Implications of light mediator neutrino interactions in cosmology

Based on:
arXiv:2101.05804
arXiv:2202.04656

NuTs Workshop

Jordi Salvadó

The near future may be very interesting!

- We will reach a precision for the large-scale structure that may reveal the mass scale for neutrinos!
- Today, the best bound for the value of neutrino masses comes from cosmology.
- The cosmologcial standard model (**LambdaCDM**) is by itself a big mystery from a particle physics perspective.

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Euclid consortium

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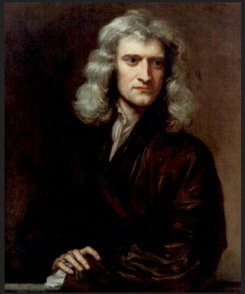
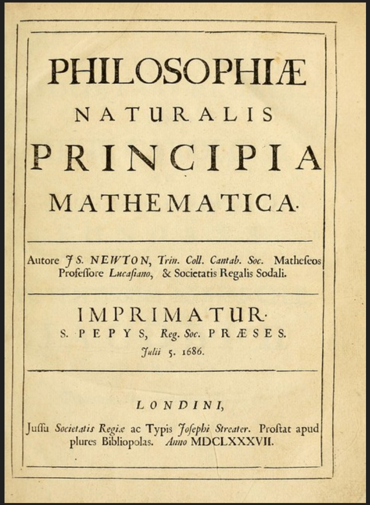
We measure the mass or we don't ***(particle physicist?)***

Deviations from LambdaCDM are expected

How do we test physics (History)



In 1687 sir Isaac Newton tell us about the first force.



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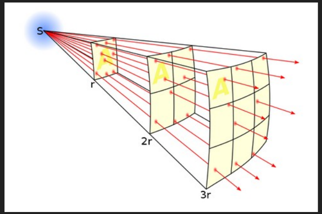

$$F = G\frac{m_1 m_2}{r^2}$$

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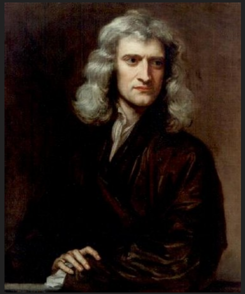

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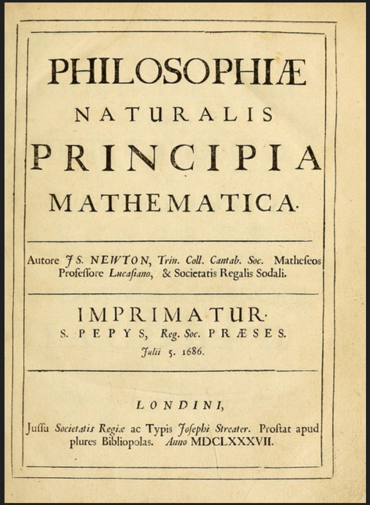

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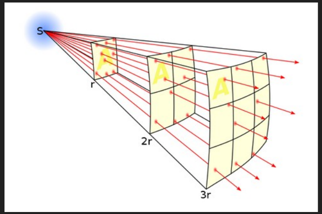

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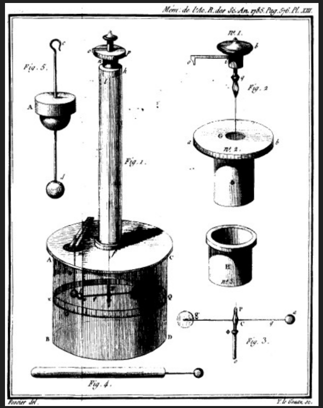
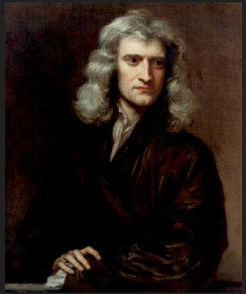
Later in 1785 Charles-Augustin de Coulomb found a second one.

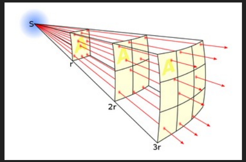


$$F = C\frac{q_1 q_2}{r^2}$$

(Disclaimer) “Ancient cultures around the Mediterranean knew that certain objects could be rubbed with cat's fur to attract light objects like feathers and papers.”

How do we test physics (History)





- Both forces add up into large number of particles!

$$F = G\frac{m_1 m_2}{r^2}$$

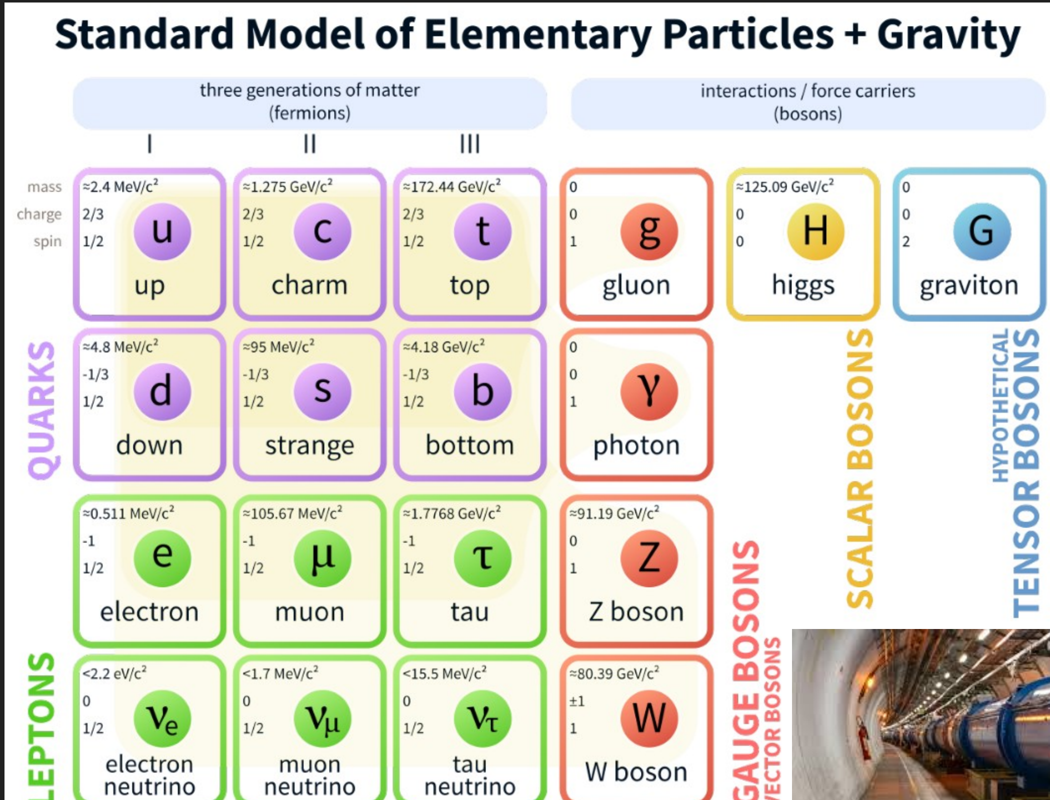
$$\frac{M_{Earth}}{m_p} \approx 10^{51}$$

$$\frac{Coulomb}{e} \approx 10^{18}$$

$$F = C\frac{q_1 q_2}{r^2}$$

- Today we understand this are indeed forces driven by massless mediators. We call them long-range forces.

Today! (Particle Content and Interactions)



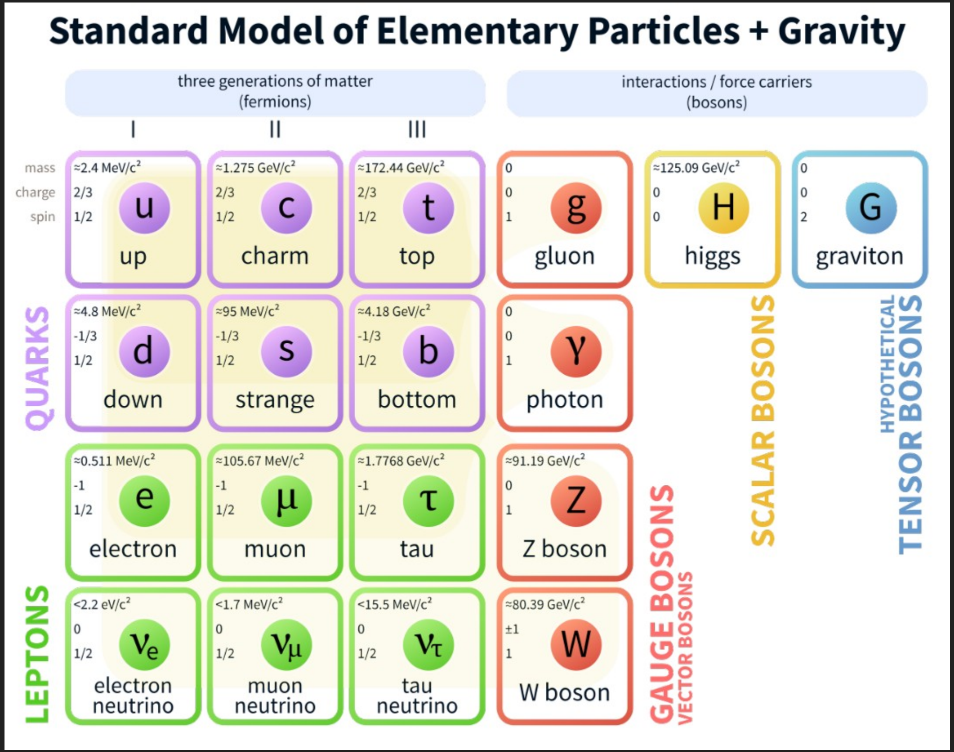
Thanks to explore particle physics at high energies we learn a lot more!

- Three families of particles
- New fundamental forces and mediators.
- The higgs responsable of the mass and electroweak symmetry breaking.

Very successful!! And more to come.

Most of the high energy physics is very hard to see at low energies due to the mediators mass.

Today! (Particle Content and Interactions *Newton way*)



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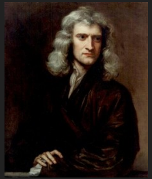
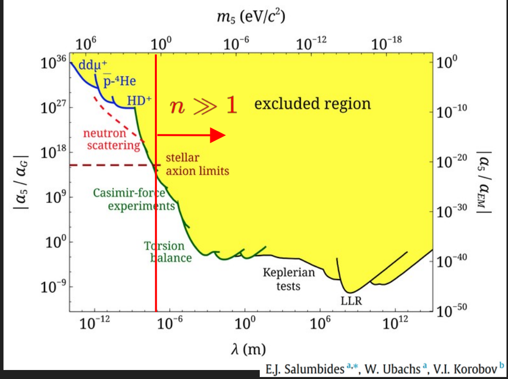


Currently different experiments and observations also put bounds to fifth forces.



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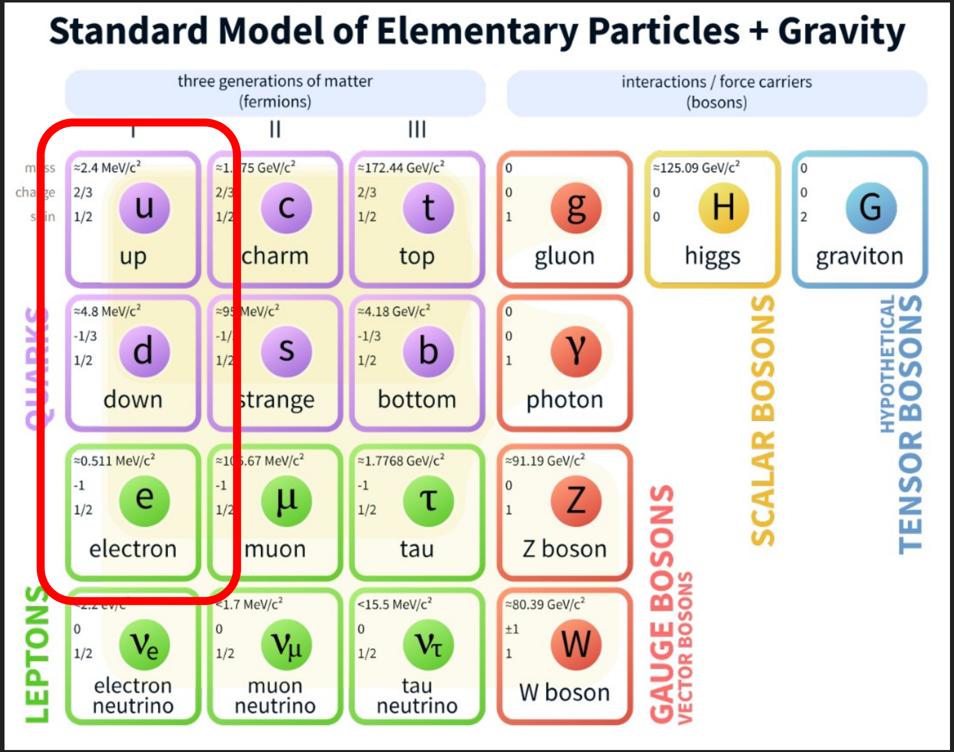

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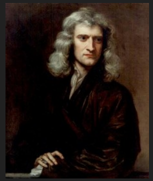

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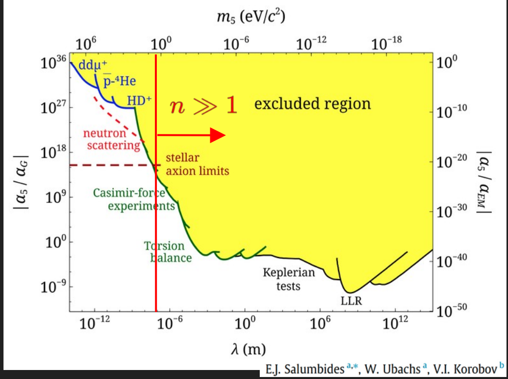

But all of them test only the first family.

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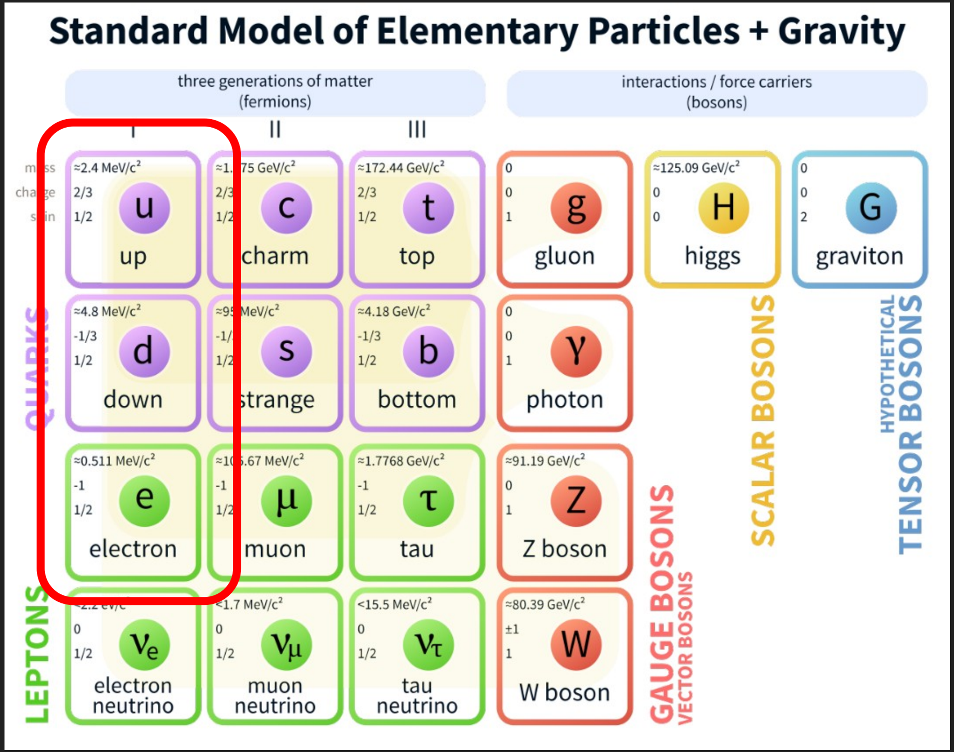

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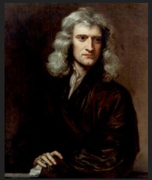

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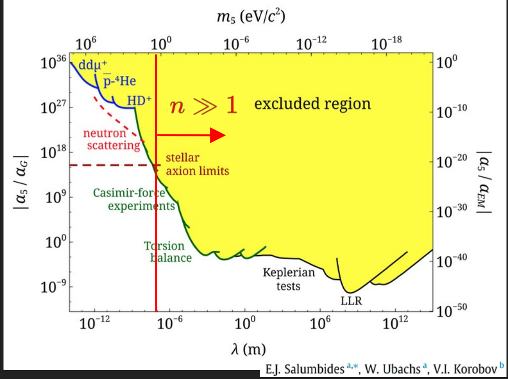

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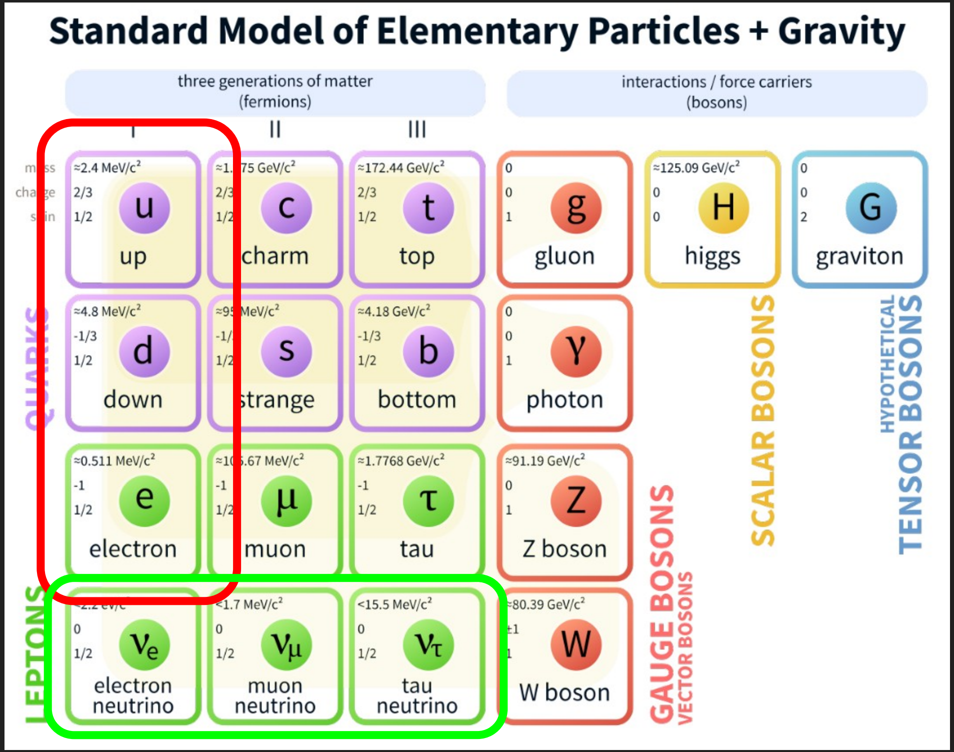

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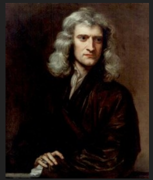

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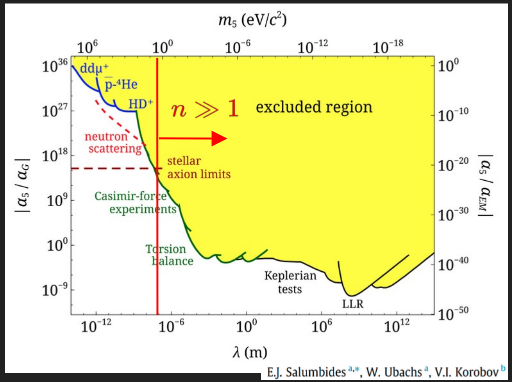

