Multimessenger Astroparticle Physics

Alessandro De Angelis
Univ. PD, INFN/INAF Padova & LIP/IST Lisboa

6. Propagation of Cosmic Rays

Multimessenger astrophysics

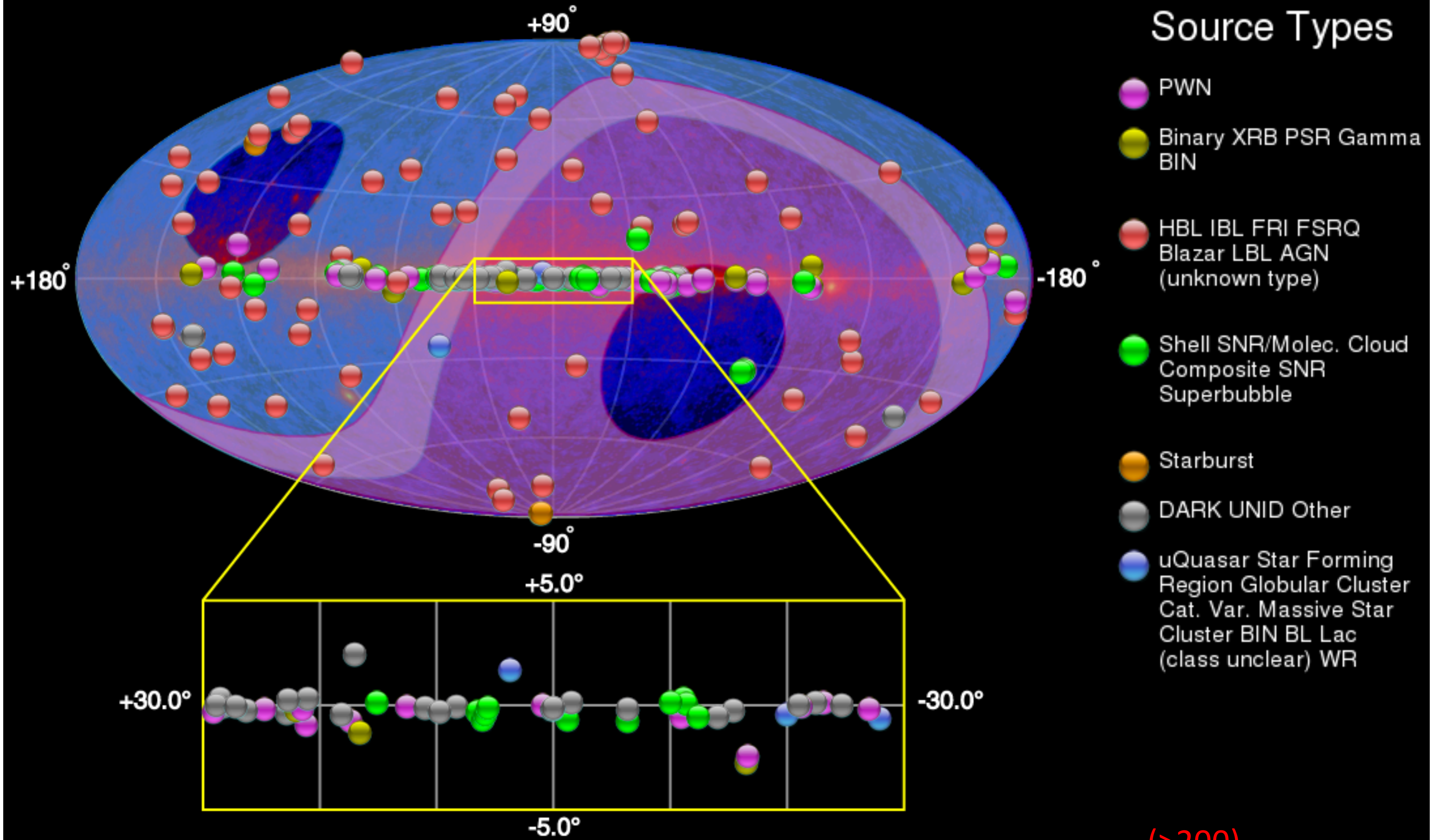
Several messengers can be used to study the properties of emitters (and btw particle physics)

- Charged cosmic rays. The more abundant, but they don't point to the sources (astronomy with charged cosmic rays is almost impossible)

$$\frac{R_L}{1\mathrm{kpc}} \simeq \frac{E/1\mathrm{EeV}}{B/1\mu\mathrm{G}}$$

- **Gamma rays.** They are suppressed with respect to protons by a factor 1000-10000
- Neutrinos. Difficult to detect, small X-section
- Gravitational waves. Recent.

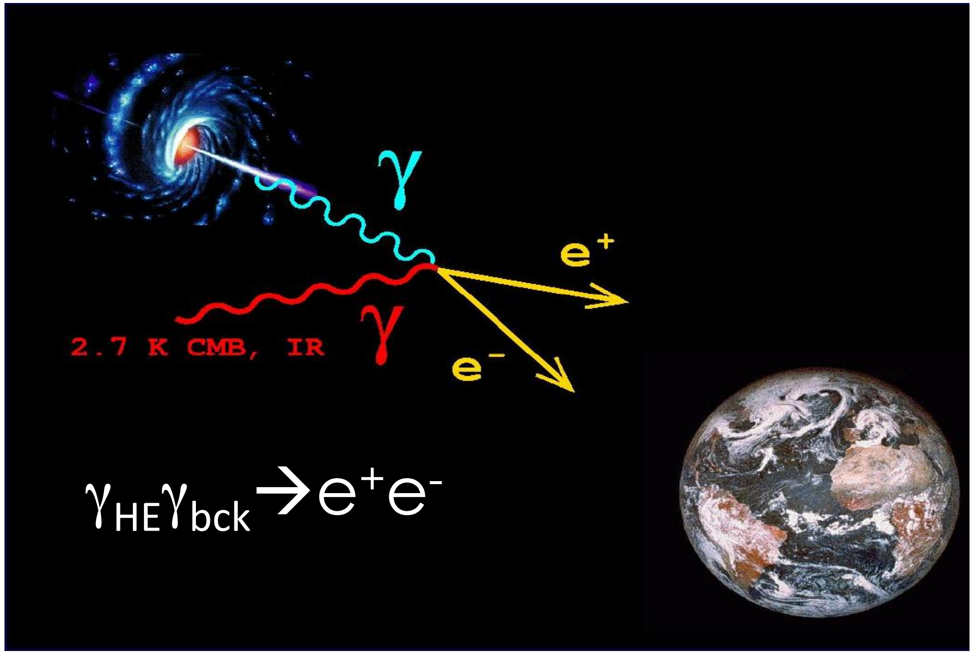
TeV sources tevcat.uchicago.edu



(>200)

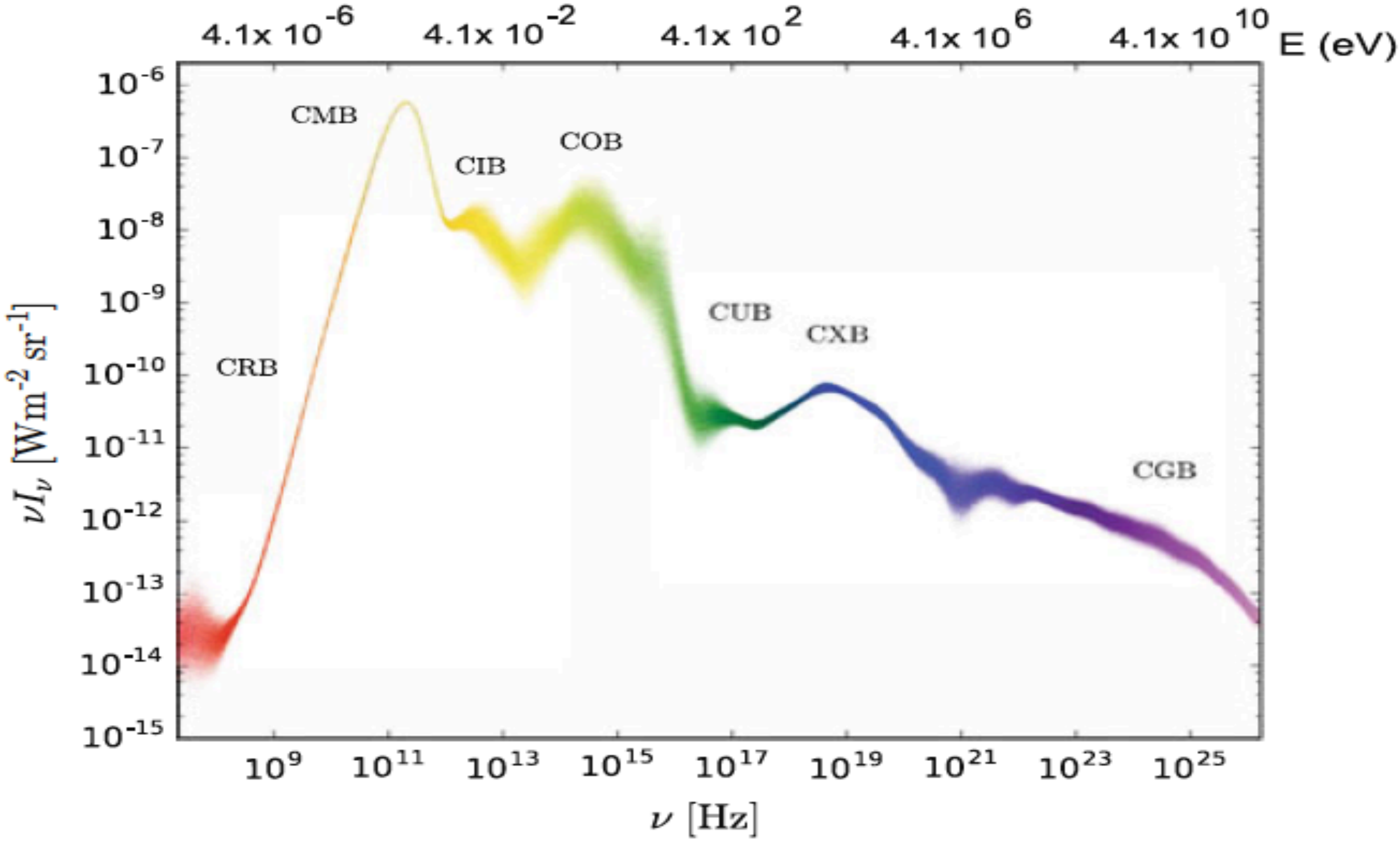
PROPAGATION OF PHOTONS

Attenuation of γ–rays

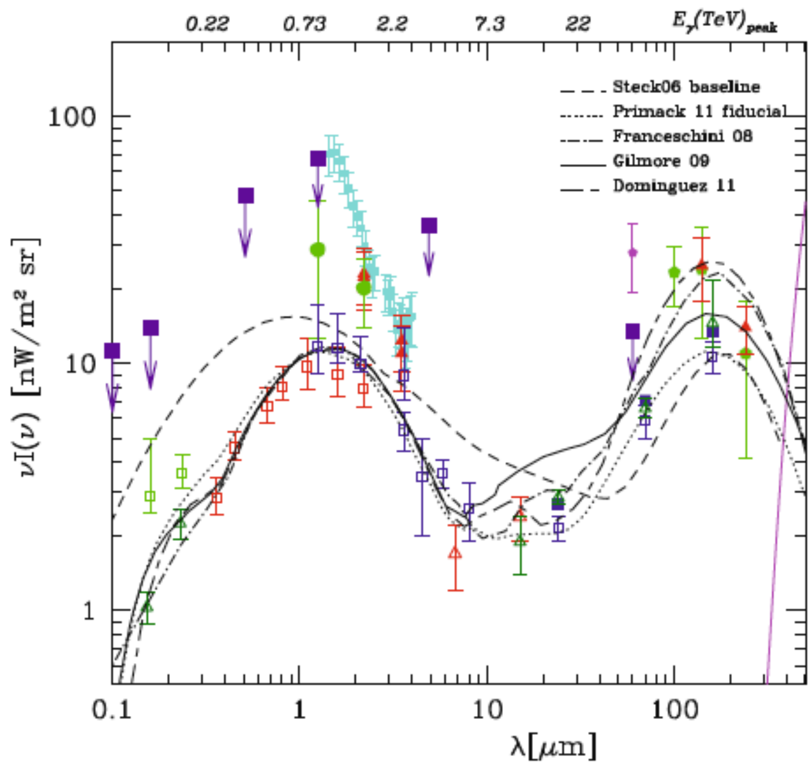


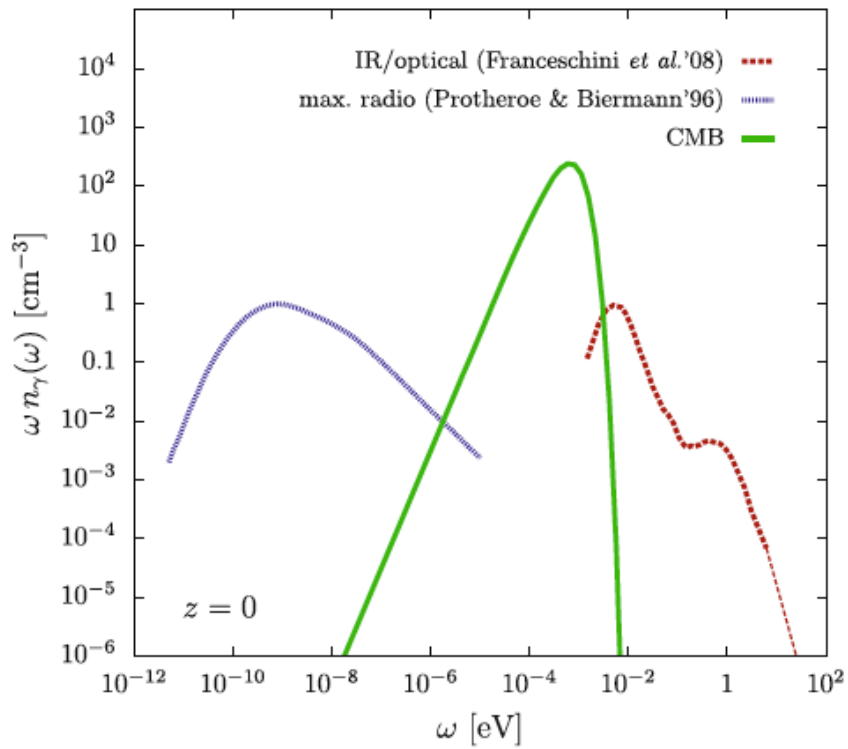
- γ-rays are effectively produced in EM and hadronic interactions
  - Energy spectrum at sources ~E^{-2}
- are effectively detected by space- and ground-based instruments
- effectively interact with matter, radiation ($\gamma\gamma \rightarrow e^+e^-$) and B-fields
- The interaction with background photons in the Universe attenuates the flux of gamma rays
- The "enemies" of VHE photons are photons near the optical region (Extragalactic Background Light, EBL)

Gamma-ray background in the Universe



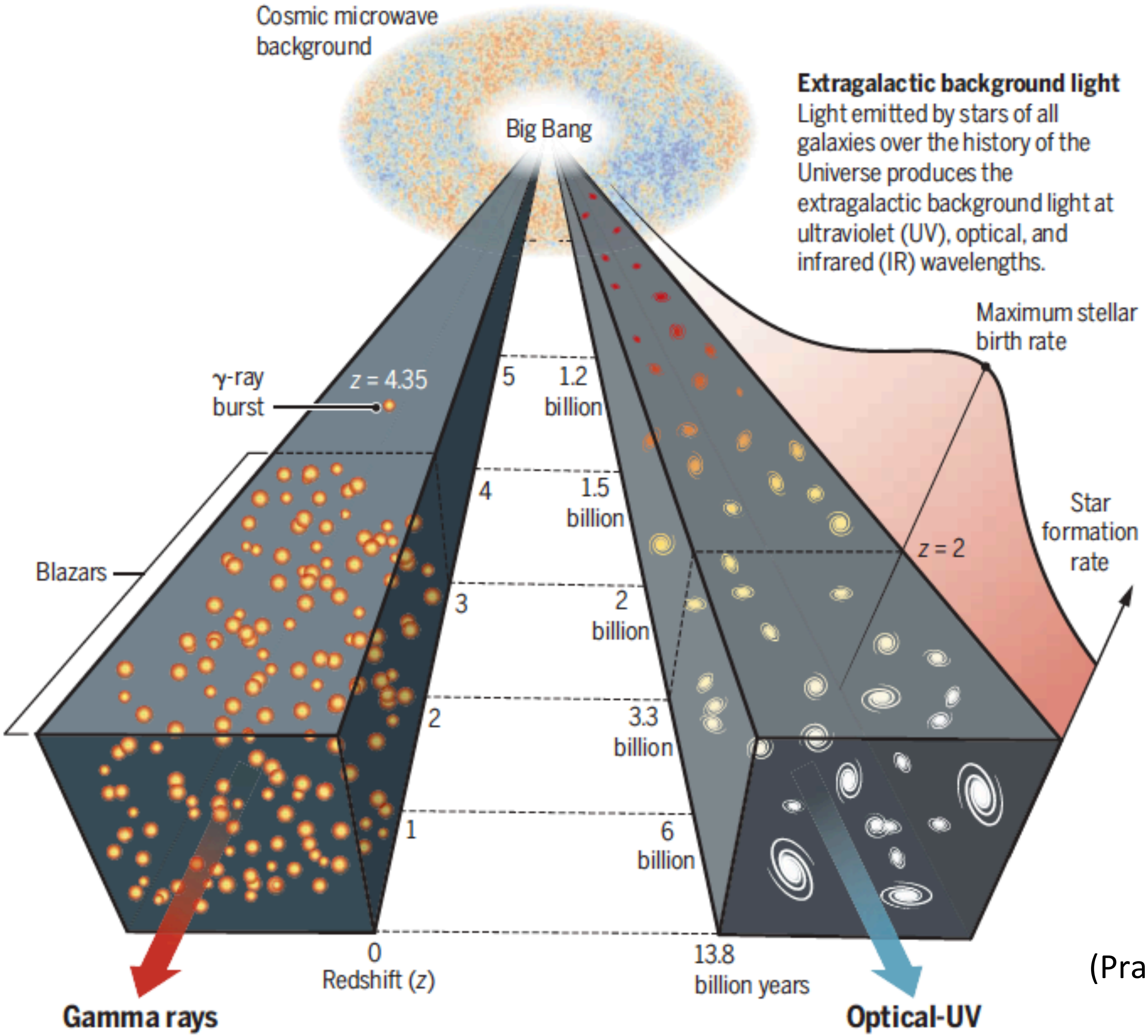
EBL





- Thermal peaks & nonthermal dstributions
- Maximum energy density: the CMB
- A region of particular interest is EBL, i.e., the light in the visible and near infrared regions.
- It is mainly composed by UV, optical, and near-infrared light emitted by stars throughout the whole cosmic history, and its re-emission to longer wavelengths by interstellar dust, which produces its characteristic double peak spectral energy distribution.
- This radiation is redshifted by the expansion of the Universe by a factor (1+ z)
- The density of EBL photons in the region near the visible can be derived by direct deep field observations, and by constraints on the propagation of VHE photons.

