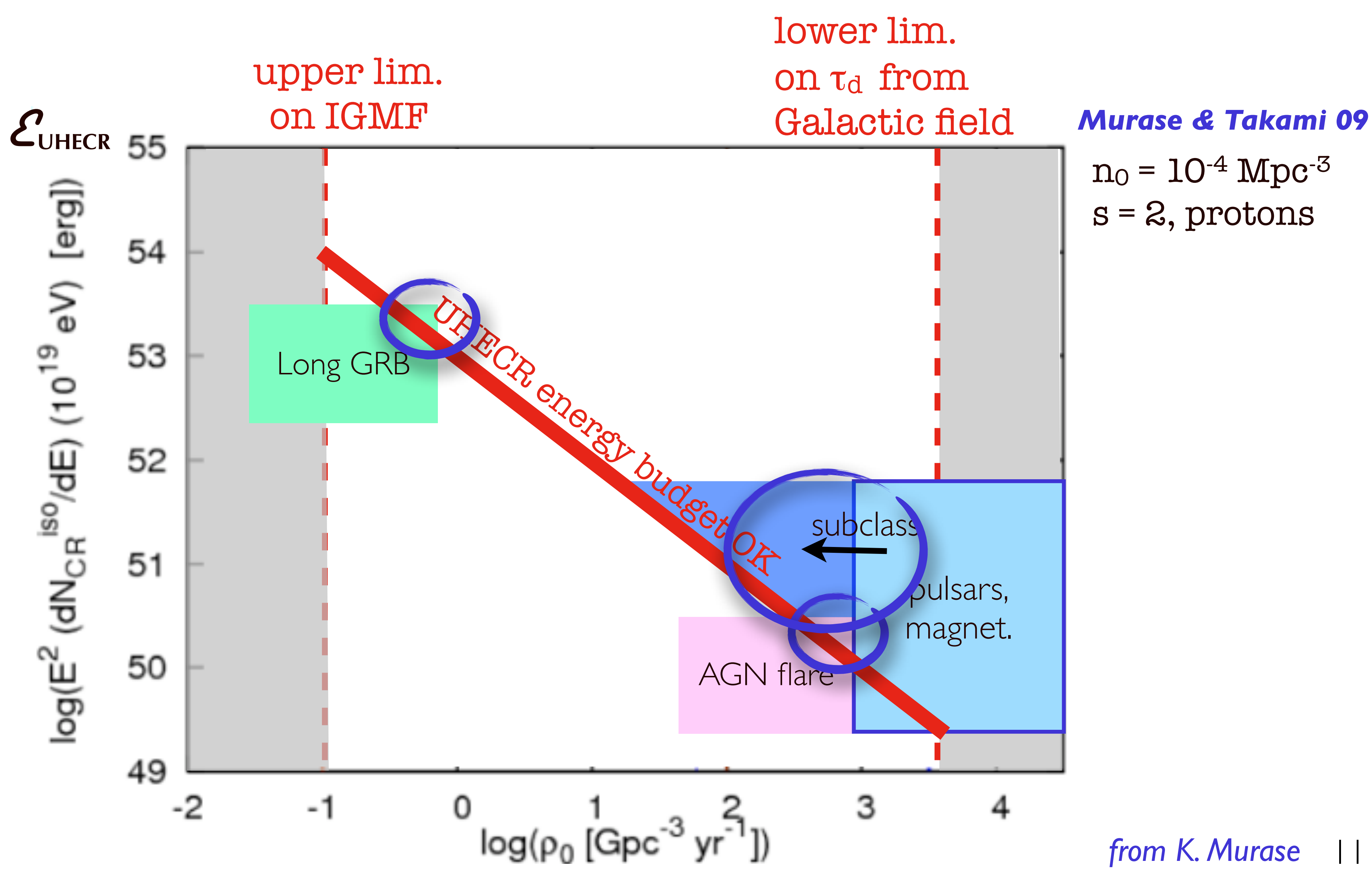
$n_0 \gtrsim 10^{-5}\ \mathrm{Mpc}^{-3}$

Kashti & Waxman 08, Takami & Sato 09, Abreu et al. 2013

for transient sources: real number density of UHE proton sources

$\rho_0 \sim n_0$ / (CR time spread τ_d)

τ_d depends on extragalactic + Galactic magnetic fields (not known)