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The cosmic neutrino background should be in mass eigenstates:

$$n_{\nu_e} \approx n_{\nu_\mu} \approx n_{\nu_\tau}$$

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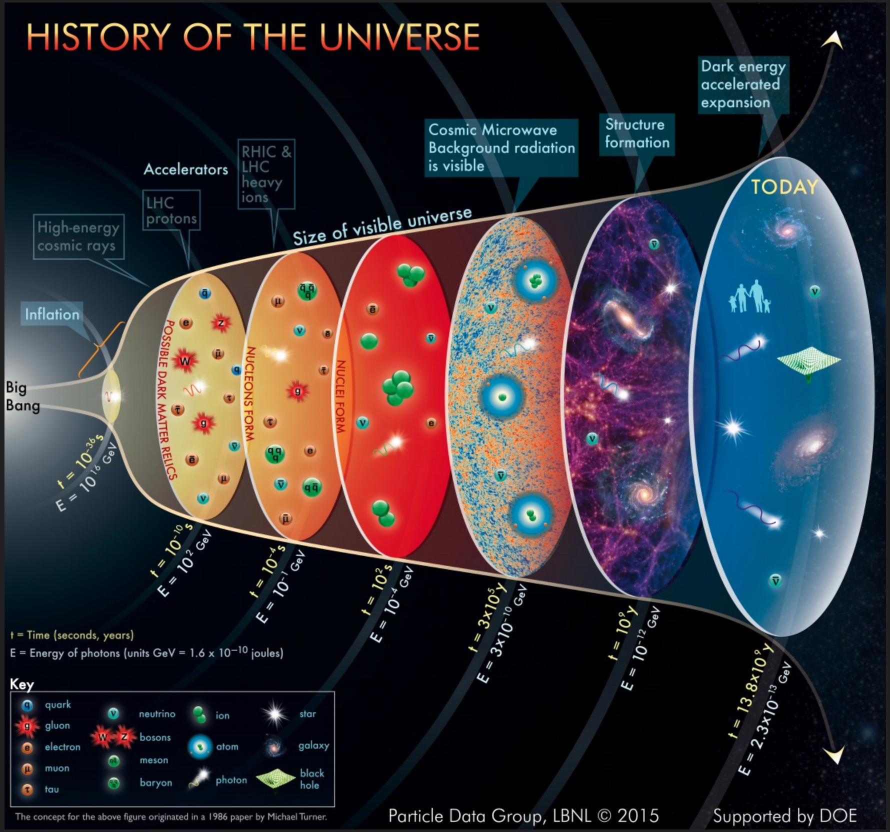
Let’s take the whole universe



The fact that the universe expands tells us:

- Densities where higher earlier in the expansion history, some examples re-scaling neutrinos:

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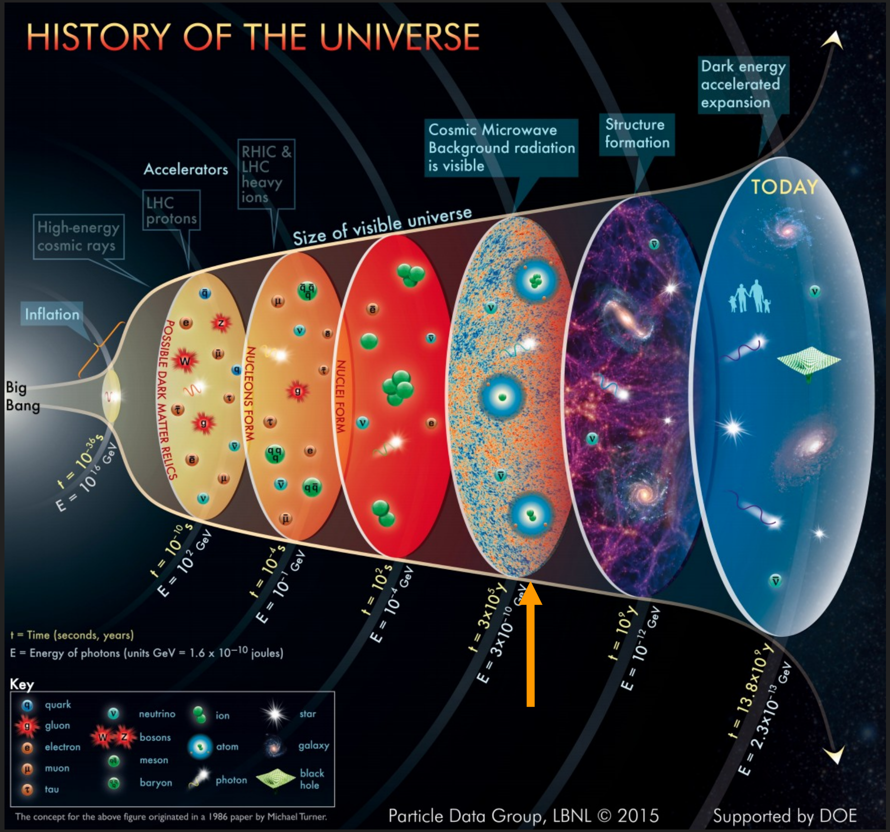

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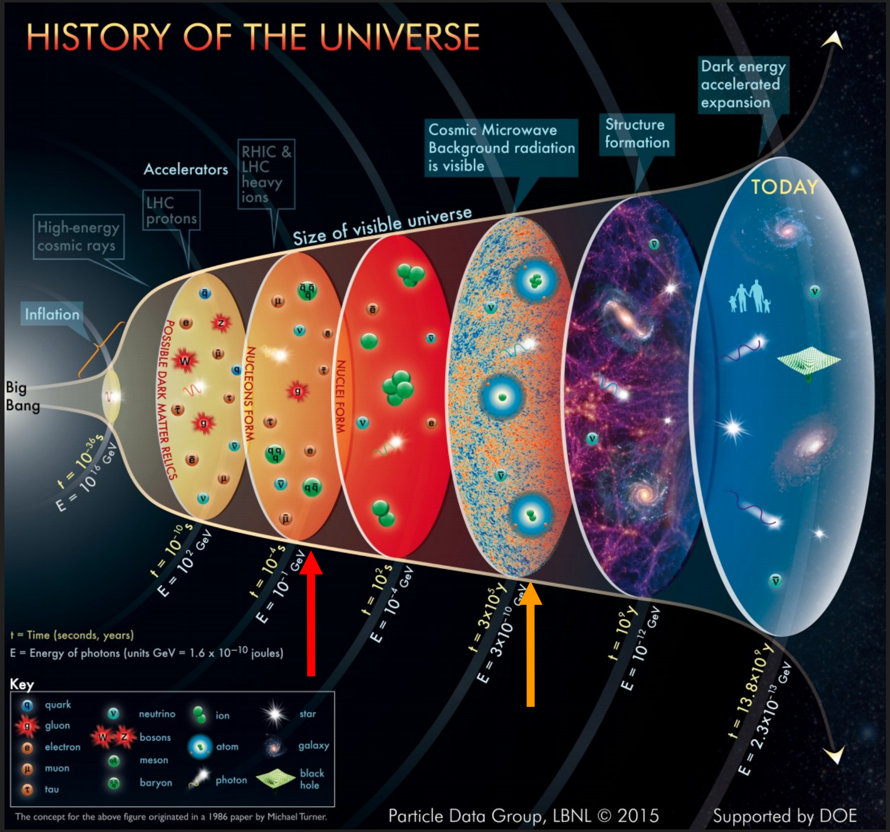

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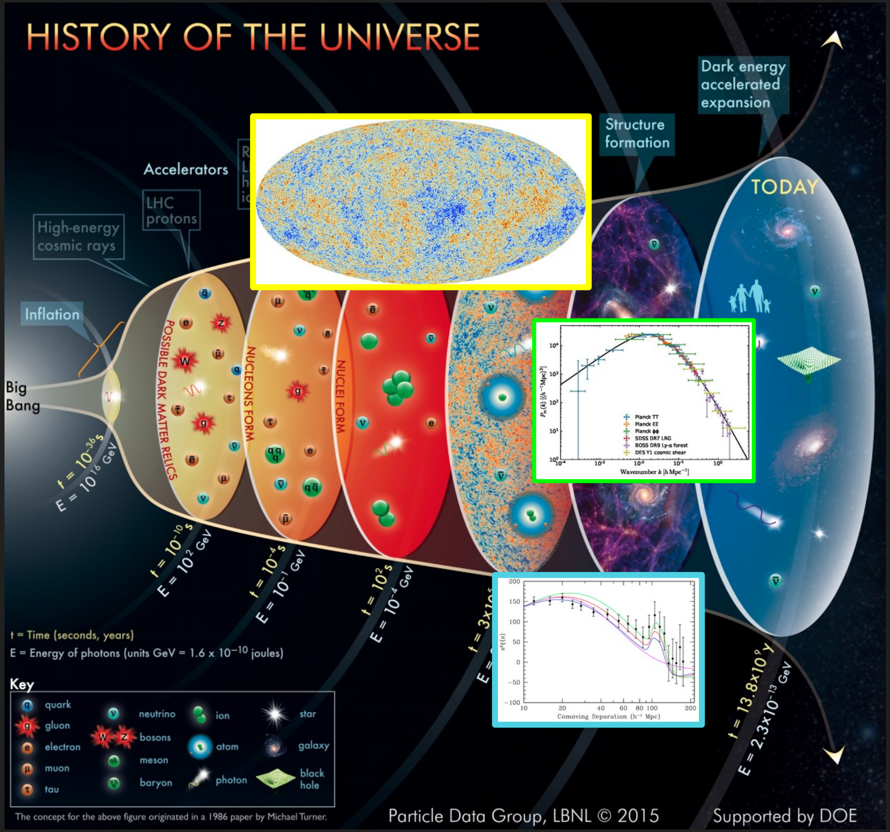

- What do we look at:

CMB data is one of the most powerful observations **Planck-2018**

The **matter spectrum**, Fourier transform of the two point correlation function.

Imprint of the CMB acoustic oscillations in the large scale structure of the universe **BAO**

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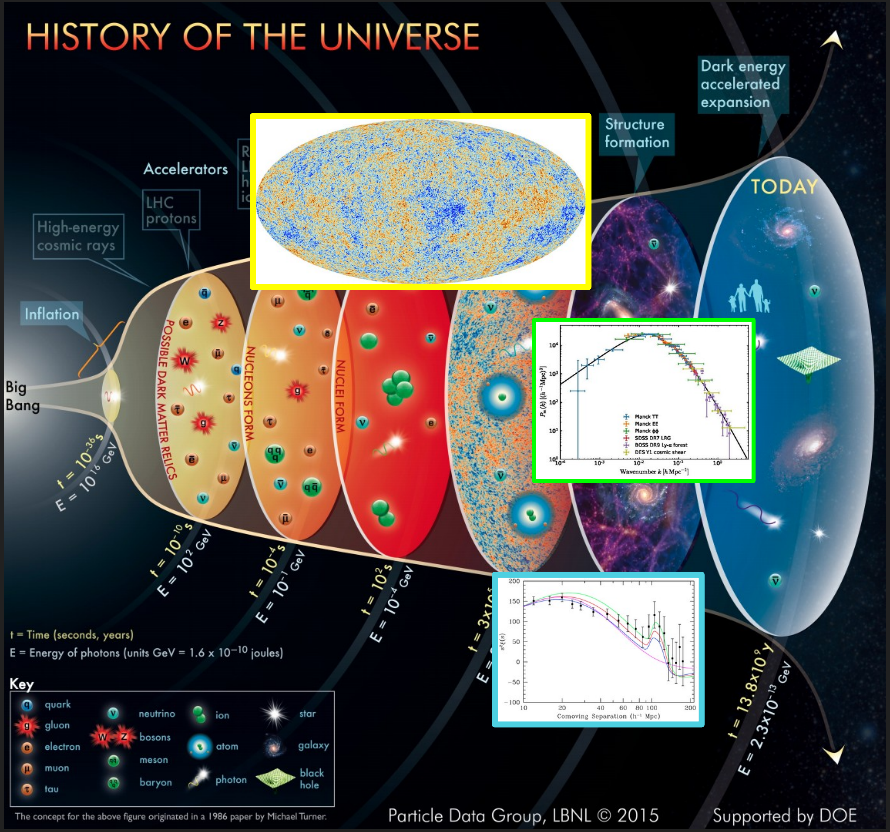

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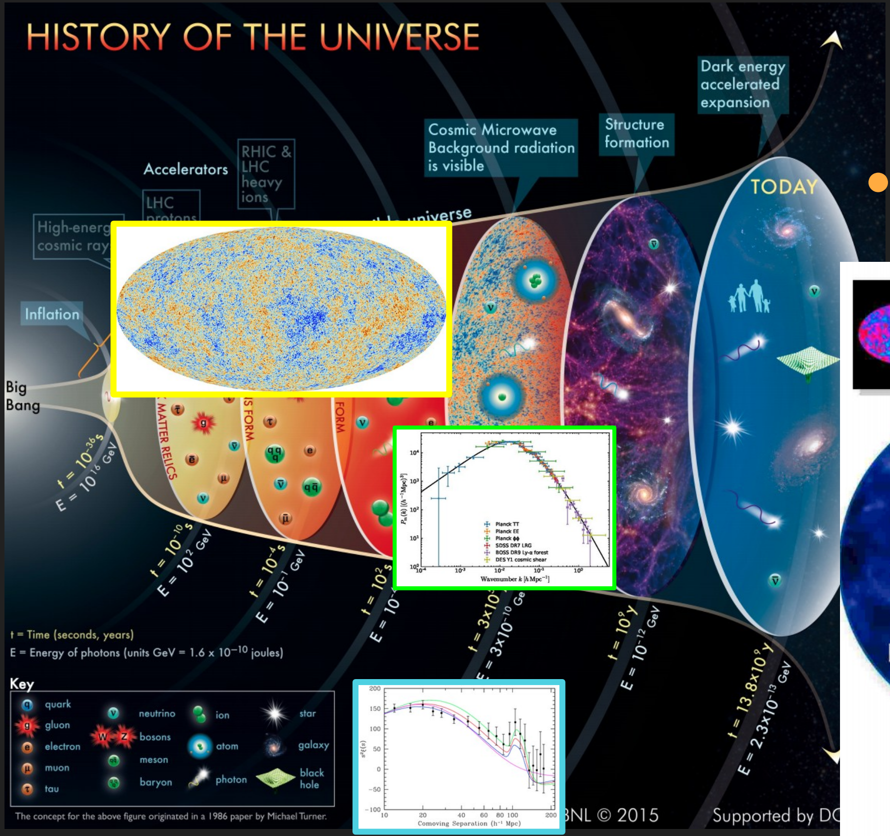
At large scales the universe is homogeneous + small perturbations:

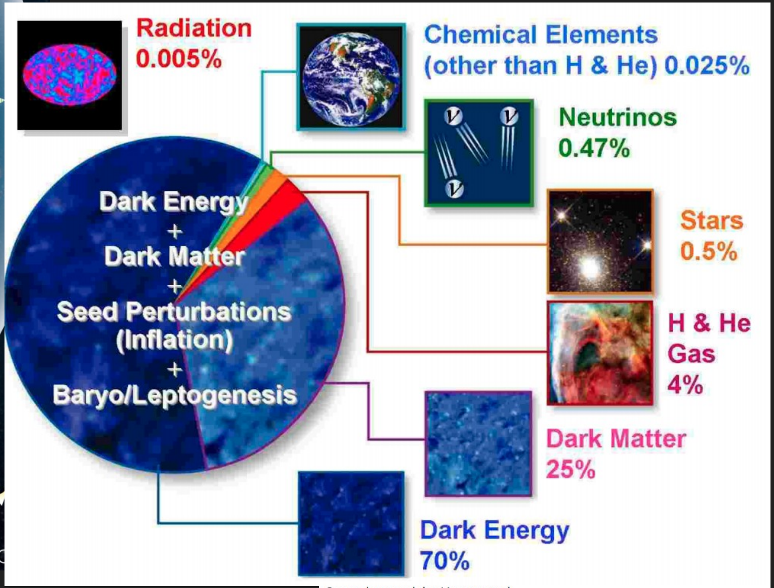
We will solve numerically the
Einstein + Boltzmann equations at first order.

Tools available:
https://github.com/lesgourg/class_public.git

universe

- The ingredients are:





Cosmology and the Unexpected

Edward W. Kolb (Chicago U., Astron. Astrophys. Ctr. and Chicago U., EFI and Chicago U., KICP)

universe

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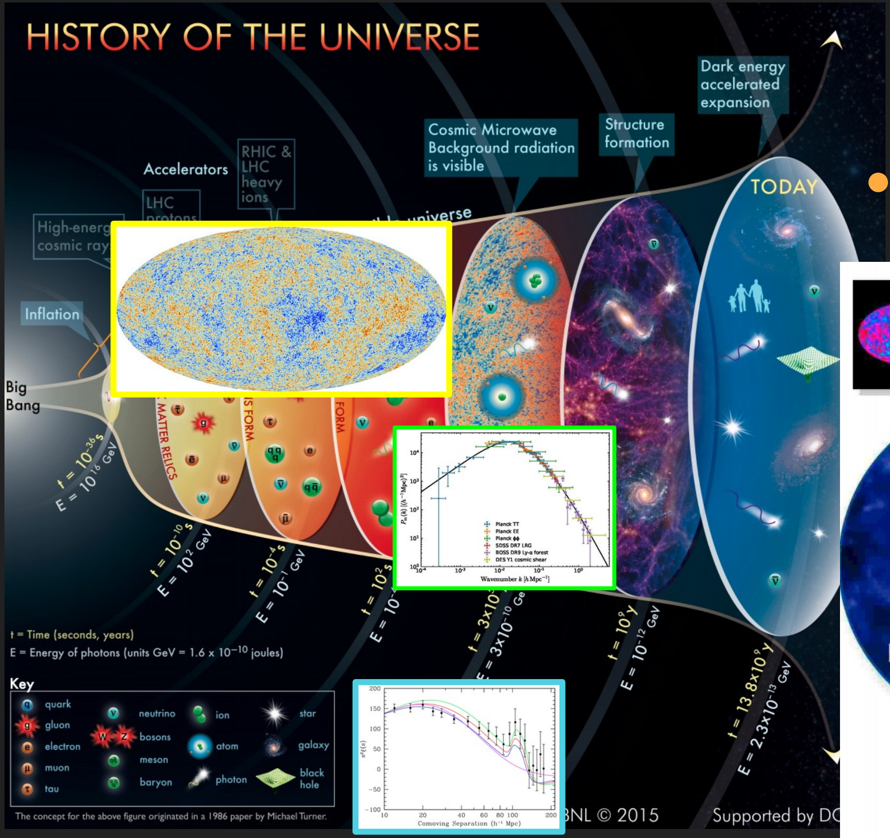

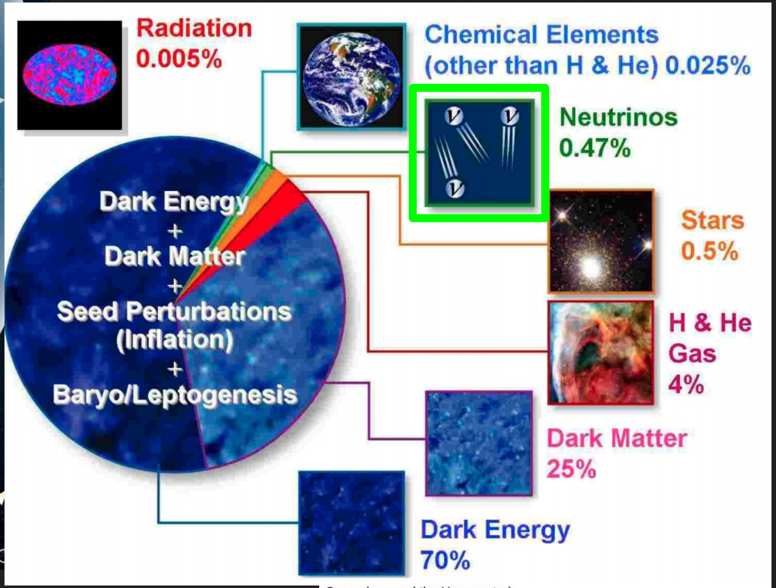

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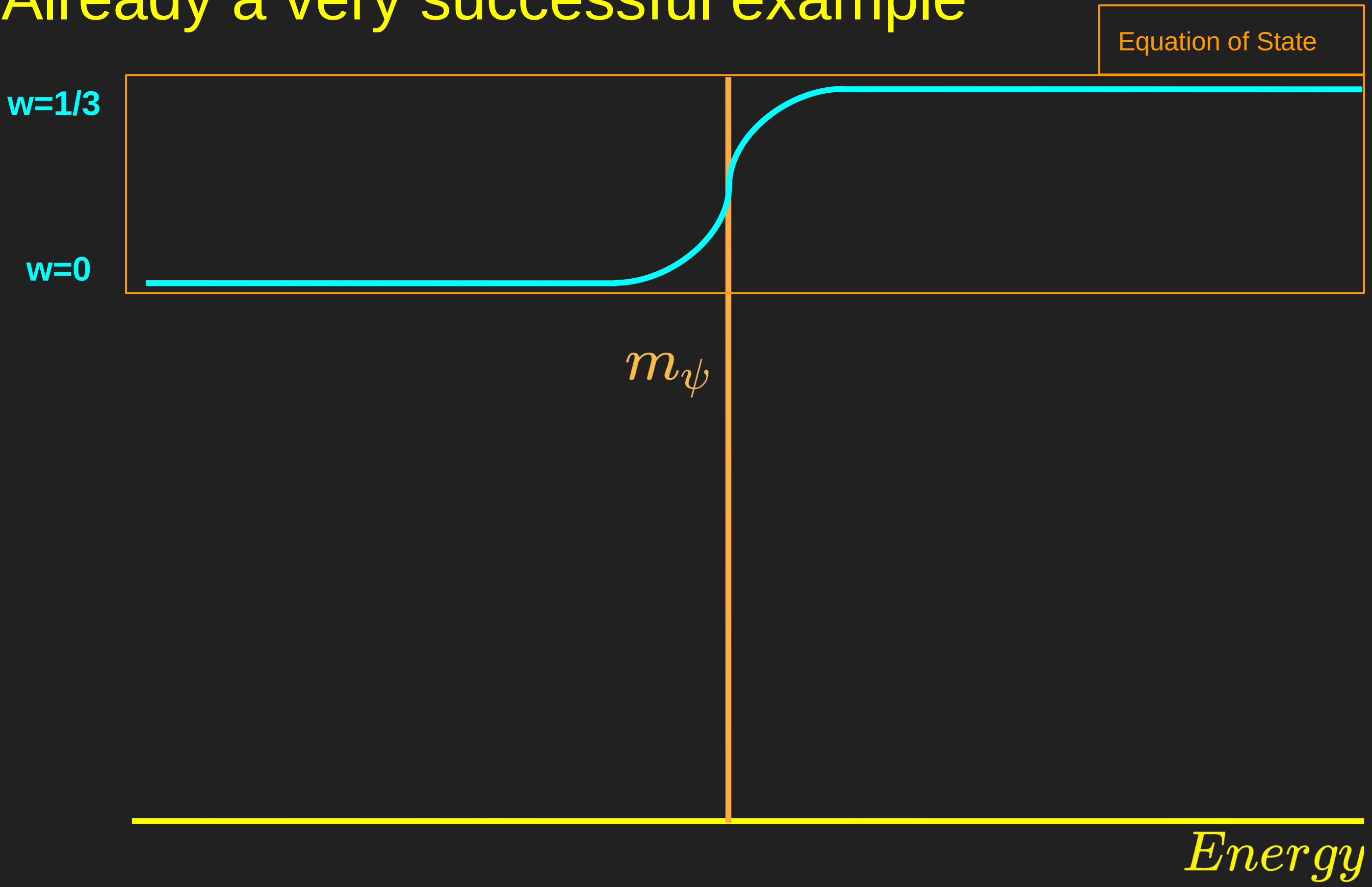
Already a very successful example

Neutrino Oscillations tell us neutrinos are massive particles!



