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

Speakers:

Series: Particle Physics

Date: October 19, 2021 - 1:00 PM

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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.

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Cosmological and Astrophysical Bounds on Sterile Neutrinos

Nashwan Sabti

Perimeter Institute – 19/11/2021

KING'S College LONDON

PERIMETER INSTITUTE

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1-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:

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

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

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

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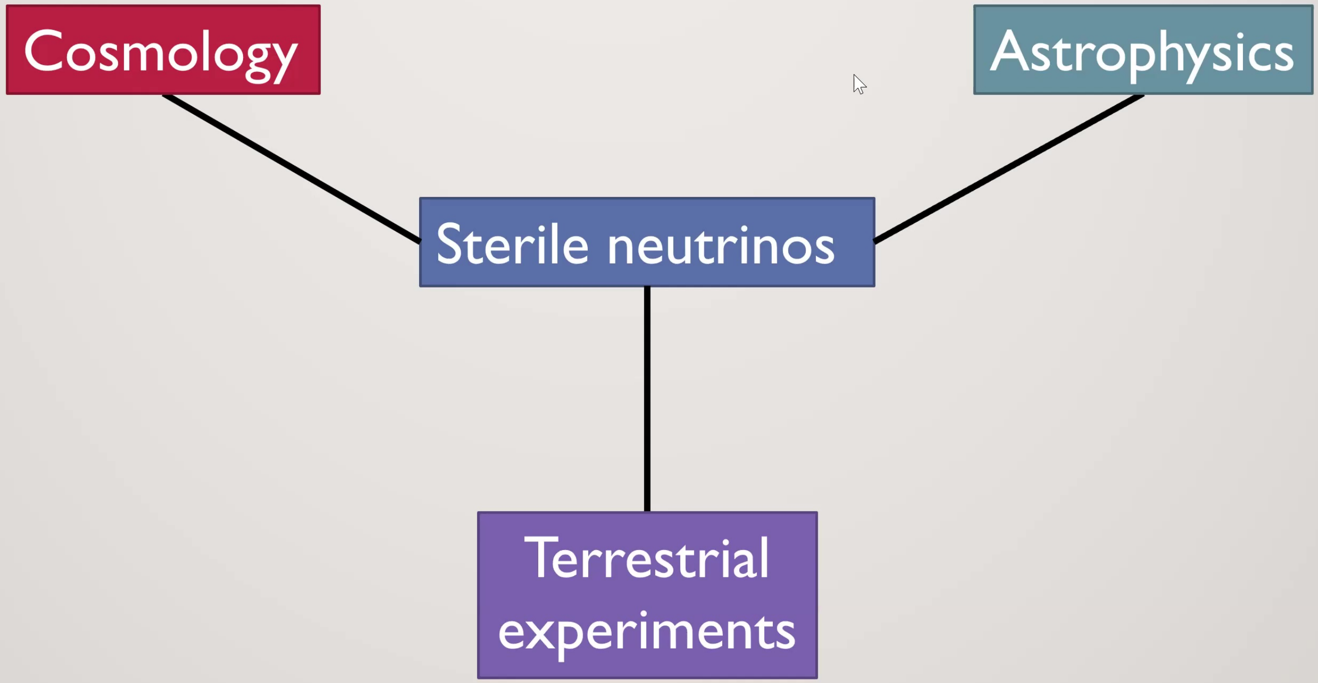

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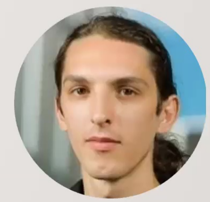
Constraints on the Mass of Fermionic Dark Matter from Dwarf Spheroidal Galaxies

In collaboration with:


James Alvey


Victoria Tiki

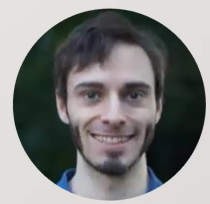

Diego Blas


Kyrylo Bondarenko


Alexey Boyarsky


Miguel Escudero


Malcolm Fairbairn


Matthew Orkney


Justin Read

Based on 2010.03572

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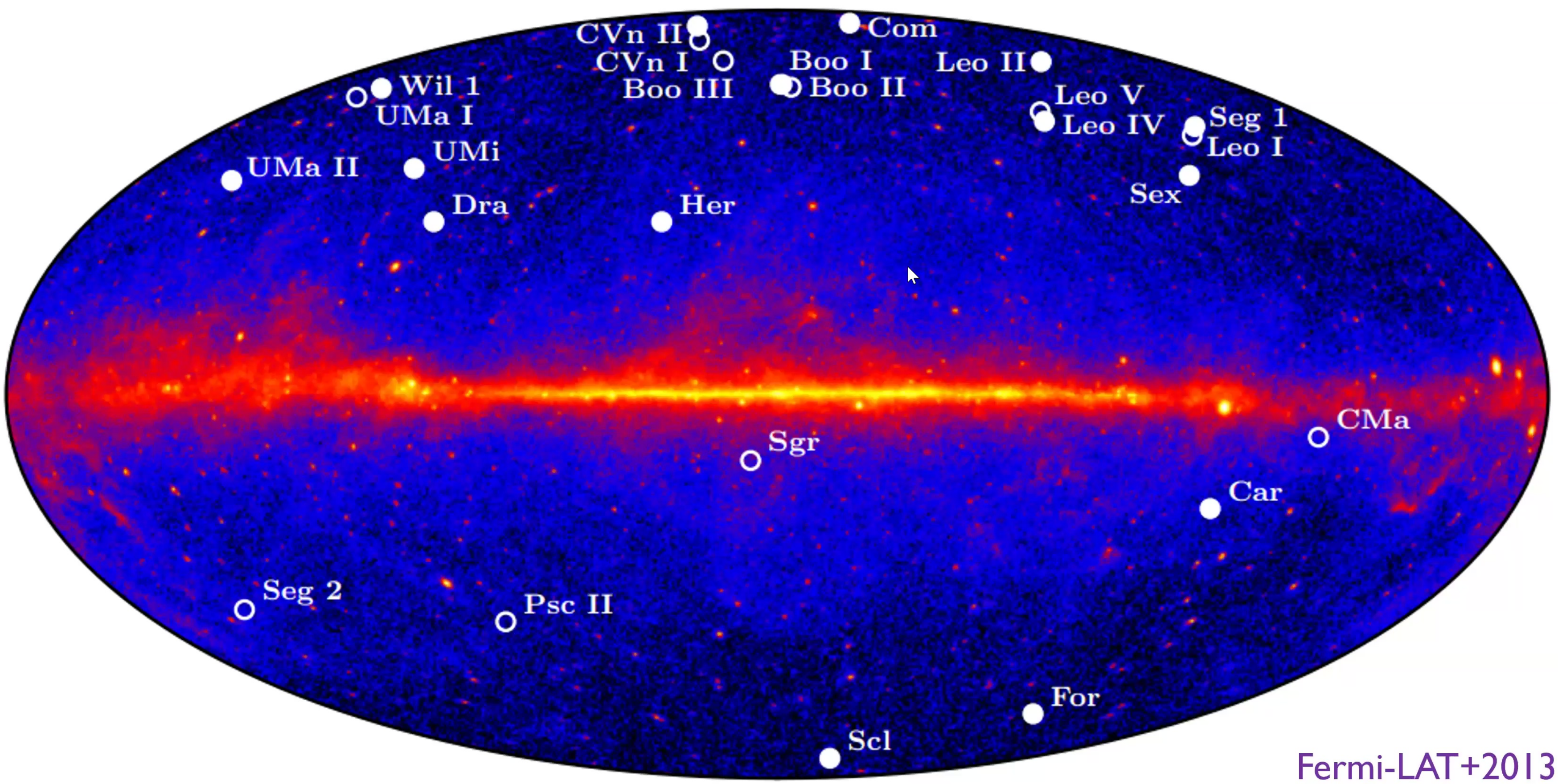
Milky Way Dwarf Spheroidal Galaxies