from K. Murase

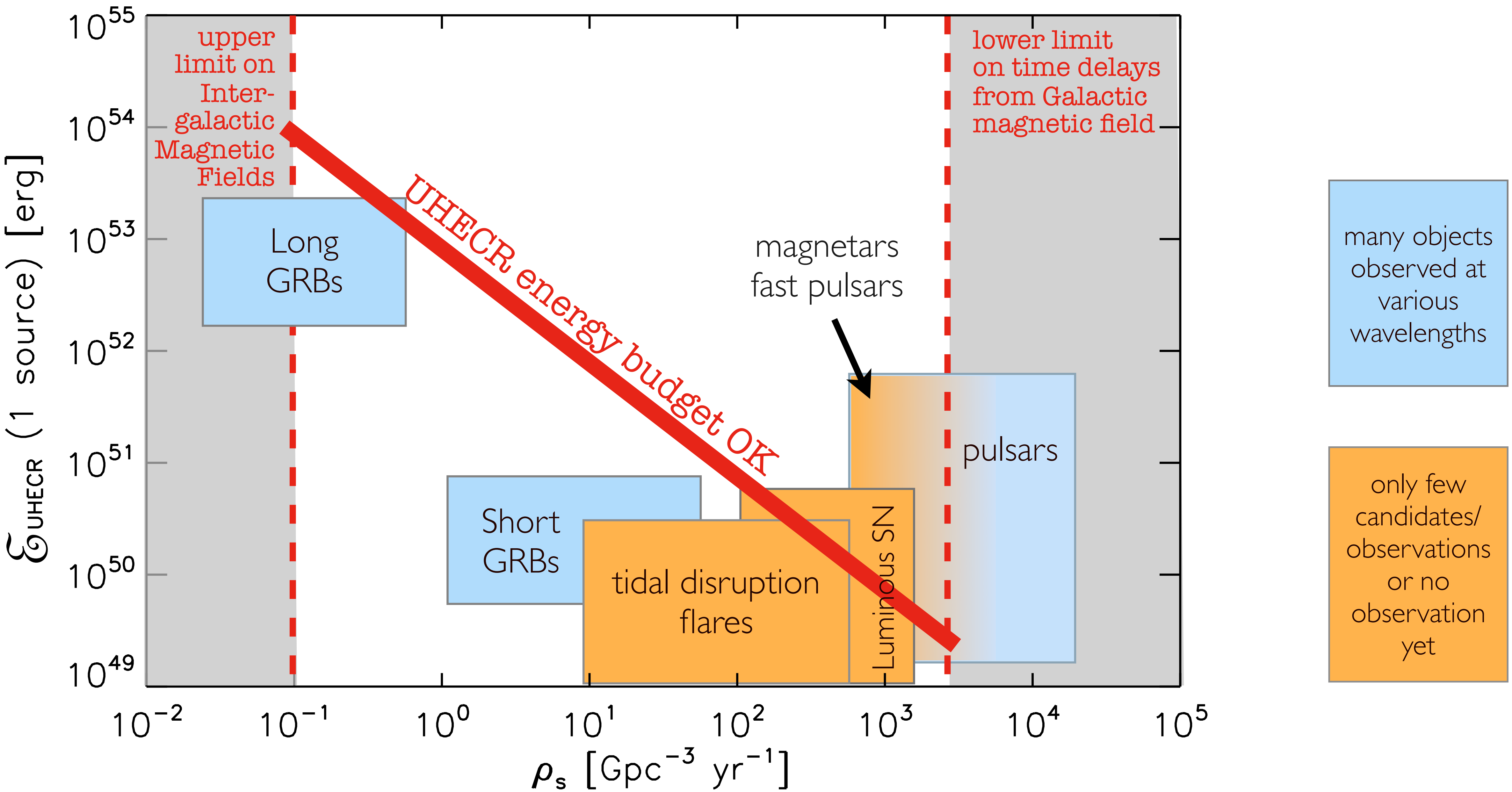
The future: explore other possible transient sources

in the transient sky are found the most violent events of the Universe

transient sources can mimick a high density source population
distribution in the sky due to time delay