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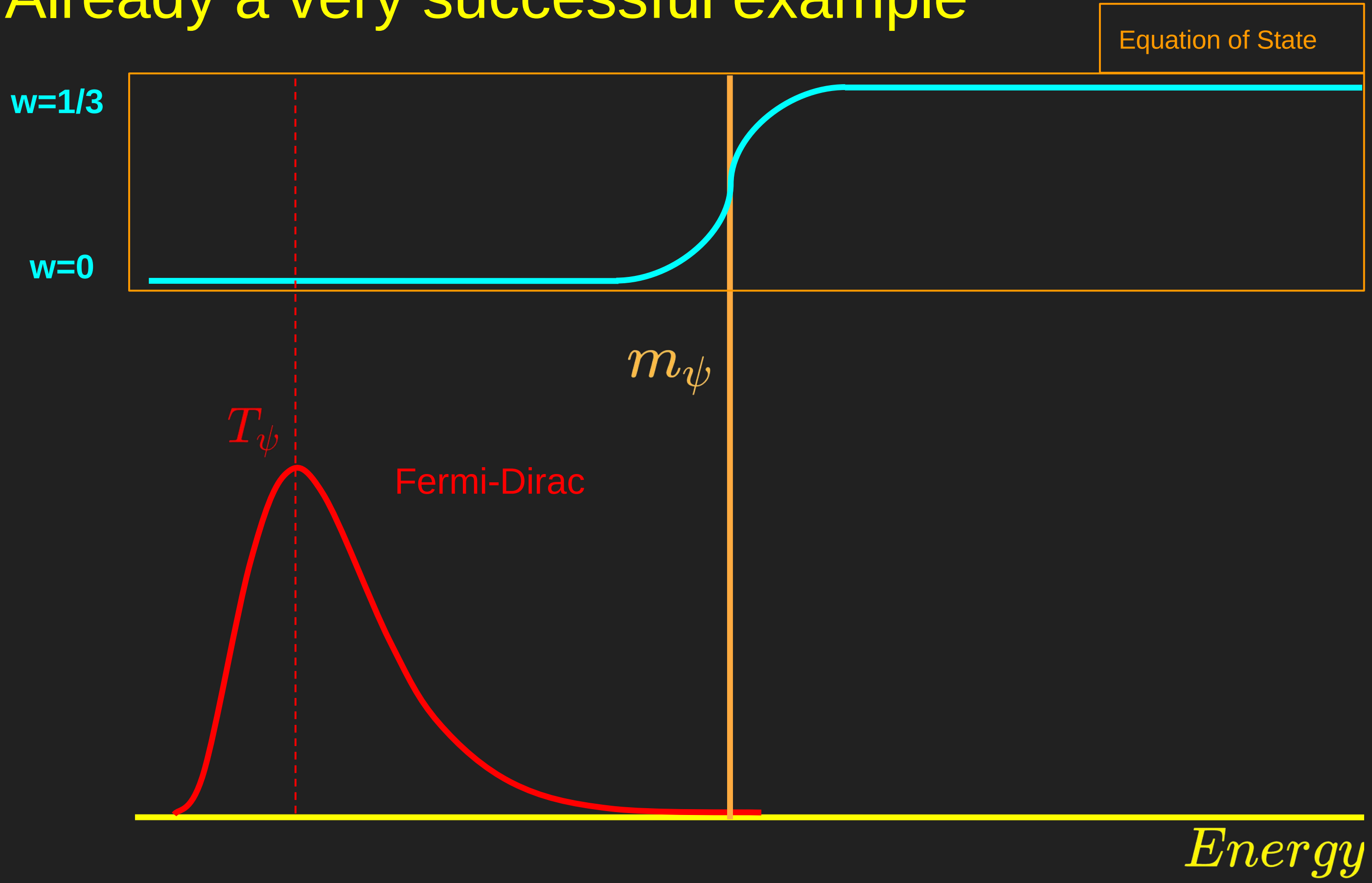

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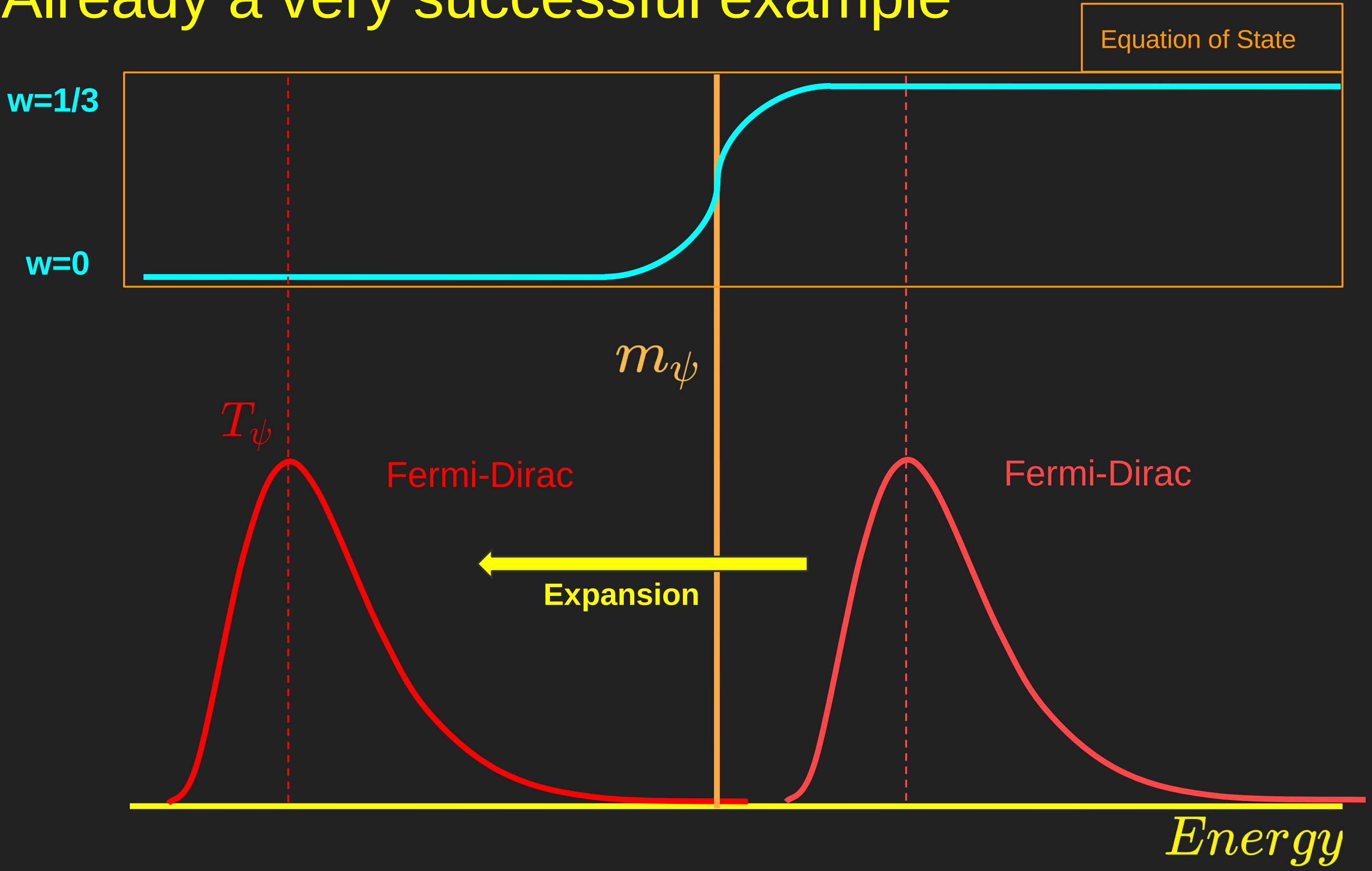

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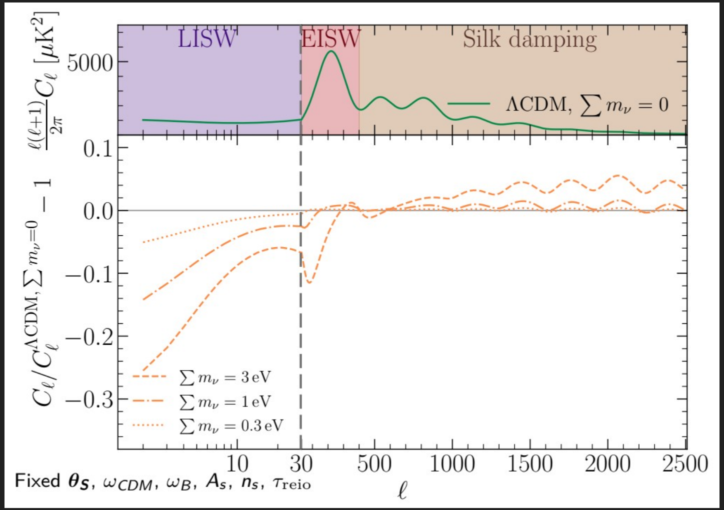
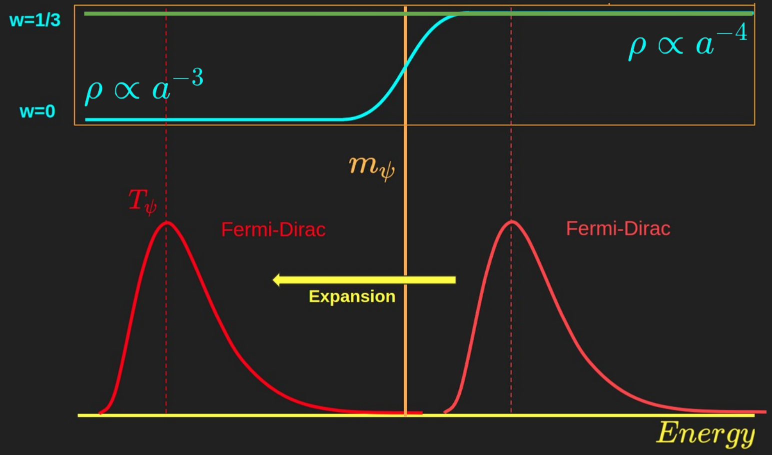
CMB is very sensitive to the expansion history.

$$H^2 \equiv \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho$$





$$\rho_\Lambda + \rho_m + \rho_r$$

$$\theta_s = \left[\int_{z_{\rm rec}}^{\infty} c_s(z)\frac{{\rm d}z}{H(z)}\right] \times \left[\int_0^{z_{\rm rec}} \frac{{\rm d}z}{H(z)}\right]^{-1}$$

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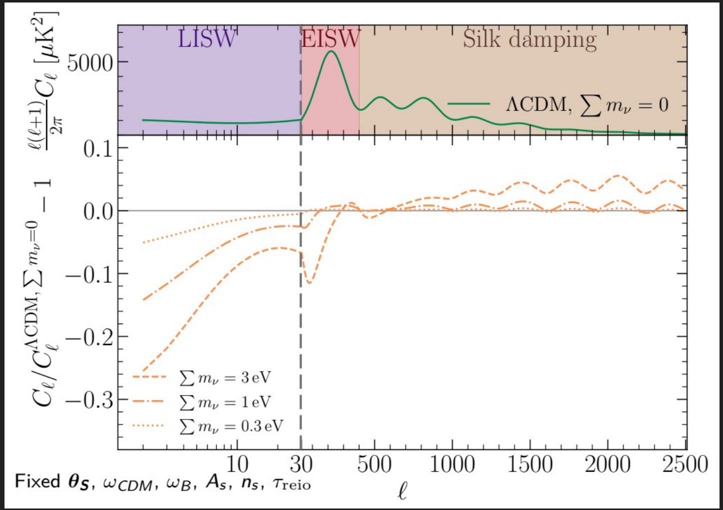

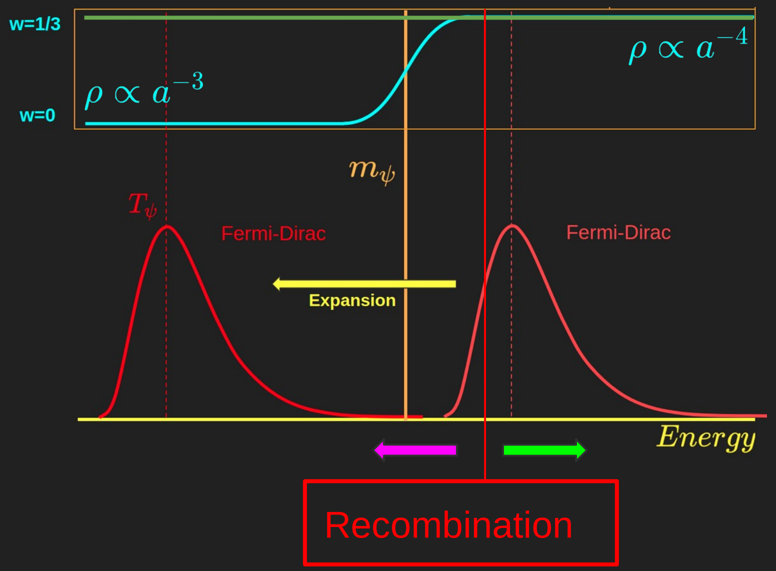

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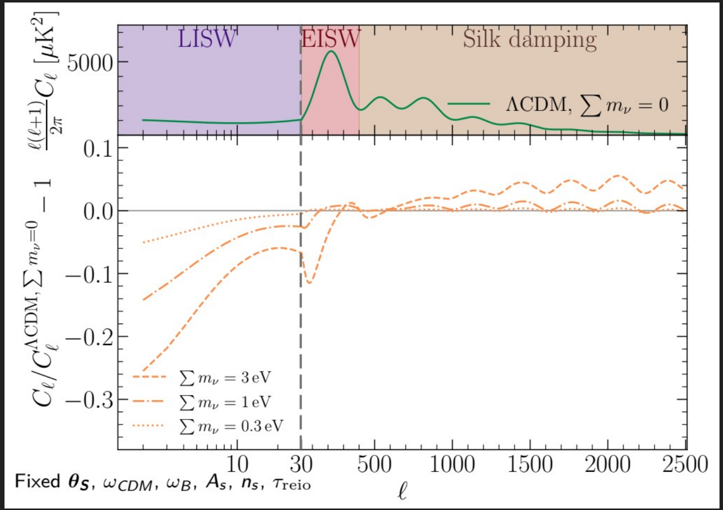
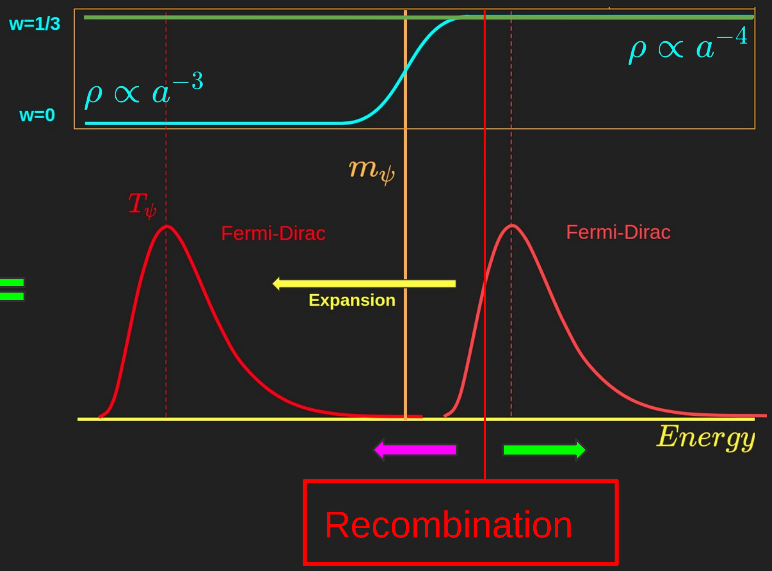


$m_\psi < T_{rec}$

H $\qquad$ H

$\rho_\Lambda \downarrow + \rho_m \uparrow$ $\qquad$ ρ_r =

Effect low l (LISW)



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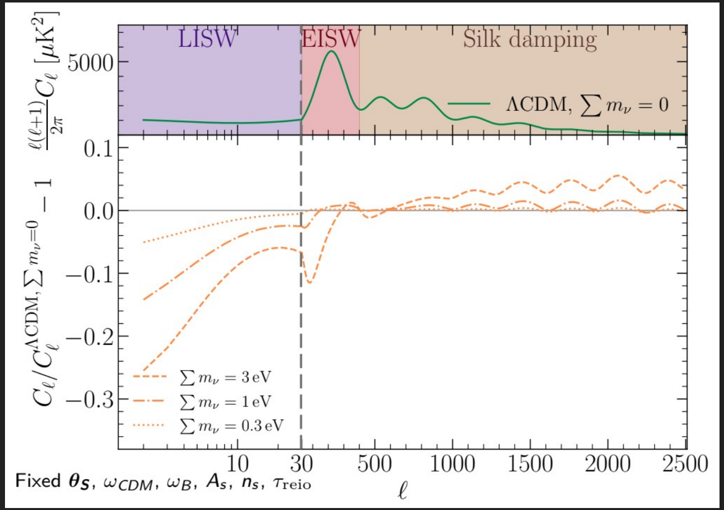

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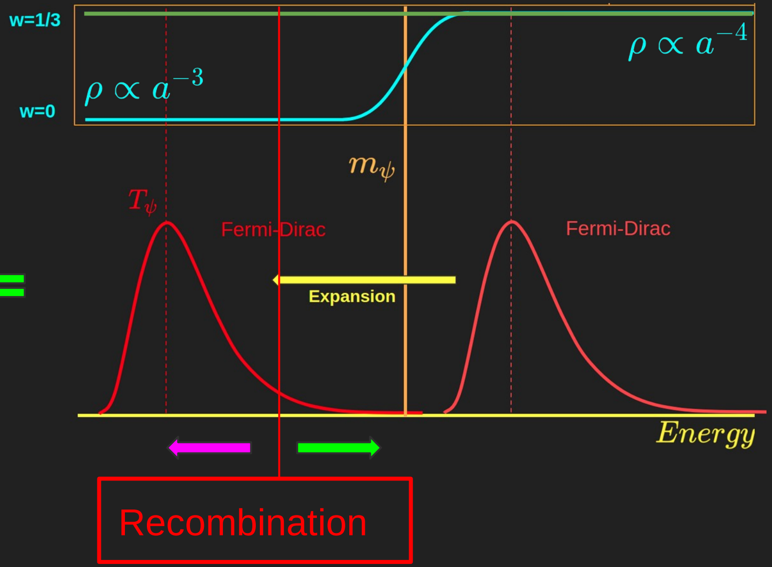

