The cosmic triad

Cosmic rays, gamma-rays and neutrinos

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ARENA Workshop 2012

June 22, Erlangen

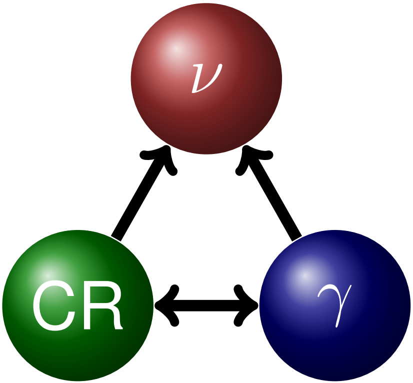
Multi-messenger paradigm

- Neutrino production is closely related to the production of cosmic rays (CRs) and γ-rays.
- Flux predictions are based on CR and γ-ray observation.
- Status summary:
  - ✘ No "surprises" yet.
  - ✔ Sensitivity has reached the level of "serious" models.

➜ Implications of neutrino limits on UHE CR sources:

Part I: Direct vs. indirect ν-limits

Part II: Cosmogenic ν's



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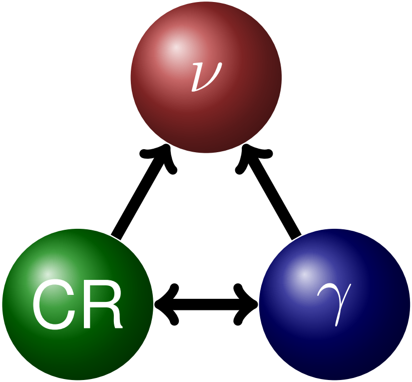

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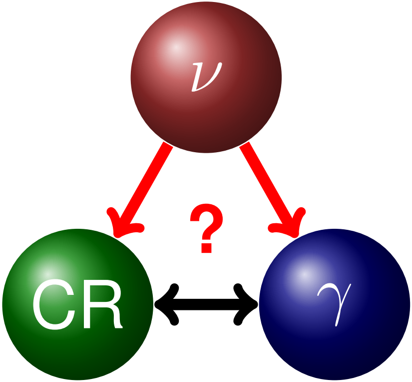
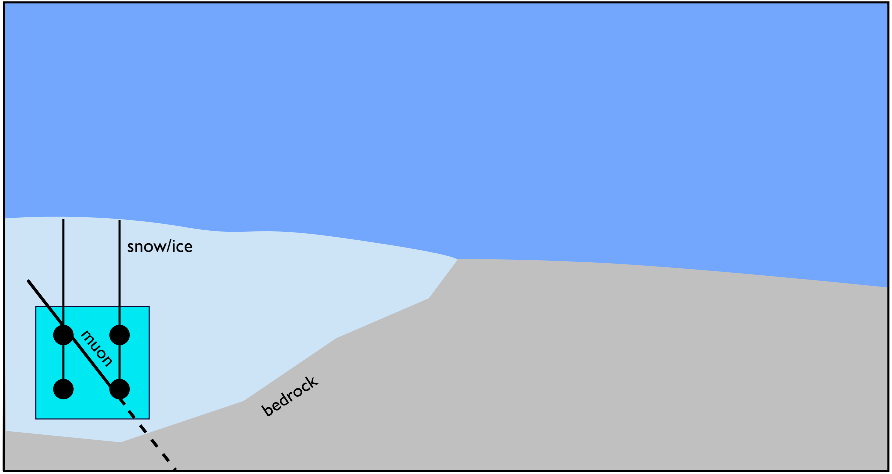


Neutrino observation at very high energies



Cherenkov radiation in transparent media (glaciers, lakes, oceans,. . .).

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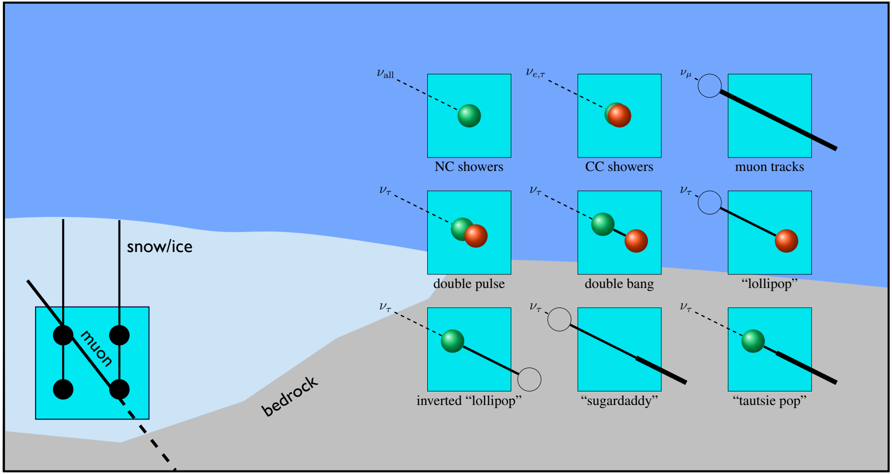

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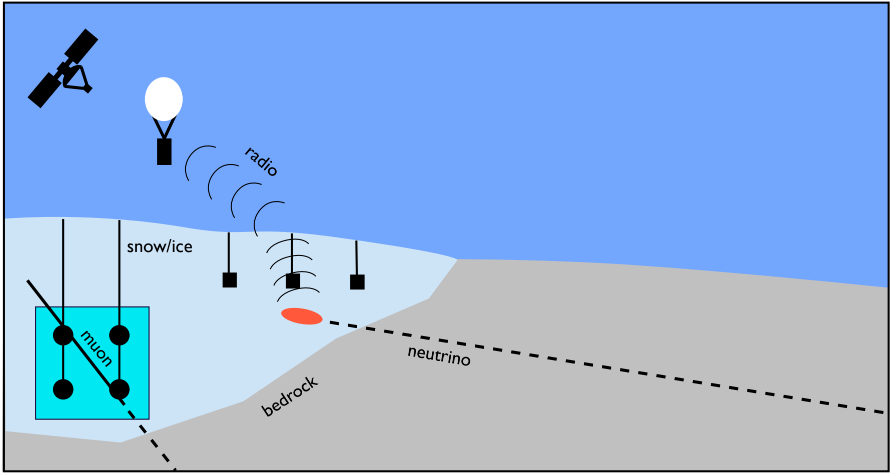
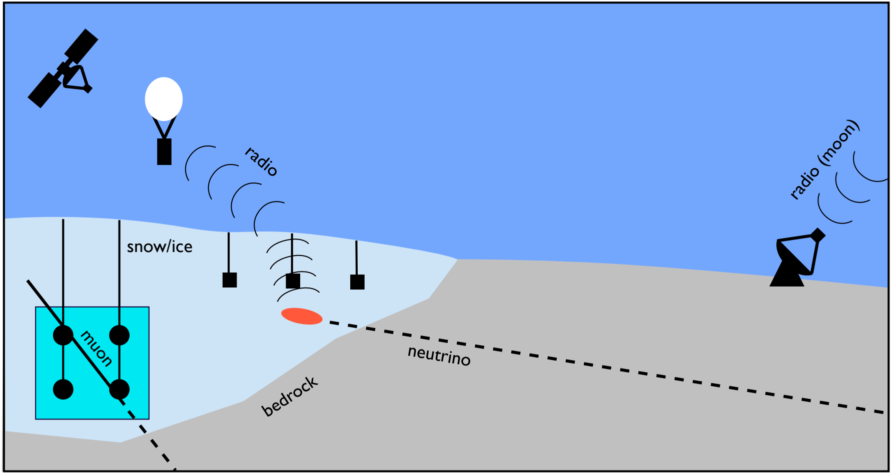


Coherent radio Cherenkov emission (Askaryan effect).
Observation in-situ, balloons or satellites.

Neutrino observation at very high energies



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Observation from lunar regolith.

