Viable, physical and descriptive models of the early Universe

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European Research Council
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Istituto Nazionale di Fisica Nucleare

→ COSMIC HISTORY

Inflation
Accelerated expansion of the Universe

Formation of light and matter

Light and matter are coupled
Dark matter evolves independently: it starts clumping and forming a web of structures

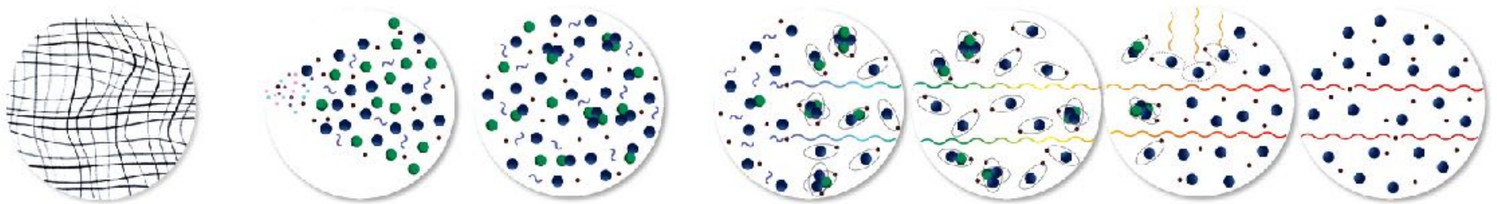
Light and matter separate
- Protons and electrons form atoms
- Light starts travelling freely: it will become the Cosmic Microwave Background (CMB)

Dark ages
Atoms start feeling the gravity of the cosmic web of dark matter

First stars
The first stars and galaxies form in the densest knots of the cosmic web

Galaxy evolution

The present Universe



• Tiny fluctuations: the seeds of future structures
• Gravitational waves?

Frequent collisions between normal matter and light

As the Universe expands, particles collide less frequently

Last scattering of light off electrons
→ Polarisation

The Universe is dark as stars and galaxies are yet to form

Light from first stars and galaxies breaks atoms apart and "reionises" the Universe

Light can interact again with electrons
→ Polarisation

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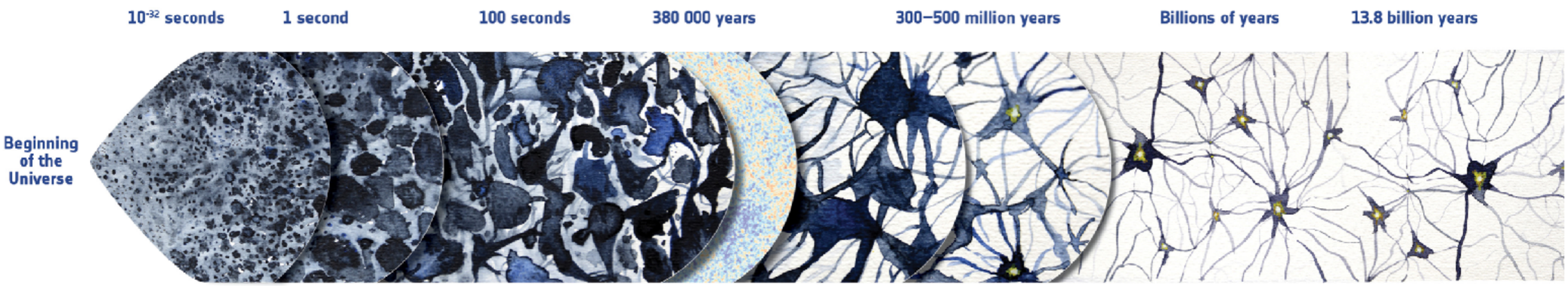
Where we are

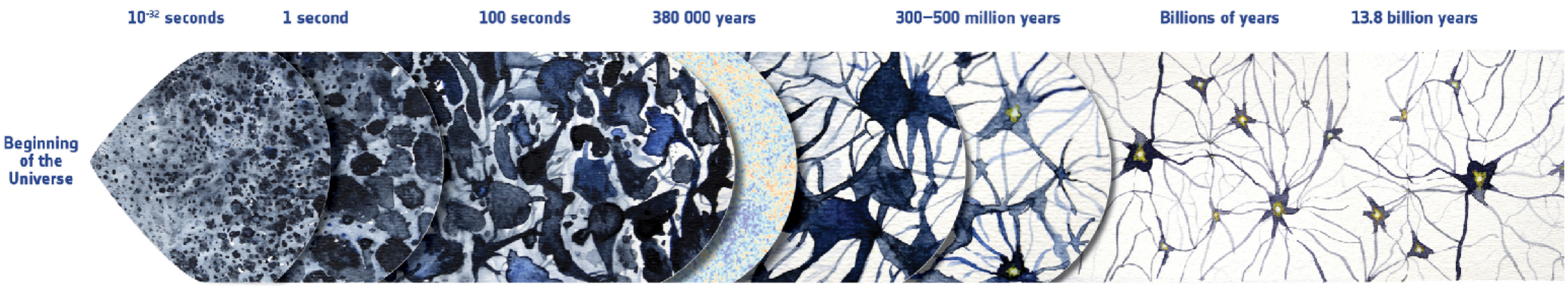


Backbones: General Relativity; Standard Model of Particle Physics; Jeans instability; Inflation

Observational pillars: Light elements abundance; CMB; tracers of LSS

Coherent, satisfying and predictive picture of the observable Universe

Where we are



LCDM is phenomenological: key unknowns at the fundamental level

LCDM is unsatisfying: statistically significant discrepancies between experiments

Where we (should?) go

Beyond LCDM: new routes to better describe the Universe; to better use the Universe as a laboratory

Where and how to look for new directions?

