Gamma-ray bursts as the sources of the ultra-high energy cosmic rays?

ACP seminar, IPMU
Kashiwa, Japan

Oct. 30, 2013

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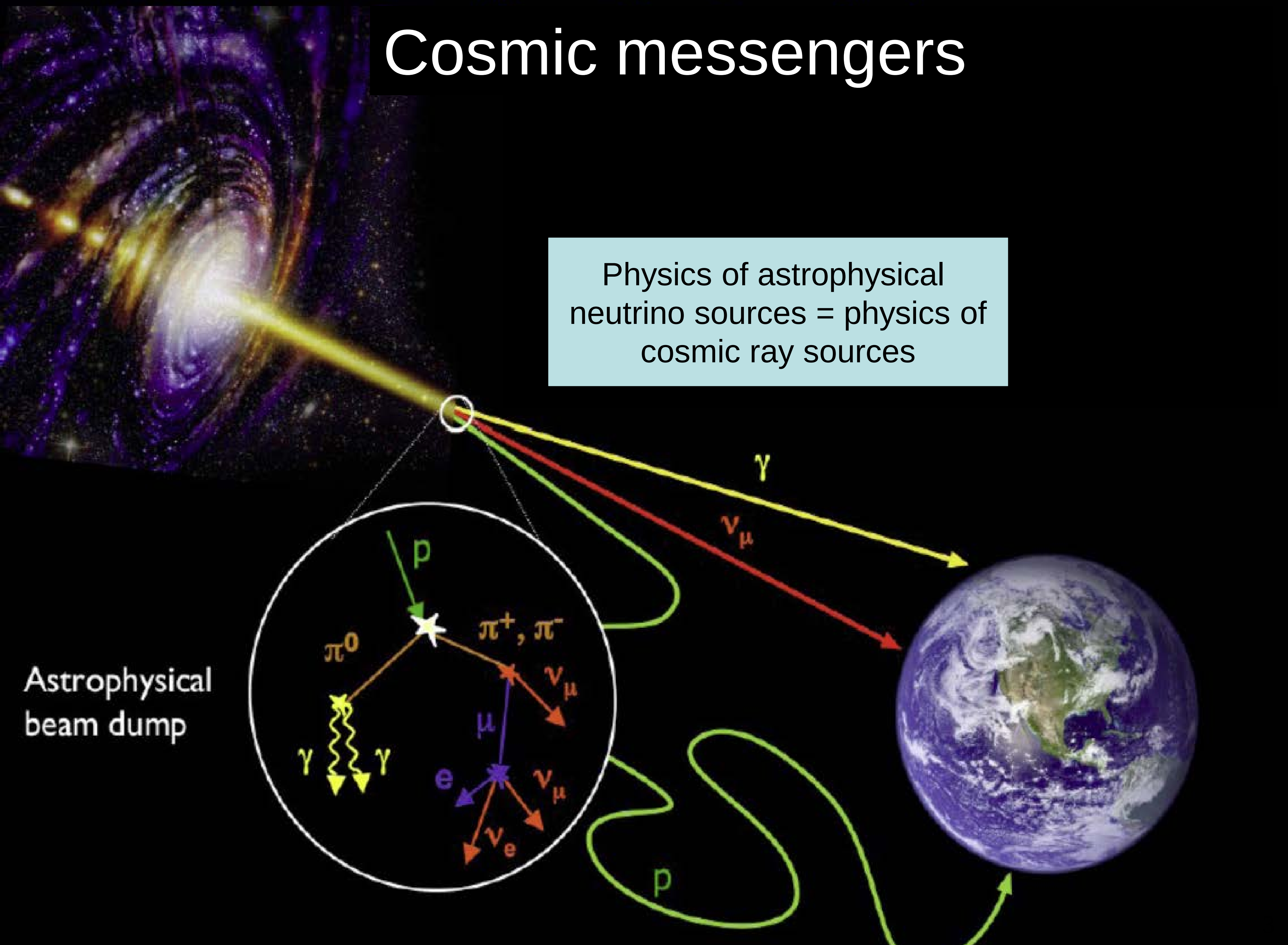
- Introduction
- Simulation of sources
- Multi-messenger astronomy:
  - Gamma-rays – neutrinos
  - Neutrinos – cosmic rays
  - Gamma-rays – cosmic rays, energy budget
- Combined source-propagation model
- Summary

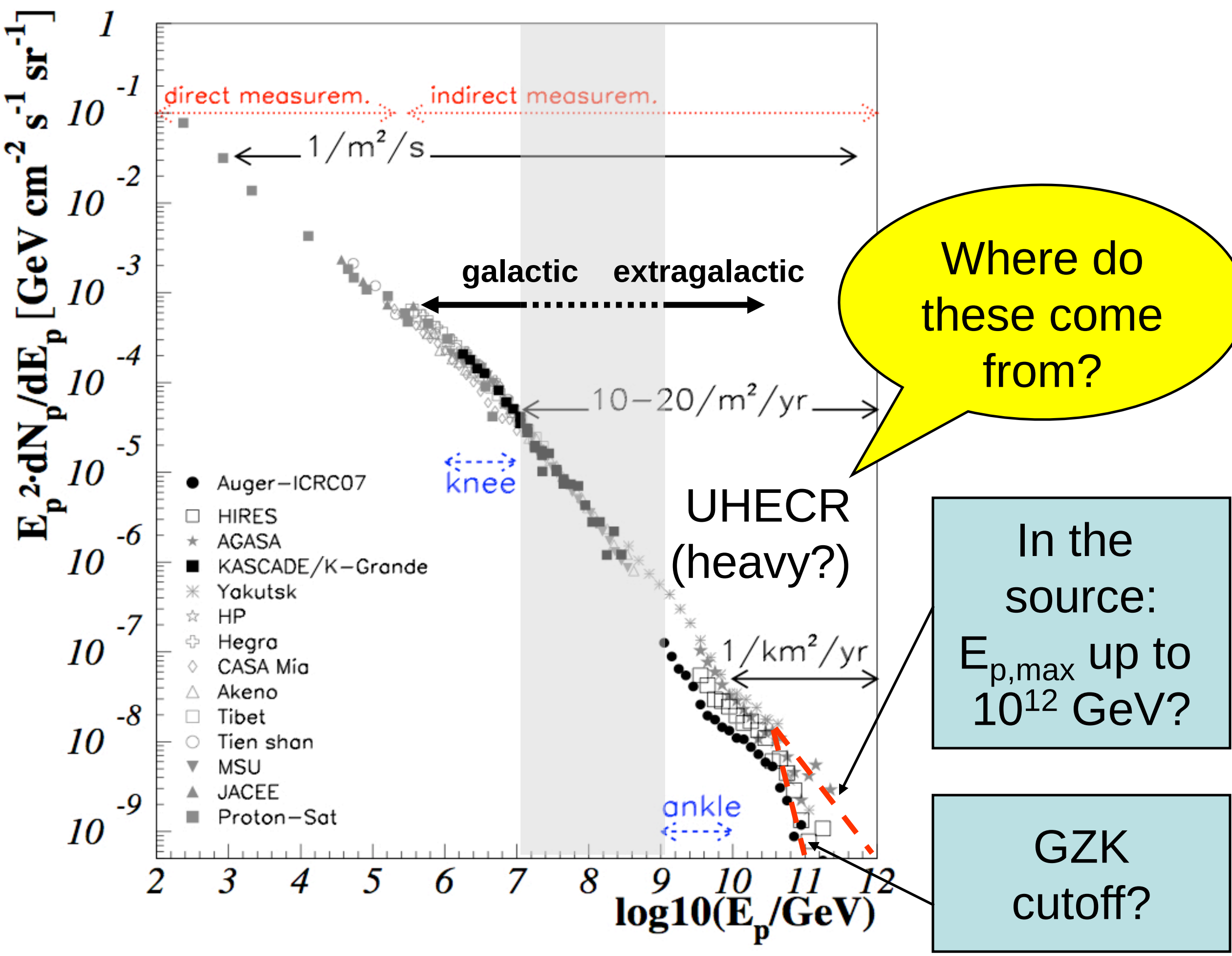
Cosmic messengers

Physics of astrophysical neutrino sources = physics of cosmic ray sources



Cosmic ray observations

- Observation of cosmic rays: **need to accelerate protons/nuclei somewhere**
- The same sources should produce neutrinos:
  - in the source (pp, pγ interactions)
  - Proton ($E > 6\ 10^{10}$ GeV) on CMB ⇨ GZK cutoff + cosmogenic neutrino flux



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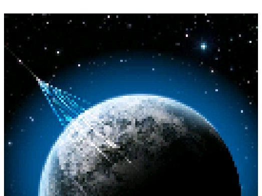
The two paradigms for extragalactic sources: AGNs and GRBs

- Active Galactic Nuclei (AGN blazars)
  - Relativistic jets ejected from central engine (black hole?)
  - Continuous emission, with time-variability
- Gamma-Ray Bursts (GRBs): transients
  - Relativistically expanding fireball/jet
  - Neutrino production e. g. in prompt phase
    (Waxman, Bahcall, 1997)

Cosmic Rays: 100 years of mystery

2012-04-18



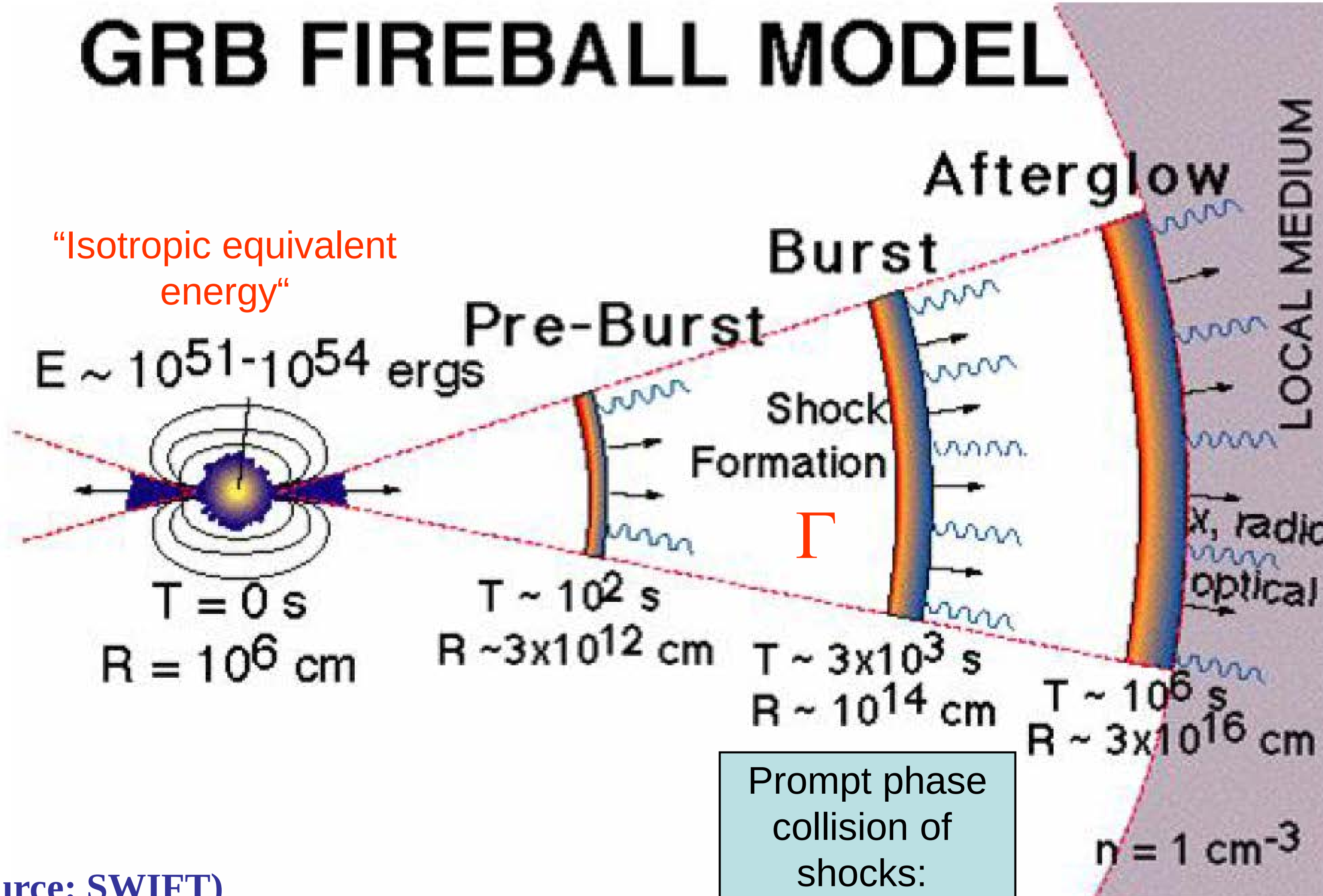
Using data from the IceCube Neutrino Observatory, astrophysicists Nathan Whitehorn and Pete Redl searched for neutrinos coming from the direction of known GRBs. And they found nothing.

Their result, appearing today in the journal Nature, challenges one of the two leading theories for the origin of the highest energy cosmic rays.

