FUNDAMENTAL PHYSICS LESSONS FROM NEW ASTROPHYSICAL WINDOWS

R. Magritte, "La condition humaine"

Pasquale Dario Serpico (CNRS - LAPTh, Annecy-le-Vieux)

ICTP - 24/06/2014

CURRENT STALE-MATE

The (Particle) SM has proven to be a **successful* theory beyond expectations**!
The guiding principle to BSM from the "hierarchy problem" argument has failed, till now.

In Cosmology... perhaps a paradox! Simple **parametric model** (ΛCDM+inflation) that:

- **works incredibly well**
- **requires some new physics** (baryon asymmetry, dark matter,...)
- **gives no handle on the scale(s) of these BSM phenomena!**‡

*but for neutrinos...

‡ but for BICEP 2... if confirmed to be primordial

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How will the Gordian knot be untangled?

*but for neutrinos...

‡ but for BICEP 2... if confirmed to be primordial

LACK OF NEW PHYSICS FROM LAB: RESCUE FROM THE SKY?

Several possibilities

What most of us wish for...

Smart theorist(s) find(s) ***a new*** solution which explains apparently uncorrelated mysteries, leading to new crucial predictions/observations.

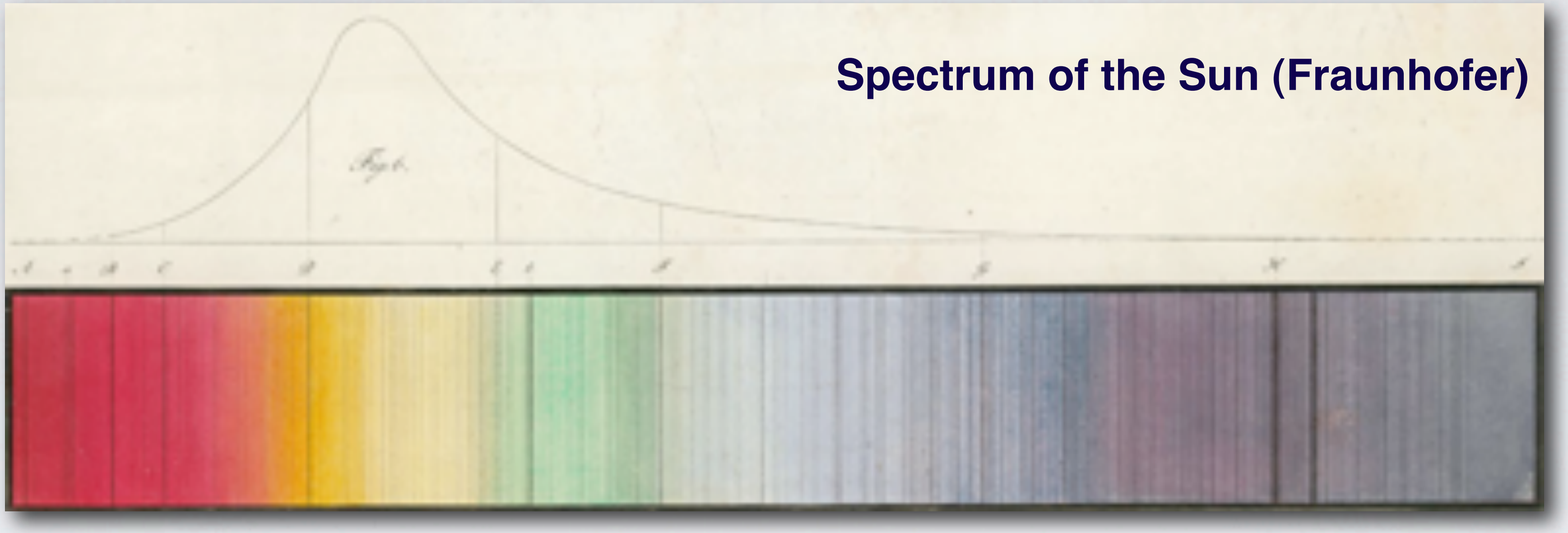
What looks to me a bit more likely: progress from **experimental discoveries**

a) Look better: we'll find what *we are looking for, where we are expecting* to find it
b) Look elsewhere: we'll (serendipitously?) find *what we are looking for* in particle physics
c) Look elsewhere: we'll find what *we are* ***not*** *looking for... which perhaps gives us other clues*

I will focus here on options b) and c), asking myself if "new astroparticle windows" can be the "elsewhere"

HISTORICAL ANSWER: YES, OF COURSE!

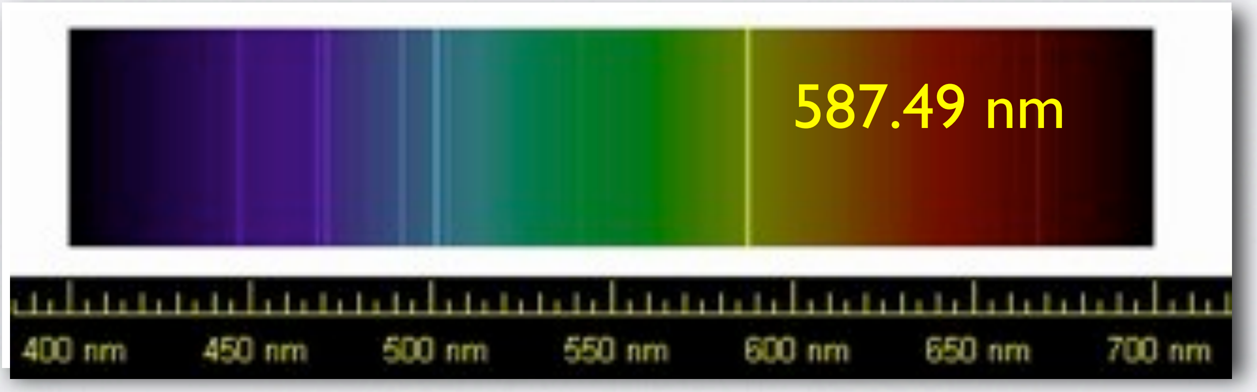
That goes back to the birth of "astroparticle physics" in XIX century!



- A "new particle" (atom) was soon identified when applying the newly discovered spectroscopic tools to the sky: **Helium** in the solar spectrum (1868 - Janssen & Lockyer)

founder & first editor of "Nature"

- First observed on Earth in 1882 (by Neapolitan physicist Luigi Palmieri, analyzing lava of Mount Vesuvius)



EXAMPLES IN EARLY XXTH CENTURY

~1932-53: Particle zoo in cosmic radiation, among which e^+ (***Anderson*** '32) *[Case b]* confirming ***Dirac's theory***, but also the puzzling μ *or strange particles* (K, Λ, Ξ, Σ)... *nobody had ordered* (cfr. I. Rabi) *[Case c]*

one of the first pictures of a positron

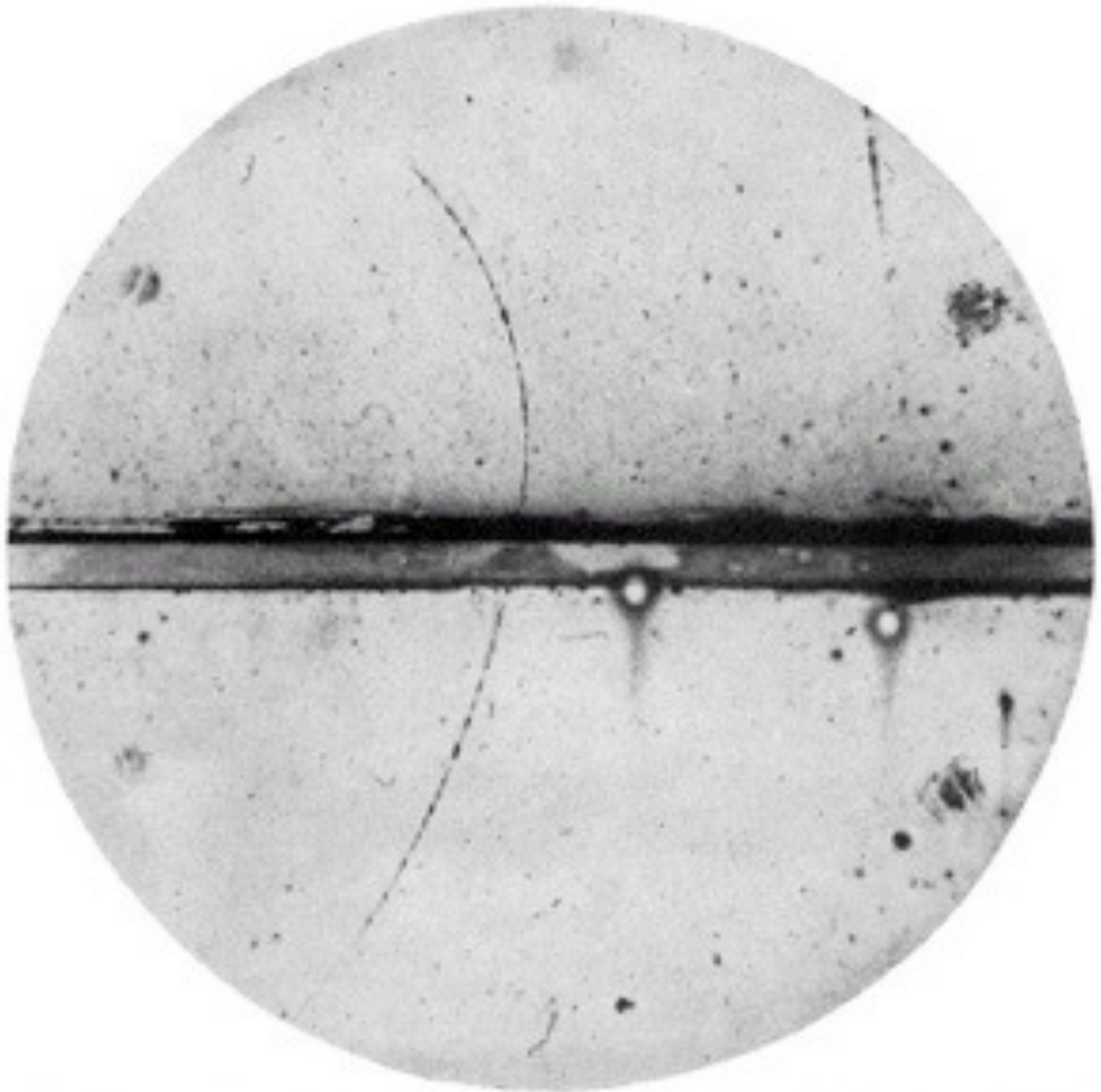


FIG. 1. A 63 million volt positron ($H\rho = 2.1 \times 10^5$ gauss-cm) passing through a 6 mm lead plate and emerging as a 23 million volt positron ($H\rho = 7.5 \times 10^4$ gauss-cm). The length of this latter path is at least ten times greater than the possible length of a proton path of this curvature.

The Nobel Prize in Physics 1936
Victor F. Hess, Carl D. Anderson

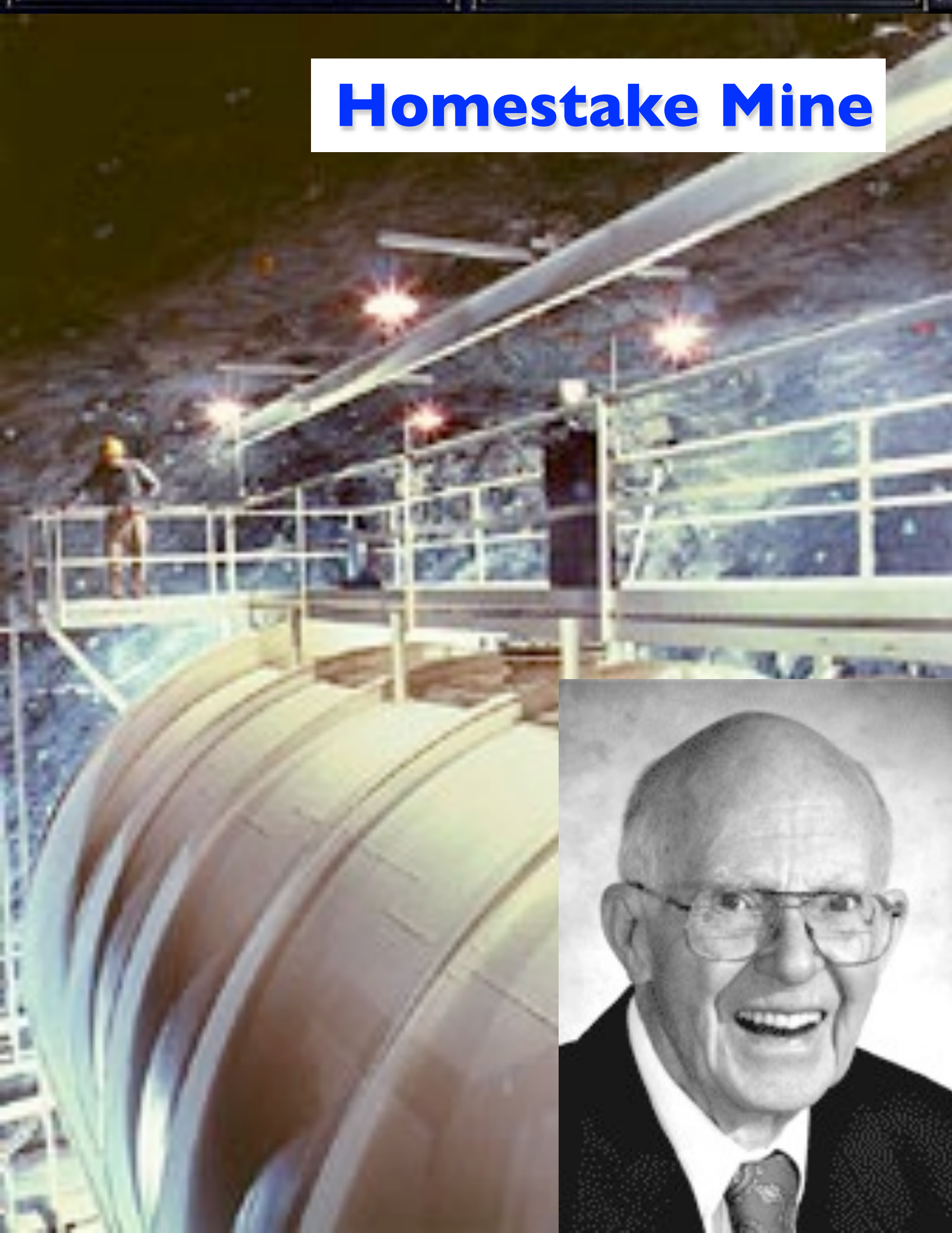
The Nobel Prize in Physics 1936

Victor Franz Hess

Carl David Anderson

The Nobel Prize in Physics 1936 was divided equally between Victor Franz Hess *"for his discovery of cosmic radiation"* and Carl David Anderson *"for his discovery of the positron"*.

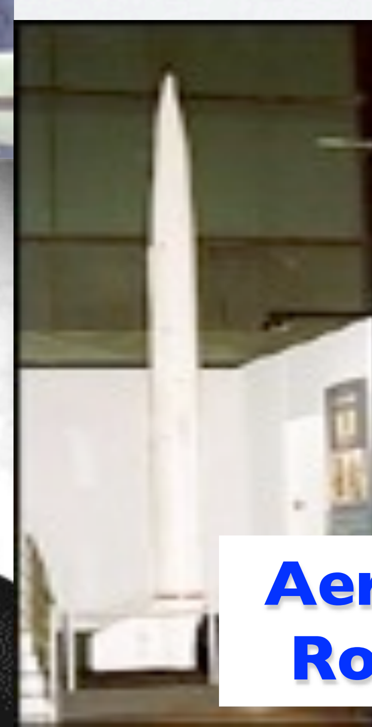
RECENT KNOWN EXAMPLES...