Fermi-LAT+2013

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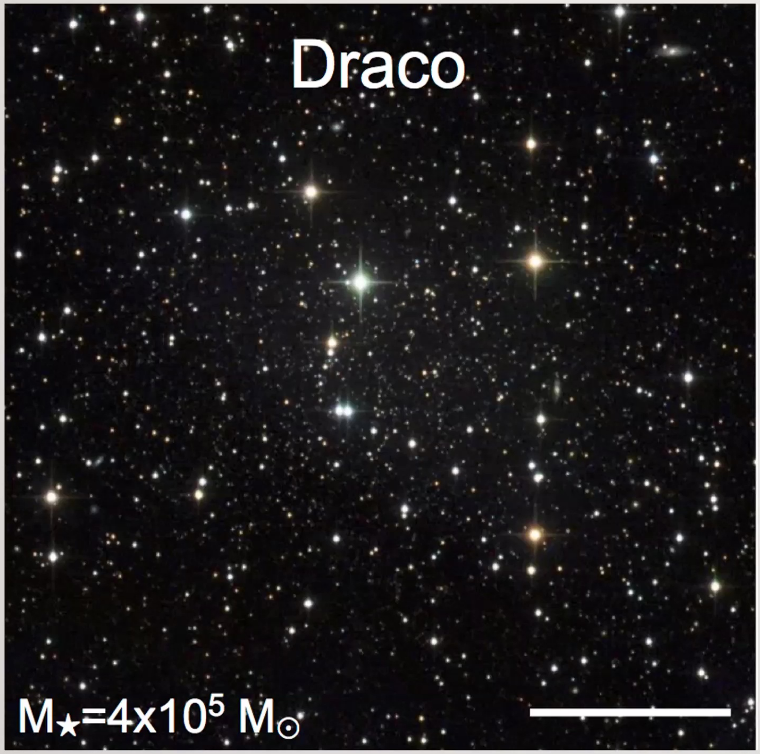
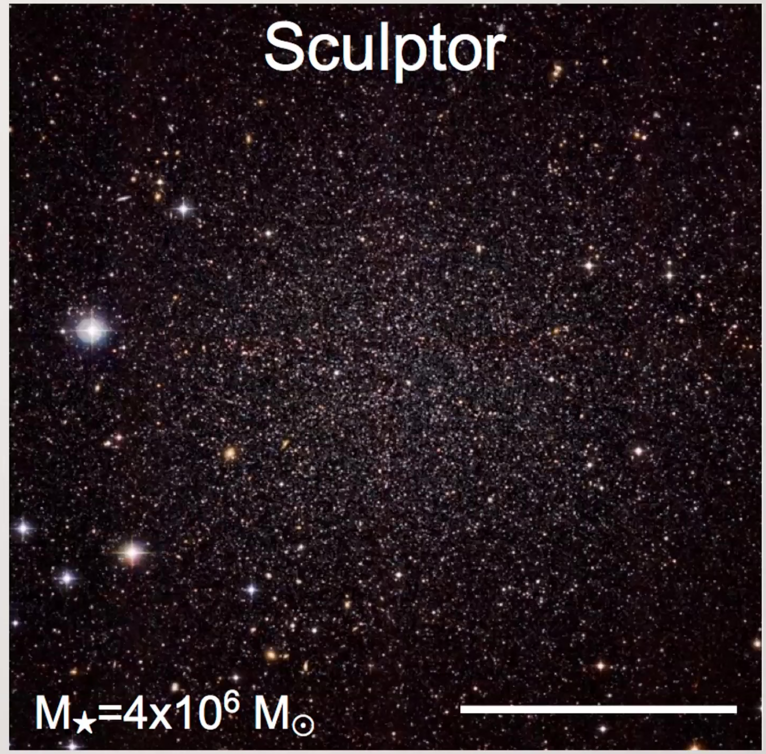


