Multimessenger astroparticle physics

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Lectures 7a: Science

Anomalous propagation of photons. Axion-Like Particles. Testing relativity and cosmology with photons.
VHE neutrinos.

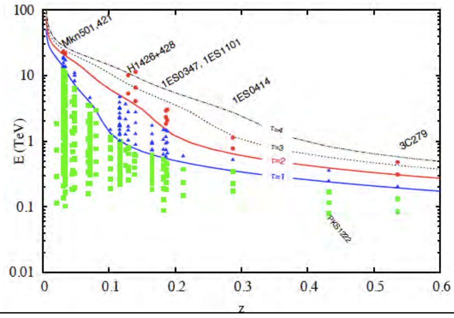
Detection of WISPs from photon propagation

Are our AGN observations consistent with theory (1) ?

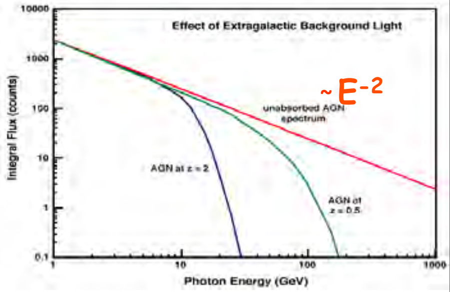
- For each AGN detected, a corresponding lower limit on the optical depth τ is calculated using a minimum EBL model
- Nonparametric test of consistency
- Disagreement with data: overall significance of 4.2 σ

=> Understand experimentally the outliers

(Horns, Meyer 2011)

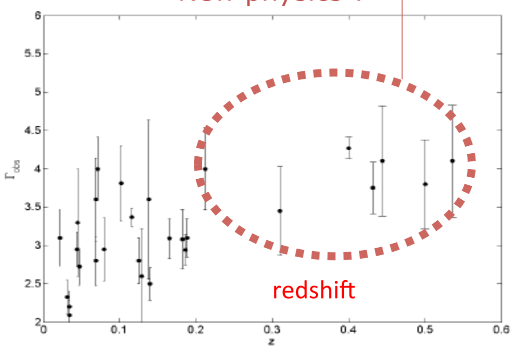


Are our AGN observations consistent with theory?



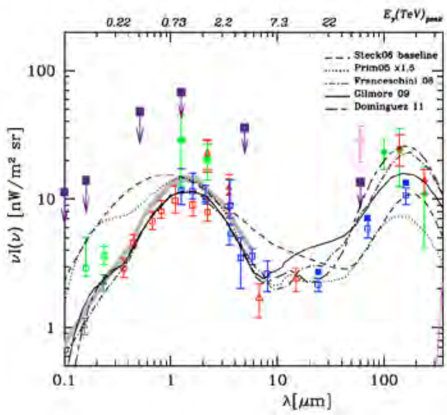
Measured spectra affected by attenuation in the EBL:

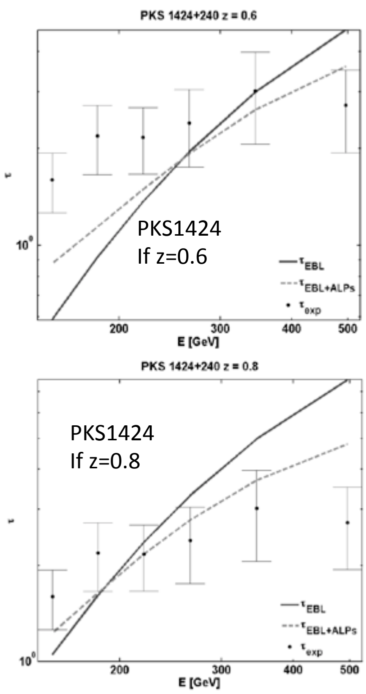
Selection bias?
New physics ?



