Stefano Gariazzo

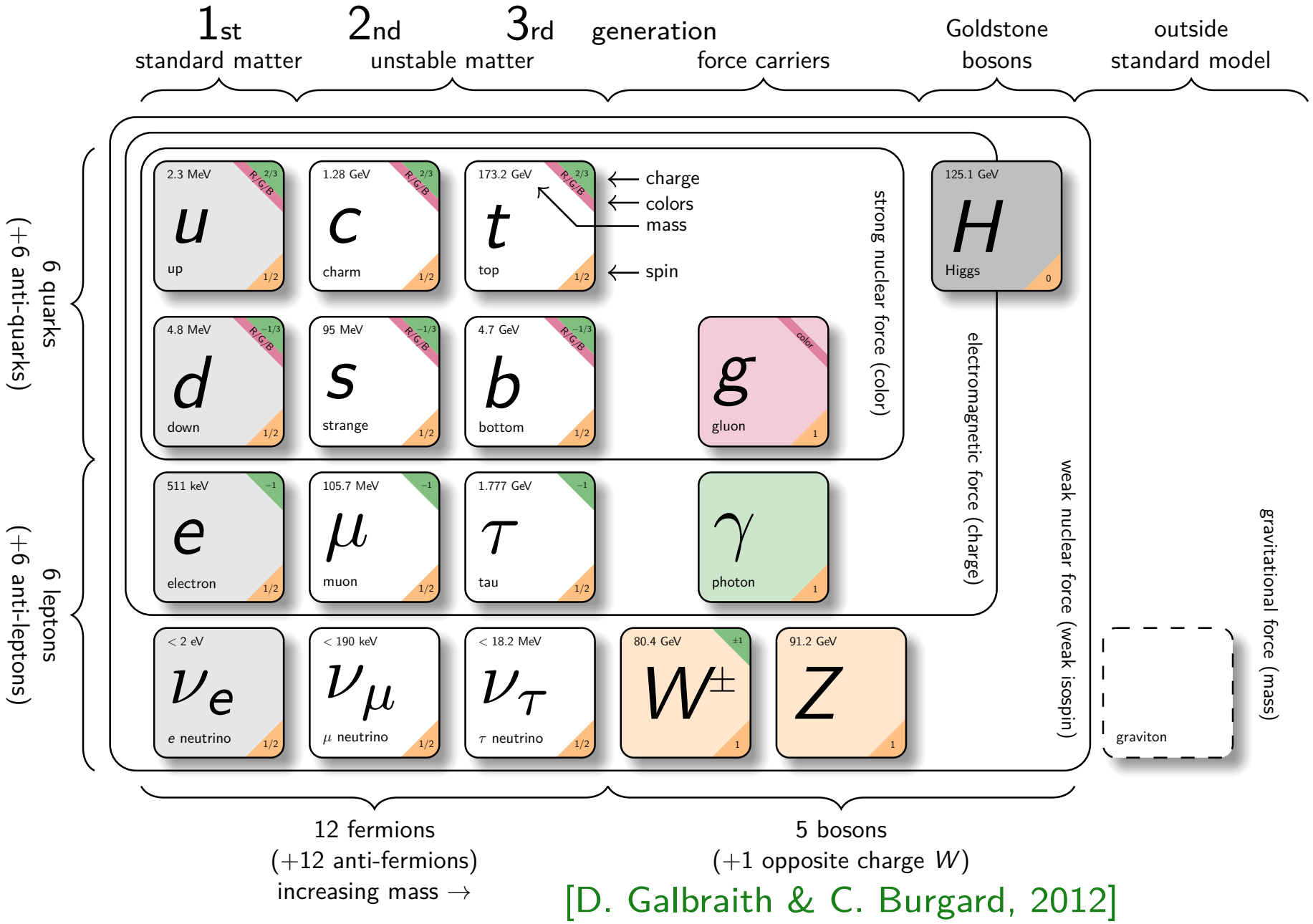
UniTO and INFN, Turin (IT)
IFIC (CSIC-UV), Valencia (ES)