Nature 484 (2012) 351

Gammy-ray emission in GRBs

“Isotropic equivalent energy“



Γ

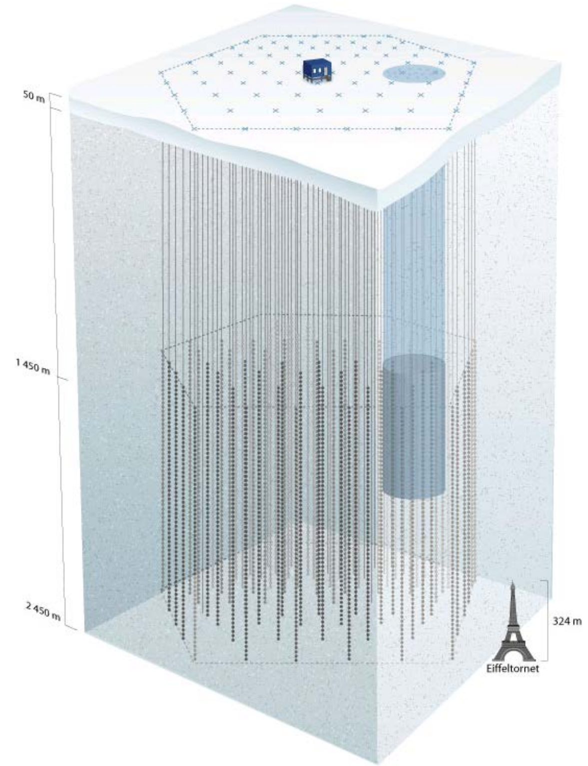
Prompt phase collision of shocks: dominant νs?

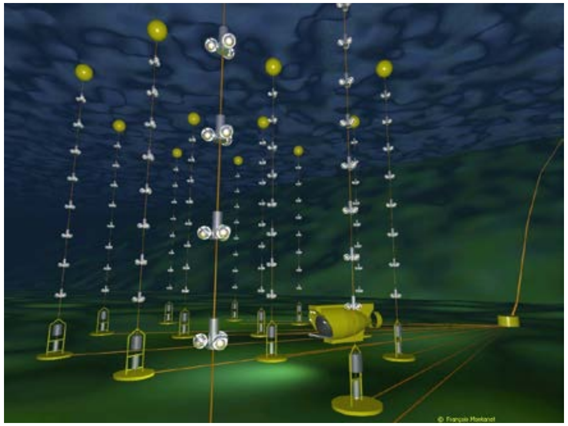
(Source: SWIFT)

Neutrino detection:

Neutrino telescopes

- Example:
  IceCube at South Pole
  Detector material: ~ 1 km^3 antarctic ice
- Completed 2010/11 (86 strings)
- Recent major successes:
  - Constraints on GRBs
    Nature 484 (2012) 351
  - 28 events in the TeV-PeV range Science (to appear)
  - ➢ **Neutrinos established as messengers of the high-energy universe!**





http://icecube.wisc.edu/

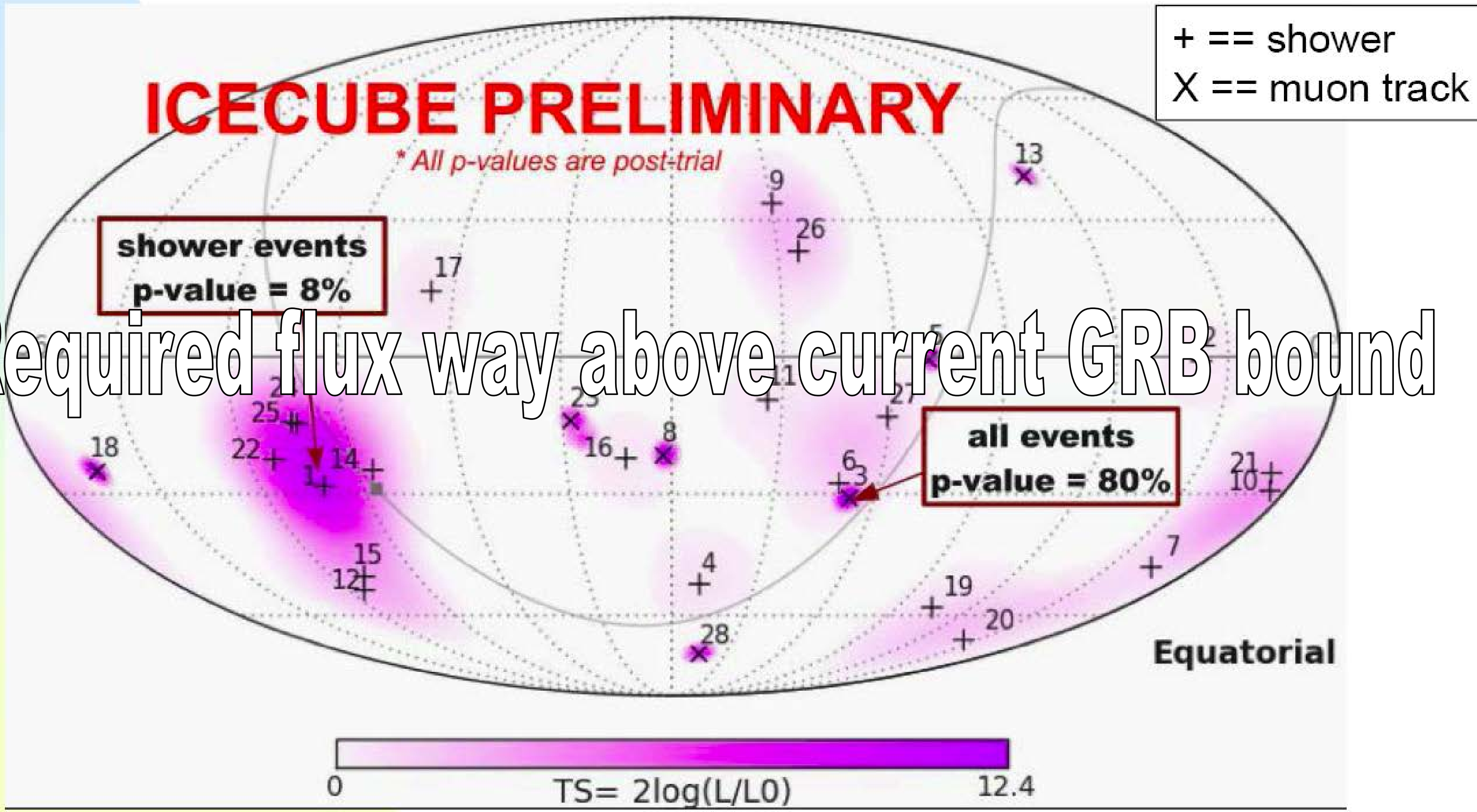
http://antares.in2p3.fr/

Contained event sky map

TeV-PeV neutrinos

Searches for clusters (source) & connection to galactic plane

p-values calculated for all 28 events & for 21 showers



Required flux way above current GRB bound

No significant source or connection to galactic plane seen

(Whitehorn @ WIPAC 2013, Klein @ ICRC 2013)

Simulation of cosmic ray and neutrino sources

(focus on proton composition …)

Cosmic ray source

(illustrative proton-only scenario, pγ interactions)

If neutrons can escape:
Source of cosmic rays

Neutrinos produced in ratio $(\nu_e:\nu_\mu:\nu_\tau)=(1:2:0)$

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

$$\pi^+ \rightarrow \mu^+ + \nu_\mu\,,$$

$$p + \gamma_{\mathrm{CMB}} \rightarrow \Delta^+ \rightarrow$$ Cosmogenic neutrinos

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

Delta resonance approximation:

$$p + \gamma \rightarrow \Delta^+ \rightarrow \begin{cases} n + \pi^+ & 1/3 \text{ of all cases} \\ p + \pi^0 & 2/3 \text{ of all cases} \end{cases}$$

π^+/π^0 determines ratio between neutrinos and high-E gamma-rays

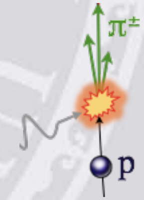
$$\pi^0 \rightarrow \gamma + \gamma$$

High energetic gamma-rays;
typically cascade down to lower E

Cosmic messengers

Source simulation: pγ

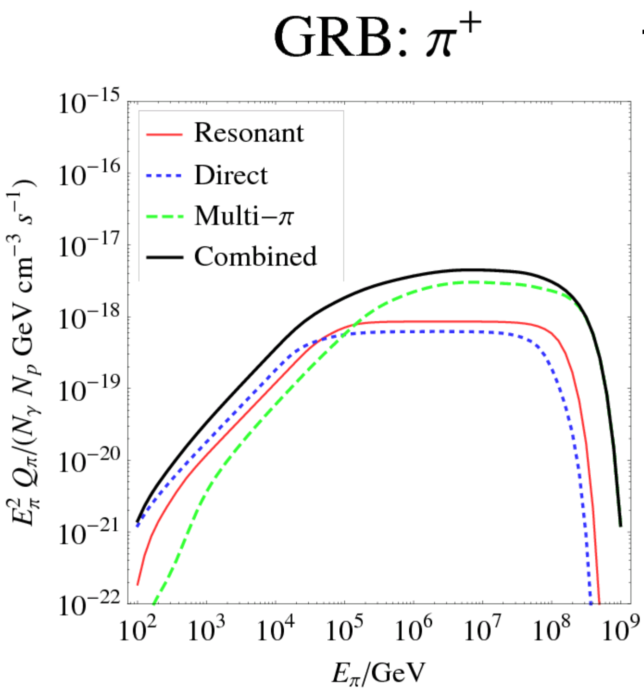
(particle physics)



- Δ(1232)-resonance approximation:

$$p + \gamma \rightarrow \Delta^{+} \rightarrow \begin{cases} n + \pi^{+} & 1/3 \text{ of all cases} \\ p + \pi^{0} & 2/3 \text{ of all cases} \end{cases}$$

- Limitations:
  - No π^- production; cannot predict $\pi^+/\ \pi^-$ ratio (Glashow resonance!)
  - High energy processes affect spectral shape (X-sec. dependence!)
  - Low energy processes (t-channel) enhance charged pion production
- Solutions:
  - SC iption of physics



from: Hümmer, Rüger, Spanier, Winter, ApJ 721 (2010) 630

NeuCosmA

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“Minimal“ (top down) ν model

Dashed arrows: include cooling and escape

$Q(E)$ [GeV^{-1} cm^{-3} s^{-1}] per time frame

$N(E)$ [GeV^{-1} cm^{-3}] steady spectrum

Input: $N'_\gamma(E')$ $N'_p(E')$ B‘

photohadronics

$Q'_{\pi^+}(E')$

Peculiarity for neutrinos:
Secondary cooling

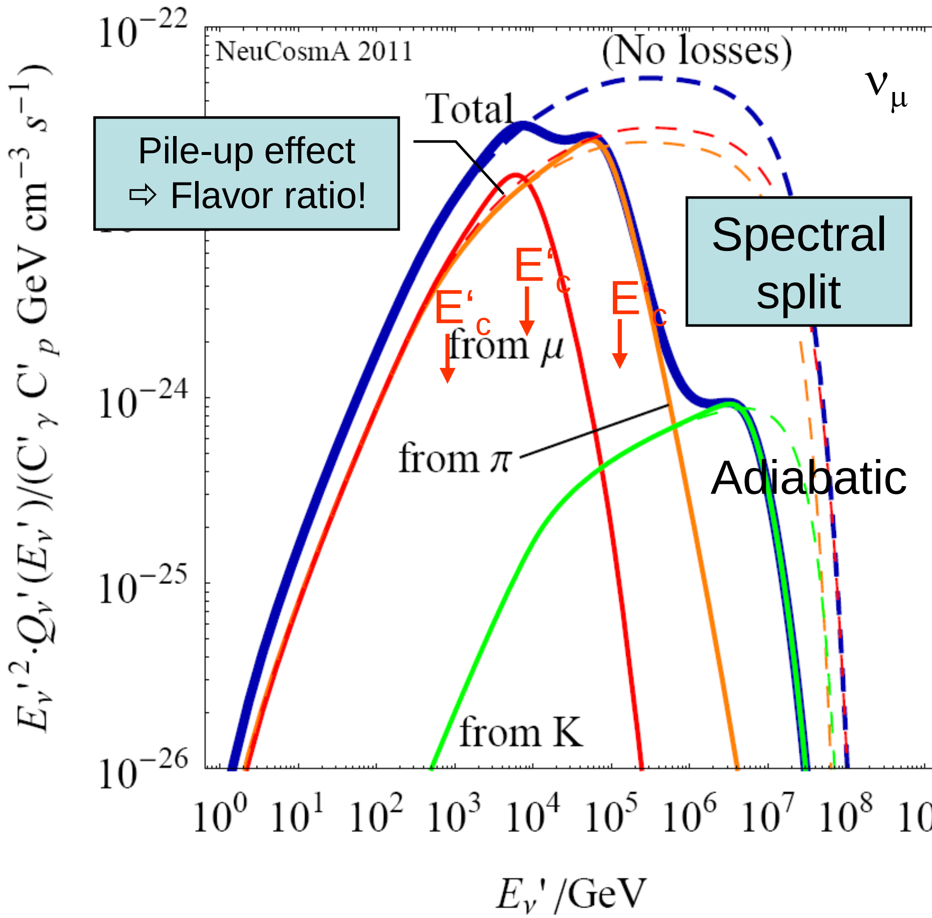
Example: GRB

Secondary spectra (μ, π, K) loss-steepend above critical energy

$$E'_c = \sqrt{\frac{9\pi\epsilon_0 m^5 c^7}{\tau_0 e^4 B'^2}}$$

- E'_c depends on particle physics only (m, τ_0), and **B'**
- Leads to characteristic flavor composition and shape
- Very robust prediction for sources? [e.g. any additional radiation processes mainly affecting the primaries will not affect the flavor composition]

Decay/cooling: charged μ, π, K



Baerwald, Hümmer, Winter, Astropart. Phys. 35 (2012) 508; also: Kashti, Waxman, 2005; Lipari et al, 2007

From the source to the detector: UHECR transport

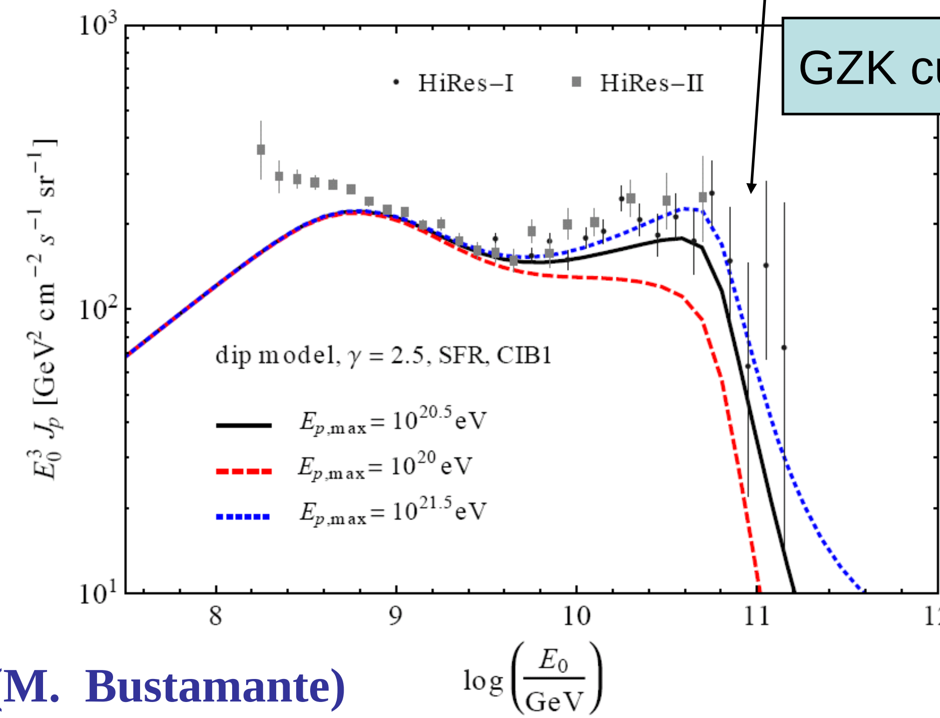
- Kinetic equation for co-moving number density:

$$\dot{Y}_p = \partial_E \left(H E Y_p \right) + \partial_E \left(b_{e^+e^-} Y_p \right) + \partial_E \left(b_{p\gamma} Y_p \right) + \mathcal{L}_{\mathrm{CR}}$$

Expansion of Universe	Pair production **Blumenthal, 1970**	Photohadronics **Hümmer, Rüger, Spanier, Winter, 2010**	CR inj.