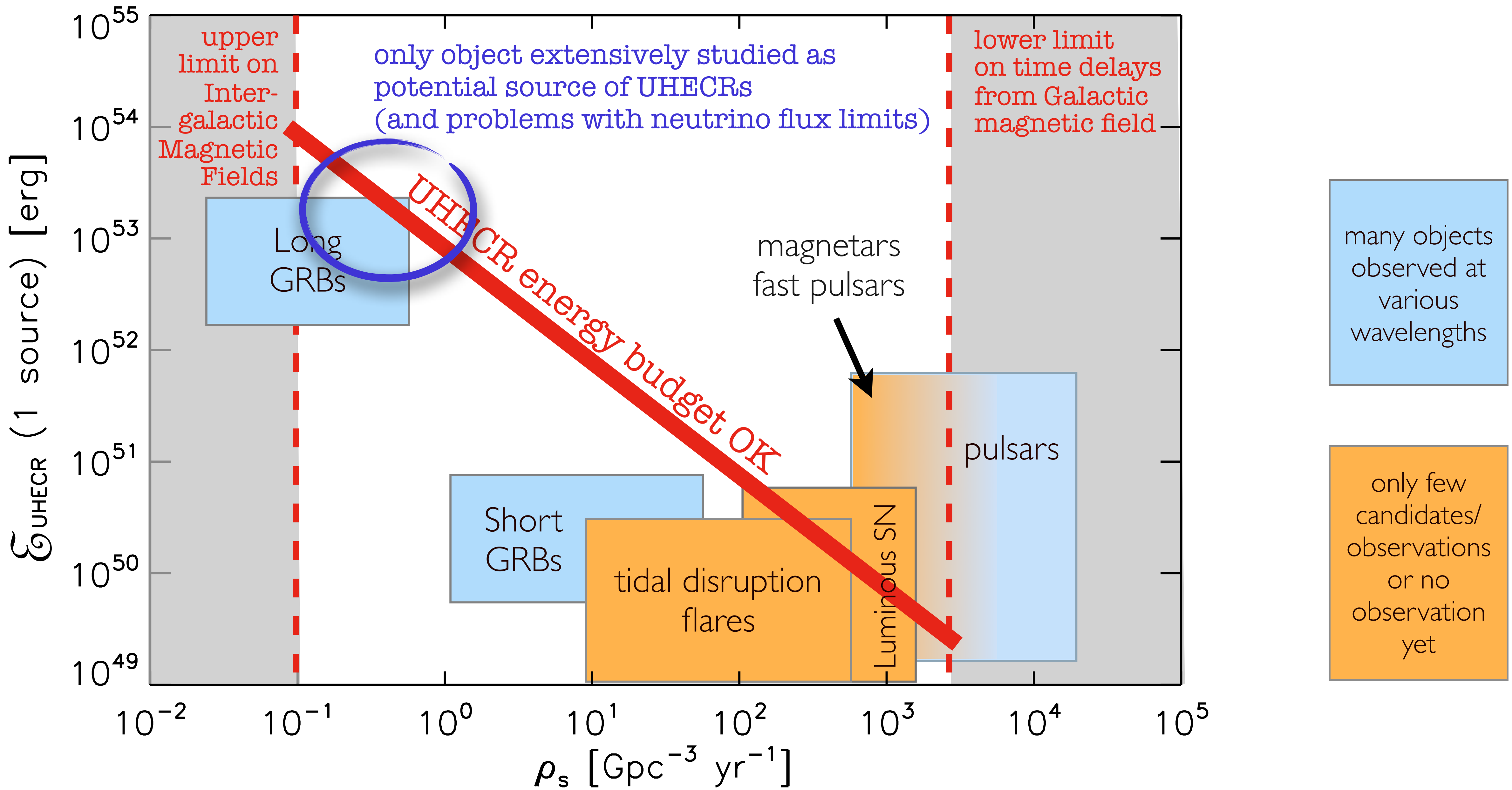
in the transient sky are found the most violent events of the Universe

transient sources can mimick a high density source population distribution in the sky due to time delay



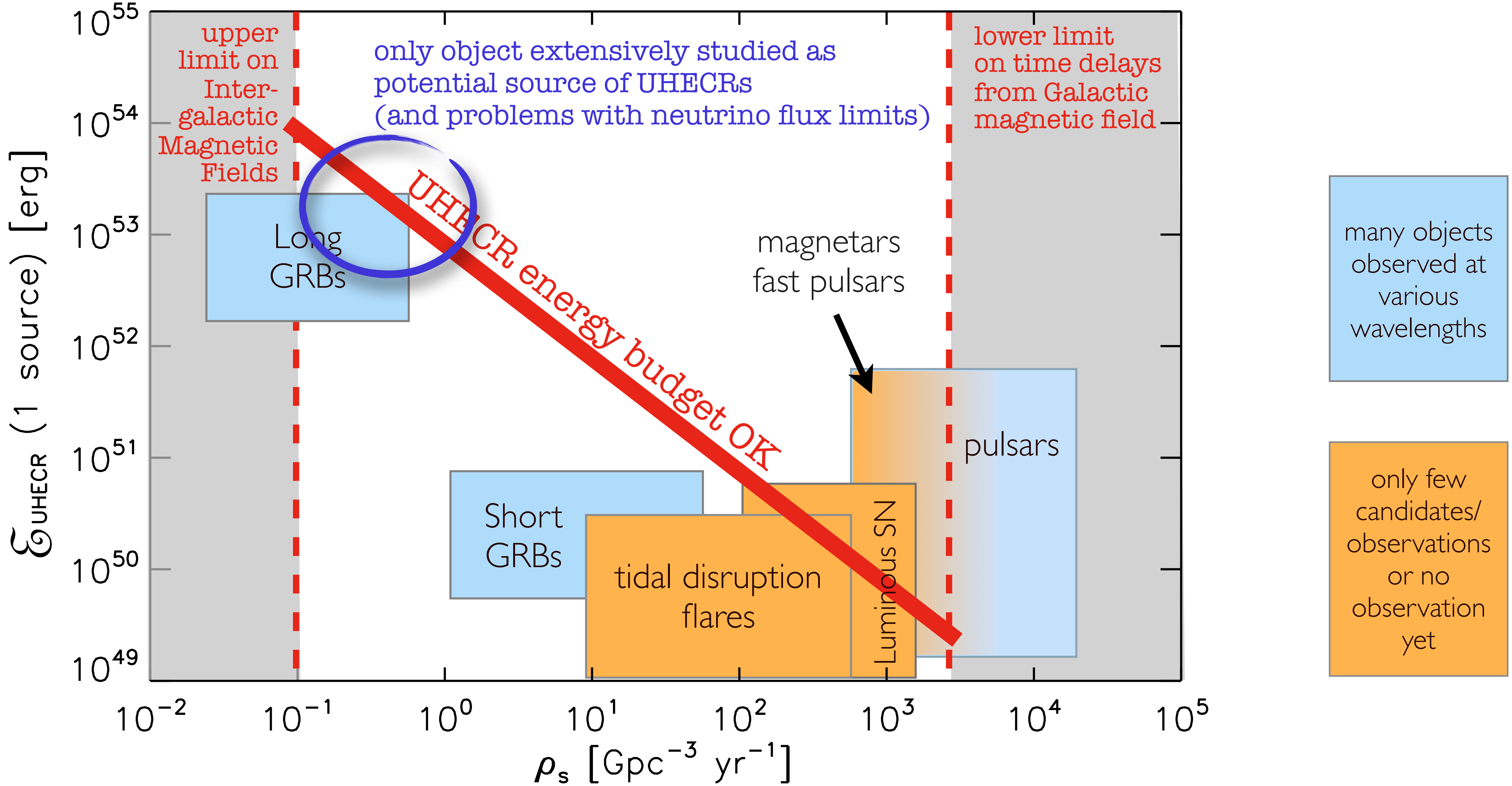
in the transient sky are found the most violent events of the Universe