stefano.gariazzo@unito.it
gariazzo@ific.uv.es

Neutrinos and cosmology

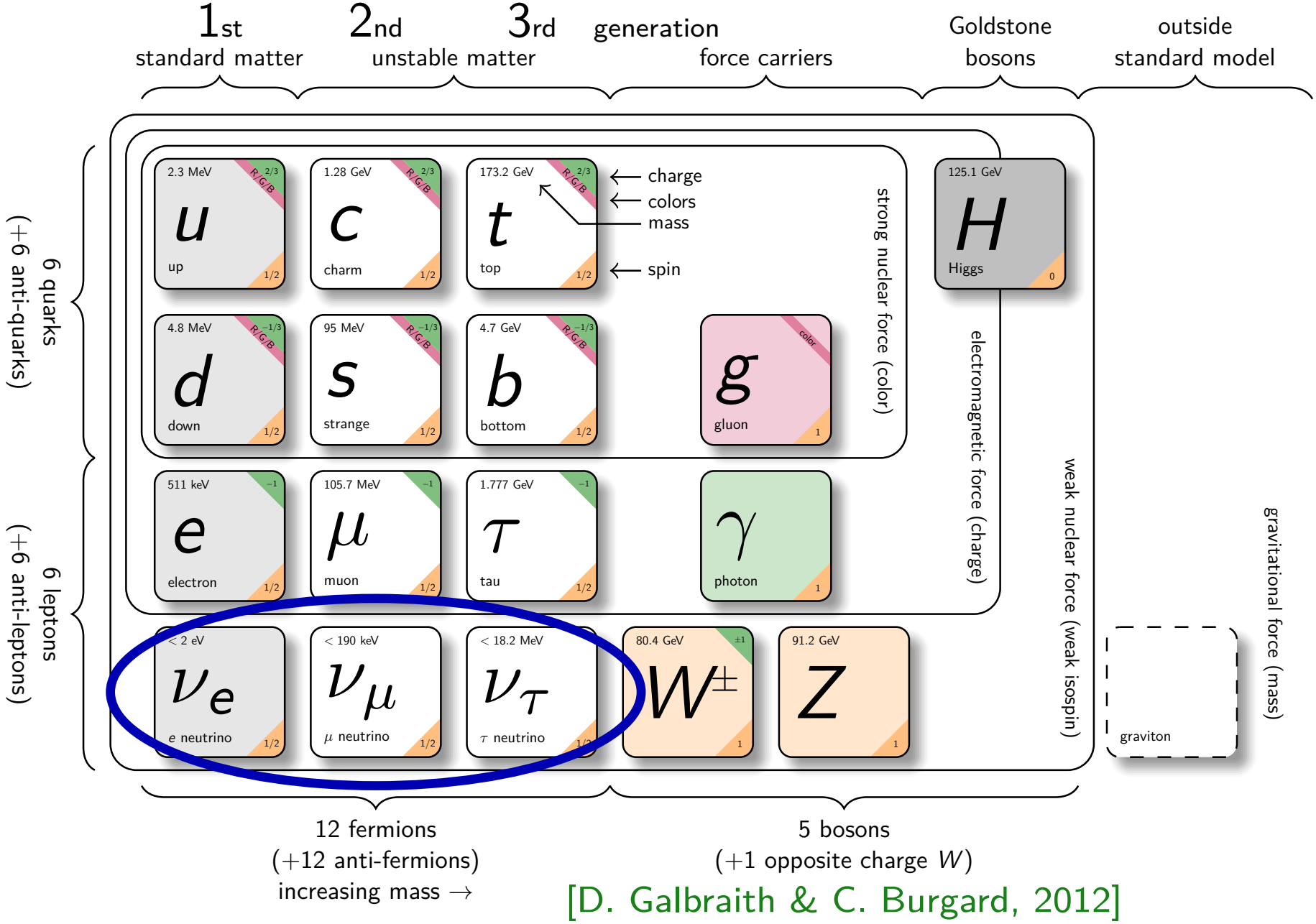
IFIC Newcomers Fest 2025, 12/12/2025

The Standard Model of Particle Physics



[D. Galbraith & C. Burgard, 2012]