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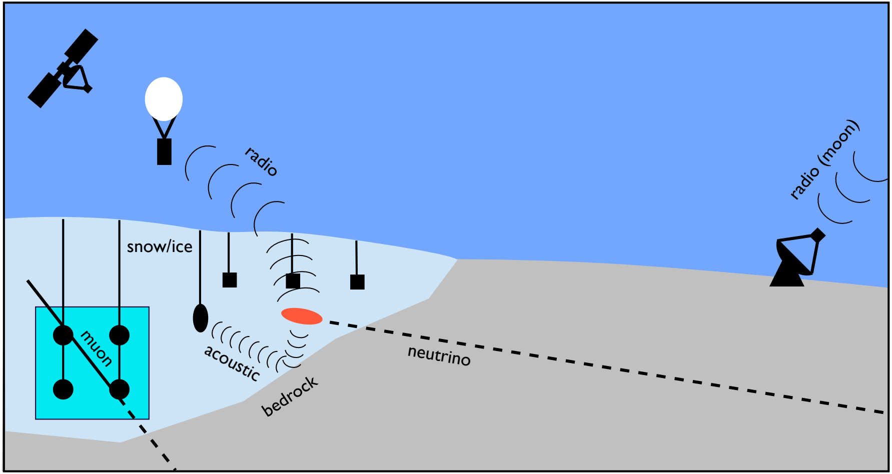
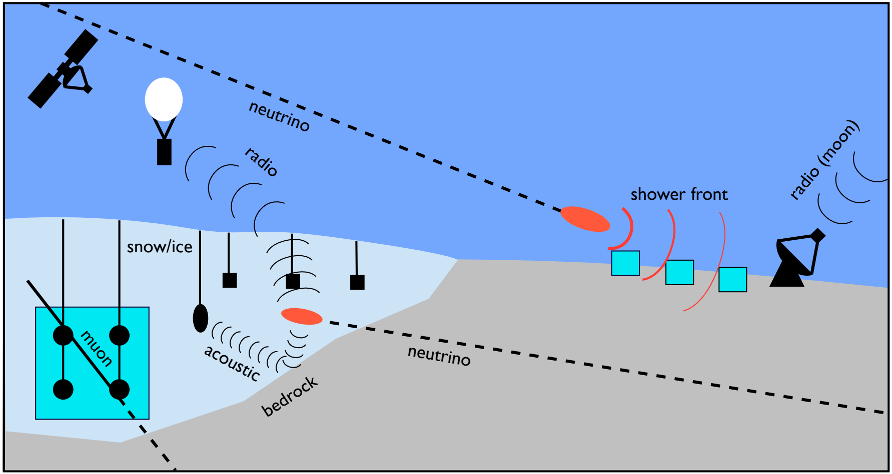


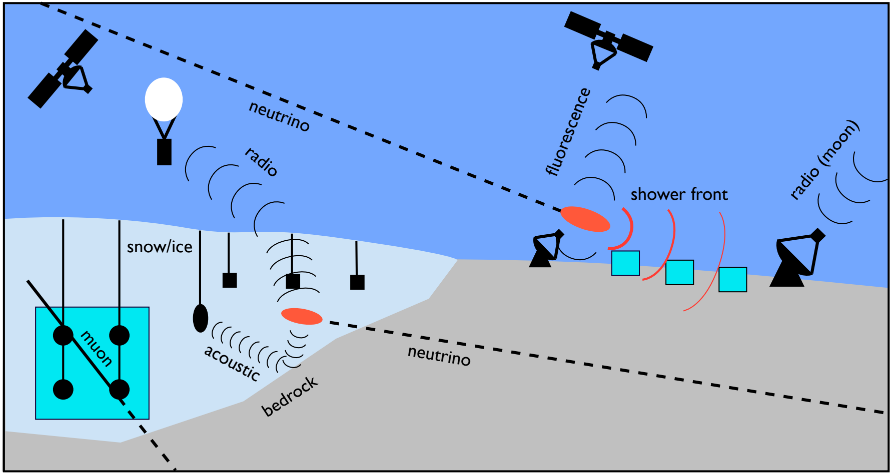
Acoustic detection?

Neutrino observation at very high energies



Deeply penetrating quasi-horizontal showers.
Observation by CR surface arrays.

Neutrino observation at very high energies



Observation by CR surface arrays and/or fluorescence detectors/satellites.

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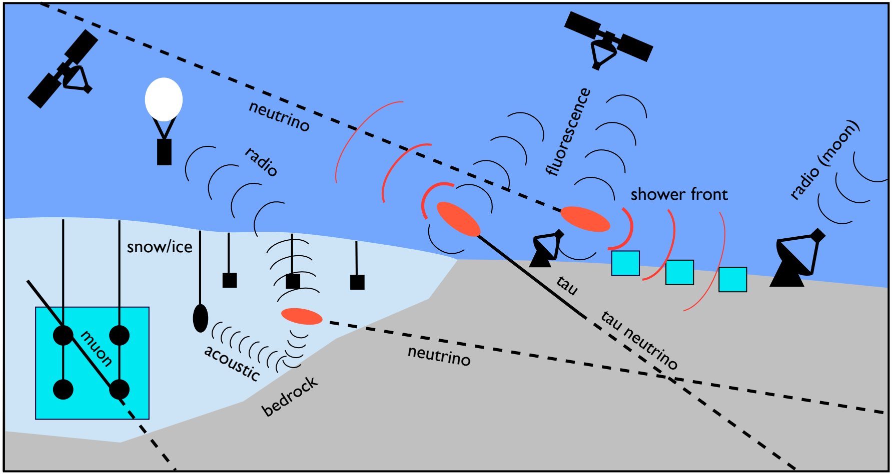
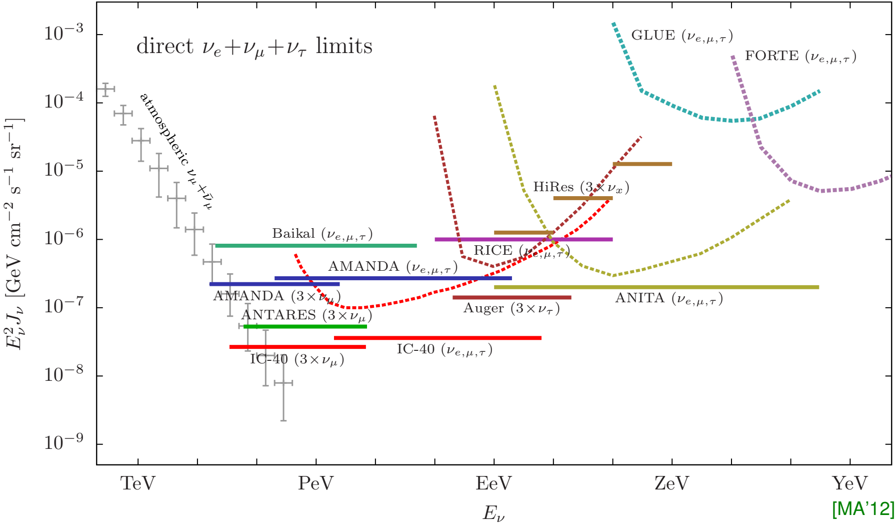


Earth-skimming tau neutrinos.

Diffuse neutrino limits



[MA'12]

Neutrino flux predictions

- pion production in CR interactions with ambient radiation

$$\pi^+ \to \mu^+\nu_\mu \to e^+\nu_e\bar{\nu}_\mu\nu_\mu$$
$$\pi^0 \to \gamma\gamma$$

- inelasticity:

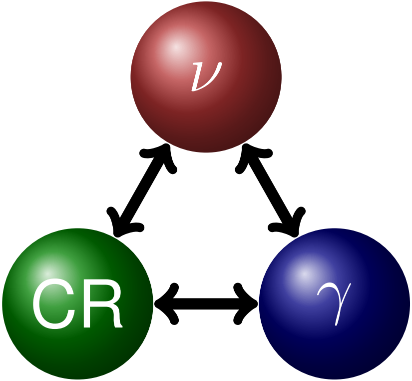
$$E_\nu \simeq E_\gamma/2 \simeq \kappa E_p/4$$

- relative multiplicity:

$$K = N_{\pi^\pm}/N_{\pi^0}$$

- pion fraction:

$$f_\pi \simeq 1 - e^{-\kappa\tau}$$



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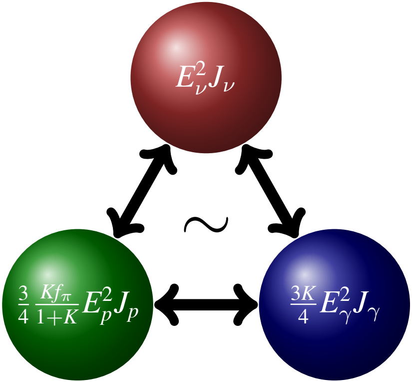

($E_\nu^2 J_\nu \sim$ energy density ω)

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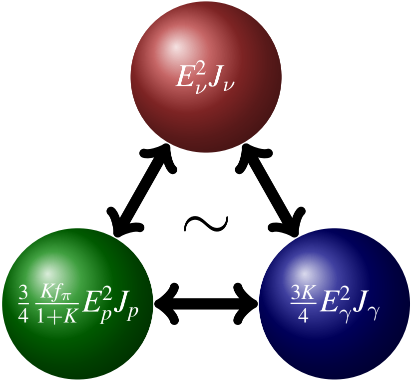
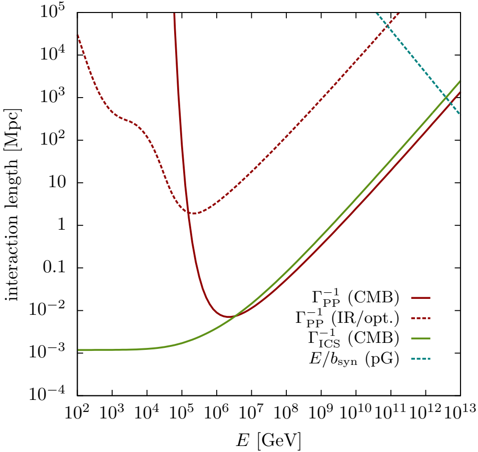


$$\omega_{\rm Fermi} \simeq 6 \times 10^{-7}\ {\rm eV/cm^3}$$
$$\omega_{\rm UHECR} \simeq 1 \times 10^{-7}\ {\rm eV/cm^3}$$
$$\omega_{\rm IC40} \lesssim 1 \times 10^{-7}\ {\rm eV/cm^3}$$

