Extragalactic astrophysics and cosmology: the neutrino window and beyond

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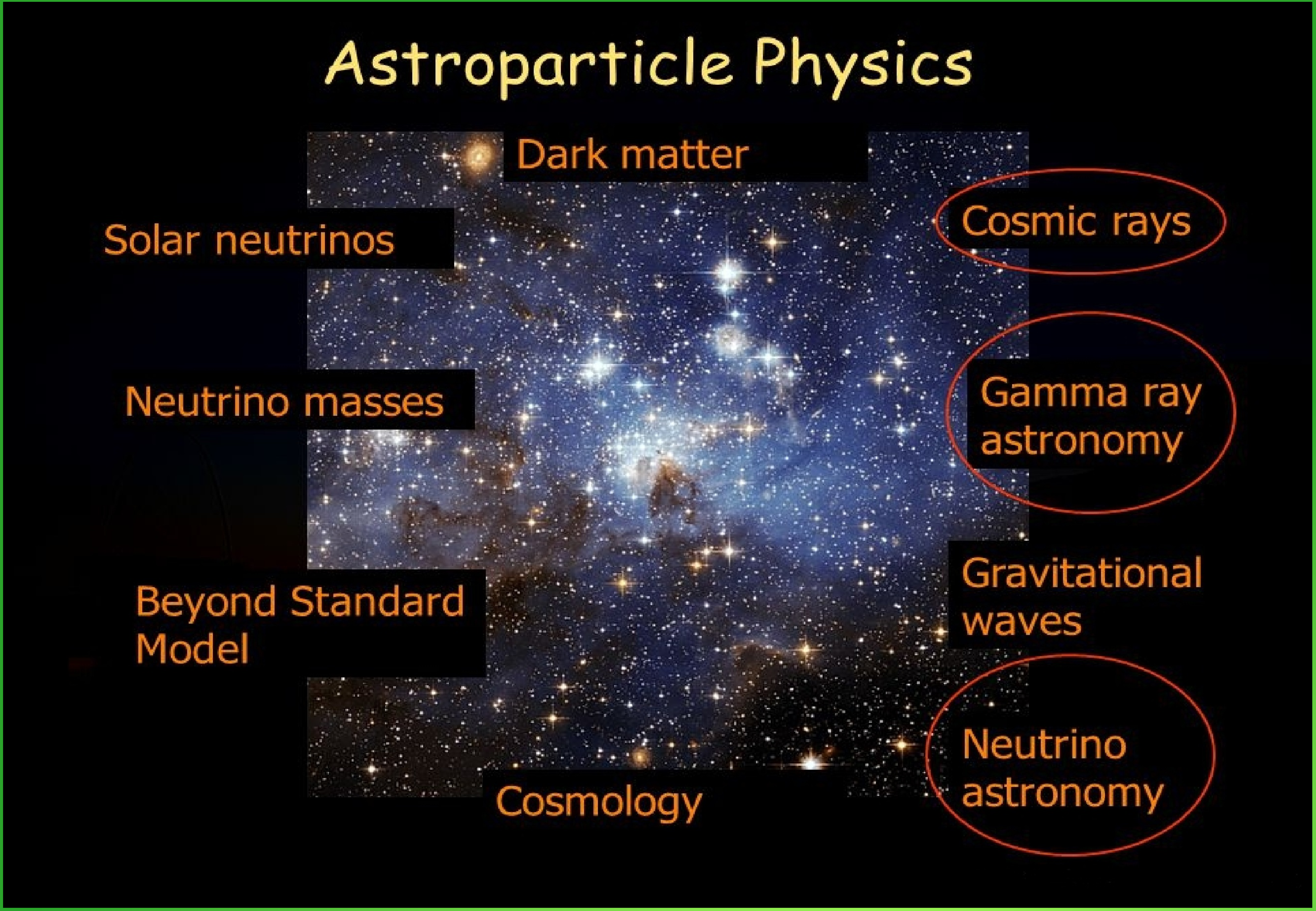
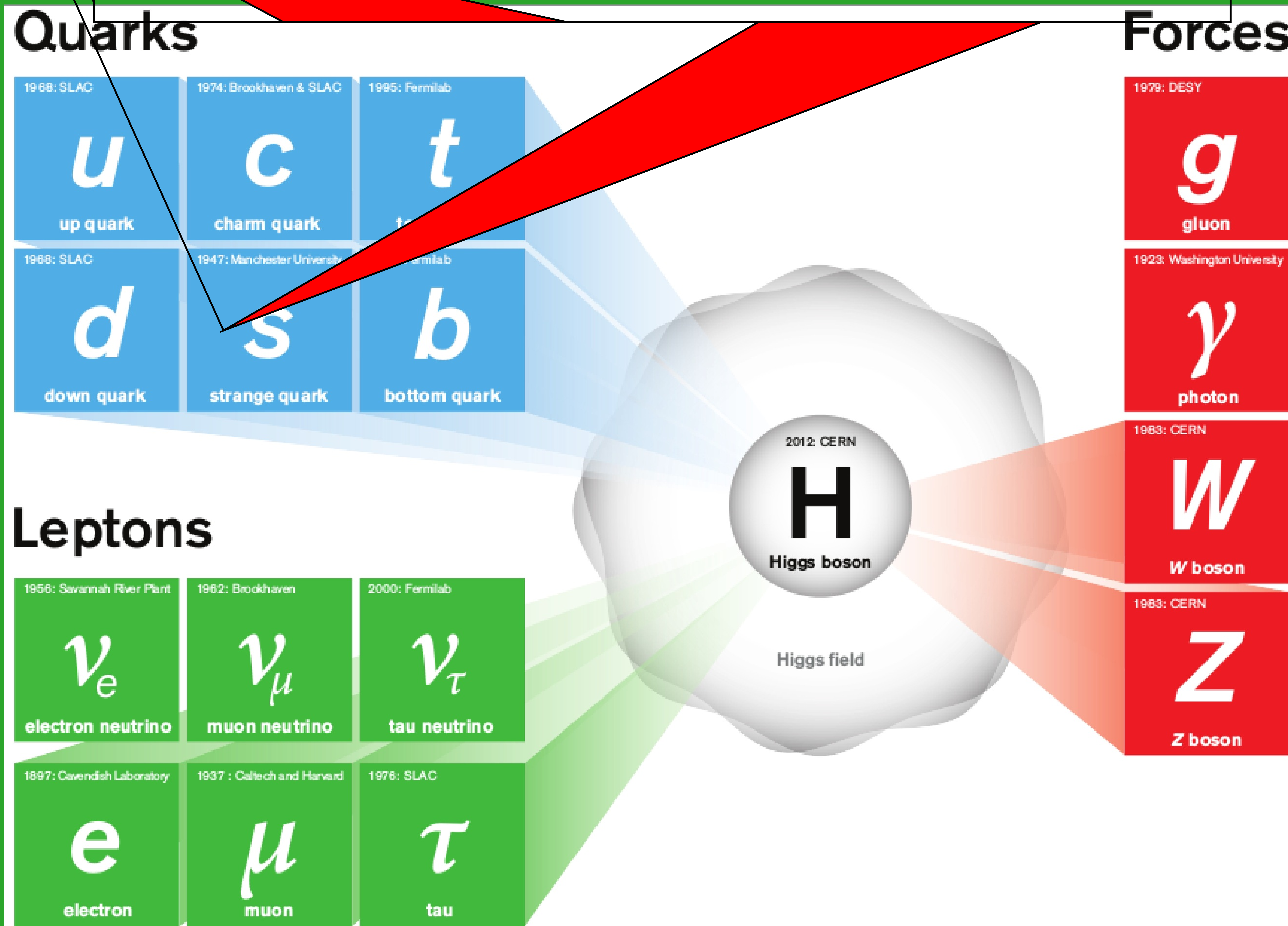
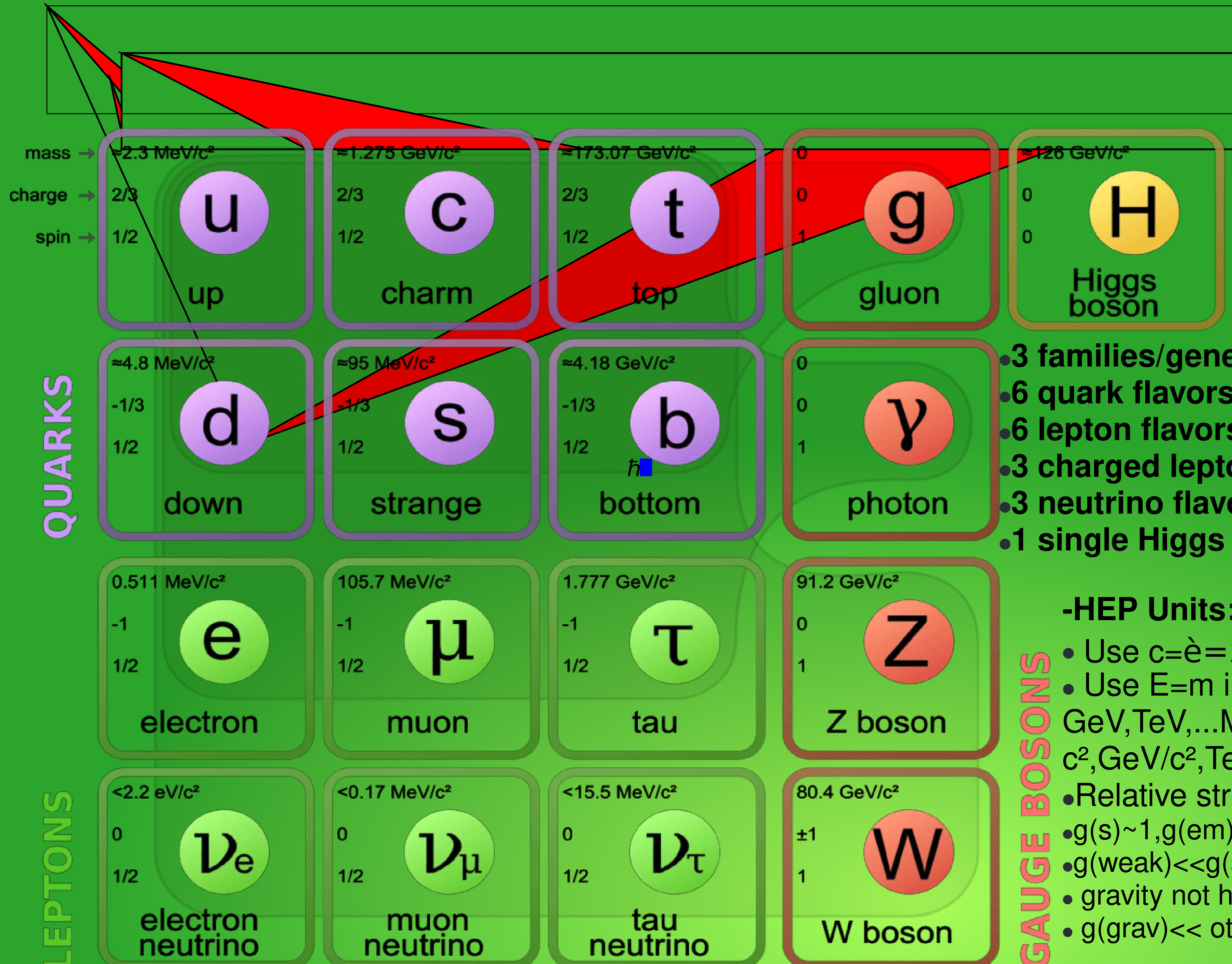
(“Brevísima” introducción a la Astronomía de neutrinos y astropartículas)

Astroparticles in a nutshell...



1. The Standard Model, SM (El modelo estándar, ME).
2. SM Neutrinos (and non SM ν's) in a nutshell.
3. Neutrino mysteries in the SM.
4. Neutrino oscillations!
5. Neutrino experiments.
6. The ν-dark matter links.
7. Neutrino astronomy.
8. Beyond ν's.
9. Conclusions.


Quarks
1968: SLAC
u
up quark
1974: Brookhaven & SLAC
c
charm quark
1995: Fermilab
t
1968: SLAC
d
down quark
1947: Manchester University
s
strange quark
b
bottom quark
Forces
1979: DESY
g
gluon
1923: Washington University
γ
photon
1983: CERN
W
W boson
1983: CERN
Z
Z boson
2012: CERN
H
Higgs boson
Higgs field
Leptons
1956: Savannah River Plant
ν_e
electron neutrino
1962: Brookhaven
ν_μ
muon neutrino
2000: Fermilab
ν_τ
tau neutrino
1897: Cavendish Laboratory
e
electron
1937 : Caltech and Harvard
μ
muon
1976: SLAC
τ
tau



- **3 families/generations.**
- **6 quark flavors.**
- **6 lepton flavors.**
- **3 charged leptons.**
- **3 neutrino flavors.**
- **1 single Higgs boson.**

-HEP Units:

- Use c=è=1ħ.
- Use E=m in GeV,TeV,...MeV/c²,GeV/c²,TeV/c²...
- Relative strengths:
- g(s)~1,g(em)~1/137,
- g(weak)<<g(s),g(em)
- gravity not here!
- g(grav)<< other g's.

$$
\begin{gathered}
\mathcal{L}_{SM} = -\tfrac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \tfrac{1}{4} g_s^2 f^{abc} f^{ade} g^b_\mu g^c_\nu g^d_\mu g^e_\nu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu - \\
M^2 W^+_\mu W^-_\mu - \tfrac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \tfrac{1}{2c_w^2} M^2 Z^0_\mu Z^0_\mu - \tfrac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - igc_w(\partial_\nu Z^0_\mu (W^+_\mu W^-_\nu - \\
W^+_\nu W^-_\mu) - Z^0_\nu (W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + Z^0_\mu (W^+_\nu \partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)) - \\
igs_w(\partial_\nu A_\mu (W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu (W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + A_\mu (W^+_\nu \partial_\nu W^-_\mu - \\
W^-_\nu \partial_\nu W^+_\mu)) - \tfrac{1}{2} g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \tfrac{1}{2} g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2 c_w^2 (Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - \\
Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + g^2 s_w^2 (A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w (A_\mu Z^0_\nu (W^+_\mu W^-_\nu - \\
W^+_\nu W^-_\mu) - 2 A_\mu Z^0_\mu W^+_\nu W^-_\nu) - \tfrac{1}{2}\partial_\mu H \partial_\mu H - 2M^2 \alpha_h H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - \tfrac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \\
\beta_h \left(\tfrac{2M^2}{g^2} + \tfrac{2M}{g} H + \tfrac{1}{2}(H^2 + \phi^0\phi^0 + 2\phi^+\phi^-) \right) + \tfrac{2M^4}{g^2}\alpha_h - \\
g\alpha_h M \left(H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^- \right) - \\
\tfrac{1}{8} g^2 \alpha_h \left(H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + 4H^2\phi^+\phi^- + 2(\phi^0)^2 H^2 \right) - \\
gMW^+_\mu W^-_\mu H - \tfrac{1}{2} g \tfrac{M}{c_w^2} Z^0_\mu Z^0_\mu H - \\
\tfrac{1}{2} ig \left(W^+_\mu (\phi^0 \partial_\mu \phi^- - \phi^- \partial_\mu \phi^0) - W^-_\mu (\phi^0 \partial_\mu \phi^+ - \phi^+ \partial_\mu \phi^0) \right) + \\
\tfrac{1}{2} g \left(W^+_\mu (H \partial_\mu \phi^- - \phi^- \partial_\mu H) + W^-_\mu (H \partial_\mu \phi^+ - \phi^+ \partial_\mu H) \right) + \tfrac{1}{2} g \tfrac{1}{c_w} (Z^0_\mu (H \partial_\mu \phi^0 - \phi^0 \partial_\mu H) + \\
M \left(\tfrac{1}{c_w} Z^0_\mu \partial_\mu \phi^0 + W^+_\mu \partial_\mu \phi^- + W^-_\mu \partial_\mu \phi^+ \right) - ig \tfrac{s_w^2}{c_w} M Z^0_\mu (W^+_\mu \phi^- - W^-_\mu \phi^+) + igs_w M A_\mu (W^+_\mu \phi^- - \\
W^-_\mu \phi^+) - ig \tfrac{1-2c_w^2}{2c_w} Z^0_\mu (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) + igs_w A_\mu (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) - \\
\tfrac{1}{4} g^2 W^+_\mu W^-_\mu \left(H^2 + (\phi^0)^2 + 2\phi^+\phi^- \right) - \tfrac{1}{8} g^2 \tfrac{1}{c_w^2} Z^0_\mu Z^0_\mu \left(H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2 \phi^+\phi^- \right) - \\
\tfrac{1}{2} g^2 \tfrac{s_w^2}{c_w} Z^0_\mu \phi^0 (W^+_\mu \phi^- + W^-_\mu \phi^+) - \tfrac{1}{2} ig^2 \tfrac{s_w^2}{c_w} Z^0_\mu H (W^+_\mu \phi^- - W^-_\mu \phi^+) + \tfrac{1}{2} g^2 s_w A_\mu \phi^0 (W^+_\mu \phi^- + \\
W^-_\mu \phi^+) + \tfrac{1}{2} ig^2 s_w A_\mu H (W^+_\mu \phi^- - W^-_\mu \phi^+) - g^2 \tfrac{s_w}{c_w} (2c_w^2 - 1) Z^0_\mu A_\mu \phi^+ \phi^- - \\
g^2 s_w^2 A_\mu A_\mu \phi^+ \phi^- + \tfrac{1}{2} ig_s \lambda^a_{ij} (\bar{q}^\sigma_i \gamma^\mu q^\sigma_j) g^a_\mu - \bar{e}^\lambda (\gamma\partial + m^\lambda_e) e^\lambda - \bar{\nu}^\lambda (\gamma\partial + m^\lambda_\nu) \nu^\lambda - \bar{u}^\lambda_j (\gamma\partial + \\
m^\lambda_u) u^\lambda_j - \bar{d}^\lambda_j (\gamma\partial + m^\lambda_d) d^\lambda_j + igs_w A_\mu \left(-(\bar{e}^\lambda \gamma^\mu e^\lambda) + \tfrac{2}{3} (\bar{u}^\lambda_j \gamma^\mu u^\lambda_j) - \tfrac{1}{3} (\bar{d}^\lambda_j \gamma^\mu d^\lambda_j) \right) + \\
\tfrac{ig}{4c_w} Z^0_\mu \{ (\bar{\nu}^\lambda \gamma^\mu (1+\gamma^5) \nu^\lambda) + (\bar{e}^\lambda \gamma^\mu (4s_w^2 - 1 - \gamma^5) e^\lambda) + (\bar{d}^\lambda_j \gamma^\mu (\tfrac{4}{3} s_w^2 - 1 - \gamma^5) d^\lambda_j) + \\
(\bar{u}^\lambda_j \gamma^\mu (1 - \tfrac{8}{3} s_w^2 + \gamma^5) u^\lambda_j) \} + \tfrac{ig}{2\sqrt{2}} W^+_\mu \left((\bar{\nu}^\lambda \gamma^\mu (1+\gamma^5) U^{lep}{}_{\lambda\kappa} e^\kappa) + (\bar{u}^\lambda_j \gamma^\mu (1+\gamma^5) C_{\lambda\kappa} d^\kappa_j) \right) + \\
\tfrac{ig}{2\sqrt{2}} W^-_\mu \left((\bar{e}^\kappa U^{lep\dagger}{}_{\kappa\lambda} \gamma^\mu (1+\gamma^5) \nu^\lambda) + (\bar{d}^\kappa_j C^\dagger_{\kappa\lambda} \gamma^\mu (1+\gamma^5) u^\lambda_j) \right) + \\
\tfrac{ig}{2M\sqrt{2}} \phi^+ \left(-m^\kappa_e (\bar{\nu}^\lambda U^{lep}{}_{\lambda\kappa} (1-\gamma^5) e^\kappa) + m^\lambda_\nu (\bar{\nu}^\lambda U^{lep}{}_{\lambda\kappa} (1+\gamma^5) e^\kappa \right) + \\
\tfrac{ig}{2M\sqrt{2}} \phi^- \left(m^\lambda_e (\bar{e}^\lambda U^{lep\dagger}{}_{\lambda\kappa} (1+\gamma^5) \nu^\kappa) - m^\kappa_\nu (\bar{e}^\lambda U^{lep\dagger}{}_{\lambda\kappa} (1-\gamma^5) \nu^\kappa \right) - \tfrac{g}{2} \tfrac{m^\lambda_\nu}{M} H (\bar{\nu}^\lambda \nu^\lambda) - \\
\tfrac{g}{2} \tfrac{m^\lambda_e}{M} H (\bar{e}^\lambda e^\lambda) + \tfrac{ig}{2} \tfrac{m^\lambda_\nu}{M} \phi^0 (\bar{\nu}^\lambda \gamma^5 \nu^\lambda) - \tfrac{ig}{2} \tfrac{m^\lambda_e}{M} \phi^0 (\bar{e}^\lambda \gamma^5 e^\lambda) - \tfrac{1}{4} \bar{\nu}_\lambda M^R_{\lambda\kappa} (1-\gamma_5) \hat{\nu}_\kappa - \\
\tfrac{1}{4} \overline{\bar{\nu}_\lambda M^R_{\lambda\kappa} (1-\gamma_5) \hat{\nu}_\kappa} + \tfrac{ig}{2M\sqrt{2}} \phi^+ \left(-m^\kappa_d (\bar{u}^\lambda_j C_{\lambda\kappa} (1-\gamma^5) d^\kappa_j) + m^\lambda_u (\bar{u}^\lambda_j C_{\lambda\kappa} (1+\gamma^5) d^\kappa_j \right) + \\
\tfrac{ig}{2M\sqrt{2}} \phi^- \left(m^\lambda_d (\bar{d}^\lambda_j C^\dagger_{\lambda\kappa} (1+\gamma^5) u^\kappa_j) - m^\kappa_u (\bar{d}^\lambda_j C^\dagger_{\lambda\kappa} (1-\gamma^5) u^\kappa_j \right) - \tfrac{g}{2} \tfrac{m^\lambda_u}{M} H (\bar{u}^\lambda_j u^\lambda_j) - \\
\tfrac{g}{2} \tfrac{m^\lambda_d}{M} H (\bar{d}^\lambda_j d^\lambda_j) + \tfrac{ig}{2} \tfrac{m^\lambda_u}{M} \phi^0 (\bar{u}^\lambda_j \gamma^5 u^\lambda_j) - \tfrac{ig}{2} \tfrac{m^\lambda_d}{M} \phi^0 (\bar{d}^\lambda_j \gamma^5 d^\lambda_j) + \bar{G}^a \partial^2 G^a + g_s f^{abc} \partial_\mu \bar{G}^a G^b g^c_\mu + \\
\bar{X}^+ (\partial^2 - M^2) X^+ + \bar{X}^- (\partial^2 - M^2) X^- + \bar{X}^0 (\partial^2 - \tfrac{M^2}{c_w^2}) X^0 + \bar{Y} \partial^2 Y + igc_w W^+_\mu (\partial_\mu \bar{X}^0 X^- - \\
\partial_\mu \bar{X}^+ X^0) + igs_w W^+_\mu (\partial_\mu \bar{Y} X^- - \partial_\mu \bar{X}^+ Y) + igc_w W^-_\mu (\partial_\mu \bar{X}^- X^0 - \\
\partial_\mu \bar{X}^0 X^+) + igs_w W^-_\mu (\partial_\mu \bar{X}^- Y - \partial_\mu \bar{Y} X^+) + igc_w Z^0_\mu (\partial_\mu \bar{X}^+ X^+ - \\
\partial_\mu \bar{X}^- X^-) + igs_w A_\mu (\partial_\mu \bar{X}^+ X^+ - \\
\partial_\mu \bar{X}^- X^-) - \tfrac{1}{2} gM \left(\bar{X}^+ X^+ H + \bar{X}^- X^- H + \tfrac{1}{c_w^2} \bar{X}^0 X^0 H \right) + \tfrac{1-2c_w^2}{2c_w} igM \left(\bar{X}^+ X^0 \phi^+ - \bar{X}^- X^0 \phi^- \right) + \\
\tfrac{1}{2c_w} igM \left(\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^- \right) + igM s_w \left(\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^- \right) + \\
\tfrac{1}{2} igM \left(\bar{X}^+ X^+ \phi^0 - \bar{X}^- X^- \phi^0 \right) .
\end{gathered}
$$

$$
\begin{aligned}
\mathcal{L} = & -\tfrac{1}{4} F_{\mu\nu} F^{\mu\nu} \\
& + i \bar{\psi} \not{D} \psi + h.c. \\
& + \bar{\psi}_i y_{ij} \psi_j \phi + h.c. \\
& + |D_\mu \phi|^2 - V(\phi)
\end{aligned}
$$

Cf. EFE:

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} + \Lambda g_{\mu\nu} = 8\pi \frac{G}{c^4} T_{\mu\nu}$$

- There are 3 neutrino species or FLAVORS. Neutrino electric charge is 0.
- The neutrinos are leptons (fermions), i.e., matter particles.
- Neutrino spin is $\mp\frac{1}{2}$. Neutrinos are left-handed. Weak Interaction violates C,P and T, and the combined symmetries (but conserve CPT).
- Neutrinos only interact under weak (electroweak) and gravity.
- The original SM predicts MASSLESS neutrinos (Weyl spinors).
- Neutrino oscillation (NO) phenomenon implies neutrinos are massive (or at least, one neutrino flavor state is massive in order to explain NO data).
- There are currently strong bounds on possible SM neutrino masses.
- Neutrinos could be described by Dirac/Majorana spinors...ELKOs?
- There could be EXTRA superheavy/supermassive (compared w.r.t. SM neutrinos) neutrino species, only leaving tracks in neutrino oscillations or exotic places...These non-active neutrinos are called STERILE NEUTRINOS.
- SM neutrinos are WARM/HOT dark matter and they can NOT account for the DM mass alone: wrong structure formation at big scales (simulations), bad number of satellite galaxies, and other issues. NON SM ν's CAN BE COLD DARK MATTER (CDM) CANDITATES.
- Neutrinos are VERY important in astrophysics and cosmology...(Even in stars, on Earth,...Many objects do emit neutrinos and or are bombarded by them, even you right now from solar neutrinos and other sources!!!!). Luckily: $G(\text{Fermi}) \ll 1$...

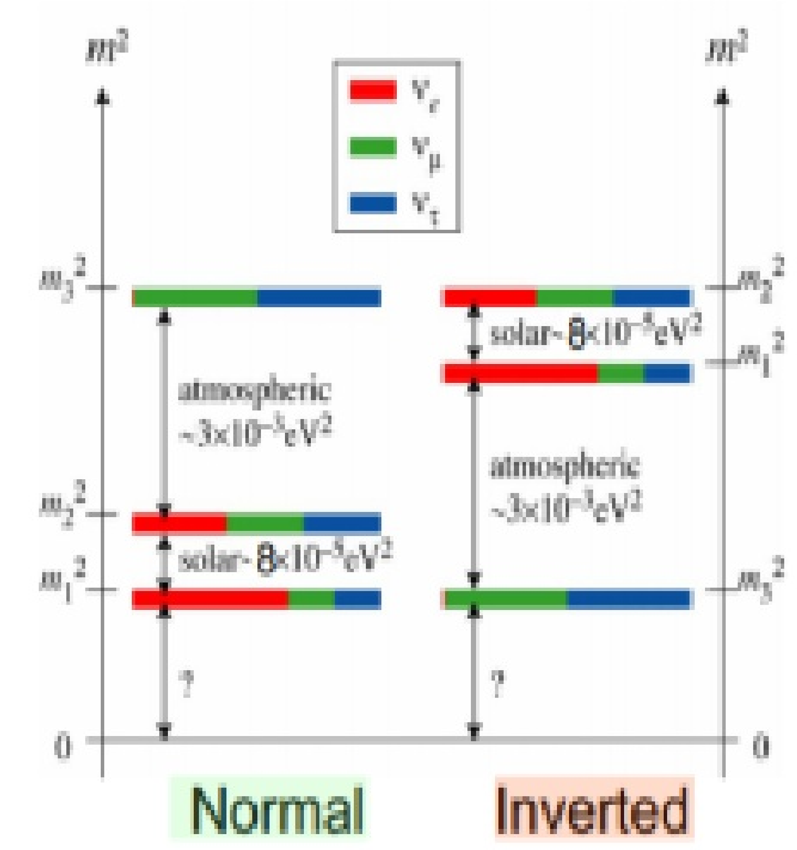
NEUTRINOS ARE MYSTERIOUS...

- **What are the SM neutrinos masses? Nobody knows (but they are in between some meV and 1eV). Is the spectrum normal,inverted or Qdeg?**
- **Are neutrinos = antineutrinos? If not, they are Dirac particles, if neutrinos are equal to antineutrinos, they are Majorana particles...**
- **Related to the previous one: can we observe NEUTRINOLESS double beta decay and other violating lepton number processes? (Only possible if SM neutrinos are Majorana particles).**
- **Are there sterile/superheavy neutrino species (extra flavors) in Nature?**
- **Can we detect the neutrinos left by the Big Bang? They form the so-called Cosmological Neutrino Background or CMB (T~1.945 K).**
- **Can we detect the cosmogenic neutrinos? Cosmogenic neutrinos are generated when HECrs interact with CMB photons producing neutrinos...**
- **Can we detect SN diffuse background (Relic Neutrino Background) left from current SN / old POP III stars?**
- **Do SM neutrinos have electric/magnetic dipole moment? Do they experiment Hidden interactions?**
- **Can we detect the coherent neutral neutrino-nuclei scattering. Important as irreducible background in current DM searches!**

Neutrino masses: Ordering versus Hierarchy

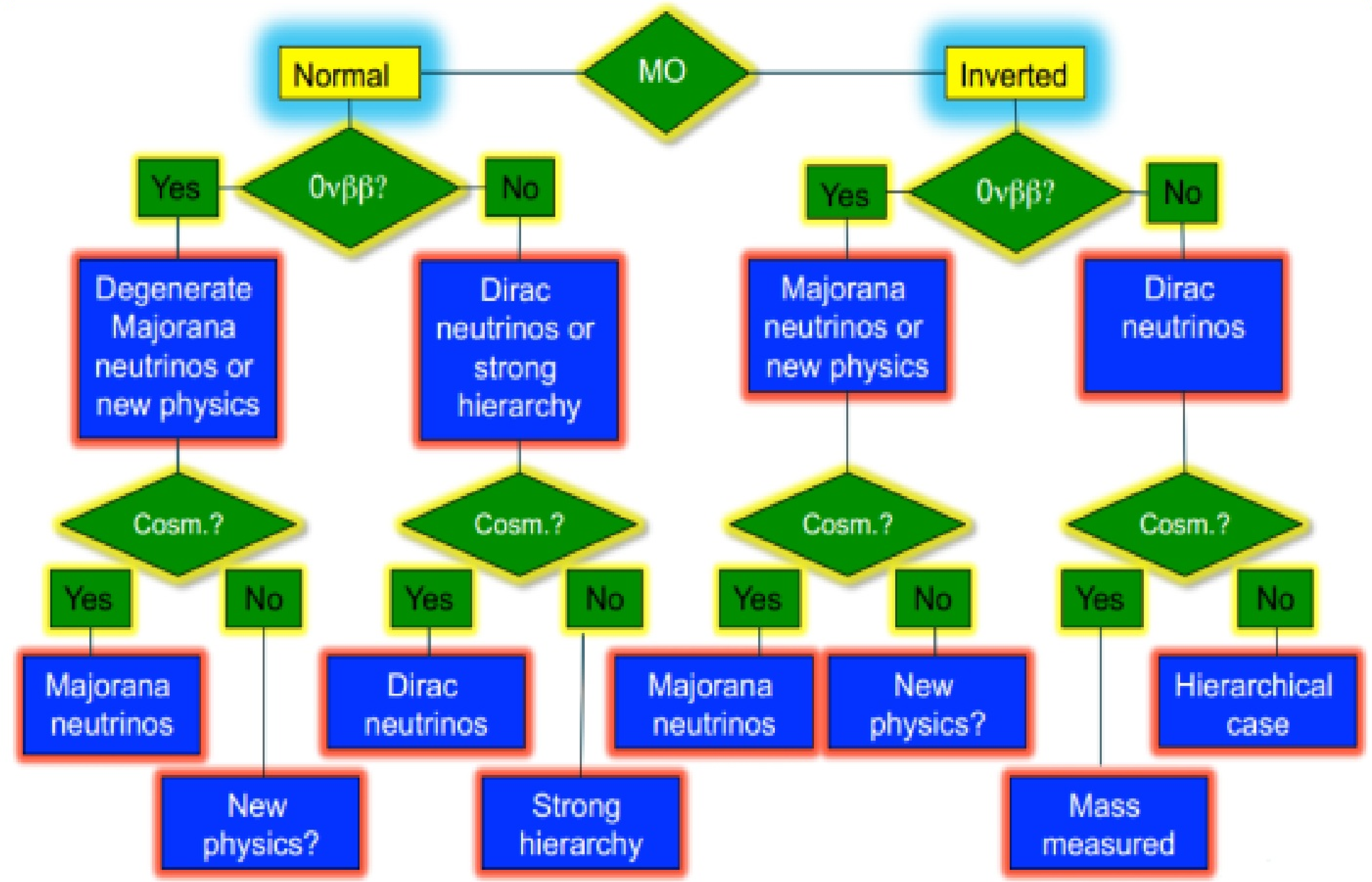
- The (atmospheric) mass **ordering** is unknown (normal or inverted)
- The absolute neutrino mass scale is unknown (< eV). Often parameterized by lightest neutrino mass: m_1 or m_3
- In theory: three cases
  - Normal **hierarchy**: $m_1 < (\Delta m_{21}^2)^{0.5}$ (**ordering**: normal)
  - Inverted **hierarchy**: $m_3 << |\Delta m_{31}^2|^{0.5}$ (**ordering**: inverted)
  - (Quasi-)**Degenerate**: $m_1 \sim m_2 \sim m_3 >> |\Delta m_{31}^2|^{0.5}$ (**ordering**: normal or inverted)

  [plus some recently growing interest in the transition regime: m_1 (for NO) ~ $|\Delta m_{31}^2|$]
- Lower bound on neutrino neutrino masses from $\Delta m_{31}^2 \sim 0.0024$ eV^2:
  Normal hierarchy: $m_3 \sim 0.05$ eV
  Inverted hierarchy: $m_1, m_2 \sim 0.1$ eV



$$\Delta m_{ij}^2 = m_i^2 - m_j^2$$

Impact of direct mass ordering (MO) measurement



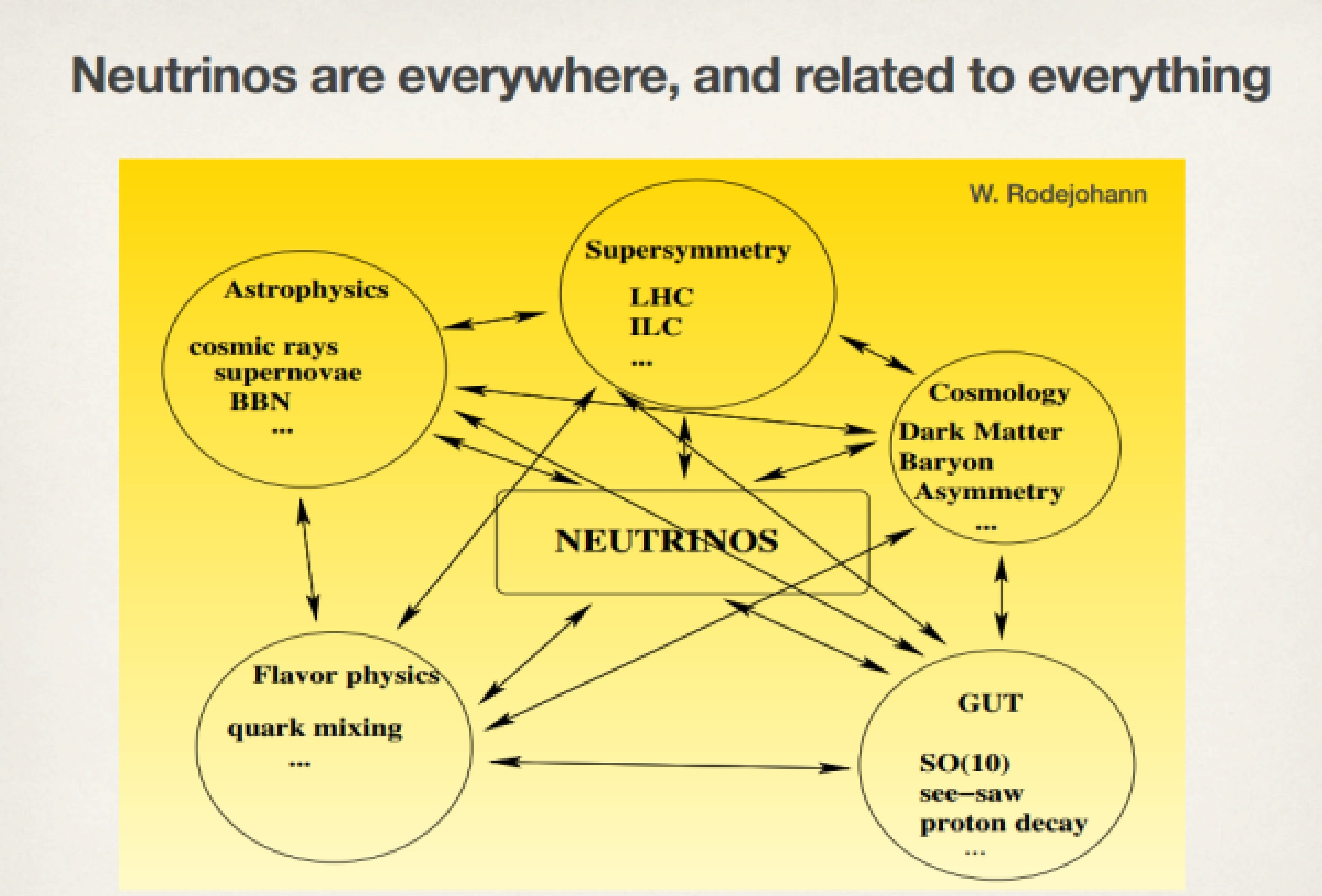
- Cosmological neutrinos (or the CνB) are inherently connected to the photon microwave background. However, there are significant differences between the two.
- Some characteristics:
  - The CνB **temperature** is related to the photon temperature (including reheating).
  - The CνB is inherently a gas of spin 1/2 particles: obey **Fermi-Dirac statistics** rather than Bose-Einstein).
  - The CνB **density** is predicted directly from the photon density.

	Bose-Einstein (γ's)	Fermi-Dirac (ν's)
Temperature (Now)	2.725 K	1.945 K
Number density	$\frac{\zeta\{3\}}{\pi^2} g T_\gamma^3$	$\frac{3}{4}\frac{\zeta\{3\}}{\pi^2} g T_\nu^3$
Energy Density	$\frac{\pi^2}{30} g T_\gamma^4$	$\frac{7}{8}\frac{\pi^2}{30} g T_\nu^4$

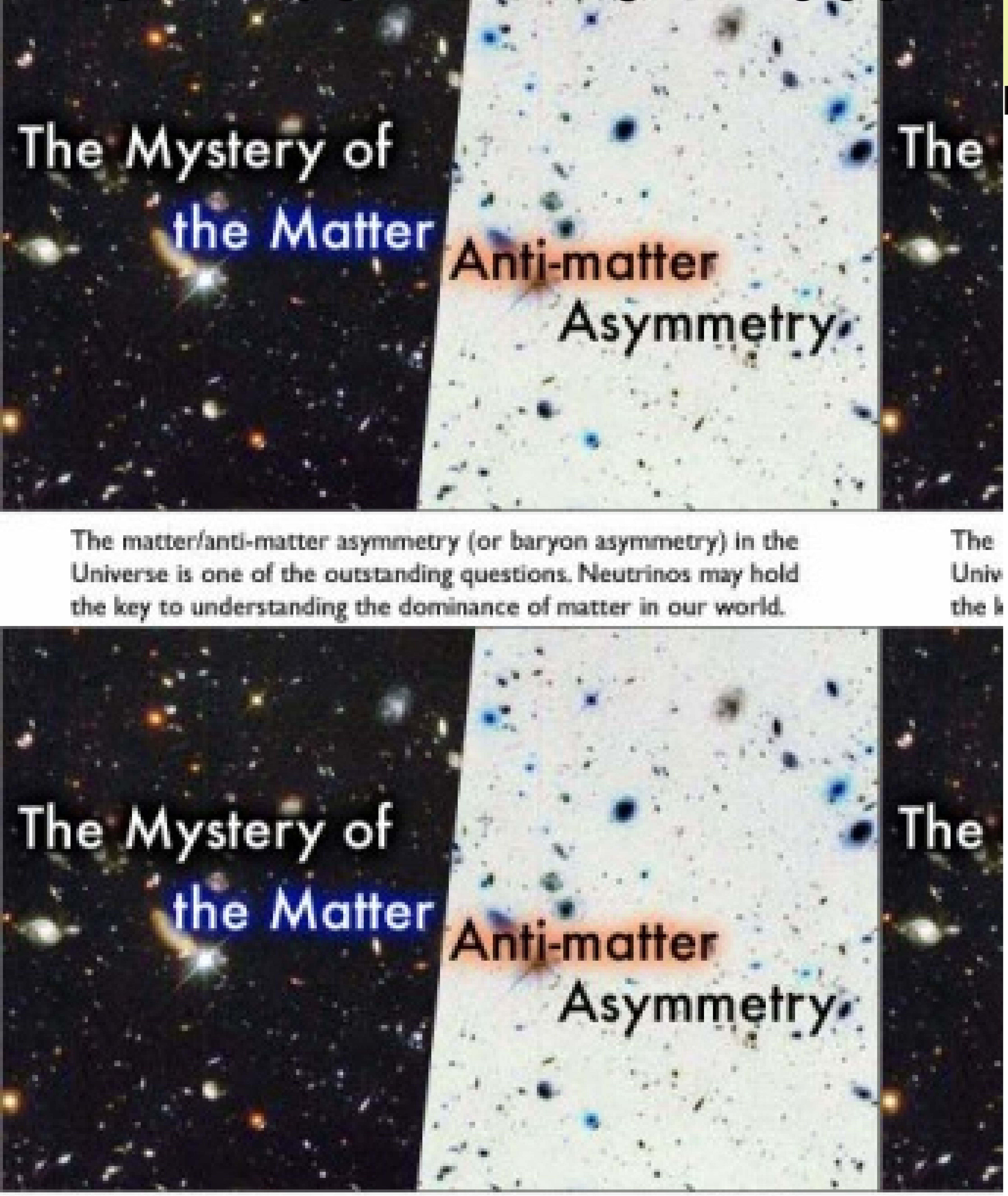
From CMB, the neutrino density is ~110 ν's/cm³ per flavor.

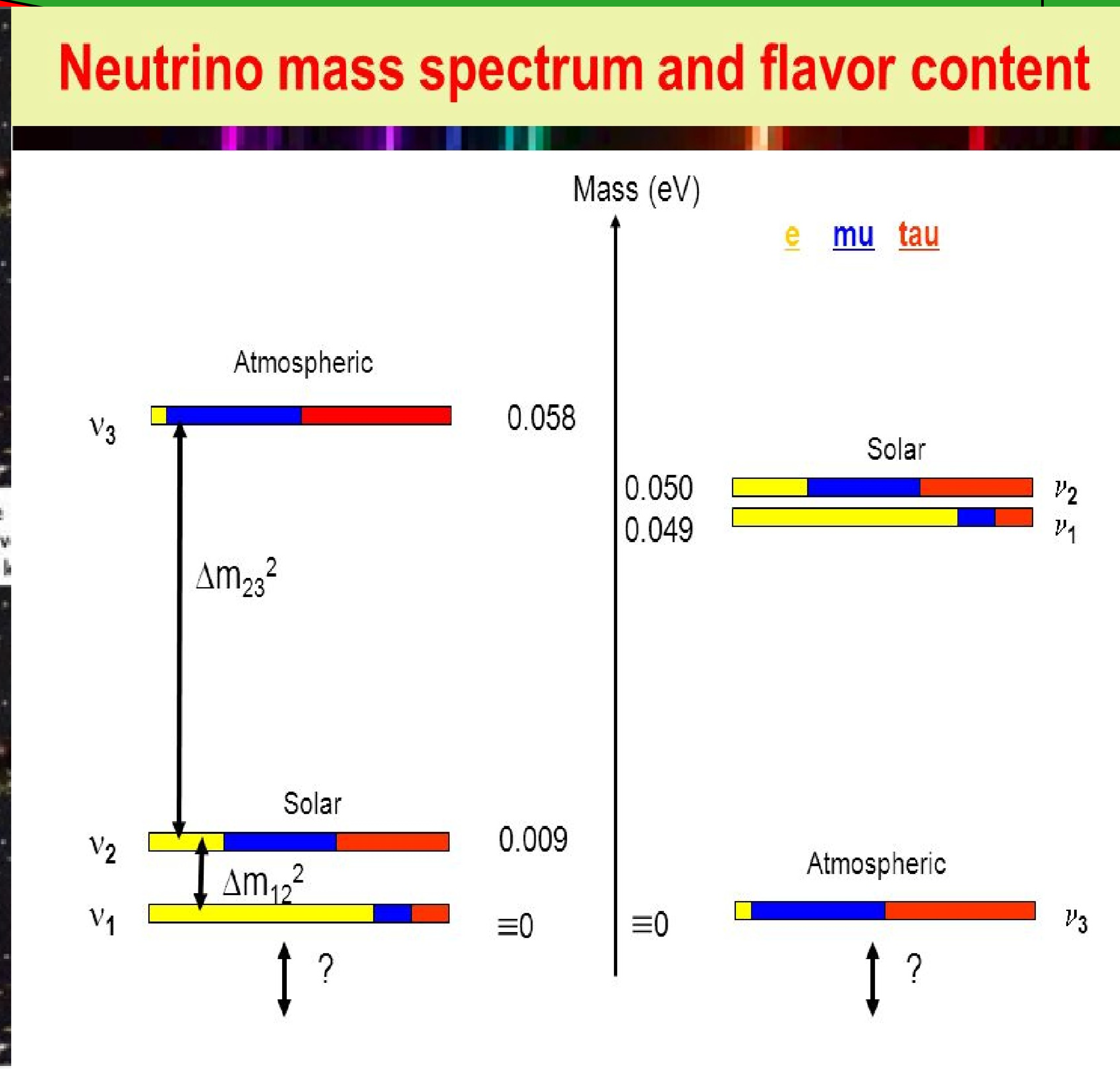
(neutrino and anti-neutrino)

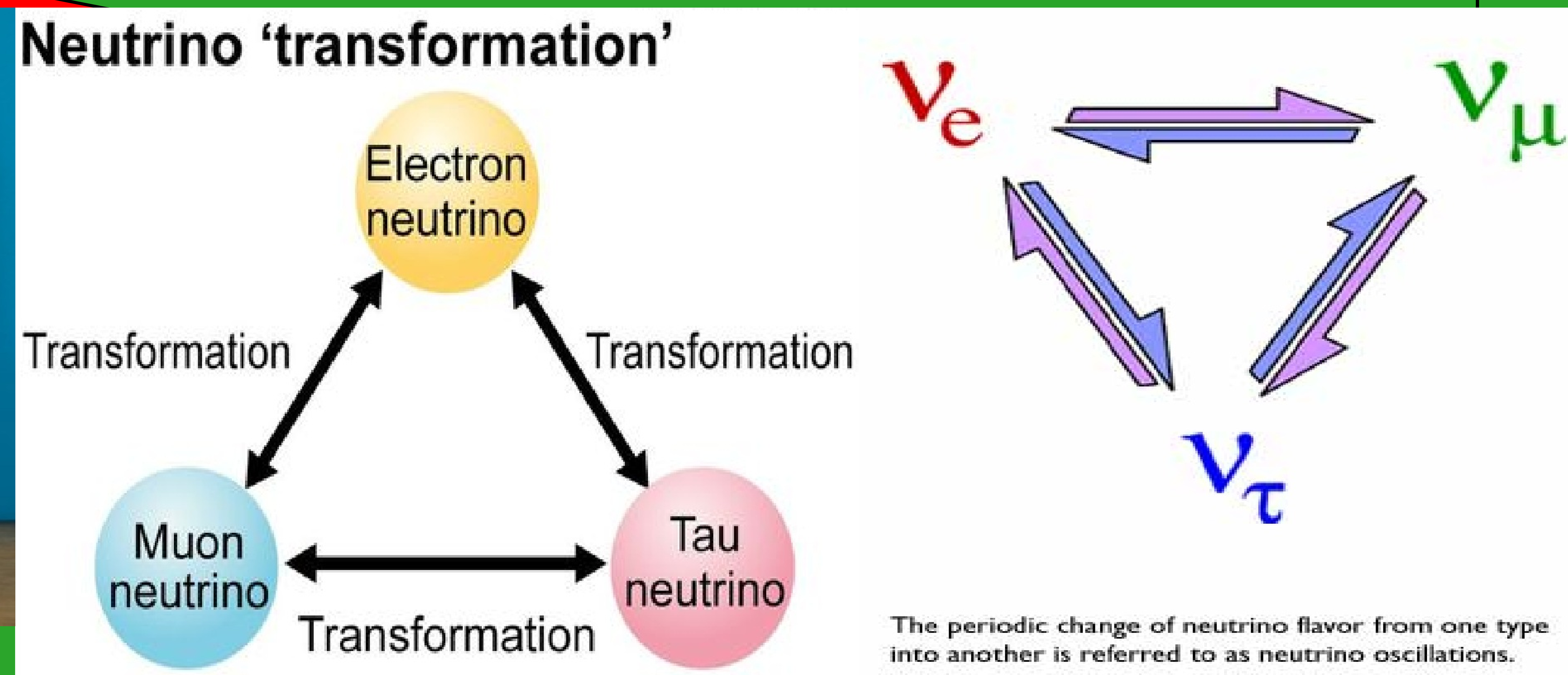
In summary:


Neutrinos are everywhere, and related to everything
W. Rodejohann
Supersymmetry
LHC
ILC
...
Astrophysics
cosmic rays
supernovae
BBN
...
Cosmology
Dark Matter
Baryon
Asymmetry
...
NEUTRINOS
Flavor physics
quark mixing
...
GUT
SO(10)
see−saw
proton decay
...