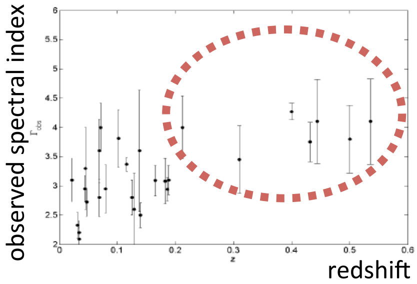
(DA, Galanti, Roncadelli; PRD 2011)

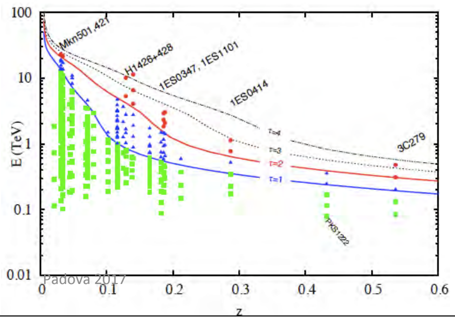
A reminder: EBL rather well constrained, and SED extrapolation from Fermi is possible





If there is a problem





Explanations from the standard ones

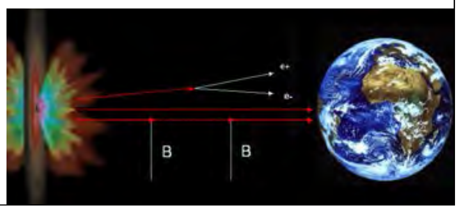
- very hard emission mechanisms with intrinsic slope < 1.5 (Stecker 2008)
- Very low EBL, plus observational bias, plus a couple of "wrong" outliers

to almost standard

- γ-ray fluxes enhanced by relatively nearby production by interactions of primary cosmic rays or ν from the same source

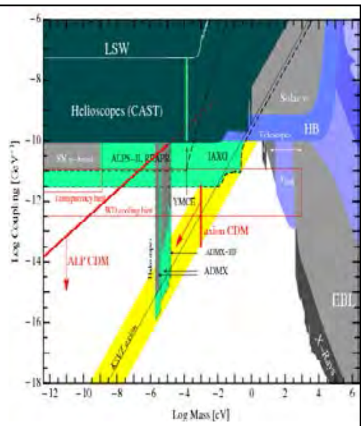
to possible evidence for new physics

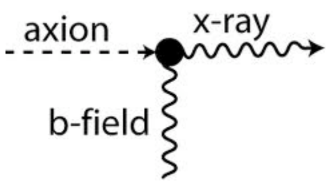
- Oscillation to a light particle coupled to the photon?



Axions and ALPs

- The "strong CP problem": CP violating terms exist in the QCD Lagrangian, but CP appears to be conserved in strong interactions
- Peccei and Quinn (1977) propose a solution: clean it up by an extra field in the Lagrangian
  - Called the "axion" from the name of a cleaning product
  - Pseudoscalar, neutral, stable on cosmological scales, feeble interaction, couples to the photon
    - Can make light shine through a wall
  - The minimal (standard) axion coupling g ∝ m; however, one can have an "ALP" in which g = 1/M is free from m
- m_a < 0.02 eV (direct searches)
- g < 10^{-10} GeV^{-1} from astrophysical bounds
- Production is not thermal, and it might be cold (ALPs can be a DM candidate)





$$\frac{m}{1\,\mathrm{eV}} \simeq \frac{1}{M/6\times10^{6}\,\mathrm{GeV}}$$

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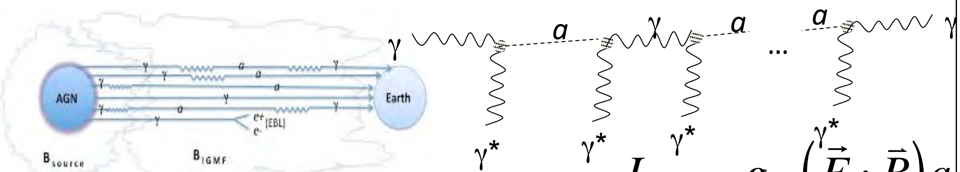
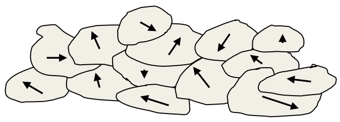
The photon-axion mixing mechanism