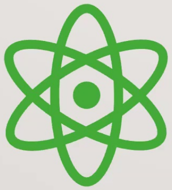


Bullock+2017

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

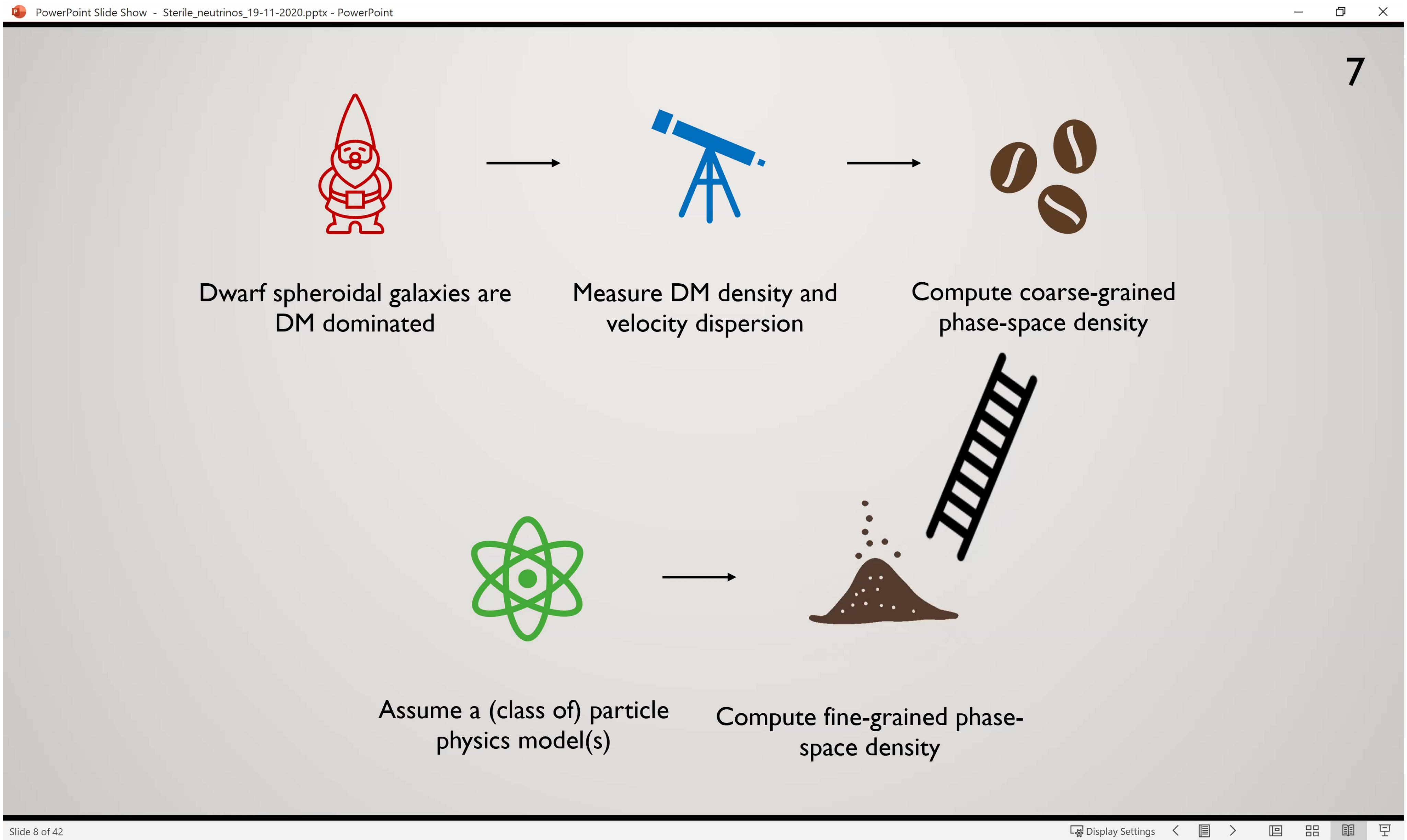
- To compute PS density, we need: *i)* DM density profile and *ii)* velocity dispersion profile

- Simplest approach: assume e.g. isothermal profile

$$\rho_{\mathrm{DM}}(r \ll r_{\mathrm{c}}) \approx \rho_0(r_{\mathrm{c}}, \sigma_{\mathrm{DM}})$$

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

- $m_\nu \gtrsim 0.1$ keV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7
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
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OBSERVING THE DM DENSITY AND VELOCITY DISPERSION

- Jeans equation:

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

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

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

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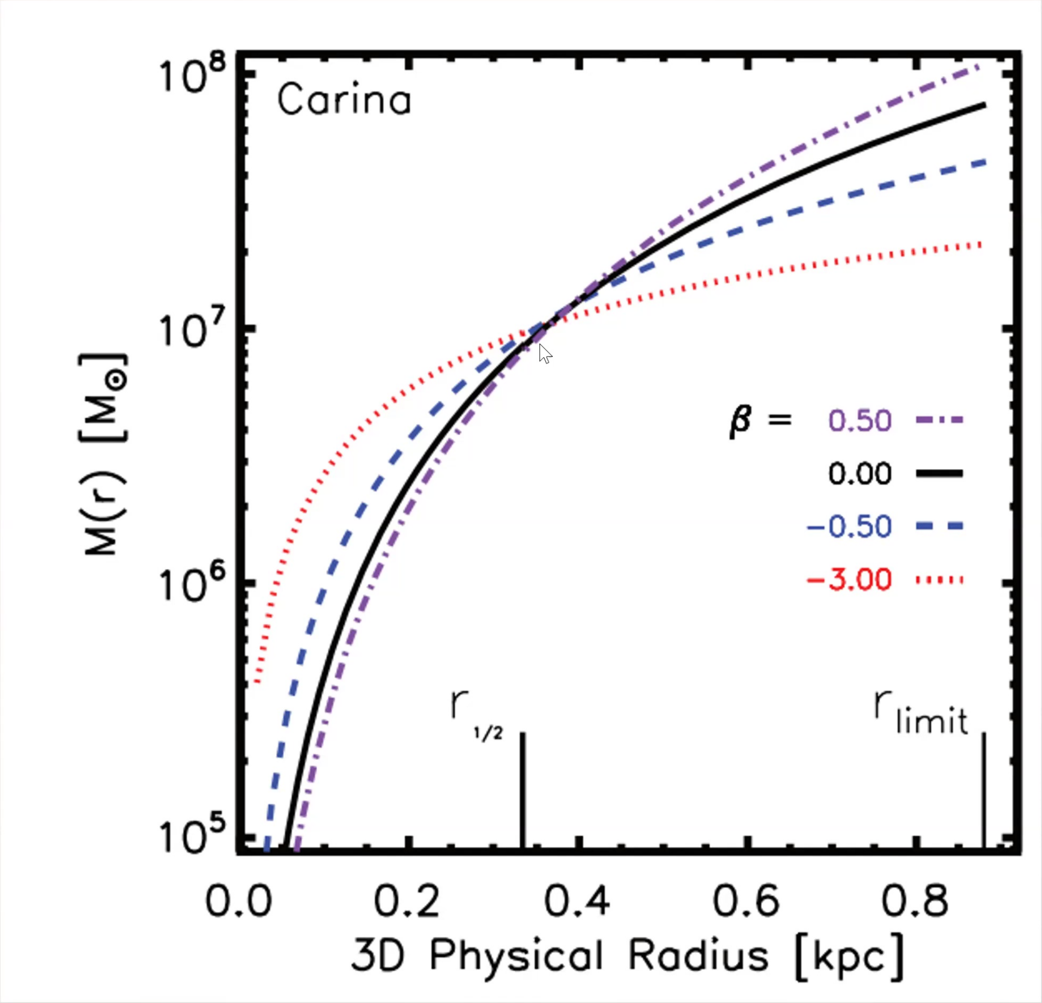