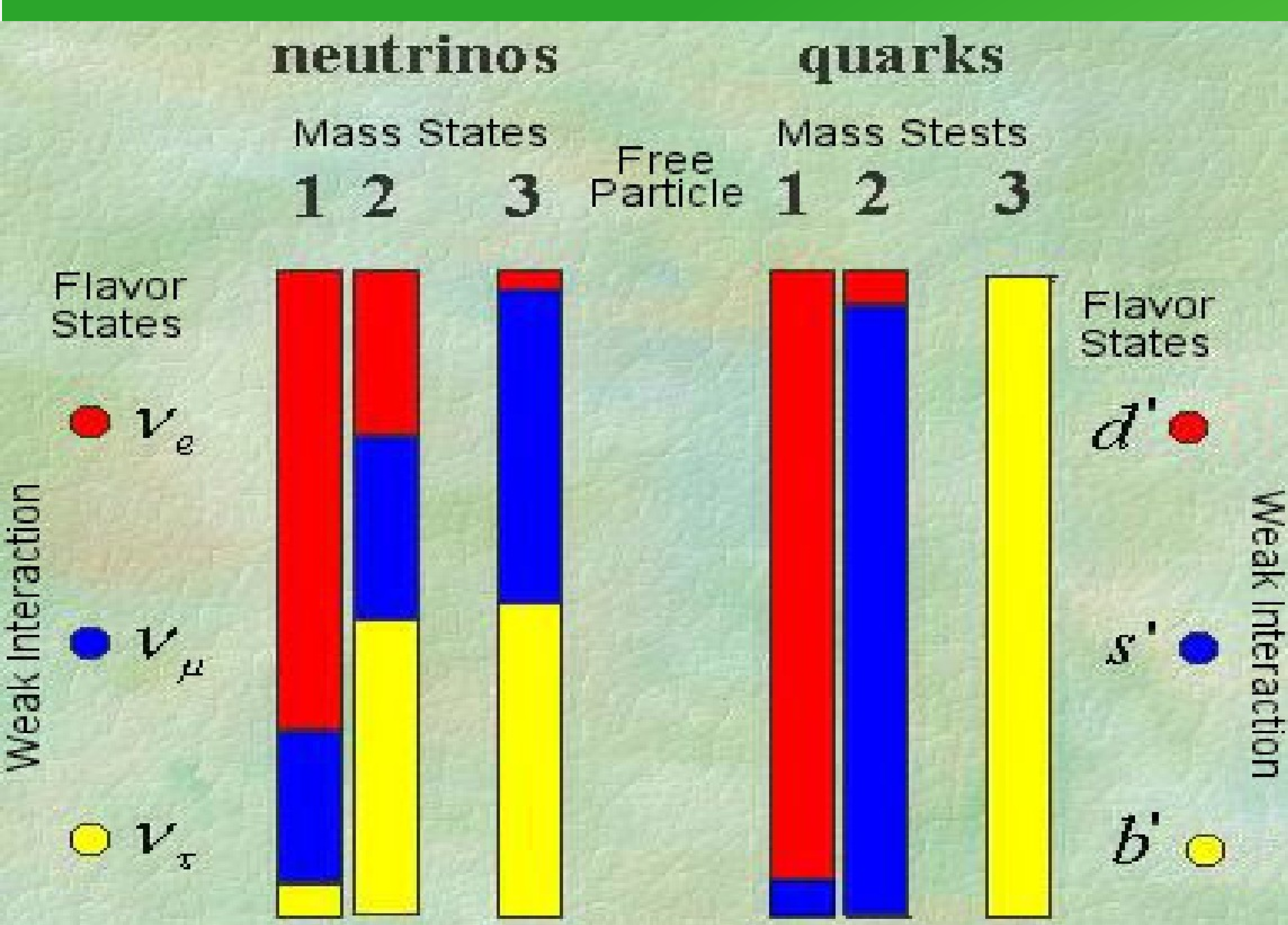
NEUTRINOS ARE MYSTERIOUS...

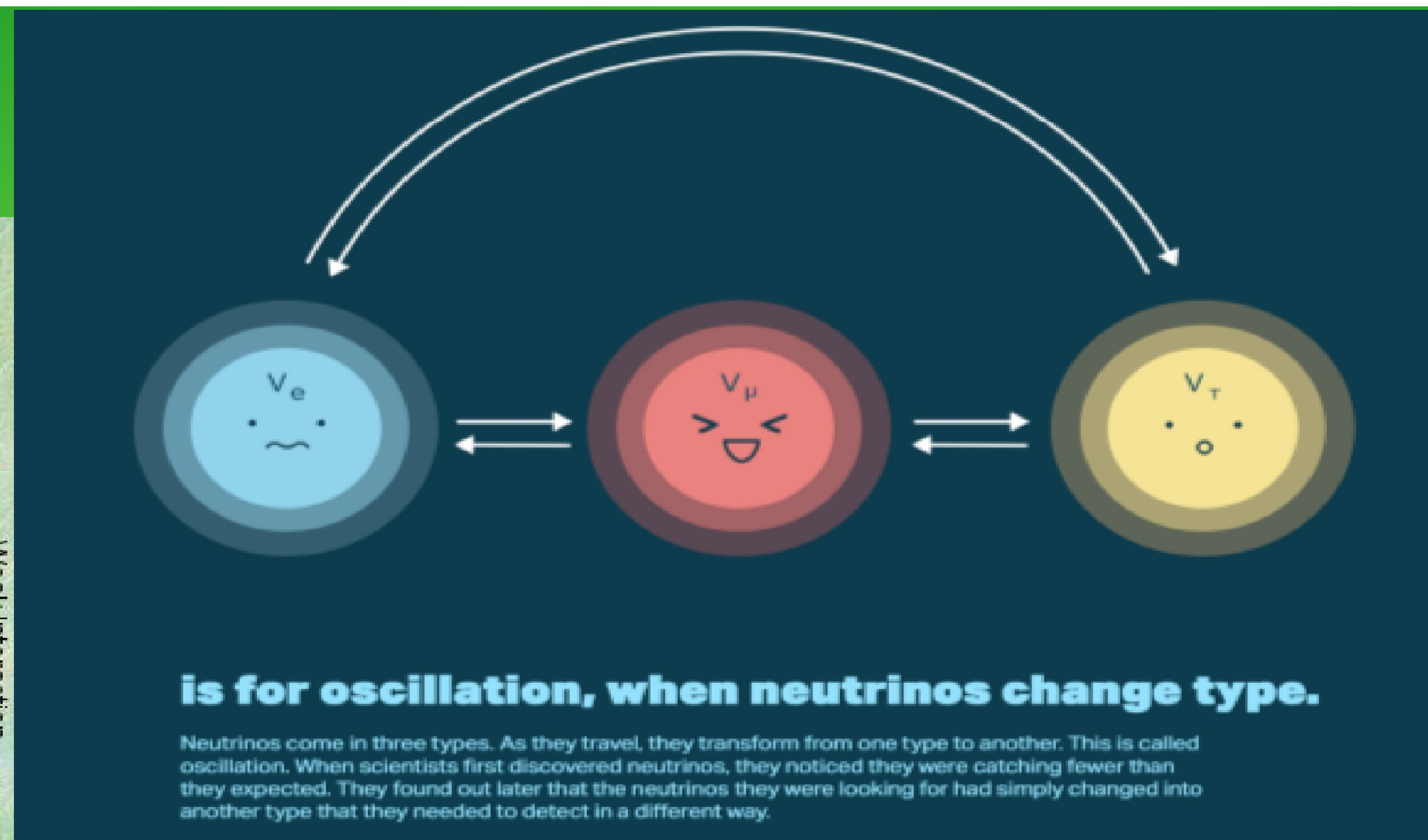






Comparison between neutrino and quark mixing on the right, do you observe the differences?





Using the oscillation framework for neutrino flavor change:

If neutrinos have mass: $|\nu_l\rangle = \sum U_{li} |\nu_i\rangle$

For three neutrinos:

$$U_{li} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

Maki-Nakagawa-Sakata-Pontecorvo (MNSP) matrix

(Double β decay only)

$$= \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & e^{-i\delta} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13} \\ 0 & 1 & 0 \\ -s_{13} & 0 & c_{13} \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{-i\alpha_2/2} & 0 \\ 0 & 0 & e^{-i\alpha_3/2+i\delta} \end{pmatrix}$$

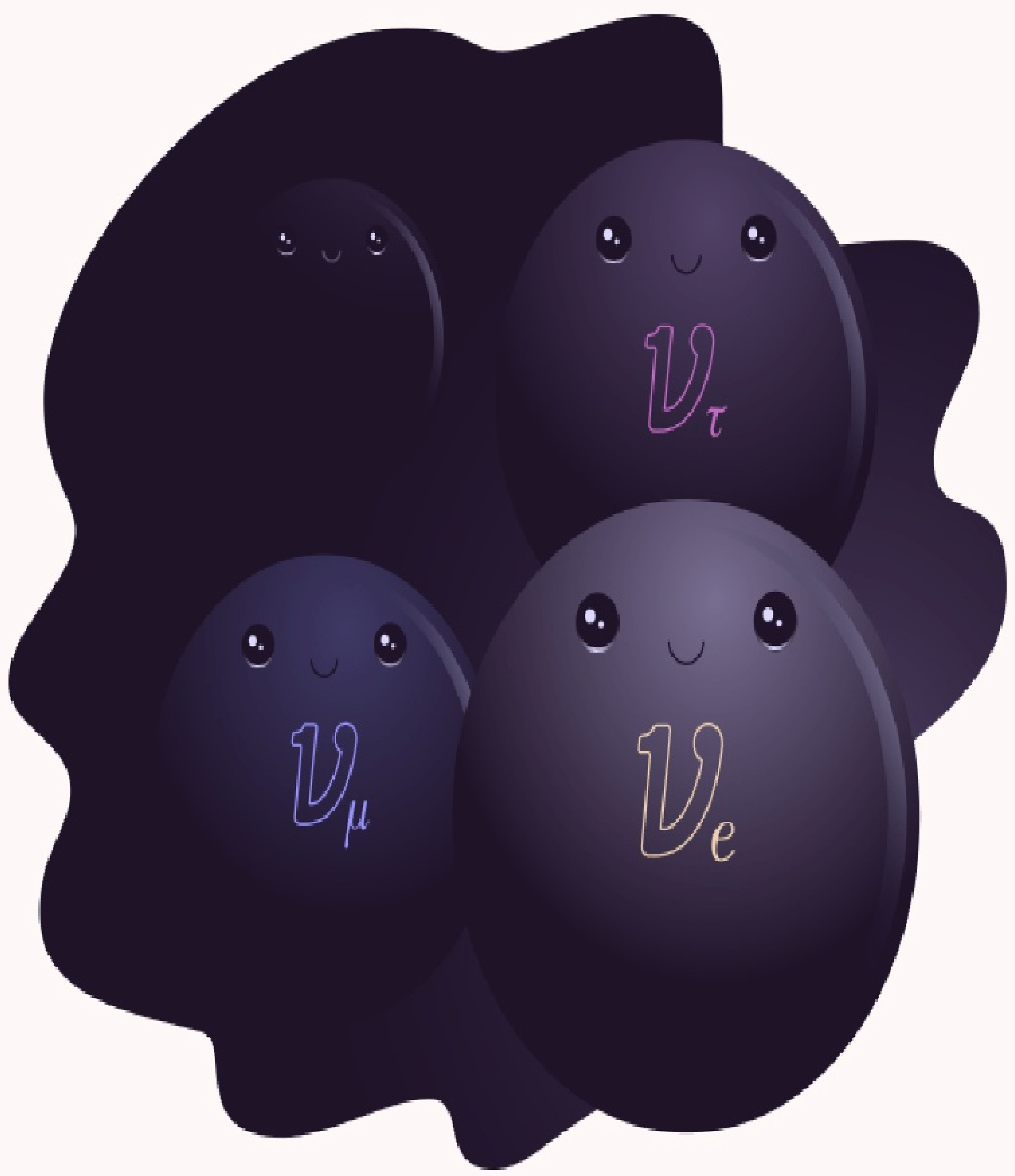
Solar,Reactor | Atmos., Accel. | CP Violating Phase | Reactor, Accel | Majorana Phases

$where\ c_{ij} = \cos\theta_{ij},\ and\ s_{ij} = \sin\theta_{ij}$

Range defined for Δm_{12}, Δm_{23}

For two neutrino oscillation in a vacuum: (valid approximation in many cases)

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta \sin^2 (1.27 \frac{\Delta m^2 L}{E})$$

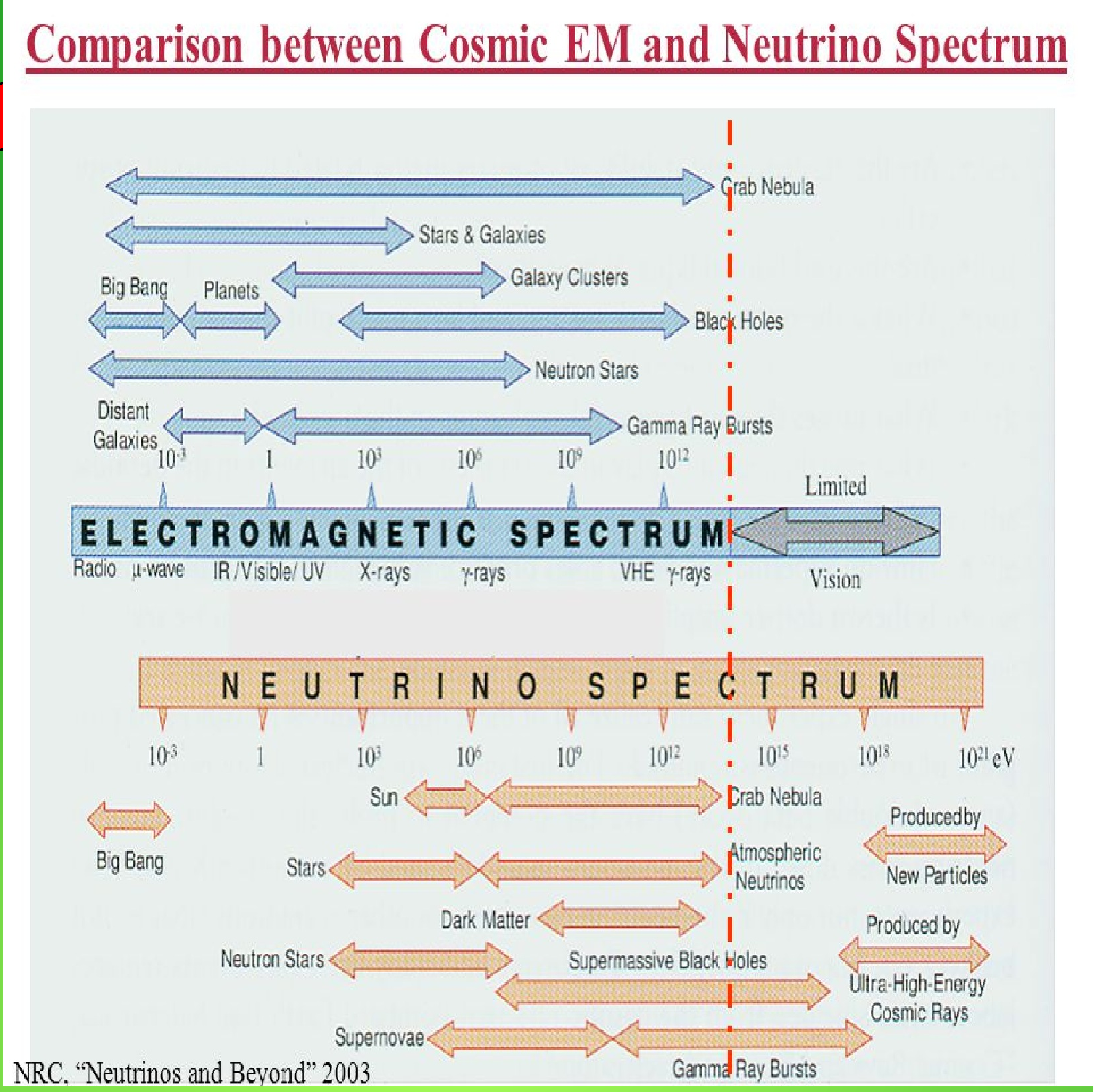


Big types of NEXTs:

- **Neutrino Oscillation Experiments (NOSEX). Subtypes: solar neutrinos, long-baseline neutrino experiments (accelerators, neutrino beams...Future muon colliders?), reactor neutrinos, atmospheric neutrinos,...**
- **NeutrinO Mass mEasurement experiments (NOMEs). Subtypes: tritium decay, cosmological weighting,...**
- **NeutrinOless Double bEta decay experiments (NODEs, $\beta\beta 0\nu$).**

And of course...

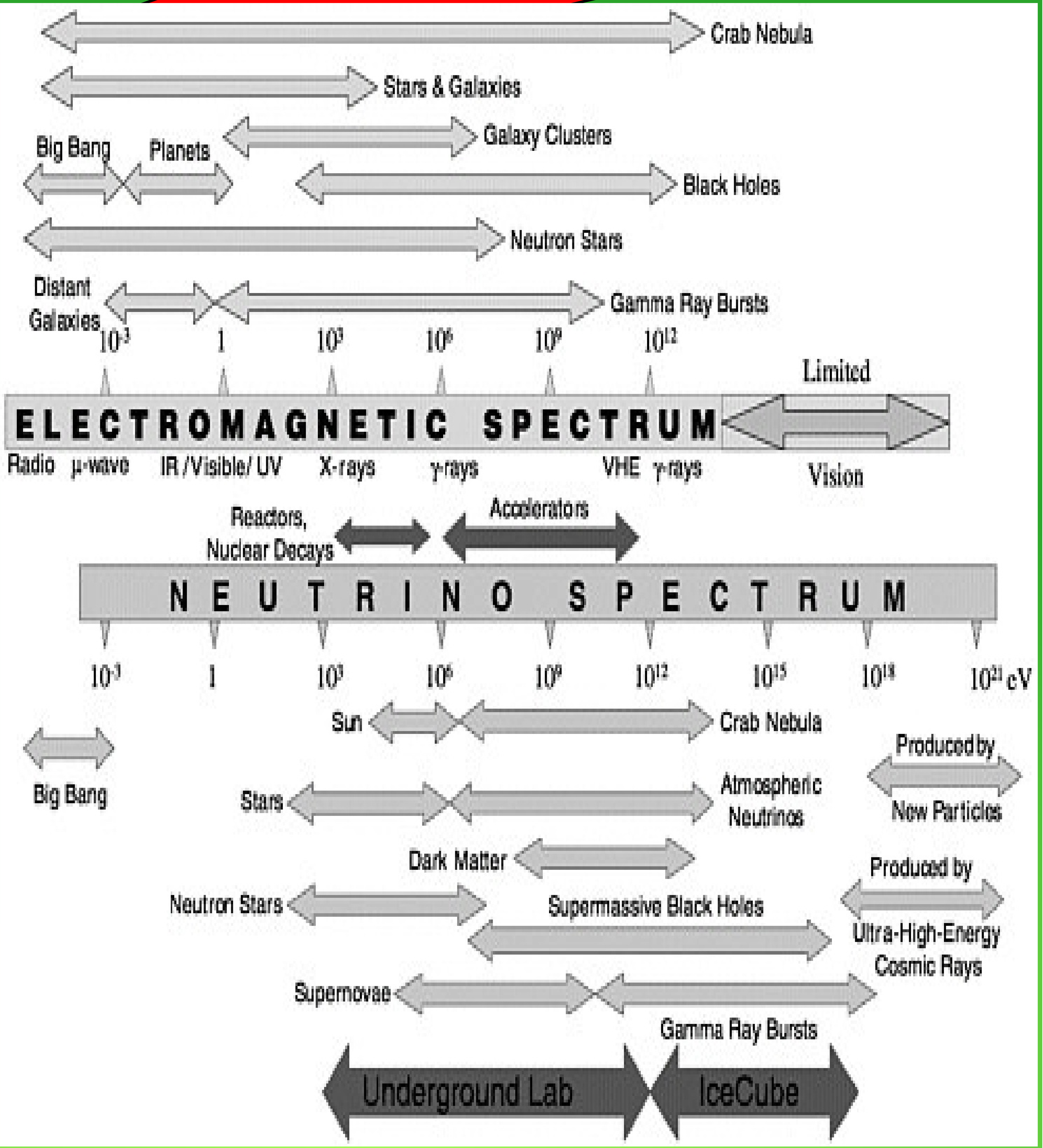
- **Neutrino observations from the sky, neutrino Astronomy/Astrophysics/ Cosmology!**



Direct Determination of Neutrino Mass

- Beta Decay
  - Tritium
  - ^{187}Re
  - Other ideas?
- Neutrino Oscillations
- Supernova timing
- Double beta decay
- Cosmology
- Z-bursts

- The mass is needed for
  - Particle physics
  - Interpretation of supernova ν signal
  - Cosmology



Various and complementary ways to measure neutrino mass

Cosmology

$$\Sigma = m_1 + m_2 + m_3$$

Oscillation

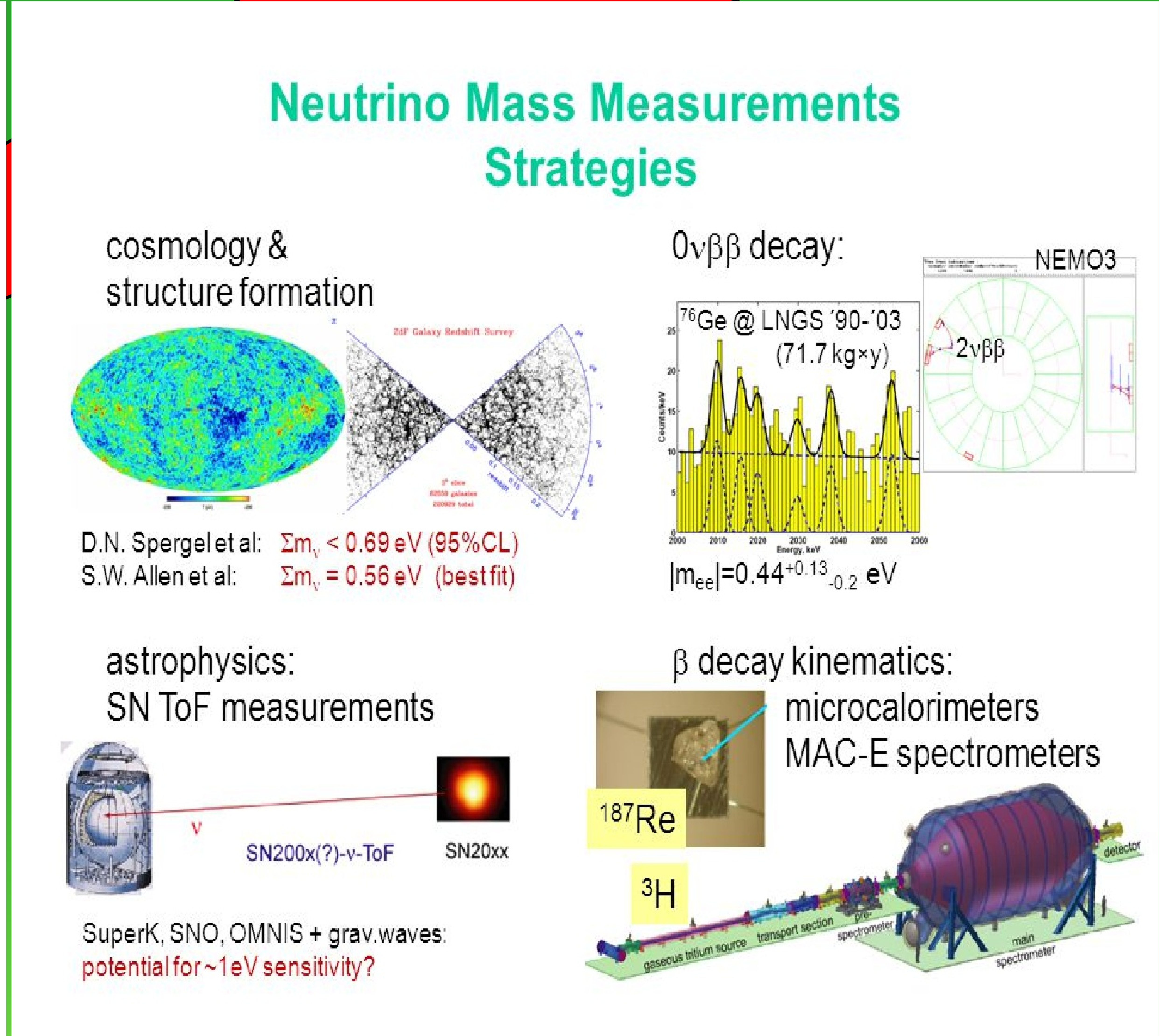
$$\delta m_{ij}^2 = m_i^2 - m_j^2$$

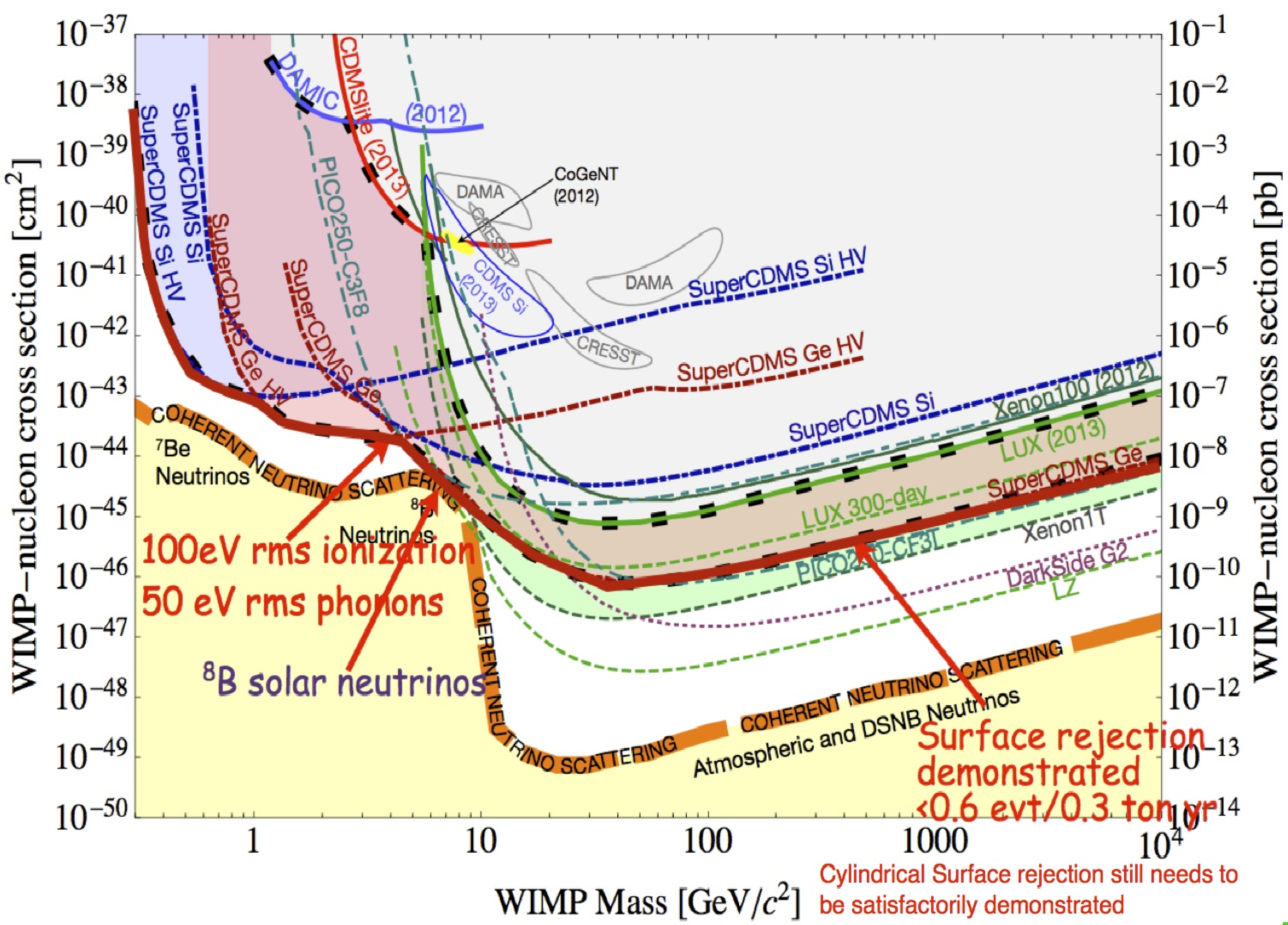
Beta decay

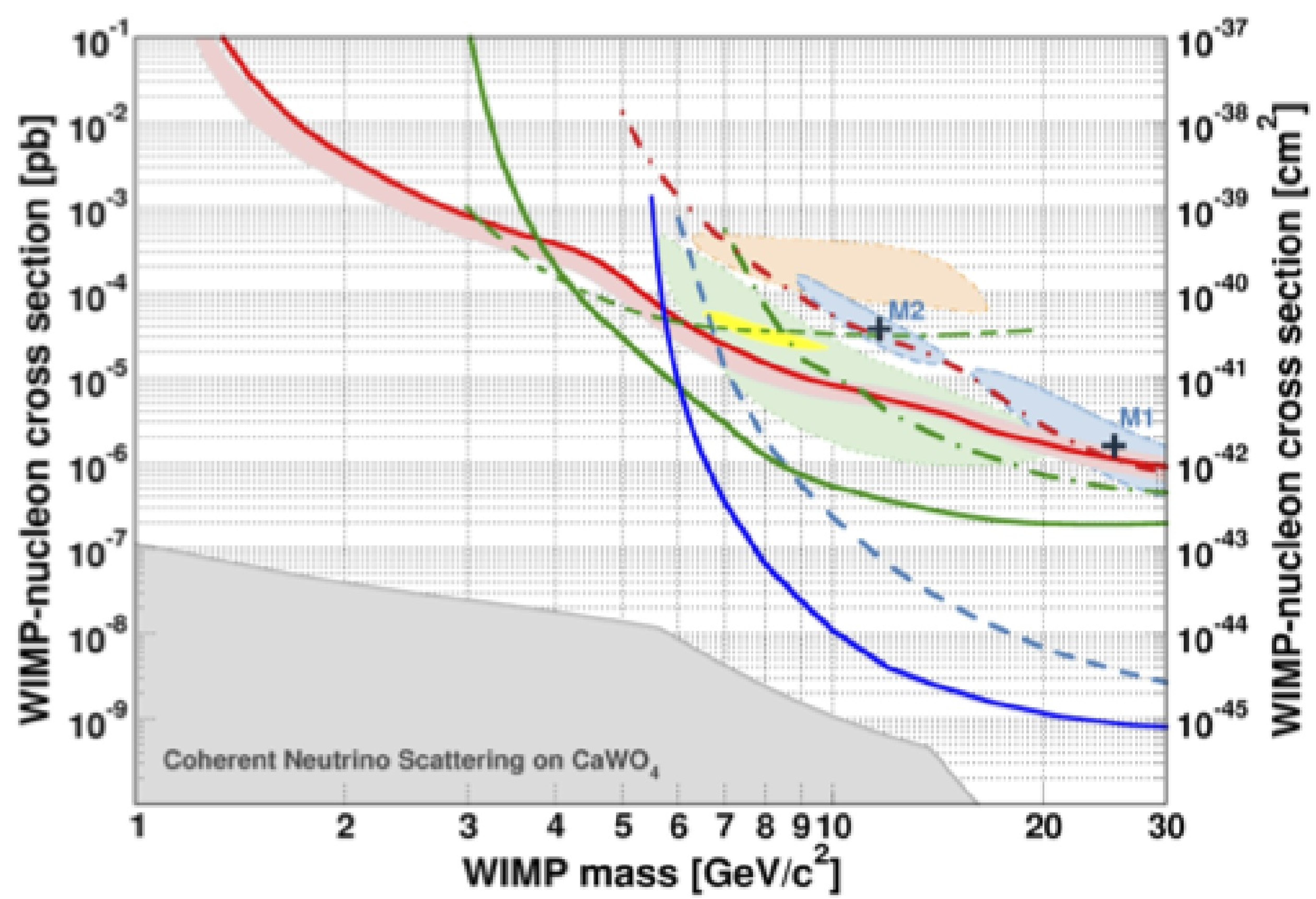
$$\langle m_\beta \rangle = \sqrt{\sum_{i=1}^{3} |U_{ei}|^2 m_i^2}$$

$2\beta0\nu$

$$\langle m_{\beta\beta} \rangle = \left| \sum_{i=1}^{3} U_{ei}^2 \cdot m_i \right|$$





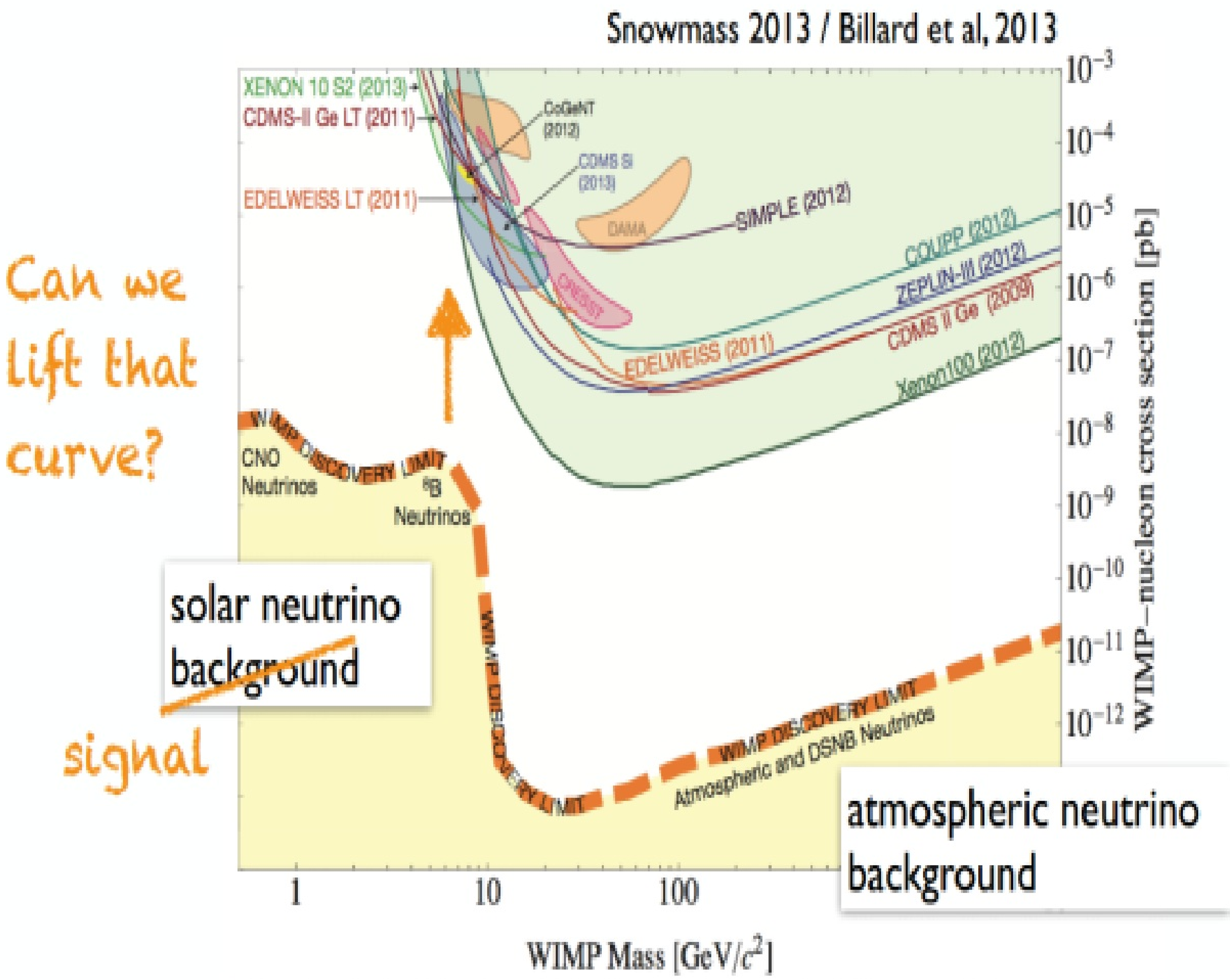


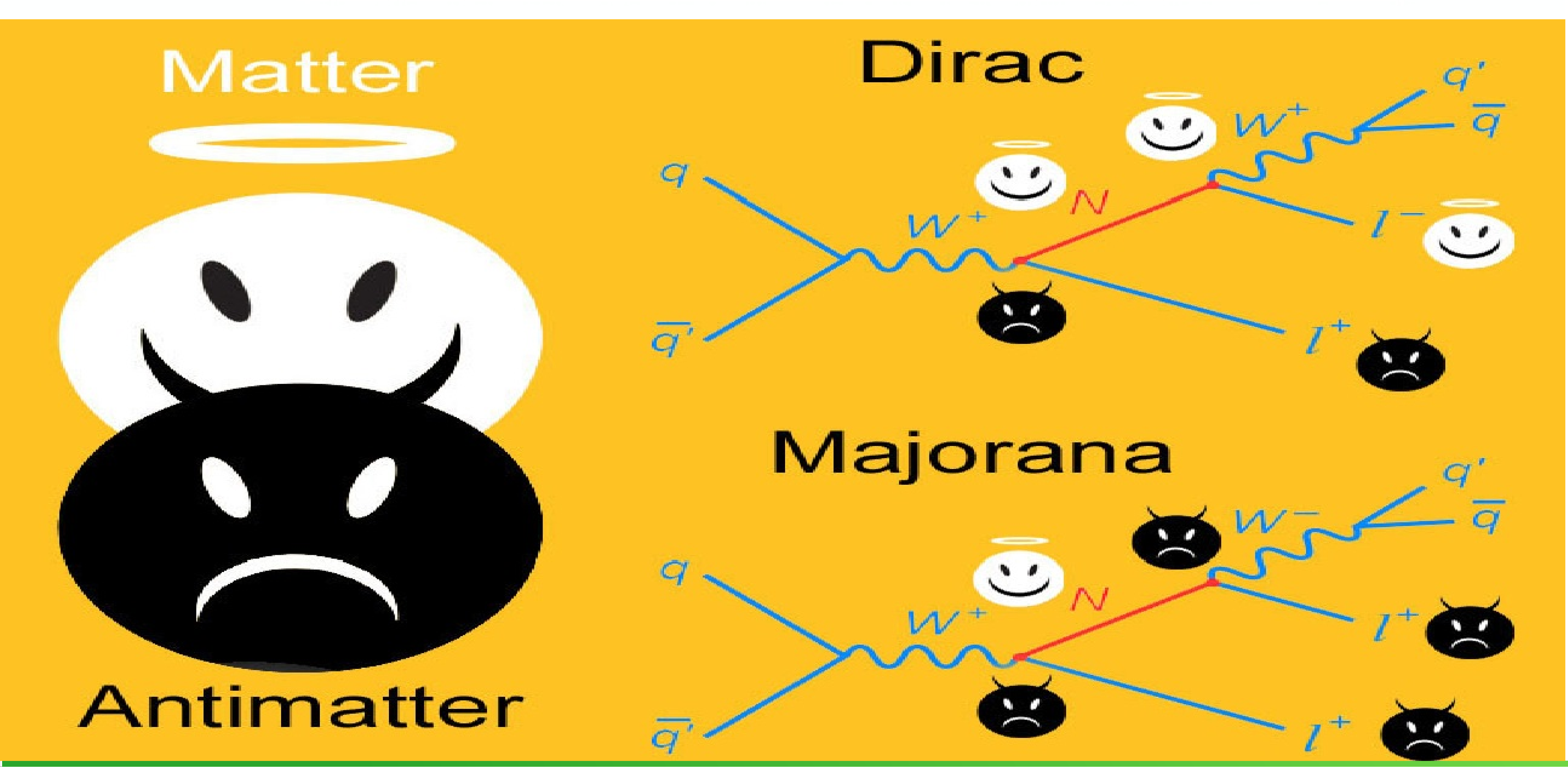
Particle physicists /astroparticle physicists measure **"interaction areas"**, something dubbed CROSS-SECTION. **Units:** 1 barn = 10^{-28} m^2=10^{-24} cm^2=100 fm^2.

Coherent neutrino-nuclei scatterings mediated by neutral current (Z-exchange) mimic DM interactions. In less of 10 years (maybe less), DM detectors will be able to detect solar neutrinos!!!!!! If DM are not found before touching the neutrino "neutral coherent wall", DM detectors will become directional... Some ideas do exist...

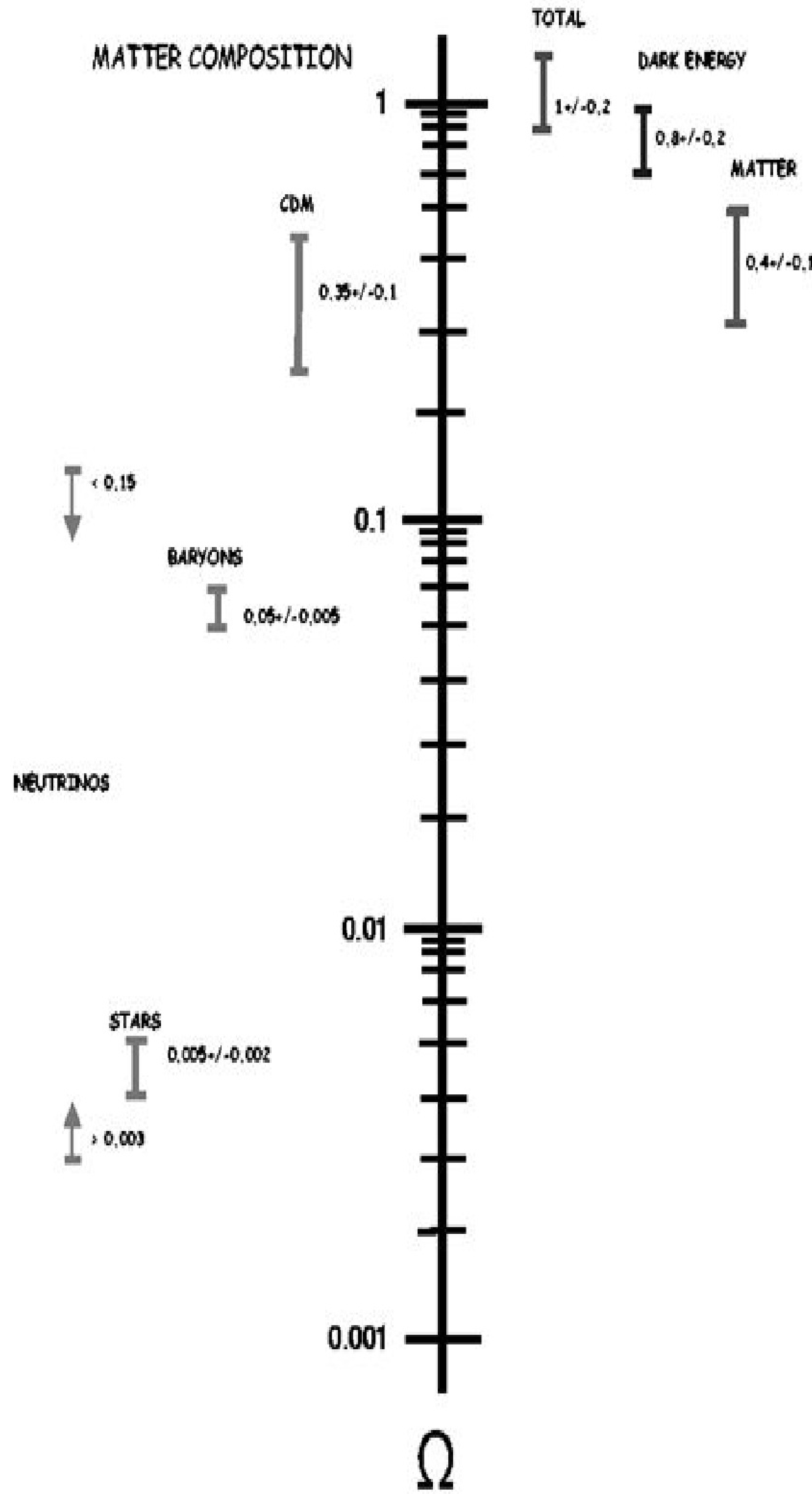
Remeber: SM neutrinos can NOT be the whole DM stuff...We need other/s particle/s...