[here $b=-dE/dt=E\, t^{-1}_{\mathrm{loss}}$]

GZK cutoff



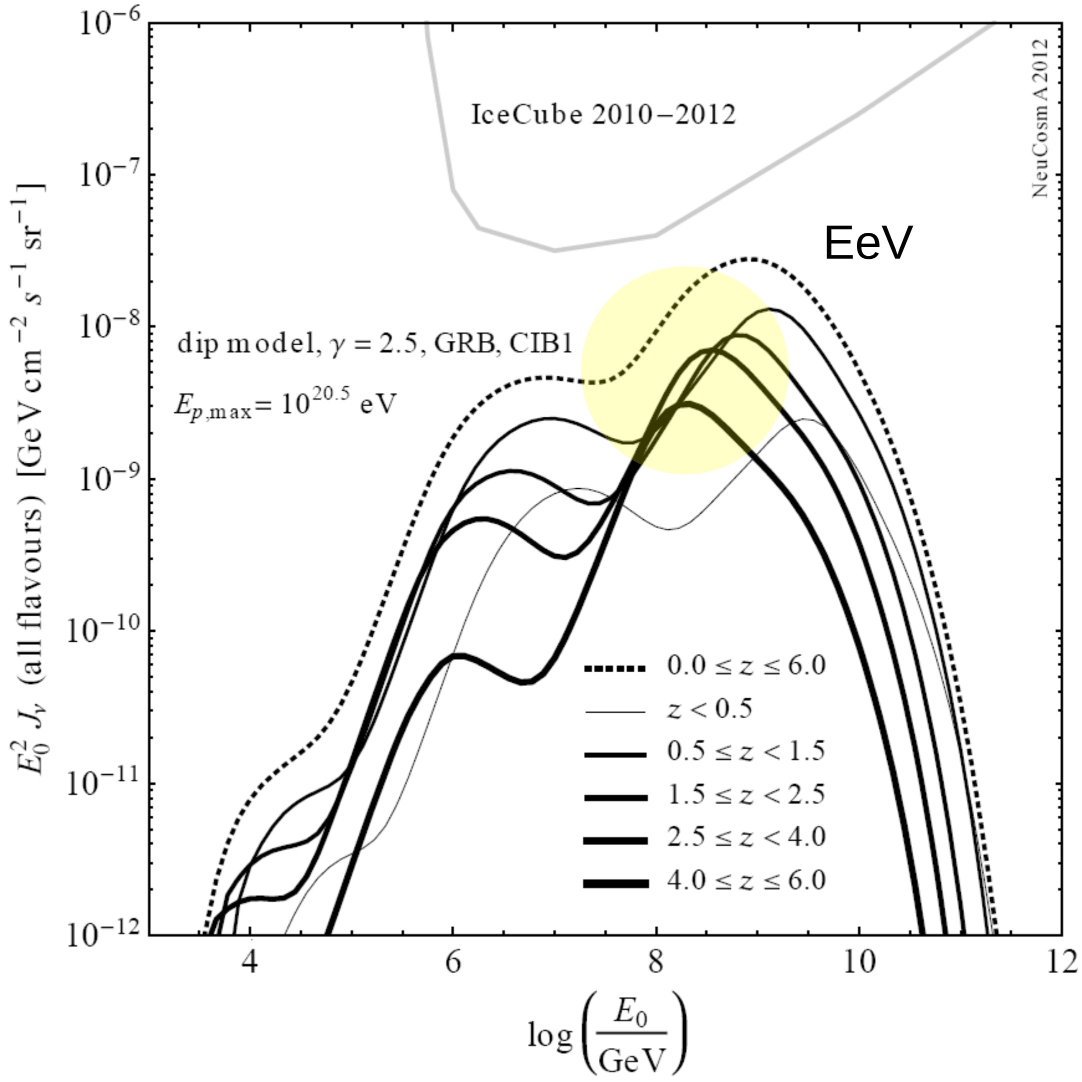
- Energy losses ⇨ UHECR must from from our local environment (~ 1 Gpc at 10^{10} GeV, ~ 50 Mpc at 10^{11} GeV)

(M. Bustamante)

Cosmogenic neutrinos

$p + \gamma_{\rm CMB} \rightarrow \Delta^+ \rightarrow$ Cosmogenic neutrinos

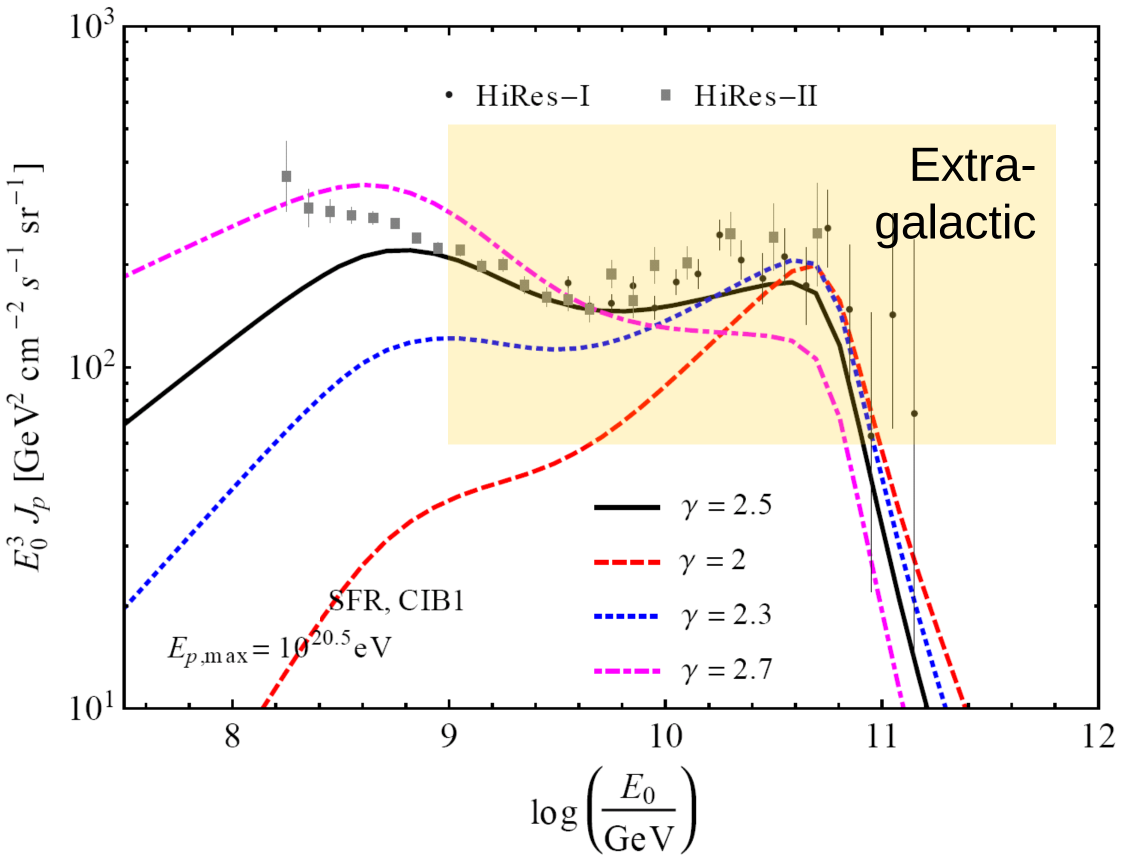
- Prediction depends on maximal proton energy, spectral index γ, source evolution, composition
- Can test UHECR beyond the local environment
- Can test UHECR injection into ISM independent of CR production model
⇨ constraints on UHECR escape



(courtesy M. Bustamante; see also Kotera, Allard, Olinto, JCAP 1010 (2010) 013)

Ankle vs. dip model

- Transition between galactic and extragalactic cosmic rays at different energies:



- Ankle model:
  - Injection index γ ~ 2 possible (⇨ Fermi shock acc.)
  - Transition at > 4 EeV
- Dip model:
  - Injection index γ ~ 2.5-2.7 (how?)
  - Transition at ~ 1 EeV
  - Characteristic shape by pair production dip

Figure courtesy M. Bustamante; for a recent review, see Berezinsky, arXiv:1307.4043

Multi-messenger physics with GRBs

The “magic“ triangle

Properties of neutrinos really unterstood?

γ

Satellite experiments
(burst-by-burst)

Model-dependent prediction

Waxman, Bahcall, PRL 78 (1997) 2292; Guetta et al., Astropart. Phys. 20 (2004) 429

⇨ GRB stacking

Partly common fudge factors: how many GRBs are actually observable? Baryonic loading? Dark GRBs? …

?

(energy budget, ensemble fluctuations, …)

e.g. Eichler, Guetta, Pohl, ApJ 722 (2010) 543; Waxman, arXiv:1010.5007; Ahlers, Anchordoqui, Taylor, 2012 …

Robust connection
if CRs only escape as neutrons produced in pγ interactions

Ahlers, Gonzalez-Garcia, Halzen, Astropart. Phys. 35 (2011) 87

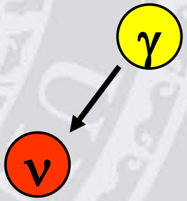
ν

CR

Neutrino telescopes
(burst-by-burst or diffuse)

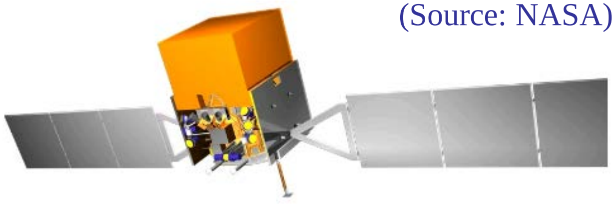
CR experiments (diffuse)

GRB stacking

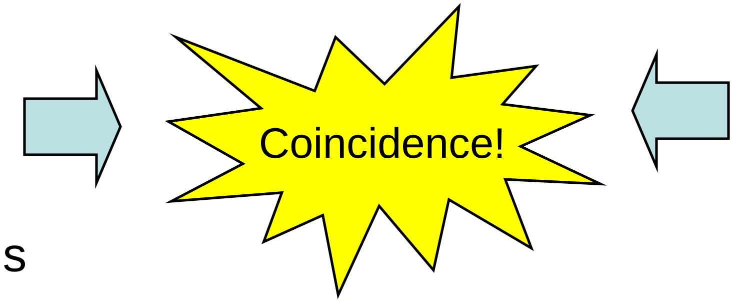


- Idea: Use multi-messenger approach (BG free)

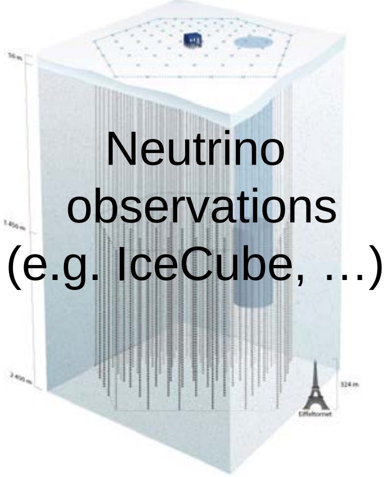
(Source: NASA)



GRB gamma-ray observations
(e.g. Fermi, Swift, etc)

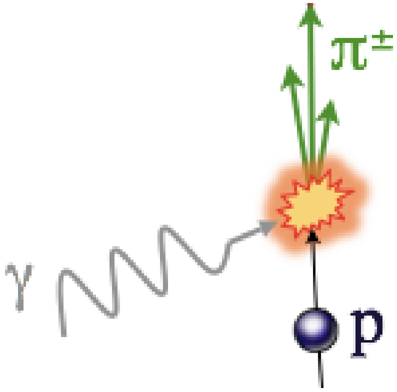


(Source: IceCube)