transient sources can mimick a high density source population distribution in the sky due to time delay



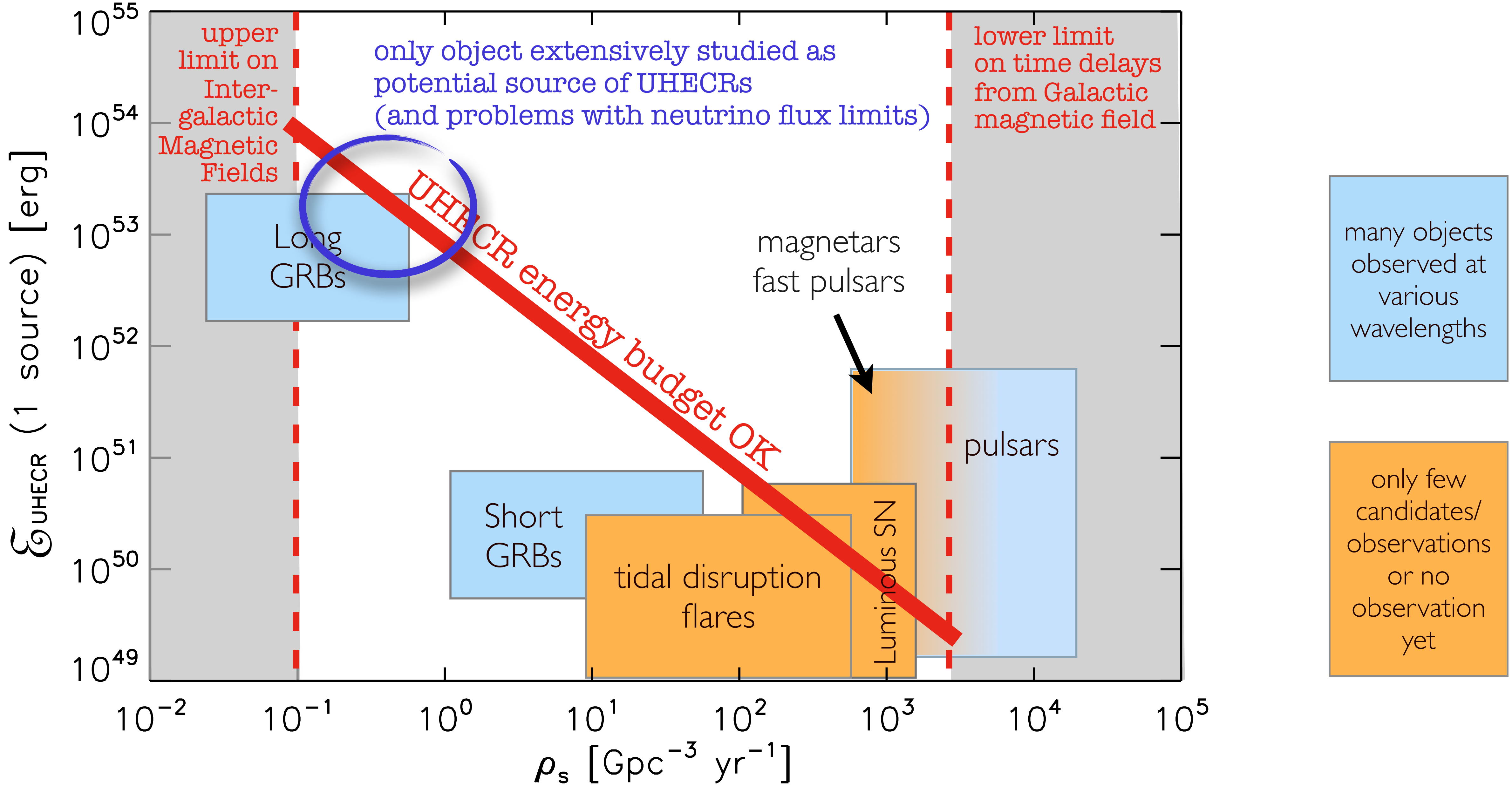
in the transient sky are found the most violent events of the Universe

transient sources can mimick a high density source population distribution in the sky due to time delay



in the transient sky are found the most violent events of the Universe

transient sources can mimick a high density source population distribution in the sky due to time delay