Gamma-ray cascades

- CMB interactions **(solid lines)** dominate in casade:
  - inverse Compton scattering (ICS)
    $e^\pm + \gamma_{\rm CMB} \to e^\pm + \gamma$
  - pair production (PP)
    $\gamma + \gamma_{\rm CMB} \to e^+ + e^-$
- PP in IR/optical background **(red dashed line)** determines the "edge" of the spectrum.
- this calculation:
  Franceschini *et al.* '08



Rapid cascade interactions produce universal GeV-TeV emission (almost) independent of injection spectrum and source distribution.
➜ **"cascade bound" for neutrinos** [Berezinsky&Smirnov'75]

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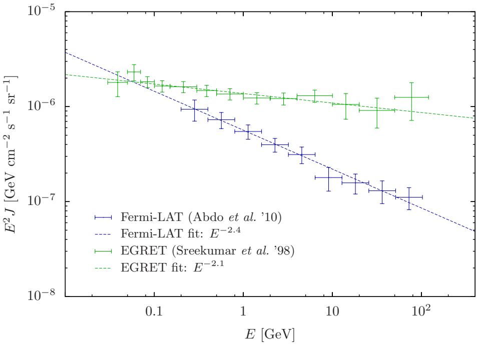
diffuse γ-ray background



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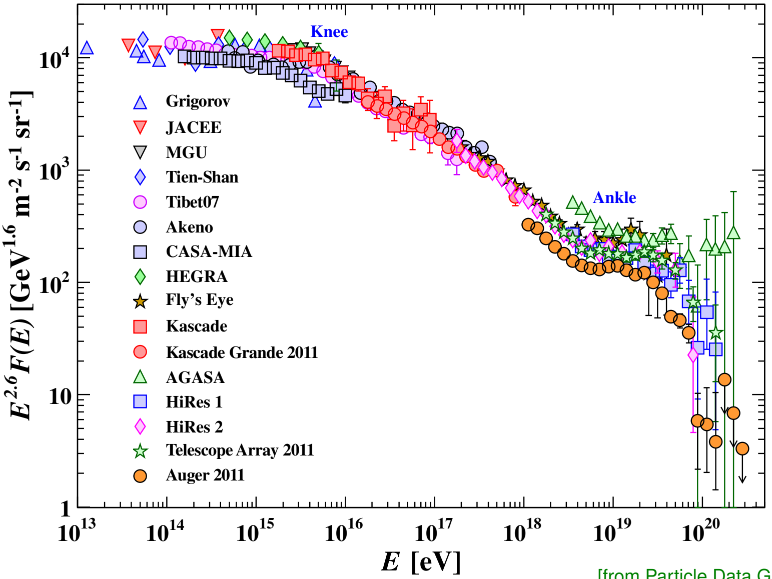
Cosmic ray spectrum



[from Particle Data Group'12]

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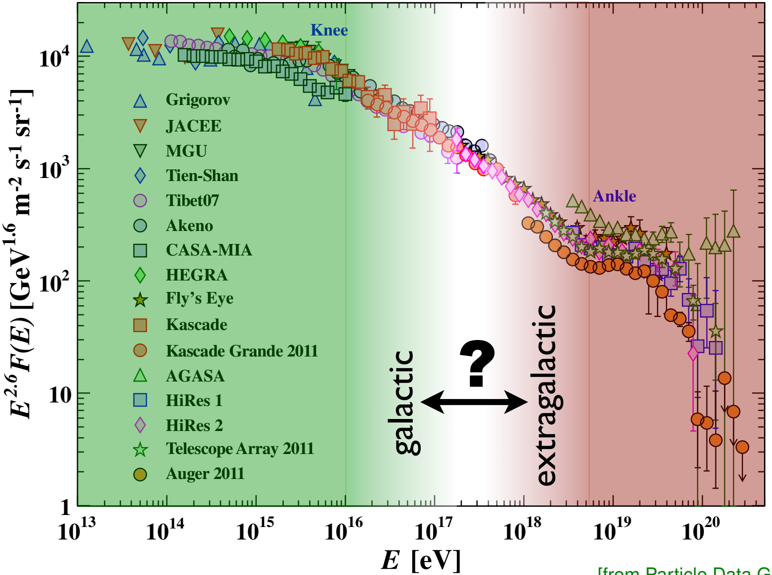

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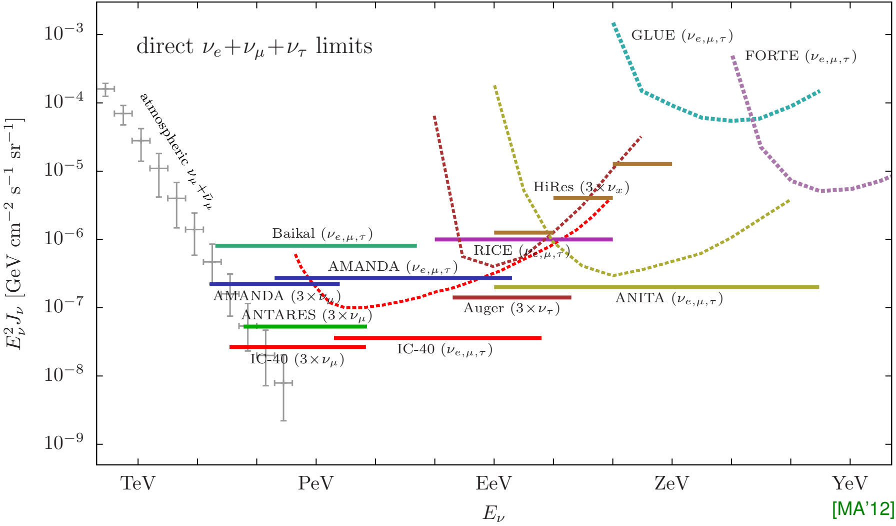

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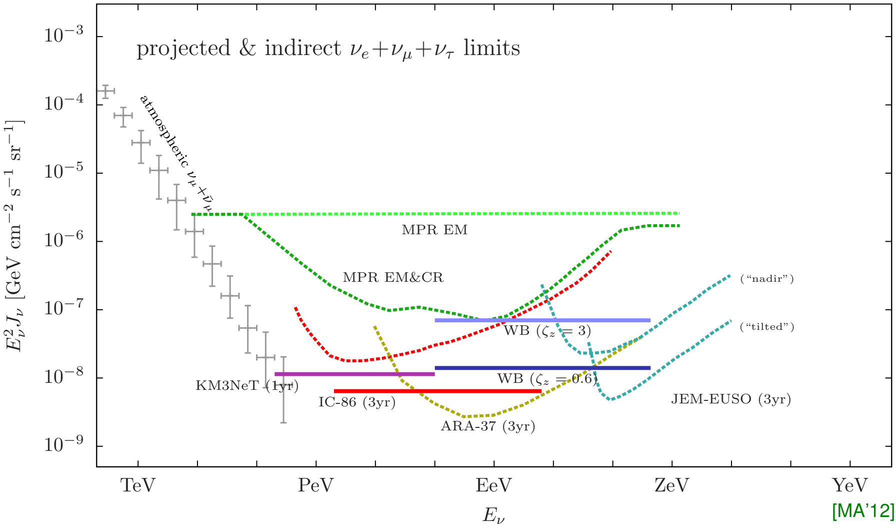


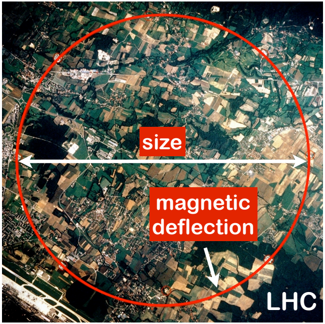
[MA'12]

Candidate sources

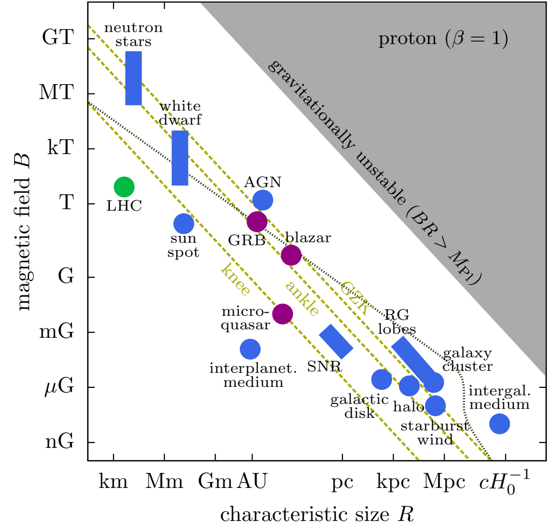
- CR acceleration is (most likely) a continuous process.

➜ Accelerators need to confine the particle by magnetic fields.