$$L_{a\gamma\gamma} = g_{a\gamma}\left(\vec{E}\cdot\vec{B}\right)a$$

- Magnetic field 1 nG < B < 1fG (AGN halos). Cells of ~ 1 Mpc

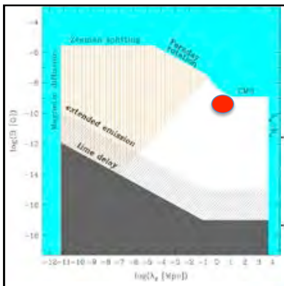


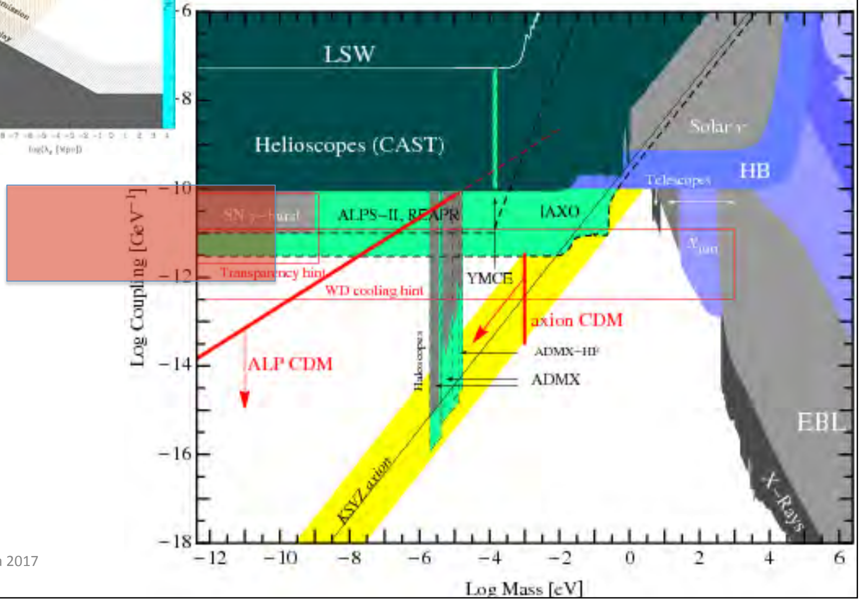
$$P_{\gamma\to a} \approx NP_1$$

$$P_1 \approx \frac{g_{a\gamma}^2 B_T^2 s^2}{4} \approx 2\times10^{-3}\left(\frac{B_T}{1\text{nG}}\frac{s}{1\text{Mpc}}\frac{g_{a\gamma}}{10^{-10}\,\text{GeV}^{-1}}\right)^2$$

- Photons-ALP mixing could enhance the transparency of the Universe:
  - Photon/ALP mixing in the intergalactic space (DA, Roncadelli & MAnsutti [DARMA], PRD2007)
  - Conversion into axion at the source, reconversion in the Milky Way (Hooper, Simet, Serpico 2008)Axion emission (Simet+, PRD2008)
  - A combination of the above

Preferred values for m, g (DARMA)





VERY EXOTIC PHYSICS (VIOLATION OF THE LORENTZ INVARIANCE+)

Is Lorentz invariance exact?

- For longtime violating Lorentz invariance/Lorentz transformations/Einstein relativity was a heresy
  - Is there an aether? (Dirac 1951)
  - Many preprints, often unpublished (=refused) in the '90s
- Then the discussion was open
  - Trans-GZK events? (AGASA collaboration 1997-8)
  - LIV => high energy threshold phenomena: photon decay, vacuum Cherenkov, GZK cutoff (Coleman & Glashow 1997-8)
  - GRB and photon dispersion (Amelino-Camelia et al. 1997)
  - Framework for the violation (Colladay & Kostelecky 1998)
  - LIV and gamma-ray horizon (Kifune 1999)

…

LIV? New form of relativity?

