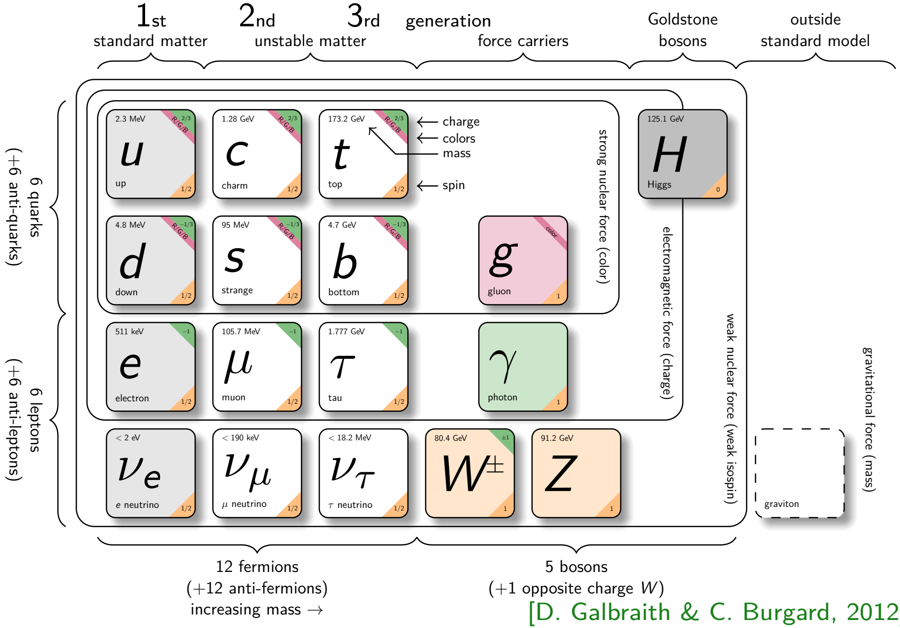
Neutrino Physics

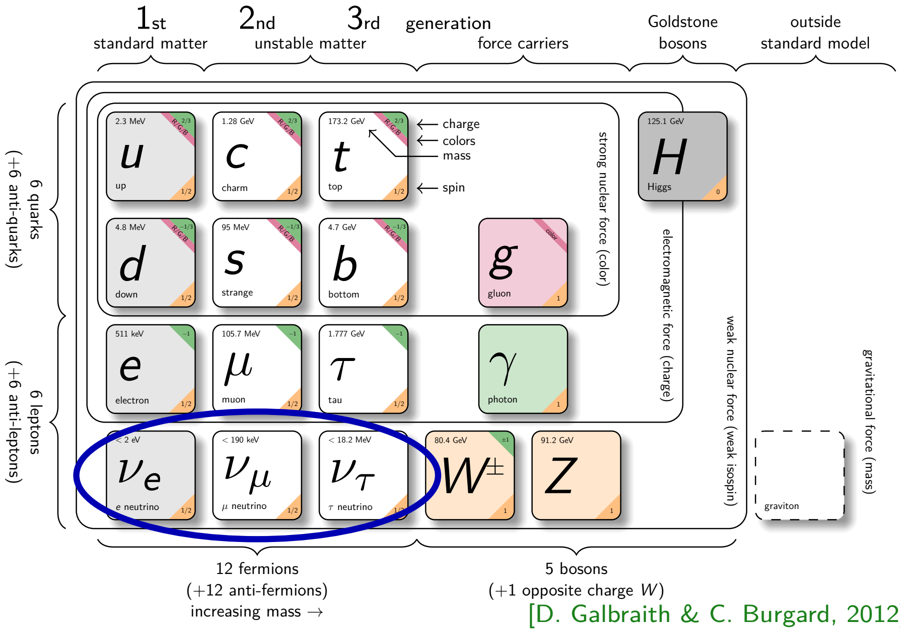
- General introduction (S. Gariazzo) – 8'
- Talks by the Fellini fellows:
  1. S. Gariazzo – 10'
     "Active and sterile neutrinos in the early universe: precision calculations"
  2. M. Lamoureux – 10'
     "Follow-up of gravitational wave events with Super-Kamiokande"
  3. G. Benato – 10'
     "Designing the next-generation $0\nu\beta\beta$ decay experiment CUPID"
- Scientific diffusion of the projects and conclusions (G. Benato) – 7'
- Discussion (M. Lamoureux) – 20'