Where we (should?) go

Preferred directions (my taste)

VIABLE: obey observational constraints - not only cosmological

PHYSICAL: tell something about underlying physics and/or not used beyond range of applicability

DESCRIPTIVE: explain/predict what I observe/will observe
(no interest in models that only live in regions beyond observational reach)

A few test cases:

- add new content
- add new interactions
- different declinations of the above

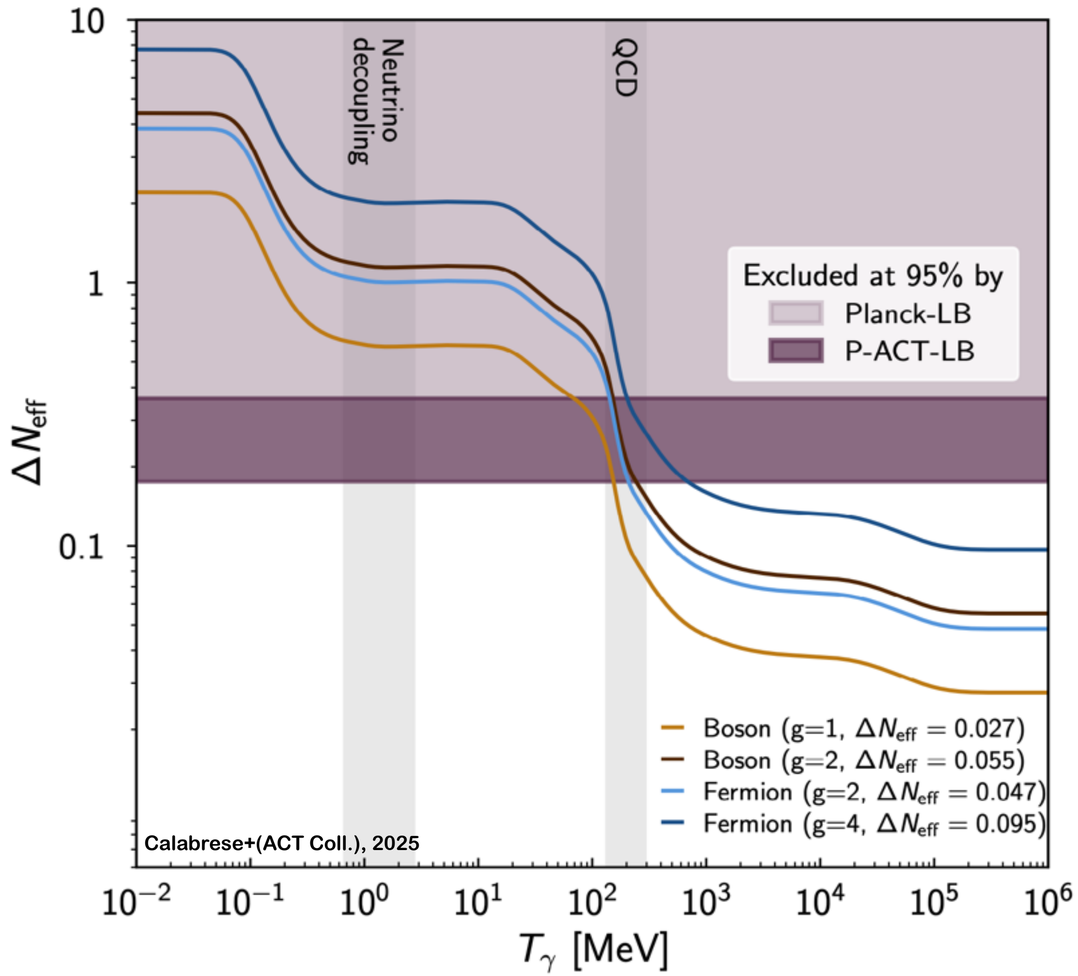
New content: light species

Add new content:

Neff as a phenomenological box (bottom-up)
Very good proxy of BSM physics at play
at BBN, CMB and in-between times

Clearly viable, physical enough, descriptive enough

$$\Omega_\gamma \rightarrow \Omega_\gamma \left[1 + \frac{7}{8} \left(\frac{4}{11} \right)^{\frac{4}{3}} \Delta N_{\rm eff} \right]$$



Background modified: light species

Modify the background:

Neff as a phenomenological box (bottom-up)
Very good proxy of BSM physics at play
at BBN, CMB and in-between times

