Neutrinos

Cosmology

Particle physics

Astronomy

J. Brunner , 29/06/2021
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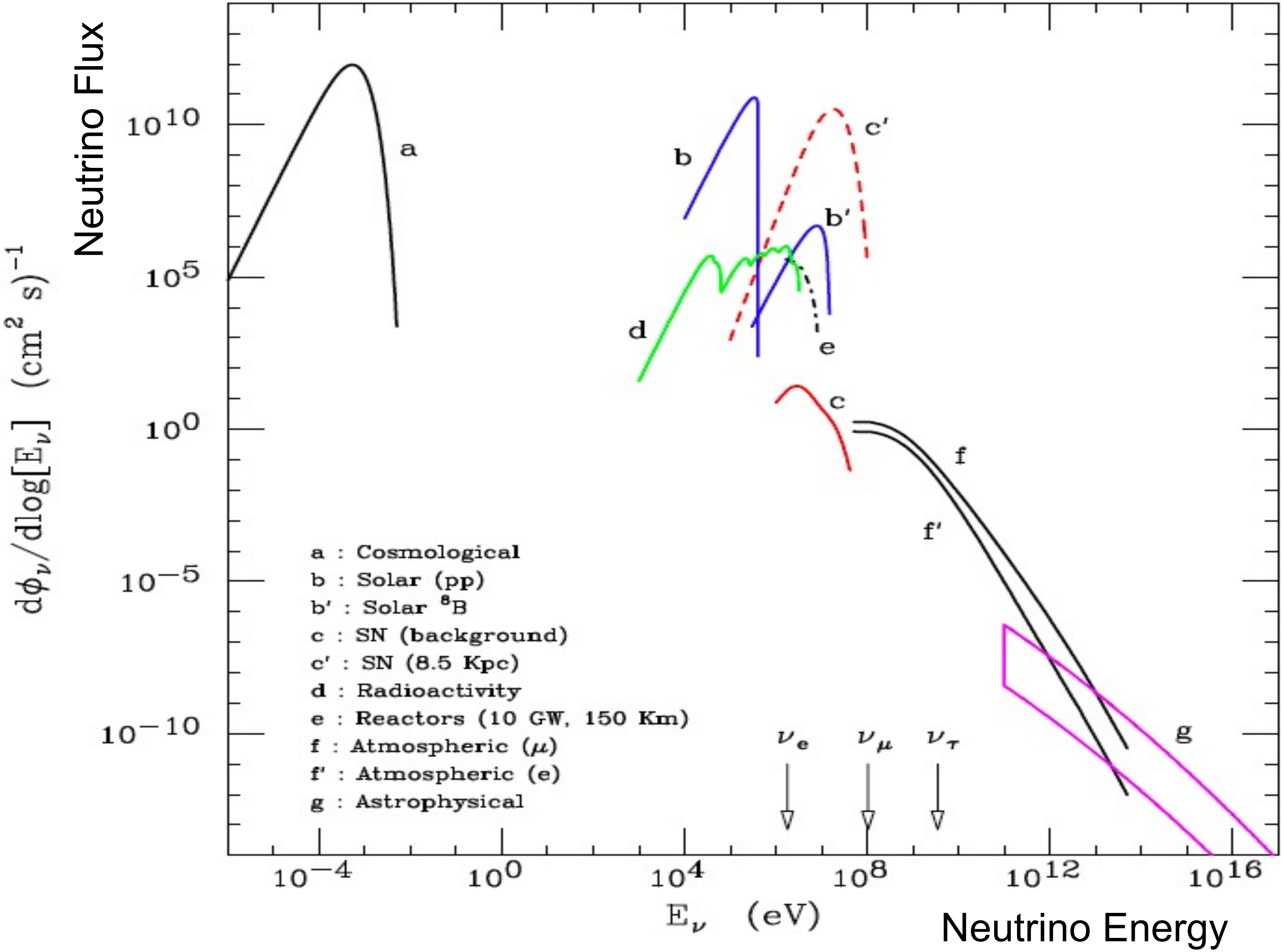
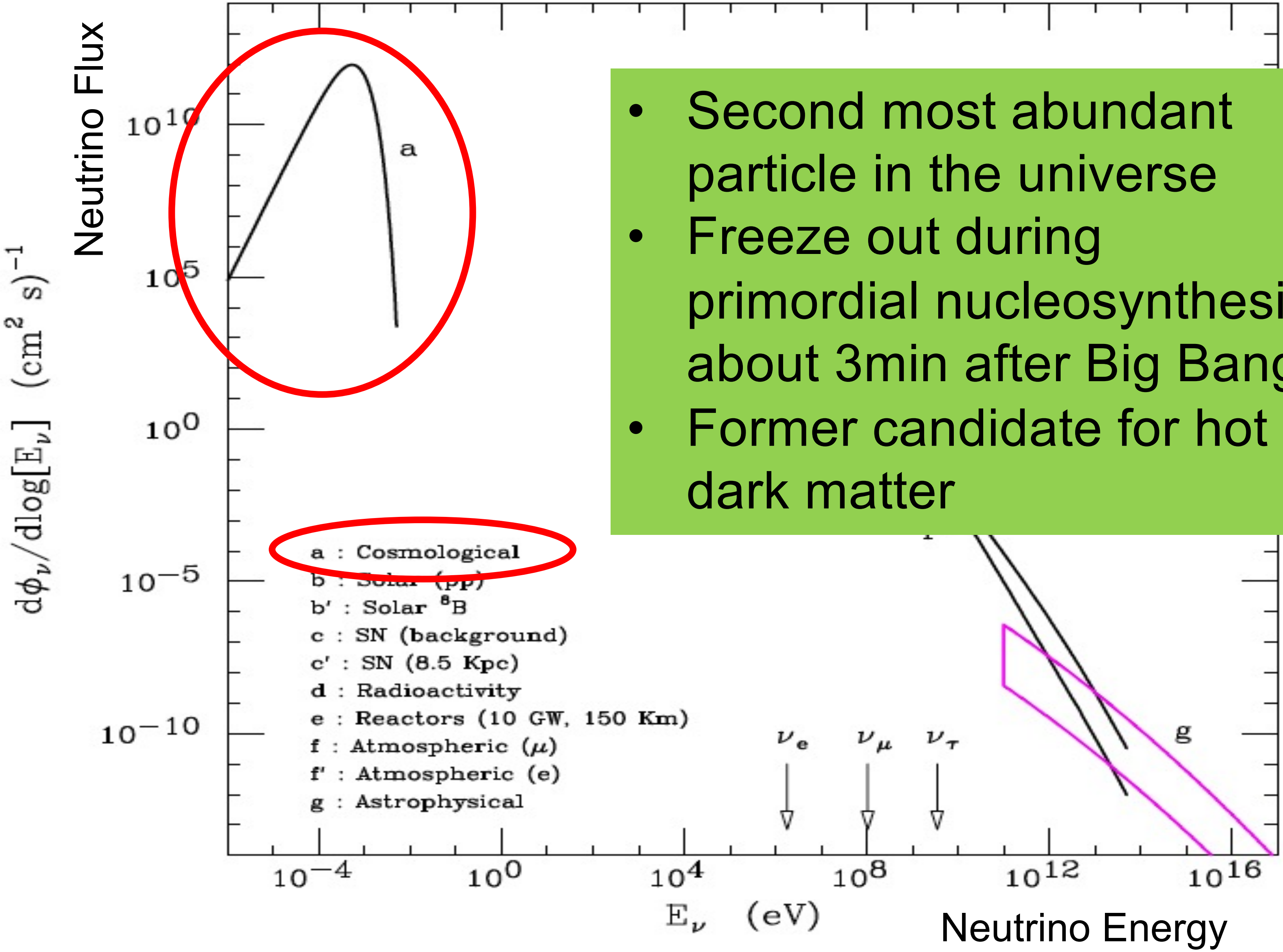
Neutrino energy spectrum



Credit : P. Lipari “Introduction to Neutrino Physics”

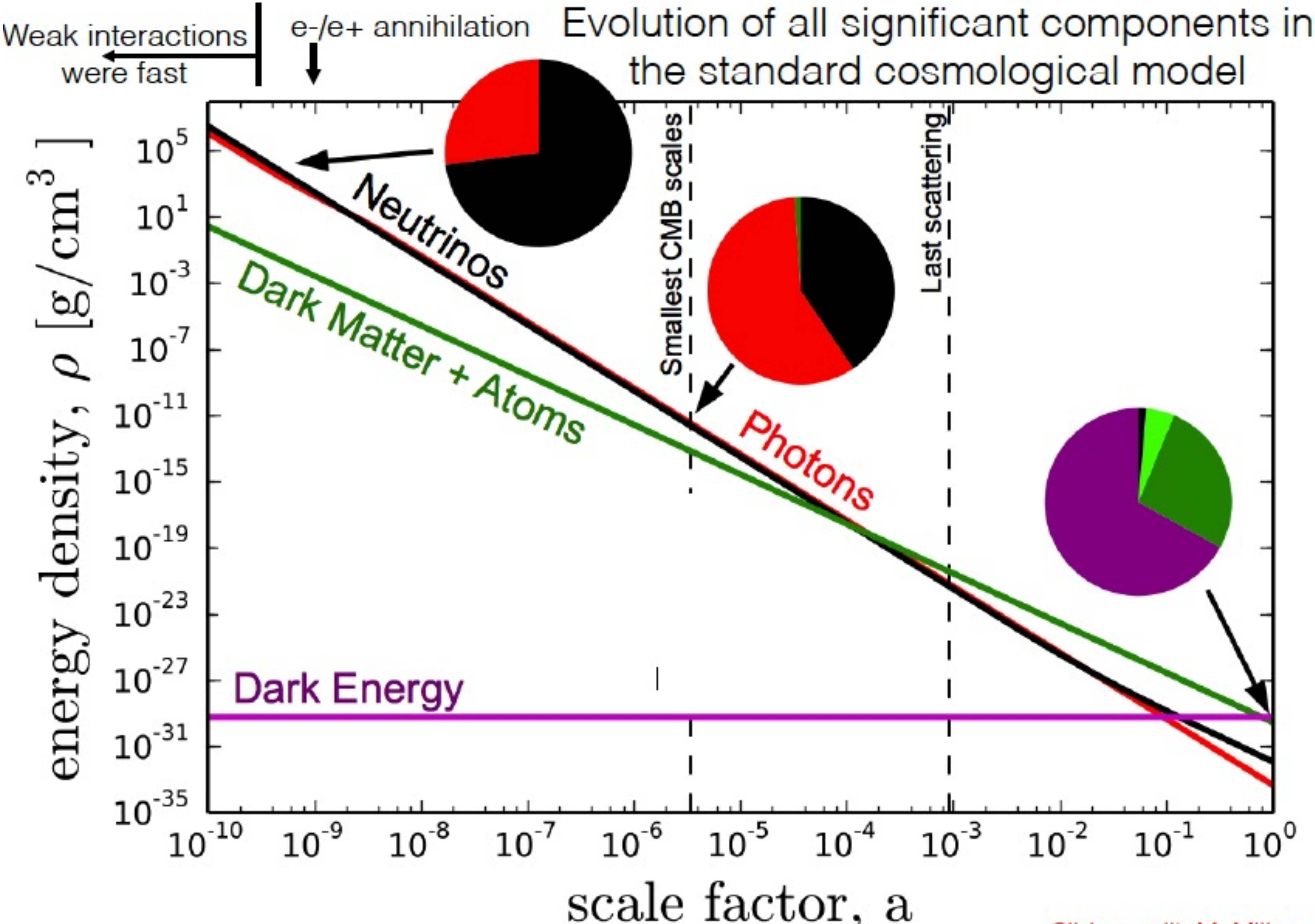
Cosmology with neutrinos



- Second most abundant particle in the universe
- Freeze out during primordial nucleosynthesis about 3min after Big Bang
- Former candidate for hot dark matter

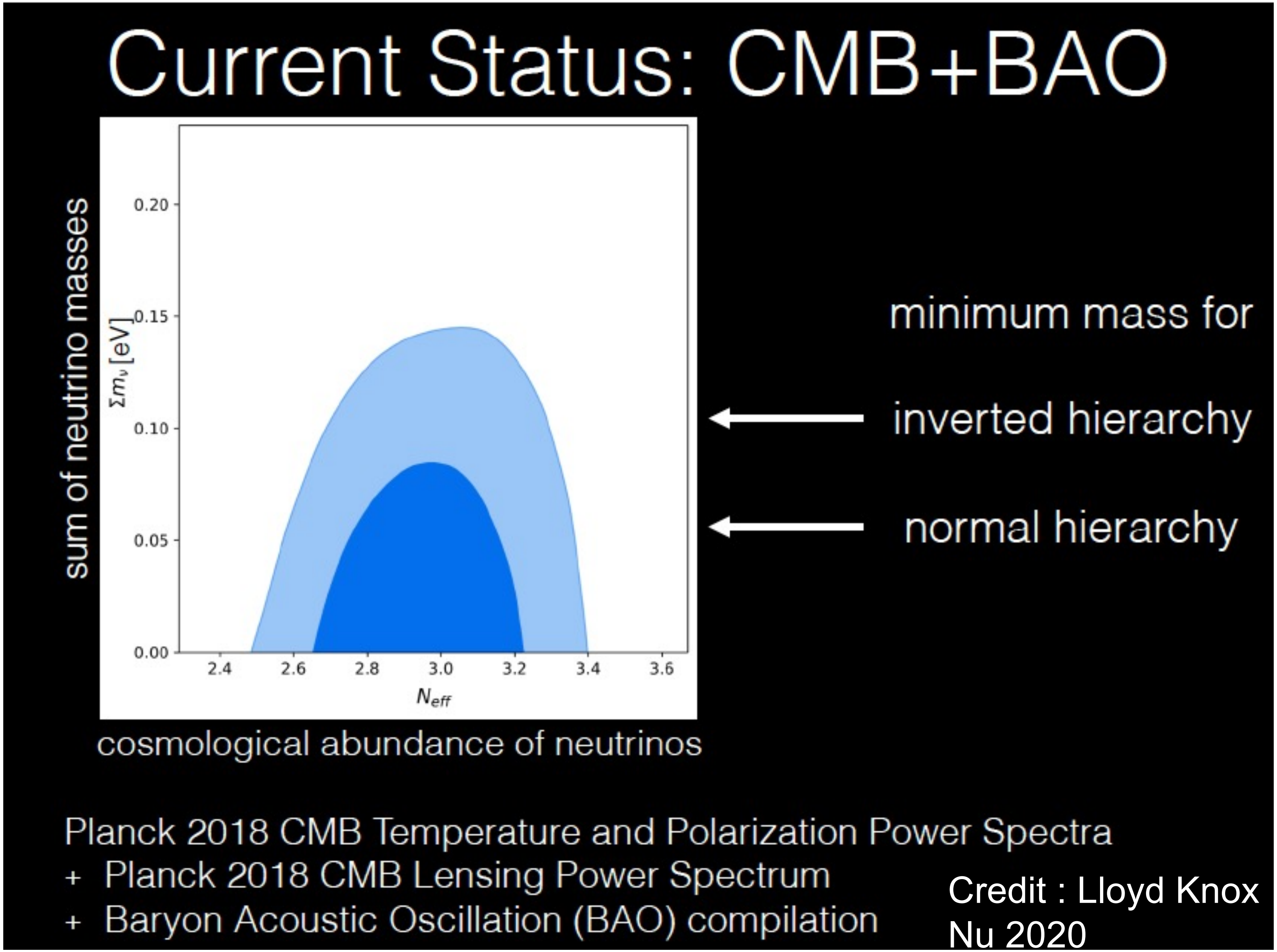
Credit : P. Lipari “Introduction to Neutrino Physics”