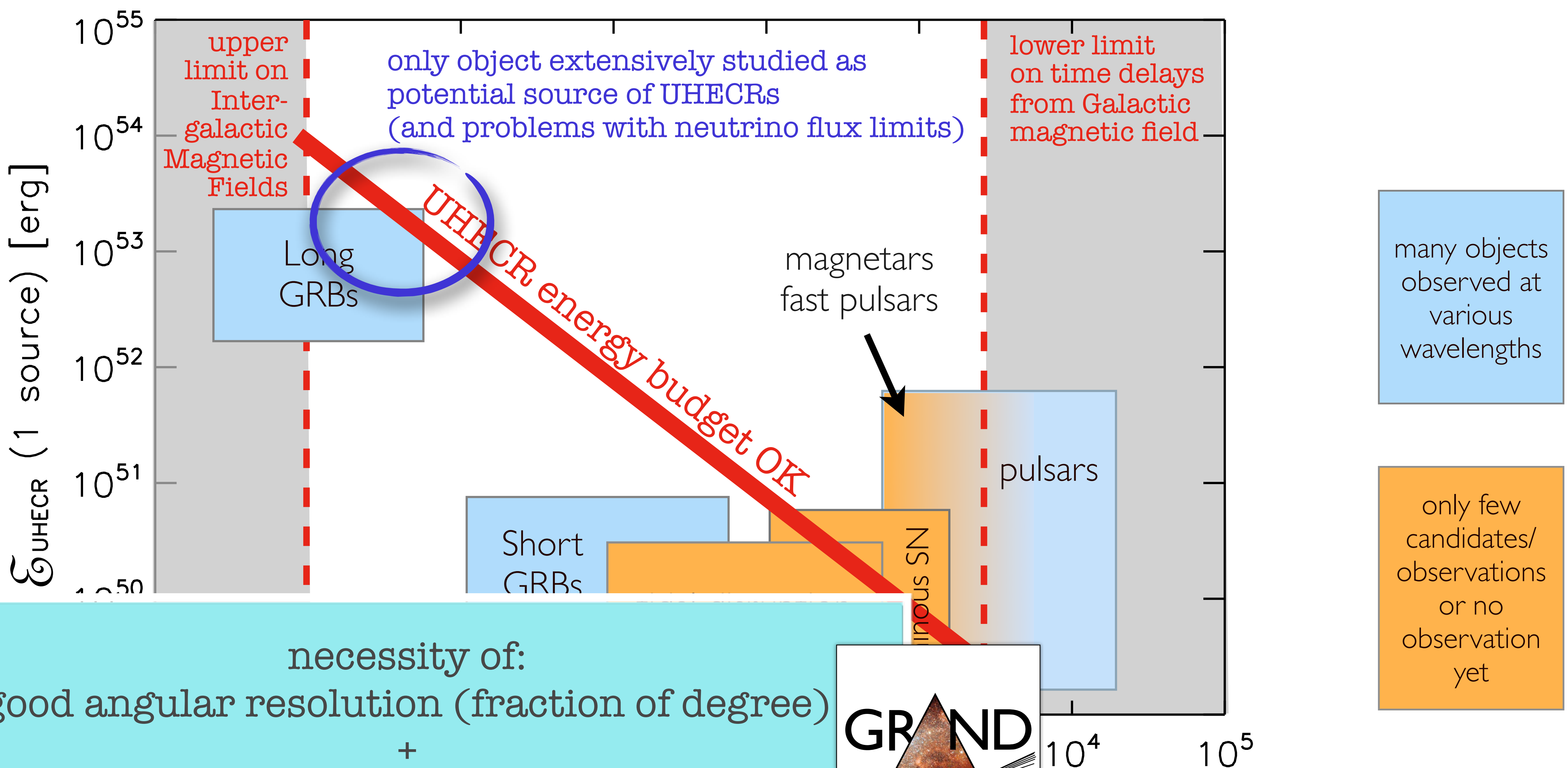


▶ correlation of neutrino events with e-m signal from transient = source identification!