Direct detection - big picture





Matter/Energy in the Universe



$\Omega_{total} = \Omega_M + \Omega_\Lambda \sim 1$

matter dark energy

Matter:

$\Omega_M = \Omega_b + \Omega_\nu + \Omega_{CDM} \sim 0.4$

baryons neutrinos cold dark matter

Baryonic matter :

$\Omega_b \sim 0.05$

stars, gas, brown dwarfs, white dwarfs

Neutrinos:

$\Omega_\nu \sim 0.003$

if M(ν) ~ 0.1 eV as from oscillations

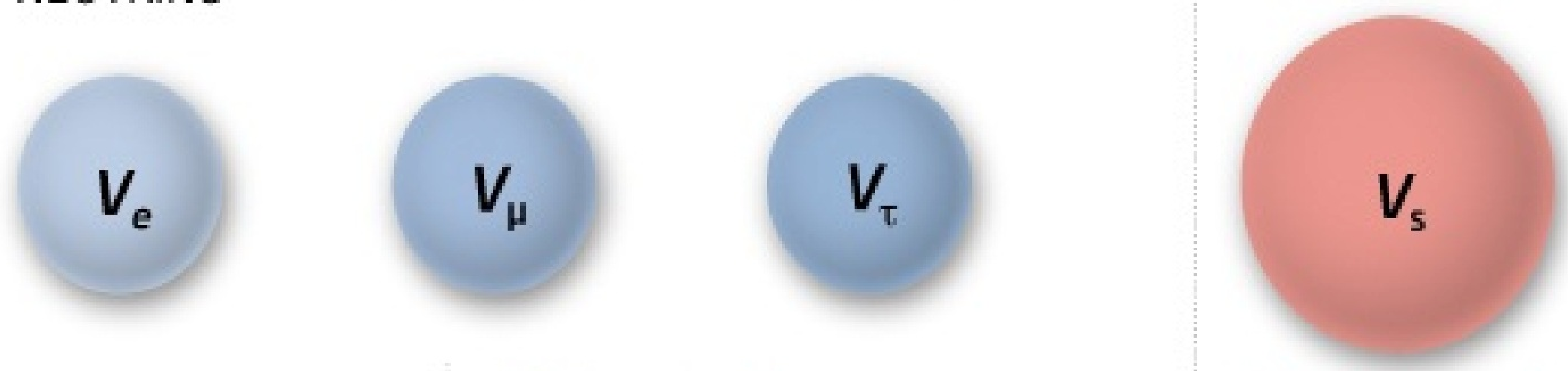
Cold Dark Matter :

$\Omega_{CDM} \sim 0.3$

WIMPS/neutralinos, axions

Desperately seeking sterile

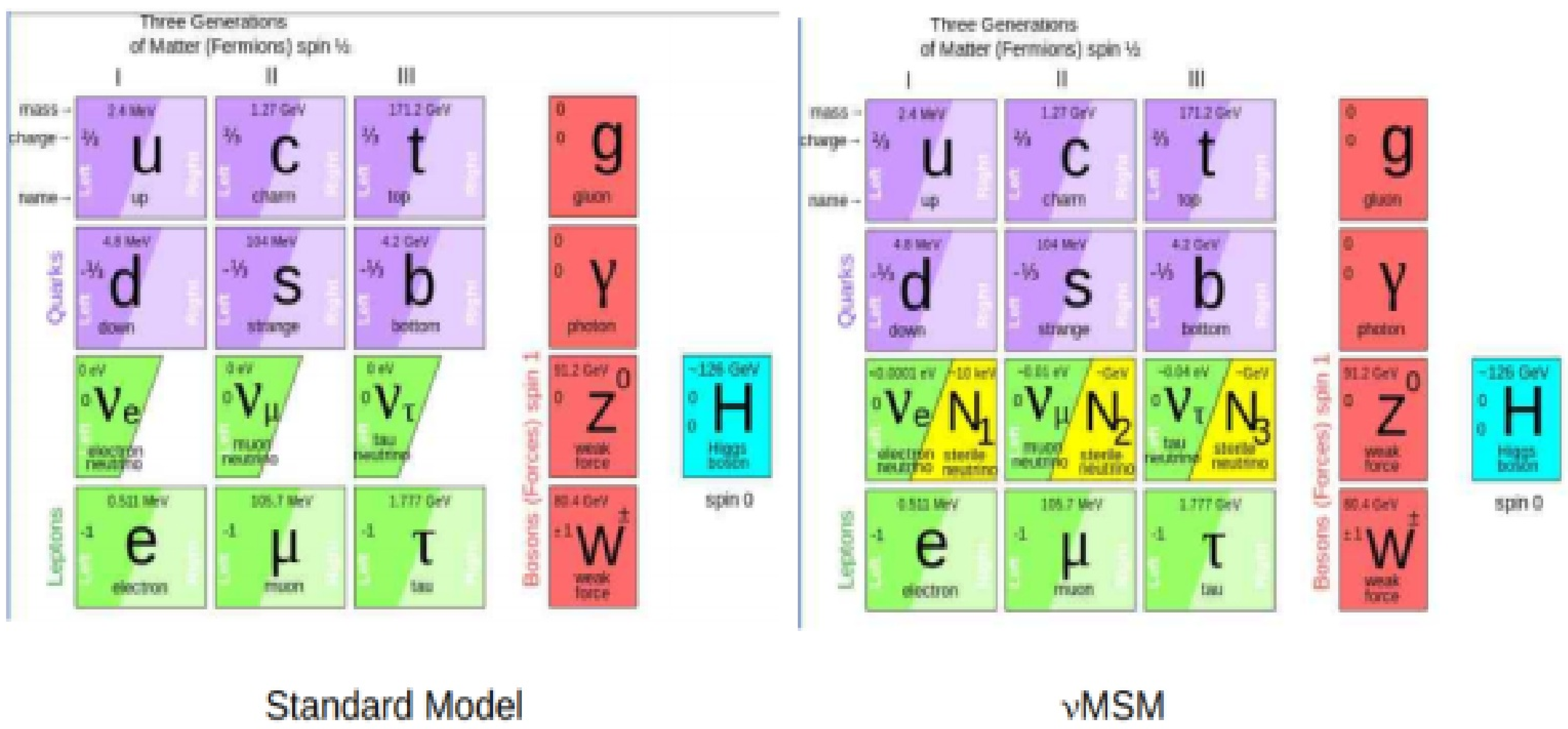
The three known types of neutrino might be "balanced out" by a bashful fourth type



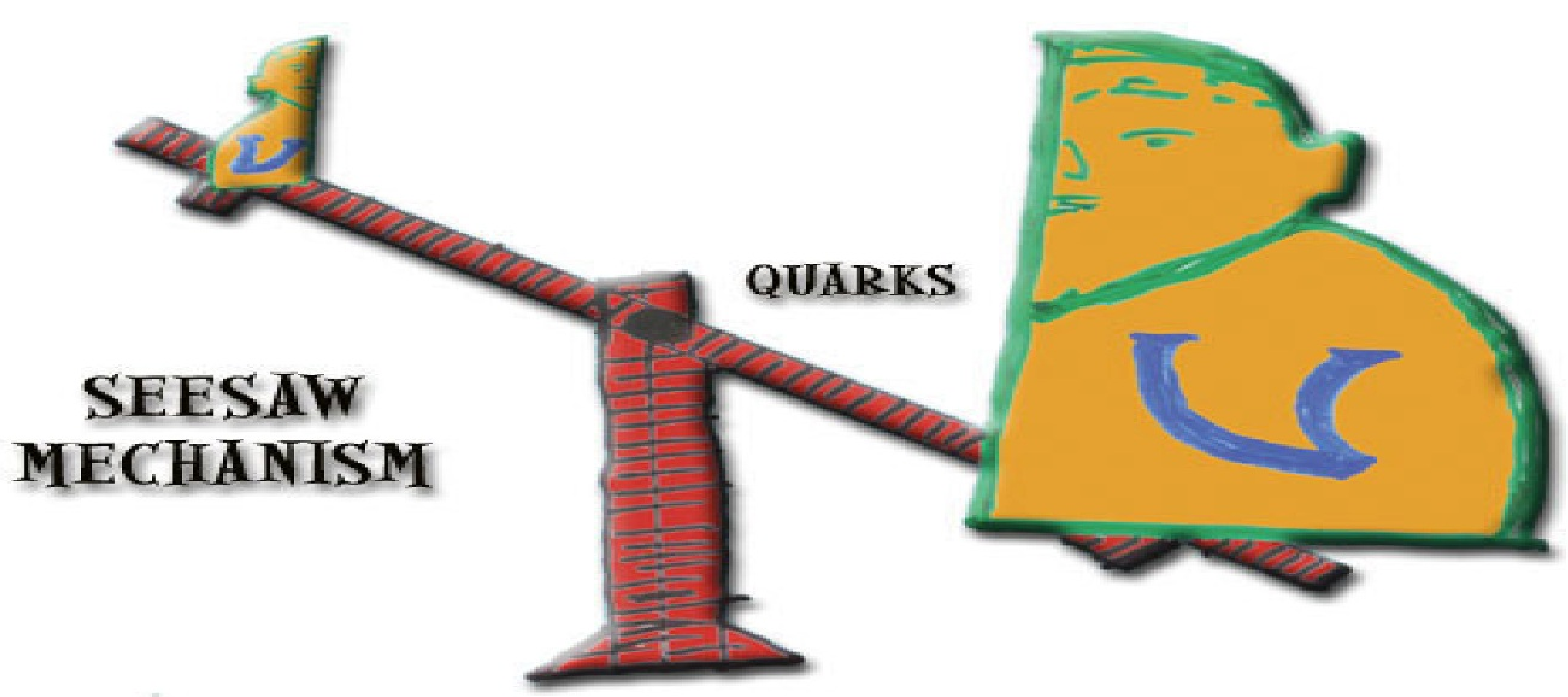
	Electron, muon, tau neutrino	Sterile neutrino
MASS	< 1 electronvolt	>1 electronvolt
FORCES THEY RESPOND TO	Weak force Gravity	Gravity
DIRECTION OF SPIN	All three "left handed"	"Right handed"

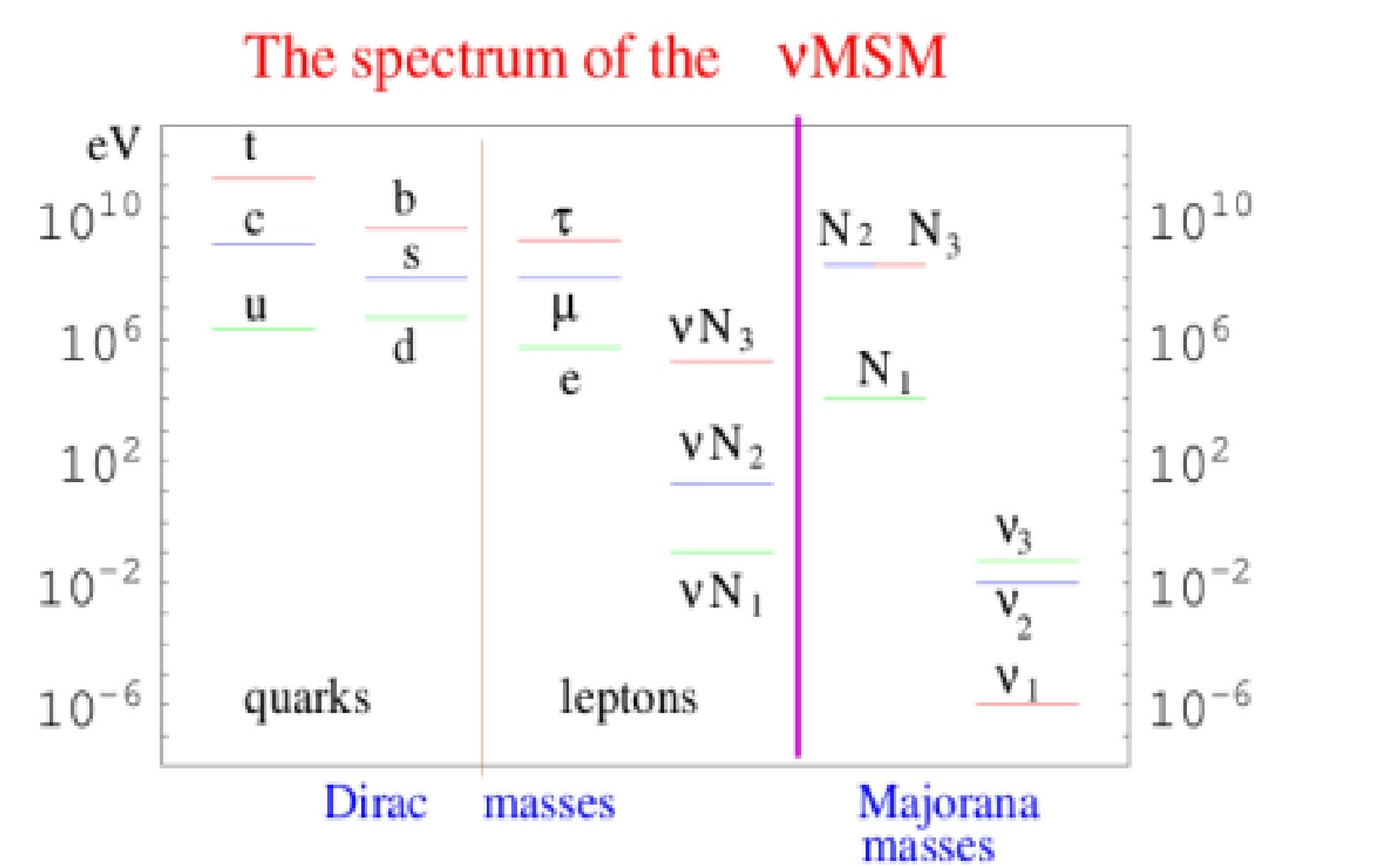
The νMSM

minimal renormalizable extension of the SM by right-handed neutrinos



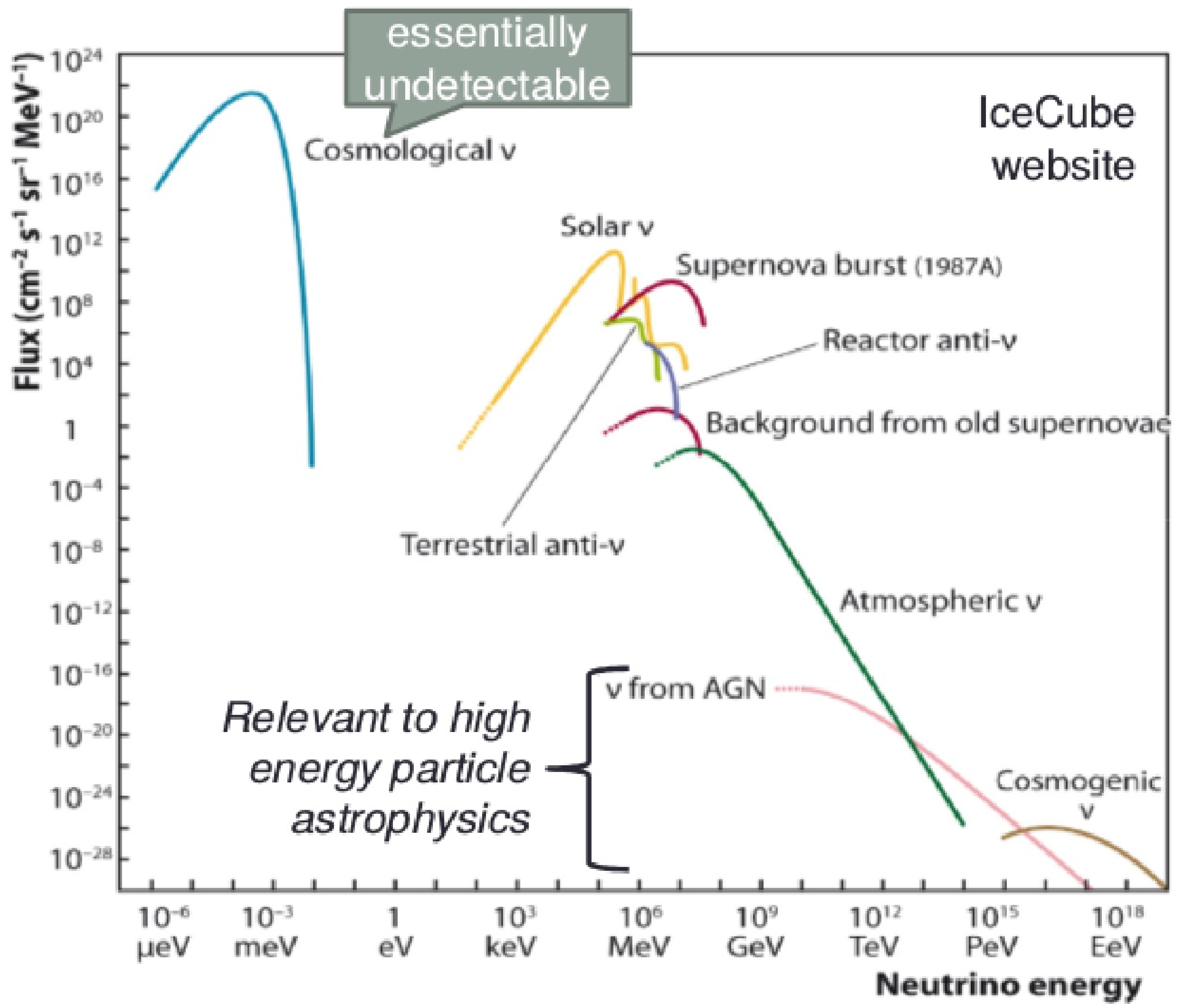
Neutrino mass via seesaw implies new energy scale (NO GUT, no Planck if right): M(nu)=m²/M(new)



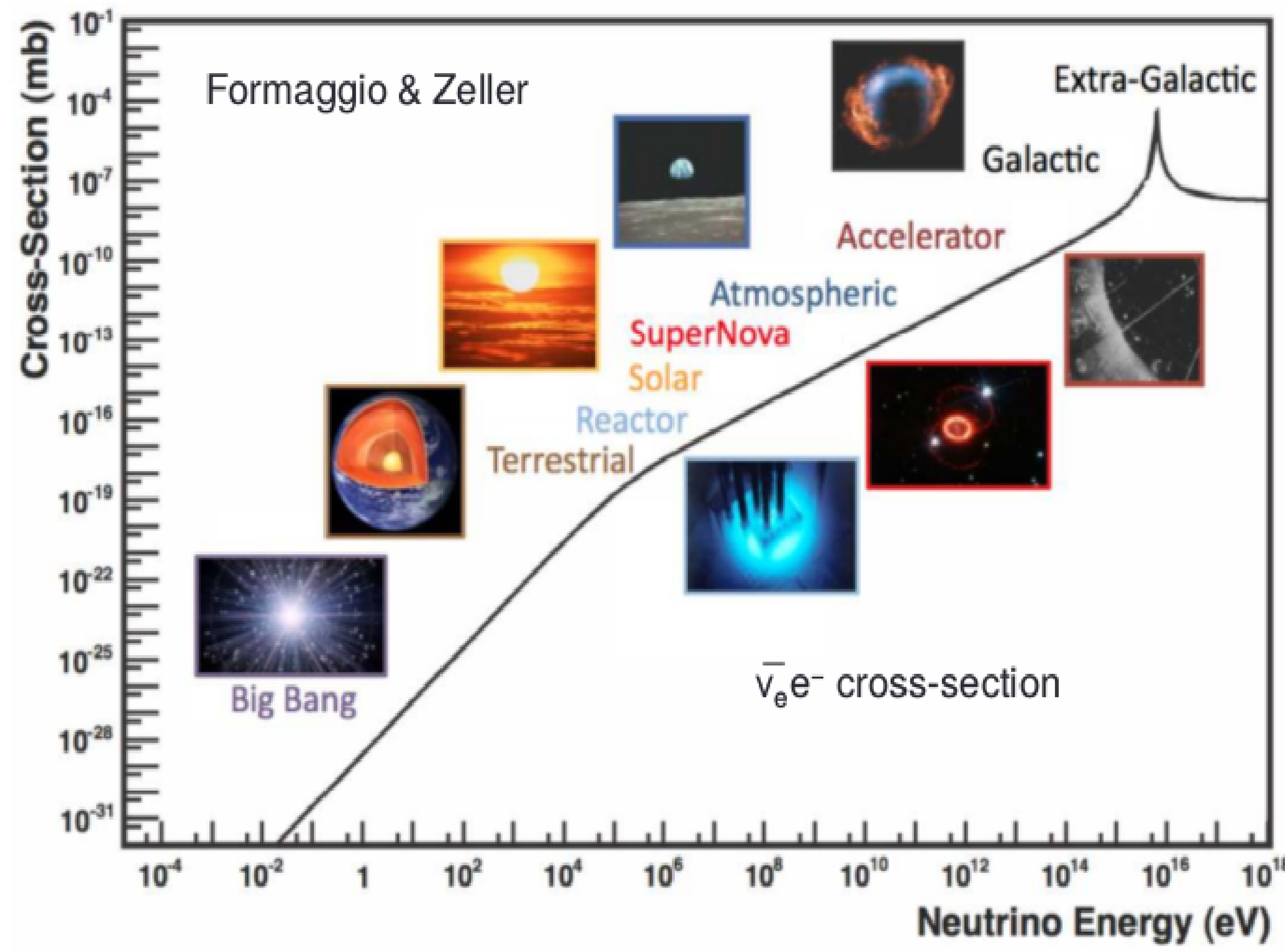


The expected mass spectrum of the νMSM. For quarks and charged leptons the experimental data is used.

Neutrino astrophysics



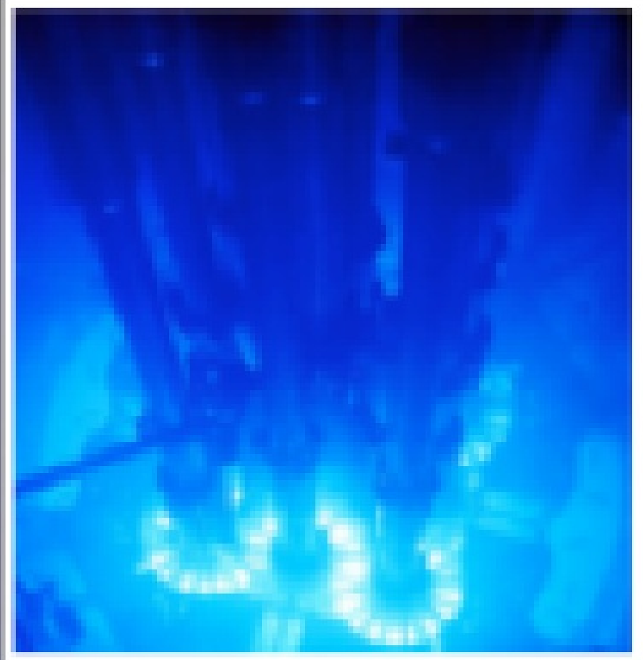
Neutrino astrophysics



Sources of astronomical neutrinos

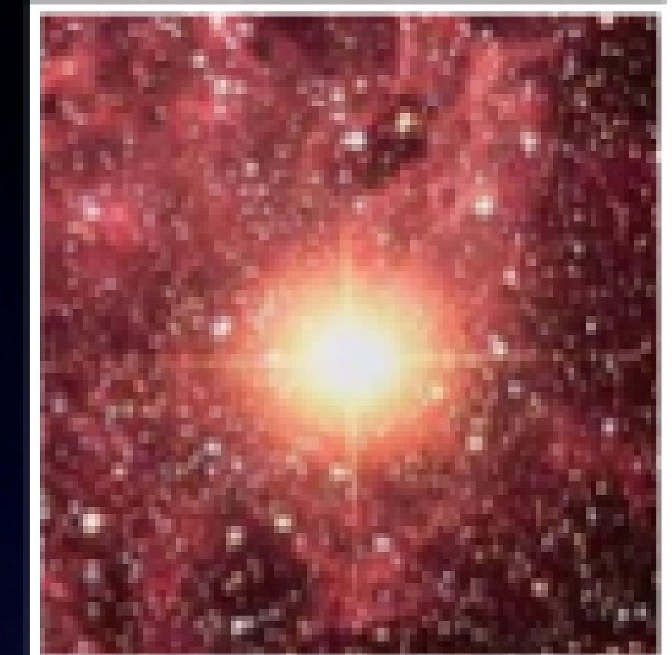
(goal: measure flavor composition, energy, intensity/fluxes, direction,....)

- Near Earth: the sun!!!! (Key in the discovery of NO). Also, geoneutrinos, atmospheric neutrinos triggered by Cosmic Rays (CR's), human based neutrinos (reactor, beams, human bodies,...)
- SN neutrinos. We are embedded in a full neutrino "sea"/"bath".
- Extremely High Energetic neutrinos (galactic, extragalactic origins,...from AGNs,binaries,...).
- Cosmological and cosmogenic neutrinos.



Neutrinos from reactors.

Detected (1950s)



Neutrinos from supernovae.

Detected (1980s)

Neutrinos from the sun.

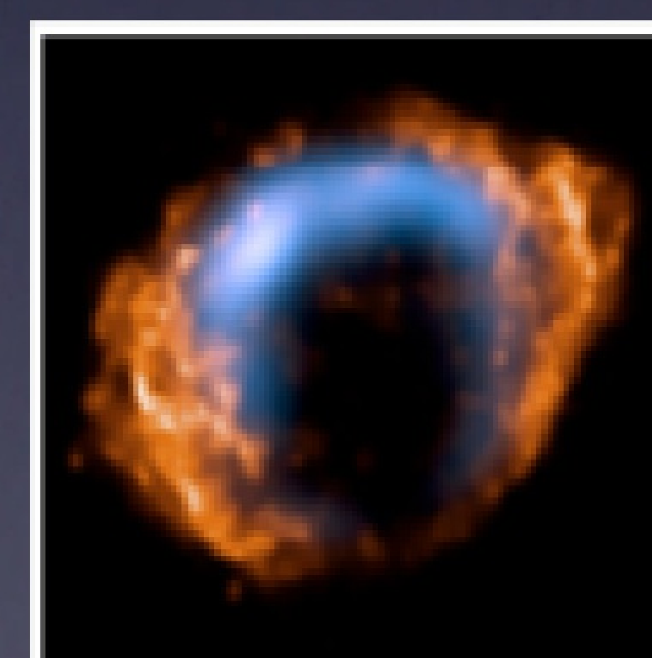
Detected (1960s)

Neutrinos from the Earth.

Detected (2000s)

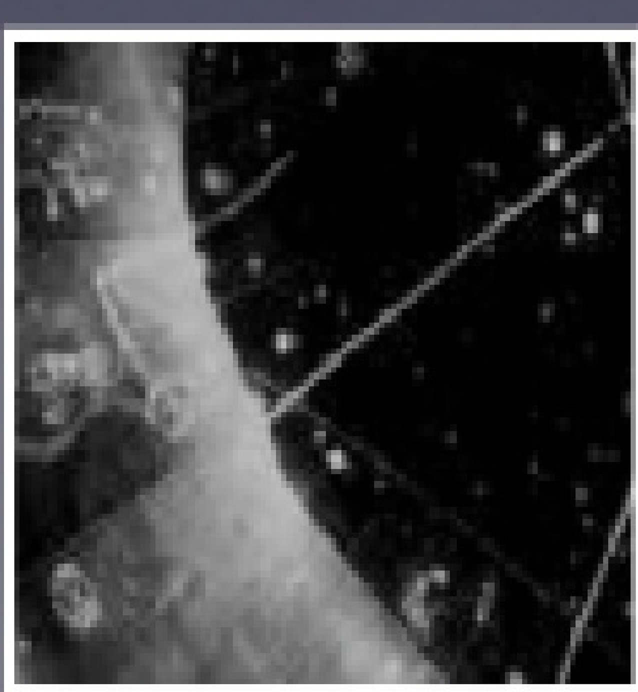
Neutrinos from the atmosphere.

Detected (1960s)



Neutrinos from galactic sources.

Not yet (but close!)



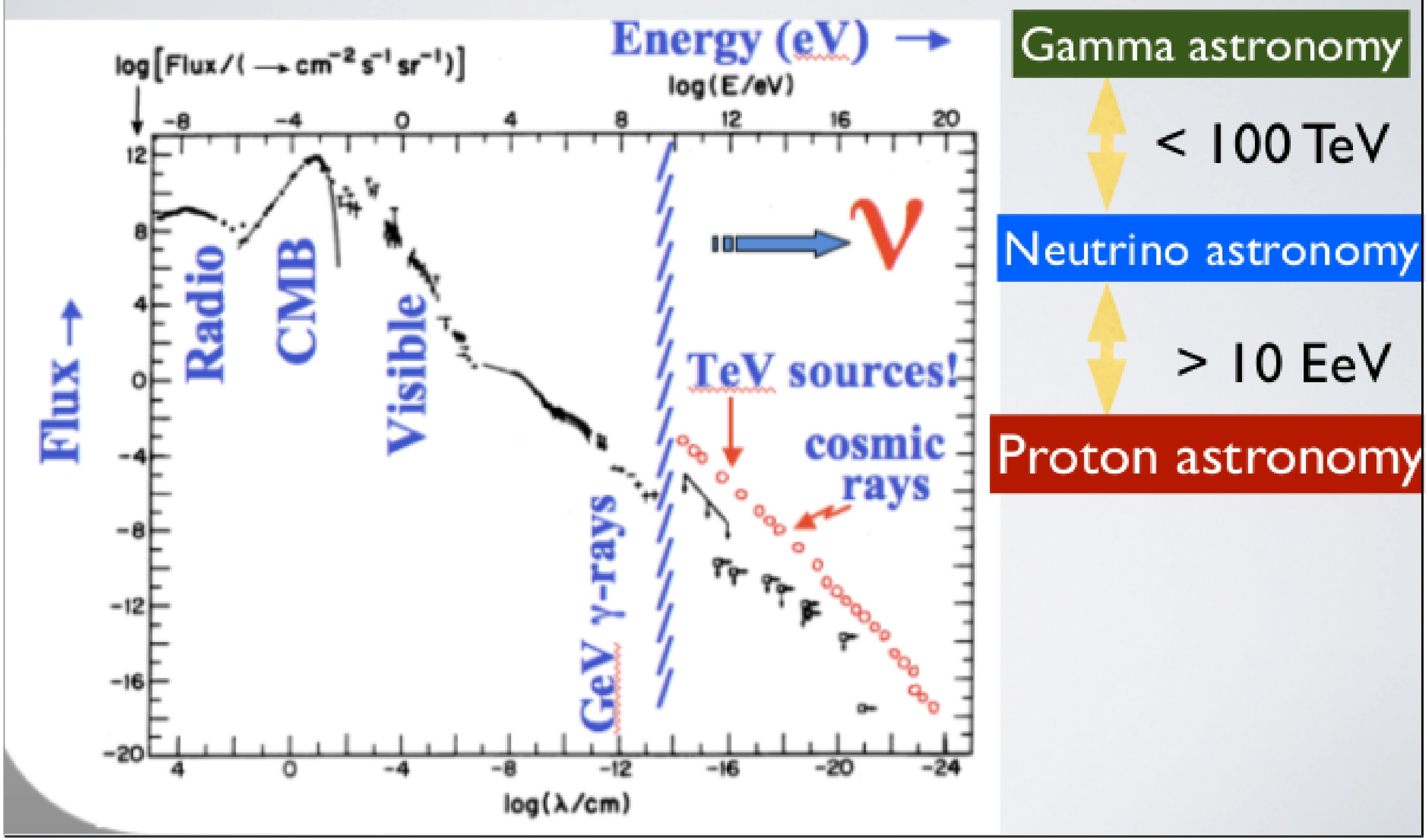
Neutrinos from accelerators.

Created & detected (1960s)

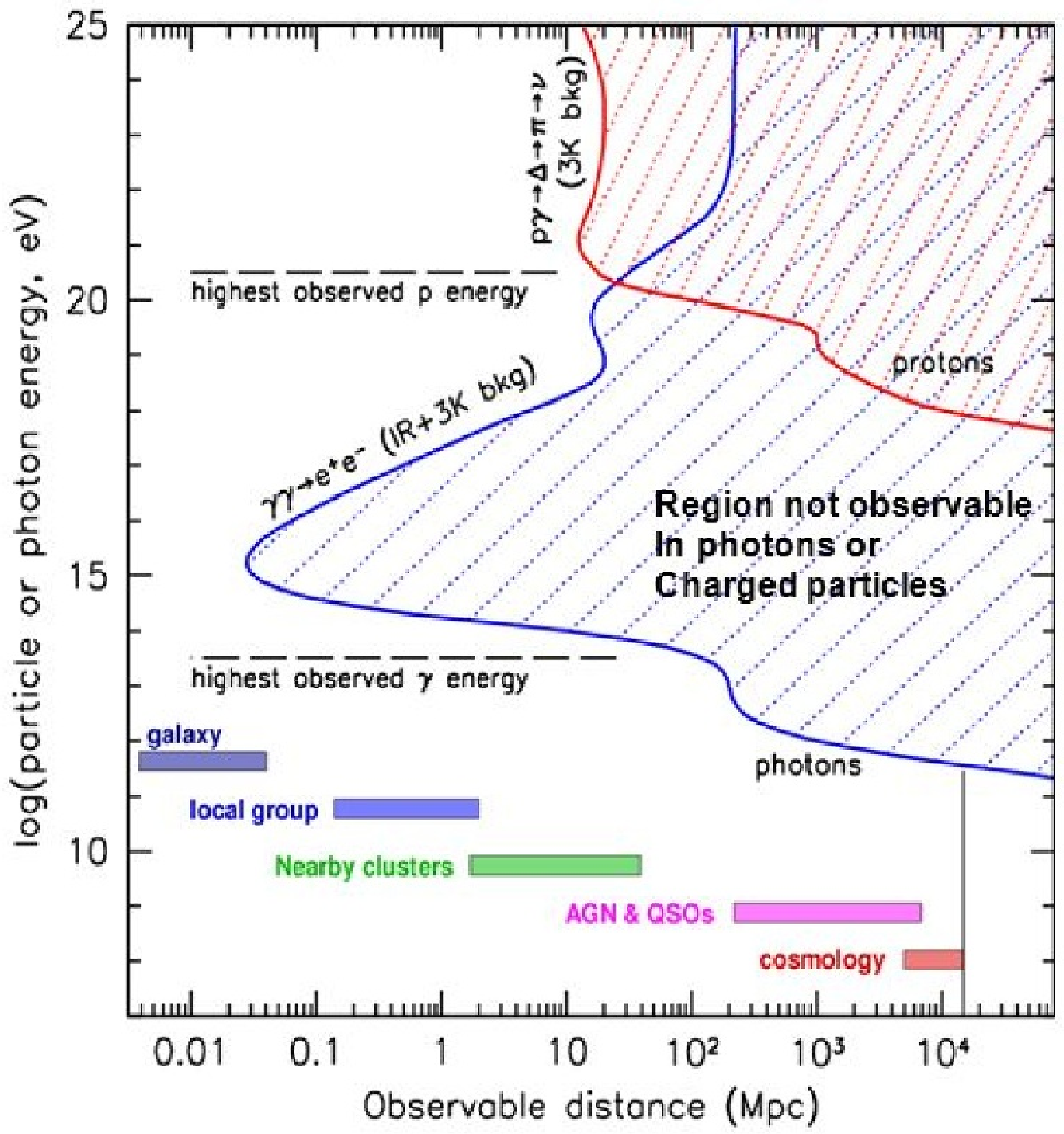
Neutrinos from the Big Bang.

Not even close...

UNDERSTANDING ACCELERATION PROCESSES IN THE UNIVERSE



Neutrinos: The only useful messengers for astrophysics at >PeV energies

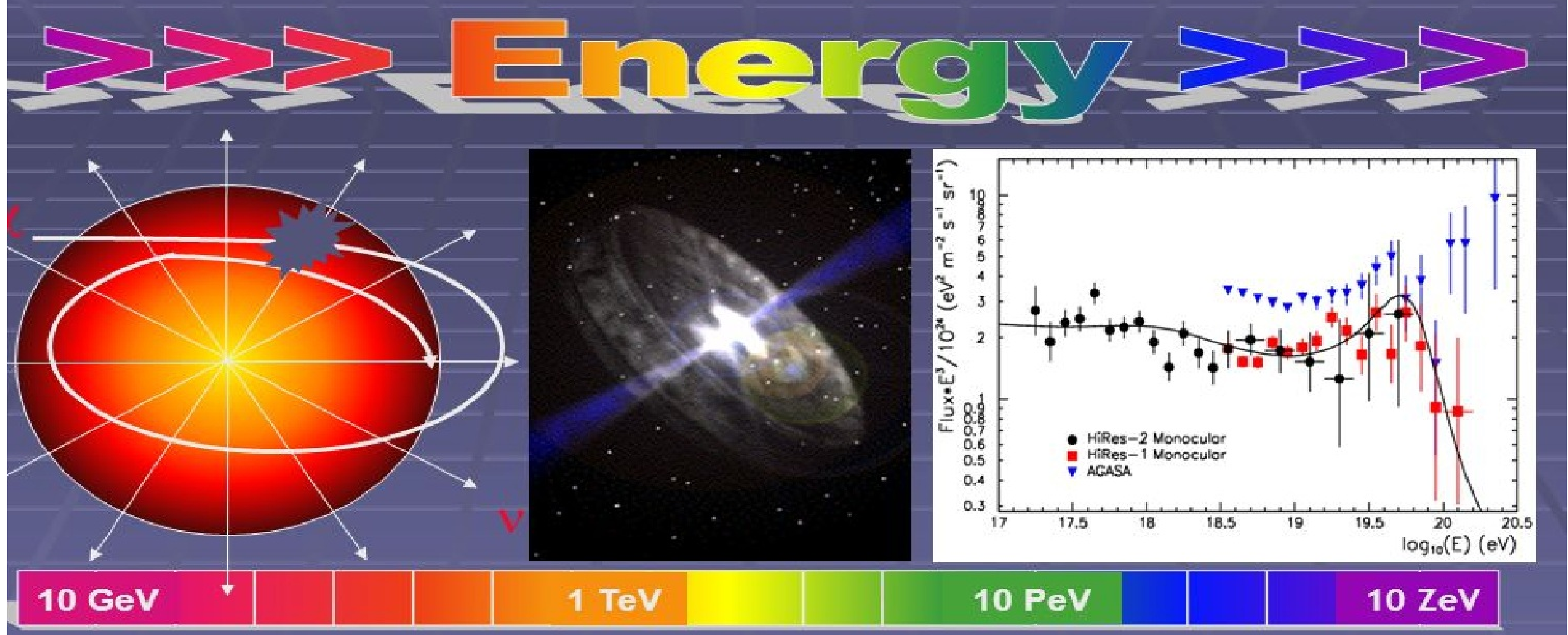


- **Photons lost above 30 TeV:** pair production on IR & μwave background
- **Charged particles:** scattered by B-fields or GZK process at all energies
- But the sources extend to 10^9 TeV !

Conclusion:

- **Study of the highest energy processes and particles throughout the universe *requires* PeV-ZeV neutrino detectors**

Scientific Programme

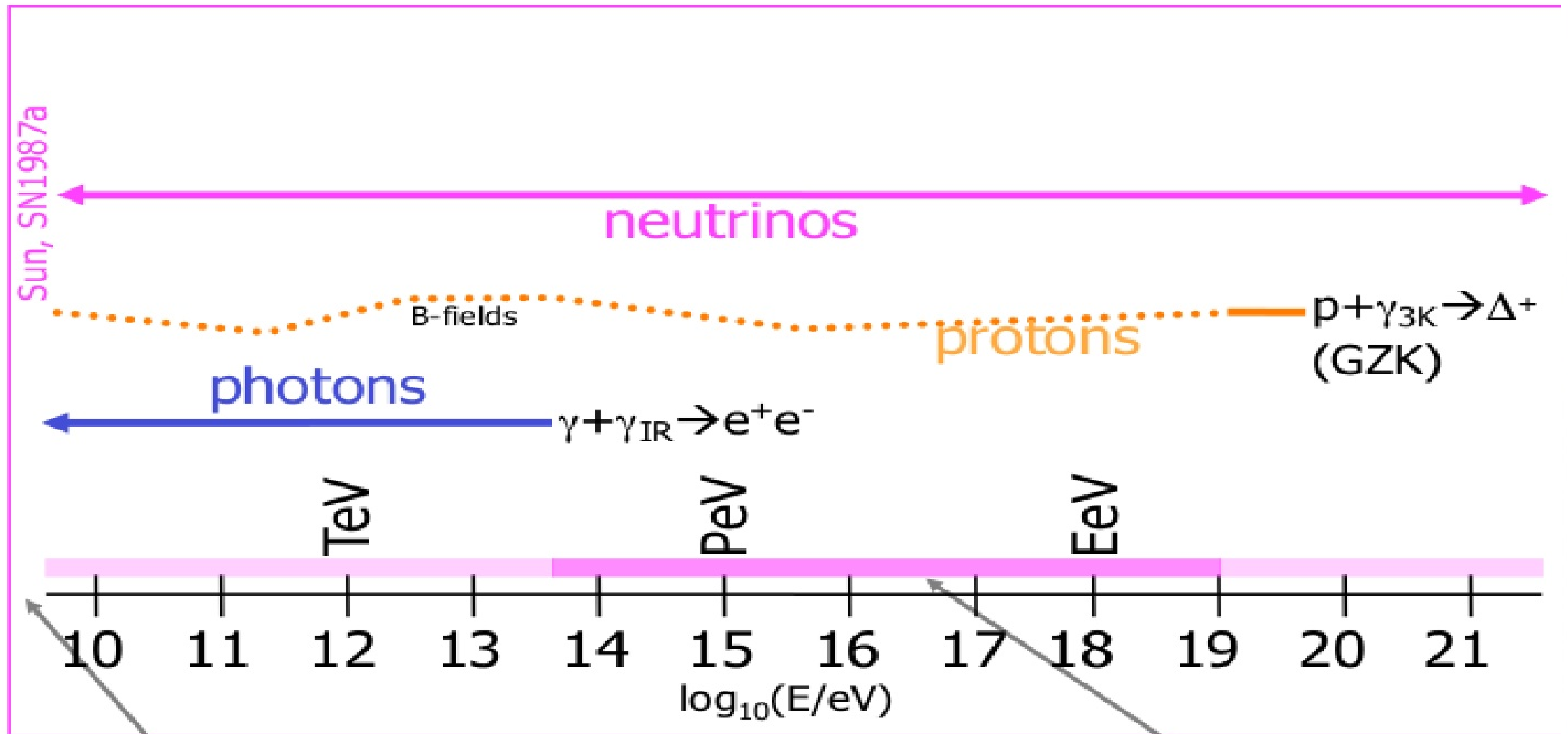


Search for neutralinos via their self-annihilation to products containing neutrinos at the centre of the Earth, Sun and Galaxy

Observation of high-energy neutrinos from (extra-)galactic astrophysical sources such as AGN, SNR, GRB, etc.

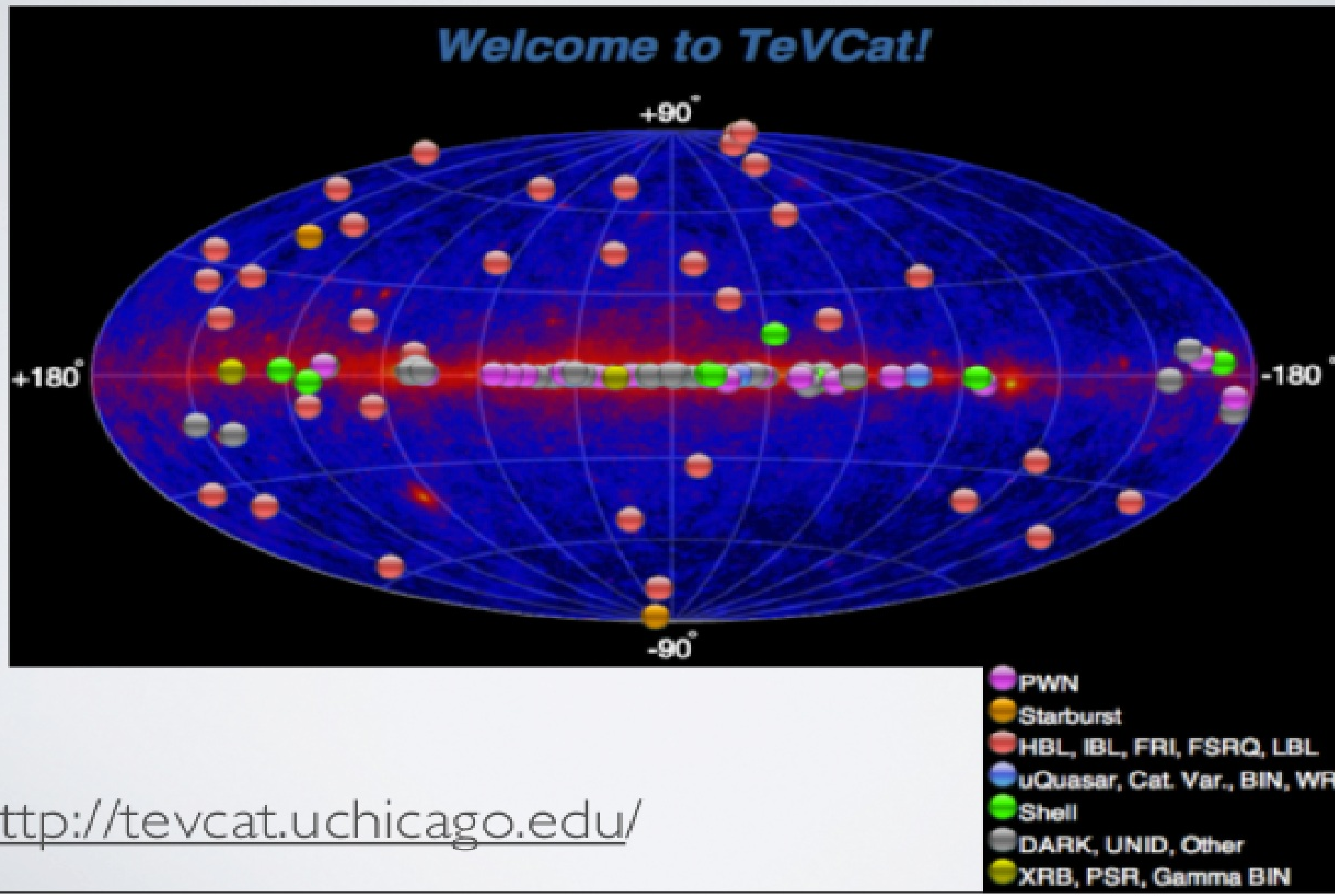
Search for UHE neutrinos from cosmogenic and other possible sources

Astronomical Messengers



CURRENT TEV SKY

More than 100 sources



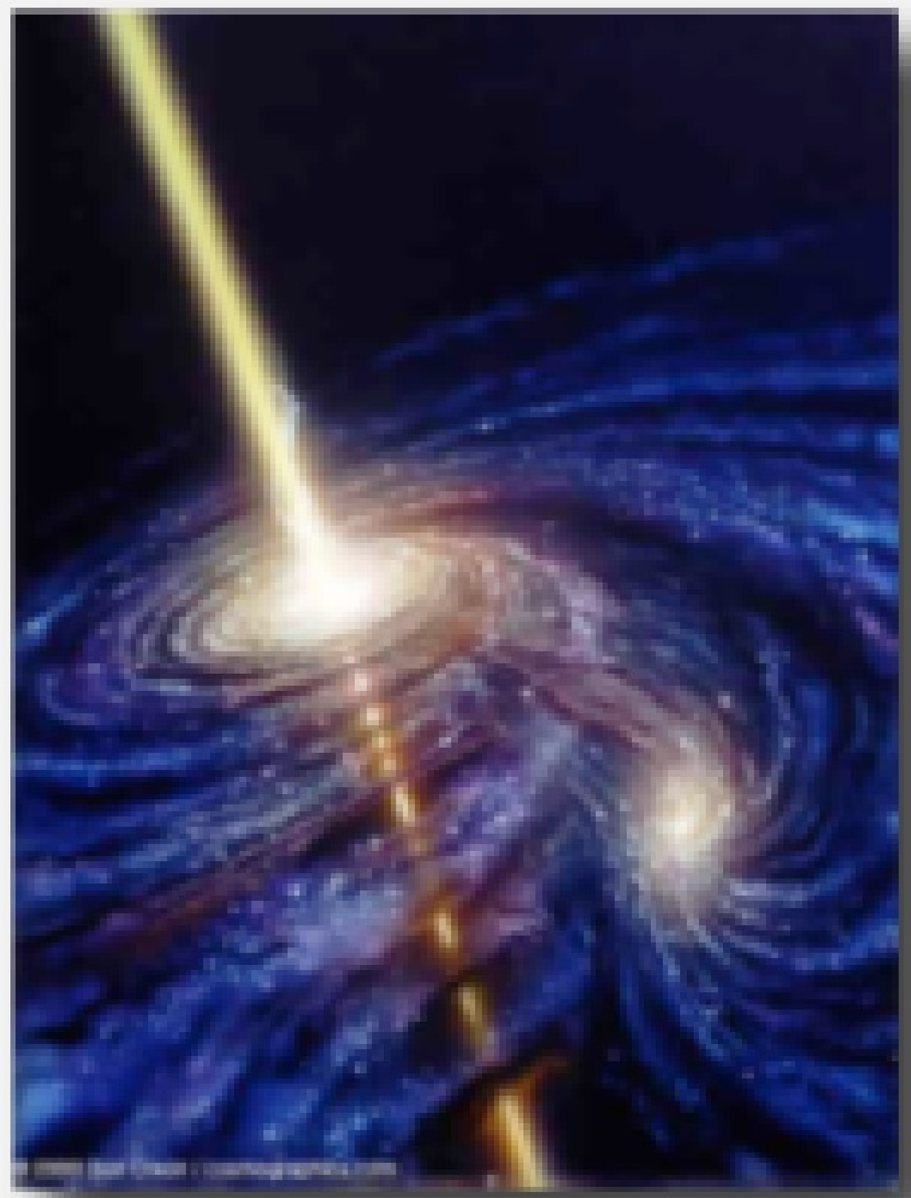
http://tevcat.uchicago.edu/

Neutrinos from the sky: potential astrophysical sources

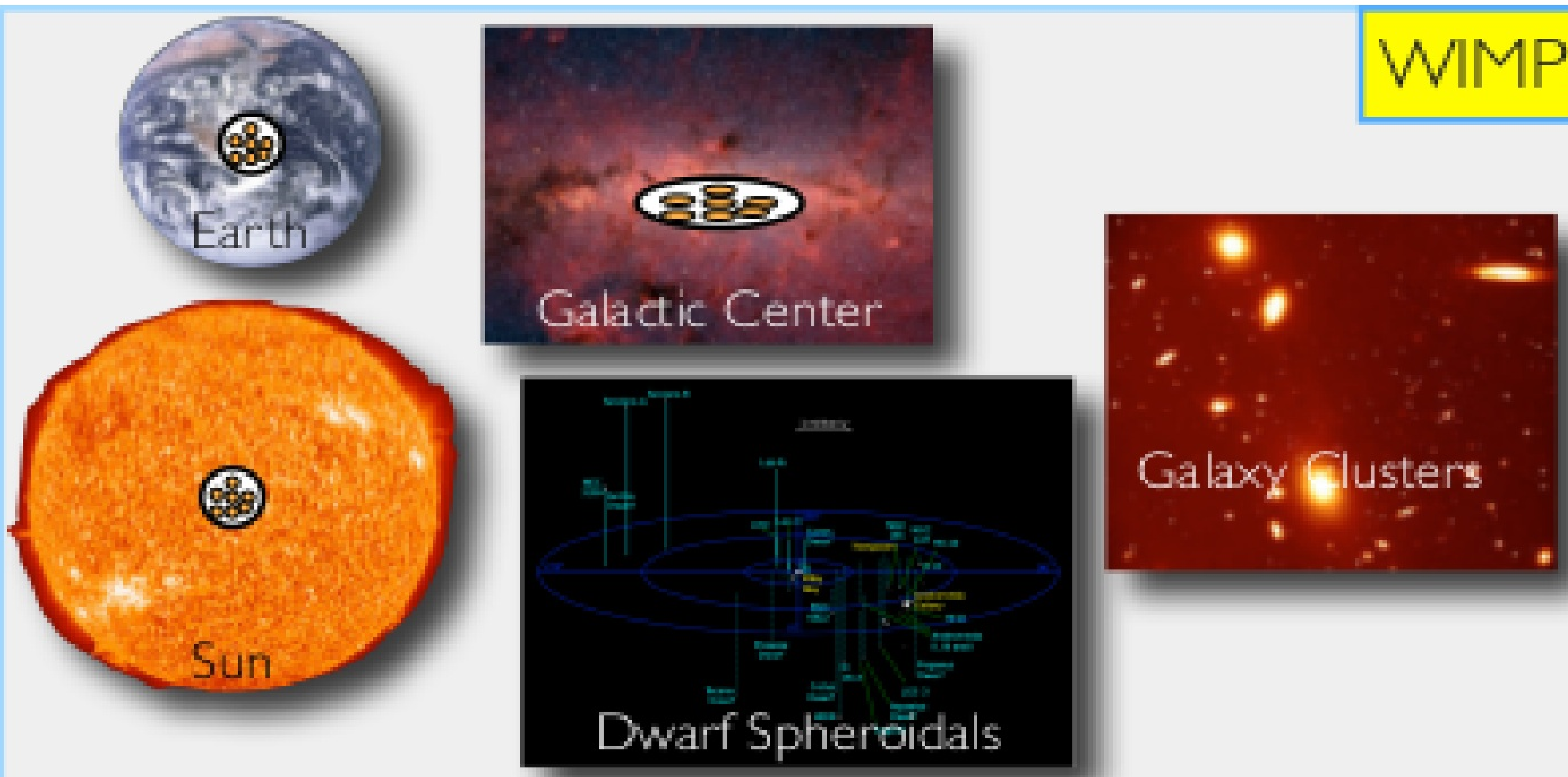
$p + (p,\gamma) \rightarrow \pi^{\pm} \rightarrow \nu$

Gamma-ray Bursts

Active Galactic Nuclei

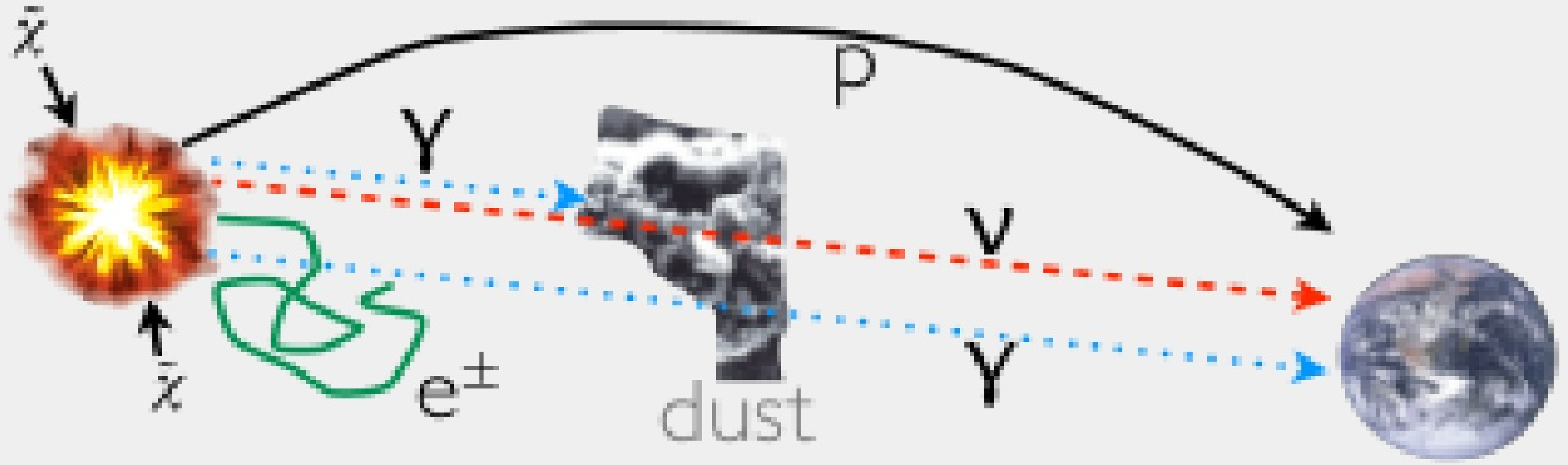


WIMPs

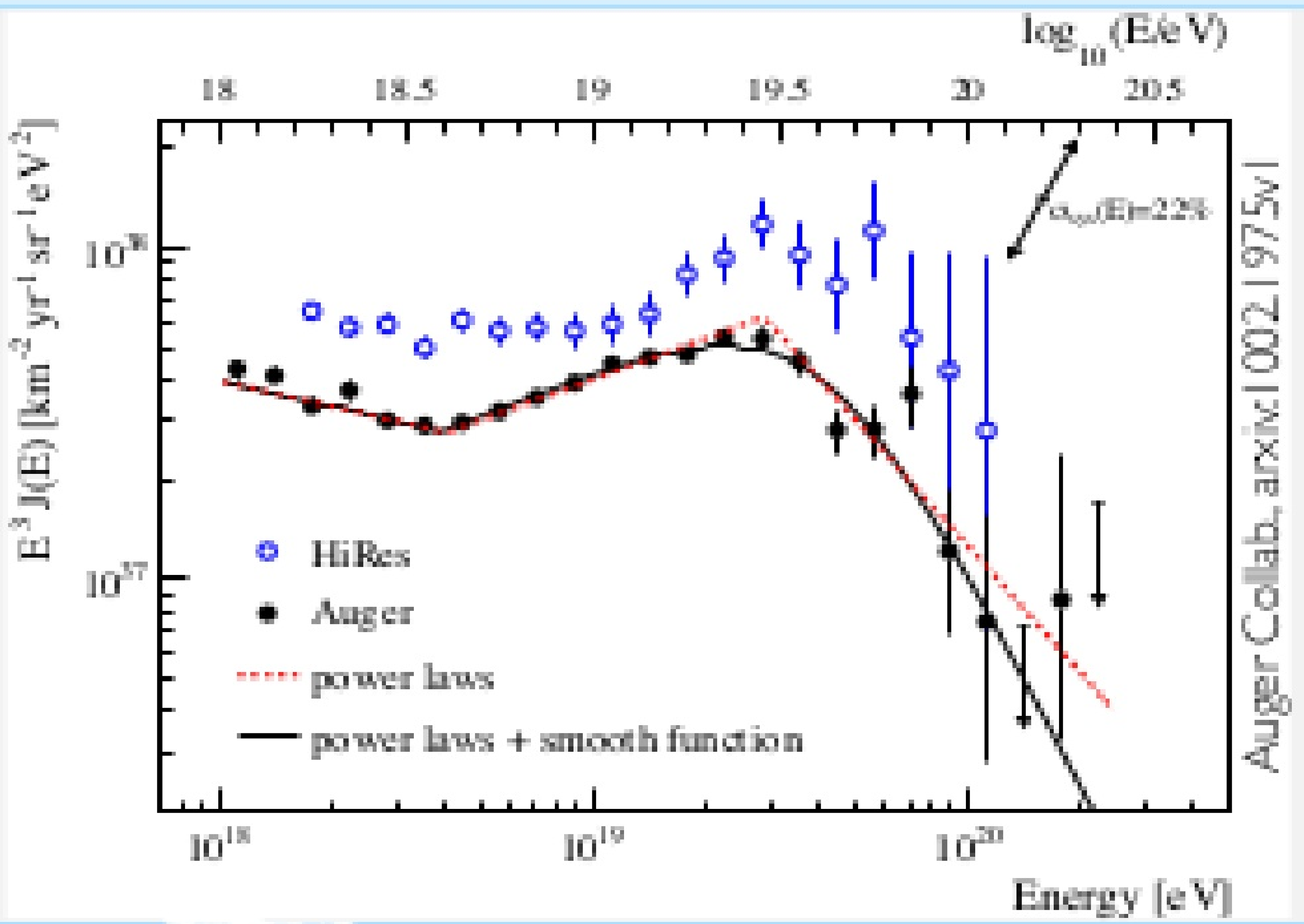


$\tilde{\chi}\,\tilde{\chi} \rightarrow W^+, Z, \tau^+, b, \ldots \rightarrow e^{\pm}, \nu, \gamma, p, D, \ldots$

$W^-, Z, \tau^-, b, \ldots \rightarrow e^{\pm}, \nu, \gamma, p, D, \ldots$



$p + \gamma_{3K} \rightarrow \Delta^+$ (GZK)



Neutrinos see a big Universe...

