Quantum Gravity phenomenology: a review and recent results

Luca Maccione
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Vulcano, 29/05/2008

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  Philosophical intuition: *reductio ad unum*
  Lack of predictability by GR (singularities...)

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- **What we need to understand quantum gravity?**
  Observe phenomena that "have to do" with QG
  Extract testable predictions from the theory

QG phenomenology

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Quantum gravity phenomenology is a recently developed field aimed at testing, observationally or experimentally possible predictions of quantum gravity frameworks.

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- **QG imprint on initial cosmological perturbations**
- **Cosmological variations of couplings**
- **Extra dimensions and low-scale QG (LHC BH)**
- **Violation of discrete symmetries (CPT)**
- **Violation of space-time symmetries**

Suggestions for Lorentz violation (at low or high energies) came from several tentative calculations in QG models:
Kostelecky-Samuel 1989, Amelino-Camelia et al. 1997-1998, Gambini-Pullin 1999, Carroll et al. 2001, Burgess et al. 2002

For review see D. Mattingly, Living Rev. Rel. 8:5,2005.

Modified dispersion relations

Many QG models lead to modified dispersion relations

From a purely phenomenological point of view, the general form of Lorentz invariance violation (LIV) is encoded into the dispersion relations

$$\boxed{E^2 = p^2 + m^2 + \Delta(p, M)}$$

$M \equiv$ spacetime structure scale, generally assumed $\approx M_{\text{Planck}} = 10^{19}$ GeV

Assuming rotation invariance
we can expand this as

$$\boxed{E^2 = p^2 + m^2 + M\eta^{(1)}|p| + \eta^{(2)}p^2 + \eta^{(3)}|p|^3/M} \quad \ldots$$

Theoretical frameworks

Of course to cast constraints on LIV using these phenomena one needs more than just the kinematics information provided by the modified dispersion relations, one also often needs to compute reaction rates and decay times, i.e. a dynamical framework…

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EFT+LV

Renormalizable, or higher dimension operators

Deformed/Doubly SR paradigm

Non-commutative spacetime
Finsler geometry

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Constraints for EFT models

Standard Model Extension
Renormalizable ops. (Low energy LIV)
(Colladay & Kostelecki, 1998)

EFT with LIV
Non-renormalizable ops, (HE LIV)
(Myers & Pospelov, 2003)

STRONG CONSTRAINTS!

Applications: QED with LV at O(E/M)

Dimension 5 Standard Model Extension: include dimension 5 LV operators in the SM preserving gauge and rotation invariance and quadratic in the fields
Myers & Pospelov, 2003

Contribution at order p^3/M to the MDR.

$$L = L_{QED} - \frac{\xi}{2M} u^m F_{ma} (u \cdot \partial)(u_n \tilde{F}^{na}) + \frac{1}{2M} u^m \bar{\psi} \gamma_m (\varsigma_1 + \varsigma_2 \gamma_5)(u \cdot \partial)^2 \psi$$

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$$\text{electrons} \quad E^2 = m^2 + p^2 + \eta_\pm (p^3/M_{\rm Pl})$$
$$\text{photons} \quad \omega^2 = k^2 \pm \xi (k^3/M_{\rm Pl})$$

$$\eta_\pm = 2(\zeta_1 \pm \zeta_2)$$

electron helicities have independent LIV coefficients

photon helicities have opposite LIV coefficients

	Positive helicity	Negative helicity
Electron	η_+	η_-
Positron	$-\eta_-$	$-\eta_+$

correspondence relation between LV coeff for electrons and positrons

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Well, this is our theory, how to test it?

Windows on Quantum Gravity

At energies << M_{Pl} only **tiny effects** are expected.
BUT there are **special situations** where these tiny corrections can be magnified to sizable effects

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BUT there are **special situations** where these tiny corrections can be magnified to sizable effects

- **sidereal variation of LV couplings**
  (the enormous number of atoms allow variations of a resonance frequency to be measured extremely accurately)
- **cosmological variation of couplings**
  (e.g. varying fine structure constant)
- **Cumulative effects**
  (e.g. color dispersion & birefringence)
- **Anomalous threshold reactions**
  (e.g. forbidden if LI holds, e.g. gamma decay, Vacuum Cherenkov)
- **Shift of standard threshold reactions**
  (e.g. gamma absorption or GZK)
- **new threshold phenomenology**
  (asymmetric pair creation and upper thresholds)

Astrophysical constraints: time of flight

Constraint on the photon LIV coefficient ξ by using the fact that different colors will travel at different speeds.

$$v_\gamma = \frac{\partial E}{\partial p} = 1 + \xi \frac{E}{E_{Pl}}$$

$$\begin{aligned} \Delta t &= \Delta v T = \xi \frac{E_2 - E_1}{M} T \\ \Delta t &\approx 10\,\mathrm{msec}\,\xi\, d_{Gpc}\, E_{GeV} \end{aligned}$$

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Problem: there is strong evidence that most GRB and AGN are not "good" objects for TOF constraints because of intrinsic time lags (different energies emitted at different times) not well understood.

Robust limits can be claimed only by a careful statistical analysis on large sample of sources: delay-redshift correlation

Ellis et al., astro-ph/0510172: Conservative limit |ξ|<10^3

Astrophysical constraints: birefringence

The birefringence constraint arises from the fact that the LV parameters for left and right circular polarized photons are opposite.

Hence, linear polarization is rotated as signal propagates

$$\theta(t) = [\omega_+ - \omega_-(k)]\, t/2 = \xi k^2 t/2M$$

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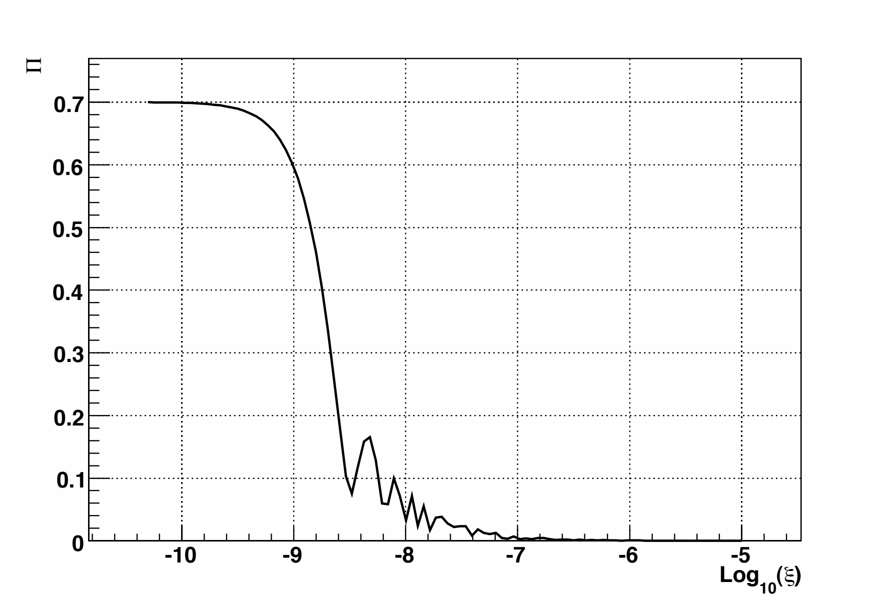
For a photon beam $\mathcal{P}(E)$ the degree of linear polarization can be computed as

$$\Pi(\xi) = \sqrt{\langle\cos(2\theta)\rangle^2_{\mathcal{P}} + \langle\sin(2\theta)\rangle^2_{\mathcal{P}}},$$

The constraint is obtained by imposing $\Pi(\xi) > \Pi_{obs}$



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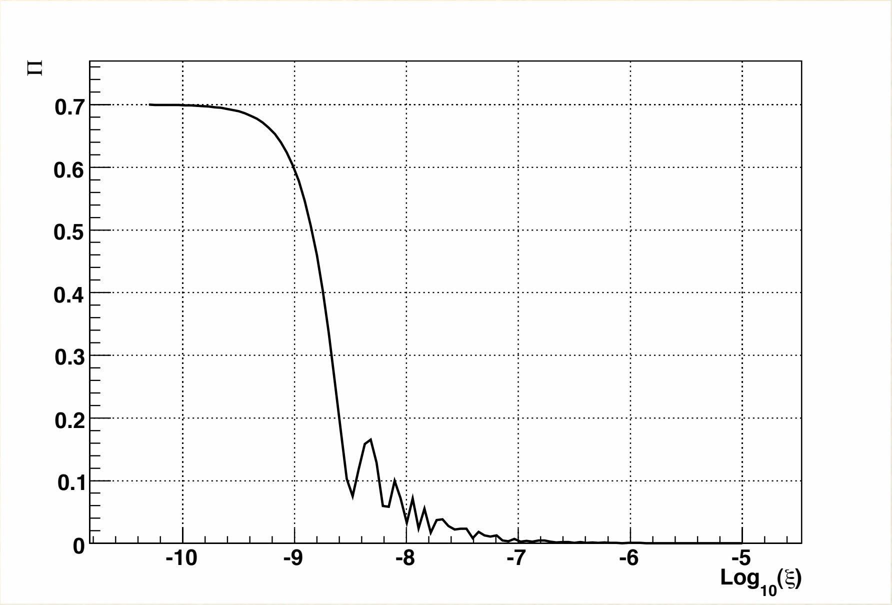

Current best constraint $|\xi| \lesssim 10^{-7}$ (Fan et al) looking at optical/UV light from distant GRB

Threshold reactions

Key point: the effect of the non LI dispersion relations can be important at energies well below the fundamental scale

$$E^2 = c^2 p^2 \left(1 + \frac{m^2 c^2}{p^2} + \eta \frac{p^{n-2}}{M^{n-2}} \right)$$

Corrections start to be relevant when the last term is of the same order as the second.
If η is order unity, then

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4	$p \approx m_\nu \sim 1$ eV	$p \approx m_e = 0.5$ MeV	$p \approx m_p = 0.938$ GeV
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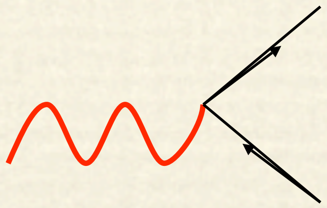
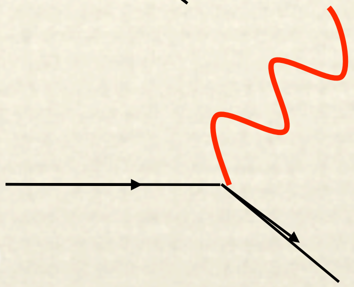
Examples...

Gamma decay $\quad \gamma \to e^+ + e^-$



$$|\eta_\pm| \lesssim 6\sqrt{3} m^2 M / k_{\rm th}^3$$

Vacuum Cherenkov
(Helicity Decay) $\quad e^\pm \to e^\pm + \gamma$



$$p_{\rm th} = \left(m^2 M / 2\eta\right)^{1/3}$$

Astrophysical constraints: synchrotron radiation

Jacobson, Liberati, Mattingly: Nature 424, 1019 (2003)
Ellis et al. Astropart.Phys.20:669-682,(2004)
R. Montemayor, L.F. Urrutia: Phys.Lett.B606:86-94 (2005)
LM,Liberati, Celotti, Kirk. JCAP 10, 013 (2007)

LI synchrotron critical frequency: $$\omega_c^{LI} = \frac{3}{2}\frac{eB\gamma^2}{m}$$

e - electron charge

m - electron mass

B - magnetic field

However in order to get a real constraint one needs a detailed re-derivation of the synchrotron effect with LIV based on EFT.

This leads to a modified formula for the peak frequency: $$\omega_c^{LIV} = \frac{3}{2}\frac{eB}{E}\gamma^3$$

$$\gamma = (1 - \mathrm{v}^2)^{-1/2} \approx \left(\frac{m^2}{E^2} - 2\eta\frac{E}{M_{QG}}\right)^{-1/2}$$

$\eta<0$

γ is a bounded function of E.
There is a maximum achievable synchrotron frequency ω^{max} for ALL electrons!

So one gets a constraint by asking $\omega^{max} \geq (\omega^{max})_{observed}$

$\eta>0$

γ diverges as p_{th} is approached. This is unphysical as also the energy loss rates diverges in this limit, however means a rapid decay of the electron energy and a violent phase of synchrotron radiation.

No immediate way to have a constraint in this case

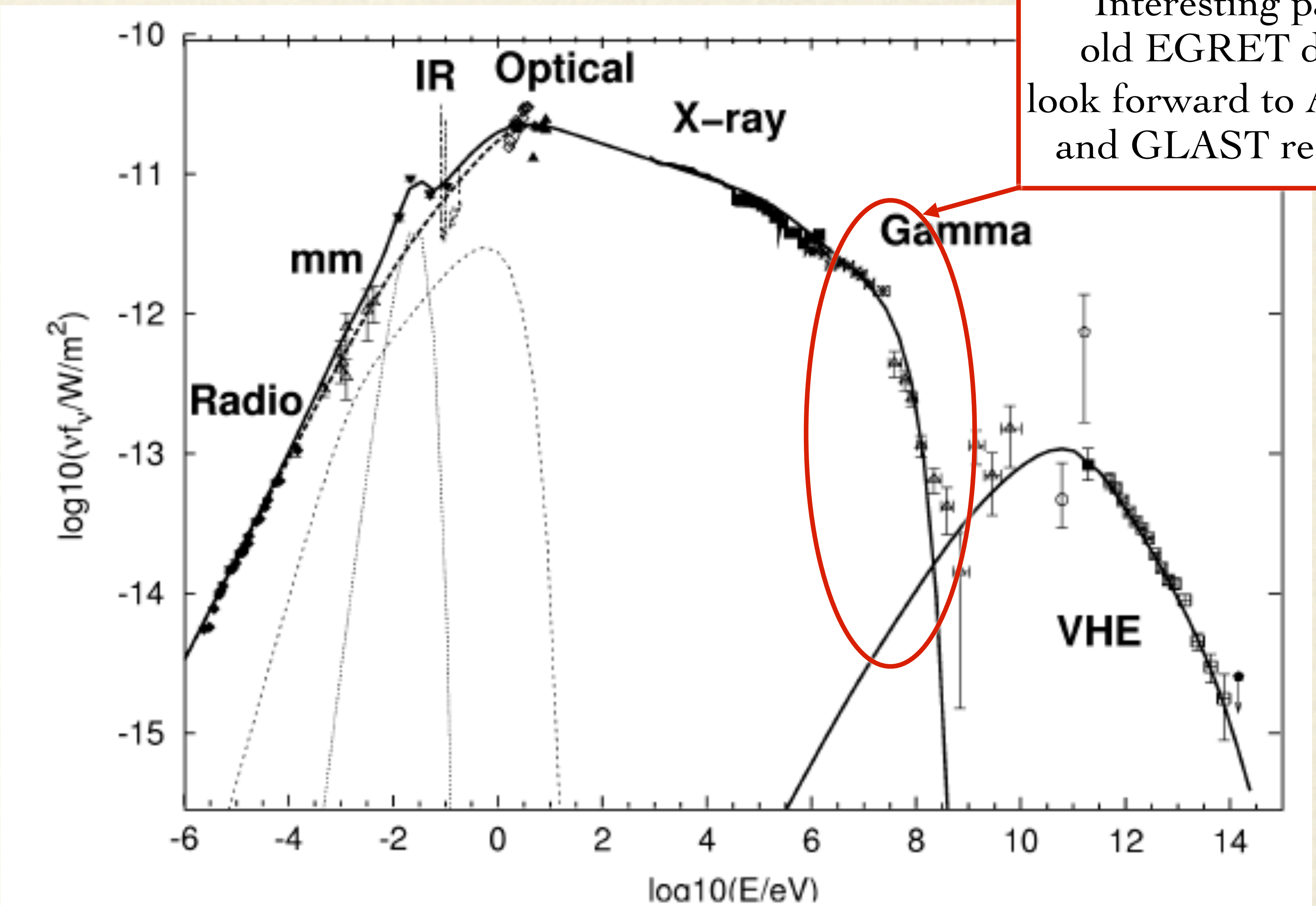
The Crab Nebula

The Crab Nebula – Remnant of a SuperNova explosion

✓ exploded in **1054 A.D.**
✓ distance **~1.9 kpc** from Earth
✓ pulsar wind powered nebula
✓ most powerful object in the sky

Well explained by synchrotron self Compton (SSC) model

- Electrons are accelerated to very high energies at pulsar
- High energy electrons emit synchrotron radiation
- High energy electrons undergo inverse Compton (mainly with synchrotron ambient photons)



Interesting part:
old EGRET data,
look forward to AGILE
and GLAST results!

Horns et Aharonian, astro-ph/0407119, Aharonian & Atoyan 1998

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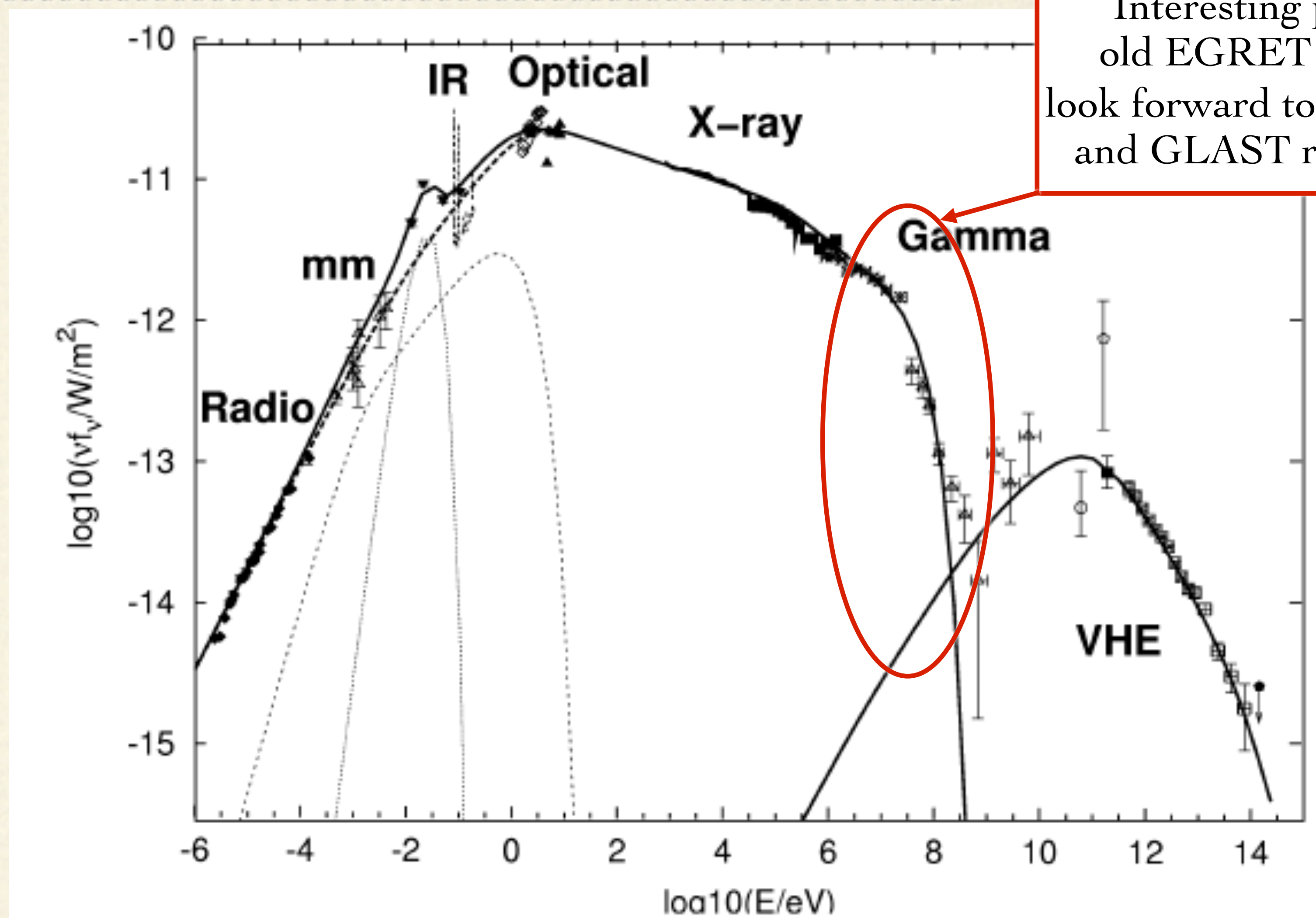

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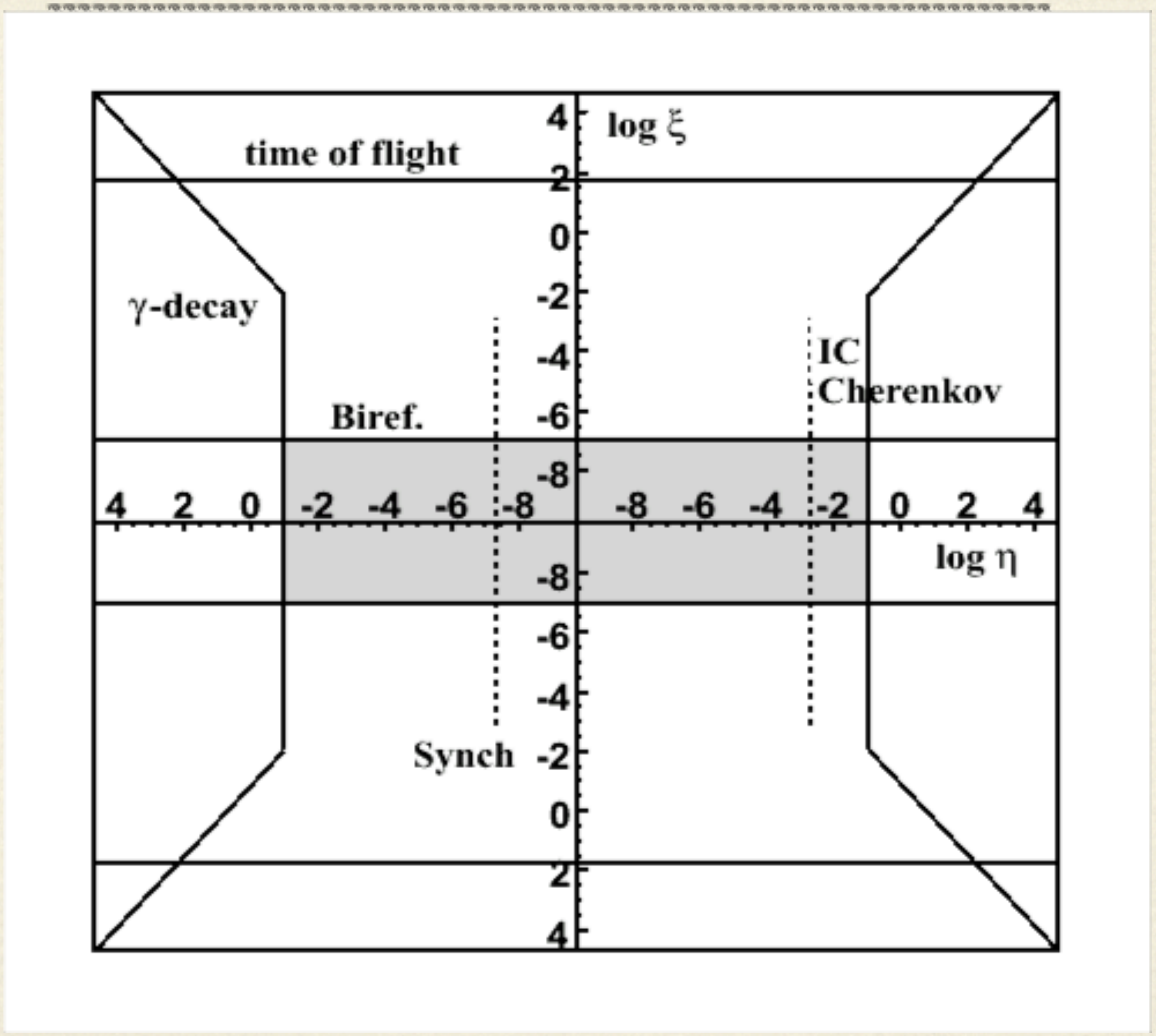
We shall assume SSC correct and use Crab observation to constrain LV.

