UHE cosmic rays & neutrinos, and the multi-messenger approach

GRK1147 status report – SS 2013

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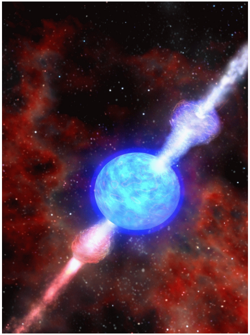
In collaboration with Philipp Baerwald and Walter Winter

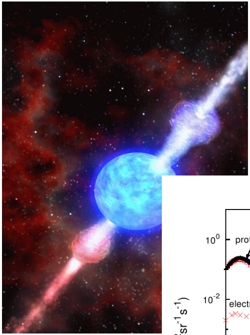
Institut für Theoretische Physik und Astrophysik
Universität Würzburg

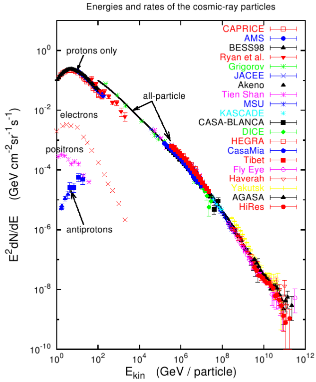
Würzburg, May 23, 2013



The multi-messenger approach

A self-consistent picture?





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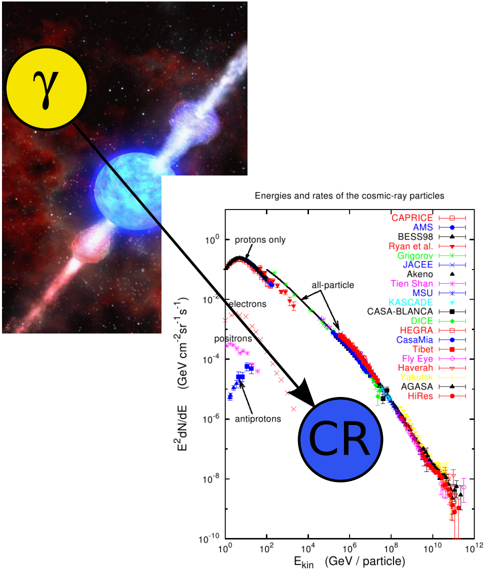
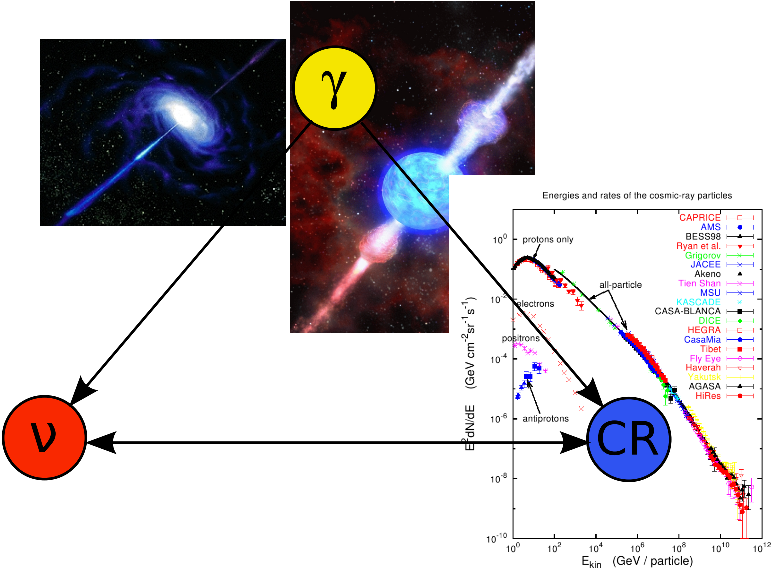
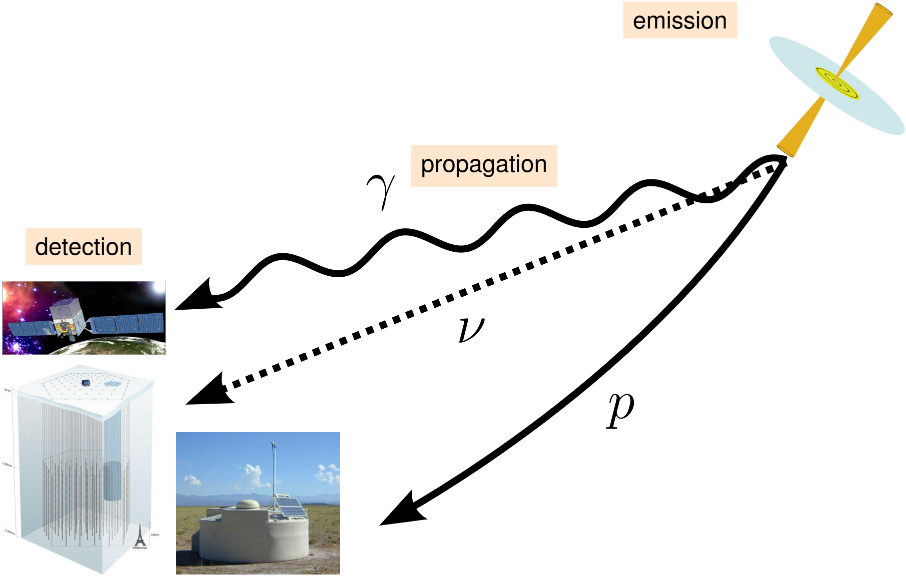



γ
ν
CR
Energies and rates of the cosmic-ray particles
protons only
all-particle
electrons
positrons
antiprotons
CAPRICE
AMS
BESS98
Ryan et al.
Grigorov
JACEE
Akeno
Tien Shan
MSU
KASCADE
CASA-BLANCA
DICE
HEGRA
CasaMia
Tibet
Fly Eye
Haverah
Yakutsk
AGASA
HiRes
$E^2 dN/dE$ (GeV cm^{-2}sr^{-1}s^{-1})
E_{kin} (GeV / particle)

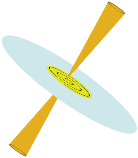
Cosmic-ray, photon, and neutrino propagation

Cosmic-ray, photon, and neutrino propagation

The current working model



emission



- magnetically-confined p's shock-accelerated up to $\sim 10^{21}$ eV
- power-law emission spectrum $\sim E^{-\alpha}$
- best candidates: GRBs (transient), AGN (flaring)
- photohadronic production of UHE γ's and ν's at the source:

$$p + \gamma_b \to \Delta^+(1232) \to \begin{cases} n + \pi^+ & (\text{BR} = 1/3) \\ p + \pi^0 & (\text{BR} = 2/3) \end{cases}$$

Gamma-rays: $\pi^0 \to \gamma + \gamma$

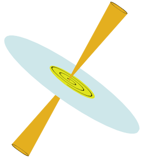
UHE ν's (direct): $\pi^+ \to \mu^+ + \nu_\mu$

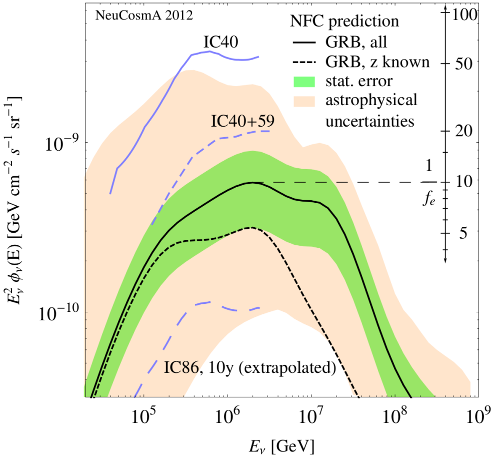
$$\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu$$

- Escaped n's become the UHECRs: $n \to p + e^- + \bar{\nu}_e$
- Additional $p\gamma$ channels (*e.g.*, higher resonances, π^- production) – implemented in NeuCosmA by Baerwald, Hümmer, Winter, Yaguna

Detailed GRB ν production (fireball model):

emission





HÜMMER, BAERWALD, WINTER, *PRL* **108**, 231101 (2012) [1112.1076]