Clearly viable, physical enough, descriptive enough

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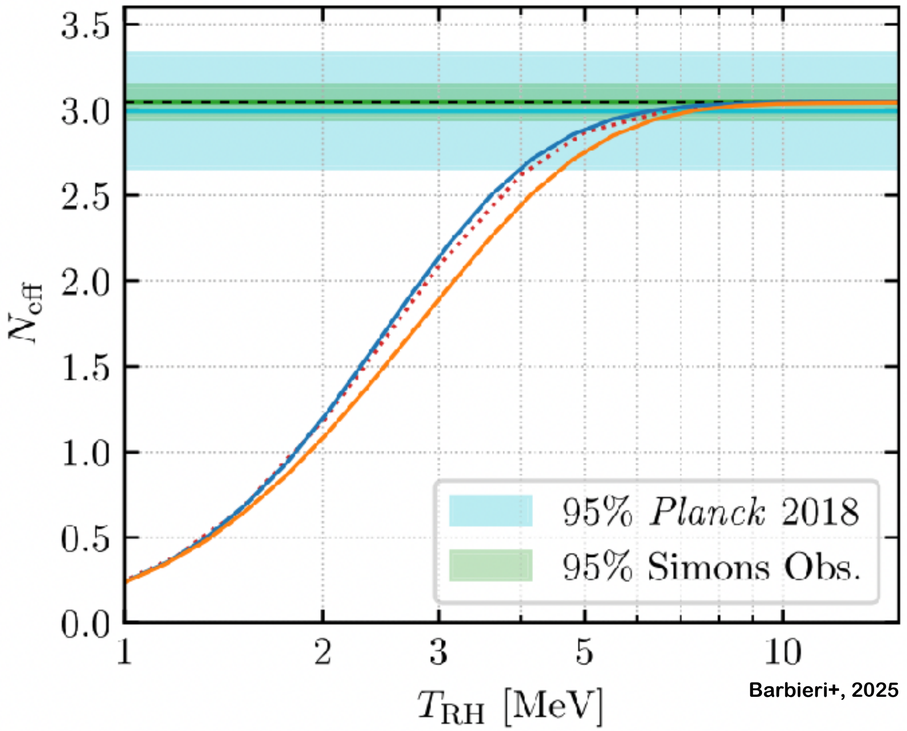


Barbieri+, 2025

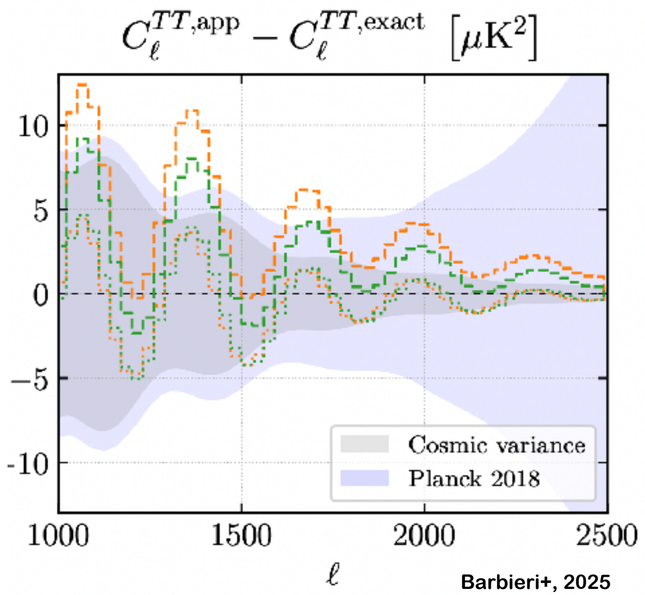
New content: light species

Neff as a more physical and descriptive model: top-down
Abandon catch-all "cozyness"
Question: real need for top-down or ok to map to individual models a posteriori?

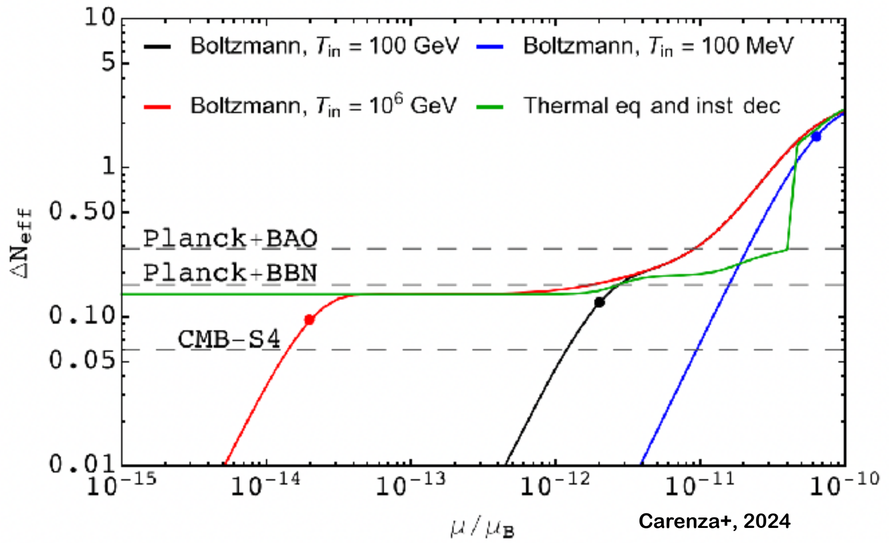
Your favourite HEP model

$$\mathcal{L}_a \supset \frac{1}{2}(\partial^\mu a)(\partial_\mu a) - \frac{1}{2}m_a^2 a^2 + \sum_\ell c_\ell \frac{\partial_\mu a}{2f_a}\bar{\ell}\gamma^\mu\gamma^5\ell + \frac{1}{4}g_{a\gamma}aF_{\mu\nu}\tilde{F}^{\mu\nu}$$

