

Title: Cosmological and Astrophysical Probes of Sterile Neutrinos - Nashwan Sabti, King's College London

Speakers:

Series: Particle Physics

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Abstract: Sterile neutrinos have been proposed to tackle a number of outstanding questions in physics, including the phenomena of dark matter, neutrino masses and the baryon asymmetry of the Universe. I will review current limits on GeV-, MeV- and keV-scale sterile neutrinos from cosmology and astrophysics. In particular, I will focus on how primordial abundance determinations, Cosmic Microwave Background observations and stellar kinematic inferences from dwarf spheroidal galaxies allow us to set robust constraints across this mass scale. I will then end with a short discussion on how sterile neutrinos could relax cosmological bounds on neutrino masses and what implications this would have for experiments like KATRIN.

Cosmological and Astrophysical Bounds on Sterile Neutrinos

Nashwan Sabti

Perimeter Institute – 19/11/2021



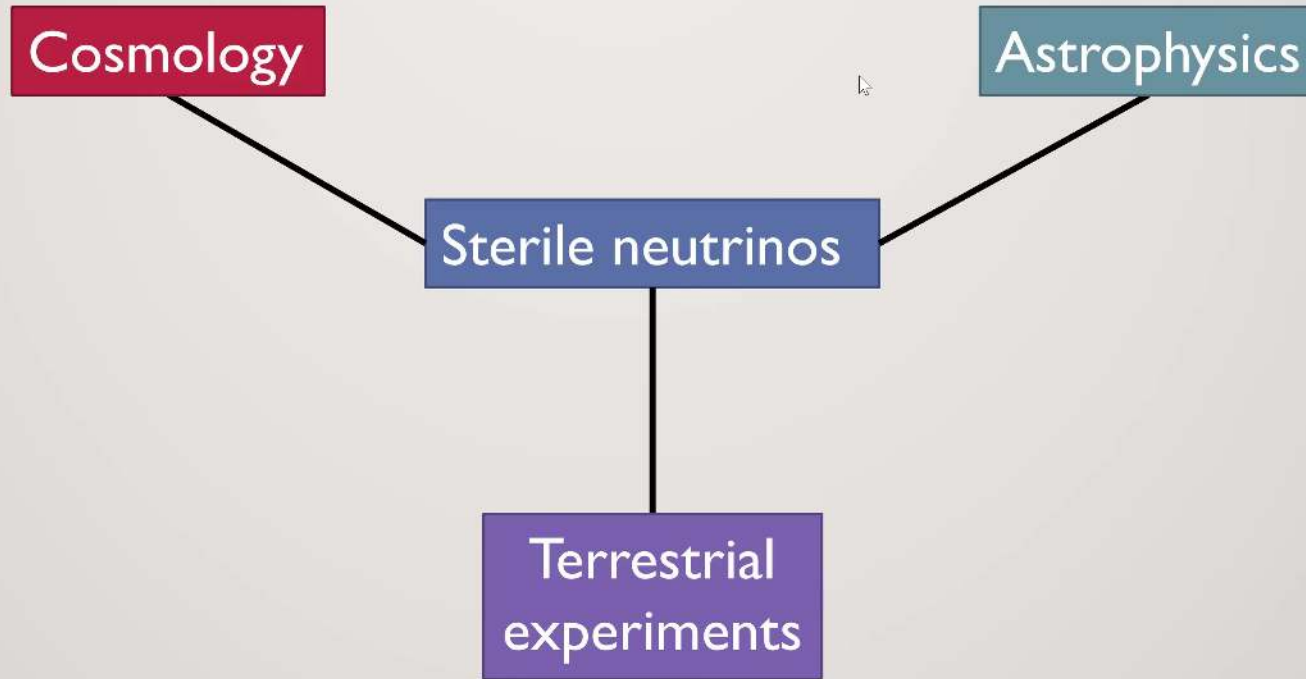
I-SLIDE SUMMARY OF STERILE NEUTRINOS

- Dark matter, neutrino masses, baryon asymmetry all require new physics
- Sterile neutrinos can accommodate for all three phenomena
- Neutrino portal:

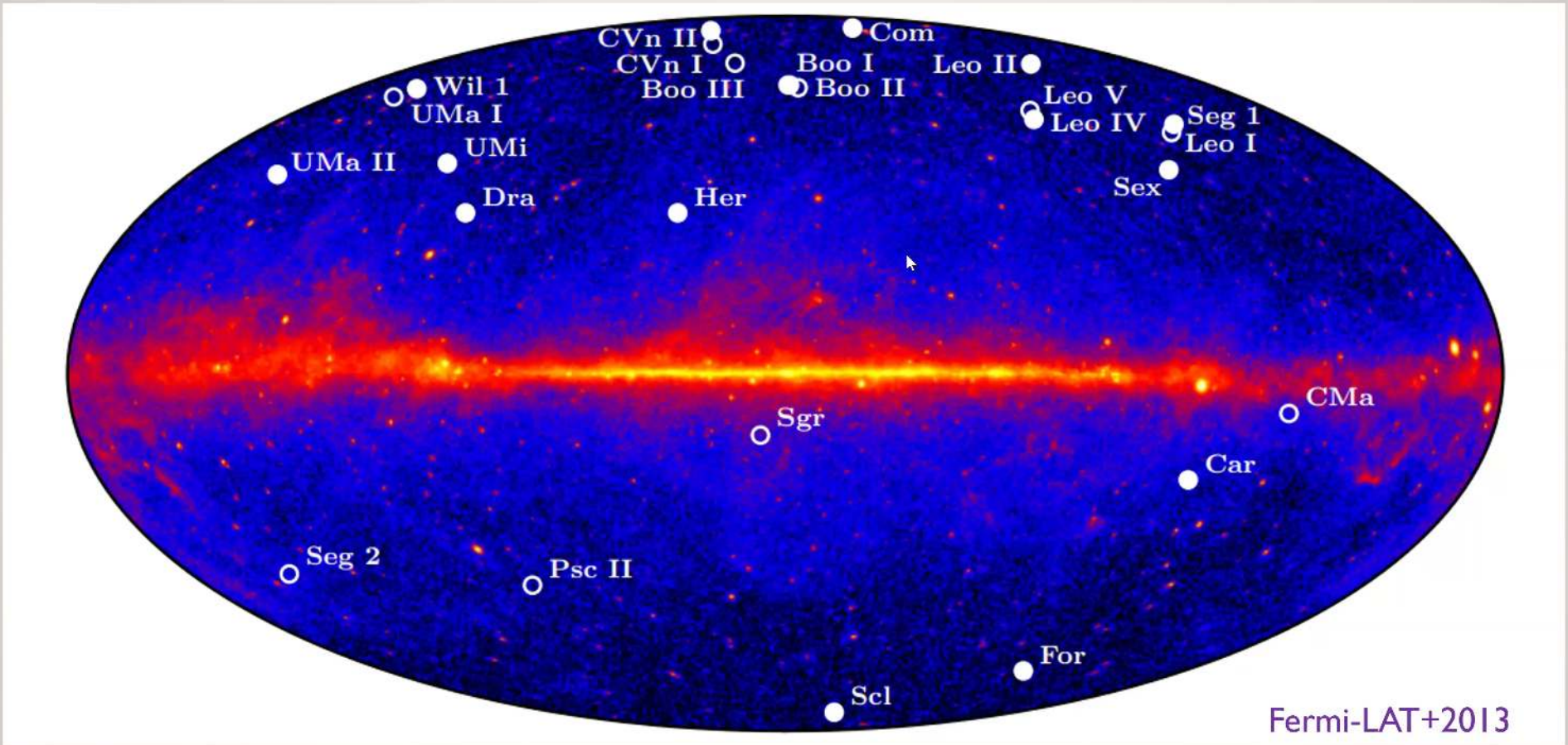
$$L_{\text{neutrino-portal}} = F_{\alpha} (\overline{L_{\alpha}} \tilde{H}) N + h.c.$$