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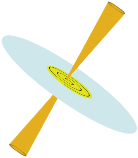
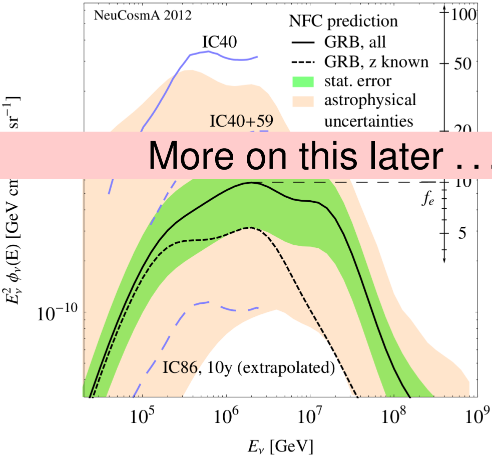
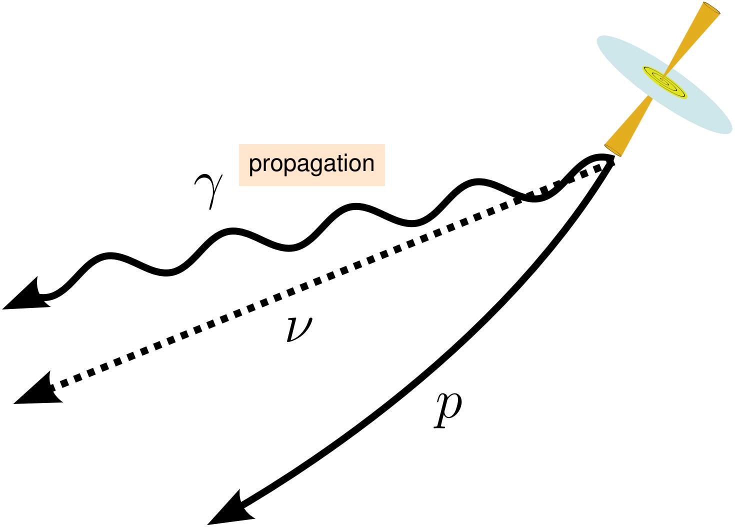




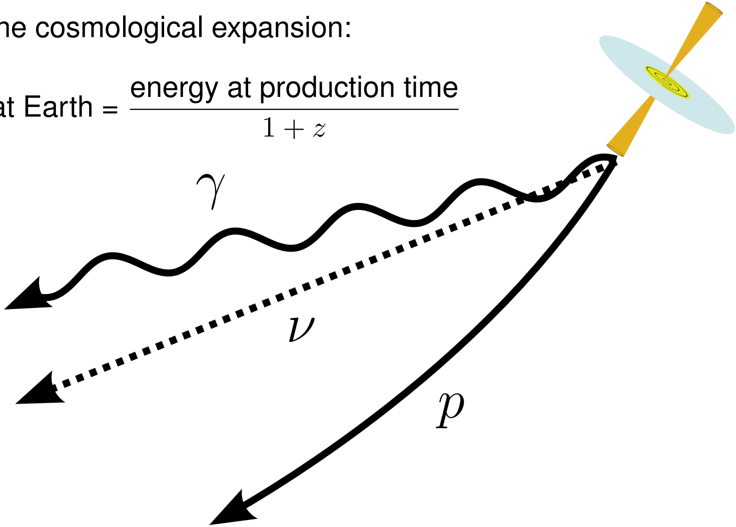
More on this later . . .

HÜMMER, BAERWALD, WINTER, *PRL* **108**, 231101 (2012) [1112.1076]

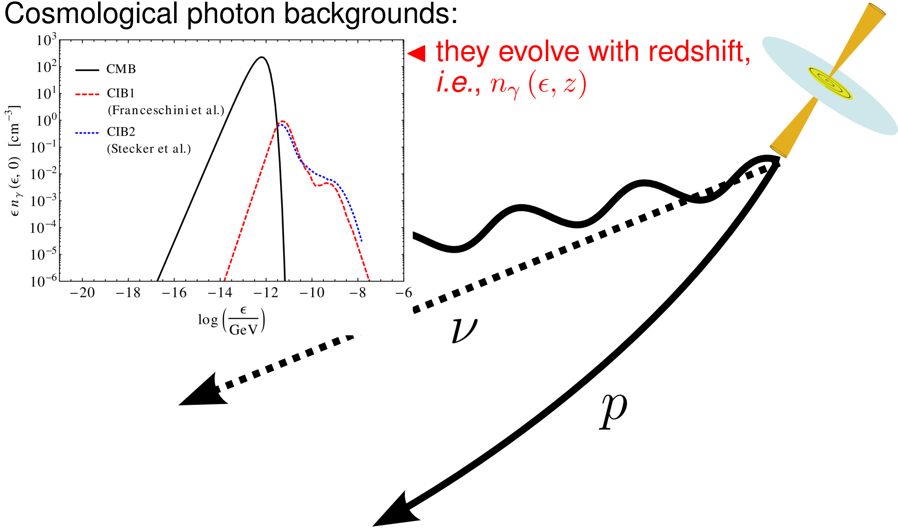

propagation
γ
ν
p

Because of the cosmological expansion:

$$\text{energy at Earth} = \frac{\text{energy at production time}}{1+z}$$



Cosmological photon backgrounds:



◀ they evolve with redshift, *i.e.*, $n_\gamma(\epsilon, z)$

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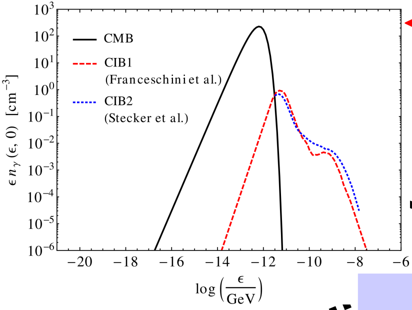

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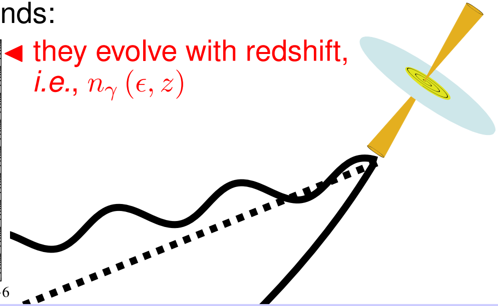


$$p + \gamma_b \to \Delta^+ \to \begin{cases} n + \pi^+ \\ p + \pi^0 \end{cases}$$

$$\pi^0 \to \gamma + \gamma$$

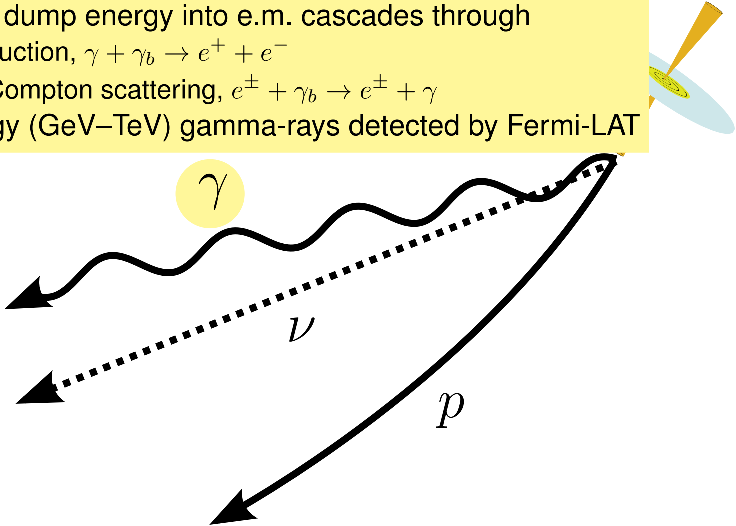
Cosmogenic ν's: $\pi^+ \to e^+ + \nu_e + \bar{\nu}_\mu + \nu_\mu$

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

γ's and $e^{\pm}$'s dump energy into e.m. cascades through

- pair production, $\gamma + \gamma_b \to e^+ + e^-$
- inverse Compton scattering, $e^{\pm} + \gamma_b \to e^{\pm} + \gamma$