- Von Ignatowsky 1911: {relativity, omogeneity/isotropy, linearity, reciprocity} => Lorentz transformations with "some" invariant c (Galilei relativity is the limit c $\rightarrow\infty$)
- CMB is kind of an aether: give away isotropy?
- QG motivation: give away linearity? (A new relativity with 2 invariants: "c" and E_P)

- In any case, let's sketch an effective theory…
  – Let's take a purely phenomenological point of view and encode the general form of Lorentz invariance violation (LIV) as a perturbation of the Hamiltonian (Amelino-Camelia+)

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A heuristic approach: modified dispersion relations (perturbation of the Hamiltonian)

- We expect the Planck mass to be the scale of the effect

$$E_P = \sqrt{hc/G} \cong 1.2\times 10^{19}\,\text{GeV}$$

$$H^2 = m^2 + p^2 \rightarrow H^2 = m^2 + p^2\left(1 + \xi\frac{E}{E_P} + \ldots\right)$$

$$H \xrightarrow[p>>]{} p\left(1 + \frac{m^2}{2p^2} + \xi\frac{p}{2E_P} + \ldots\right)$$

$$v = \frac{\partial H}{\partial p} \cong 1 - \frac{m^2}{2p^2} + \xi\frac{p}{E_P} \Rightarrow \boxed{v_\gamma \cong 1 + \xi\frac{E}{E_P}}$$

=> effect of dispersion relations at cosmological distances can be important at energies well below Planck scale:

$$\boxed{\Delta t_\gamma \cong T\Delta E\frac{\xi}{E_P}}$$

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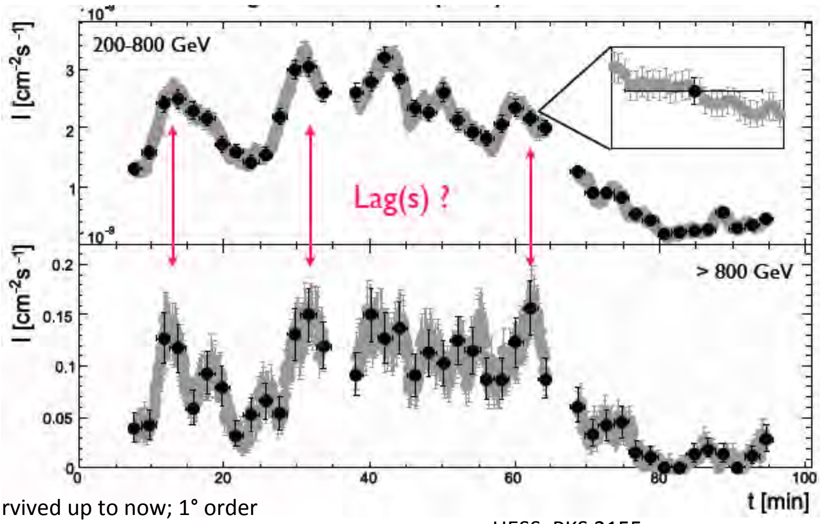
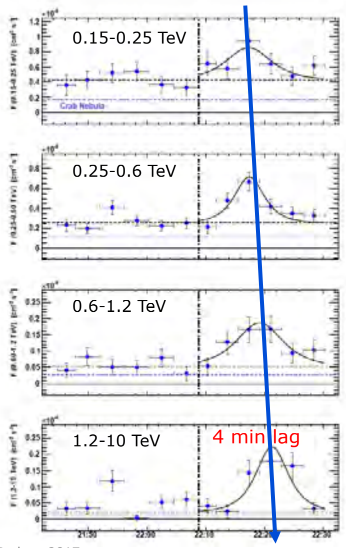
Rapid variability is the name of the game



No claim survived up to now; 1° order effects unlikely

HESS, PKS 2155

Apart from one positive claim
(MAGIC, Mkn 501 2007)
Finally interpreted as a source effect



$E_{QG,1} > 7.6\ E_P$

$E_{QG,2} > 1.3\text{x}10^{11}$ GeV

Mostly based on one GRB from Fermi

2nd order? Cherenkov rules!

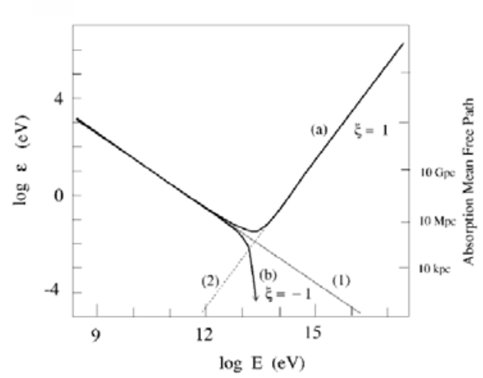
$$(\Delta t)_{obs} \cong \frac{3}{2}\left(\frac{\Delta E}{E_{s2}}\right)^2 H_0^{-1}\int_0^z dz' \frac{(1+z')^2}{\sqrt{\Omega_M (1+z')^3 + \Omega_\Lambda}}$$