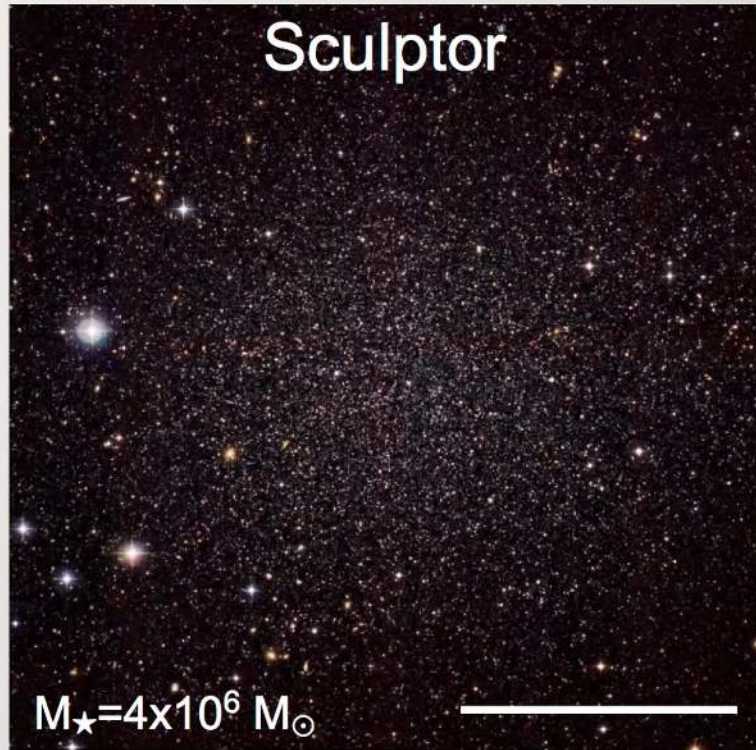
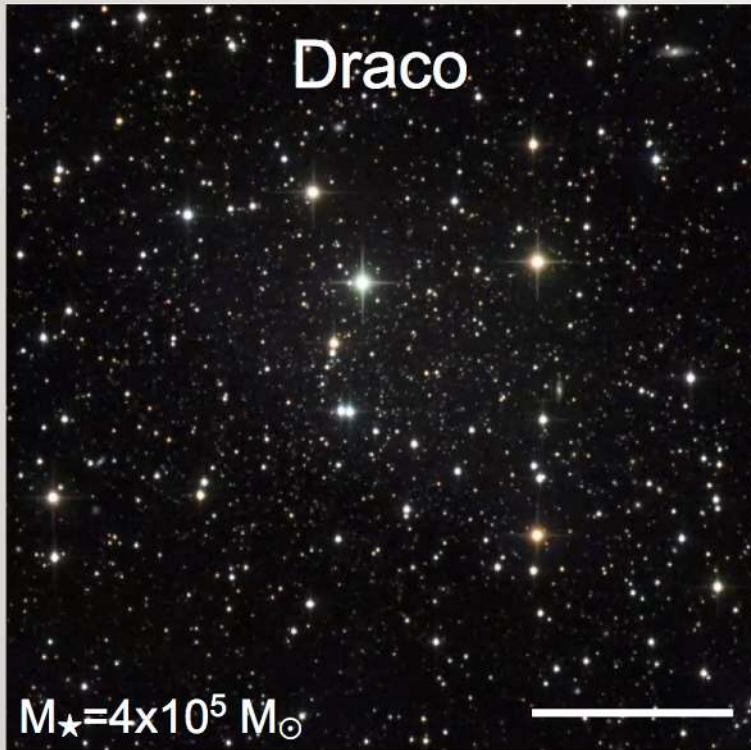
- Causes mixing between active neutrinos and sterile neutrinos
- Induces neutrino-like interactions for sterile neutrinos, suppressed by small mixing angles

$$\Gamma_{\text{sterile neutrino}} \sim \theta^2 \Gamma_{\text{active neutrino}}$$



Milky Way Dwarf Spheroidal Galaxies





Bullock+2017



Dwarf spheroidal galaxies are DM dominated



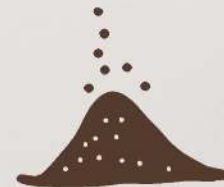
Measure DM density and velocity dispersion



Compute coarse-grained phase-space density



Assume a (class of) particle physics model(s)



Compute fine-grained phase-space density

OBSERVING THE DM DENSITY AND VELOCITY DISPERSION

- To compute PS density, we need: *i)* DM density profile and *ii)* velocity dispersion profile
- Simplest approach: assume e.g. isothermal profile

$$\rho_{\text{DM}}(r \ll r_c) \approx \rho_0(r_c, \sigma_{\text{DM}})$$

and $\sigma_{\text{DM}} \approx \sigma_{\text{star}}$

- $m_\nu \gtrsim 0.1 \text{ keV}$



Dwarf spheroidal galaxies are DM dominated



Measure DM density and velocity dispersion



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OBSERVING THE DM DENSITY AND VELOCITY DISPERSION

- Jeans equation:

$$\frac{1}{v} \frac{\partial}{\partial r} (v \sigma_r^2) + 2 \frac{\beta(r) \sigma_r^2}{r} = - \frac{GM(r)}{r^2}, \quad \beta = 1 - \frac{\sigma_t^2}{\sigma_r^2}$$

- Observe line-of-sight velocity and projected tracer density:

$$\sigma_{\text{LOS}}^2(R) = \frac{2}{\Sigma(R)} \int_R^\infty \left(1 - \beta \frac{R^2}{r^2} \right) v \sigma_r^2 \frac{r dr}{\sqrt{r^2 - R^2}}$$

OBSERVING THE DM DENSITY AND VELOCITY DISPERSION

- Introduce virial shape parameters:

$$\text{VSP1} = \int_0^{\infty} \Sigma \langle v_{\text{LOS}}^4 \rangle R dR = \frac{2}{5} \int_0^{\infty} v(5 - 2\beta) \sigma_r^2 G M R dR$$

$$\text{VSP2} = \int_0^{\infty} \Sigma \langle v_{\text{LOS}}^4 \rangle R^3 dR = \frac{4}{35} \int_0^{\infty} v(7 - 6\beta) \sigma_r^2 G M R^3 dR$$

Merrifield & Kent 1990

- GravSphere [Read+2017](#)

OBSERVING THE DM DENSITY AND VELOCITY DISPERSION

- Solve 2nd Jeans equation for DM:

$$\frac{1}{v_{\text{DM}}} \frac{\partial}{\partial r} (v_{\text{DM}} (\sigma_r^{\text{DM}})^2) + 2 \frac{\beta_{\text{DM}}(r) (\sigma_r^{\text{DM}})^2}{r} = - \frac{GM(r)}{r^2}$$

OBTAINING PHASE-SPACE CONSTRAINTS

- Bounds from Pauli's principle – model independent

$$\text{Fermi velocity: } v_F = \left(\frac{6\pi^2 \rho(r)}{gm^4} \right)^{1/3}$$

$$v_F < v_{\text{esc}} \rightarrow m_{\text{deg}} > \left(\frac{6\pi^2 \rho(r)}{gv_{\text{esc}}^3(r)} \right)^{\frac{1}{4}} \Bigg|_{r_{\text{min}}} = 0.27^{+0.30}_{-0.14} \text{ keV } (2\sigma)$$

OBTAINING PHASE-SPACE CONSTRAINTS

- Bounds from Liouville's theorem – model dependent

$$F_{\text{coarse}}^{\text{late}} \leq F_{\text{fine}}^{\text{late}} \leq F_{\text{fine}}^{\text{primordial}} = m^4 f_{\text{max}}$$

Averaging Liouville's th.