Evolution of all significant components in the standard cosmological model



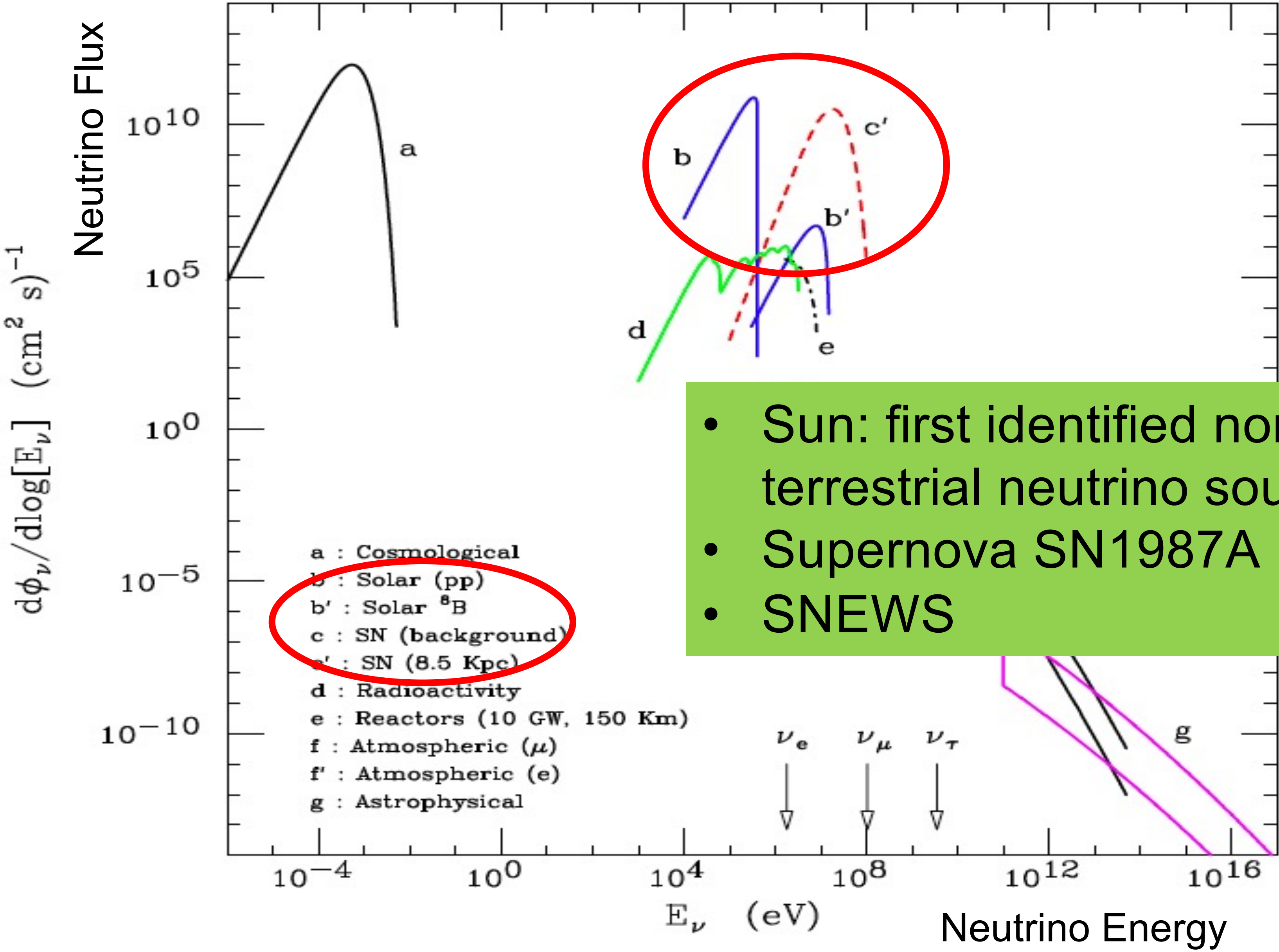
Slide credit: M. Millea

Total neutrino mass and number of flavours



Credit : Lloyd Knox
Nu 2020

Astronomy with neutrinos



- Sun: first identified non-terrestrial neutrino source
- Supernova SN1987A
- SNEWS

Credit : P. Lipari “Introduction to Neutrino Physics”

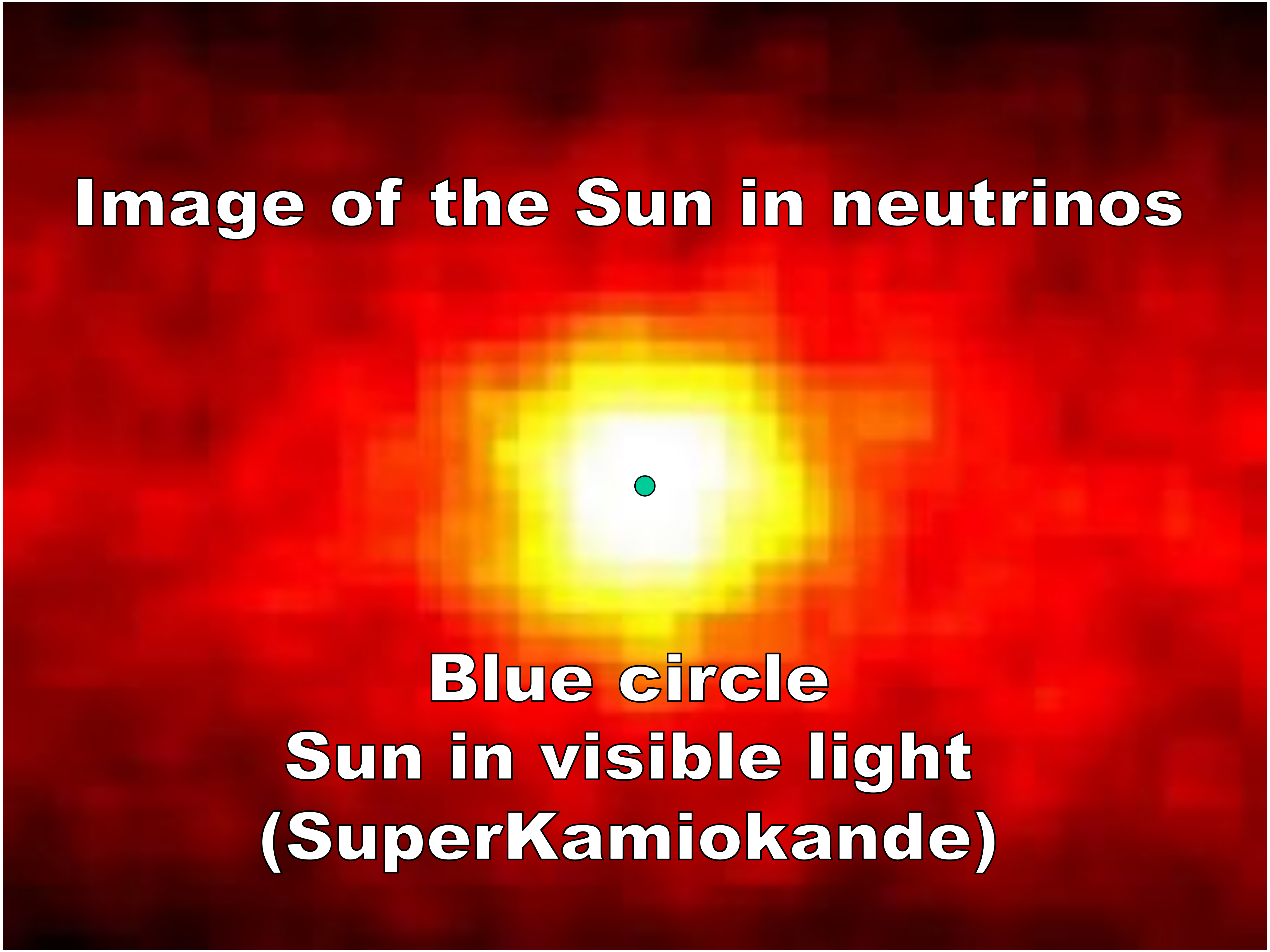
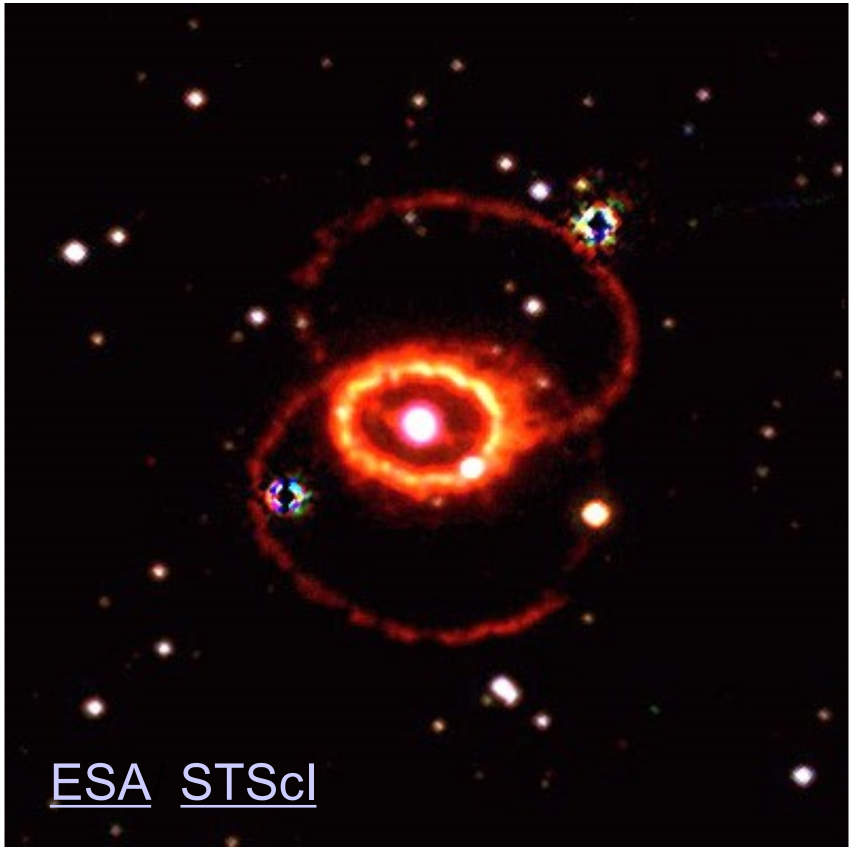


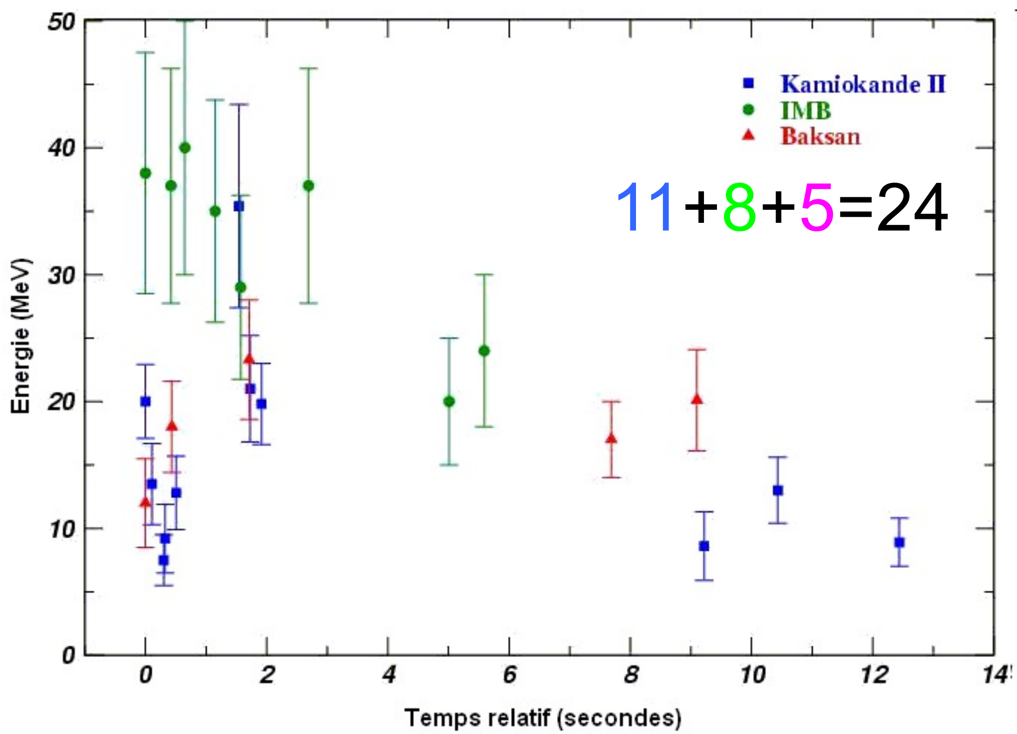
Image of the Sun in neutrinos
Blue circle
Sun in visible light
(SuperKamiokande)

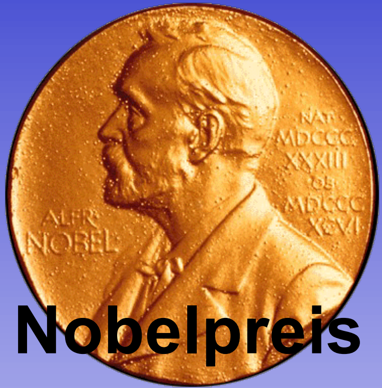
Neutrinos from SN 1987A

- 24 Neutrinos detected in 3 experiments



SN 1987A few years later





Nobelpreis 2002

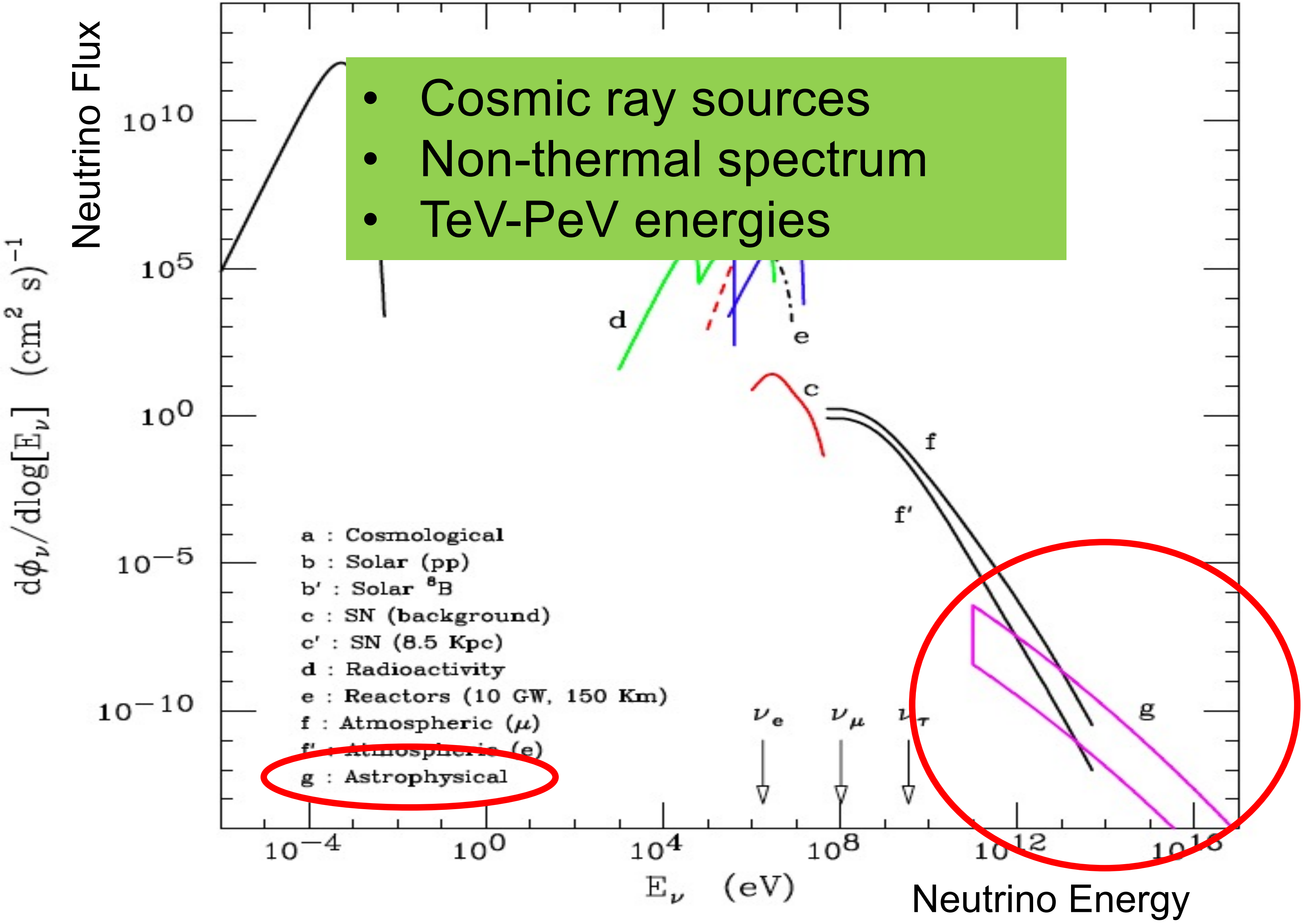
.. Opening the neutrino window to the universe

Raymond Davis jr.