- The diffuse extragalactic background light (EBL) is all the accumulated radiation in the Universe due essentially to star formation processes
- This radiation covers a wavelength range between ~0.1 and 600 μm (consider the redshift and the reprocessing)
- After the CMB, the EBL is the second-most energetic diffuse background
- Understanding EBL is fundamental
  - To know the history of star formation
  - To model VHE photon propagation for extragalactic VHE astronomy. VHE photons coming from cosmological distances are attenuated by pair production with EBL photons. This interaction is dependent on the SED of the EBL.
- Therefore, it is necessary to know the SED of the EBL in order to study intrinsic properties of the emission in the VHE sources.
- To determine EBL:
  - Galaxy count + diffuse model
  - Attenuation of sources



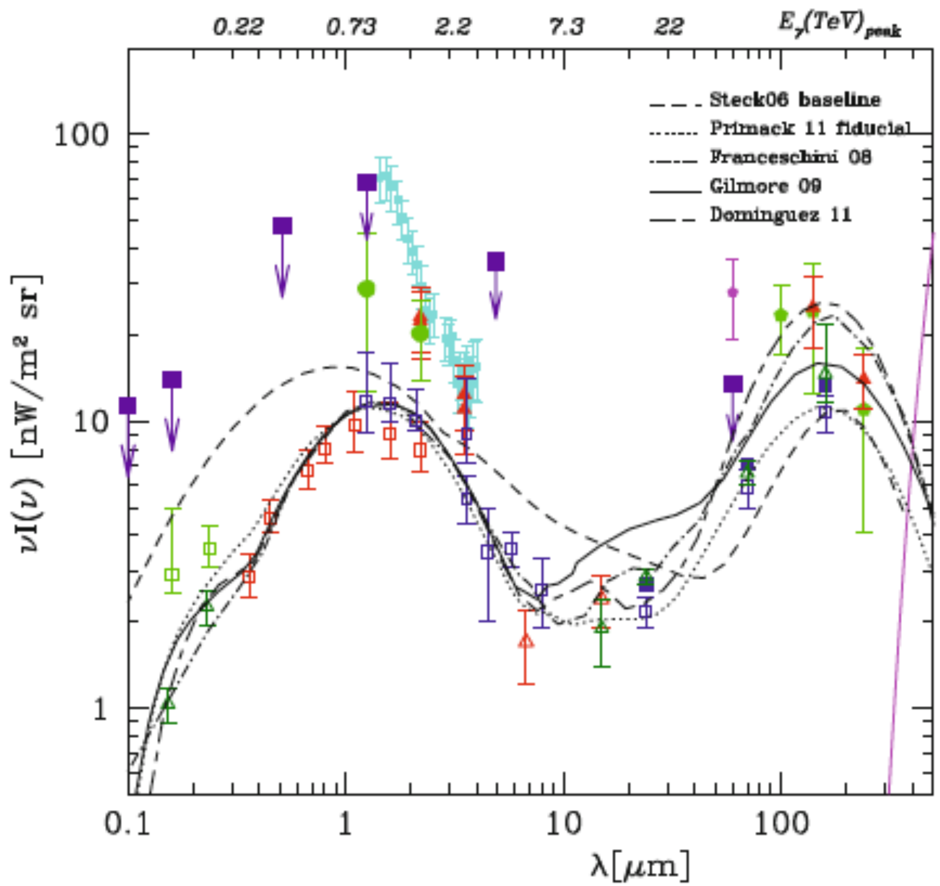
(Prandini 2018)

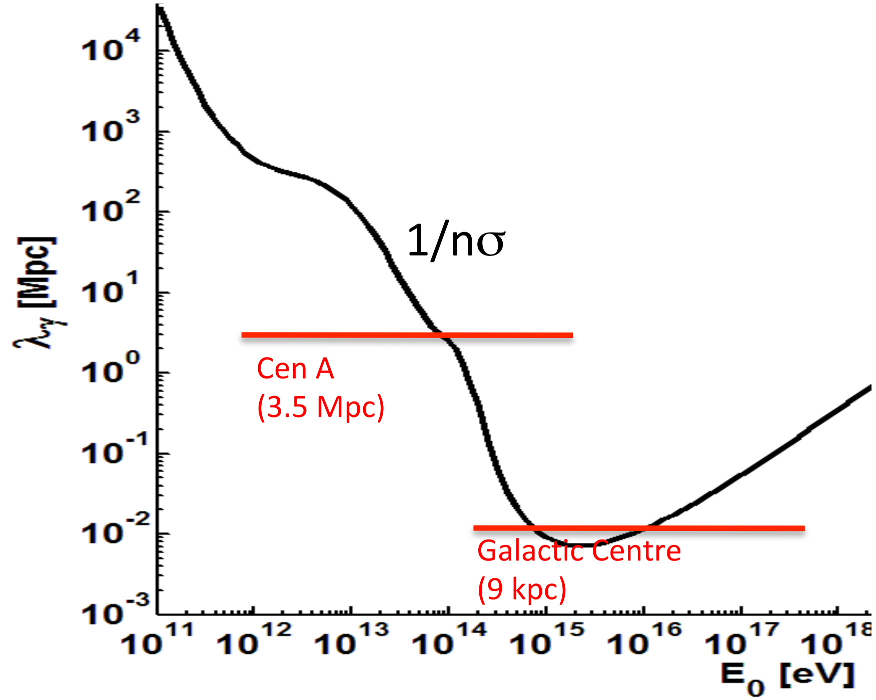
$$\gamma_{VHE}\gamma_{bck} \rightarrow e^+e^-$$

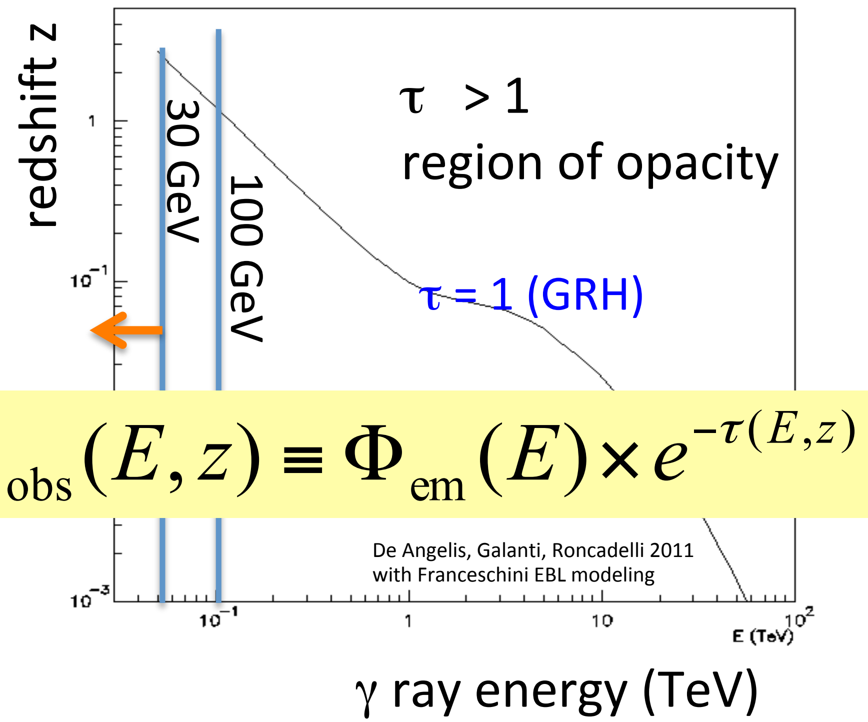
$$\sigma(\beta) \sim \frac{2\pi\alpha^2}{3m_e^2} W(\beta) \simeq 1.25 \cdot 10^{-25}\, W(\beta)\ \mathrm{cm}^2$$

$$W(\beta) = (1-\beta^2)\left[2\beta(\beta^2-2) + (3-\beta^4)\ \ln\left(\frac{1+\beta}{1-\beta}\right)\right]$$

Max for: $\epsilon(E) \simeq \left(\frac{900\ \mathrm{GeV}}{E}\right)$ eV

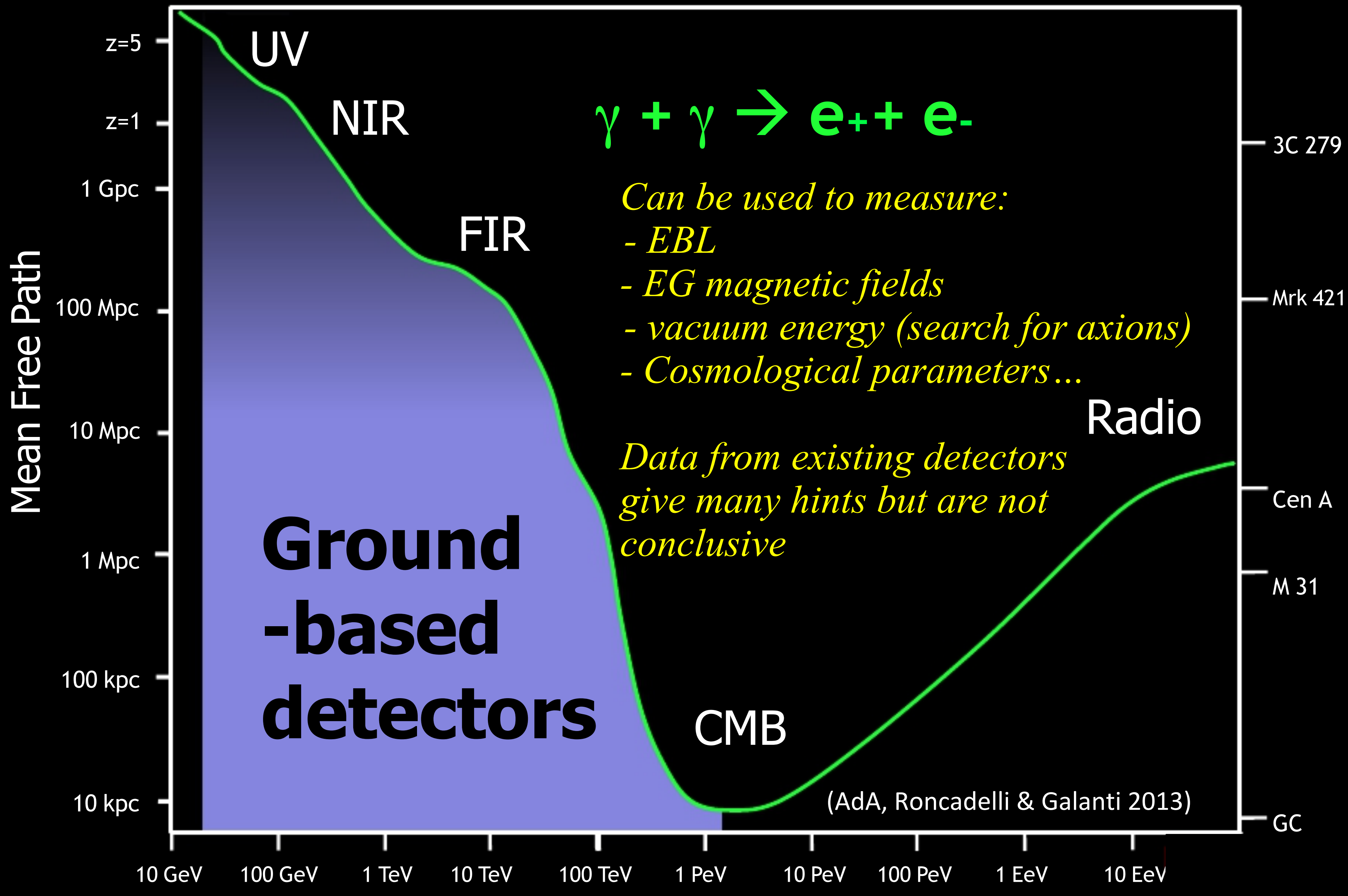






$$\Phi_{obs}(E,z) \equiv \Phi_{em}(E) \times e^{-\tau(E,z)}$$

The γ horizon: nuisance and resource

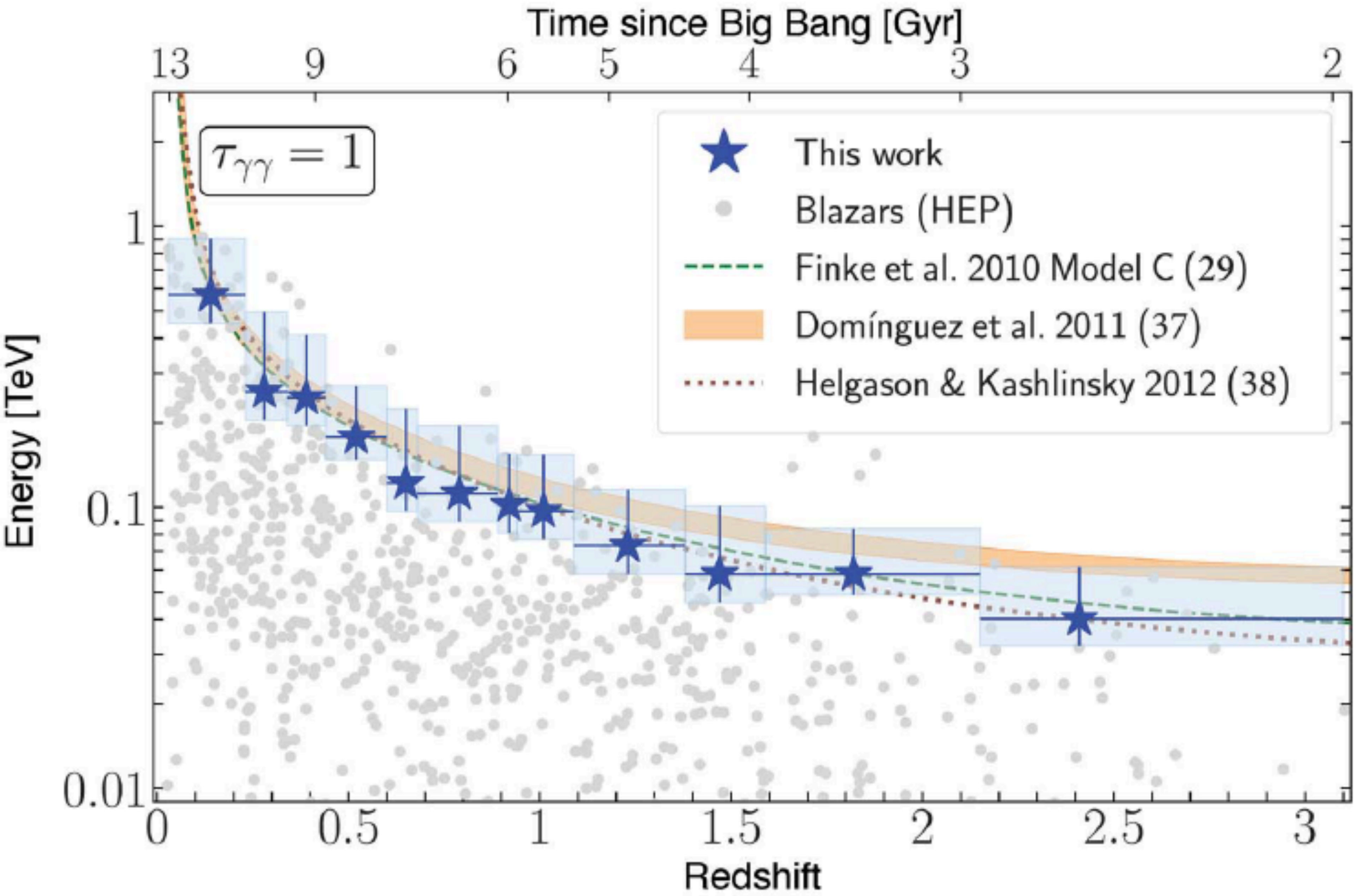


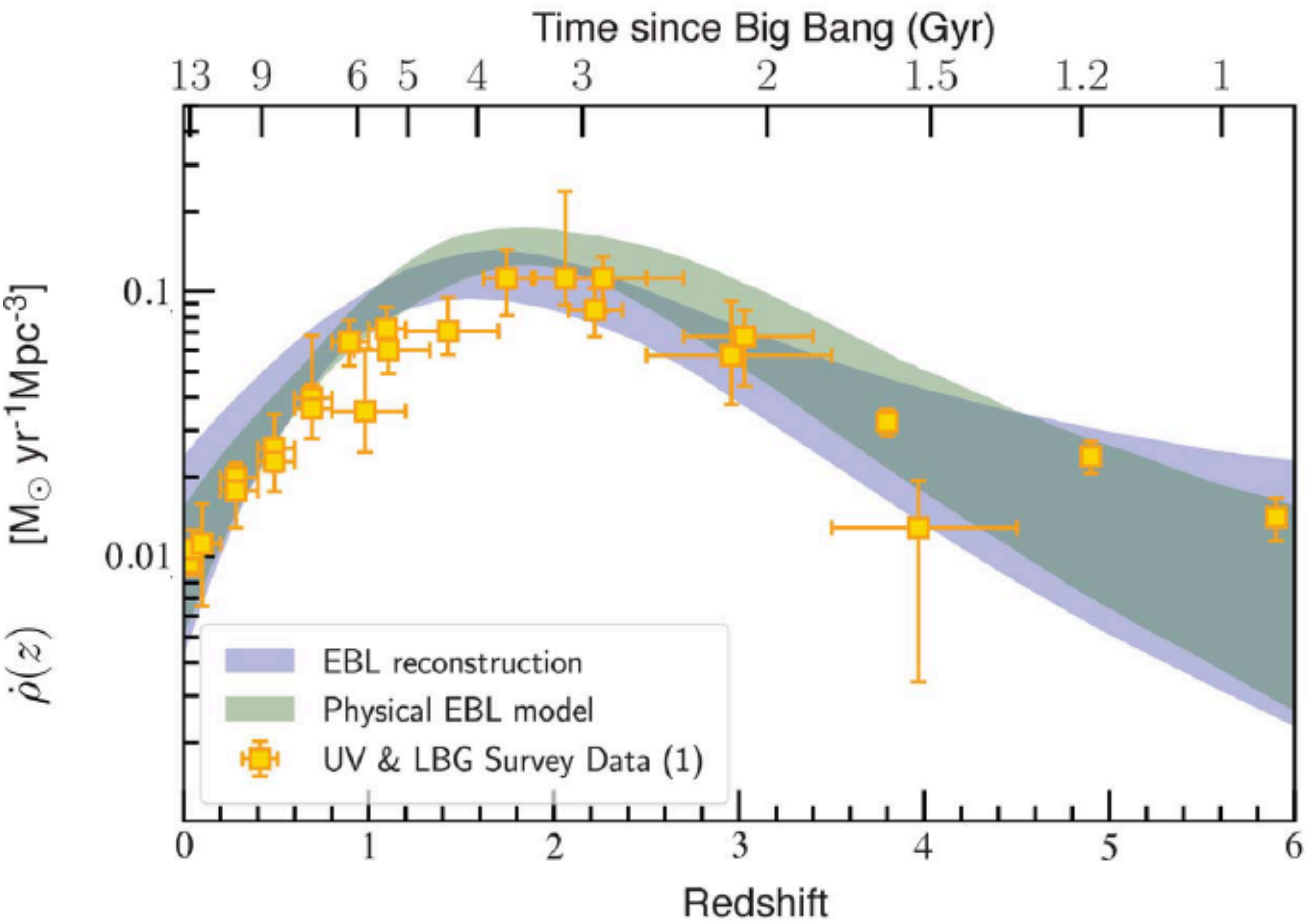
$\gamma + \gamma \rightarrow e_+ + e_-$

Can be used to measure:
- *EBL*
- *EG magnetic fields*
- *vacuum energy (search for axions)*
- *Cosmological parameters…*