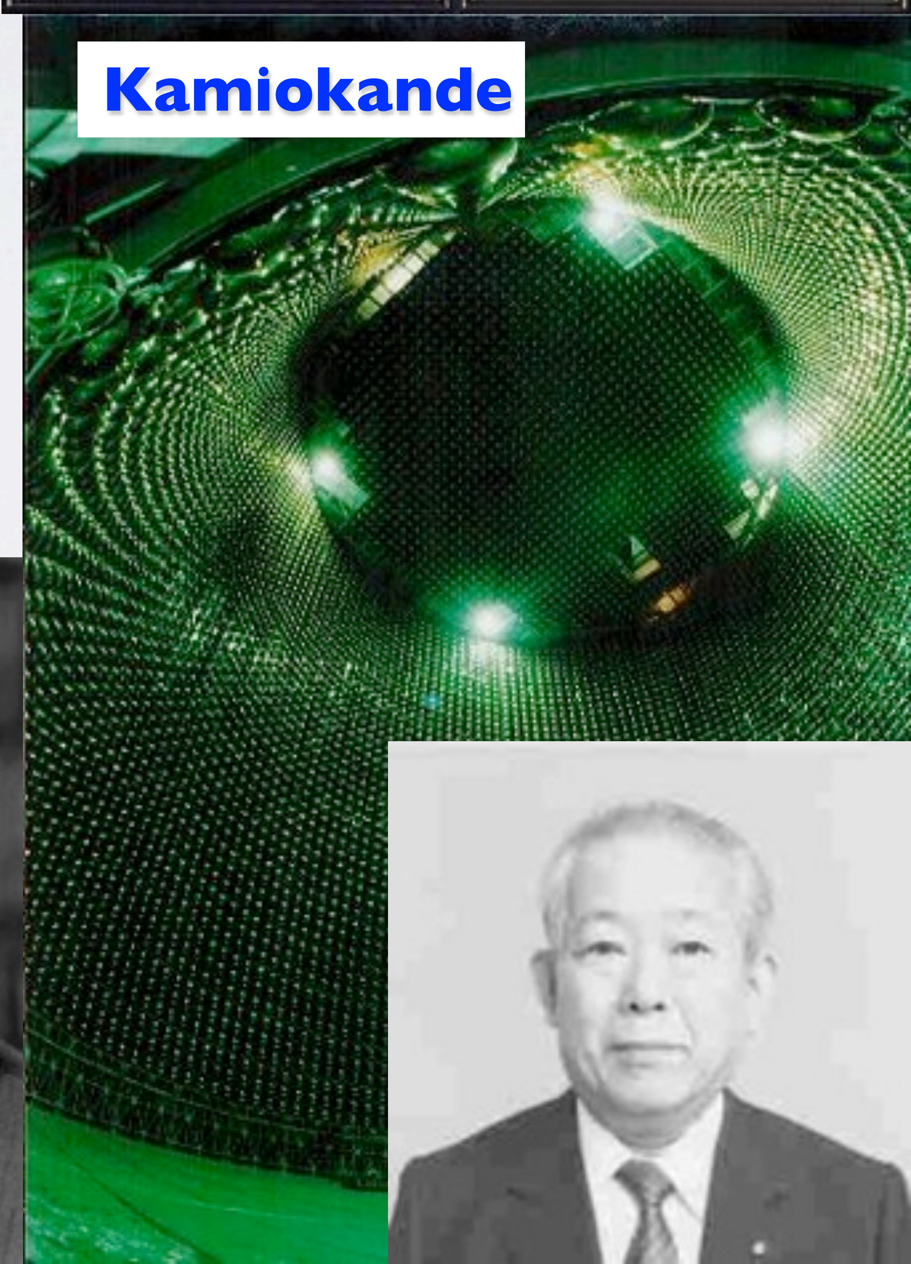


X-ray astrophysics

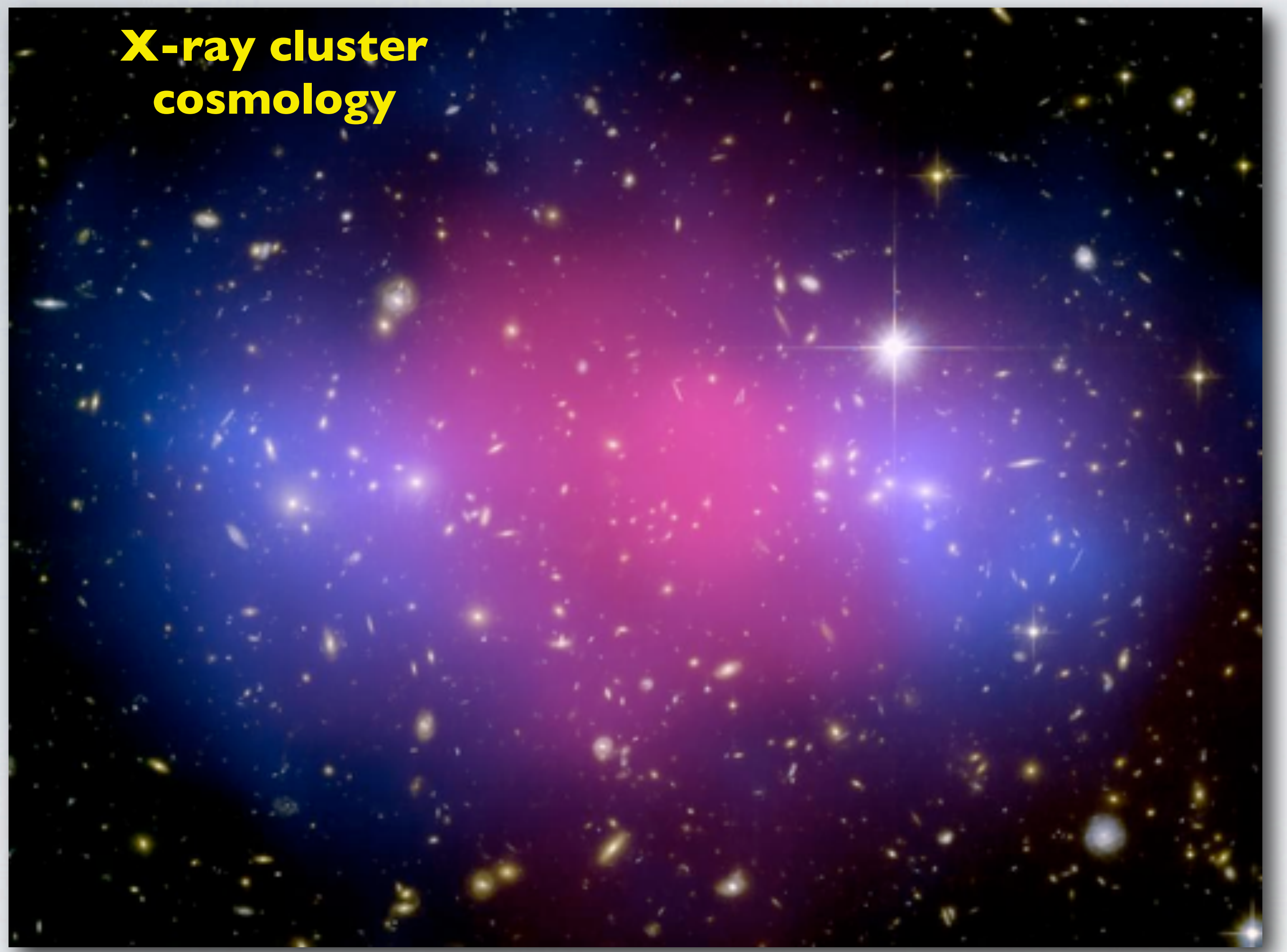
ν astrophysics

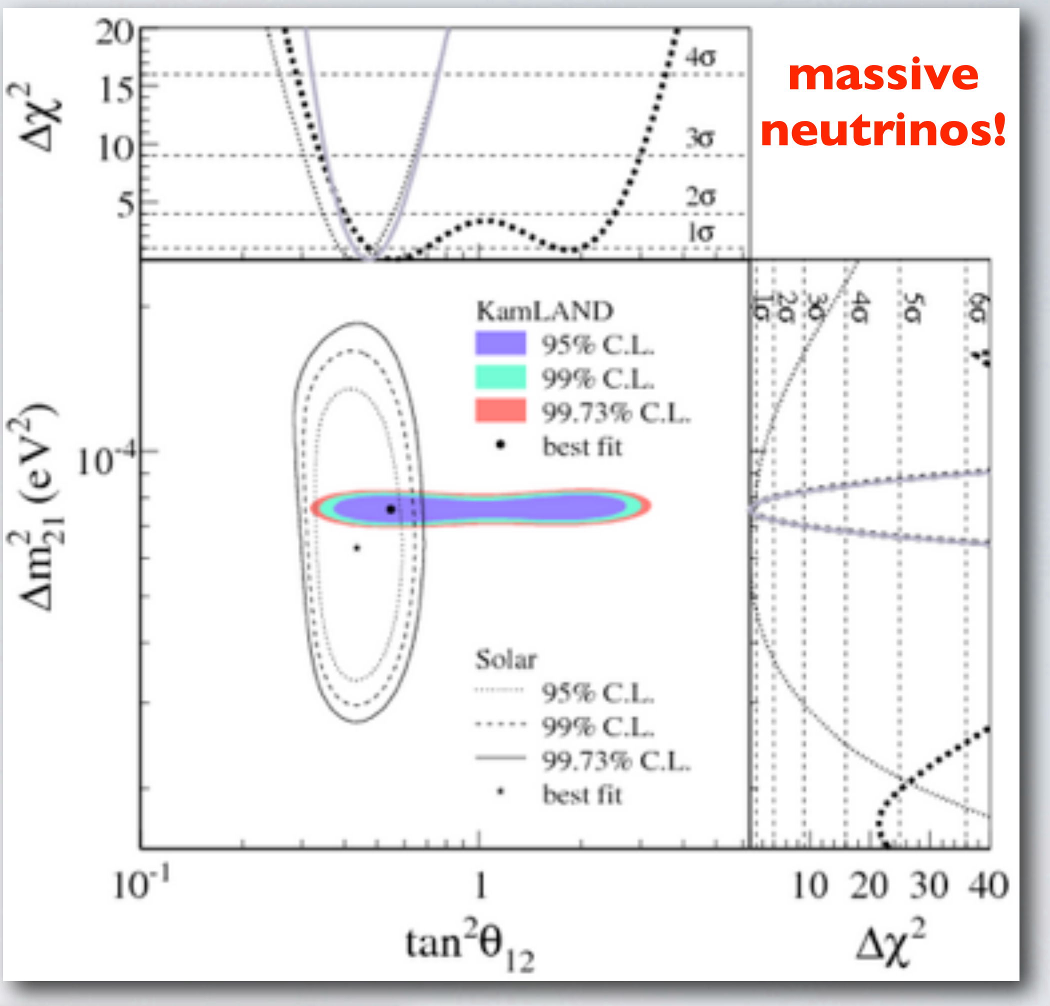
Nobel Prize 2002

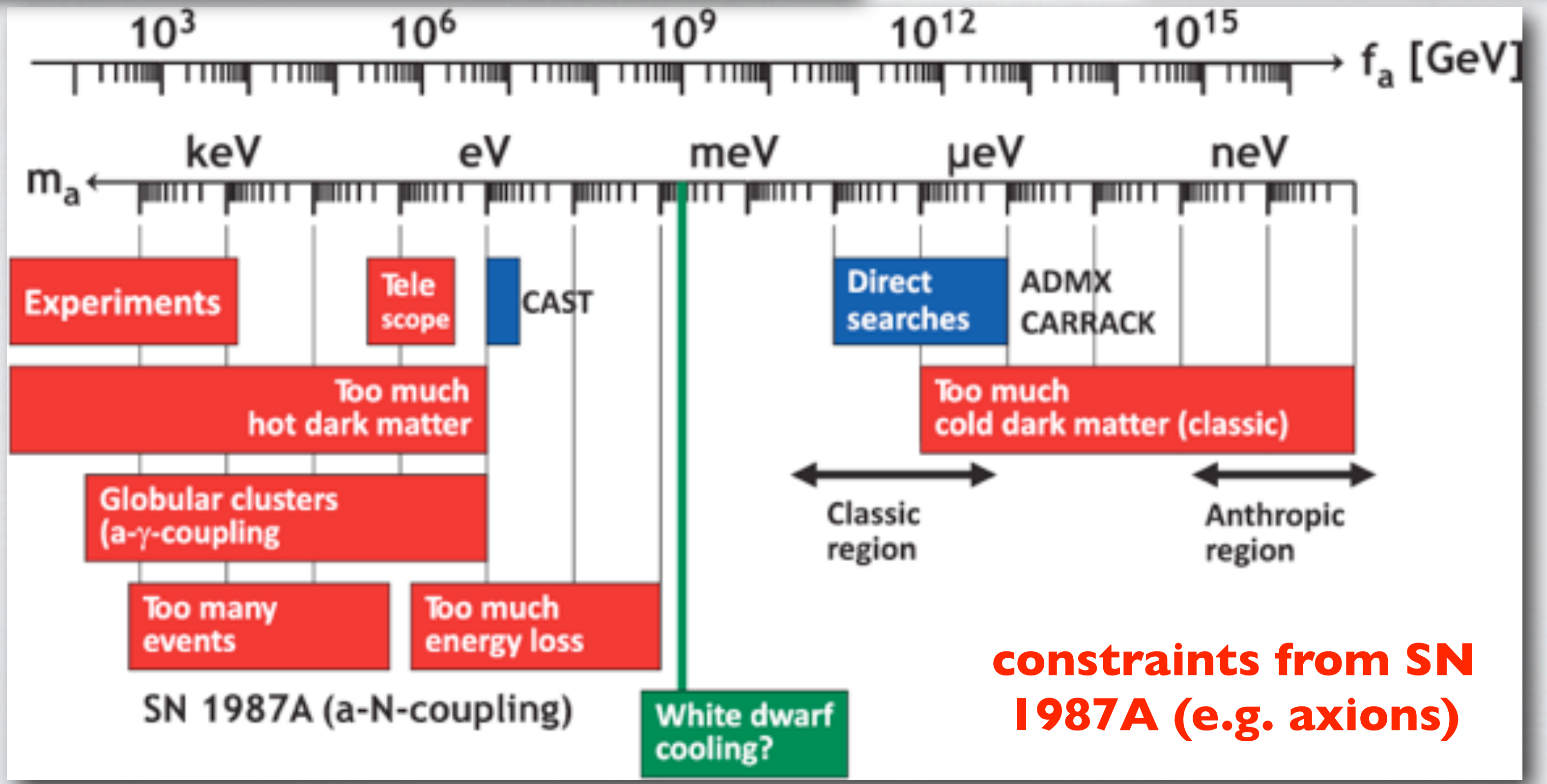




...PAVING THE WAY TO "APPLICATIONS"!







GOOD NEWS:

Plenty of potential "new windows of opportunities"!
An incomplete list:

- High energy neutrino astrophysics
- CMB polarization
- High-z/dark ages universe (21 cm, weak lensing, etc.)
- CMB spectral distortions (probing period between BBN and recombination & small scales $P(k)$)
- Gravitational waves (including new strategies such as atomic interferometry or pulsar timing array...)
- ...