Lower-energy (GeV–TeV) gamma-rays detected by Fermi-LAT

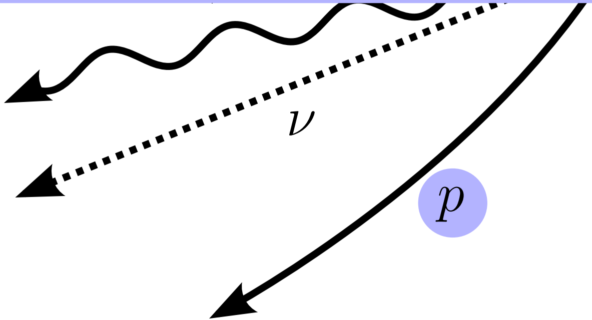


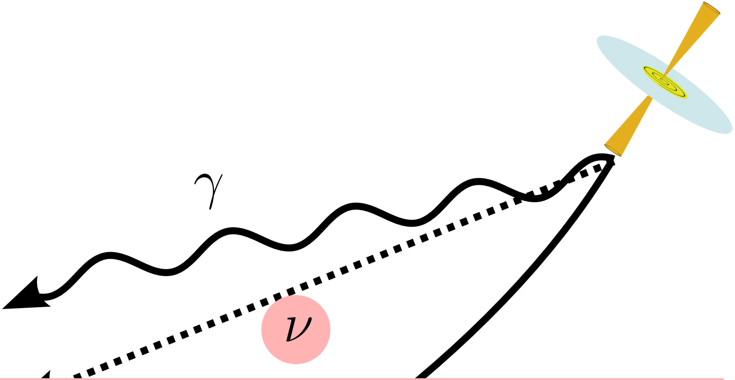
p's are deflected by extragalactic magnetic fields
⇒ except for the most energetic ones, they are **not** expected to point back to the sources } Pierre Auger found weak correlation with known AGN positions

They lose energy through:

- pair production, $p + \gamma_b \rightarrow p + e^+ + e^-$
- photohadronic interactions, $p\gamma_b$

} depend on the redshift evolution of the cosmological γ backgrounds

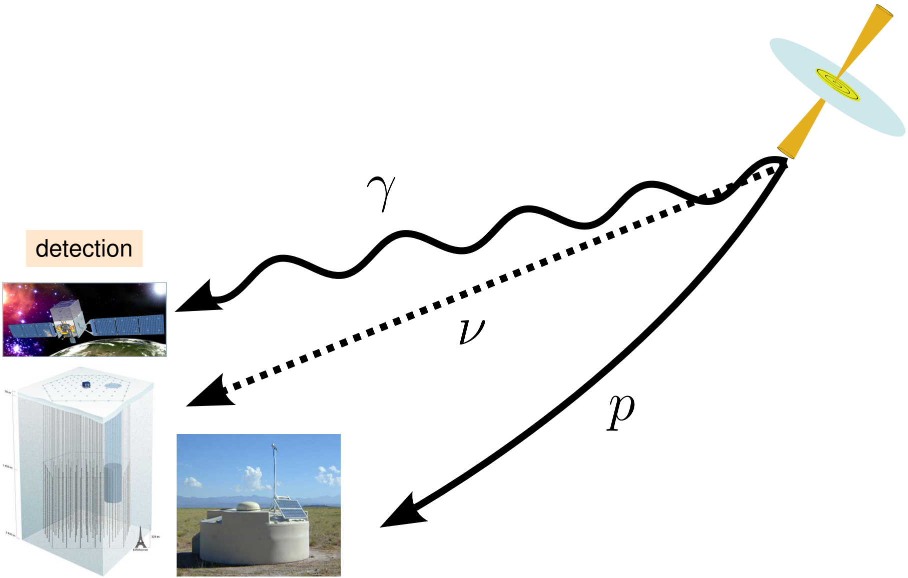




Initial UHE ν flavour fluxes: $\nu_e : \nu_\mu : \nu_\tau = 1 : 2 : 0$

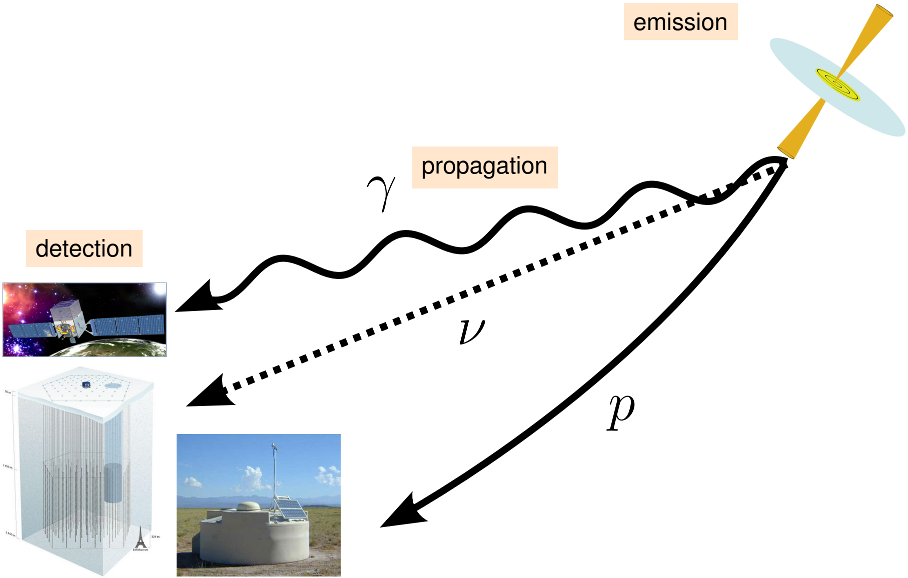
Probability of $\nu_\alpha \to \nu_\beta$ transition: $P_{\alpha\beta}\left(E_0, z\right)$

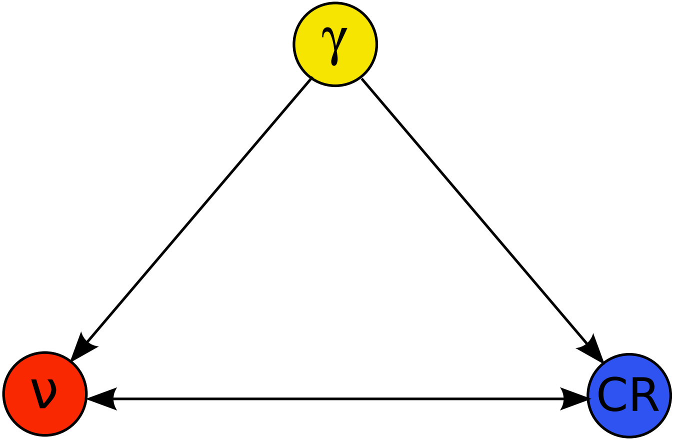
Flavour oscillations redistribute the fluxes
– at Earth: $\nu_e : \nu_\mu : \nu_\tau \approx 1 : 1 : 1$ (might be changed by exotic physics!)


γ
ν
p
detection

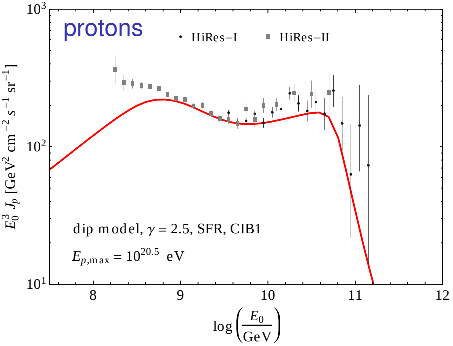
Cosmic-ray, photon, and neutrino propagation

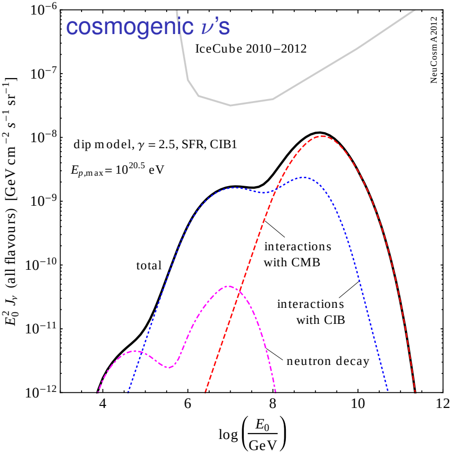
The current working model




γ
ν
CR

Our (MB, W. WINTER) code propagates UHE p's, ν's, γ's to Earth:





Fast and flexible:
can change emission and propagation parameters

We use a Boltzmann equation to transport protons to Earth:

- Comoving number density of protons (GeV^{-1} cm^{-3}):

$$Y_p(E,z) = a^3(z)\, n_p(E,z) = n_p(E,z) / (1+z)^3 \ ,$$

with n_p the real number density

- Transport equation (E: energy in source frame):

$$\dot{Y}_p = \partial_E (HEY_p) + \partial_E (b_{e^+e^-} Y_p) + \partial_E (b_{p\gamma} Y_p) + \mathcal{L}_{\text{CR}}$$