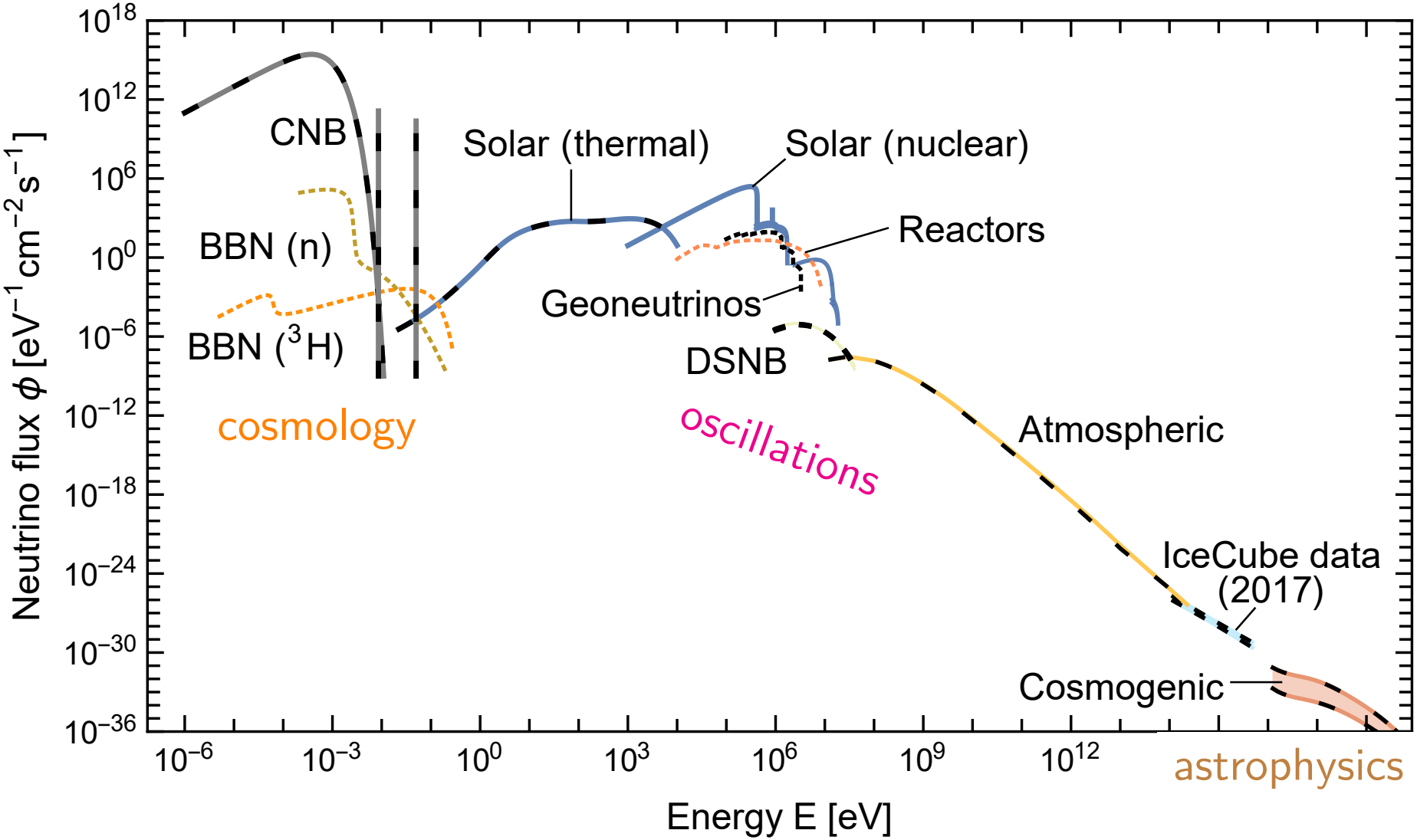
The Standard Model of Particle Physics



[D. Galbraith & C. Burgard, 2012]

Neutrino spectrum

[Vitagliano+, RMP 92 (2020)]



neutrinos at all energies provide valuable information!

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

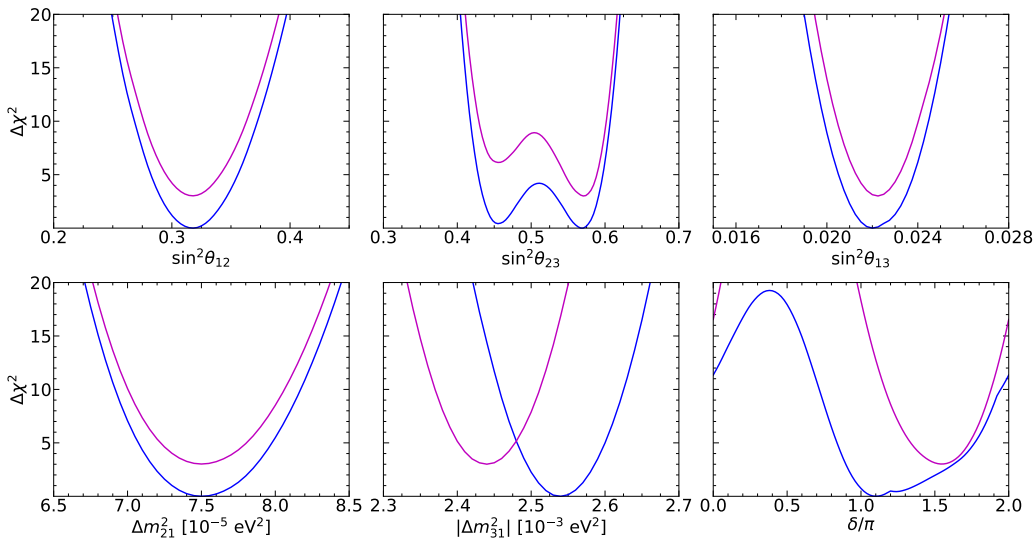
Current knowledge of the 3 active ν mixing: [JHEP 02 (2021) update]

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

$$\Delta m^2_{21} = (7.50^{+0.22}_{-0.20}) \cdot 10^{-5}\ \text{eV}^2$$
$$|\Delta m^2_{31}| = (2.54 \pm 0.03) \cdot 10^{-3}\ \text{eV}^2\ (\text{NO})$$
$$= (2.44 \pm 0.03) \cdot 10^{-3}\ \text{eV}^2\ (\text{IO})$$

$$10 \sin^2(\theta_{12}) = 3.18 \pm 0.16$$
$$10^2 \sin^2(\theta_{13}) = 2.200^{+0.069}_{-0.062}\ (\text{NO})$$
$$= 2.225^{+0.064}_{-0.070}\ (\text{IO})$$
$$10 \sin^2(\theta_{23}) = 4.55 \pm 0.13 U 5.71 \pm 0.12\ (\text{NO})$$
$$= 5.71^{+0.14}_{-0.17}\ (\text{IO})$$

$$\delta/\pi = 1.10^{+0.27}_{-0.12}\ (\text{NO})$$
$$= 1.54 \pm 0.14\ (\text{IO})$$



mass ordering still unknown

δ still unknown

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

Neutrinos and their masses

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

Normal ordering (NO)