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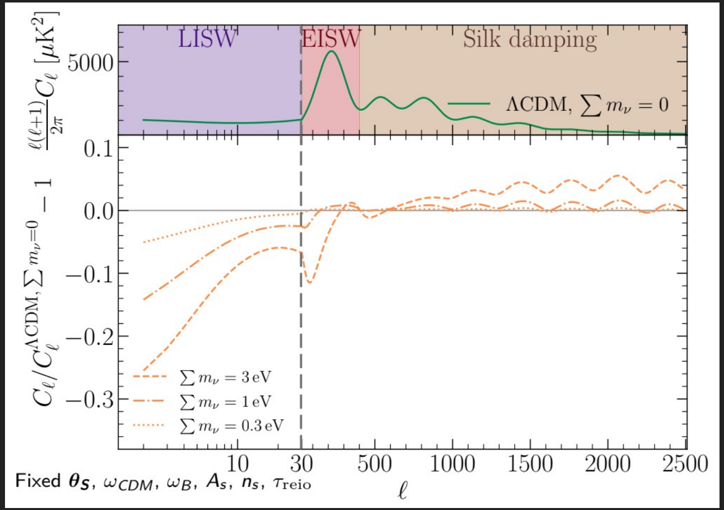

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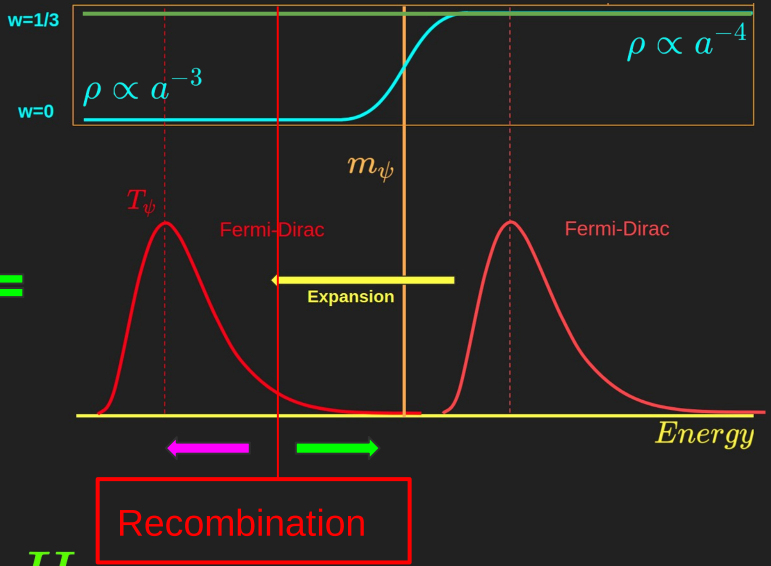

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Very sensitive (EISW and Damping)

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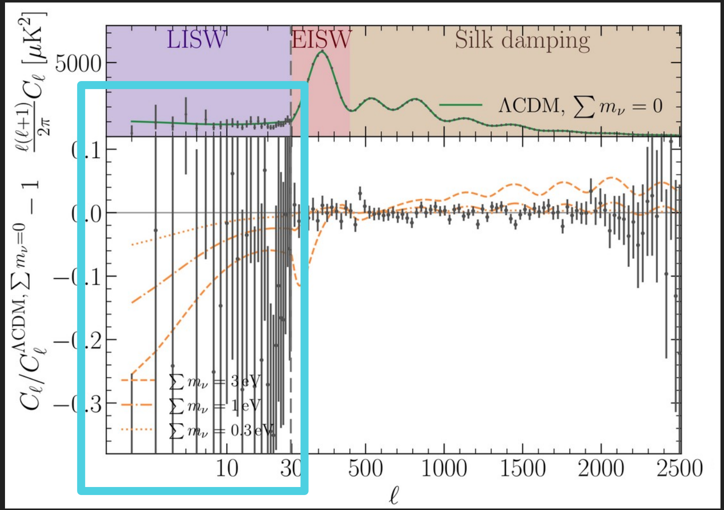

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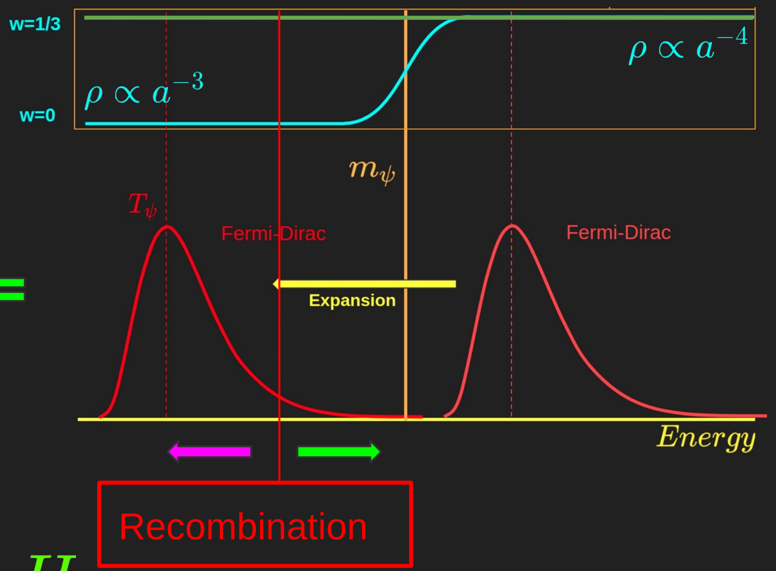

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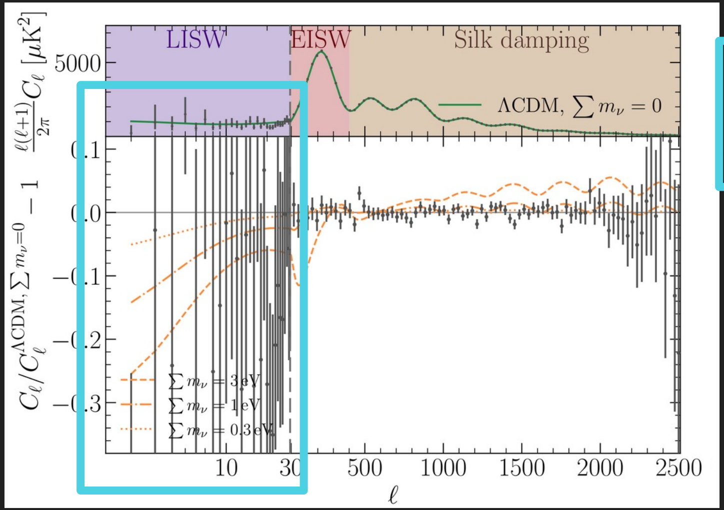

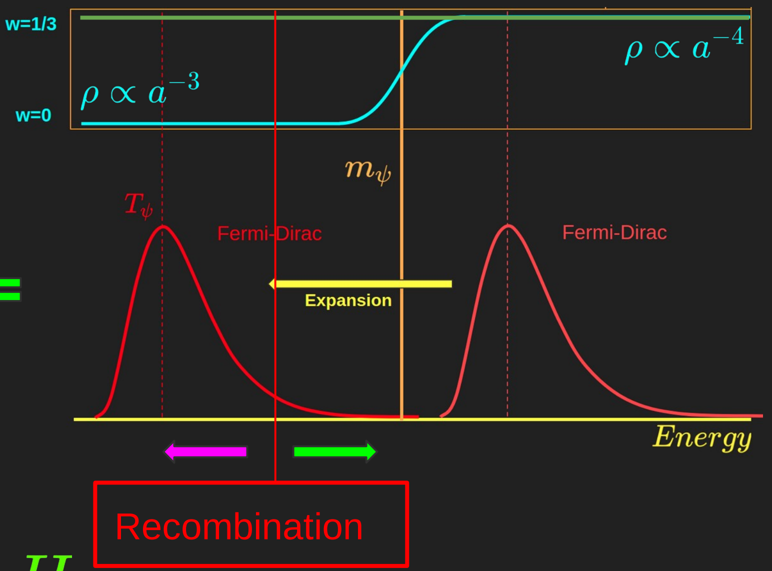

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H: $\rho_\Lambda \downarrow + \rho_m \uparrow$ — H: $\rho_r \downarrow + \rho_m \uparrow$ — $\rho_\Lambda + \rho_m + \rho_r$

Very sensitive (EISW and Damping)

$$\theta_s = \left[\int_{z_{\rm rec}}^{\infty} c_s(z)\frac{dz}{H(z)}\right] \times \left[\int_0^{z_{\rm rec}} \frac{dz}{H(z)}\right]^{-1}$$

Large scale structure may be even more sensitive to small neutrino masses.

J. Lesgourgues, G. Mangano, G. Miele, S. Pastor, Neutrino Cosmology (2013)

Ideal? Gas of neutrinos

- Large number of neutrinos. ***(macroscopic enhancement)***
- Expected similar amount of each family. (probably the only test of second and third family long range forces)
- The dynamics of the universe is essentially sensitive to the equation of state.

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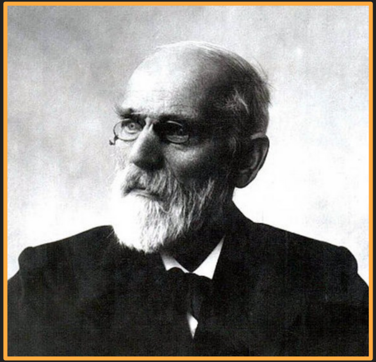

Corrections to the ideal gas equation of state may be important even for week interactions: **Johanes Van der Waals**, Virial Expansion, …

Can we test neutrino properties (beyond the mass)?

Widely studied!

~Massless   Heavy

$$\boxed{D_t} f(x,p,t) = \boxed{C[f(x,p,t)]}$$

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$$L_{\rm Horizon} \approx 10^{34} eV^{-1} \quad \Longleftrightarrow \quad L_{\rm int} \approx 10^{-9} eV^{-1}$$

A few orders of magnitude to be explored!

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Works by: Yvonne Wong and Miguel Escudero

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$1/\mathrm{Mpc} \approx 10^{-29}\,\mathrm{eV}$

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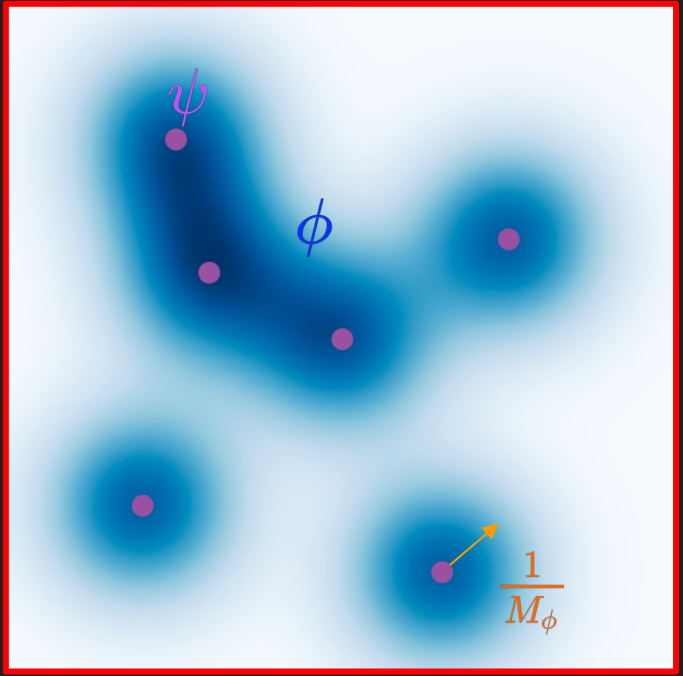
$$L_\phi \in \{10^2\,\mathrm{km}, 10^{19}\,\mathrm{km}\}$$

We want to stay in this range to isolate and better illustrate the relevance of this effects.

A simple setup

We will study the “simplest” case, a light scalar field:

$$\mathcal{S} = \int \sqrt{-g}\,\mathrm{d}^4x \left(-\frac{1}{2} D_\mu \phi D^\mu \phi - \frac{1}{2} M_\phi^2 \phi^2 + i\bar{\psi}\not{D}\psi - m_0 \bar{\psi}\psi - g\phi\bar{\psi}\psi \right)$$



- The scalar field will extend in a range given by its mass.
- Non trivial effects are expected when the interaction range is of order of the interparticle distance.

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Let’s have a look a the equations of motion:

Dirac Equation:

$$i\not{D}\psi - (m_0 + g\phi)\psi = 0$$

Klein-Gordon Equation:

$$\underbrace{-D_\mu D^\mu \phi}_{\supset 3H\dot{\phi}} + M_\phi^2 \phi = -g\bar{\psi}\psi$$

- Fermions have a effective mass given by the value of the scalar field.

$$\tilde{m}(\phi) \equiv m_0 + g\phi$$

- The scalar field is suppressed by large momentum (relativistic fermions)

$$M_\phi^2\phi = -g \int \mathrm{d}^3p \frac{\tilde{m}(\phi)}{\sqrt{p^2 + \tilde{m}(\phi)^2}} f(p)$$

$\bar{\psi}\psi$ → $f(p) = \frac{\mathfrak{g}}{(2\pi)^3} \frac{1}{e^{p/T} + 1}$

Phenomenological Regimes

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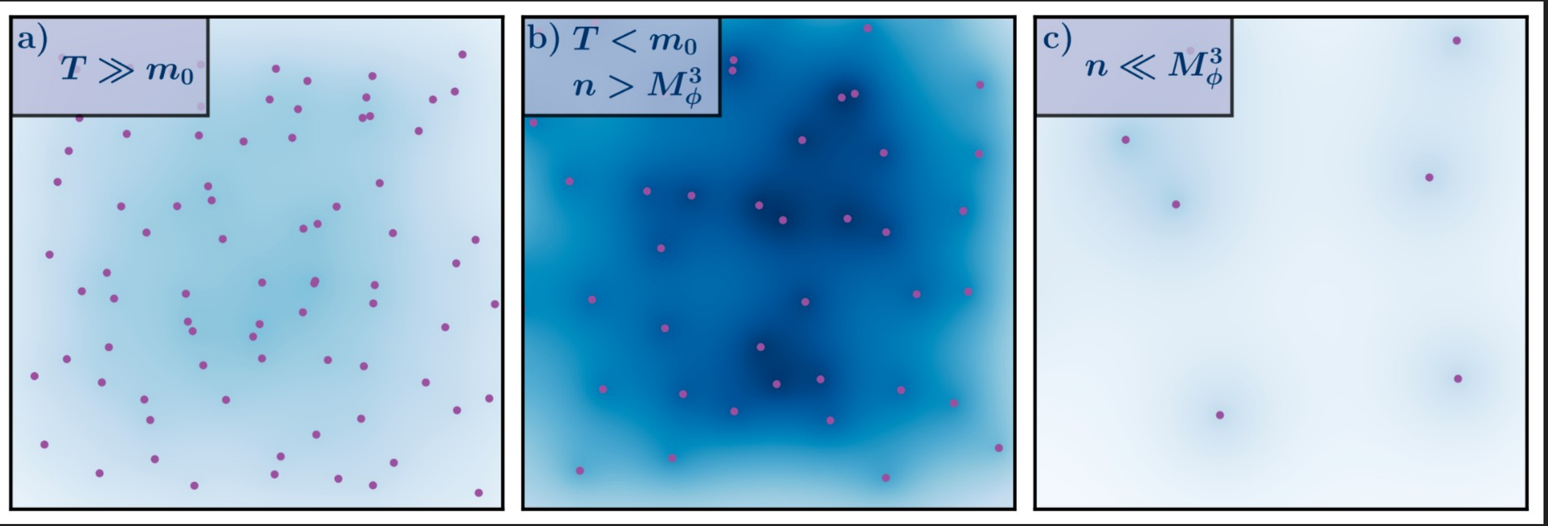

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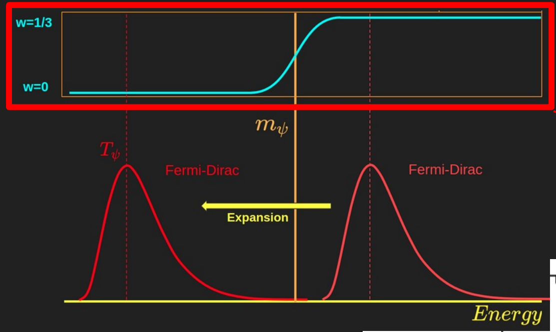
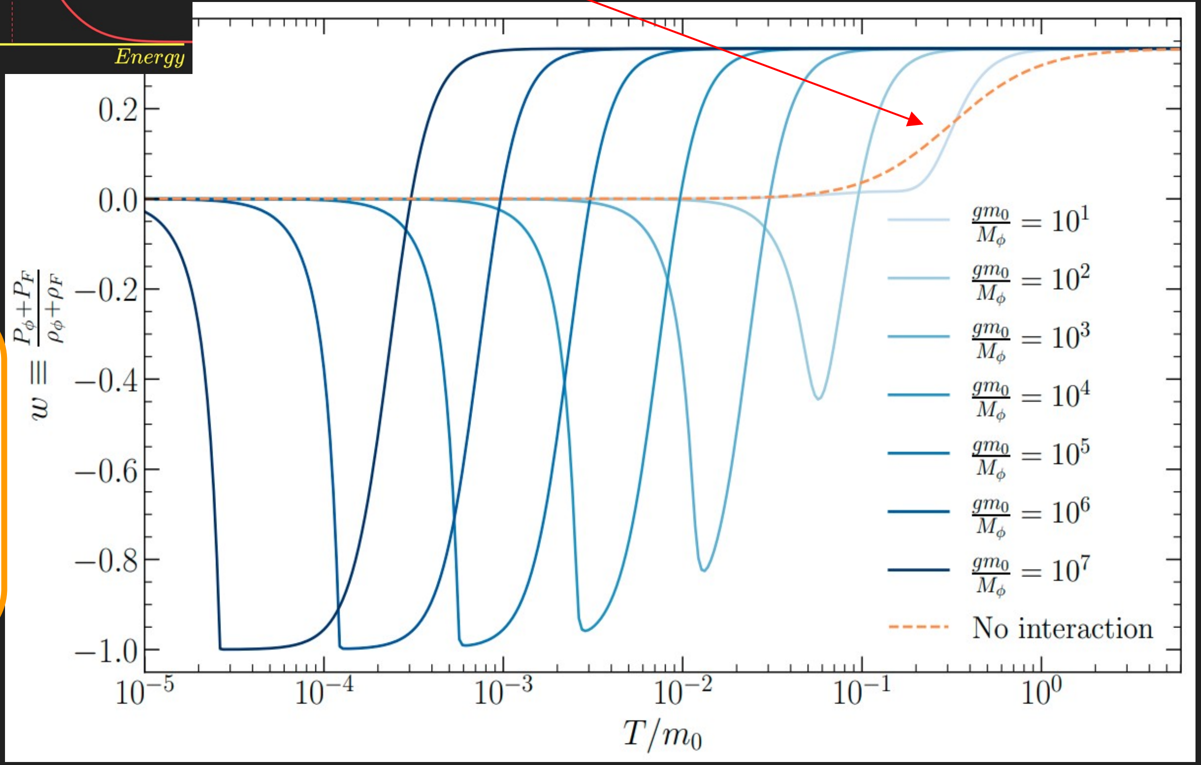


Expansion



$$P_\phi = -\frac{1}{2} M_\phi^2 \phi^2$$

$$P_F = \int \mathrm{d}^3 p \frac{p^2}{3\sqrt{p^2 + \tilde{m}^2}} f(p)$$

$$\rho_\phi = \frac{1}{2} M_\phi^2 \phi^2$$

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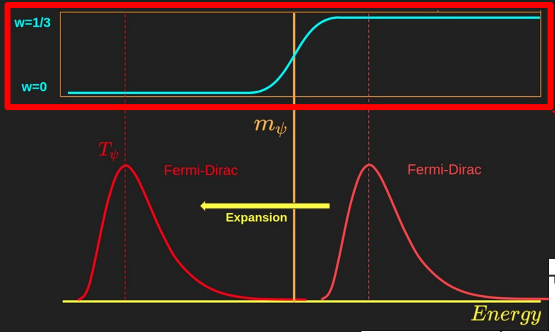
How the Universe Evolves?