OBSERVABLE UNIVERSE

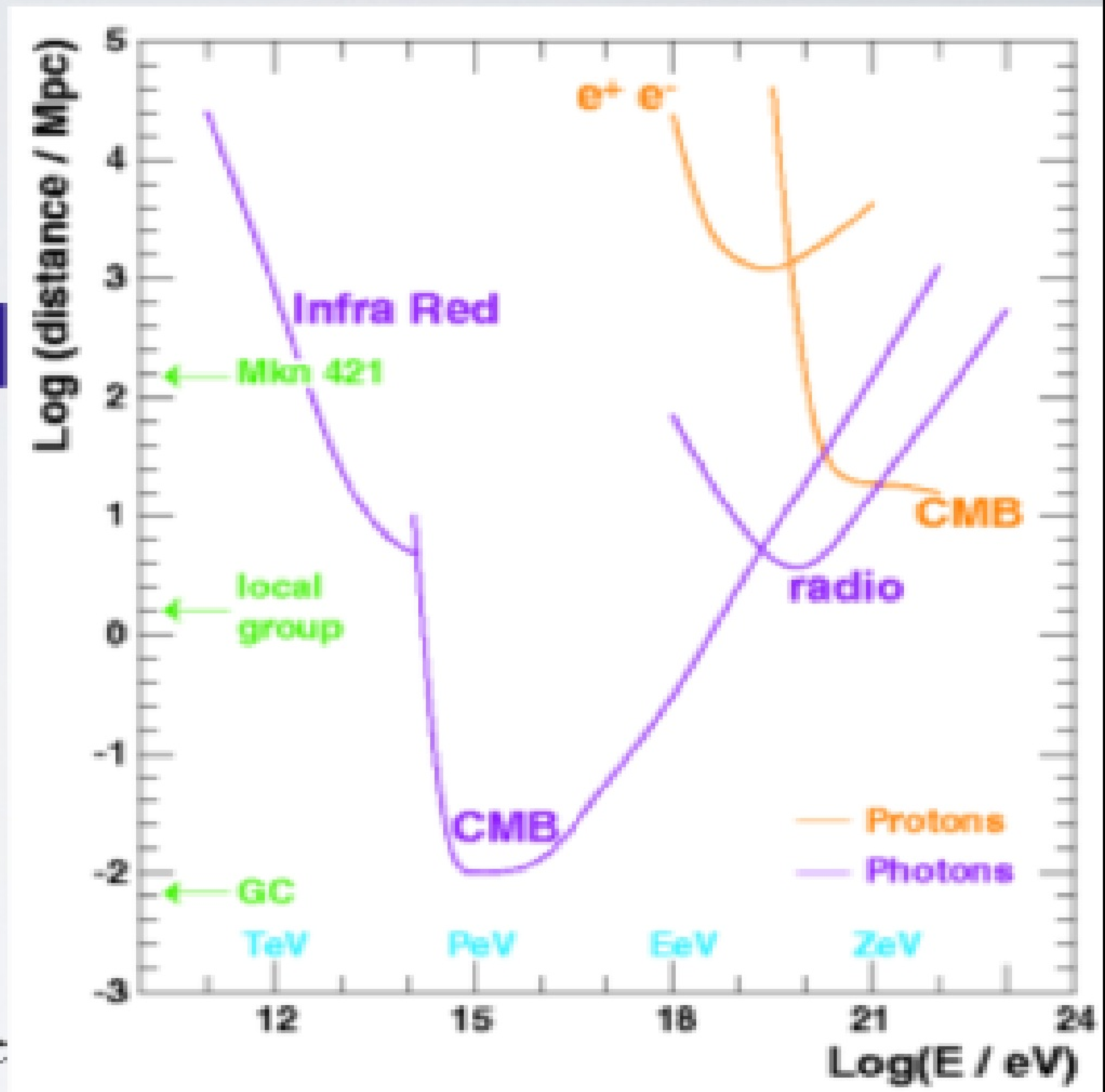
Reference values:

Galactic Centre	8 kpc
Local group (Andromeda M31)	0.725 Mpc
Mrk 421	~ 136 Mpc

Universe c/H_0 = 13.7 billion yrs
(for a reference scale: eg z=1 ~ 6.6 Gpc)

neutrons decay: $\Upsilon ct = E/m\ ct \sim 10$ kpc for $E \sim 10^{18}$ eV

1 Mpc = 3.26 Mly = 3.1 10^{24} cm



Interaction on cosmological backgrounds:

Interactions on cosmic backgrounds		threshold	mean free path
γ-rays:	$\gamma + \gamma_{2.7K}$	$>10^{14}$eV	10 Mpc
proton:	$p + \gamma_{2.7K} \rightarrow \pi^0 + X$	$>5.10^{19}$eV	50 Mpc
neutrinos:	$\nu + \nu_{1.95K} \rightarrow Z + X$		

$$E_{res} = \frac{M_Z^2}{2m_\nu} \cong 4\times10^{21}\left(\frac{1\text{eV}}{m_\nu}\right)\text{eV}$$

GZK horizon:

$$L_\gamma = \frac{1}{\sigma_{p-\gamma_{CMB}} n_\gamma} \sim \frac{1}{10^{-28}\,\text{cm}^2 \times 400\text{cm}^{-3}} \sim 10\ \text{Mpc}$$

The neutrino horizon is comparable to the universe!

$$L_\nu = \frac{1}{\sigma_{res}\times n} = \frac{1}{5\times10^{31}cm^2\times112cm^{-3}} \approx 6Gpc$$

T. J. Weiler, Phys. Rev. Lett. 49, 234 (1982)
Beacom's Lectures

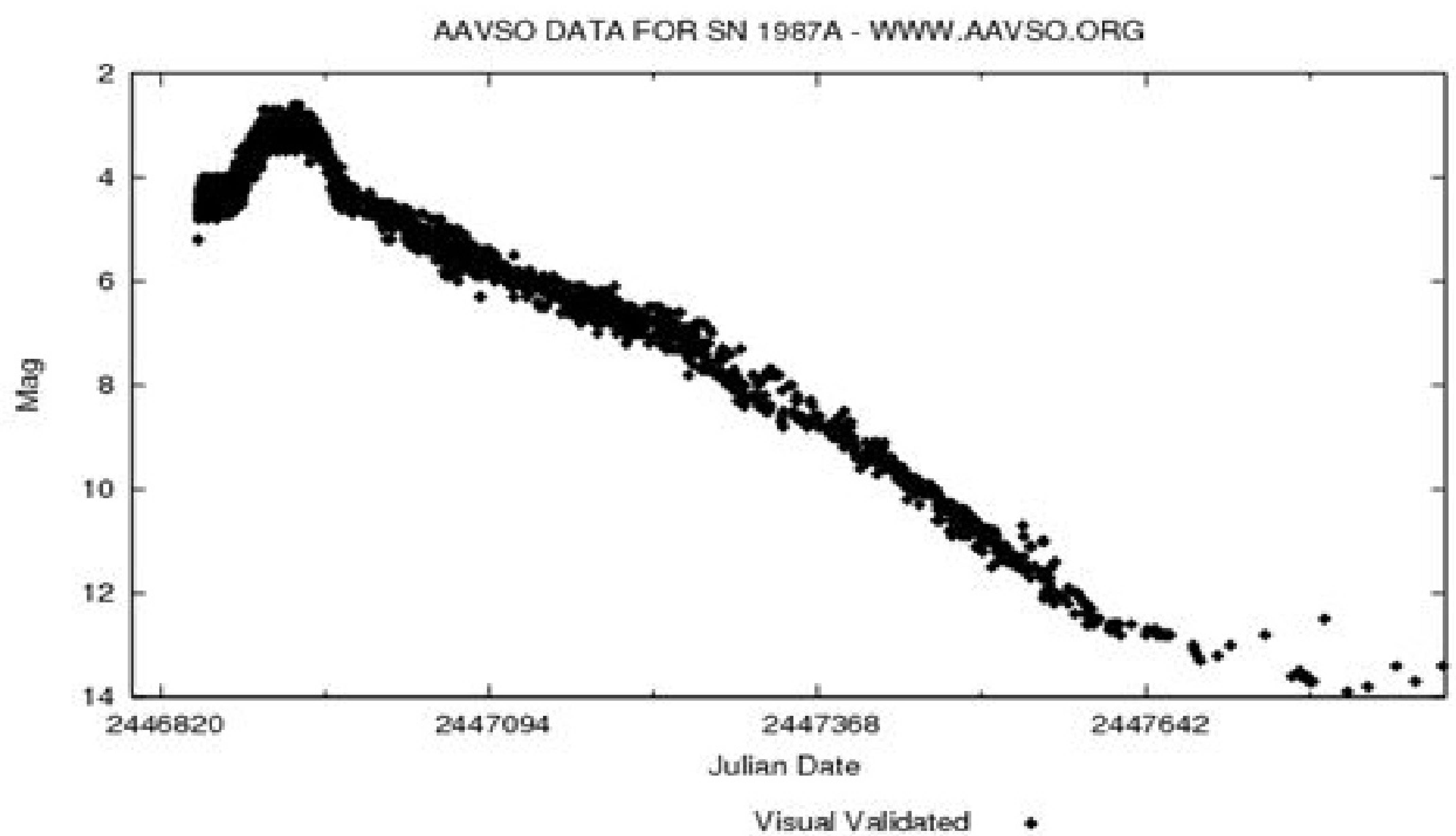
Early tryumph of neutrino astronomy (Kamiokande and SN1987A):

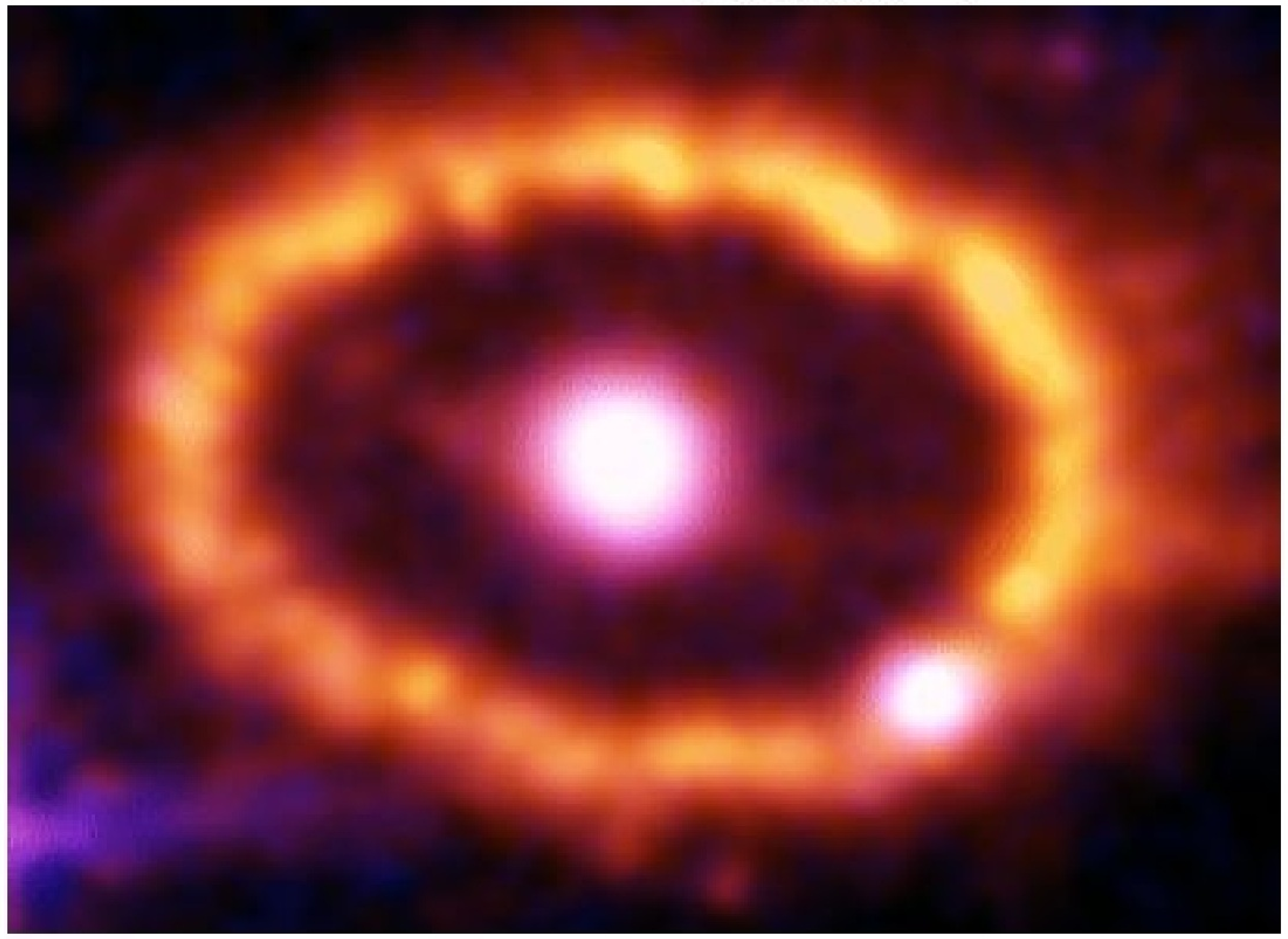
The Detection of Neutrinos from SN 1987A

- Burst of Neutrinos detected at several neutrino detectors on Feb 23 1987
- Time span of about 12.5 seconds about 3 hours before the arrival of photons

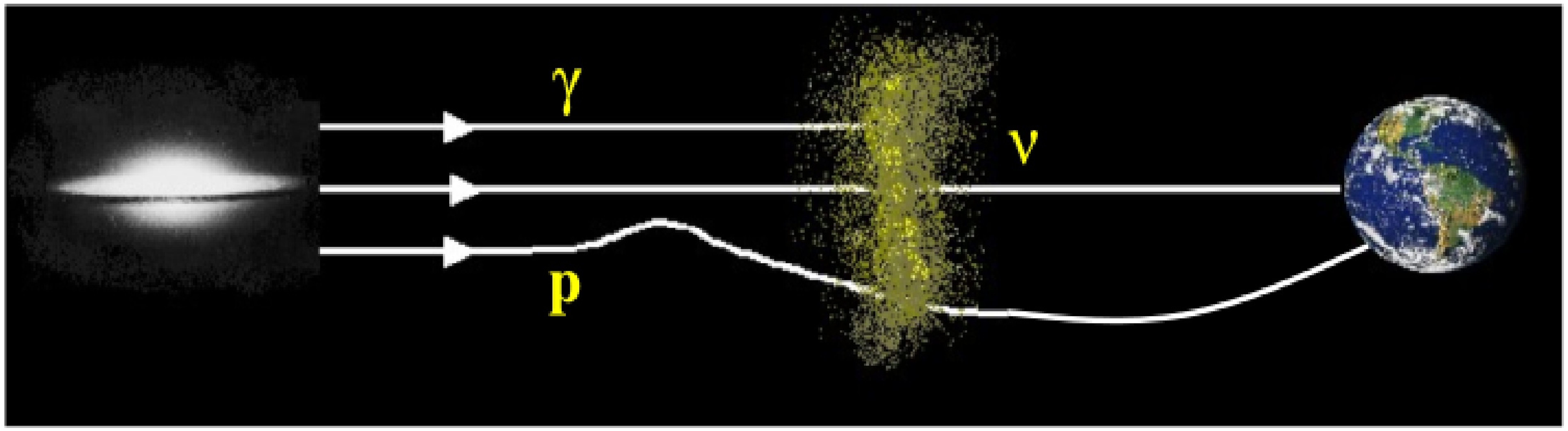
↓

- Confirmation of core collapse model of supernovae!!!!
- Upper limit on neutrino mass of 16eV
- Still searching for other signs of compact object

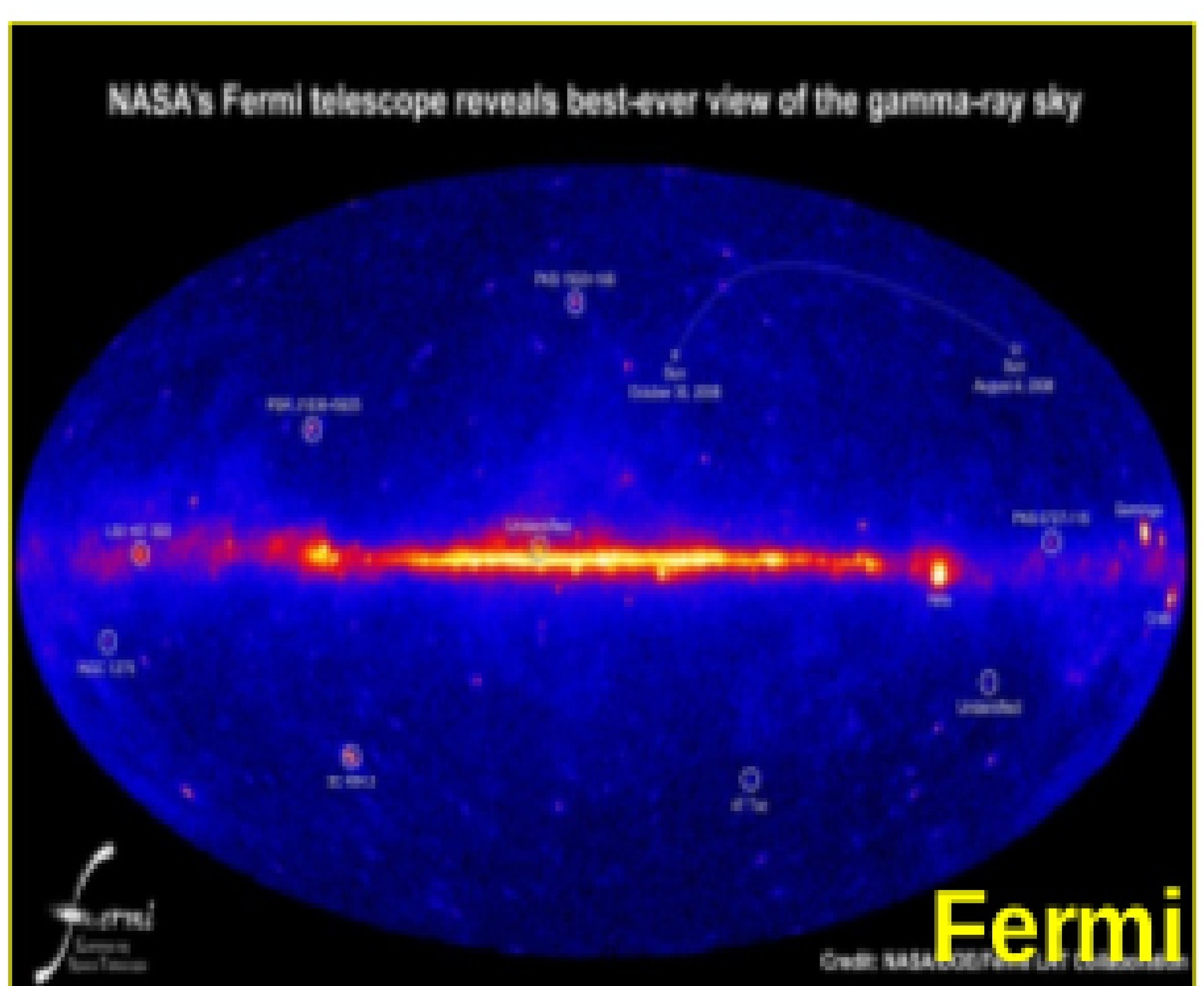




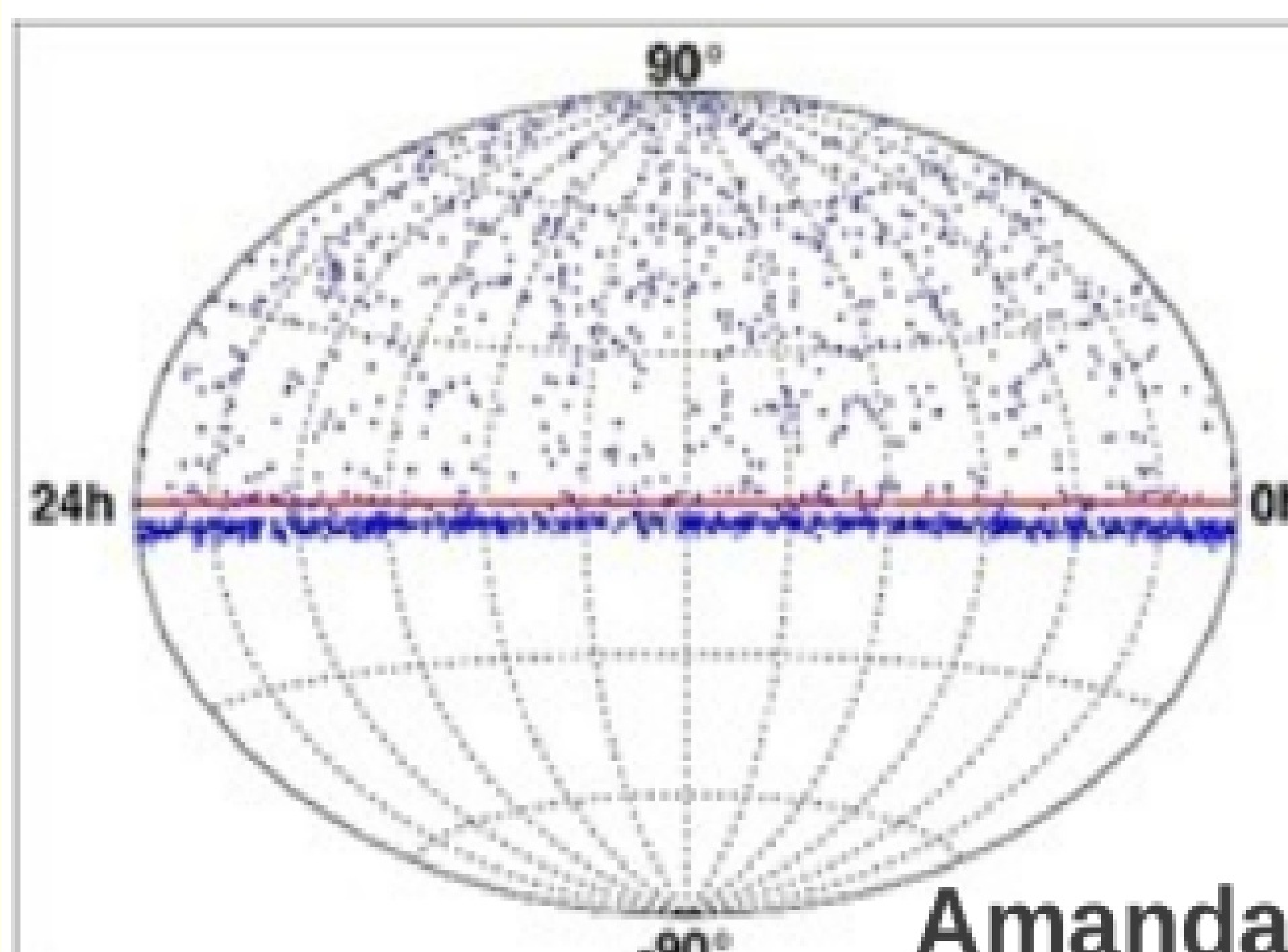
multi-messenger astronomy



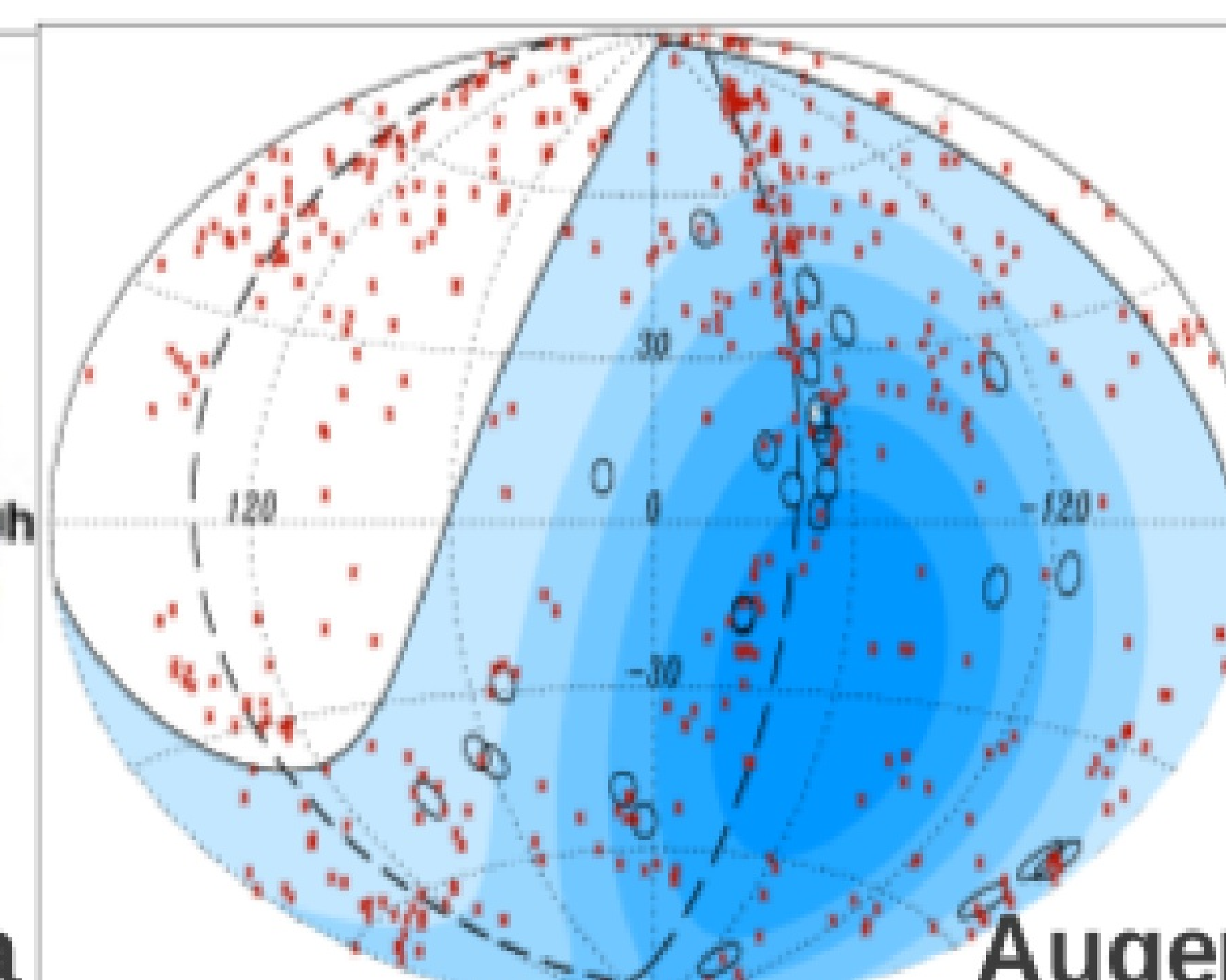
γ rays



neutrinos

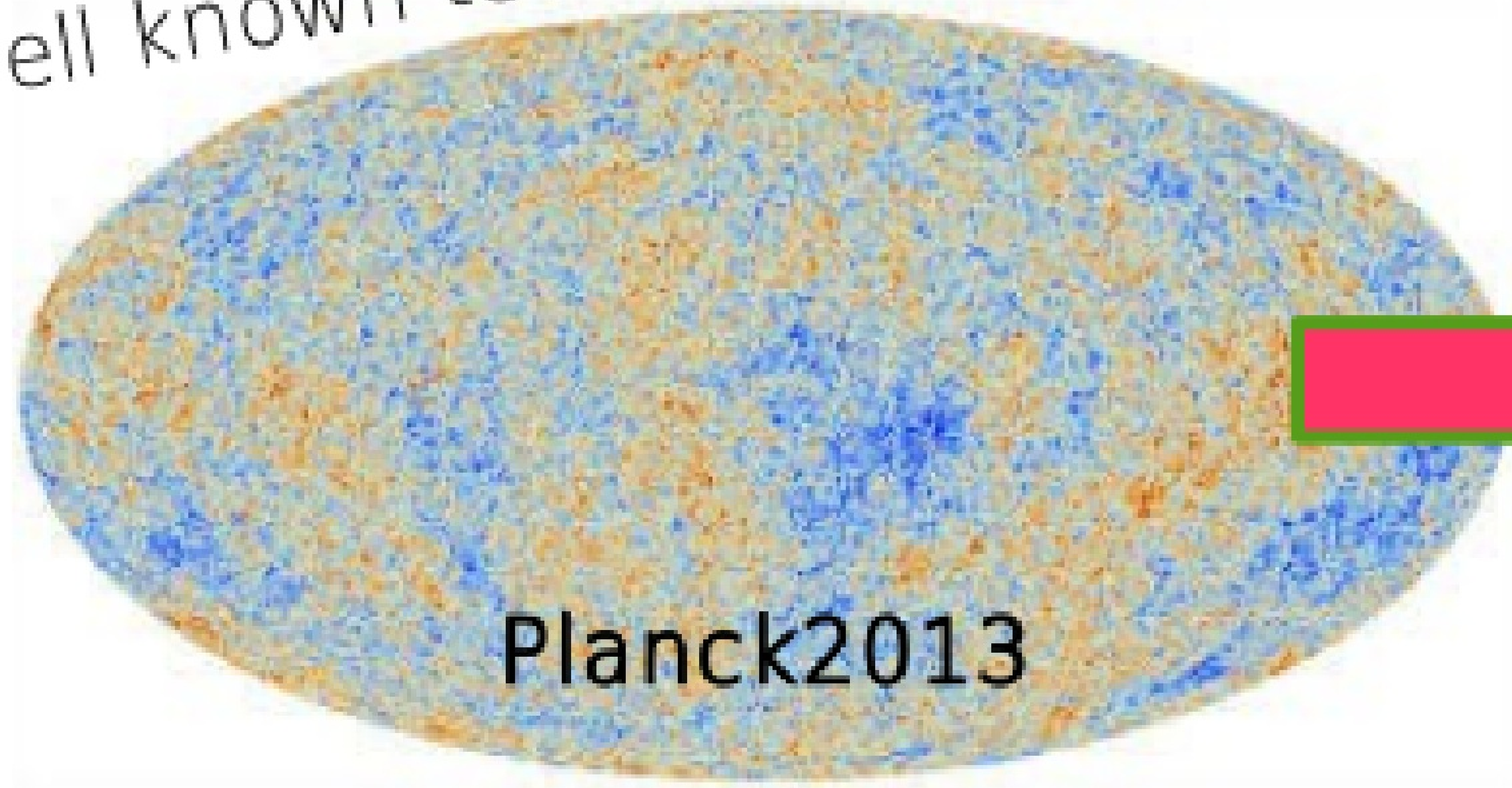


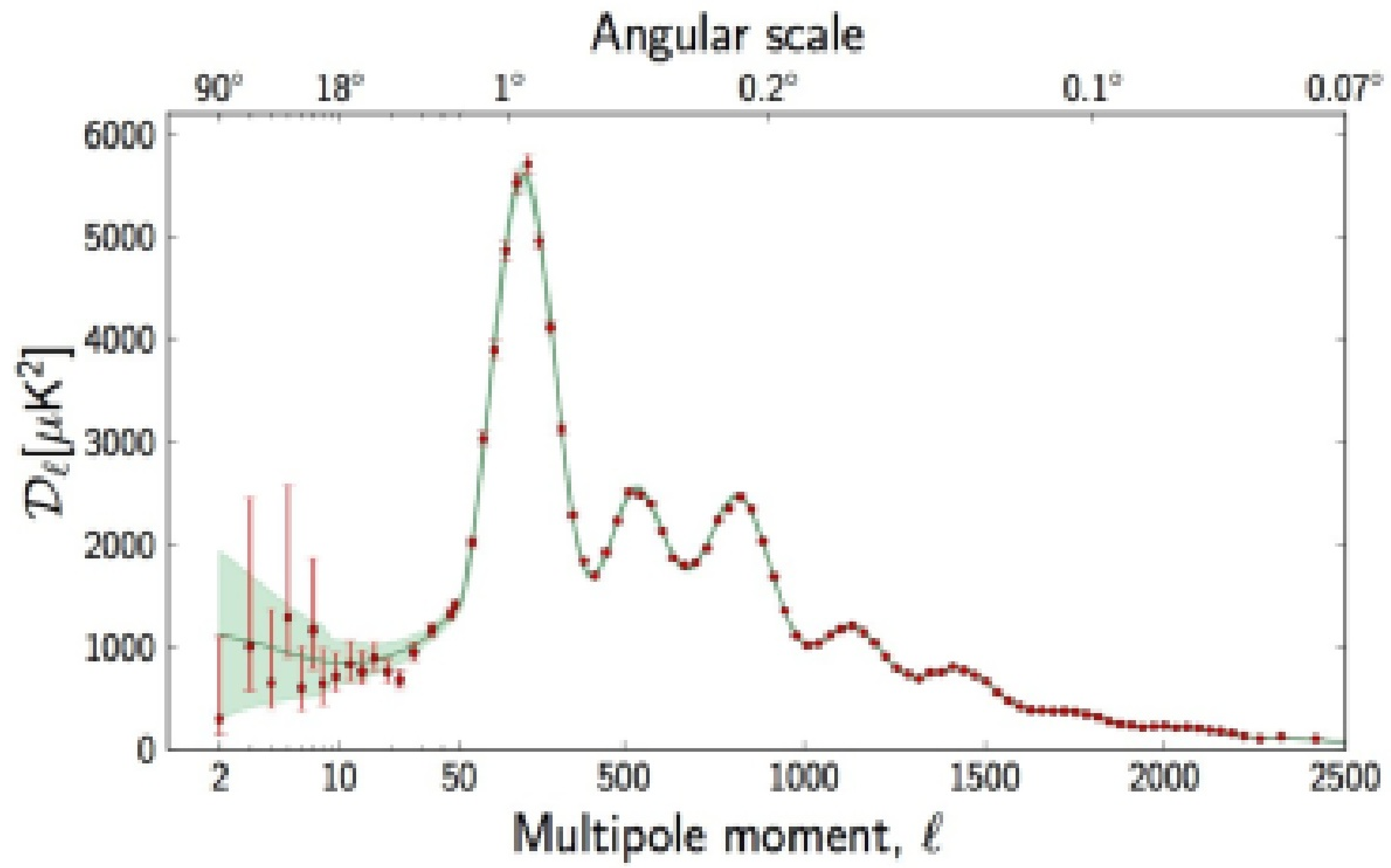
UHE Cosmic rays

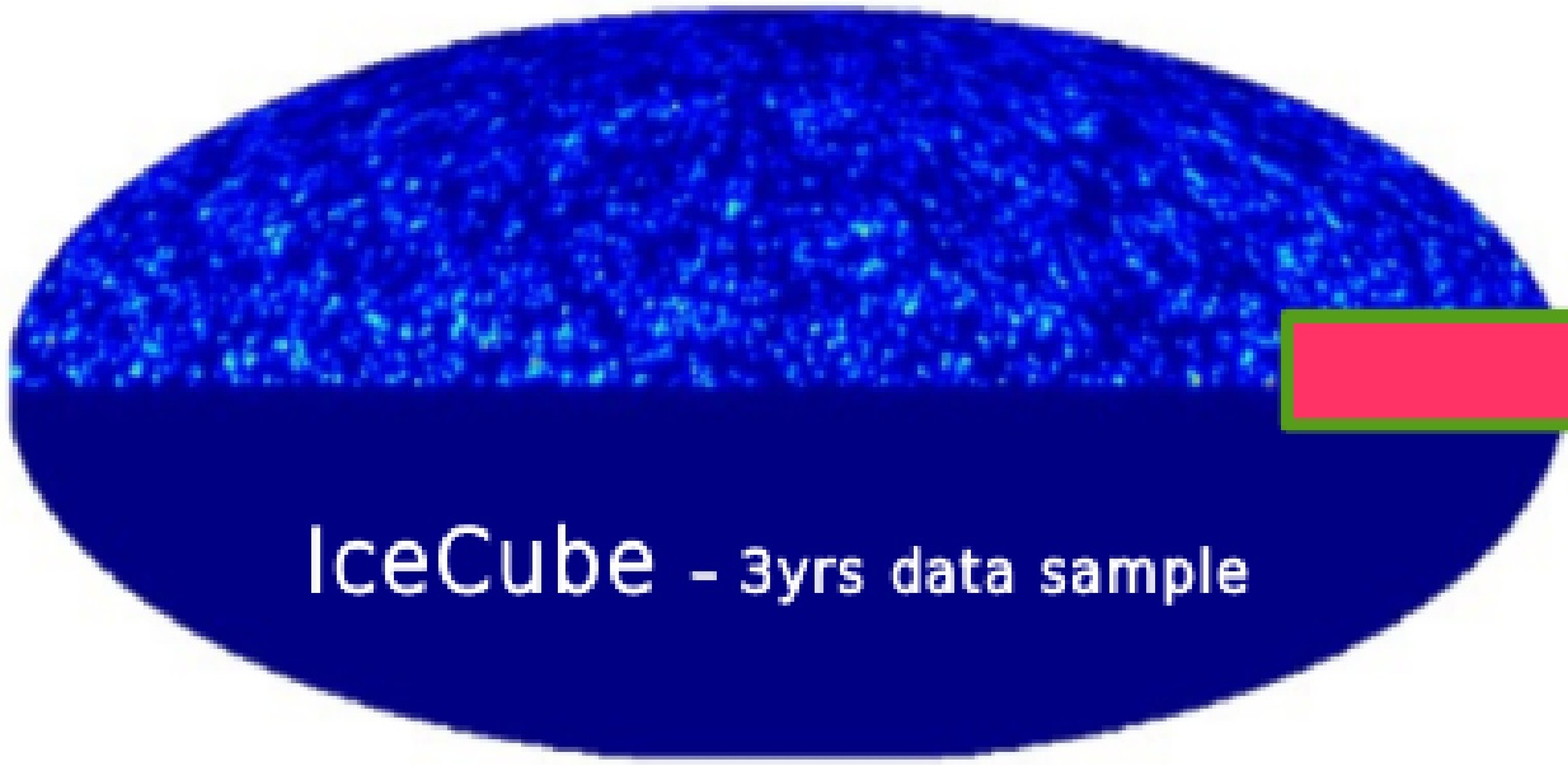


A multipole expansion of the neutrino skymap

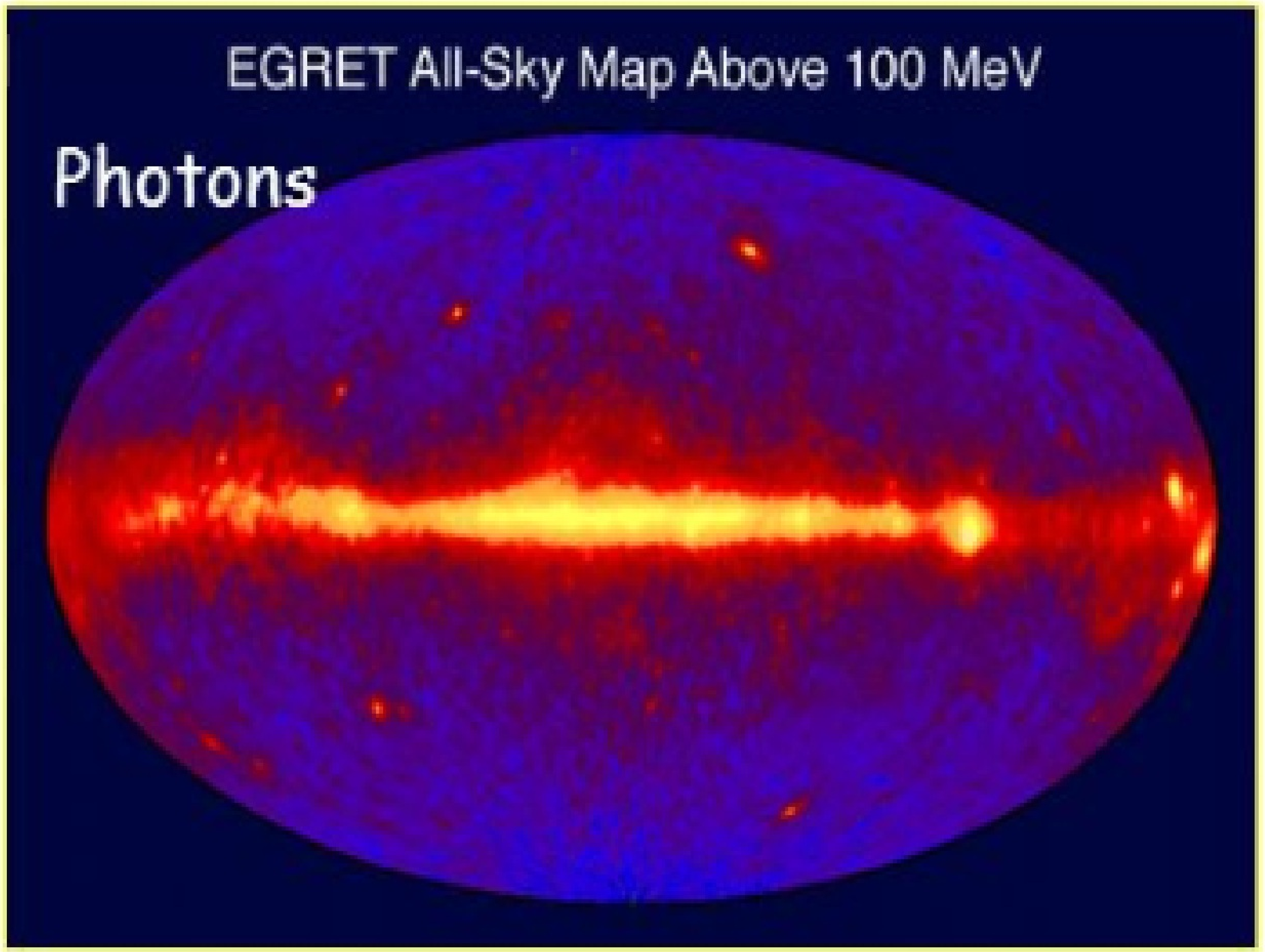
Well known technique in CMB analysis!



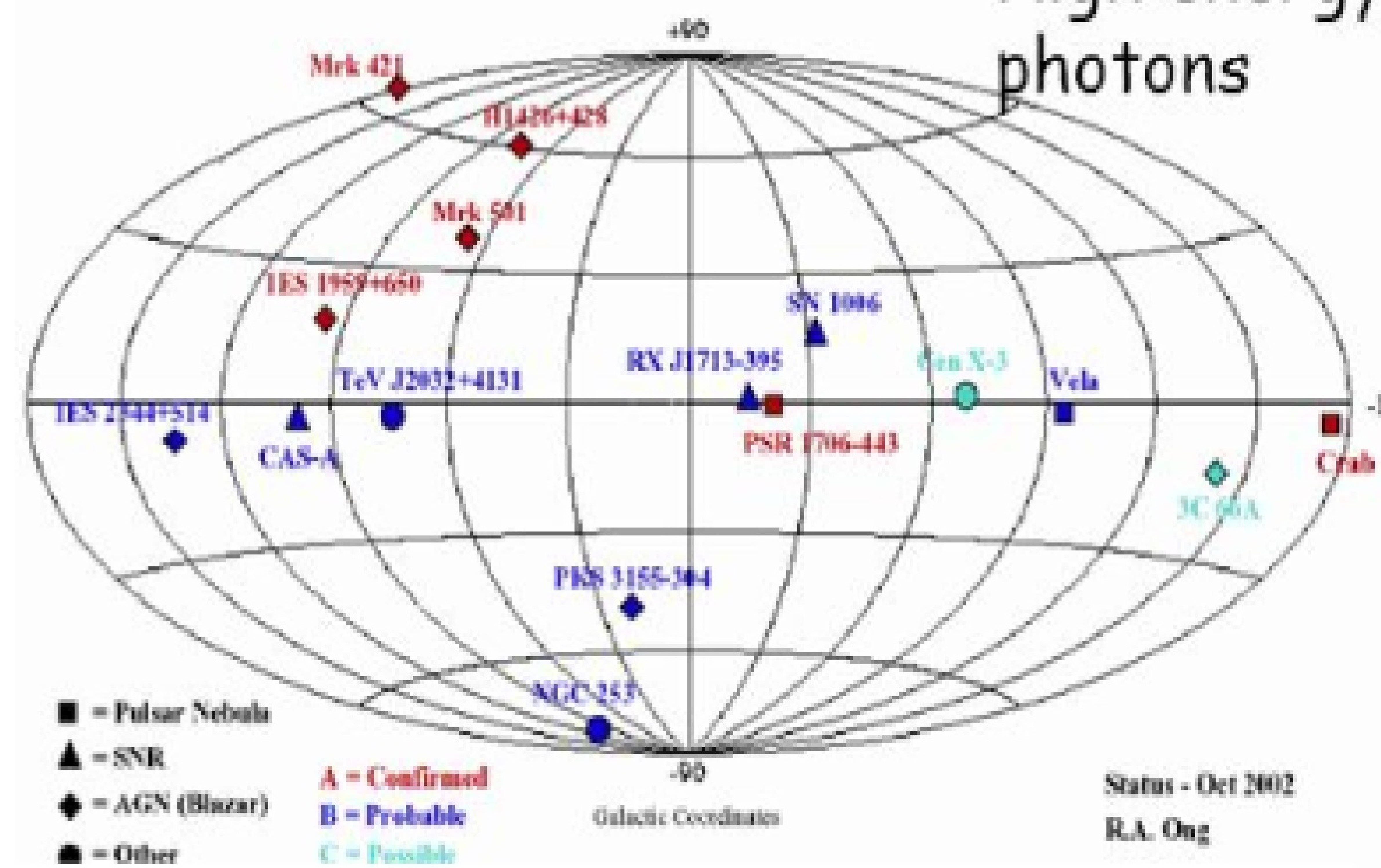


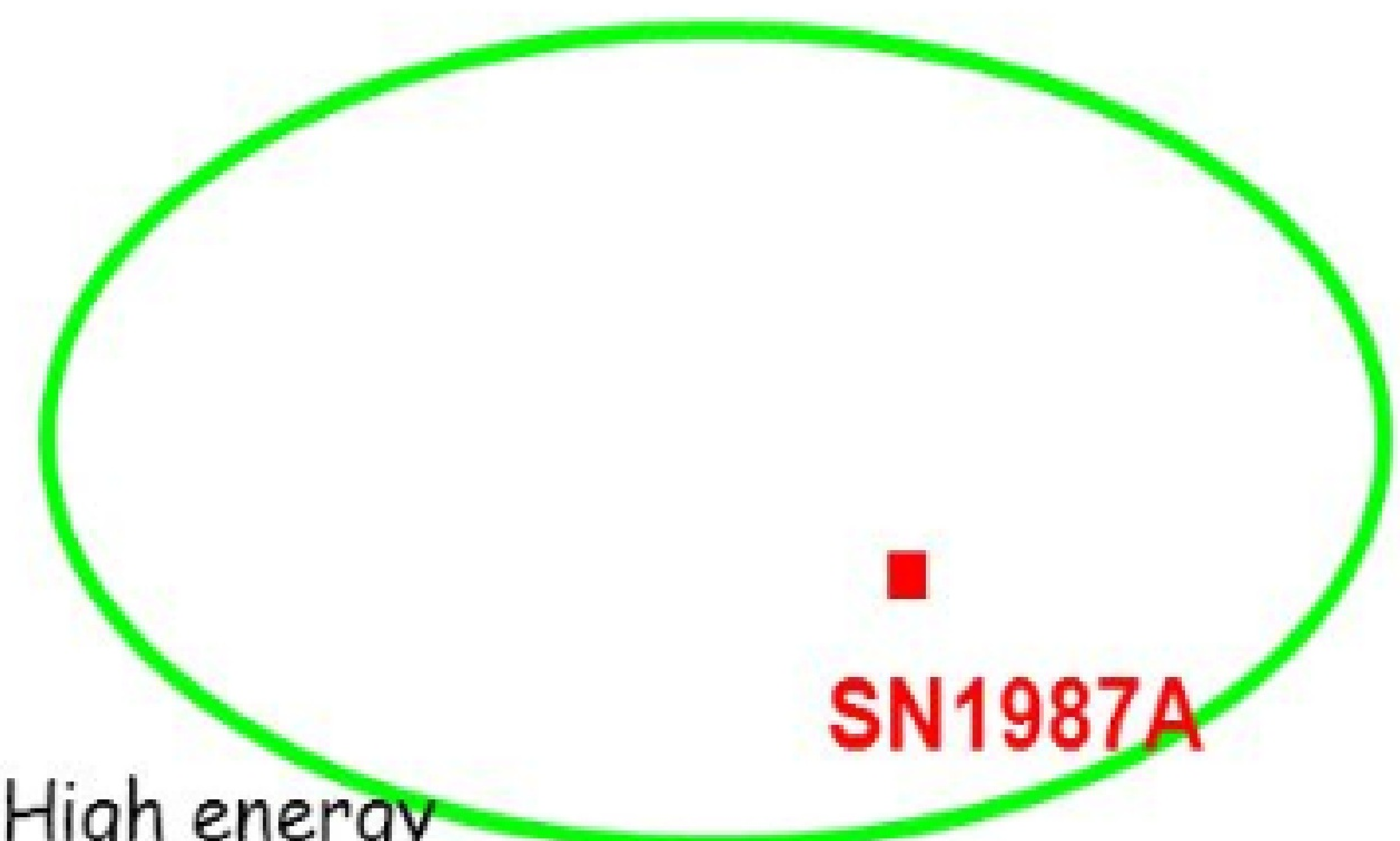


?