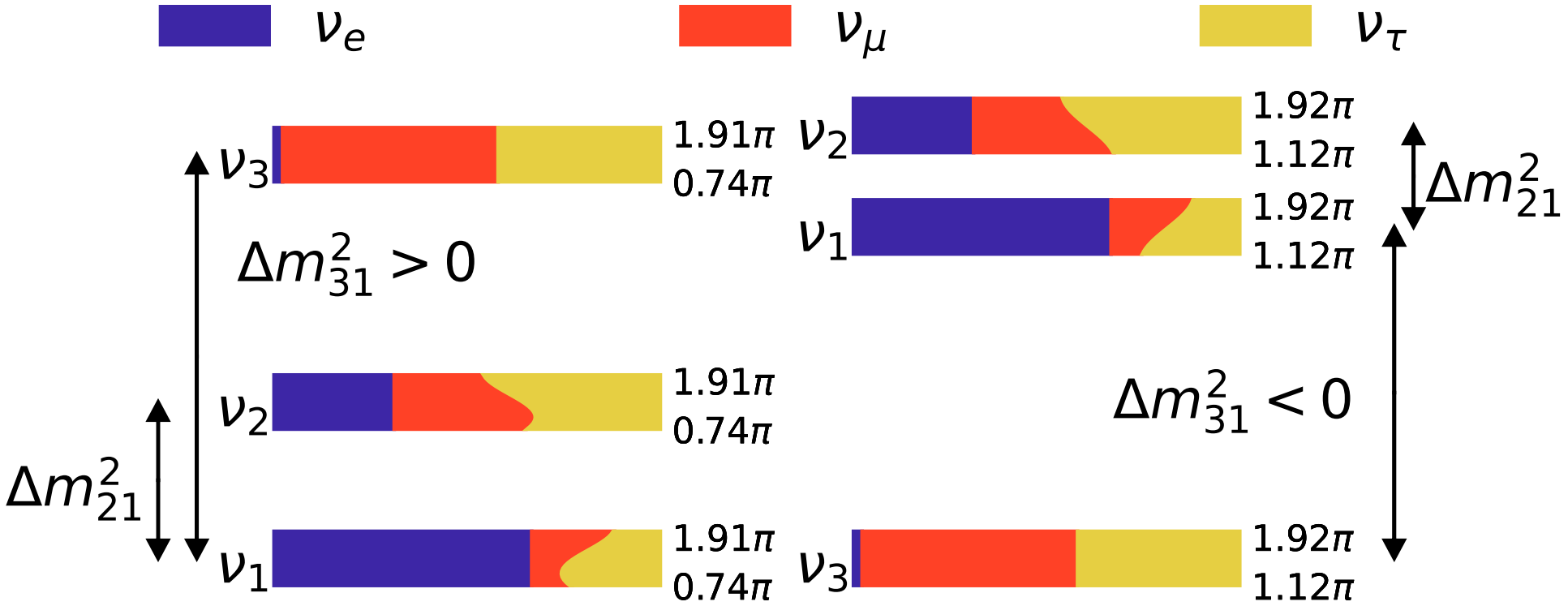
$m_1 < m_2 < m_3$

$\sum m_k \gtrsim 0.06$ 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 $\sum m_\nu$?

Phenomenology of neutrino physics

What can we learn about neutrino mixing and masses?

- Global fit of mixing parameters: [JHEP 02 (2021) and update, in prep.]

with M. Tórtola, J. Valle, O. Mena

- Mass ordering:
  - review [Frontiers 5 (2018)],
  - Bayesian methods [JCAP 03 (2018), JCAP 10 (2022)],
  - DUNE phenomenology [PRD 100 (2019)]

with M. Tórtola, O. Mena

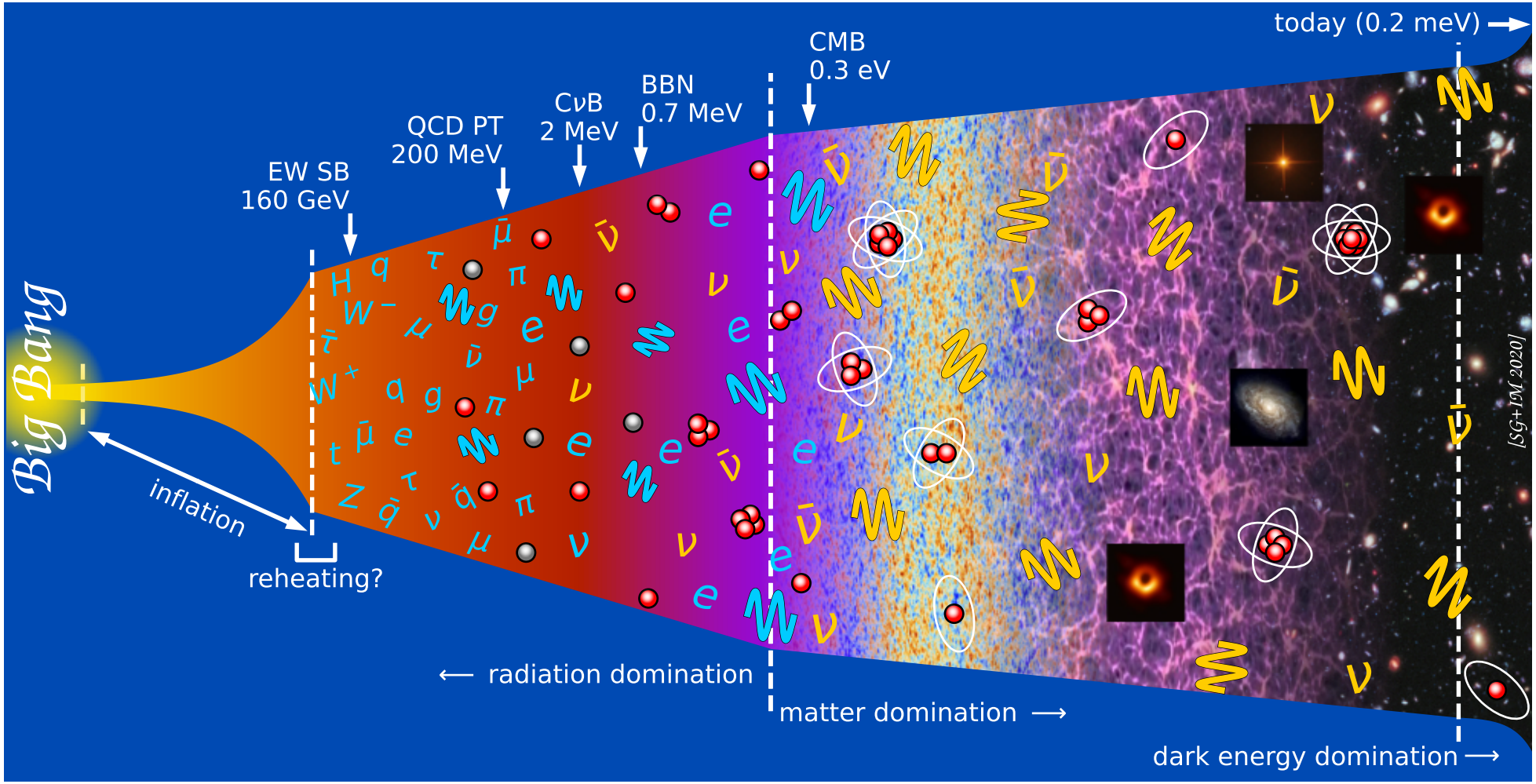
- Absolute mass scale:
  - cosmological constraints [PRD 106 (2022), PRD 108 (2023)],
  - tension terrestrial-cosmological observations [PDU 40 (2023)]