The future: explore other possible transient sources

in the transient sky are found the most violent events of the Universe

transient sources can mimick a high density source population distribution in the sky due to time delay



necessity of:
good angular resolution (fraction of degree)
+
multi-wavelength transient monitoring

GRAND

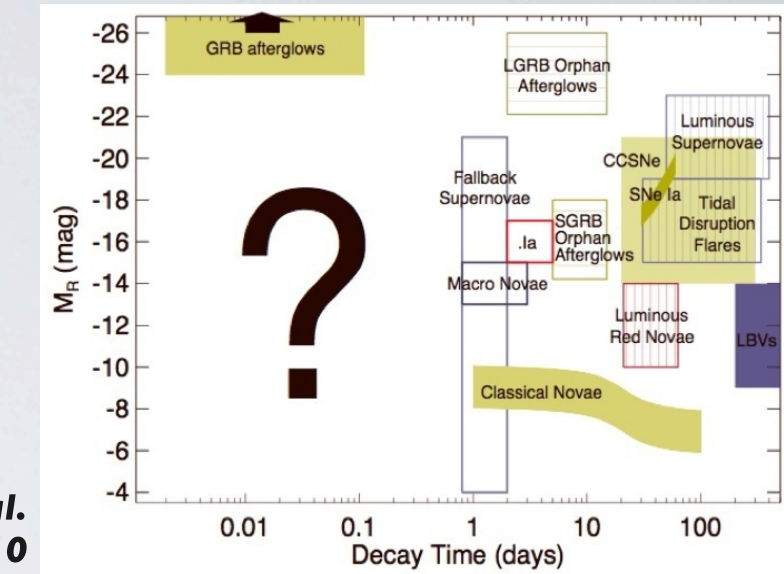
▷ correlation of neutrino events with e-m signal from transient = source identification!

Why now? Transient multi-messenger astroparticle physics is happening NOW

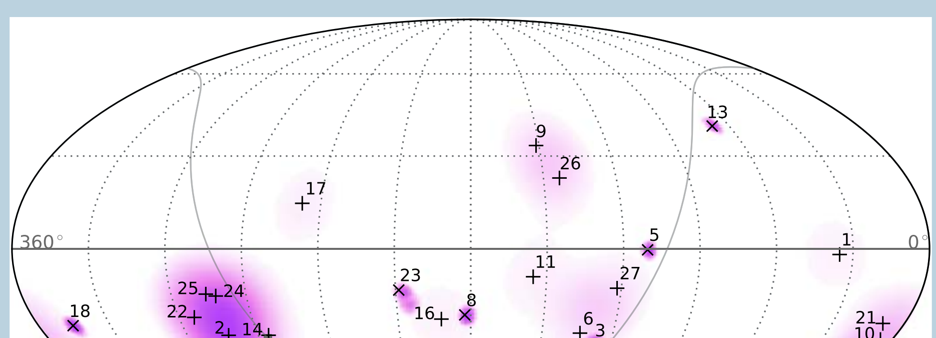
- γ HESS-2, HAWC, CTA
- ν Antares, IceCube, ANITA, ARA, ARIANNA
- CR Auger upgrade, JEM-EUSO
- GW LIGO, Einstein Telescope