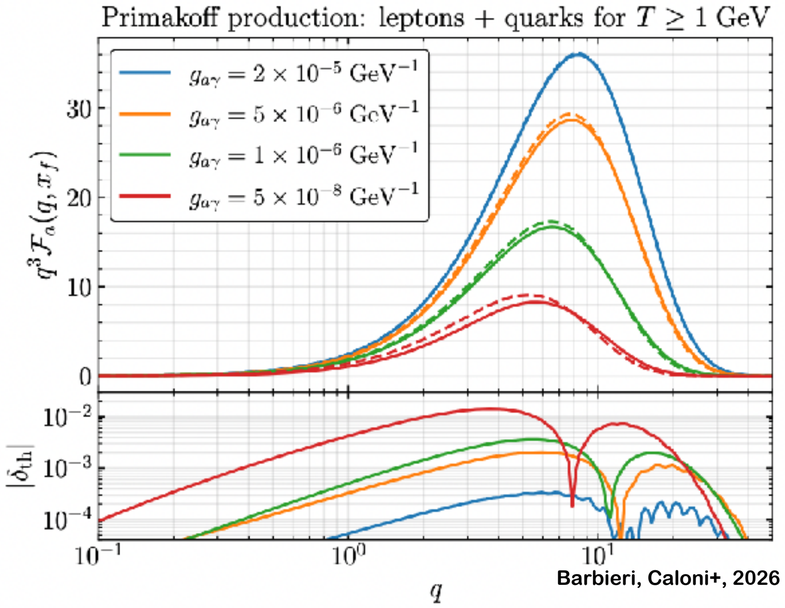
$$\Delta N_{\rm eff}$$



Barbieri+, 2025



Carenza+, 2024

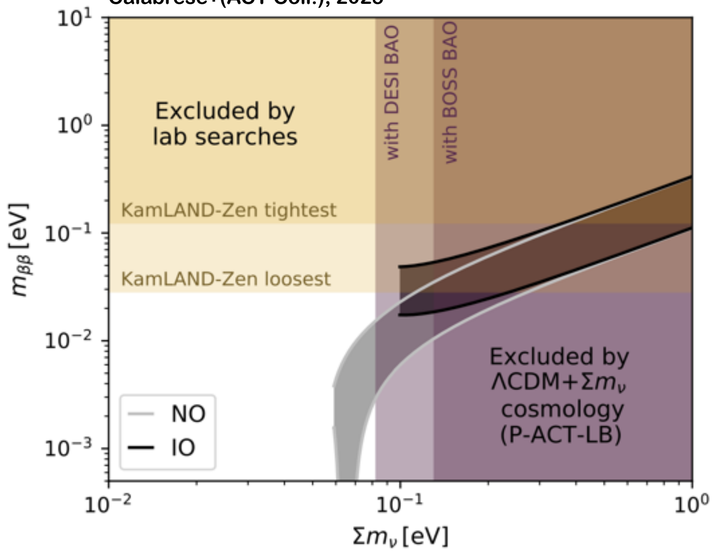


Barbieri, Caloni+, 2026

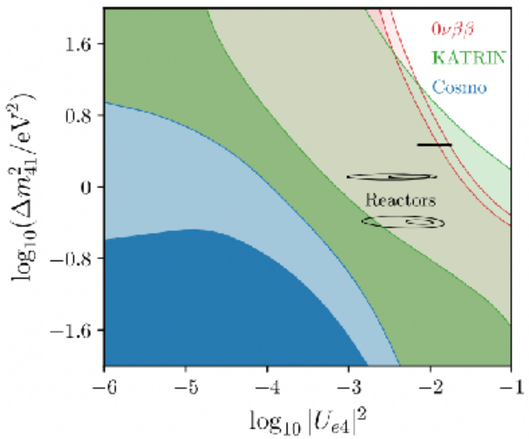
New content: light species

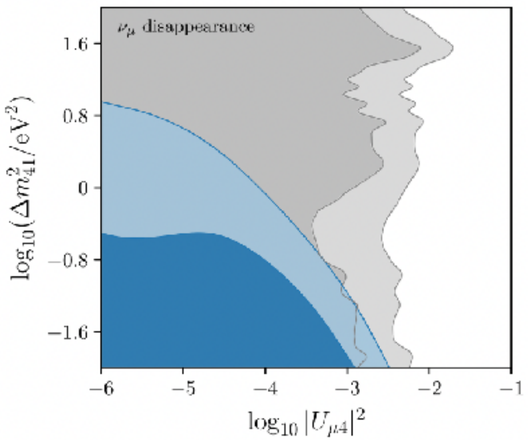
See Massi's talk tomorrow

Calabrese+(ACT Coll.), 2025



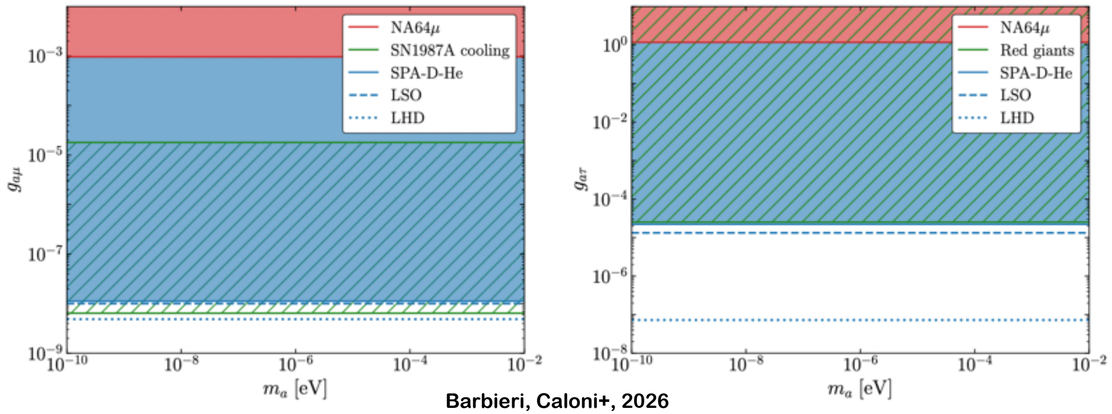
Hagstotz+, 2021



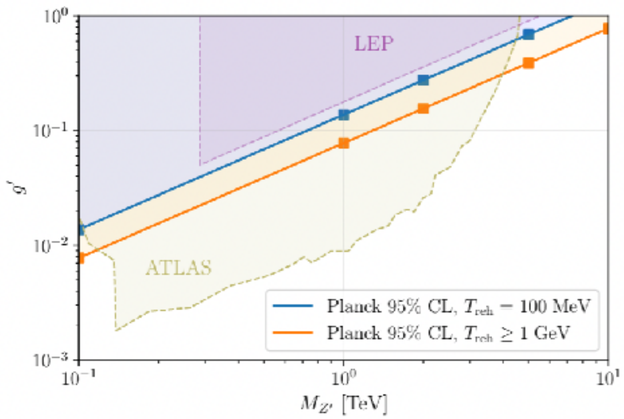


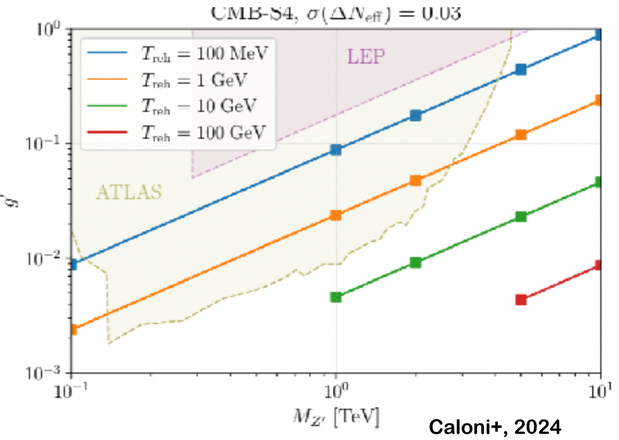
Descriptive:

The synergy with non-cosmo constraints is key in supporting-ruling out models (sterile neutrinos, ALPs, …)