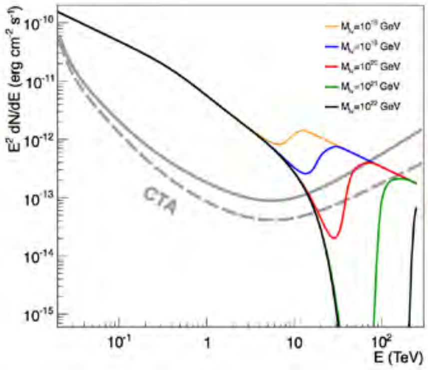
$E_{s2} > 10^{11}$ GeV (~$10^{-9}\ M_P$) (HESS, MAGIC, Fermi)

Kifune 1999: modified GRH due to LIV (increases or decreases depending on the sign of ξ)

LIV provides effective mass to photons → $m_\gamma^2 = \xi \frac{E_\gamma^{2+\alpha}}{E_{LIV}^{\alpha}}$

Protheroe&Meyer, Phys.Lett.B 93 (2000)





Fairbairn et al, arXiv:1401.8178 (2014)

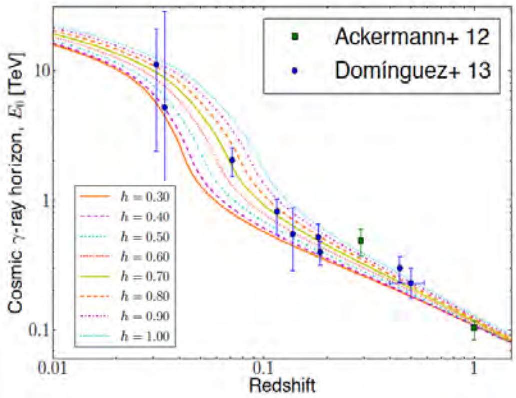
But: factorization questioned (Liberati, Sonego, …)

A win-win game: if no anomalous physics, determination of cosmological parameters

- Fluxes of VHE photons reaching the Earth have been attenuated due to the EBL density from observed spectra

⇒ Determine cosmological constants from observed HE spectra vs. fitted from lower energy

(Blanch & Martinez 2005; Dominguez & Prada 2013)

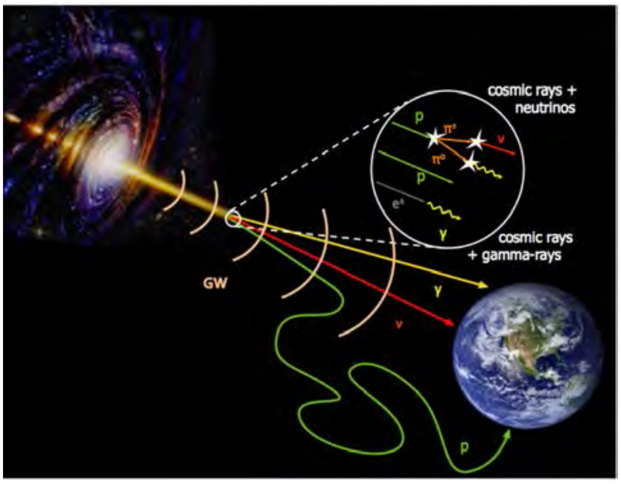


Cosmology

$$\tau(E,z) = \int_0^z \left(\frac{dl}{dz'}\right) dz' \int_0^2 d\mu \frac{\mu}{2} \int_{\varepsilon_{th}}^{\infty} d\varepsilon' \; \sigma_{\gamma\gamma}(\beta') n(\varepsilon', z')$$

$$\left|\frac{dt}{dz'}\right| = \frac{1}{H_0(1+z')E(z')}$$

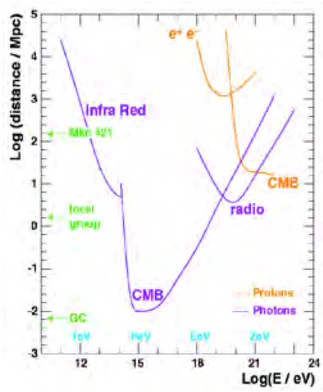
$$E(z') = \sqrt{\Omega_m(1+z')^3 + \Omega_\Lambda}$$