with O. Mena

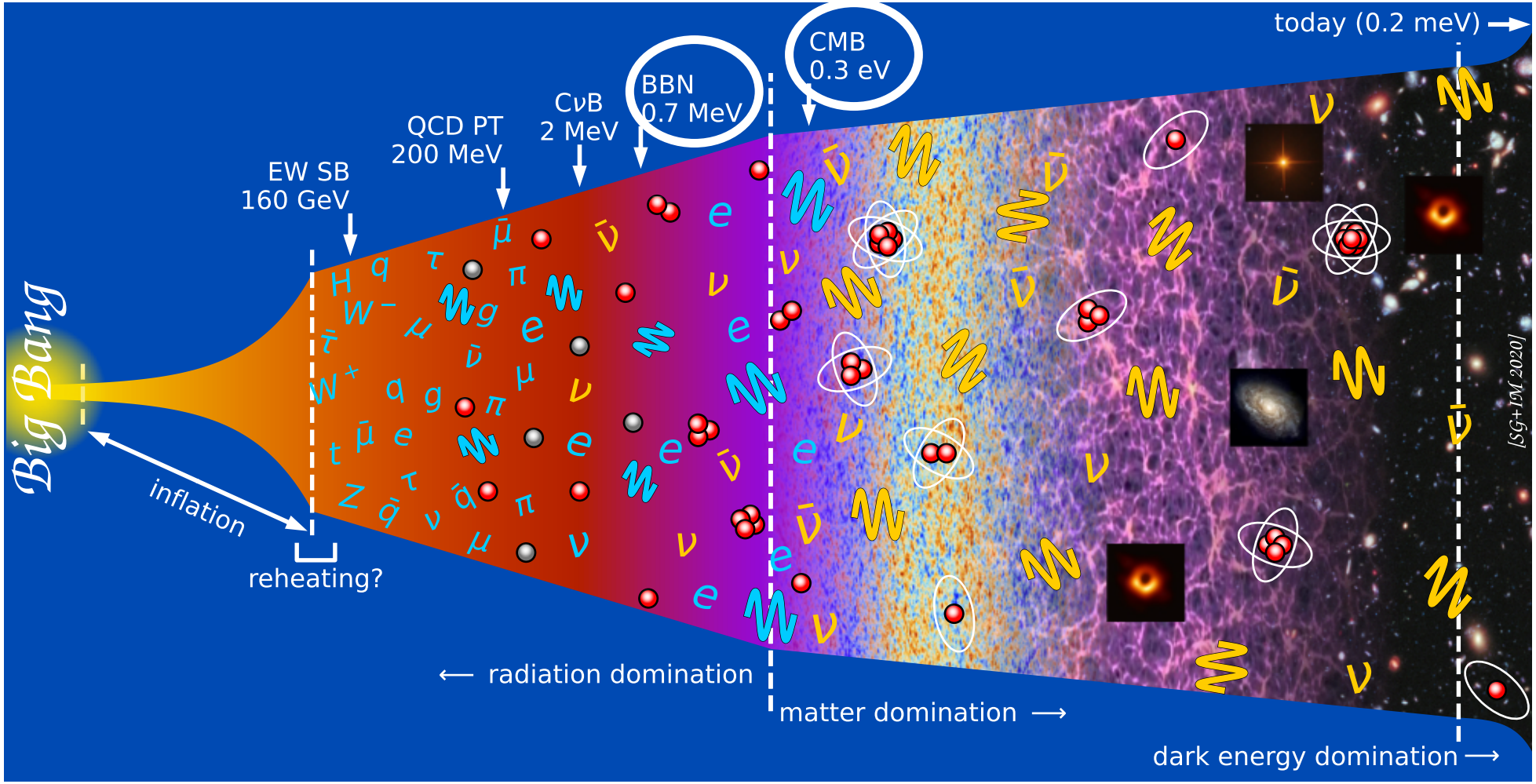
- Additional states:

light sterile neutrinos at short baselines
[JPG 43 (2016), JHEP 06 (2017), PLB 782 (2018)]