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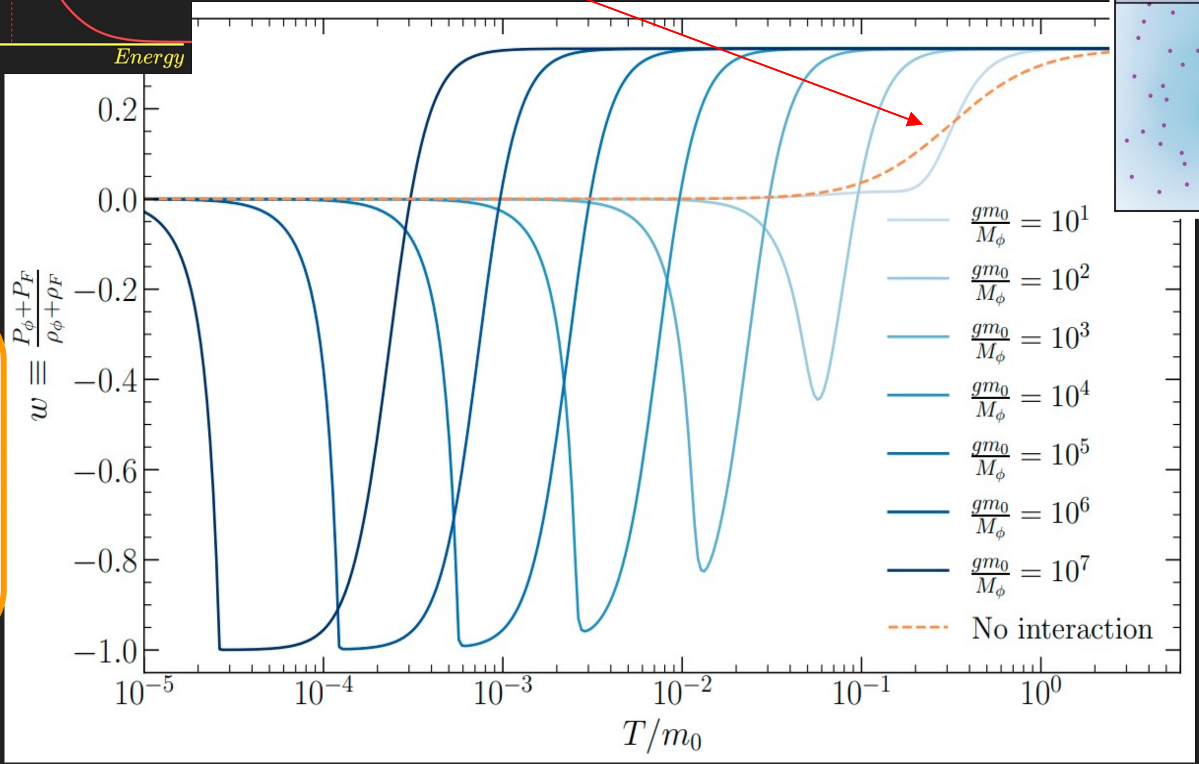

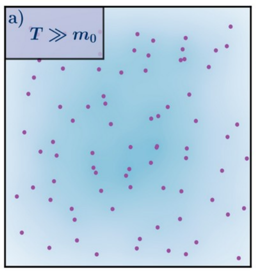

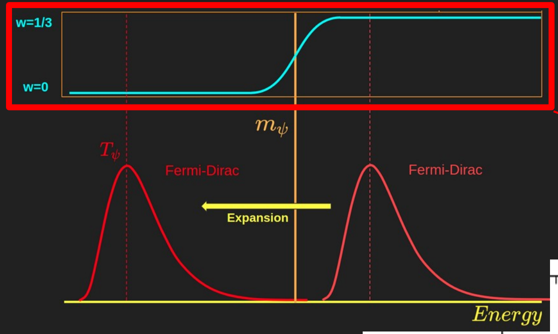

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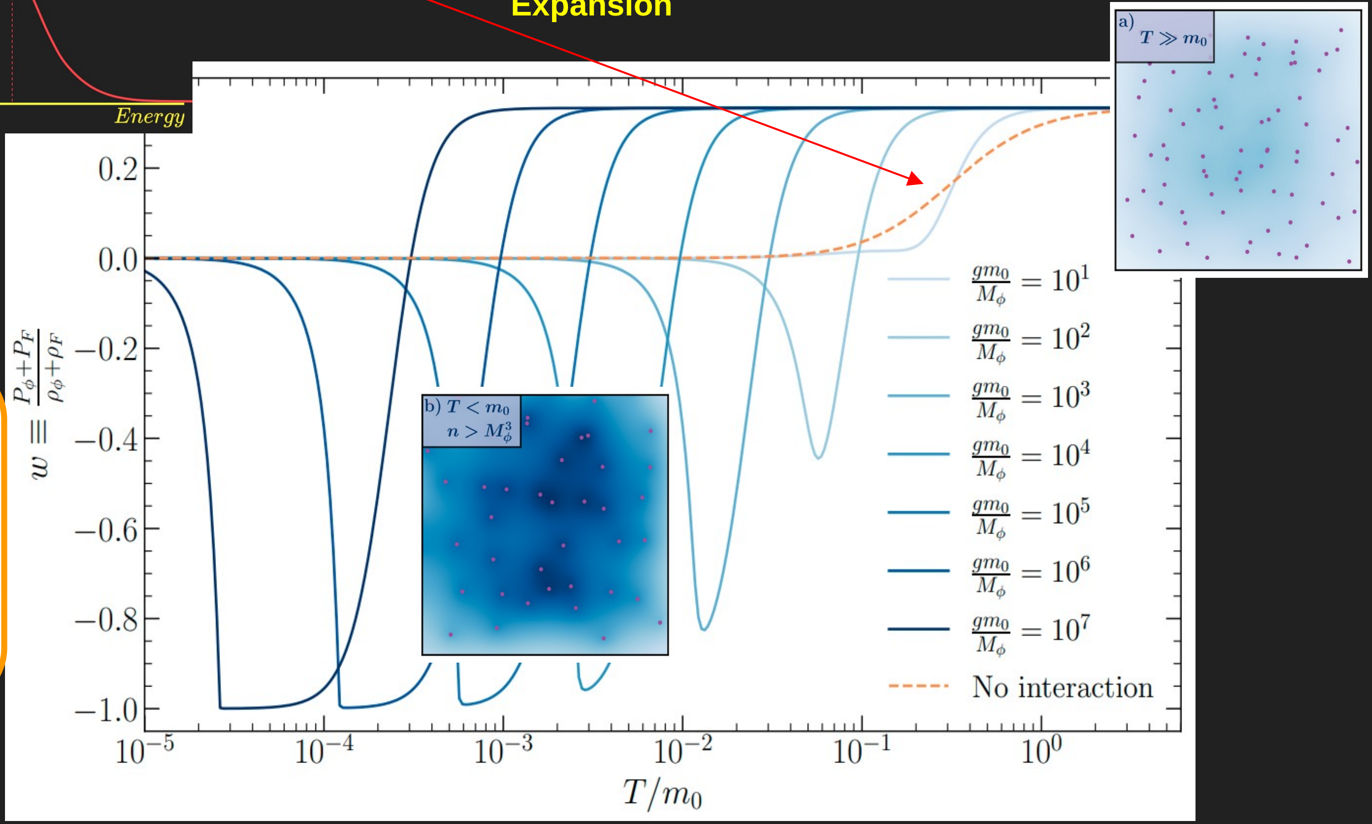

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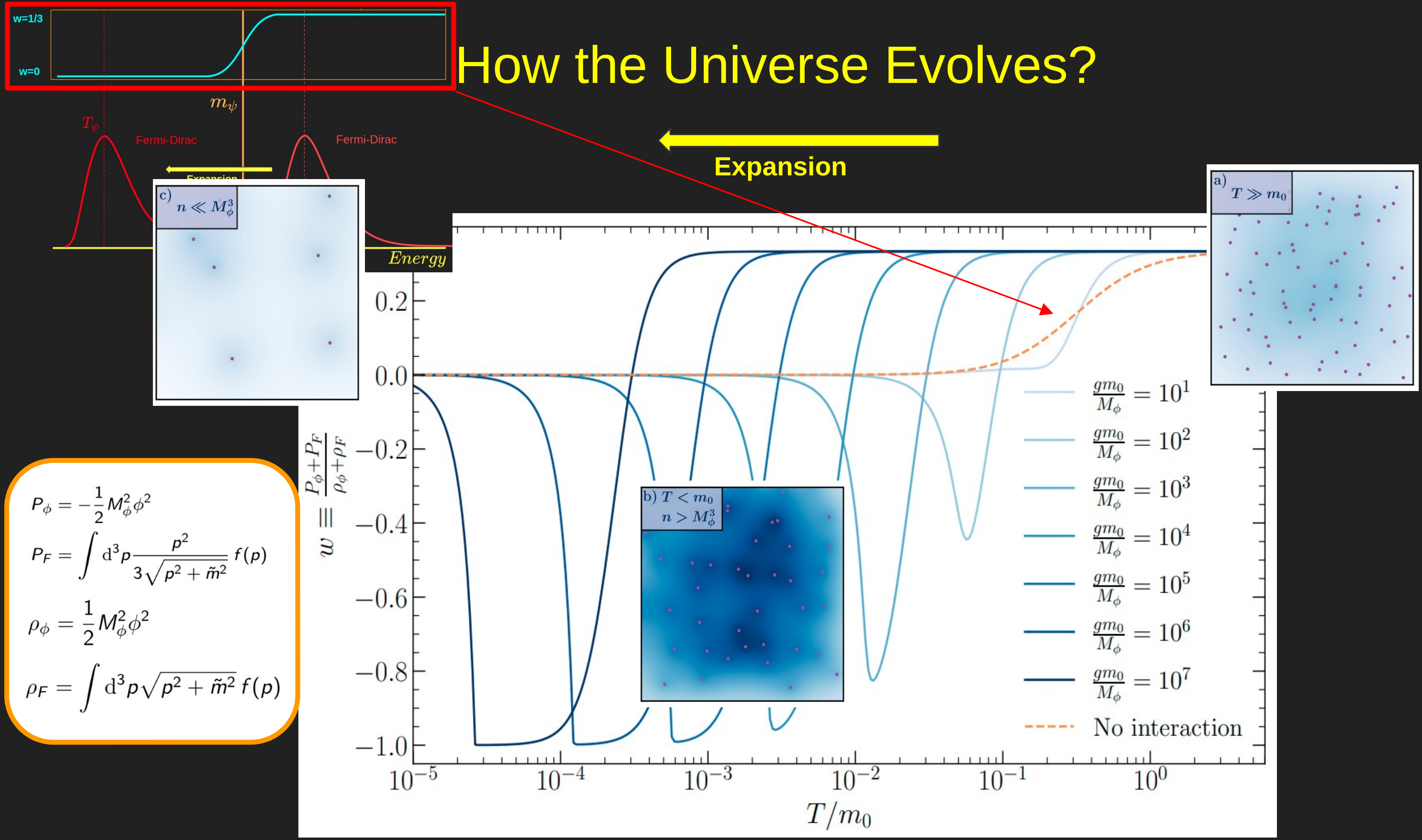

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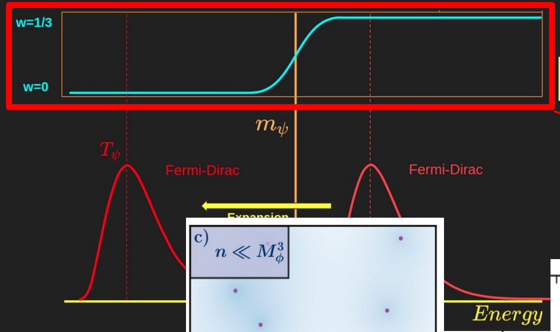

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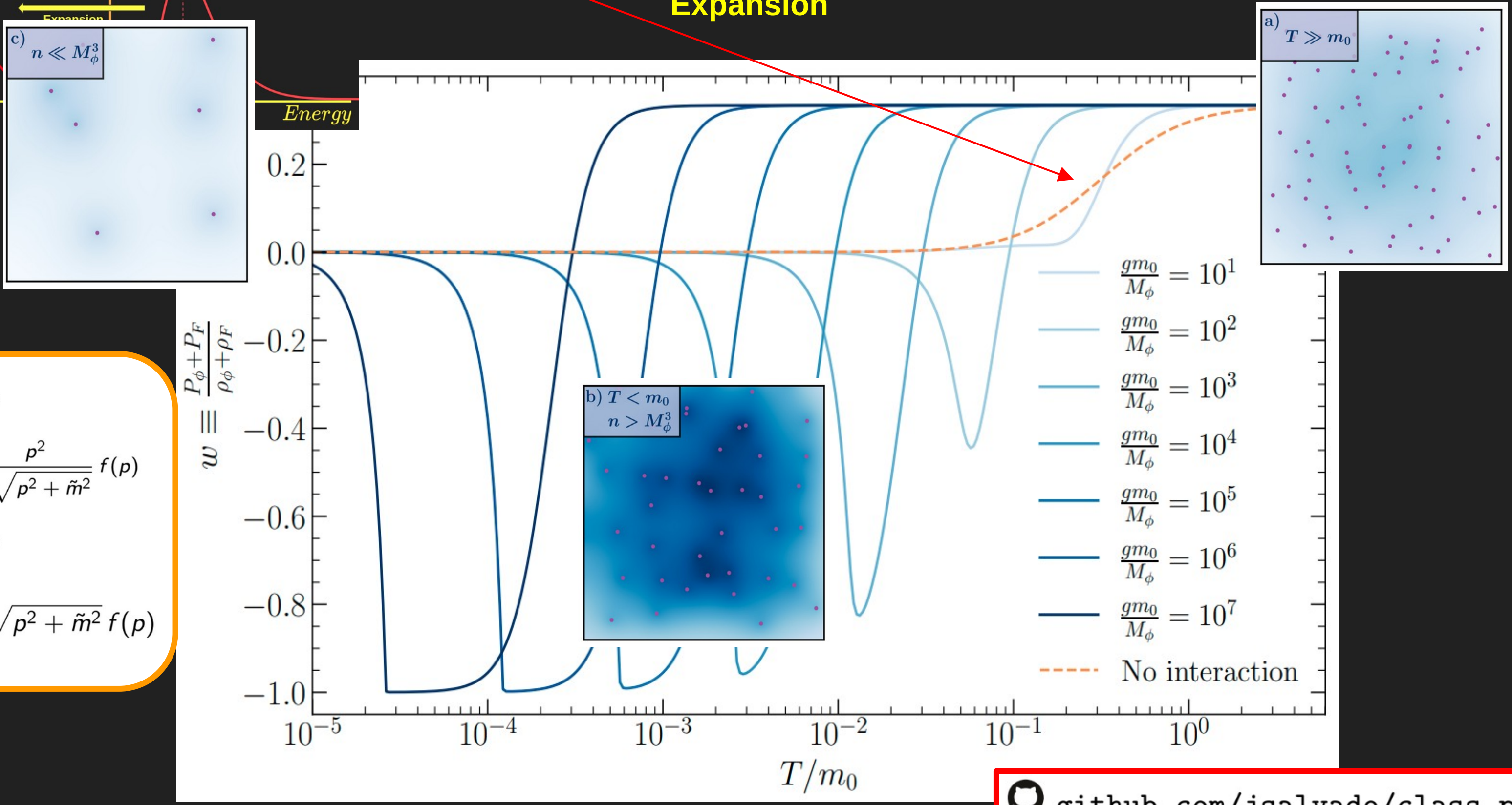

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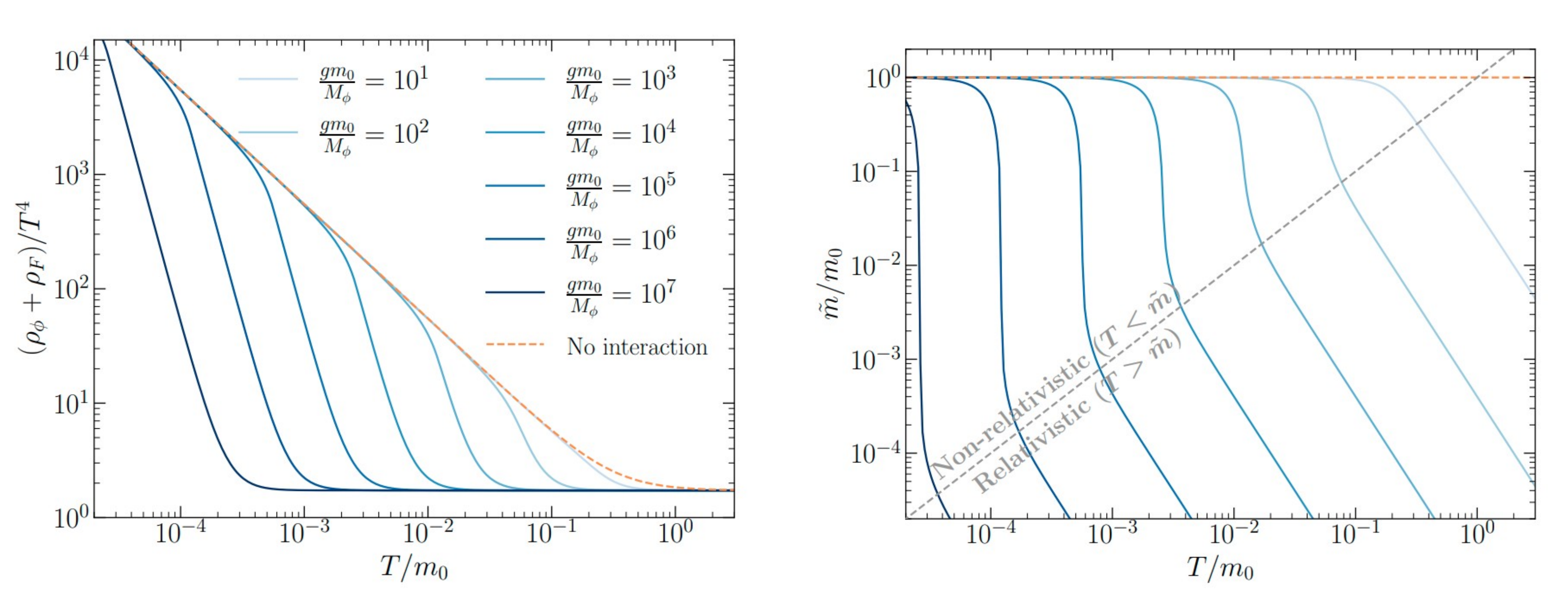
github.com/jsalvado/class_public_lrs

How the Universe Evolves?

Expansion



Energy density

$$\rho_\phi = \frac{1}{2} M_\phi^2 \phi^2 \; ; \; \rho_F = \int \mathrm{d}^3 p \sqrt{p^2 + \tilde{m}^2}\, f(p)$$

Effective neutrino mass

On the stability of Dark Energy with Mass-Varying Neutrinos

Niayesh Afshordi, Matias Zaldarriaga (Harvard), Kazunori Kohri (Harvard/Osaka)

Perturbations (instability)

$$f = f_0(q)[1 + \Psi(\vec{q}, \tau, \vec{x})]$$

$$\Psi_0' = -\frac{qk}{\varepsilon}\Psi_1 - \phi' \frac{\mathrm{d}\log f_0}{\mathrm{d}\log q},$$

$$\Psi_1' = \frac{qk}{3\varepsilon}(\Psi_0 - 2\Psi_2) - \left[\varepsilon\psi + g\delta\phi\frac{\tilde{m}}{\varepsilon}a^2\right]\frac{k}{3q}\frac{\mathrm{d}\log f_0}{\mathrm{d}\log q},$$

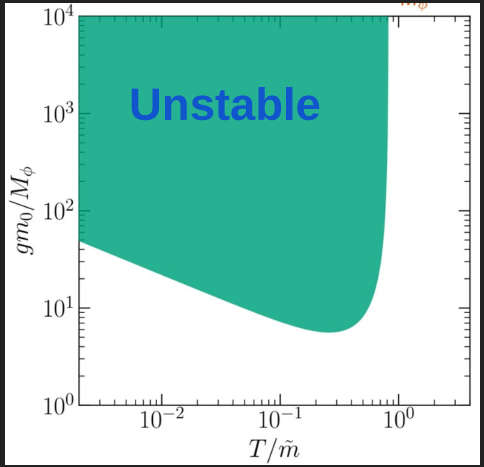
$$\Psi_\ell' = \frac{qk}{(2\ell+1)\varepsilon}[\ell\Psi_{\ell-1} - (\ell+1)\Psi_{\ell+1}] \quad \forall \ell \geq 2.$$

$$\phi = \phi_0(\tau) + \delta\phi(\vec{x}, \tau)$$

For $M_\phi \gg H$,

$$\delta\phi \simeq \frac{-g\frac{4\pi}{a^2}\int \mathrm{d}q\, q^2 \frac{\tilde{m}}{\varepsilon} f_0(q)\Psi_0(\vec{q}, \tau, \vec{k})}{(k/a)^2 + M_\phi^2 + M_T^2}$$

$$M_T^2 \equiv g^2 \int \mathrm{d}^3 p \frac{p^2}{[p^2 + \tilde{m}^2]^{3/2}} f_0(p).$$



The new interaction is much stronger than gravity.

It's unstable for most of the parameter space.