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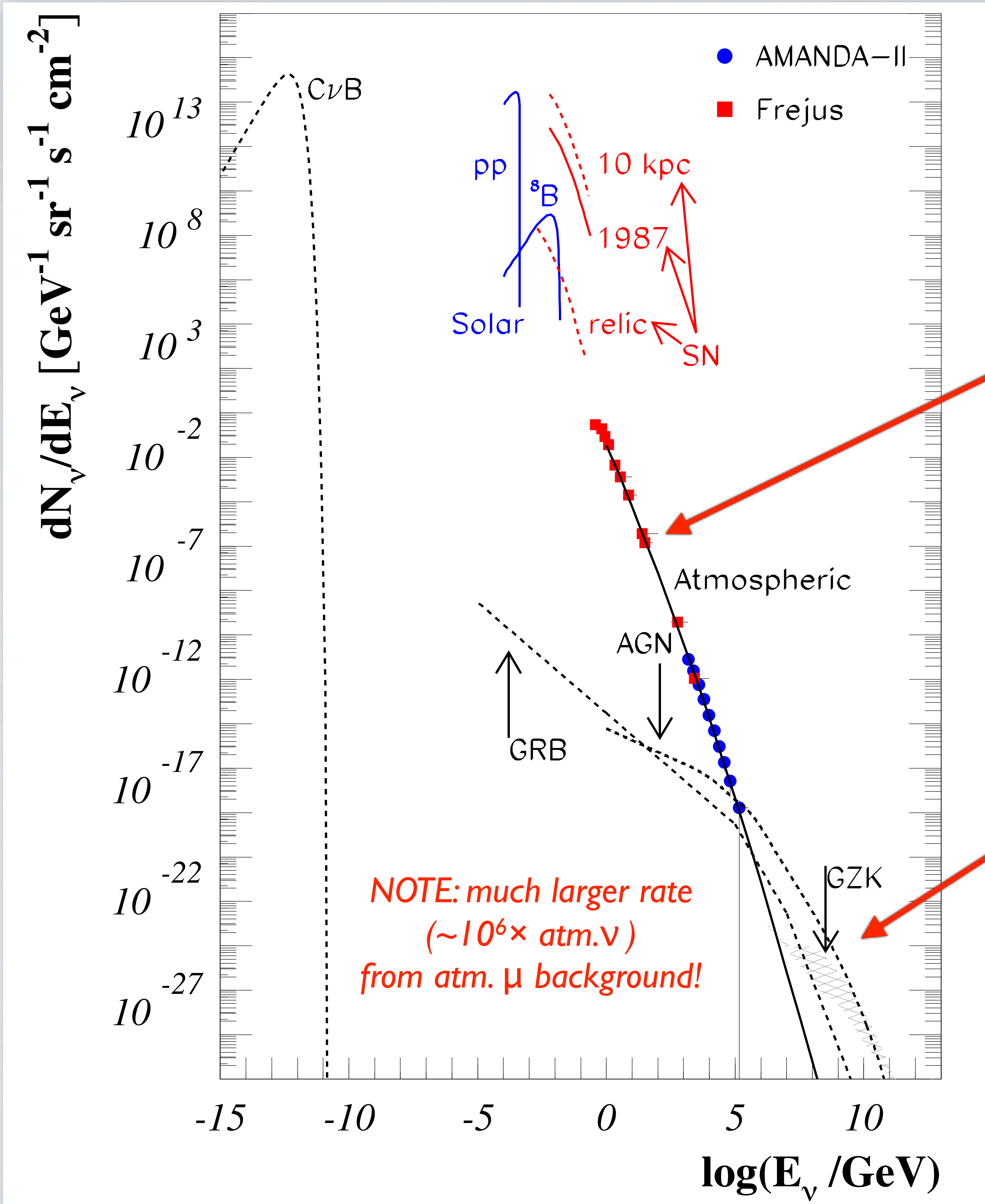
Impossible to provide an exhaustive review, rather:

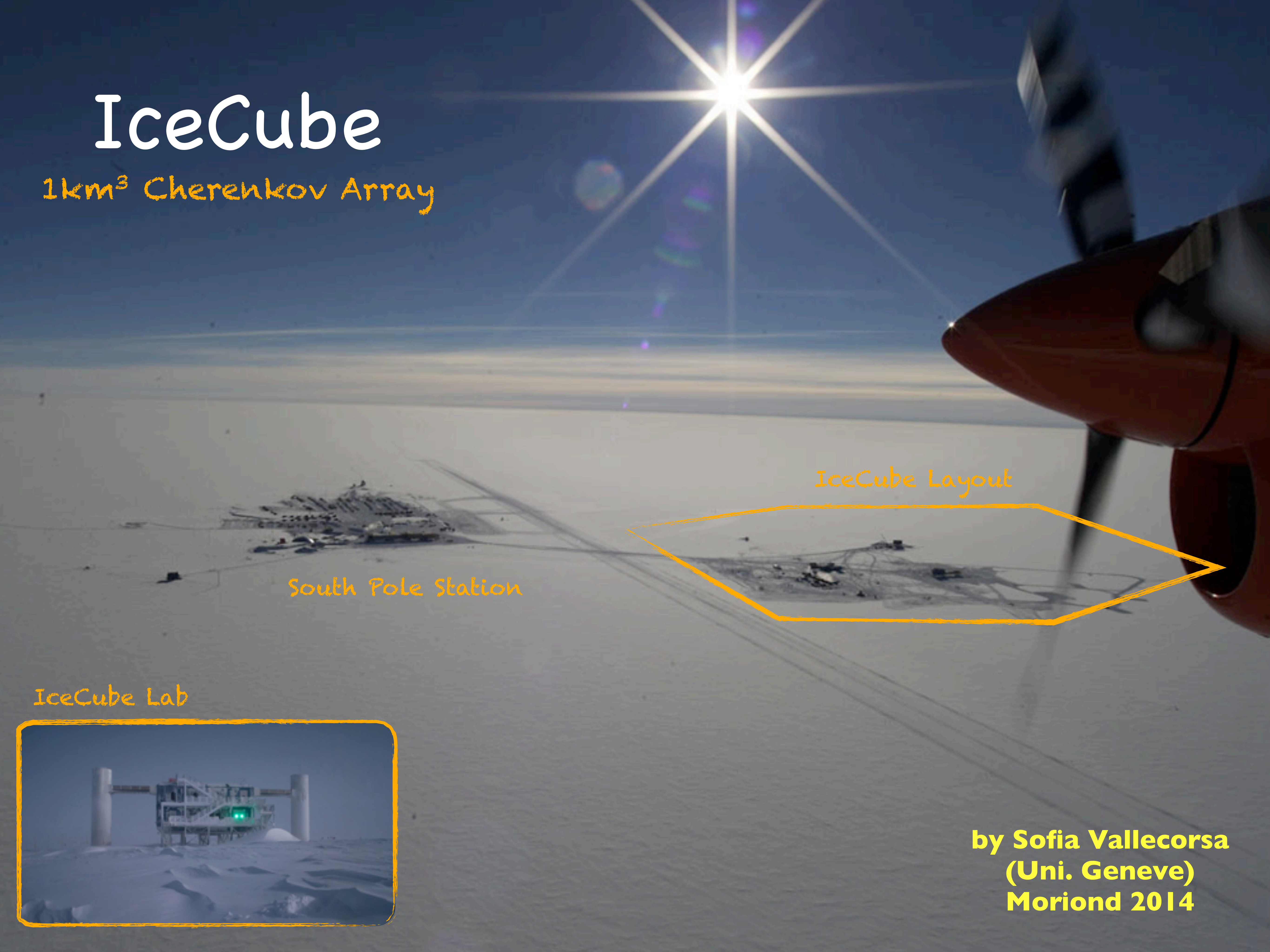
- I will provide a "proof of principle" example that discoveries of type b) and type c) might still take place today, following the opening of a new astrophysical window *(here high-energy neutrino astrophysics)*
- Serendipitous, unexpected signals from the long-sought Dark Matter? (Case b)
- Hints for/constraints from less expected "new physics": a couple of examples (Case c)

THE NEUTRINO SKY

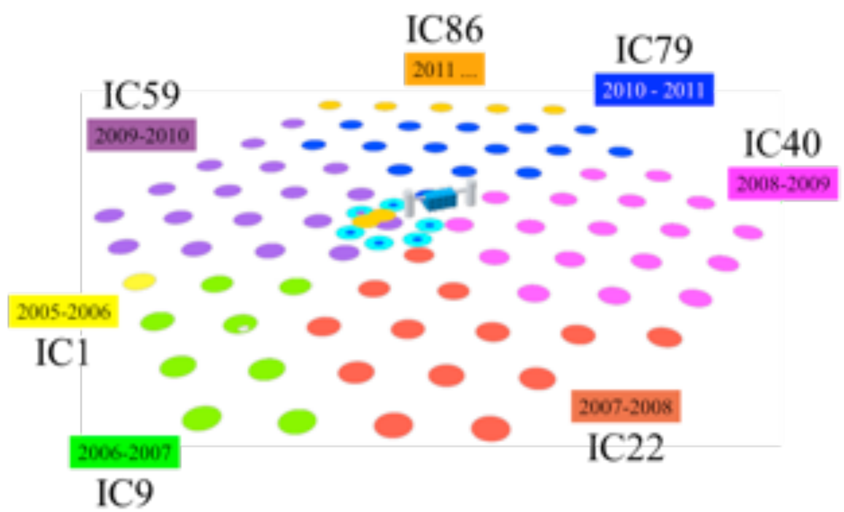


"ν background"
(as well as "beam" for the atmospheric oscillation studies)

"target signals"


IceCube
1km^3 Cherenkov Array
IceCube Layout
South Pole Station
IceCube Lab
by Sofia Vallecorsa
(Uni. Geneve)
Moriond 2014

The detector



~1 Gton instrumented volume

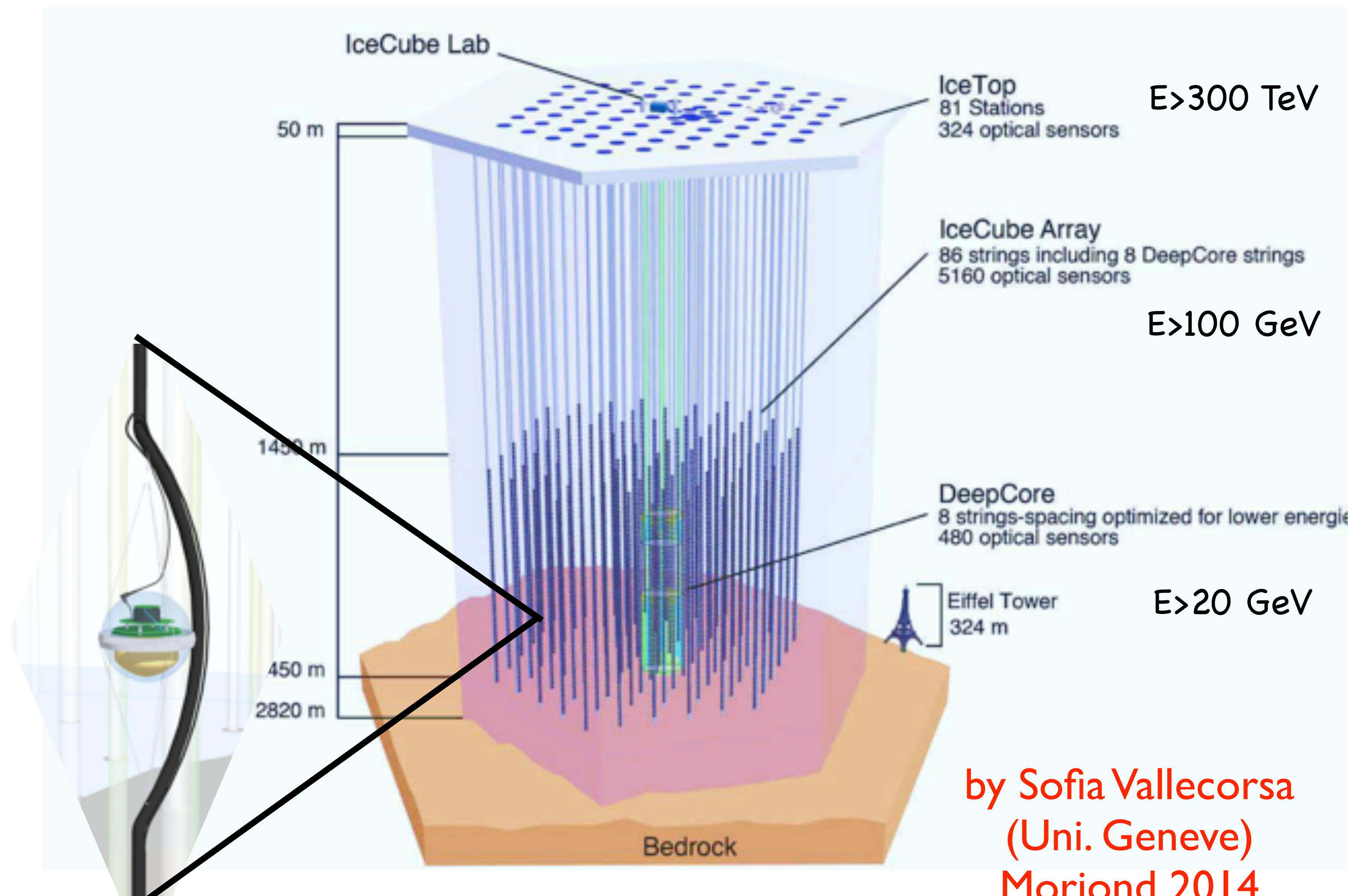
- Completed in December 2010
- >99% of DOMs survived installation
- Expect >97% operational in 2025

Digital Optical Module:

- 10inch PMT
- Electronic digitization
- Communication

DeepCore:

- High efficiency PMT
- ~4xIC sensor density
- 20 Mton detector



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Moriond 2014

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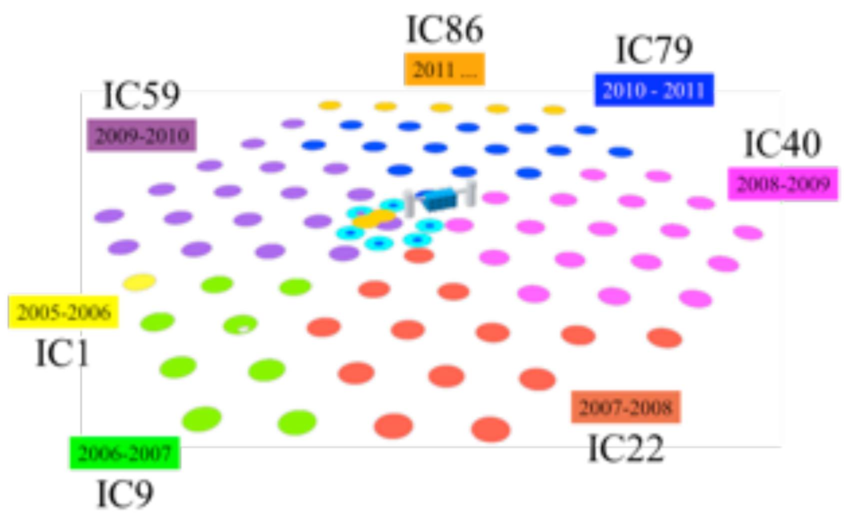

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km^3 size dictated by requirement to have O(1-100) events/year for typical expectations & standard $\sigma_{\nu N}$

DeepCore:

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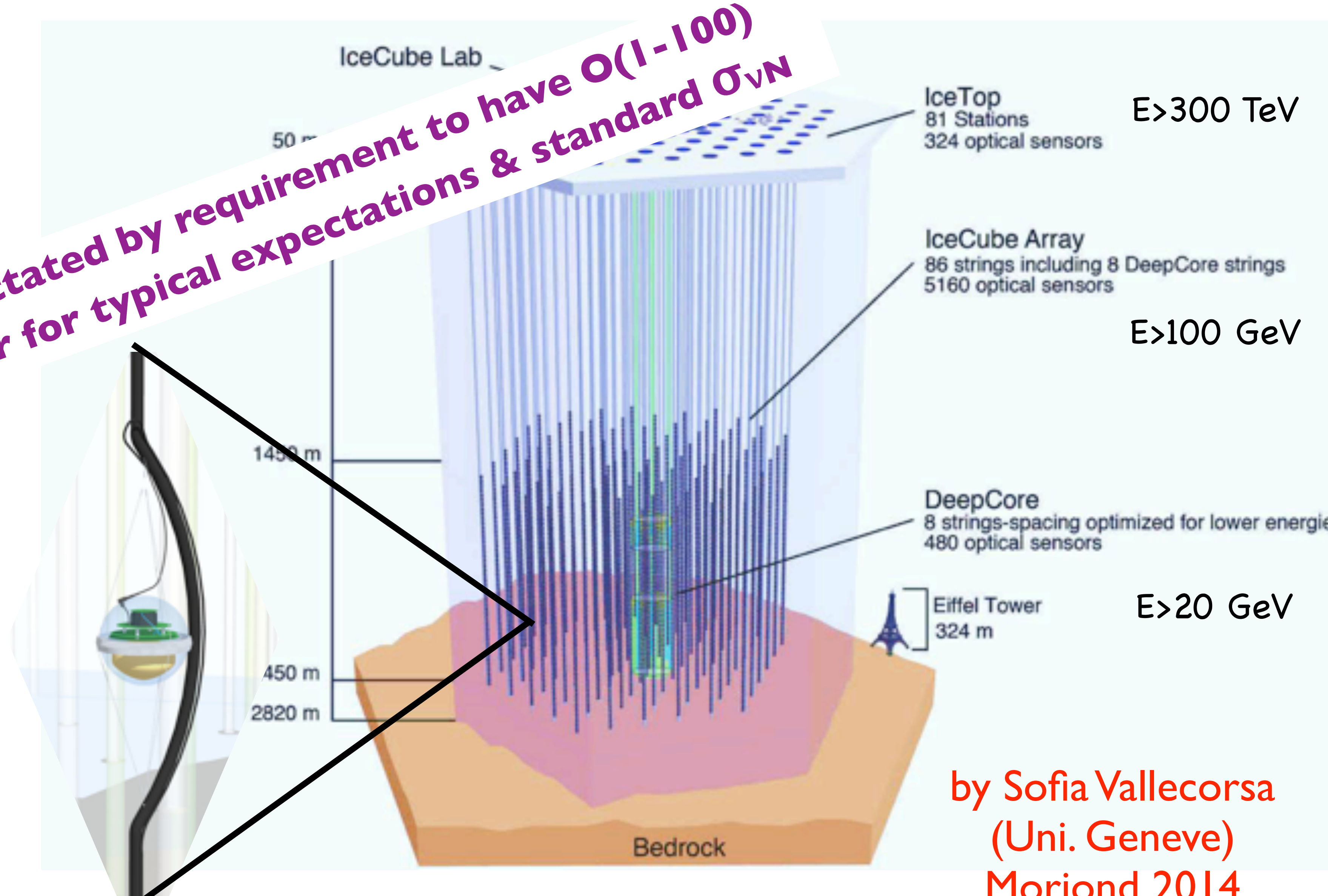