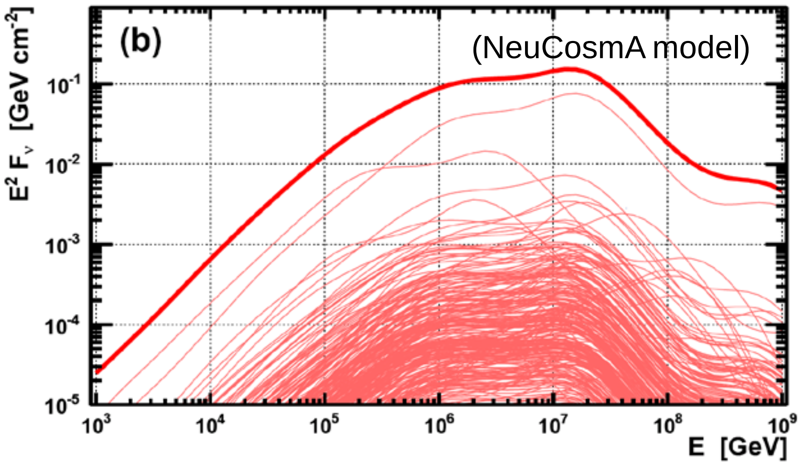


- Predict neutrino flux from observed photon fluxes event by event

Observed:
broken power law
(Band function)



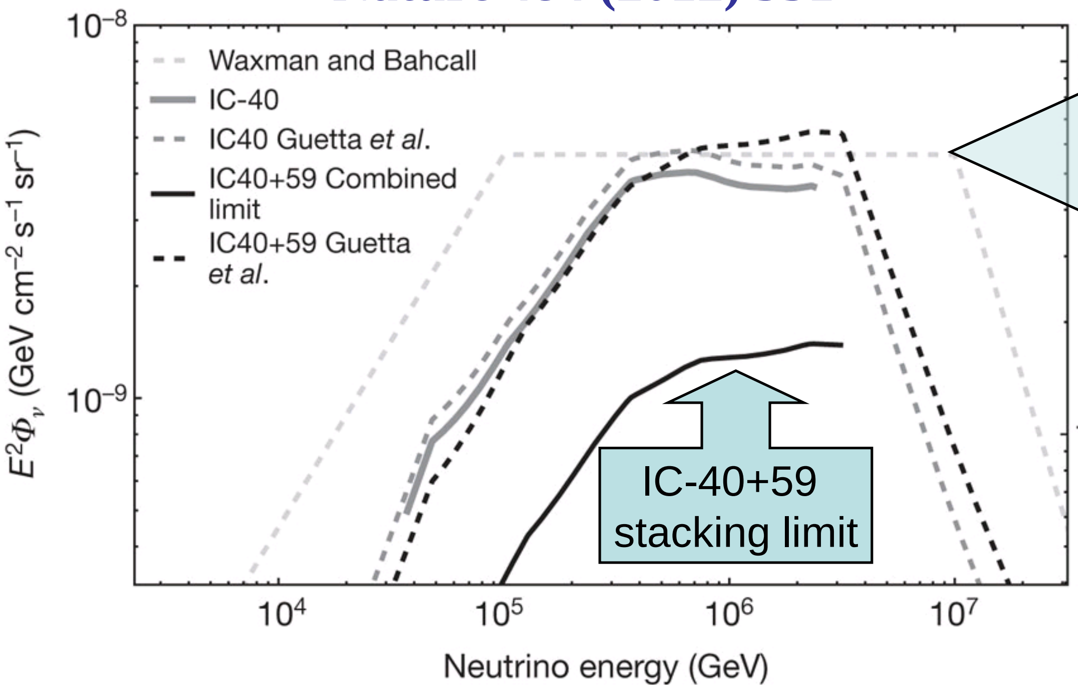
E^{-2} injection



(Example: ANTARES, arXiv:1307.0304)

Gamma-ray burst fireball model:
IC-40+59 data meet generic bounds

Nature 484 (2012) 351



Generic flux based on the assumption that GRBs are the sources of (highest energetic) cosmic rays
(Waxman, Bahcall, 1999; Waxman, 2003; spec. bursts: Guetta et al, 2003)

- Does IceCube really rule out the paradigm that GRBs are the sources of the ultra-high energy cosmic rays?

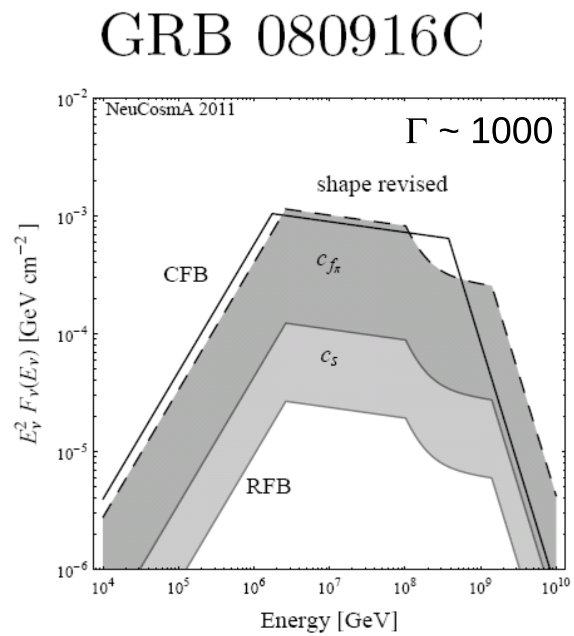
Revision of neutrino flux predictions

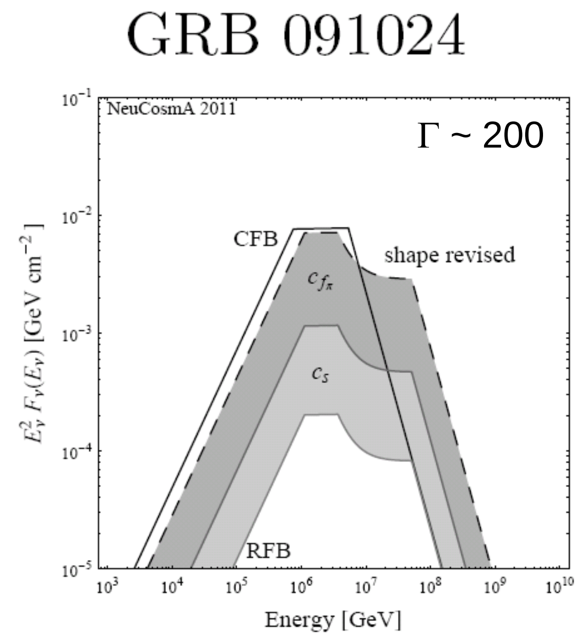
Analytical recomputation of IceCube method (CFB):

$c_{f\pi}$: corrections to pion production efficiency

c_S: secondary cooling and energy-dependence of proton mean free path

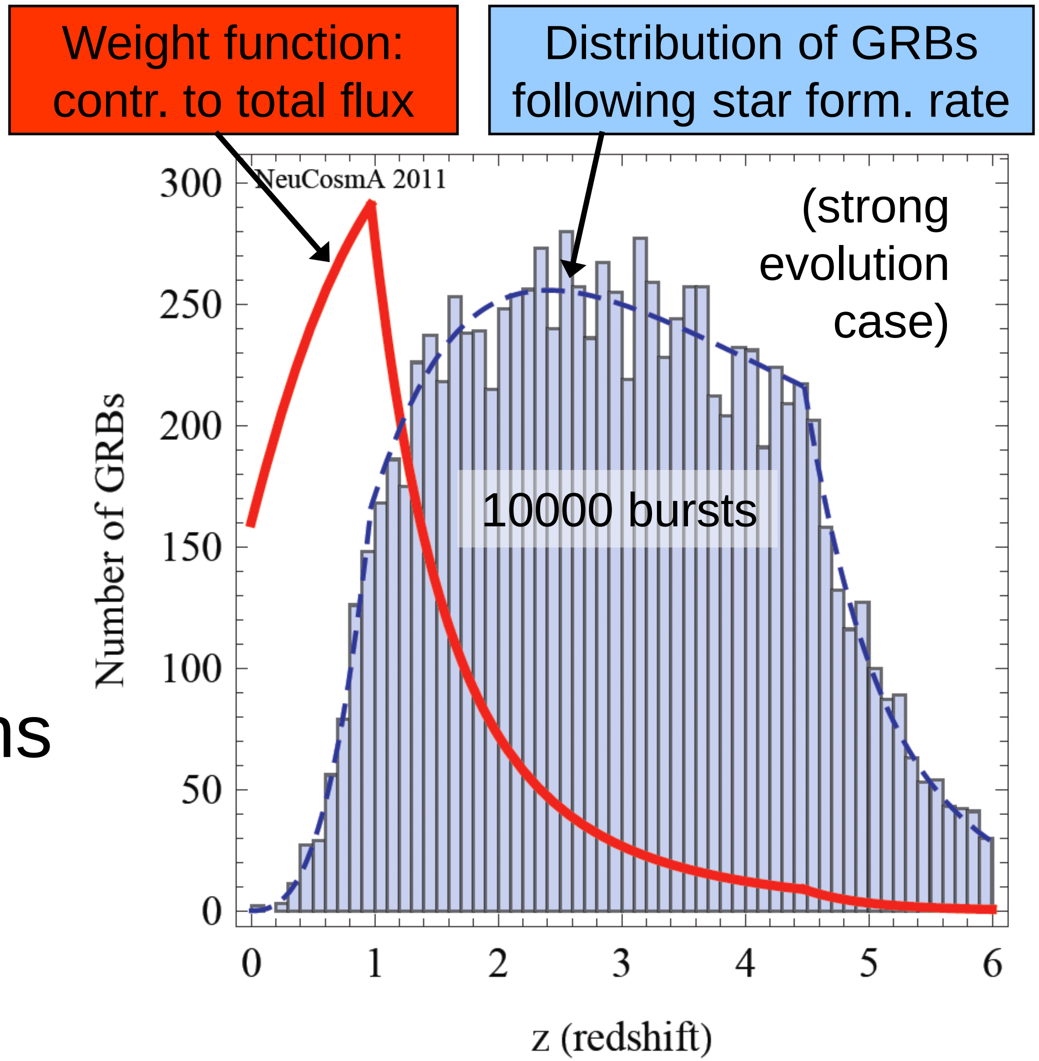
(see also Li, 2012, PRD)





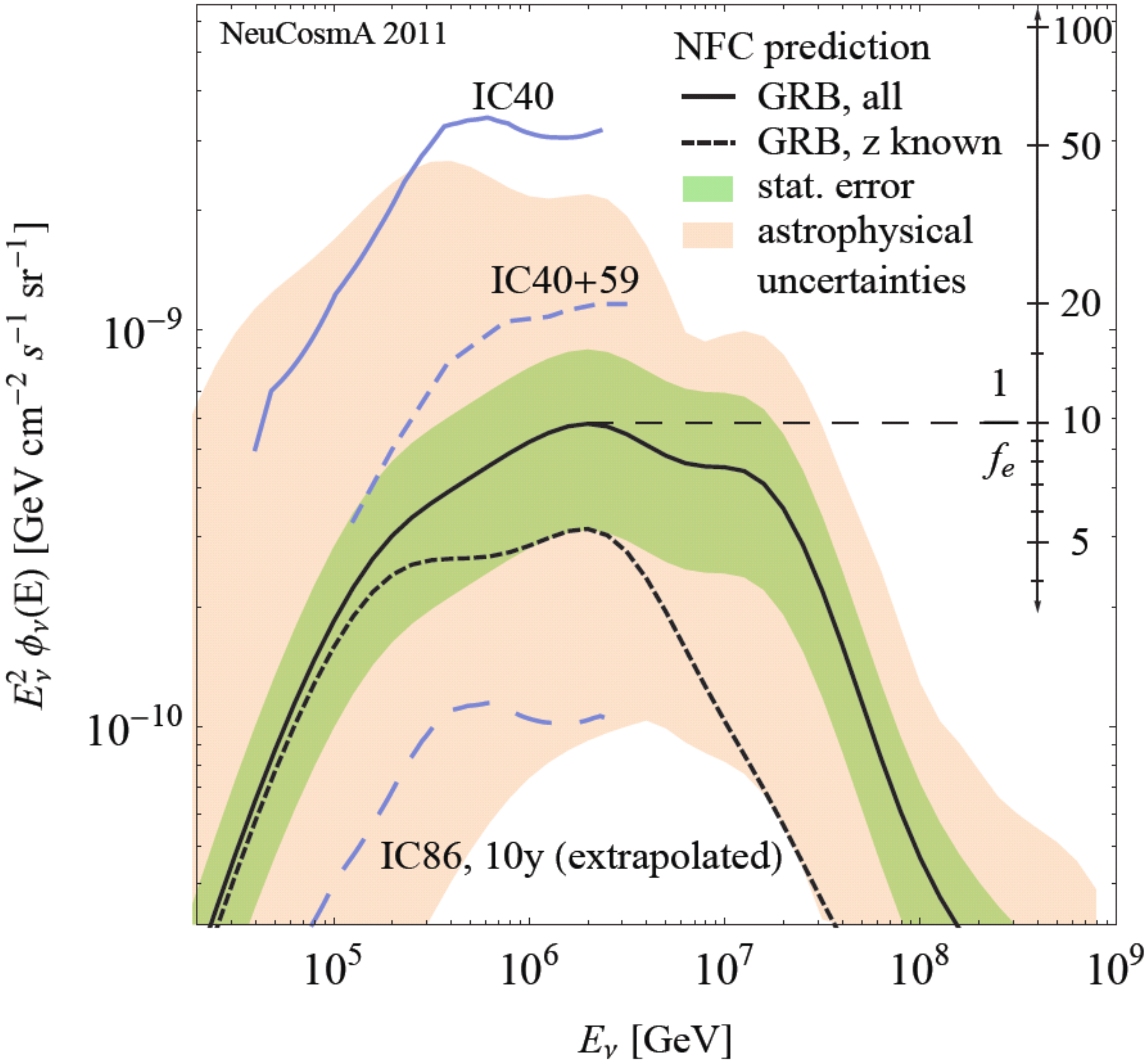
Systematics in aggregated fluxes

- z ~ 1 “typical“ redshift of a GRB
- Peak contribution in a region of low statistics
  - Ensemble fluctuations of quasi-diffuse flux