- $E_{\max} \sim$ size × field strength



Hillas plot



Conceivable neutrino fluxes

- Typical neutrino energy from $p\gamma$ interactions (in boosted environments):

$$E_p \simeq \frac{1}{40}\Gamma^2 \frac{m_\Delta^2 - m_p^2}{4\omega} \simeq 4\mathrm{PeV}\,\Gamma^2 \left(\frac{\mathrm{eV}}{\omega_{\mathrm{eV}}}\right)$$

  - *cosmogenic neutrinos* ($\Gamma = 1$ / $E_\gamma \simeq 10$ meV): $E_\nu \simeq 1$ EeV
    [Berezinsky&Zatsepin'69]
  - *prompt neutrino emission in GRBs* ($\Gamma \simeq 300$ / $E_\gamma \simeq 1$ MeV): $E_\nu \simeq 1$ PeV
    [Waxman&Bahcall'97]
  - *optical afterglow emission in GRBs* ($\Gamma \simeq 10$ / $E_\gamma \simeq 1$ eV): $E_\nu \simeq 1$ EeV
    [Waxman&Bahcall'00;Murase&Nagataki'06;Murase'07]
  - *external radiation in line-emitting blazars* ($\Gamma \simeq 10$ / $E_\gamma \simeq 0.1$ MeV): $E_\nu \simeq 10$ TeV
    [Atoyan&Dermer'01]
  - *UV emission from AGN disk* ($\Gamma \simeq 1$ / $E_\gamma \simeq 10$ eV): $E_\nu \simeq 1$ PeV
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- Neutrinos form pp interactions $E_\nu \lesssim 0.05E_p$ can dominate in dense environments:
  - *precursor neutrinos of GRBs*: $E_\nu \lesssim 100$ TeV
    [Razzaque/Meszaros/Waxman'03]
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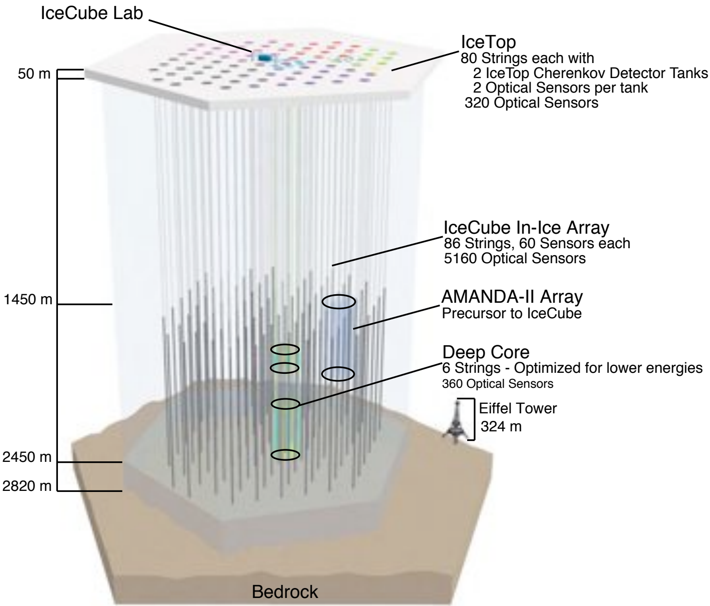
IceCube search for burst neutrinos



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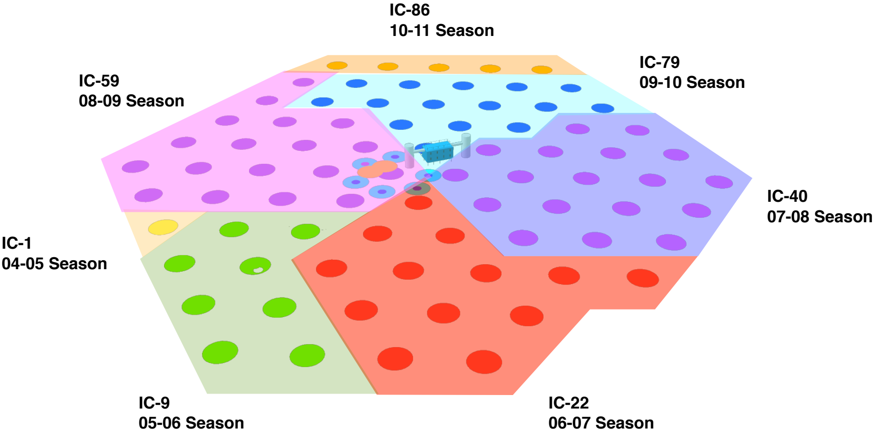


[courtesy of M. Santander]

IC40+59 results

- Limits on neutrino emission coincident with 215 (85) northern (southern) sky GRBs between April 2008 and May 2010 ("IC40+59"). [Abbasi *et al.*'11;'12]

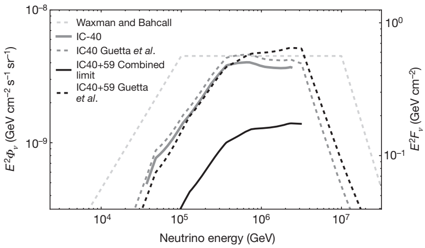
➜ **Model-dependent** limit for prompt emission model.

➜ **Model-independent** limit for general neutrino coincidences (no spectrum assumed) with sliding time window $\pm\Delta t$ from burst.

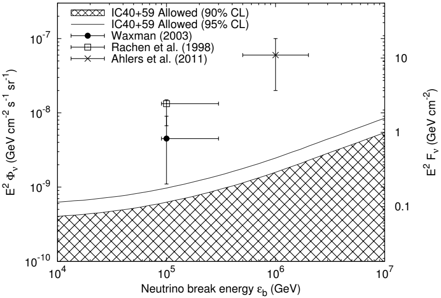
- **Stacked flux** below "benchmark" prediction of burst neutrino emission by a factor 3-4. [Guetta *et al.*'04]

- IceCube limit below **benchmark diffuse models** normalized to UHE CR data. [Waxman&Bahcall'03; Rachen *et al.*'98]

L_γ normalization



UHE CR normalization



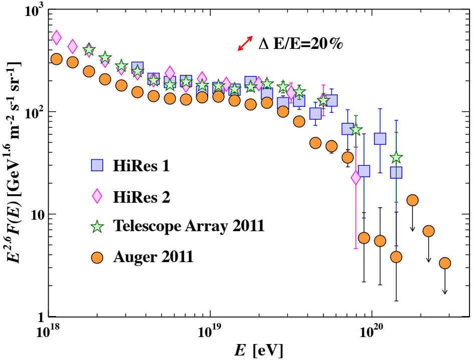
Cosmogenic neutrinos

- "Guaranteed" neutrino production from UHE CR propagation in cosmic radiation background. [Greisen&Zatsepin'66;Kuzmin'66;Berezinsky&Zatsepin'70]

➜ resonant proton interaction $p\gamma \to \Delta \to n\pi^+$ with CMB: $E_{\rm CR} < E_{\rm GZK} \simeq 40{\rm EeV}$

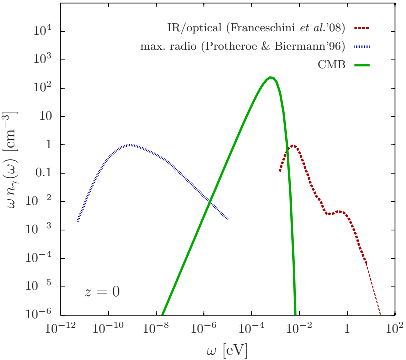
➜ peak neutrino contribution at $E_\nu \simeq 1{\rm EeV}$

UHE CR spectrum

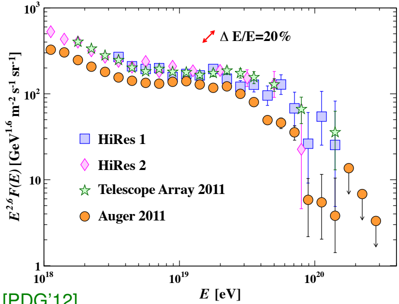


[Particle Data Group'12]

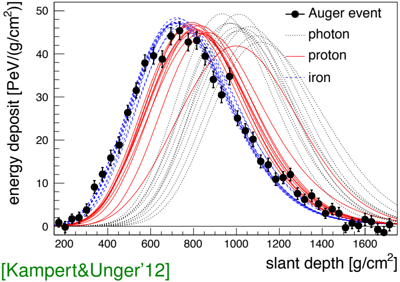
radiation background



UHE CR observation

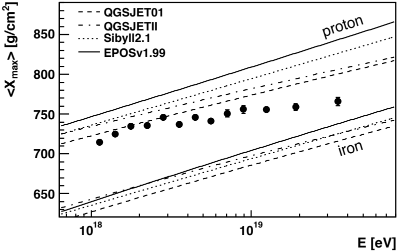


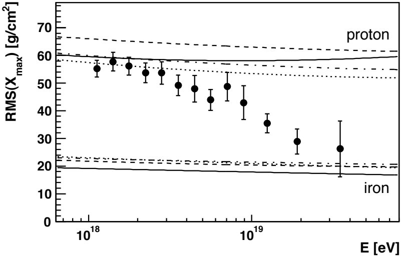
[PDG'12]



[Kampert&Unger'12]