Masatoshi Koshiba

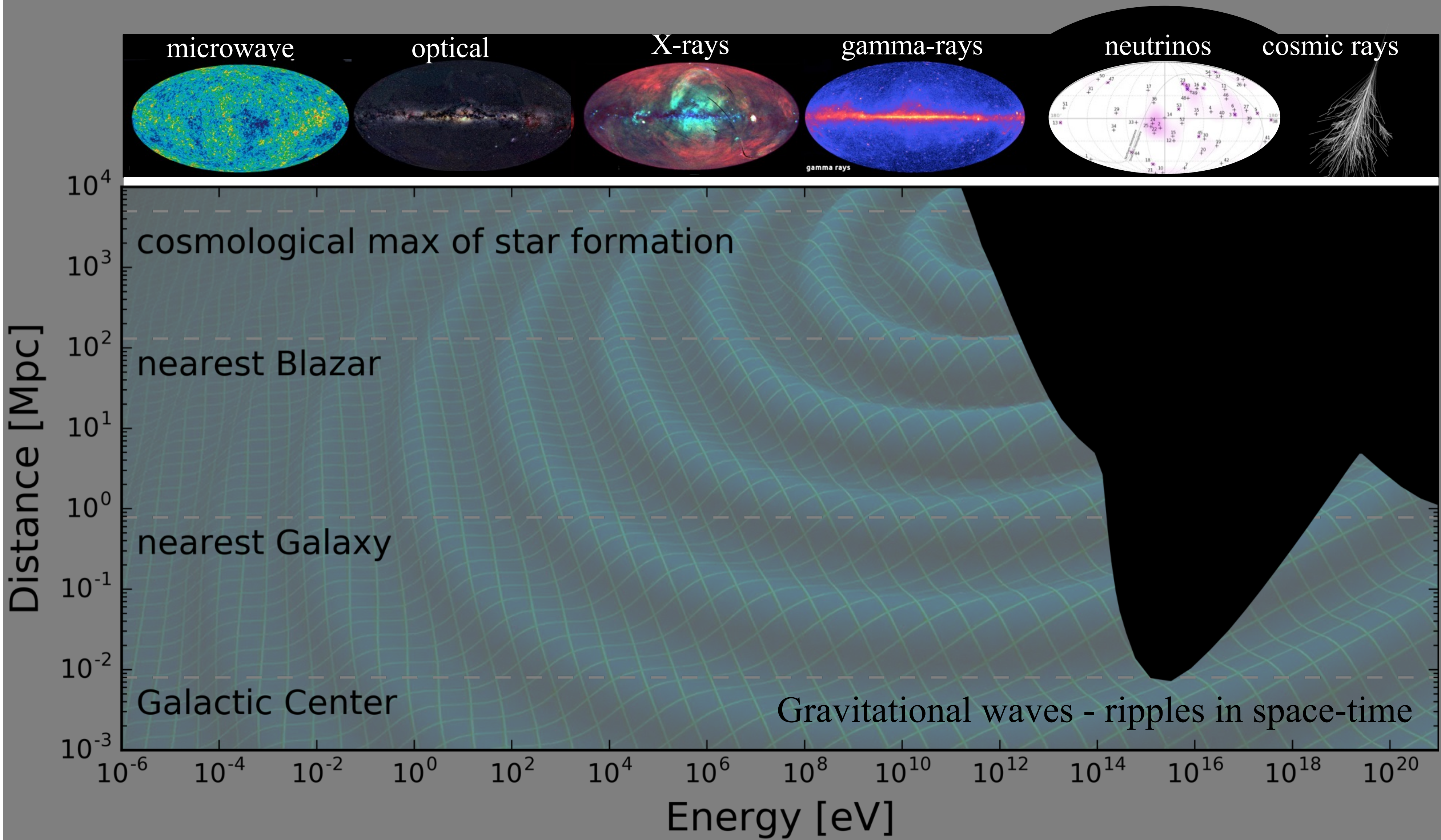
Astronomy with neutrinos

- Cosmic ray sources
- Non-thermal spectrum
- TeV-PeV energies



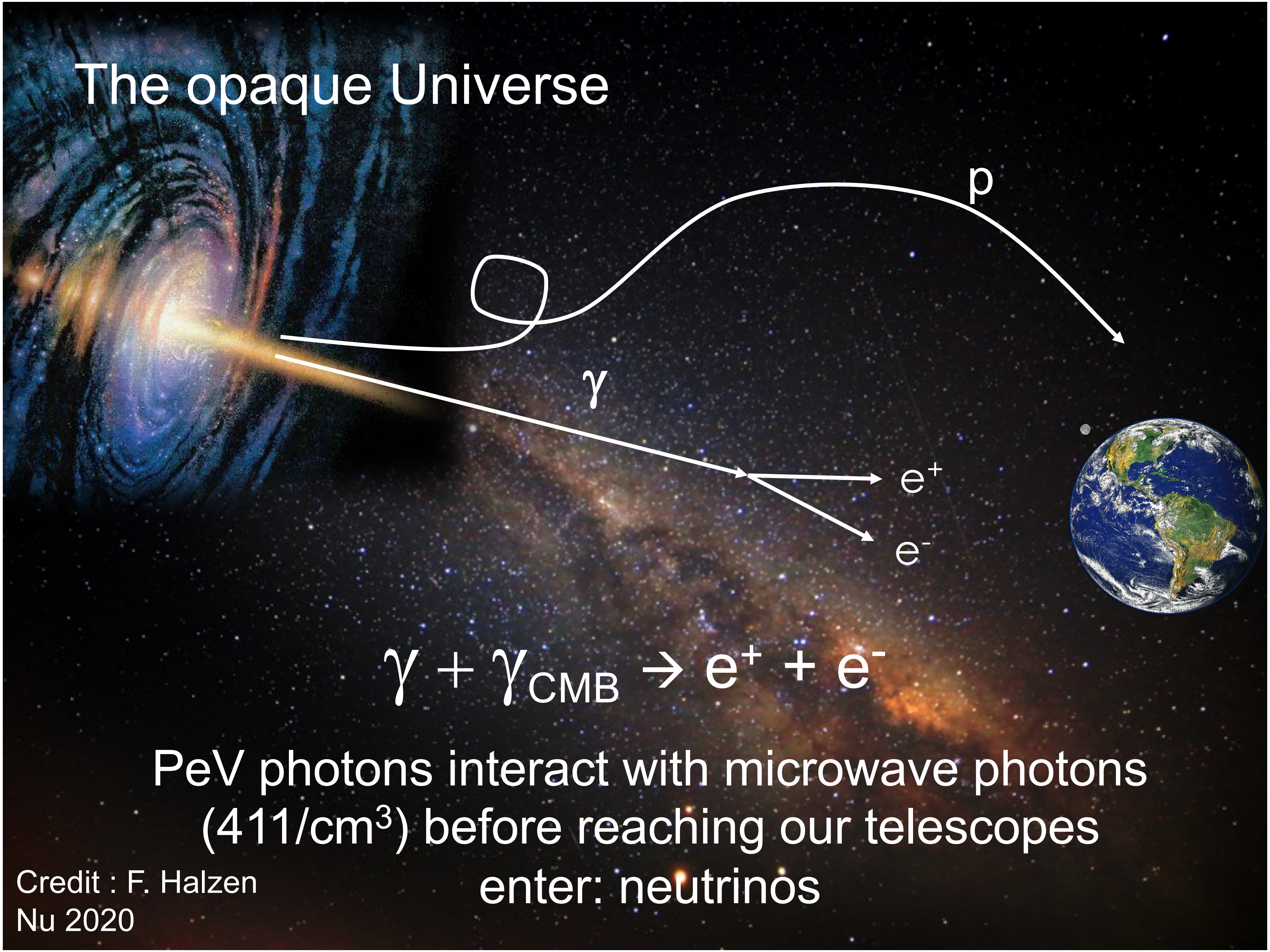
Credit : P. Lipari “Introduction to Neutrino Physics”

highest energy "radiation" from the Universe: neutrinos and cosmic rays

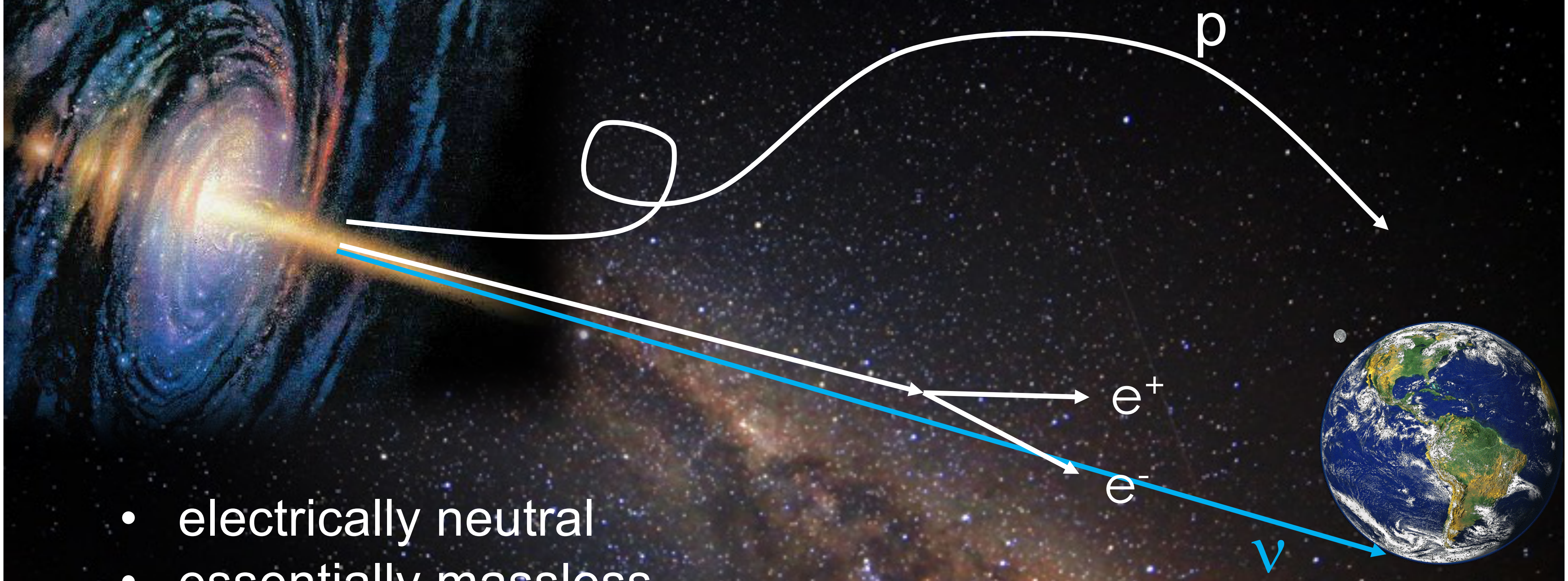


Credit : F. Halzen
Nu 2020

Universe is opaque above ~100 TeV energy


The opaque Universe
p
γ
e+
e-
$\gamma + \gamma_{CMB} \rightarrow e^+ + e^-$
PeV photons interact with microwave photons
(411/cm^3) before reaching our telescopes
enter: neutrinos
Credit : F. Halzen
Nu 2020

Neutrinos? Perfect Messenger



- electrically neutral
- essentially massless
- essentially unabsorbed
- tracks nuclear processes
- reveal the sources of cosmic rays