(Baerwald, Hümmer, Winter, Astropart. Phys. 35 (2012) 508)

Quasi-diffuse prediction



- Numerical fireball model cannot be ruled out yet with IC40+59 for same parameters, bursts, assumptions
- Peak at higher energy!
  [at 2 PeV, where two cascade events have been seen]

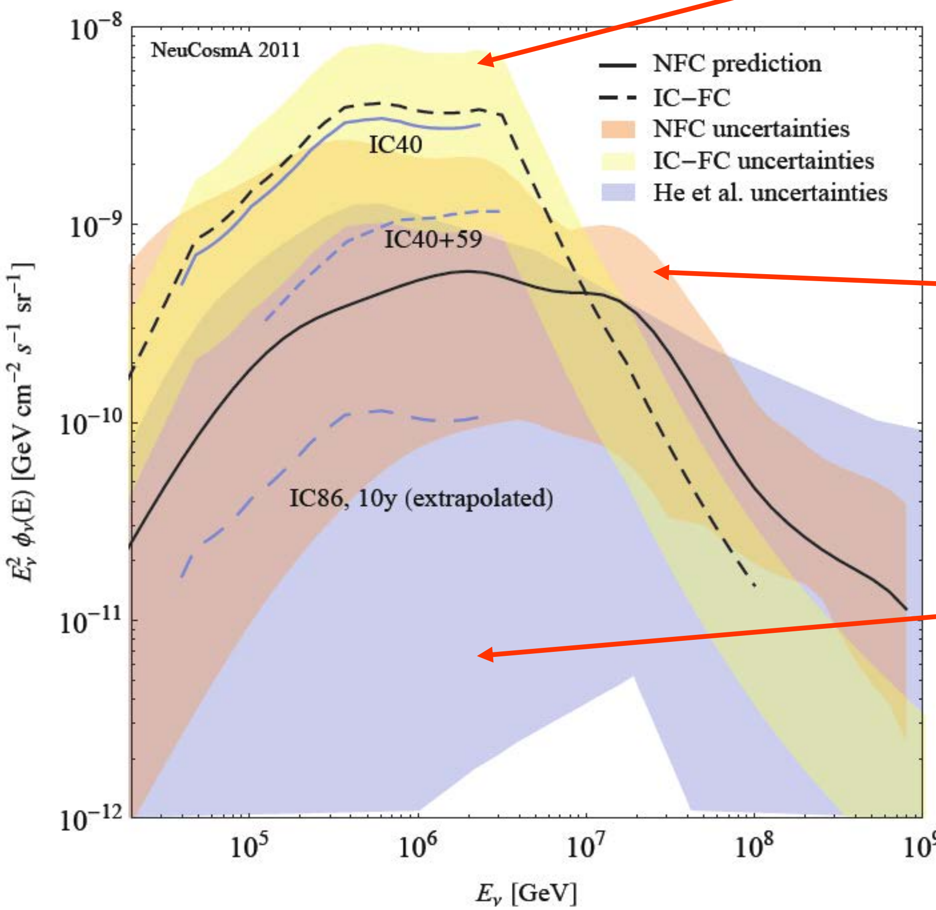
"Astrophysical uncertainties":
t_v: 0.001s … 0.1s
Γ: 200 …500
α: 1.8 … 2.2
$\varepsilon_e/\varepsilon_B$: 0.1 … 10

(Hümmer, Baerwald, Winter, Phys. Rev. Lett. 108 (2012) 231101)

Model dependence

Not only normalization, but also uncertainties depend on assumptions:

Model dependence



(figure courtesy of Philipp Baerwald)

Internal shock model, target photons from synchrotron emission/inverse Compton

from Fig. 3 of IceCube, Nature 484 (2012) 351; uncertainties from Guetta, Spada, Waxman, Astrophy J. 559 (2001) 2001

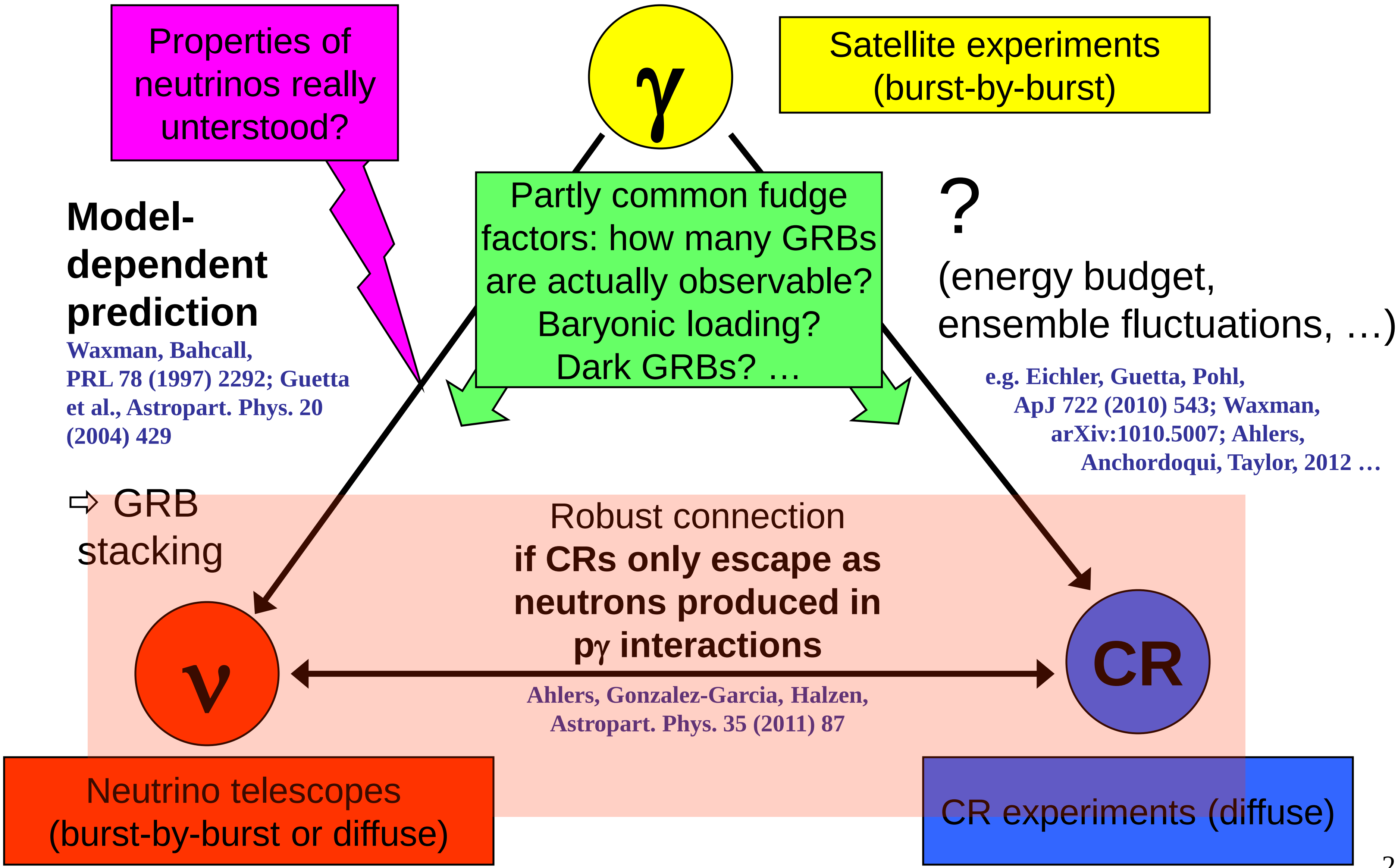
Internal shock model, target photons from observation, origin not specified

from Fig. 3 of Hümmer et al, PRL 108 (2012) 231101

Dissipation radius not specified (e. g. magnetic reconnection models), target photons from observation, origin not specified

from Fig. 3 of He, Murase, Nagataki, et al, ApJ. 752 (2012) 29

Neutrinos-cosmic rays



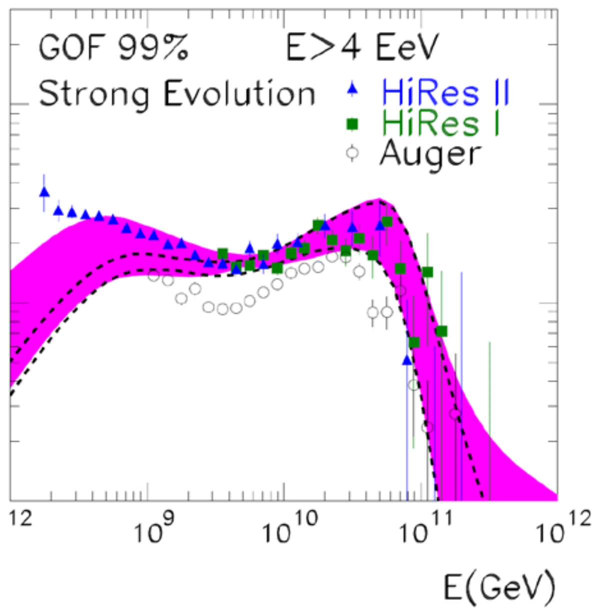
The “neutron model“

ν ⟷ CR

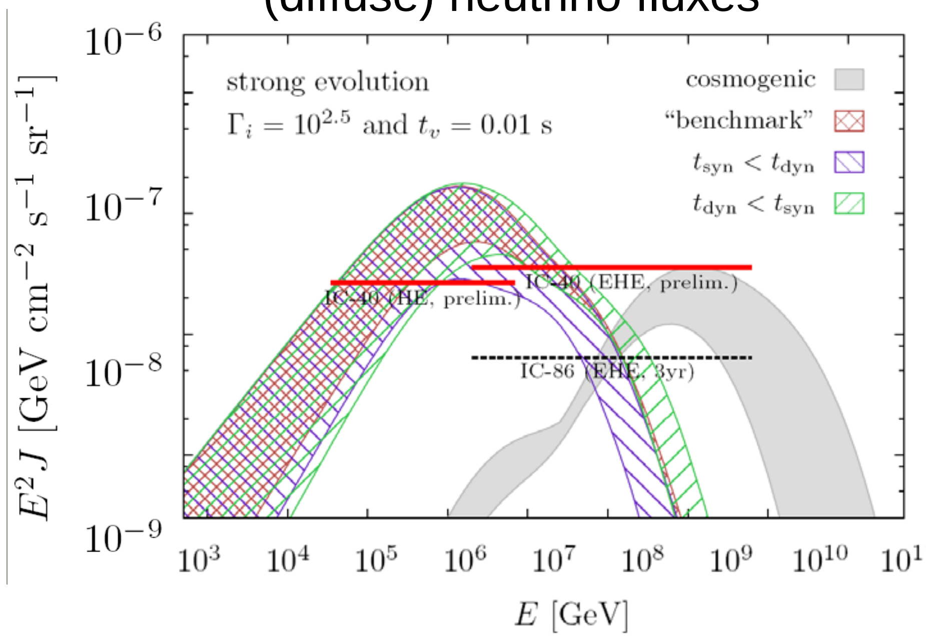
- If charged π and n produced together:

$$p + \gamma \rightarrow \Delta^+ \rightarrow \begin{cases} n + \pi^+ & 1/3 \text{ of all cases} \\ p + \pi^0 & 2/3 \text{ of all cases} \end{cases}$$

Fit to UHECR spectrum



Consequences for (diffuse) neutrino fluxes



Ahlers, Gonzalez-Garcia, Halzen, Astropart. Phys. 35 (2011) 87

➢ Baryonic loading? CR leakage? Ensemble fluctuations? **(Ahlers, Anchordoqui, Taylor, 2012; Kistler, Stanev, Yuksel, 2013; …)**

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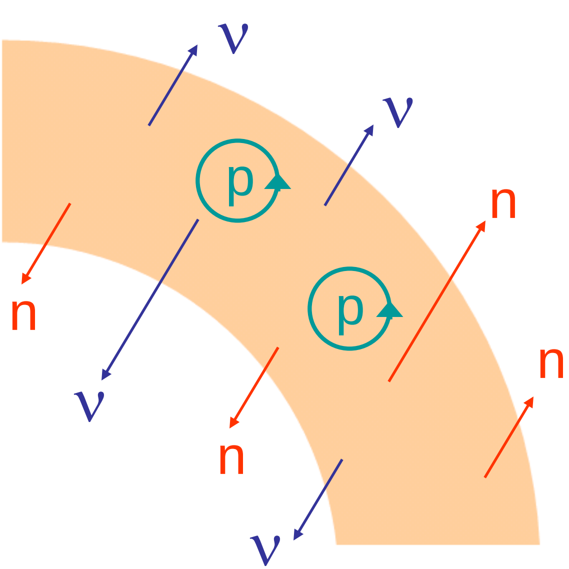
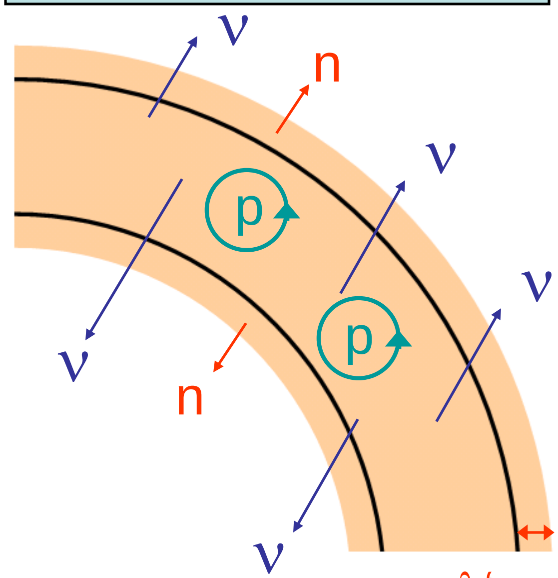
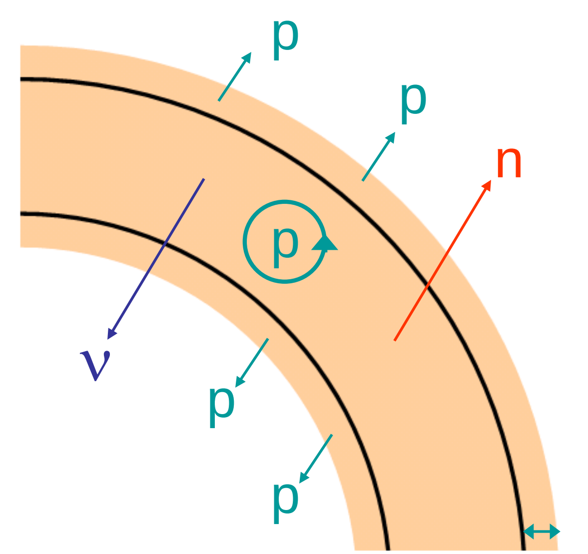
CR escape mechanisms