Auger composition





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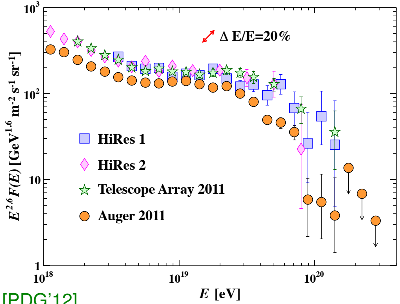
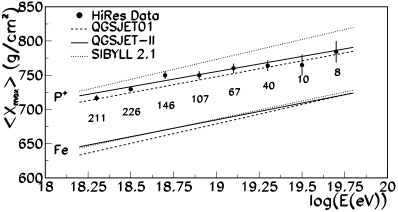
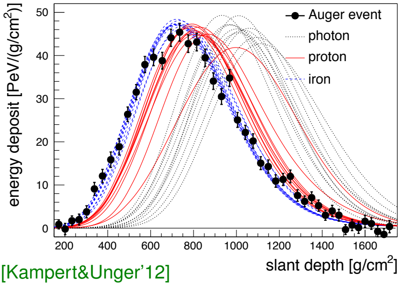


[PDG'12]

HiRes composition





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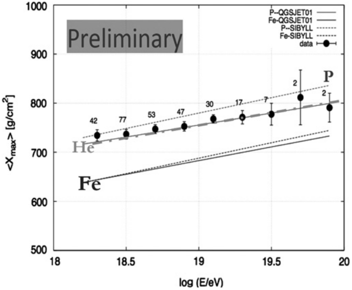
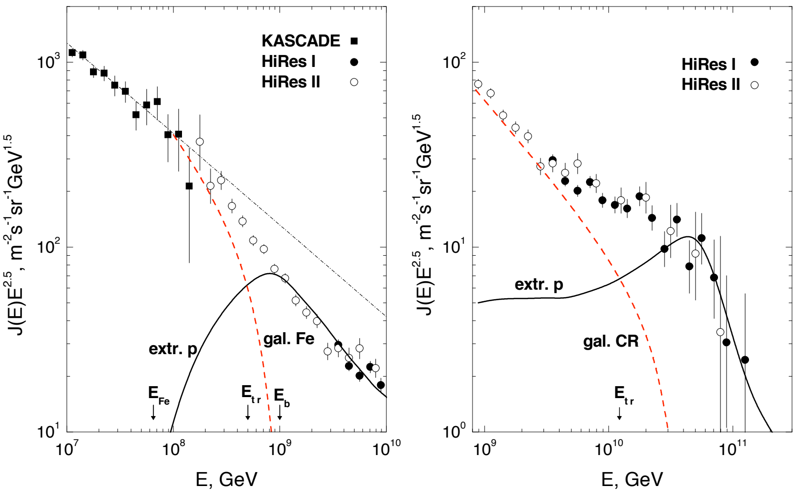


Galactic to extragalactic crossover

"dip-transition" vs. "ankle-transition"



[*e.g.* Aloisio *et al.*'06]

Diffuse CR fluxes

- **spatially homogeneous and isotropic** distribution of sources
- Boltzmann equation of comoving number density ($Y = n/(1+z)^3$):

$$\dot{Y}_i = \partial_E(HEY_i) + \partial_E(b_i Y_i) - \Gamma_i\, Y_i + \sum_j \int \mathrm{d}E_j\, \gamma_{ji} Y_j + \mathcal{L}_i\,,$$

H : Hubble rate
b_i : continuous energy loss
γ_{ji} (Γ_i) : differential (total) interaction rate

- **power-law** proton emission rate:

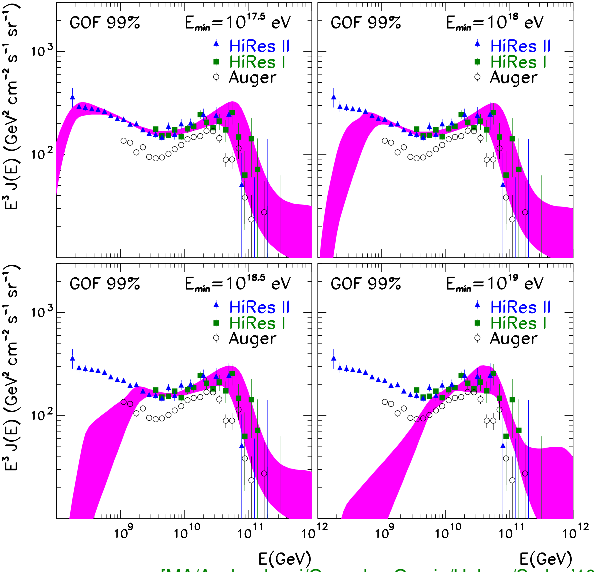
$$\mathcal{L}_p(0,E) \propto (E/E_0)^{-\gamma} \exp(-E/E_{\rm max}) \exp(-E_{\rm min}/E)$$

- **redshift evolution** of source emission or distribution:

$$\mathcal{L}_p(z,E) = \mathcal{L}_p(0,E)(1+z)^n \Theta(z_{\rm max} - z)\Theta(z - z_{\rm min})$$

Proton-dominance in UHE CRs?

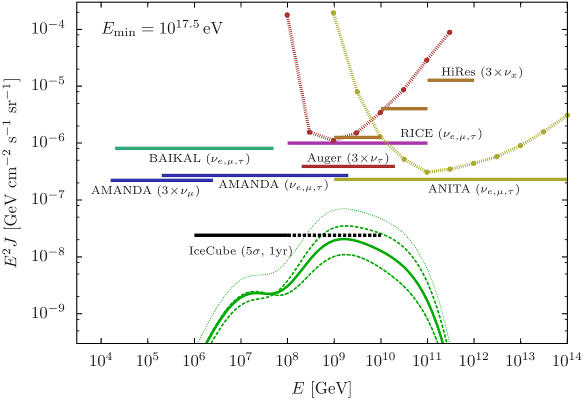
- GoF based on Hires-I/II data ($\Delta E/E \simeq 25\%$)
- *fixed:*
  $E_{\rm max} = 10^{21}$ eV
  $z_{\rm min} = 0$ / $z_{\rm max} = 2$
- *priors:*
  $2.1 \leq \gamma \leq 2.9$
  $2 \leq n \leq 6$
  $\omega_{\rm cas} \leq \omega_{\rm Fermi}$
- range of spectra: 99% C.L.
- increasing crossover energy from 2nd knee to ankle



[MA/Anchordoqui/Gonzalez-Garcia/Halzen/Sarkar'10]

Cosmogenic neutrinos from CR protons

- Cascade bound, $\omega_{\rm cas} \leq \omega_{\rm Fermi}$, reduces the cosmogenic neutrino flux **(dotted green line)** by a factor 2-4.
- Range of cosmogenic neutrino fluxes **(dashed green line)** increase along with the cross-over energy and lies within reach of present & future neutrino observatories.



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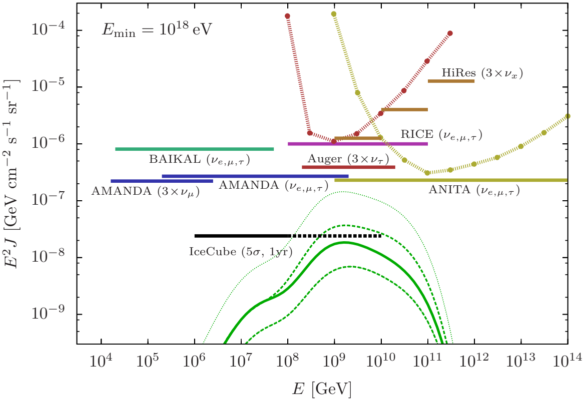

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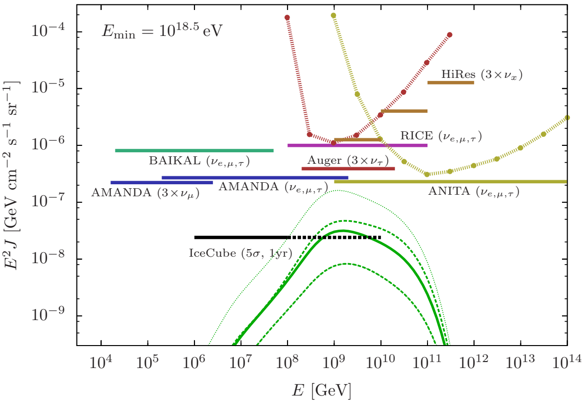
- Range of cosmogenic neutrino fluxes **(dashed green line)** increase along with the cross-over energy and lies within reach of present & future neutrino observatories.