For our region of interest: Neutrinos will collapse much faster that any cosmological scale O(100yrs) and in structures much smaller than any cosmological scale O(100km-pc) (More about this objects in Alexei Yu. Smirnov, Xun-Jie Xu arXiv:2201.00939)

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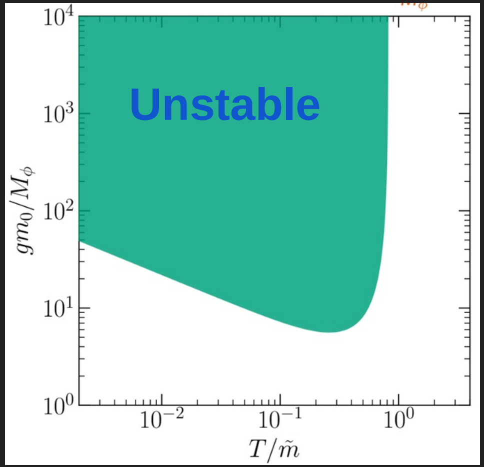
From a cosmological perspective: we can just switch to a non-relativistic "dust" made of neutrino nuggets when the instability happens.



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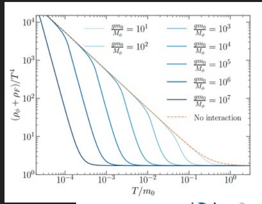
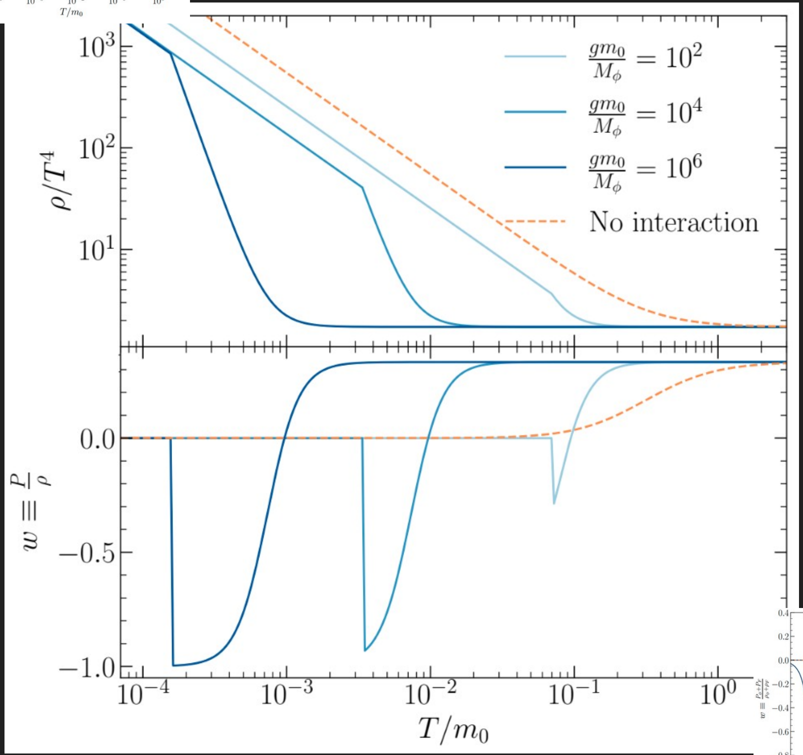
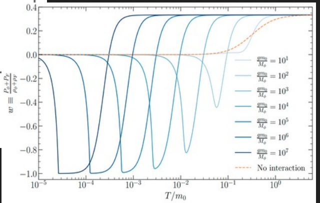


Expansion





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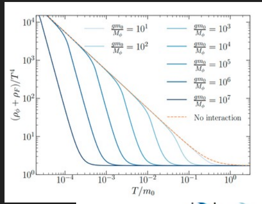

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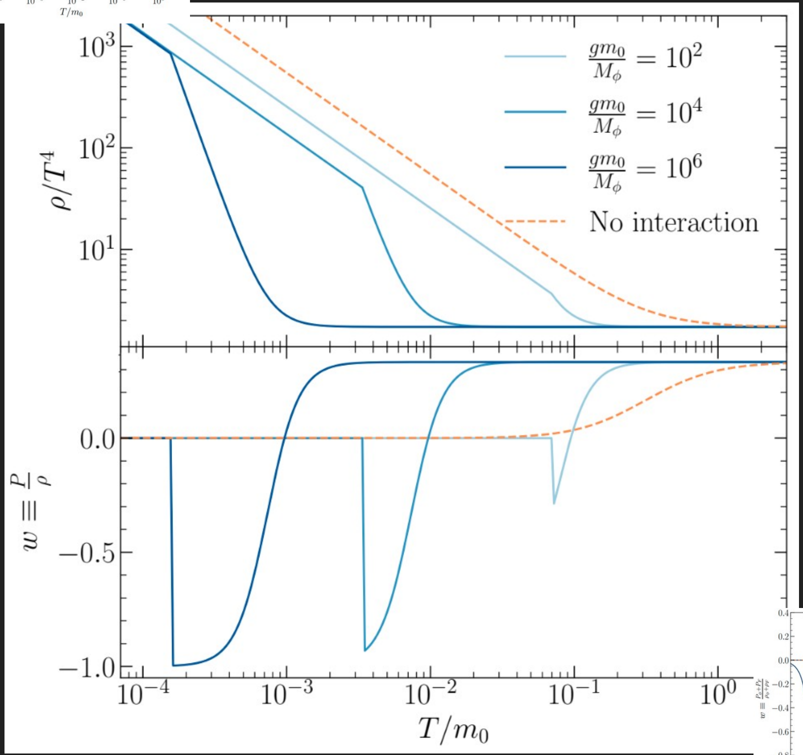

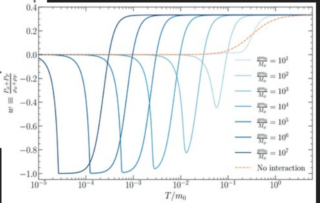

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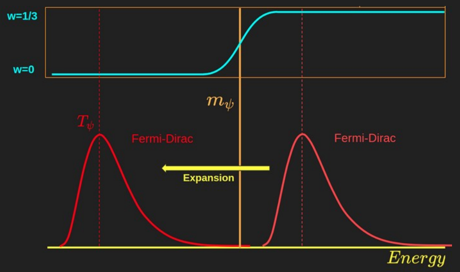
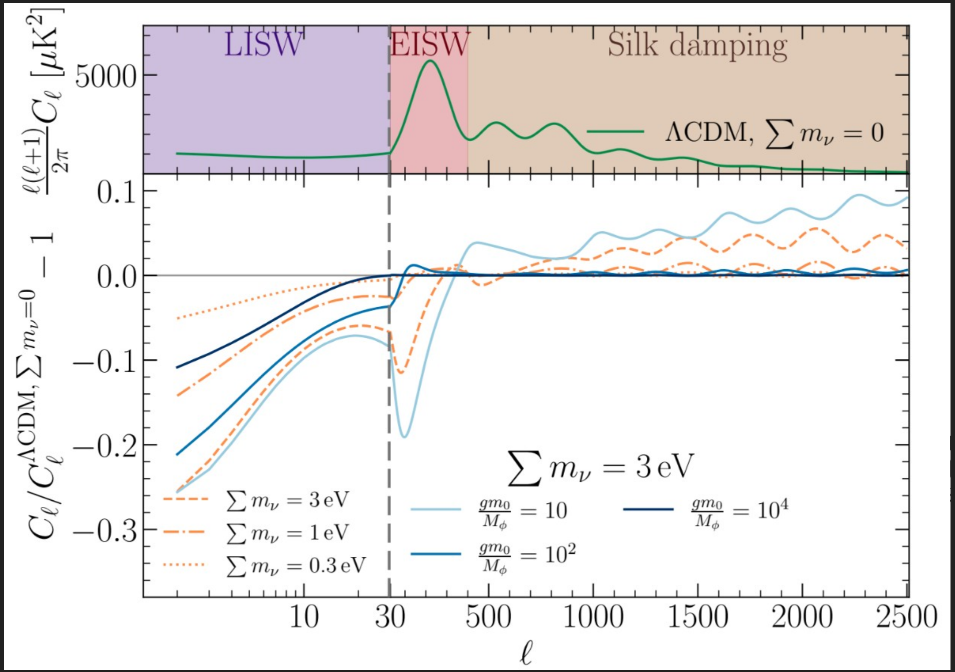
Physics implemented in:

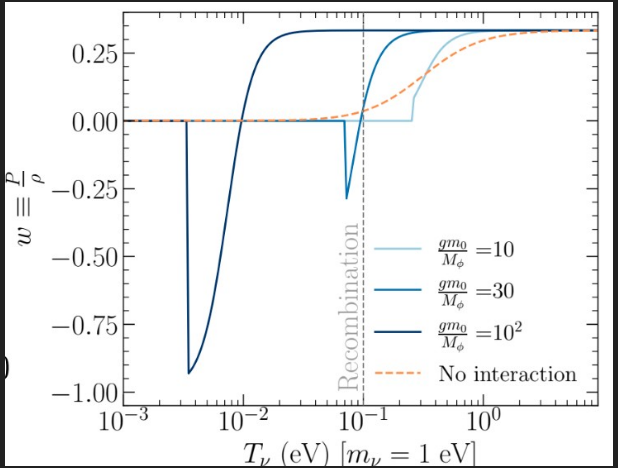
github.com/jsalvado/class_public_lrs

Impact in the CMB

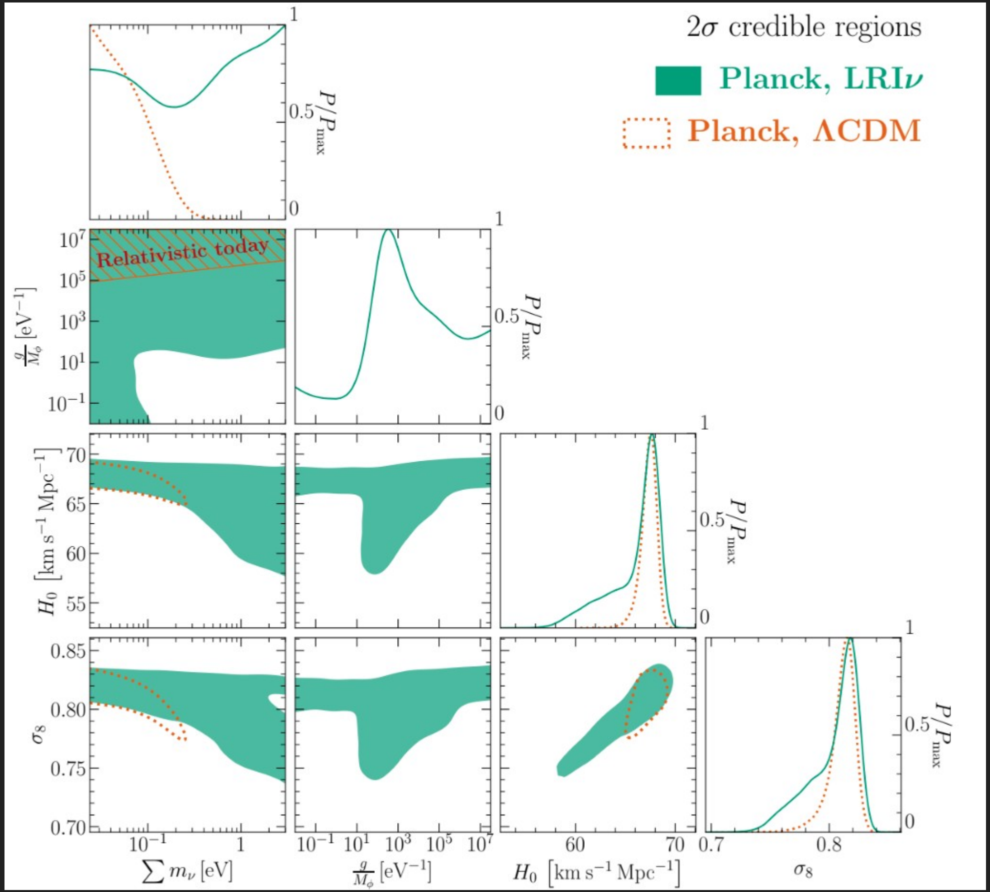


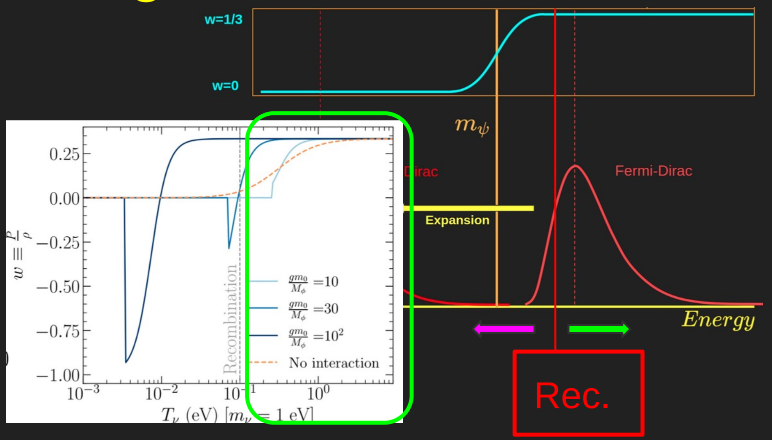
- The new physics dramatically change the equation of state, i.e. the transition to non-relativistic. This may strongly affect the CMB





What is the CMB data telling us?





$$\theta_s = \left[\int_{z_{\rm rec}}^{\infty} c_s(z)\,\frac{{\rm d}z}{H(z)}\right] \times \left[\int_0^{z_{\rm rec}} \frac{{\rm d}z}{H(z)}\right]^{-1}$$

- The CMB mass bound gets dramatically relaxed with the new weak long range physics.
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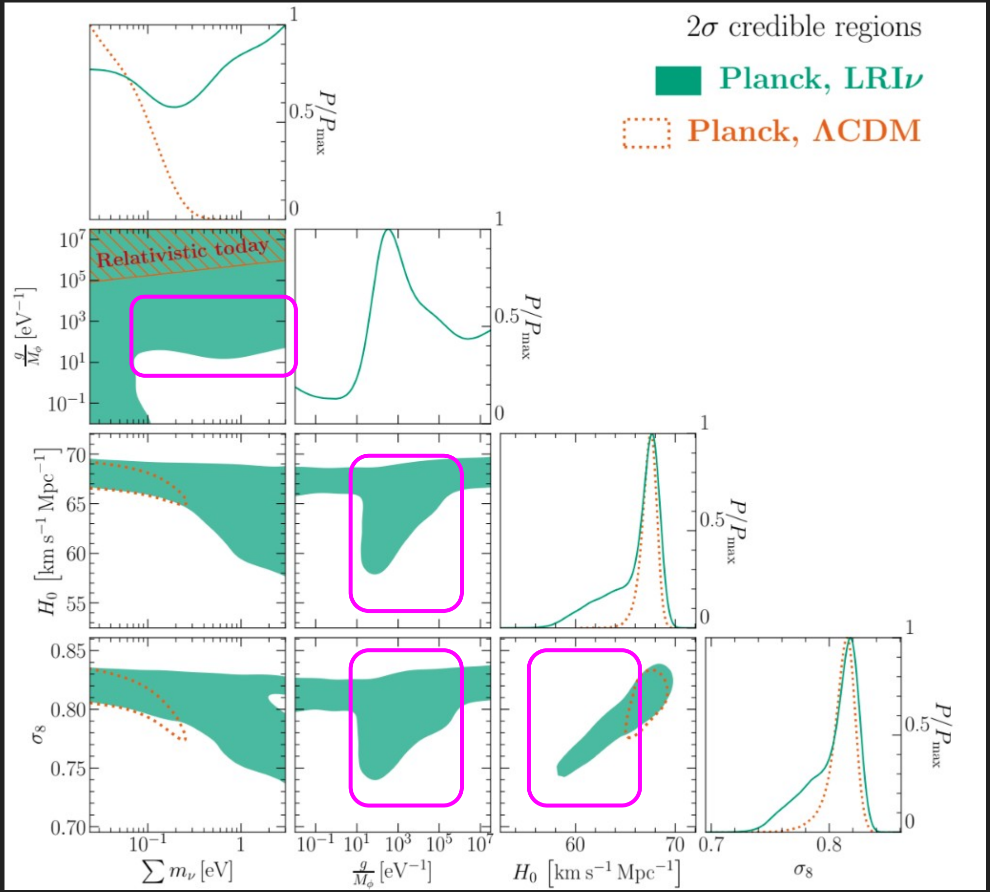

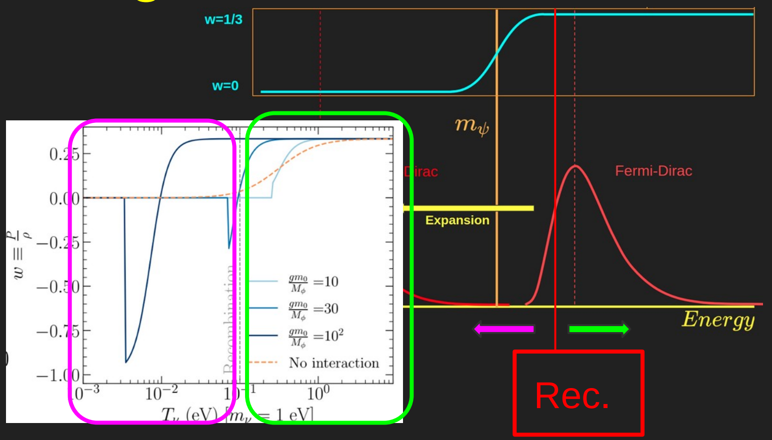

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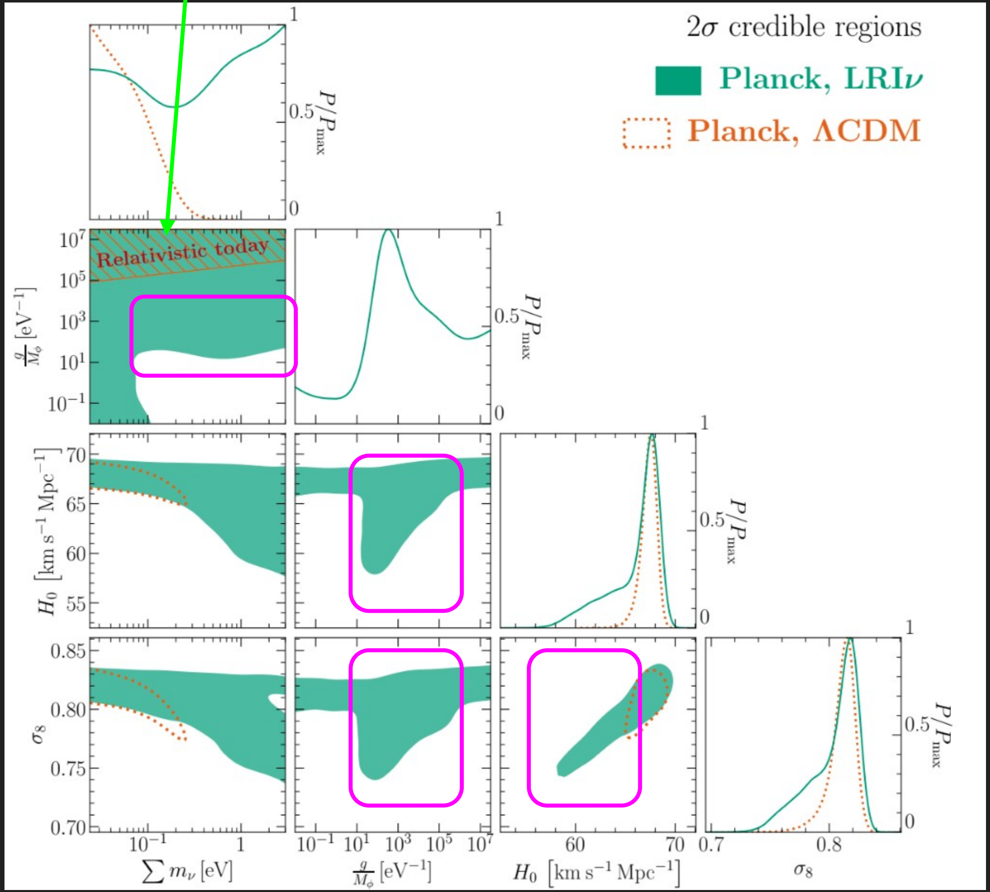