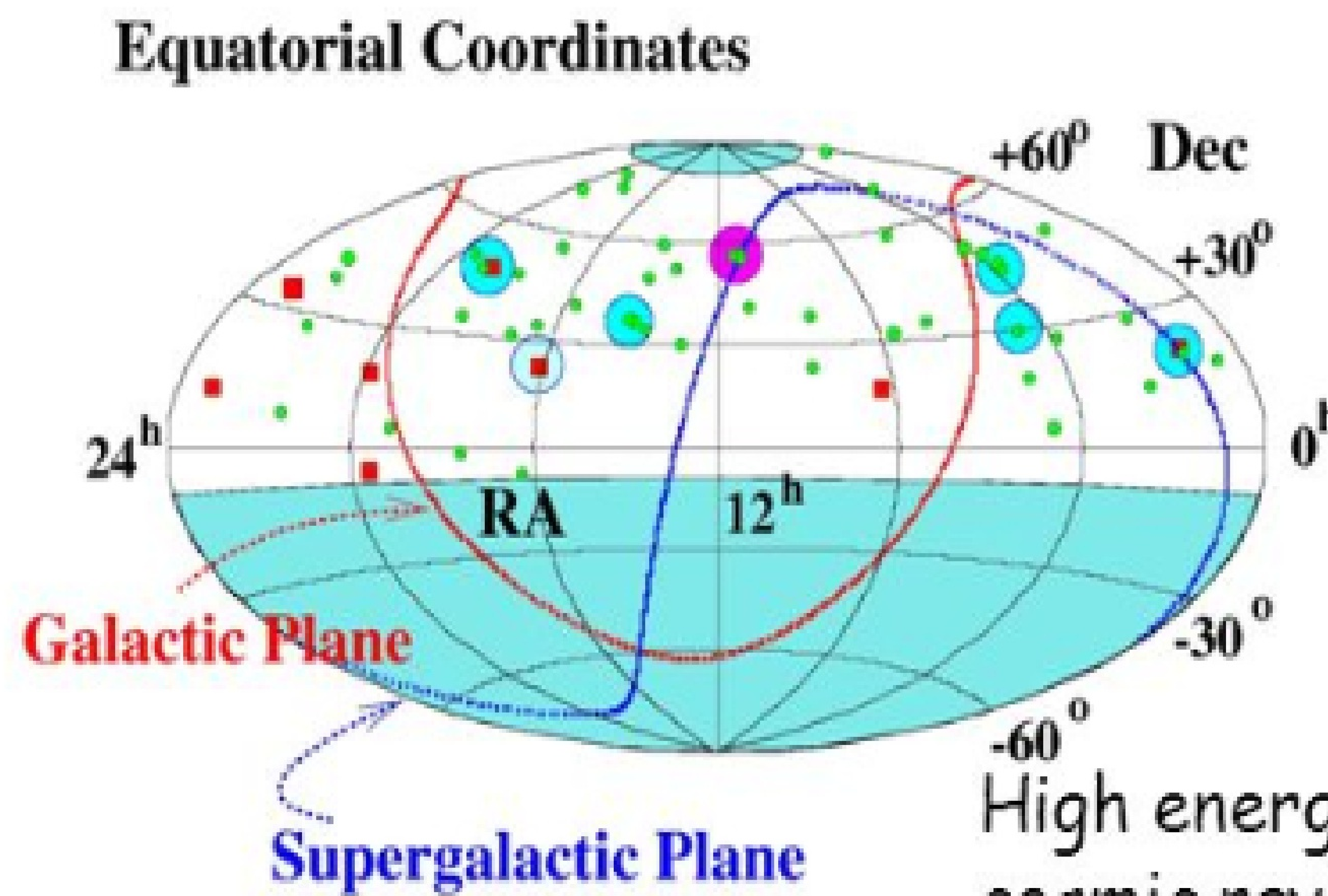


High energy photons



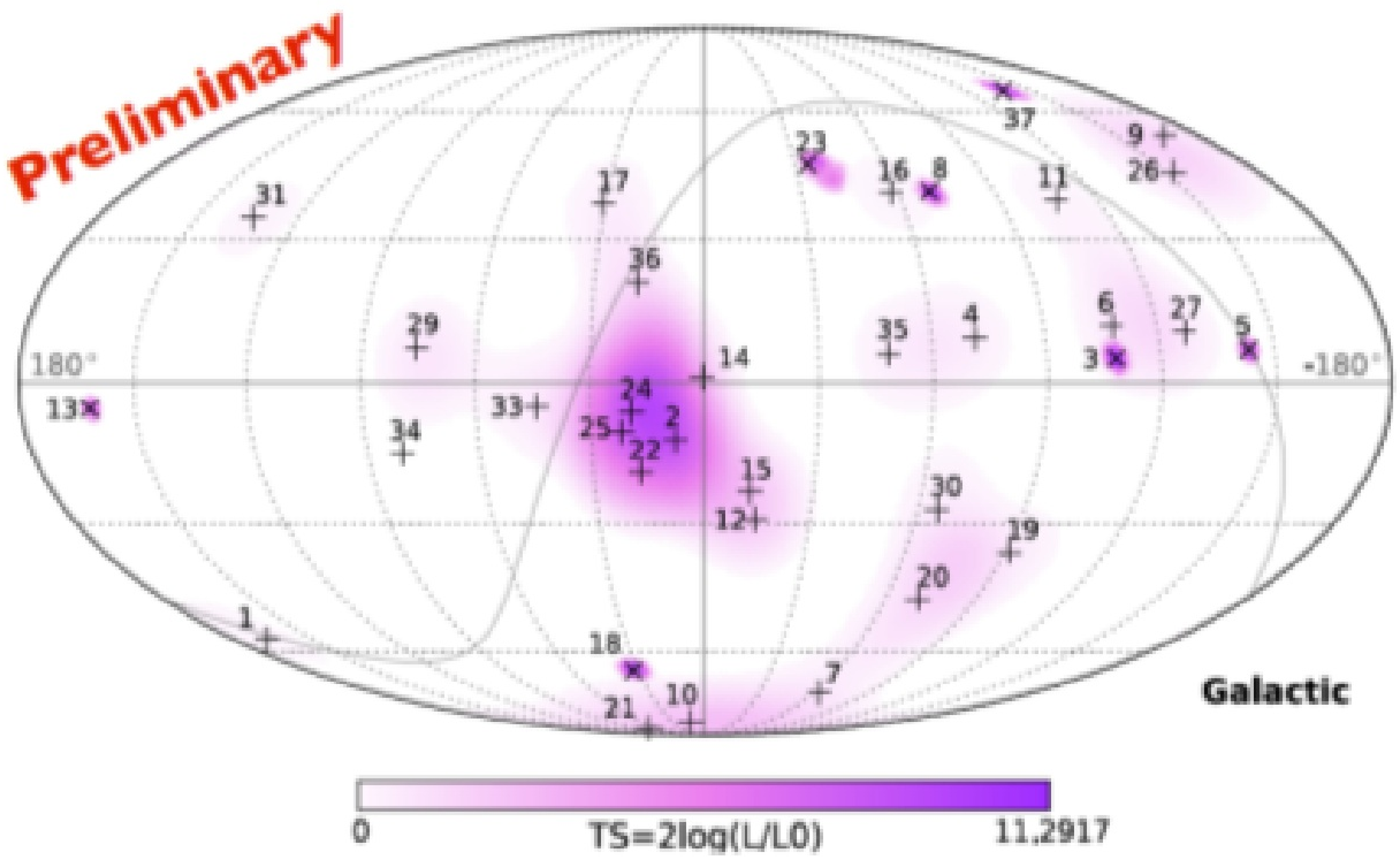


High energy neutrinos



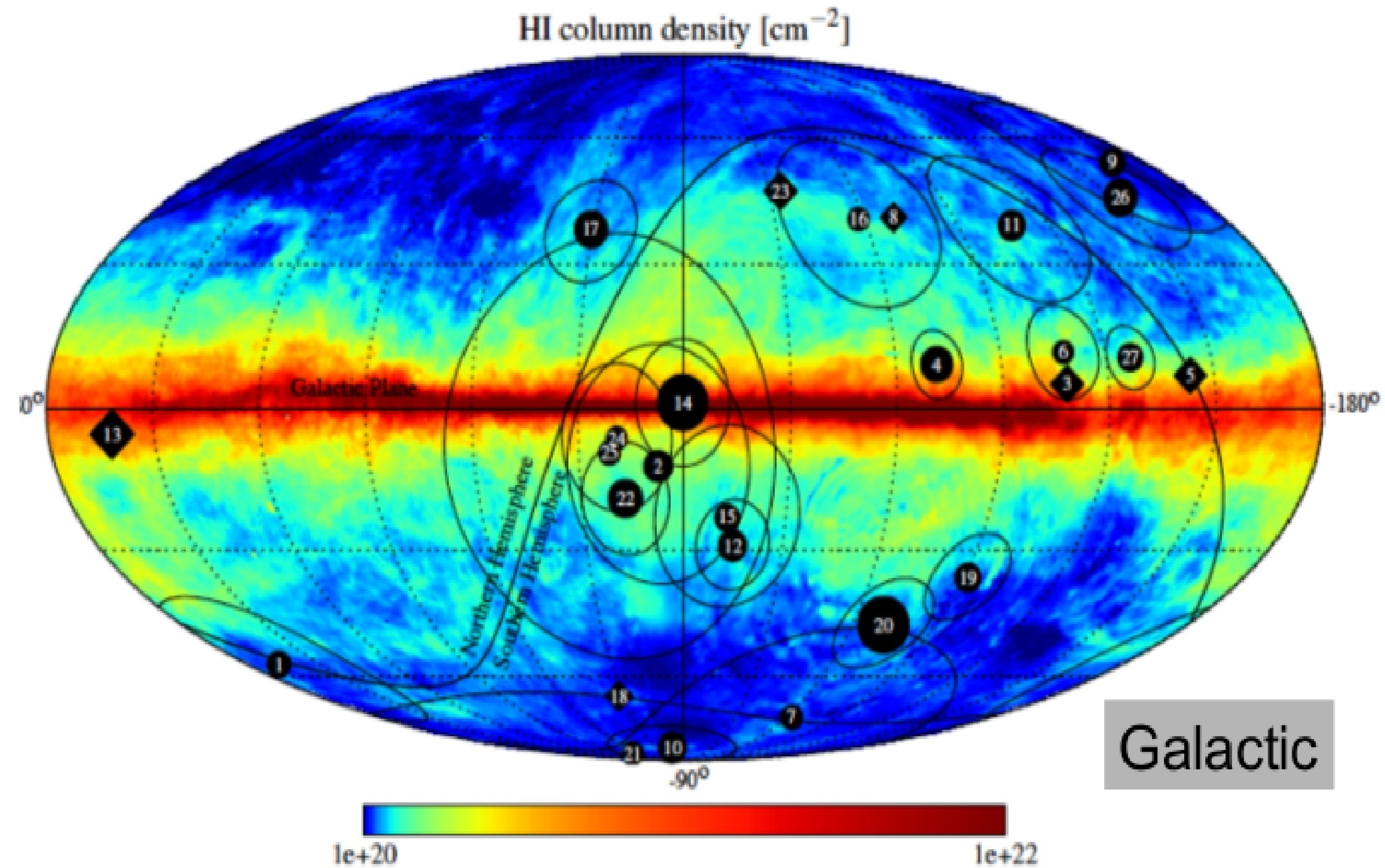
High energy cosmic rays

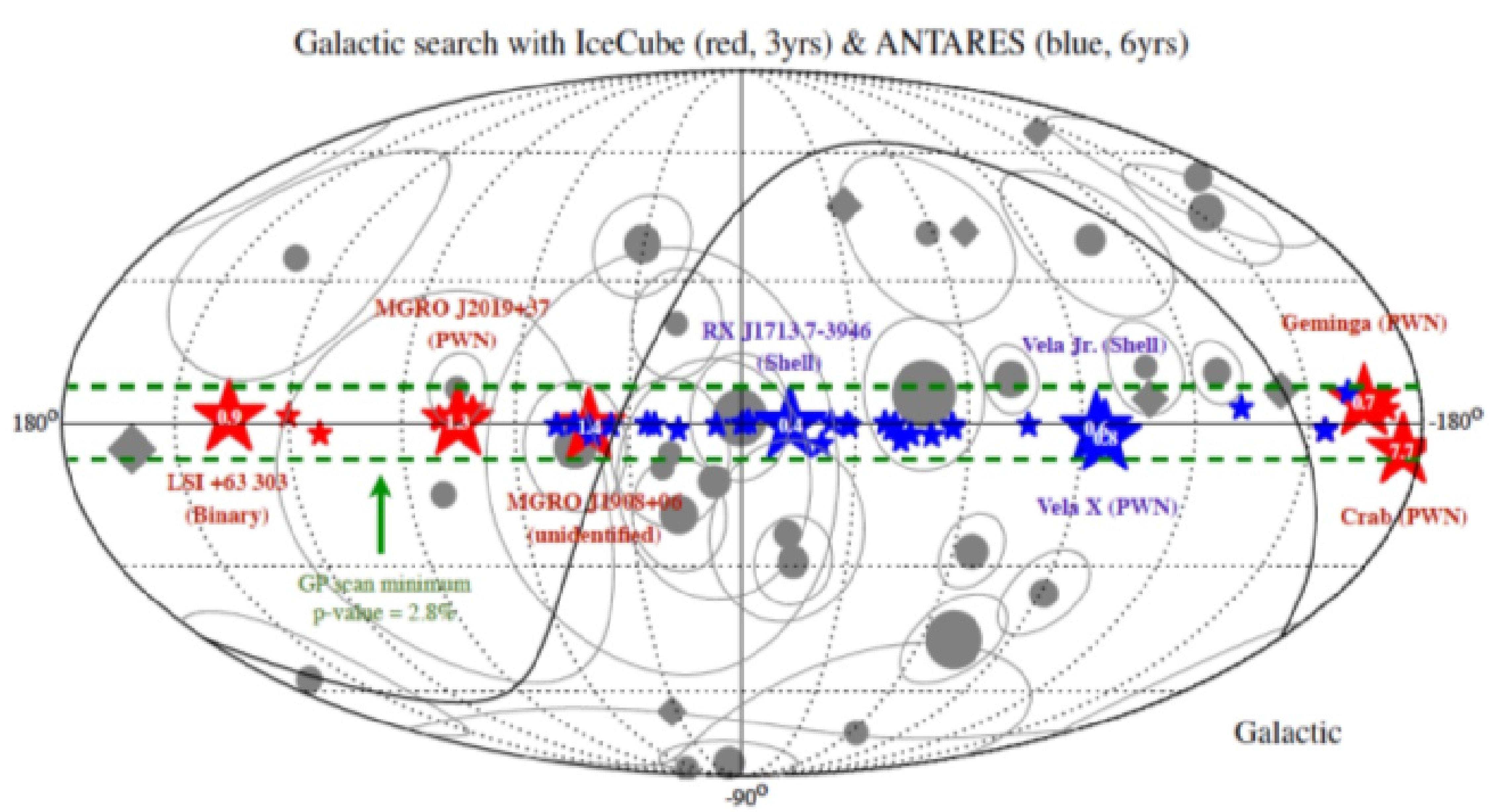
where do they come from (3 year data)?



hottest spot 7.2%: consistent with diffuse flux with fllavor 1:1:1?

correlation with Galactic plane: TS of 2.8% for a width of 7.5





we are close to detecting neutrinos from known high energy gamma ray emitters

Issues:

- No point sources identified.
- Galactic or extragalactic origin?
- Low statistics: we need more data!!!!

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- No point sources identified.
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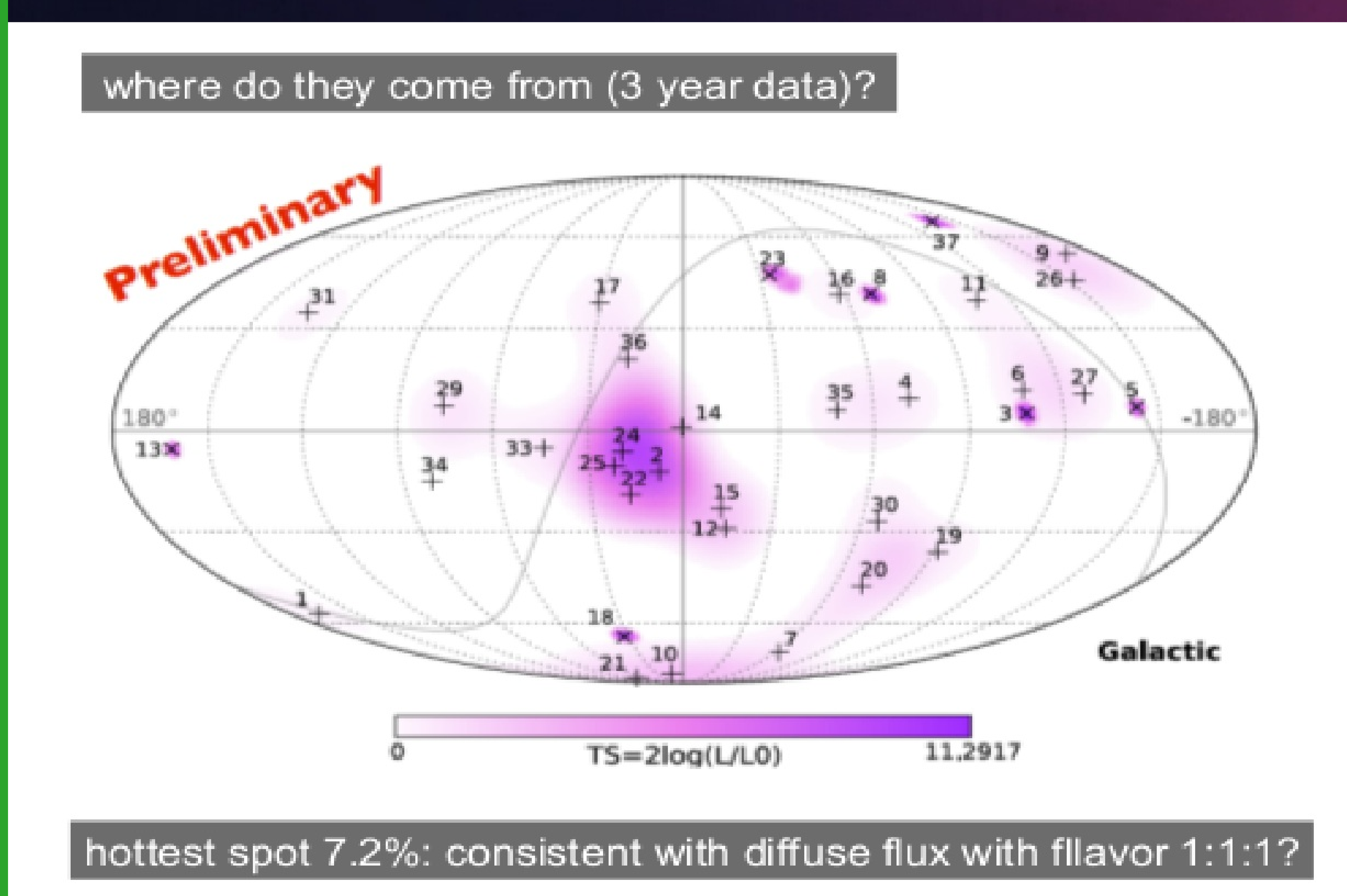
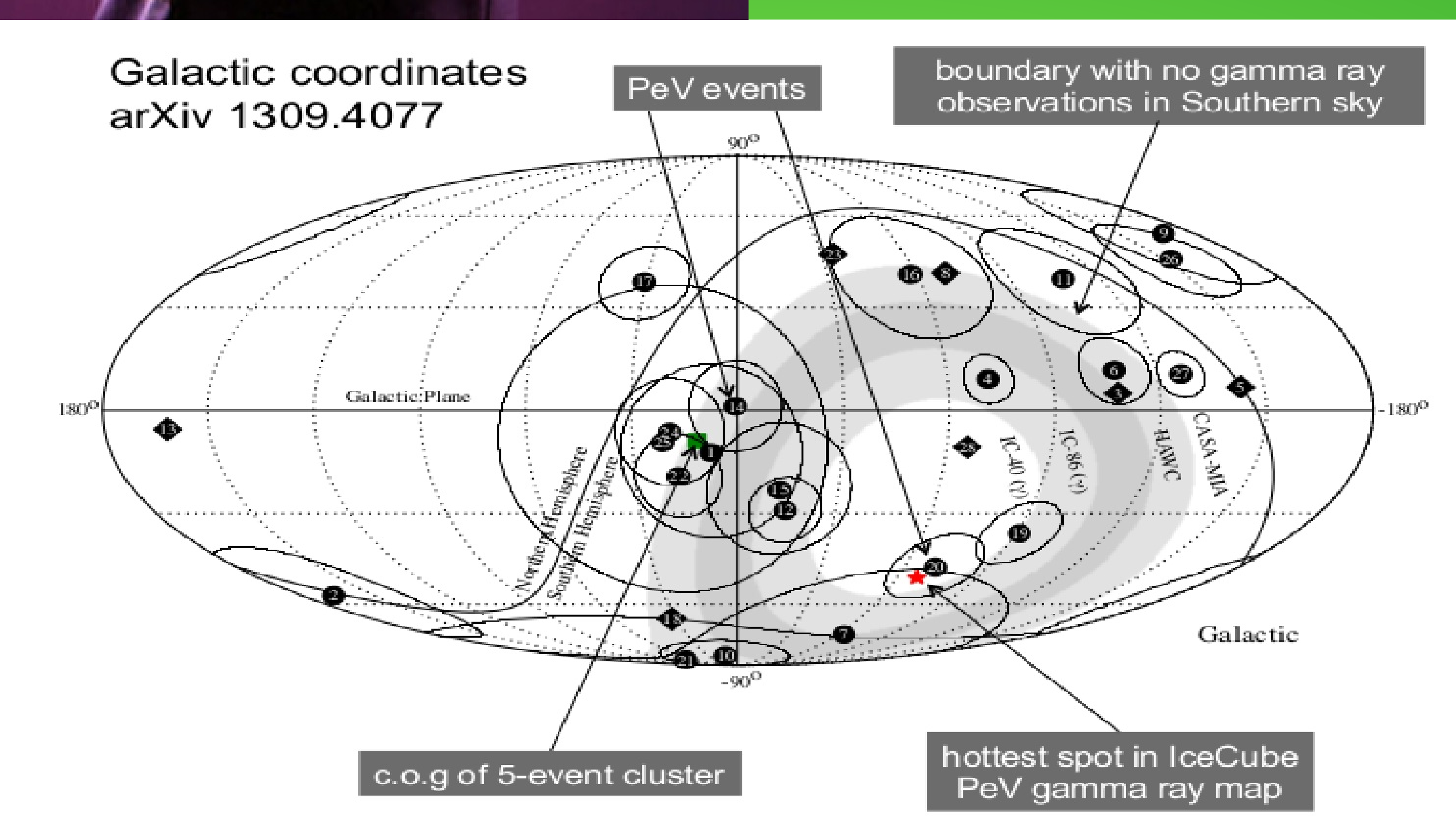
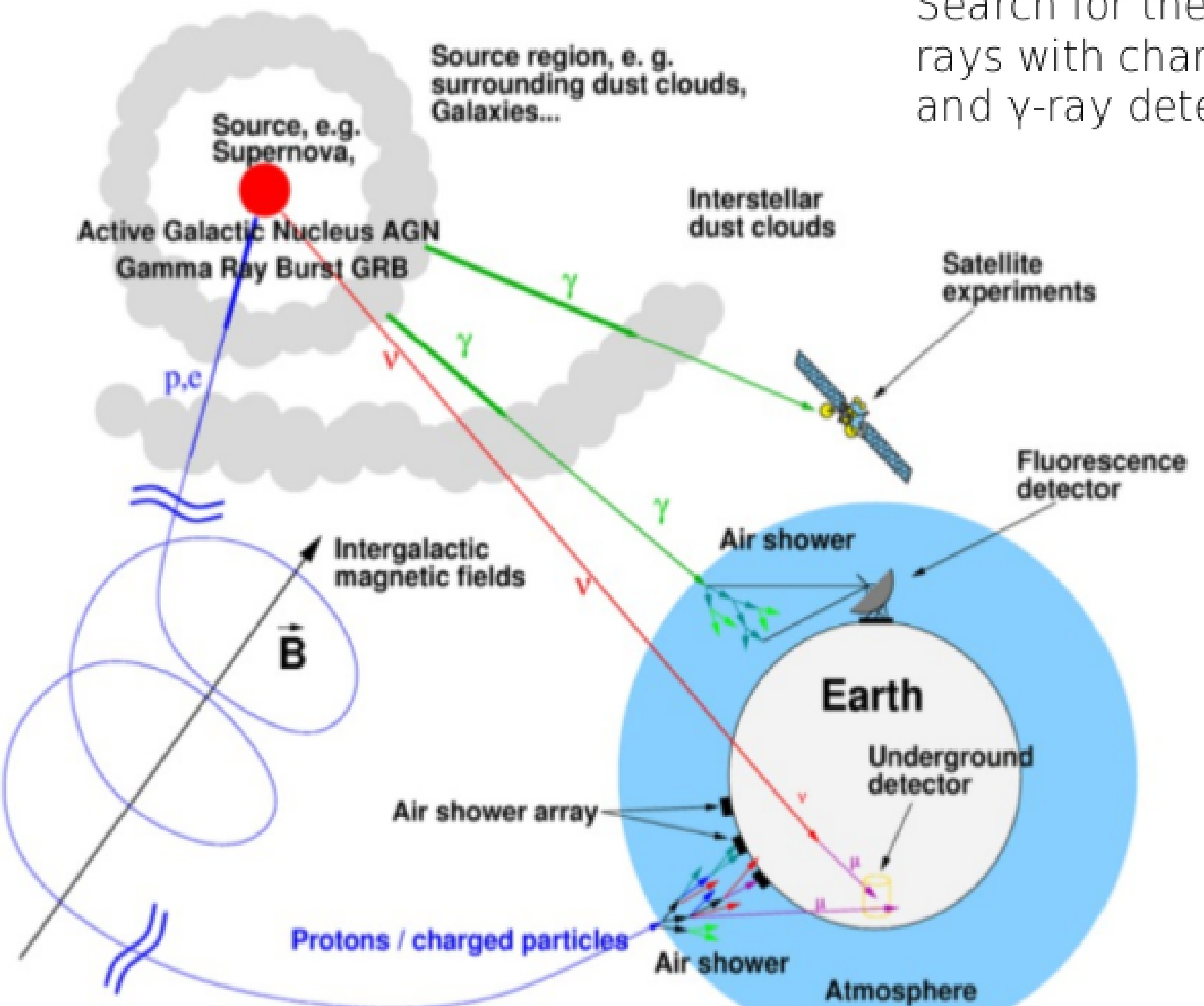




Multimessenger astronomy

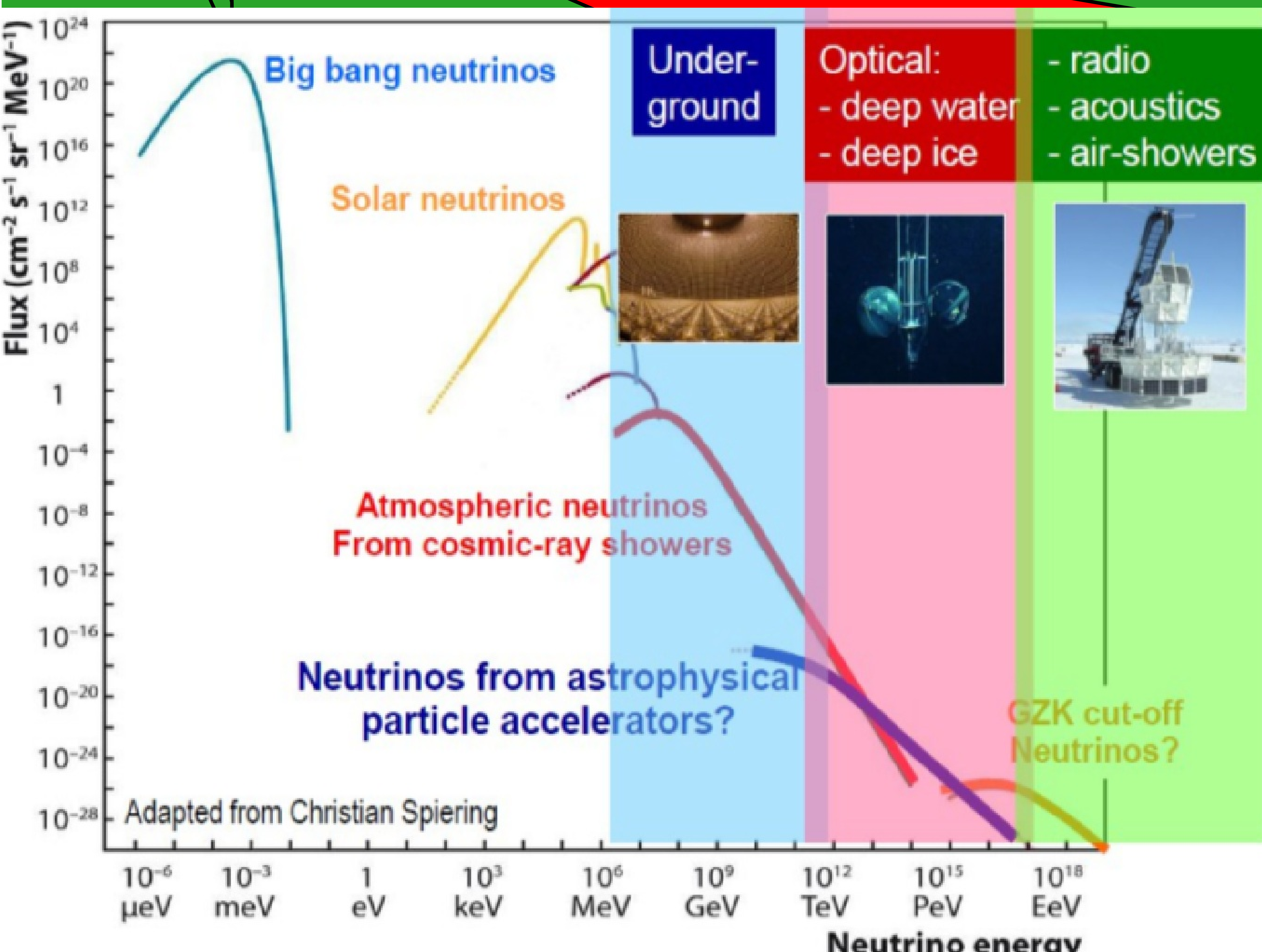


Search for the sources of cosmic rays with charged particle, neutrino and γ-ray detectors

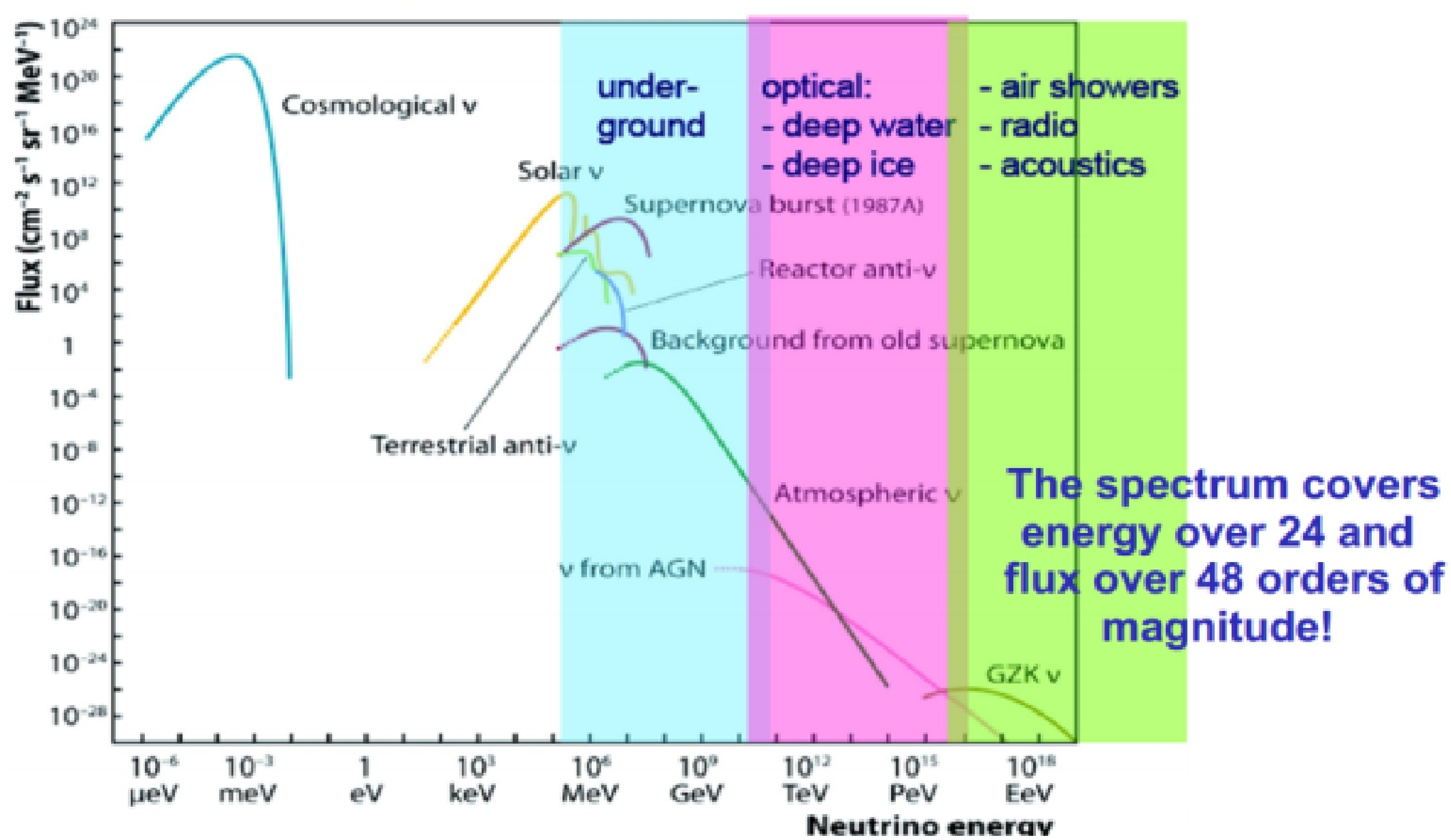
Charged particles:
- Deflection in magnetic fields → lose pointing

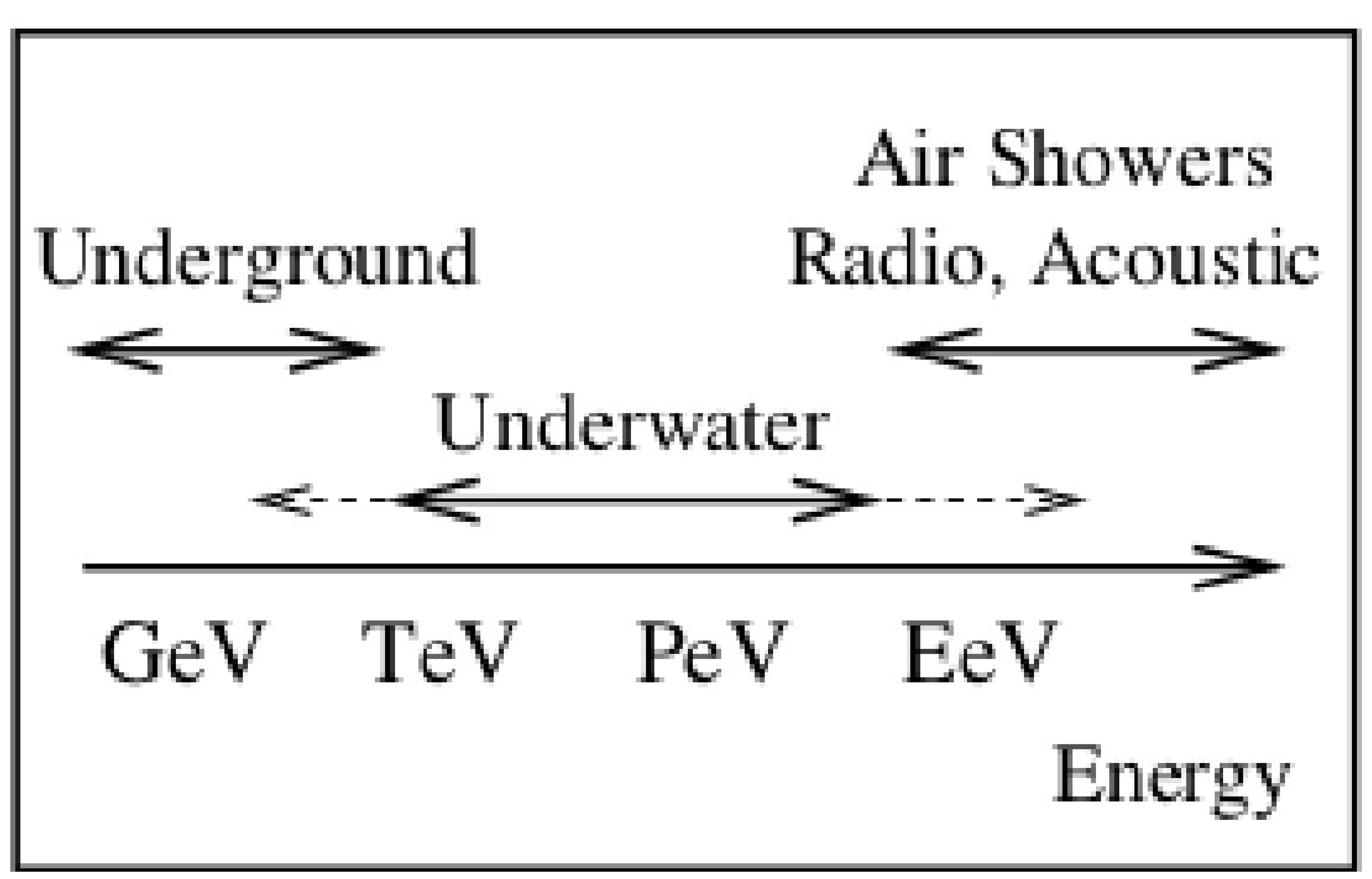
γ-rays:
- Absorption in dust, CMB

Neutrinos:
- Low interaction cross section, neutral → ideal messenger particles, detection challenging



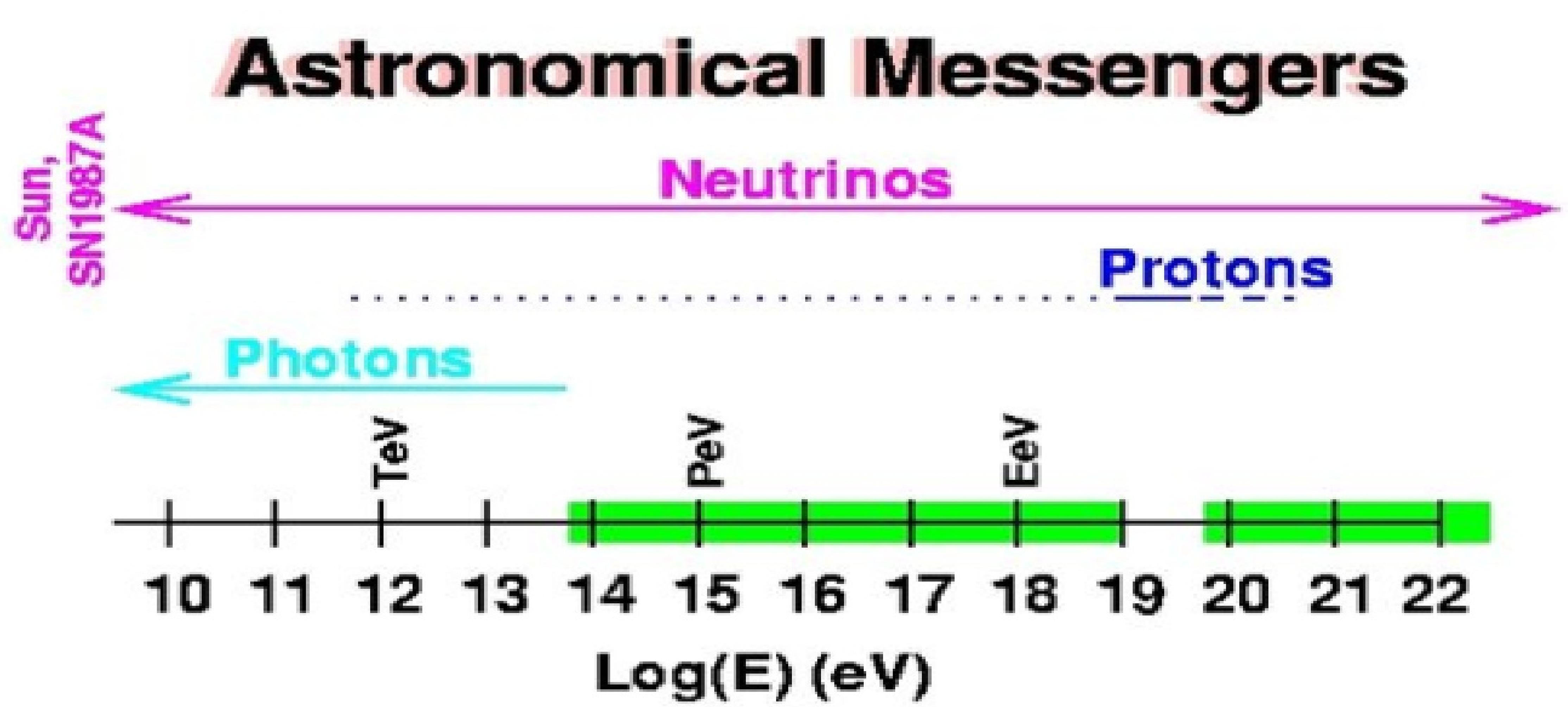
Energy spectrum of all neutrinos



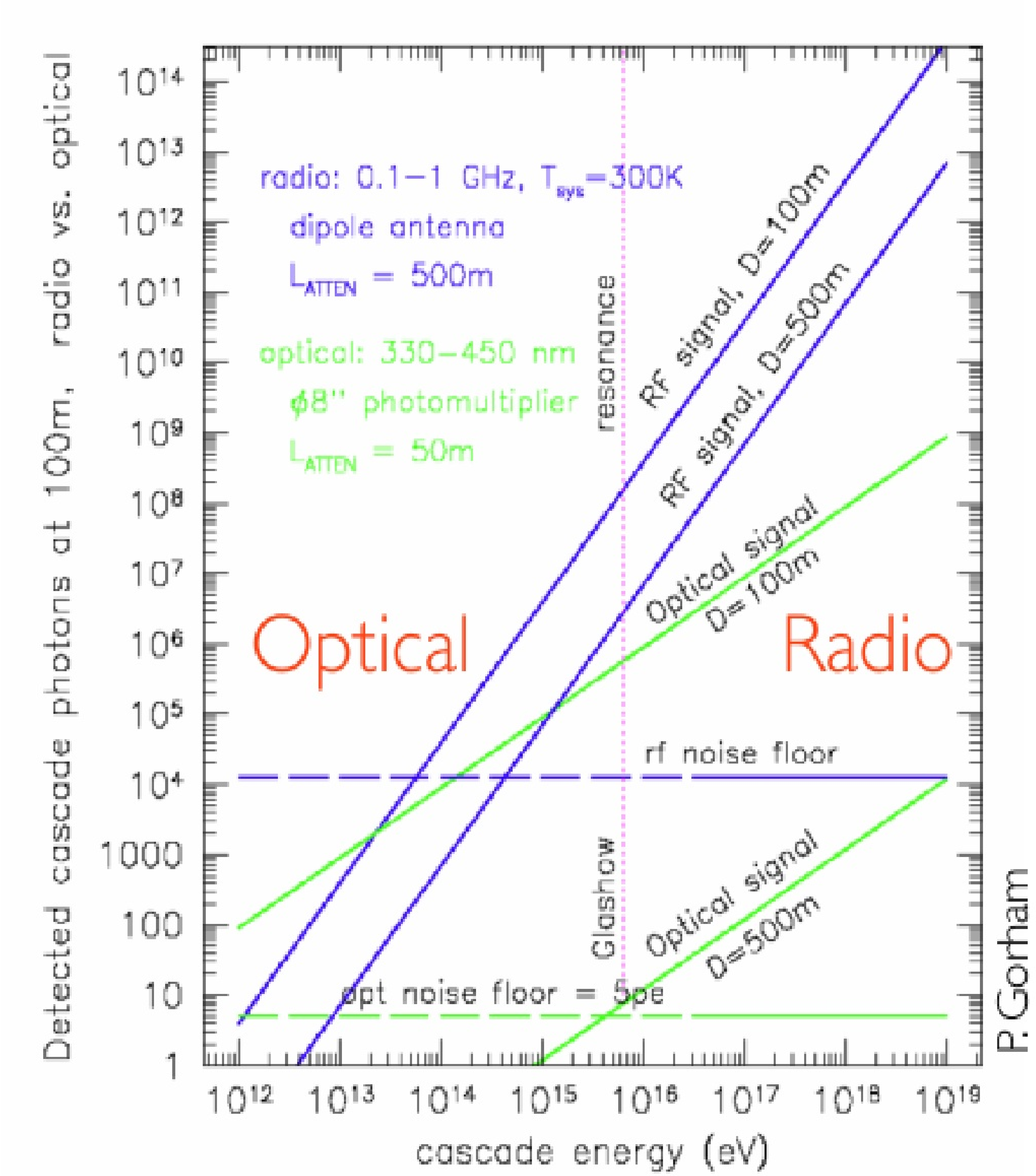


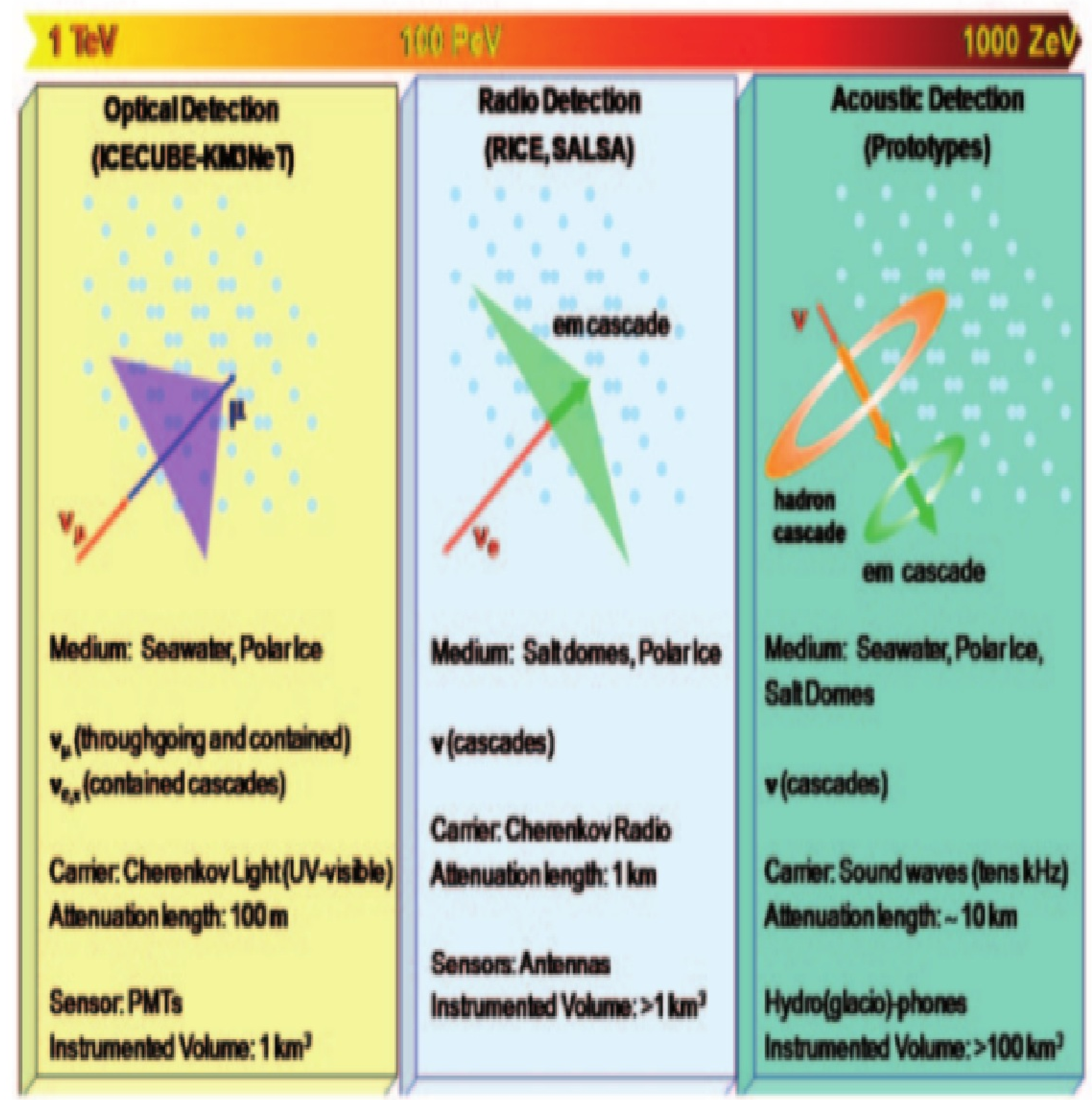
Energy range of the various detection techniques (see below). Optical Cherenkov detectors, although optimized to the TeV-PeV range, are sensitive also at lower and higher energies, as indicated by the dashed lines.