Baerwald, Bustamante, Winter, Astrophys.J. 768 (2013) 186

Optically thin (to neutron escape)	Optically thick (to neutron escape)	Direct proton escape (UHECR leakage)







- One neutrino per cosmic ray
- Protons magnetically confined

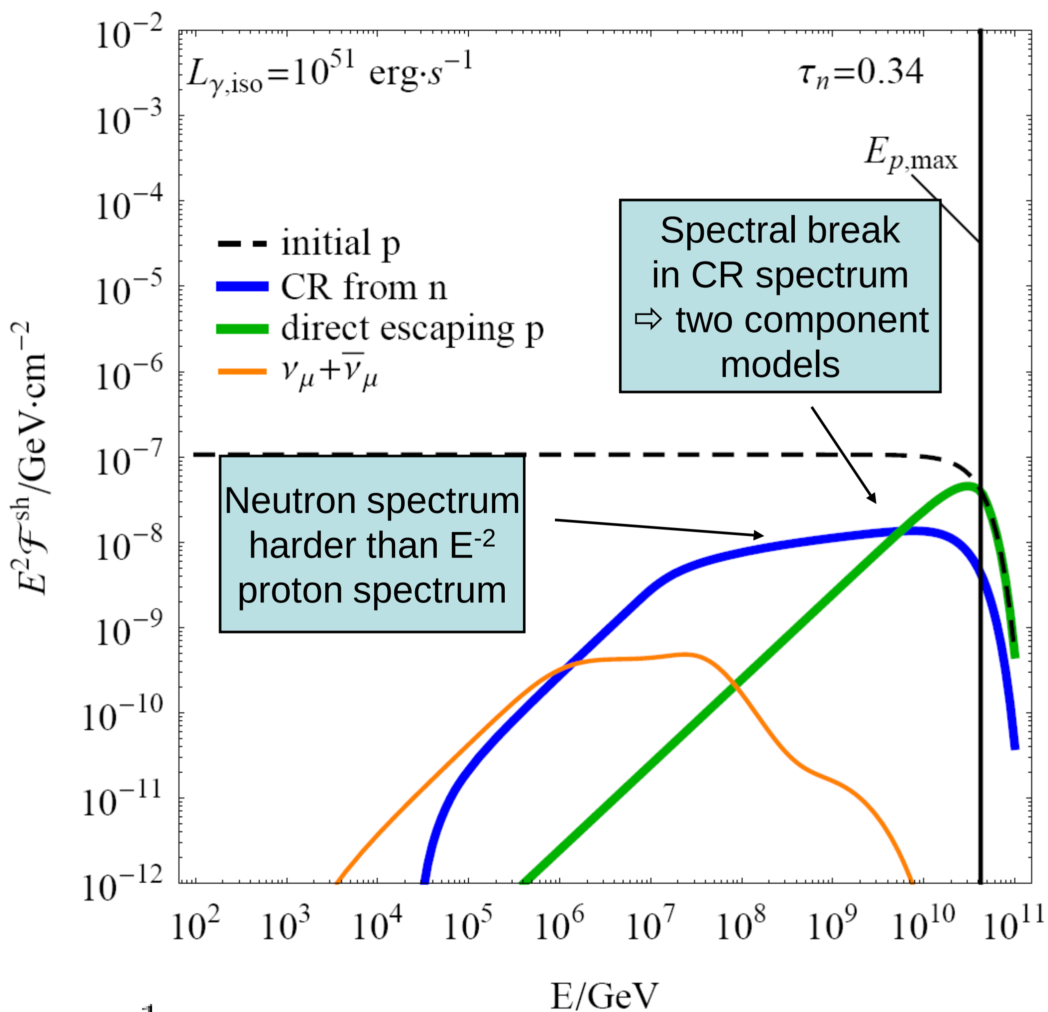
- Neutron escape limited to edge of shells
- Neutrino prod. relatively enhanced

- $p\gamma$ interaction rate relatively low
- Protons leaking from edges dominate

A typical (?) example

- For high acceleration efficiencies: R'_L can reach shell thickness at highest energies (if $E'_{p,max}$ determined by t'_{dyn})

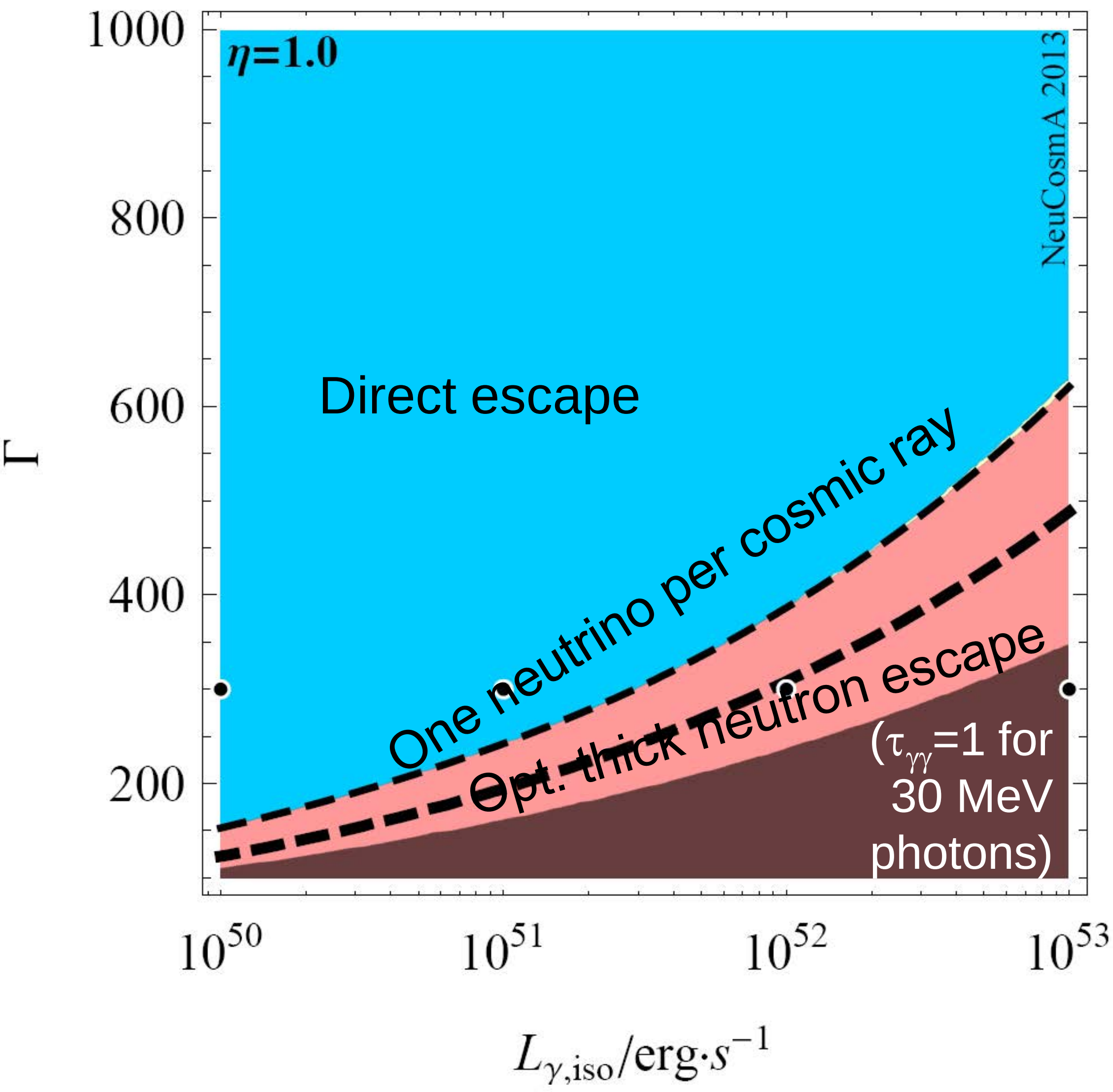
➢ UHECR from optically thin GRBs will be direct escape-dominated



(Baerwald, Bustamante, Winter, Astrophys.J. 768 (2013) 186)

$\Gamma = 300,\ t_v = 0.01\,\mathrm{s},\ T_{90} = 10\,\mathrm{s},\ \eta = 1,$
$\epsilon_e/\epsilon_B = 1,\ f_e = 0.1,\ \alpha_\gamma = 1,\ \beta_\gamma = 2,\ \varepsilon'_{\gamma,b} = 1\,\mathrm{keV},$ and $z = 2.$

Parameter space?



- The challenge: need high enough E_p to describe observed UHECR spectrum
- ➢ The acceleration efficiency η has to be high
- ➢ Can evade the "one neutrino per cosmic ray" paradigm

(Baerwald, Bustamante, Winter, Astrophys.J. 768 (2013) 186)

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Cosmic energy budget

Properties of neutrinos really unterstood?

γ

Satellite experiments (burst-by-burst)

Model-dependent prediction

Waxman, Bahcall, PRL 78 (1997) 2292; Guetta et al., Astropart. Phys. 20 (2004) 429

⇨ GRB stacking

Partly common fudge factors: how many GRBs are actually observable? Baryonic loading? Dark GRBs? …

?

(energy budget, ensemble fluctuations, …)

e.g. Eichler, Guetta, Pohl, ApJ 722 (2010) 543; Waxman, arXiv:1010.5007; Ahlers, Anchordoqui, Taylor, 2012 …

Robust connection **if CRs only escape as neutrons produced in pγ interactions**

Ahlers, Gonzalez-Garcia, Halzen, Astropart. Phys. 35 (2011) 87

ν

CR

Neutrino telescopes (burst-by-burst or diffuse)

CR experiments (diffuse)

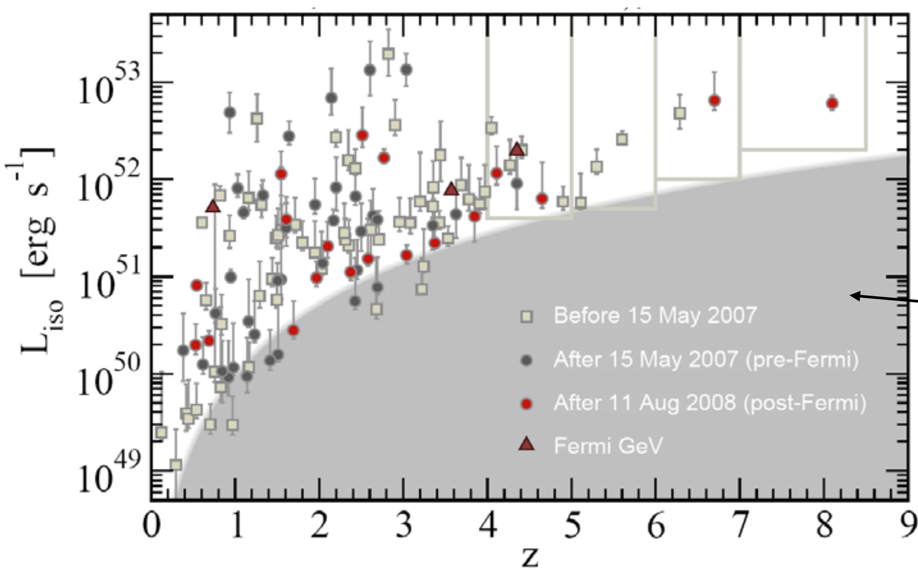
Gamma-ray observables?

- Redshift distribution

~ $(1+z)^\alpha$

SFR

$$\frac{d\dot{N}}{dz} = F(z)\,\frac{\mathcal{E}(z)\,\dot{\rho}_*(z)}{\langle f_{\rm beam}\rangle}\,\frac{dV/dz}{1+z}$$



(Kistler et al, Astrophys.J. 705 (2009) L104)

- Can be integrated over.

  Total number of bursts in the observable universe

$$\dot{N}_{\rm tot} = \int_0^\infty \frac{d\dot{N}}{dz}\,\frac{1}{F(z)}\,dz$$

Threshold correction

➢ Can be directly determined (counted)!