Palomar Transient Factory, LSST, SKA

new transients being discovered



Wozniak et al. White paper 2010

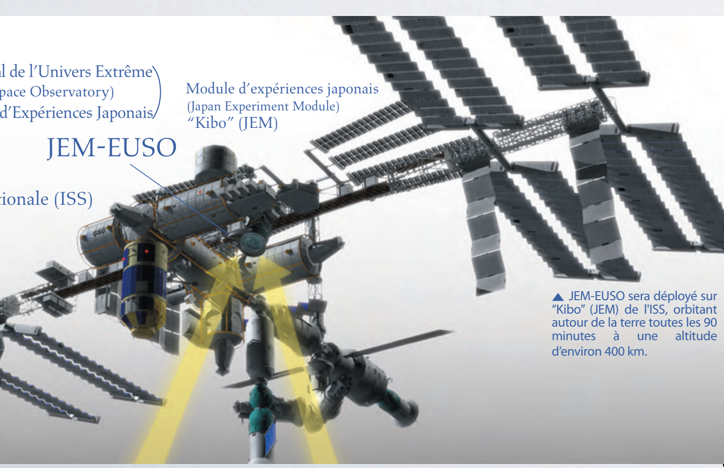


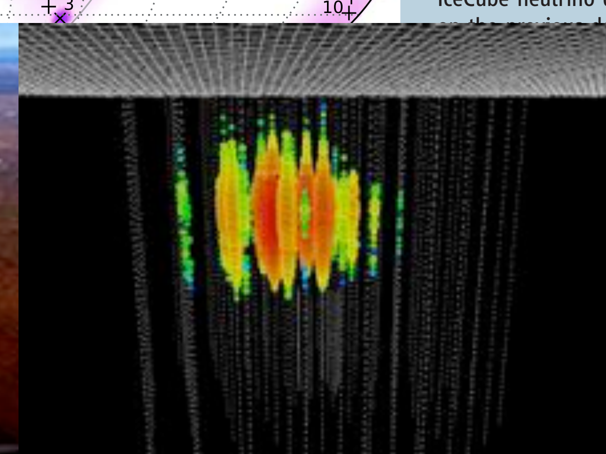
RESEARCH ARTICLE

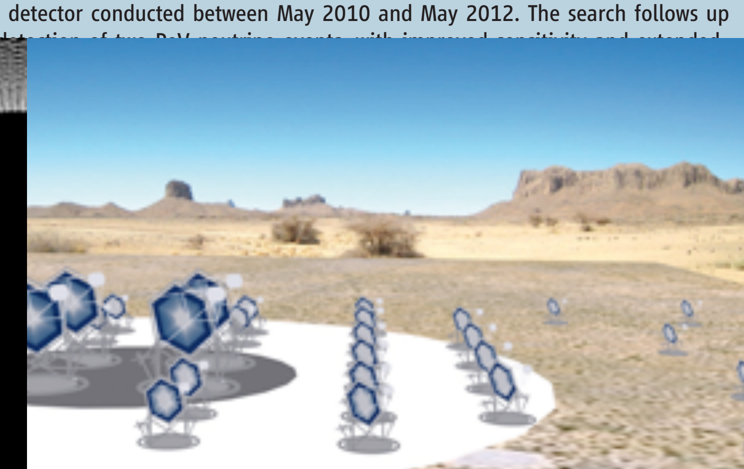
Evidence for High-Energy Extraterrestrial Neutrinos at the IceCube Detector

IceCube Collaboration*

We report on results of an all-sky search for high-energy neutrino events interacting within the IceCube neutrino detector conducted between May 2010 and May 2012. The search follows up





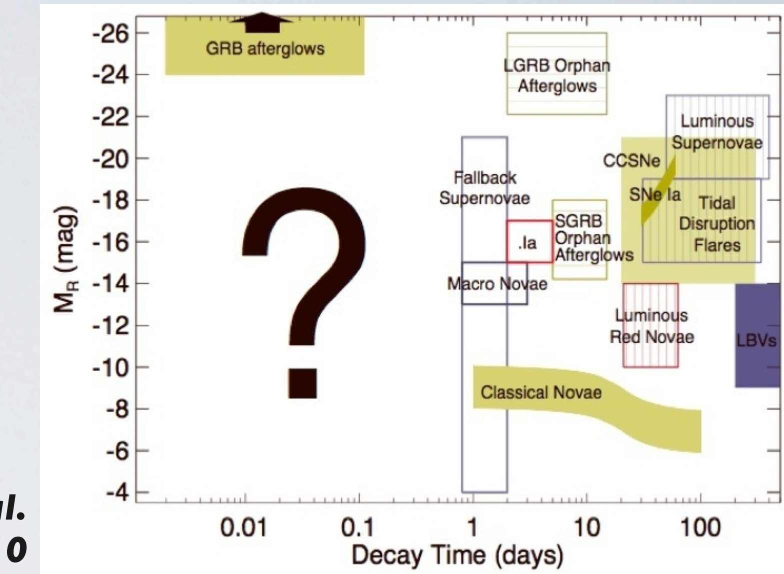


Why now? Transient multi-messenger astroparticle physics is happening NOW

γ	HESS-2, HAWC, CTA
ν	Antares, IceCube, ANITA, ARA, ARIANNA
CR	Auger upgrade, JEM-EUSO
GW	LIGO, Einstein Telescope

Palomar Transient Factory, LSST, SKA

new transients being discovered



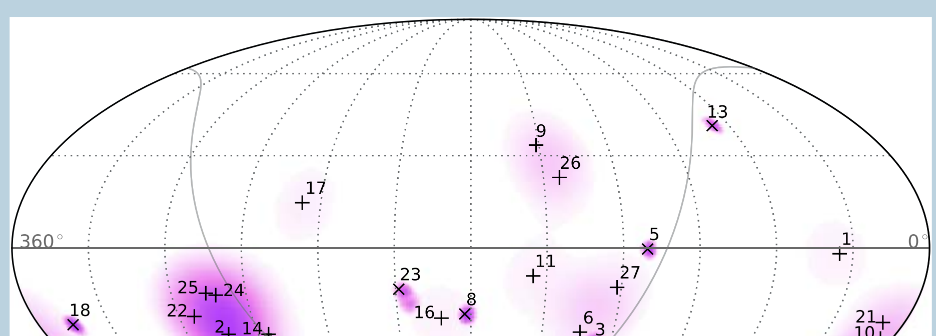
Wozniak et al. White paper 2010

synergies!

ex: ANTARES/IceCube to constrain neutrinos from blazars
ANTARES Coll. 2015 arXiv:1501.07843