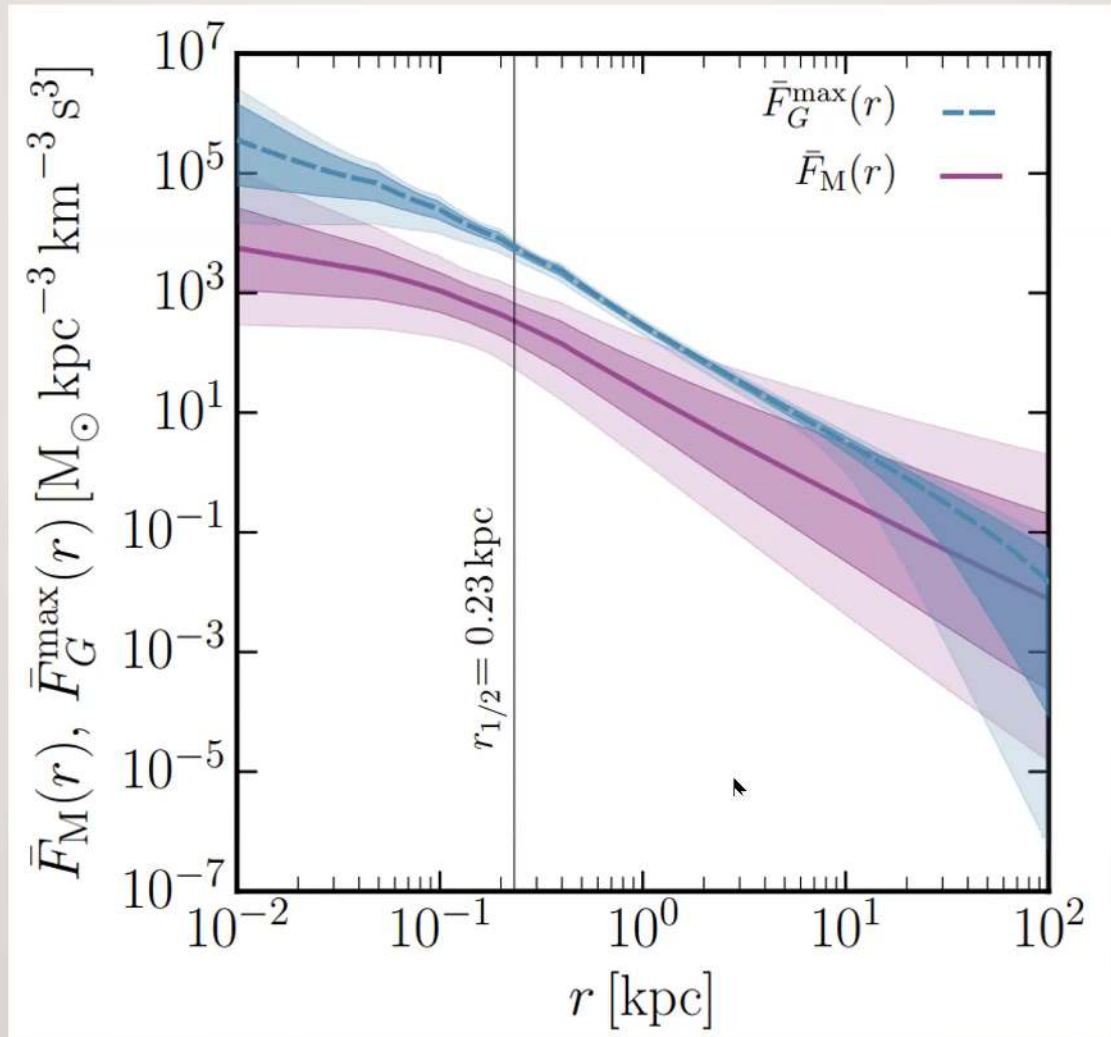
OBTAINING PHASE-SPACE CONSTRAINTS

- Maximal coarse-graining:

$$\overline{F}_M(r) = \frac{\rho(r)}{\frac{4\pi}{3} v_{\text{esc}}^3(r)} \leq m^4 f_{\text{max}}$$

- Gaussian coarse-graining:

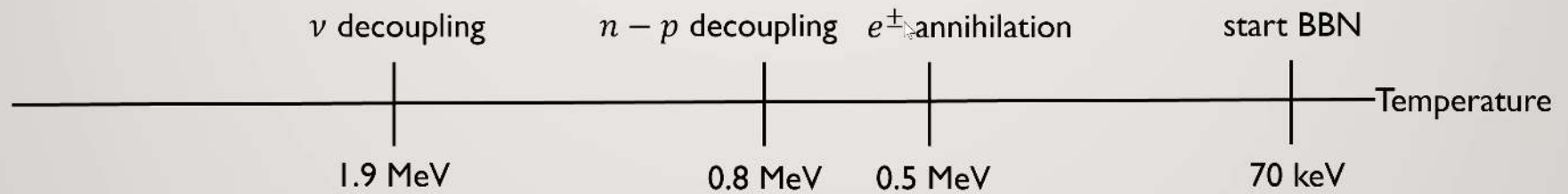
$$\overline{F}_G(r) = \frac{\rho(r)}{(2\pi)^{3/2} \sigma_r \sigma_t^2} \leq m^4 f_{\text{max}}$$



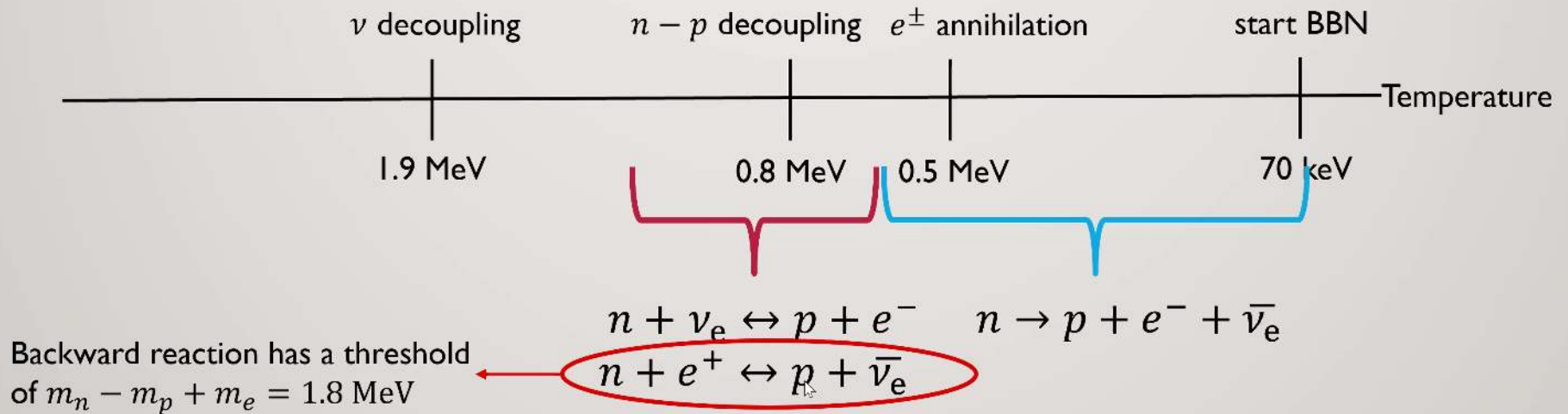
SUMMARY

- Improved Jeans analysis allows to probe the DM density profile in dwarf spheroidal galaxies at small radii
- Phase-space density is higher in the inner regions and allows for stronger limits
- This method provides robust lower bounds on fermionic dark matter