Barbieri, Caloni+, 2026





Caloni+, 2024

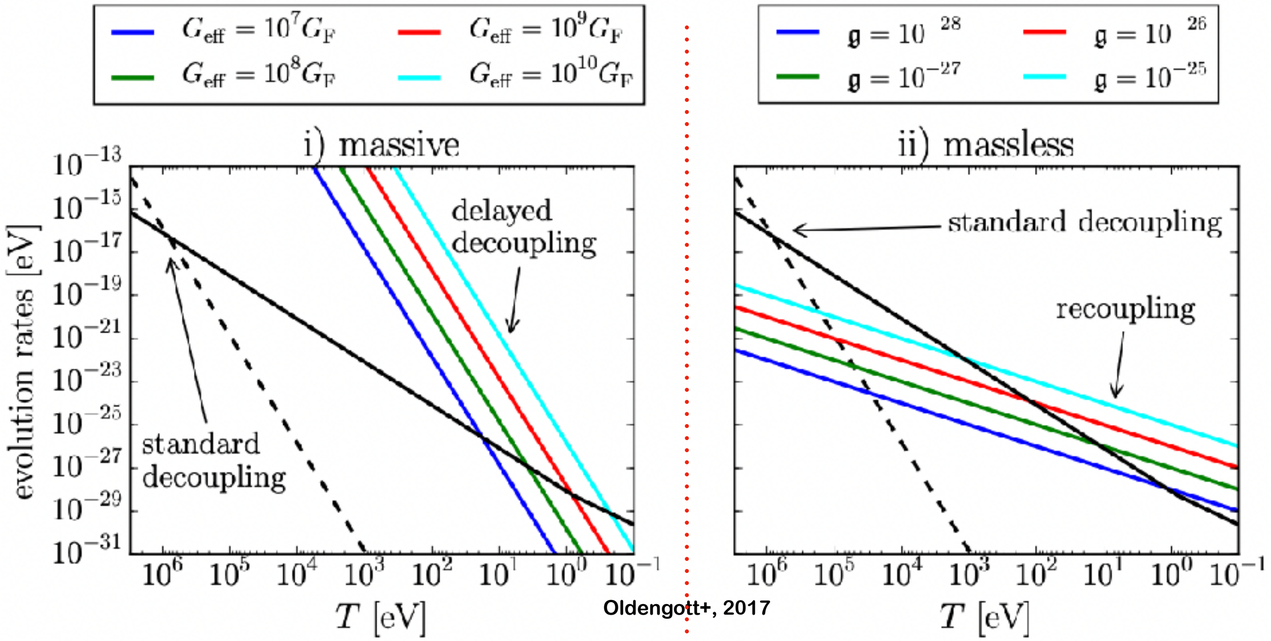
New interactions: neutrino NSI

$$\Gamma_{\rm NSI} = G_{\rm eff}^2 T^5$$

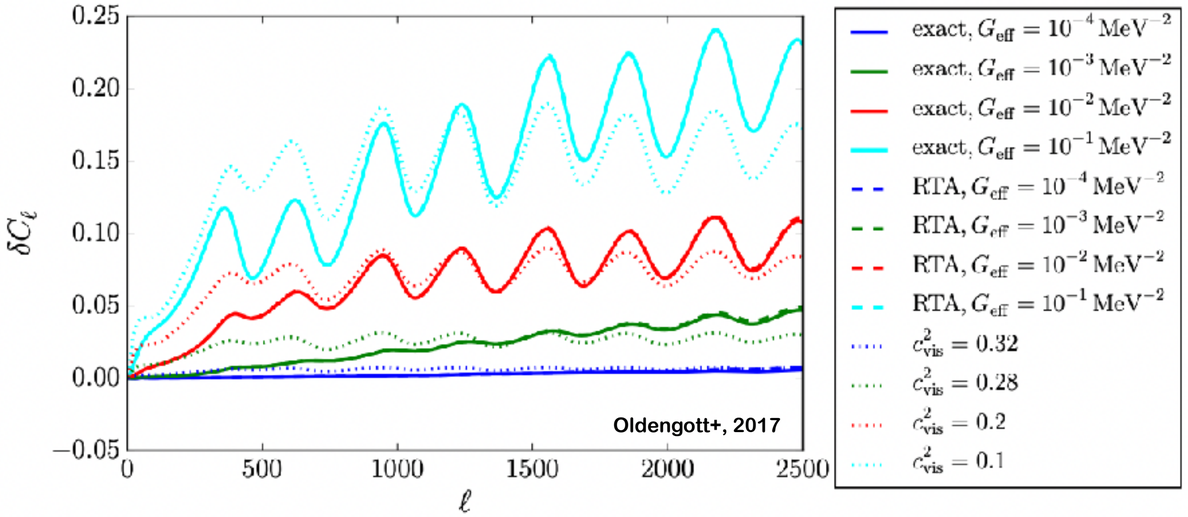
$\log_{10}(G_{\rm eff}\,{\rm MeV}^2) \lesssim -2.1$ MIν

$\log_{10}(G_{\rm eff}\,{\rm MeV}^2) = -1.33^{+0.21}_{-0.14}$ SIν