Resume...

Jacobson et al. Annals Phys. 321 (2006) 150



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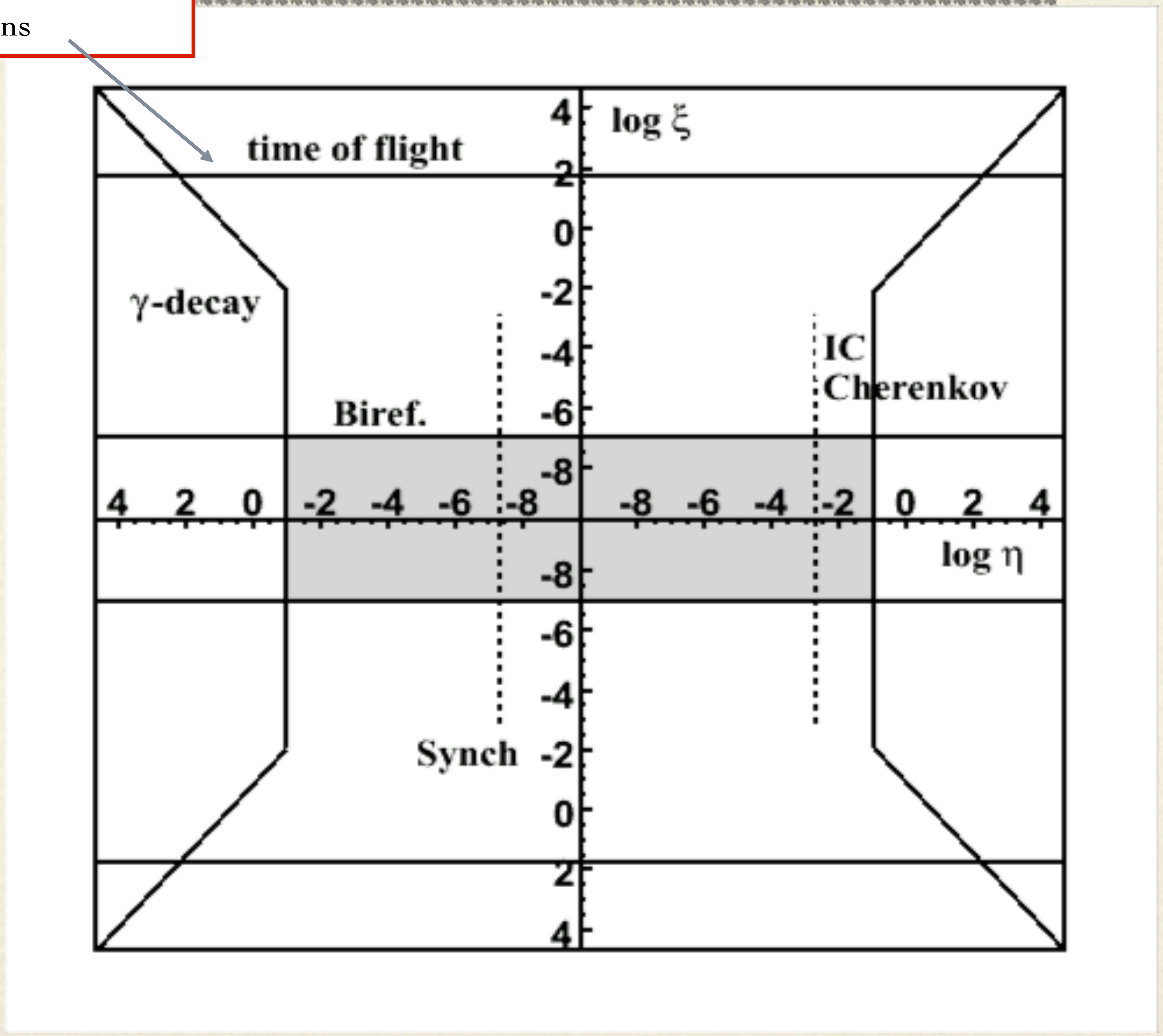
Jacobson et al. Annals Phys. 321 (2006) 150

delay in arrival time of different colors or polarizations



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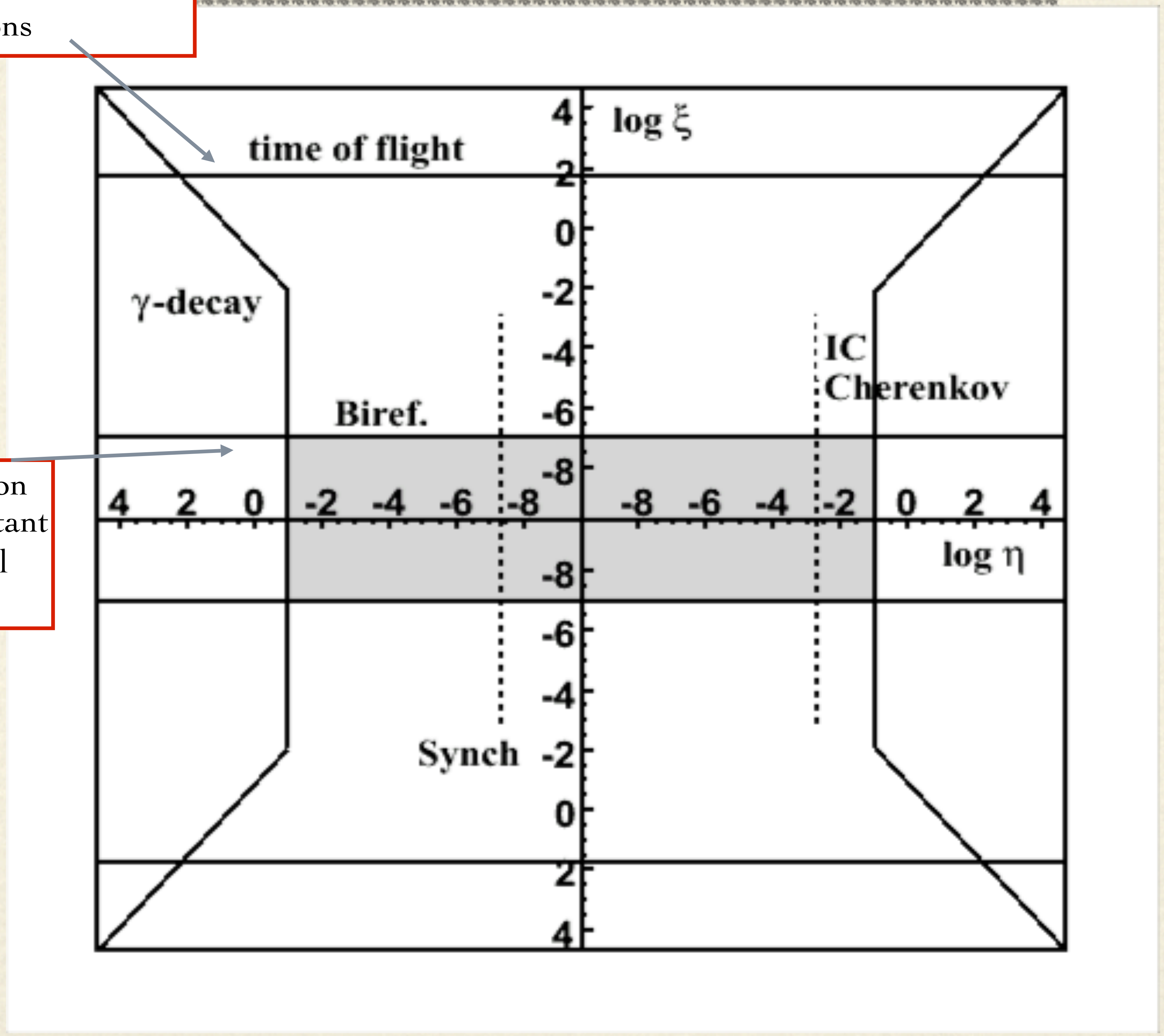

polarization/depolarization of the radiation form a distant source (e.g. UV/Optical from GRB)

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Observation of 80 TeV photons from the Crab Nebula (HEGRA)

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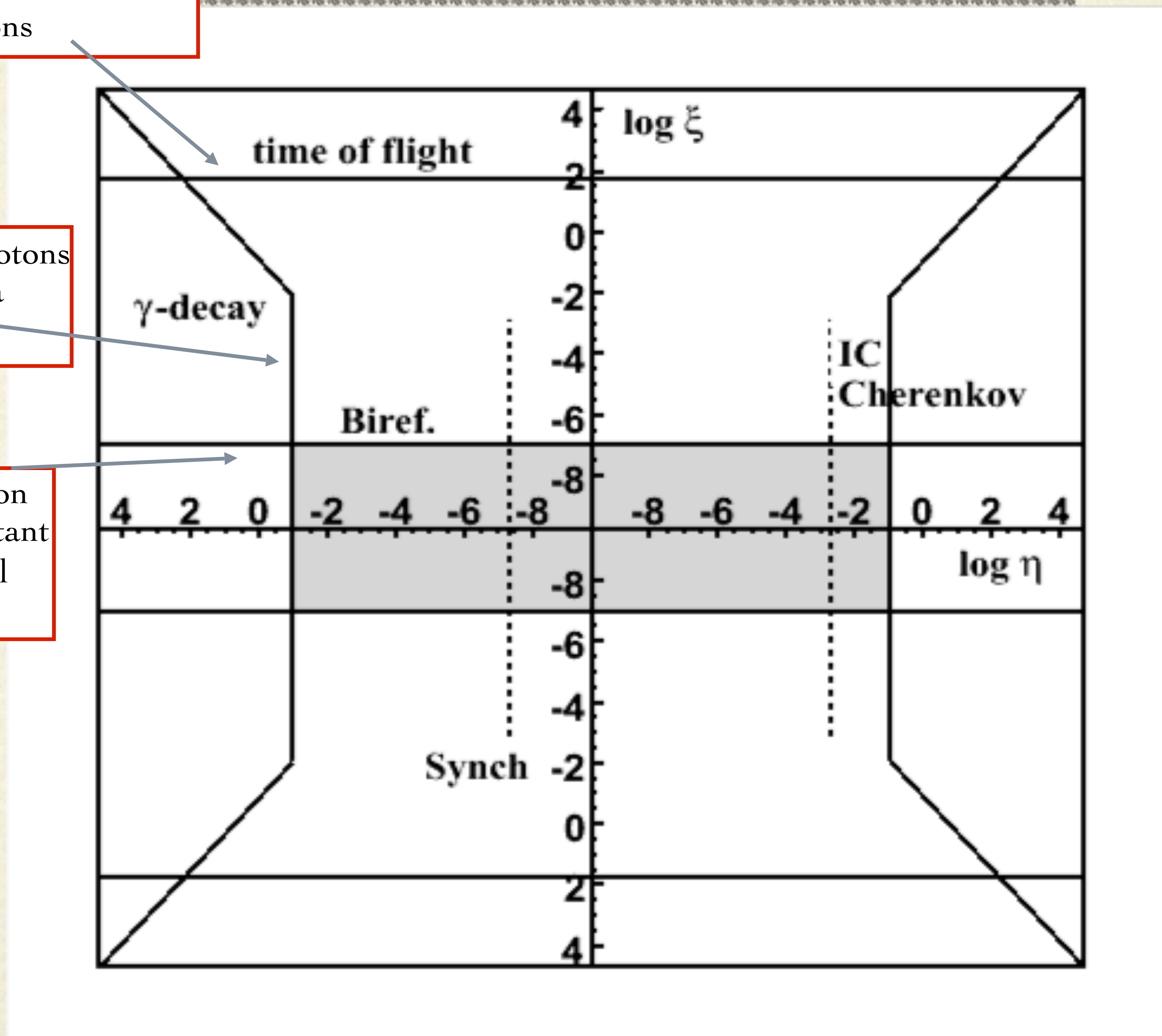

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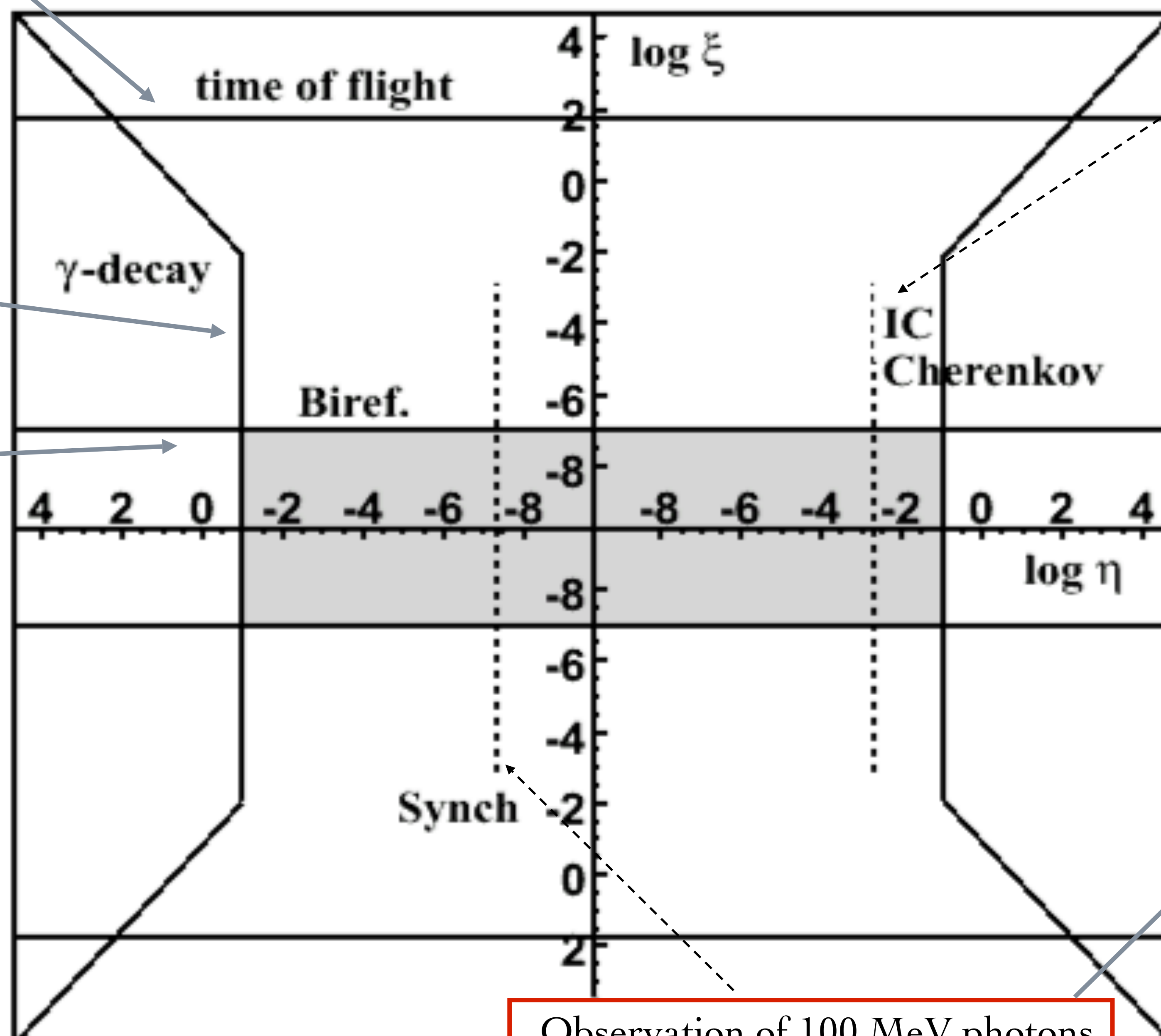

Observation of 80 TeV photons from the Crab Nebula (HEGRA)

<u>Not a constraint:</u> each of them always satisfied by at least one of $\pm\eta_\pm$. Even if just one population is assumed for synch+IC only one $\pm\eta_\pm$ needs to be between the to dotted lines in the grey region.