The Standard Model of Particle Physics



[D. Galbraith & C. Burgard, 2012]

The Standard Model of Particle Physics

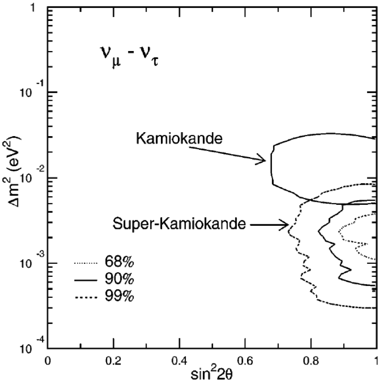


[D. Galbraith & C. Burgard, 2012]

Neutrino oscillations

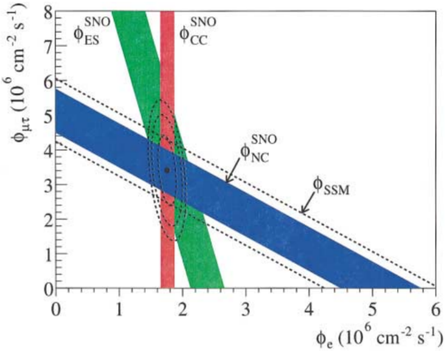
Major discoveries:

[SuperKamiokande, 1998]



first discovery of $\nu_\mu \to \nu_\tau$ oscillations from atmospheric ν

[SNO, 2001-2002]



first discovery of $\nu_e \to \nu_\mu, \nu_\tau$ oscillations from solar ν

Nobel prize in 2015

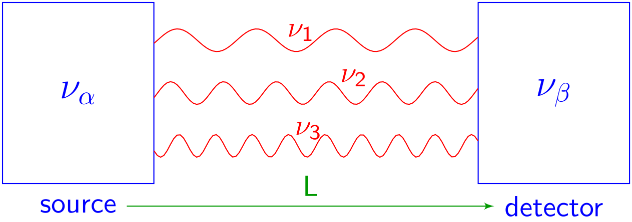
Two neutrino bases

flavor neutrinos ν_α

$|\nu_\alpha\rangle = \sum_k U_{\alpha k}|\nu_k\rangle$

massive neutrinos ν_k

$$|\nu(t=0)\rangle = |\nu_\alpha\rangle = U_{\alpha 1}|\nu_1\rangle + U_{\alpha 2}|\nu_2\rangle + U_{\alpha 3}|\nu_3\rangle$$



$$|\nu(t>0)\rangle = |\nu_\beta\rangle = U_{\alpha 1}\, e^{-iE_1 t}|\nu_1\rangle + U_{\alpha 2}\, e^{-iE_2 t}|\nu_2\rangle + U_{\alpha 3}\, e^{-iE_3 t}|\nu_3\rangle \neq |\nu_\alpha\rangle$$

$E_k^2 = p^2 + m_k^2$ ⟵ define ⟶ $t = L$

$$P_{\nu_\alpha \to \nu_\beta}(L) = |\langle \nu_\alpha | \nu(L)\rangle|^2 = \sum_{k,j} U_{\beta k} U^*_{\alpha k} U^*_{\beta j} U_{\alpha j} \exp\left(-i\frac{\Delta m^2_{kj} L}{2E}\right)$$

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

The mixing matrix

U can be parameterized using 3 angles (θ_{12}, θ_{13}, θ_{23}) and max 3 (1 Dirac δ, 2 Majorana [$\exists$ only for Majorana ν]) phases

$$U = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\text{mainly atmospheric and LBL accelerator disappearance}} \underbrace{\begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix}}_{\text{mainly SBL reactors and LBL accelerator appearance}} \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{mainly solar and LBL reactors}} M$$

Majorana phases irrelevant for oscillation experiments ← M

Relevant for example in neutrinoless double-beta decay

$s_{ij} \equiv \sin\theta_{ij}$; $c_{ij} \equiv \cos\theta_{ij}$

SBL = short baseline; LBL = long baseline

Three Neutrino Oscillations

$$\nu_\alpha = \sum_{k=1}^{3} U_{\alpha k}\nu_k \quad (\alpha = e, \mu, \tau)$$

$U_{\alpha k}$ described by 3 mixing angles θ_{12}, θ_{13}, θ_{23} and one CP phase δ