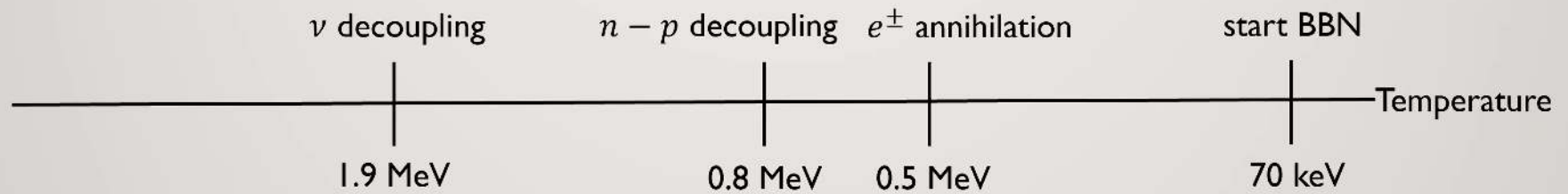
Timeline of relevant events in the early Universe



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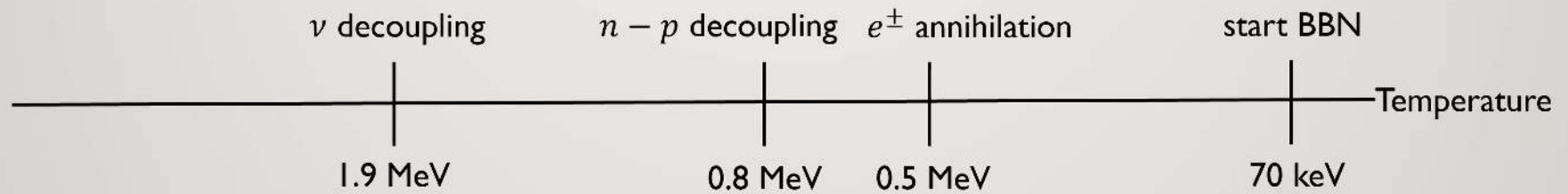
$$N_{\text{eff}}^{\text{SM}} = 3.044$$

$$N_{\text{eff}}^{\text{Planck+BAO}} = 2.99 \pm 0.17$$

$$Y_{\text{p}}^{\text{SM}} = 0.24709$$

$$Y_{\text{p}}^{\text{PDG}} = 0.245 \pm 0.003$$

Timeline of relevant events in the early Universe



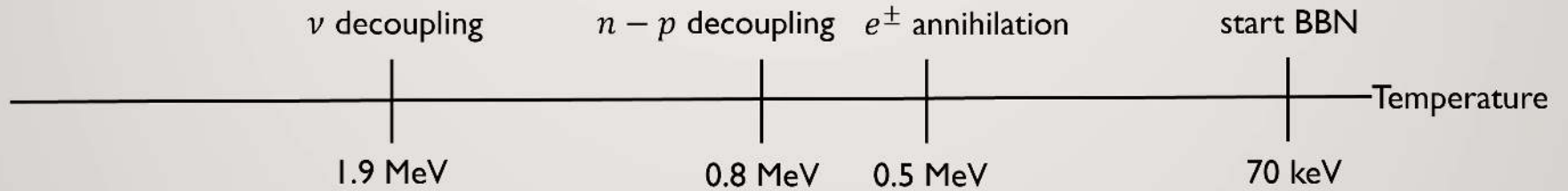
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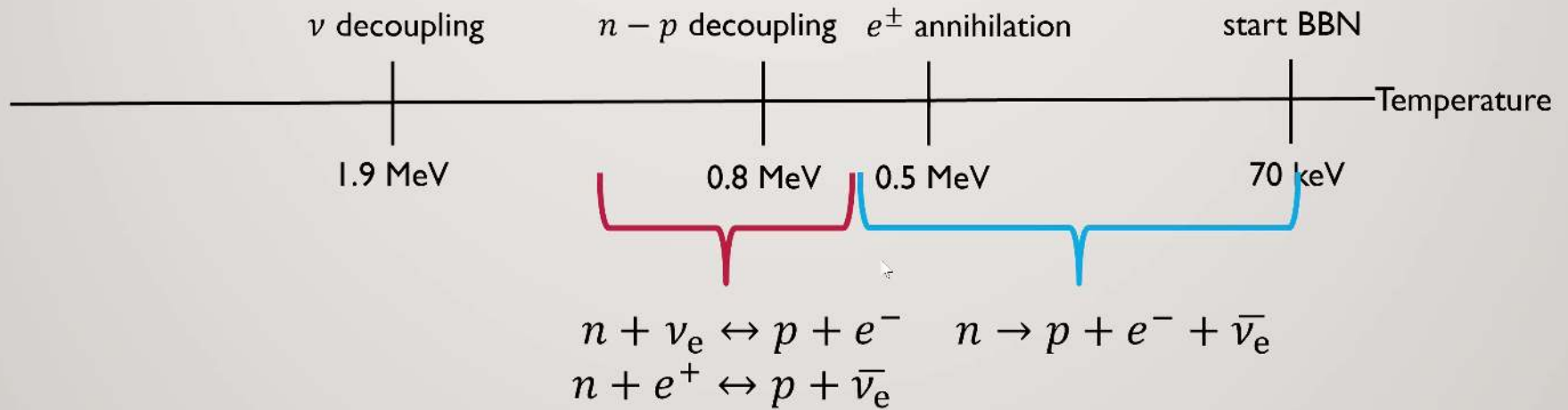
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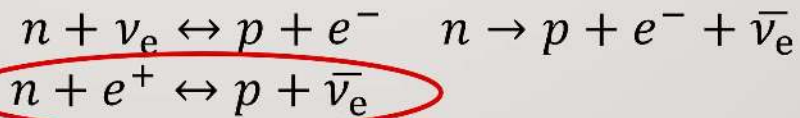
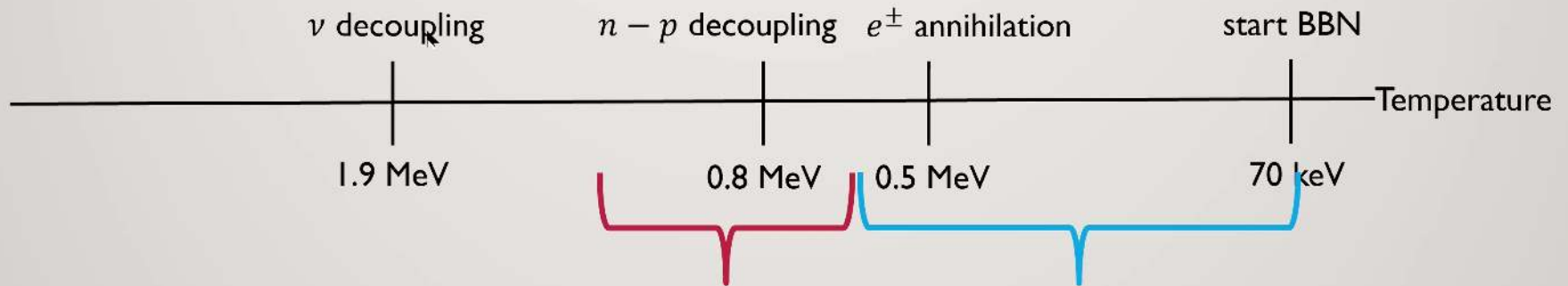
What happens if a SN decays before ν decoupling?



What happens if a SN decays during ν decoupling?