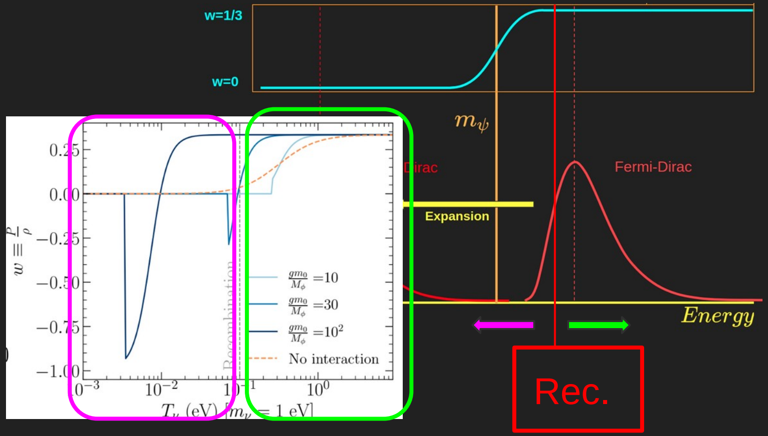

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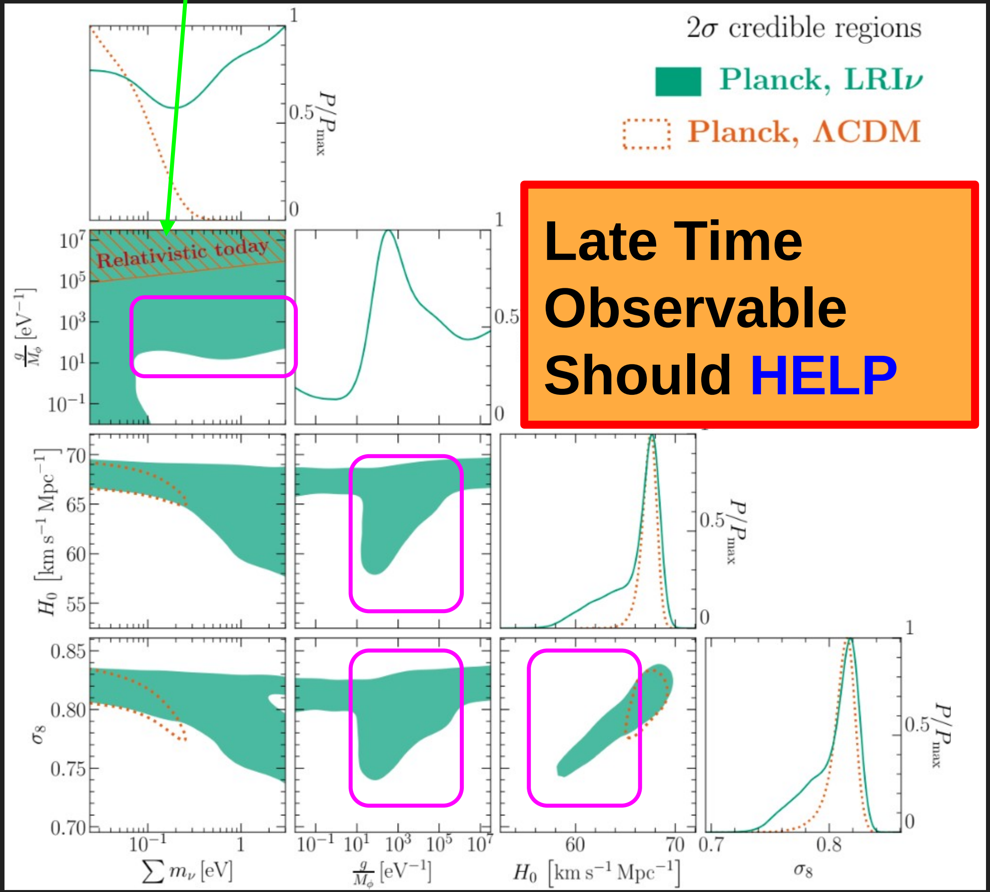
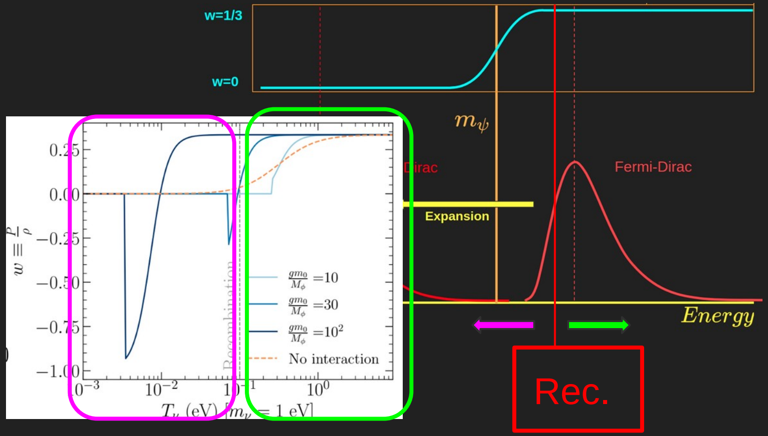


Late Time Observable Should HELP



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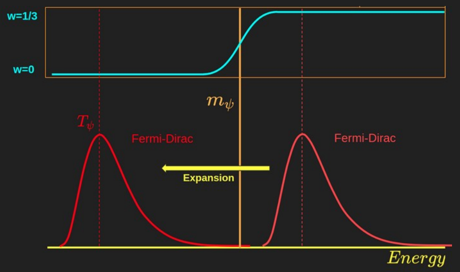
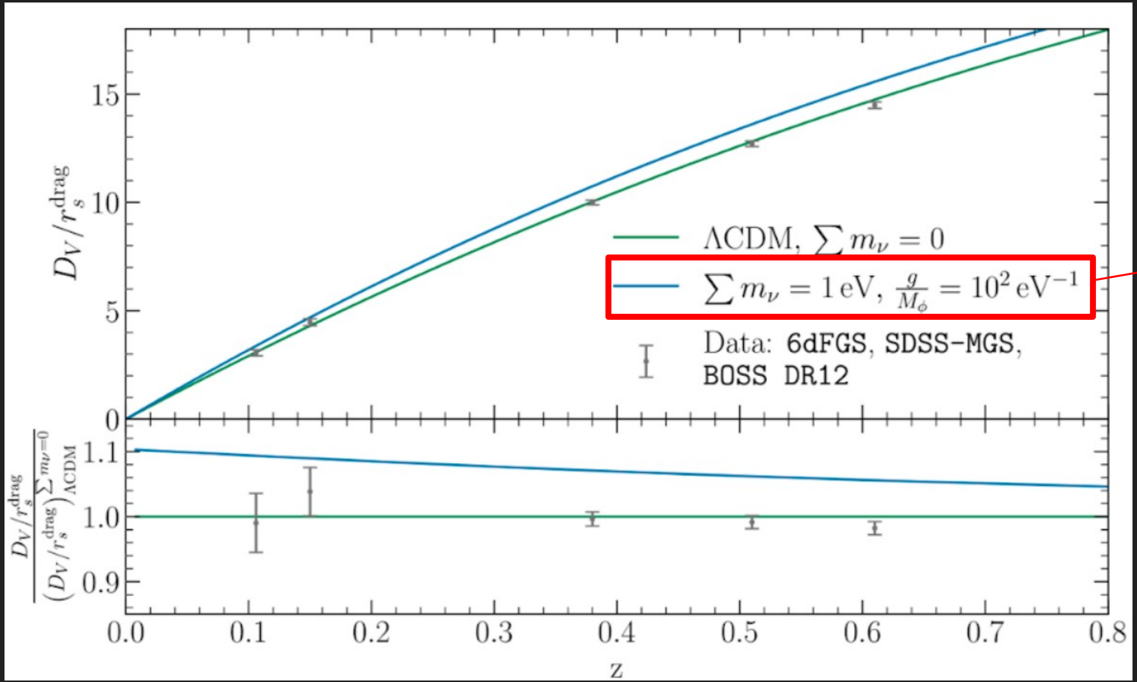
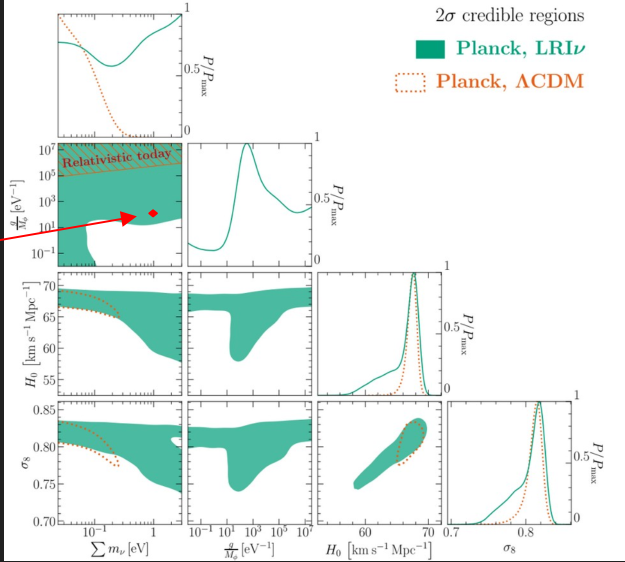
Impact on BAO



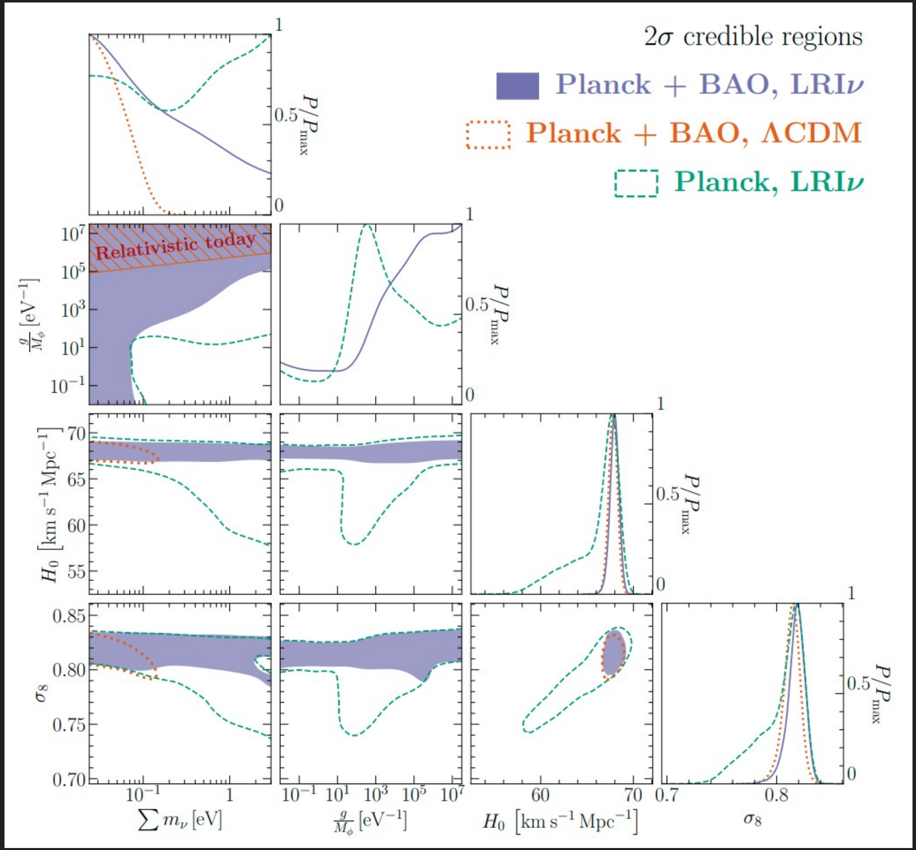
$$\frac{\int_{z_{\mathrm{drag}}}^{\infty} c_s \frac{\mathrm{d}z'}{H(z')}}{\left[\frac{z}{H(z)}\left(\int_0^z \frac{\mathrm{d}z'}{H(z')}\right)^2\right]^{1/3}}$$

- BAO data may exclude part of the allowed region.





What is the current data telling us?

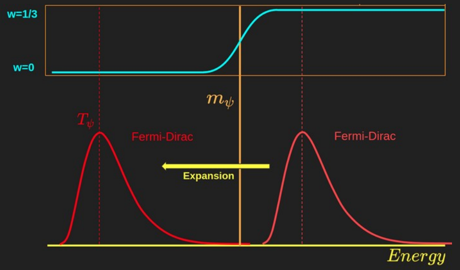


- BAO data plays an important role.
- But the new long range weakly coupled physics still relaxes drastically the cosmological mass bound.

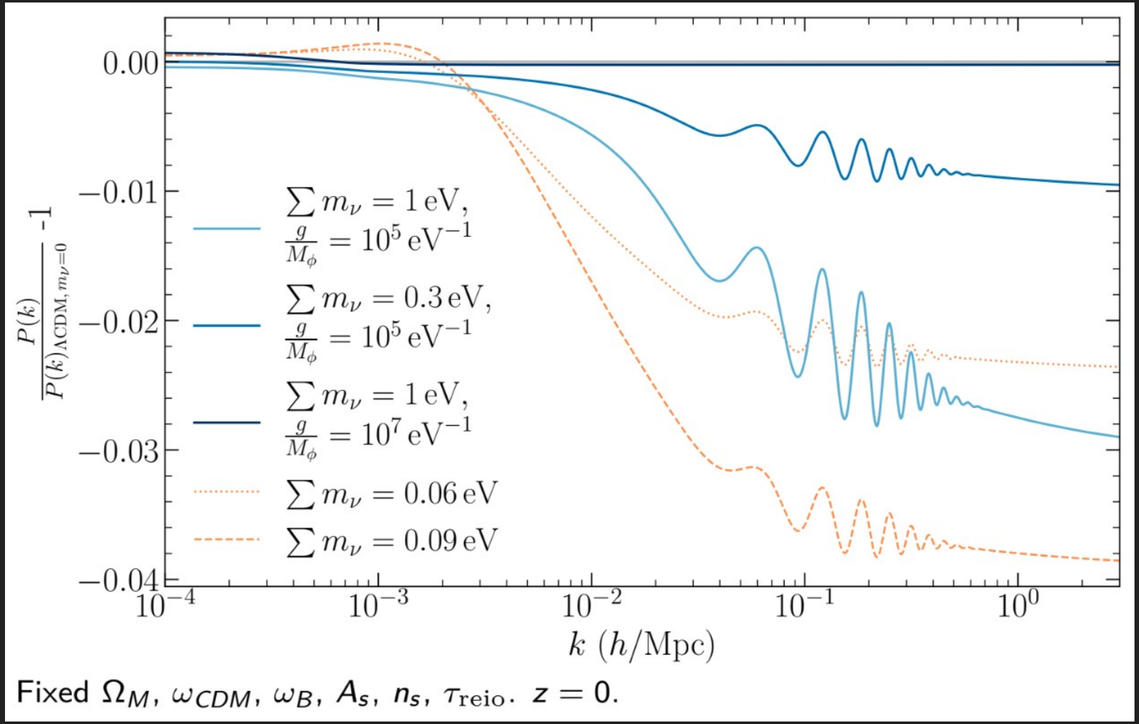
Complementarity with other experiments:

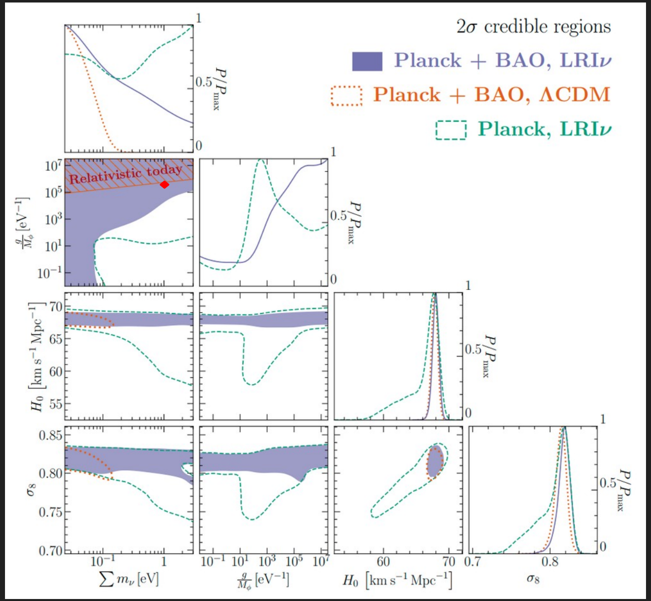
- Neutrino oscillations may already tell something about a part of the parameter space.
- A positive result by KATRIN may still point to new physics.

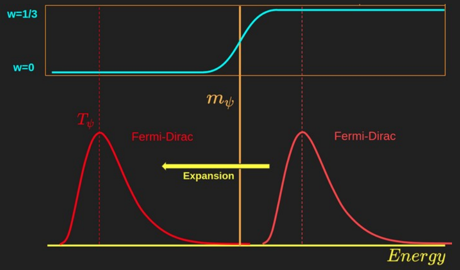
Full Power Spectrum by EUCLID



- Potential future sensitivity of 0.06eV







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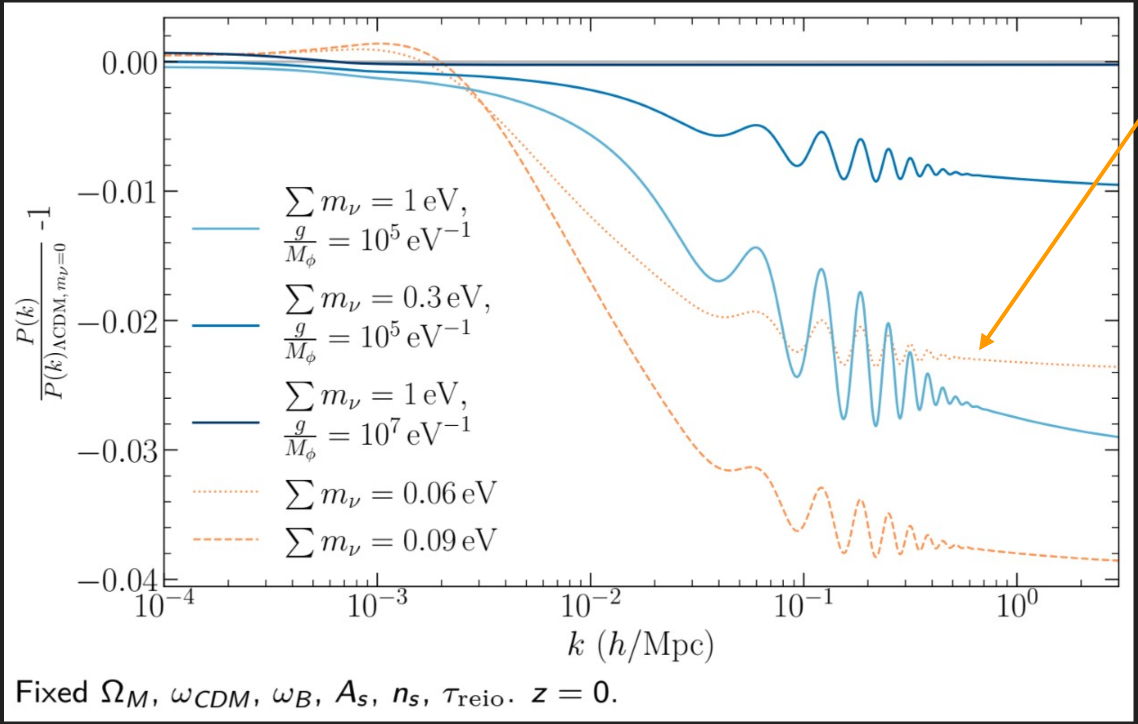