- … but difficult to detect

Credit : F. Halzen
Nu 2020

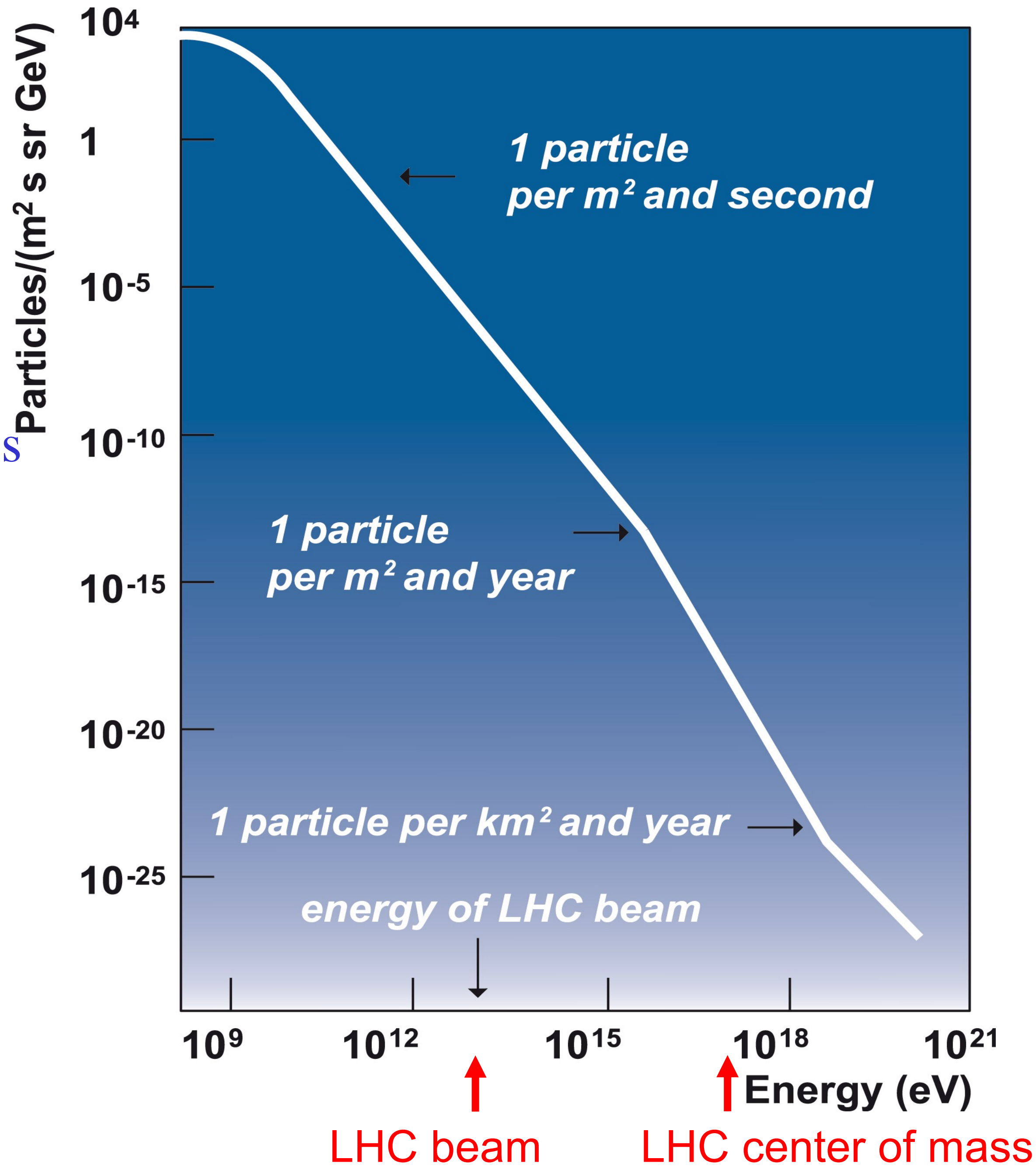
Spectrum of cosmic rays

Non-thermal Spectrum

Can be explained by → shock wave acceleration

Direct discovery of CR sources not yet successful

Much higher energies than at LHC can be reached



Shock wave acceleration

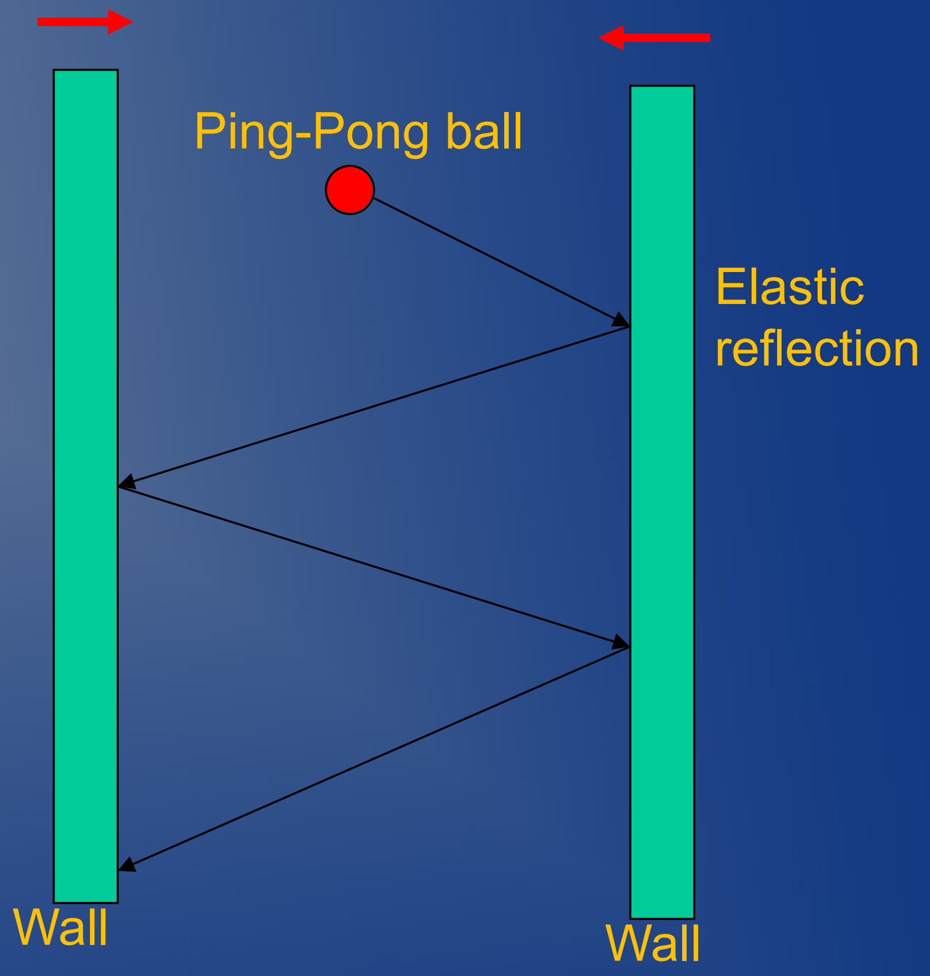
Ball picks up energy from moving walls at each rebound