➢ **Order 1000 yr^{-1}**

Consequence: Local GRB rate

- The local GRB rate can be written as

$$\dot{n}_{\mathrm{GRB}} = \frac{1}{\mathrm{Gpc}^3\,\mathrm{yr}} \frac{\dot{N}_{\mathrm{tot}}\,[\mathrm{yr}^{-1}]}{968} \frac{1}{f_z}$$

where f_z is a cosmological correction factor:

SFR model	α	f_z	$\left.\dot{\tilde{n}}_{\mathrm{GRB}}\right\|_{z=0}$ $[\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}]$
Hopkins & Beacom (2006)	1.2	25.15	0.08
	0.0	5.65	0.35
Wanderman & Piran (2010)	0.0	7.70	0.26
Madau & Porciani (2000)			
SF1	0.0	9.89	0.21
SF2	0.0	14.42	0.14
SF3	0.0	14.36	0.14

(for 1000 observable GRBs per year)

(Baerwald, Bustamante, Halzen, Winter, to appear)

Required UHECR injection

- Required energy ejected in UHECR per burst:

$$E_{\mathrm{CR}}^{[10^{10},10^{12}]} = 10^{53}\,\mathrm{erg} \cdot \frac{\dot{\varepsilon}_{\mathrm{CR}}^{[10^{10},10^{12}]}}{10^{44}\,\mathrm{erg\,Mpc^{-3}\,yr^{-1}}} \cdot \frac{968\,\mathrm{yr}^{-1}}{\dot{N}_{\mathrm{tot}}} \cdot f_z$$

~1.5 to fit UHECR observations

~5-25

- In terms of γ-ray energy:

Fraction of energy in CR production?

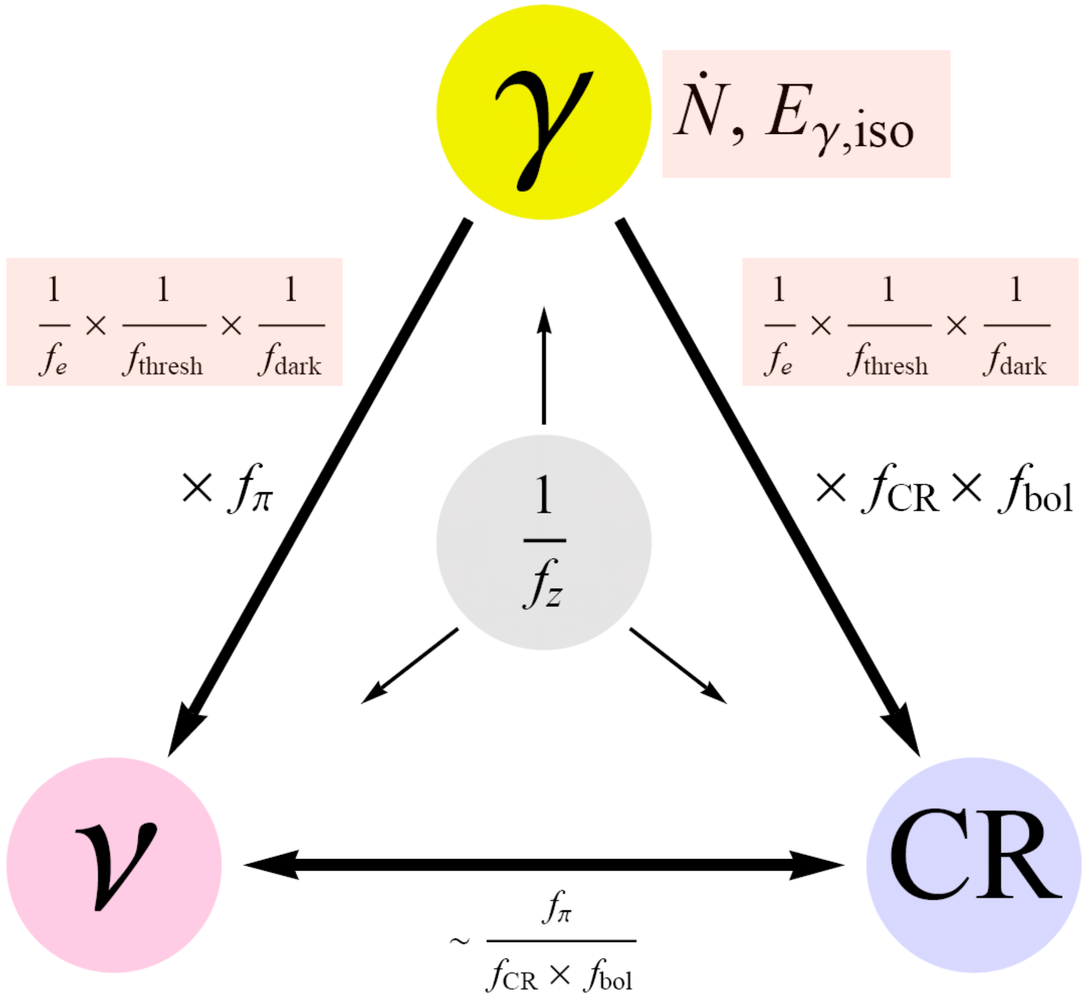
How much energy in UHECR?

$$E_{\mathrm{CR}}^{[10^{10},10^{12}]} = f_{\mathrm{CR}} \frac{f_{\mathrm{bol}}}{f_e} E_{\gamma,\mathrm{iso}}$$

Energy in protons vs. electrons (IceCube def.)

➢ Baryonic loading f_e^{-1}~50-100 for E^{-2} inj. spectrum (f_{bol} ~ 0.2), $E_{\gamma,\mathrm{iso}} \sim 10^{53}$ erg, neutron model (f_{CR} ~ 0.4)
[IceCube standard assumption: f_e^{-1}~10]

Impact factors



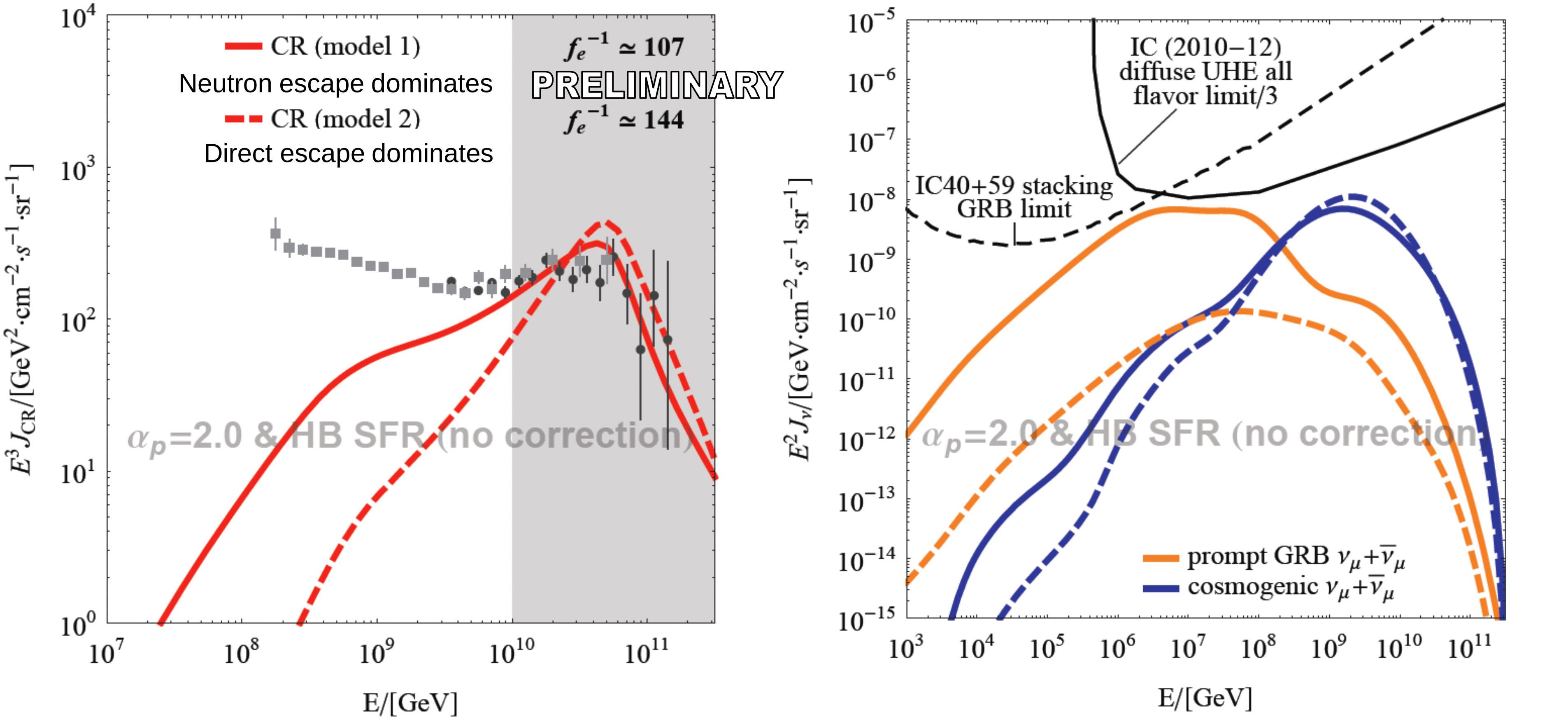
Same.
Focus on $1/f_e$
in following

Depends on
model for UHECR escape

(Baerwald, Bustamante, Halzen, Winter, to appear)

Combined source-prop. model fit
(cosmic ray ankle model transition, α_p ~ 2)

- Cosmic ray leakage (dashed) can evade prompt neutrino bound with comparable f_e^{-1}:

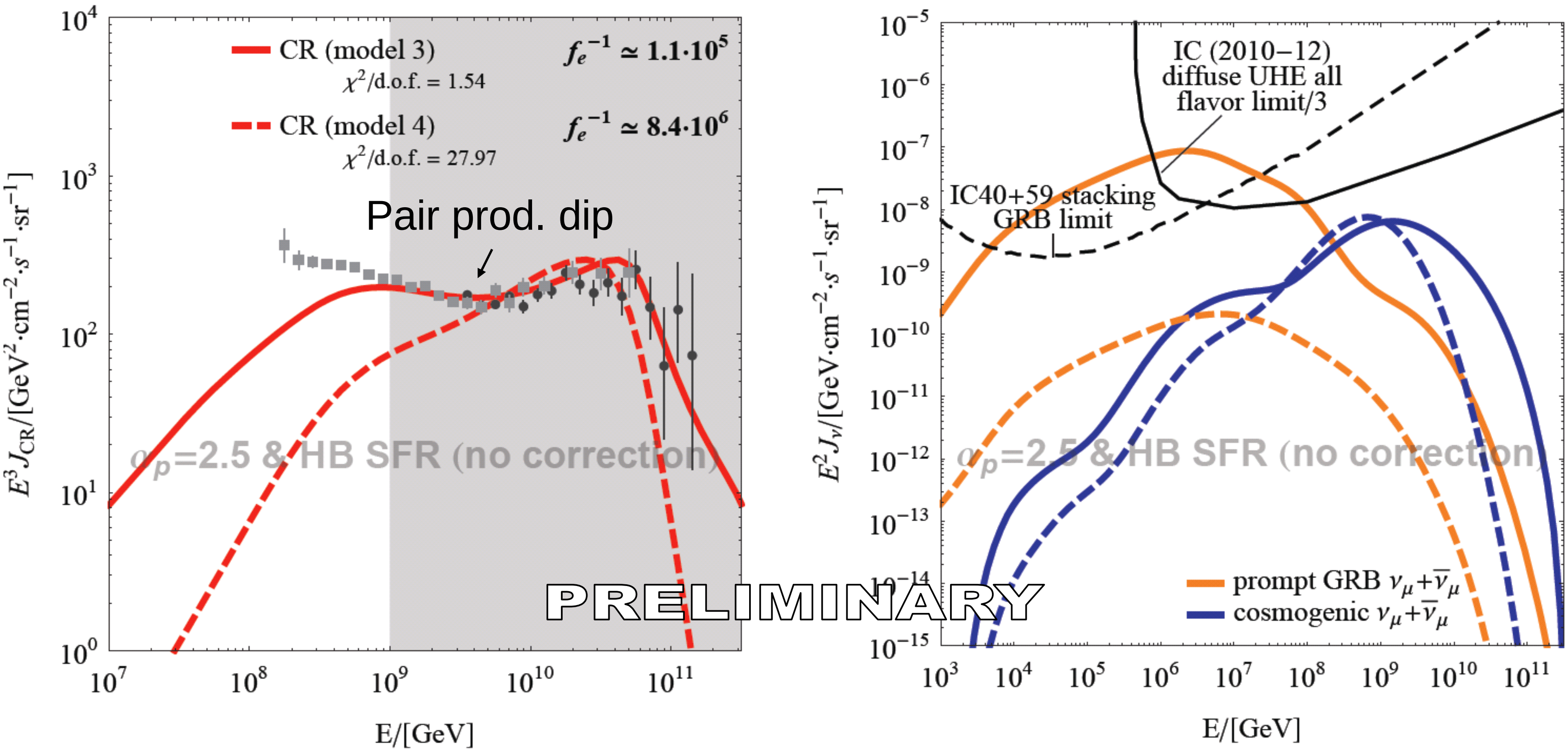


(Baerwald, Bustamante, Halzen, Winter, to appear)

Combined source-prop. model fit

(cosmic ray dip model transition, α_p ~ 2.5)