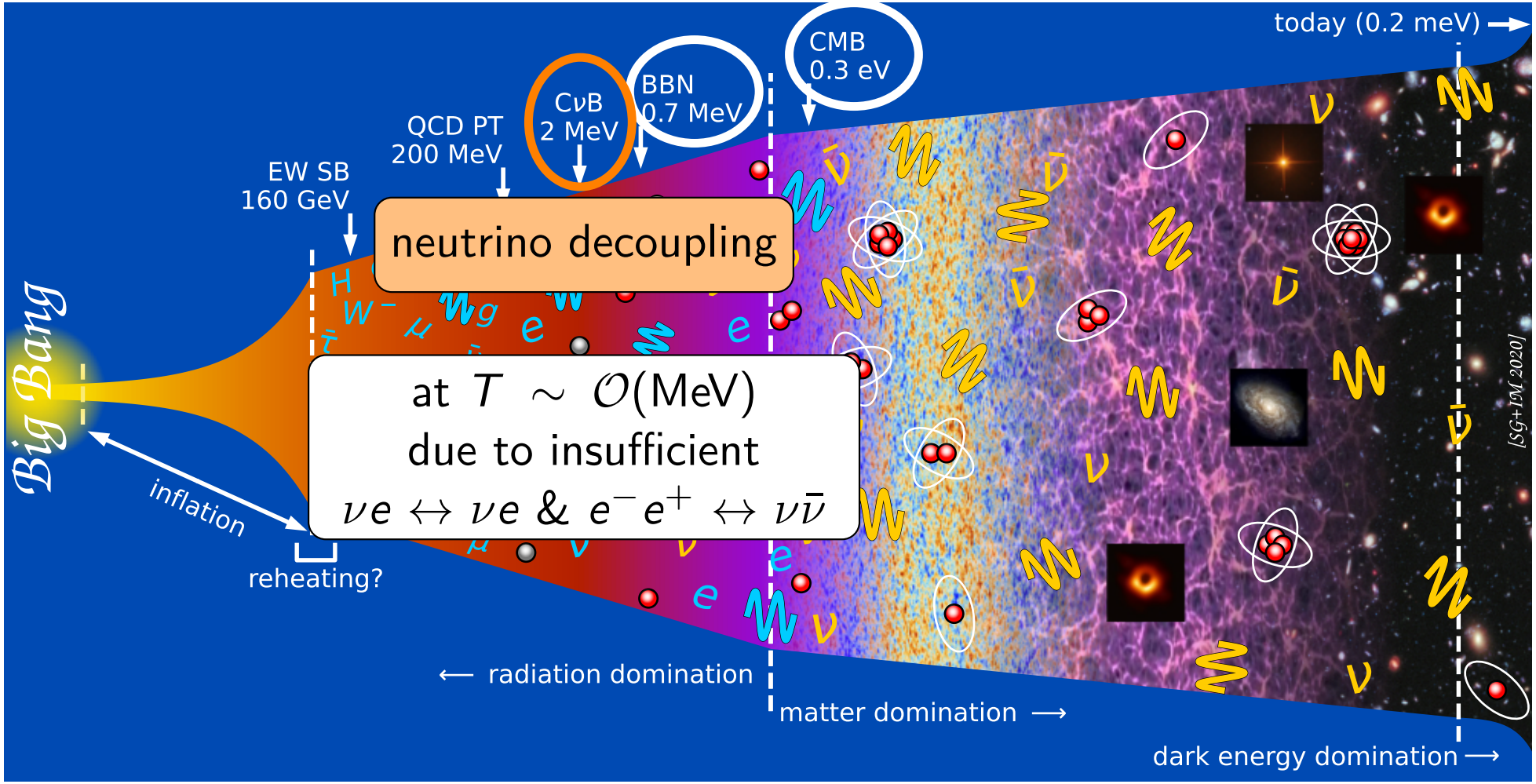
History of the universe



History of the universe



History of the universe



Phenomenology of relic neutrinos

Phenomenology related to relic neutrinos is very rich:

- Decoupling processes:
  - standard decoupling [JCAP 04 (2021)], asymmetries [in preparation]
  - modified interactions [PLB 820 (2021), JCAP 08 (2025)] or neutrino number [JCAP 07 (2019), PRD 104 (2021)],
  - modified cosmology: low-reheating [PRL 135 (2025), in preparation], additional particles [JCAP 12 (2023)]

with S. Pastor, G. Barenboim, N. Barbieri, P. Muñoz, A. Sánchez-Vargas

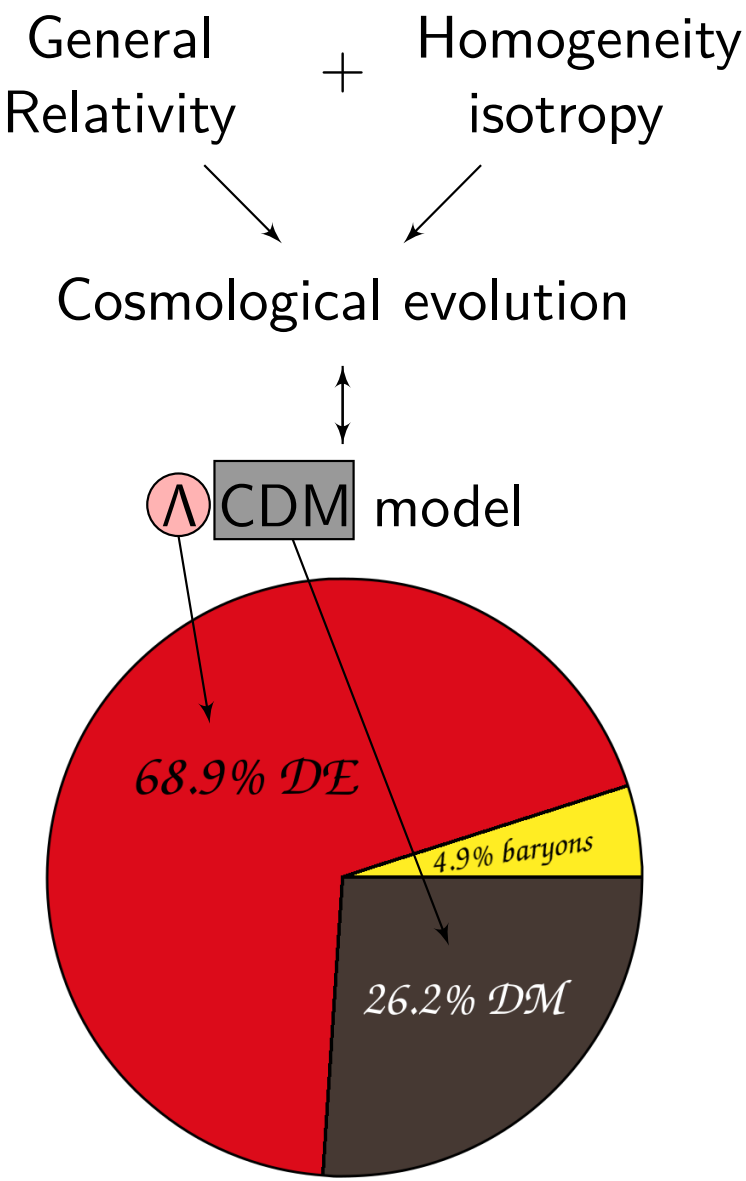
- Neutrino propagation: clustering in the MW [JCAP 01 (2020)], also including modified interactions [in preparation]