Ball → electrons, protons

Wall1: e.g. Supernova remnant

Wall2: surrounding material

Elastic reflection: magnetic fields

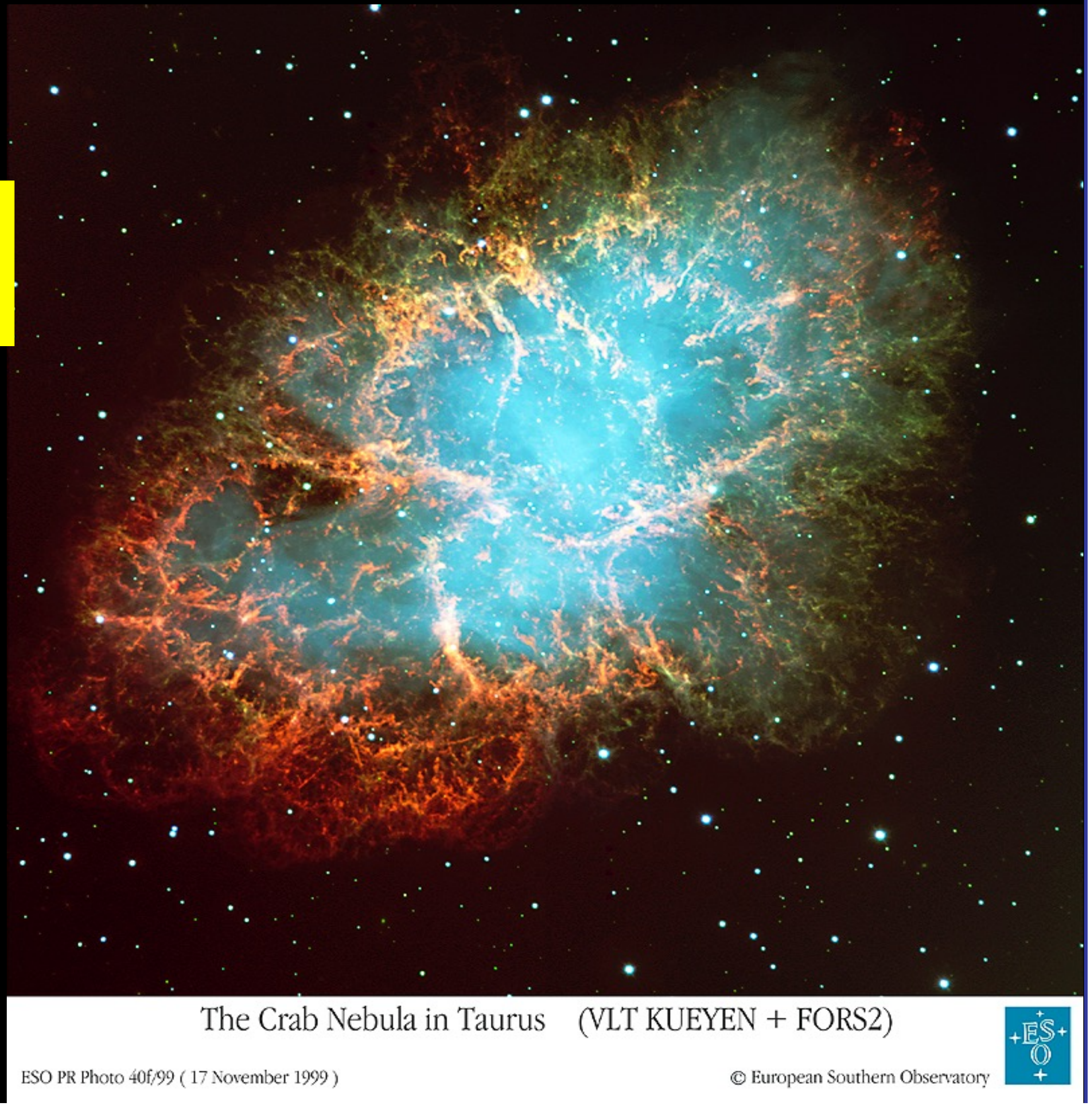


Supernova-Remnants: shock waves with interstellar medium

Up to 10^{16} eV

Supernova from year 1054

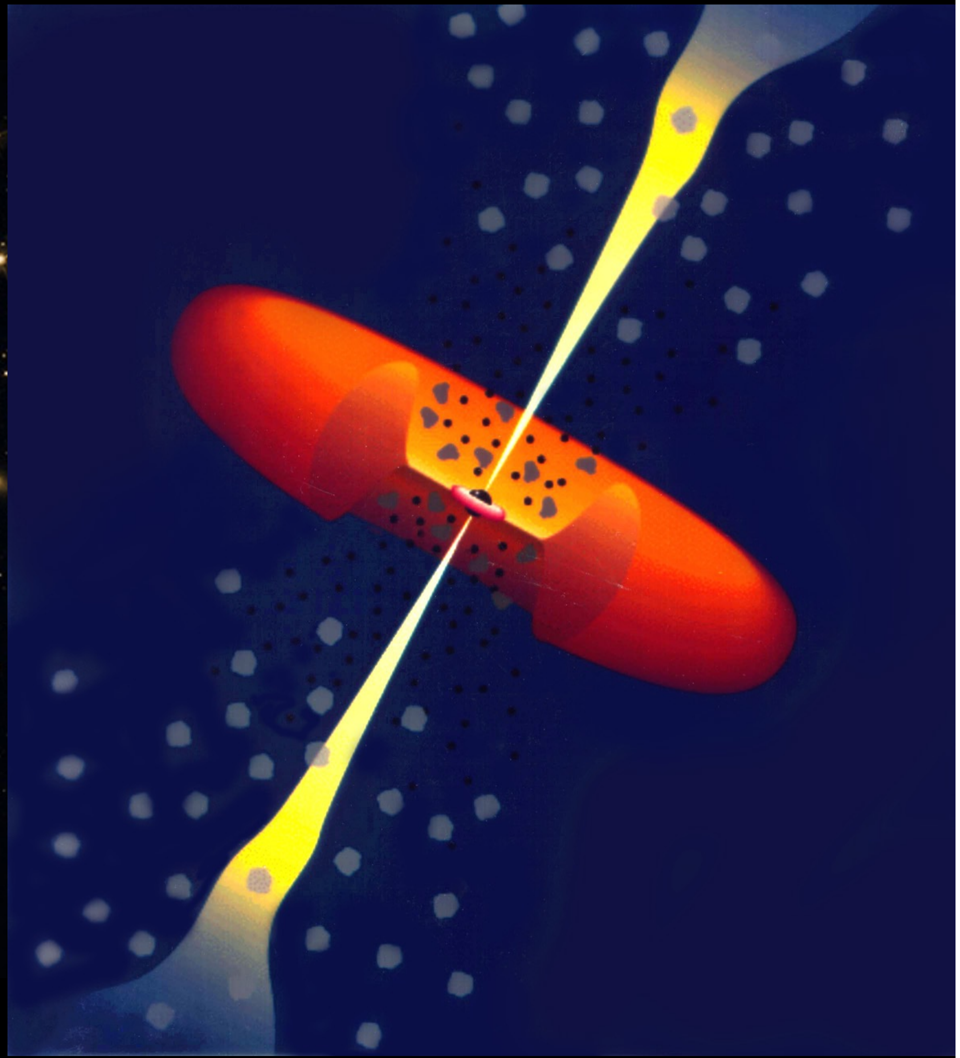
Crab Nebula

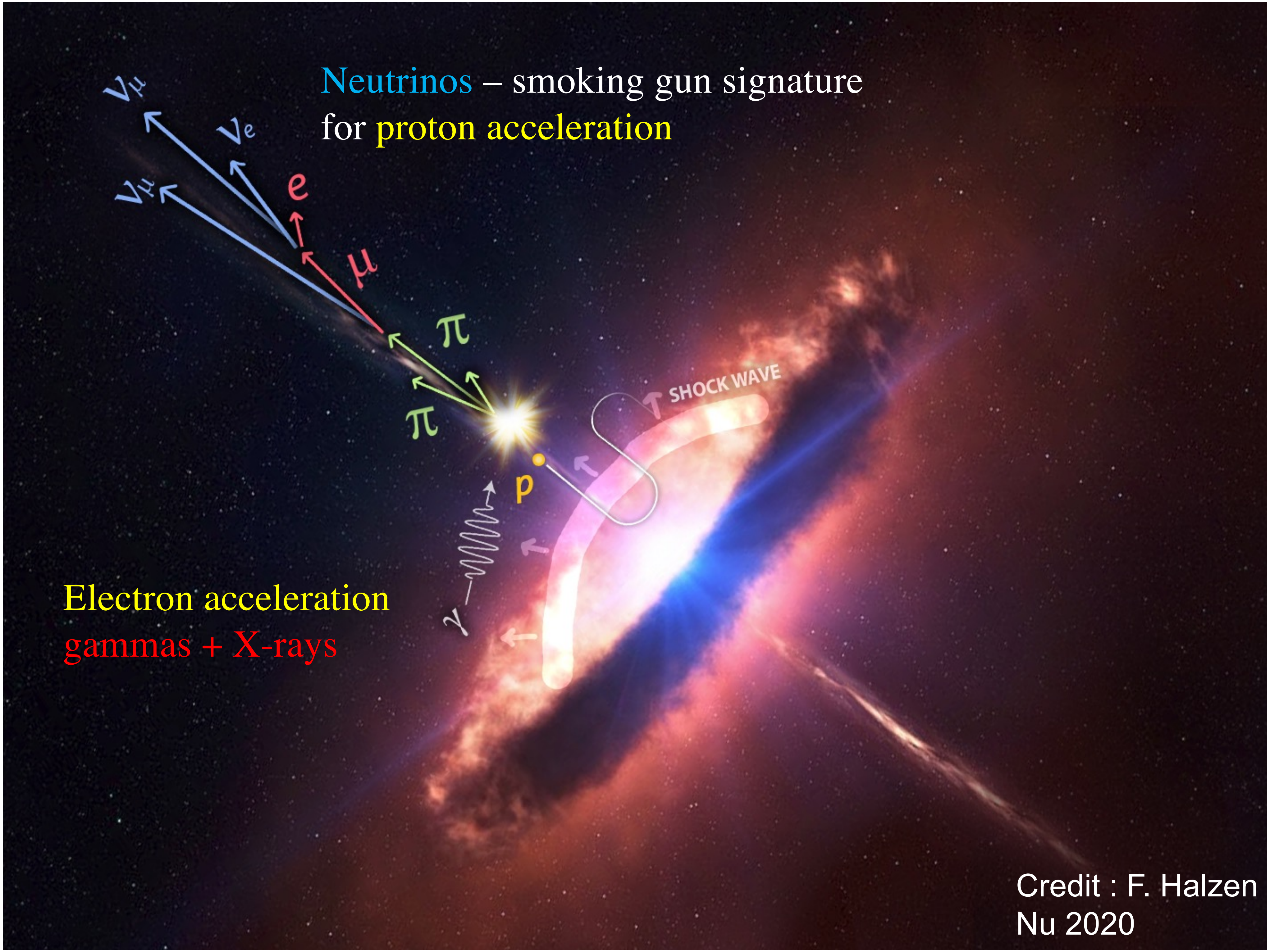


Active galactic nuclei accretion disks and jets

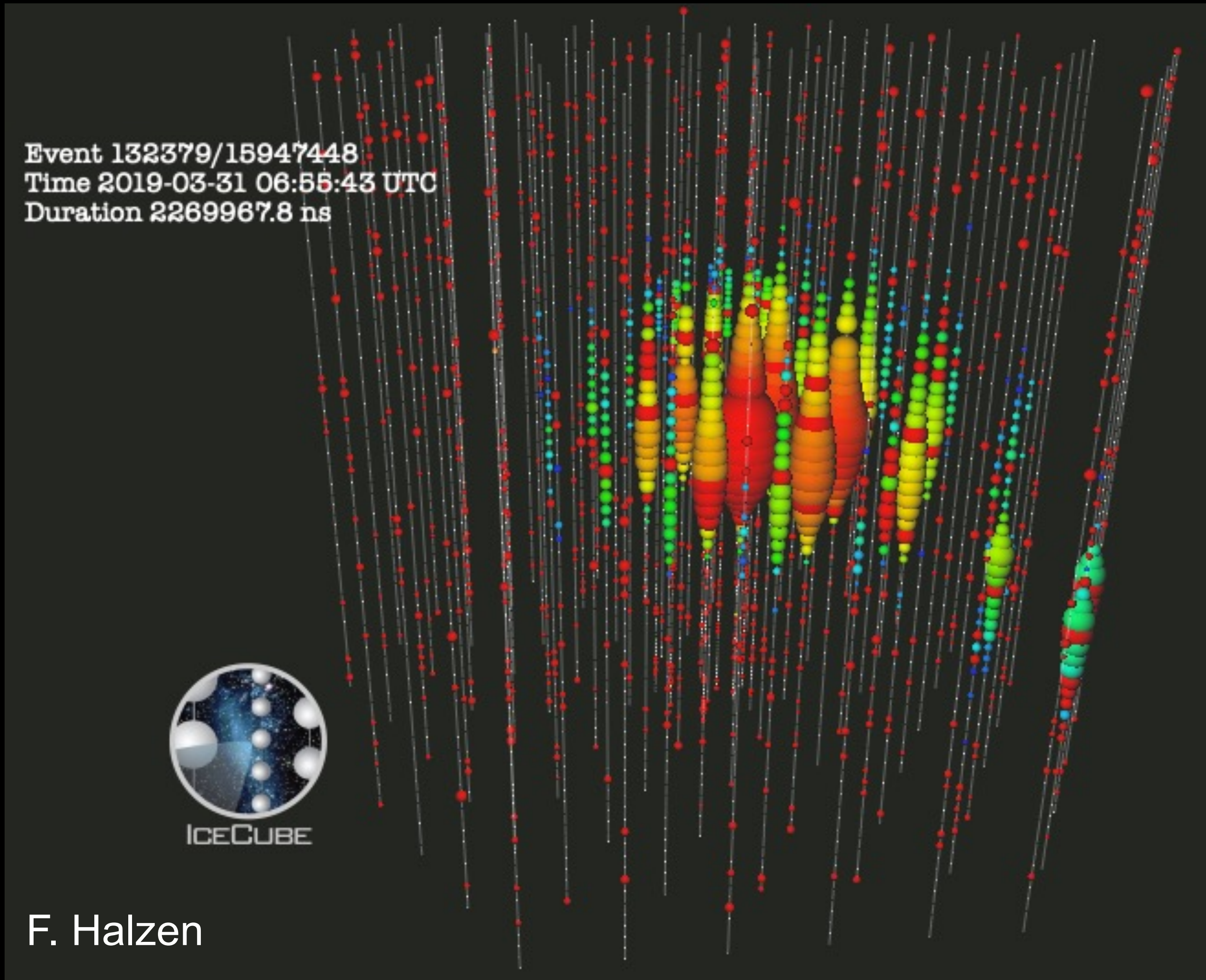
Up to 10^{20} eV

Cygnus A
Radio : NSF/NRAO/AUI/VLA
Optical : NASA/STScI
X-Ray : NASA/CXC/SAO




Neutrinos – smoking gun signature
for proton acceleration
ν_μ
ν_e
ν_μ
e
μ
π
π
p
γ
SHOCK WAVE
Electron acceleration
gammas + X-rays
Credit : F. Halzen
Nu 2020

IC190331: 5.300 PeV deposited inside the detector



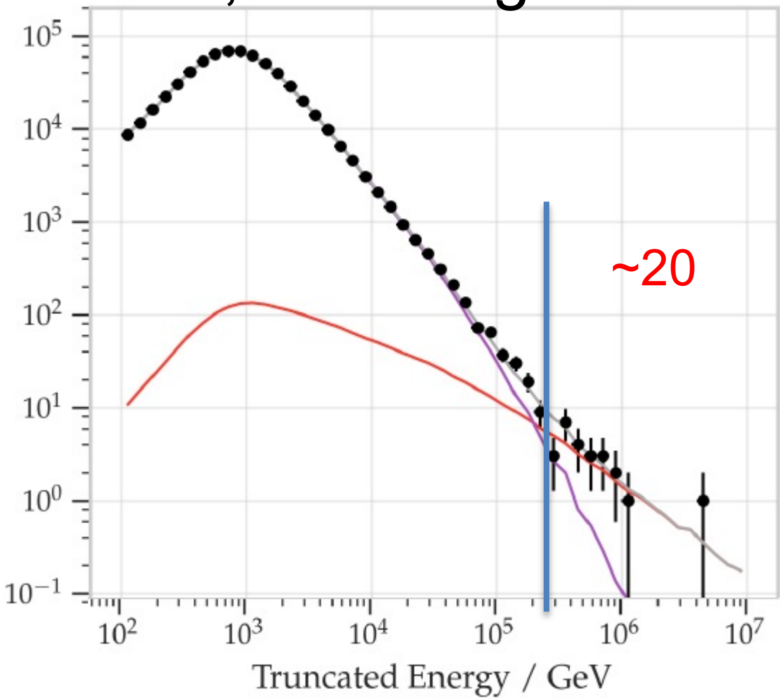
initial neutrino energy 10~20 PeV

Diffuse astrophysical neutrinos flux in IceCube

https://arxiv.org/pdf/1908.09551.pdf
10 years of data taking

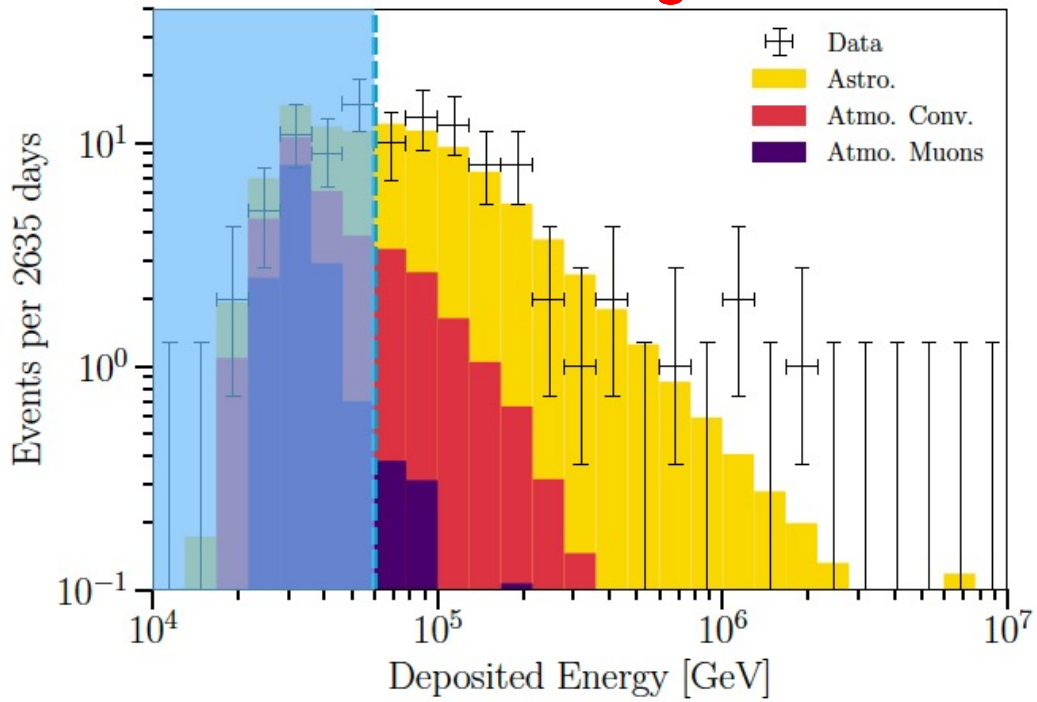
https://arxiv.org/abs/2011.03545
7.5 years of data taking

650,000 Ereignisse



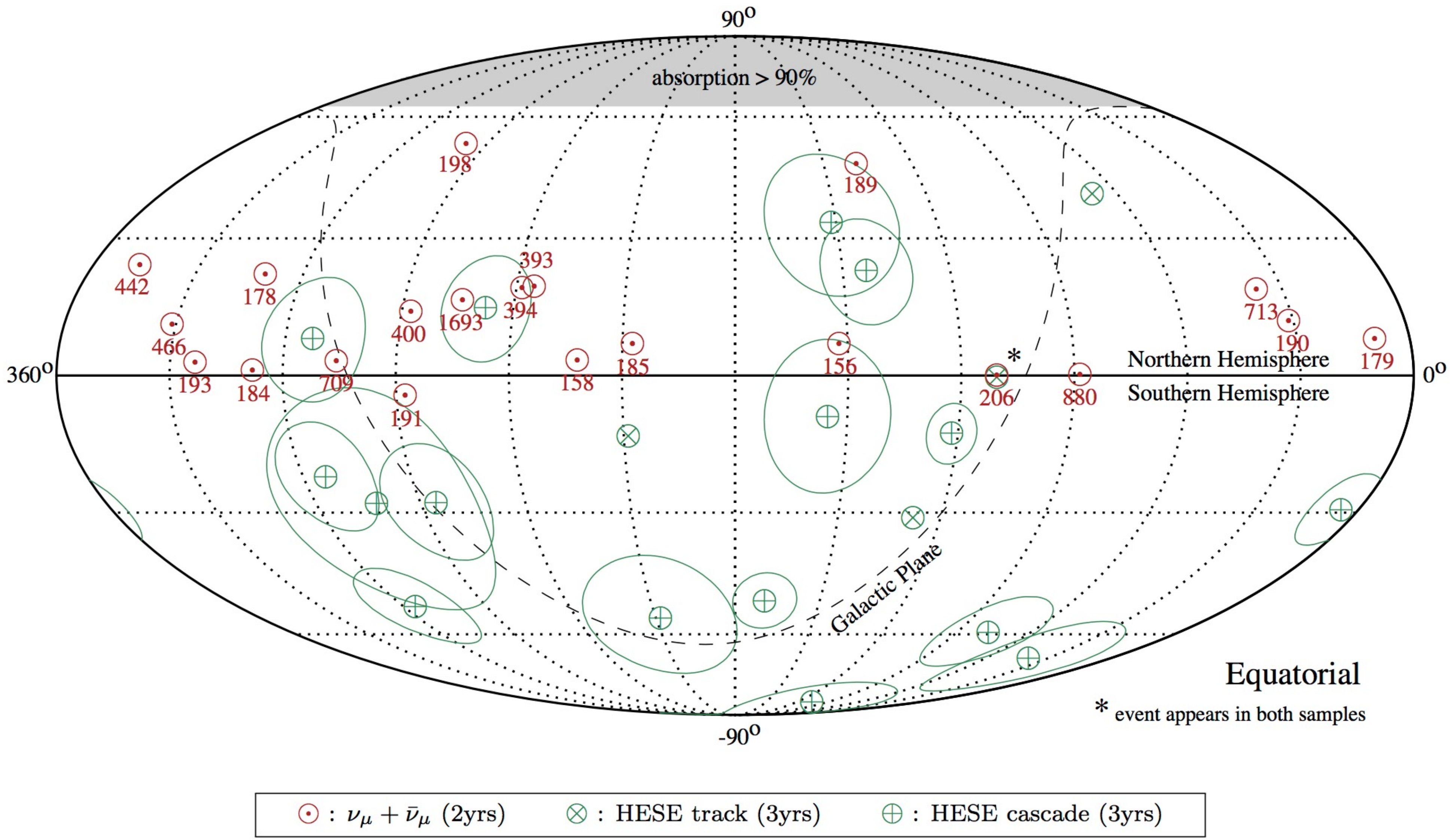
Upgoing Tracks

42 + 60 Ereignisse



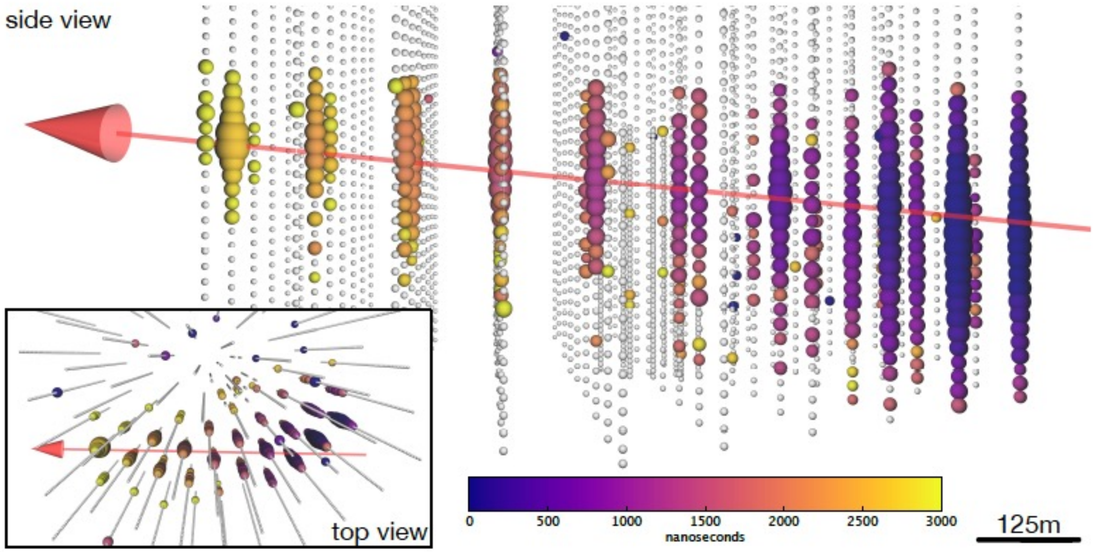
High Energy Starting Events

Skymap of astrophysical neutrinos in IceCube

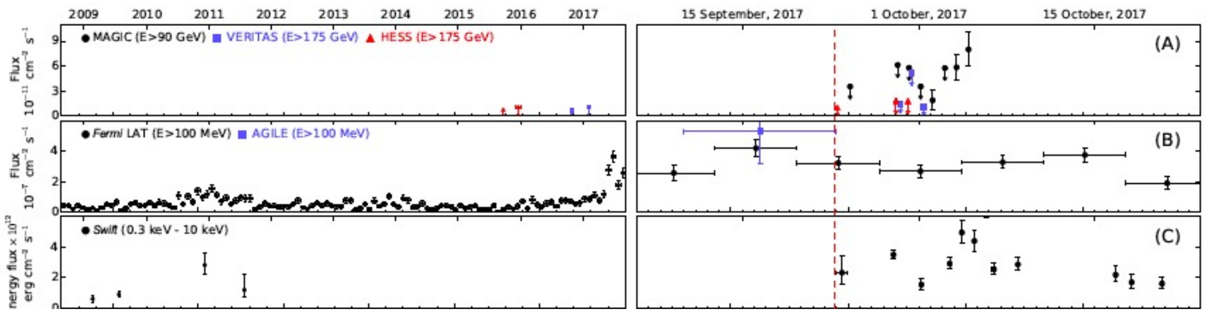


First point source candidat ?