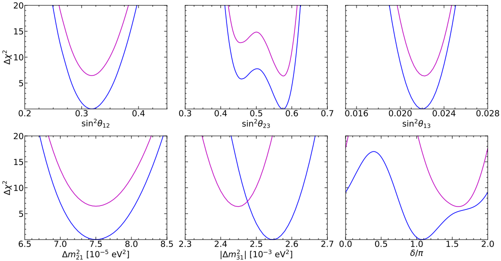
Current knowledge of the 3 active ν mixing: [JHEP 02 (2021)]

NO/NH: Normal Ordering/Hierarchy, $m_1 < m_2 < m_3$ IO/IH: Inverted O/H, $m_3 < m_1 < m_2$

$$\Delta m^2_{21} = (7.50^{+0.22}_{-0.20}) \cdot 10^{-5}\ \mathrm{eV}^2$$
$$|\Delta m^2_{31}| = (2.55^{+0.02}_{-0.03}) \cdot 10^{-3}\ \mathrm{eV}^2\ (\mathrm{NO})$$
$$= (2.45^{+0.02}_{-0.03}) \cdot 10^{-3}\ \mathrm{eV}^2\ (\mathrm{IO})$$

$$10\sin^2(\theta_{12}) = 3.18 \pm 0.16$$
$$10^2\sin^2(\theta_{13}) = 2.200^{+0.069}_{-0.062}\ (\mathrm{NO})$$
$$= 2.225^{+0.064}_{-0.070}\ (\mathrm{IO})$$
$$10\sin^2(\theta_{23}) = 5.74 \pm 0.14\ (\mathrm{NO})$$
$$= 5.78^{+0.10}_{-0.17}\ (\mathrm{IO})$$

$$\delta/\pi = 1.08^{+0.13}_{-0.12}\ (\mathrm{NO})$$
$$= 1.58^{+0.15}_{-0.16}\ (\mathrm{IO})$$



mass ordering still unknown

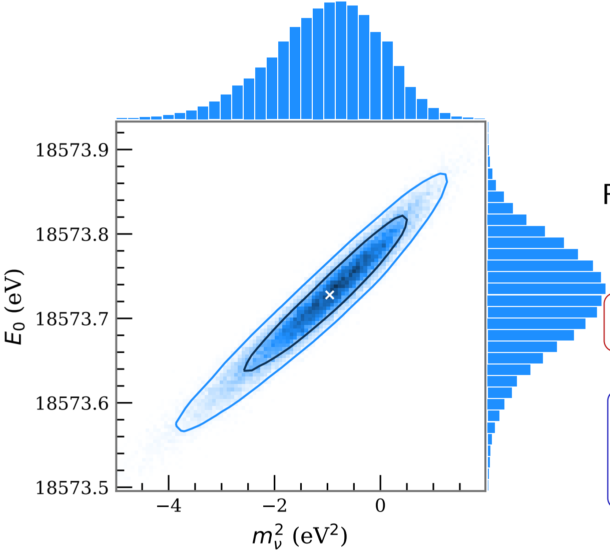
δ still unknown

see also: `http://globalfit.astroparticles.es`

Absolute neutrino mass scale

[KATRIN, PRL 123 (2019)]

strongest bound on $m_\nu (\equiv m_{\bar{\nu}_e})$ are from KATRIN



$m_\nu^2 = -1.0^{+0.9}_{-1.1}$ eV^2

Upper limit 90%:

$m_\nu < 1.1$ eV

Feldman-Cousins 90%:

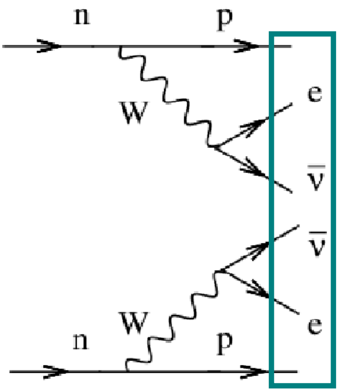
$m_\nu < 0.8$ eV

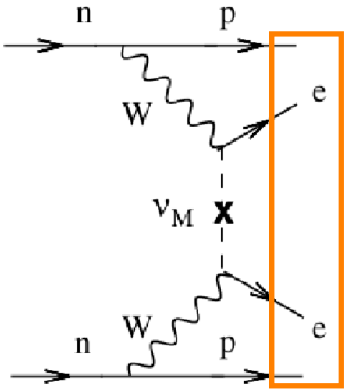
statistics dominated!

expected final sensitivity (90%):

$m_\nu \lesssim 0.2$ eV

Neutrino nature: Dirac or Majorana?





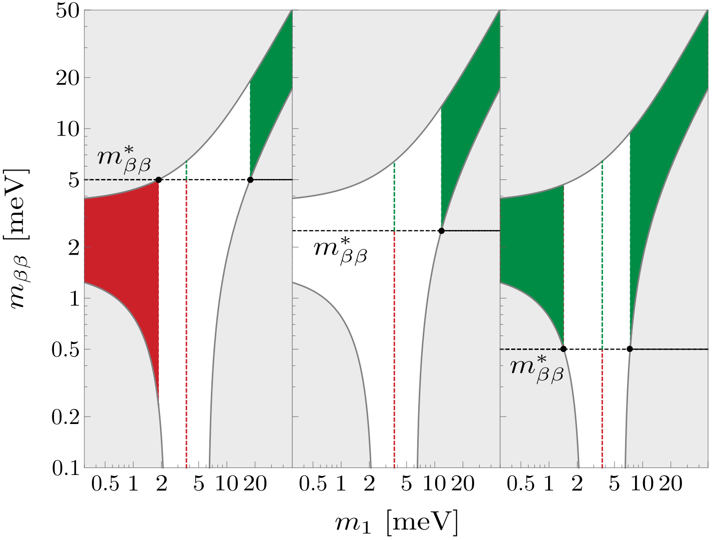
Black Box theorem:

Discovery of neutrinoless double-β decay implies Majorana mass term

[Schechter&Valle, 1982]

Neutrino nature: Dirac or Majorana?

[Agostini, Benato+, PRD 2020]

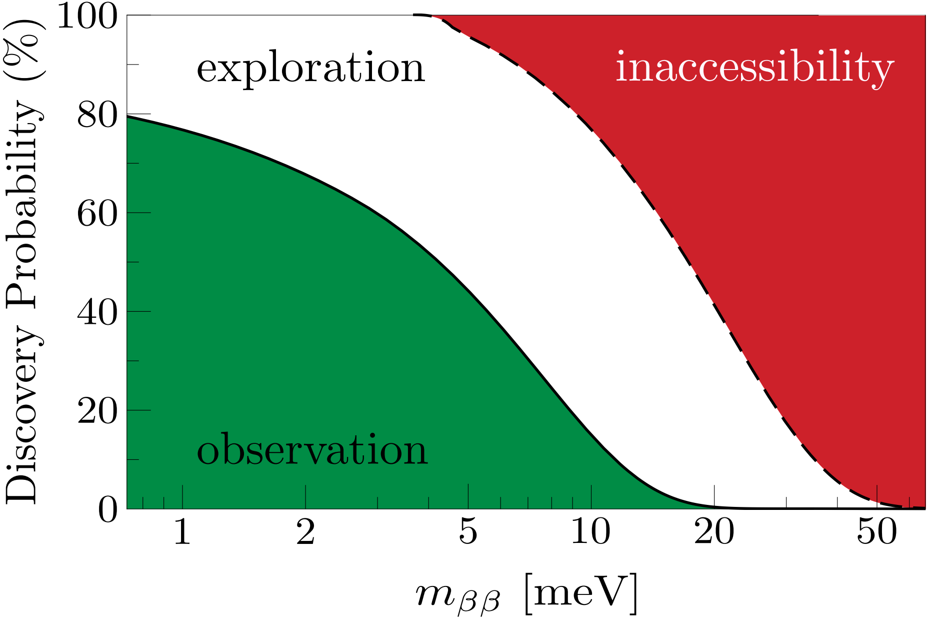


$$m_{\beta\beta} = \left|\sum_k e^{i\alpha_k}\, U_{ek}^2\, m_k\right|$$

$m^*_{\beta\beta}$ sensitivity

Neutrino nature: Dirac or Majorana?