ACT+Planck+DESI
LCDM+NSI
Calabrese+, 2025



Oldengott+, 2017



$$\Gamma_{\rm NSI} \propto g_{\rm eff}^4 T$$

$$g_{\rm eff}^4 < 1.3 \times 10^{-27}$$

ACT+Planck+DESI
LCDM+NSI
Calabrese+, 2025

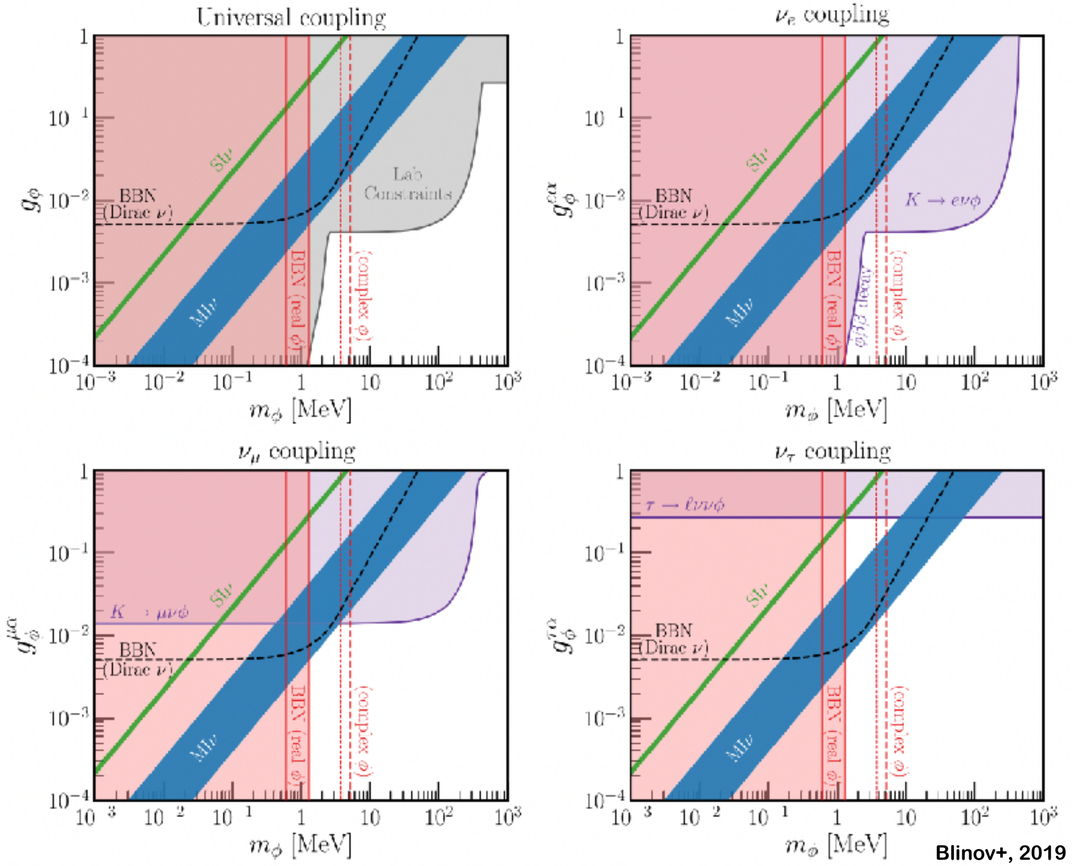
Detailed comparison still missing
due to more complicated physics scenario
and evolution equations