$\partial_E (HEY_p)$: adiabatic losses

$\partial_E (b_{e^+e^-} Y_p)$: pair production losses

$\partial_E (b_{p\gamma} Y_p)$: photohadronic losses

$\mathcal{L}_{\text{CR}}$: CR injection from sources

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- Cast into an equation in z by using $dz = -dt\,(1+z)\,H(z)$:

$$\partial_z Y(E,z) = \frac{-1}{(1+z)\,H(z)} \{\partial_E [H(z)\, EY(E,z)] + \partial_E [b_{e^+e^-}(E,z)\, Y(E,z)] + \partial_E [b_{p\gamma}(E,z)\, Y(E,z)] + \mathcal{L}_{\mathrm{CR}}(E,z)\}$$

… and evolve numerically from $z_{\max} \geq 6$ down to $z = 0$

Easily test different CR production and propagation models:

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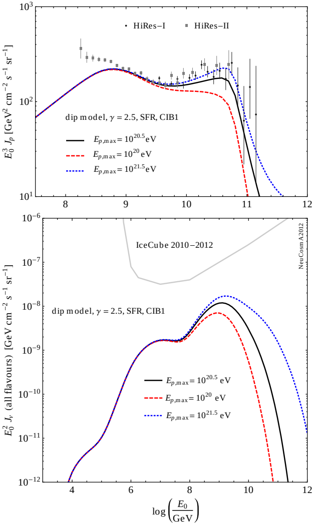

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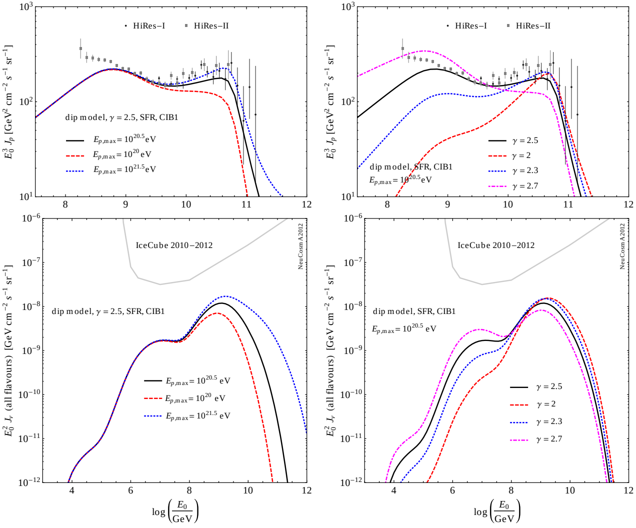
- change p injection spectrum $\sim E^{-\gamma}$:



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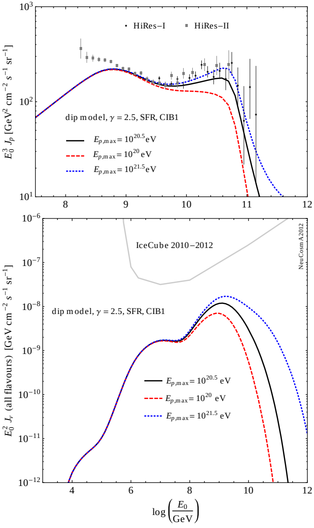

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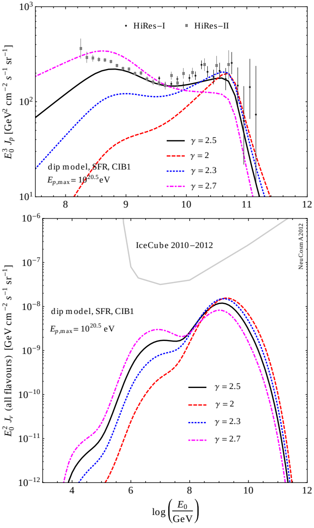
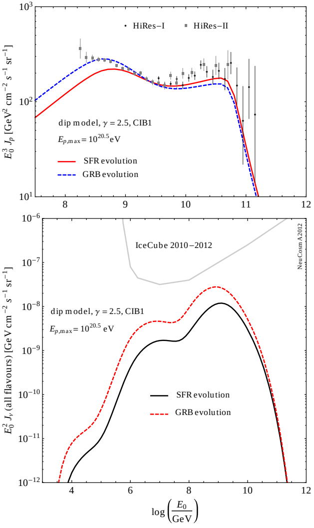


- change the redshift evolution of sources:



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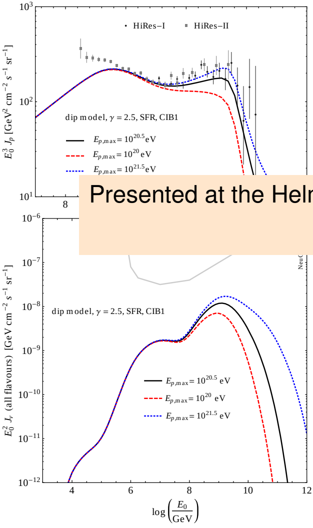

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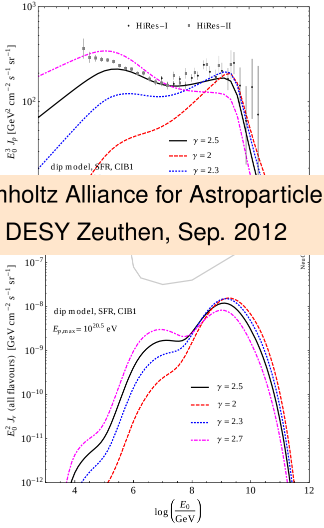

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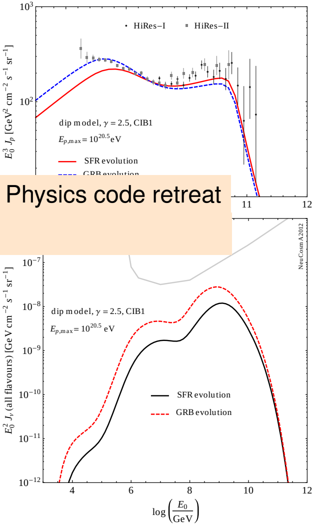

Presented at the Helmholtz Alliance for Astroparticle Physics code retreat
DESY Zeuthen, Sep. 2012

Our proposal: a two-component model of CR emission

P. Baerwald, MB, W. Winter, *Astrophys. J.* **768**, 186 (2013) [1301.6163]

To be presented at the 2013 International Cosmic Ray Conference

Standard UHECR and UHE ν scenario:

$$p\gamma \to \Delta^+ \to n\pi^+ \to \begin{cases} \pi^+ \to \mu^+\nu_\mu \to \bar{\nu}_\mu e^+ \nu_e \nu_\mu \\ n \to p e^- \bar{\nu}_e \end{cases} \xrightarrow{\text{propagation}} \begin{array}{l} \nu_e : \nu_\mu : \nu_\tau = 1:1:1 \\ p \text{ seen as UHECR} \end{array}$$

It hinges on:

1. p's magnetically confined, only n's escape
2. p's interact at most once, n's do not (*optically thin source*)

Under the "one ν per CR" hypothesis, GRBs cannot be the sole source of UHECRs (AHLERS *et al.*, ICECUBE COLLABORATION).

ICECUBE COLLABORATION, *Nature* **484**, 351 (2012)
M. AHLERS, M. GONZÁLEZ-GARCÍA, F. HALZEN *Astropart. Phys.* **35**, 87 (2011)

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Solution: let us be a bit more realistic ...

IceCube Collaboration, *Nature* **484**, 351 (2012)
M. Ahlers, M. González-García, F. Halzen *Astropart. Phys.* **35**, 87 (2011)

What if 1 and 2 are violated?