TXS 0506+056. – Blazar (Quasar with Jet pointing towards us)
5.7 billion light years, highly variable
Neutrino **IceCube-170922A** 290 TeV

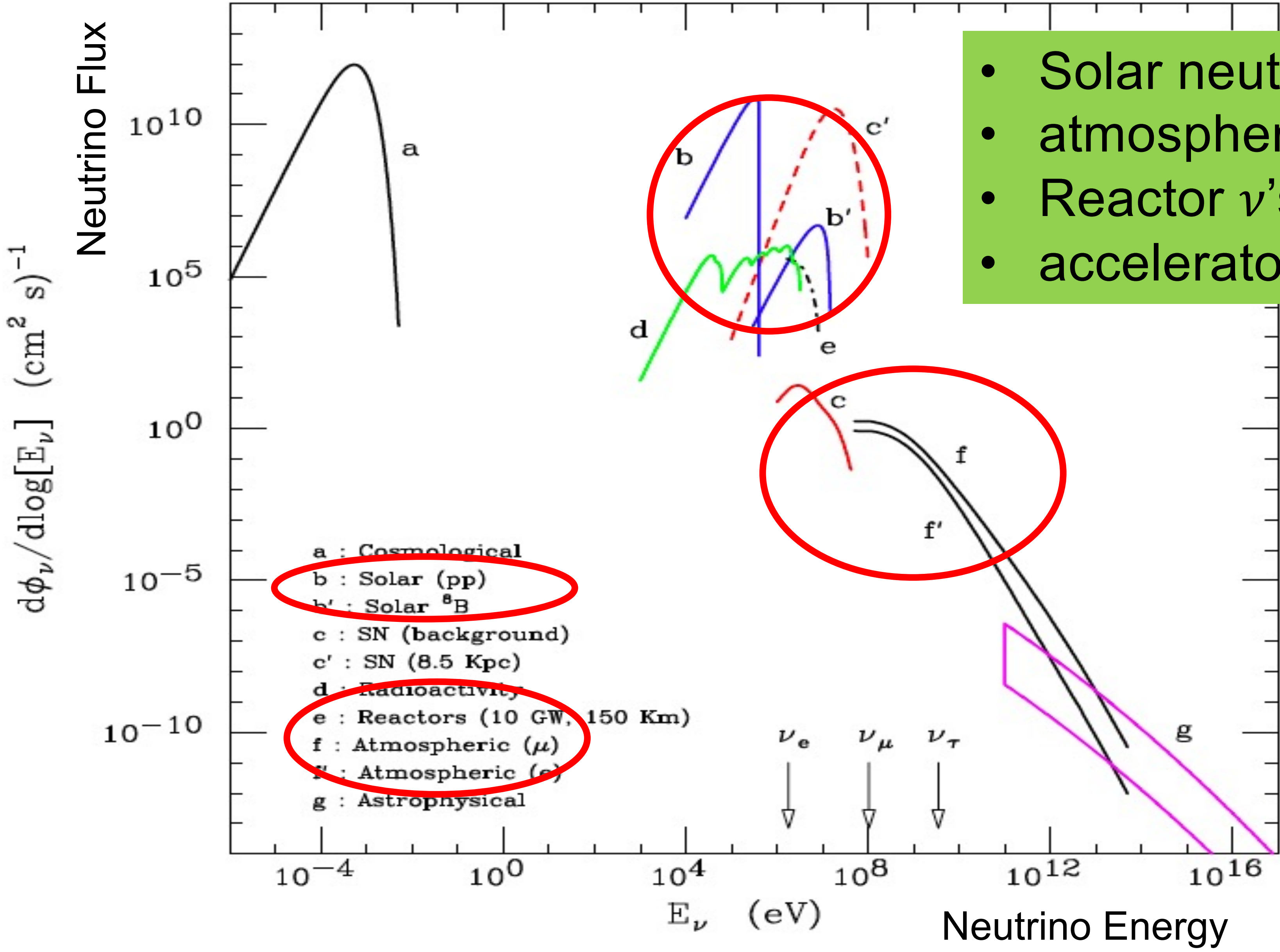


Flare in x-ray and gamma rays



https://arxiv.org/pdf/1807.08816.pdf

Neutrinos properties



- Solar neutrino ν's
- atmospheric ν's
- Reactor ν's
- accelerators

Credit : P. Lipari “Introduction to Neutrino Physics”

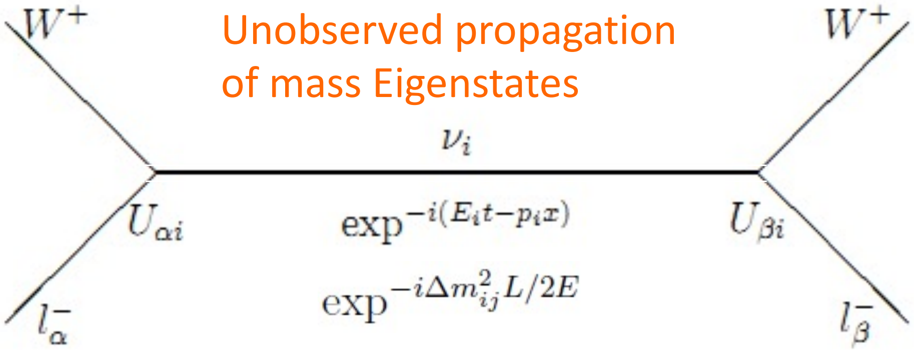
Neutrino Oscillations

- Weak Eigenstates are superposition of mass Eigenstates

$$\nu_\alpha = \sum_i U_{\alpha i} \nu_i$$

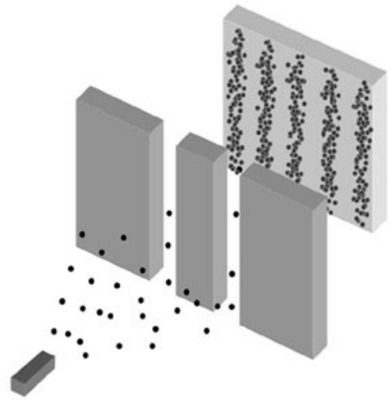
Neutrino production via CC interaction

Neutrino detection via CC interaction



Neutrino flavour defined via charged leptons

Equivalence to double slit experience



Coherent sum

$$P(\alpha \to \beta) = |\sum_i U_{\beta i} \ \exp^{-i(E_i t - \vec{p_i}\vec{x})} \ U^*_{\alpha i}|^2.$$

Classic: incoherent sum

$$P(\alpha \to \beta) = \sum_i |U_{\alpha i}|^2 |U_{\beta i}|^2$$

Table of elementary particle

- Mass Eigenstates are referred to

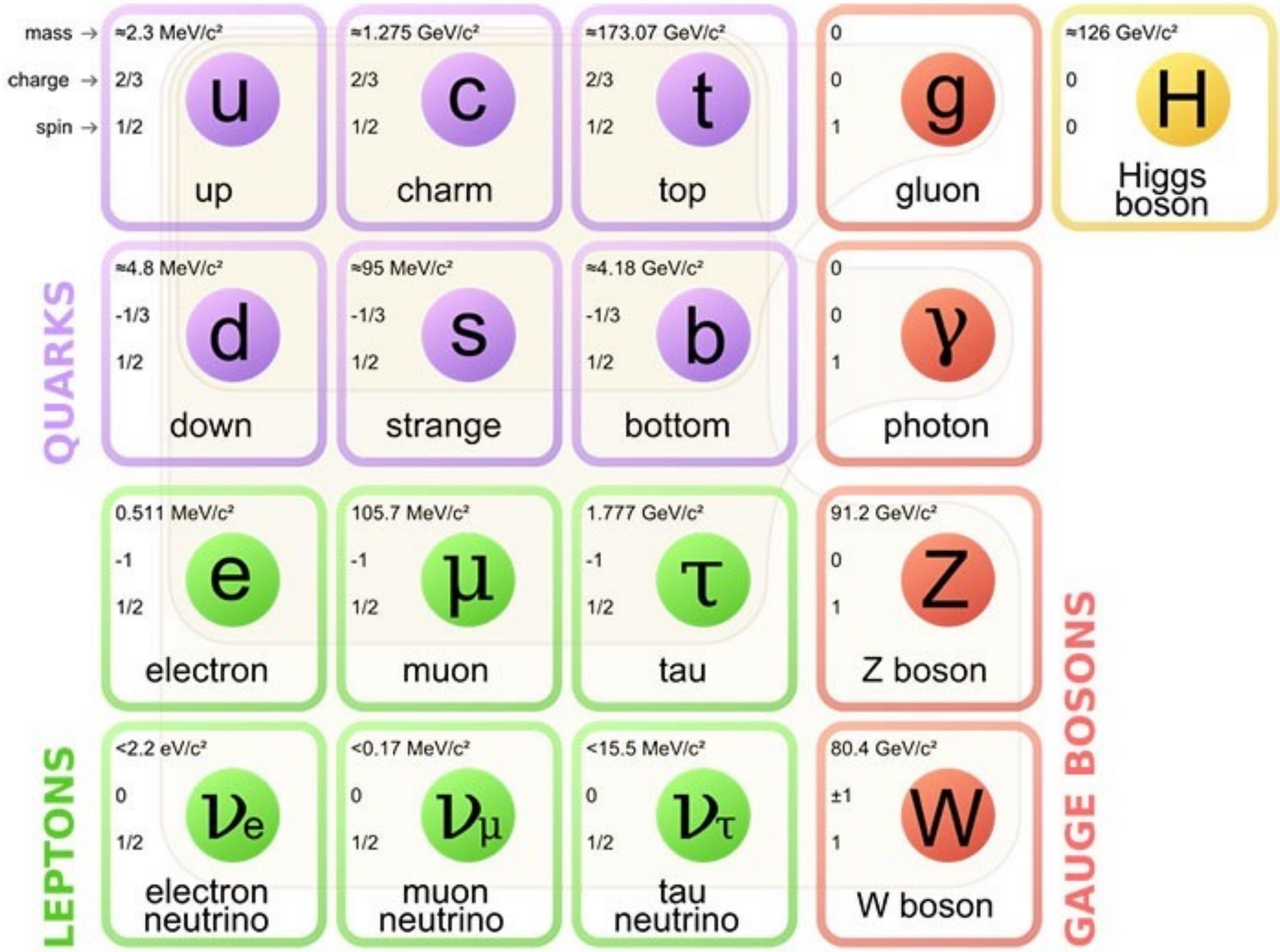


Table of elementary particle

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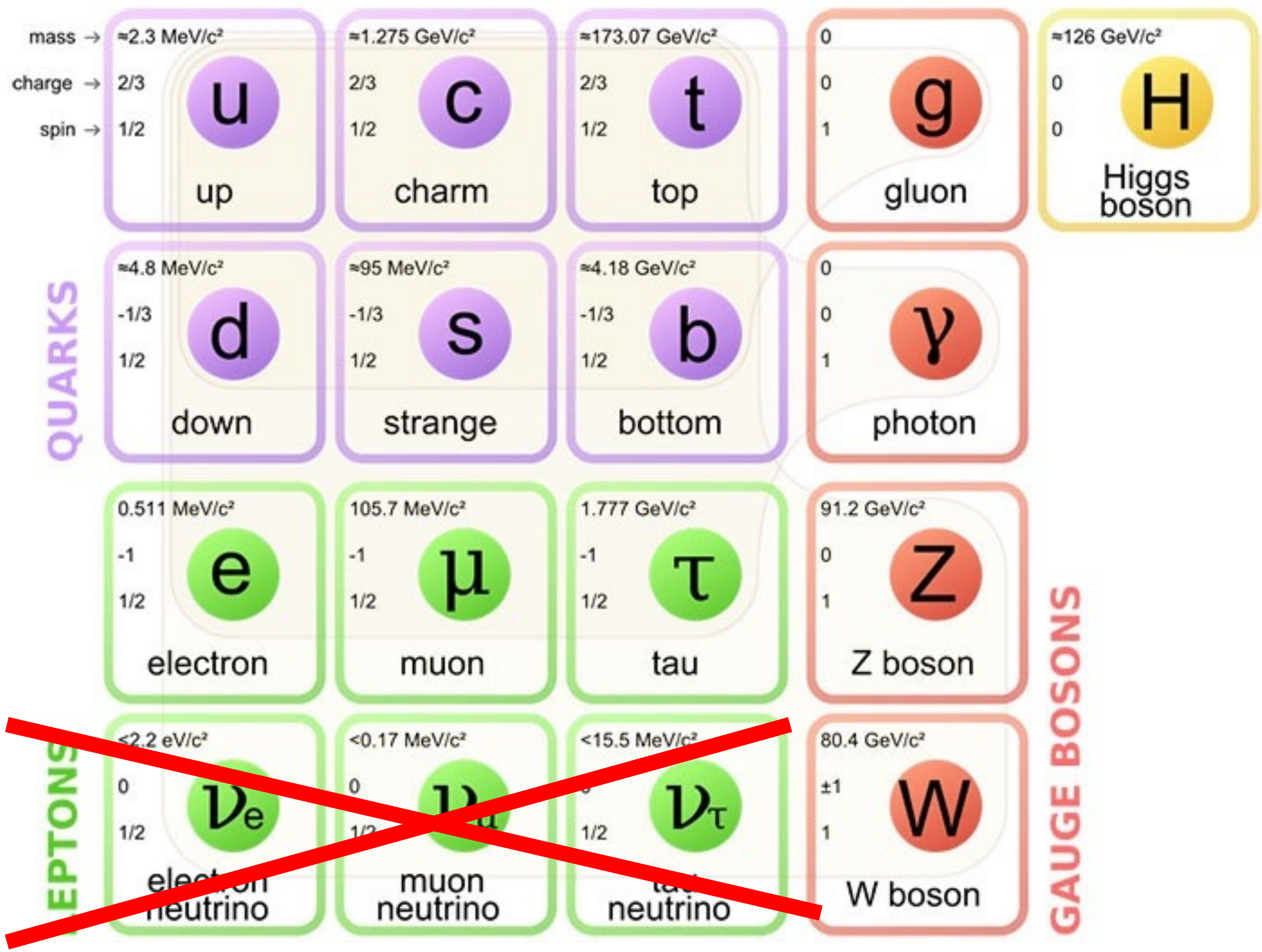
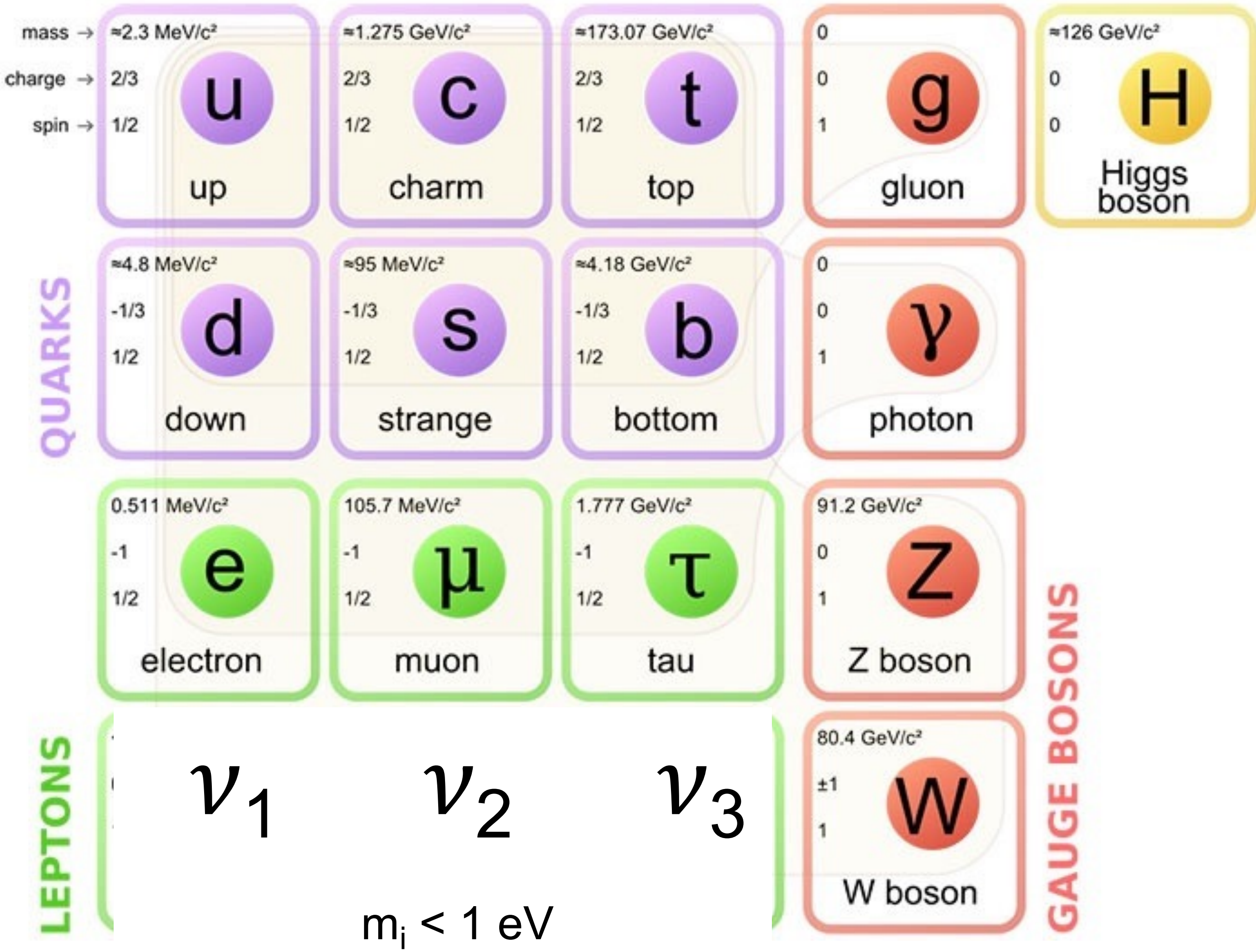