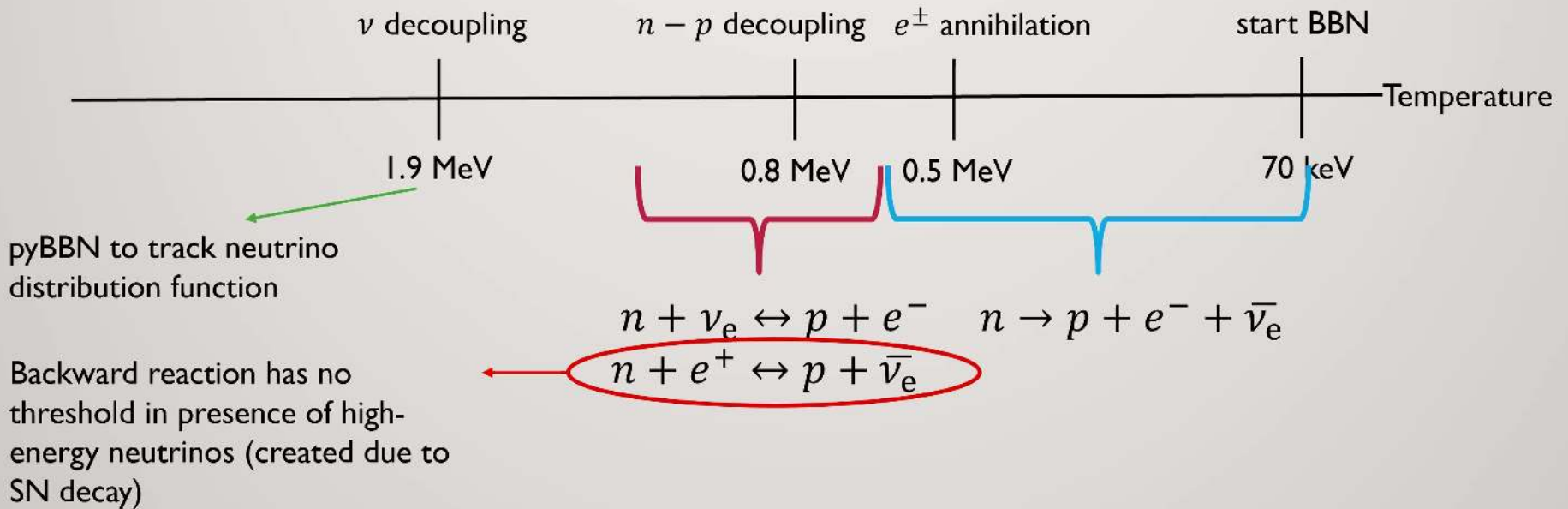


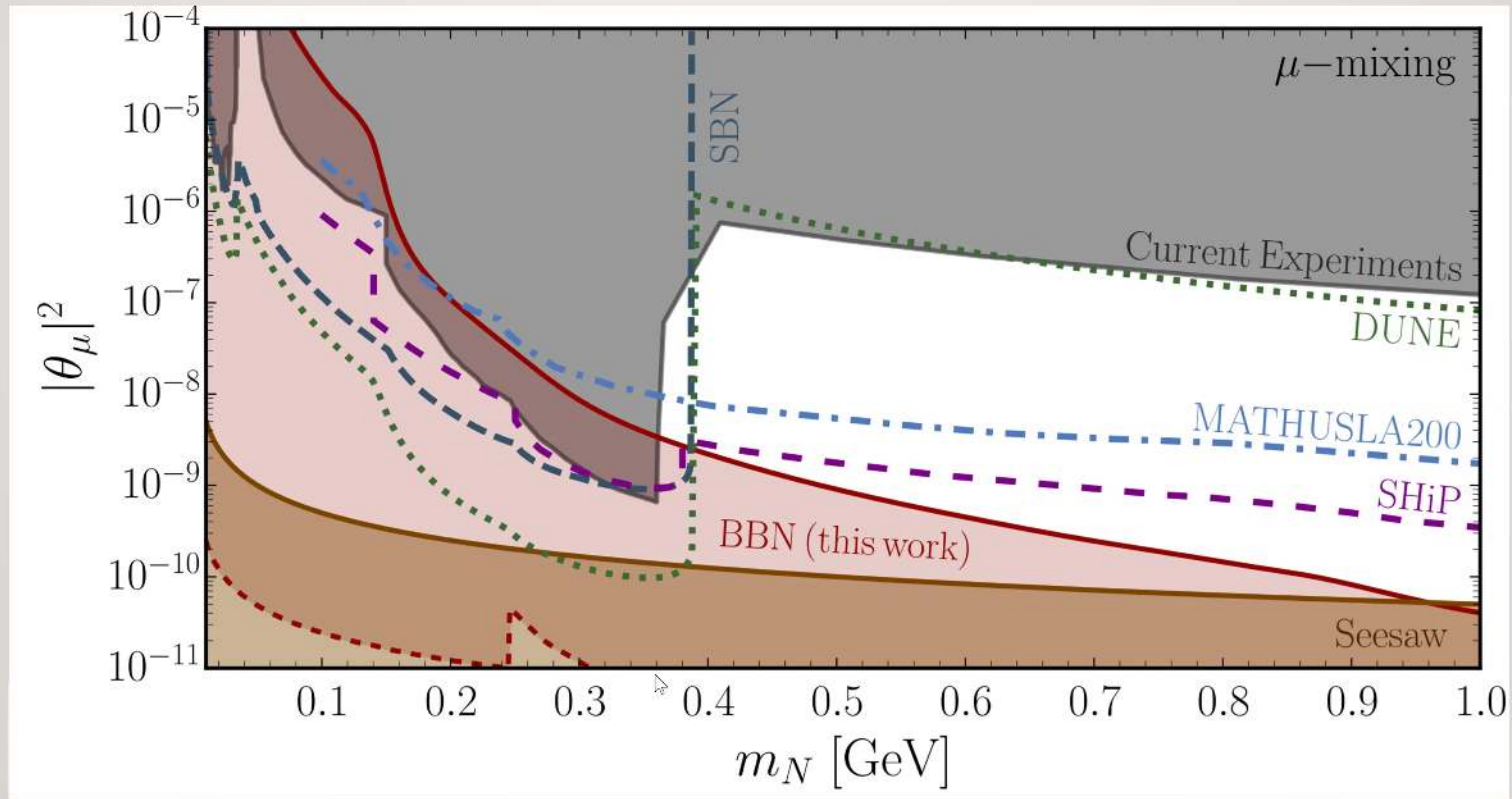
What happens if a SN decays during ν decoupling?



Backward reaction has no threshold in presence of high-energy neutrinos (created due to SN decay)