New interactions: neutrino NSI

See Massi's talk tomorrow

Physical and descriptive

Consider assumptions in the model: coupling, neutrino "spectrum", etc



Blinov+, 2019

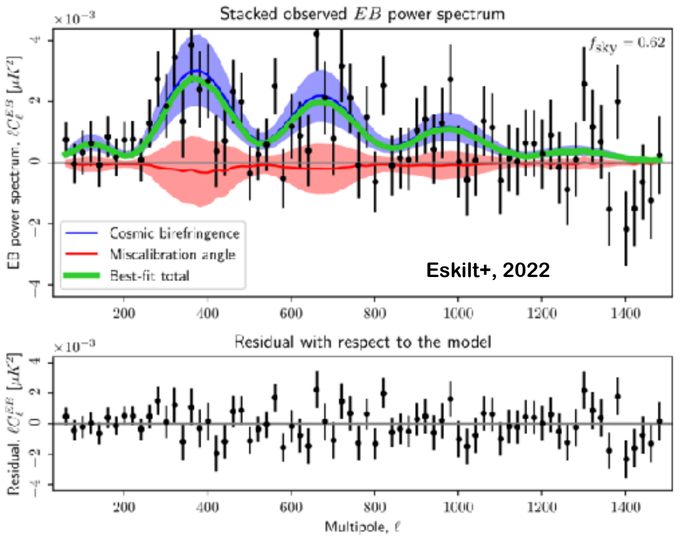
Viable

Comparison with lab is key

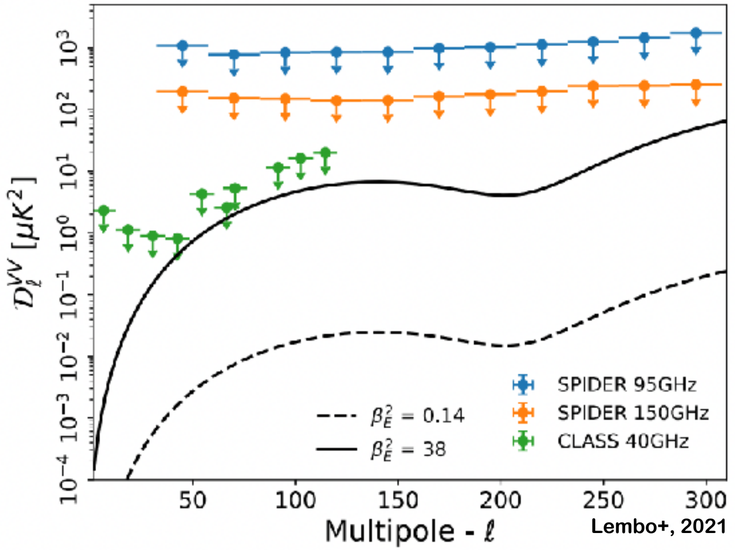
New interactions: BSM EM

$$\frac{d\mathbf{S}}{ds} = \rho \wedge \mathbf{S}, \quad \mathbf{S} = (Q, U, V)$$

BSM EM interactions can induce several cosmological consequences: birefringence, circular polarisation, Faraday rotation, …



Eskilt+, 2022



Lembo+, 2021

Viable

Models can be tested and constrained. Some appear to be BSM hints…
Very good complementarity with astro/lab

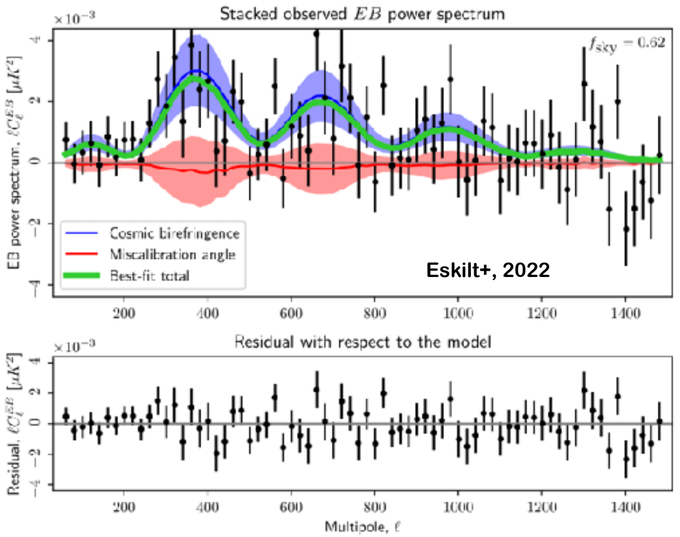
Physical and descriptive

Phenomenological approach can/must be linked to high-energy models (Chern-Simons, QG, …)
New observational windows (cross-corr, V-mode searches)

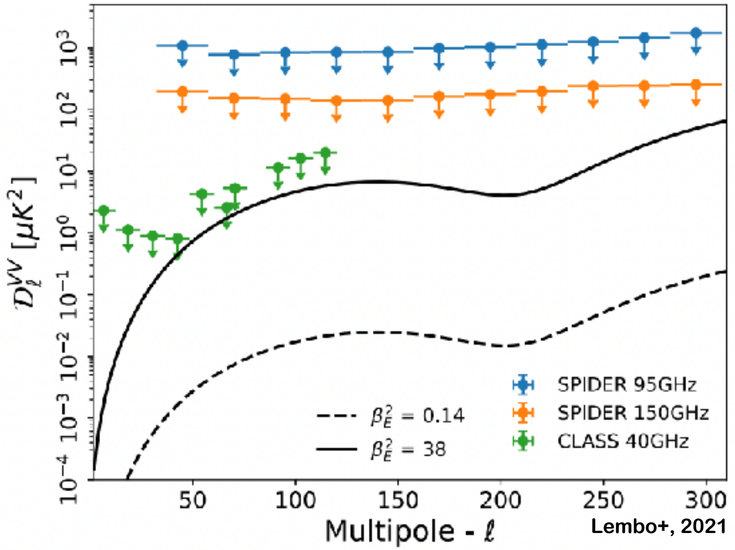
New interactions: BSM EM

$$\frac{d\mathbf{S}}{ds} = \rho \wedge \mathbf{S}, \quad \mathbf{S} = (Q, U, V)$$

BSM EM interactions can induce several cosmological consequences: birefringence, circular polarisation, Faraday rotation, …