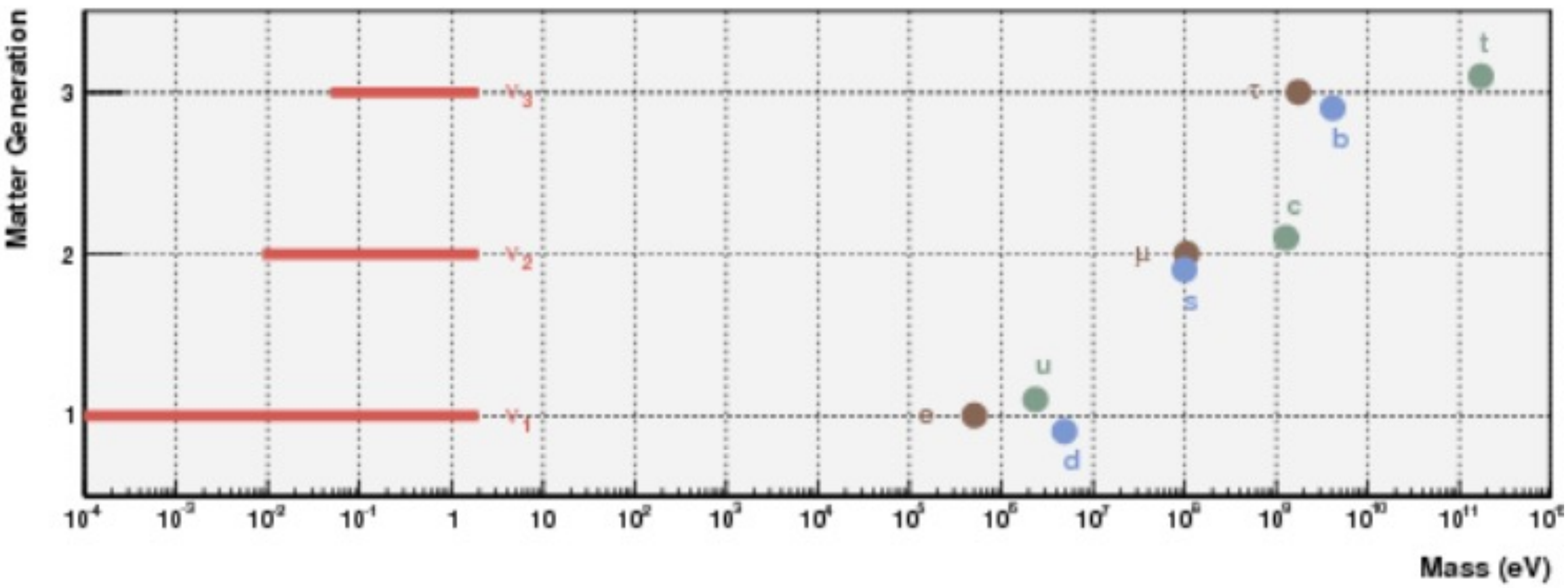
Table of elementary particle

- Mass Eigenstates are referred to



Neutrino Masses

- Much smaller than other fermion masses
- Do neutrinos follow the mass/family rule?



Neutrino masses

- Different mass combinations are measured
- Cosmology : $\sum m_i$
- Oscillations : $m_i^2 - m_j^2$
- beta decay $m_{\nu_e} = \sqrt{\sum_i |U_{ei}|^2 m_{\nu_i}^2}$
- Double beta decay $\langle m_{\beta\beta} \rangle = |\sum_i |U_{ei}|^2 m_{\nu_i} e^{i\alpha_i}|$

Neutrino mixing and oscillations

Pontecorvo – Maki – Nakagawa - Sakata (PMNS) matrix

weak eigenstates

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

mass eigenstates

3 mixing angles + 1 phase

$(c_{ij} \equiv \cos\theta_{ij}, \quad s_{ij} \equiv \sin\theta_{ij})$

$$U = \begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{pmatrix} \begin{pmatrix} c_{13} & & s_{13} \cdot e^{i\delta} \\ & 1 & \\ -s_{13} \cdot e^{i\delta} & & c_{13} \end{pmatrix} \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} 1 & & \\ & e^{i\alpha} & \\ & & e^{i\beta} \end{pmatrix}$$

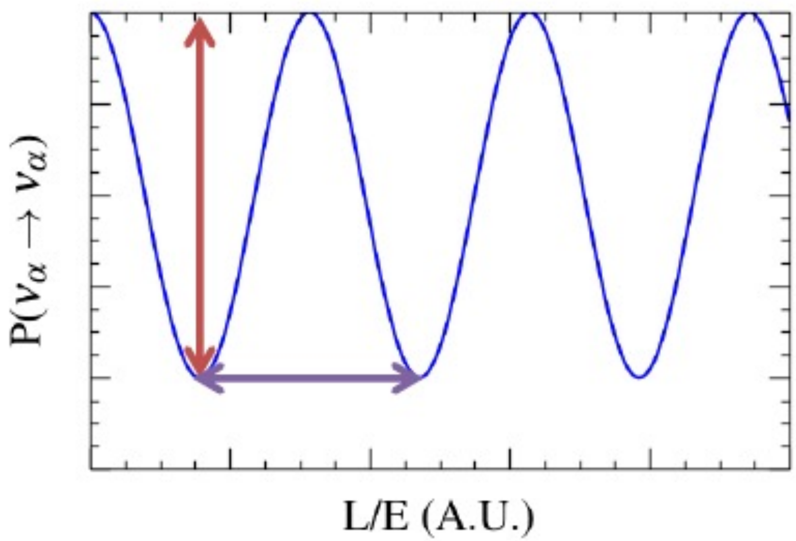
Solar Reactors	Reactor	Atmospheric Accelerators	Majorana Phases

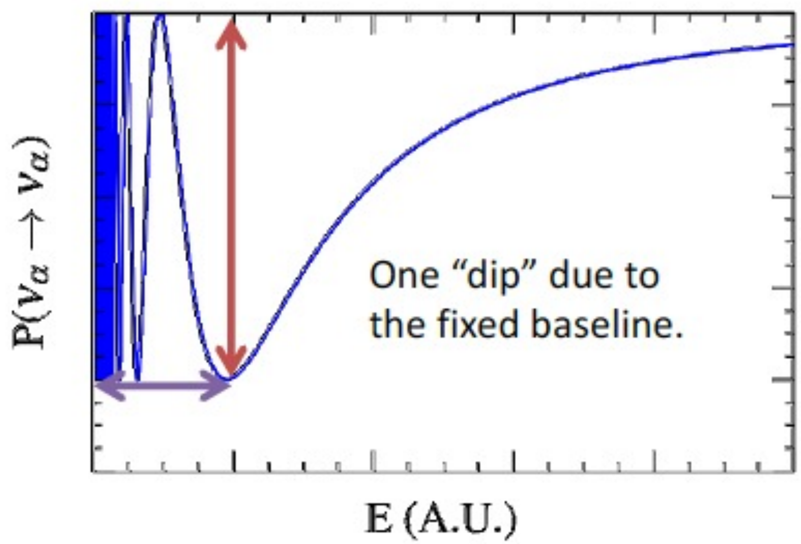
Oscillation experiments

- Disappearance

Sub-dominant term due to small θ_{13}

$$P(\nu_\mu \to \nu_\mu) \approx 1 - \left(\sin^2(2\theta_{13}) \sin^2(\theta_{23}) + \cos^4(\theta_{13}) \sin^2(2\theta_{23}) \right) \sin^2\left(\frac{\Delta m^2 L}{4E} \right)$$

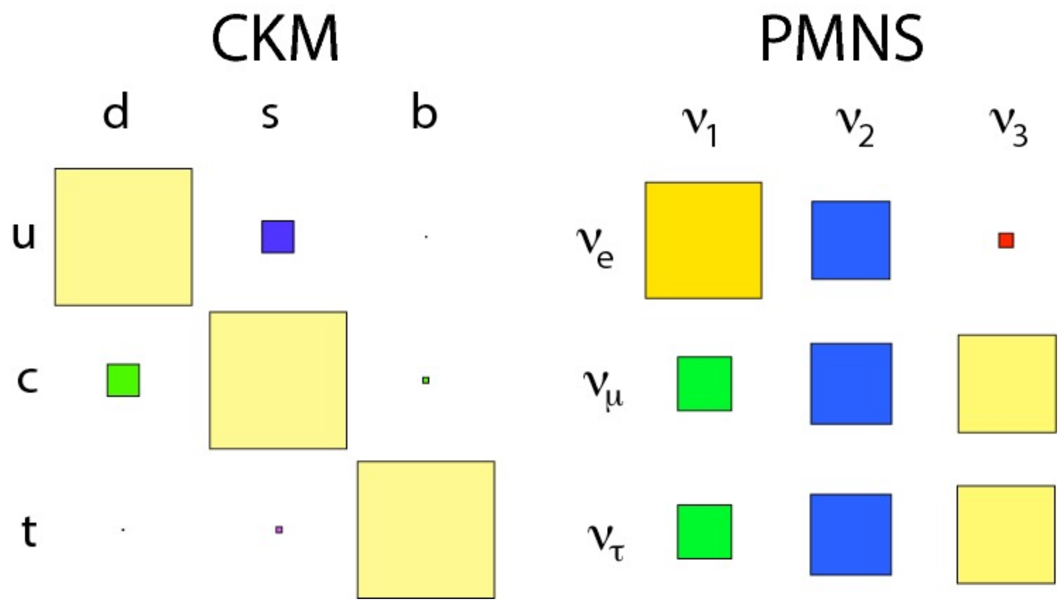




Nunokawa, Parke, Valle, in "CP Violation and Neutrino Oscillations", Prog.Part.Nucl.Phys. 60 (2008) 338-402.

Mixing matrix

- Structure of CKM and PMNS matrix very different
- Non-diagonal structure of PMNS-matrix not understood



arXiv:1212.6374

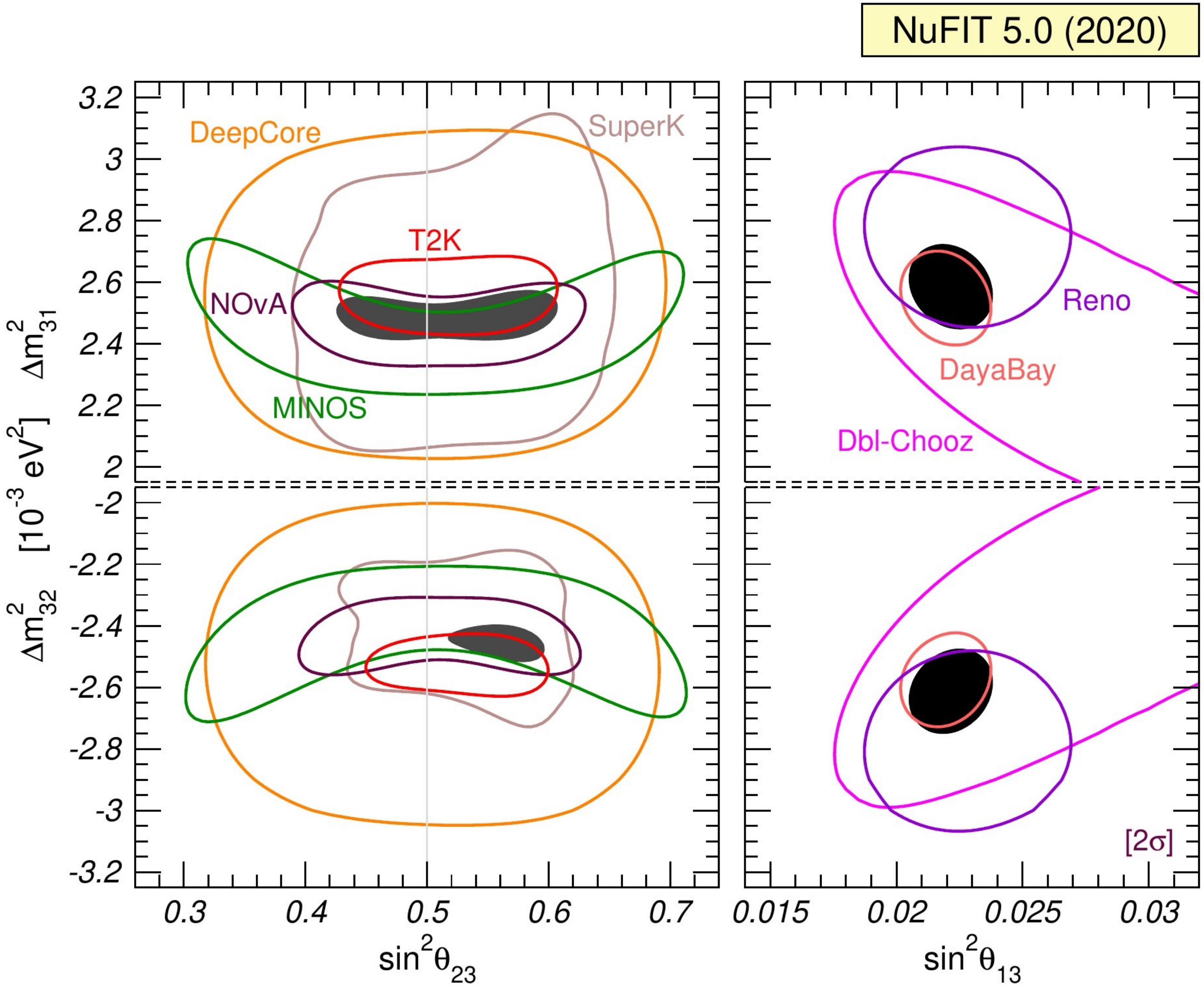
Current Status

NuFIT 5.0 (2020)

without SK atmospheric data		Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 2.7$)	
		bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
	$\sin^2\theta_{12}$ 4.1%	$0.304^{+0.013}_{-0.012}$	$0.269 \to 0.343$	$0.304^{+0.013}_{-0.012}$	$0.269 \to 0.343$
	$\theta_{12}/^\circ$ 2.3%	$33.44^{+0.78}_{-0.75}$	$31.27 \to 35.86$	$33.45^{+0.78}_{-0.75}$	$31.27 \to 35.87$
	$\sin^2\theta_{23}$ 6.2%	$0.570^{+0.018}_{-0.024}$	$0.407 \to 0.618$	$0.575^{+0.017}_{-0.021}$	$0.411 \to 0.621$
	$\theta_{23}/^\circ$ 4.2%	$49.0^{+1.1}_{-1.4}$	$39.6 \to 51.8$	$49.3^{+1.0}_{-1.2}$	$39.9 \to 52.0$
	$\sin^2\theta_{13}$ 3.0%	$0.02221^{+0.00068}_{-0.00062}$	$0.02034 \to 0.02430$	$0.02240^{+0.00062}_{-0.00062}$	$0.02053 \to 0.02436$
	$\theta_{13}/^\circ$ 1.5%	$8.57^{+0.13}_{-0.12}$	$8.20 \to 8.97$	$8.61^{+0.12}_{-0.12}$	$8.24 \to 8.98$
	$\delta_{CP}/^\circ$	195^{+51}_{-25}	$107 \to 403$	286^{+27}_{-32}	$192 \to 360$
2.7%	$\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$
1.1%	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$+2.514^{+0.028}_{-0.027}$	$+2.431 \to +2.598$	$-2.497^{+0.028}_{-0.028}$	$-2.583 \to -2.412$