MULTIMESSENGER ASTROPHYSICS (Neutrinos and gravitational waves)

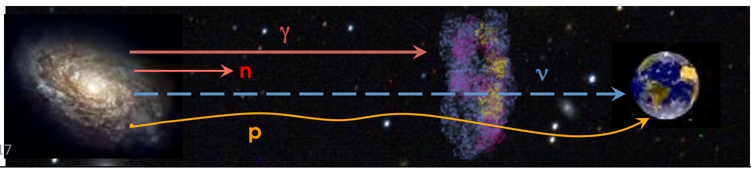
Why Neutrino Astronomy?

Photon and proton mean free range path



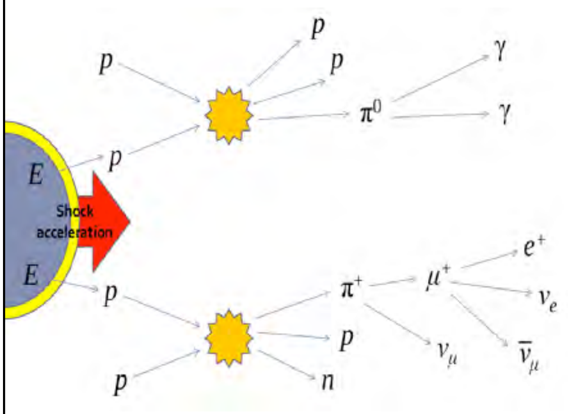
- Neutrino Astronomy is a quite recent and very promising experimental field.

- Advantages:
  - Photons: interact with CMB and matter (r~10 kpc @100 TeV)
  - Protons: interact with CMB (r~10 Mpc @10^{11} GeV) and undergo magnetic fields ($\Delta\theta$>1º, E<$5\cdot10^{10}$ GeV)
  - Neutrons: are not stable (r~10 kpc @10^{9} GeV)
- Drawback: large detectors (~GTon) needed.



γ and ν in cosmic accelerators:

Hadronic mechanisms produce both



Neutral mesons decay in **photons**:
$\pi^0 \rightarrow \gamma\gamma$
charged mesons decay in **neutrinos**:
$\pi^+ \rightarrow \nu_\mu + \mu^+$
$\mu^+ \rightarrow \nu_\mu + \nu_e + e^+$
$\pi^- \rightarrow \nu_\mu + \mu^-$
$\mu^- \rightarrow \nu_\mu + \nu_e + e^-$

$\#\nu \sim 3\#\gamma$

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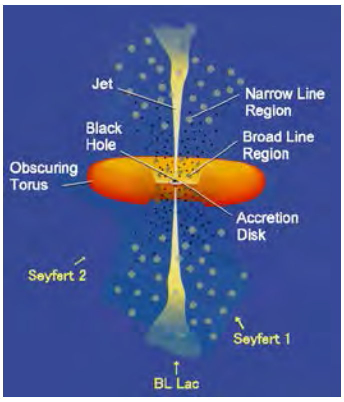
Astrophysical Sources: same as for gamma-rays

- Galactic sources: these are near objects (few kpc) so the luminosity requirements are much lower.
  - Supernova remnants
  - Micro-quasars
  - …
- Extra-galactic sources: Most powerful sources in the Universe
  - AGNs
  - GRBs



- Active Galactic Nuclei includes Seyferts, quasars, radio galaxies and blazars.
- Standard model: a super-massive (10^6-10^8 M_o) black hole towards which large amounts of matter are accreted.