Data from existing detectors give many hints but are not conclusive

739 VHE sources by Fermi and gamma horizon



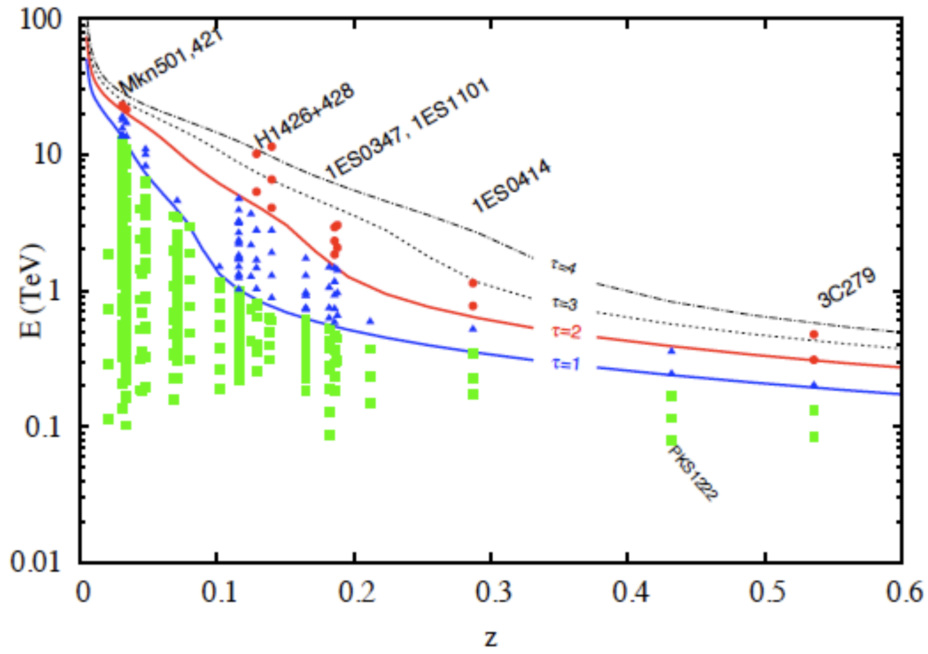

Time since Big Bang (Gyr)
13
9
6
5
4
3
2
1.5
1.2
1
0.1
0.01
$\dot{\rho}(z)$ [$M_\odot$ yr^{-1}Mpc^{-3}]
EBL reconstruction
Physical EBL model
UV & LBG Survey Data (1)
0
1
2
3
4
5
6
Redshift

Are our AGN observations consistent with theory?

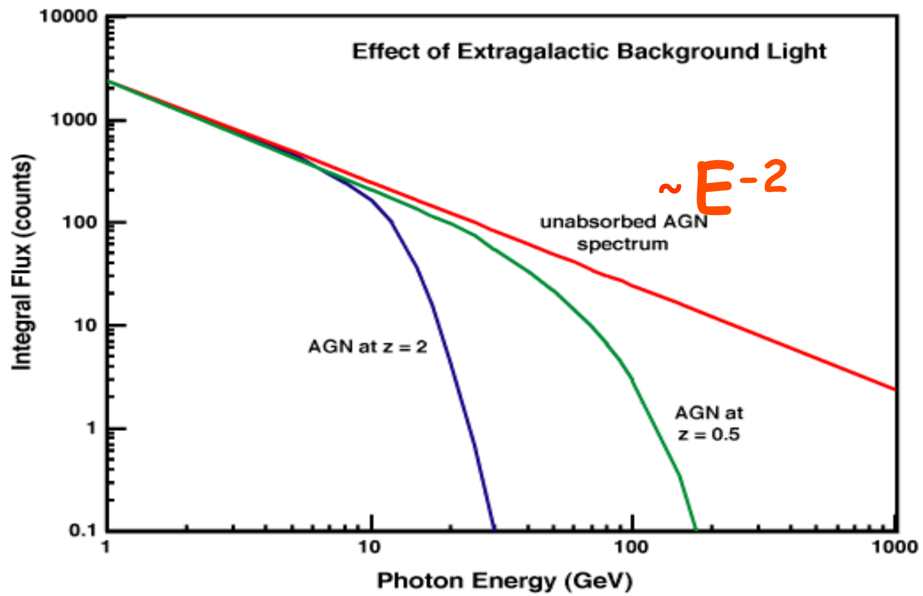
- For each AGN detected, a corresponding lower limit on the optical depth τ is calculated using a minimum EBL model
- Nonparametric test of consistency
- Disagreement with data: overall significance of ~4 σ

=> <u>Understand experimentally the outliers</u>

(Horns, Meyer 2011)

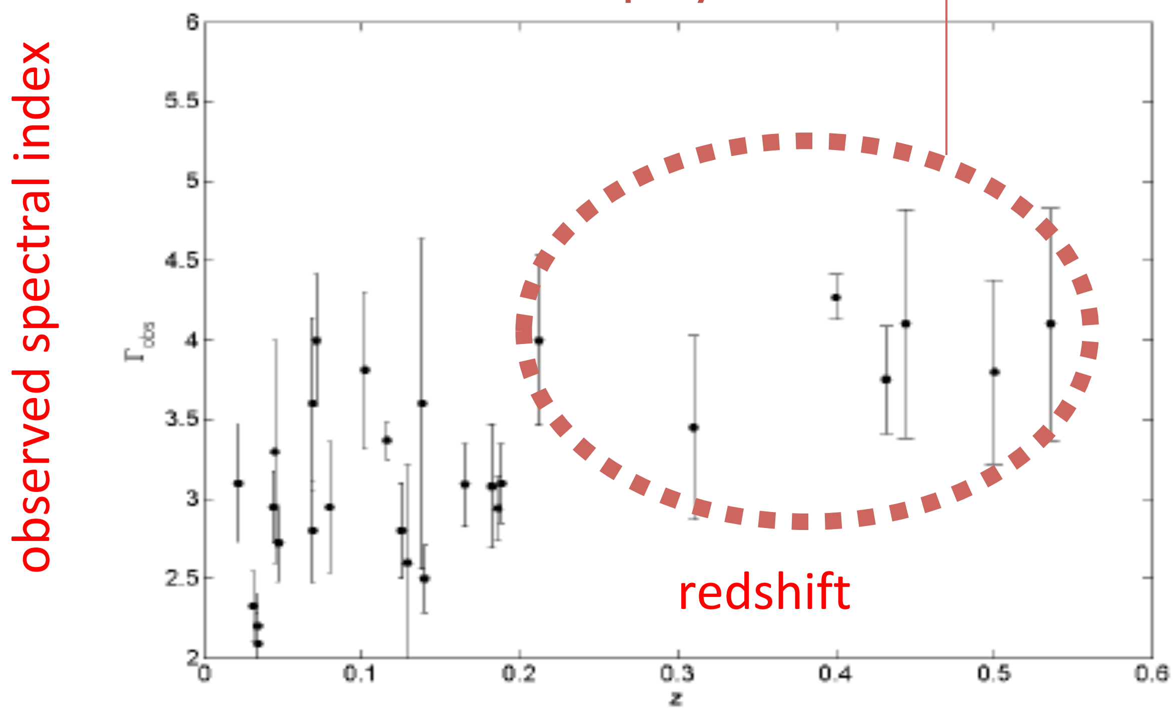


Are our AGN observations consistent with theory?



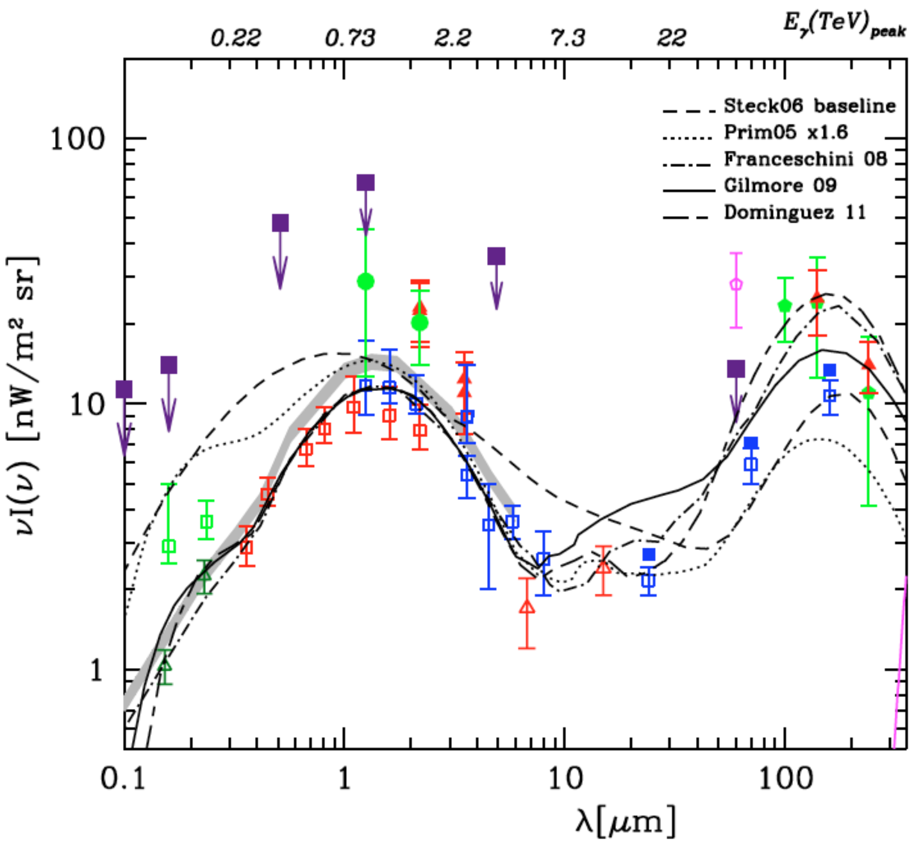
Measured spectra affected by attenuation in the EBL:

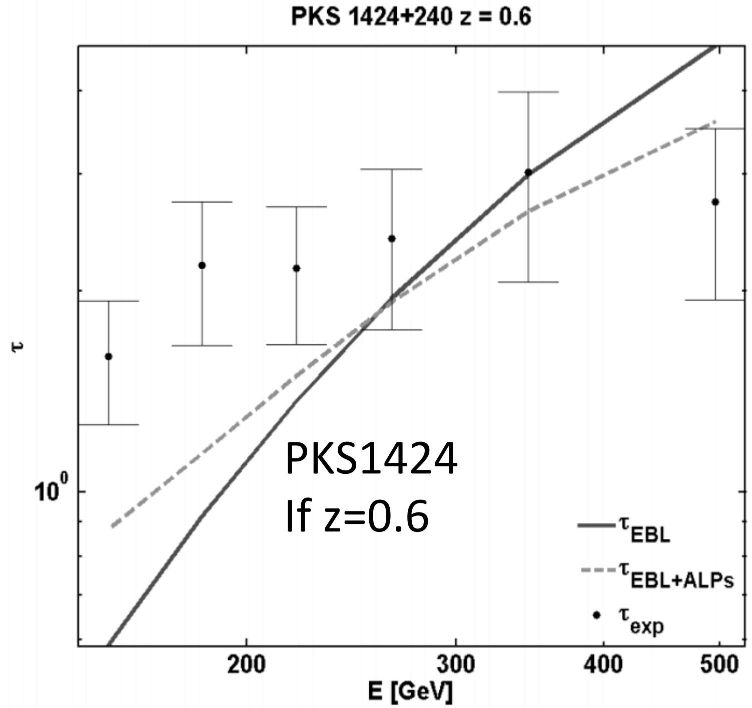
Selection bias?
New physics ?

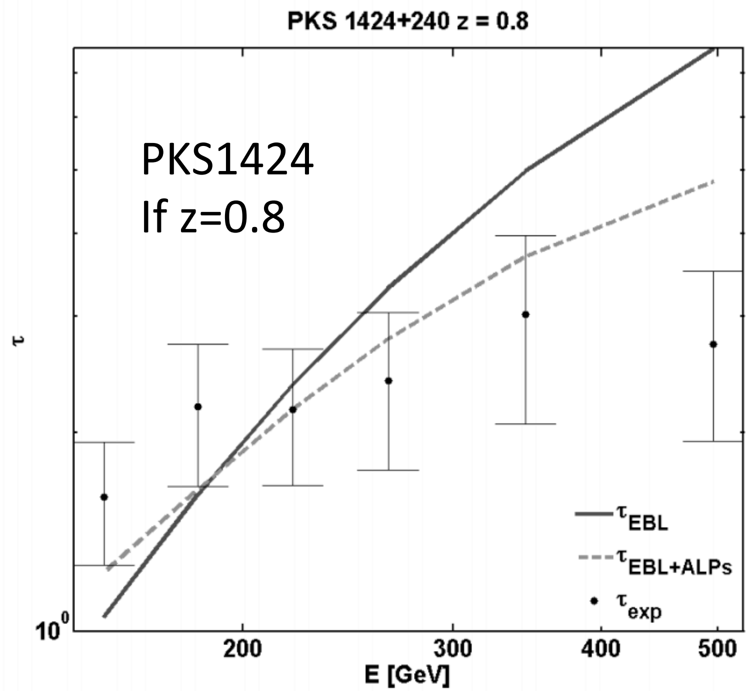


(DA, Galanti, Roncadelli; PRD 2011)

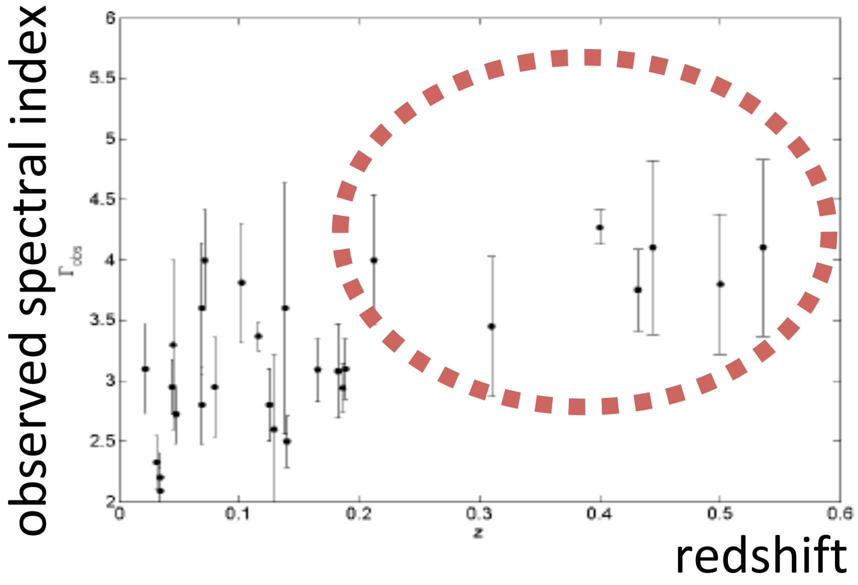
A reminder: EBL rather well constrained, and SED extrapolation from Fermi is possible

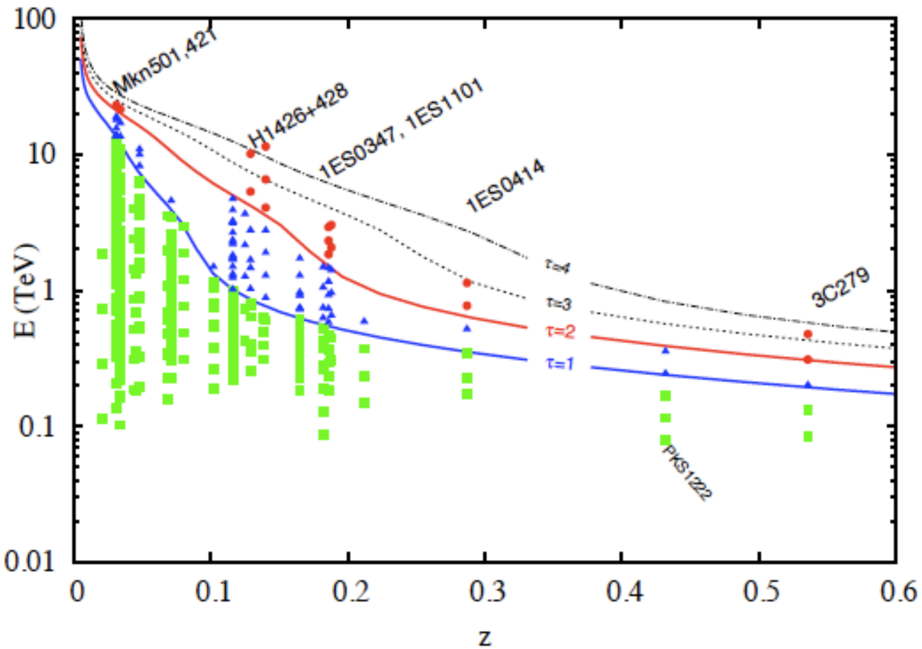






If there is a problem





Explanations from the standard ones

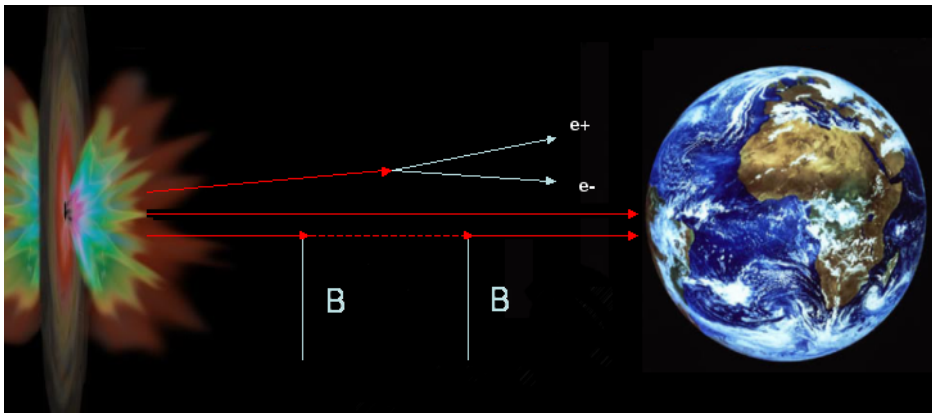
- very hard emission mechanisms with intrinsic slope < 1.5 (Stecker 2008)
- Very low EBL, plus observational bias, plus a couple of “wrong” outliers

to almost standard

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

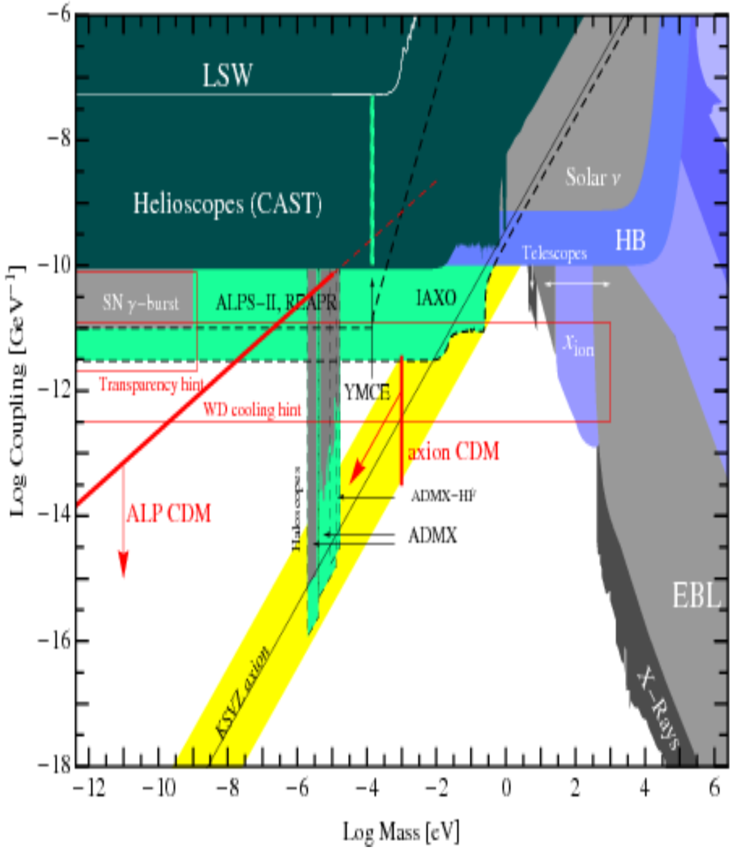
to possible evidence for new physics

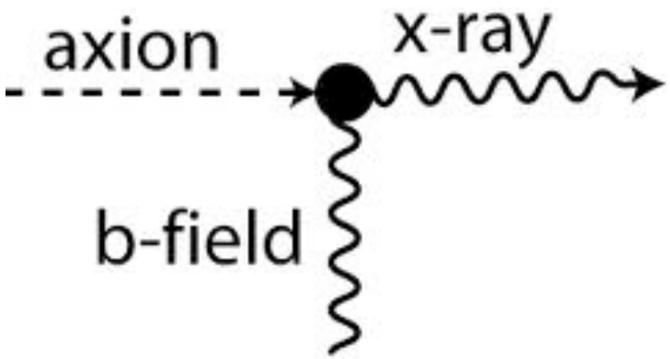
- Oscillation to a light particle coupled to the photon?



Axions and ALPs

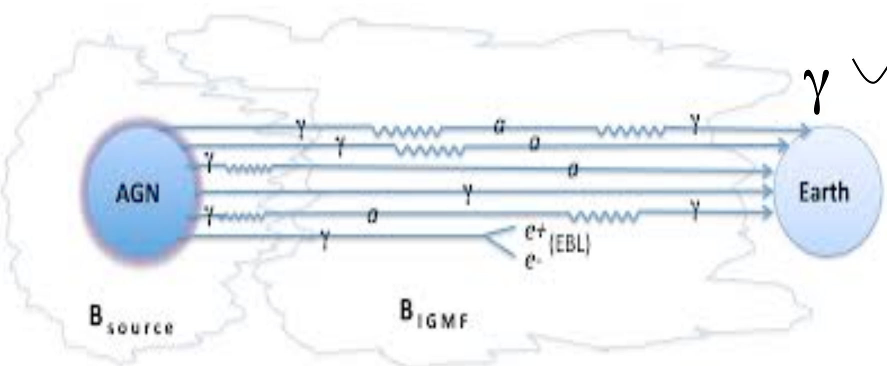
- The “strong CP problem”: CP violating terms exist in the QCD Lagrangian, but CP appears to be conserved in strong interactions
- Peccei and Quinn (1977) propose a solution: clean it up by an extra field in the Lagrangian
  - Called the “axion” from the name of a cleaning product
  - Pseudoscalar, neutral, 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)

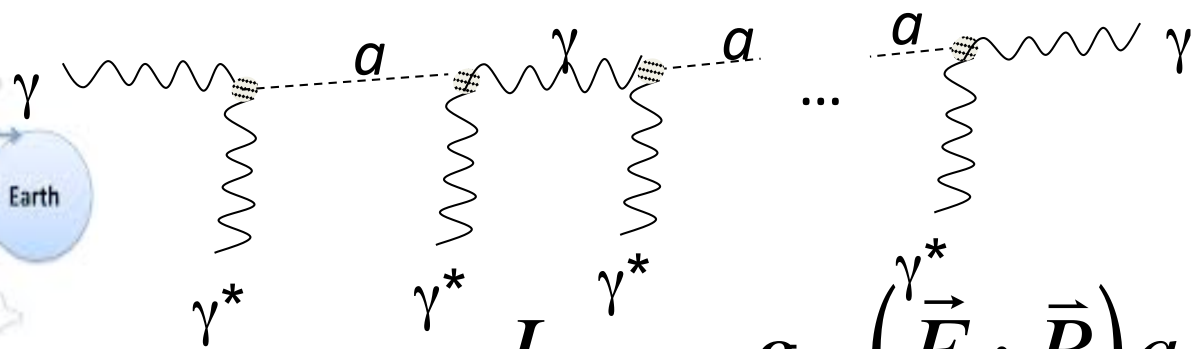




$$\frac{m}{1\,\mathrm{eV}} \simeq \frac{1}{M/6\times 10^{6}\,\mathrm{GeV}}$$

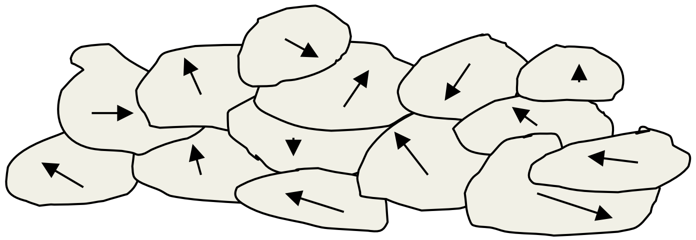
The photon-axion mixing mechanism





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

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

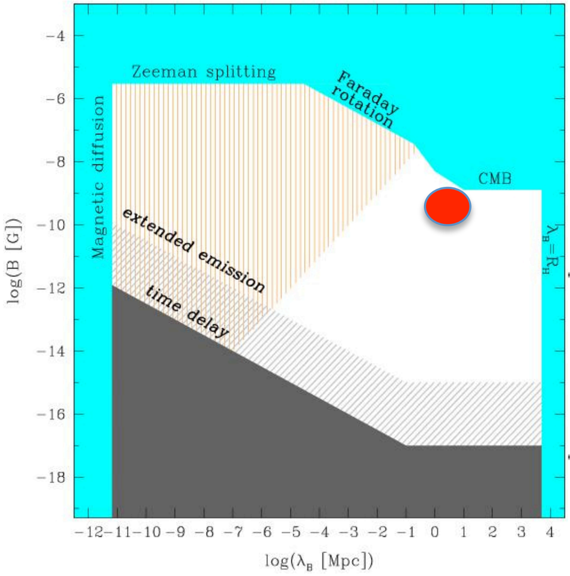


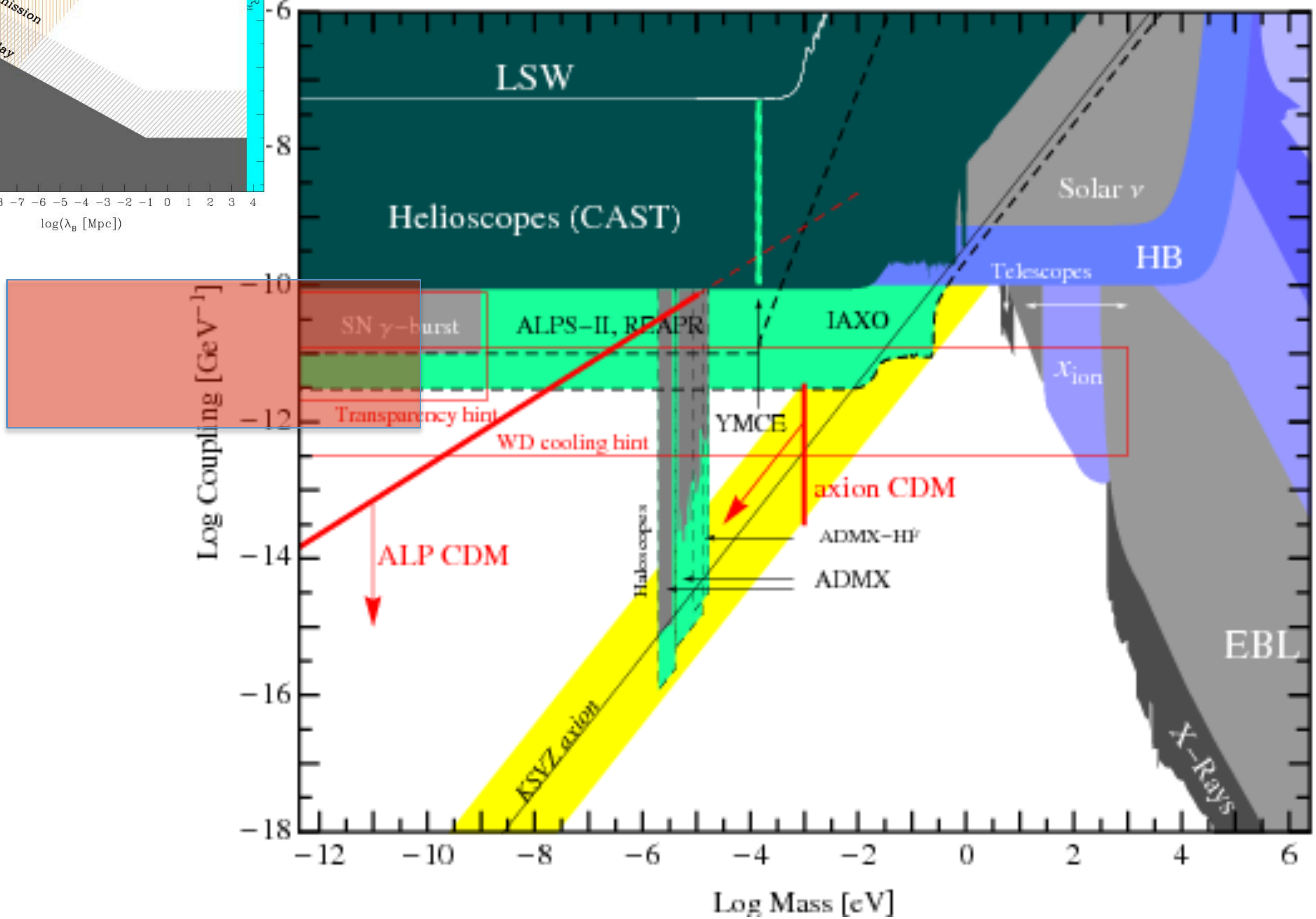
$$P_{\gamma\to a} \approx NP_1$$

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

- 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 $c \to \infty$)
- 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+)

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

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

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

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

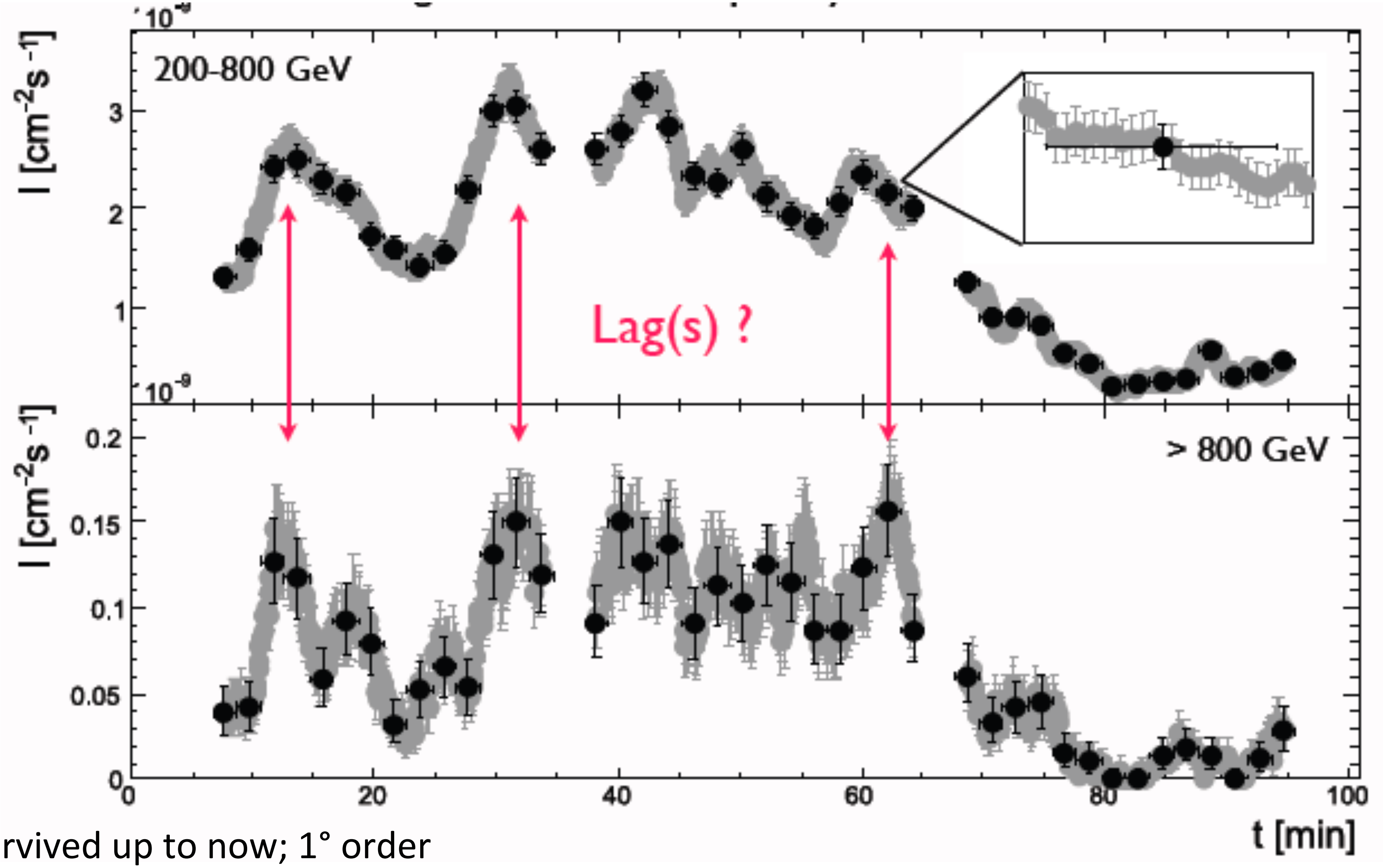
$$H \xrightarrow[p>>]{} p\left(1 + \frac{m^2}{2p^2} + \xi\frac{p}{2E_P} + \ldots\right)$$

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

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

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

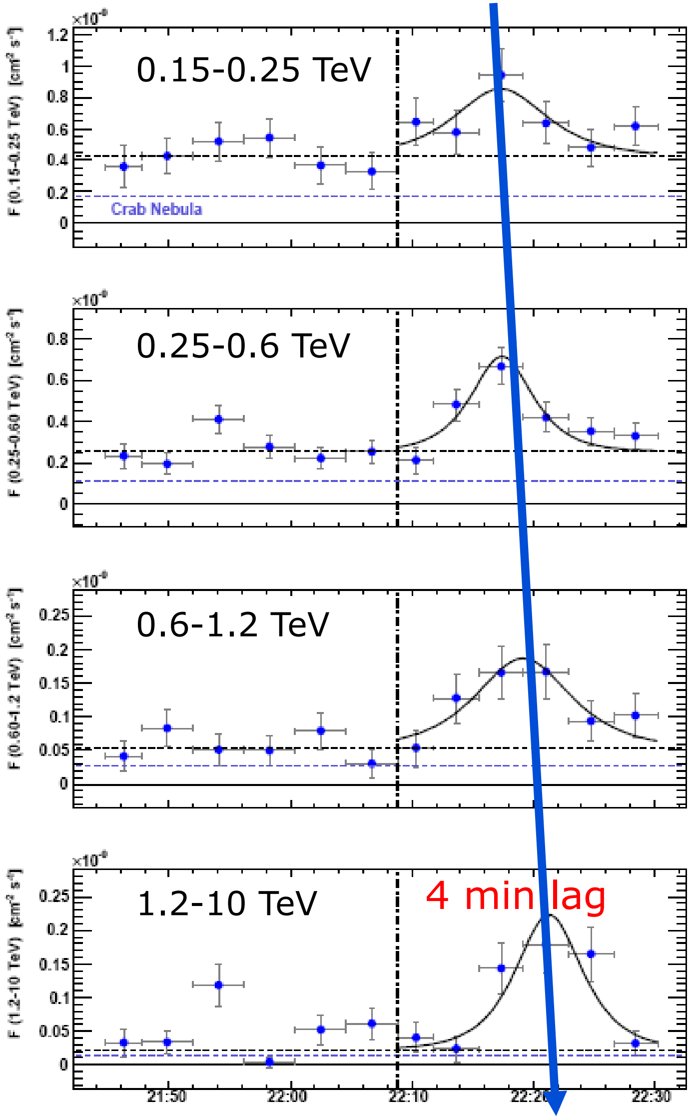
Rapid variability is the name of the game



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



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

$E_{QG,2} > 1.3\times10^{11}$ GeV

Mostly based on one GRB from Fermi

2nd order? Cherenkov rules!