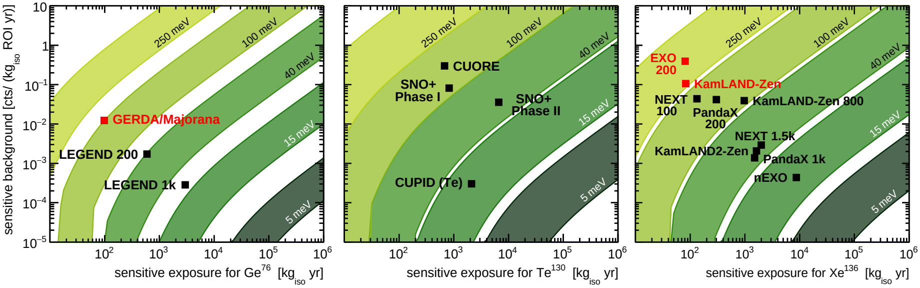
[Agostini, Benato+, PRD 2020]



Neutrino nature: Dirac or Majorana?

[Agostini, Benato+, PRD 2017]

Perspectives of current, planned and future experiments:

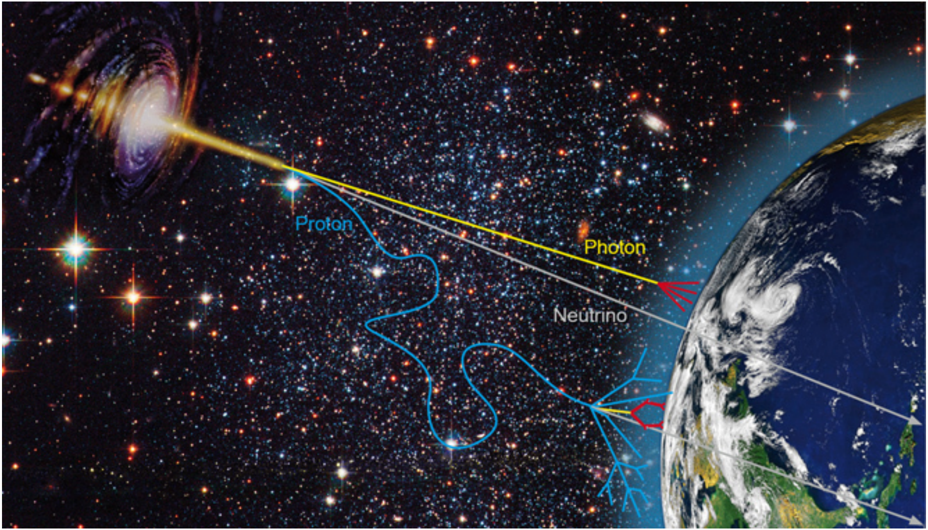


Some of these experiments are already ongoing

Much to discover in the next years!

See talk by G. Benato

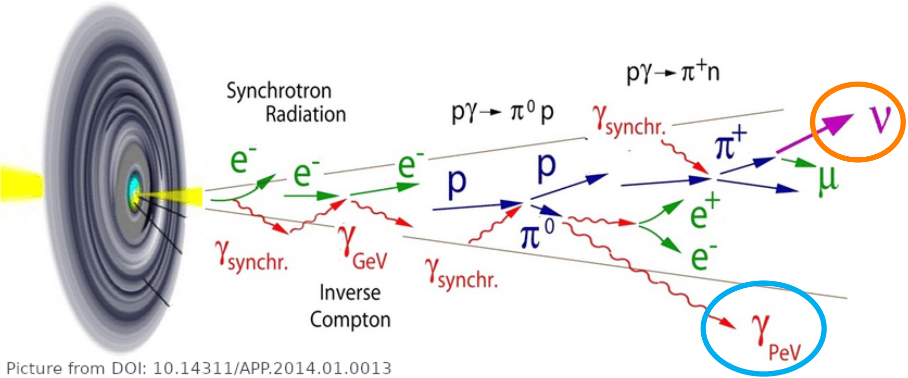
Neutrinos for multi-messenger searches



neutrinos can travel large distances without interacting!