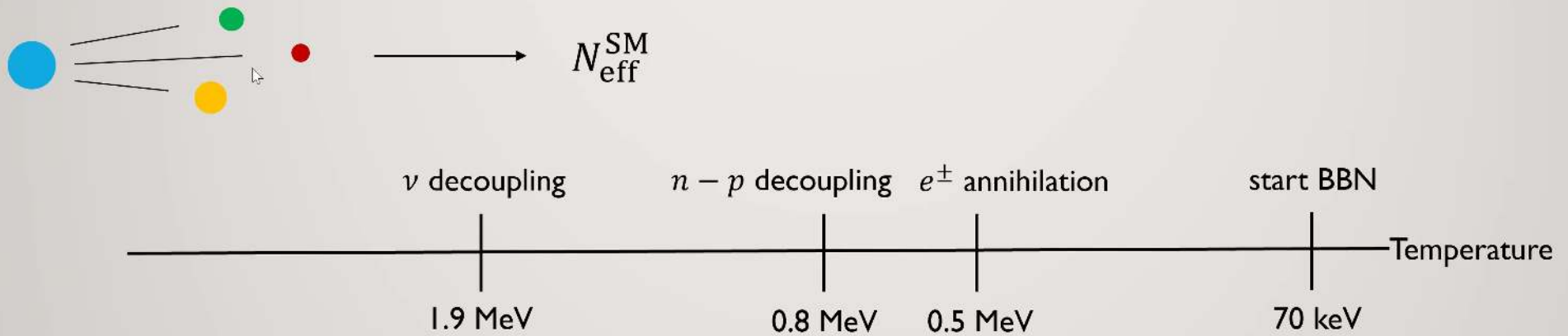
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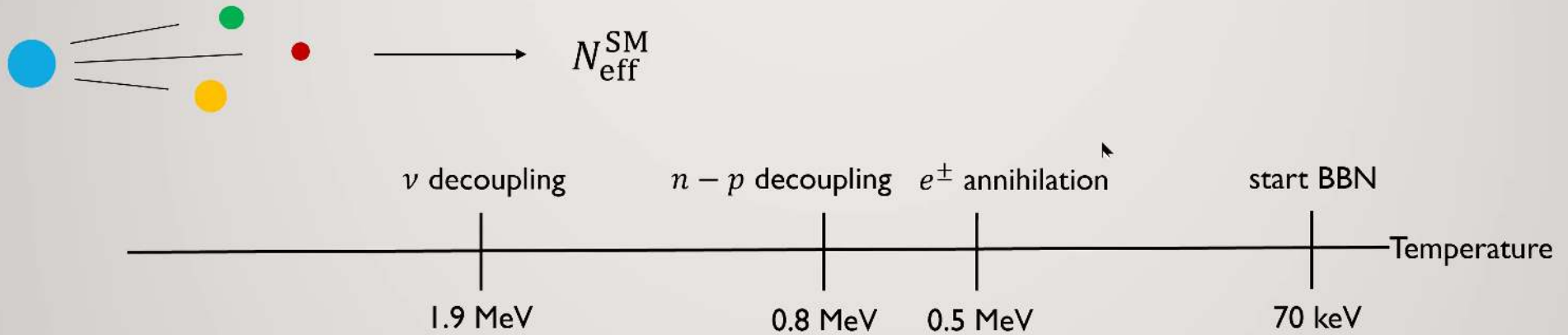


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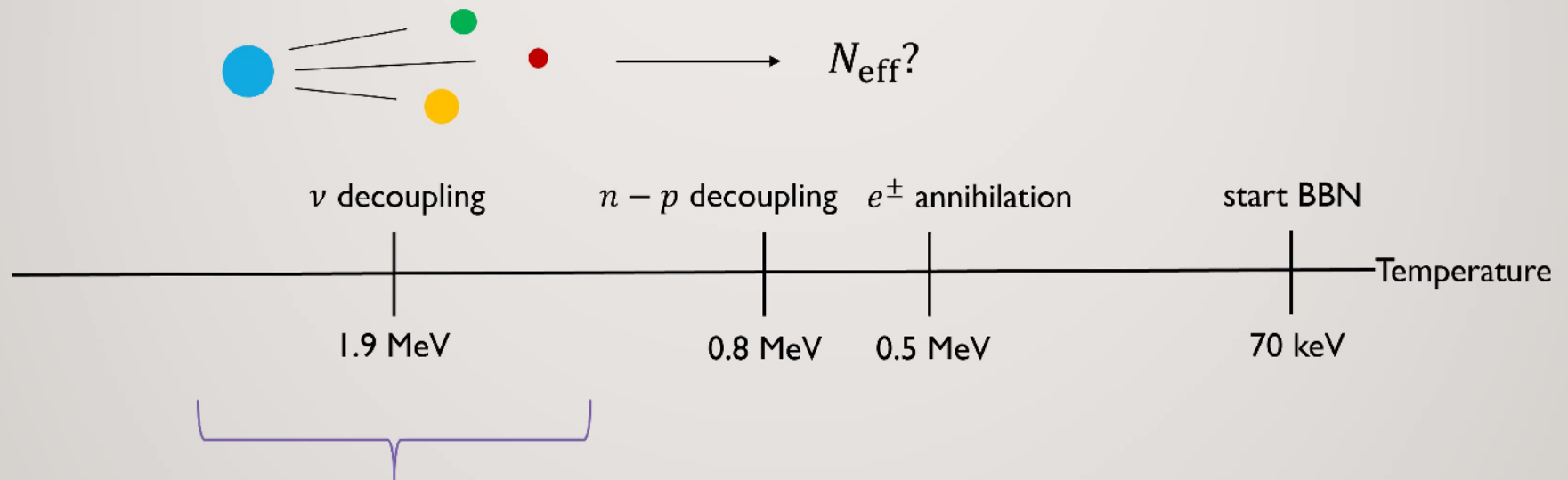
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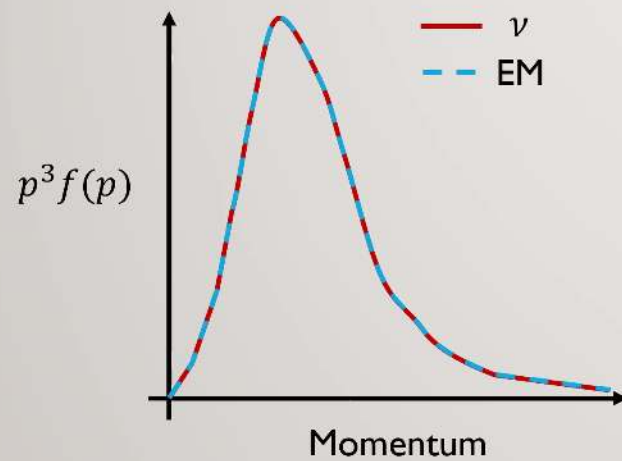
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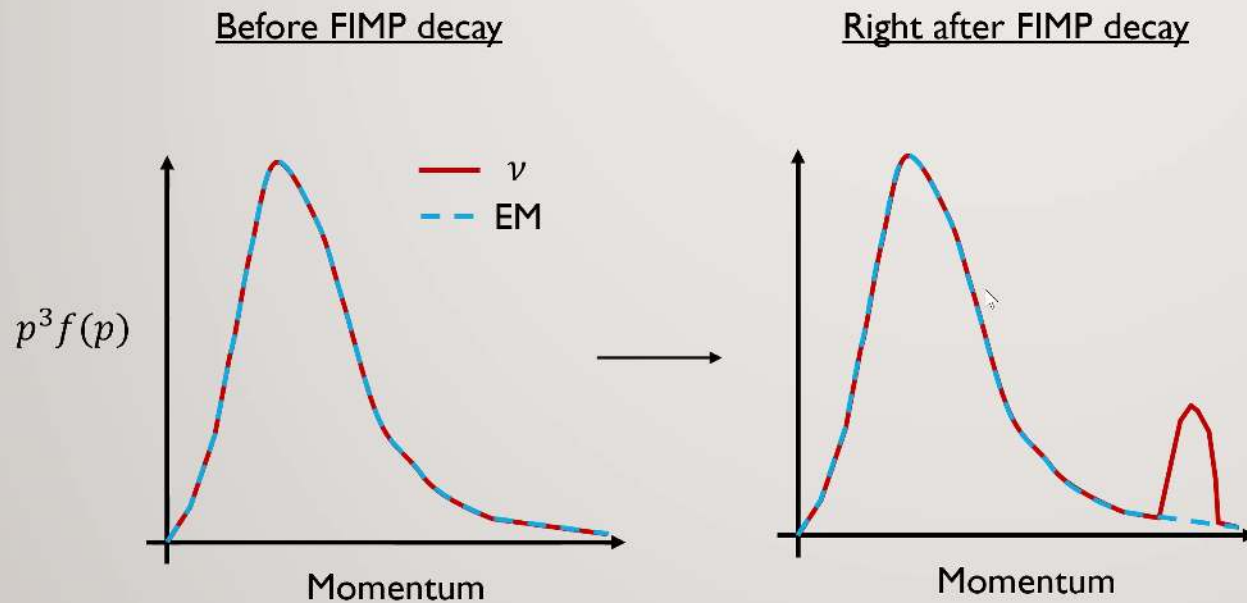
- ν decoupling not instantaneous
- cross-section $\sigma \propto E_\nu^2$
- ν s with higher energies stay longer in equilibrium

What is the actual mechanism behind this effect?