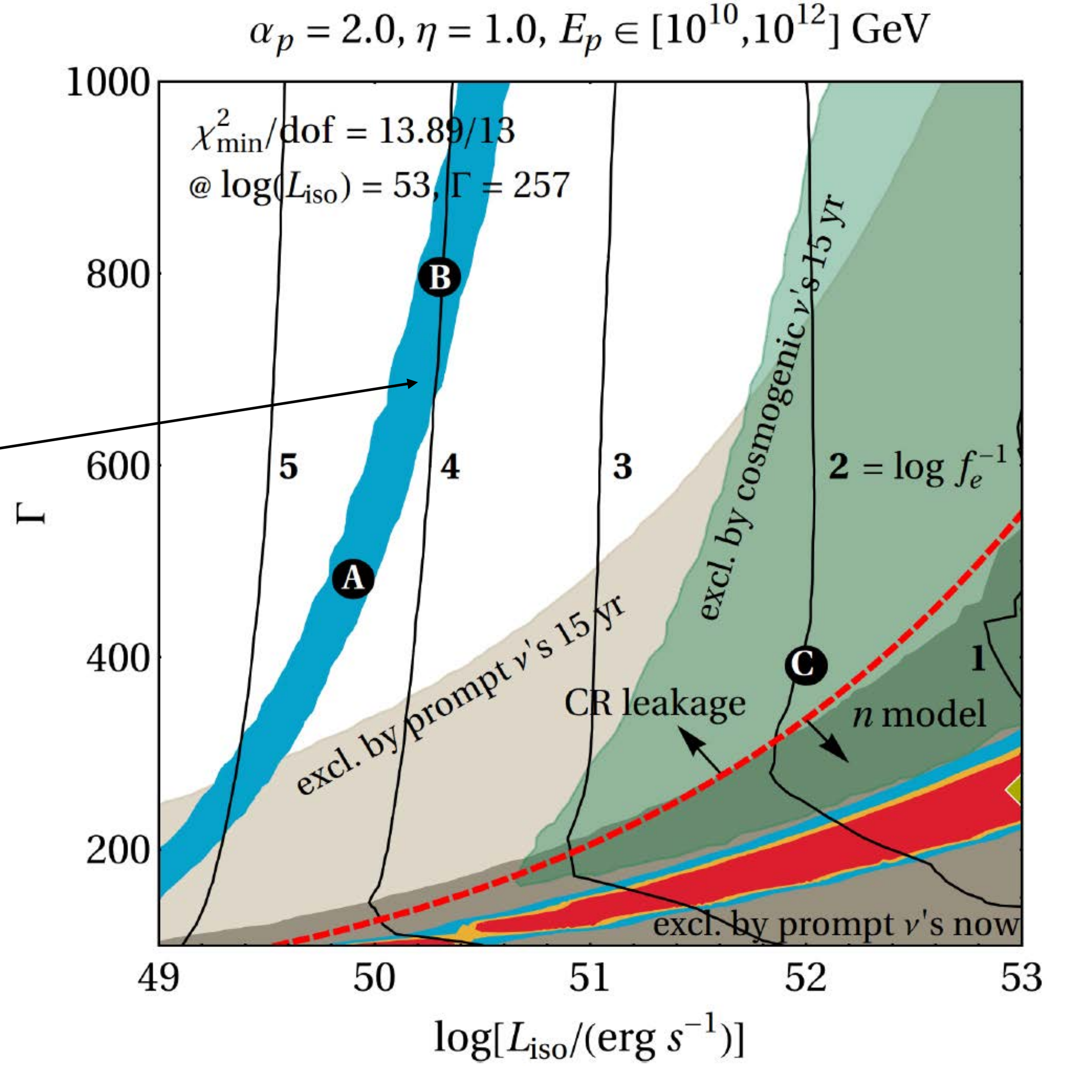
- Dip-model transition requires extremely large baryonic loadings (bol. correction!):



(Baerwald, Bustamante, Halzen, Winter, to appear)

Parameter space?

- Results depends on shape of additional escape component, acceleration efficiency
- This example: branch surviving future IceCube bounds requires large baryonic loadings to fit UHECR observations



(Baerwald, Bustamante, Halzen, Winter, to appear)

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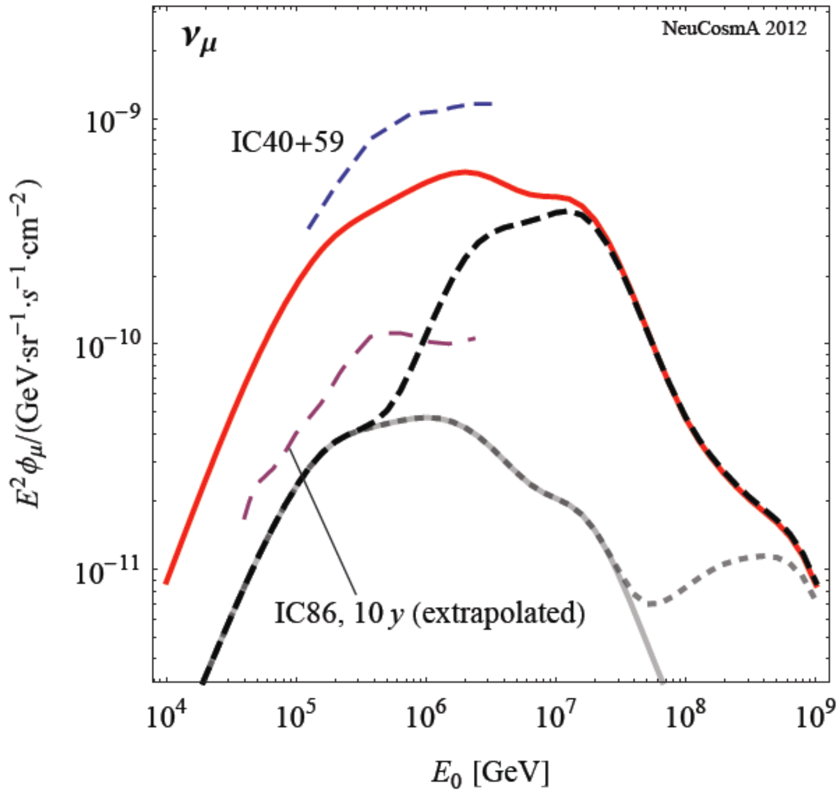
Summary

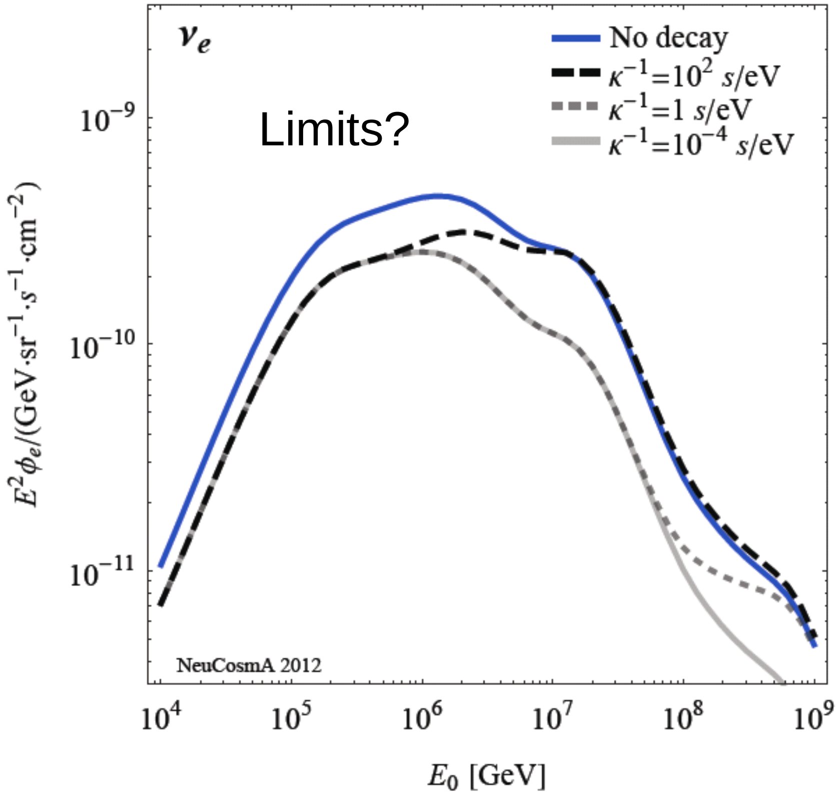
- GRB explanation of UHECR requires large baryonic loadings >> 10; still plausible in "ankle model" for UHECR transition
- Neutron model for UHECR escape already excluded by neutrino data
- Future neutrino bounds will strongly limit parameter space where pion production efficiency is large
- Possible ways out:
  - GRBs are *not* the exclusive sources of the UHECR
  - Cosmic rays escape by mechanism other than pion production plus much larger baryonic loadings than previously anticipated
    [applies not only to internal shock scenario …]
  - The cosmic rays and neutrinos come from different collision radii (dynamical model with collisions at different radii)?

Backup

What if: Neutrinos decay?

Decay hypothesis: ν_2 and ν_3 decay with lifetimes compatible with SN 1987A bound





- Reliable conclusions from flux bounds require cascade (ν_e) measurements! Point source, GRB, etc analyses needed!

Baerwald, Bustamante, Winter, JCAP 10 (2012) 20

IceCube method ...normalization

- Connection γ-rays – neutrinos

½ (charged pions) x
¼ (energy per lepton)

Energy in protons

$$\int_0^\infty \mathrm{d}E_\nu\; E_\nu F_\nu(E_\nu) = \frac{1}{8}\,\frac{1}{f_e}\,\left(1-(1-\langle x_{p\to\pi}\rangle)^{\Delta R/\lambda_{p\gamma}}\right)\int_{1\,\mathrm{keV}}^{10\,\mathrm{MeV}} \mathrm{d}E_\gamma\; E_\gamma F_\gamma(E_\gamma)$$

Energy in neutrinos

Fraction of p energy converted into pions f_π

Energy in electrons/ photons

- Optical thickness to pγ interactions:

$$\frac{\Delta R}{\lambda_{p\gamma}} = \left(\frac{L_\gamma^{\mathrm{iso}}}{10^{52}\,\mathrm{erg\,s^{-1}}}\right)\left(\frac{0.01\,\mathrm{s}}{t_{\mathrm{var}}}\right)\left(\frac{10^{2.5}}{\Gamma_{\mathrm{jet}}}\right)^4\left(\frac{\mathrm{MeV}}{\epsilon_\gamma}\right)$$

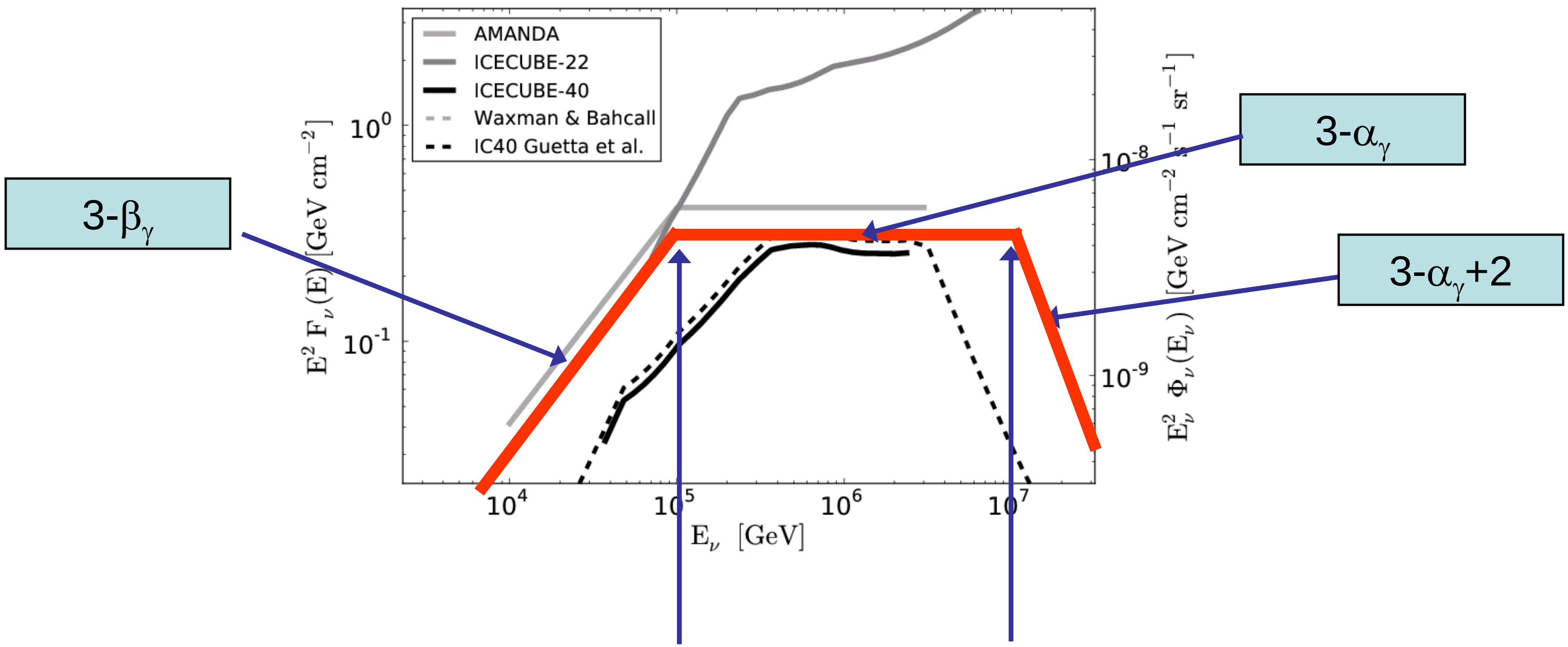
[in principle, $\lambda_{p\gamma} \sim 1/(n_\gamma\,\sigma)$; need estimates for n_γ, which contains the size of the acceleration region]

(Description in arXiv:0907.2227; see also Guetta et al, astro-ph/0302524; Waxman, Bahcall, astro-ph/9701231)

IceCube method ... spectral shape

- Example:

$$F_\gamma(E_\gamma) = \frac{\mathrm{d}N(E_\gamma)}{\mathrm{d}E_\gamma} = f_\gamma \times \begin{cases} \left(\frac{\epsilon_\gamma}{\mathrm{MeV}}\right)^{\alpha_\gamma} \left(\frac{E_\gamma}{\mathrm{MeV}}\right)^{-\alpha_\gamma} & \text{for } E_\gamma < \epsilon_\gamma \\ \left(\frac{\epsilon_\gamma}{\mathrm{MeV}}\right)^{\beta_\gamma} \left(\frac{E_\gamma}{\mathrm{MeV}}\right)^{-\beta_\gamma} & \text{for } E_\gamma \geq \epsilon_\gamma \end{cases}$$



First break from break in photon spectrum (here: $E^{-1} \Rightarrow E^{-2}$ in photons)

Second break from pion cooling (simplified)