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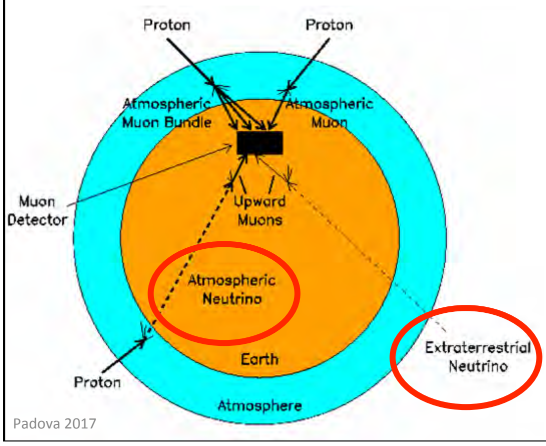
Need large volumes
Fight against background from atmospheric ν/μ
High energies (ν cross section)

- Atmospheric muons dominate by many order of magnitude the neutrino-induced muons.
- Upward-going particles are the best candidates for extraterrestrial ν .



Atmospheric neutrinos represent the irreducible background for νT

Upward-going muons (or horizontal muons) ARE neutrino-induced!

But don't go much beyond 1 PeV, or Earth will become opaque

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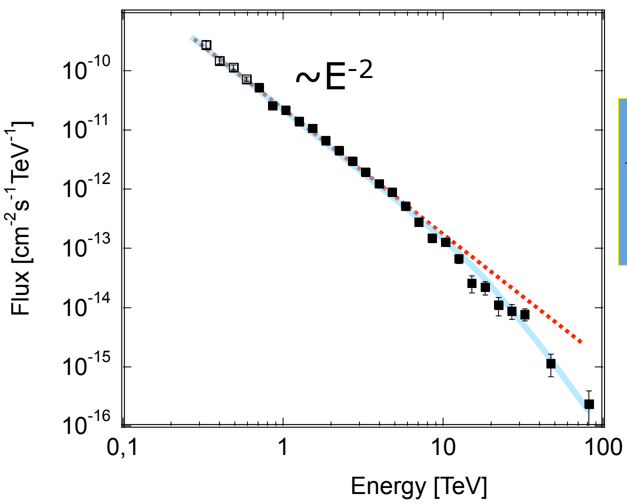
A source candidate: RX J1713.7-3946



RX J1713.7-3946 seen by HESS (gamma rays)

$$E^2_{\nu,\gamma}\frac{d\Phi_{\nu,\gamma}}{dE_{\nu,\gamma}} = $$
$$= 10^{-11}\ \text{TeV cm}^{-2} s^{-1}$$

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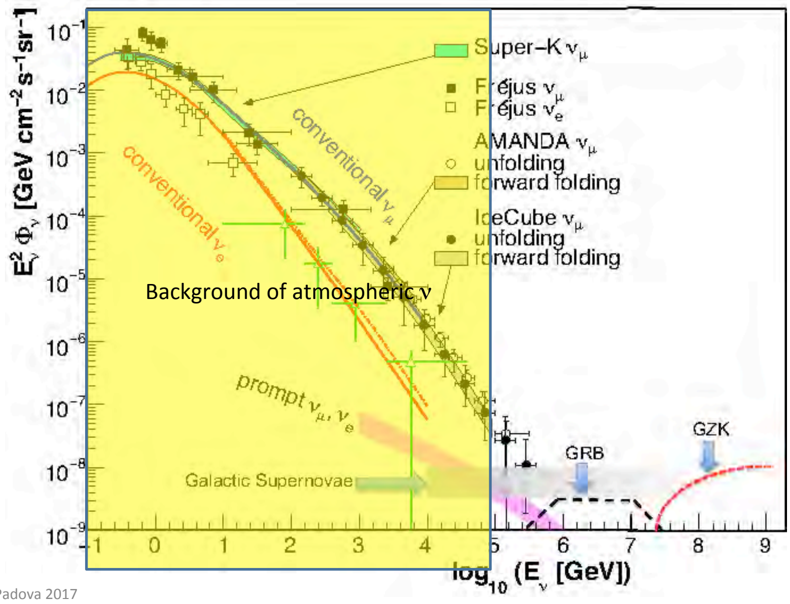
Diffuse flux of cosmic ν