Observation of 100 MeV photons from the Crab Nebula (EGRET)

A new approach: look at spectra

- **Re-compute** the full Crab spectrum relaxing the hypothesis of Lorentz Invariance.
  - Understand LIV Fermi mechanism
  - Take into account new processes: Helicity decay and Vacuum Cherenkov
- **Fix most of the free parameters** (magnetic field strength, electron energy density…) from **low frequency observations** (well defined procedure, see later)
- **Check** that LV modifications enter only in the high energy part of the spectrum
- **Compare** with experimental points and make constraints **(chi-square analysis)**.

ok at spectra

hypothesis of Lorentz Invariance.

y and Vacuum Cherenkov
strength, electron energy
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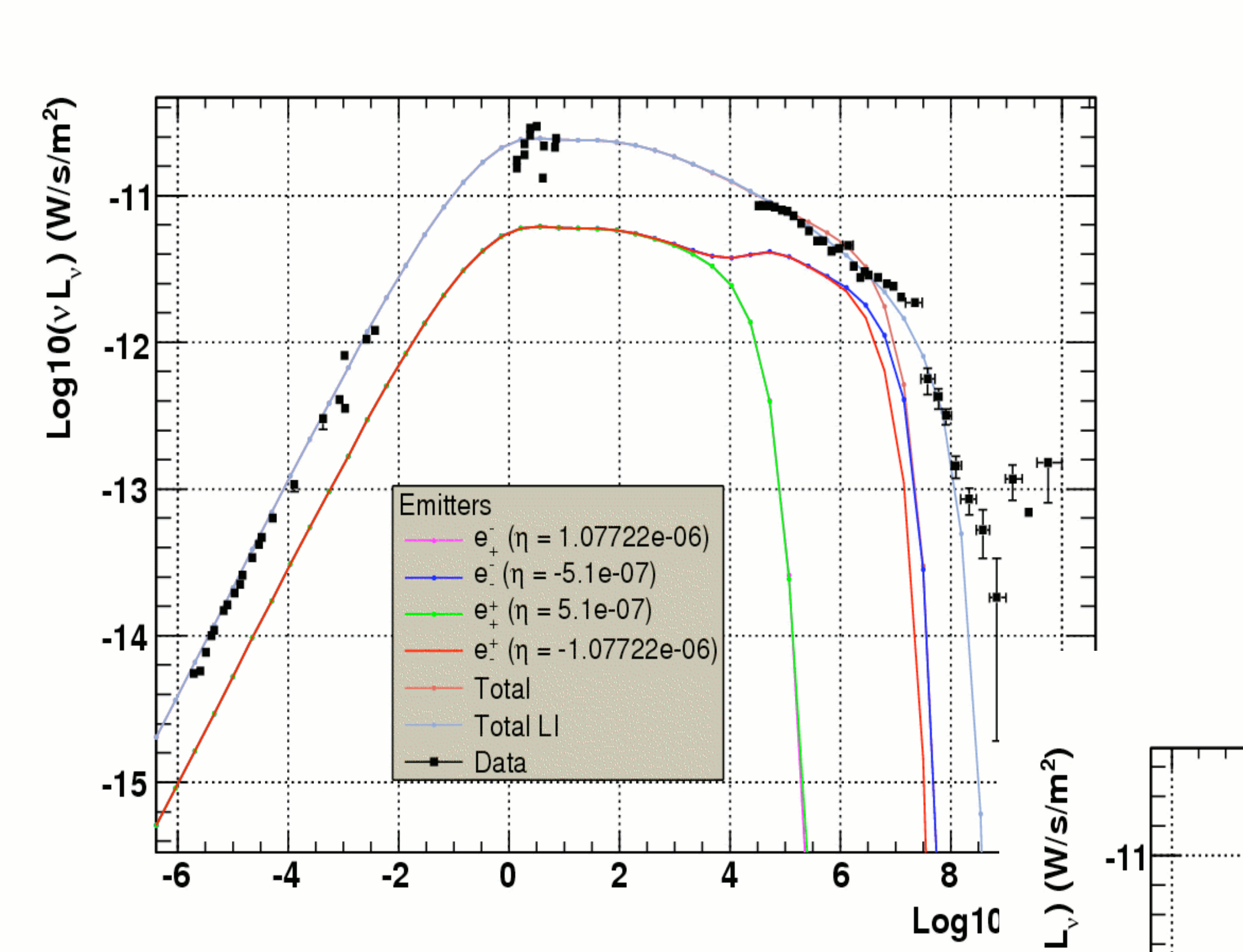
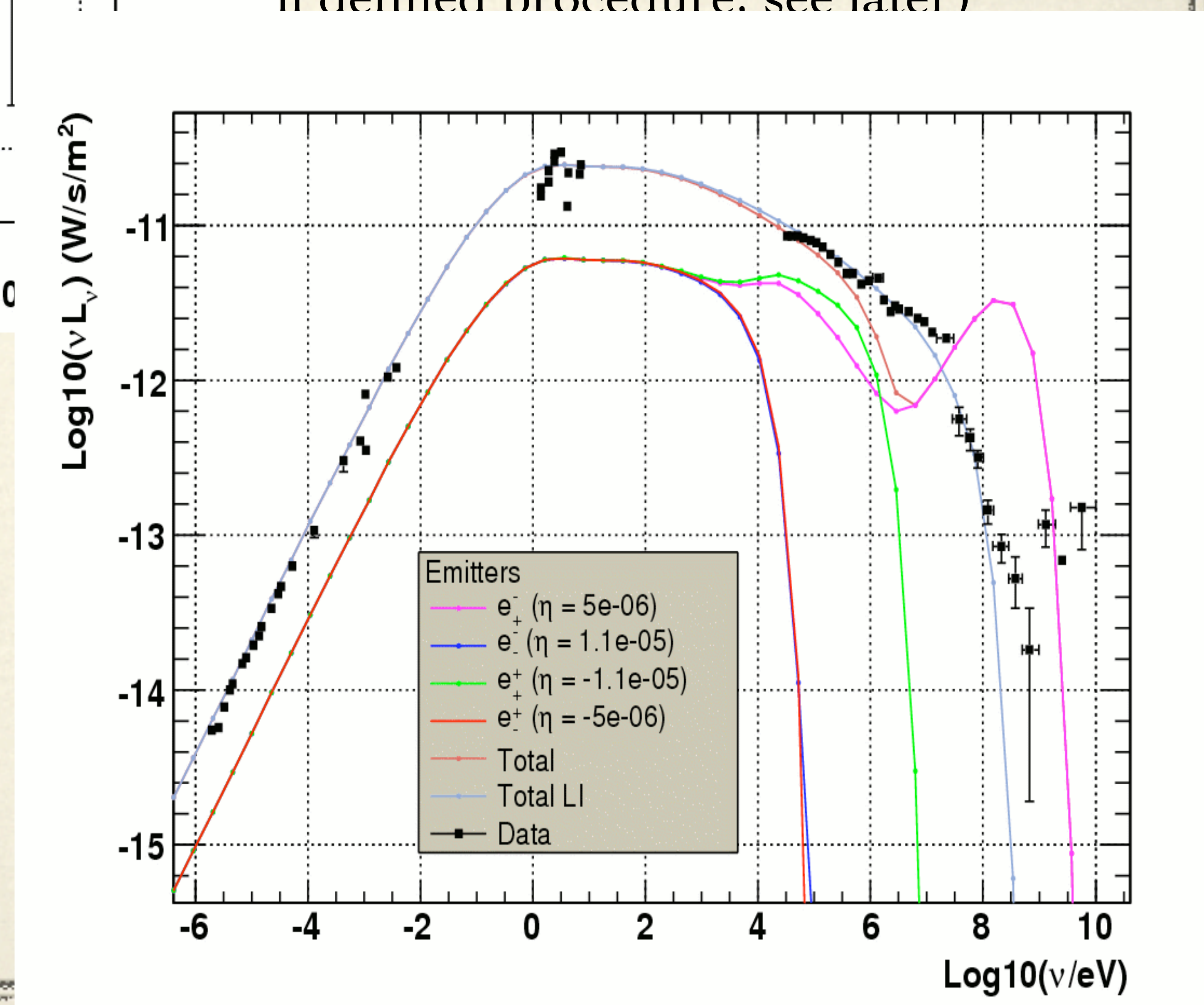
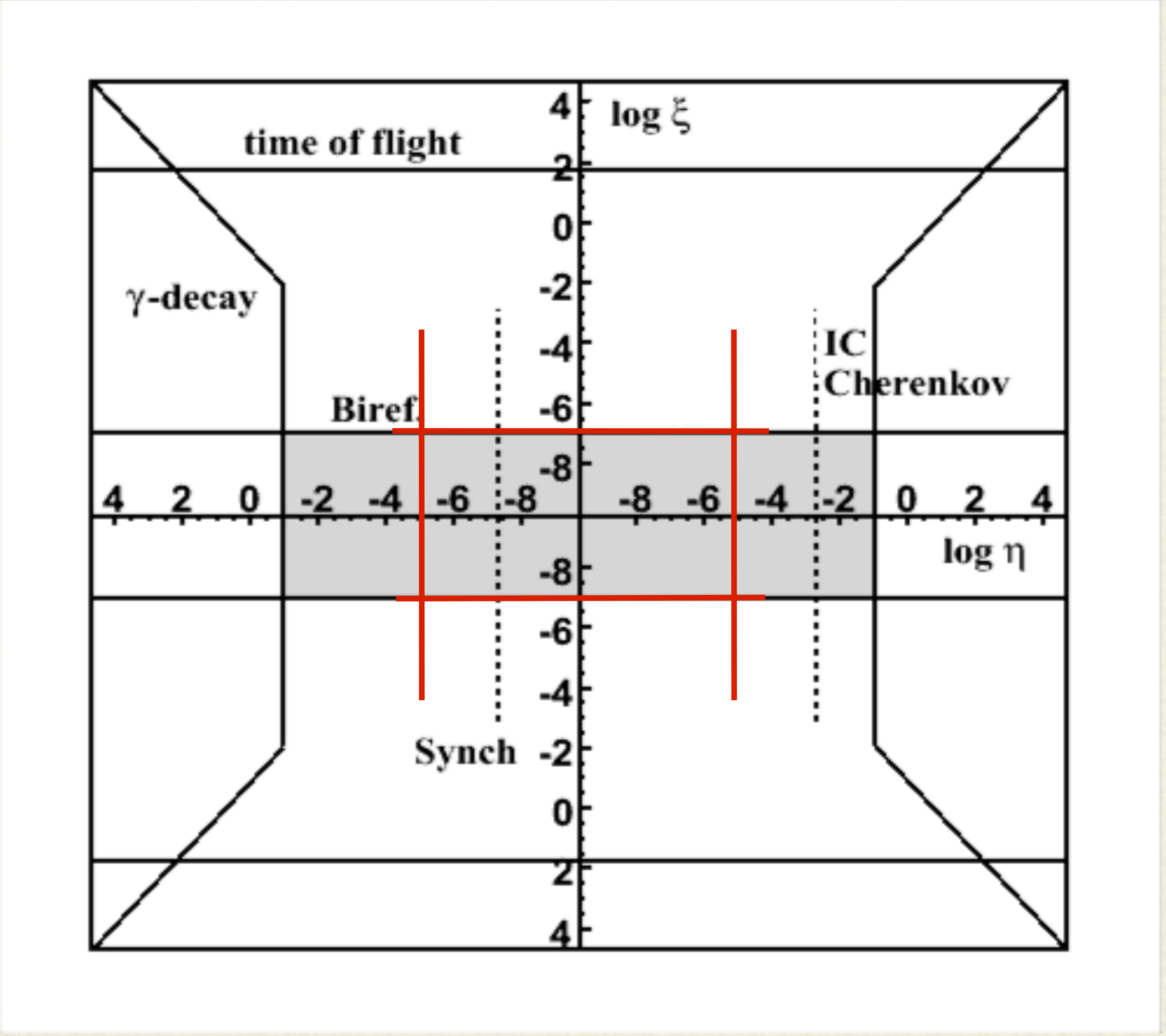




More details:
L.M., S.Liberati, A.Celotti, J.Kirk, JCAP 10, 013 (2007)

New resume...



log ξ
time of flight
γ-decay
Biref.
IC
Cherenkov
log η
Synch
4
2
0
-2
-4
-6
-8

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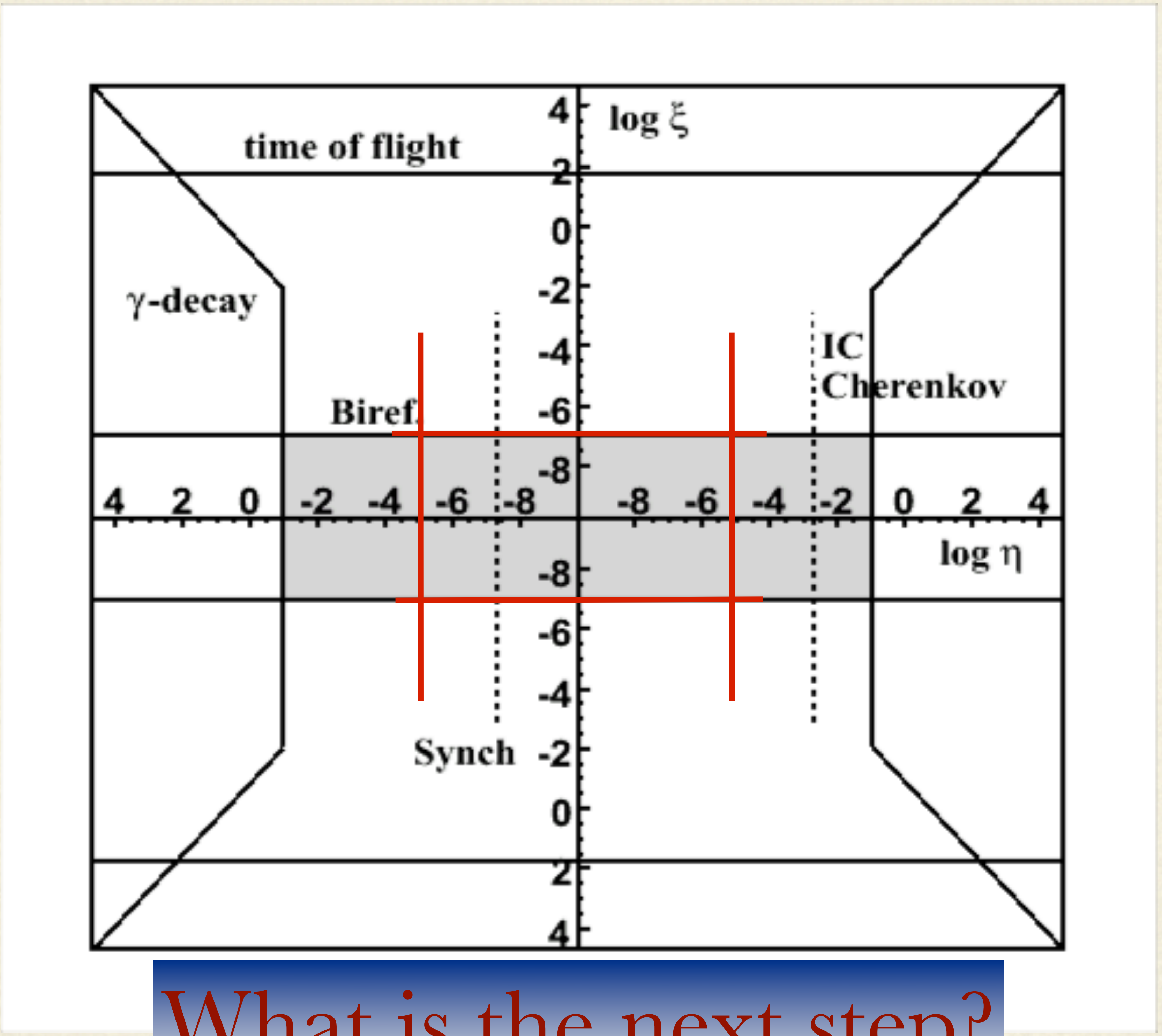

What is the next step?

An open problem: is small LV natural?

[Collins et al. PRL93 (2004)]

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while we would expect them O(1).
Then attention focused on dim 5 and higher,
non-renomalizable operators

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Then attention focused on dim 5 and higher, **non-renomalizable operators**

However, in this case **radiative (loop) corrections** involving integrals up to the natural cutoff M will generate the terms associated to low energy operators which are unacceptable observationally if $\eta^{(NR)} \approx O(1)$.

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To make low energy LV small seems hard...

This need not be the case if a custodial symmetry or other mechanism protects the low energy operators from violations of Lorentz symmetry.

E.g. **SUSY protects dim<5 operators**

BUT dim 5 theory not viable: SUSY breaking leads to not enough suppressed dim 3 operators

However **CPT+SUSY push allowed operators to dim 6**... when SUSY broken $\eta^{(2)} \approx O(E_{SUSY}/M)^2$

E.g. gr-qc/0402028 (Myers-Pospelov) or hep-ph/0404271 (Nibbelink-Pospelov) or gr-qc/0504019 (Jain-Ralston)...

O(E²/M²) LV

SME not complete but we know a lot about.

	Fermions	Photon
CPT even	$-\frac{i}{E_{Pl}^2}\bar{\psi}(u\cdot D)\Box(u\cdot\gamma)(\tilde{\alpha}_L^{(6)}P_L+\tilde{\alpha}_R^{(6)}P_R)\psi$ $-\frac{i}{E_{Pl}^2}\bar{\psi}(u\cdot D)^3(u\cdot\gamma)(\alpha_L^{(6)}P_L+\alpha_R^{(6)}P_R)\psi$	$-\frac{1}{2E_{Pl}^2}\beta^{(6)}F^{\mu\nu}u_\mu u^\sigma(u\cdot\partial)^2F_{\sigma\nu}$
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But keep in mind **neutrinos**!

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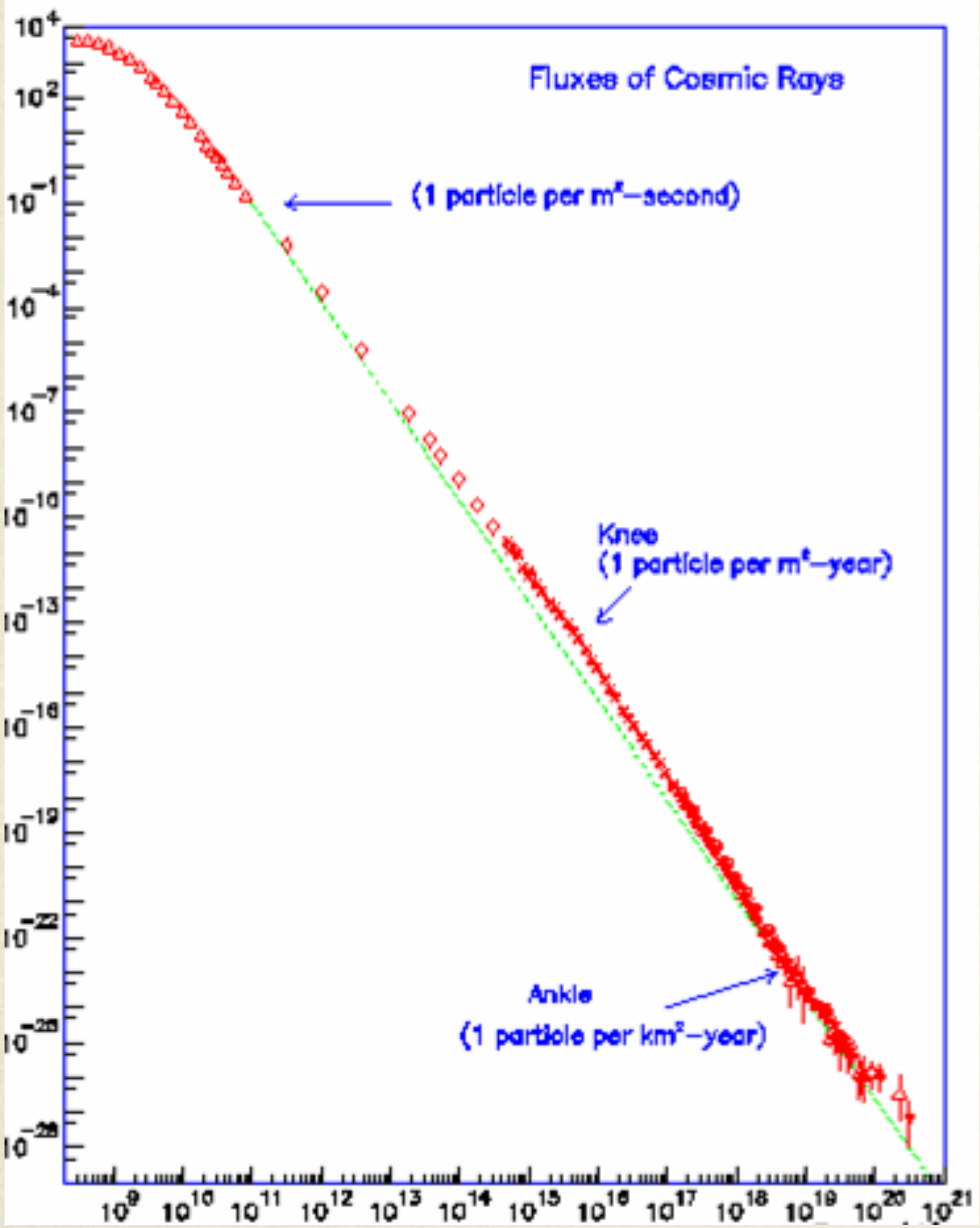
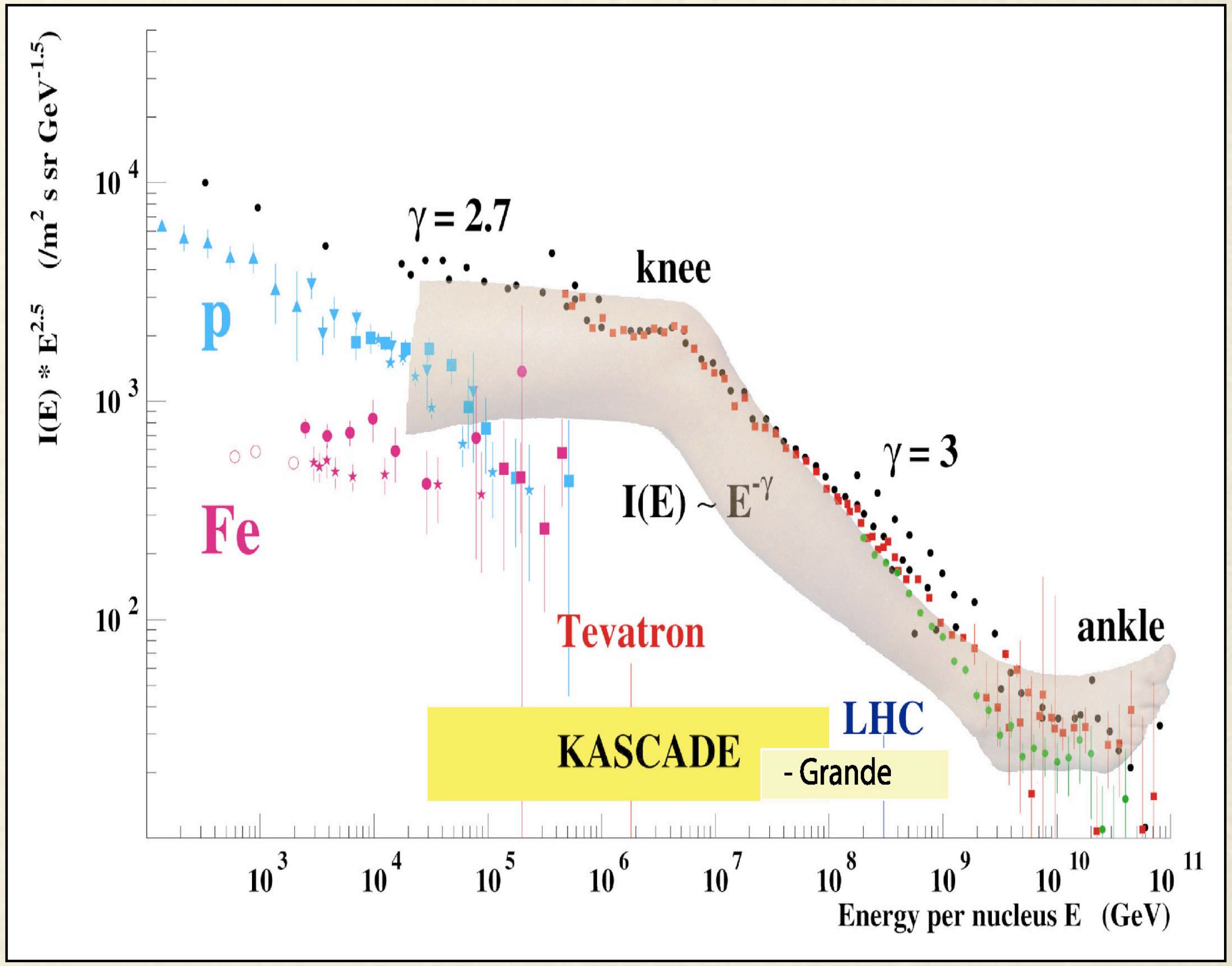
Further complication: protons (and pions) are not elementary particles.
How to cook up their MDR from that of the constituent quarks??
At present, the answer is not clear.
For the moment, let's assume the following