Cosmogenic neutrinos

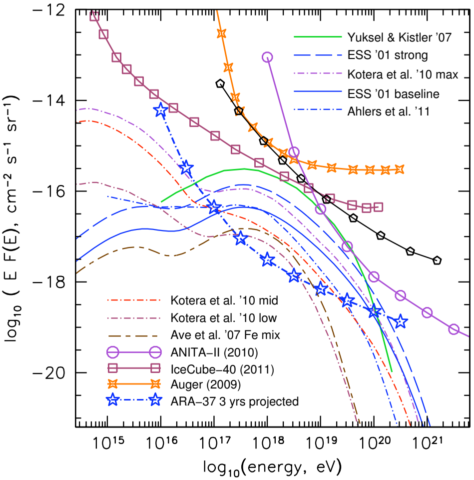


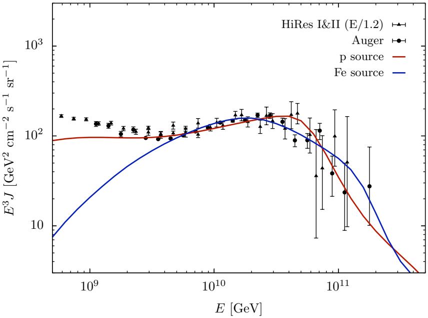
TABLE II: Expected numbers of events N_ν from several UHE neutrino models, comparing published values from the 2008 ANITA-II flight with predicted events for a three-year exposure for ARA-37.

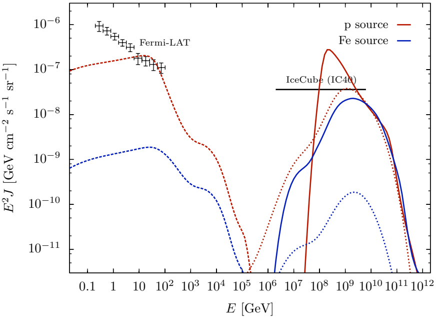
Model & references N_ν:	ANITA-II, (2008 flight)	ARA, 3 years
Baseline cosmogenic models:		
Protheroe & Johnson 1996 [27]	0.6	59
Engel, Seckel, Stanev 2001 [28]	0.33	47
Kotera,Allard, & Olinto 2010 [29]	0.5	59
Strong source evolution models:		
Engel, Seckel, Stanev 2001 [28]	1.0	148
Kalashev *et al.* 2002 [30]	5.8	146
Barger, Huber, & Marfatia 2006 [32]	3.5	154
Yuksel & Kistler 2007 [33]	1.7	221
Mixed-Iron-Composition:		
Ave *et al.* 2005 [34]	0.01	6.6
Stanev 2008 [35]	0.0002	1.5
Kotera, Allard, & Olinto 2010 [29] upper	0.08	11.3
Kotera, Allard, & Olinto 2010 [29] lower	0.005	4.1
Models constrained by Fermi cascade bound:		
Ahlers *et al.* 2010 [36]	0.09	20.7
Waxman-Bahcall (WB) fluxes:		
WB 1999, evolved sources [37]	1.5	76
WB 1999, standard [37]	0.5	27

[ARA'11]

Best-fit range of GZK neutrino predictions ($\sim$two orders of magnitude!) cover various evolution models and source compositions.

Composition dependence of UHE CR sources





- UHE CR emission toy-model:
  - 100% proton: $n = 5$ & $z_{\max} = 2$ & $\gamma = 2.3$ & $E_{\max} = 10^{20.5}$ eV
  - 100% iron: $n = 0$ & $z_{\max} = 2$ & $\gamma = 2.3$ & $E_{\max} = 26 \times 10^{20.5}$ eV
- Diffuse spectra of cosmogenic γ-rays (dashed lines) and neutrinos (dotted lines) **vastly different**. [MA&Salvado'11]

Propagation of CR nuclei

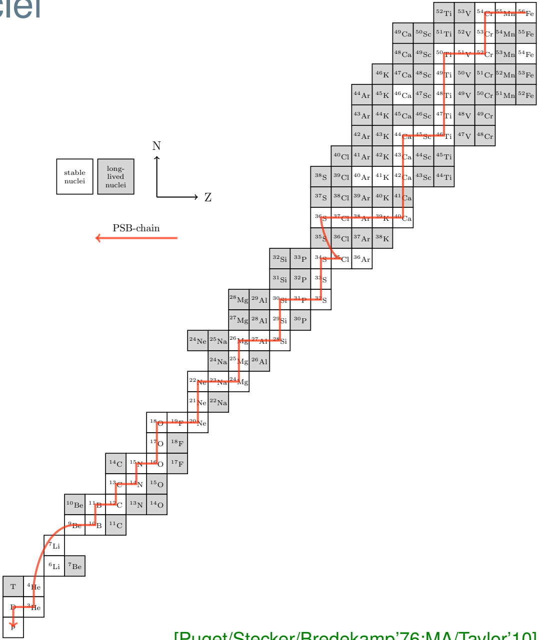
- fast photo-disintegration of nuclei (mass number $A = N + Z$) beyond the giant dipole resonance (GDR):

$$\lambda_{\rm GDR} \sim \frac{4}{A}\,\text{Mpc}$$

✘ strong influence of mass composition at very high energy

➜ BUT: **conserves total number of nucleons** with nucleon energy E/A!

➜ **Neutrino production (mostly) via γ-nucleon interaction!**



[Puget/Stecker/Bredekamp'76;MA/Taylor'10]

Approximate* scaling law of energy densities

$$\omega_\nu \propto \underbrace{\sum_i A_i^{2-\gamma_i}\frac{E_{\rm th}^2 \mathcal{Q}_i(E_{\rm th})}{2-\gamma_i}}_{\text{composition}} \times \underbrace{\int_0^{z_{\rm max}} {\rm d}z \frac{(1+z)^{n+\gamma_i-4}}{H(z)}}_{\text{evolution}}$$

* **disclaimer**:

- source composition $\mathcal{Q}_i$ with mass number A_i and index γ_i
- applies only to models with large rigidity cutoff $E_{{\rm max},i} \gg A_i \times E_{\rm GZK}$

previous examples ($z_{\rm max} = 2$ & $\gamma = 2.3$):

- 100% proton: $n = 5$ & $E_{\rm max} = 10^{20.5}$ eV
  $\omega_\gamma \propto 1 \times 12$
- 100% iron: $n = 0$ & $E_{\rm max} = 26 \times 10^{20.5}$ eV
  $\omega_\gamma \propto 0.27 \times 0.5$

✔ **relative difference:** ~ 82.

Nucleon Cascade

- Observed composition is result of source composition and nucleon cascades.
- **Backtracking** conserves energy per nucleon.

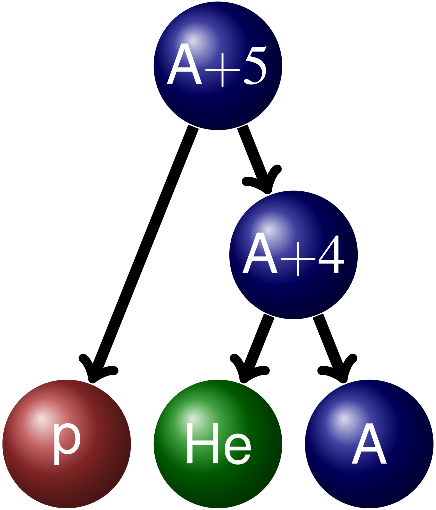
✘ Bethe-Heitler (BH) loss breaks this approximation

$$b_{A,\mathrm{BH}}(E) \simeq Z^2 \times b_{p,\mathrm{BH}}(E/A)$$

➜ **Minimal cosmogenic neutrino** production from fit to Auger data assuming:

- **maximal** backtracking
- **minimal** BH loss

➜ **minimal** nucleon emissivity



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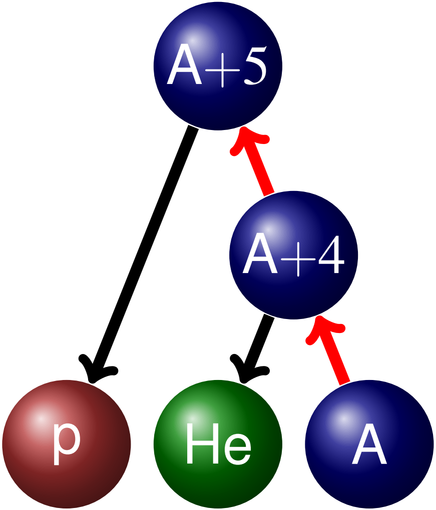


Guaranteed cosmogenic neutrinos

➜ nucleon spectrum for observed mass number $A_{\rm obs}$:

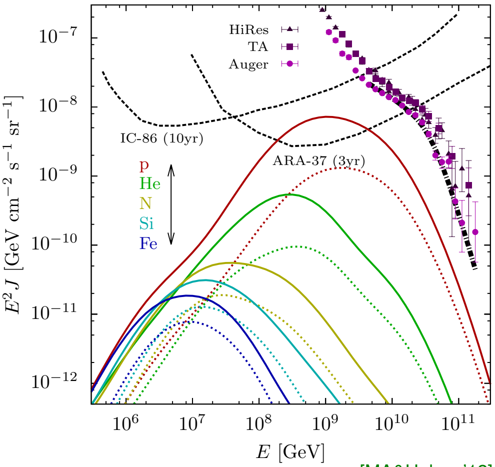
$$J_N^{\rm min}(E_N) = A_{\rm obs}^2 J_{\rm CR}(A_{\rm obs}E_N)$$