Wolf+2009

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OBSERVING THE DM DENSITY AND VELOCITY DISPERSION

- Introduce virial shape parameters:

$$\mathrm{VSP1} = \int_0^\infty \Sigma\langle v_{\mathrm{LOS}}^4\rangle R\,\mathrm{d}R = \frac{2}{5}\int_0^\infty \nu(5-2\beta)\sigma_r^2 GMR\,\mathrm{d}R$$

$$\mathrm{VSP2} = \int_0^\infty \Sigma\langle v_{\mathrm{LOS}}^4\rangle R^3\,\mathrm{d}R = \frac{4}{35}\int_0^\infty \nu(7-6\beta)\sigma_r^2 GMR^3\,\mathrm{d}R$$

Merrifield & Kent 1990

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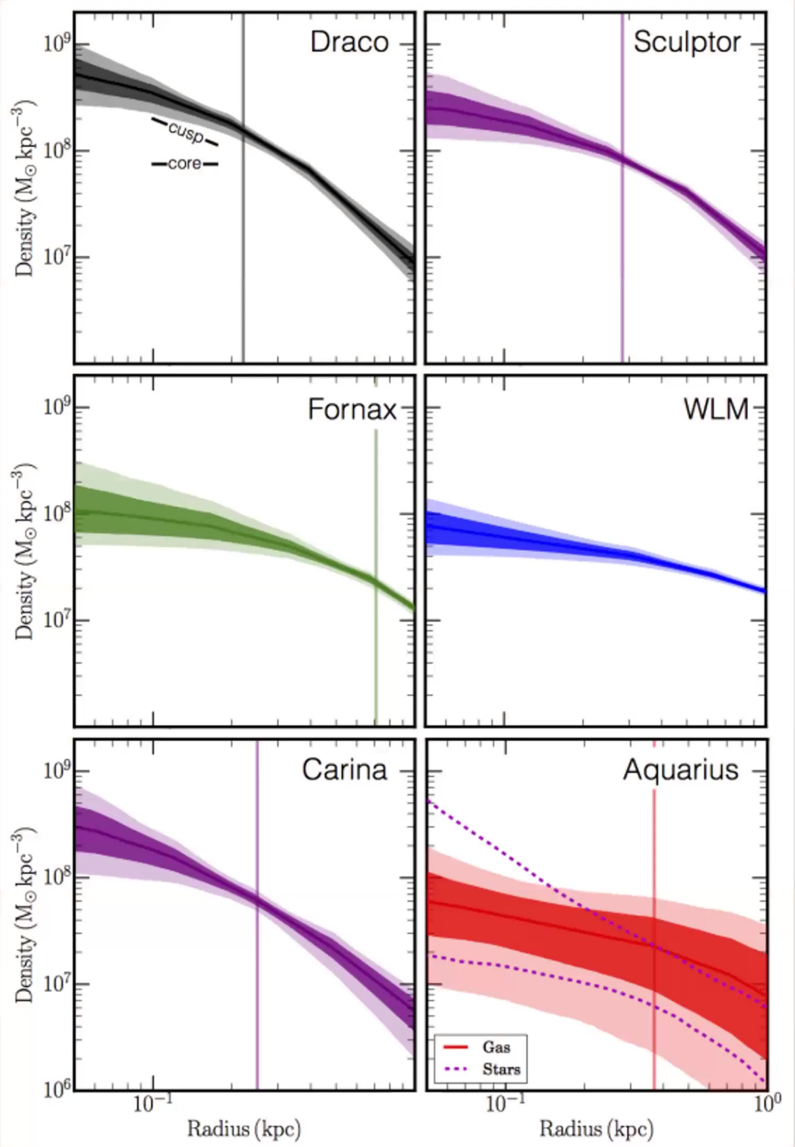

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Read+2018

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OBSERVING THE DM DENSITY AND VELOCITY DISPERSION

- Introduce virial shape parameters:

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

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

Merrifield & Kent 1990

- GravSphere Read+2017

OBSERVING THE DM DENSITY AND VELOCITY DISPERSION

- Solve 2nd Jeans equation for DM:

$$\frac{1}{\nu_{\mathrm{DM}}}\frac{\partial}{\partial r}\left(\nu_{\mathrm{DM}}\left(\sigma_r^{\mathrm{DM}}\right)^2\right)+2\,\frac{\beta_{\mathrm{DM}}(r)\left(\sigma_r^{\mathrm{DM}}\right)^2}{r}=-\frac{GM(r)}{r^2}$$