- p's "leak out", not accompanied by (direct) ν production
- multiple p interactions enhance the ν flux
- in *optically thick sources*, only n's at the borders escape

Particles can escape from within a shell of thickness λ'_{mfp}:

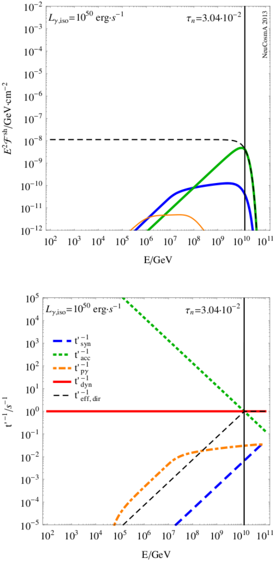
$$\lambda'_{p,\text{mfp}}\left(E'\right) = \min\left[\Delta r', R'_L\left(E'\right), ct'_{p\gamma}\left(E'\right)\right]$$
$$\lambda'_{n,\text{mfp}}\left(E'\right) = \min\left[\Delta r', ct'_{p\gamma}\left(E'\right)\right]$$

Optical depth:

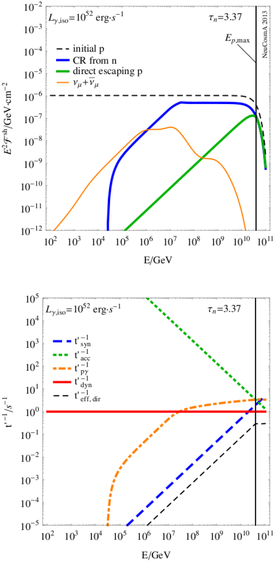
$$\tau_n = \left.\frac{t_{p\gamma}^{-1}}{t_{\text{dyn}}^{-1}}\right|_{E_{p,\max}} = \begin{cases} \lesssim 1\,, & \text{optically thin source} \\ > 1\,, & \text{optically thick source} \end{cases}$$

Our proposal: a two-component model of CR emission

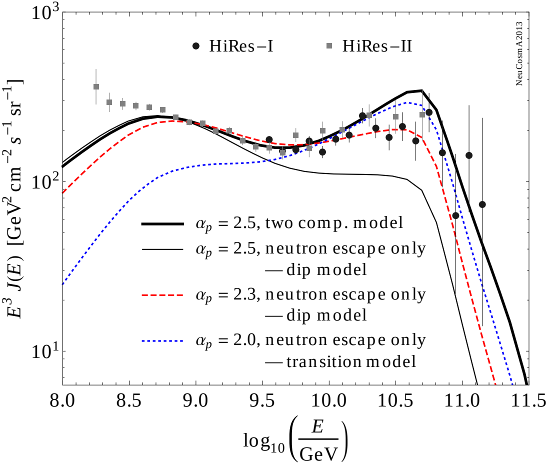
optically thin source:



optically thick source:



UHECR flux at Earth from n and direct p escape:



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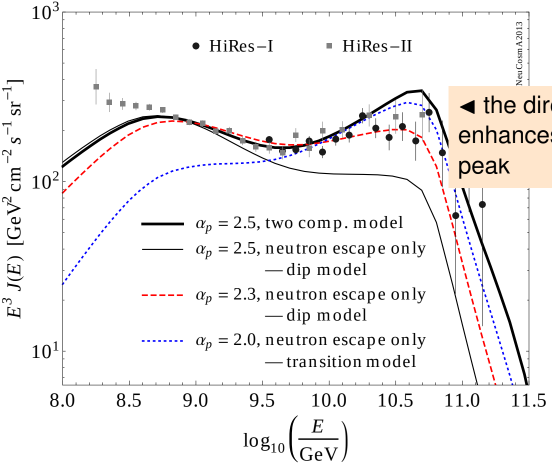

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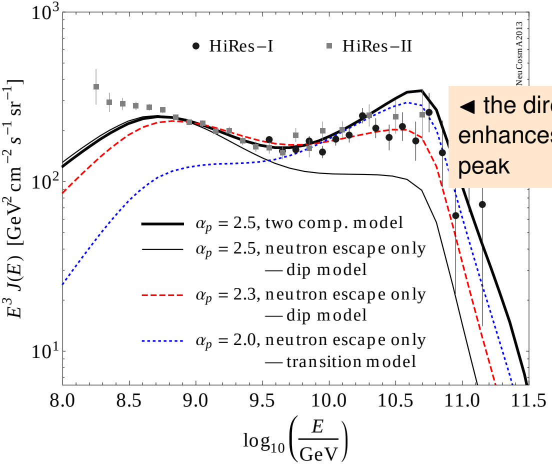


◀ the direct p escape enhances the high-energy peak

Our two-component model *is* able to fit the UHECR data

Exotic physics during propagation: neutrino decay

P. Baerwald, MB, W. Winter, *JCAP* **1210**, 020 (2012) [1208.4600]

Presented at the 2013 DPG meeting

Neutrinos are stable particles … *are they?*

So far, they seem to be

Bounds on "lifetimes" $\kappa^{-1} \equiv \tau_0/m$ of eigenstates $\nu_{1,2,3}$:

- $\kappa_1^{-1} \gtrsim 10^5$ s eV^{-1} (from SN 1987A)
- $\kappa_2^{-1} \gtrsim 10^{-4}$ s eV^{-1} (from solar ν's)
- $\kappa_3^{-1} \gtrsim 10^{-10}$ s eV^{-1} (from atm. and long-baseline)

Very long baselines might reveal their true unstable nature

$\Rightarrow$ cosmological neutrinos

If $\nu_{1,2,3}$ decay, their populations are governed by

$$\frac{dN_i}{dt} = -\lambda_i N_i$$

with the decay rate (s^{-1})

$$\lambda_i \equiv \frac{1}{\tau_i} = \frac{m_i}{\tau_{i,0}} \frac{1}{E} \equiv \frac{\kappa_i}{E}$$

Consider only decay into products invisible to the detector

Neutrinos are ultra-relativistic, so $t \approx L$
— if they are produced at a source with redshift z,

$L(z) \equiv$ light-travel, or lookback distance

$\nu_\alpha \to \nu_\beta$ flavour-transition probability, oscillations washed out:

$$P_{\alpha\beta} = \sum_{i=1}^{3} |U_{\alpha i}|^2 \, |U_{\beta i}|^2 \qquad (\alpha, \beta = e, \mu, \tau)$$

What if neutrinos decay?

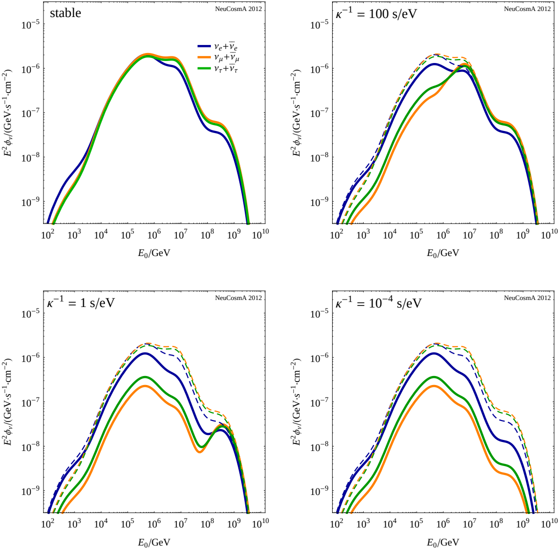
$$P_{\alpha\beta}(E_0, z) = \sum_{i=1}^{3} |U_{\alpha i}|^2 \, |U_{\beta i}|^2 \underbrace{\frac{N_i(E_0, z)}{N_i^0(E_0)}}_{D_i(E_0, z) \leq 1}$$

Damping factor $D_i(E_0, z)$ found by solving the decay equation

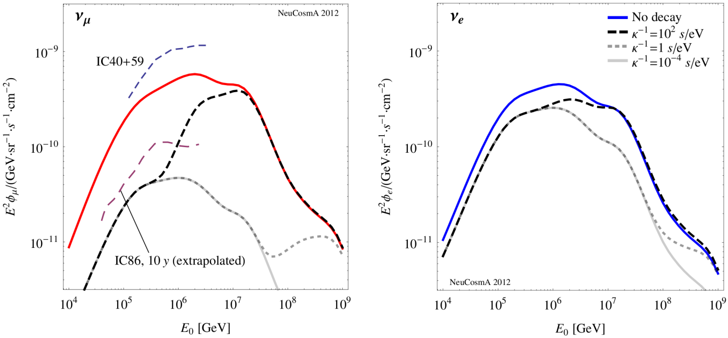
When solving, take into account:

1. $L = L(z)$
2. Cosmological expansion: $E(z) = (1 + z) E_0$

Keep ν_1 stable (from SN 1987A) and let $\nu_{2,3}$ decay:



Quasi-diffuse flux (stacking the 117 GRBs from IC-40 analysis):



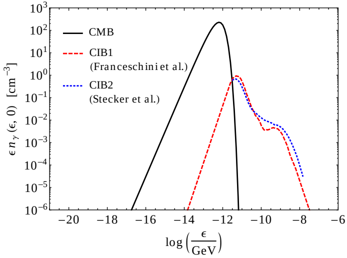
No reliable information on astrophysical neutrino sources can be obtained from muon tracks only

What are we working on now?

Enhanced UHE neutrino flux from varying the CIB

Unlike the CMB, the cosmic infrared background (CIB) photon spectrum is subject to large uncertainties, especially at high redshift ($z \gtrsim 4$).