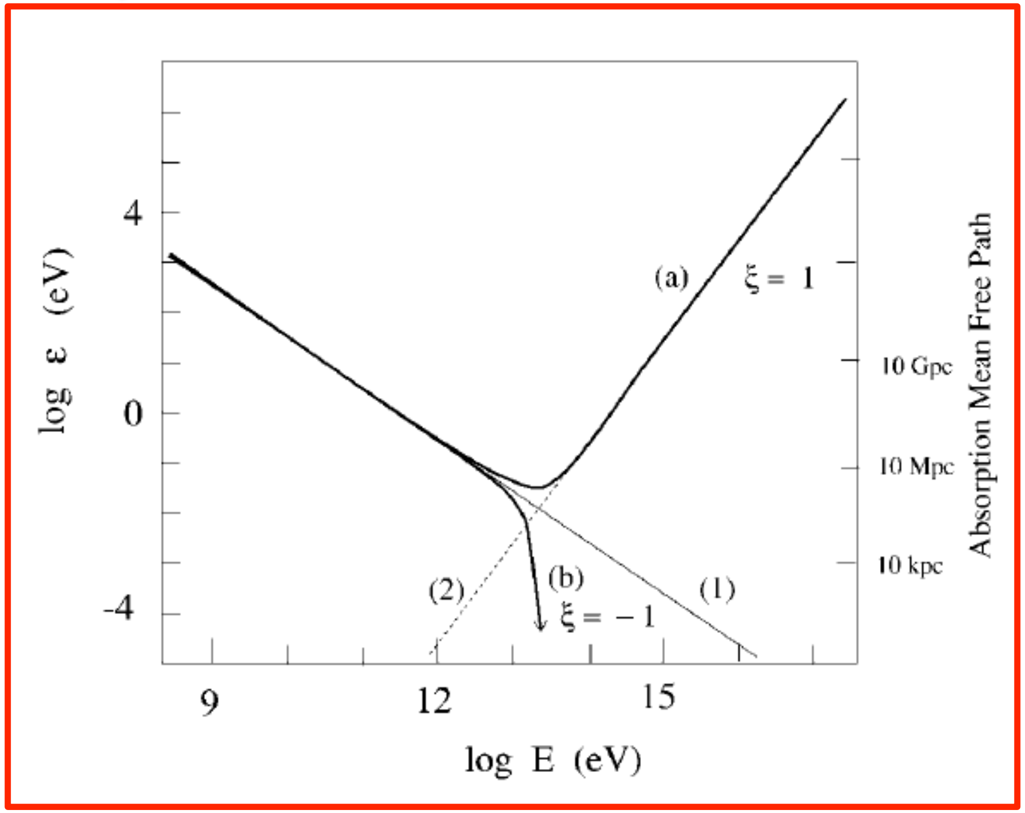
$$(\Delta t)_{obs} \cong \frac{3}{2}\left(\frac{\Delta E}{E_{s2}}\right)^2 H_0^{-1}\int_0^z dz' \frac{(1+z')^2}{\sqrt{\Omega_M (1+z')^3 + \Omega_\Lambda}}$$

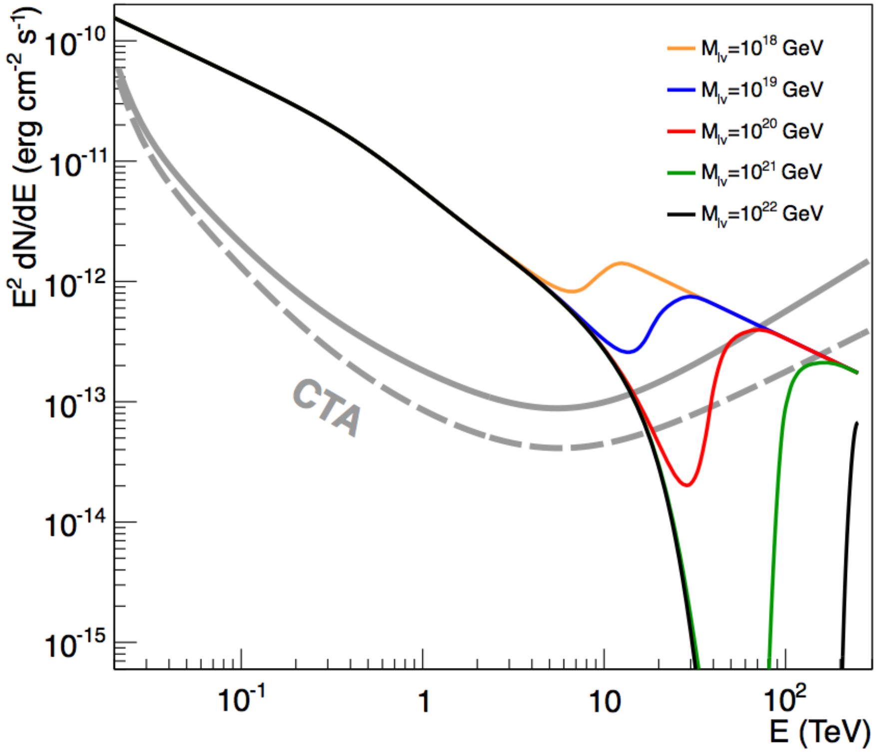
$E_{s2} > 10^{11}$ GeV (~10^{-9} M_P) (HESS, MAGIC, Fermi)

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)

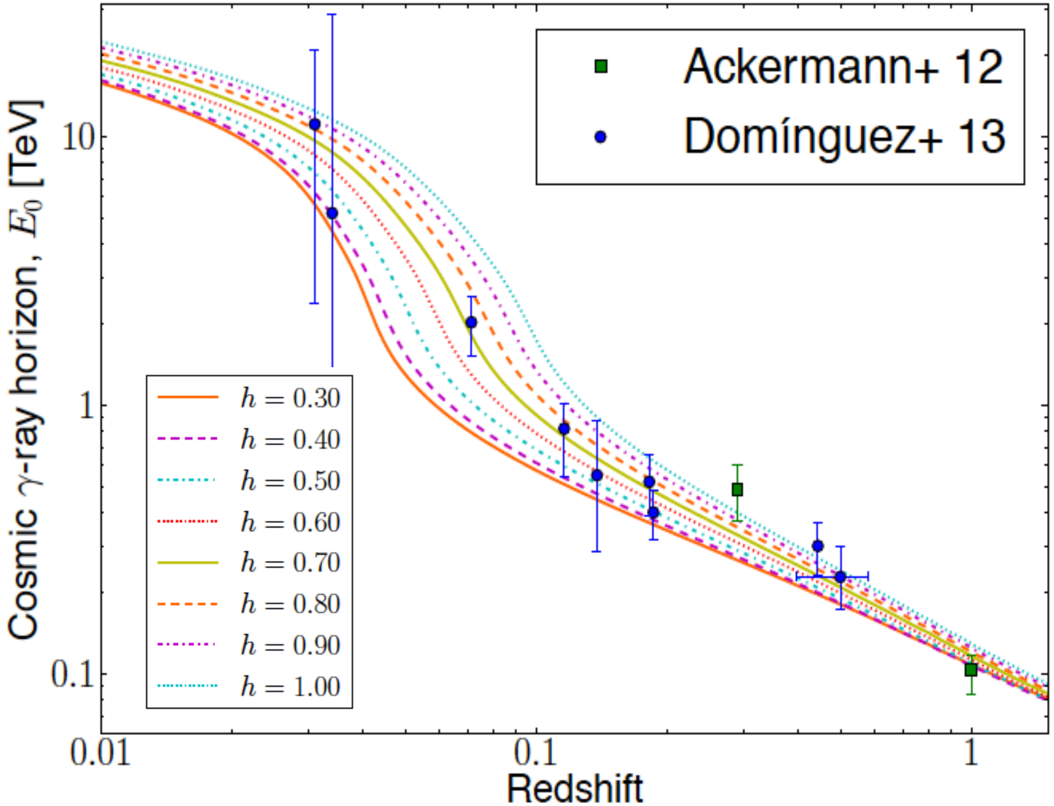
But: factorization questioned (Liberati, Sonego, …)

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

$\Rightarrow$ Determine cosmological constants from observed HE spectra vs. fitted from lower energy

(Blanch & Martinez 2005; Dominguez & Prada 2013)

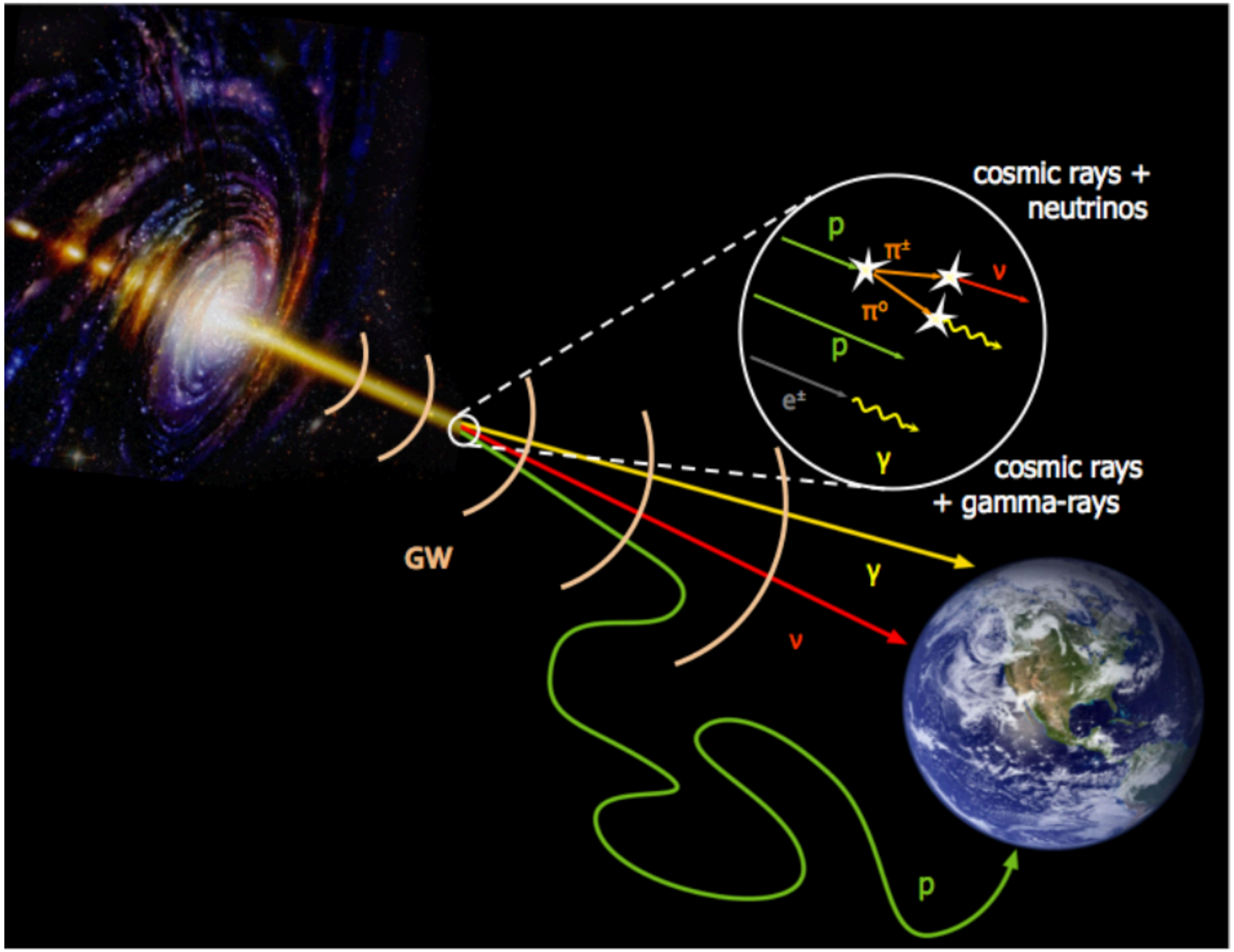


Cosmology

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

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

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



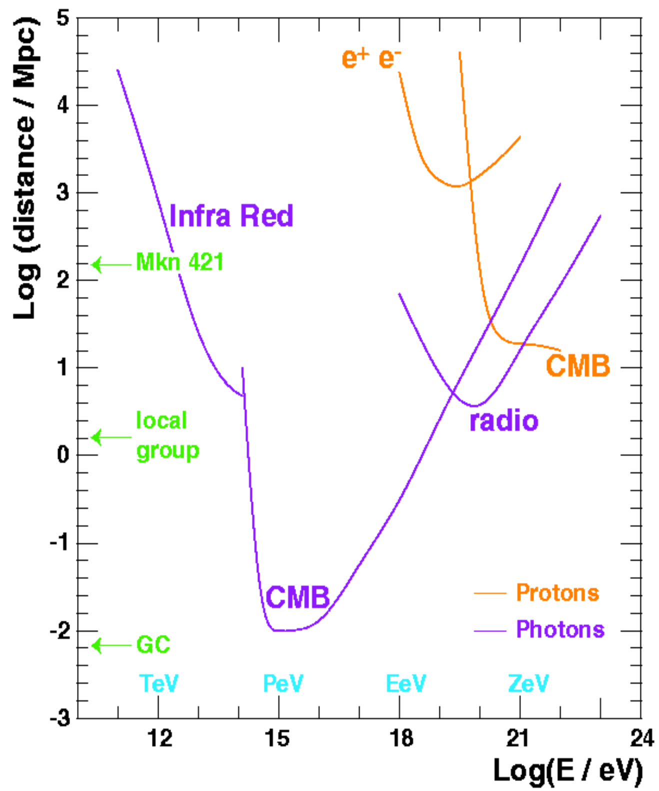
MULTIMESSENGER ASTROPHYSICS
(Neutrinos and gravitational waves)

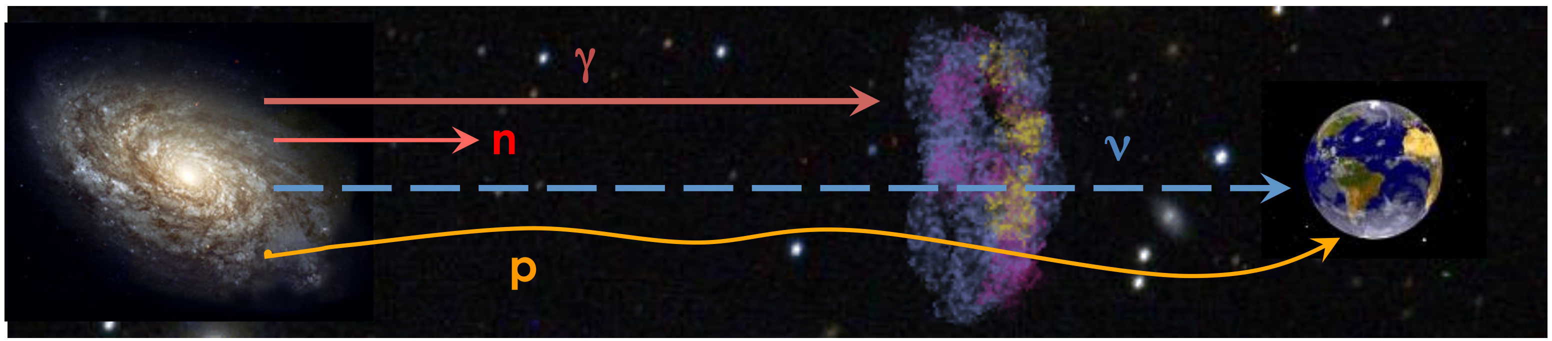
Why Neutrino Astronomy?

- 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<5·10^{10} GeV)
  - Neutrons: are not stable (r~10 kpc @10^9 GeV)
- Drawback: large detectors (~GTon) needed.