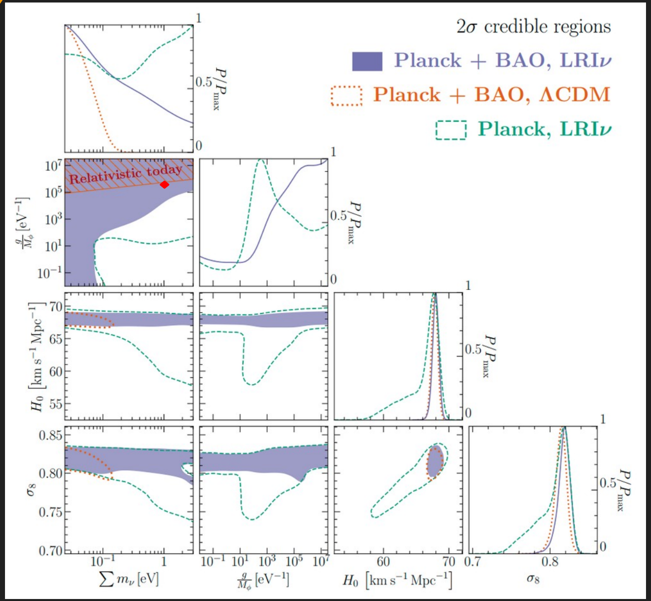

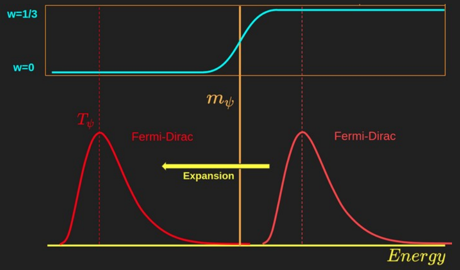

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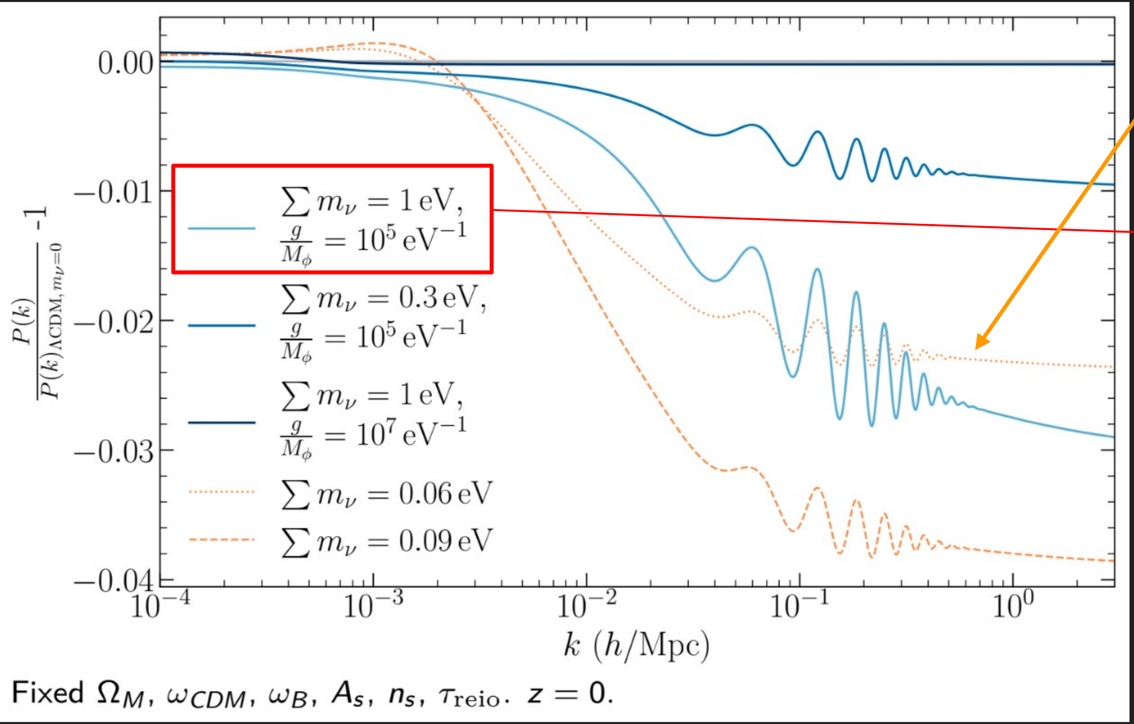

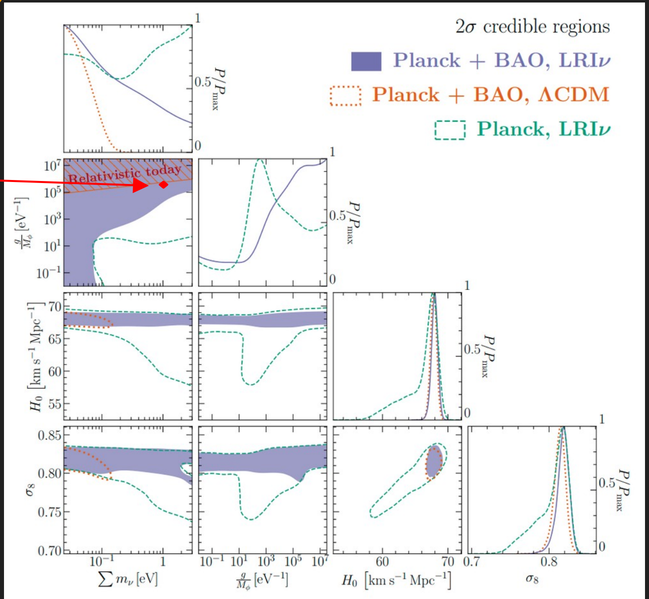

Full Power Spectrum by EUCLID

Next we will see to possible future outcomes for EUCLID result on neutrino masses

We create mock data consistent with:

Full Power Spectrum by EUCLID

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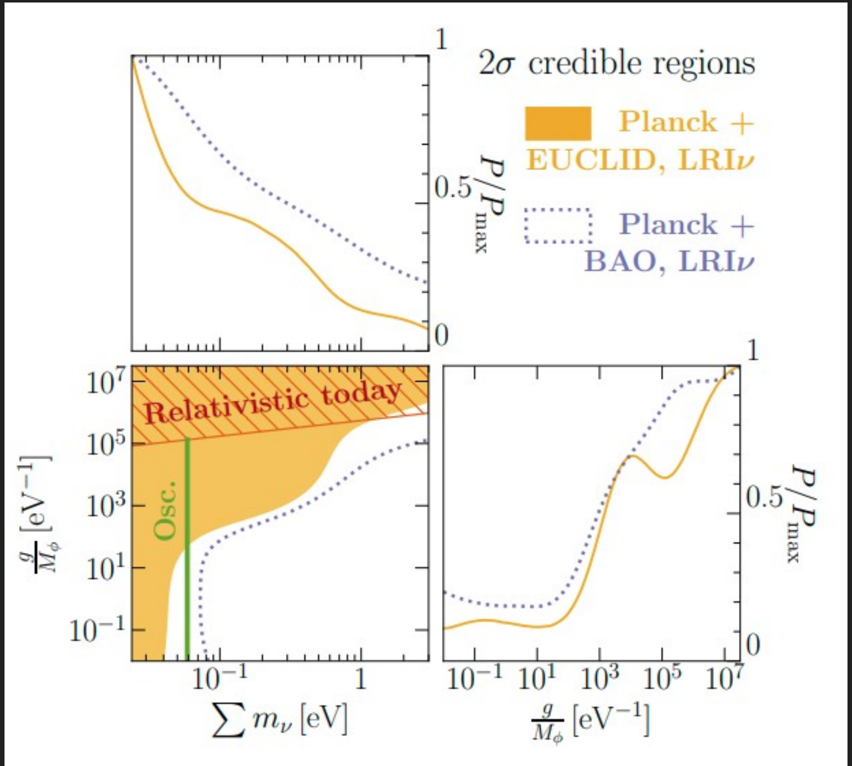
Apparent contradiction between cosmology and experiments



(a) $\sum m_\nu^{\rm true} = 0.024\,{\rm eV}$

Complementarity with experiments:

- EUCLID may exclude the minimum mass allowed by oscillation physics.

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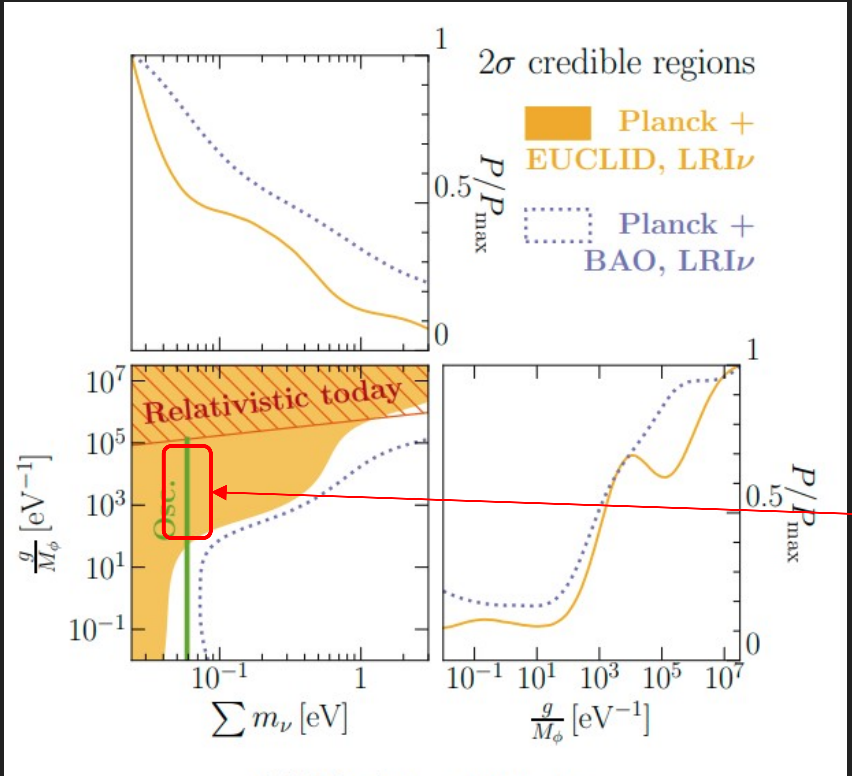

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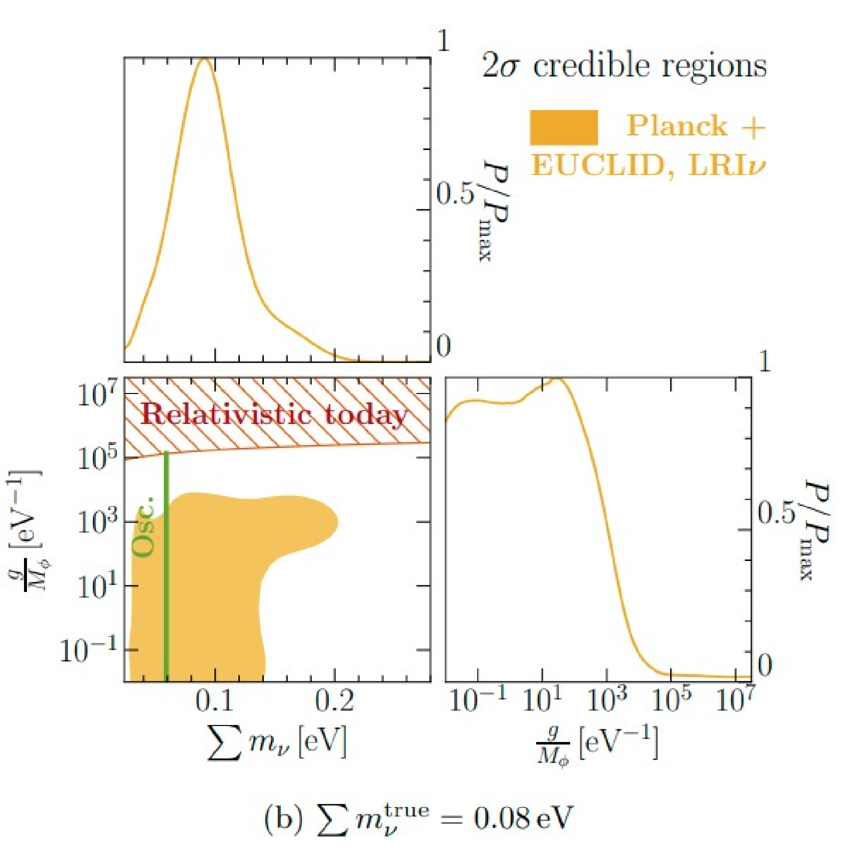
Hint for new physics

The future is even better? (“expected” result by Euclid)



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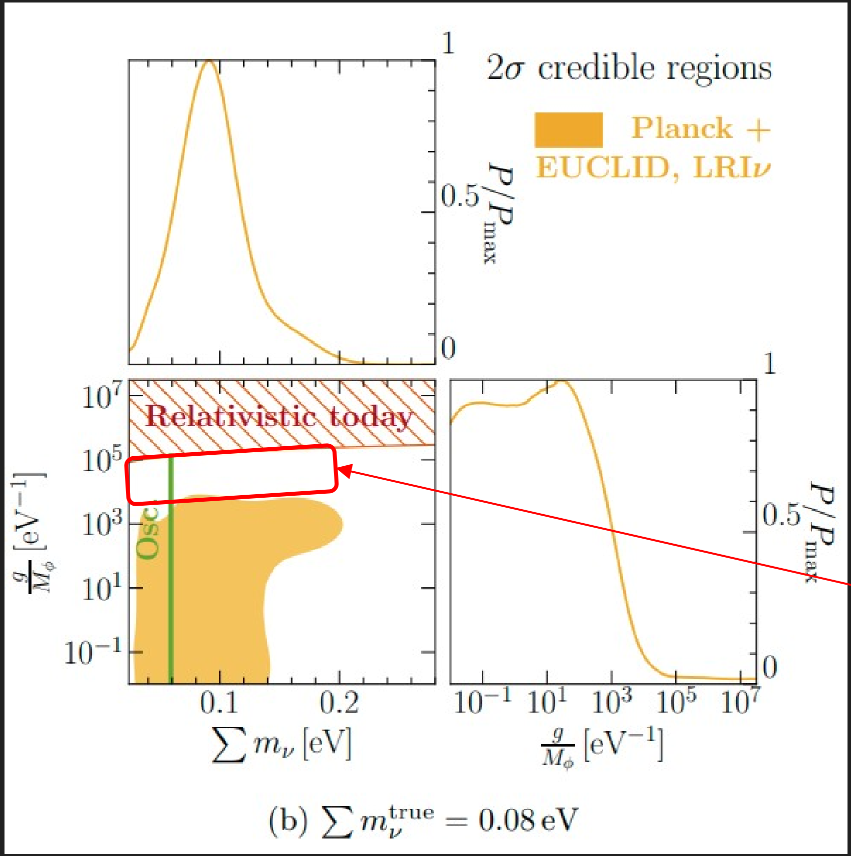


Complementarity with experiments:

- EUCLID may explore part of an still unexplored parameter space.

We may exclude part of the new-physics parameter space.

May be some current anomalies are already hints

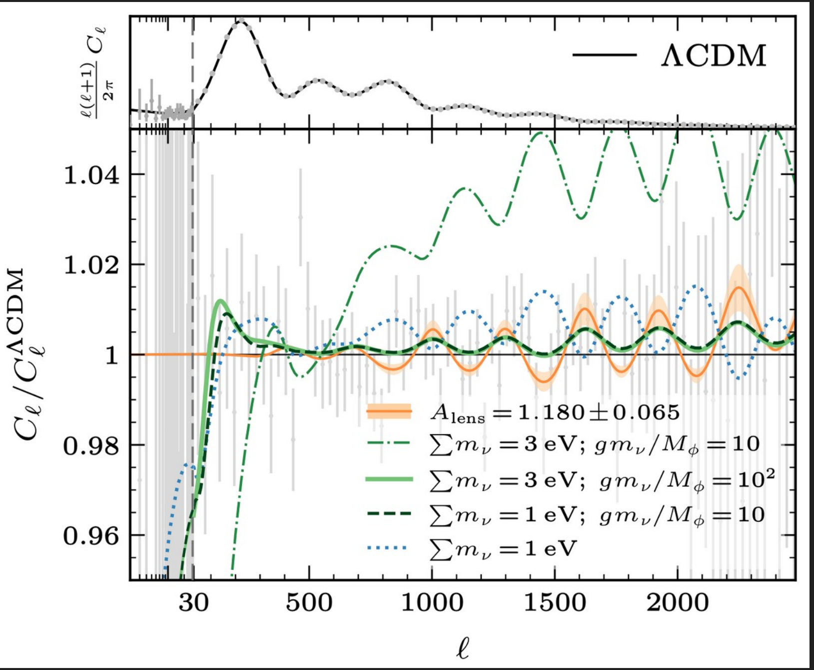
- Hubble anomaly: Statistically significant but it involves very different measurements **(Scalar long range don't help)**
- **The lensing anomaly** is the only one that comes from a single experimental setup. Seams to be robust under changes of foregrounds and statistical techniques.

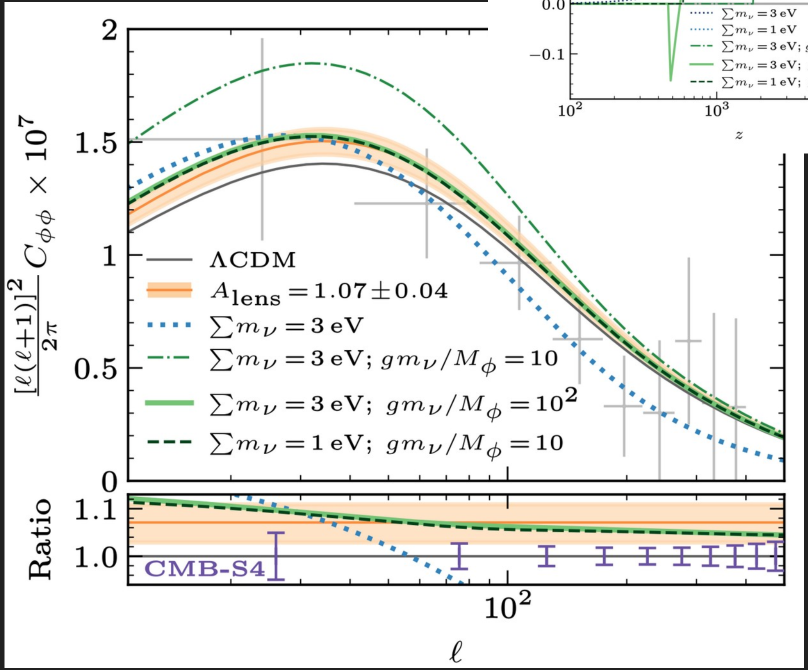
What is it?

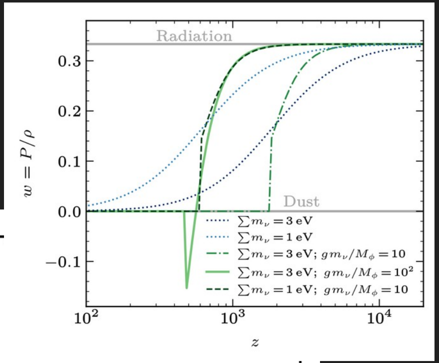
- The fit to the planck data predicts a lensing effect due to the CMB traveling along the large scale structures of the universe ***(A_len = 1)***
- But the measurements by planck seam to be inconsistent: A_len deviates to larger values at about 2-sigma.

May be some current anomalies are already hints

With Ivan Esteban and Olga Mena
arXiv:2202.04656

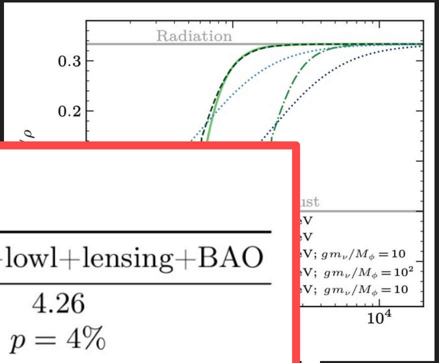






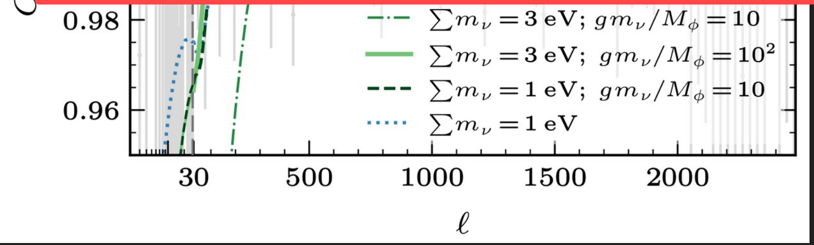
May be some current anomalies are already hints

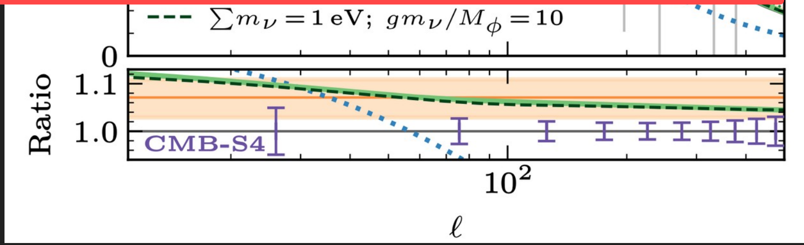
With Ivan Esteban and Olga Mena
arXiv:2202.04656



$$\Delta\chi^2_{\rm eff} = \chi^2_{\rm eff}(A_{\rm lens}=1) - \chi^2_{\rm eff}(A_{\rm lens}\neq 1)$$

	TTTEEE+lowl	TTTEEE+lowl+lensing	TTTEEE+lowl+lensing+BAO
Plik (reference): ΛCDM	9.66 $p = 0.2\%$	3.43 $p = 6\%$	4.26 $p = 4\%$
Plik (reference): Self-interactions	4.87 $p = 3\%$	0.76 $p = 38\%$	2.71 $p = 10\%$
CamSpec (alternative): ΛCDM	4.82 $p = 3\%$	2.01 $p = 16\%$	1.96 $p = 16\%$
CamSpec (alternative): Self-interactions	2.06 $p = 15\%$	1.39 $p = 24\%$	1.79 $p = 18\%$





Conclusions

- Neutrinos are pretty exotic particles with an still unknown mass mechanism. Study them is very well motivated
- With neutrinos we can test 5th long range forces with the three families *(a la Newton)*
- Cosmology is great to test particle physics properties, with the potential to study an still unexplored parameter space. The effects are very relevant for weak long range new physics (hard for experiments)
- The interplay between new physics and neutrino masses in cosmology is phenomenologically very rich and it reveals the importance of both: Cosmology and Particle Physics Experiments to get the whole picture

Keep and eye and don't disregard anomalies

Thanks!