Eskilt+, 2022

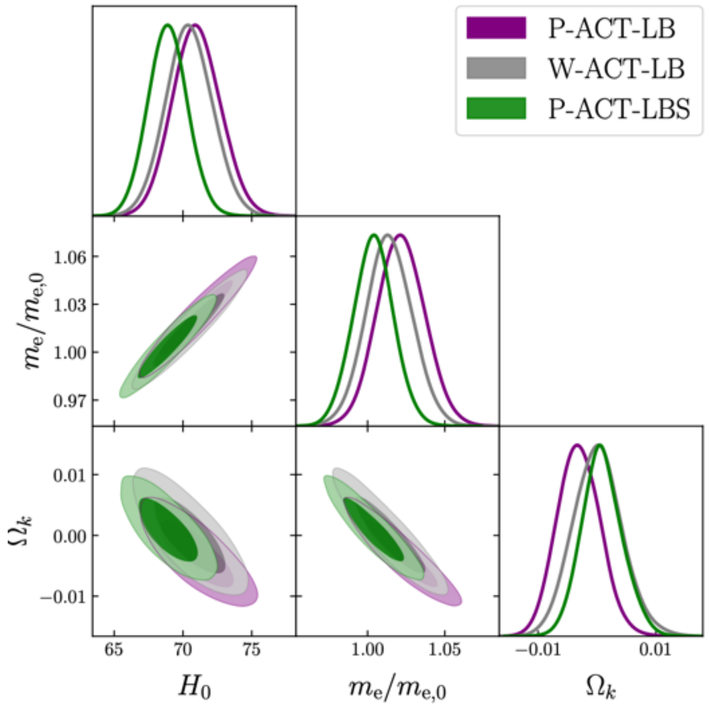


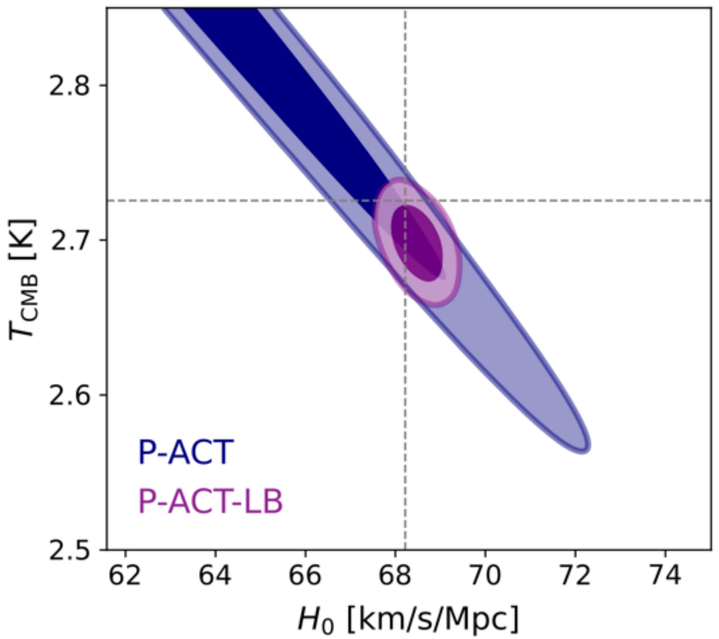
Lembo+, 2021

Key question is:
What if we the signal is confirmed? What is it telling to us?
Link to HEP and/or external evidence cannot be avoided

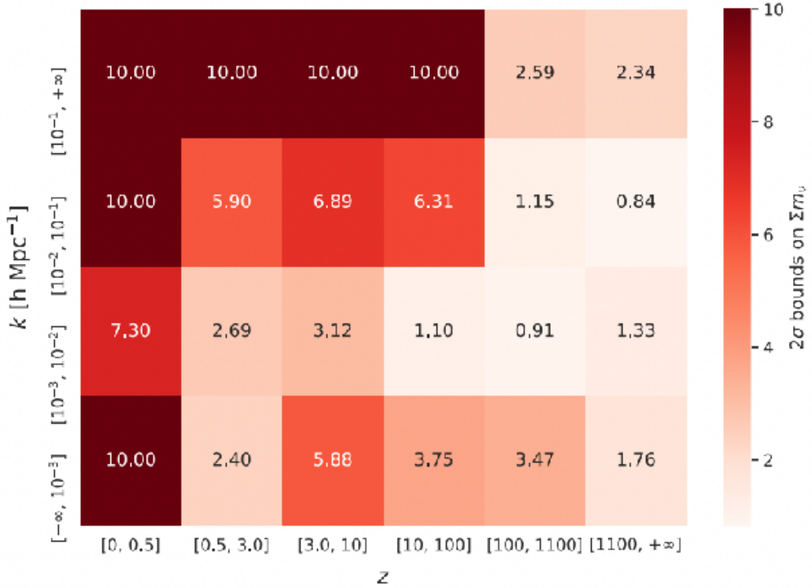
(Kind of) New interactions

Phenomenological variation of fundamental constants/masses/TCMB





Calabrese+, 2025



Wang+, 2025

Physical and descriptive

Only if tied to specific high-energy model (i.e., cannot exist only as a solution to H0 tension)

Non-phenomenological implementation sometimes very different from pheno approach

Useful as a diagnostic tool

Conclusions

Sure thing: we need to explore beyond-LCDM territory

Exploration can/must be phenomenological and data-driven (i.e, predictive)

Conclusions must be physical: link to fundamental physics must exist (viable at large)

Synergy with complementary probes is key to confirm/rule out findings