Neutrinos probe a new energy domain unexplored by conventional optical, X-Ray and Gamma Ray astronomy

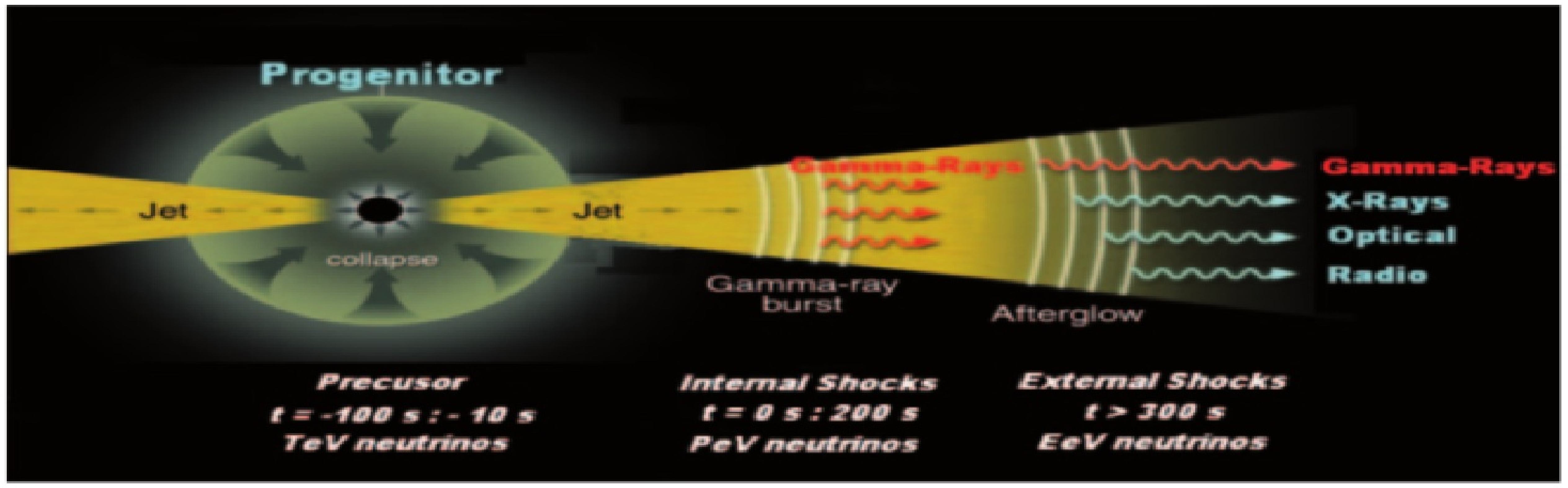


Detector regimes: optical vs. radio





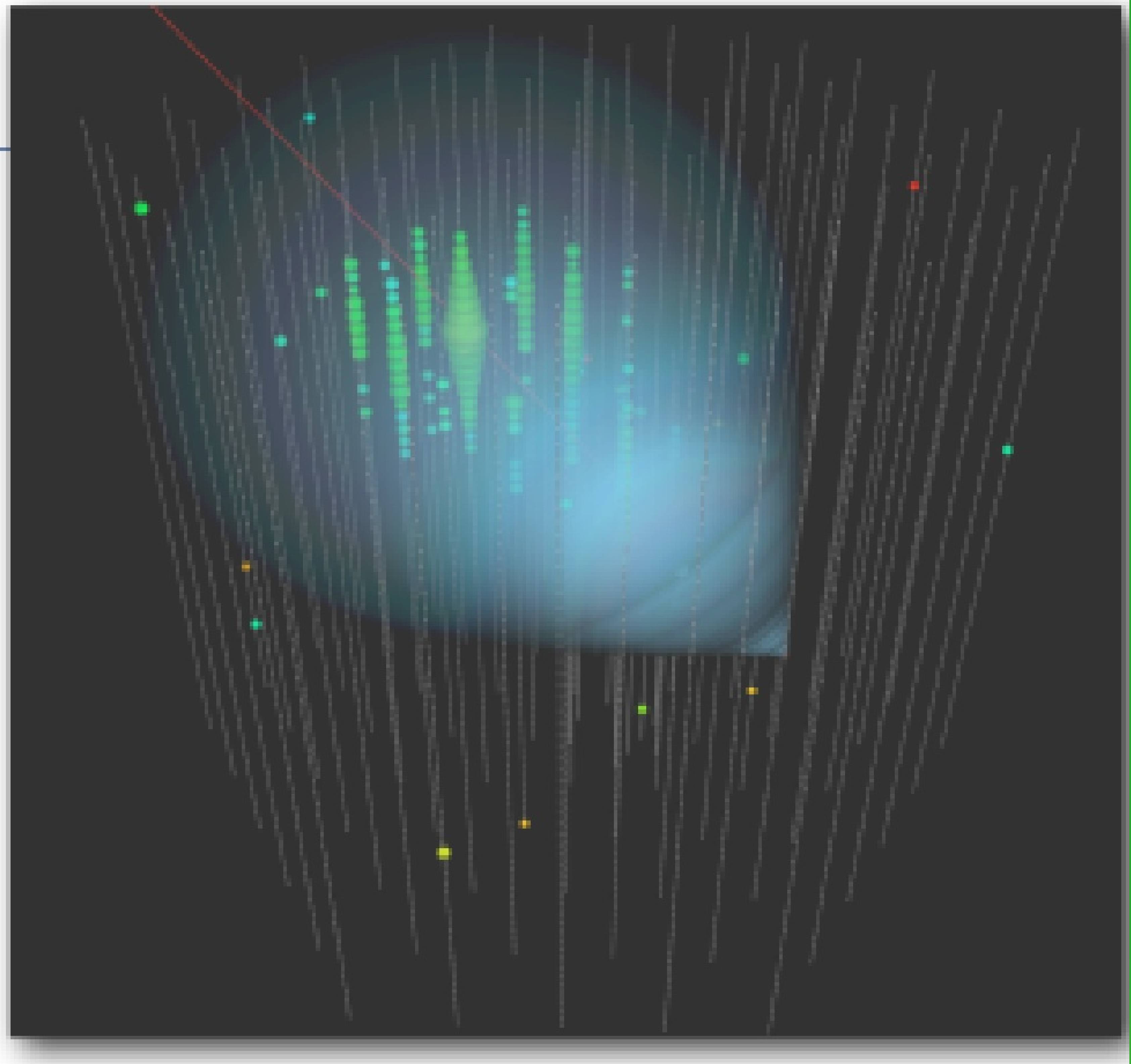
– Detection techniques for high-energy astrophysical neutrinos as a function of the ν energy range.



– The standard scenario for GRBs. Neutrino fluxes are emitted in different stages of the jet propagation: inside the progenitor shell (precursor), in the jet internal shocks (fireball) and in the jet external shocks (afterglow).

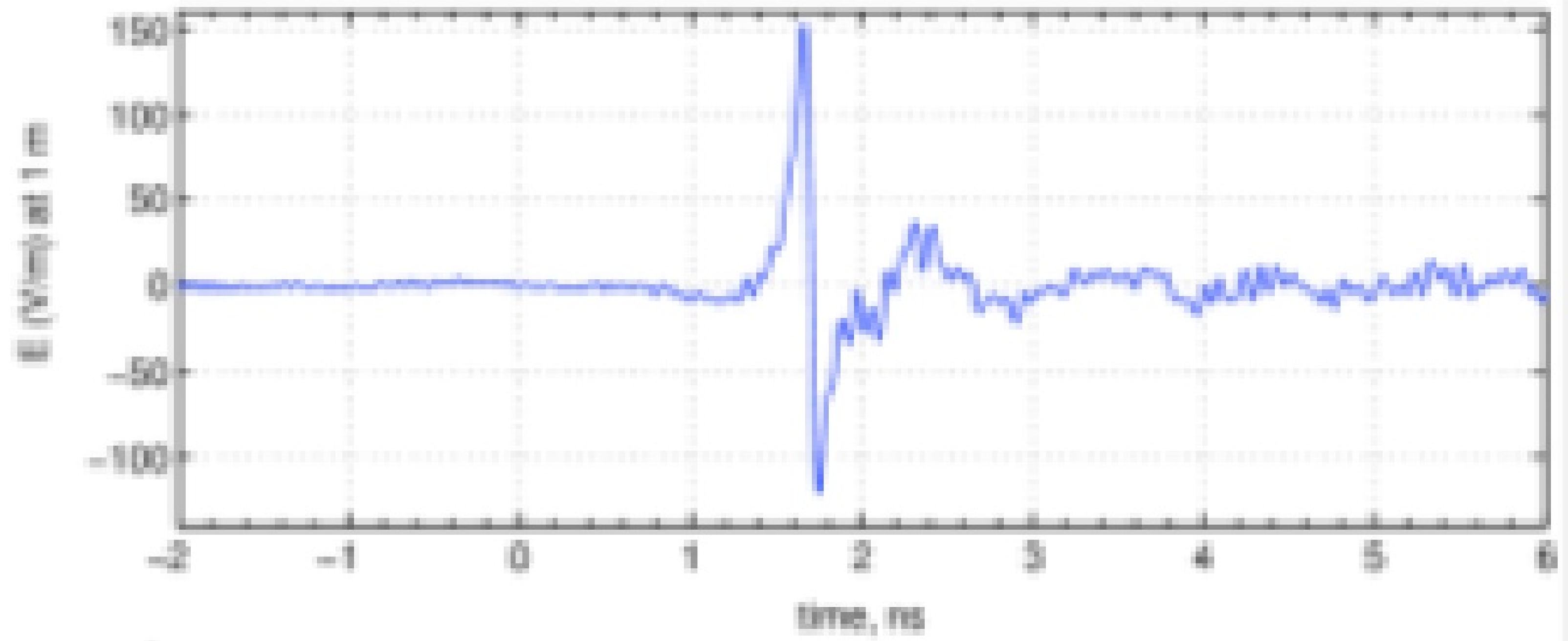
Principles of high energy ν detection

- Water Cherenkov
  - ν-induced charged particles emit a detectable pattern of Cherenkov radiation
  - backgrounds from cosmic ray μ and atmospheric ν reduced via event timing, direction, energy and vetoing techniques
- Radio Askaryan
  - radio λ's are comparable to size of ν-induced shower of charged particles; resulting coherent radiation can be very powerful
  - demonstrated at SLAC with 28 GeV shower × 10^9 particles/shower directed into a block of ice
- Penetrating or upward-going air shower
  - air Cherenkov (Auger)
- Acoustic
  - localized ν-induced heating: sharp sonic pulse
  - tests in polar icecap yielded too small λ_{att}
    - water could be better, but need water without noisy sea creatures & boats (the Dead Sea?)



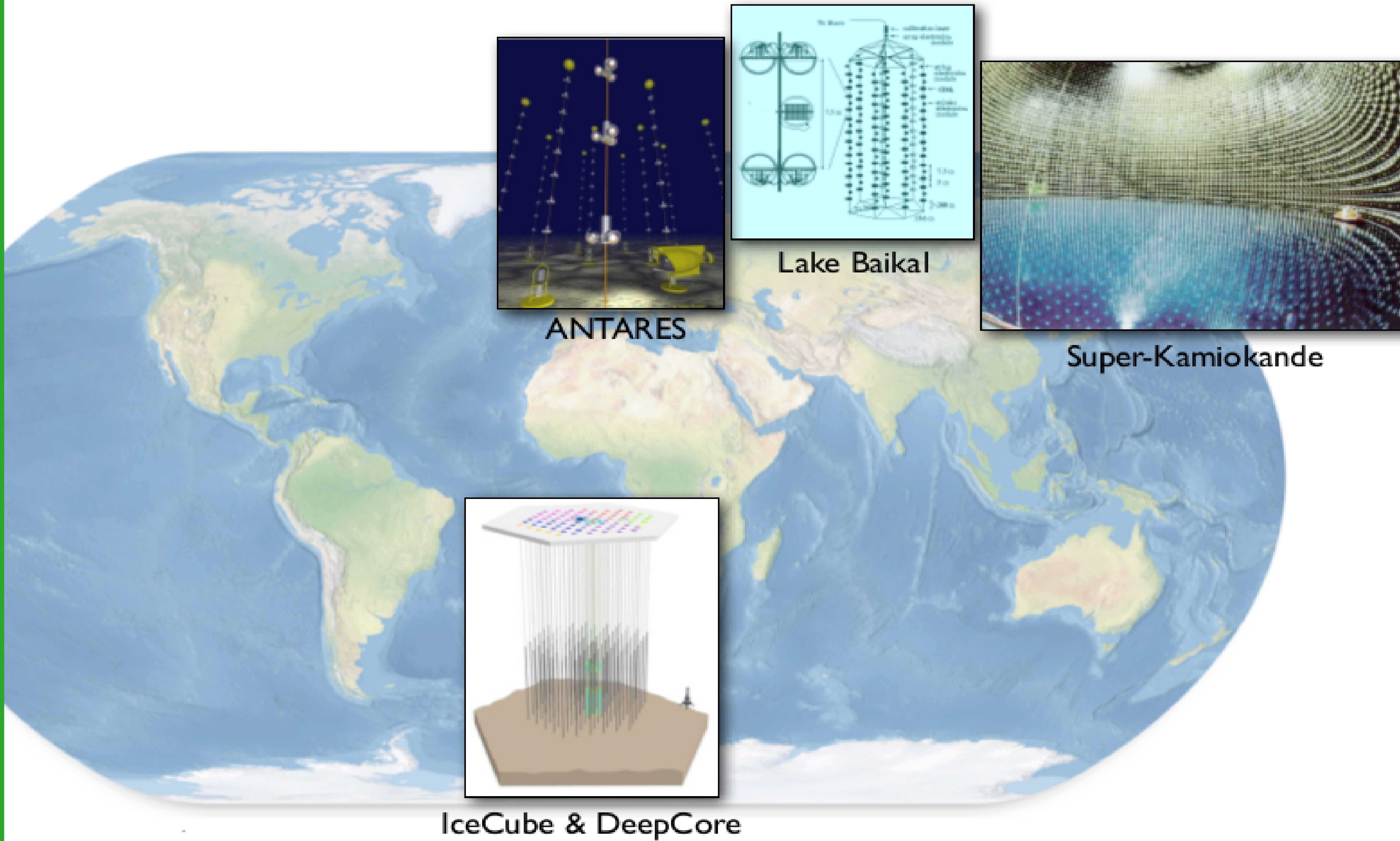
Simulated downward-going cosmic-ray muon in IceCube

Askaryan Effect Observed at SLAC



ANITA Coll. PRL (2007)

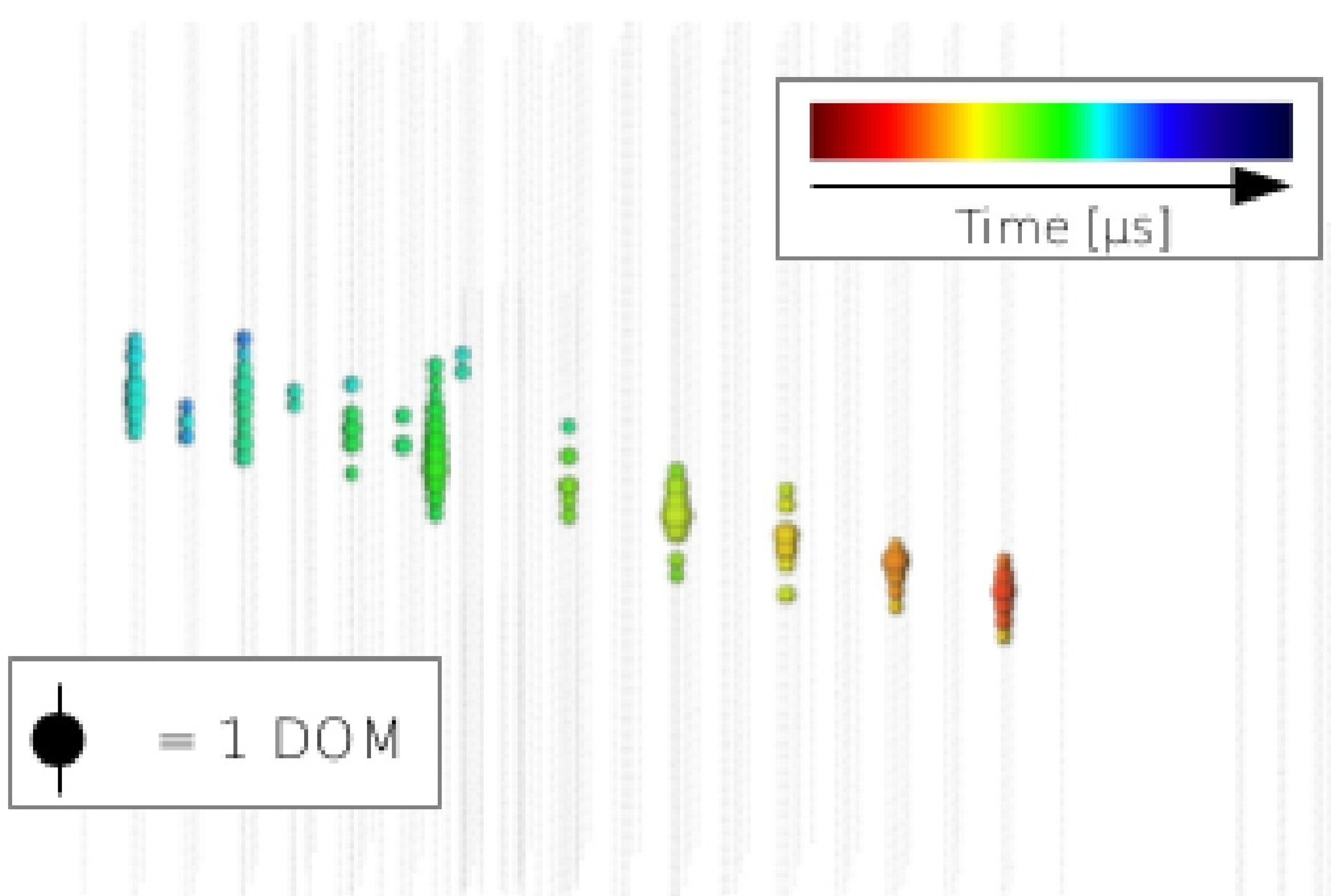
Operating large optical water Cherenkov detectors



Neutrino event signatures

Muon neutrino, CC

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



track

~ 30 TeV ν_μ

(simulation)

Very good angular resolution:
< 1°

Energy reconstruction difficult:
$\Delta \log(E_\mu) \sim 0.22$

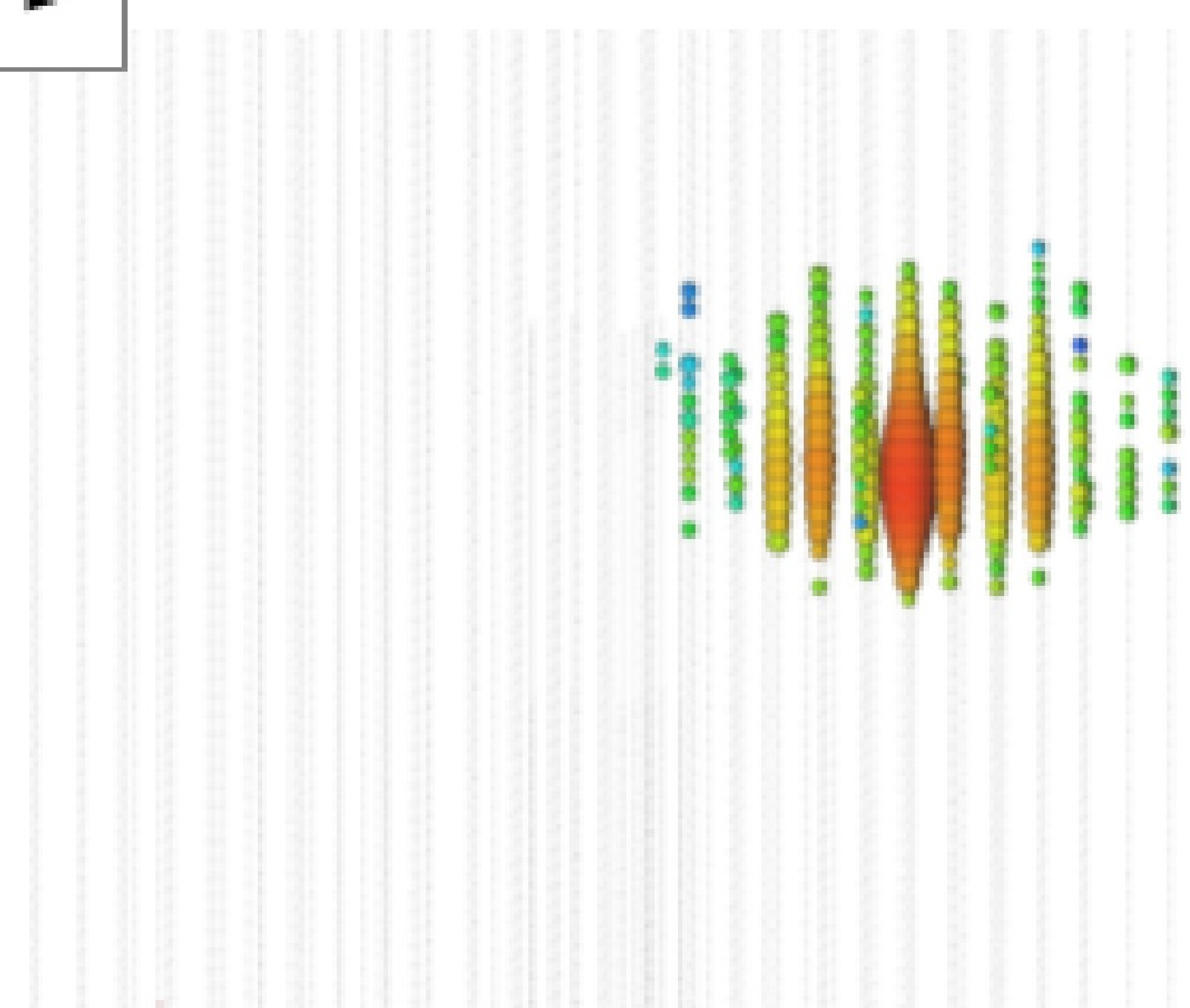
(NIM A 703, 190-198 (2013))

Electron neutrino, CC

$\nu_e + N \rightarrow e + X$

All flavors, NC

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



shower

~ 150 TeV ν_e

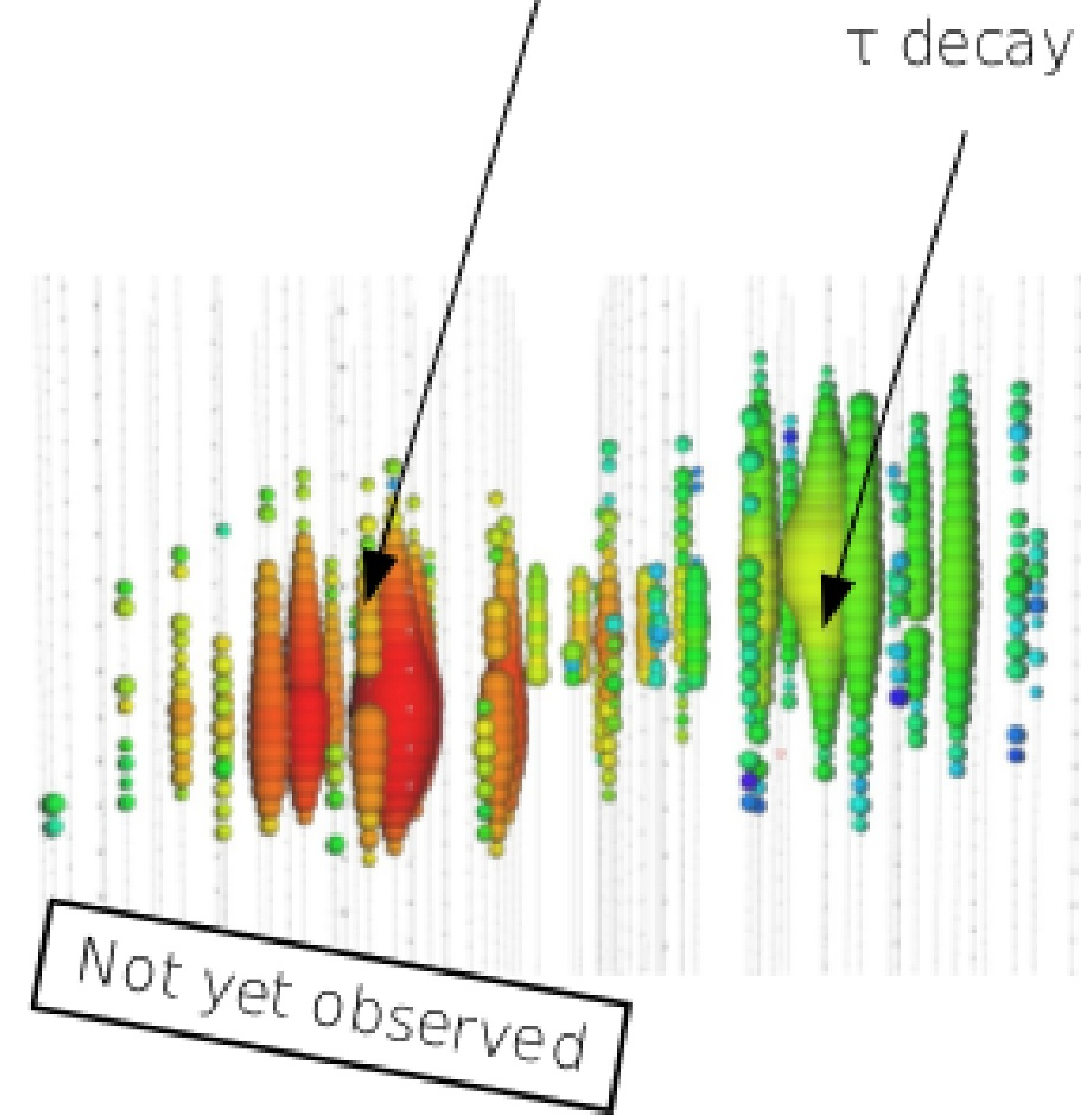
(simulation)

Angular resolution challenging:
~ 10°

Very good energy reconstruction:
$\Delta \log(E_\mu) \sim 0.22$

Tau neutrino, CC

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



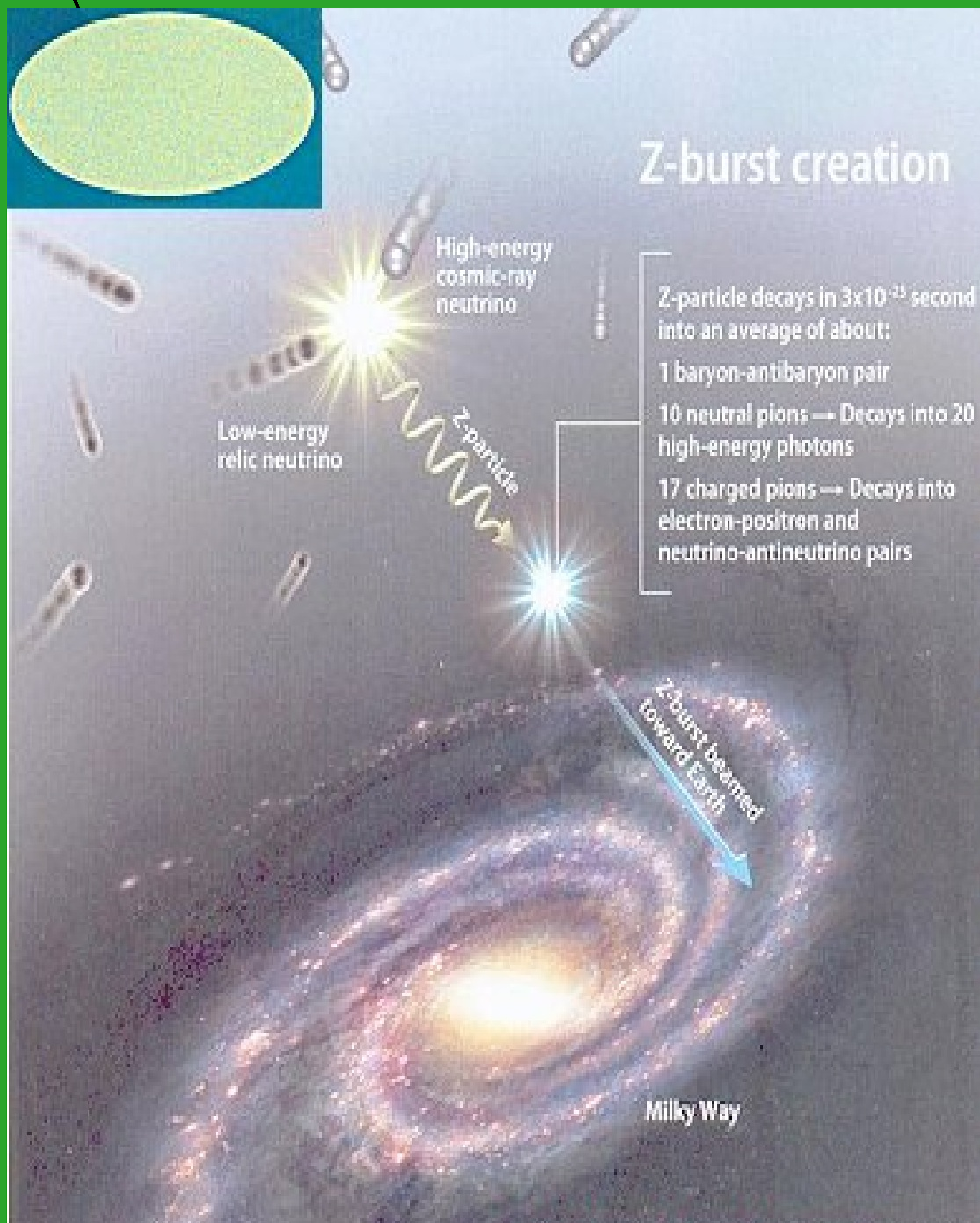
"double bang"

~ 1 PeV ν_τ

(simulation)

Interesting signature:

- Low atmospheric background
- Good energy resolution
- Good angular resolution



ULTRAHIGH-ENERGY NEUTRINOS in cosmic rays rarely should interact with the Big Bang's relic neutrinos, creating a Z-particle and a pronounced dip in the cosmic-ray energy spectrum. ASTRONOMY/ROEN KELLY

Z-bursts

Gelmini, Varieschi & Weiler, hep-ph/0404272

Hypothesis: the extreme-energy CR spectrum is produced by neutrinos from distant sources. The neutrinos can annihilate at the Z pole on relic neutrinos to produce the observable EE CR. (A GZK-style cutoff for neutrinos).

$$E_{res} = \frac{M_Z^2}{2\, m_\nu} = 4 \times 10^{21}\text{eV} \left(\frac{\text{eV}}{m_\nu}\right)$$

If cutoff is at 2 x 10^{20} eV, then m_ν > 20 eV, in disagreement with expt. EE CR thus likely not neutrino Z-burst debris.

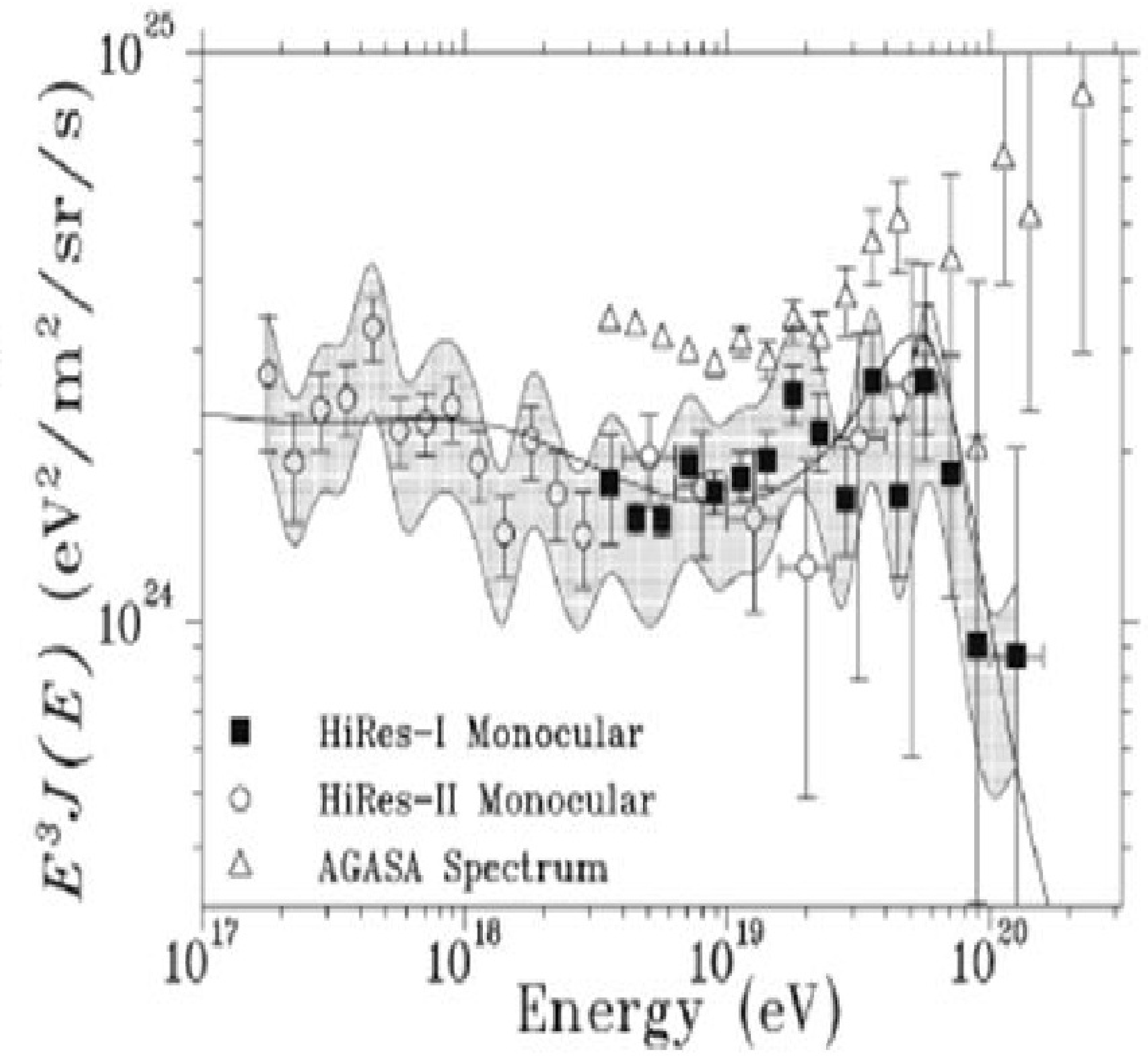
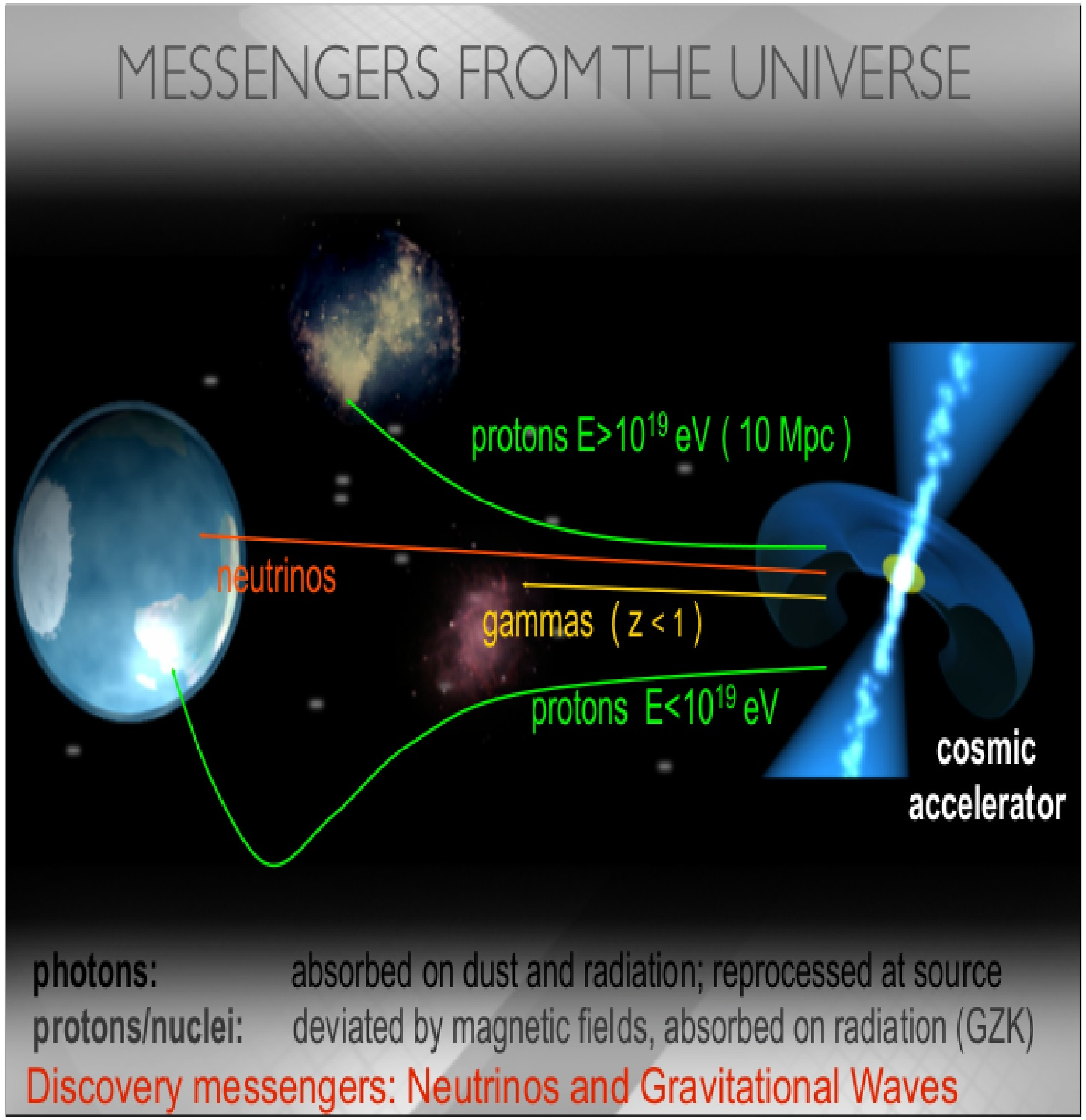
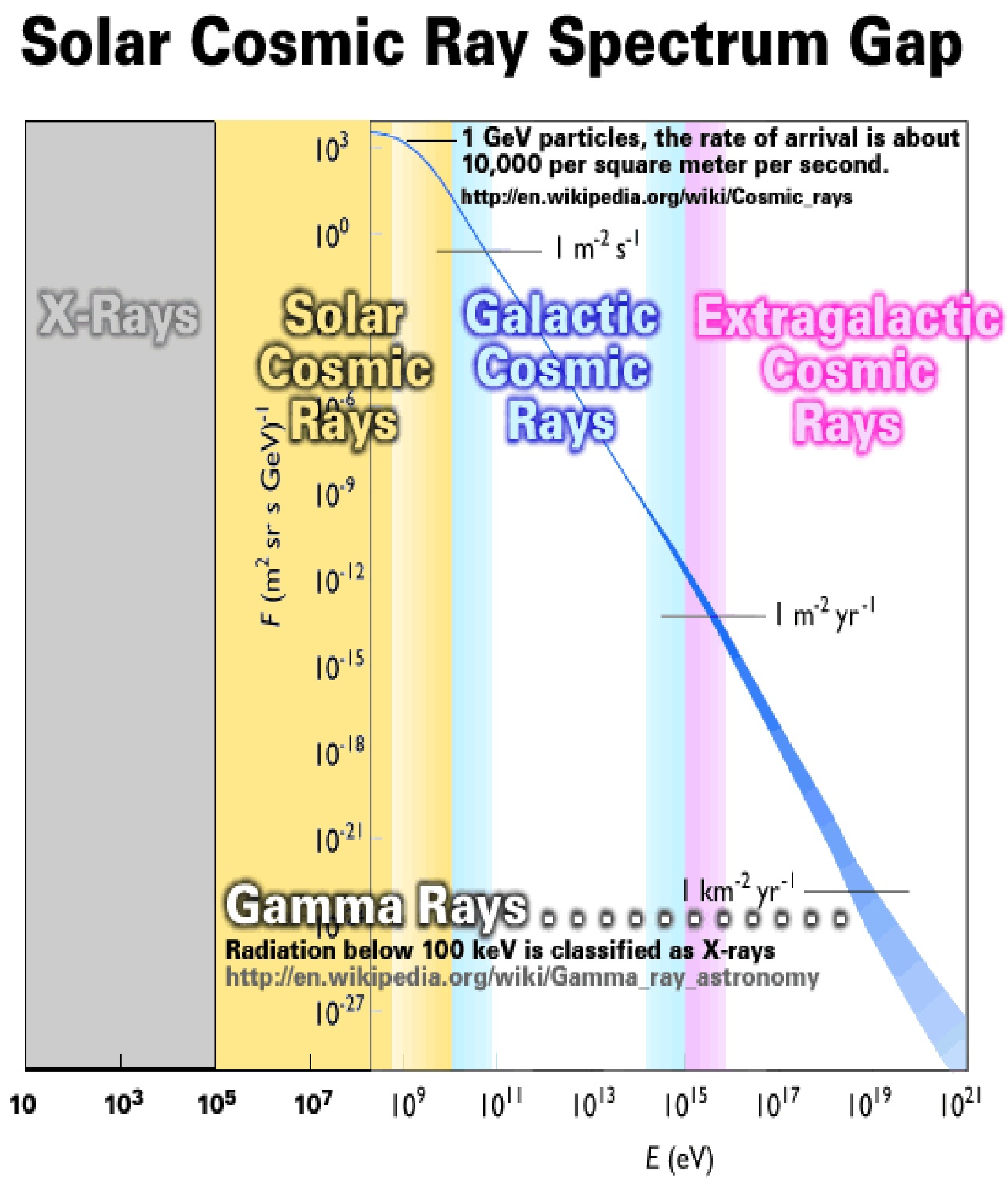


FIG. 4. Combined HiRes monocular spectrum. The squares and circles represent the HiRes-I and II differential flux $J(E)$, multiplied by E^3. The error bars are statistical only, and the systematic uncertainties are indicated by the shaded region. The line is a fit to the data of a model, described in the text, of galactic and extragalactic cosmic ray sources. The AGASA spectrum [15] is shown by triangles for comparison.

Abbasi et al., PRL 92, 151101

Only Extreme, very Extreme and likely unknown X-treme astronomy is left...And GW's!
BUT...Cosmis rays are yet mysterious...



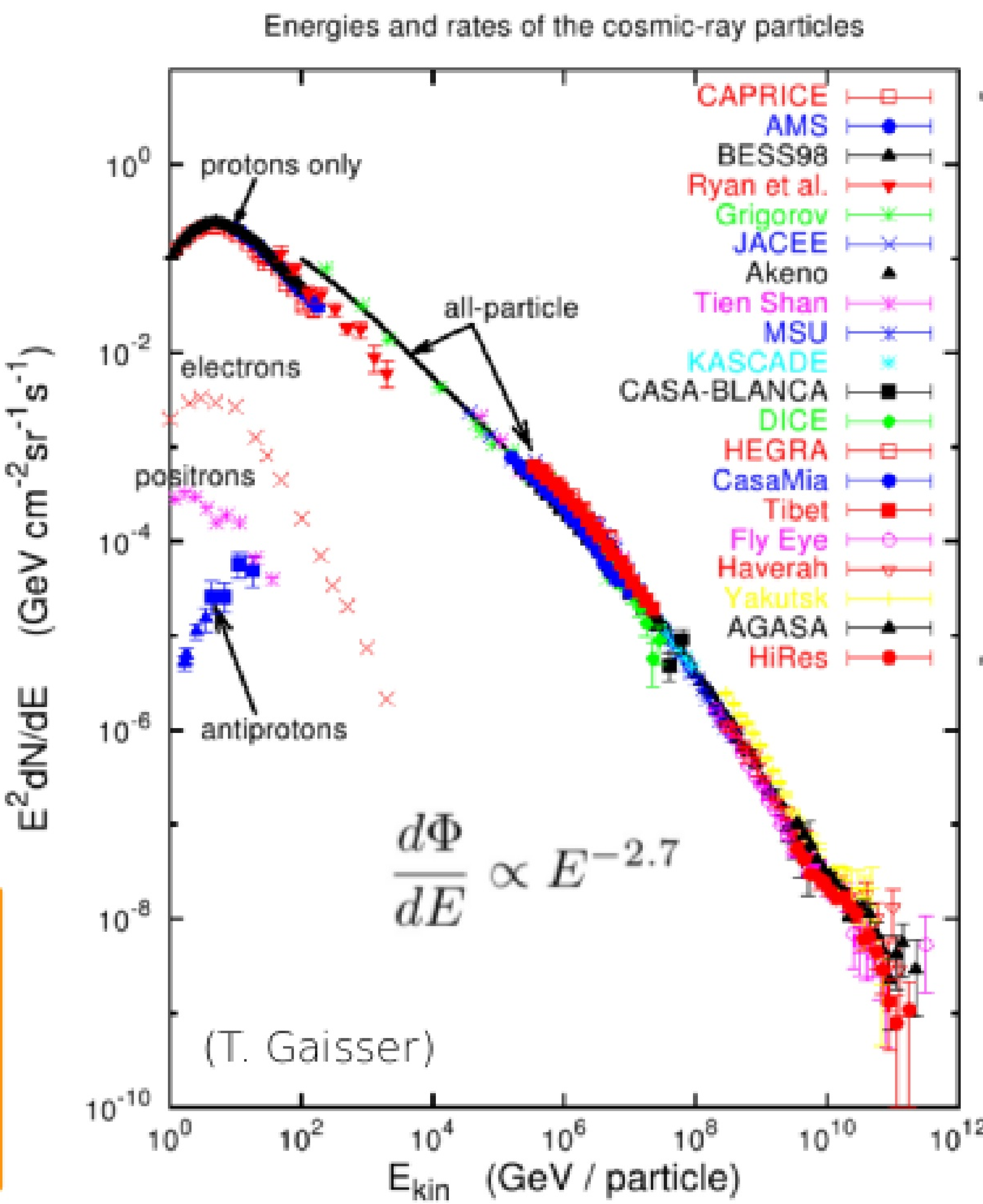


Cosmic rays: a century old puzzle

Discovered by Victor Hess in 1912

What is the acceleration mechanism?

What are the sources?

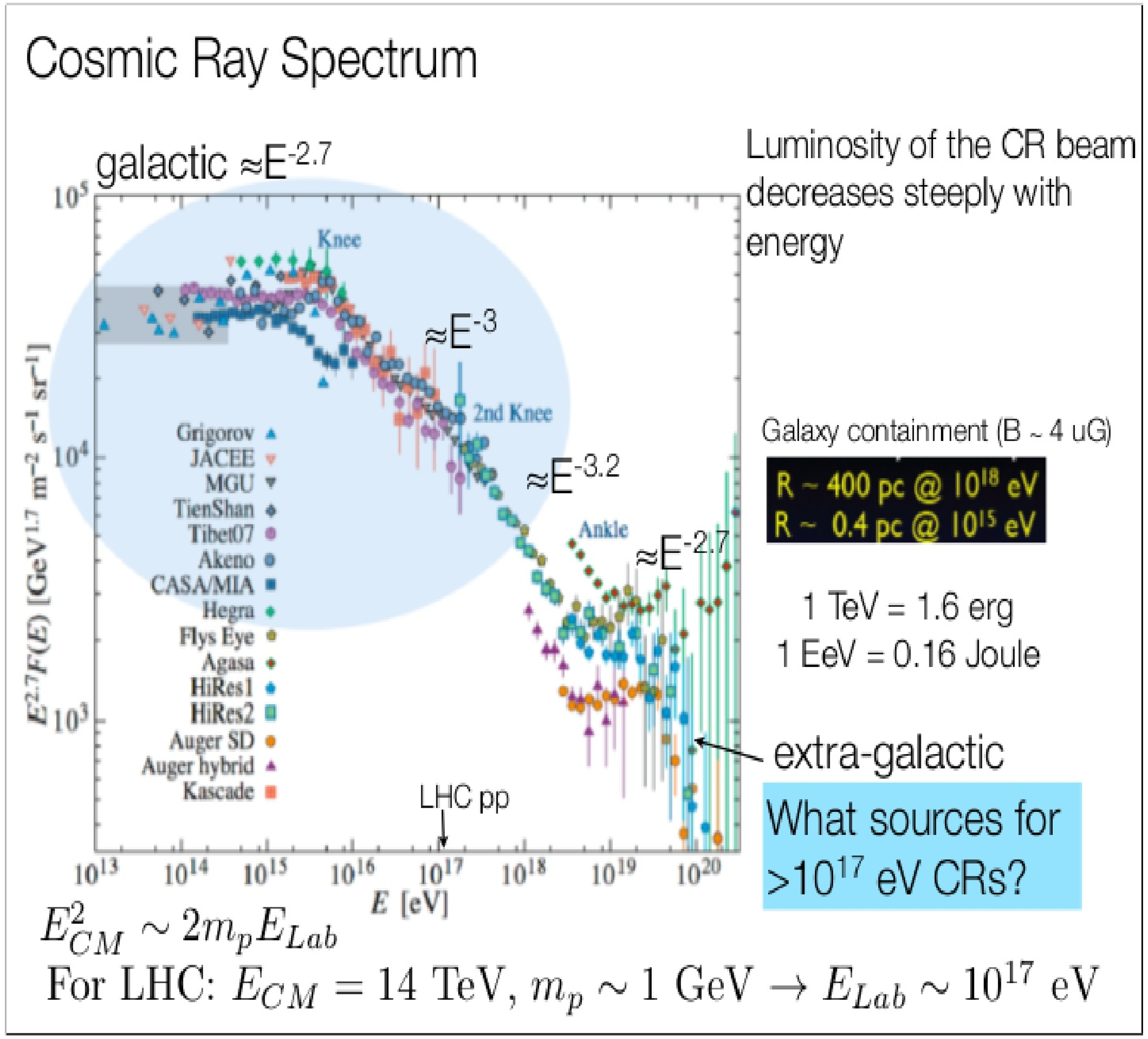


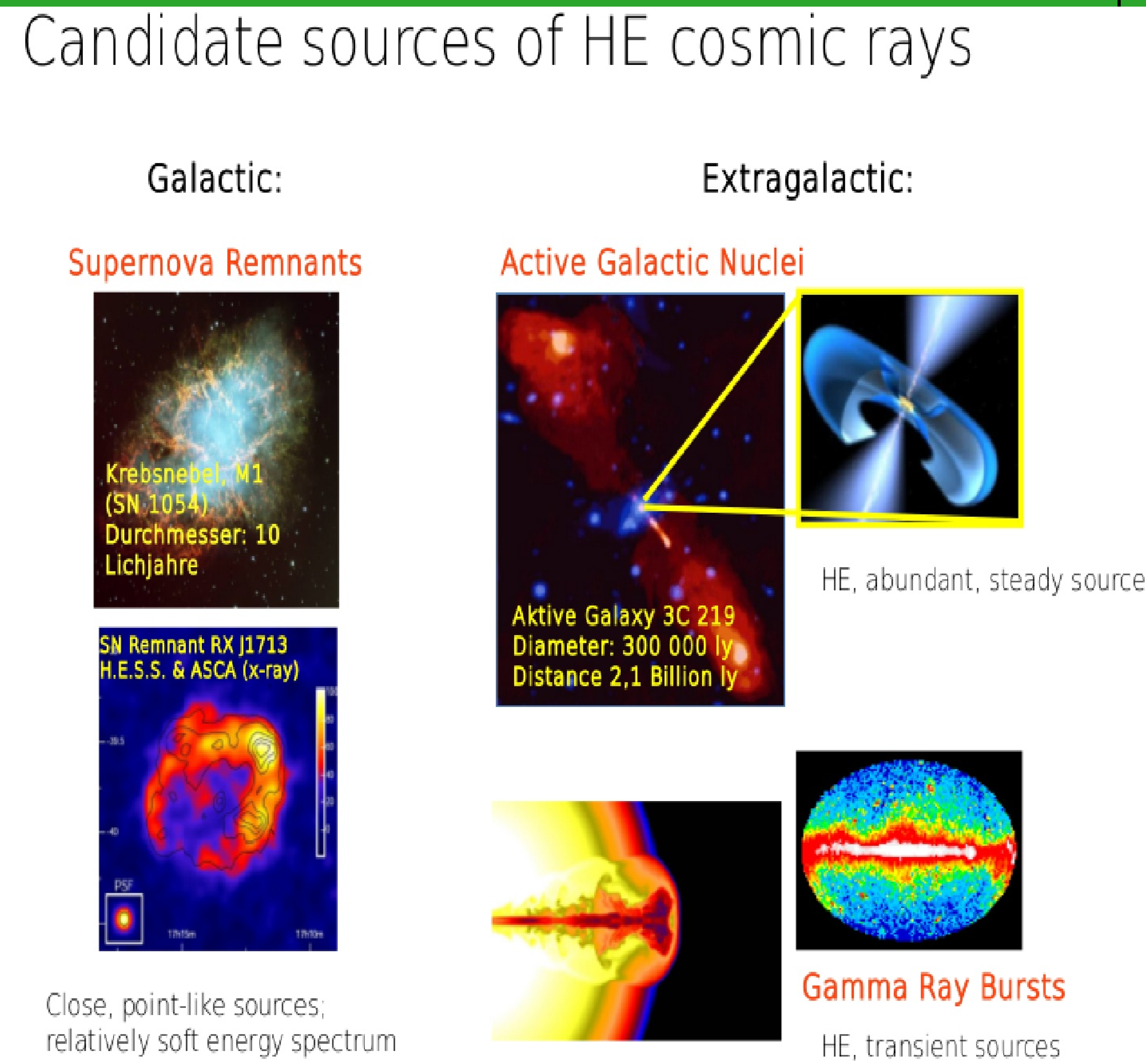
Spectrum of charged cosmic rays

Measured by many experiments!