Perfect for studying far sources in multi-messenger context

Neutrinos for multi-messenger searches

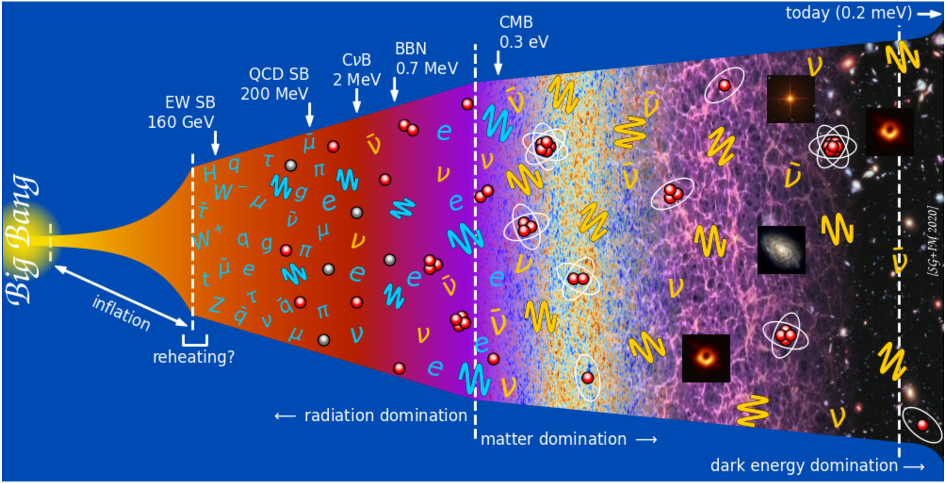


More info obtained if combining photons and neutrinos

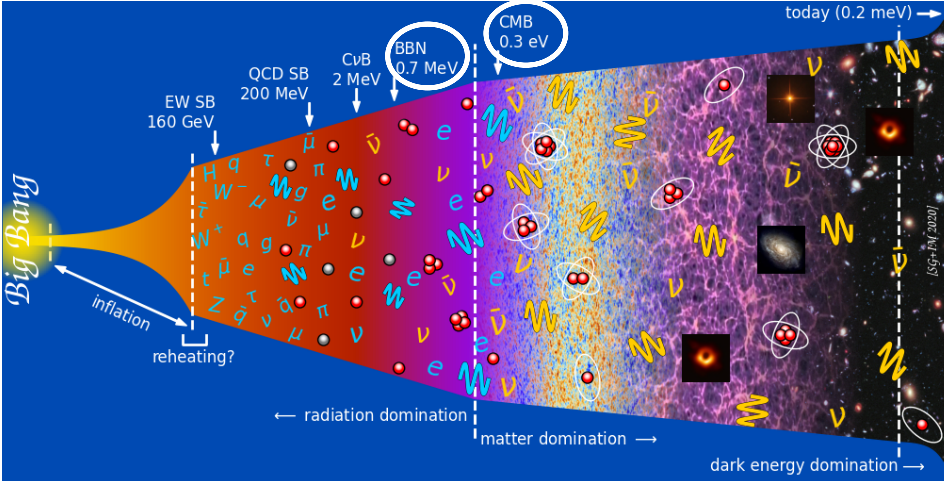
(and gravitational waves?)