$$E^2 = m_p^2 + p^2 \pm \eta_\pm^{(4)}\frac{p^4}{M_{\rm Pl}^2}$$

UHECRs phenomenology



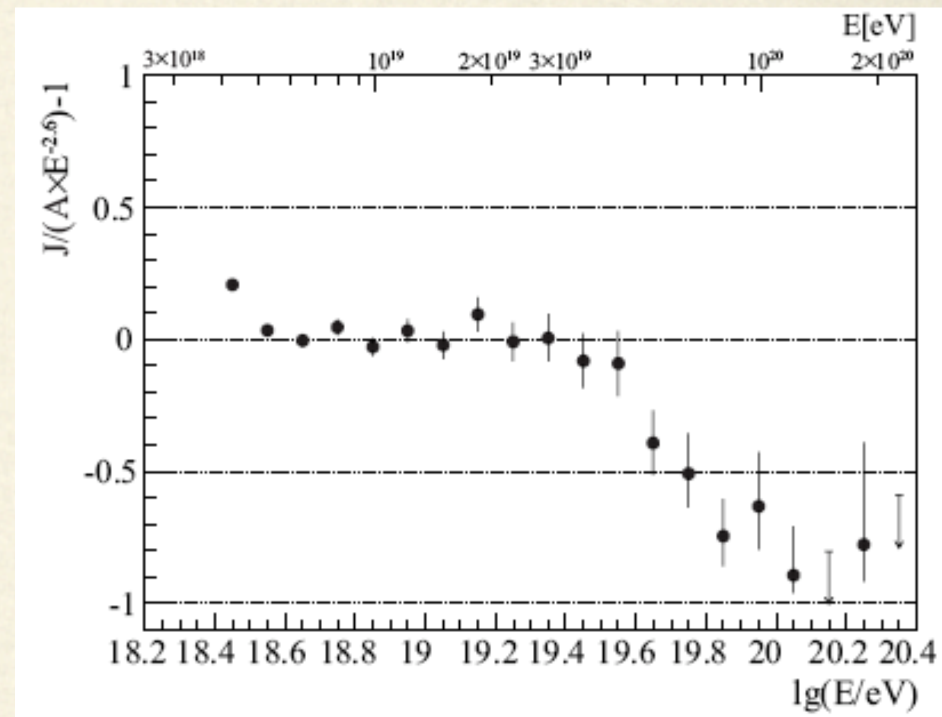


GZK

<u>The Greisen-Zatsepin-Kuzmin (GZK) effect:</u>

attenuation of proton spectrum due to resonant photo-pion-production

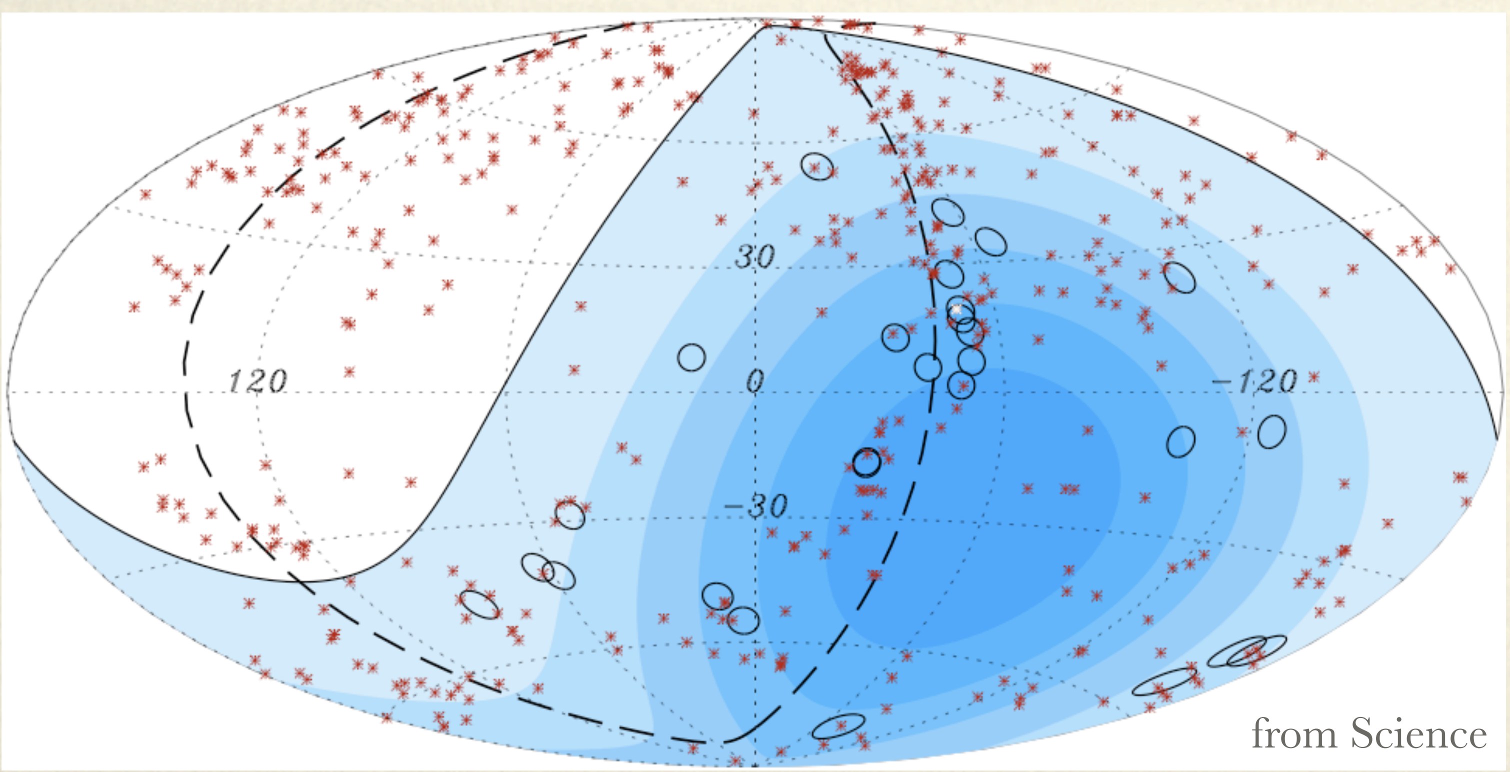
$p + \gamma \to p + \pi^0 (n + \pi^+)$ mainly through the interaction with the CMB



Early claim by HiReS

Abbasi R. *et al* (HiRes Collaboration), 2007 *Preprint* astro-ph/0703099

Confirmed by AUGER data



Further confirmation: found **correlation** between UHECR arrival directions and some extragalactic source

Present limits: GZK

There are limits in many simplified cases

n=4

Coleman & Glashow **Phys. Rev. D 59, 116008 (1999)**

$$\eta_\pi - \eta_p < 5\times 10^{-24}(\omega/\bar\omega)^2 \qquad \bar\omega = kT_{CMB} = 0.235\,\mathrm{meV}$$

n=5

Aloisio, Blasi, Grillo... ($\eta_1=\eta_2=\eta_\pi$)

astro-ph/0001258

Jacobson, Liberati, Mattingly

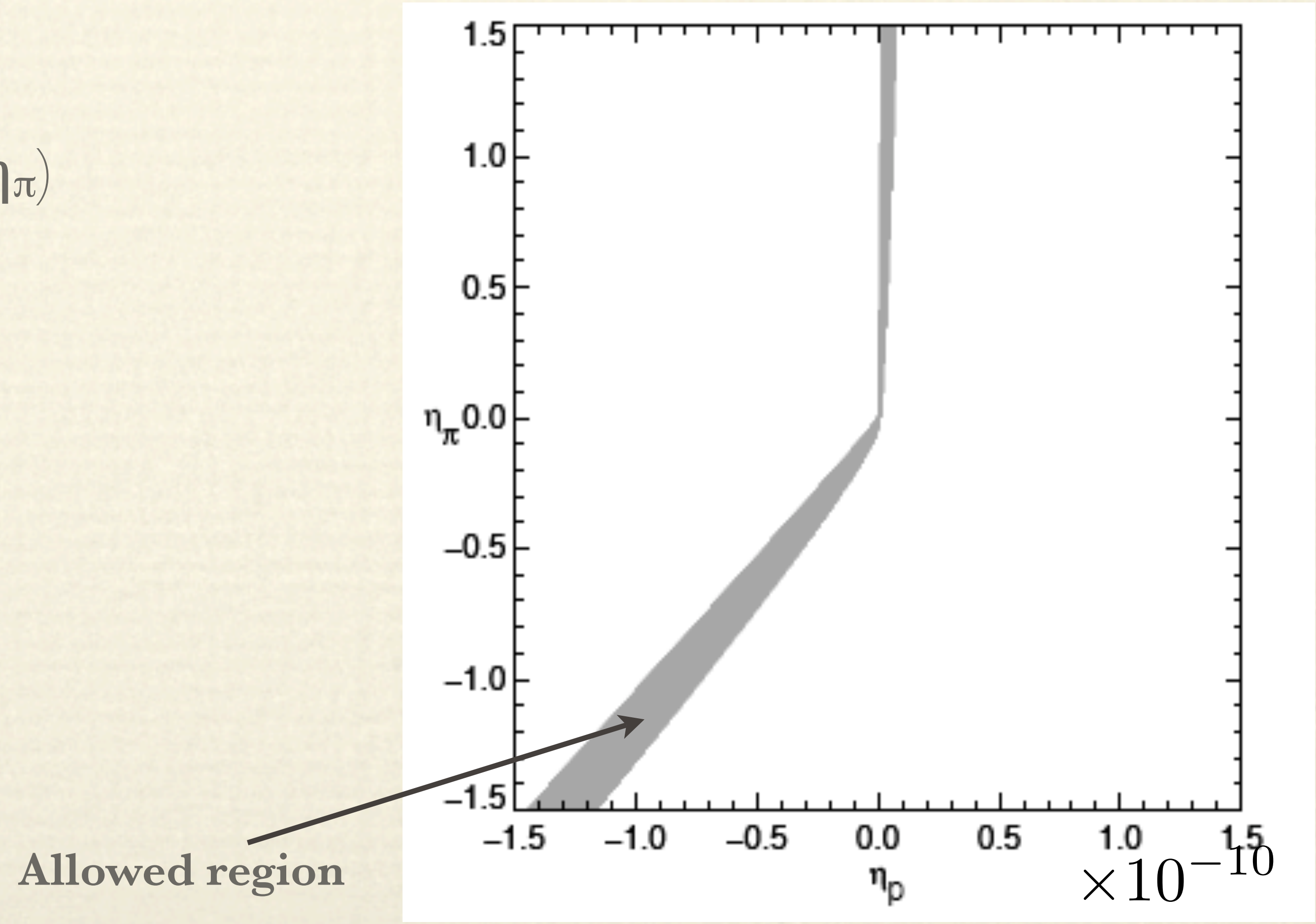
($\eta_1=\eta_2\neq\eta_\pi$)

gr-qc/0209264

Loop QG

Alfaro, Palma

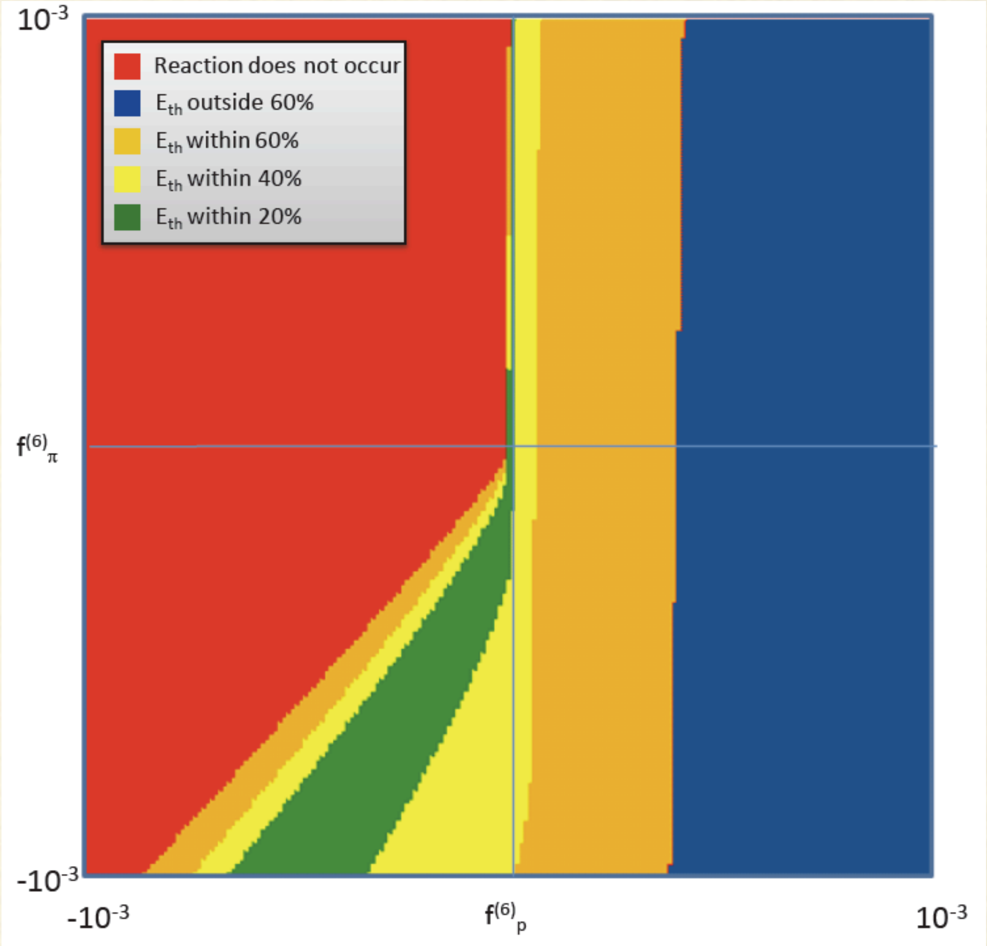
hep-th/0208193



Present limits: GZK

n=6

D. Mattingly ($\eta_1=\eta_2\neq\eta_\pi$)
Proceedings of "From Quantum to Emergent Gravity: Theory and Phenomenology", SISSA, June 2007



Though the analysis is stringent, most of the parameter space, mainly in the negative quadrant, is still allowed.

This kind of analysis just looks at the presence and position of the cut-off. But LIV also affects other aspects of UHECR propagation which lead to a distortion of the UHECR spectrum at Earth.

A more thorough study of the whole spectrum around and above 10^{19} eV should then allow to place better constraints.

UHECR constraints: pair production

Galaverni, Sigl, arXiv:0708.1737
LM, S. Liberati, arXiv:0805.2548

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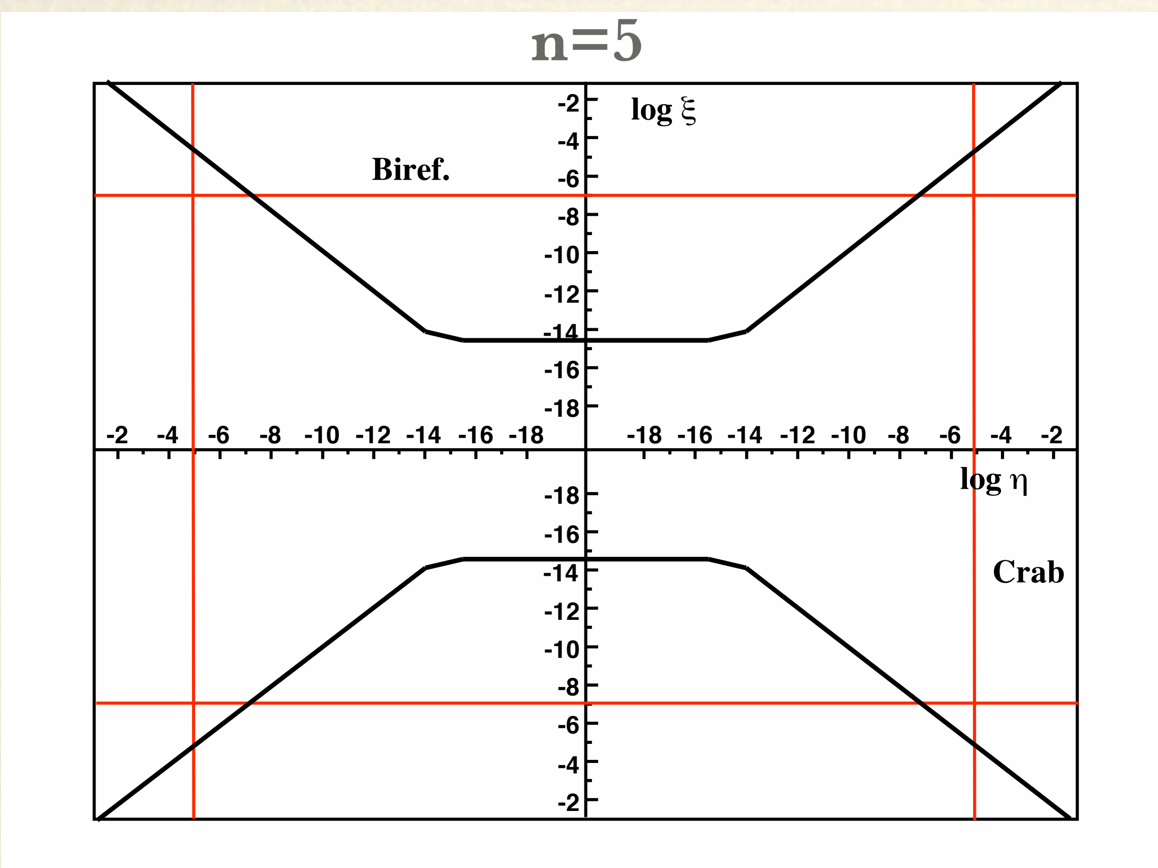

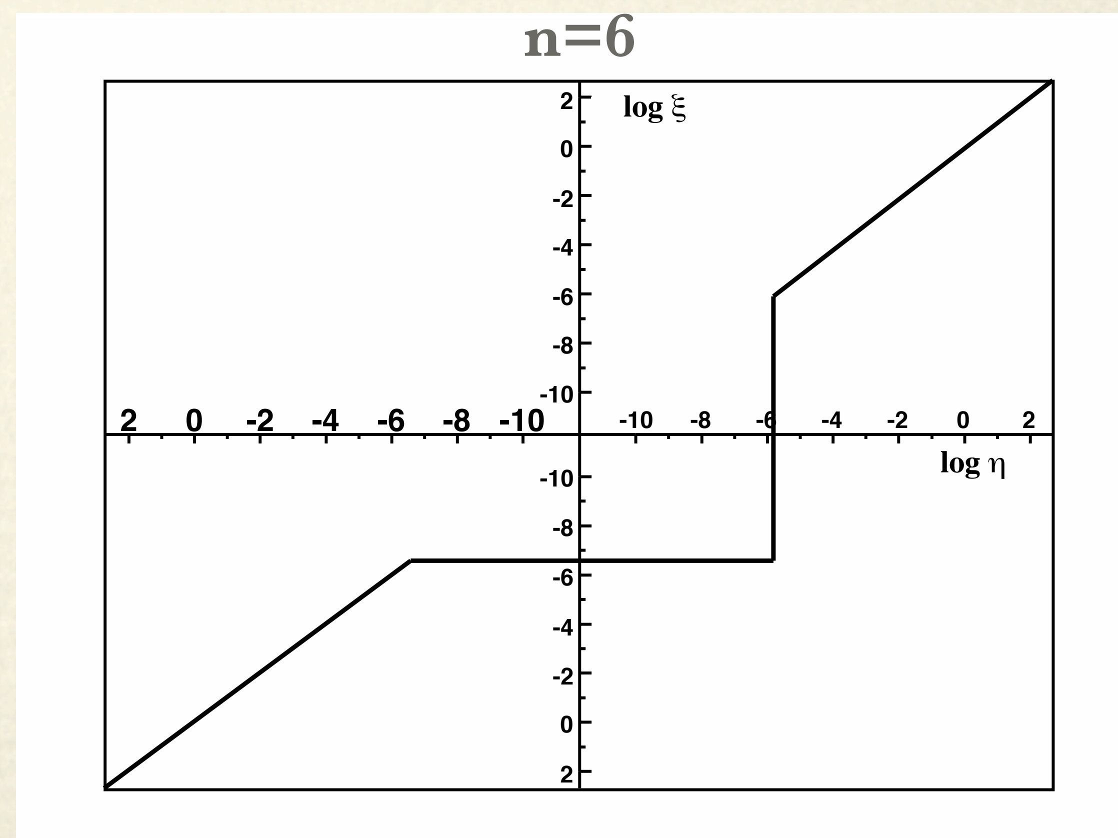

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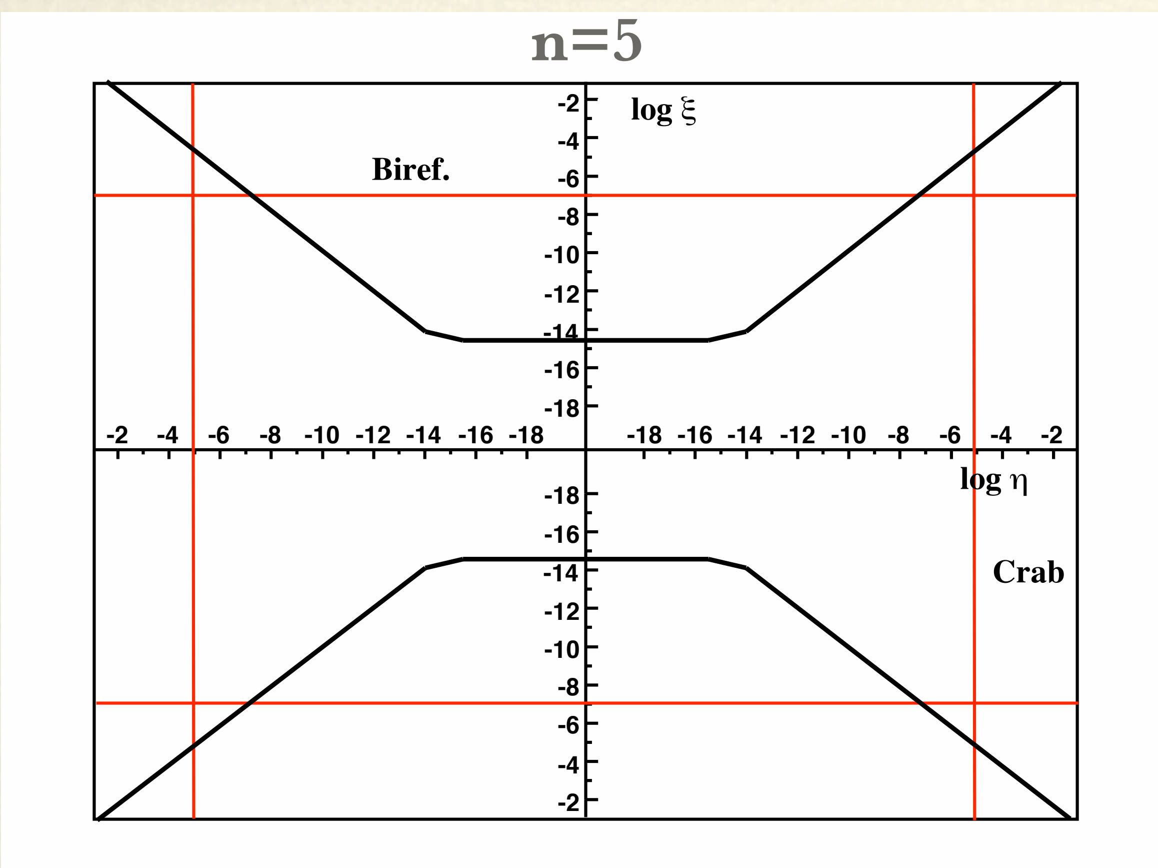