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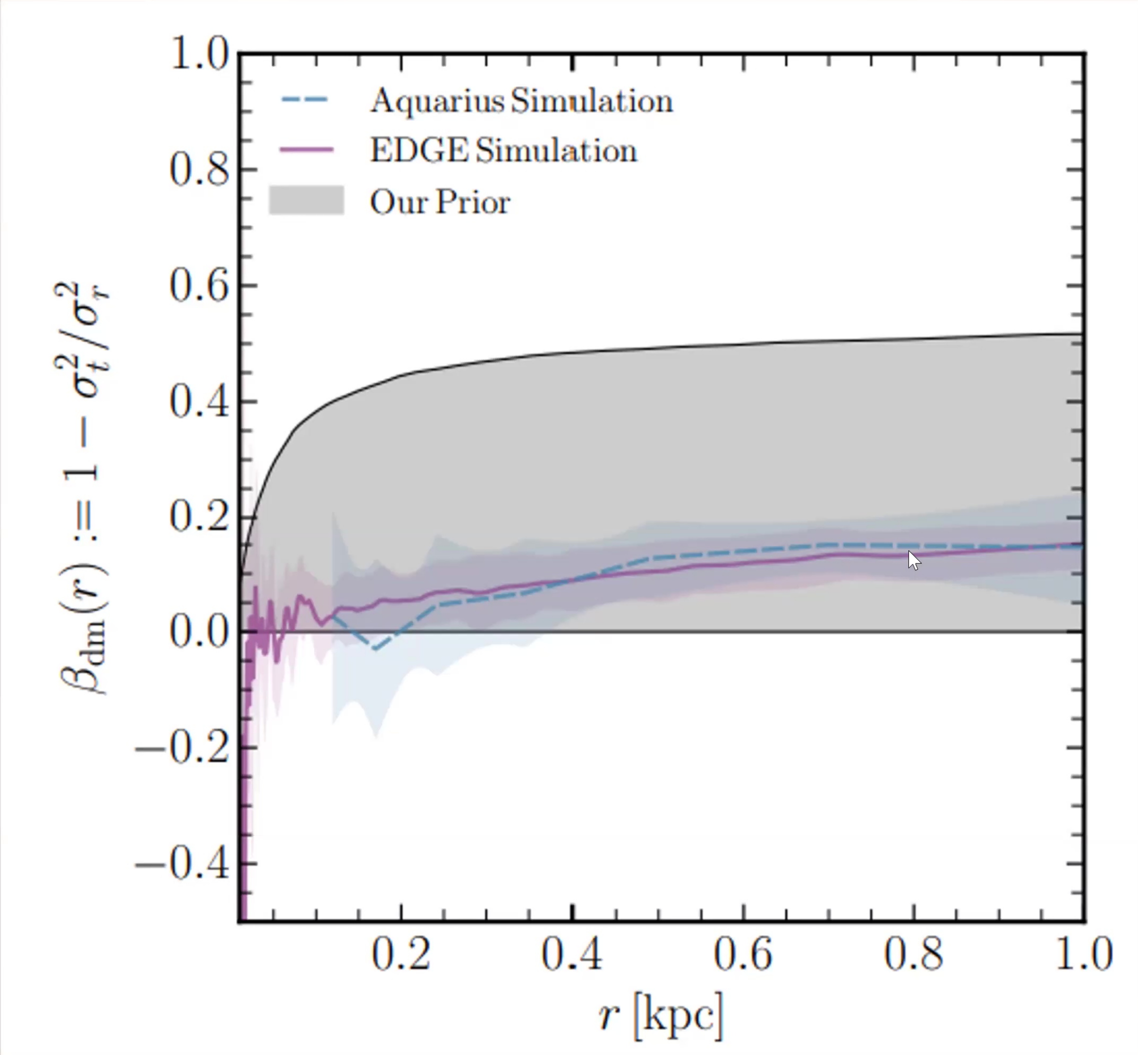

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OBTAINING PHASE-SPACE CONSTRAINTS

- Bounds from Pauli's principle – model independent

Fermi velocity: $v_{\mathrm{F}} = \left(\frac{6\pi^2 \rho(r)}{g m^4}\right)^{1/3}$

$$v_{\mathrm{F}} < v_{\mathrm{esc}} \longrightarrow m_{\mathrm{deg}} > \left.\left(\frac{6\pi^2 \rho(r)}{g v_{\mathrm{esc}}^3(r)}\right)^{\frac{1}{4}}\right|_{r_{\min}} = 0.27^{+0.30}_{-0.14}\ \mathrm{keV}\ (2\sigma)$$

OBTAINING PHASE-SPACE CONSTRAINTS

- Bounds from Liouville's theorem – model dependent

$$F^{\mathrm{late}}_{\mathrm{coarse}} \leq F^{\mathrm{late}}_{\mathrm{fine}} \leq F^{\mathrm{primordial}}_{\mathrm{fine}} = m^4 f_{\mathrm{max}}$$

Averaging

Liouville's th.

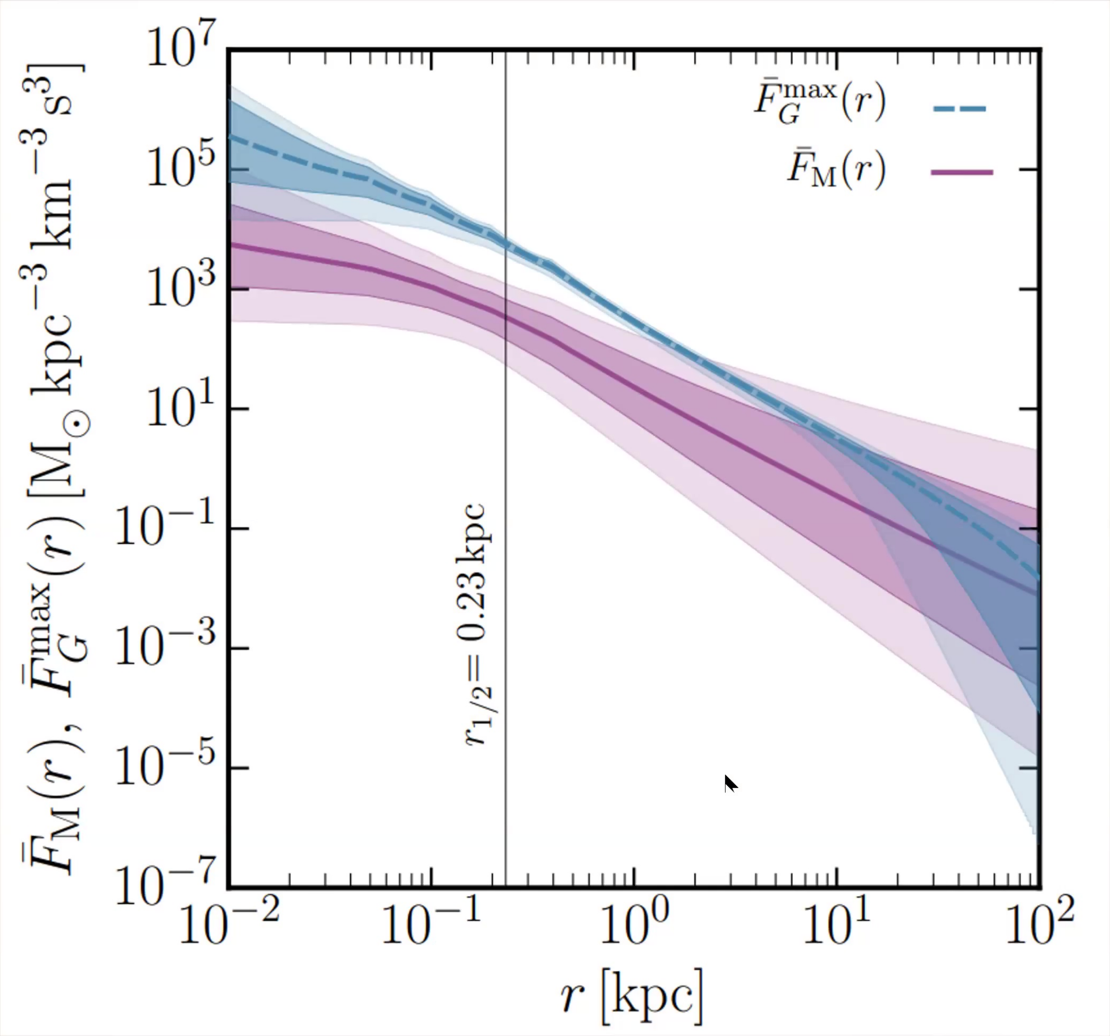
OBTAINING PHASE-SPACE CONSTRAINTS

- Maximal coarse-graining:

$$\overline{F_{\mathrm{M}}}(r) = \frac{\rho(r)}{\frac{4\pi}{3} v_{\mathrm{esc}}^{3}(r)} \leq m^4 f_{\max}$$

- Gaussian coarse-graining:

$$\overline{F_{\mathrm{G}}}(r) = \frac{\rho(r)}{(2\pi)^{3/2}\sigma_r \sigma_t^2} \leq m^4 f_{\max}$$


$\bar{F}_G^{\rm max}(r)$
$\bar{F}_{\rm M}(r)$
$r_{1/2}$= 0.23 kpc
$\bar{F}_{\rm M}(r)$, $\bar{F}_G^{\rm max}(r)$ [M$_\odot$ kpc^{-3} km^{-3} s^3]
r [kpc]
10^{7}
10^{5}
10^{3}
10^{1}
10^{-1}
10^{-3}
10^{-5}
10^{-7}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}

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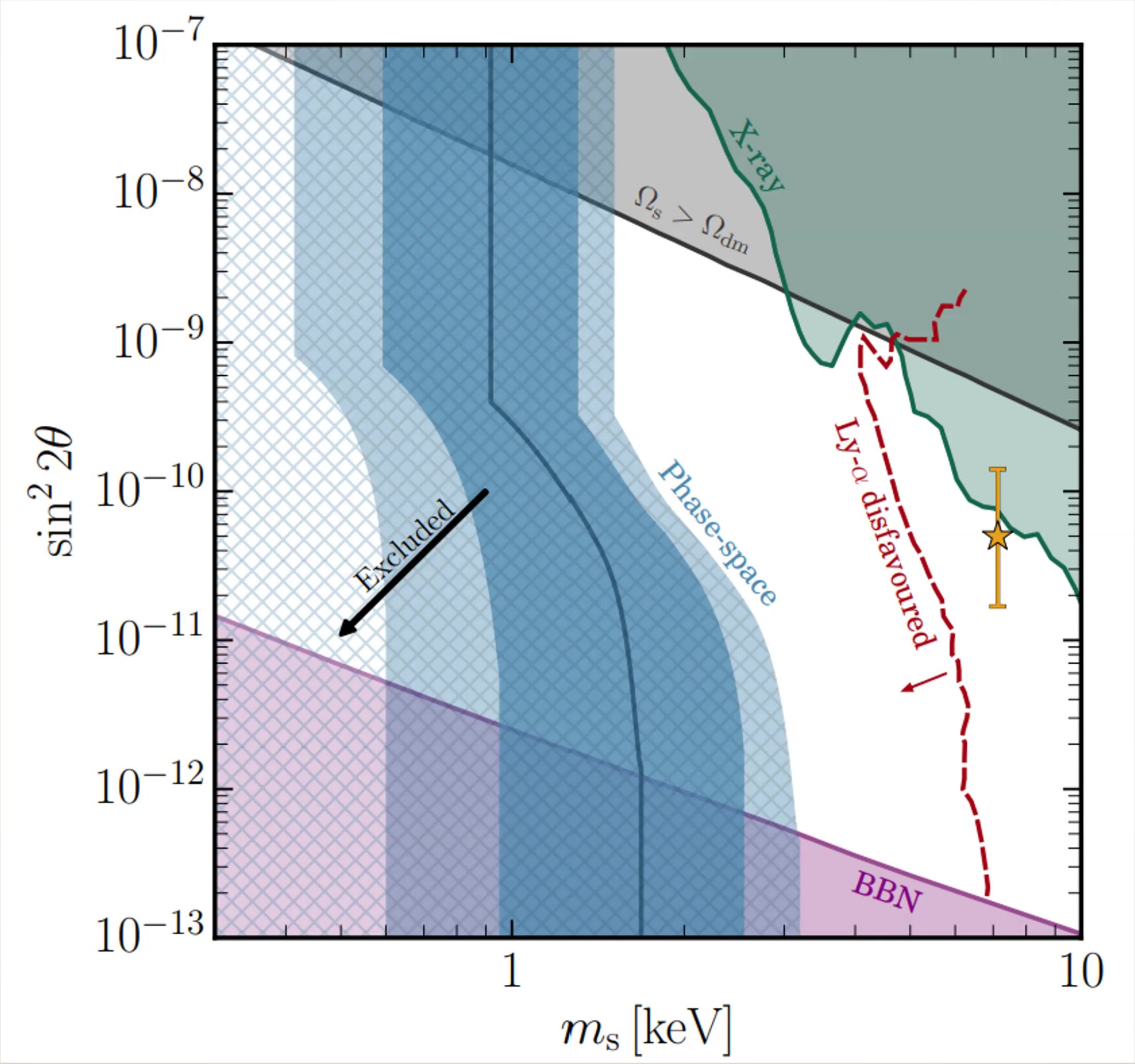