see talk by M. Lamoureux

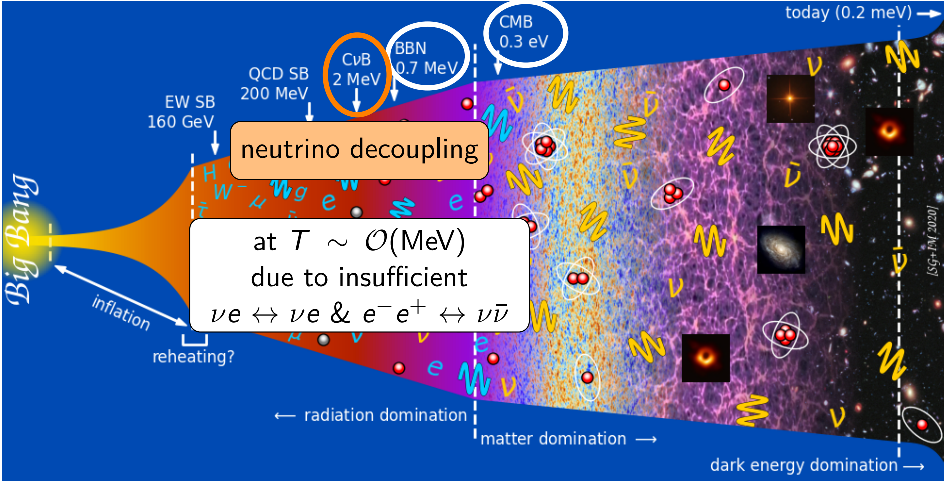
History of the universe



History of the universe



History of the universe



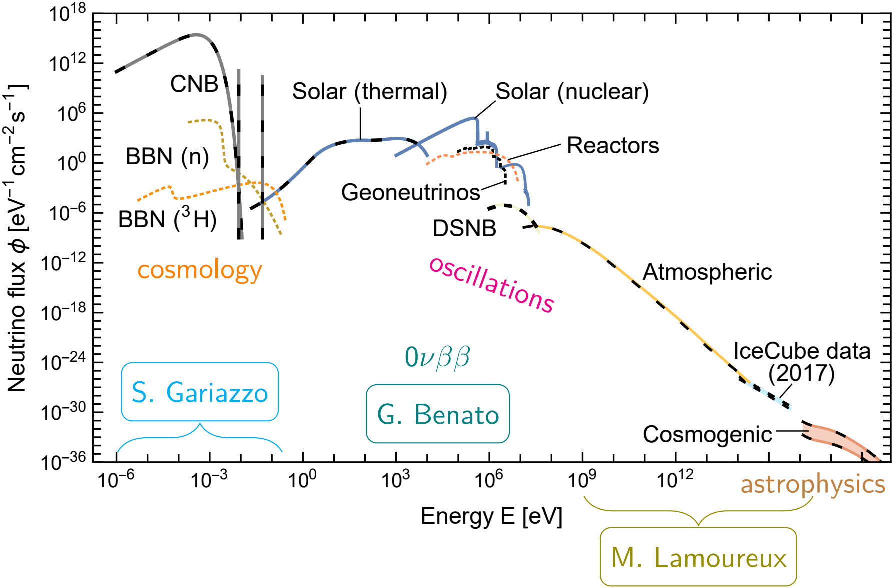
neutrino decoupling

at $T \sim \mathcal{O}(\mathrm{MeV})$
due to insufficient
$\nu e \leftrightarrow \nu e$ & $e^- e^+ \leftrightarrow \nu \bar{\nu}$

see talk by S. Gariazzo

Neutrino spectrum

[Vitagliano+, RMP 92 (2020)]



neutrinos at all energies provide valuable information!

1 Backup

Neutrinos and their masses

[de Salas+, Frontiers 5 (2018) 36]

Normal ordering (NO)

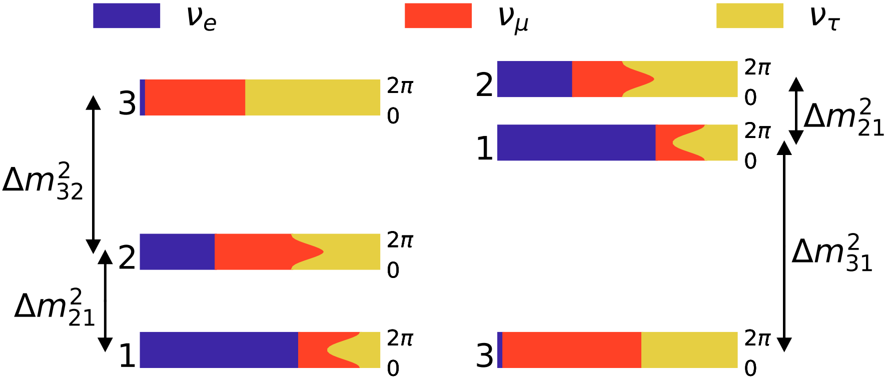
$m_1 < m_2 < m_3$

$\sum m_k \gtrsim 0.06$ eV

Inverted ordering (IO)