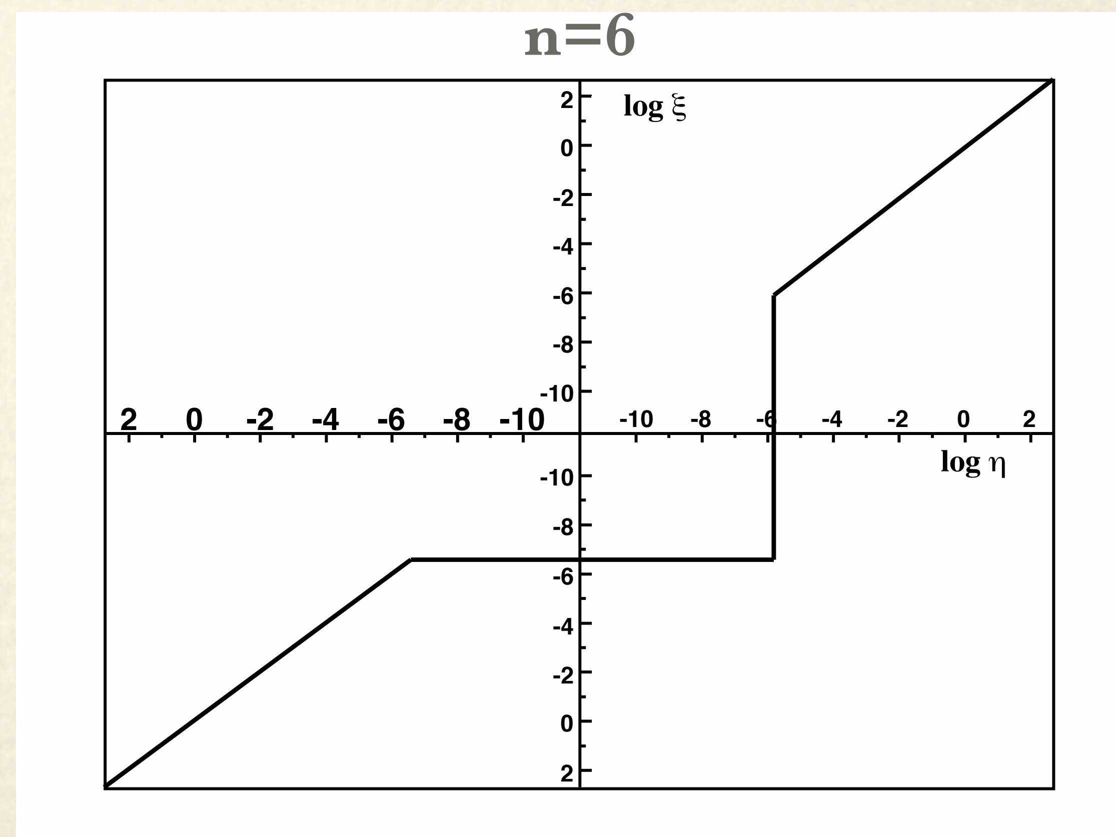

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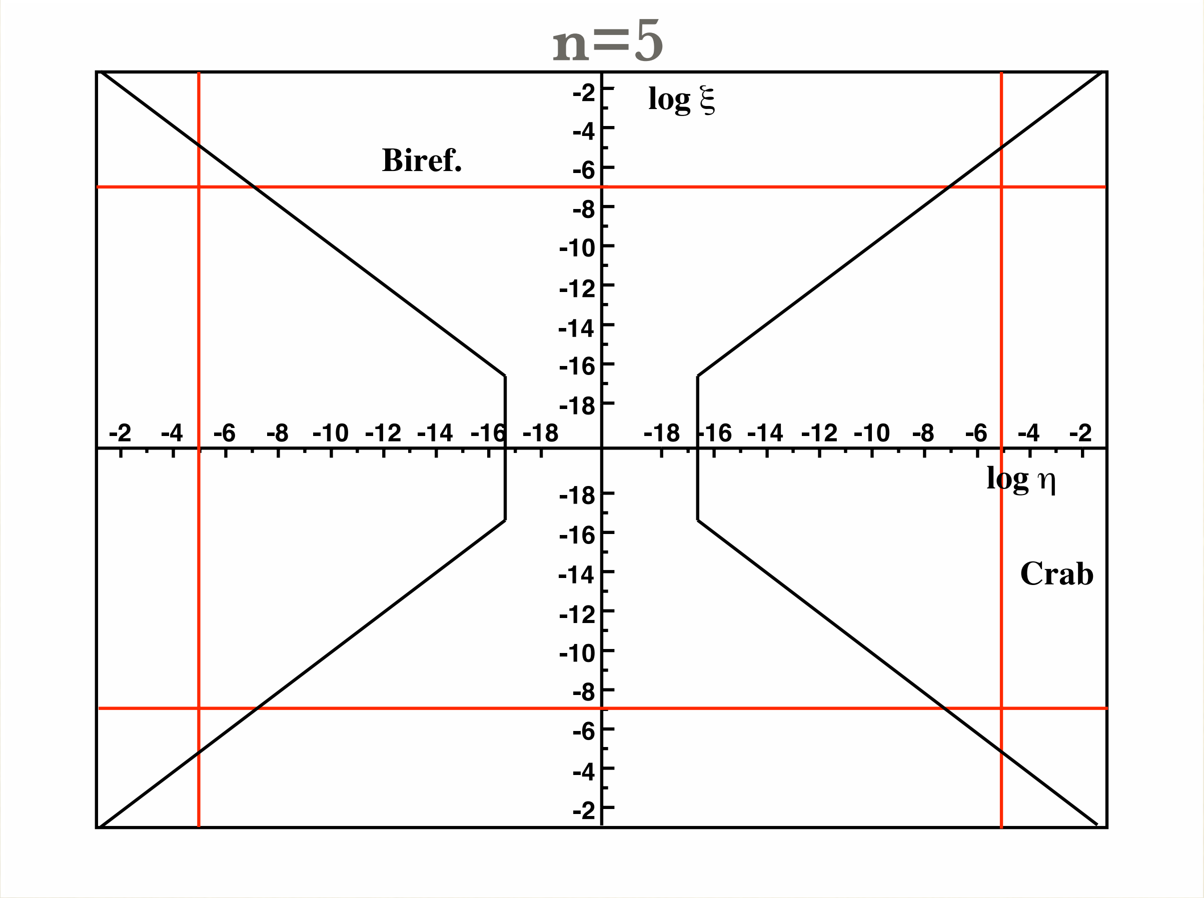

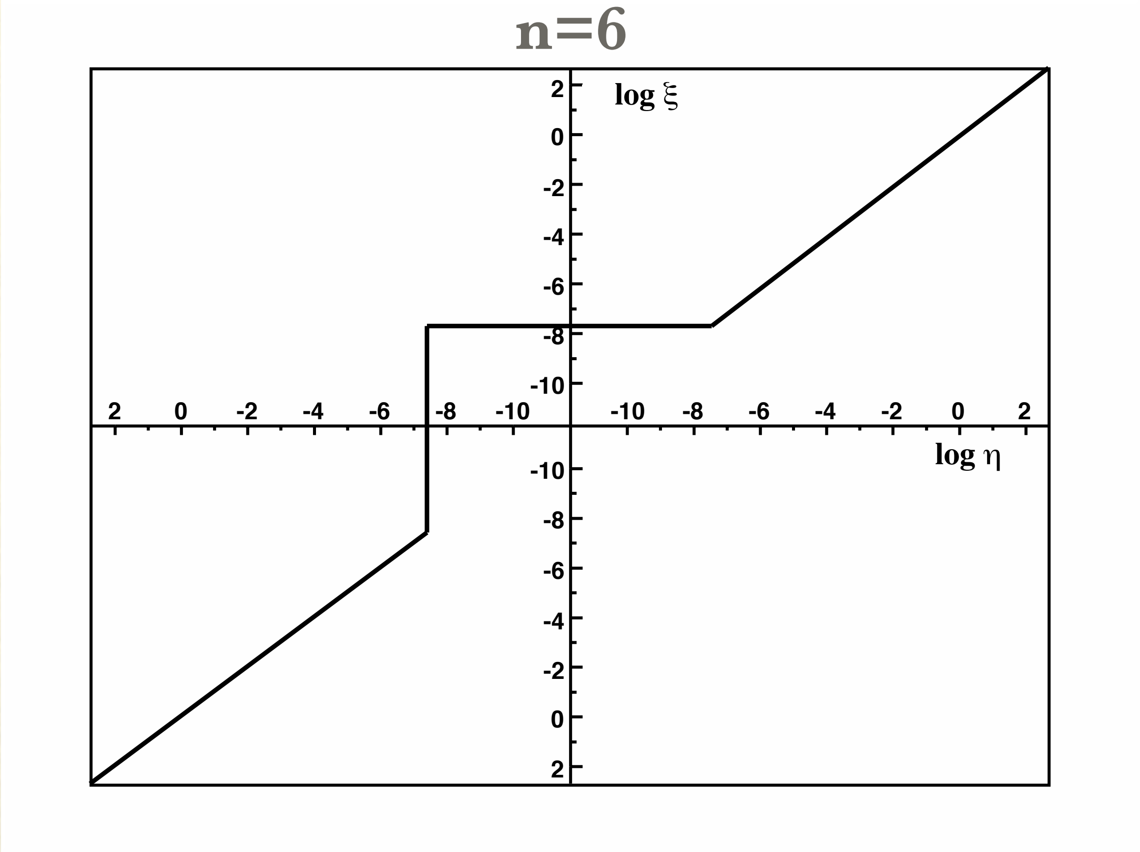

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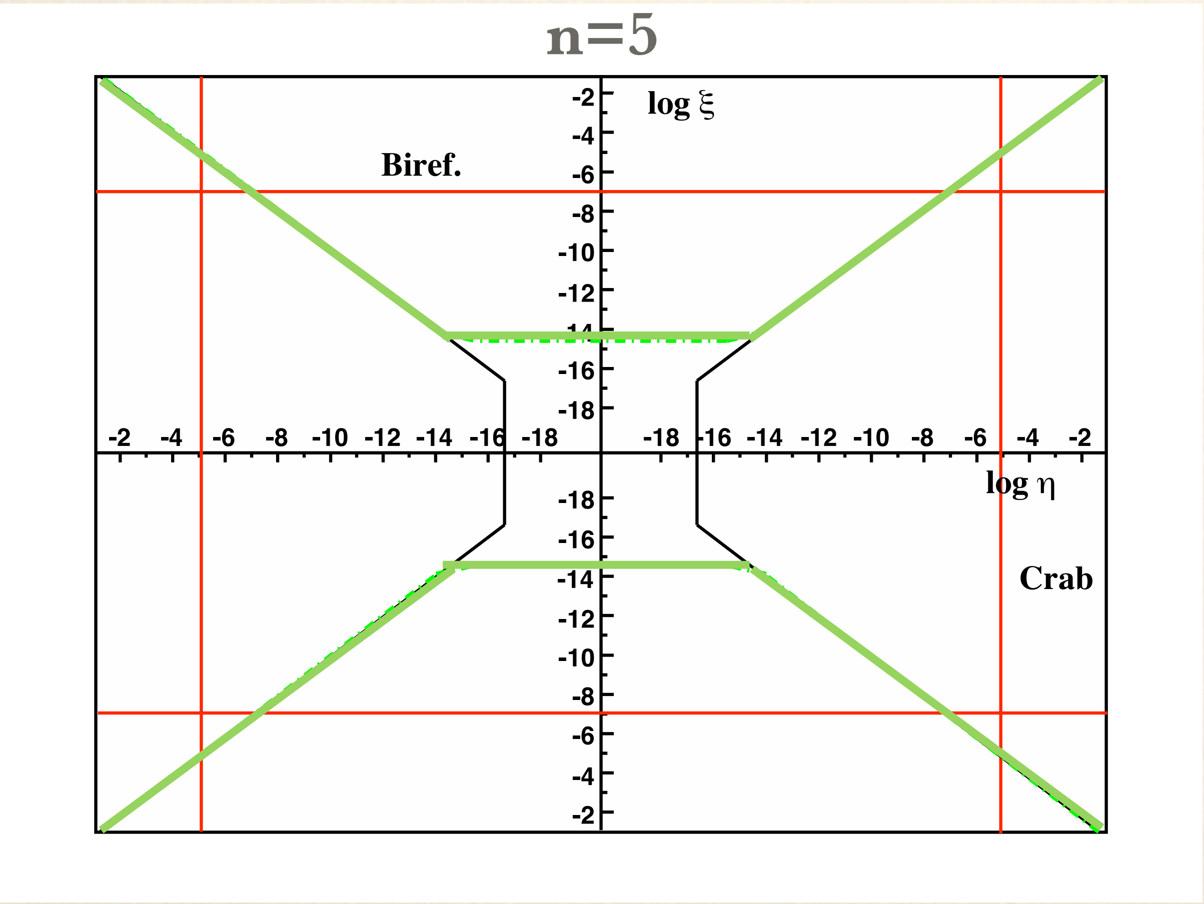

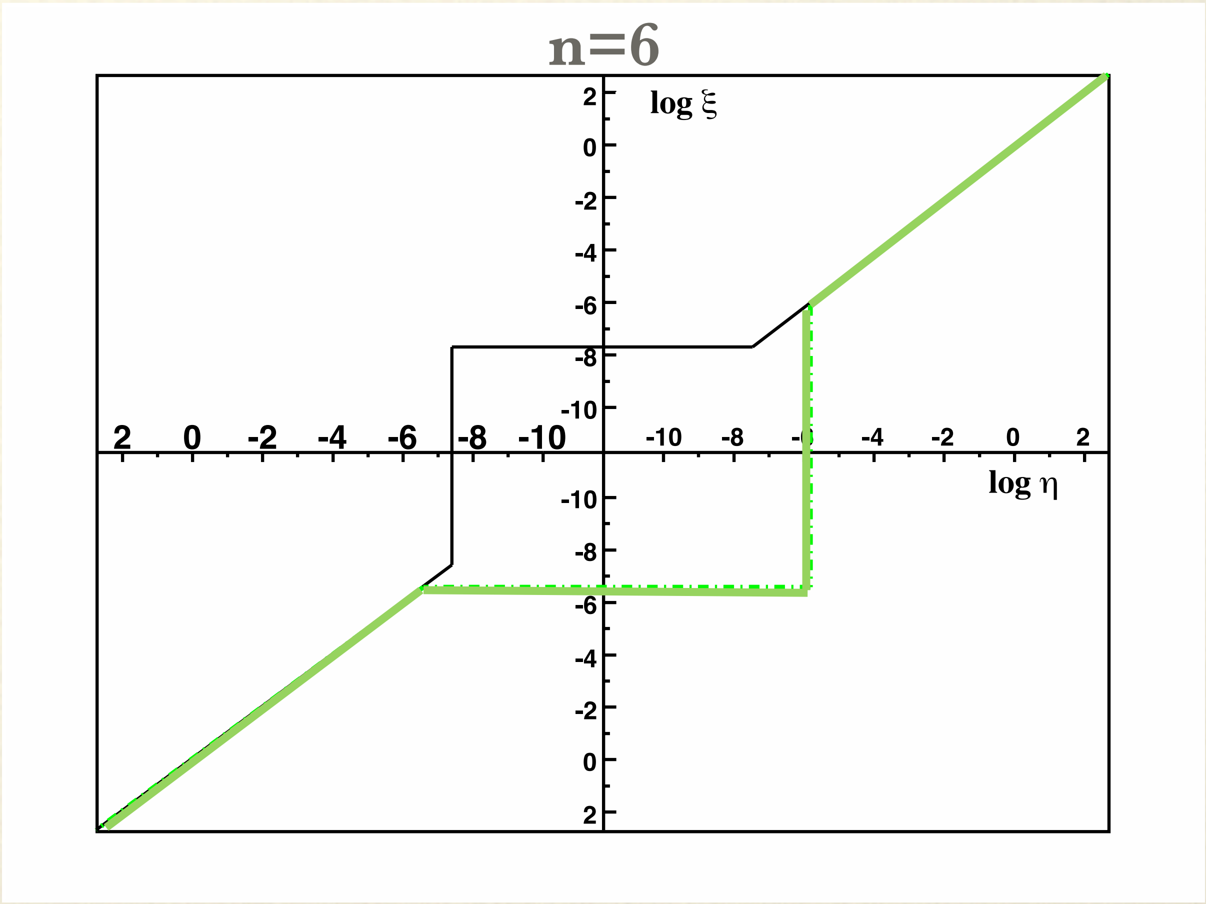

Conclusions and Outlook

- **HE astrophysics observations indeed provide significant information on fundamental physics**
- ***O(E/M)* LIV severely constrained**
- **Robust limits obtained exploiting broad-band information about astrophysical objects (Crab). To look at *spectra* is very effective**
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The end

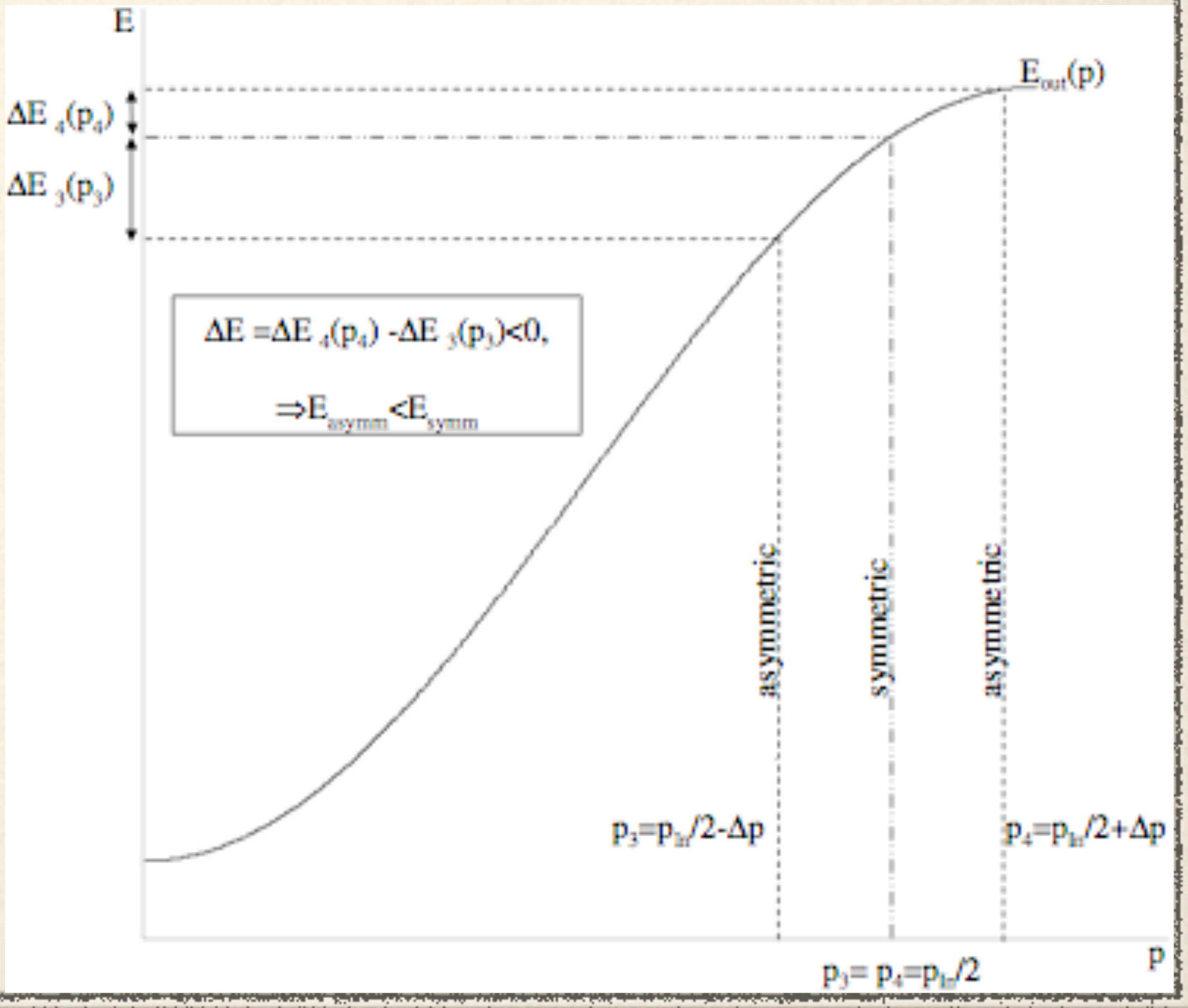
❖ **Asymmetric configurations:**

Pair production can happen with asymmetric distribution of the final momenta

$$\Delta E_f = \left.\frac{\partial^2 E_0}{\partial p^2}\right|_{p=p_s} (\Delta p)^2$$

$$\text{if} \quad \left.\frac{\partial^2 E_0}{\partial p^2}\right|_{p=p_s} < 0$$

Sufficient condition for asymmetric Threshold.