Tuesday afternoon
+ Wednesday morning sessions

GRAND

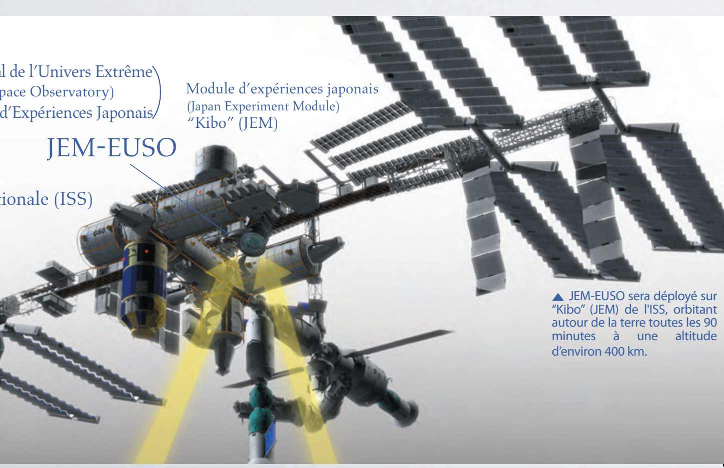


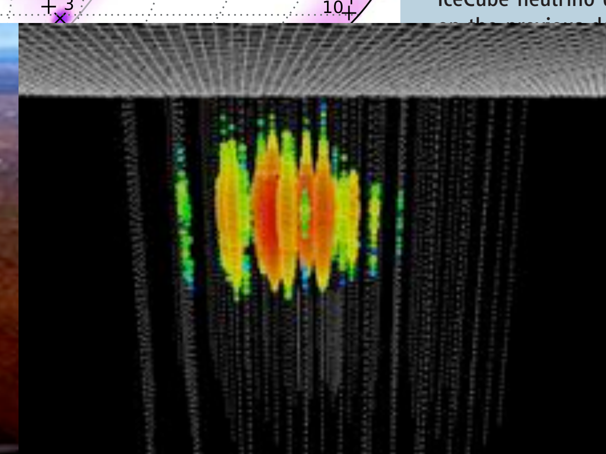
RESEARCH ARTICLE

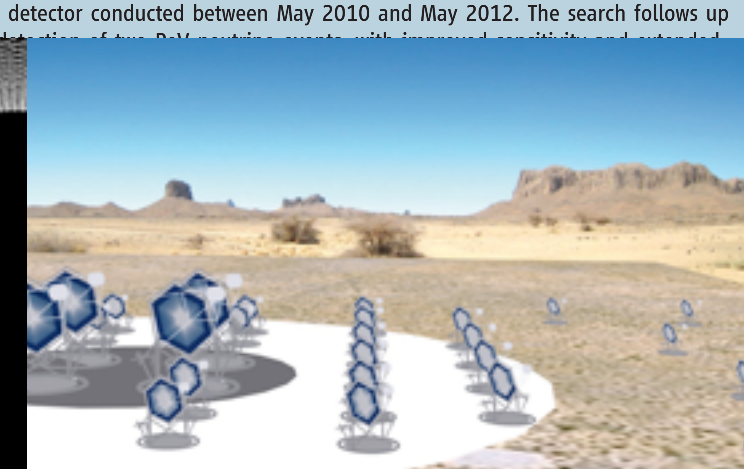
Evidence for High-Energy Extraterrestrial Neutrinos at the IceCube Detector

IceCube Collaboration*

We report on results of an all-sky search for high-energy neutrino events interacting within the IceCube neutrino detector conducted between May 2010 and May 2012. The search follows up





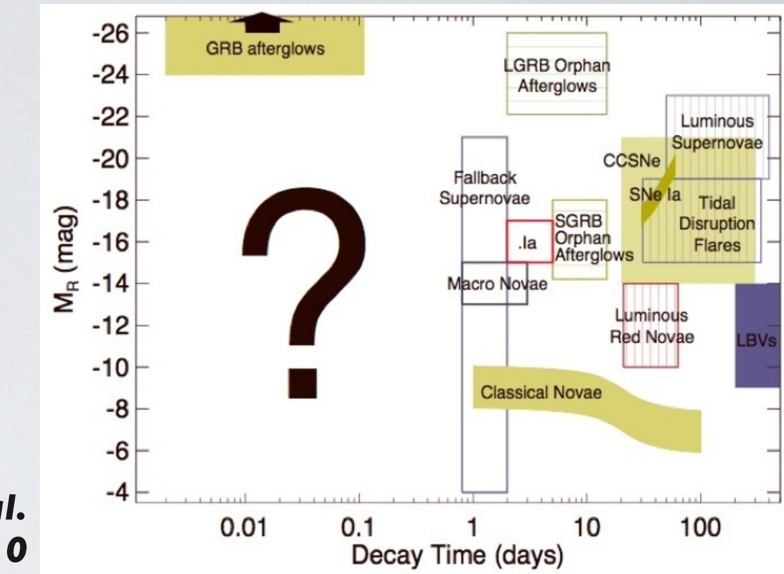


Why now? Transient multi-messenger astroparticle physics is happening NOW

- γ HESS-2, HAWC, CTA
- ν Antares, IceCube, ANITA, ARA, ARIANNA
- CR Auger upgrade, JEM-EUSO
- GW LIGO, Einstein Telescope

Palomar Transient Factory, LSST, SKA

new transients being discovered



Wozniak et al. White paper 2010

synergies!

ex: ANTARES/IceCube to constrain neutrinos from blazars
ANTARES Coll. 2015 arXiv:1501.07843

Tuesday afternoon + Wednesday morning sessions

other science cases for GRAND?

- detection of cosmic-rays at the ankle energy
- explore fundamental neutrino properties
- Epoch of Reionization
- LOFAR/SKA type science case?

Monday evening + Wednesday morning sessions