- dependence on cosmic evolution of sources:
  - no evolution (dotted)
  - star-formation rate (solid)

➜ **ultimate test** of UHE CR proton models with **ARA-37**

➜ generalization to arbitrary composition via

$$J_N^{\rm min}(E_N) = \sum_i f_i(A_iE_N)A_i^2 J_{\rm CR}(A_iE_N)$$



[MA&Halzen'12]

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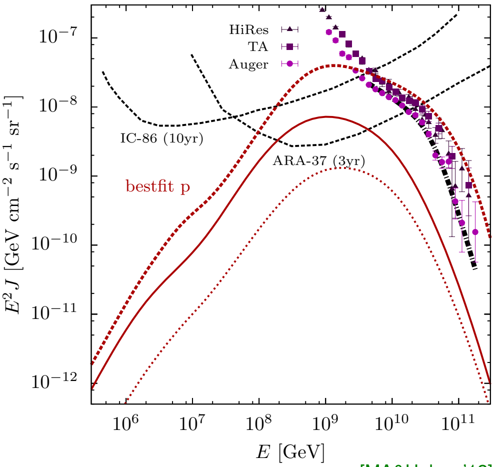

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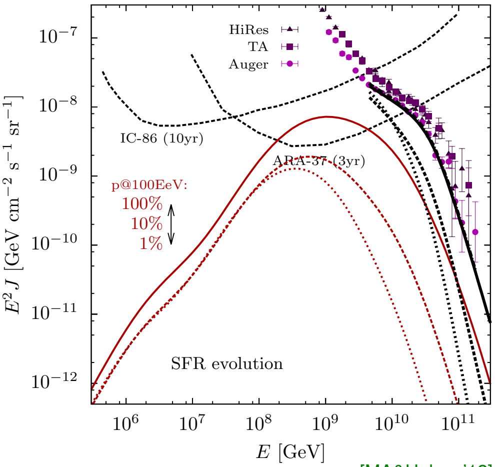

[MA&Halzen'12]

Summary

- ✔ Neutrino (non-)observatories have reached a sensitivity to **constrain** multi-messenger signals – γ-rays and UHE CRs – with “minimal” assumptions.
- ✘ **No surprises yet:** very high energy neutrino sky is dark.
- ➜ Neutrino “diagnostics” of UHE CR models; most effectively at PeV energies
- Present neutrino limits challenge GRBs as the sources of UHE CRs; standard (“benchmark”) diffuse GRB neutrino predictions are ruled out by the IC40+59 results.
- ✔ IceCube also in reach of EeV cosmogenic neutrino flux predictions from proton-dominated CR models.
- ➜ Definite test of proton-dominated CR models with future extensions ARA or ARIANNA.

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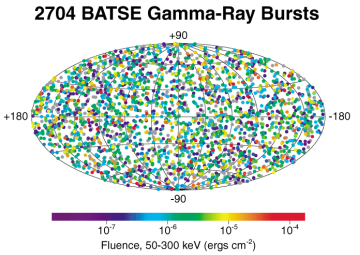
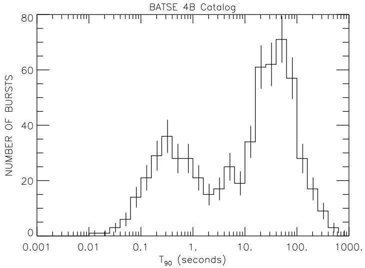
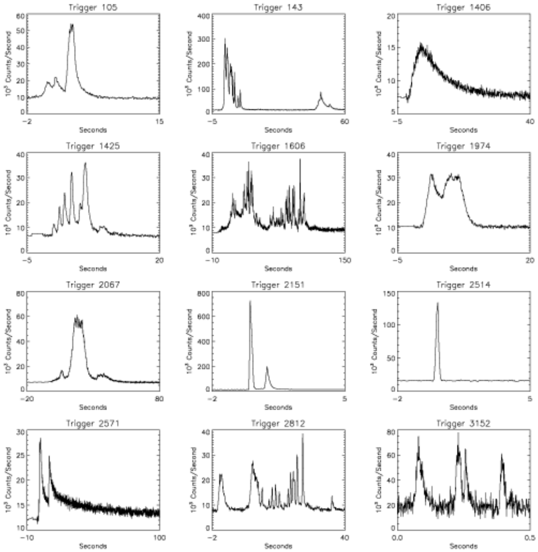
Thank you for your attention!

Appendix

Gamma-ray bursts (GRBs)







Gamma-ray bursts & UHE CRs

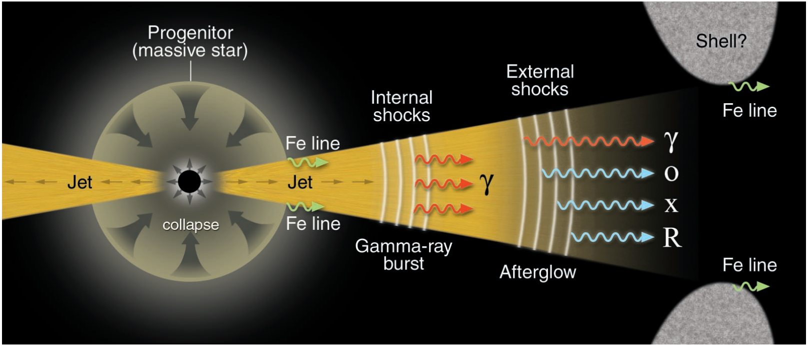
- possible sources of UHE CRs:
  - ✔ comparable **energy density**: $10^{53}\,\mathrm{erg}\,\mathrm{t_{Hubble}}^{-3}\,\mathrm{day}^{-1} \simeq 10^{44}\,\mathrm{erg}\,\mathrm{Mpc}^{-3}\,\mathrm{yr}^{-1}$
  - ✔ fulfill necessary conditions on time-scales (dynamical, cooling, acceleration) to reach **ultra-high energies** [Hillas'84]
  - ✔ acceleration of UHE CRs possible, *e.g.*, in **internal or external reverse shocks** [Vietri'95;Waxman'95]

➜ *smoking gun signal*: **neutrino production**

- Neutrino emission of GRBs is one of the best-tested models: [IceCube, Nature'12]
  - ✔ **cosmological sources** ("one per day and 4π")
  - ✔ **wealth of data** from Swift and Fermi
  - ✔ good information on **timing and location** (➜ background reduction)

GRB neutrino emission

- Neutrino production at various stages of GRB, *e.g.*
  - ➜ **precursor** pp and $p\gamma$ interactions in stellar envelope; also possible for "failed" GRBs [Razzaque,Meszaros&Waxman'03]
  - ➜ **burst** $p\gamma$ interactions in internal shocks [Waxman&Bahcall'97]
  - ➜ **afterglow** $p\gamma$ interactions in reverse external shocks [Waxman&Bahcall'00;Murase&Nagataki'06;Murase'07]



[Meszaros'01]

Burst neutrino emission

- neutrinos from meson production, *e.g.*

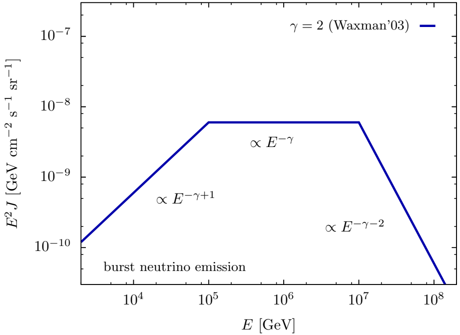
$$\pi^+ \to \mu^+ \nu_\mu \to e^+ \nu_e \bar{\nu}_\mu \nu_\mu$$

- spectra shaped by burst and proton spectrum and synchrotron loss of pions and muons before decay

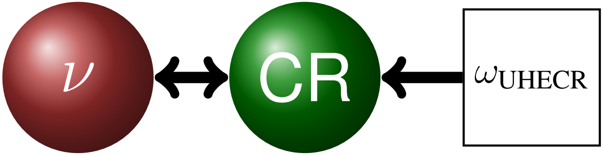
[Waxman & Bahcall'97]

- for typical burst spectra this c s a "plateau" of neutrinos

$$100\,\mathrm{TeV} \lesssim E_\nu \lesssim 10\,\mathrm{PeV}$$



➜ **Different models for absolut normalization:**



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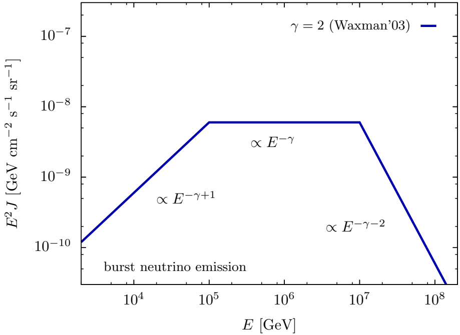

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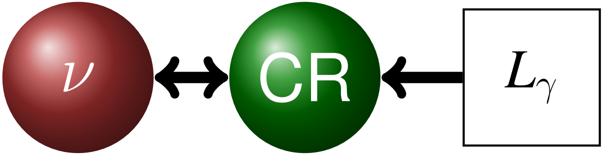