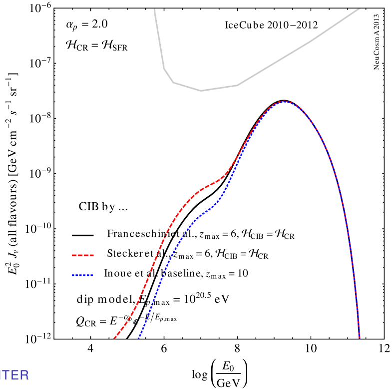
Different models of the CIB . . .



cosmic rays propagate

$p + \gamma \to \nu + \ldots$

. . . result in different predictions of the cosmogenic ν flux



MB, C. Evoli (DESY Hamburg), G. Sigl (DESY Hamburg), W. Winter

Enhanced UHE neutrino flux from varying the CIB

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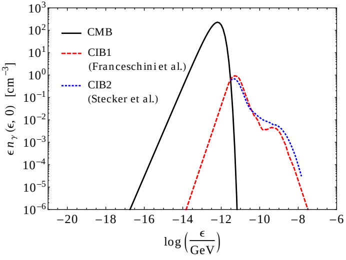
Different models of the CIB ...

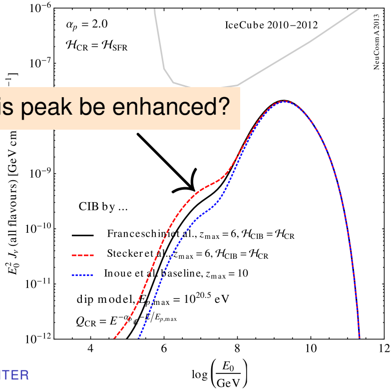


cosmic rays propagate

$p + \gamma \to \nu + \ldots$

... result in different predictions of the cosmogenic ν flux

can this peak be enhanced?



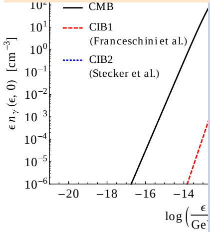
MB, C. Evoli (DESY Hamburg), G. Sigl (DESY Hamburg), W. Winter

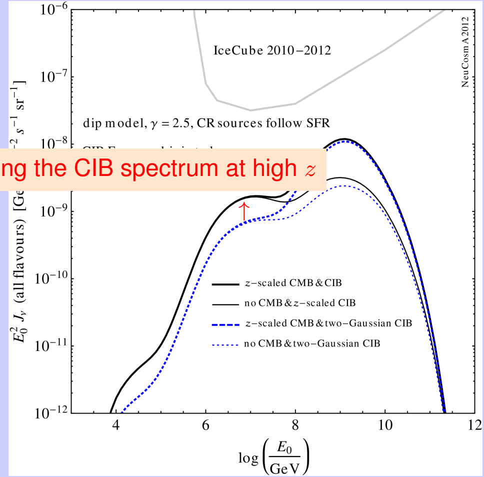
Enhanced UHE neutrino flux from varying the CIB

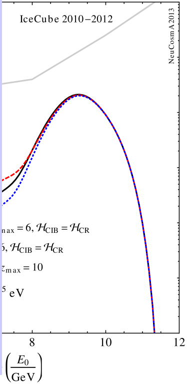
Unlike the CMB, t… spectrum is subject to large u…).

Different models … …rent predictions …genic ν flux

perhaps, by increasing the CIB spectrum at high z



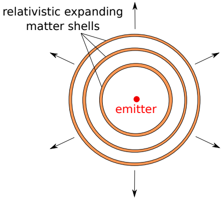




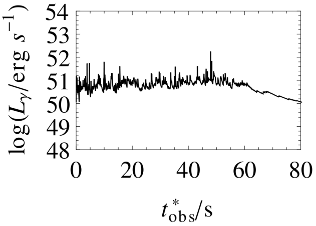
MB, C. EVOLI (DESY HAM…

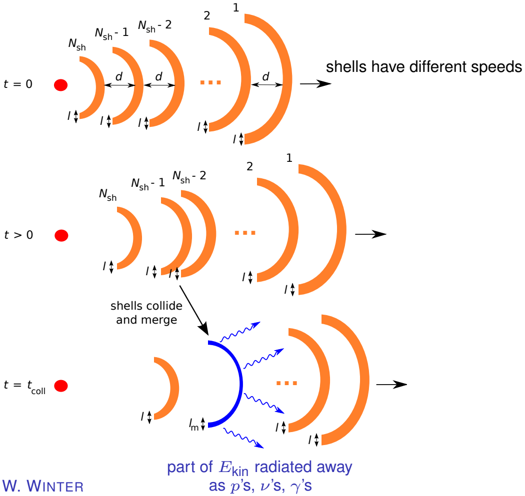
Time-evolution simulation of the fireball model

We numerically simulate expansion and collision of matter shells in a GRB:



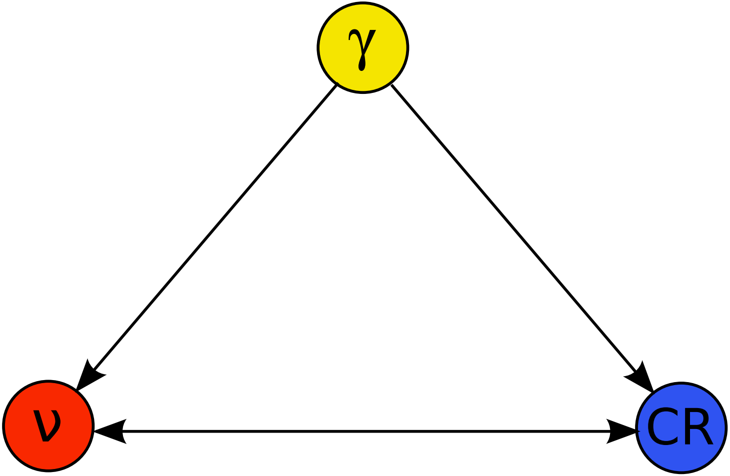
Artificial lightcurve of the simulated burst:





P. BAERWALD, MB, K. MURASE (IAS, PRINCETON), W. WINTER

CR energy budget, γ–CR–ν connection, and GRB rate



M. Ahlers (U. Wisconsin), P. Baerwald, MB,
F. Halzen (U. Wisconsin), W. Winter, N. Whitehorn (U. Wisconsin)

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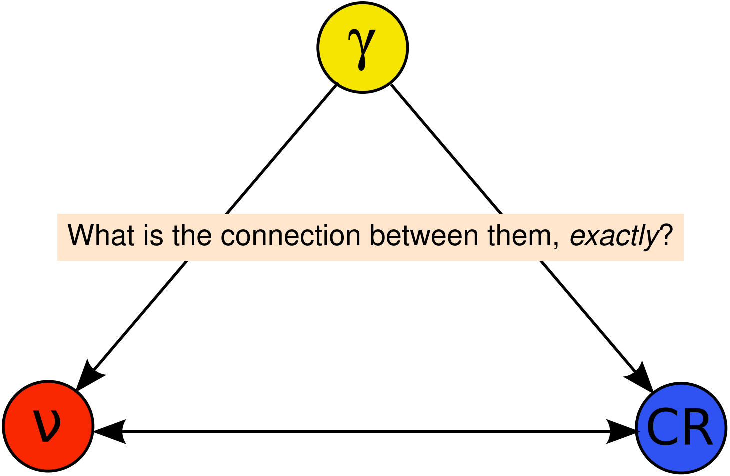

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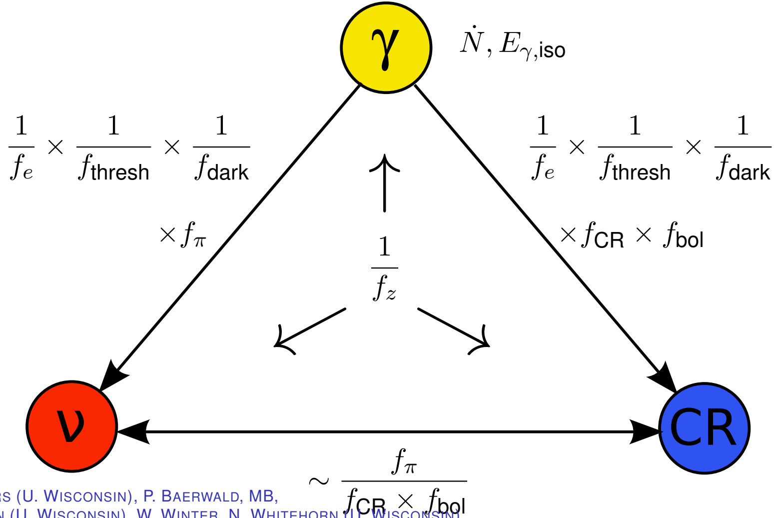

M. Ahlers (U. Wisconsin), P. Baerwald, MB,
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Summary and conclusions

We have used NeuCosmA to explore GRB neutrino decay

We have developed a CR propagation code ...