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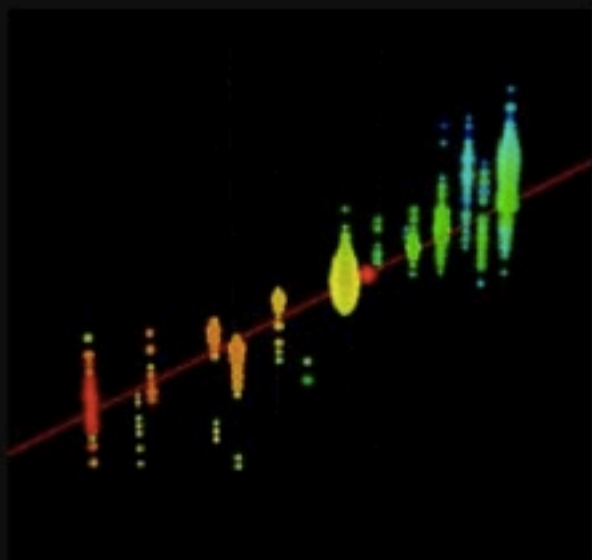
Neutrino signals

CC Muon Neutrino

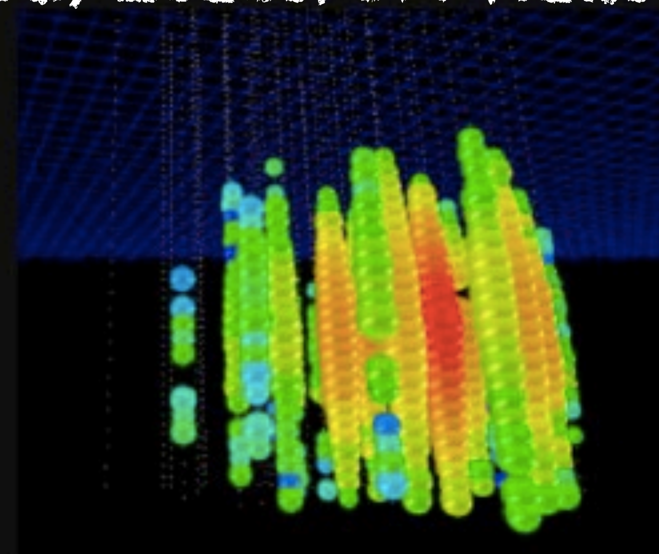


$$\nu_\mu + N \rightarrow \mu + X$$

track (data)

factor ~ 2 energy resolution
< 1° angular resolution (high energy)

NC/Electron Neutrino



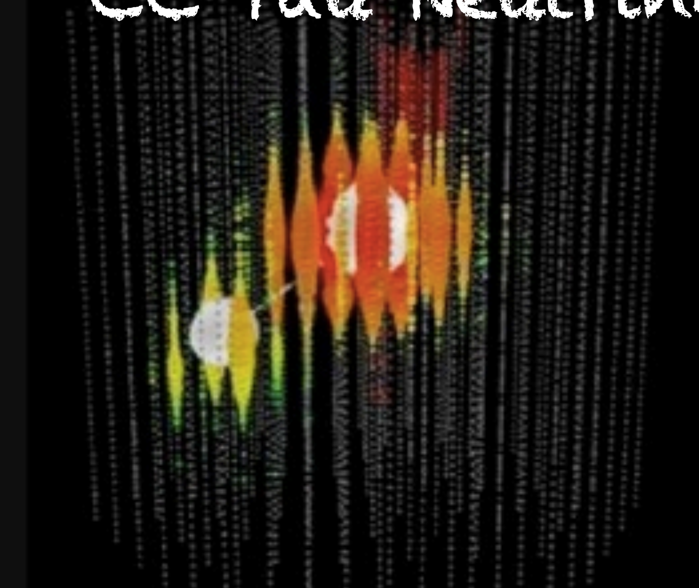
$$\nu_e + N \rightarrow e + X$$

$$\nu_x + N \rightarrow \nu_x + X$$

cascade (data)

± 15% energy resolution
~ 10° angular resolution (>100TeV)

CC Tau Neutrino



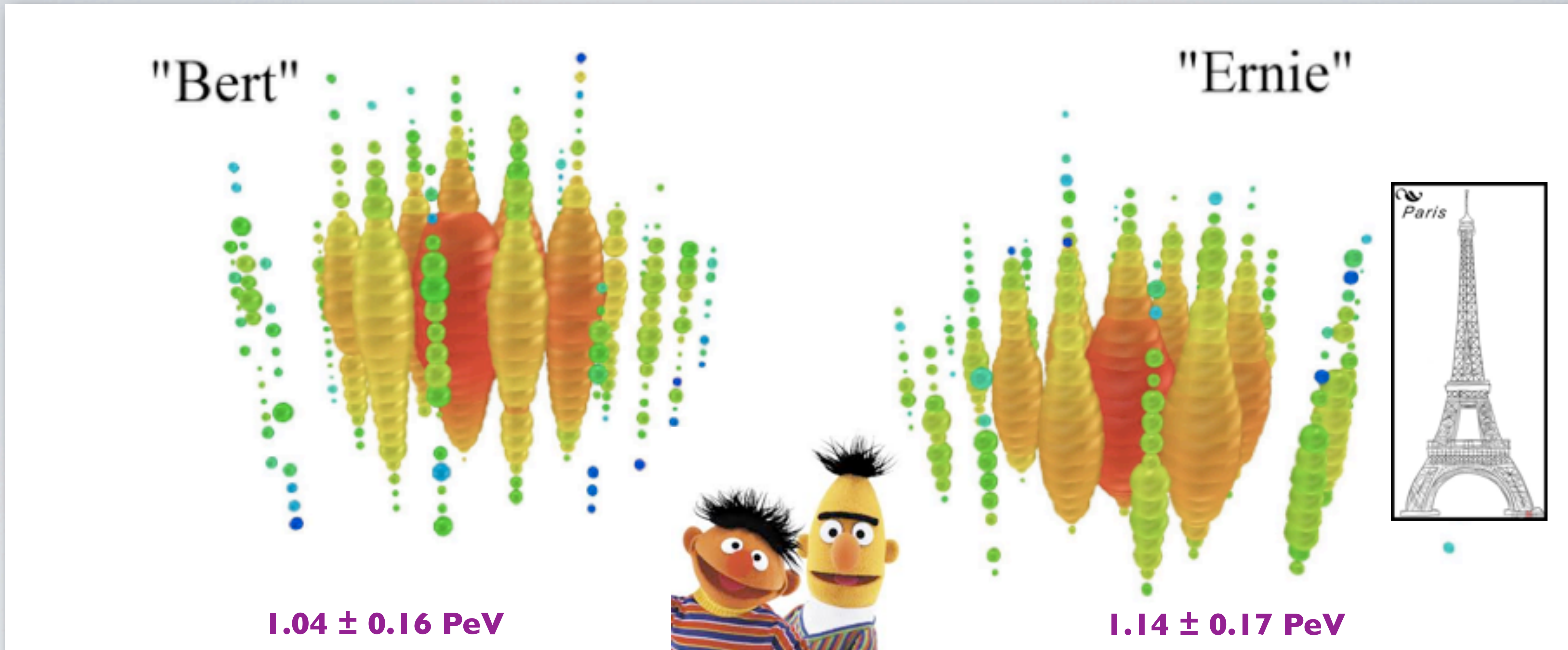
$$\nu_\tau + N \rightarrow \tau + X$$

“double-bang” and other signatures (simulation)

(not yet observed)

by Sofia Vallecorsa
(Uni. Geneve)
Moriond 2014

WELCOME TO BERT & ERNIE



[...] The probability to observe two or more candidate events under the atmospheric background-only hypothesis is 2.9×10^{-3} (2.8σ) taking into account the uncertainty on the expected number of background events. These two events could be a first indication of an astrophysical neutrino flux, the moderate significance, however, does not permit a definitive conclusion at this time.

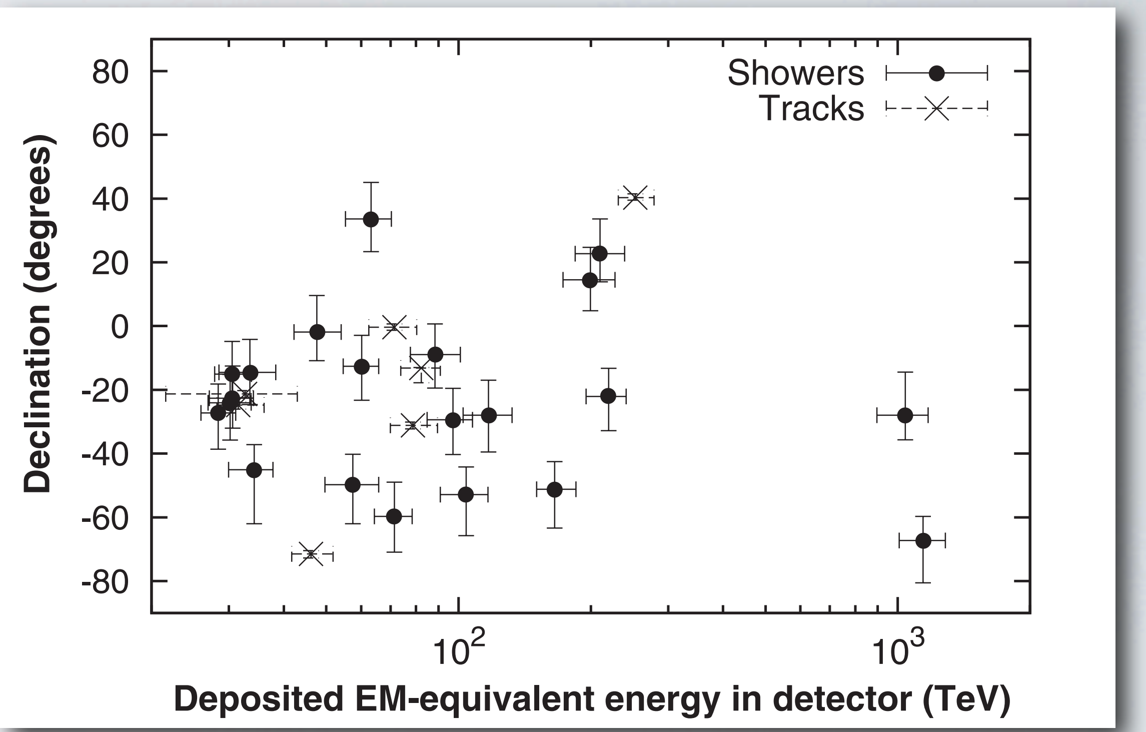
M. G. Aartsen et al. [IceCube Collaboration],
"First observation of PeV-energy neutrinos with IceCube,"
Phys. Rev. Lett. 111, 021103 (2013) [arXiv:1304.5356].

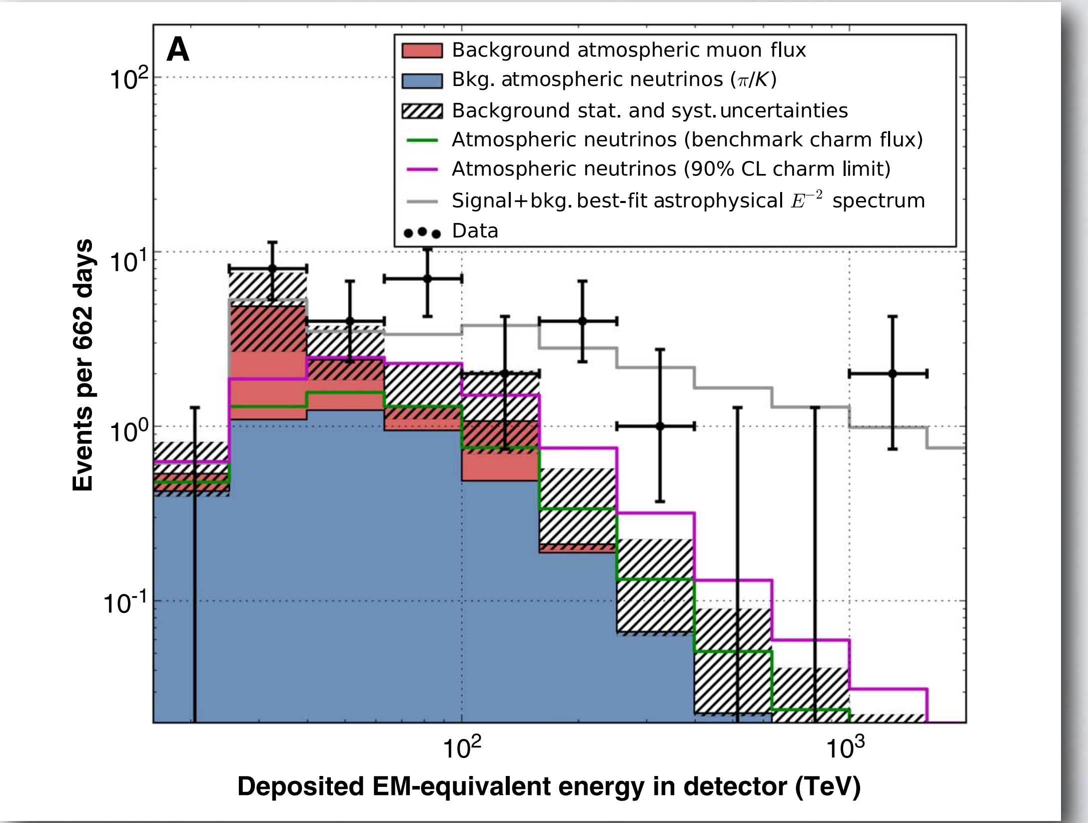
A NEW WINDOW TO THE UNIVERSE!

M. G. Aartsen et al. [**IceCube** Collaboration], "**Evidence for High Energy Extraterrestrial Neutrinos at the IceCube Detector,"** Science 342, no. 6161, 1242856 (2013) [arXiv:1311.5238]

- First, **2 shower** events just above the **PeV** found at the lower edge of a search motivated by cosmogenic neutrinos, **2.8 σ excess**
- Later, extension to **lower energies** (down to 30 TeV): overall **28 events** (both **showers and tracks**) wrt $10.6^{+5.0}_{-3.6}$ background expected (**>4 σ**! ordinary atm. origin rejected at **5.7 σ**)
- E-distribution, angular distribution and flavour composition consistent with a isotropic signal (fully Galactic plane disfavored, but could have Galactic component)

Birth of high energy neutrino astronomy!





IceCube-79,86 (662 days live time)

A NEW WINDOW TO THE UNIVERSE!