with S. Pastor, P. Ghedini

- Direct detection of relic neutrinos: PTOLEMY [JCAP 07 (2019)]
- Indirect constraints on ν properties after decoupling: $N_{\rm eff}$ [PRD 108 (2023)], chemical potential [in preparation], ...

with O. Mena, P. Ghedini, D. Wang, ...

Cosmological parameters



[Planck Collaboration, 2018]

ΛCDM model described by 6 base parameters:

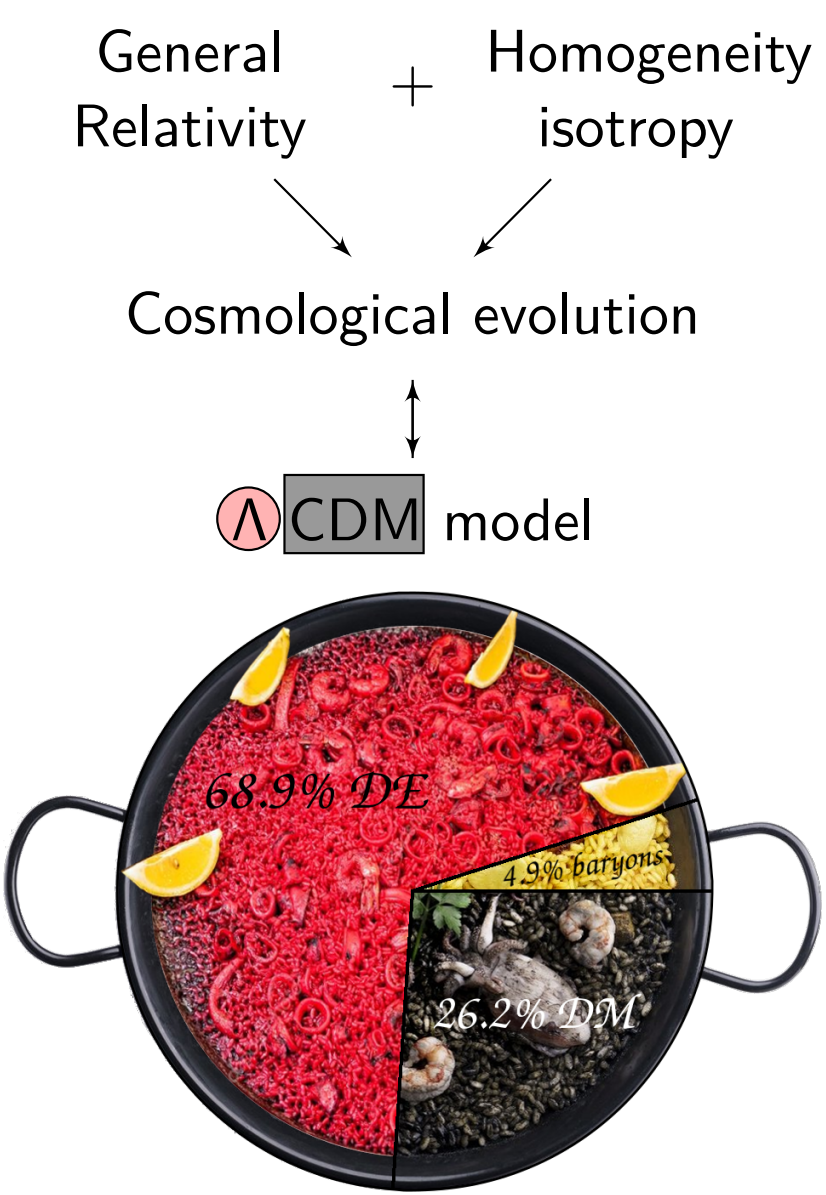
- $\omega_b = \Omega_b h^2$ baryon density today;
- $\omega_c = \Omega_c h^2$ CDM density today;
- τ optical depth to reionization;
- θ angular scale of acoustic peaks;
- n_s tilt and
- A_s amplitude of the power spectrum of initial curvature perturbations.

Other quantities can be studied:

- H_0 Hubble parameter today;
- σ_8 mean matter fluctuations at small scales;

...

Cosmological parameters



[Planck Collaboration, 2018]

ΛCDM model described by 6 base parameters:

- $\omega_b = \Omega_b h^2$ baryon density today;
- $\omega_c = \Omega_c h^2$ CDM density today;
- τ optical depth to reionization;
- θ angular scale of acoustic peaks;
- n_s tilt and
- A_s amplitude of the power spectrum of initial curvature perturbations.