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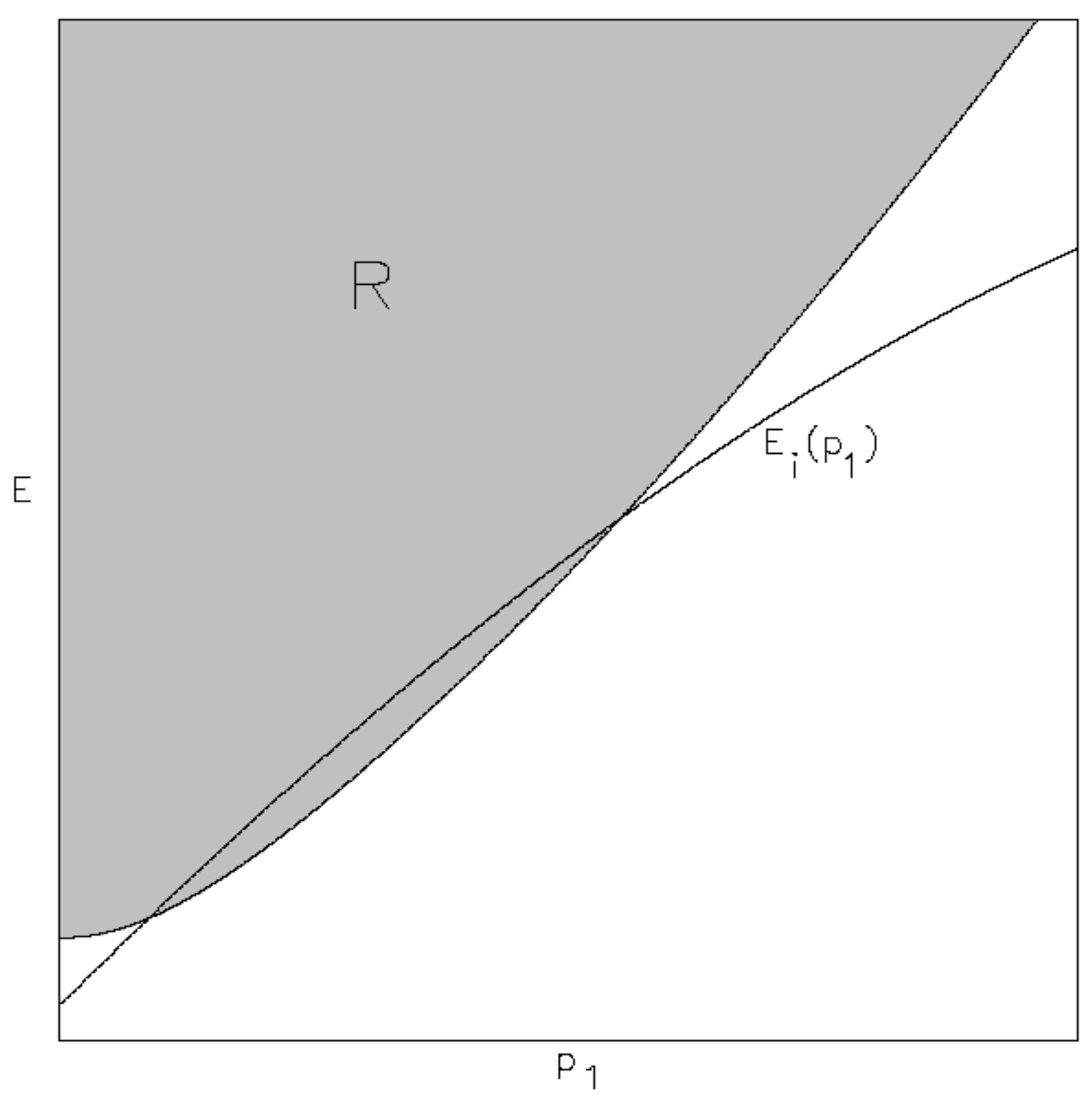

❖ **Upper thresholds:**

The range of available energies of the incoming particles for which the reactions happens is changed.

Lower threshold can be shifted and upper thresholds can be introduced

If LI holds there is never an upper threshold

However the presence of different coefficients for different particles allows E_i to intersect two or more times E_f switching on and off the reaction!

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Threshold reactions

Key point: the effect of the non LI dispersion relations can be important at energies well below the fundamental scale

$$E^2 = c^2 p^2 \left(1 + \frac{m^2 c^2}{p^2} + \eta \frac{p^{n-2}}{M^{n-2}}\right)$$

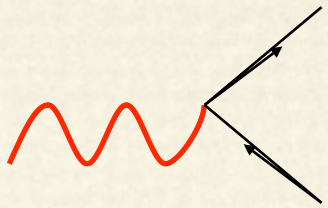
Corrections start to be relevant when the last term is of the same order as the second.
If η is order unity, then

$$\frac{m^2}{p^2} \approx \frac{p^{n-2}}{M^{n-2}} \Rightarrow p_{crit} \approx \sqrt[n]{m^2 M^{n-2}}$$

n	p_{crit} for ν_e	p_{crit} for e^-	p_{crit} for p^+
4	$p \approx m_\nu \sim 1$ eV	$p \approx m_e = 0.5$ MeV	$p \approx m_p = 0.938$ GeV
5	~1 GeV	~10 TeV	~1 PeV
6	~100 TeV	~100 PeV	~3 EeV

Astrophysical constraints: LV QED

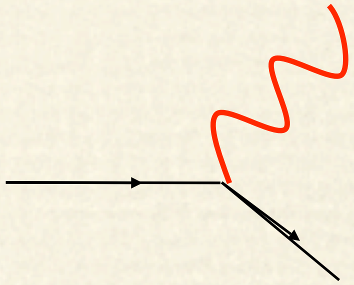
Gamma decay $\gamma \to e^+ + e^-$



- Lorentz violation allows the conservation of energy-momentum.
- Well above threshold it is very fast as the decay rate goes like Γ»E^2/M.
- 10 TeV photons would decay in approximately 10^{-8} seconds.
- If we see very high energy gamma rays from distant sources at least one photon polarization must travel on cosmological distances. I.e. they must be below threshold.
- If |ξ|«|η| the constraint has the form

$$\boxed{|\eta_\pm| \lesssim 6\sqrt{3}m^2 M/k_{\rm th}^3}$$

Vacuum Cherenkov (Helicity Decay) $e^\pm \to e^\pm + \gamma$



- Depending on parameters one can have emission of soft or hard photon.
- Once the reaction can happen it is very fast as the rate of energy loss goes like dE/dt≈E^3/M ⇒ 10 TeV electron would lose most of its energy in ≈10^{-9} seconds.
- The observation of the propagation of some high energy electrons implies that at least one helicity state cannot decay in either of the photon helicities.
- Hence the constraint can be worked out for one of the ±$\eta_\pm$ and ξ.

$$\boxed{p_{\rm th} = \left(m^2 M/2\eta\right)^{1/3}}$$

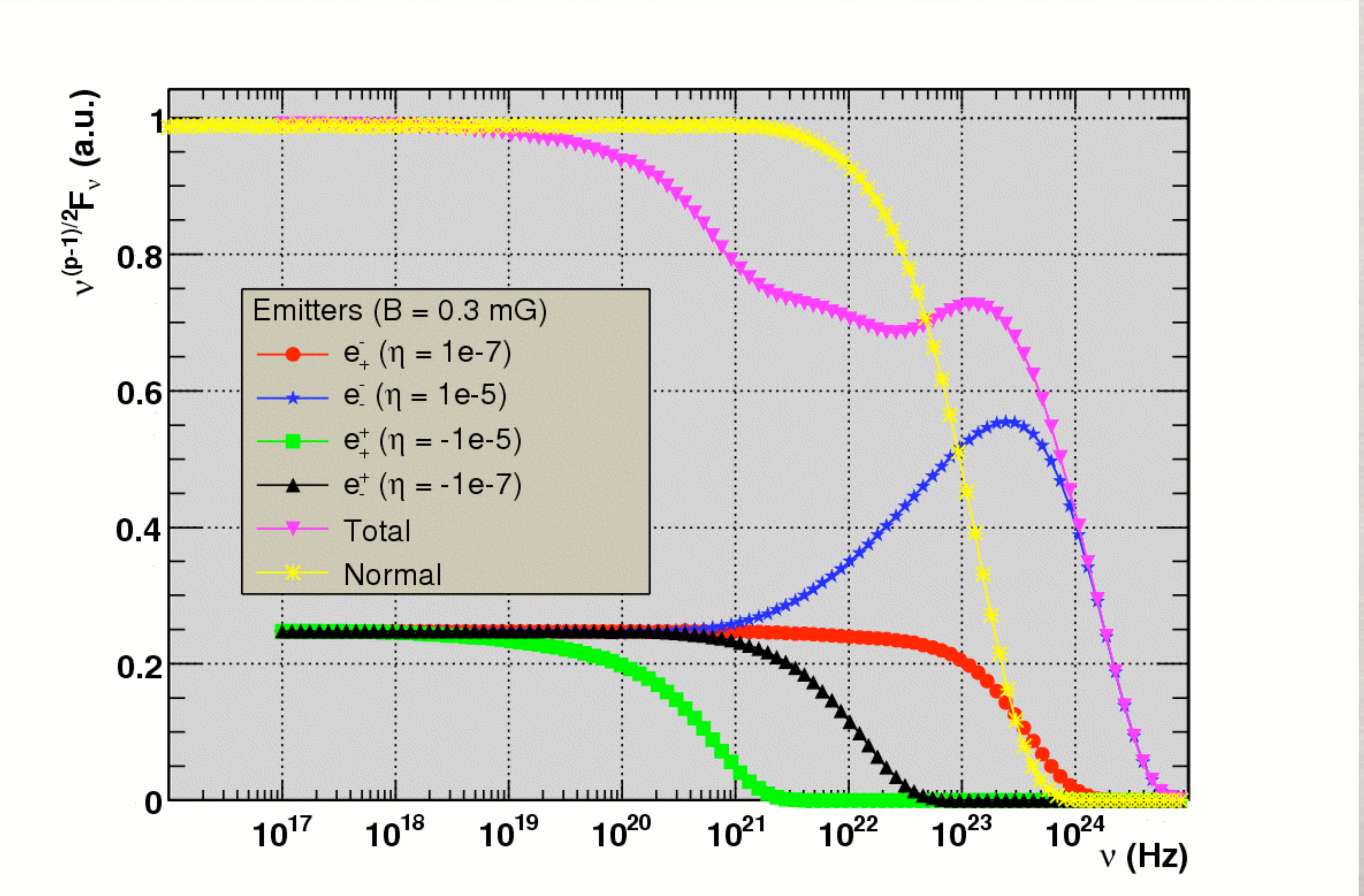
X

Modified Synchrotron: Idealized injection spectrum and no other effects.

Test of the code for the LI case. General behavior of the LIV case.

Yellow curve: the normalized LI spectrum from the code correctly reproduce the expected analytical result

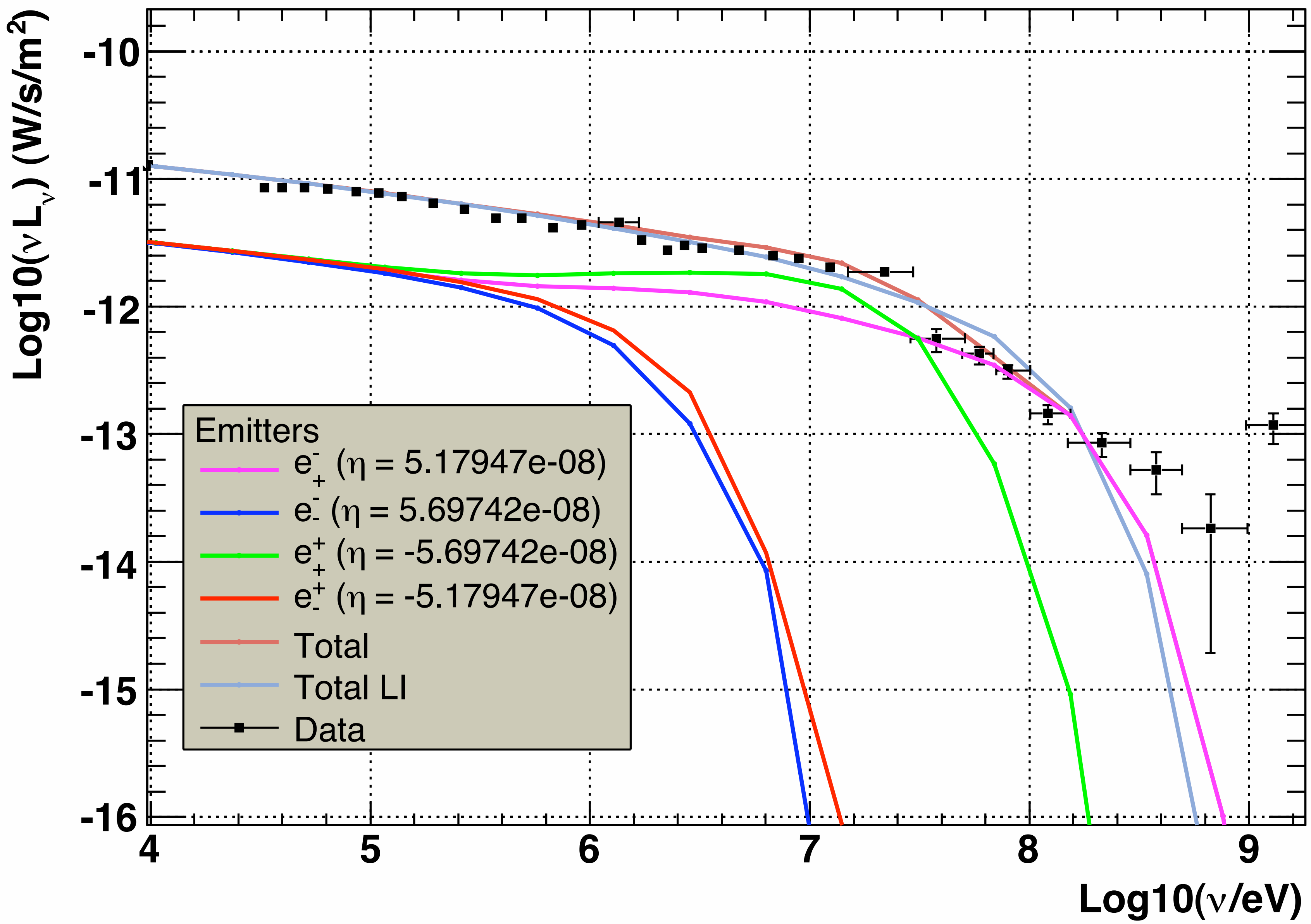
Magenta curve: LIV synchrotron. Hump in the η>0 populations, early decay of the η<0 ones



Best fit

Our analysis shows a best fit for $\eta_+ \cdot \eta_- > 0$ (i.e. for LV) with $(\eta_+, \eta_-) \sim (5.2\times10^{-8}, 5.7\times10^{-8})$

This is because LV allows to fit better an unexplained hump in the MeV range of the Crab synchrotron



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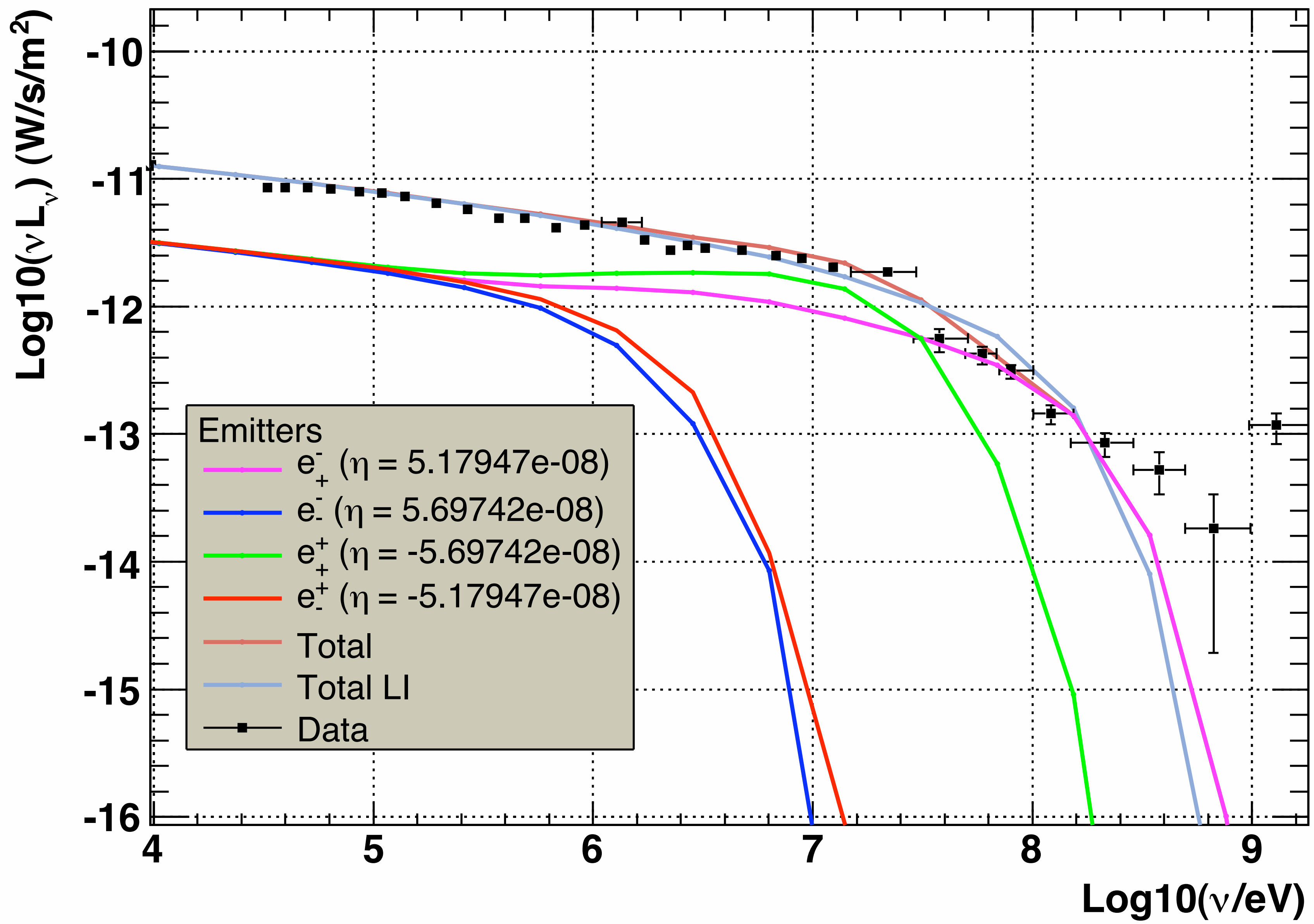
Should we get excited (scared)?!?!

Not yet...