Composition: ~ 90% protons; followed by helium and heavier nuclei

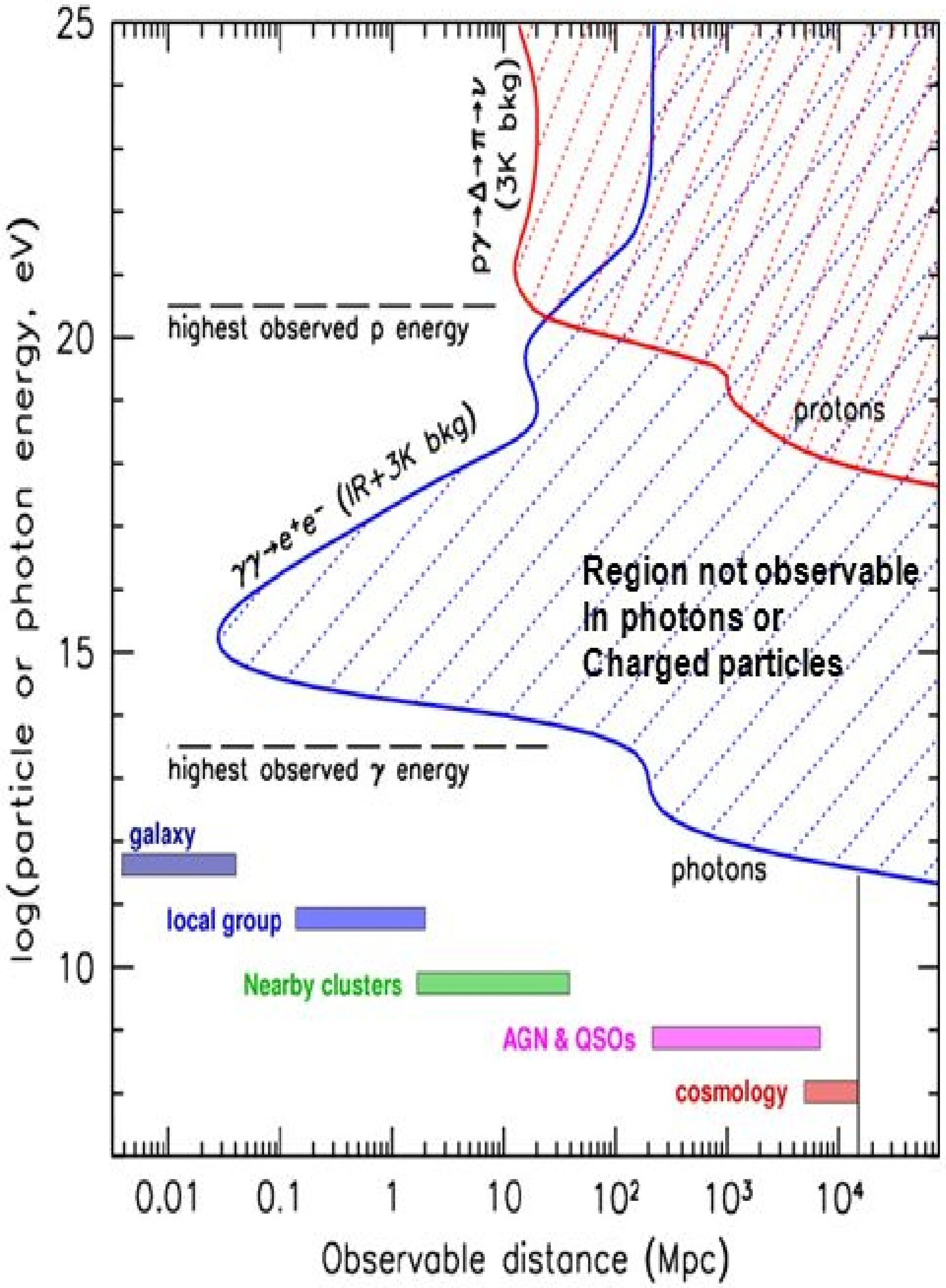
Electron flux ~ 1/100 of proton flux





- Cosmic ray astronomy complementary to neutrino astronomy.
- Gamma ray astronomy complementary to neutrino astronomy.
- X-ray astronomy complementary to neutrino astronomy.
- Neutrino astronomy adds a new window and it is related to other important branches of Astronomy and Astrophysics. Neutrino astronomy is a cosmic key...
- GW astronomy will likely be complementary as well...

Neutrinos: The only useful messengers for astrophysics at >PeV energies

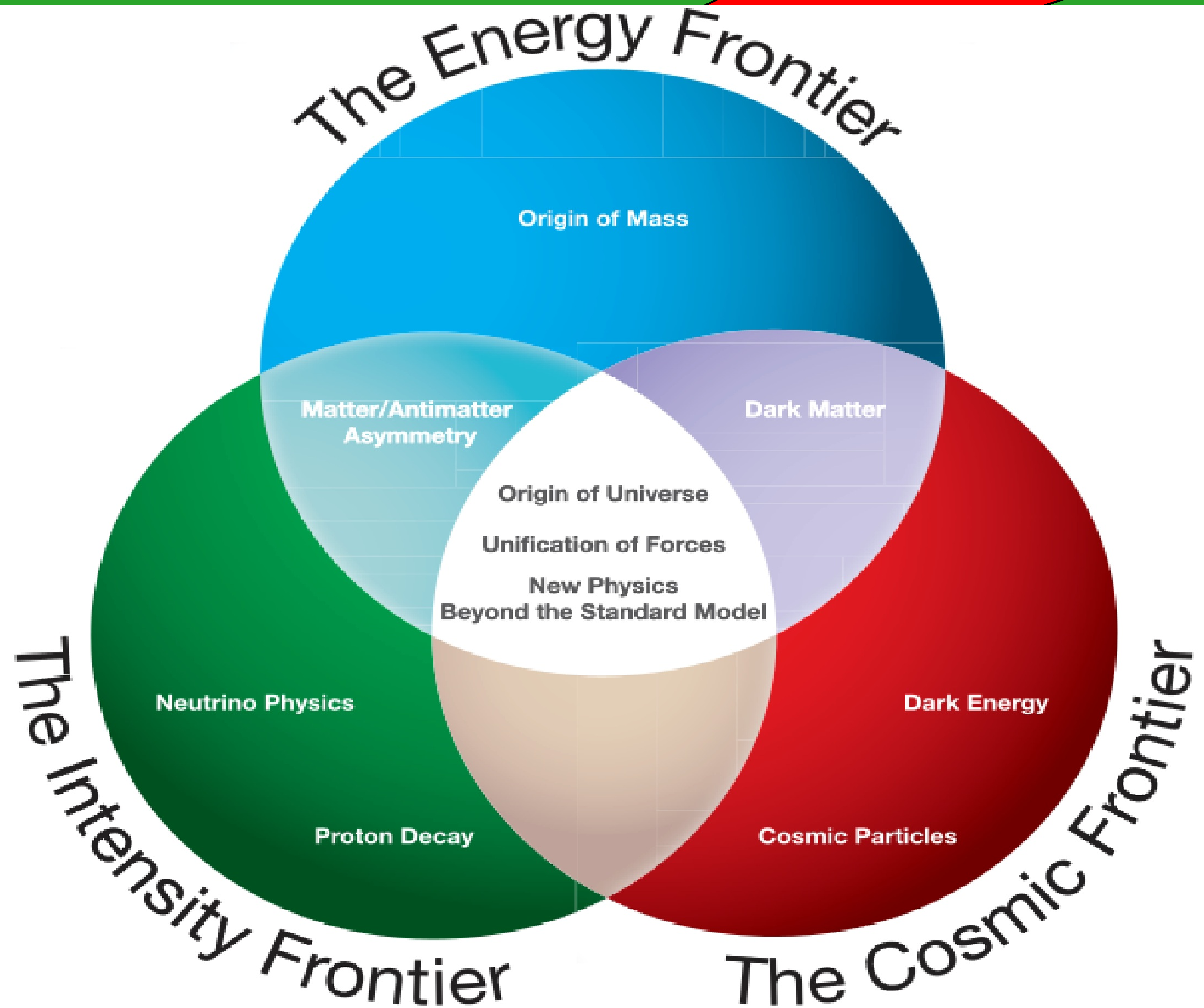


- **Photons lost above 30 TeV:** pair production on IR & μwave background
- **Charged particles:** scattered by B-fields or GZK process at all energies
- But the sources extend to 10^9 TeV !

Conclusion:

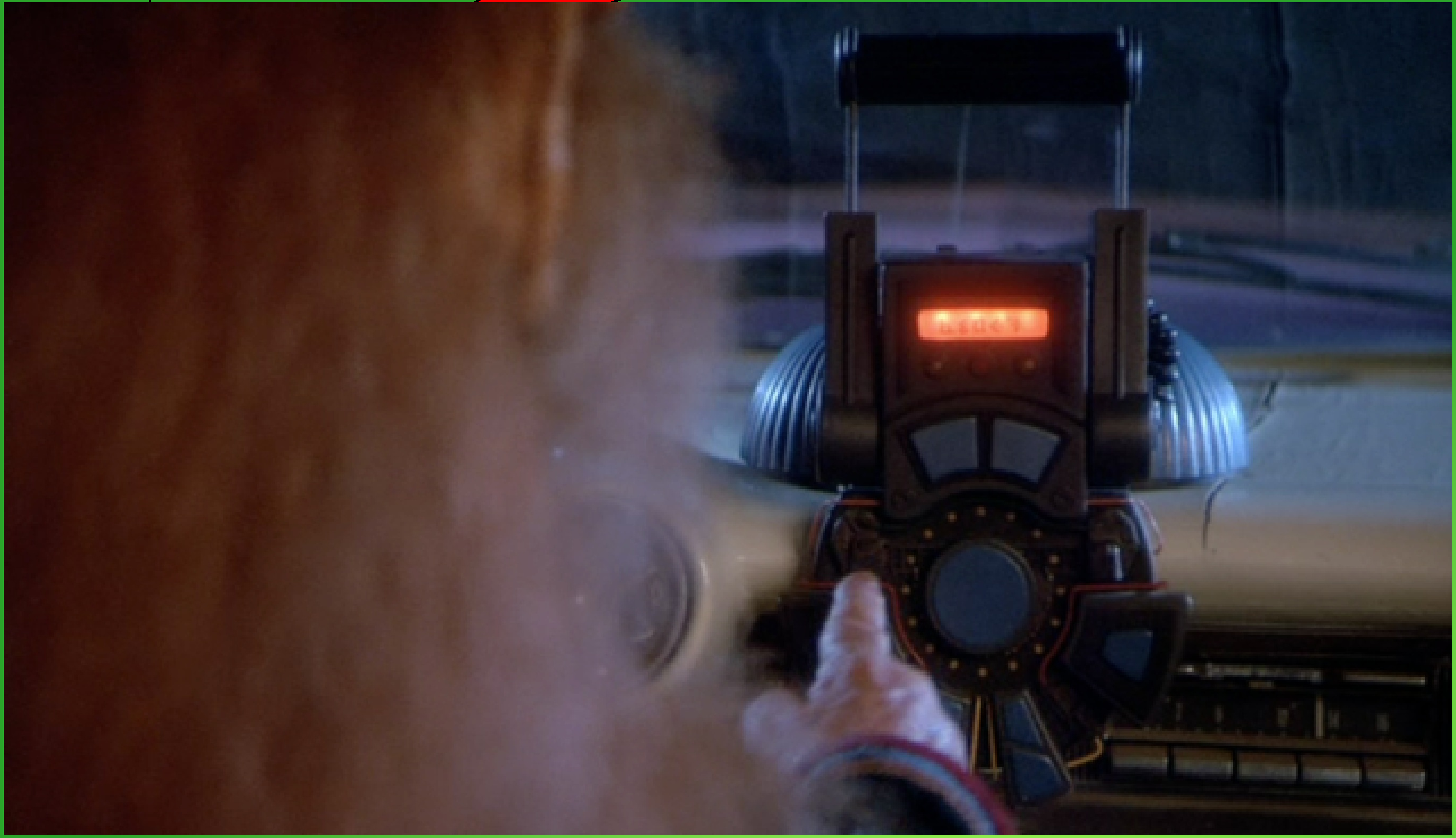
- **Study of the highest energy processes and particles throughout the universe *requires* PeV-ZeV neutrino detectors**

- The neutrino window is open and providing new information about the Universe (galactical and extragalactical zones!)!
- Many questions are yet unsolved!
- Neutrinos (and GW) astronomy are the current and future tools of a radically different kind of Astronomy, with an horizon wider than photon and proton astronomy.
- Neutrino astronomy is complementary to classical photon astronomy.
- Interdisciplinary links between all the areas: multimessenger, multiband, multiparticle/multifield era!!!!!!

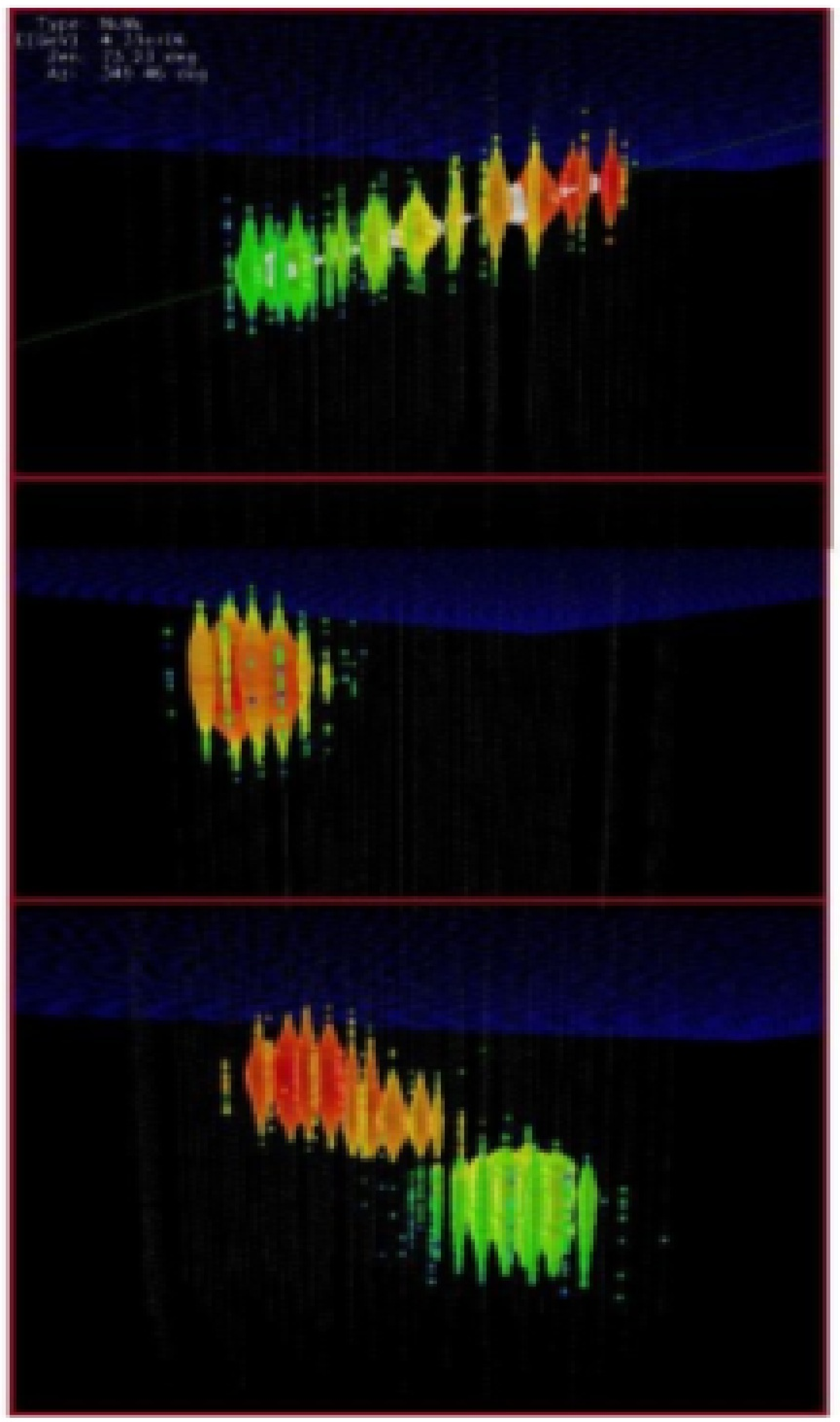


The Energy Frontier
Origin of Mass
Matter/Antimatter Asymmetry
Dark Matter
Origin of Universe
Unification of Forces
New Physics Beyond the Standard Model
Neutrino Physics
Proton Decay
Dark Energy
Cosmic Particles
The Intensity Frontier
The Cosmic Frontier

Thank you!!!!



One may even distinguish neutrino flavors



(a)

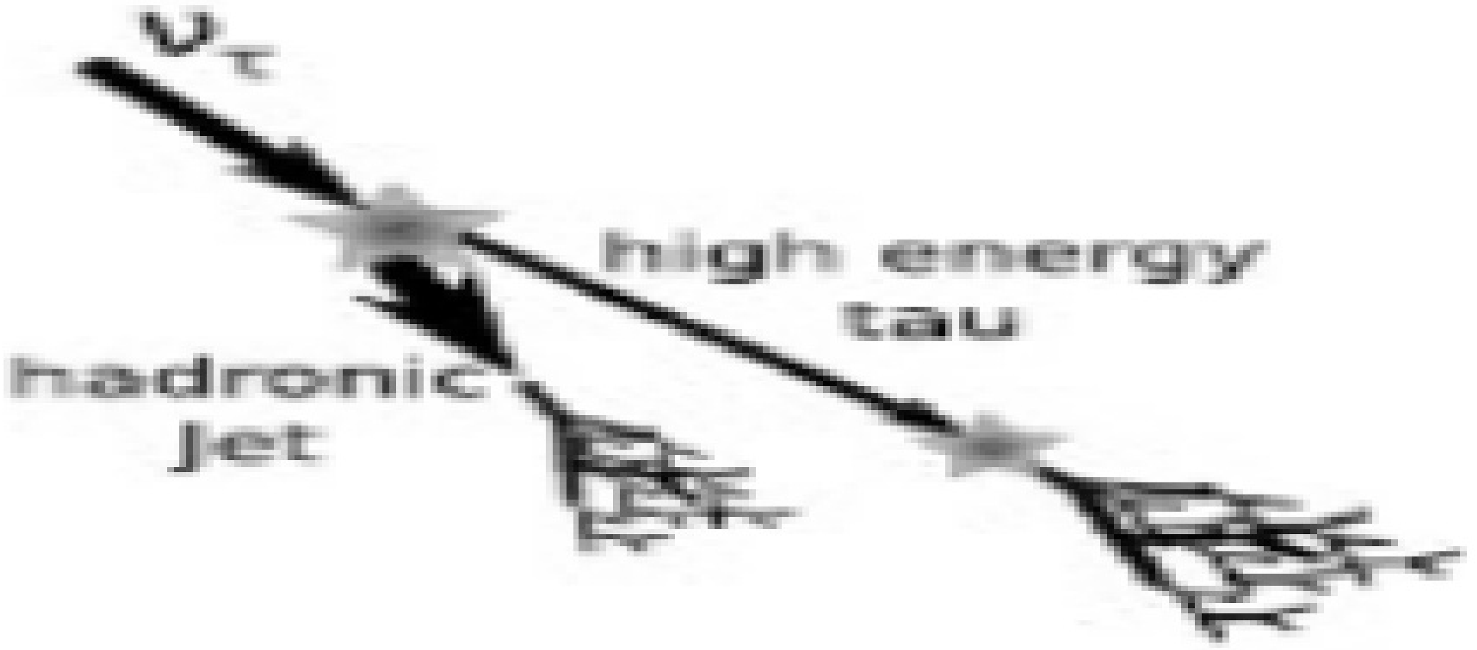
(b)

(c)

muon neutrino (track)

electron neutrino (cascade, also from NC)

tau neutrino (double bang)

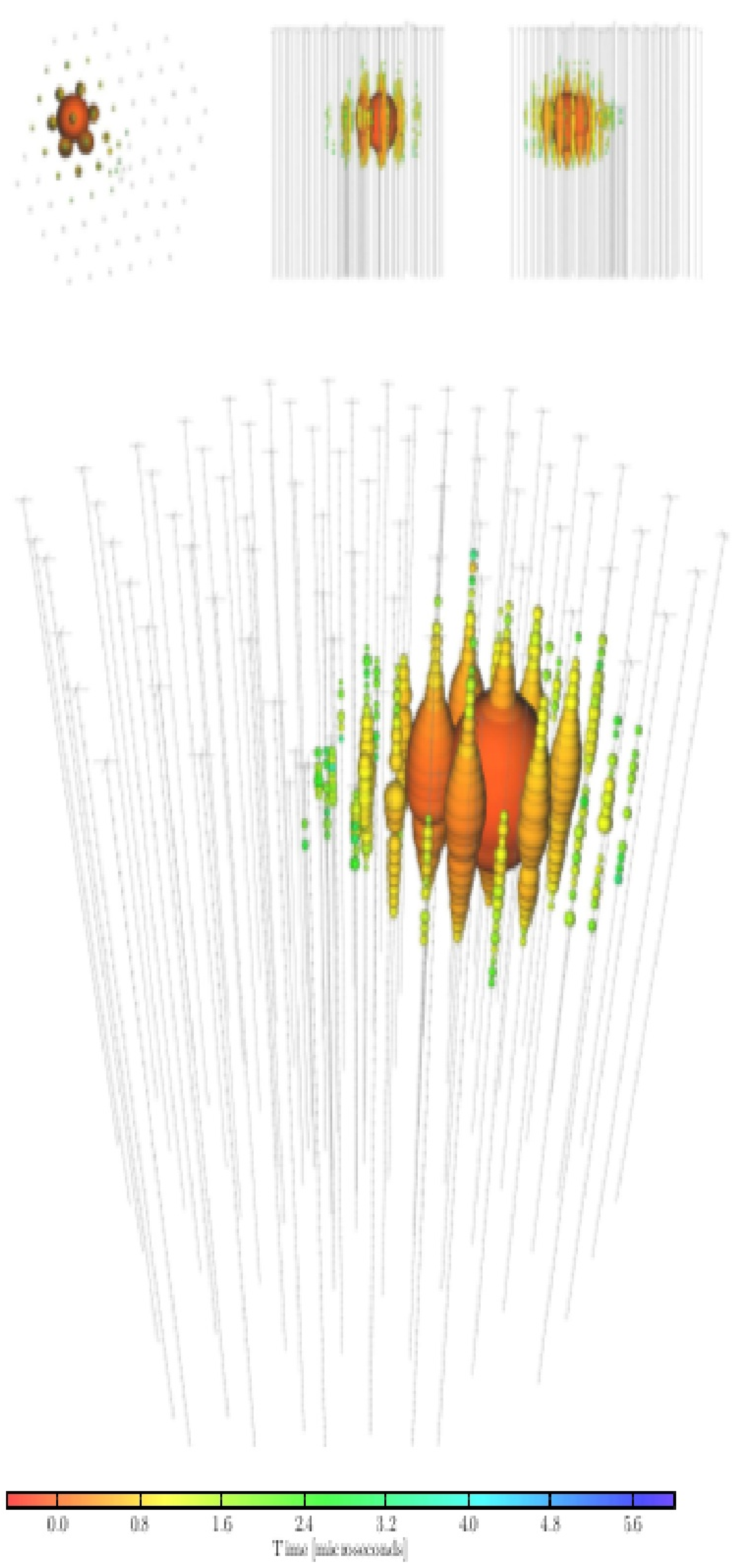



28 High Energy Events
Strangepork
Animal
Beaker
Kermit
Ernie
Bert
CrazyHarry
Gonzo
LewZealand
Camilia
GuySmiley
Oscar
MissPiggy
LinkHogthrob
28 High Energy Events
Floyd
Teeth
Pepe
SamEagle
Snuffleupagus
Rizzo
SwedishChef
Sweetums
Zoot
BunsenHoneydew
Rowlf
Scooter
CountVonCount
Fozzy

The IceCube high energy starting events analysis

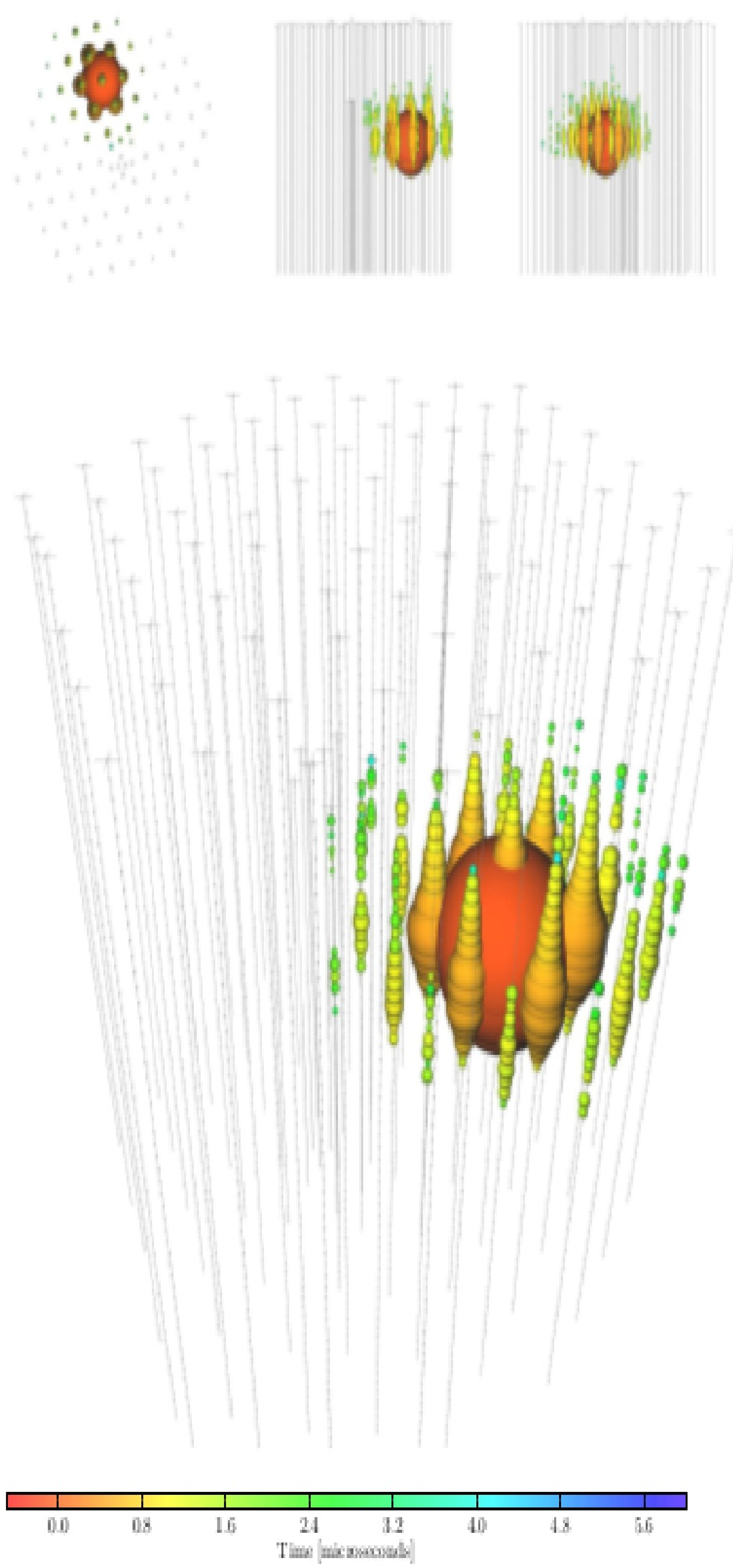
The result of the search... 28 events! (each named after a Muppet; shown in order of appearance)

EVENT 14



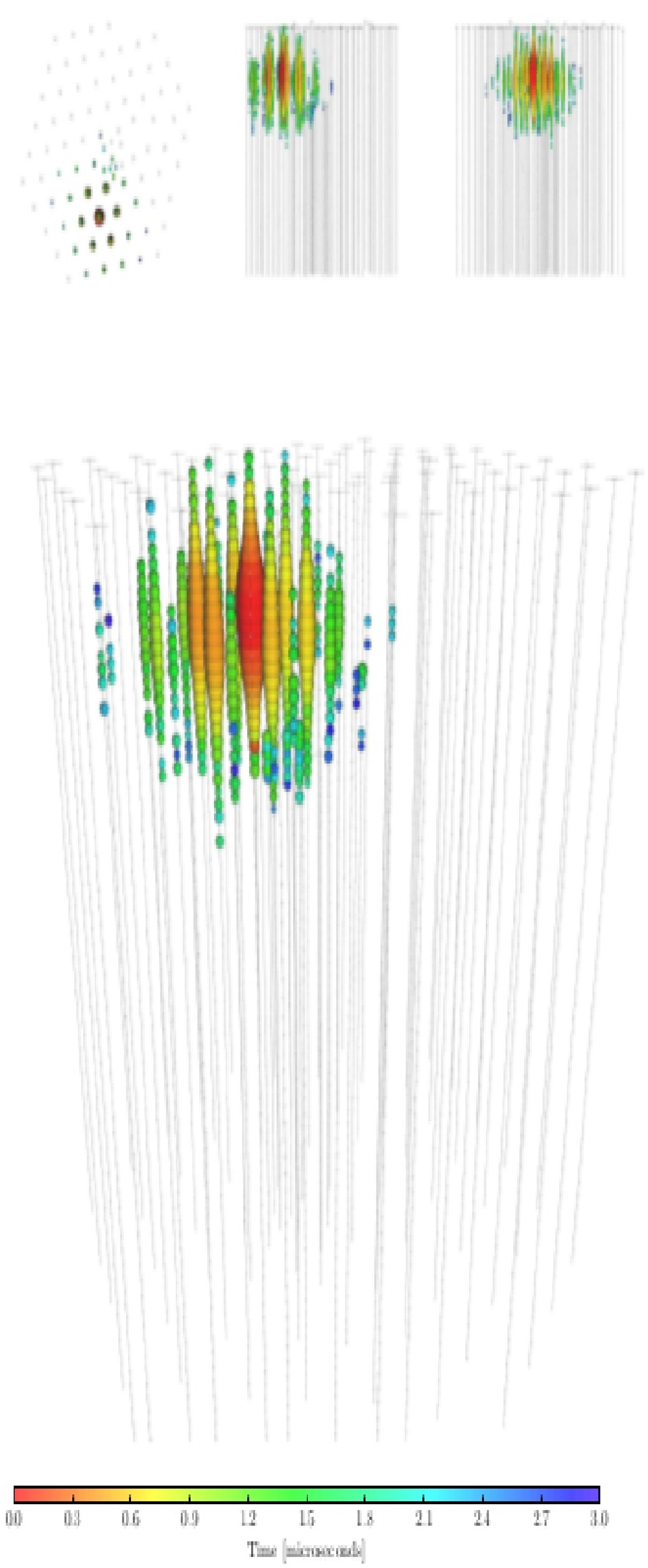
Deposited Energy (TeV)	Time (MJD)	Declination (deg.)	RA (deg.)	Med. Ang. Resolution (deg.)	Topology
$1040.7^{+131.6}_{-144.4}$	55782.5161816	−27.9	265.6	13.2	Shower

EVENT 20



Deposited Energy (TeV)	Time (MJD)	Declination (deg.)	RA (deg.)	Med. Ang. Resolution (deg.)	Topology
$1140.8^{+142.8}_{-132.8}$	55929.3986232	−67.2	38.3	10.7	Shower

EVENT 35

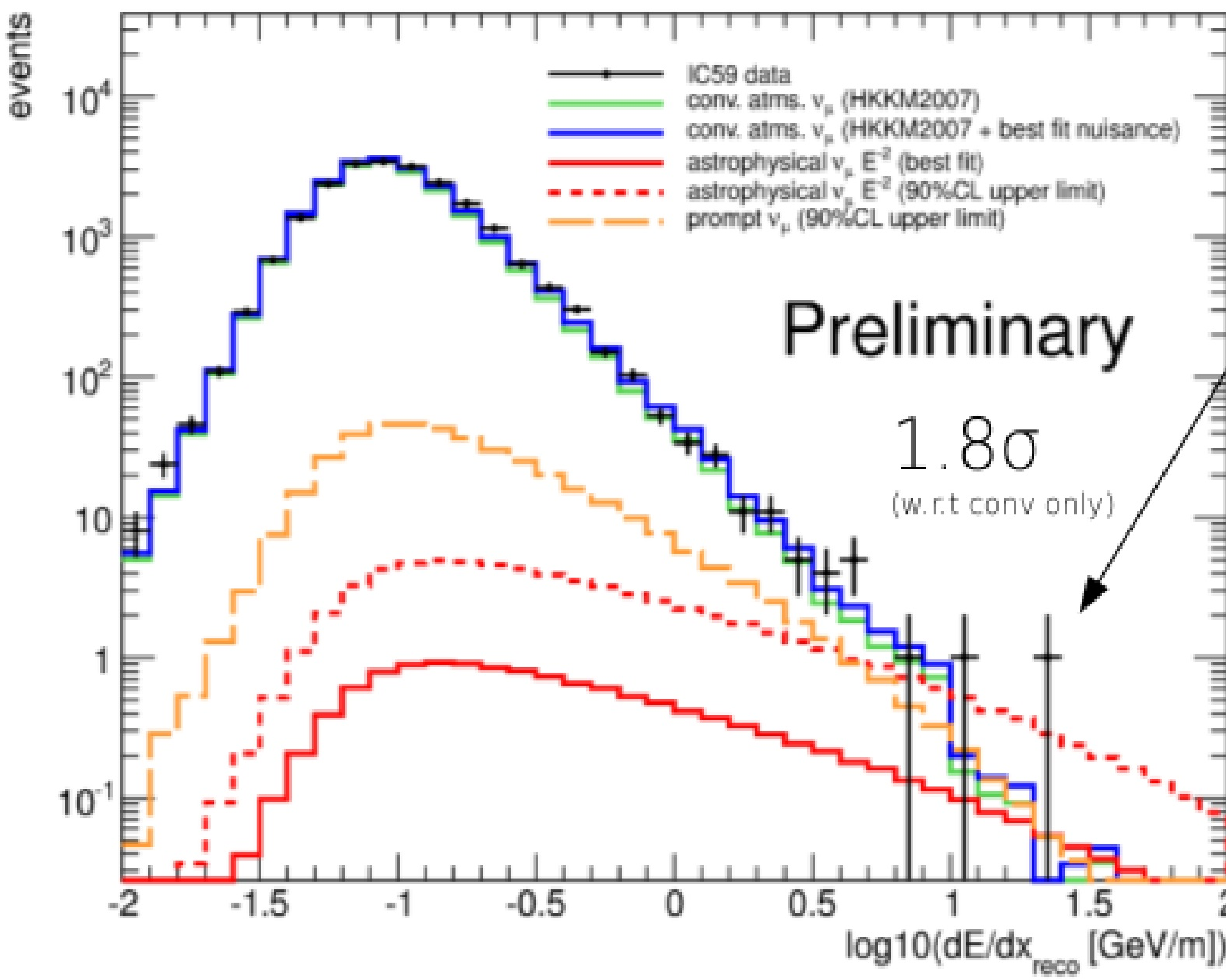


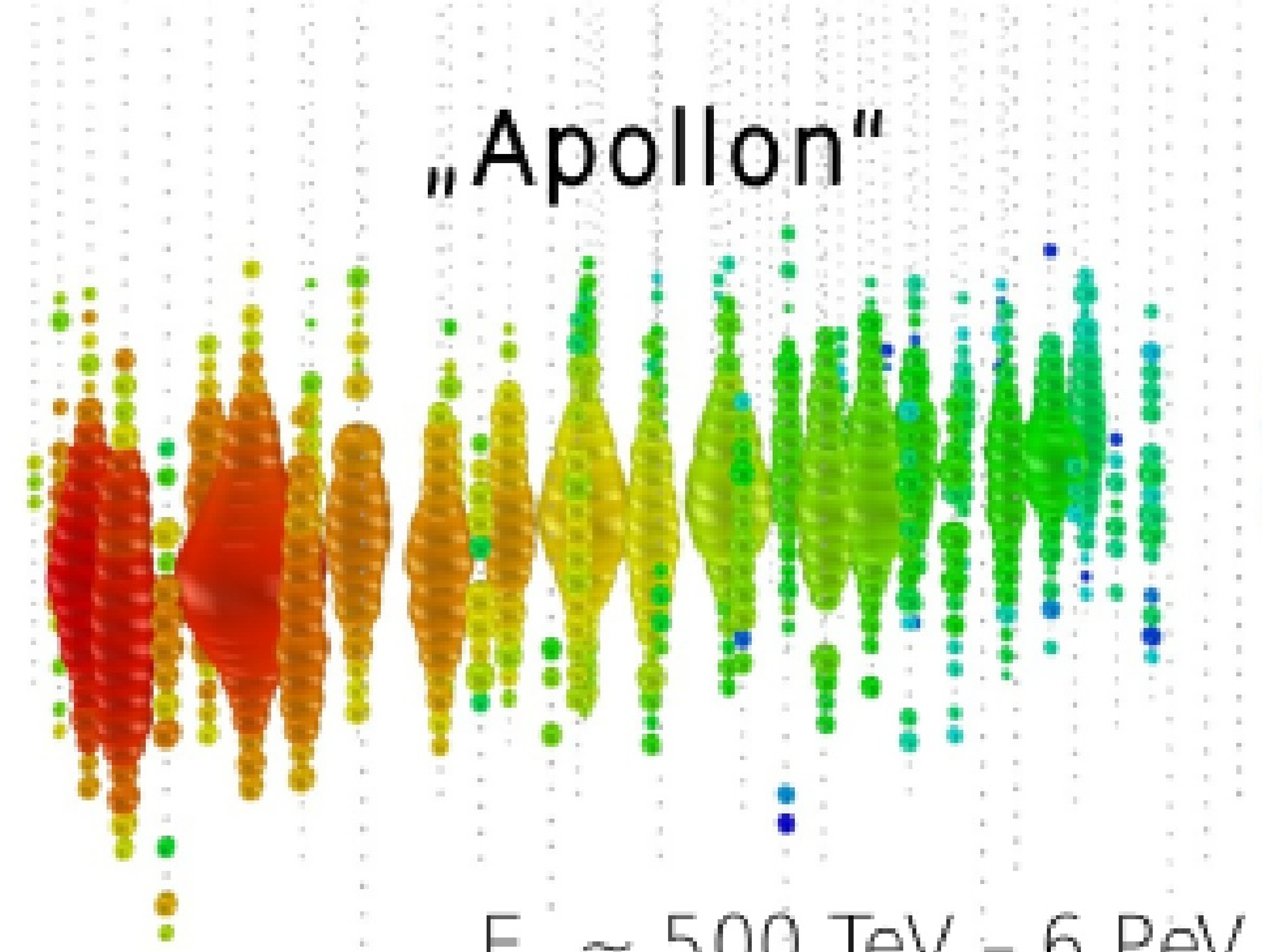
Deposited Energy (TeV)	Time (MJD)	Declination (deg.)	RA (deg.)	Med. Ang. Resolution (deg.)	Topology
2004^{+236}_{-262}	56265.1338677	−55.8	208.4	15.9	Shower

First hints on an extraterrestrial neutrino signal

Tracks:

A. Schukraft, RWTH Aachen





E_ν ~ 500 TeV – 6 PeV

Showers:

2.7σ
(w.r.t conv+prompt)

E. Middell, DESY

Extremely HE events:

2.8σ
(w.r.t conv+prompt)

A. Ishihara, K. Mase, Chiba U
Phys. Rev. Lett. 111 (2013) 021103

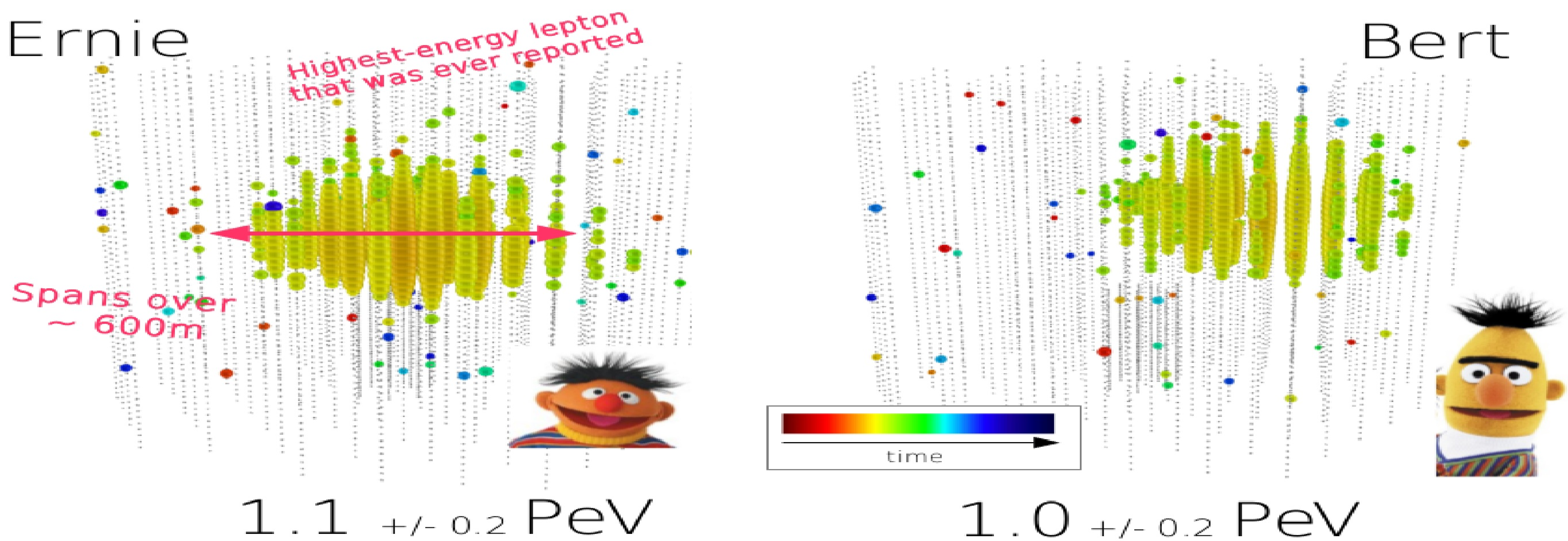
Best fit:

Prompt atmospheric neutrinos: 0
Astrophysical flux: $0.24 * 10^{-8}$ GeV cm^{-2} s^{-1} sr^{-1}

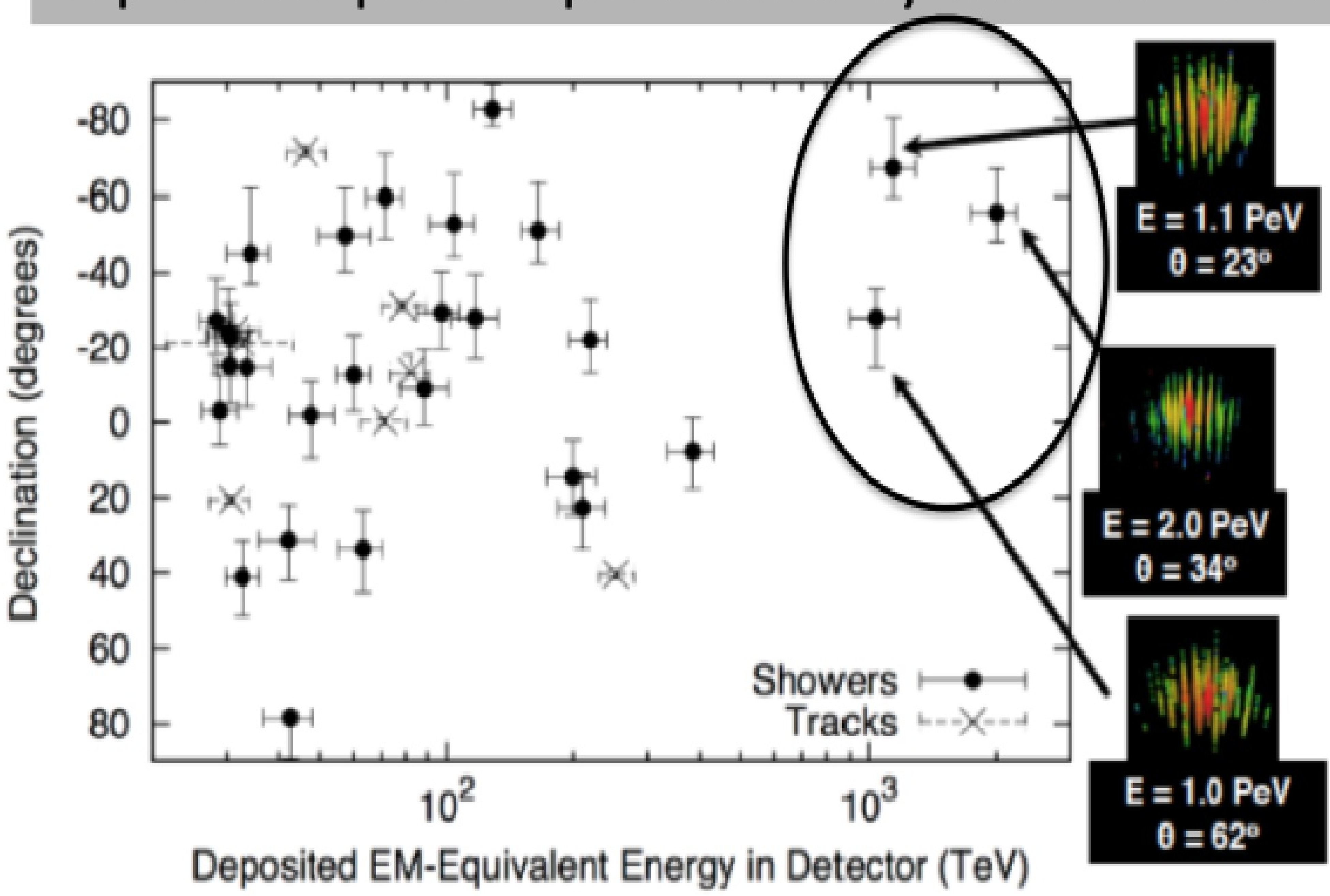
These 2 events were at the lower end of the energy sensitivity for the analysis. They were given names fitting for such giant high energy neutrinos...