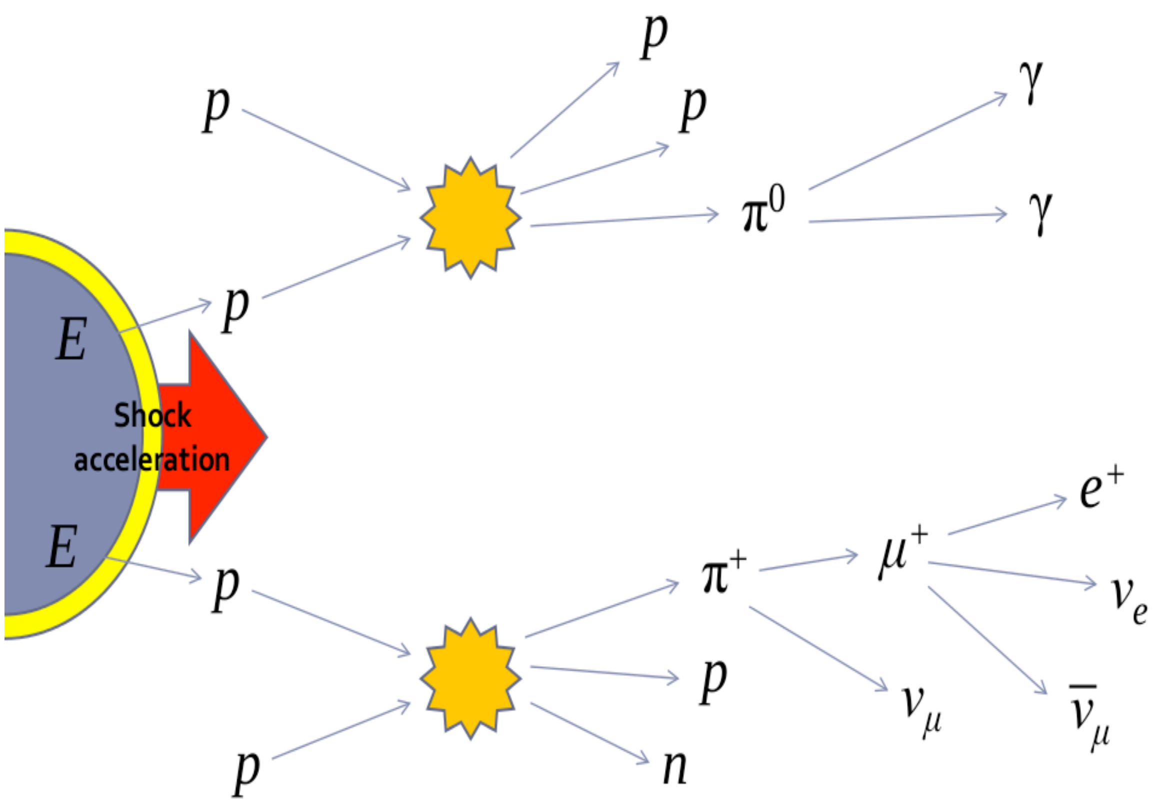
Photon and proton mean free range path





γ and ν in cosmic accelerators:

Hadronic mechanisms produce both



Neutral mesons decay in **photons**:

$\pi^o \rightarrow \gamma\gamma$

charged mesons decay in **neutrinos**:

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

$\mu^+ \rightarrow \nu_\mu + \nu_e + e^+$

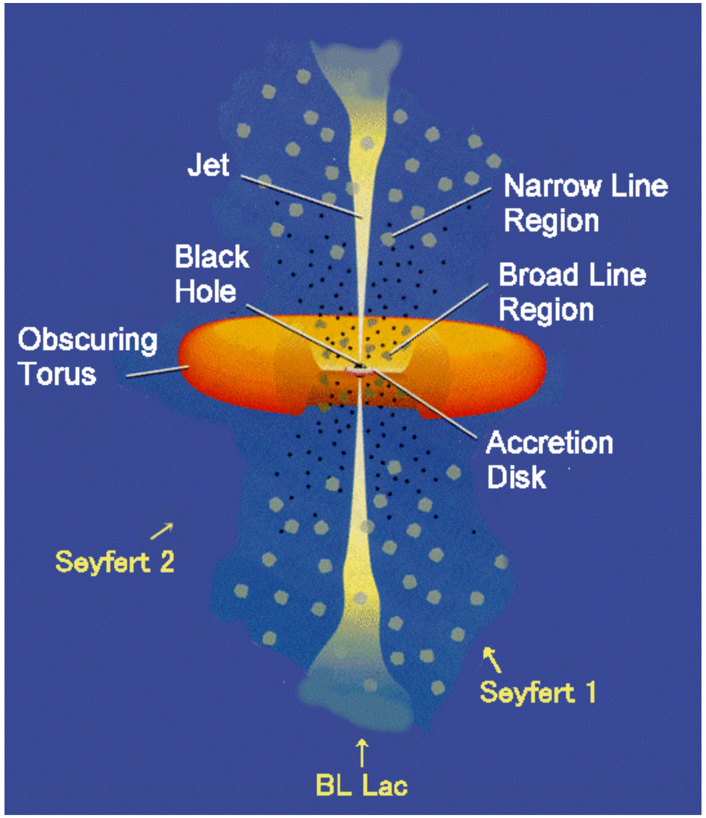
$\pi^- \rightarrow \nu_\mu + \mu^-$

$\mu^- \rightarrow \nu_\mu + \nu_e + e^-$

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

Astrophysical Sources: same as for gamma-rays

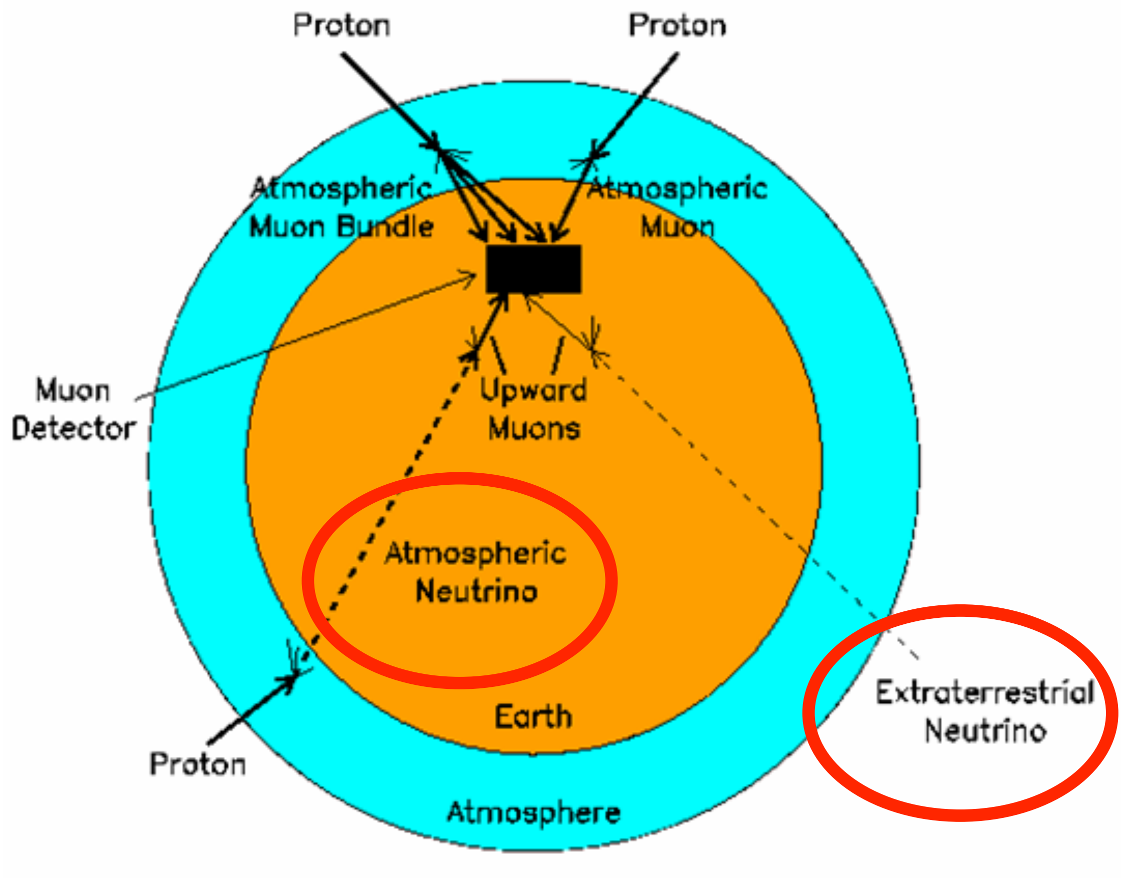
- Galactic sources: these are near objects (few kpc) so the luminosity requirements are much lower.
  - Supernova remnants
  - Micro-quasars
  - …
- Extra-galactic sources: Most powerful sources in the Universe
  - AGNs
  - GRBs



- 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.

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 .



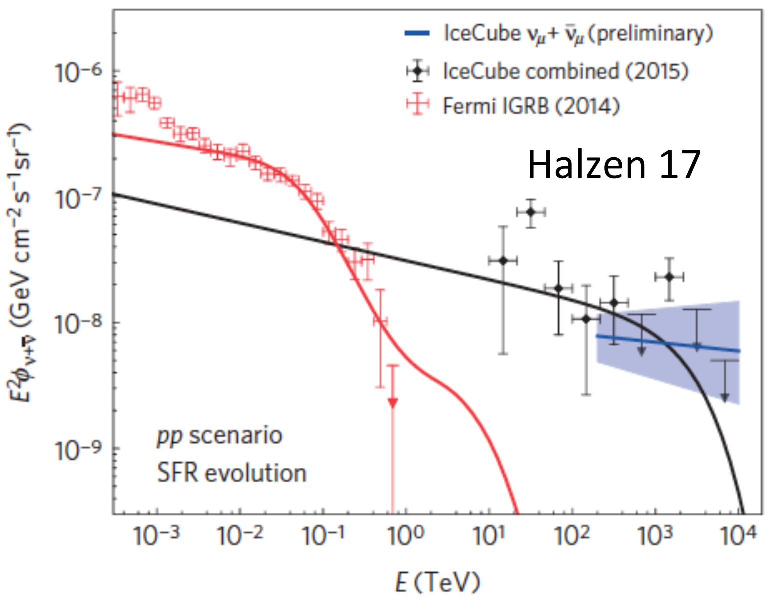
Atmospheric neutrinos represent the irreducible background for νT

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

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

Diffuse flux of neutrinos

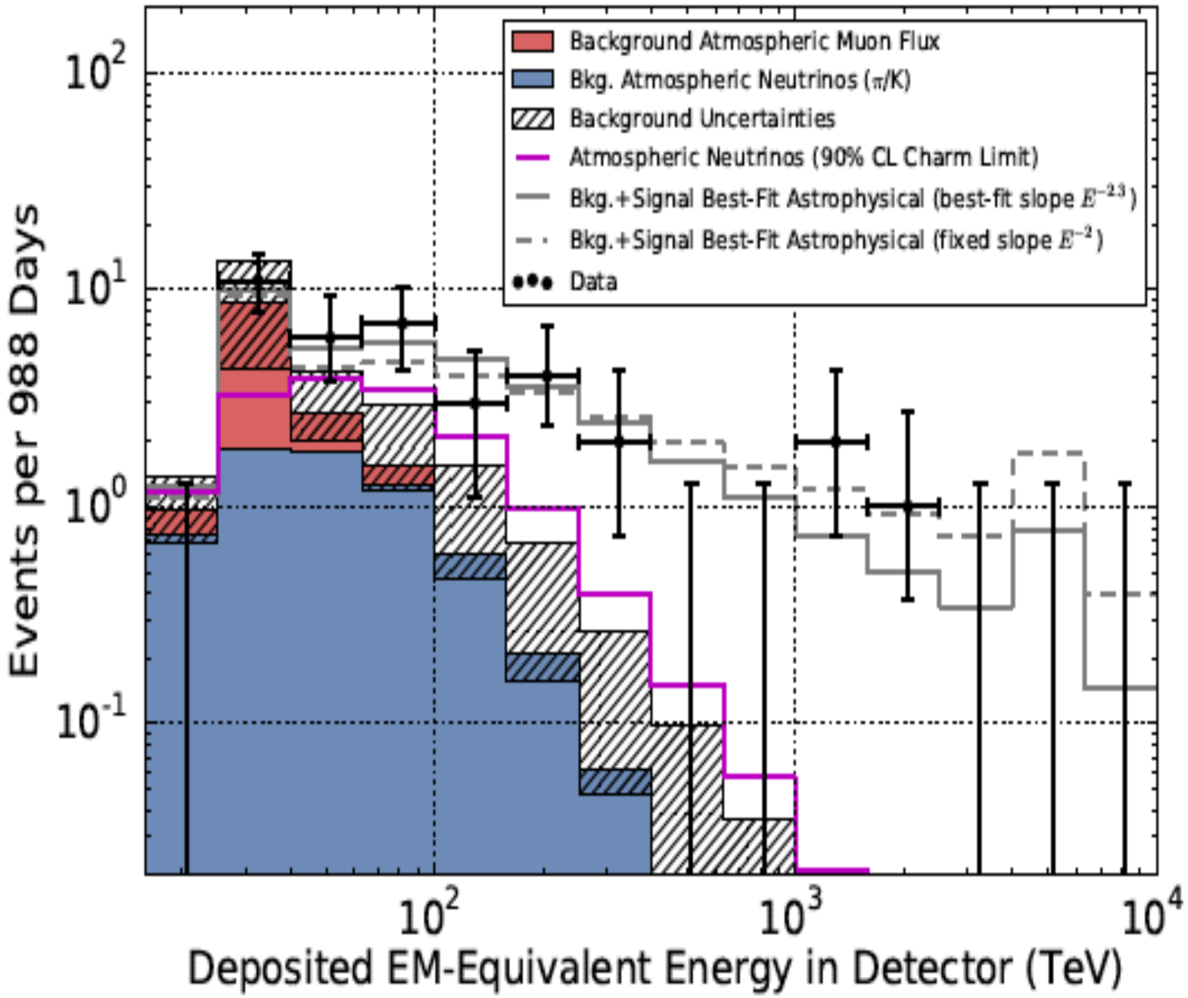
- Gamma rays are likely to be reprocessed in the photon gas, to shower and degrade they energy - this explains the shift in the E distribution of the extragalactic background of γ vs. ν



Excess of HE events over the background (IceCube 2014)

- Atmospheric muons
- Atmospheric neutrinos

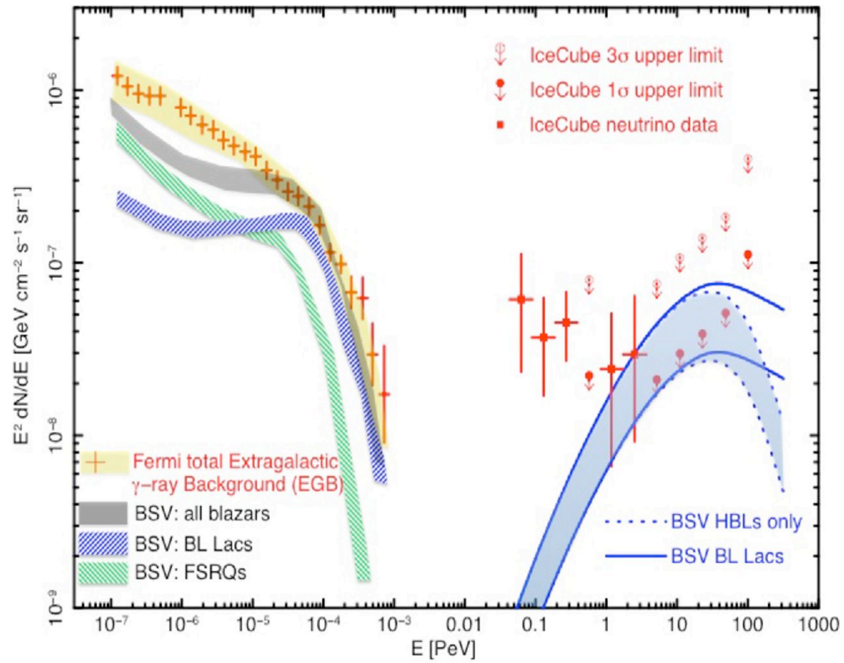
=> Yes, astrophysical neutrinos exist



~1 astrophysical neutrino/month for 1 km3 detector

γ - ν connection

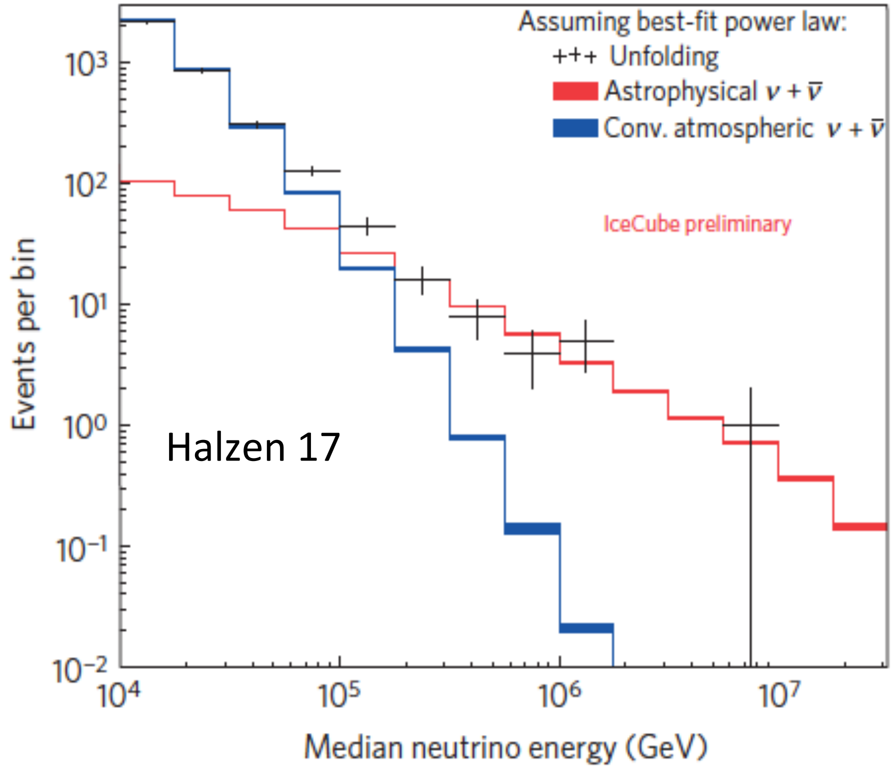
Giommi, Padovani, Resconi 17



- Looking for excess at high energies
  - Decomposing the diffuse γ-ray bkg
  - Needs models
- Looking for clusters of neutrino events in the sky
  - Point source searches
  - Needs bigger neutrino detectors (present rate is ~ 1ν/month/km^3)
- Looking for coincidences gamma rays/neutrinos
  - Multimessenger search: requires space and time coincidences with other probes (GW, photons; in this last case time delays are possible)

What we "know"

- Looking for excess at high energies (decomposing the diffuse γ-ray / neutrino bkg; time coincidences with GRB)
  - IceCube flux:
    - GRBs < 6%
    - Blazars <30%
    - Star Forming Galaxies <30%
  - Little room for pp scenarios
- Clusters
  - Nothing yet
    - 3 doubtful associations w/ blazars



Recently, first detection of (HE, VHE) gamma-ray excess positionally and temporally consistent with an IceCube EHE neutrino (EHE170922).

IceCube-170922A: IceCube observation of a high-energy neutrino candidate event

Fermi-LAT detection of increased gamma-ray activity of TXS 0506+056, located inside the IceCube-170922A error region.