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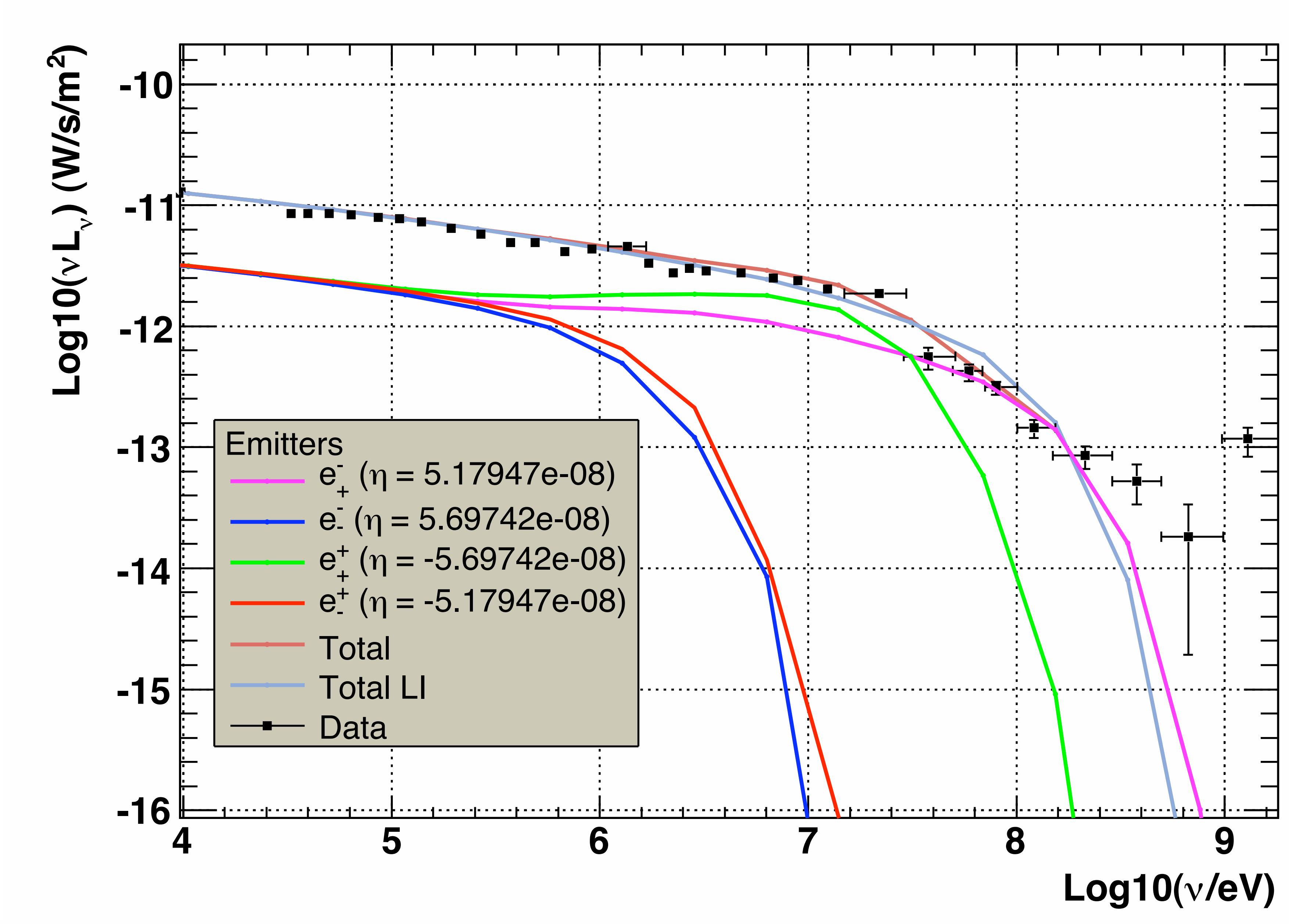


- The statistical significance of the difference between the χ^2 values of the best fit (LV) model and the standard LI of the result can be assessed with the so called F-test.
- Accordingly, the LI model and the best fit LV model are **statistically indistinguishable at 95% CL.**
- Therefore, these features cannot be considered, at present, as evidence of LV.
- However, the F-variable is found to be 1.11 against a critical value of 1.67
- So significant improvements in the data may permit the two possibilities to be disentangled. Since the features responsible for the best fit of the LV case are mainly located in the 40-250 MeV range, the next coming GLAST experiment should be able to provide the required accuracy... MORE SOON...

Renormalization Group effects

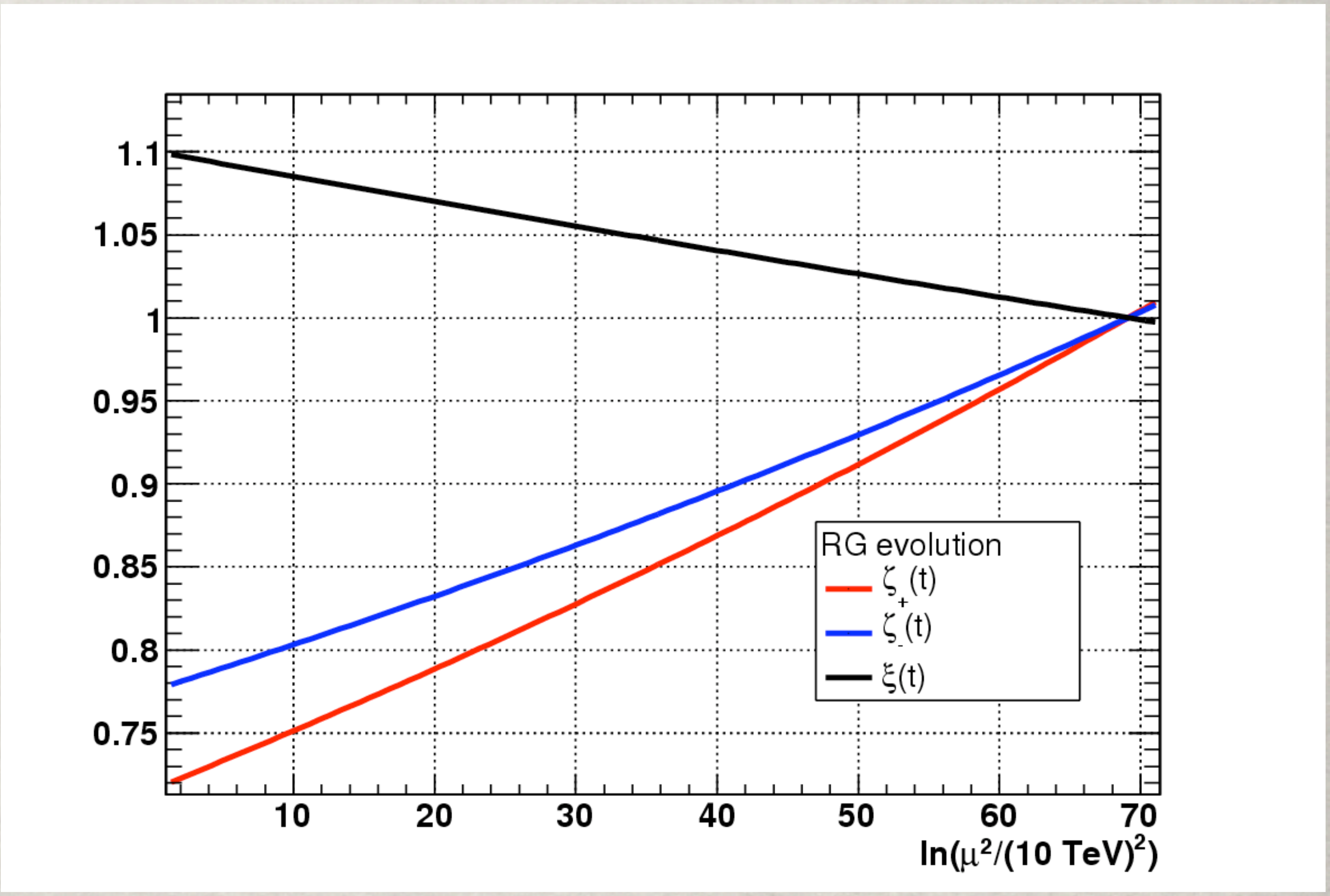
The constraints are robust against RG effects

RG equations in M&P QED recently computed (**Bolokhov & Pospelov, hep-ph/0703291**)

$$\begin{cases} \boxed{\dfrac{d\zeta_1}{dt} = \dfrac{25}{12}\dfrac{\alpha}{\pi}\zeta_1} \\ \boxed{\dfrac{d\zeta_2}{dt} = \dfrac{25}{12}\dfrac{\alpha}{\pi}\zeta_2 - \dfrac{5}{12}\dfrac{\alpha}{\pi}\xi} \\ \boxed{\dfrac{d\xi}{dt} = \dfrac{1}{12}\dfrac{\alpha}{\pi}\zeta_2 - \dfrac{2}{3}\dfrac{\alpha}{\pi}\xi} \end{cases}$$

$$\eta_\pm = 2(\varsigma_1 \pm \varsigma_2)$$

The running is only logarithmic

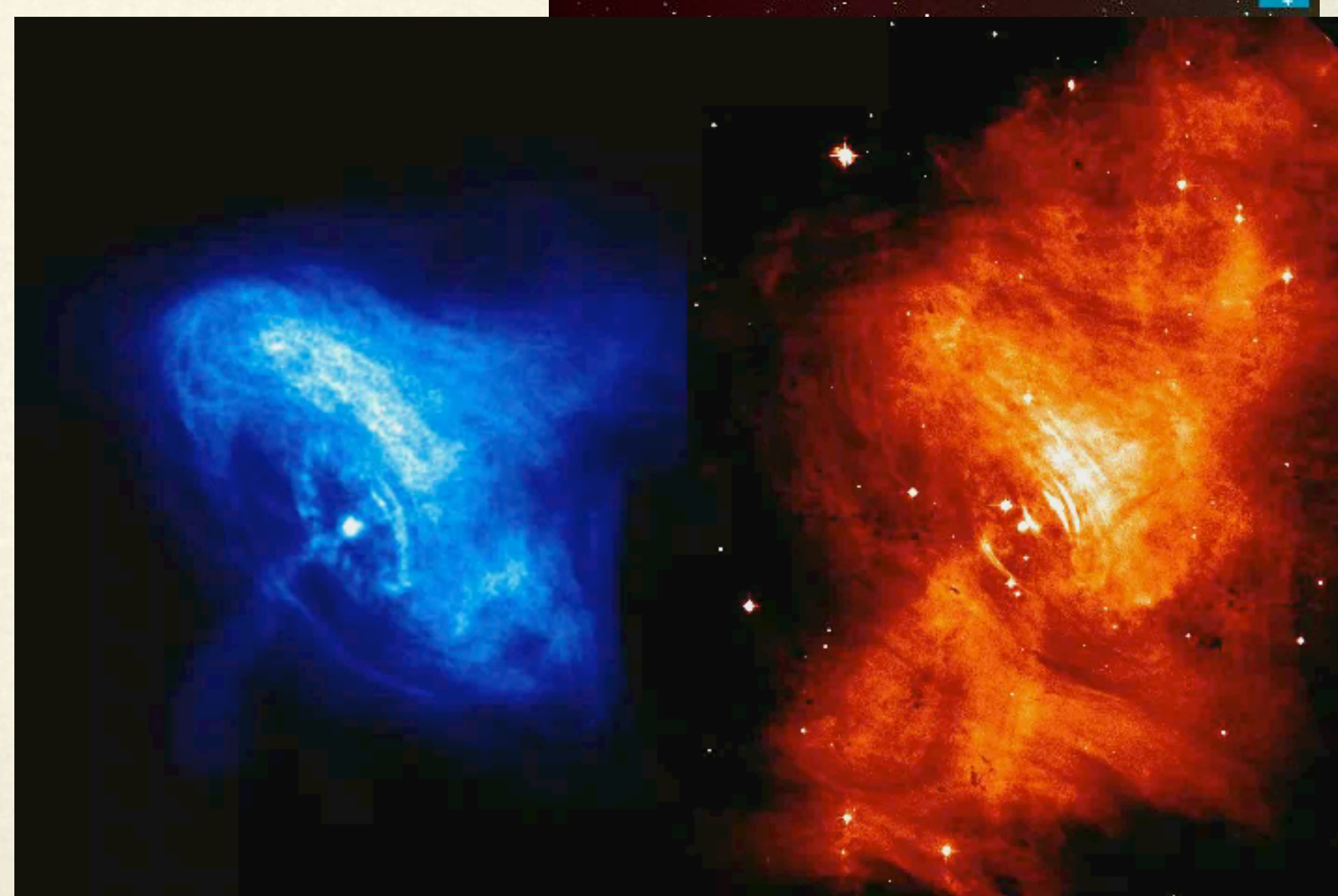


constraint scale → Planck scale

The Crab Nebula

The Crab Nebula – Remnant of a SuperNova explosion

- ✓ exploded in **1054 A.D.**
- ✓ distance **~1.9 kpc** from Earth
- ✓ pulsar wind powered nebula
- ✓ most powerful object in the sky
- ✓ spectrum spans **21 decades in frequency**, from radio to ~80 TeV
- ✓ **leptonic origin** of the radiation
- ✓ **electrons accelerated to > PeV**
- ✓ **theoretical model** understood only roughly at radio frequencies but enough at >keV energies. (**Kennel & Coroniti, 1984**)



E < 1 GeV ⟶ **synchrotron**
E > 1 GeV ⟶ **IC scattering**

LIV effects on the “GZK cutoff”

LI threshold $$E_{th} = \frac{m_\pi(2m_p + m_\pi)}{4\omega_0} \simeq 5\times 10^{19}\mathrm{eV}\left(\frac{\omega_0}{1.3\,\mathrm{meV}}\right)^{-1}$$

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LIV threshold

$$4p_1\omega_0 x(1-x) - m_p^2 x^2 - m_\pi^2(1-x) + \boxed{\frac{p_1^n}{M^{n-2}} x(1-x)\left[\eta_1 - \eta_2(1-x)^{n-1} - \eta_\pi x^{n-1}\right]} = 0$$

LV contribution

η_1,η_2 refer to the protons, η_π to the pion

$$x = p_{\rm pion}/p_{\rm proton} = \frac{m_\pi}{m_p + m_\pi} \simeq 0.13$$

in the LI case

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η_1,η_2 refer to the protons, η_π to the pion

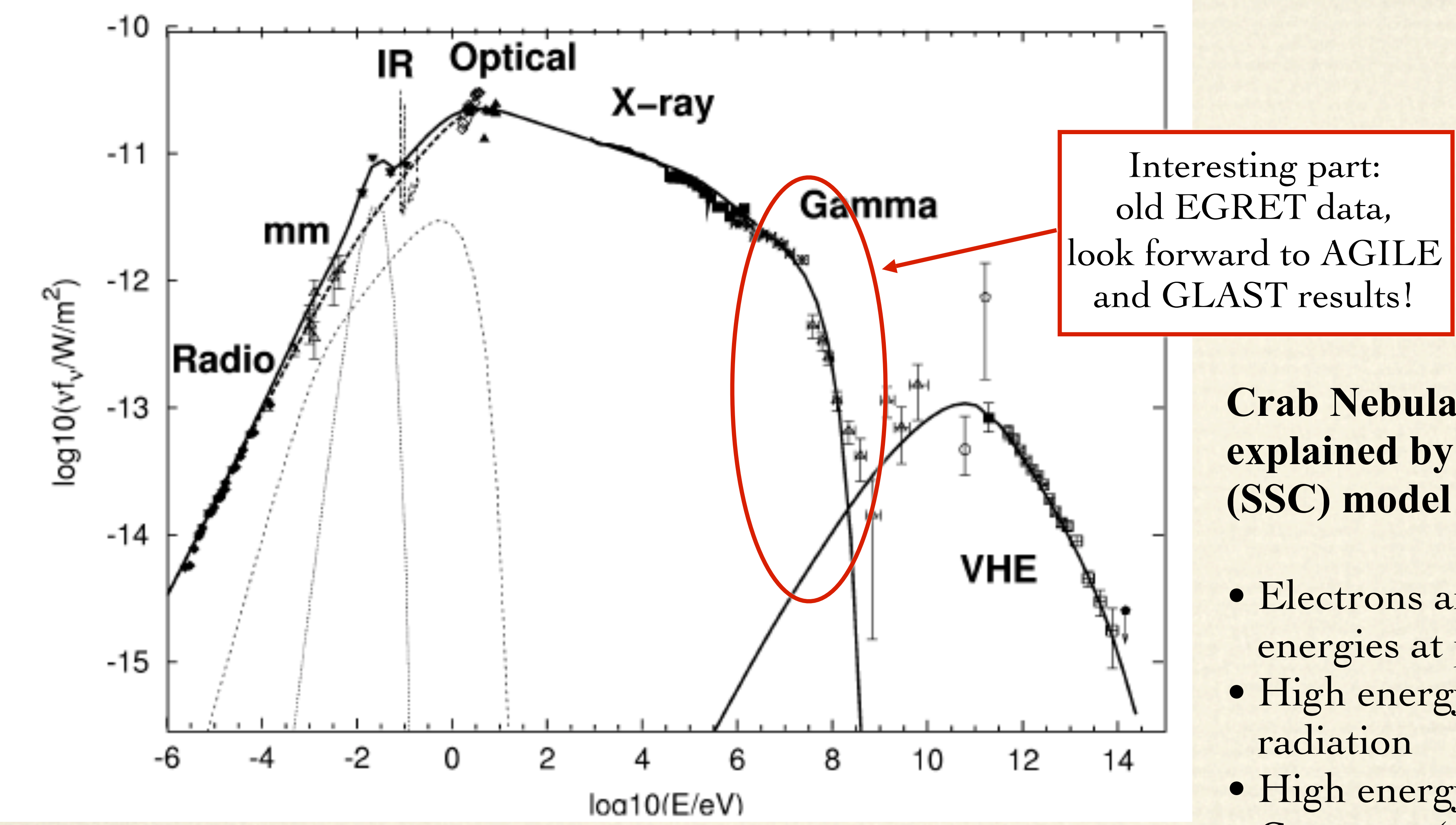
$$x = p_{\mathrm{pion}}/p_{\mathrm{proton}} = \frac{m_\pi}{m_p + m_\pi} \simeq 0.13$$ in the LI case

Other processes affecting UHECR propagation

Vacuum Cherenkov emission (analogous to the electron case)

e^+/e^- pair production gets modifications: this could affect the “ankle”

The Crab Nebula spectrum



Horns et Aharonian, astro-ph/0407119, Aharonian & Atoyan 1998

Crab Nebula (as well as other PWN) well explained by synchrotron self Compton (SSC) model

- Electrons are accelerated to very high energies at pulsar
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- High energy electrons undergo inverse Compton (mainly with synchrotron ambient photons)

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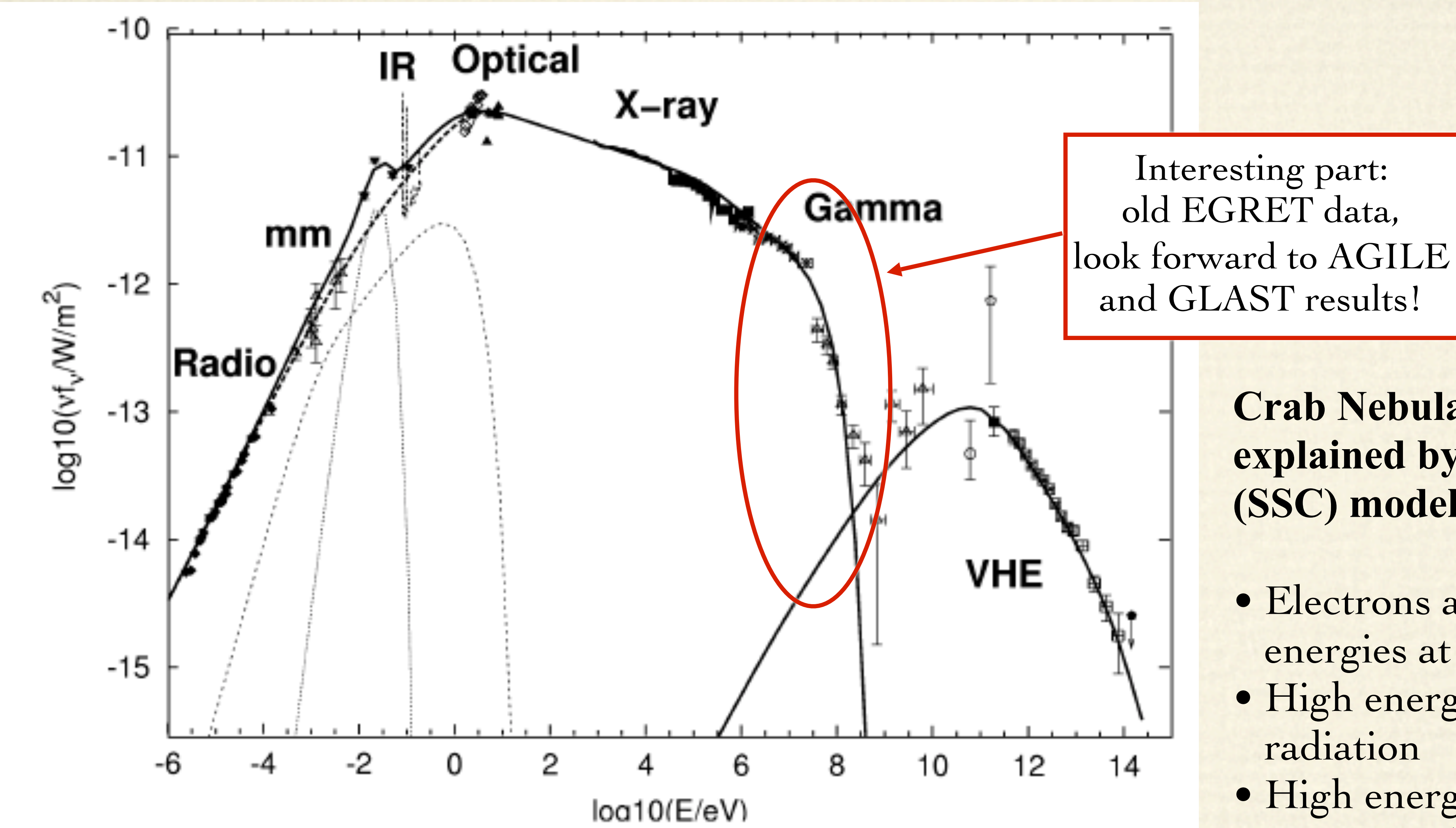

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We shall assume SSC correct and use Crab observation to constrain LV.