The "atmospheric" oscillation parameters

- Situation after ":Neutrino 2020"

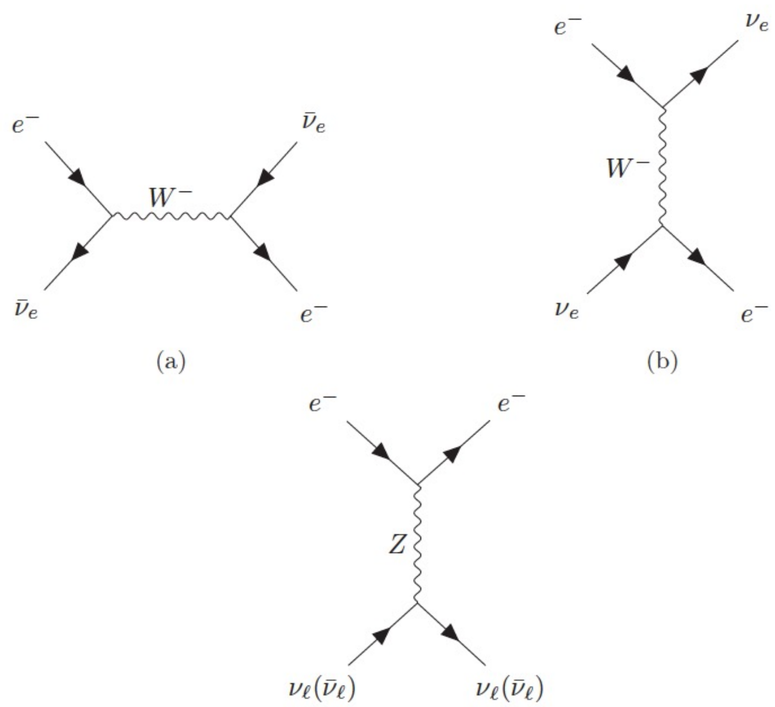


Neutrino oscillations in matter

Propagation of electron (anti-)neutrinos in the Earth affected by matter potential (Mikheyev-Smirnov-Wolfenstein effect)

Forward scattering on electrons
$\Rightarrow$ change of effective mass for the electron neutrinos
$\Rightarrow$ change of oscillation pattern

=> Sensitive to Neutrino Mass hierarchy



Resonance Effect in Matter

- ν_e see additional potential due to W-exchange in ν+e → ν+e scattering
- Illustration for constant electron density n_e
- At resonant energy θ_{13} maximal

  changes sign with n_e via ν / $\overline{\nu}$

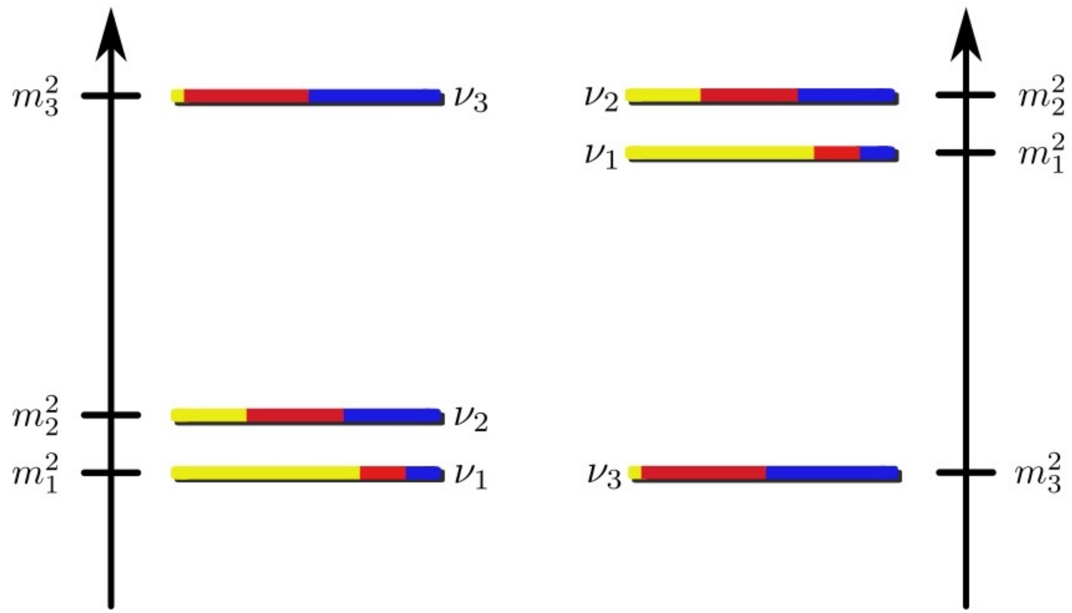
  changes sign with Δm^2 → mass hierarchy !

$$
\begin{aligned}
\sin 2\theta_{13}^m &= \sin(2\theta_{13})/R \quad ; \quad (\Delta m_{31}^2)^m = \Delta m_{32}^2/2[1+A+R] \\
\theta_{23}^m &= \theta_{23} \quad ; \quad (\Delta m_{32}^2)^m = \Delta m_{32}^2 R \\
\theta_{12}^m &= \pi/2 \quad ; \quad (\Delta m_{21}^2)^m = \Delta m_{32}^2/2[1+A-R]
\end{aligned}
$$

$$
\begin{aligned}
R &= \sqrt{(A-\cos 2\theta_{13})^2 + (\sin 2\theta_{13})^2} \\
A &= 2\sqrt{2} G_F n_e E / \Delta m_{32}^2 .
\end{aligned}
$$

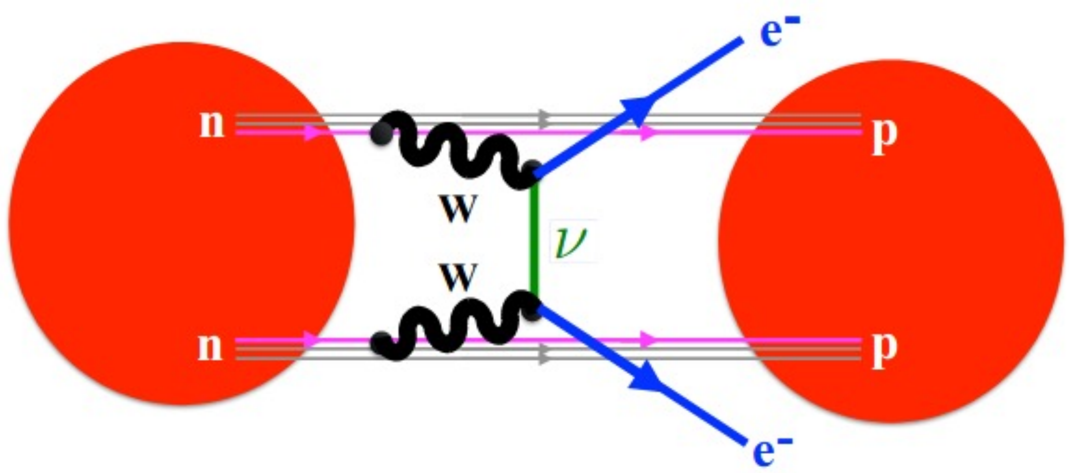
Possible mass pattern

- Naming/Color convention
  - Index 1, 2, 3 : increasing contribution of electron state
  - Electron Muon Tau
- Matter effect in sun fixes $m_2 > m_1$
- No matter effects to measure Δm_{31}^2 → sign unconstraint
- 2 schemes survive



Dirac versus Majorana

- Neutrinoless double beta decay
- Only known method to test Majorana nature of neutrinos
- Internal neutrino must flip helicity, suppressed with $(m/Q)^2$
- Neutrino – Antineutrino oscillations suppressed with $(m/E)^2 \sim 10^{-12}$ hopeless
- Side effect of Majorana mass term : Dirac field splits into two Majorana fields → automatically introduces sterile ν's (eV – LSND, keV – warm dark matter, 10^{15} eV – Seesaw)

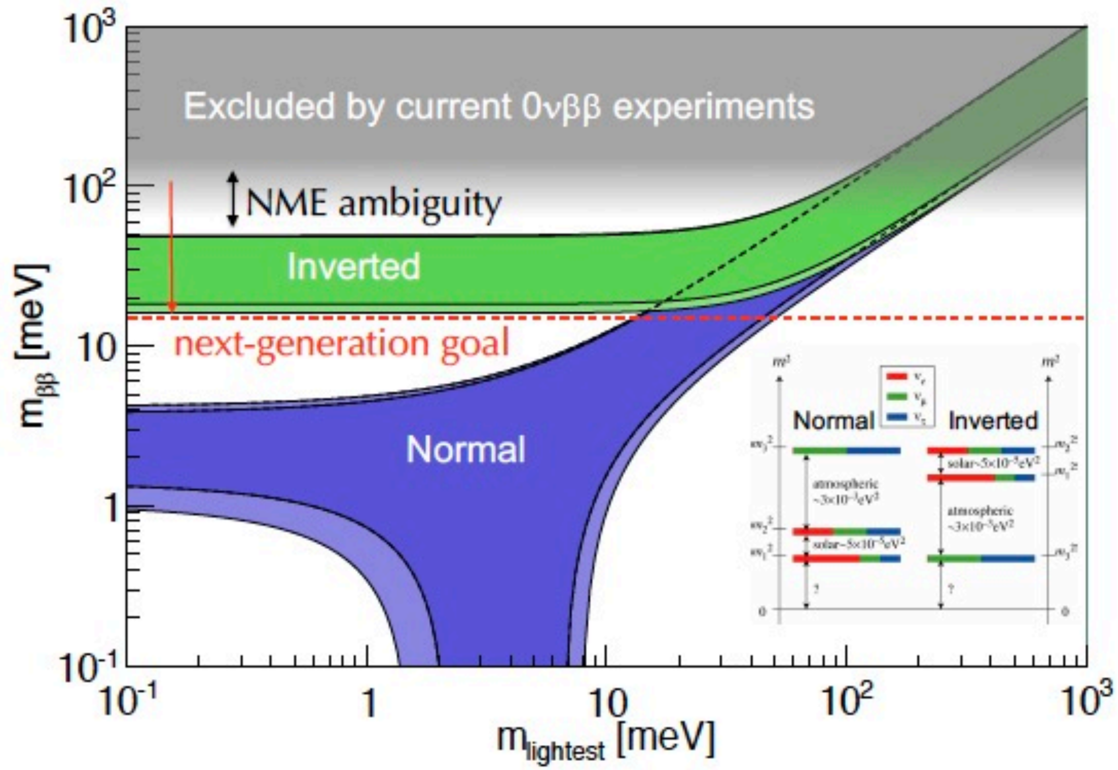


Double beta decay experiments

Current Limits and Future Goals

- Present best limits:
  - ^{136}Xe (KamLAND-Zen): $T_{1/2} > 10^{26}$ yrs
  - ^{76}Ge (GERDA): $T_{1/2} > 10^{26}$ yrs
  - ^{130}Te (CUORE): $T_{1/2} > 3\times10^{25}$ yrs
- Future goal:
  ~2 OoM improvement in $T_{1/2}$
  - Covers IO
  - Up to 50% of NO
  - Factor of ~few in Λ
  - An aggressive experimental goal

$$\frac{1}{T_{1/2}} = G_{01}\, g_A^4 \left(M^{0\nu} + \frac{g_\nu^{NN}\, m_\pi^2}{g_A^2} M_{\rm cont}^{0\nu} \right)^2 \frac{m_{\beta\beta}^2}{m_e^2}$$



Credit : J. Detwiler
Nu 2020

Open Questions

- Neutrino Astronomy
  - Cosmic ray sources
  - Understanding of Supernova explosions
- Neutrino Oscillation Experiments
  - Is CP violated in the lepton sector : δ_{CP} ?
  - Normal / inverted mass hierarchy ?
  - Is θ_{23} maximal ? If not : which octant ?
- Double Beta Decays
  - Neutrinos : Dirac / Majorana particles ?
- Beta Decays / Cosmology
  - Absolute Neutrino mass scale ?

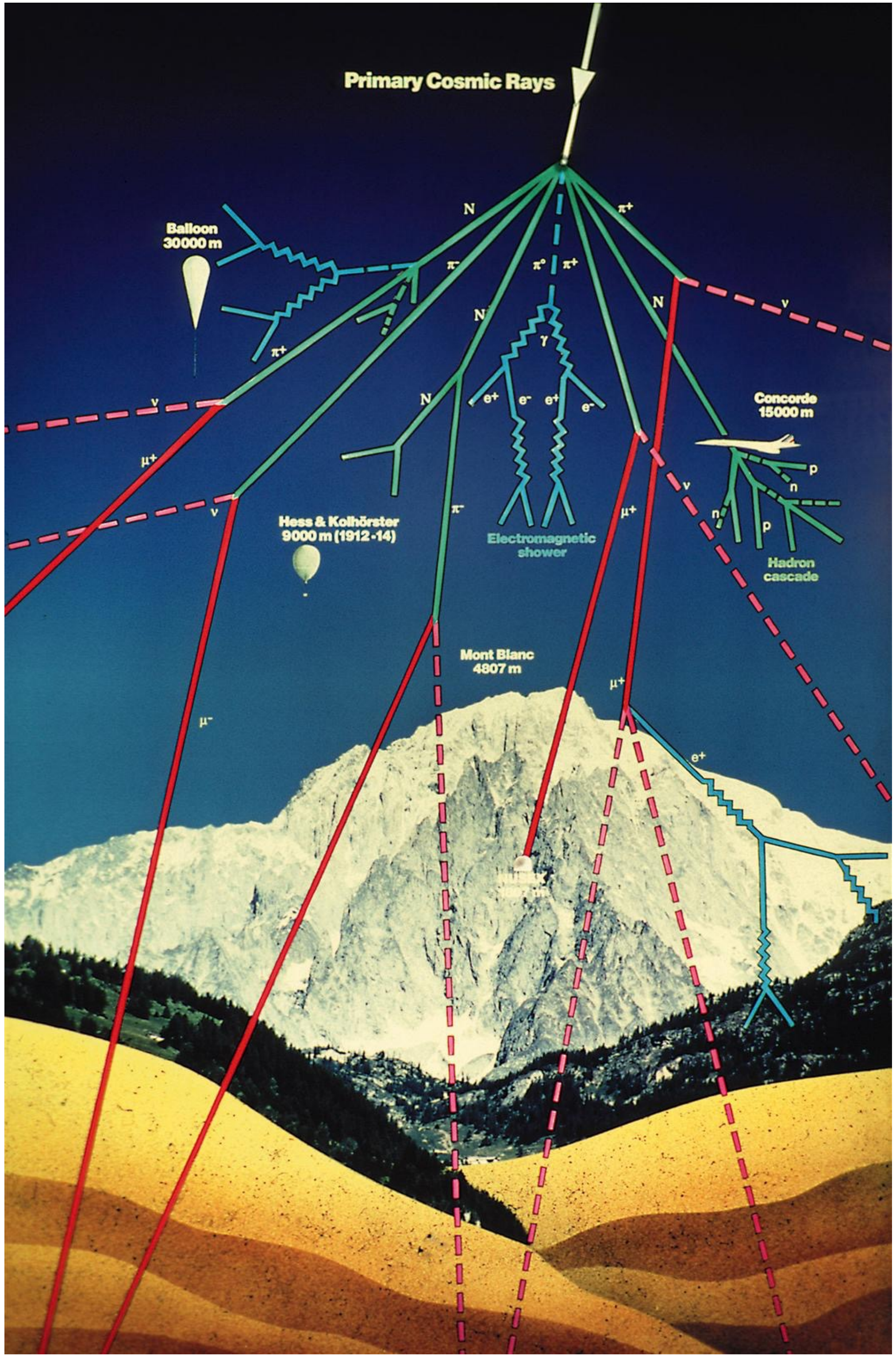
Backup

Atmospheric Neutrinos

Cosmice ray showers in upper atmoshere

background für Neutrino Astronomy

Signal for measuring neutrino properties



Expected flux in underground detector