AGILE confirmation of gamma-ray activity from the IceCube-170922A error region

Further Swift-XRT observations of IceCube 170922A

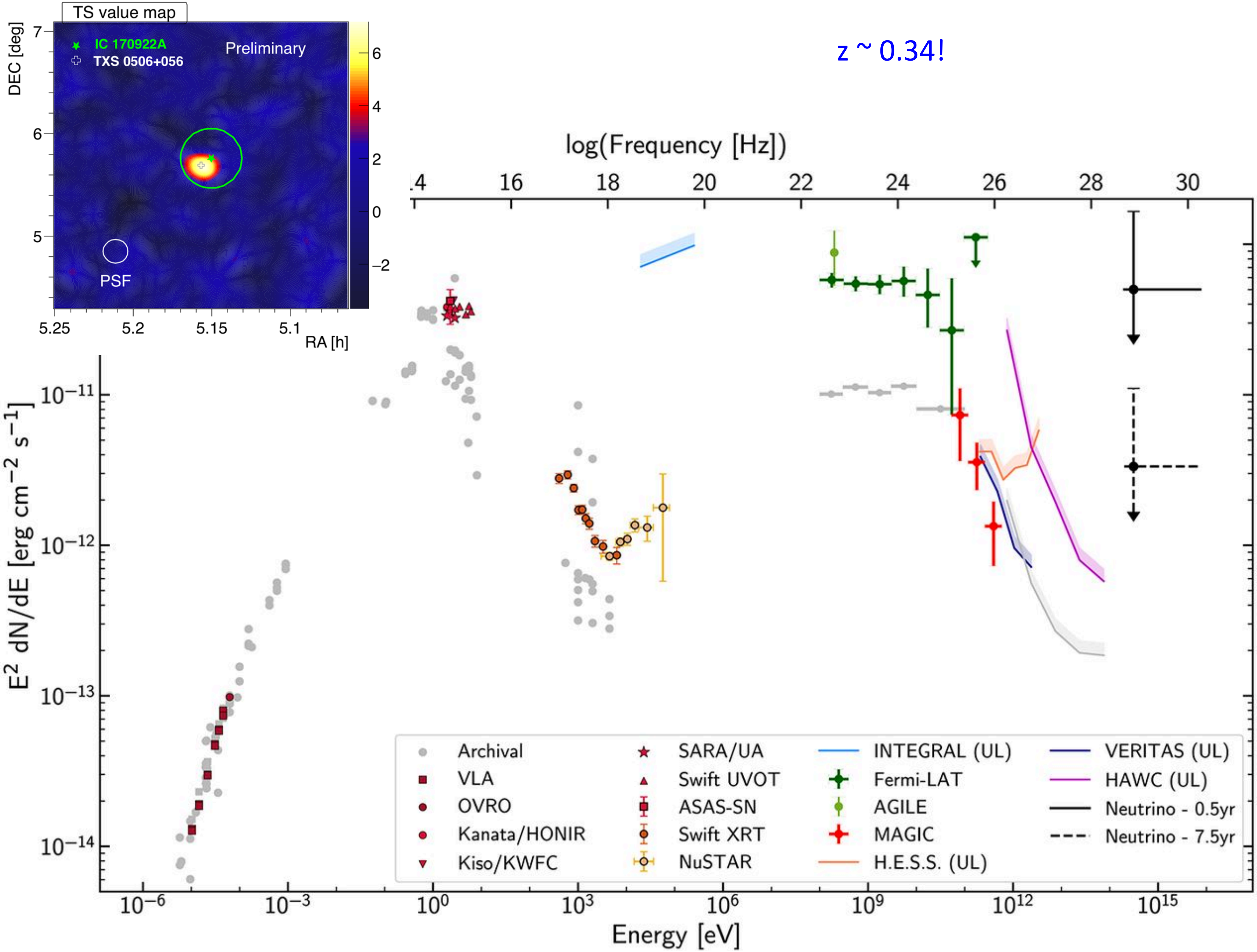
First-time detection of VHE gamma rays by MAGIC from a direction consistent with the recent EHE neutrino event IceCube-170922A

Most ϒ-ray detections > 5σ

Related

10845	Joint Swift XRT and NuSTAR Observations of TXS 0506+056
10844	Kanata optical imaging and polarimetric follow-ups for possible IceCube counterpart TXS 0506+056
10840	VLT/X-Shooter spectrum of the blazar TXS 0506+056 (located inside the IceCube-170922A error box)
10838	MAXI/GSC observations of IceCube-170922A and TXS 0506+056
10833	VERITAS follow-up observations of IceCube neutrino event 170922A
10831	Optical photometry of TX0506+056
10830	SALT-HRS observation of the blazar TXS 0506+056 associated with IceCube-170922A
10817	First-time detection of VHE gamma rays by MAGIC from a direction consistent with the recent EHE neutrino event IceCube-170922A
10802	HAWC gamma ray data prior to IceCube-170922A
10801	AGILE confirmation of gamma-ray activity from the IceCube-170922A error region
10799	Optical Spectrum of TXS 0506+056 (possible counterpart to IceCube-170922A)
10794	ASAS-SN optical light-curve of blazar TXS 0506+056, located inside the IceCube-170922A error region, shows increased optical activity
10792	Further Swift-XRT observations of IceCube 170922A
10791	Fermi-LAT detection of increased gamma-ray activity of TXS 0506+056, located inside the IceCube-170922A error region.
10787	H.E.S.S. follow-up of IceCube-170922A
10773	Search for counterpart to IceCube-170922A with ANTARES

z ~ 0.34!

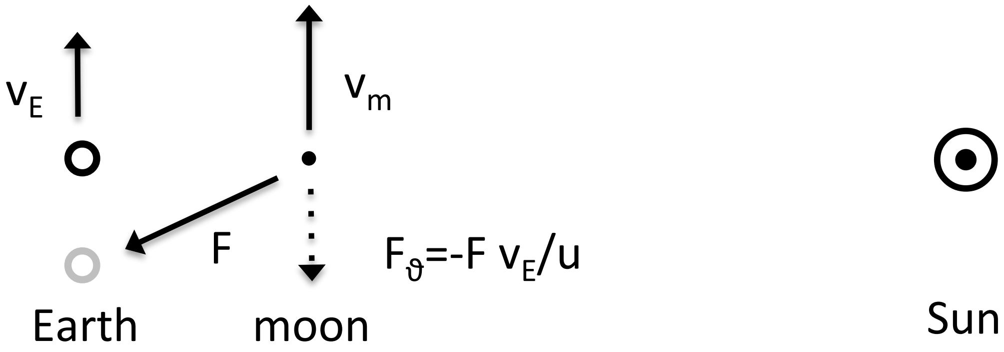

TS value map
IC 170922A
TXS 0506+056
Preliminary
PSF
DEC [deg]
RA [h]
log(Frequency [Hz])
E^2 dN/dE [erg cm^{-2} s^{-1}]
Energy [eV]
Archival
VLA
OVRO
Kanata/HONIR
Kiso/KWFC
SARA/UA
Swift UVOT
ASAS-SN
Swift XRT
NuSTAR
INTEGRAL (UL)
Fermi-LAT
AGILE
MAGIC
H.E.S.S. (UL)
VERITAS (UL)
HAWC (UL)
Neutrino - 0.5yr
Neutrino - 7.5yr

PROPAGATION OF GRAVITATIONAL WAVES

What is the speed of propagation of gravity?

- Newton's formulation of the gravitational force law requires that each particle with mass respond instantaneously to every other particle with mass irrespective of the distance between them. Poisson equation, according to which, when the mass distribution of a system changes, its gravitational field instantaneously adjusts => "infinite" speed. Does not explain the precession of Mercury's perihelion
- Einstein's theory (explains the precession of the Mercury orbit): changes in gravity propagate at a speed c.
- What about the direction of the gravitational field? What is the retardation in a retarded potential?

The argument by Laplace (1805)



We now switch to the rest frame of the Earth, where this retarding force changes the energy $E = -GMm/2R$ of the Earth-Moon system at the rate

$$\frac{dE}{dt} = \mathbf{F}\cdot\mathbf{v} = F_\theta v_m = \frac{GMm}{2R^2}\frac{dR}{dt} = -\frac{GMmv_mV_E}{R^2u}, \qquad \frac{dR}{dt} = -\frac{2v_mV_E}{u} = -2\sqrt{\frac{GM}{R}}\frac{V_E}{u}, \quad (2)$$

noting that in the rest frame of the Earth the centripetal acceleration of the moon is $v_m^2/R \approx GM/R^2$ for $M \gg m$ and $v_m \ll u$. Integrating eq. (2), we find that

$$R^{3/2} = R_0^{3/2} - 3\sqrt{GM}\frac{V_E}{u}t = R_0^{3/2} - 3v_0\sqrt{R_0}\frac{V_E}{u}t = R_0^{3/2}\left(1 - \frac{6\pi V_E t}{uT_0}\right), \quad (3)$$

where R_0 is the Earth-Moon distance at time $t = 0$, when the Moon's velocity is $v_0 = 2\pi R_0/T_0$ in terms of the Moon's orbital period T_0.

Hence, the effect of the finite speed u of propagation of gravity in Laplace's model is that the Moon would fall onto the Earth after time

$$\Delta t = \frac{cT_0}{6\pi V_E}\frac{u}{c} \approx \frac{3\times10^8\ \mathrm{m/s}\cdot 2.5\times10^6\ \mathrm{s}}{20\cdot 3\times10^4\ \mathrm{m/s}}\frac{u}{c} \approx 10^9\frac{u}{c}\ \mathrm{s} \approx 300\frac{u}{c}\ \text{years}$$

$u/c > 10^{11}$

Experimental: propagation of GW170817

- Time delay between the EM component and the GW component < 2s over a distance of ~ 50 Mpc:

  $$|1-u/c| < 2s/(50\ \mathrm{Mpc}\ c) \sim 10^{-32}$$

- Is it the same thing? No: The speed of physical changes in a gravitational or EM field should not be confused with "changes" in the behavior of static fields that are due to pure observer-effects. These changes in direction of a static field are the same for an observer when a distant charge is moving, as when an observer moves with respect to a distant charge. Thus, constant motion of an observer with regard to a static charge and its extended static field does not change the field, which extends to infinity, and does not propagate. Irrespective of motion the field continues to point to the "real" direction of the charge, at all distances from the charge.

GW are not the gravitational field

- Gravitational waves are produced in acceleration of masses with spherical asymmetry. They propagate at the speed of light, stressing and compressing spacetime; distances in space increase and decrease with a steady cadence in two directions at 90 degrees to each other, orthogonal to the direction of motion of the wave.
  - The effect is very small: for a released energy corresponding to about 3 solar masses like in the first event detected by LIGO in 2015, the relative strain at Earth is about 10^{-22} – i.e., the distance between the Earth and the Sun changes by about the size of an atom.
  - The light wavelength is not changed: this fact is at the basis of interpherometric measurements.
- Gravitational waves can penetrate regions of space that EM waves cannot.

PROPAGATION OF CHARGED COSMIC RAYS

Magnetic fields in the Universe

$$\frac{R_L}{1\text{kpc}} \simeq \frac{E/1\text{EeV}}{B/1\mu\text{G}}$$

Different from Galactic cosmic rays, despite of intense efforts during the last few decades, the origin and structure of cosmic (i.e., extragalactic) magnetic fields remain elusive. Observations have detected the presence of nonzero magnetic fields in galaxies, clusters of galaxies, and in the bridges between clusters. The determination of the strength and topology of large-scale magnetic fields is crucial also because of their role in the propagation of ultrahigh-energy cosmic rays and, possibly, on structure formation.

Large-scale magnetic fields are believed to have a cellular structure. Namely, the magnetic field B is supposed to be have a correlation length λ, randomly changing its direction from one domain to another but keeping approximately the same strength. Correspondingly, a particle of unit charge and energy E emitted by a source at distance $d \gg \lambda$ performs a random walk and reaches the Earth with angular spread

$$\theta \simeq 0.25^\circ \left(\frac{d}{\lambda}\right)^{1/2} \left(\frac{\lambda}{1\,\text{Mpc}}\right) \left(\frac{\text{B}}{1\,\text{nG}}\right) \left(\frac{10^{20}\,\text{eV}}{E}\right) . \tag{10.36}$$

The present knowledge of the extragalactic magnetic fields (EGMF), also called intergalactic magnetic field (IGMF), allows setting the following constraints:

$$B \simeq 10^{-9}\text{G} - 10^{-15}\text{G} \tag{10.37}$$

$$\lambda \simeq 0.1\,\text{Mpc} - 100\,\text{Mpc} \tag{10.38}$$

Magnetic fields in the Universe, in summary

Outside the Galaxy:

$$B \simeq 10^{-9}\mathrm{G} - 10^{-15}\mathrm{G}$$

$$\lambda \simeq 0.1\,\mathrm{Mpc} - 100\,\mathrm{Mpc}$$

In the Galaxy:

The configuration and size of the large-scale magnetic field in the Milky Way disk is still a matter of debate; however, some experimental facts are estabilshed.

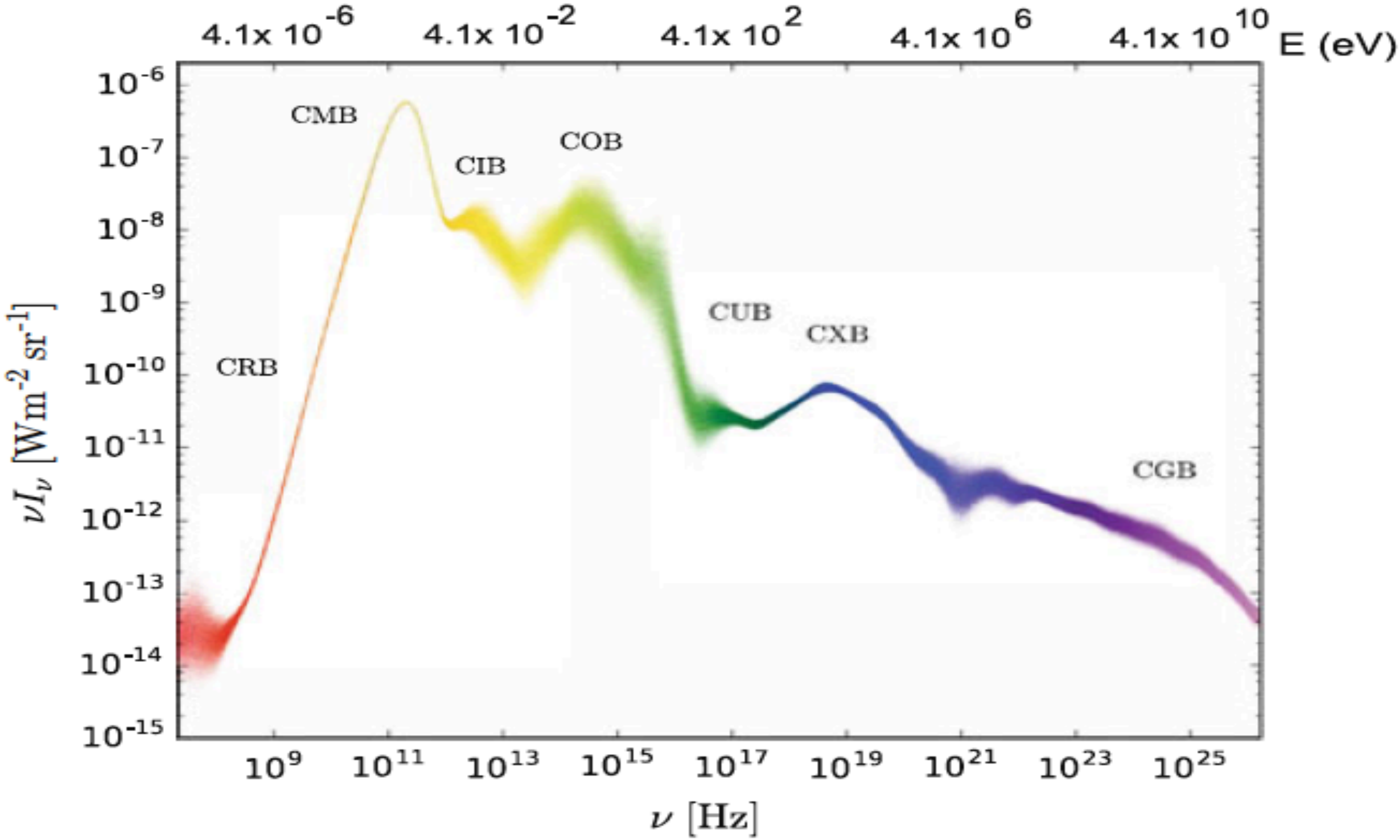
- The total field strength near the Sun is estimated to be around 6 μG, from observed synchrotron emissivities and from the flux of cosmic rays.
- The strength of the Galactic large-scale magnetic field as obtained from Faraday rotation of pulsars and extragalactic sources is around 2 μG, which is the typical magnetic field value in the disk. These estimates mostly result from rotation/dispersion measures of data from pulsars.
- Towards the Galactic center, the magnetic field strength increases. Estimates from synchrotron emission give a total field strength of about 10 μG at a Galactocentric radius of 3 kpc.

Outside the bulge, the B lines seem to roughly follow the spiral arms, in agreement with other spiral galaxies observed.

$$\frac{R_L}{1\mathrm{kpc}} \simeq \frac{E/1\mathrm{EeV}}{B/1\mu\mathrm{G}}$$

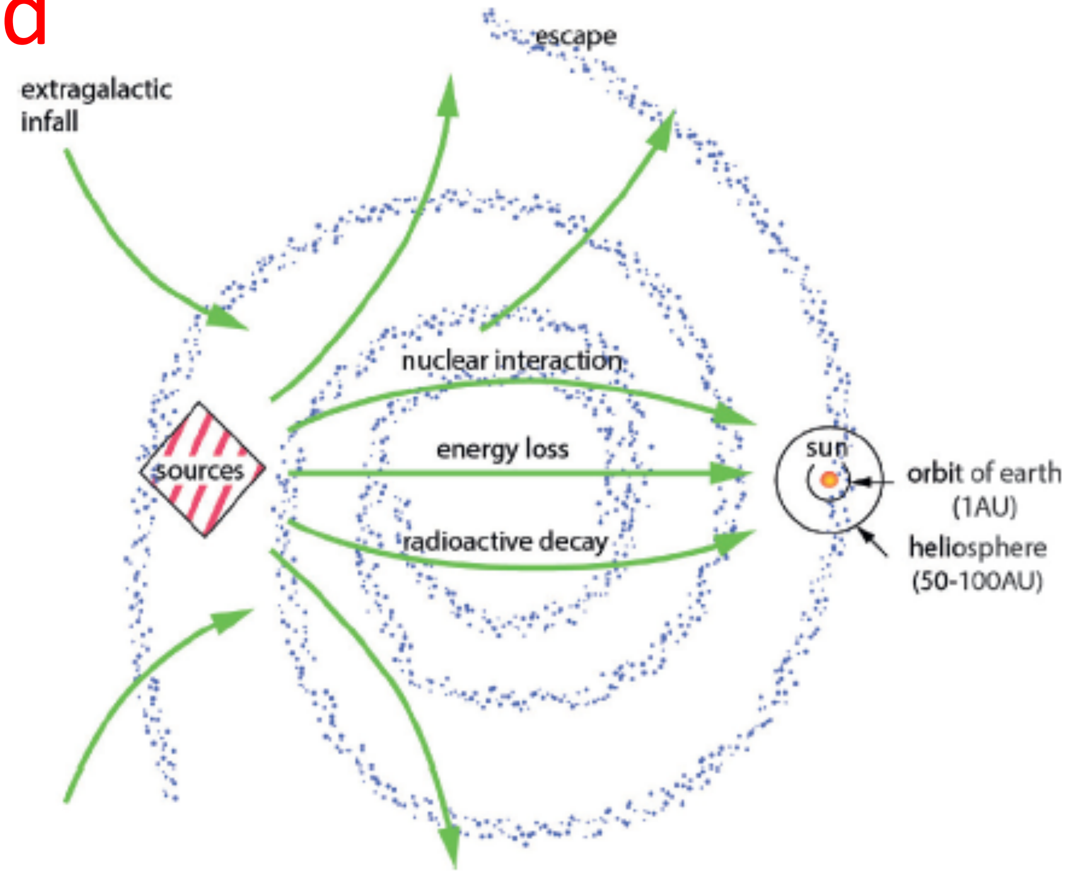
Backgrounds in the Universe

~10 % of the baryonic matter in molecular clouds (ISM)
But the dominant background is from photons – thermal and non-thermal



Propagation of charged CR in the Galaxy

- CR produced in our Galaxy suffer
  - diffusion from B ~ 1μG ,
  - convection by Galactic winds,
  - spallation in the ISM,
  - radioactive decays
  - energy losses or gains (reacceleration).
- At some point they may arrive to Earth or just escape the Galaxy. LECR can stay within the Galaxy for quite long times (~10^7 years).



$$\frac{\partial N_i}{\partial t} = C_i + \mathbf{\nabla}\cdot\left(D\mathbf{\nabla}N_i - \mathbf{V}N_i\right) + \frac{\partial}{\partial E}\left(b\left(E\right)N_i\right) +$$

$$-\left(n\beta c\sigma_i^{\mathrm{spall}} + \frac{1}{\gamma\tau_i^{\mathrm{decay}}} + \frac{1}{\hat{\tau}_i^{\mathrm{esc}}}\right)N_i +$$

$$+\sum_{j>i}\left(n\beta c\sigma_{ji}^{\mathrm{spall}} + \frac{1}{\gamma\tau_{ji}^{\mathrm{decay}}}\right)N_j\,.$$

Different chemical species

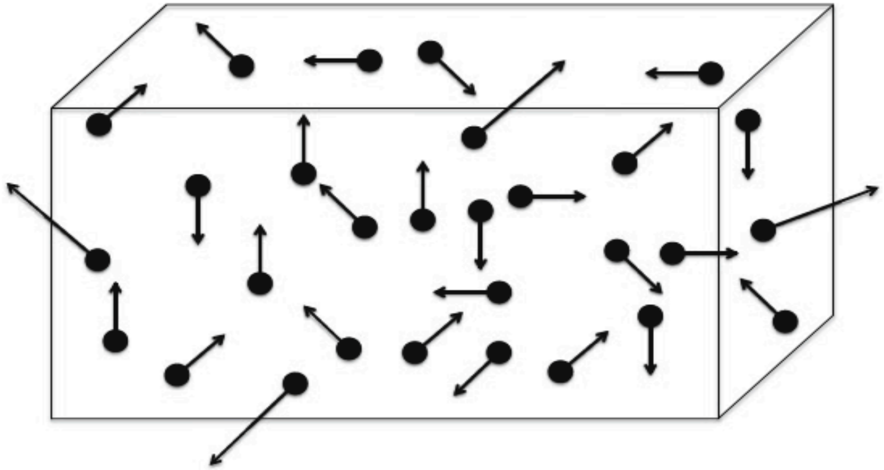
- The material formed in the early phase of the universe, at the time of the primordial nucleosynthesis, was in mass ~3/4 protons and ~1/4 He nuclei. All heavier nuclei present in the periodic table of elements are produced by nucleosynthesis in stars or interactions.
- Stellar nucleosynthesis is the process of nuclear fusions inside stars, producing energy to support their gravitational contraction. Nuclear fusion in stars proceeds until the formation of nuclei with $A \leq 60$. The involved nuclear reactions do not increase the abundance of light nuclei (Lithium, Beryllium, and Boron) as these elements act as catalysts of nuclear reactions.
- The heavier elements up to iron are only synthesized in massive stars with $M > 8M_{Sun}$. Once Fe becomes the primary element in the core of a star, further compression does not ignite nuclear fusion anymore; the star is unable to thermodynamically support its outer envelope. This initiates the gravitational collapse.
- All nuclei formed during stellar nucleosynthesis are released in the Galaxy and could be used for the formation of new stars.

$$
\begin{aligned}
\frac{\partial N_i}{\partial t} = C_i + \boldsymbol{\nabla} \cdot (D\boldsymbol{\nabla} N_i - \mathbf{V} N_i) + \frac{\partial}{\partial E}\left(b\left(E\right) N_i\right) + \\
-\left(n\beta c\sigma_i^{\text{spall}} + \frac{1}{\gamma\tau_i^{\text{decay}}} + \frac{1}{\hat{\tau}_i^{\text{esc}}}\right) N_i + \\
+\sum_{j>i}\left(n\beta c\sigma_{ji}^{\text{spall}} + \frac{1}{\gamma\tau_{ji}^{\text{decay}}}\right) N_j \,.
\end{aligned}
$$

- The term C_i on the right side accounts for the sources (injection spectrum).
- The second term accounts for diffusion and convection:
  - $\boldsymbol{\nabla} \cdot (D\boldsymbol{\nabla} N)$ describes diffusion: when at a given place N is high compared to the surroundings (a local maximum of concentration), particles will diffuse out and their concentration will decrease. The net diffusion is proportional to the Laplacian of the number density through a parameter D called diffusion coefficient or diffusivity, whose dimensions are a length squared divided by time;
  - $(\boldsymbol{\nabla} \cdot \mathbf{V})N$ describes convection (or advection), which is the change in density because of a flow with velocity $\mathbf{V}$.
- The third term accounts for the changes in the energy spectrum due to energy losses or reacceleration – we assume that energy is lost, or gained, at a rate $dE/dt = -b(E)$.
- The fourth term accounts for the losses due to spallation, radioactive decays, and probability of escaping the Galaxy. n is the number density of the interstellar medium (ISM).
- The fifth term accounts for the gains due to the spallation or decays of heavier elements.

These equations may thus include all the physics process and all spatial and energy dependence but the number of parameters is large and the constraints from experimental data (see below) are not enough to avoid strong correlations between them. The solutions can be obtained in a semi-analytical way or numerically using sophisticated codes (e.g., GALPROP), where three-dimensional distributions of sources and the interactions with the ISM can be included.

Leaky-Box Model

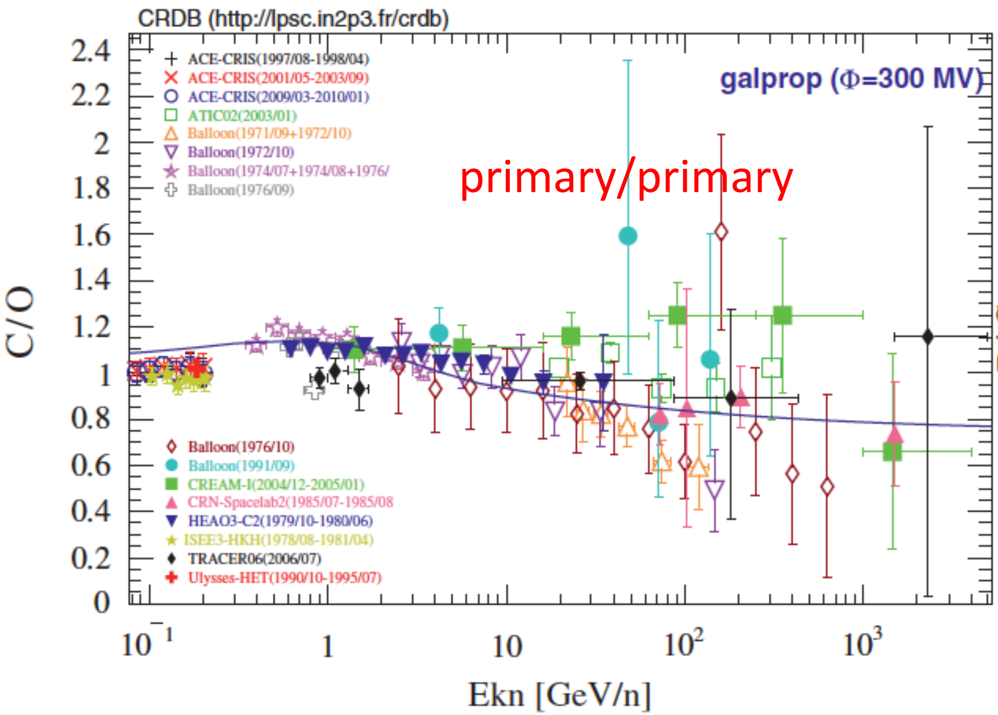


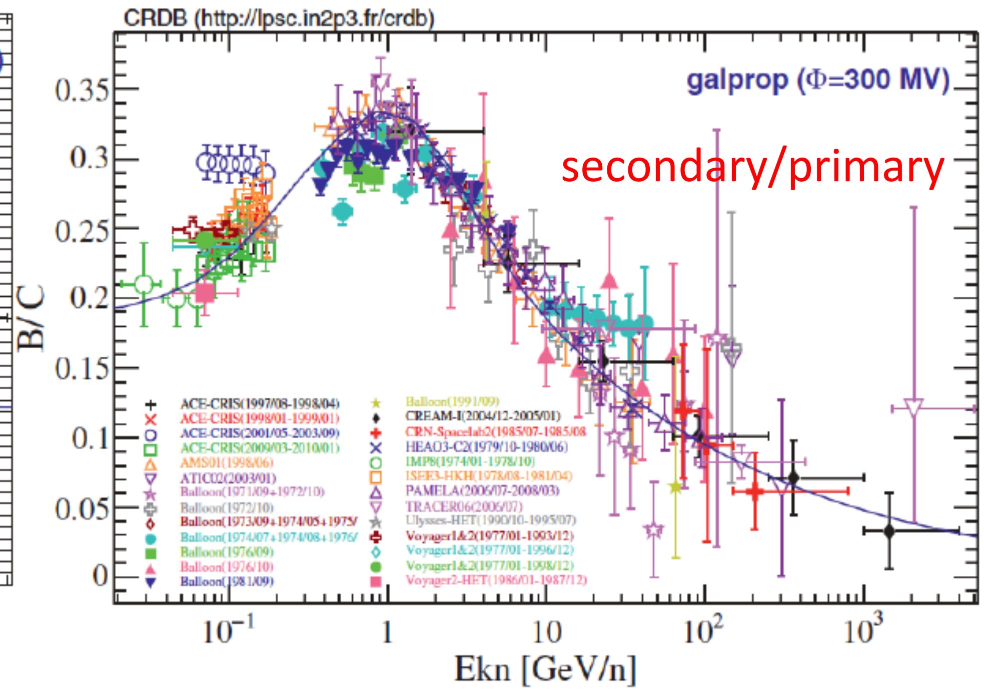
The stationary equation of the leaky box can be written as:

$$0 \simeq C_i - N_i \left(n\beta_i c\sigma_i^{\text{spall}} + \frac{1}{\gamma_i \tau_i^{\text{decay}}} + \frac{1}{\tau_i^{\text{esc}}} \right) + \sum_{j>i} N_j \left(n\beta_j c\sigma_{ji}^{\text{spall}} + \frac{1}{\gamma_j \tau_{ji}^{\text{decay}}} \right) . \tag{10.45}$$

Here once again the first term on the right side accounts for the sources and the second and the third, respectively, for the losses (due to spallation, radioactive decays, and escape probability) and the gains (spallation or decays of heavier elements). In a first approximation, the dependence of the escape time on the energy and the charge of the nucleus can be computed from the diffusion equations, the result being $\beta\tau_i^{\text{esc}} \mathrel{\substack{\propto\\ \sim}} (Z_i/p)^\delta$. For the values of size and magnetic field typical of the Milky Way, $\delta \sim 0.6$.

Tuning to data



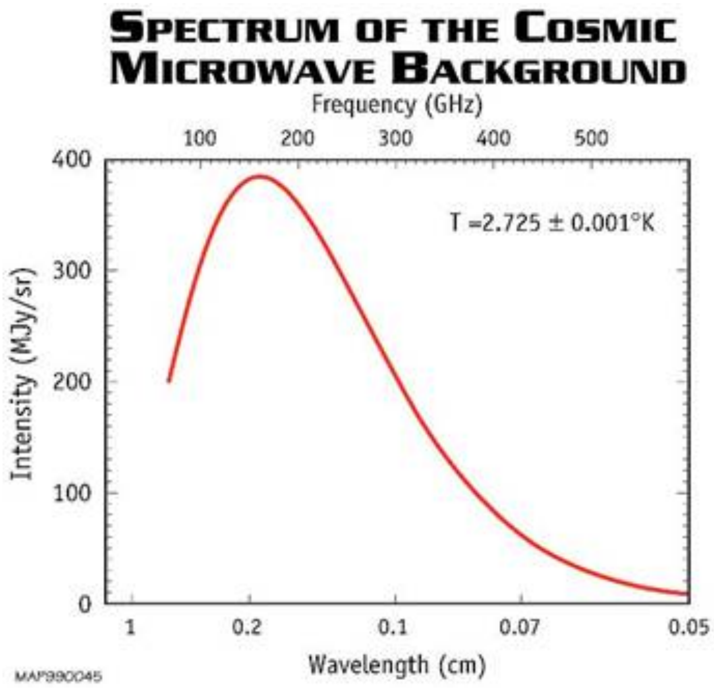


While primary/primary ratios (Fig. 10.24, left) basically do not depend on the energy, the secondary/primary ratio (Fig. 10.24, right) shows a strong dependence for high energies as a result of the increase of the probability of escape.

One should note that in the propagation of electrons and positrons the energy losses are much higher (dominated by synchrotron radiation and inverse Compton scattering) and the escape probability much higher. Thus leaky-box like models do not apply to electrons and positrons.

Maximum energy of CRs: The GZK cutoff

- The Universe is permeated of CMBR at ~2.7 K (~160 GHz)
- Energy
  $E\gamma^{\,CMBR} = h\nu \sim 2\pi\times 6\cdot 10^{-22}$ MeV·s × $160.2\cdot 10^{9}$Hz ~ $6\cdot 10^{-4}$ eV
- Number density of CMB photons ~400/cm^3 (the most abundant photon background in Nature)
- Interaction of CR with CMBR sets a limit on maximum energy of CR



The $G_{reisen}Z_{atsepin}K_{uzmin}$ cutoff

- Photoproduction:

$$\gamma^{CMBR}+p \rightarrow \Delta(1230) \quad \rightarrow n+\pi^{+}$$
$$\rightarrow p+\pi^{0}$$

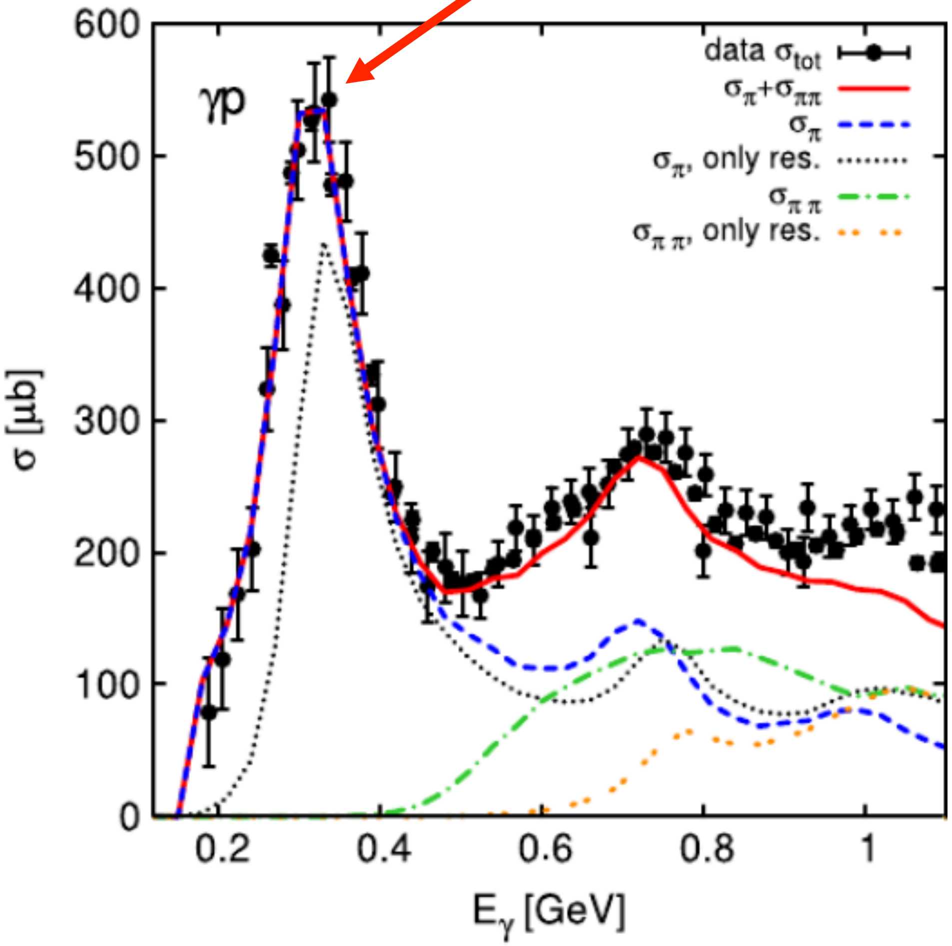
- Needs the system (p, γ^{CMBR}) to be above the Δ mass threshold
- The process is resonant: very large xross section

$$\sigma_0^{P} \approx 250\ \mu b$$

(10x pp)

Cross section for Δ production

$\sigma_0^P \approx 250\ \mu b$



Photoproduction threshold

$$\left| \left(E_p, \sqrt{E_p^2 - m_p^2}, 0, 0 \right) + \left(E_\gamma^{CMB}, -E_\gamma^{CMB}, 0, 0 \right) \right|^2 = m_\Delta^2$$

$$\Rightarrow 4 E_p E_\gamma^{CMB} \cong m_\Delta^2 - m_\Delta^2$$

- The threshold energy/momentum is

$$p_p^{GZK} \approx 3 \cdot 10^{20}\,\mathrm{eV}$$

- And the mean free path

$$\lambda = (\sigma_{\gamma p} n_\gamma)^{-1} \cong 10^{25}\,\mathrm{cm} \cong 3\ \mathrm{Mpc}$$

Conclusion

- Charged cosmic rays cannot be used for astronomy
  - Diffusion of CR with change of chemical species offers anyway important information on the ISM and on magnetic fields
- Gamma rays suffer absorption from $\gamma\gamma$ -> ee; the target photons are near IR/visible/near UV
  - The EBL backround is important for astrophysics
  - The interaction probability is a key to fundamental physics & new particles

  However, most astrophysics (presently) comes from gamma rays
- Neutrinos are a good probe, complementary to photons, and their flux is related; however, difficult to detect.
  - Neutrino astrophysics has just started
- Gravitational waves travel unimpeded at speed c; however, localization of the sources is very approximate => need multimessenger