IceCube's first PeV events

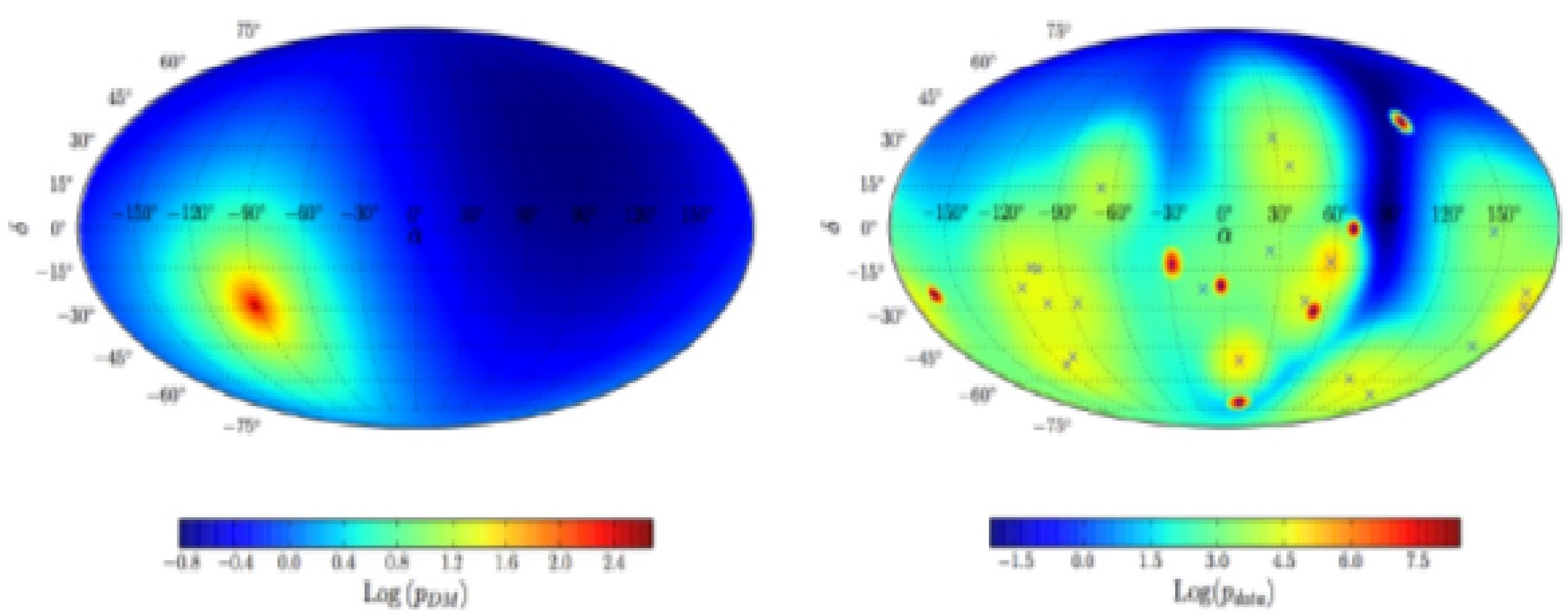
A. Ishihara, K. Mase, Chiba U
Phys. Rev. Lett. 111 (2013) 021103



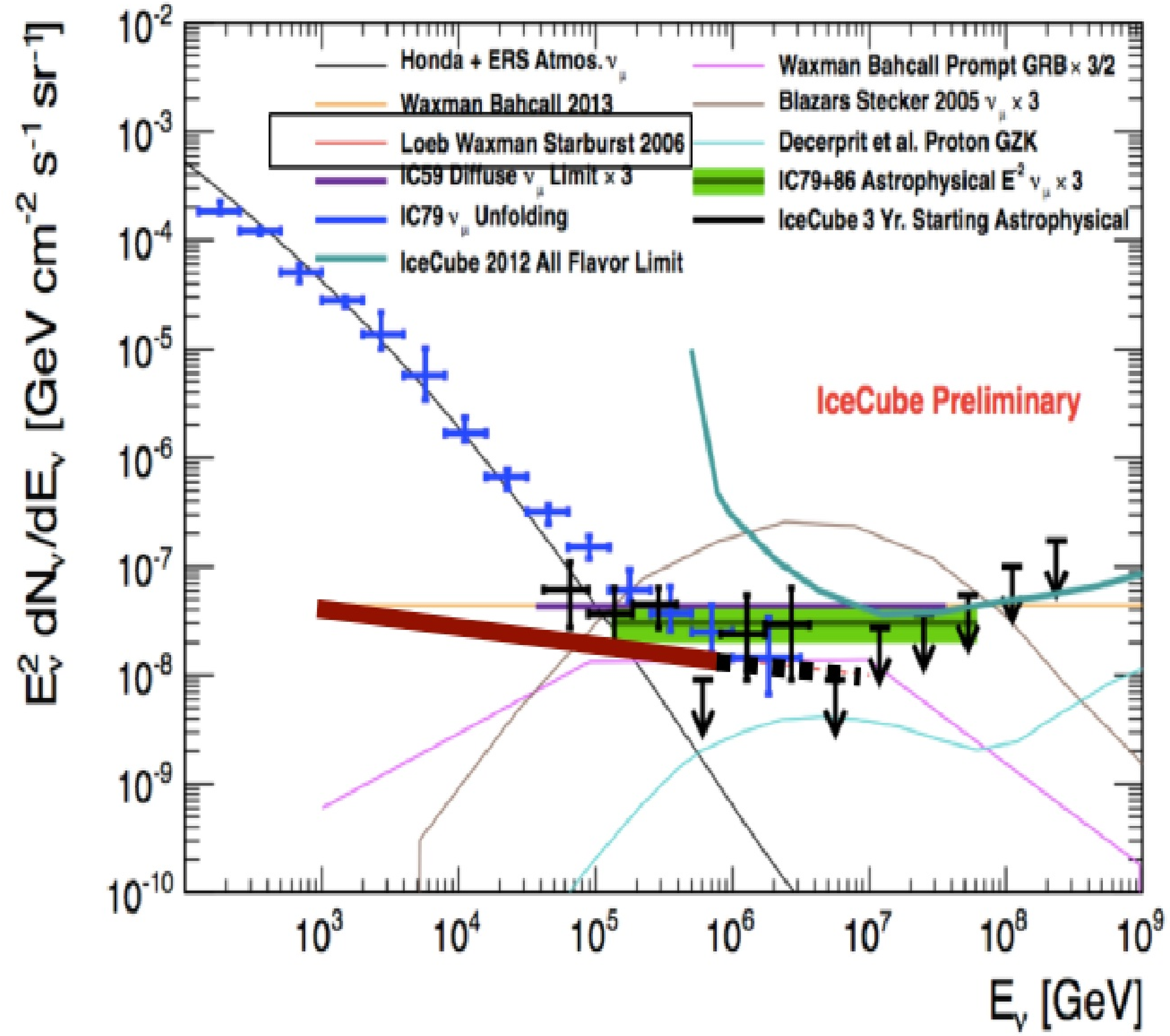
expect surprises: produced by Galactic dark matter halo?



decay of PeV-mass dark matter particle



starburst galaxies

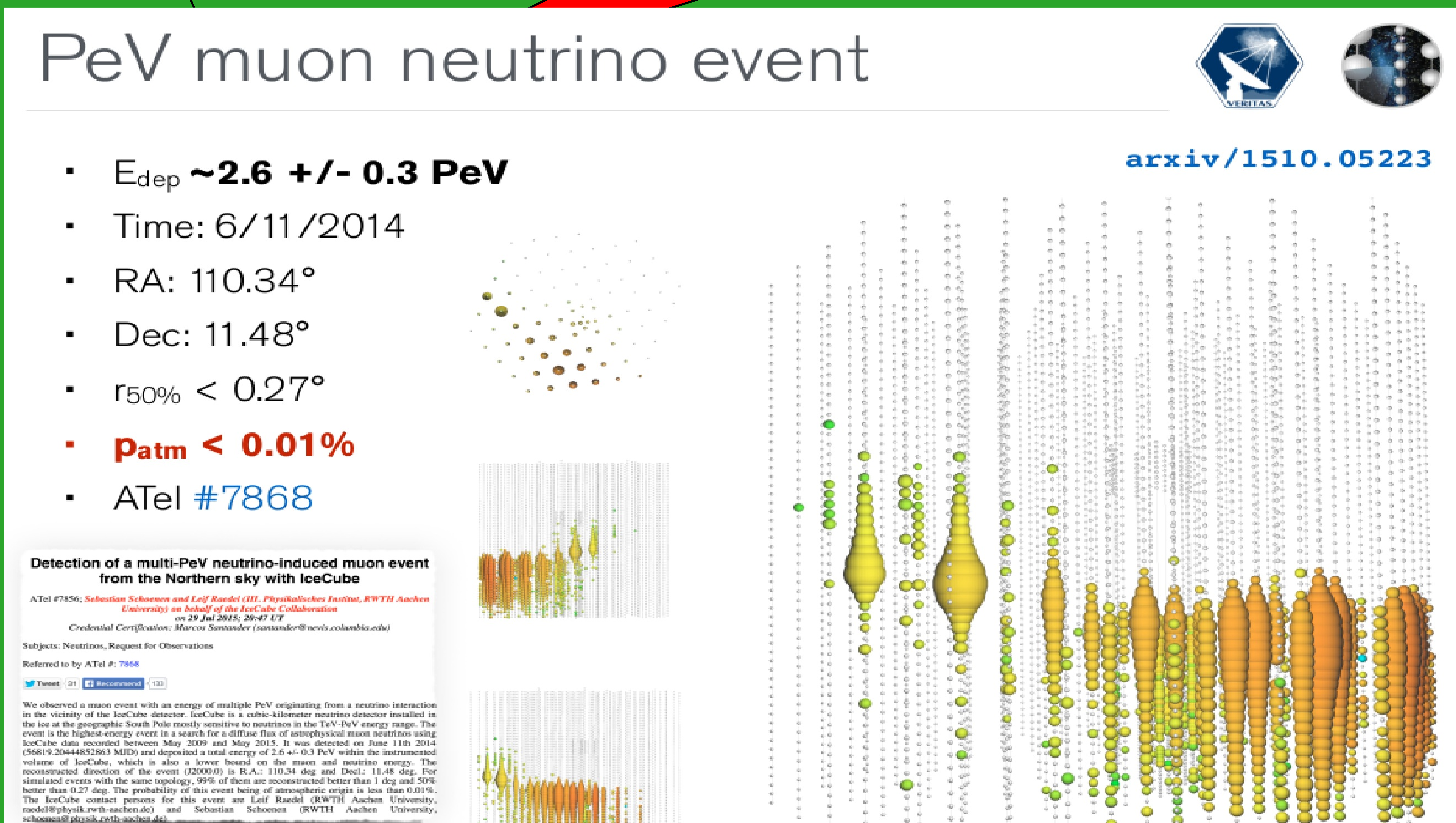


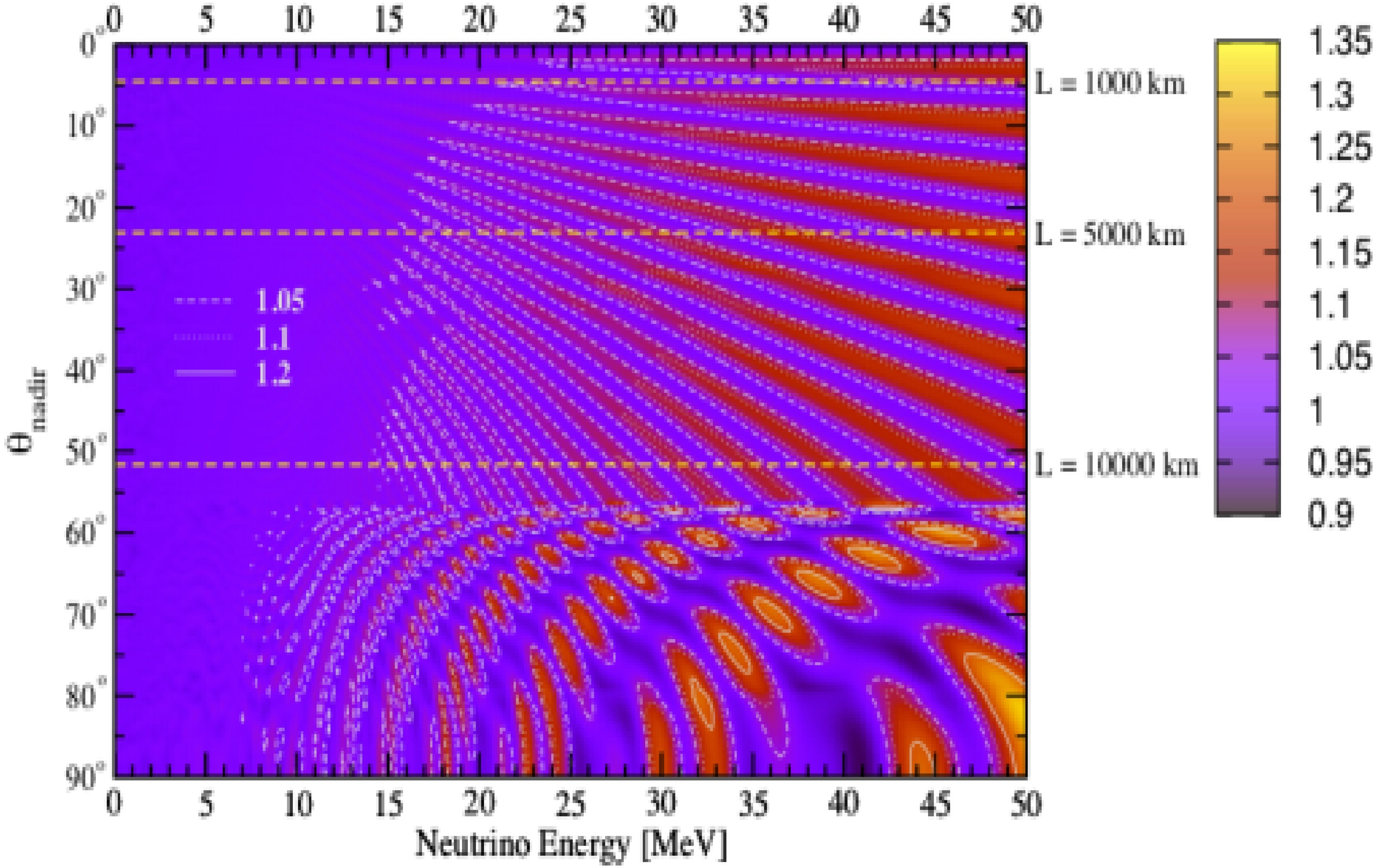
More events and EHE neutrinos are expected to come next years, changing everything we know on them and their origins/sources!!!!!!

Big Bird event (event 35) here: http://icecube.wisc.edu/news/view/227

The IceCube astrophysical neutrino flux is consistent with predictions for radio-loud AGN...But: Why do we not detect PeV neutrinos from every bright blazar?

Most neutrinos originate from faint, unresolved sources!!!!



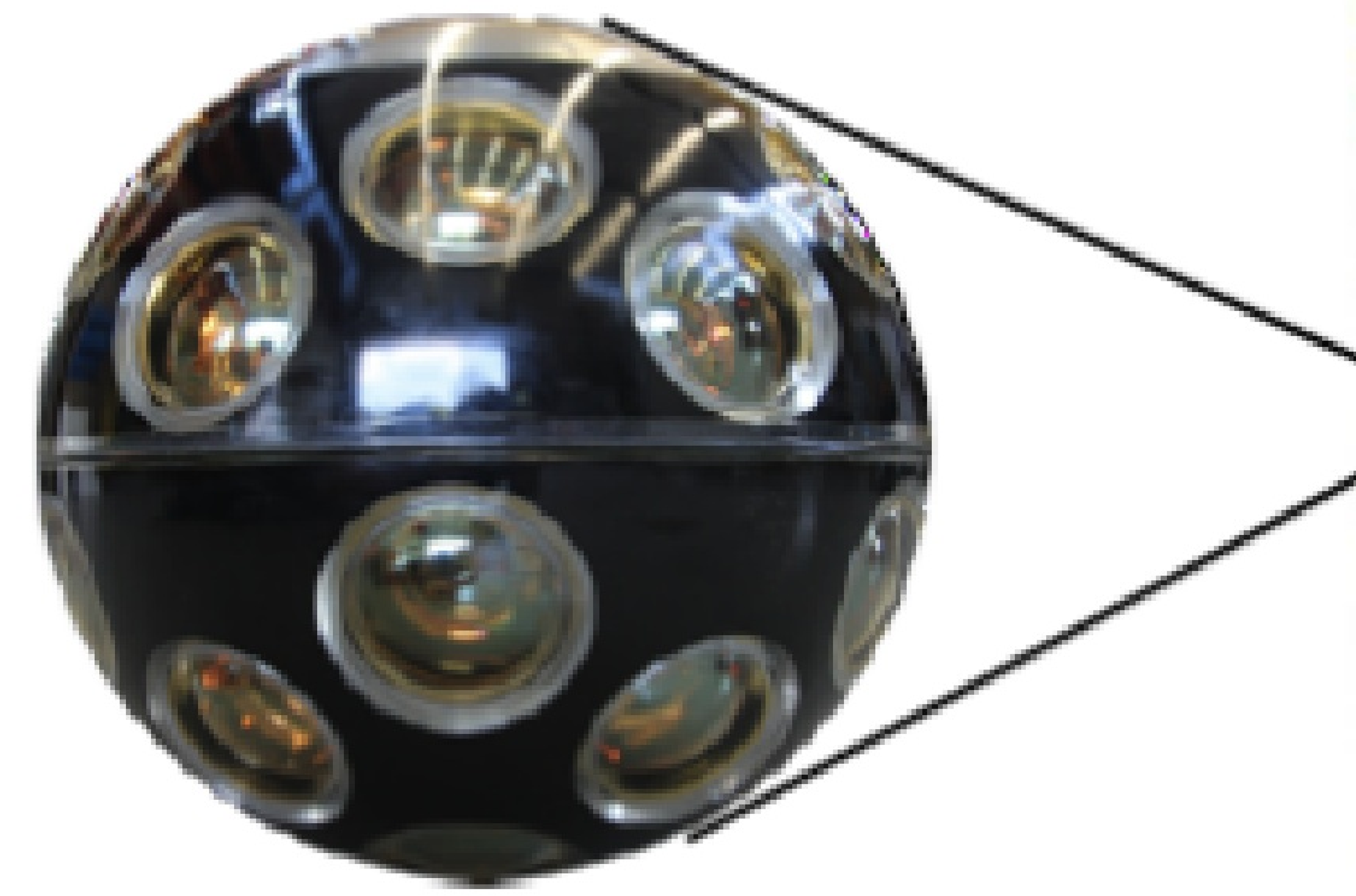


Neutrino Oscillogram, iso-contour plot of the ratio $P^{\oplus}(\bar{\nu}_1 \to \bar{\nu}_e)/c_{12}^2$ in the plane of the neutrino energy and the nadir angle. Note that unity for this ratio corresponds to the case where the Earth matter effect is absent.

KM3NeT – Next generation neutrino telescope in the Mediterranean Sea

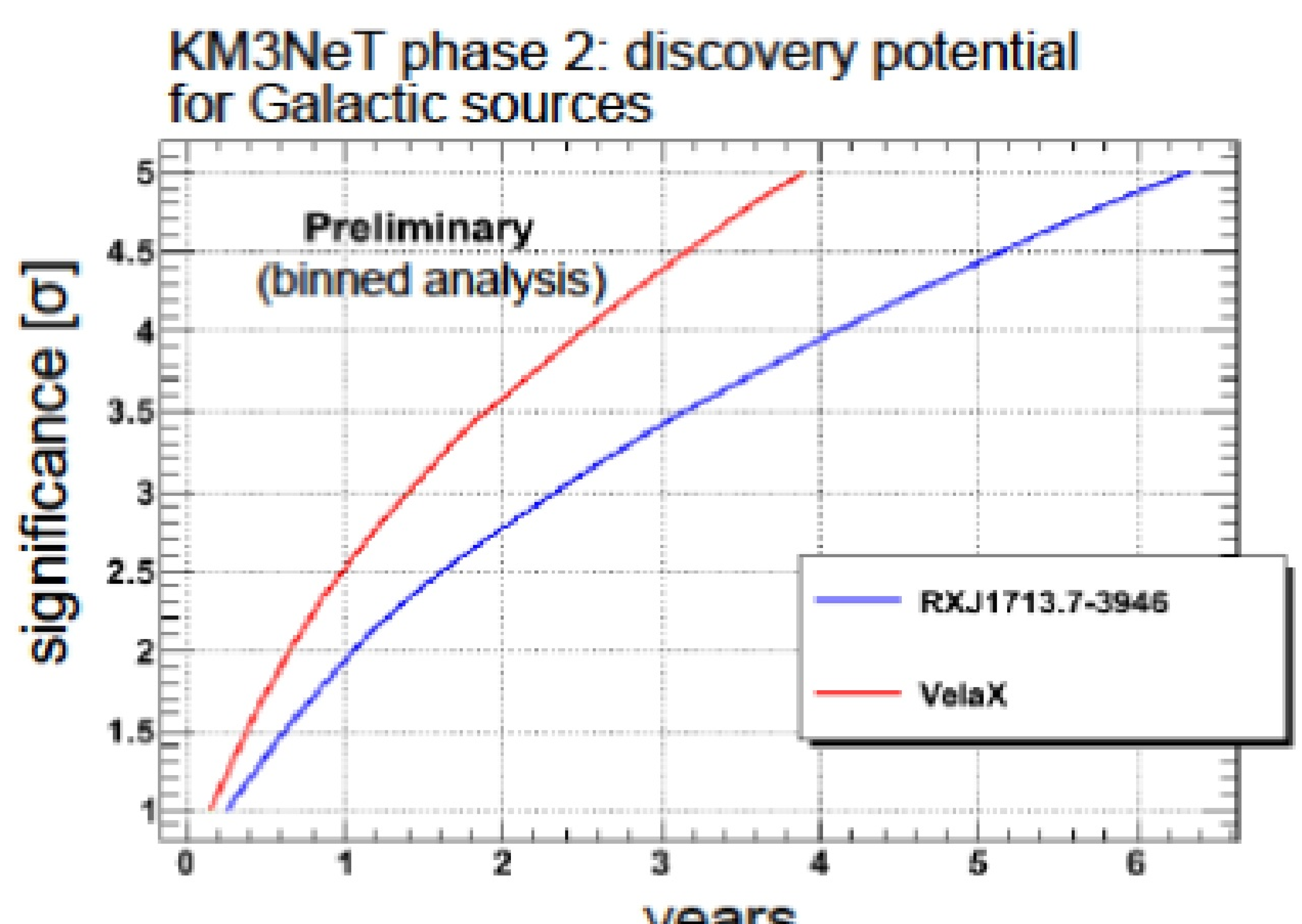
New Research Infrastructure

- network of cabled observatories
- innovative sensor design with 31× 3" PMTs (3× sensitive area 10" PMT)
- instr. vol. 3–6 km^3 (12,000 sensors)



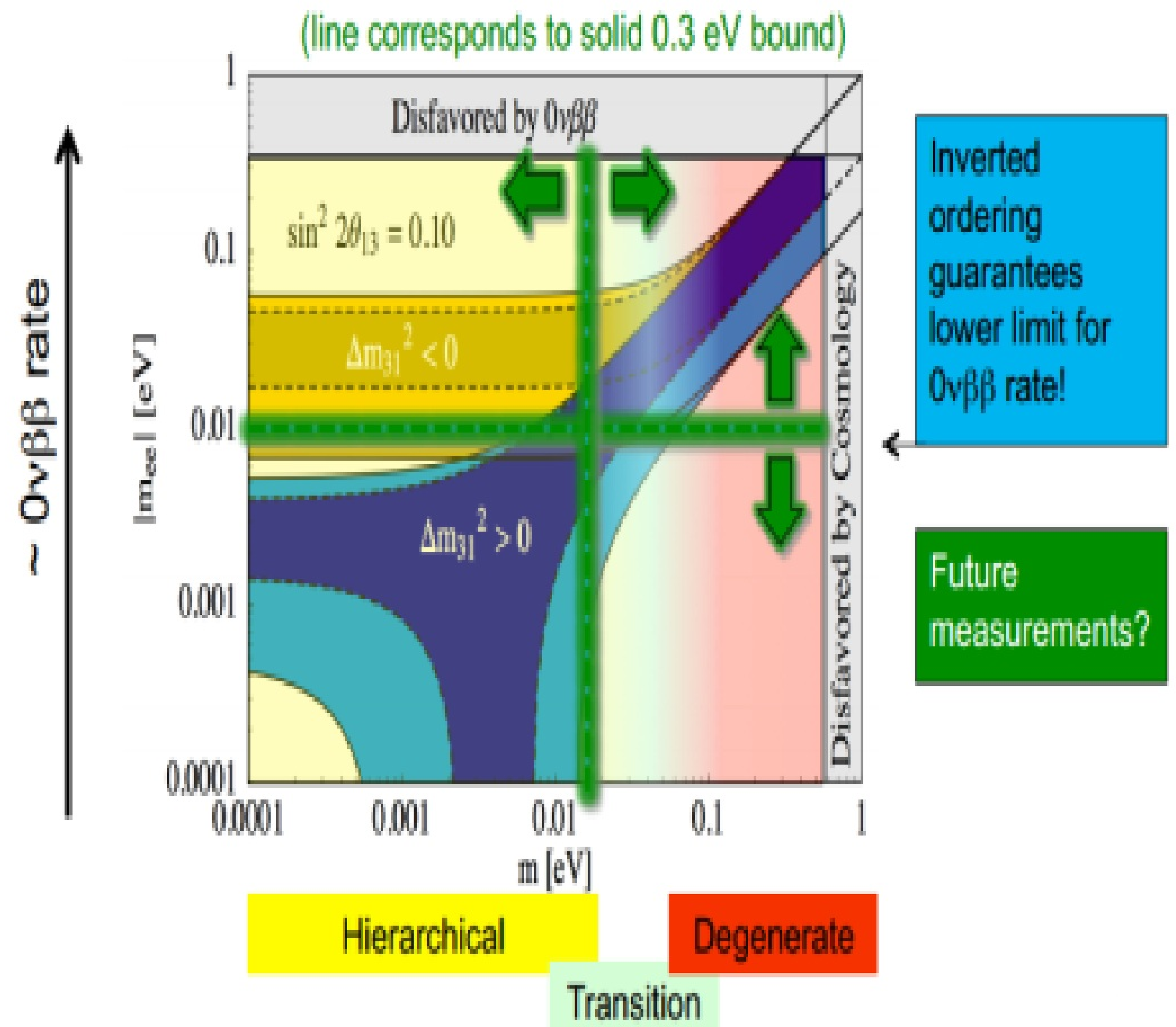
Phased implementation

- Phase 1: proof of feasibility (31 M€, funded)
- Phase 1.5: measure IceCube signal (80–90 M€, Letter of Intent)
- Phase 2: neutrino astronomy (220–250 M€, ESFRI roadmap)

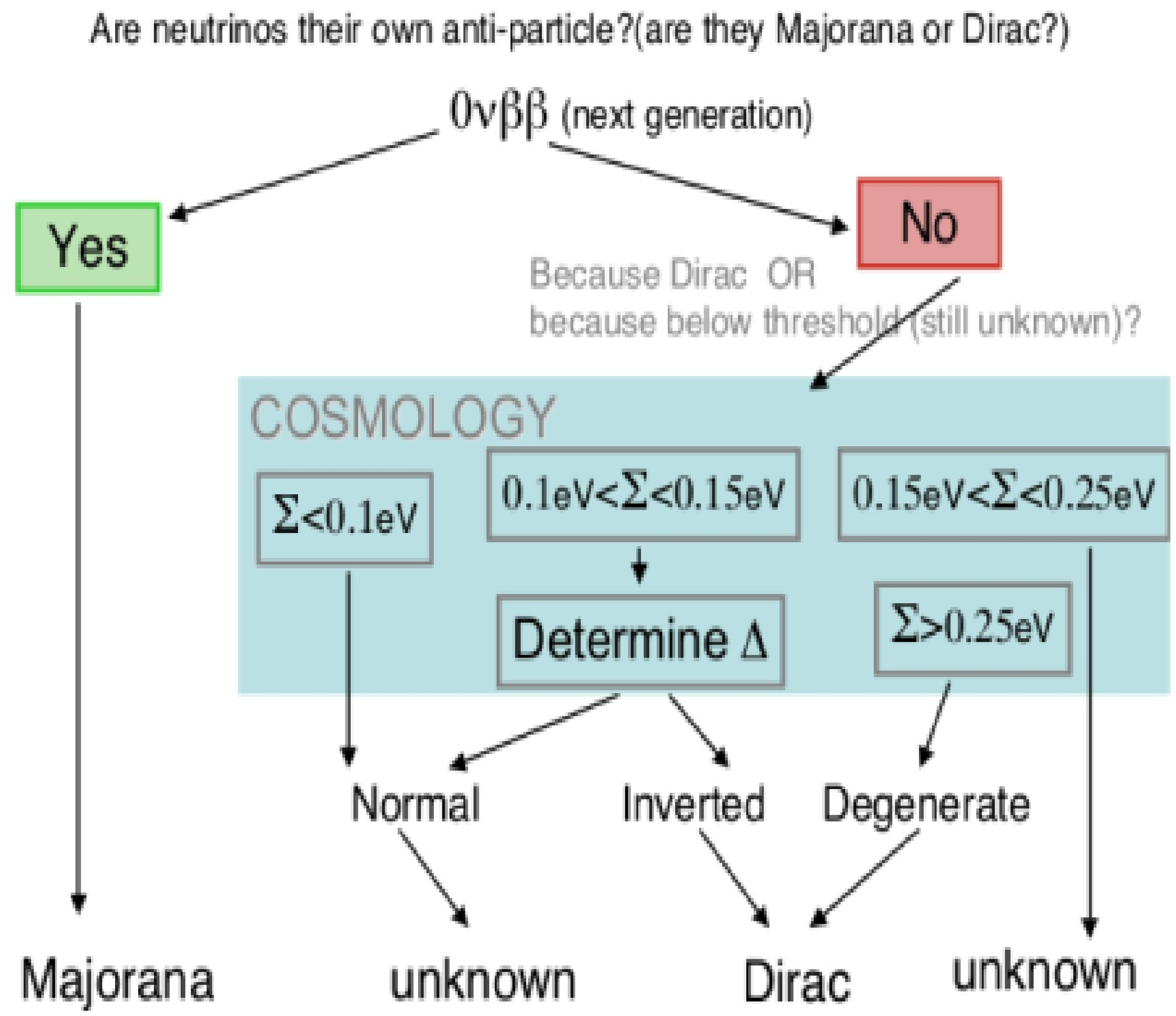


Neutrinoless double beta decay

- If neutrinos are Majorana neutrinos, they will mediate $0\nu\beta\beta$.
- The $0\nu\beta\beta$ rate depends on the hierarchy in degenerate regime:

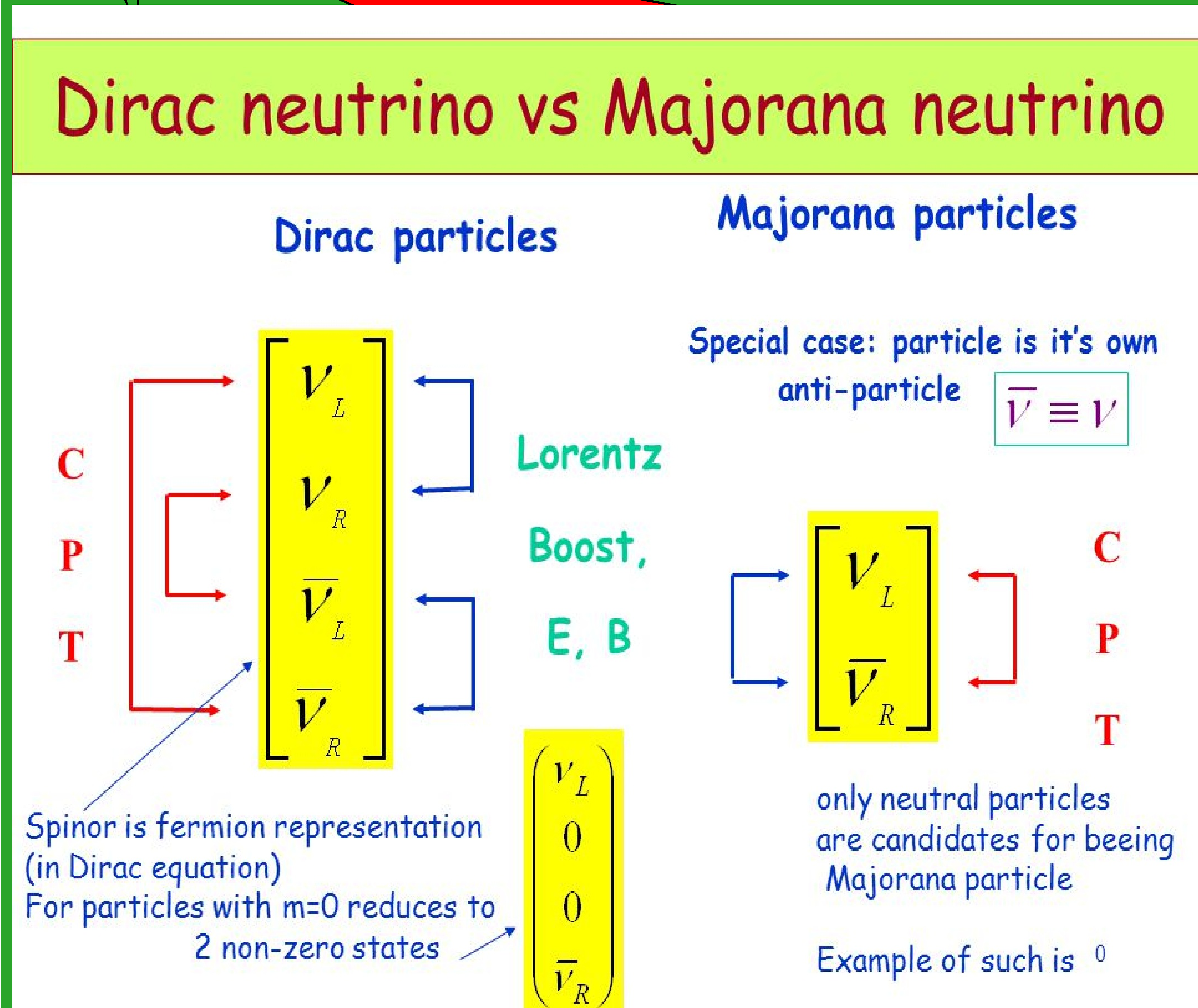


(from: Lindner, Merle, Rodejohann, hep-ph/0512143; see talk by Martin Hirsch)



Role of cosmology in determining the nature of neutrino mass. Future neutrinoless double beta decay ($0\nu\beta\beta$) experiments and future cosmological surveys will be highly complementary in addressing the question of whether neutrinos are Dirac or Majorana particles. Next generation means near future experiments whose goal is to reach a sensitivity to the neutrinoless double beta decay effective mass of 0.01 eV. We can still find two small windows where this combination of experiments will not be able to give a definite answer, but this region is much reduced by combining $0\nu\beta\beta$ and cosmological observations.

Dirac or Majorana? Hierarchical or degenerate? Active or sterile? What do you prefer?



Dirac or Majorana?

We can probe quantum spacetime (minimal length hypotheses) with NOSEX! (See P. Nicolini et al.):

$$P_\ell(\nu_\alpha \to \nu_\beta) = \sum_{k,j=1}^{3} U^*_{\alpha k} U_{\beta k} U_{\alpha j} U^*_{\beta j} e^{-i \frac{\Delta m^2_{kj}}{2E} \exp(-\ell^2 E^2) L}.$$

$$P(\nu_\alpha \to \nu_\beta) = \sin^2(2\theta) \sin^2\left(\frac{\Delta m^2 L}{4E} e^{-\ell^2 E^2}\right).$$

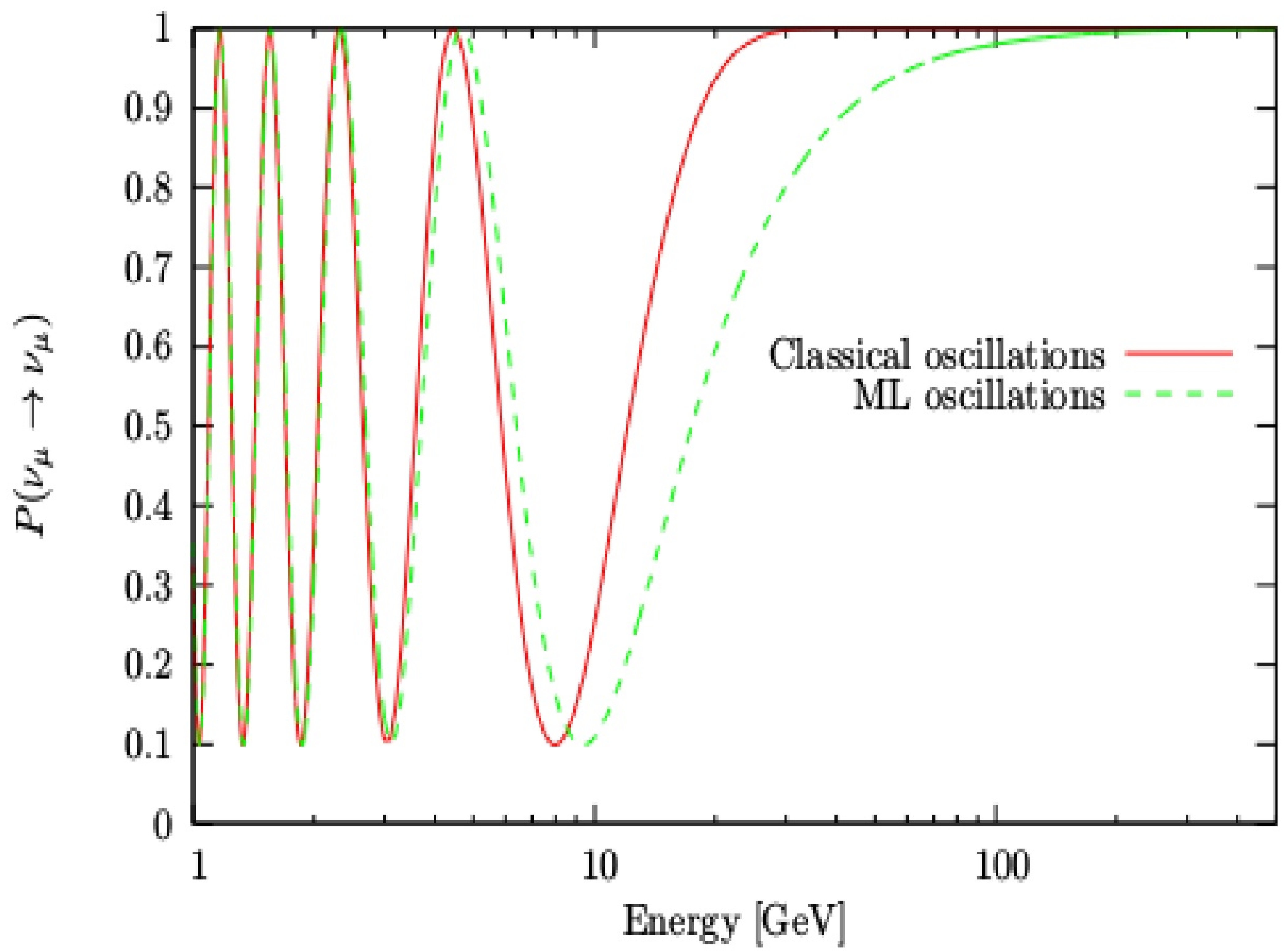


Figure 1. Comparison of classical and minimal length oscillations for the two-flavour case with $\Delta m^2 = 2.3 \cdot 10^{-3}$ eV^2, $\sin^2(2\theta) = 0.9$, baseline $L = 5000$ km and $\ell^{-1} = 10$ GeV.

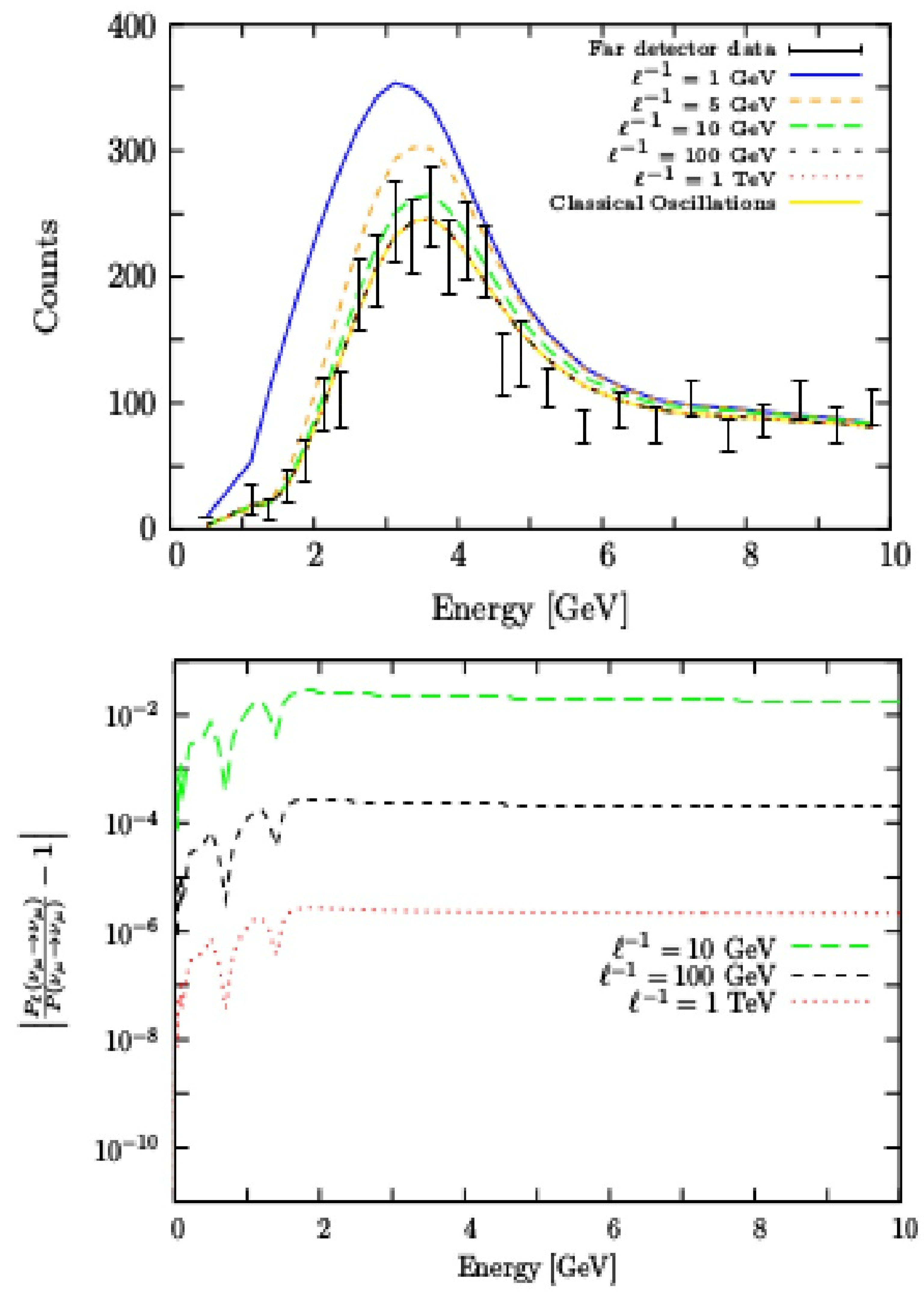
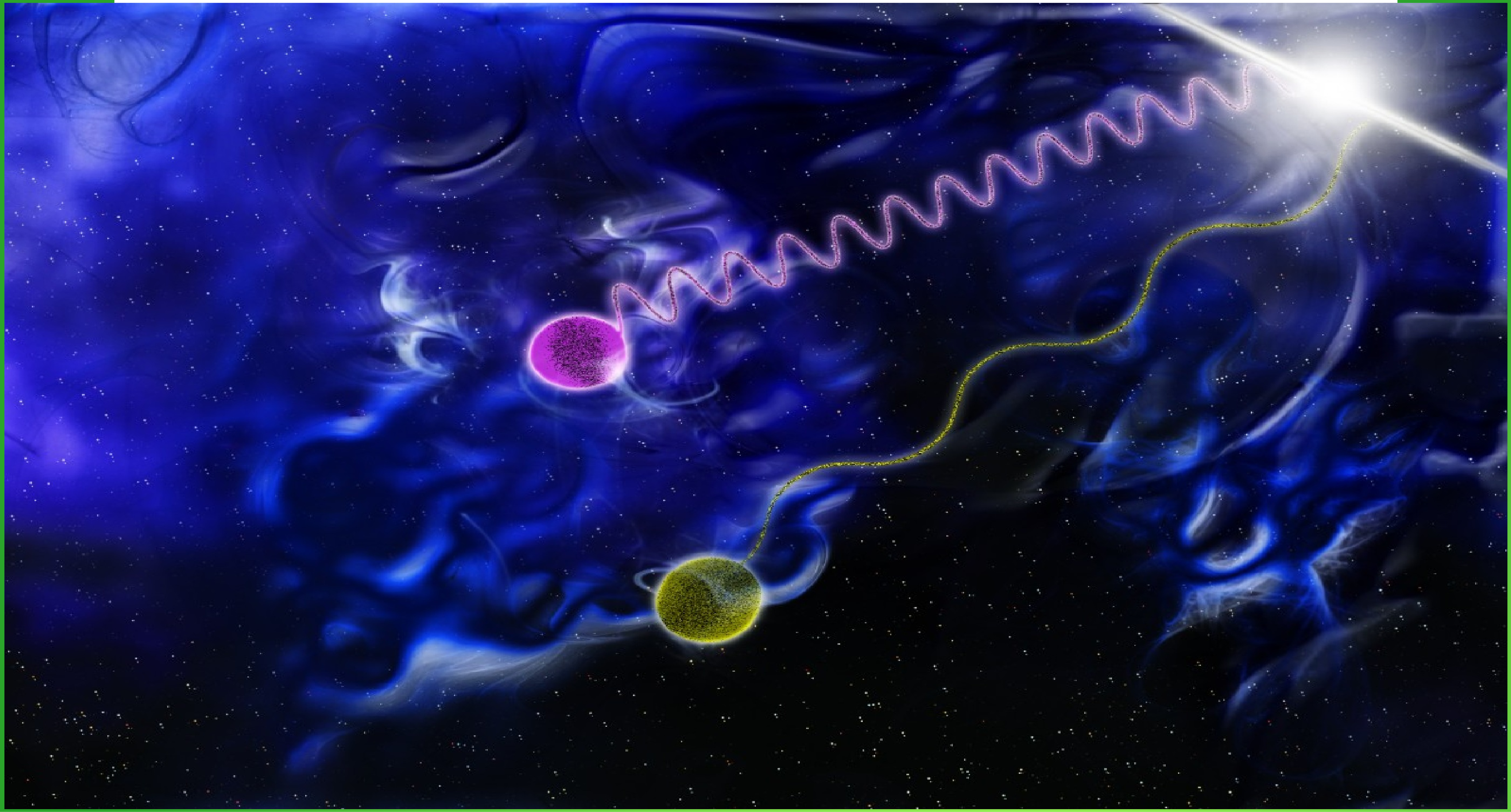
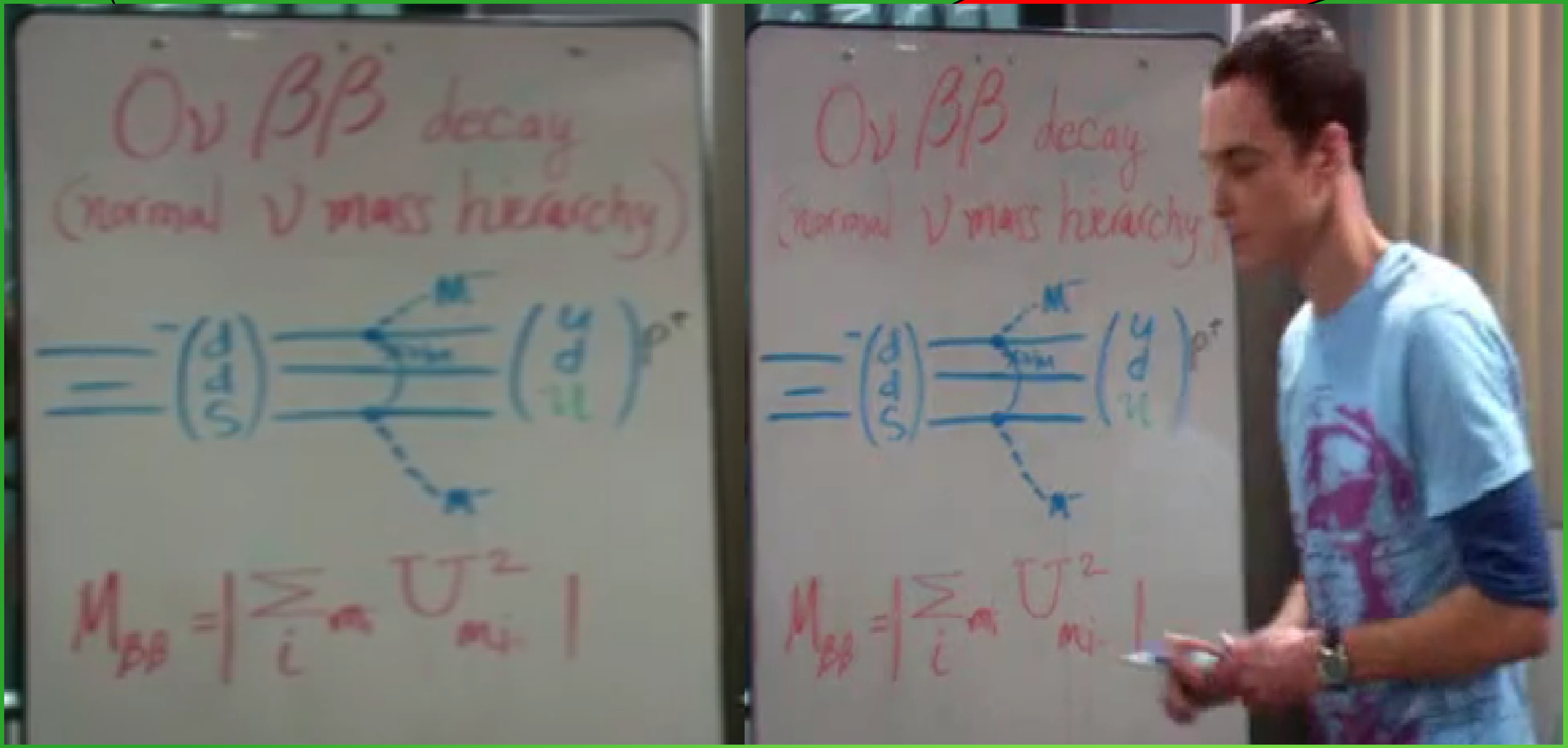


Figure 2. Upper part: Expected neutrino flux for the minimal length model with different fundamental scales from $\ell^{-1} = 1$ GeV to $\ell^{-1} = 1$ TeV (from top to bottom) for a $\nu_\mu \to \nu_\mu$ transition with baseline $L = 734$ km. MINOS data taken from [25].
Lower part: Relative differences in the oscillation probabilities for different fundamental scales.

We can probe quantum spacetime (minimal length hypotheses) with NOSEX! (See P. Nicolini et al.):

$$P_\ell(\nu_\alpha \to \nu_\beta) = \sum_{k,j=1}^{3} U^*_{\alpha k} U_{\beta k} U_{\alpha j} U^*_{\beta j} e^{-i\frac{\Delta m^2_{kj}}{2E}\exp(-\ell^2 E^2) L}. \quad P(\nu_\alpha \to \nu_\beta) = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E} e^{-\ell^2 E^2}\right).$$





THE END!