- ... considers the full photohadronics,
- ... computes the cosmogenic ν's and energy in e.m. cascades,
- ... is fast and flexible, and
- ... allows to test different production and propagation models

We have introduced a two-component model of cosmic-ray emission

Still loads of room for exploiting NeuCosmA + CR propagation code

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Still loads of room for exploiting NeuCosmA + CR propagation code

Recent detection of 28 UHE ($\lesssim$ PeV) events by IceCube
signals the beginning of the UHEν era!

Backup slides

NeuCosmA

We use a sophisticated prediction of the GRB neutrino flux (HÜMMER ET AL.):

- full background photon spectrum (not only peak energy)
- energy dependence of the mean free path of protons
- cooling of secondaries
- high-energy photopion processes
- neutrinos from decay of $\mu^{\pm}$, $\pi^{\pm}$, K, n
- helicity dependence of μ decays
- flavour mixing (affected by neutrino decays)

One order of magnitude below prediction of benchmark models used by IceCube

S. HÜMMER, P. BAERWALD, W. WINTER, *PRL* **108**, 231101 (2012) [1112.1076]

S. HÜMMER, M. RUGER, F. SPANIER, W. WINTER, *Astrophys. J.* **721**, 630 (2010) [1002.1310]

Interaction with the photon backgrounds

- Energy loss rate (GeV s^{-1}):

$$b(E) \equiv \frac{dE}{dt}$$

- For pair production $p\gamma \longrightarrow pe^+e^-$:

$$b_{e^+e^-}(E, z) = -\alpha r_0^2 \left(m_e c^2\right)^2 c \int_2^\infty d\xi n_\gamma \left(\frac{\xi m_e c^2}{2\gamma}, z\right) \frac{\phi(\xi)}{\xi^2}$$

  - n_γ: isotropic photon background (GeV^{-1} cm^{-3})
  - ξ: photon energy in units of $m_e c^2$
  - proton energy: $E = \gamma m_p c^2$ ($\gamma \gg 1$)
  - $\phi(\xi)$: (tabulated) integral in energy of outgoing e^-

G. Blumenthal, *Phys. Rev.* **D 1**, 1596 (1970)
H. Bethe, W. Heitler, *Proc. Roy. Soc.* **A146**, 83 (1934)

Interaction with the photon backgrounds (cont.)

Photohadronic interactions – $p\gamma$ interaction rate (s^{-1} per particle):

$$\Gamma_{p\gamma\to p'b}(E,z) = \frac{1}{2}\frac{m_p^2}{E^2}\int_{\frac{\epsilon_{\text{th}} m_p}{2E}}^{\infty} d\epsilon \frac{n_\gamma(\epsilon,z)}{\epsilon^2}\int_{\epsilon_{\text{th}}}^{2E\epsilon/m_p} d\epsilon_r \epsilon_r \sigma_{p\gamma\to p'b}^{\text{tot}}(\epsilon_r)$$

1. For given values of E and z, NeuCosmA calculates the cooling rate $t_{p\gamma}^{-1} \equiv -(1/E)\, b_{p\gamma}$ (s^{-1}) as

$$t_{p\gamma}^{-1}(E,z) = \sum_i^{\text{all channels}} \Gamma_{p\to p}^i(E,z)\, K^i \ ,$$

   with $K^i E$ the loss of energy per interaction
2. From this, we calculate back $b_{p\gamma}$ (GeV s^{-1}) ...
3. ... and the corresponding energy-loss term in the transport equation, $\partial_E(b_{p\gamma} Y_p)$.

S. Hümmer, M. Rüger, F. Spanier, W. Winter, *Astrophys. J.* **721**, 630 (2010) [1002.1310]

Photon background redshift scaling – CMB

- Local CMB spectrum (GeV^{-1} cm^{-3}):

$$n_\gamma^{\text{CMB}}(\epsilon, z=0) = \frac{1}{\pi^2}\frac{1}{(\hbar c)^3}\frac{\epsilon^2}{e^{\epsilon/(k_B T)}-1}$$

- Following $\dot{Y}_\gamma = \partial_E (HEY_\gamma)$, with $Y_\gamma \propto a^3 n_\gamma$, it scales as

$$n_\gamma^{\text{CMB}}(\epsilon, z) = (1+z)^3\, n_\gamma^{\text{CMB}}(\epsilon/(1+z), z=0)$$

- This induces the scaling of the energy loss rate,

$$b(E,z) = (1+z)^2\, b((1+z)E, 0)$$

- This adiabatic scaling is exact for the CMB – not so for the CIB

Photon background redshift scaling – CIB

- The CIB spectrum has been measured up to $z = 2$
- Redshift dependence:

$$n_\gamma^{\text{CIB}}\left(\epsilon\left(1+z\right), z\right) = \left(1+z\right)^2 \int_z^\infty dz' \frac{1}{H\left(z'\right)} \mathcal{L}_{\text{CIB}}\left(\epsilon\left(1+z'\right), z'\right)$$

$\mathcal{L}_{\text{CIB}}$: comoving injection rate of IR photons (depends on source evolution – *more on this later*)

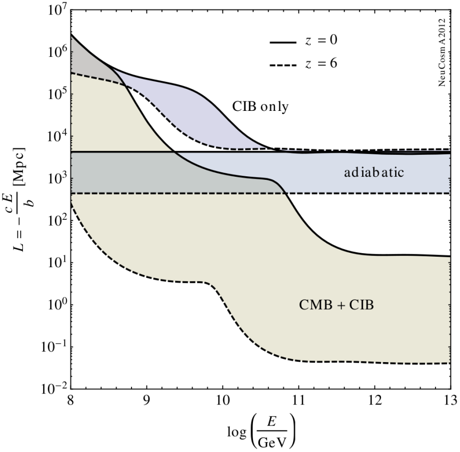
- Following [M. Ahlers, L.A. Anchordoqui, S. Sarkar, *PRD* **79**, 083009 (2009) [0902.3993]], we used

$$n_\gamma^{\text{CIB}}\left(\epsilon, z\right) \simeq \frac{1}{1+z} \frac{N_{\text{CIB}}\left(z\right)}{N_{\text{CIB}}\left(0\right)} n_\gamma^{\text{CIB}}\left(\epsilon / \left(1+z\right), 0\right)$$

- Other CIB scalings possible
  – the code can easily accommodate for them

Interaction lengths

Note that $L_{\text{CIB}} \gg L_{\text{CMB}}$:



Matches, e.g., H. Takami, K. Murase, S. Nagataki, K. Sato, *Astropart. Phys.* **31**, 201 (2009) [0704.0979]

Proton injection rate

$$\mathcal{L}_{\text{CR}}(E,z) = \mathcal{H}(z)\, Q_{\text{CR}}(E,z)$$

Q_{CR}: injection rate at source (GeV^{-1} Mpc^{-3} s^{-1})
$\mathcal{H}$: cosmological evolution of sources (adimensional)

$$Q_{\text{CR}}(E,z) \propto E^{-\gamma} e^{-E/E_{p,\max}}$$

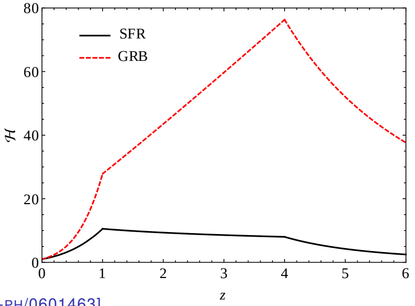
e.g., star formation rate (HOPKINS & BEACOM),

$$\mathcal{H}_{\text{SFR}}(z) = \begin{cases} (1+z)^{3.4} & , z < 1, \\ N_1 (1+z)^{-0.3} & , 1 \leq z < 4 \\ N_1 N_4 (1+z)^{-3.5} & , z \geq 4 \end{cases}$$

with $N_1 = 2^{3.7}$ and $N_4 = 5^{3.2}$ …

…or GRB rate (KISTLER *et al.*),

$$\mathcal{H}_{\text{GRB}}(z) = (1+z)^{1.4}\, \mathcal{H}_{\text{SFR}}(z)$$



A.M. HOPKINS, J.F. BEACOM, *Astrophys. J.* **651**, 142 (2006) [ASTRO-PH/0601463]
M. AHLERS, M. GONZÁLEZ-GARCÍA, F. HALZEN, *Astropart. Phys.* **35**, 87 (2011) [1103.3421]
M.D. KISTLER *et al.*, *Astrophys. J.* **705**, L104 (2009) [0906.0590]