Neutrino production from $p\gamma$

- internal photon spectrum inferred from observed luminosity (L_γ)

$$\frac{L_\gamma}{4\pi} \underbrace{\frac{1}{r_{\rm dis}^2 \Gamma^2}}_{\text{inferred/modeled}} \simeq \int {\rm d}\epsilon\, \epsilon\, n_\gamma(\epsilon)$$

- opacity of $p\gamma$ collision ($\epsilon_{\rm min} = (m_\Delta^2 - m_p^2)/4E_p$)

$$\tau_{p\gamma}(E_p) = \frac{t_{\rm dyn}}{t_{p\gamma}(E_p)} \simeq t_{\rm dyn} \underbrace{\left(\frac{\pi}{2} \frac{\Gamma_\Delta \sigma_0 m_\Delta^3}{m_\Delta^2 - m_p^2}\right)}_{0.04} \frac{m_p^2}{{E_p}^2} \int_{\epsilon_{\rm min}} \frac{{\rm d}\epsilon}{\epsilon^2} n_\gamma(\epsilon)$$

- pion to proton spectrum with inelasticity $\kappa \simeq 0.2$

$$E_\pi^2 J_\pi(E_\pi) \simeq \underbrace{\left(1 - e^{-\kappa \tau_{p\gamma}(E_p)}\right)}_{f_\pi(E_p)} E_p^2 J_p(E_p)$$

- final neutrino spectra after meson/muon **cooling in magnetic fields**

GRB flux normalization

- Neutrino predictions depend on model and normalization:

A GRB as **the** source of UHE CRs?

→ calculate the pion energy fraction f_π in $p\gamma$ interactions
→ normalize to UHE CRs [Waxman & Bahcall'97]

A' GRB as **the** source of UHE CR neutrons?

→ independent of f_π
→ normalize to UHE CRs [Rachen & Mészáros'98; MA, Gonzalez-Garcia & Halzen'11]

B GRB as **one** source of (UHE) CRs?

→ use bolometric energy arguments about internal energy densities U in shock

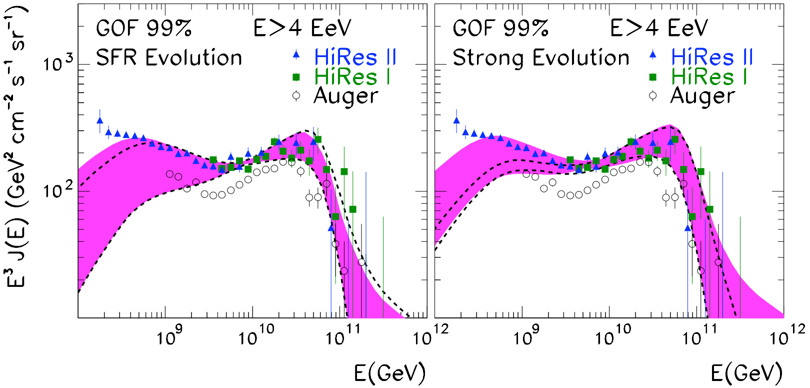
$$U_B = \epsilon_B U_{\rm tot} \qquad U_e = \epsilon_e U_{\rm tot} \qquad U_p = \epsilon_p U_{\rm tot}$$

→ by construction, $\epsilon_B + \epsilon_e + \epsilon_p \lesssim 1$, but otherwise **not well constrained**
→ calculate the pion energy fraction f_π in $p\gamma$ interactions
→ normalize to CRs in individual bursts, $U_p = (\epsilon_p/\epsilon_e)U_{\rm burst}$ [Guetta *et al.*'04;He *et al.*'12]

GRB model-dependence

- The parameters Γ_i, ϵ_p and ϵ_e are in general fudge-factors; some indirect observation by GRB afterglow emission.
- Model hierarchy: "**A ➜ B**" or "**not B ➜ not A**"
- Heavy nuclei acceleration in internal shocks?
  - issues for model **A**; large internal shock radii and/or large Lorentz factors needed to reach UHEs [Wang,Razzaque&Meszaros'08;Murase *et al.*'08]
  - generally lower neutrino luminosity due to limited photon density
- Diffuse limits have also dependence on the stochasticity of the tested GRB ensemble. [Baerwald,Hümmer&Winter'11]
- Revised calculations of pion fraction f_π produce *lower values* than the standard parametrization [Li'11; Baerwald,Hümmer&Winter'11;He *et al.*'12]
- CR production via neutron emission (model **A'**) relates neutrinos and CR protons *independent* of the absolute value f_π; scenario largely ruled out by IC40+59. [MA/Gonzalez-Garcia/Halzen'11]

Neutron emission (model **A'**)



- fit of spectrum to HiRes data above ankle: $\mathcal{L}(0,E) \propto E^{-\gamma}/(1+(E_{\rm p,b}/E))e^{-E/E_{\rm max}}$
- "SFR" : evolution following star formation rate [Hopkins&Beacom'06;Yuksel *et al.*'08]
- "strong" : $\mathcal{L}_{\rm strong}(z,E) = (1+z)^{1.4}\,\mathcal{L}_{\rm SFR}(z,E)$ [Yuksel&Kistler'06]

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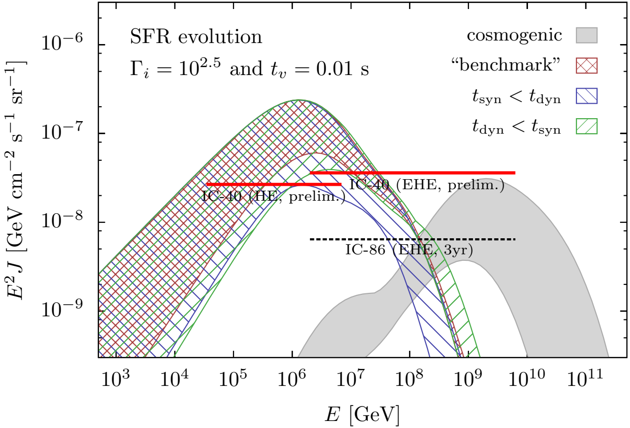

- **model A'** hypothesis: UHE CRs production in GRBs via **neutron emission**
- scan over luminosity range $0.1 < (\varepsilon_B/\varepsilon_e)L_{\gamma,52} < 10$

➜ fit requires softer injection spectra

[MA/Gonzalez-Garcia/Halzen'11]

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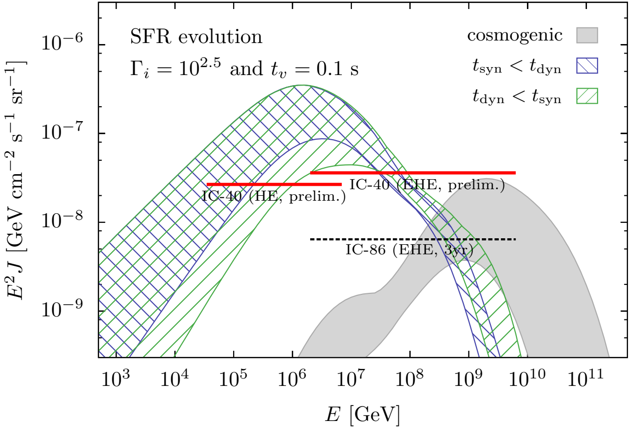

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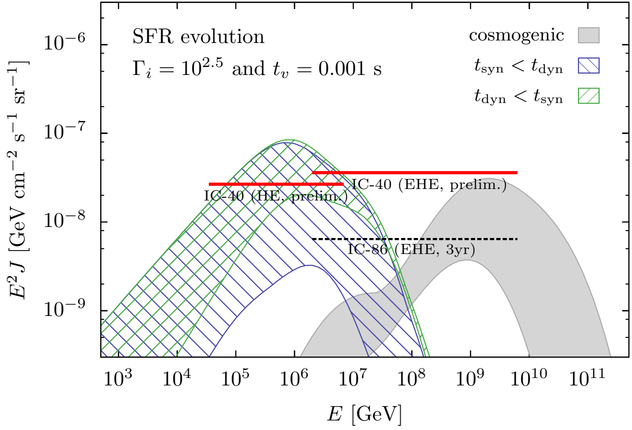

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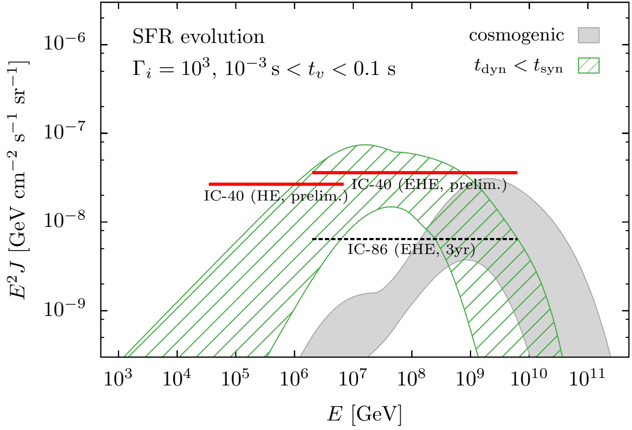

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