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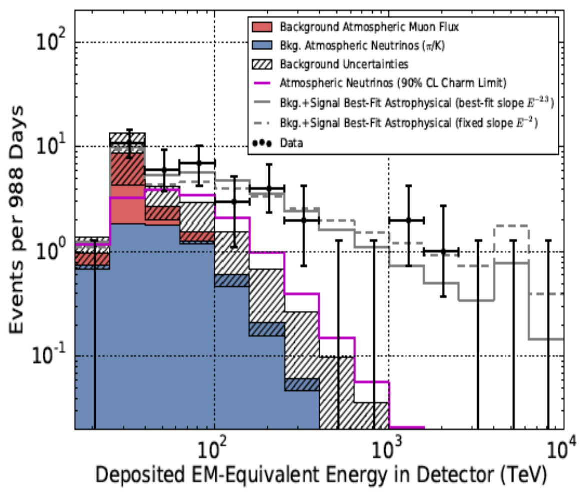
Excess of HE events over the background (IceCube 2014)

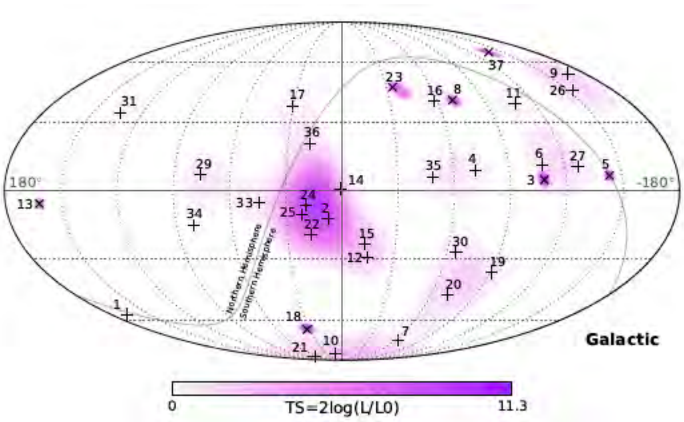
- Atmospheric muons
- Atmospheric neutrinos

=> Yes, astrophysical neutrinos exist

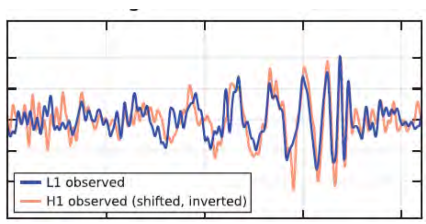


Excess of 22 events in 3 years from 30 TeV to 2 PeV (total of 37) with significance of 5.7σ;
3 events above 1 PeV

But their correlation with known or unknown sources is not significant



Gravitational waves



- A science experimentally started just now
- GW should be produced in binary mergers
  - Short GRBs?
  - Gammas delayed by ~ 1s?
- See next lecture

Summary of Lecture 7a

- Interesting perspects for fundamental physics from astroparticle physics
- Dark matter:
  - A standard WIMP below 400 GeV is on reach for HE gamma detectors, if the particles was in thermal equilibrium and $<\sigma v>$ is the same as at freeze-out
    - Dwarph spheroidals (no need for background models) and the GC region (a mess from the point of view of astronomy) are the favorite targets

    Needs a laboratory experiment to confirm
  - Can find indirect evidence for ALPs, but then <u>badly</u> needs a laboratory experiment to confirm
- Tests of fundamental physics/LIV: linear models appear disfavored, and our sensitivity at 2° order is far from the Planck scale (but we can do cosmology)
- Multimessenger astrophysics (just starting) will teach us more...
  - Protons cannot be used for astronomy (but they give os O(100 TeV) c.m. energies
  - We just detected astrophysical neutrinos (<~8/year with $1km^3$ detector), and we know that probably a several-km^3 detector is needed do to astronomy
  - Gravitational waves: maybe the answer is just around the corner

Exercises

1. *Neutrinos from SN1987A.* Neutrinos from SN1987A, at an energy of about 50 MeV, arrived in a bunch lasting 13 s from a distance of 50 kpc, 3 h before the optical detection of the supernova.What can you say on the neutrino mass? What can you say about the neutrino speed (be careful...)?
2. *Time lag in light propagation.* Suppose that the speed *c* of light depends on its energy E in such a way that

$$c(E) \simeq c_0 \left(1 + \xi \frac{E^2}{E_P^2} \right)$$

where E_P is the Planck energy (second-order Lorentz Invariance Violation). Compute the time lag between two VHE photons as a function of the energy difference and of the redshift *z*.