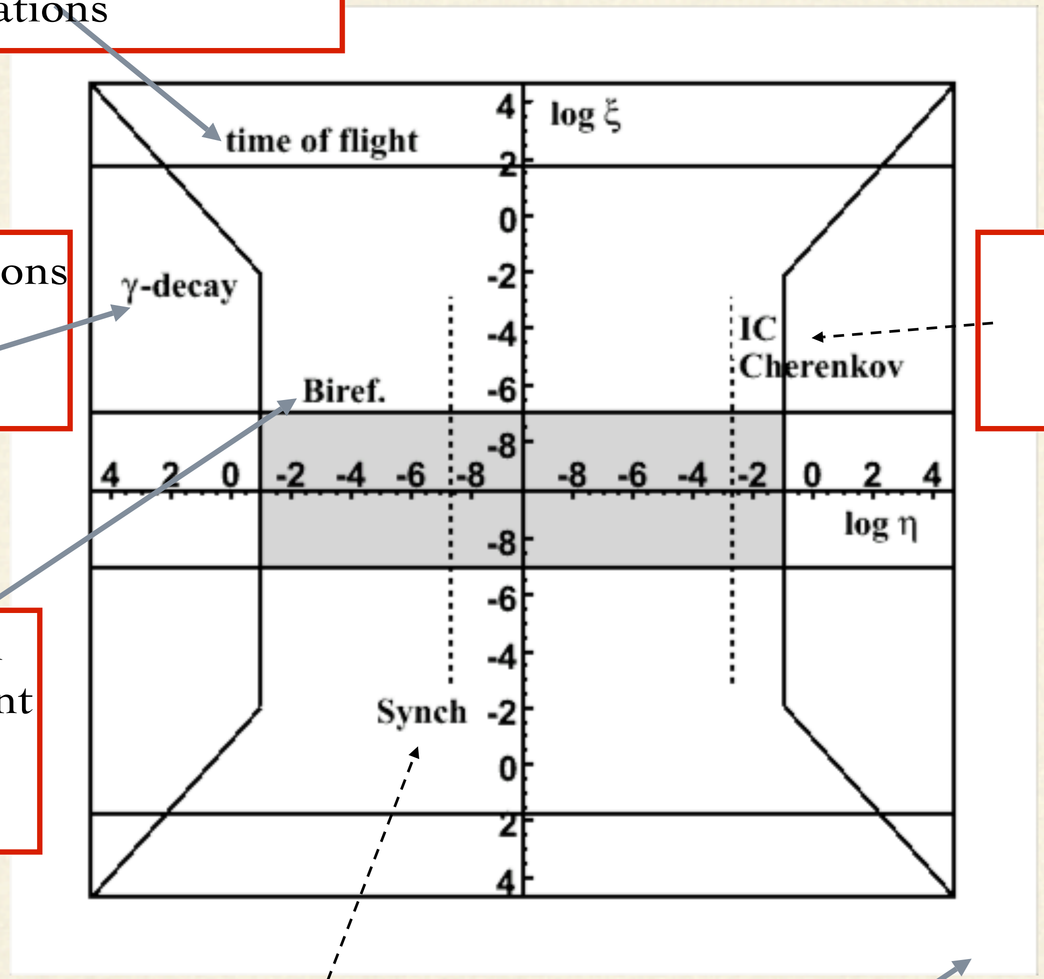
Constraints...

see **Jacobson et al. Annals Phys. 321 (2006) 150** for more details

delay in arrival time of different colors or polarizations

Observation of 80 TeV photons from the Crab Nebula (HEGRA)

polarization/depolarization of the radiation form a distant source (e.g. UV/Optical from GRB)



Observation of 80 TeV photons from the Crab Nebula (HEGRA)

Observation of 100 MeV photons from the Crab Nebula (EGRET)

Not a constraint: each of them always satisfied by at least one of $\pm\eta_\pm$.
Even if just one population is assumed for synch+IC only one $\pm\eta_\pm$ needs to be between the to dotted lines in the grey region.

Constraints...

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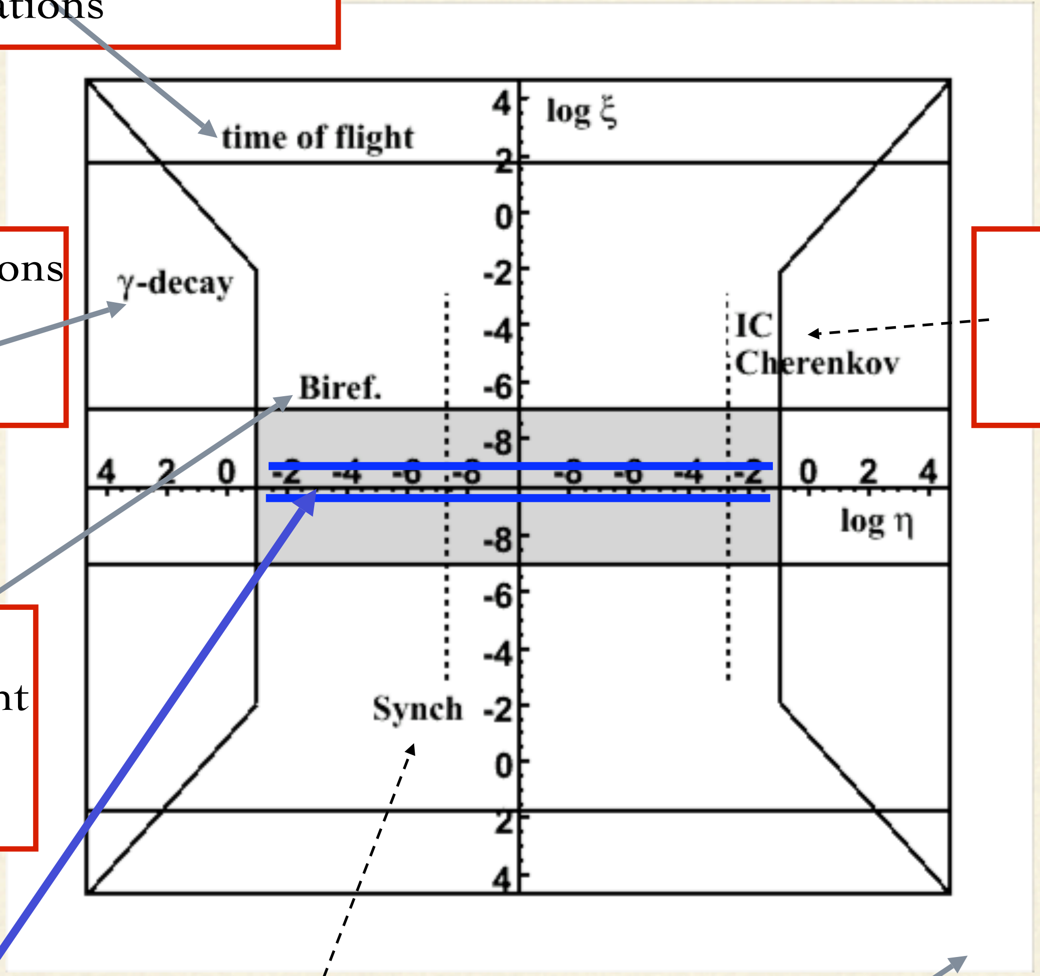
Observation of 80 TeV photons from the Crab Nebula (HEGRA)

polarization/depolarization of the radiation form a distant source (e.g. UV/Optical from GRB)



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Not a constraint: each of them always satisfied by at least one of $\pm\eta_{\pm}$. Even if just one population is assumed for synch+IC only one $\pm\eta_{\pm}$ needs to be between the to dotted lines in the grey region.

from UHECR analysis

Observation of 100 MeV photons from the Crab Nebula (EGRET)

LV model for the Crab Nebula

LM, Liberati, Celotti, Kirk, JCAP 10 (2007), 13

Emitters spectrum: *1st order Fermi mechanism.*

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Since it is essentially a **kinematic mechanism**, we can safely deduce the **power-law spectrum to be in γ rather than in energy** (see paper for further discussion). The presence of an intrinsic maximal energy that can be produced by this mechanism is implemented via an exponential cutoff

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Effect of the Helicity Decay:

- The helicity decay has no threshold.
- This has to compete with the **spin-rotation** (which mixes helicities) induced by the magnetic field. This reaction conserves the electron energy and does not interfere with the HD.
- The helicity decay becomes effective when $\boxed{p_{\rm HD}^{(\rm eff)} \geq 930\,{\rm GeV}\,(B/300\,\mu G)^{1/8}\,|\Delta\eta|^{-3/8}}$

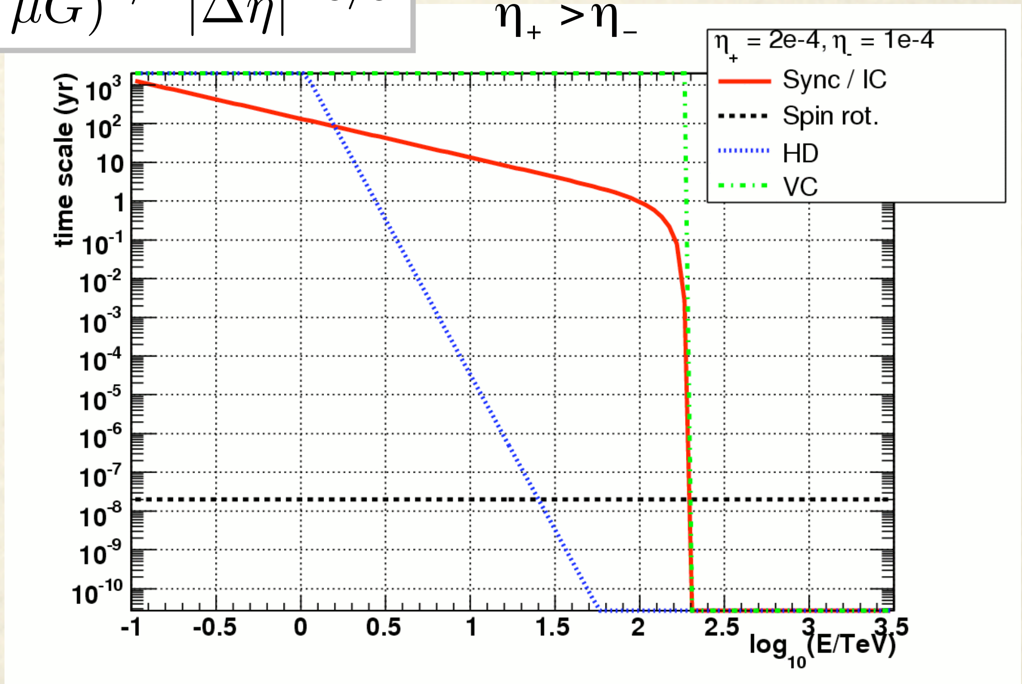
Populations:

charge

	low energy (E < few TeV)	high energy (E > 10 TeV)
e^-_+	1/4	0
e^-_-	1/4	1/2
e^+_-	1/4	0
e^+_+	1/4	1/2

“helicity” state

$\eta_+ > \eta_-$



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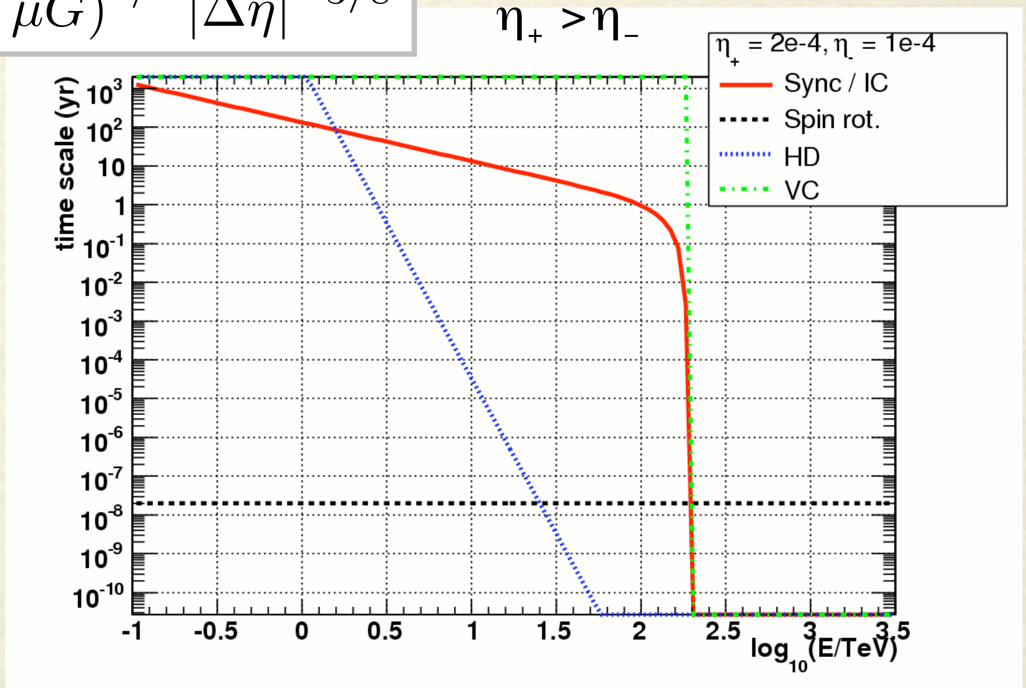
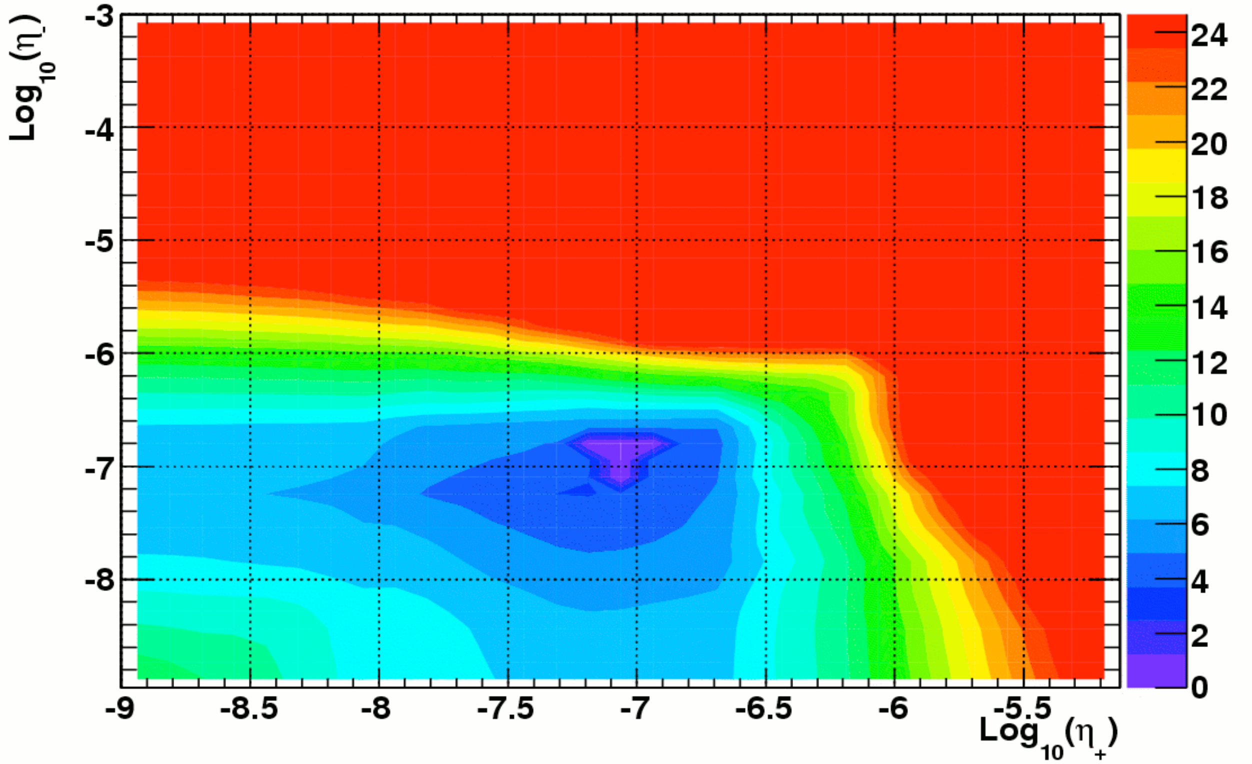


High energy cut-off: set by Vacuum Cherenkov $E_{VC} = \left(m^2 M / 2\eta\right)^{1/3} \approx 10\ {\rm TeV}\,\eta^{-1/3}$

Constraints

We adopt a χ^2 strategy to impose constraints on LV parameters.

Reduced χ^2 contour plot $\eta_+ \cdot \eta_- > 0$

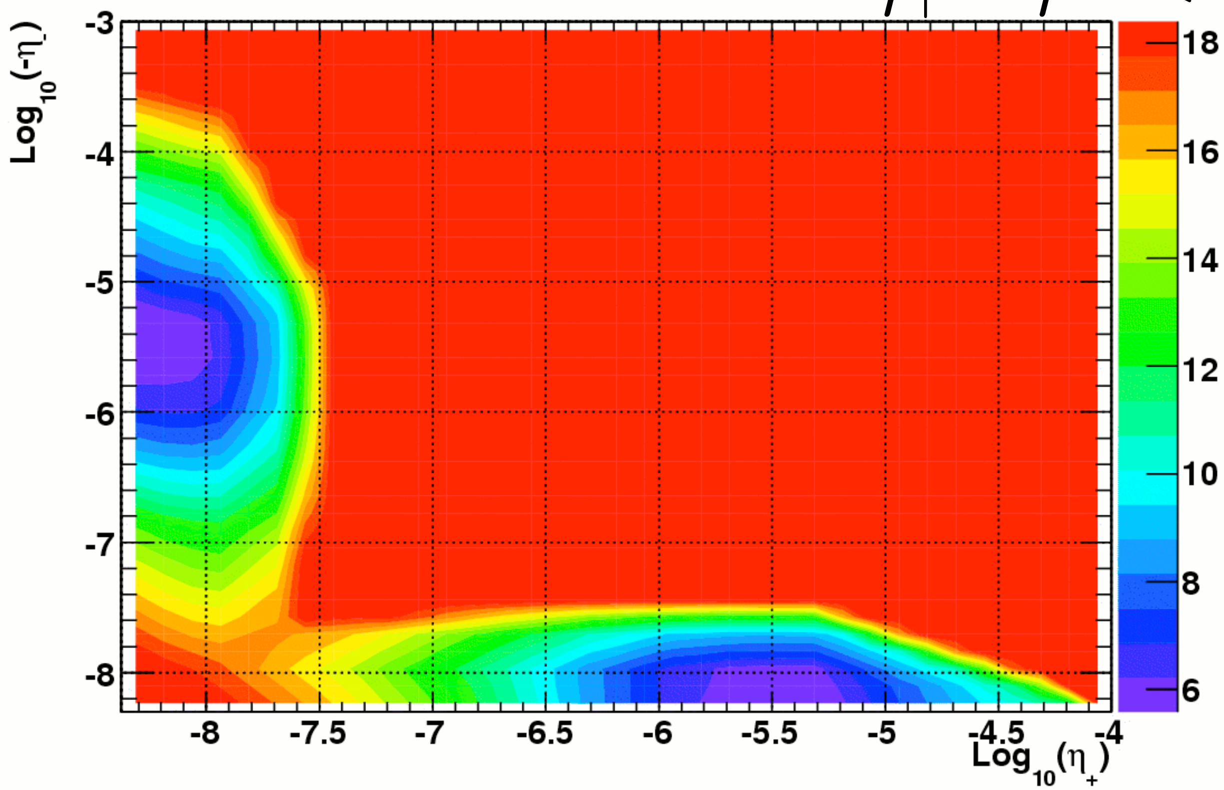


90% CL exclusion $\chi^2 > 8$

95% CL exclusion $\chi^2 > 10$

99% CL exclusion $\chi^2 > 13$

$\eta_+ \cdot \eta_- < 0$



O(E/M) LV is excluded at 95% CL at the 10^{-5} level!

Lorentz violation: a first glimpse of QG?

Suggestions for Lorentz violation (at low or high energies) came from several tentative calculations in QG models:

For review see D. Mattingly, Living Rev. Rel. 8:5,2005.

Lorentz violation: a first glimpse of QG?

Suggestions for Lorentz violation (at low or high energies) came from several tentative calculations in QG models:

- **string theory tensor VEVs (Kostelecky-Samuel 1989)**
- **space-time foam scenarios (Amelino-Camelia et al. 1997-1998)**
- **semiclassical spin-network calculations in Loop QG (Gambini-Pullin 1999)**
- **non-commutative geometry (Carroll et al. 2001)**
- **some brane-world backgrounds (Burgess et al. 2002)**
- **condensed matter analogues of "emergent gravity" (Unruh 1981)**

For review see D. Mattingly, Living Rev. Rel. 8:5,2005.