Other quantities can be studied:

- H_0 Hubble parameter today;
- σ_8 mean matter fluctuations at small scales;

...

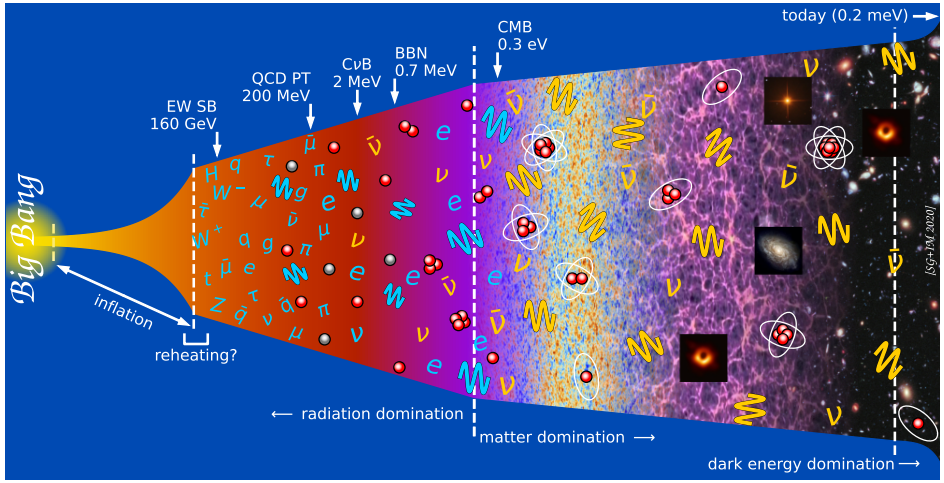
Cosmology

Universe content and properties through cosmological observations?
with O. Mena, D. Wang

- Neutrino mass constraints:
  - updated bounds [PRD 110 (2024), PRD 108 (2023), . . .],
  - bayesian methods [EPJC 80 (2020), PRD 99 (2019)],
  - non-standard scenarios [PRD 112 (2025)]
  - [book contribution (2025)]
- Dark energy/dark matter: [PRD 105 (2022), PRD 106 (2022)]
- Curvature: [PDU 33 (2021)]
- Dark radiation:
  - review [Universe 8 (2022)]
  - axions [PRD 107 (2023)]
  - interacting neutrinos [JCAP 12 (2020), JCAP 06 (2022)]
- Hubble tension: [book contribution (2023)]

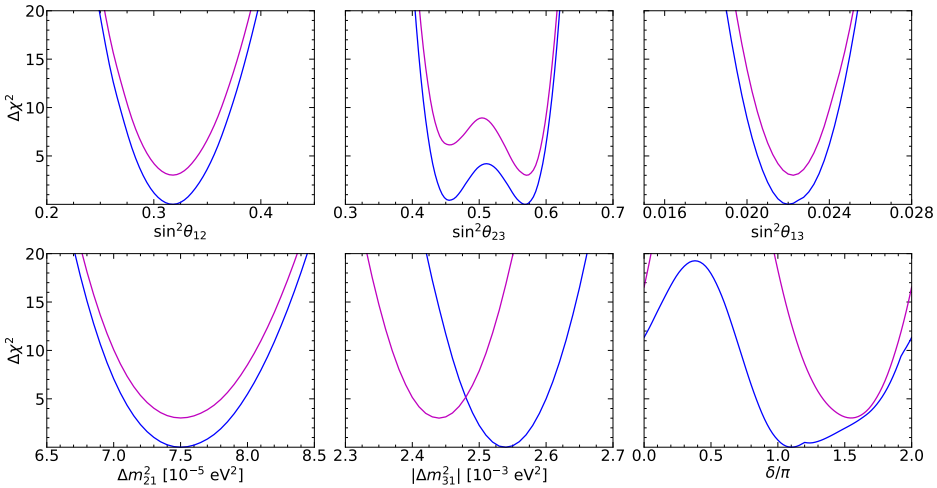
Summary

Early universe (ν dec., BBN, ...)

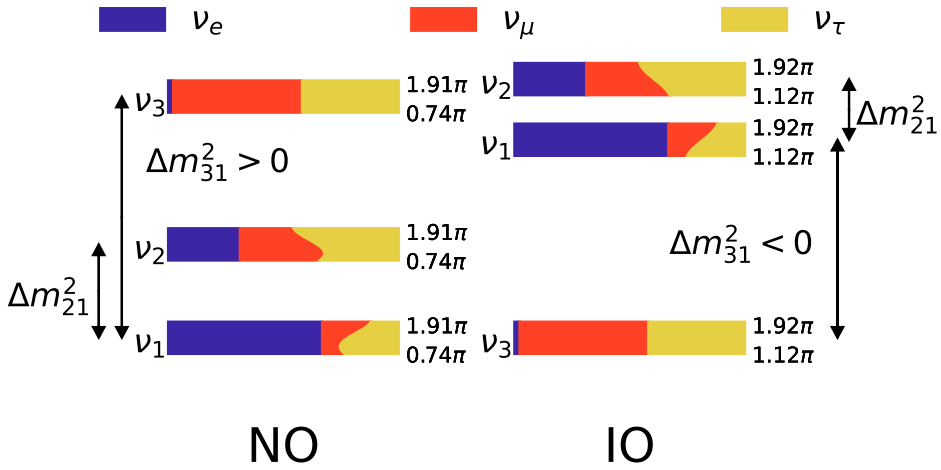


Universe content and history

Neutrino oscillations



Neutrino masses and mixings



Thanks for your attention!