$m_3 < m_1 < m_2$

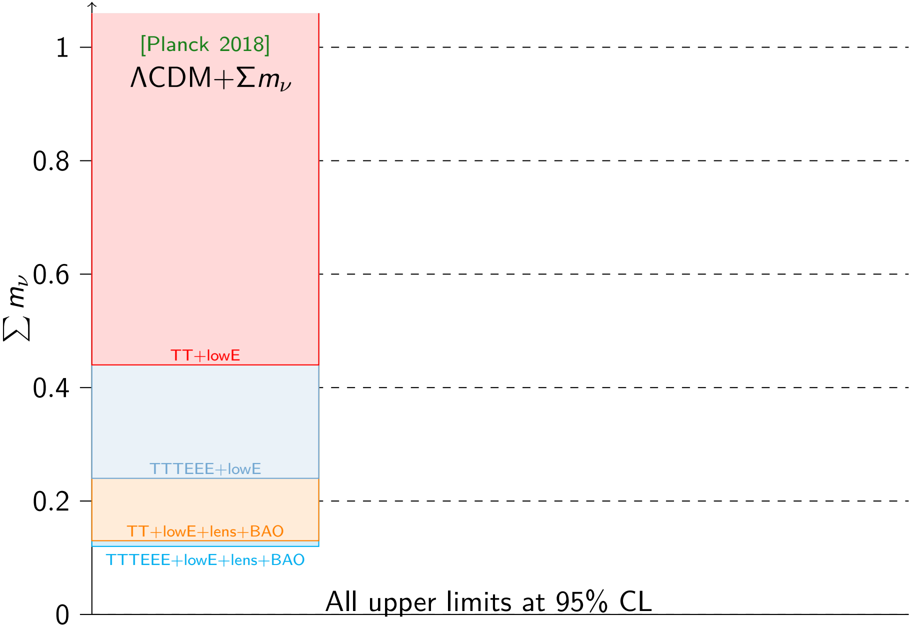
$\sum m_k \gtrsim 0.1$ eV



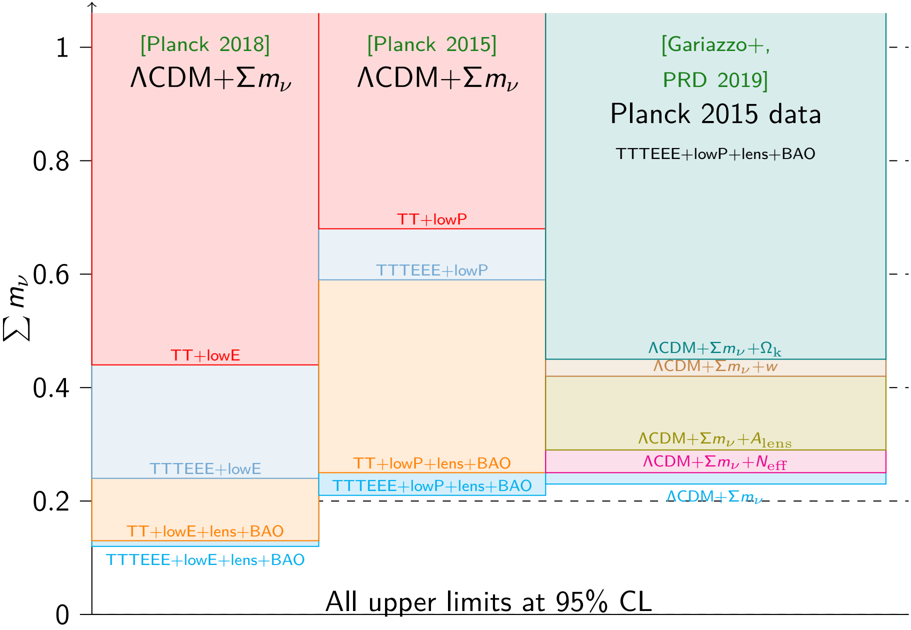
Absolute scale unknown!

Can we constrain the mass ordering using bounds on $\sum m_\nu$?

Cosmological neutrino mass bounds



Cosmological neutrino mass bounds



Cosmological neutrino mass bounds