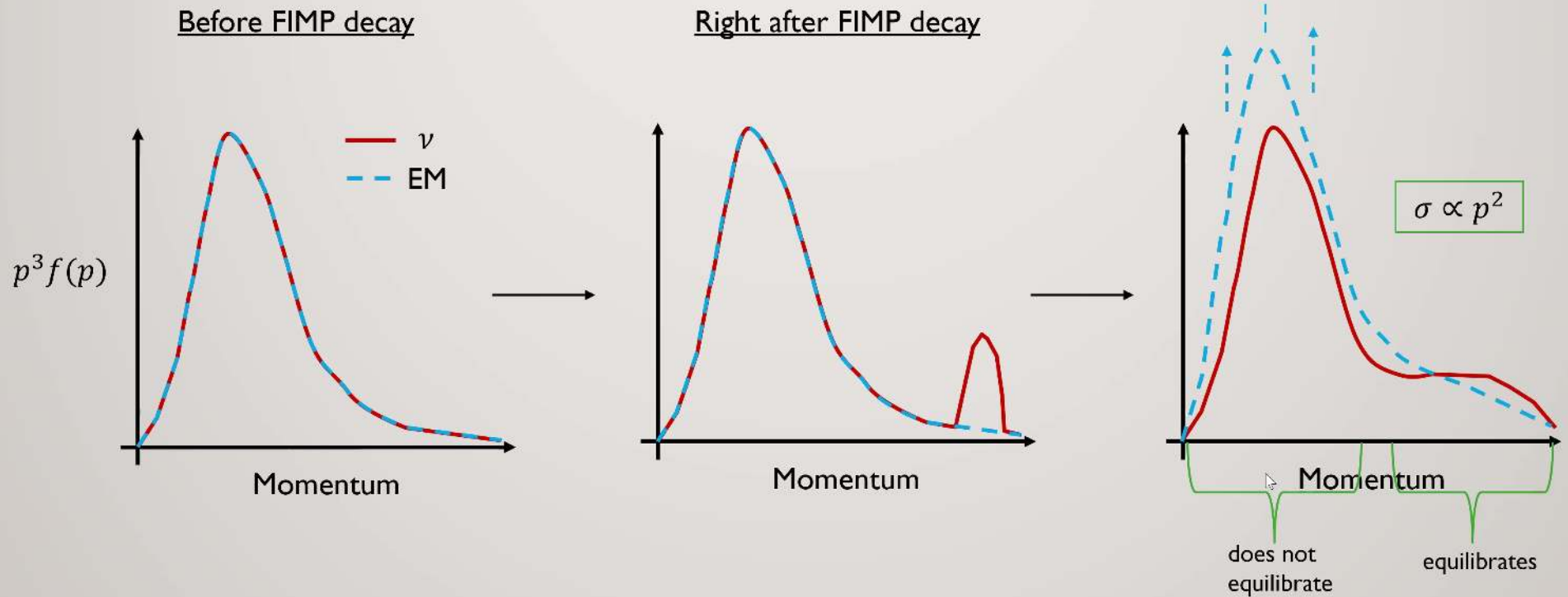
Before FIMP decay

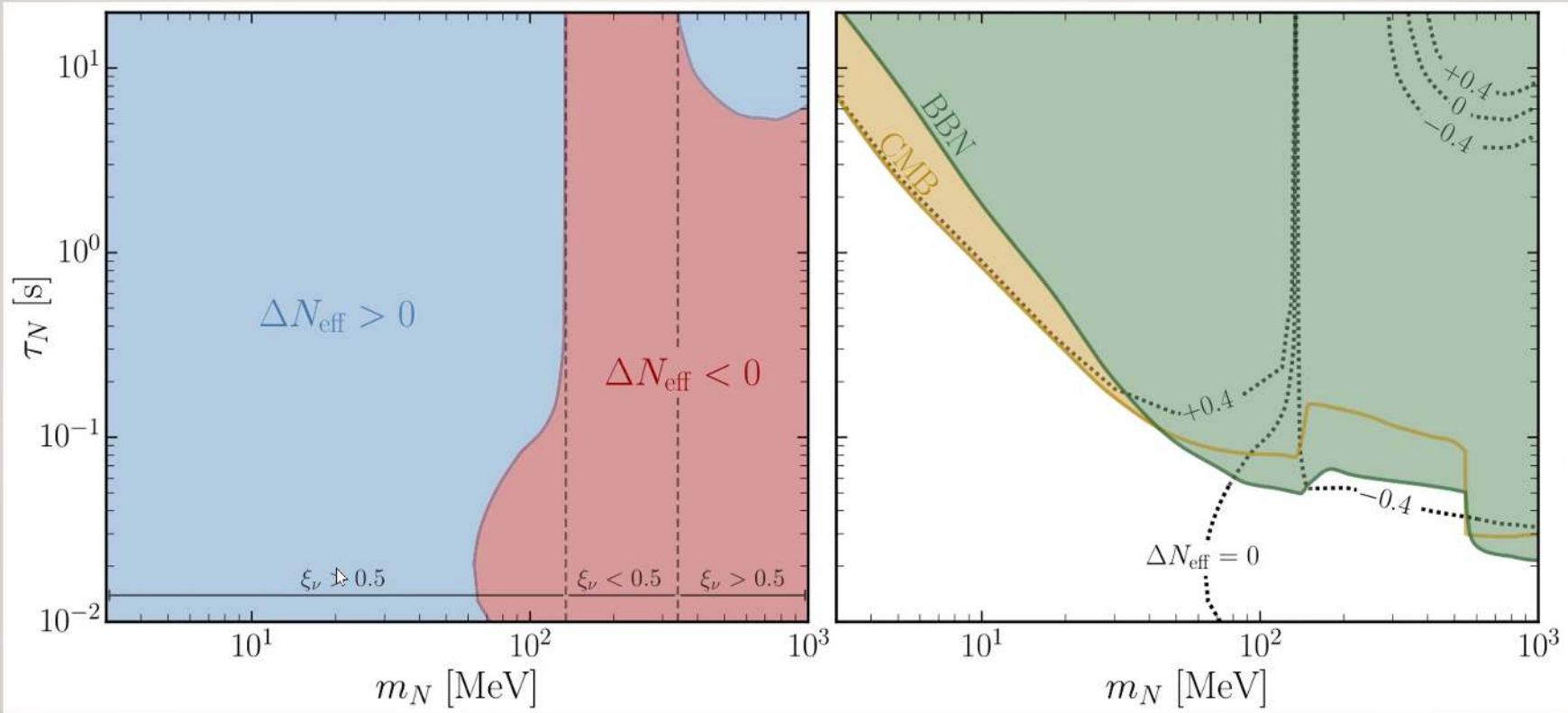


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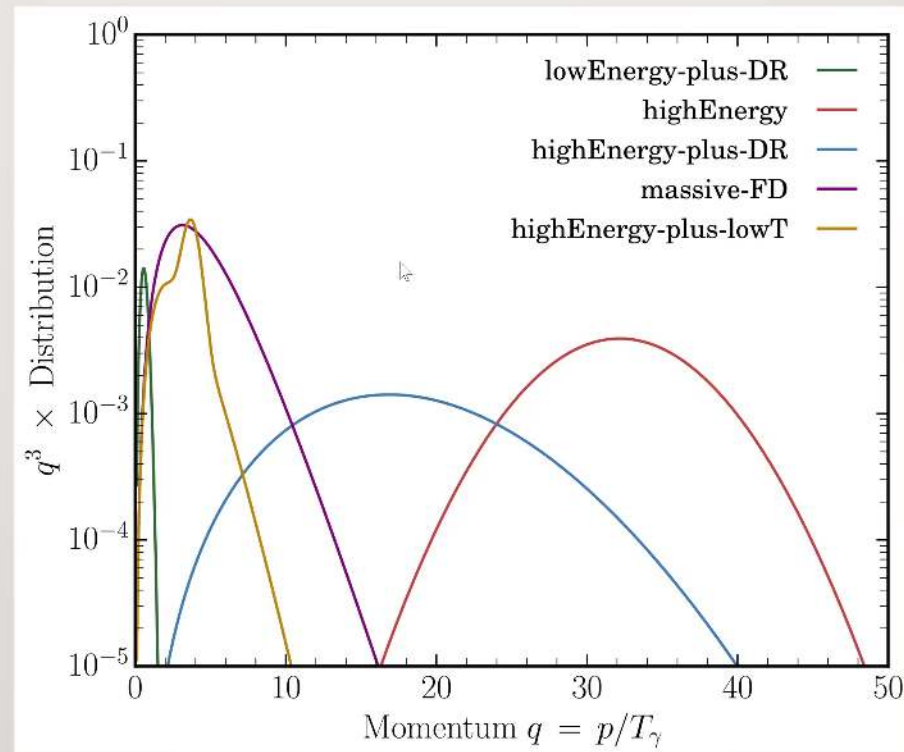




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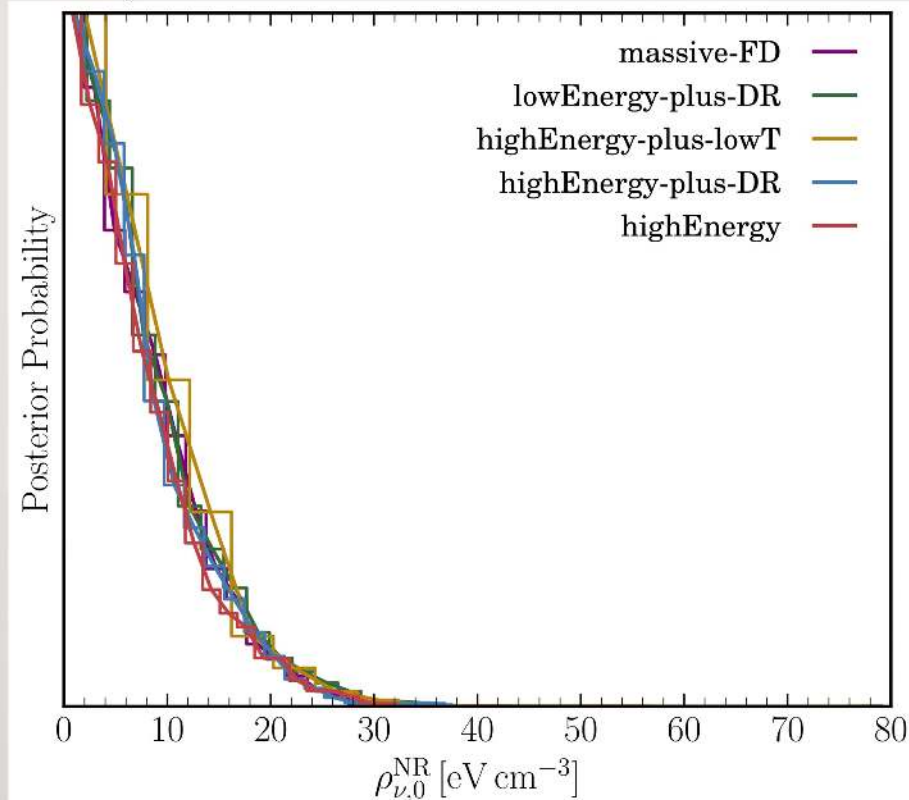
Signatures at neutrino experiments?

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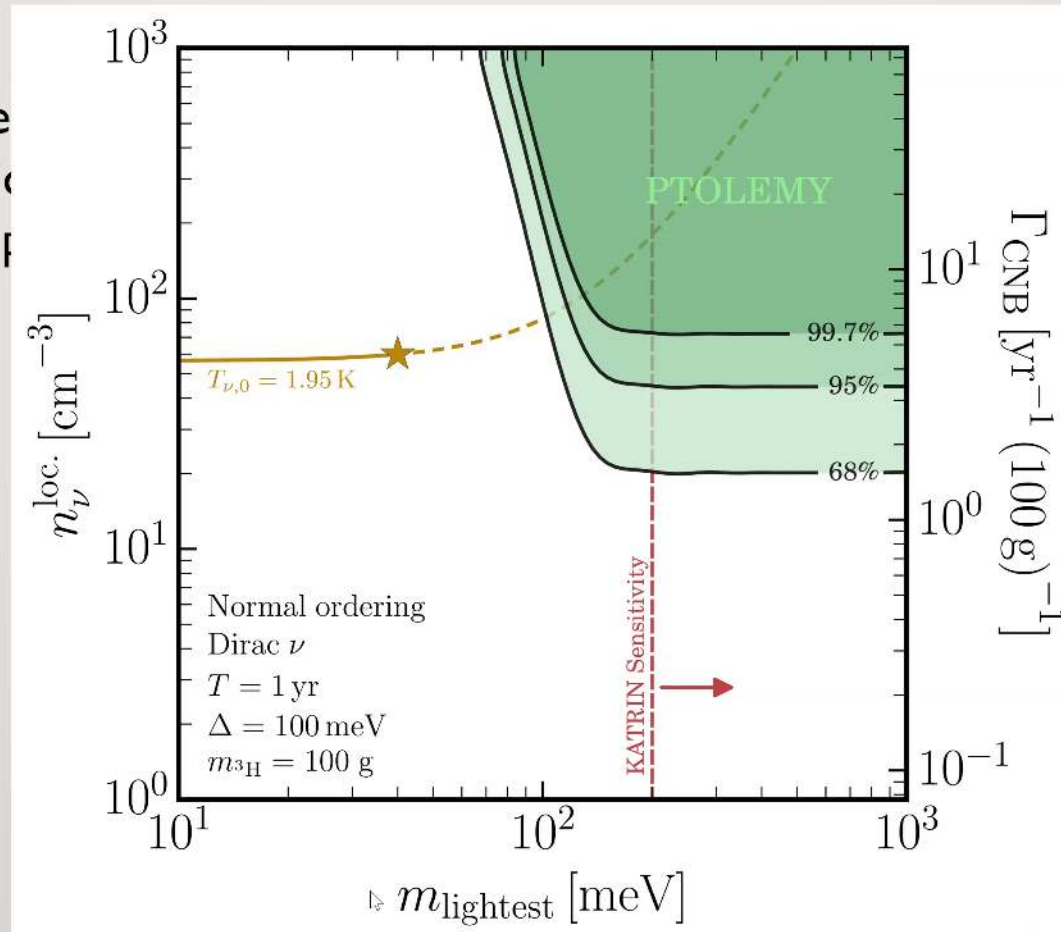


Signatures at neutrino experiments?

- With current CMB data, we are not able to measure sum of neutrino masses
- Cosmological mass bound can thus be relaxed with SN (NS, Boyarsky, Lesgourgues et al., to appear)

Signatures at neutrino experiments?

- With current
- Cosmological
- Detection p



neutrino masses
 (Lesgourgues et al., to appear)
 PTOLEMY, ...

(NS, Alvey, Escudero,
 Schwetz, to appear)

SUMMARY

- BBN and the CMB provide robust lower bounds on the lifetime of sterile neutrinos
- SN (and FIMPs in general) can decrease N_{eff} even if they inject most of their energy into neutrinos
- Possible signatures at KATRIN/PTOLEMY in the near future?

THANK YOU 😊