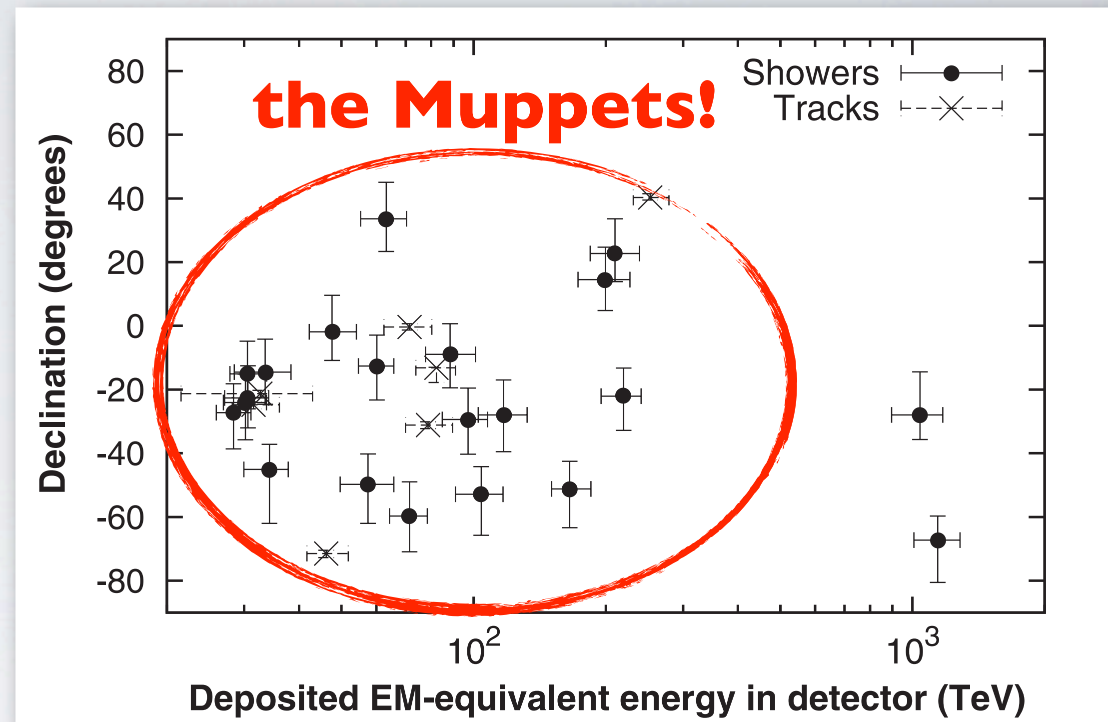
...tion], "**Evidence for High ...at the IceCube Detector,"** ...Xiv:1311.5238]

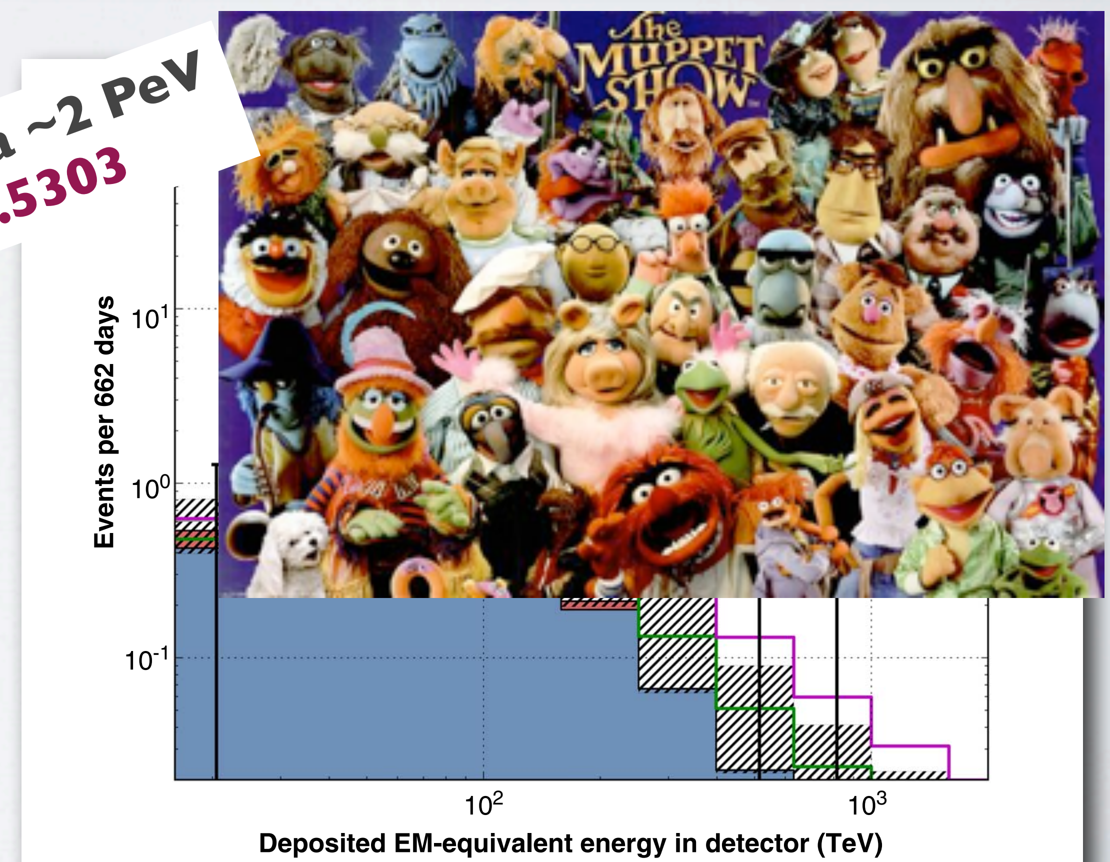
...t above the **PeV** ... search motivated ...**8 σ excess**

...**energies** (down ...**ts** (both ...t $10.6^{+5.0}_{-3.6}$ ...! ordinary atm...

Recent update (37 events) including a ~2 PeV cascade event ("Big Bird") 1405.5303

- E-distribution, ang... ...on and flavour compositio... ...sistent with a isotropic signal (fully Galactic plane disfavored, but could have Galactic component)





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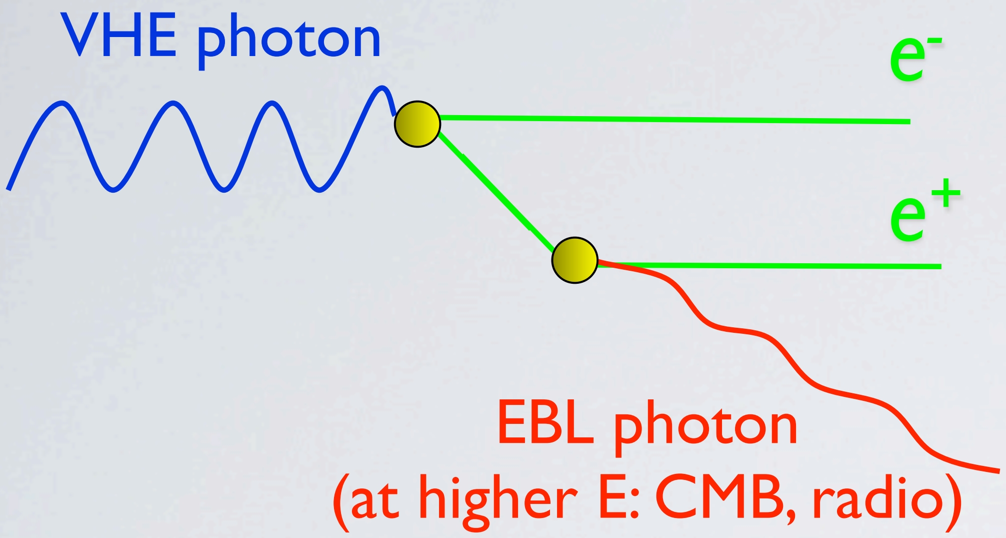
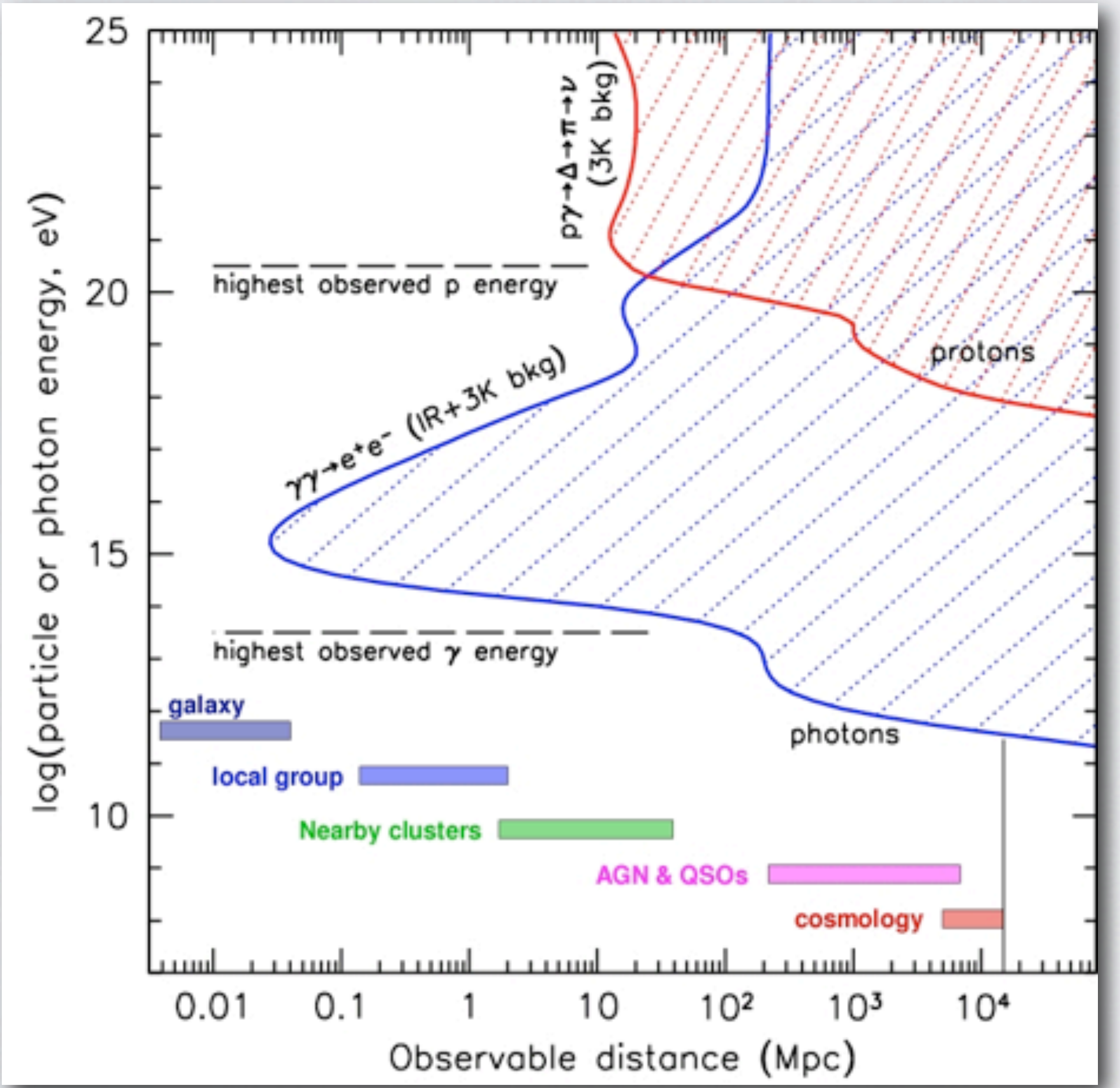
BEYOND THE TEV DARKNESS!



The Universe is opaque to VHE γ's, due to EBL (extragalactic background light, UV to IR) absorption. The 10-100 GeV (Fermi) range is the last e.m. probe of the *deep* universe



note: *@ PeV even extragalactic CR are not likely to arrive to us: typical diffusion time > lifetime of the universe already @ E~10^{17} eV*

M. Lemoine 2004,
R. Aloisio and V.S. Berezinsky 2004

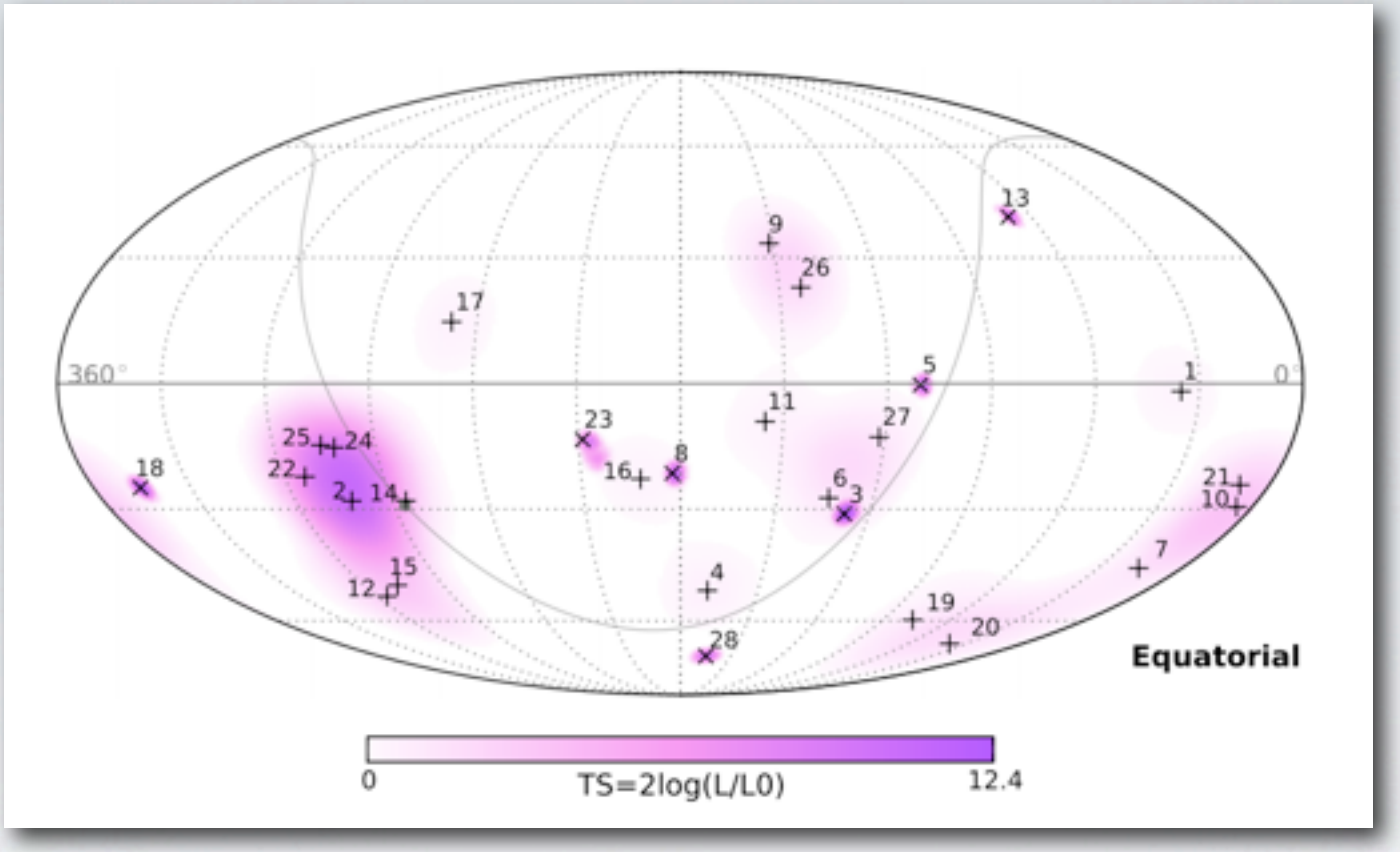
A DARK MATTER ORIGIN?

B. Feldstein, A. Kusenko, S. Matsumoto and T. T. Yanagida, PRD 88, 1, 015004 (2013) [arXiv:1303.7320] *("PeV line" only)*

A. Esmaili and PS, "Are IceCube neutrinos unveiling PeV-scale decaying dark matter?," JCAP 1311, 054 (2013) *(all events)*

...

PROBLEMS WITH ASTRO INTERPRET.?



While it is likely that astrophysical sources are responsible for those events, some features allow one to entertain the possibility of a DM origin, notably

I. no events beyond ~2 PeV (vs. ~8 expected if flux set to a ~E^{-2} astrophys. benchmark)

II. dip of events in the 0.4-1 PeV range (but still $\leq 2\,\sigma$ fluct.)

III. Observed ratio downgoing/upgoing (>1 due to Earth absorption) events ~ **6**
Accounting for μ contamination, down to **4.5+-1.0**
Expected for an isotropic E^{-2} astro-background ~**1.8**

P. Lipari, arXiv:1308.2086

IV. Some excess towards GC, but no Galactic Plane correlation
(7 of the contained events in 30° x 30°, 8% chance prob.)

L_ν(0.06-2 PeV)~5 10^{36} erg/s
L_γ(>1 TeV)~7 10^{34} erg/s

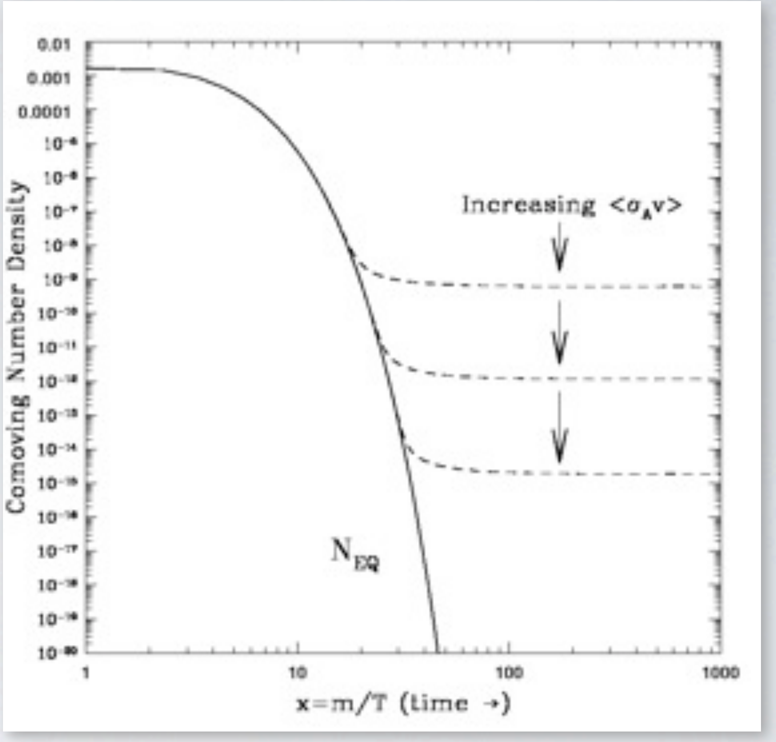
WHAT IF DUE TO DARK MATTER?

Can it be a WIMP?

$$X\bar{X} \longleftrightarrow \ell\bar{\ell}$$

Stable, massive particles in chemical equilibrium down to ***T<<m*** (required for **cold** DM!), suffer exponentially suppression of their abundance.

what is left depends on the decoupling time, or their annihilation cross section: the weaker, the more abundant...



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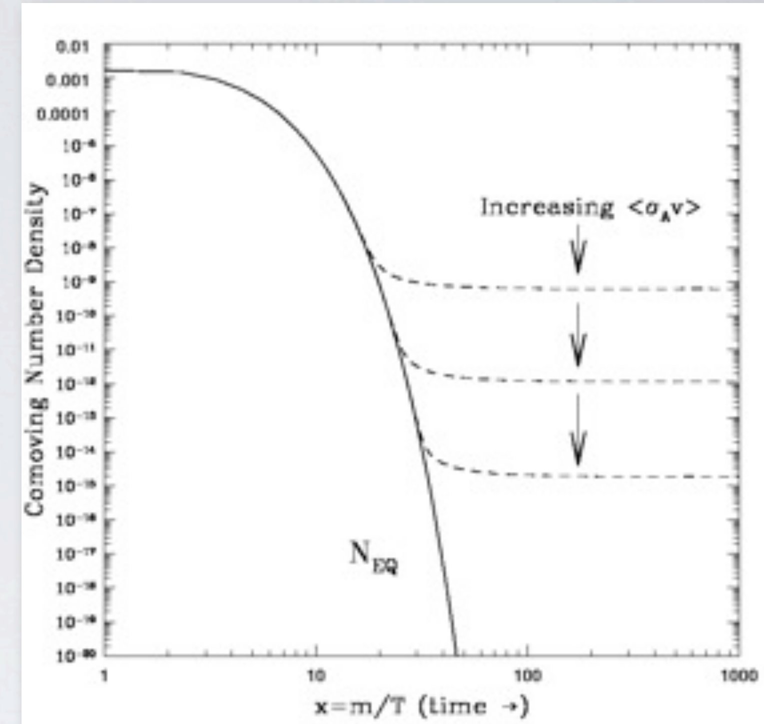


A textbook calculation proves that

$$\Omega_X h^2 \simeq \frac{0.1\,\mathrm{pb}}{\langle \sigma v\rangle}$$

Too high m_X ⇒ too small annihilation ⇒ too large th. abundance to match observations

But cross-section cannot be arbitrarily high! **Unitarity bound**

$$\sigma_J^{\max} v_{\rm rel} \approx \frac{4\pi(2J+1)}{m_X^2 v_{\rm rel}} \approx \frac{3\times 10^{-22}(2J+1)\mathrm{cm}^3/\mathrm{s}}{(m_X/\mathrm{TeV})^2}$$

$$\Omega_X h^2 \geq 1.7(3.4)\times 10^{-6}\sqrt{m_X/T_F}(m_X/\mathrm{TeV})^2$$

$$m_X \lesssim \mathcal{O}(100)\ \mathrm{TeV}$$

K. Griest and M. Kamionkowski, PRL 64, 615 (1990).

must be non-thermal DM

ONE ALTERNATIVE PRODUCTION

From inflaton decay, into DM or into particles cascading and decaying into DM (and typically for low reheating)

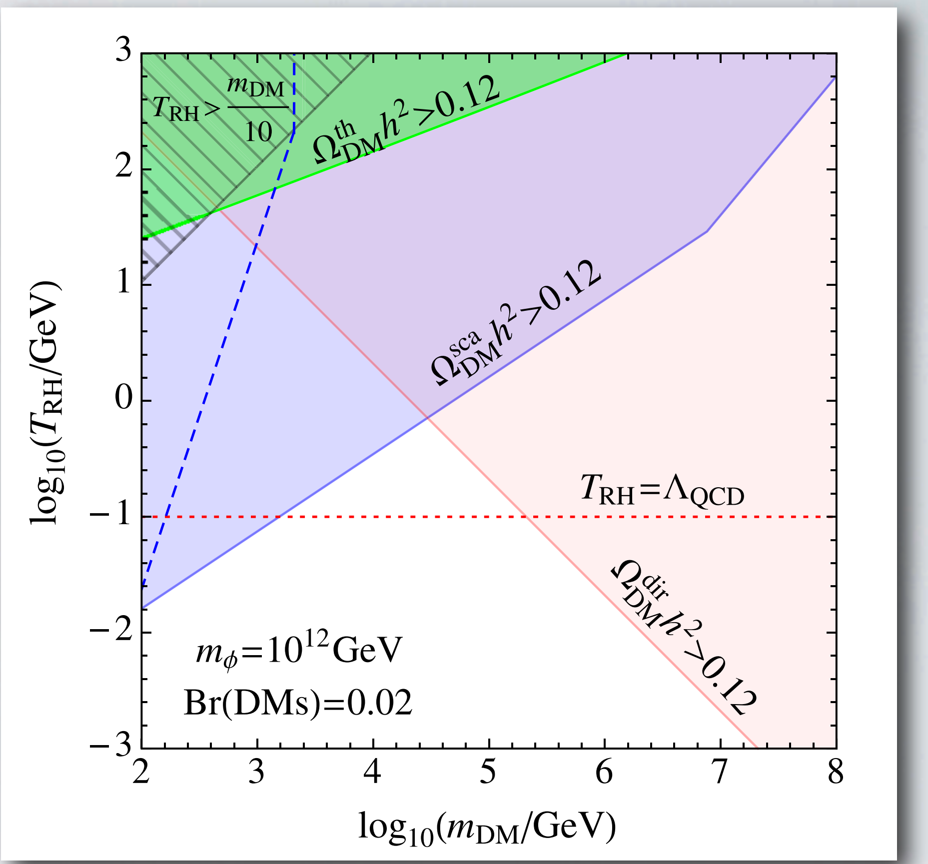
$$n_X|_{T_{\rm RH}} = {\rm Br}(\phi \to X)\, n_\phi|_{T_{\rm RH}}$$

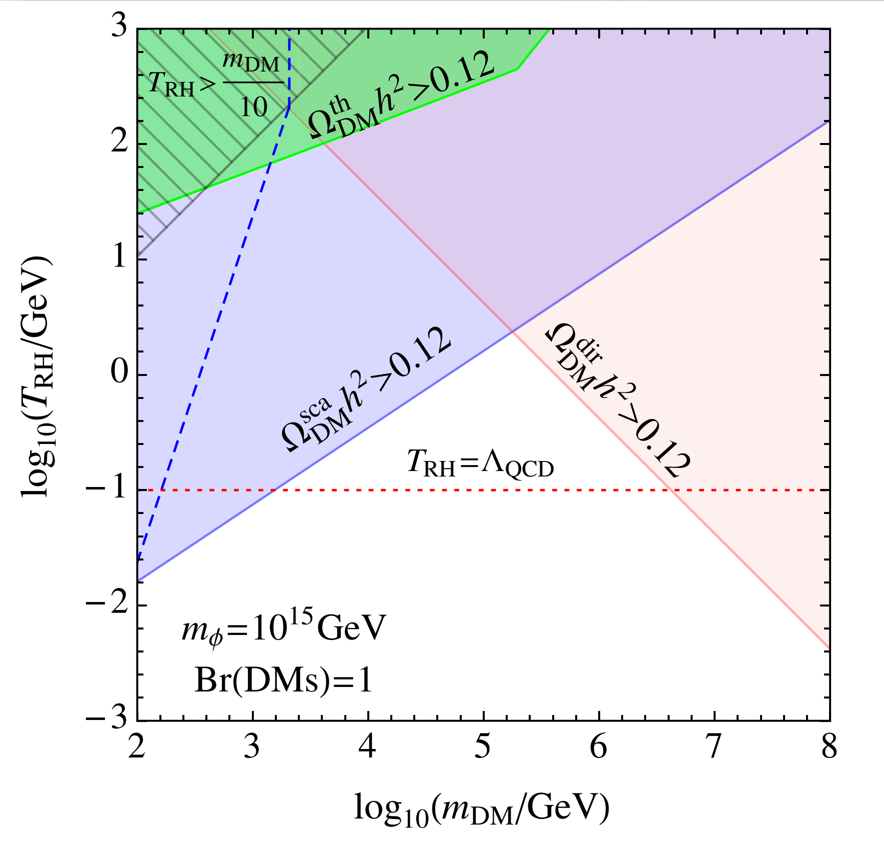
$$\frac{n_X}{s}\Big|_{\rm now} = T_{\rm RH}\frac{3\,n_X}{4\,\rho_\phi}\Big|_{T_{\rm RH}} \simeq \frac{3\,T_{\rm RH}}{4\,m_\phi}{\rm Br}(\phi \to X)$$

or, accounting from indirect production (via cascade and decay products of inflaton decays)

$$\frac{n_X}{s}\Big|_{\rm now} \simeq \frac{3\,T_{\rm RH}}{4\,m_\phi}\sum_i {\rm Br}(\phi \to i)\mu_i$$

K. Harigaya, M. Kawasaki, K. Mukaida and M. Yamada, "Dark Matter Production in Late Time Reheating," PRD 89, 083532 (2014) [1402.2846]





SIGNAL SHOULD COME VIA DECAY

The right o.o.m. can be obtained by invoking Planck suppressed operators (plus GUT-related or B-L breaking or...)

$$\Gamma \sim \left(\frac{\Lambda}{m_{\rm Pl}}\right)^2 \left(\frac{m_X}{m_{\rm Pl}}\right)^4 m_X$$

More details on model-building e.g. in Feldstein, A. Kusenko, S. Matsumoto and T. T. Yanagida, PRD 88, 1, 015004 (2013) [arXiv:1303.7320]

ex.: R-parity violating gravitinos, hidden sector gauge bosons, ... alternatively and singlet fermions in an extra dimension...

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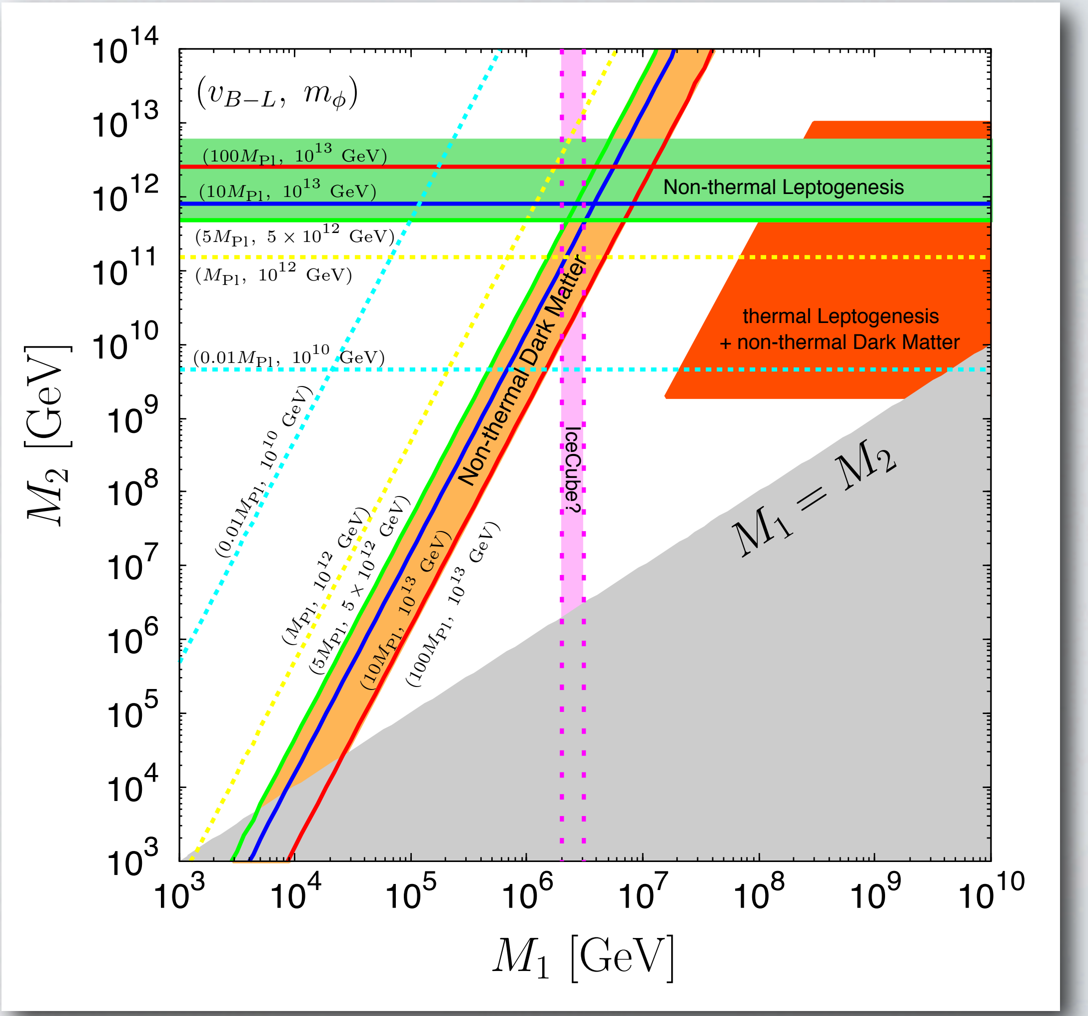
ex.: R-parity violating gravitinos, hidden sector gauge bosons, ... alternatively and singlet fermions in an extra dimension...

Alternatively, from "right-handed" neutrino decays (in leptons and gauge bosons/higgses)

$$\Gamma \sim \frac{|y|^2 m_X}{16\pi} \qquad y \sim 10^{-29}$$

Caveat: many unnatural small parameters... still a problem for anyone?

Plus: can "embed" it into a more complete model, also accounting for inflation (B-L breaking "higgs"), leptogenesis, even BICEP 2...



T. Higaki, R. Kitano and R. Sato, "Neutrinoful Universe," arXiv:1405.0013

PHENO ASPECTS: #1

- Both Galactic and extragalactic contributions present, roughly comparable in size

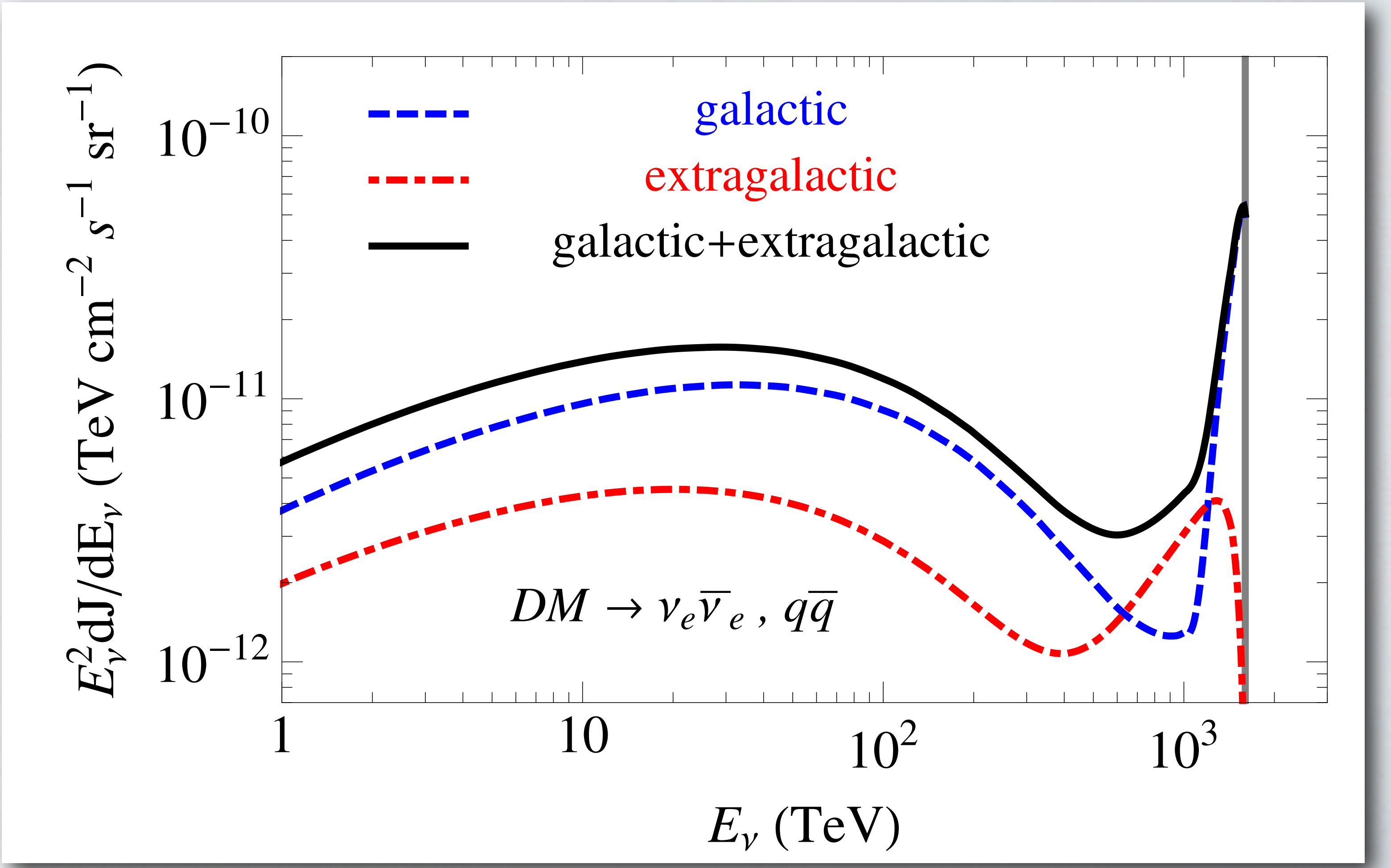
$$\frac{\mathrm{d}J_{\mathrm{h}}}{\mathrm{d}E_\nu}(l,b) = \frac{1}{4\pi\, m_{\mathrm{DM}}\, \tau_{\mathrm{DM}}} \frac{\mathrm{d}N_\nu}{\mathrm{d}E_\nu} \int_0^\infty \mathrm{d}s\; \rho_{\mathrm{h}}[r(s,l,b)]$$

$$\frac{\mathrm{d}J_{\mathrm{eg}}}{\mathrm{d}E_\nu} = \frac{\Omega_{\mathrm{DM}}\rho_{\mathrm{c}}}{4\pi m_{\mathrm{DM}}\tau_{\mathrm{DM}}} \int_0^\infty \mathrm{d}z\, \frac{1}{H(z)} \frac{\mathrm{d}N_\nu}{\mathrm{d}E_\nu}[(1+z)E_\nu]$$

very different situation with respect to annihilating DM!

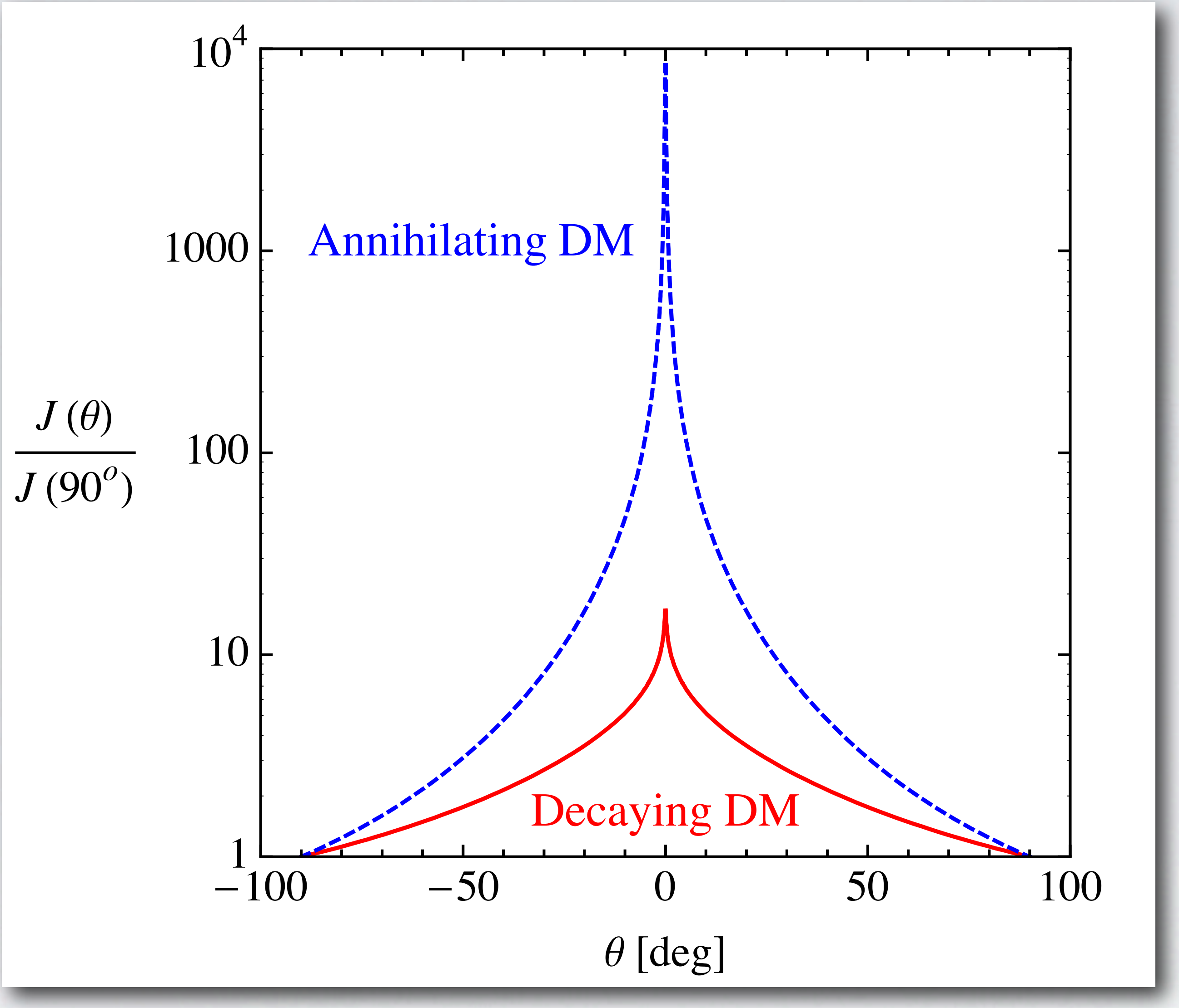
Small uncertainties since *"the clumpiness factor" does not enter* the leading term, only cosmological parameters and global Galactic properties (e.g. total DM mass) matter.

Even the Galactic profile only matters mildly for angular studies, not for the normalization of the signal



PHENO ASPECTS: #2

- almost isotropic, slight anisotropy towards inner Galaxy due to off-center position of the Sun with respect to the GC (much milder and less uncertain than for annihilation!)



- In a 30° aperture cone around the Gal. Center, one expects about twice the number of events than for an isotropic flux (~15% vs 7%)

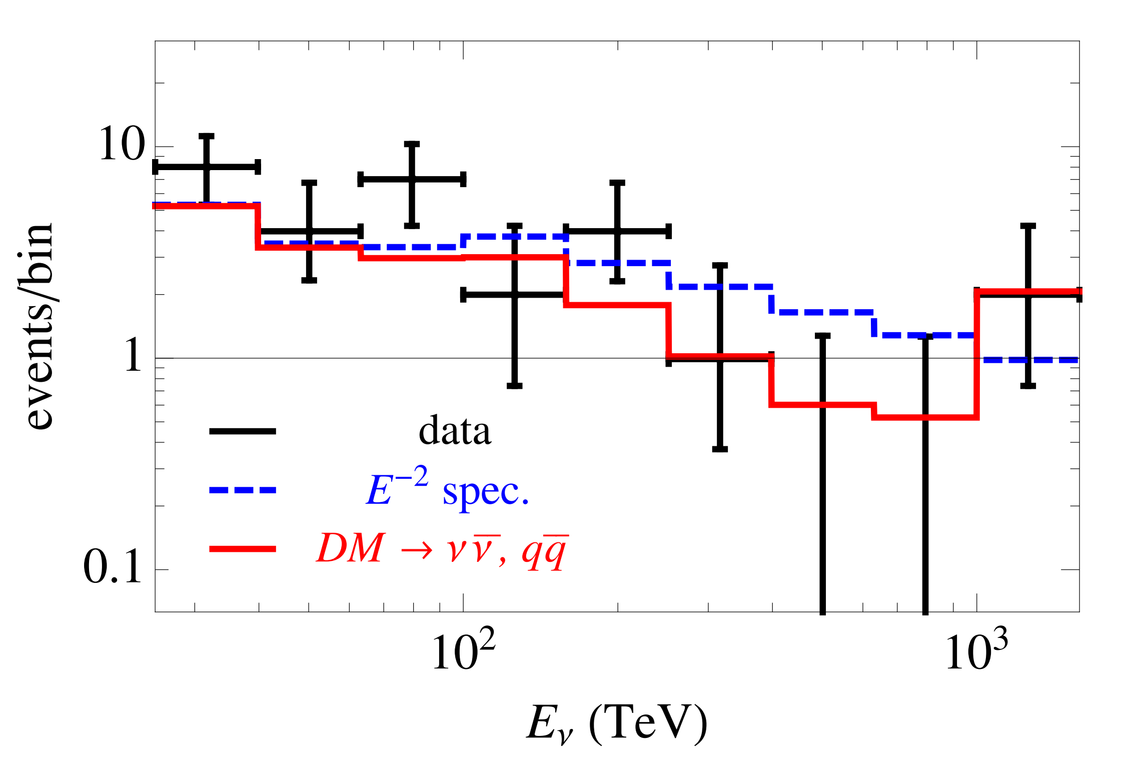
- Currently hard to tell apart, but interesting test possible over O(10) yr timescale.

PHENO ASPECT: #3

- Abrupt energy cutoff expected above 1-2 PeV
- Dip expected for a mix of hard+soft channels, e.g. leptonic + hadronic/cascade contribution.

$$\frac{\mathrm{d}N_\nu}{\mathrm{d}E_\nu} = (1 - b_\mathrm{H}) \left.\frac{\mathrm{d}N_\nu}{\mathrm{d}E_\nu}\right|_\mathrm{S} + b_\mathrm{H} \left.\frac{\mathrm{d}N_\nu}{\mathrm{d}E_\nu}\right|_\mathrm{H} .$$

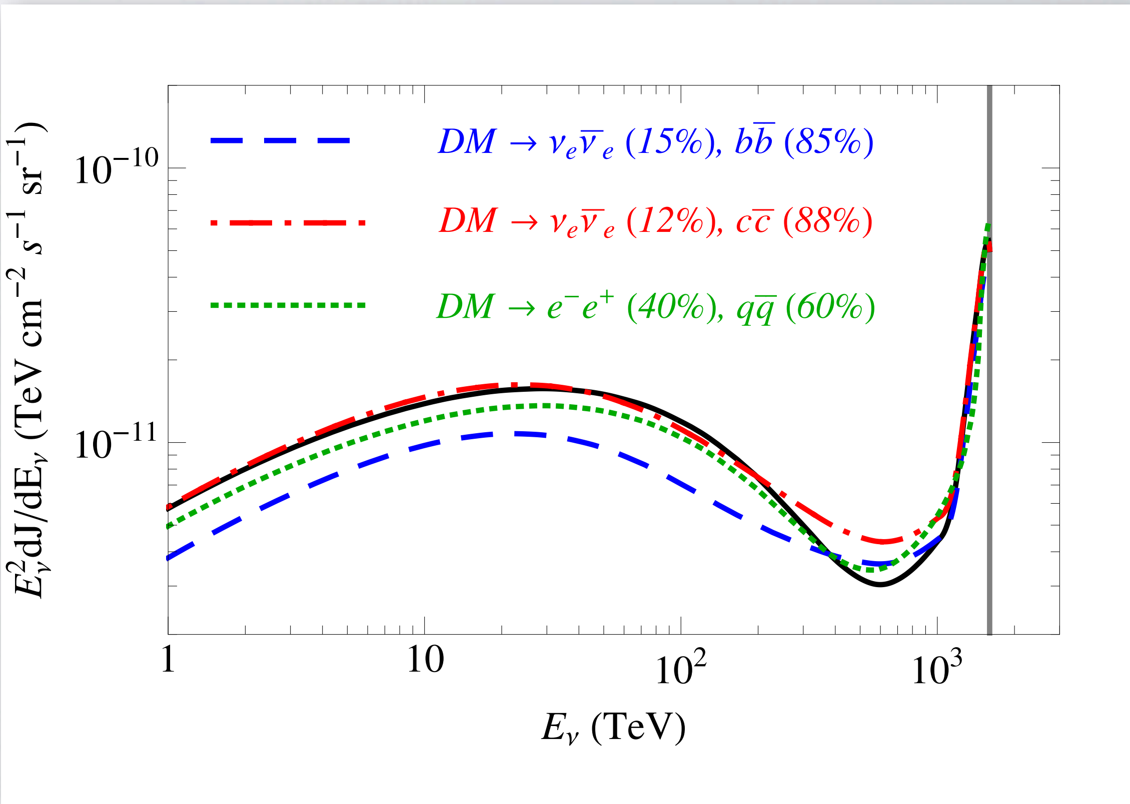
Loosely, low-E tail fixes Γ, b_H Γ the PeV "line"



- Accommodated in a variety of final states/b.r./ lifetimes (i.e. not particularly fine-tuned, e.g. decay via operators containing *LH* OK, no specific flavor structure), typically

$$\Gamma^{-1} \sim 1 \div 3 \times 10^{27}\, s$$

$$b_H \sim 0.1 \div 0.4$$



- Associated to measurable gamma flux (below current bounds, but not by huge factors)

In a few words: Scenario testable with forthcoming IceCube data!

MORE EXOTICS...

LEPTOQUARKS?

"We interpret the PeV shower events observed by the IceCube collaboration as an s-channel enhancement of neutrino-quark scattering by a leptoquark that couples to the flavor and light quarks. With a leptoquark mass around 0.6 TeV and a steep $E^{-2.3}$ neutrino flux, charged-current scattering gives cascade events at 1 PeV and neutral-current scattering gives cascade events at 0.5 PeV. This mechanism is also consistent with the paucity of muon-track events above 100 TeV"

V. Barger and W. Y. Keung, Phys. Lett. B 727, 190 (2013) [1305.6907].

$$\nu_\tau + q \to \text{LQ} \to \tau + q$$
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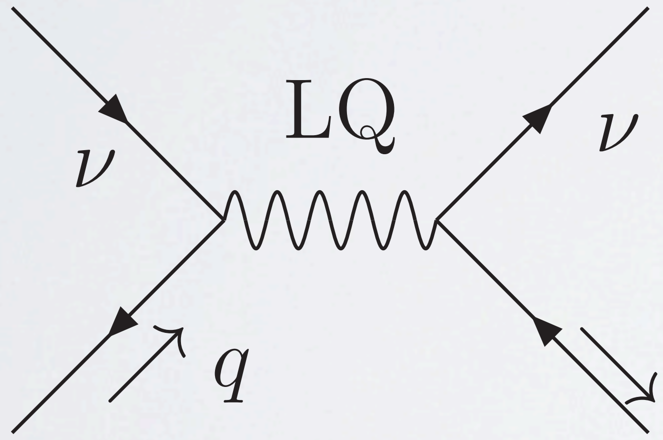
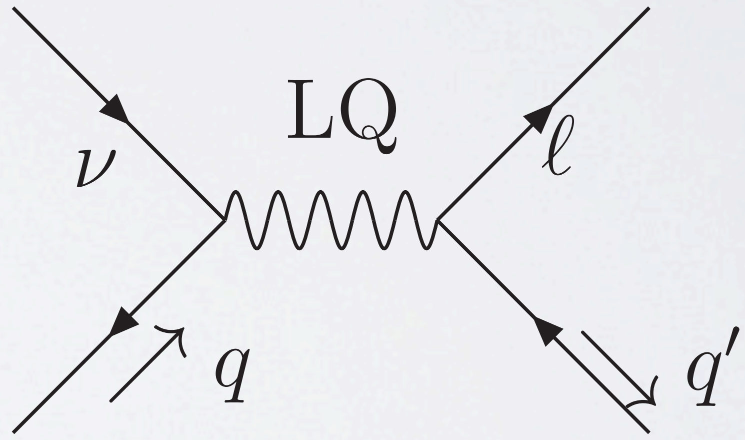




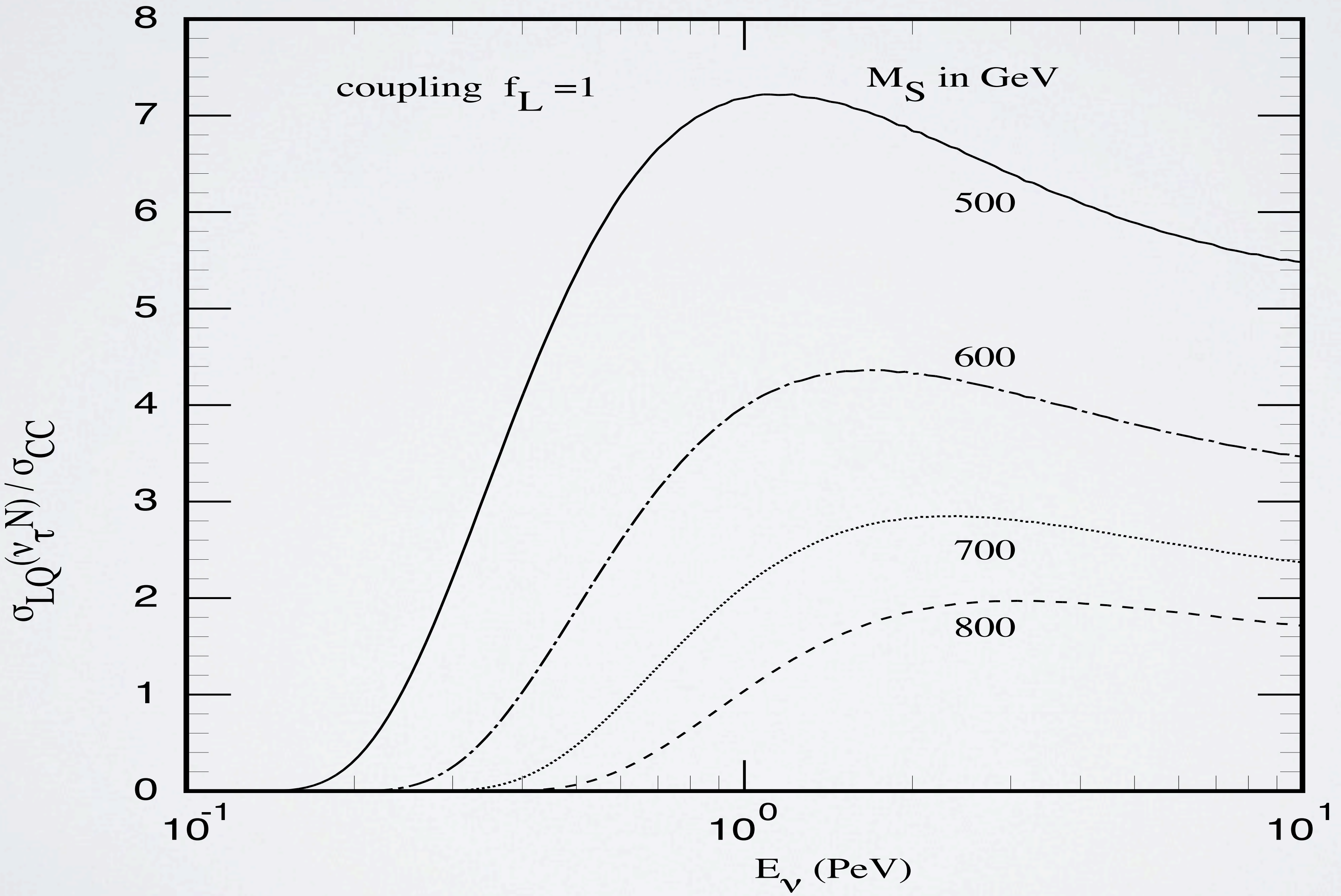
$$\mathcal{L}_{\text{LQ}} = f_L S^\dagger (u,d)_L \, \varepsilon \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L + f_R S^\dagger u_R \tau_R + \text{ h.c.}$$

scalar S of charge -1/3, which couples to the first generation quarks and the 3rd generation lepton

LEPTOQUARKS?

Intrinsic Flux: astrophysical & with a steeper spectrum than normally inferred; "bump" at PeV due to the opening of new channel. Peculiar predictions:

- E-shape (dip due to CC vs NC type of reactions)
- flavour composition (little tracks due to tau excess)
- collider signatures (quoted CMS bound from LHC-7 of 525 GeV...)



V. Barger and W. Y. Keung, Phys. Lett. B 727, 190 (2013) [1305.6907].

PARAMETERIZING LORENTZ VIOLATION

Lorentz invariance violation (LIV) effect can be phenomenologically parametrized in terms of **δ**

$$\delta = \left(\frac{v}{v_0}\right)^2 - 1\,, \quad v = \frac{\partial E}{\partial p}\,, v_0 = \frac{p}{\sqrt{p^2+m^2}}\,,$$

assuming that there is at least one frame in which space and time translations and spatial rotations are exact symmetries (typically the lab one), there one can write

$$E^2 = p^2 + m^2 + f(p,\ldots)$$

with *f* containing e.g. cubic or quartic powers of *p* inducing "linear" (n=1) or "quadratic" (n=2) deviations, respectively, from LI occurring at a mass scale M_{QG}.

$$\delta = \left(\frac{v}{v_0}\right)^2 - 1 \simeq \frac{v_0}{E}\frac{\partial f}{\partial p} \simeq \pm\left(\frac{E}{M_{\rm QG}}\right)^n$$

REMEMBER OPERA?

Initial claim of evidence for $\delta \simeq 5 \times 10^{-5}$ OPERA collab.1109.4897

argued internally inconsistent with CERN beam survival due to fast allowed "Cherenkov" decay $\nu \to \nu\, e^+\, e^-$ A. G. Cohen and S. L. Glashow, PRL 107, 181803 (2011) [1109.6562]

For finite (but much smaller!) **δ**, same channel open at PeV scale if:

$$E_\nu \gtrsim 2\, m_e/\sqrt{\delta} \simeq \mathrm{PeV}\sqrt{10^{-18}/\delta}$$

with a loss rate

$$\Gamma_{e^\pm} = \frac{1}{14}\frac{G_F^2 E^5 \delta^3}{192\,\pi^3} = 2.55 \times 10^{53} \delta^3 E_{\mathrm{PeV}}^5\ \mathrm{Mpc}^{-1}$$

Little Problem: here we do not know the initial beam flux!
How to translate this observation into a constraint?

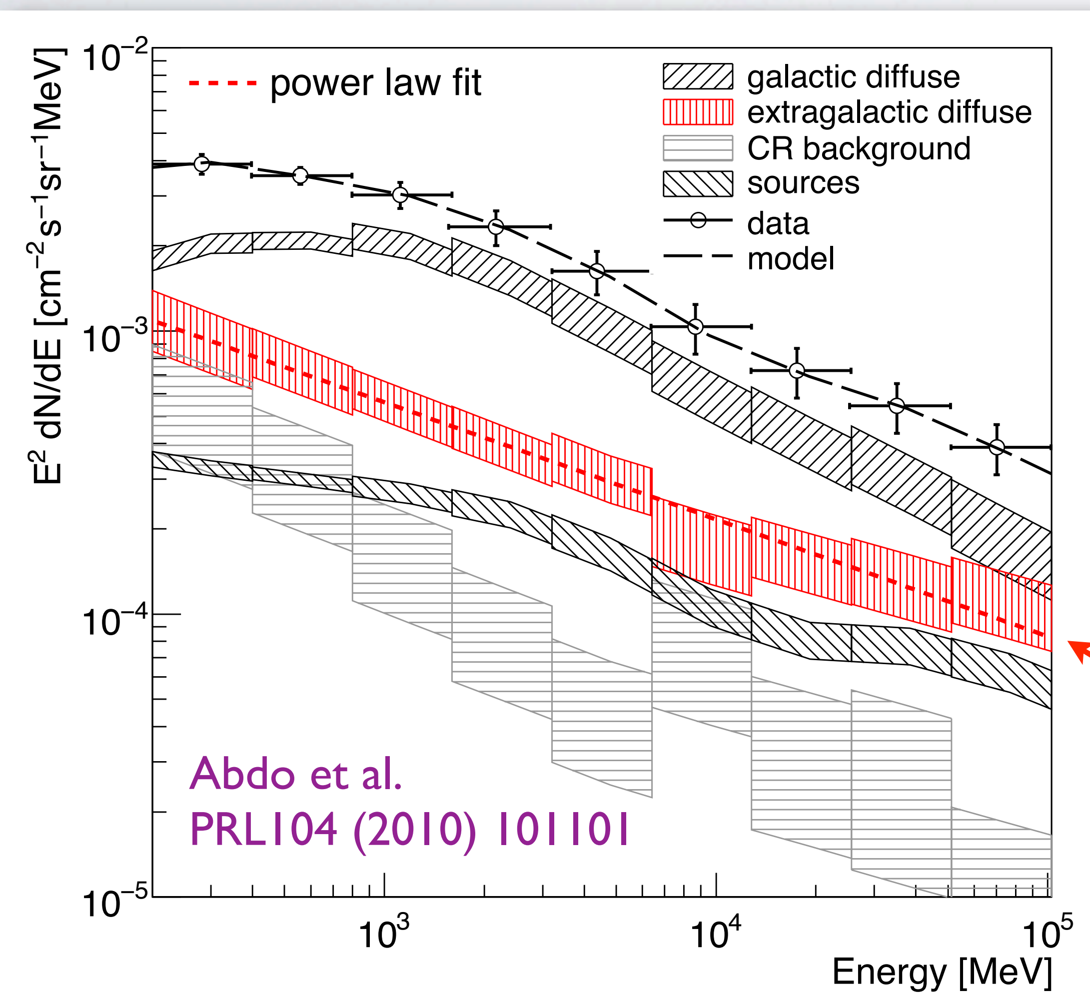
E. Borriello, S. Chakraborty, A. Mirizzi and PS,
"Stringent constraint on neutrino Lorentz-invariance violation from the two IceCube PeV neutrinos,"
Phys. Rev. D 87, no. 11, 116009 (2013)

COSMIC APPLICATION

The e$^{\pm}$ pairs from the decay induce e.m. cascades, with gammas being reprocessed in the ~1-100 GeV band of the gamma extragalactic background.

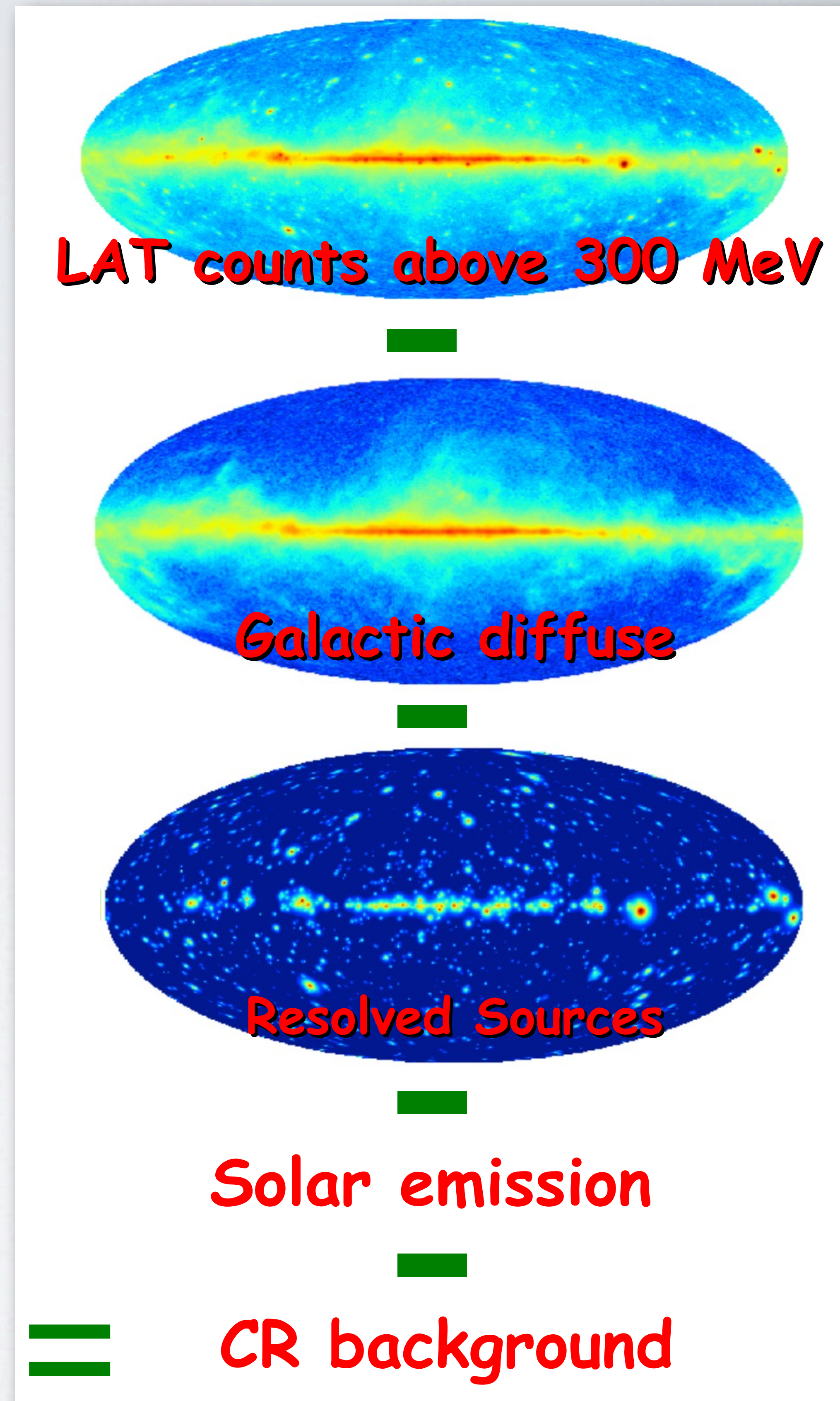
Fermi-LAT puts an **upper limit** to the total energy density stored in the initial **neutrino** flux!

$$\omega_\gamma = \frac{4\pi}{c}\int_{E_1}^{E_2} E\,\frac{d\varphi_\gamma}{dE}\,\mathrm{d}E \lesssim 5.7\times10^{-7}\,\mathrm{eV/cm^3}\,.$$



spectrum
~E$^{-2.41\pm0.05}$
I(>0.1GeV)= (1.03±0 .17)× 10^{-5} cm^{-2} s^{-1} sr^{-1}

IGRB
(consistent with being isotropic)
=



A HUGE JUMP IN CONSTRAINTS!

Energy density inferred from the observed 2 events is:

$$\omega_\nu^{\rm obs} = \frac{4\pi}{c}\int_{1\,\rm PeV}^{1.2\,\rm PeV} E\,\frac{d\varphi_E}{dE}\,{\rm d}E \simeq 2.7\times 10^{-9}\,{\rm eV/cm^3}\,,$$

So, if this is the relic of a huge, suppressed flux, the maximum tolerable suppression is

$$e^{-\Gamma\,d} \gtrsim \frac{\omega_\nu^{\rm obs}}{\omega_\gamma} \sim 10^{-2}$$

For cosmologically distant sources d> Gpc, which implies that

$\delta < 2.6\times 10^{-19}$ i.e. channel closed, $\delta < 10^{-18}$

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weaker bound (but better than existing ones) follows from the process $\nu \to \nu\gamma$
which is however independent on the assumptions on the LIV bound in the e-sector
(this also follows from direct bounds from Crab flare, see F.W. Stecker, APP 56, 16 (2014))

Note I: purely Galactic origin for the totality of the signal excluded by angular distribution study, plus lack of plausible origin... and even in that case one would gain over existing bounds

Note II: for **δ** close to the opening of the channel, one may clearly 'induce the PeV cutoff' via LIV, F.W. Stecker and S.T. Scully, 1404.7025

SUMMARY

- The era of high energy neutrino astrophysics has started!
- The event rates are in the ballpark of what expected for astrophysical fluxes, but the flux spectrum (and angular distribution) show some departures from expectations.
- If significant/confirmed, they will either give clue on astrophysical sources or strengthen "exotic" interpretations:

  - Decaying, non-thermal dark matter?
  - Leptoquarks?
  - Lorentz violation?
  - ...

- Independently of ***taste*** (i.e the appeal that these scenarios have on each one of us) they share an important feature: they are **testable**!

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Final remark

any new astrophysical window has soon or later opened unexpected possibilities to fundamental physics probes (what of CMB cosmology without "microwave telescopes"?) No reason to believe that this time will be different! Maybe we have not thought yet of the most clever way to use this opportunity...

...LET'S NOT WASTE IT!

Courtesy ANITA Collaboration, Antarctica

Thank you