Discretised Boltzmann equation

- Use $x \equiv \log_{10}(E)$
- Discrete variable $Y_i(x) \equiv Y(z_i, x)$

$$
\begin{aligned}
\frac{Y_{i+1}(x) - Y_i(x)}{\Delta z} \\
= -\frac{1}{(1+z_i) H(z_i)} \Big\{ \frac{\log_{10} e}{E} \big[\partial_x (H(z) E Y_i(x)) \\
+ \partial_x (b_{e^+e^-}(x, z_i) Y_i(x)) + \partial_x (b_{p\gamma}(x, z_i) Y_i(x)) \big] \\
+ \mathcal{L}_{\text{CR}}(x, z_i) \Big\}
\end{aligned}
$$

- Spectrum evolved from $z = 6$ to $z = 0$ in steps $\Delta z = 5 \times 10^{-5}$
- $Y_i(x)$ calculated at $N_x = 60$ values at each z_i – then interpolated
- Protons injected down to $z = 0.02$ (inhomogeneity sets in)
- Typical running time (including CMB + CIB interactions, and cosmogenic ν production): $\sim$ 120 s (on an i7 processor)

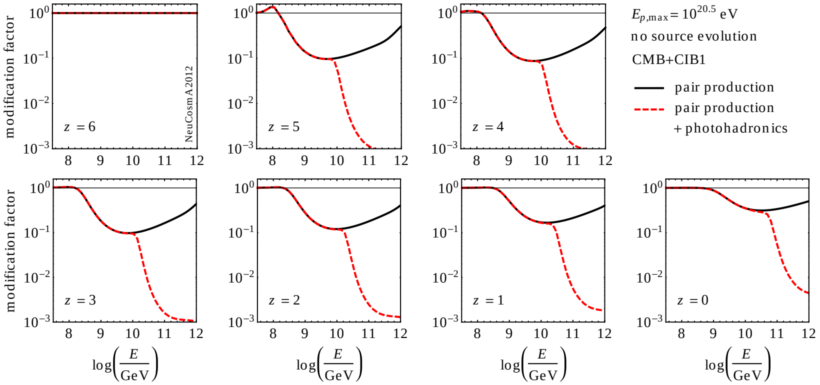
A few extra tricks for speed-up

- NeuCosmA already calculates the photohadronics fast
- Protons and neutrons are treated as the same species:
  – valid between 10^9 GeV and 4×10^{11} GeV
  - below: diffusion effects due to magnetic fields
  - above: neutron interaction time < decay time

  T. STANEV, ECONF C040802, L020 (2004) [ASTRO-PH/0411113]
- Local ($z = 0$) $b_{e^+e^-}$ and $b_{p\gamma}$ on the CMB calculated only once, and then scaled to different z
  - $\sim$ 120 s (w/ scaling) vs. $\sim$ 40 min (w/o scaling)
- CIB interactions calculated only every 500 redshift steps
  - since CIB interaction length $\gg$ CMB length
- Cosmogenic neutrino flux calculated only every 1000 steps, for the same reason

UHECR propagation: modification factor

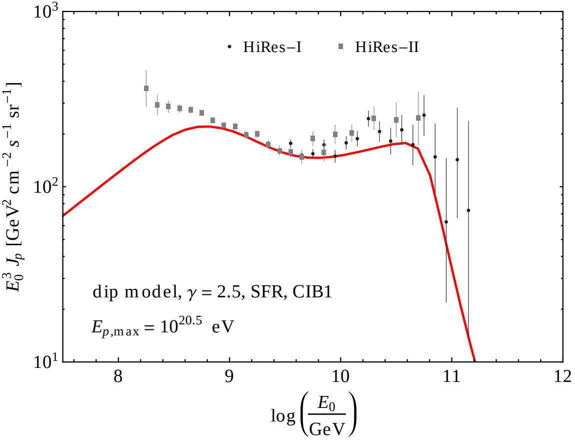
$$\text{modification factor} = \frac{Y_p\,(\text{adiabatic+CMB+CIB losses})}{Y_p\,(\text{adiabatic losses only})}$$



Matches the results from R. Aloisio *et al.*, *Astropart. Phys.* **27**, 76 (2007) [astro-ph/0608219]

UHECR propagation: proton spectrum normalisation

Proton flux at Earth $J_p(E_0) \equiv (c/4\pi)\, n_p(E_0, 0)$ normalised to HiRes data (*Phys. Rev. Lett.* **100**, 101101 (2008) [ASTRO-PH/0703099]):



Cosmogenic ν flux: the "guaranteed" UHE ν flux

- We *have* measured UHECRs *and* the CMB and CIB
- $\therefore$ There is a "guaranteed" flux of UHE ν's coming from

$$p + \gamma \longrightarrow \Delta^+ (1232) \longrightarrow n + \pi^+$$

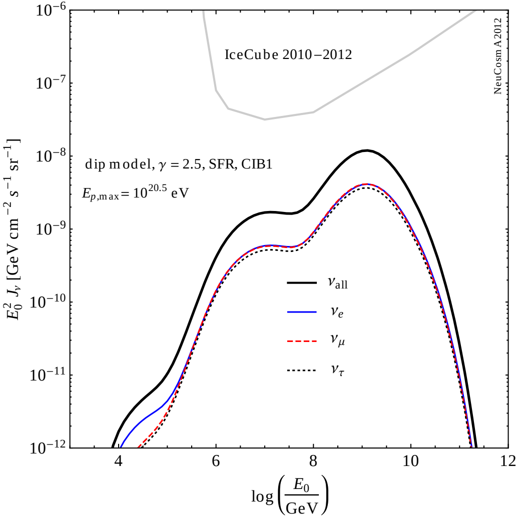
and the decays

$$\pi^+ \longrightarrow \mu^+ \nu_\mu \longrightarrow \bar{\nu}_\mu e^+ \nu_e \nu_\mu$$
$$n \longrightarrow p e^- \bar{\nu}_e$$

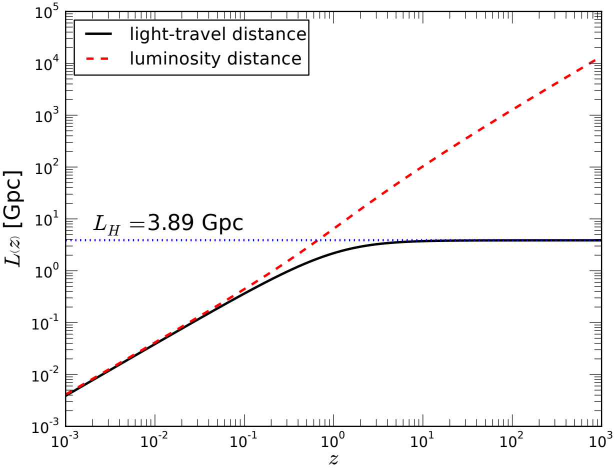
- Additional contributions (higher resonances, multi-pion production) implemented in NeuCosmA
- Our code calculates this cosmogenic, or GZK, ν flux given the proton injection at the sources

V. Berezinksy, G. Zatsepin, *Phys. Lett. B* **28**, 423 (1969)
F. Stecker, *Astrophys. J.* **228**, 919 (1979)

Cosmogenic ν flux: per flavour



Neutrino decay: light-travel distance



Neutrino decay: selected GRBs

Four sample bursts:

	SB	GRB080916c	GRB090902b	GRB091024
α	1	0.91	0.61	1.01
β	2	2.08	3.80	2.17
$\epsilon_{\gamma,\text{break}}$ [MeV]	1.556	0.167	0.613	0.081
Γ	$10^{2.5}$	1090	1000	195
t_v [s]	0.0045	0.1	0.053	0.032
T_{90} [s]	30	66	22	196
z	2	4.35	1.822	1.09
$\mathcal{F}_\gamma$ [erg cm^{-2}]	$1 \cdot 10^{-5}$	$1.6 \cdot 10^{-4}$	$3.3 \cdot 10^{-4}$	$5.1 \cdot 10^{-5}$
L_γ^{iso} [erg s^{-1}]	10^{52}	$4.9 \cdot 10^{53}$	$3.6 \cdot 10^{53}$	$1.7 \cdot 10^{51}$

SB: standard burst

S. HÜMMER, P. BAERWALD, AND W. WINTER,
PRIVATE NOTE ON NEUTRINO EMISSION FROM GRBS IN THE FIREBALL MODEL

Neutrino decay: flavour ratio

Flavour ratio $R = \phi_\mu / (\phi_e + \phi_\tau)$: