GRBs at Neutrino Telescopes

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UW-Madison

Gamma-Ray Burst 2012 Conference
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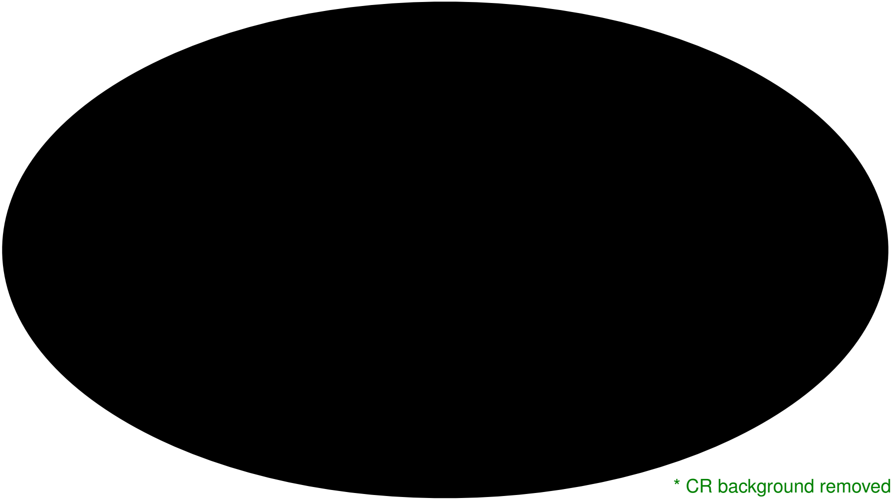
Neutrino sky map* at very high energies

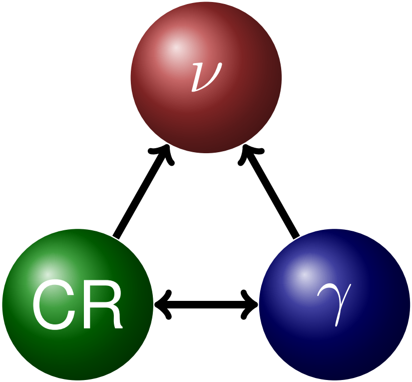


* CR background removed

Multi-messenger paradigm

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

➜ Implications of neutrino limits on multi-messenger production, *e.g.* in **Gamma-ray Bursts**.



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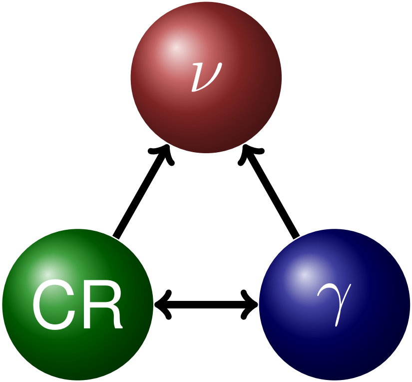

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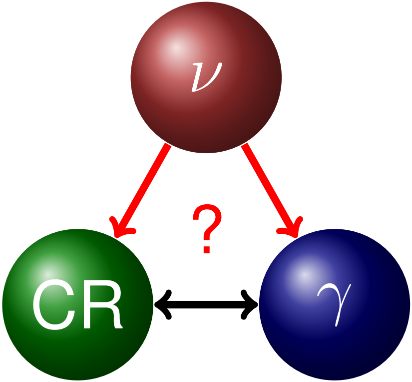
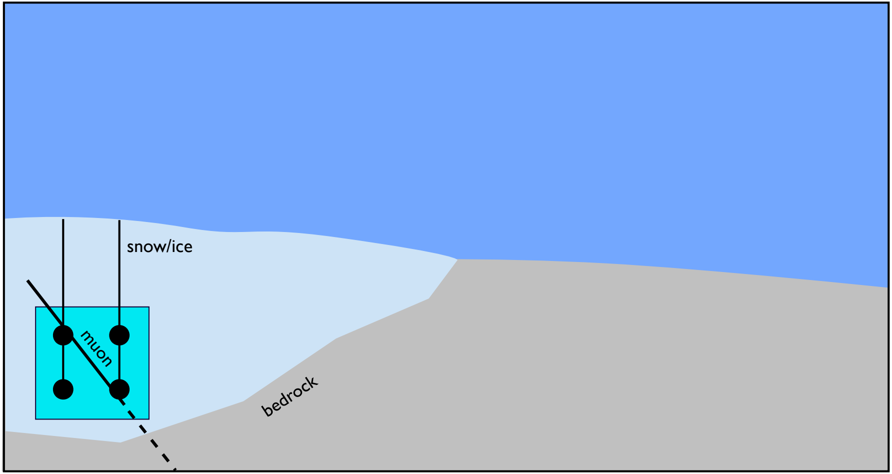


Neutrino observation at very high energies



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

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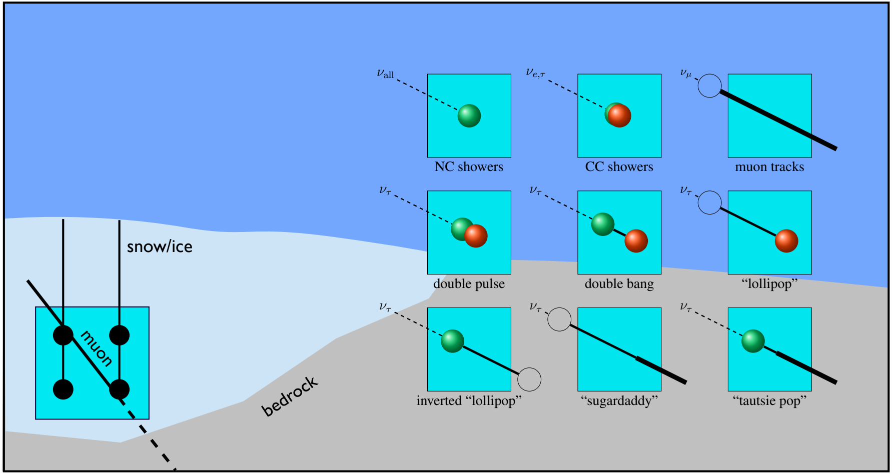

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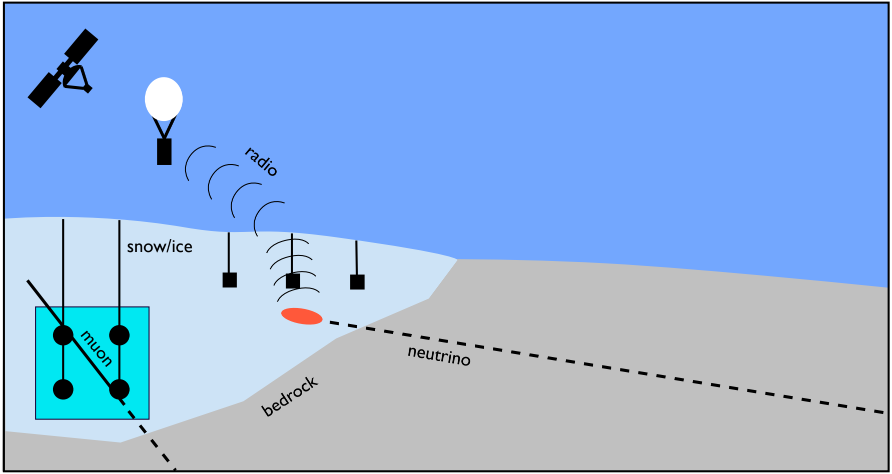
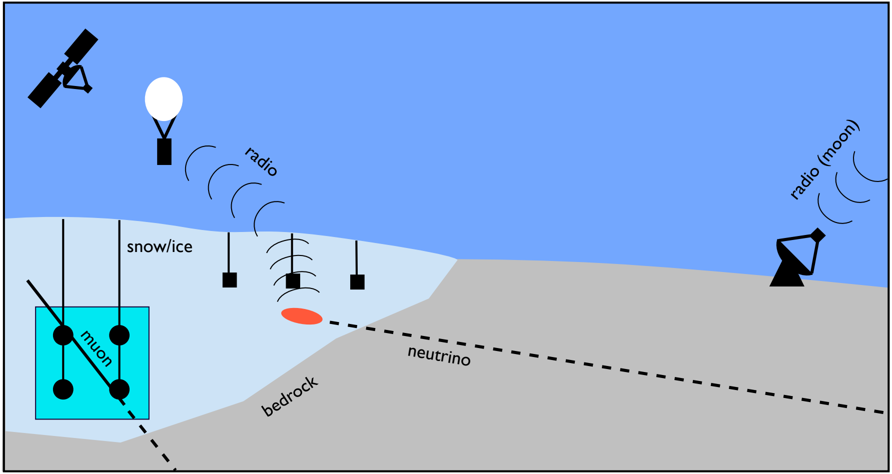


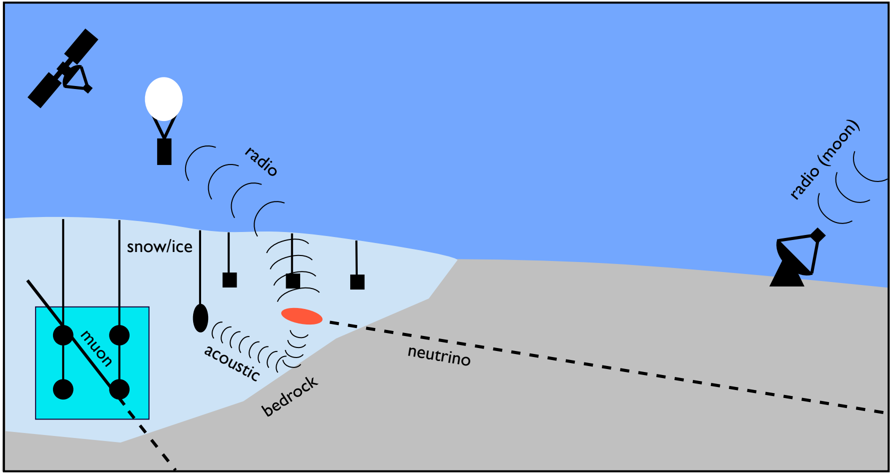
Coherent radio Cherenkov emission (Askaryan effect).
Observation in-situ, balloons or satellites.

Neutrino observation at very high energies



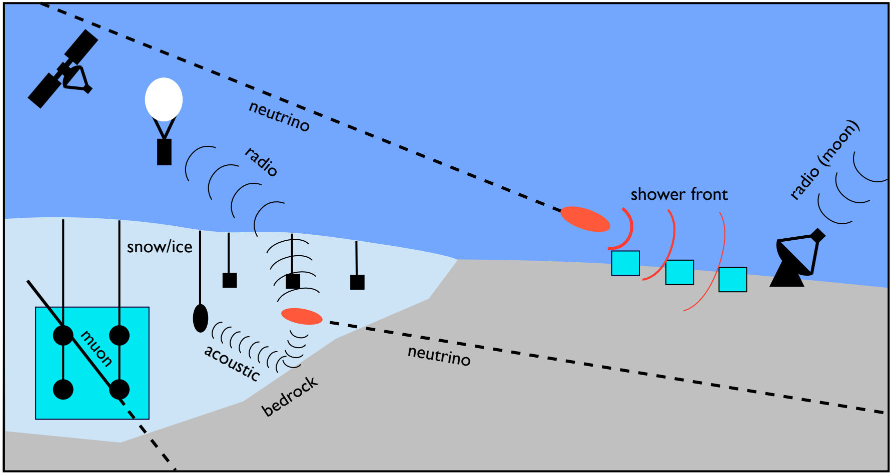
Coherent radio Cherenkov emission (Askaryan effect).
Observation from lunar regolith.

Neutrino observation at very high energies



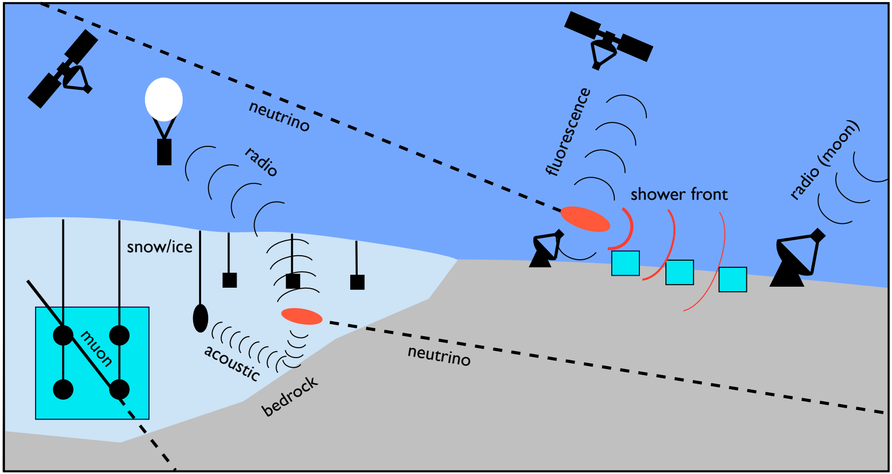
Acoustic detection?

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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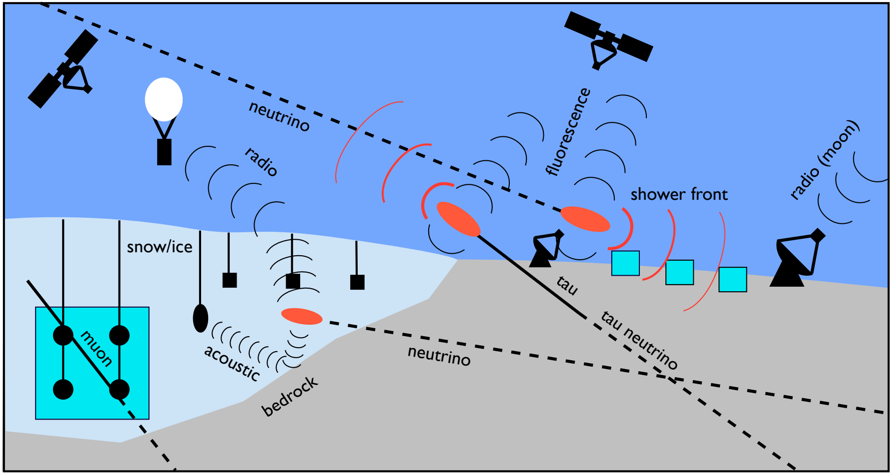
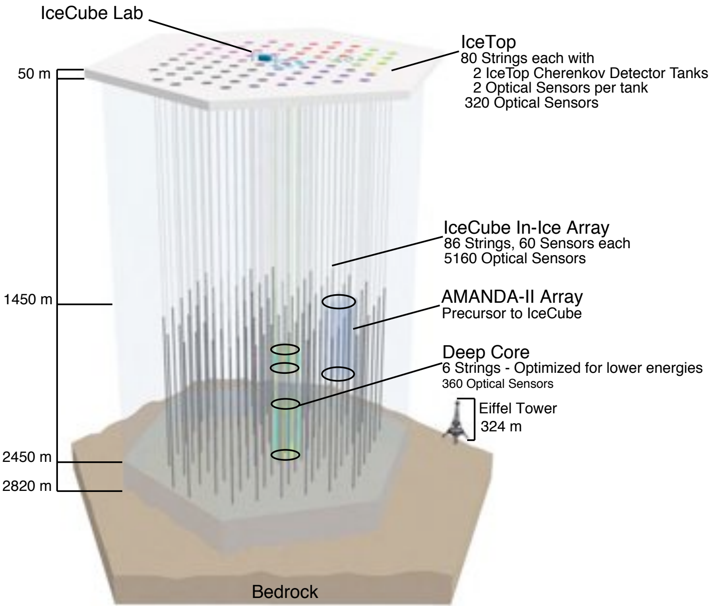


Earth-skimming tau neutrinos.

IceCube in Depth



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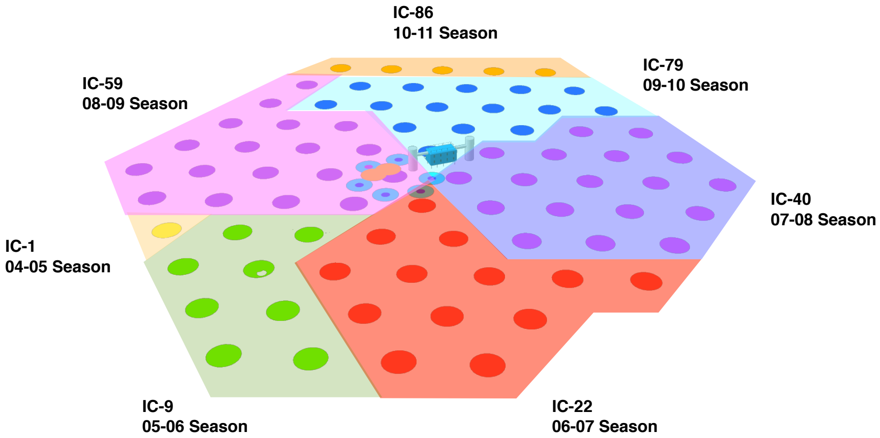
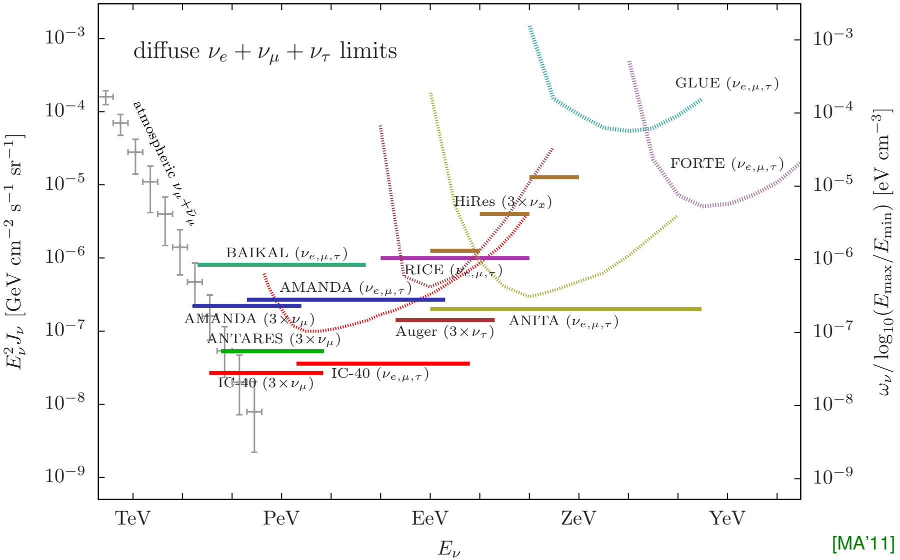


[courtesy of M. Santander]

Neutrino limits at very high energies



[MA'11]

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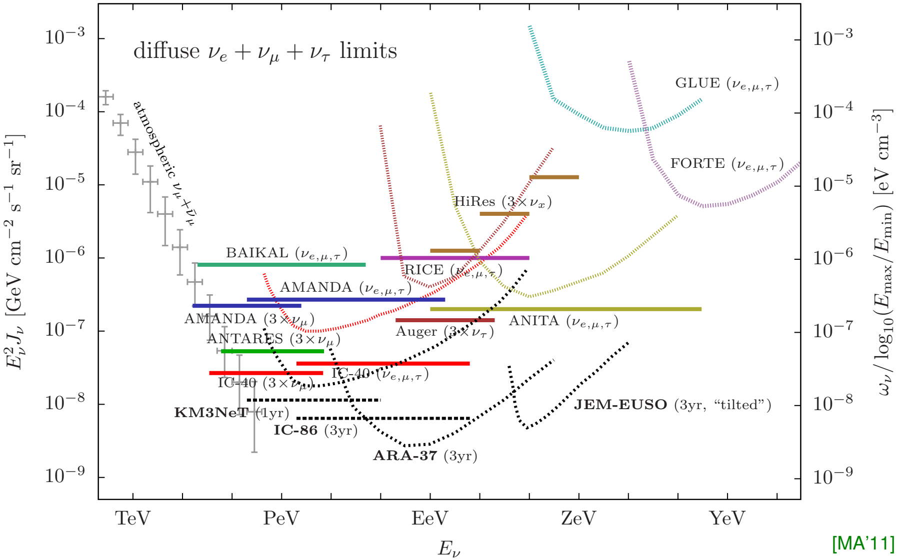


[MA'11]

How dark is the neutrino sky?

- pion production in CR interactions with ambient **gas and radiation**

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

- inelasticity:

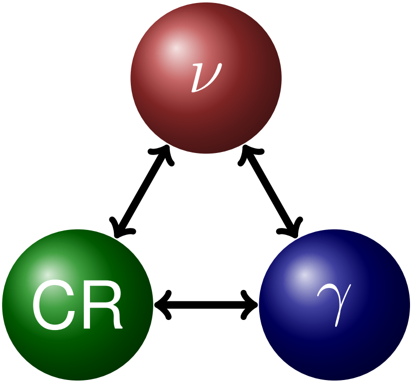
$$E_\nu \simeq E_\gamma/2 \simeq \kappa E_p$$

- relative multiplicity:

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

- pion fraction:

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



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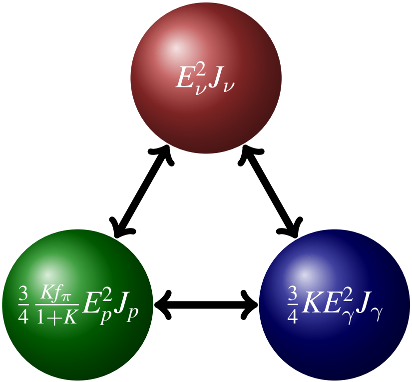

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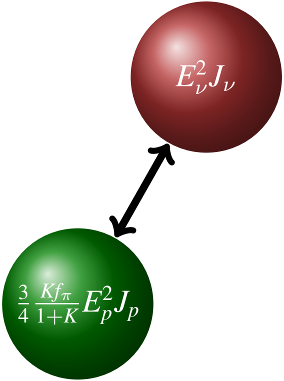
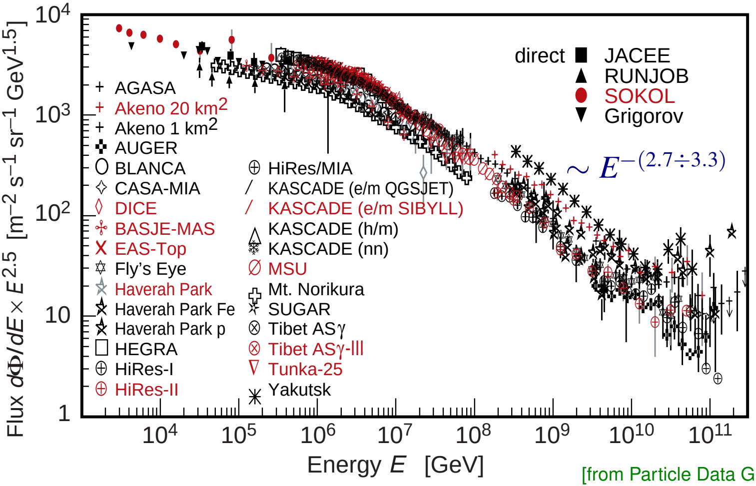


The cosmic leg

The all-particle spectrum (as $E^{2.5} \times F$) of cosmic rays.



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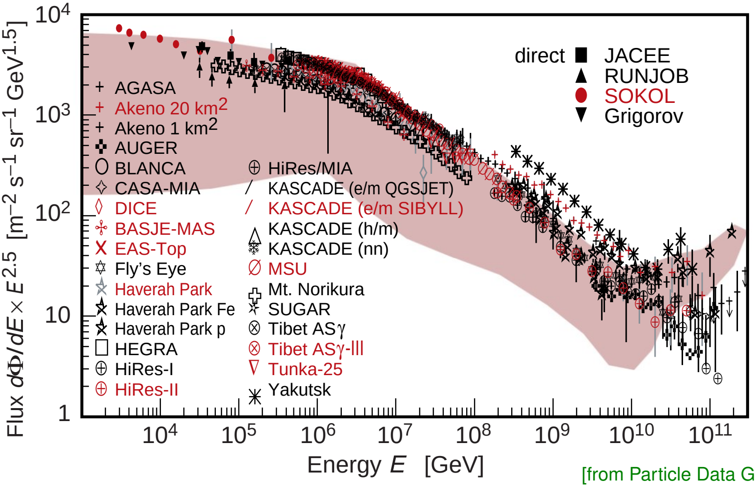

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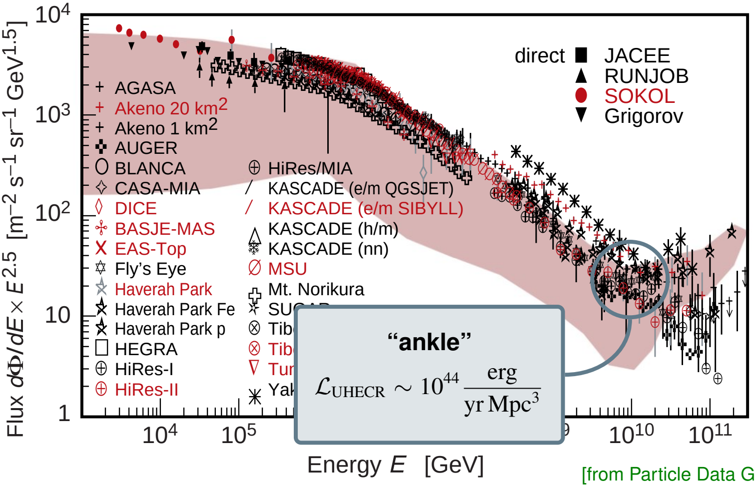

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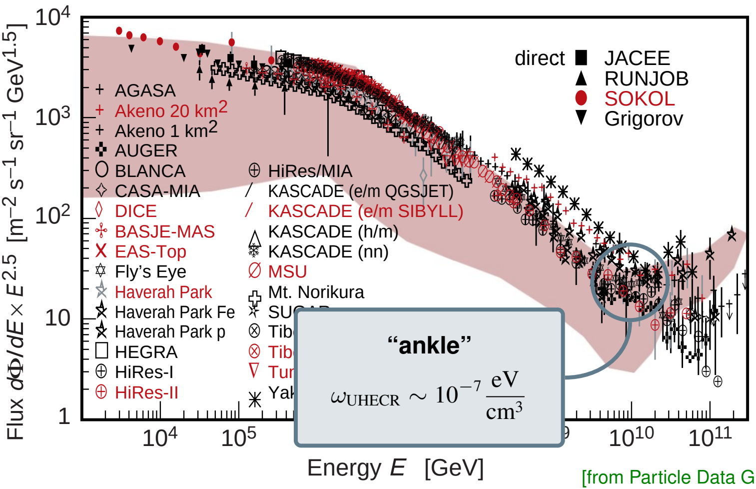


"ankle"

$$\omega_{\rm UHECR} \sim 10^{-7}\,\frac{\rm eV}{\rm cm^3}$$

[from Particle Data Group '05]

GRBs & UHECRs

- Neutrino emission of GRBs is one of the best-tested models:
  [IceCube Coll., Nature'12]

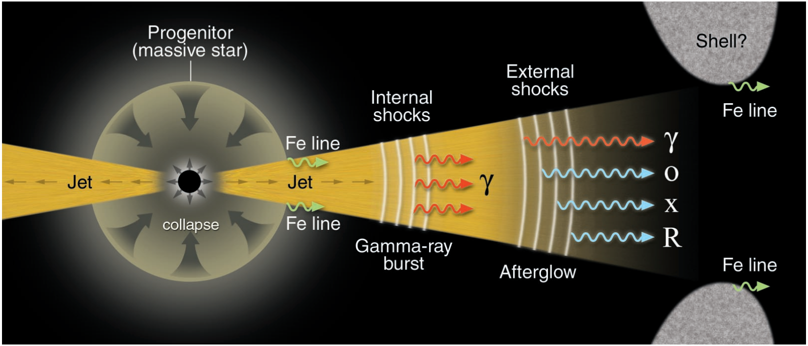
  ✔ cosmological sources ("one per day")
  ✔ wealth of data from Swift and Fermi
  ✔ good information on timing and location
  ✔ in some cases, optical follow-up (distance and source parameters)

- possible sources of UHE CRs; comparable energy density
- GRBs fulfill **necessary conditions** on time-scales (dynamical, cooling, acceleration) to reach ultra-high energies (UHE). [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 production from $p\gamma$ collisions possible over a wide energy range, *e.g.*, via Δ-resonance $p\gamma \to \Delta \to n\pi^+$

$$E_\nu \simeq \frac{\kappa}{4}\Gamma^2\frac{m_\Delta^2 - m_p^2}{4\omega} \simeq 1\mathrm{PeV}\left(\frac{\Gamma}{300}\right)^2\left(\frac{\mathrm{MeV}}{\omega}\right)$$

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]

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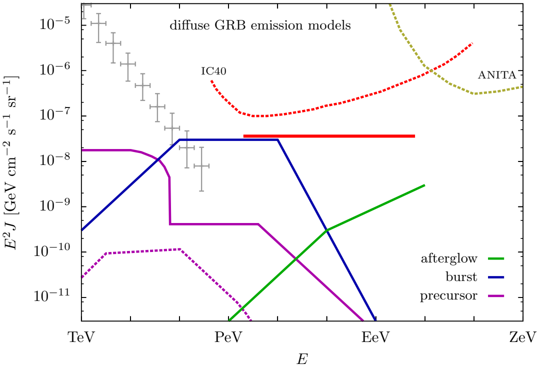

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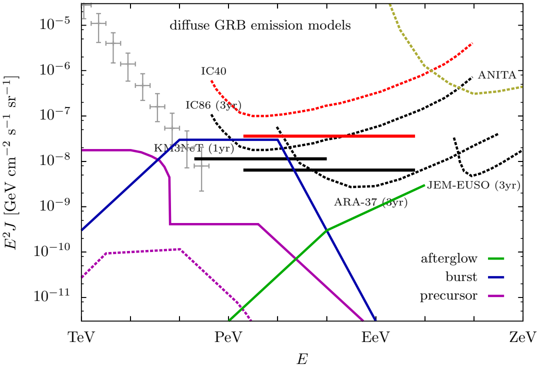


Burst Neutrino Emission

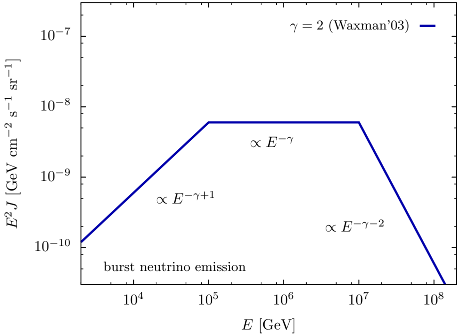
- neutrinos from meson production, *e.g.*

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

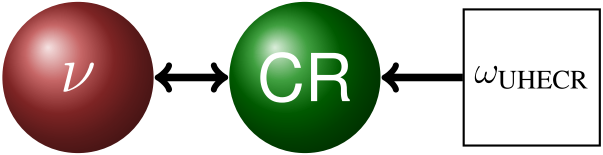
- spectra shaped by burst and proton spectrum and synchrotron loss of pions and muons before decay
[Waxman & Bahcall'97]

- for typical burst spectra this creates a "plateau" of neutrinos

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



➜ **Different models for absolut normalization:**



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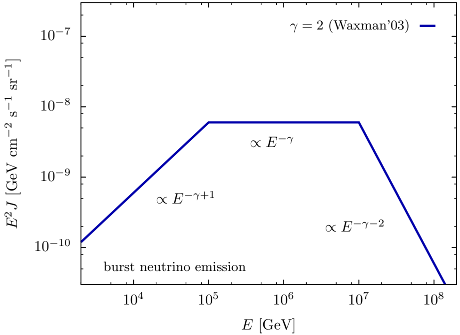

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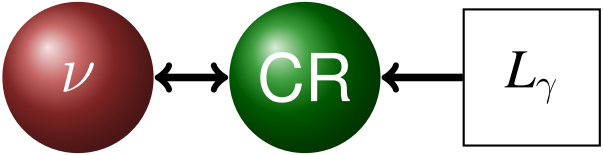


Normalization

- 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

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

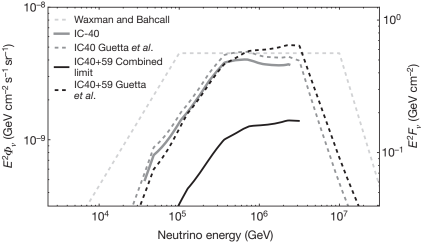
➜ by construction, $\epsilon_B + \epsilon_e + \epsilon_p \lesssim 1$, but otherwise **not well constrained**
➜ calculate the pion energy fraction f_π in $p\gamma$ interactions
➜ normalize to CRs in individual bursts, $U_p = (\epsilon_p/\epsilon_e)U_{\rm burst}$ [Guetta *et al.*'04;He *et al.*'12]

IC40+59 results I

- Limits on neutrino emission coincident with 215 GRBs between April 2008 and May 2010. [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.
- One event 30s after GRB 091026A ("Event 1") most likely background.
- Stacked point-source flux below "benchmark" prediction of burst neutrino emission by a factor 3-4. [Guetta *et al.*'04]

➜ **see P-VII-5 by A. Homeier**

"model-dependent"



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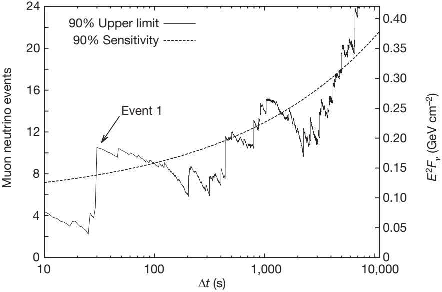


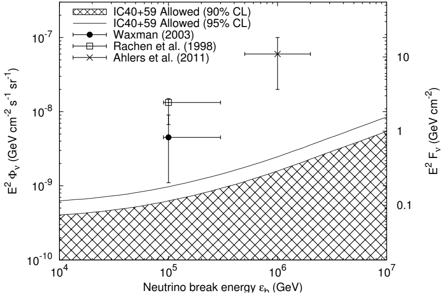
IC40+59 results II

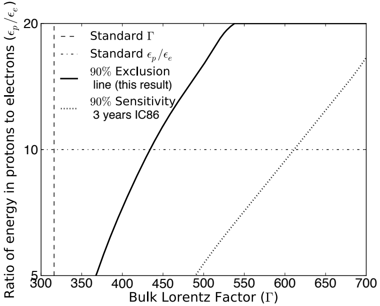
- Conversion to diffuse flux via cosmic GRB rate.
- Limit on burst neutrino emission ($|\Delta t| = 28s$) depends on neutrino break energy (break in optical depth).
- IceCube limit below "benchmark" diffuse models normalized to UHE CR data. [Waxman&Bahcall'03; Rachen *et al.*'98]

➜ **IceCube's results challenge GRBs as the sources of UHE CRs!**

- Results from model-dependent analysis translate into bounds of GRB parameters. [Guetta *et al.*'04]

➜ **Neutron emission models largely ruled out.** [MA, Gonzalez-Garcia & Halzen'11]





Further comments

- 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. (➜ talk by Ph. Baerwald) [Baerwald,Hümmer&Winter'11]
- Revised calculations of pion fraction f_π produce *lower values* than the standard parametrization (➜ talk by Ph. Baerwald) [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]

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- Model hierarchy: "**A ➜ B**" or "**not B ➜ not A**"
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  - 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. (➜ talk by Ph. Baerwald) [Baerwald,Hümmer&Winter'11]
- Revised calculations of pion fraction f_π produce *lower values* than the standard parametrization (➜ talk by Ph. Baerwald) [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]

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.
- ✘ Implications of IceCube's "model-dependent" analysis are model-dependent.
  (➜ next talk by Ph. Baerwald)
- ➜ Continued effort in future analysis with improved models and increased data.

Appendix

Neutrino production from $p\gamma$

- internal photon spectrum inferred from observed luminosity (L_γ)

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

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

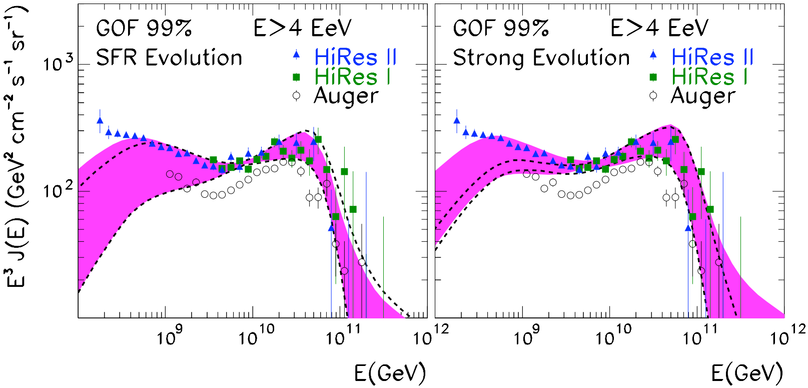
$$\tau_{p\gamma}(E_p) = \frac{t_{\rm dyn}}{t_{p\gamma}(E_p)} \simeq t_{\rm dyn} \underbrace{\left(\frac{\pi}{2}\frac{\Gamma_\Delta \sigma_0 m_\Delta^3}{m_\Delta^2 - m_p^2}\right)}_{0.04} \frac{m_p^2}{{E_p}^2} \int\limits_{\epsilon_{\rm min}} \frac{{\rm d}\epsilon}{\epsilon^2} n_\gamma(\epsilon)$$

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

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

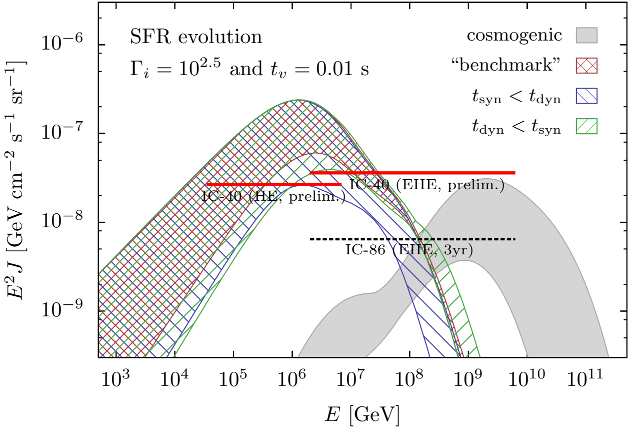
- final neutrino spectra after meson/muon **cooling in magnetic fields**

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]

Neutron emission (model **A'**)



- **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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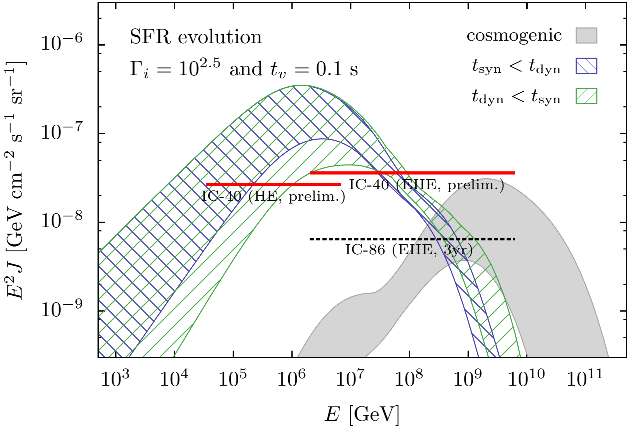

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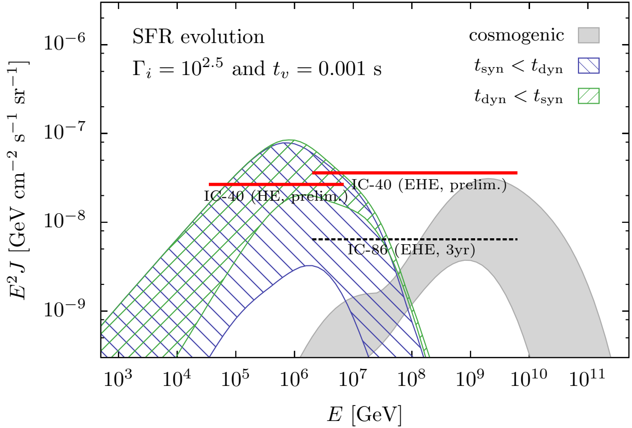

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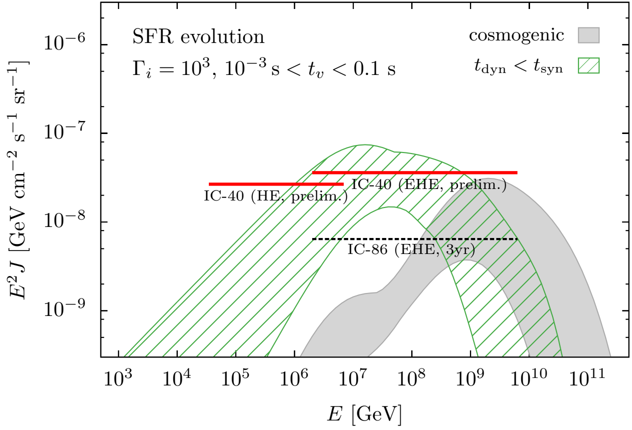

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