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SUMMARY

- 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

Bounds on the Lifetime of Sterile Neutrinos from primordial nucleosynthesis

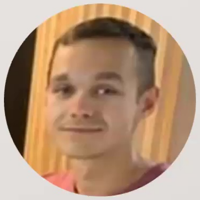
In collaboration with

Alexey Boyarsky

Maksym Ovchynnikov

Vsevolod Syvolap

Anastasiia Filimonova

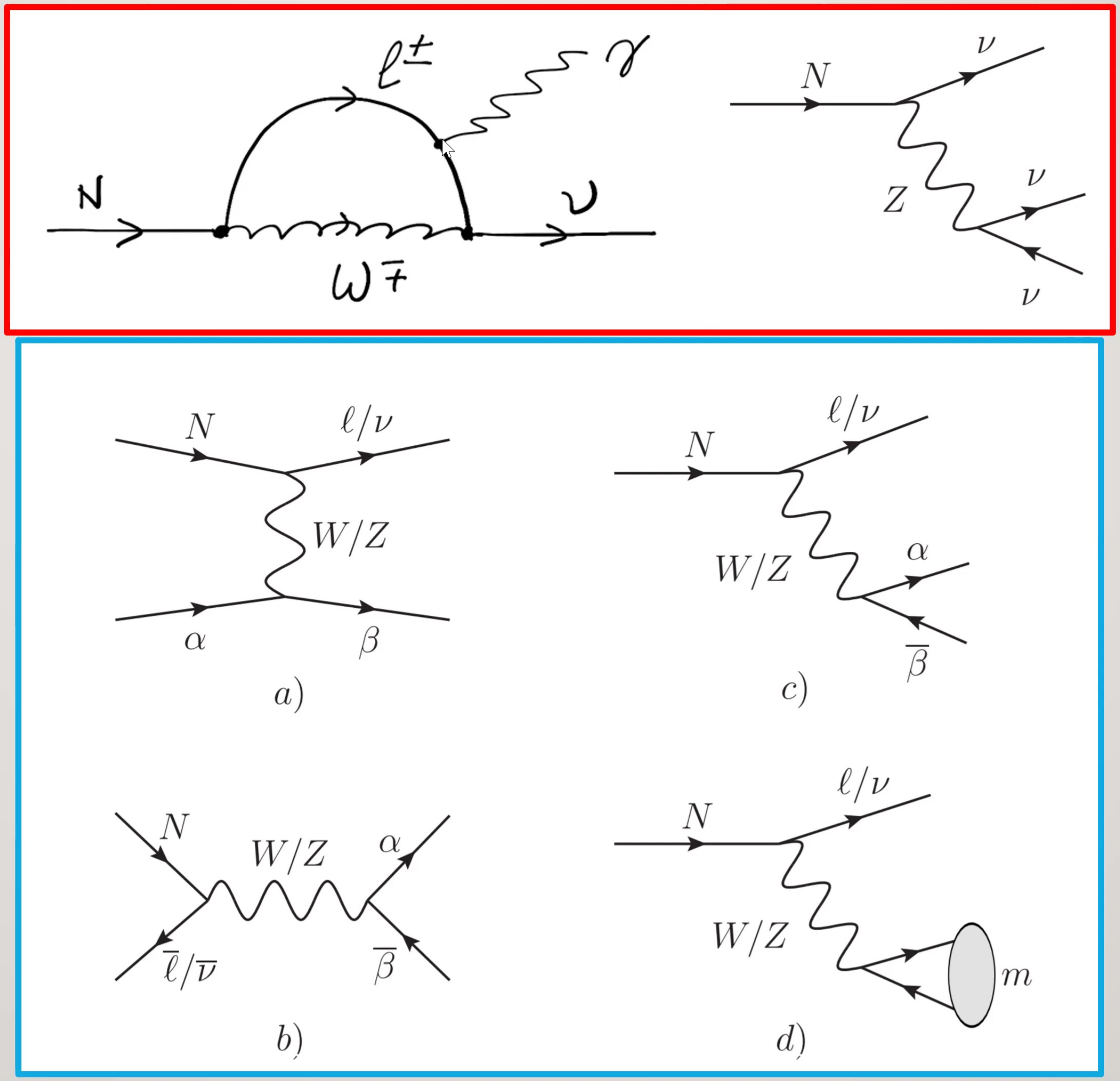


Andrii Magalich

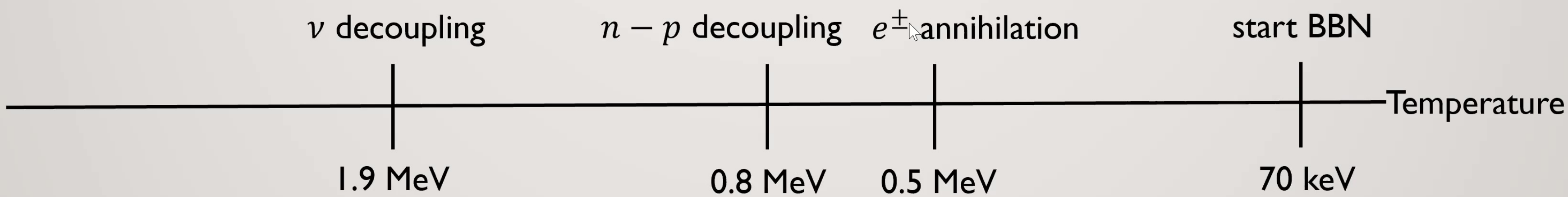
Based on 2006.07387 and 2103.09831

keV scale:

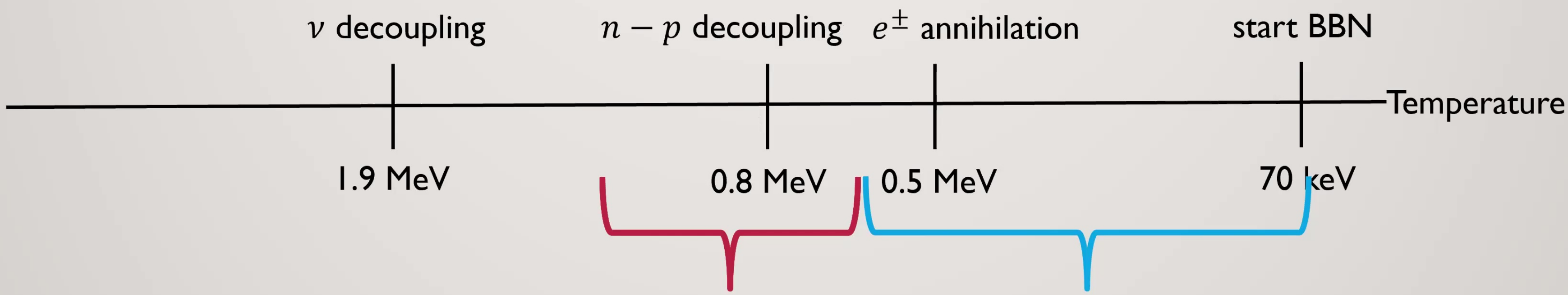
MeV - GeV scale:



Timeline of relevant events in the early Universe



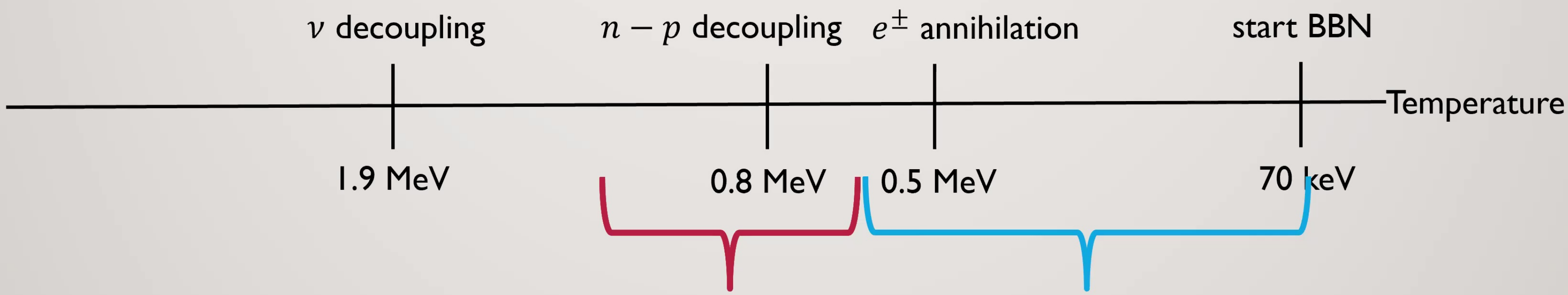
Timeline of relevant events in the early Universe



$$n + \nu_e \leftrightarrow p + e^- \qquad n \rightarrow p + e^- + \bar{\nu}_e$$

$$n + e^+ \leftrightarrow p + \bar{\nu}_e$$

Timeline of relevant events in the early Universe

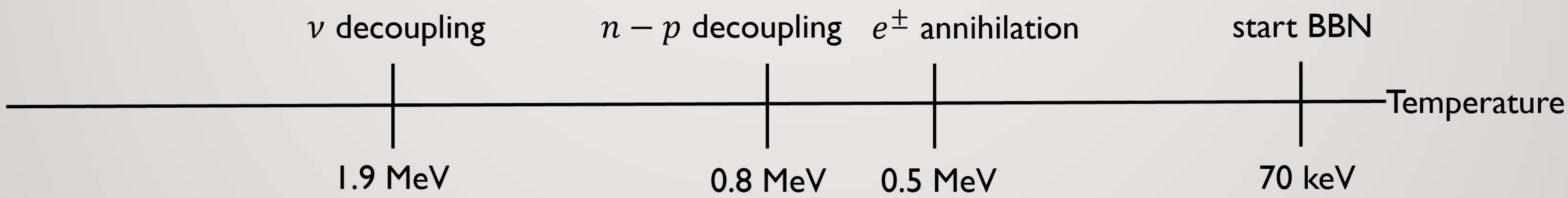


$n + \nu_e \leftrightarrow p + e^-$ $\quad$ $n \rightarrow p + e^- + \bar{\nu}_e$

$n + e^+ \leftrightarrow p + \bar{\nu}_e$

Backward reaction has a threshold of $m_n - m_p + m_e = 1.8$ MeV

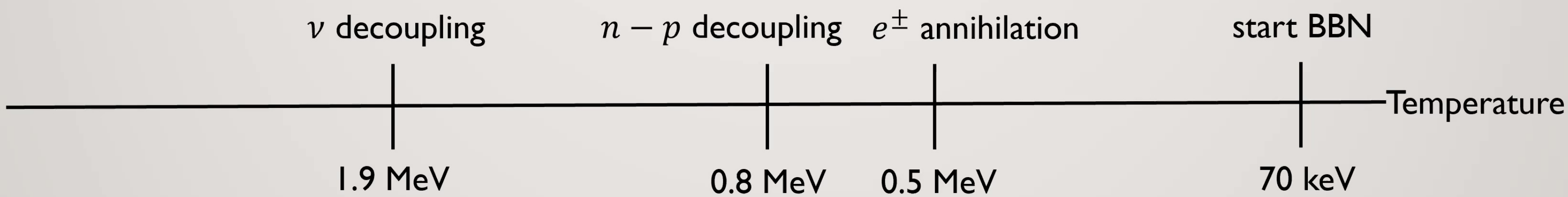
Timeline of relevant events in the early Universe



$$N_{\text{eff}}^{\text{SM}} = 3.044 \qquad N_{\text{eff}}^{\text{Planck+BAO}} = 2.99 \pm 0.17$$

$$Y_{\text{p}}^{\text{SM}} = 0.24709 \qquad Y_{\text{p}}^{\text{PDG}} = 0.245 \pm 0.003$$

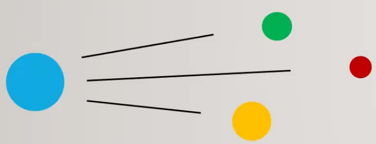
Timeline of relevant events in the early Universe



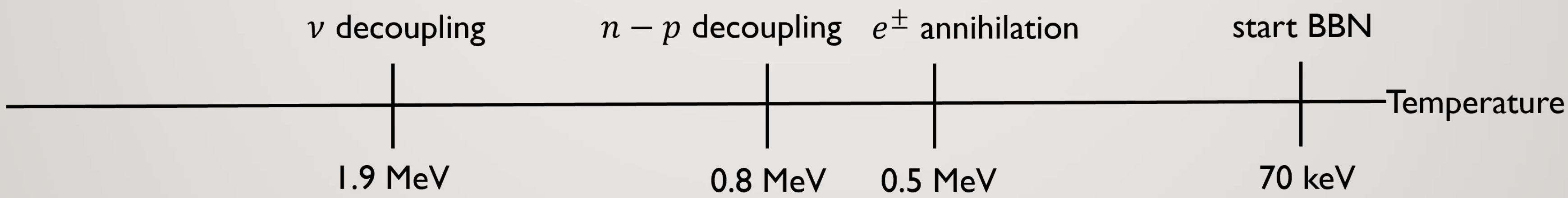
$N_{\text{eff}}^{\text{SM}} = 3.044$ $\quad$ $N_{\text{eff}}^{\text{Planck+BAO}} = 2.99 \pm 0.17$

$Y_{\text{p}}^{\text{SM}} = 0.24709$ $\quad$ $Y_{\text{p}}^{\text{PDG}} = 0.245 \pm 0.003$

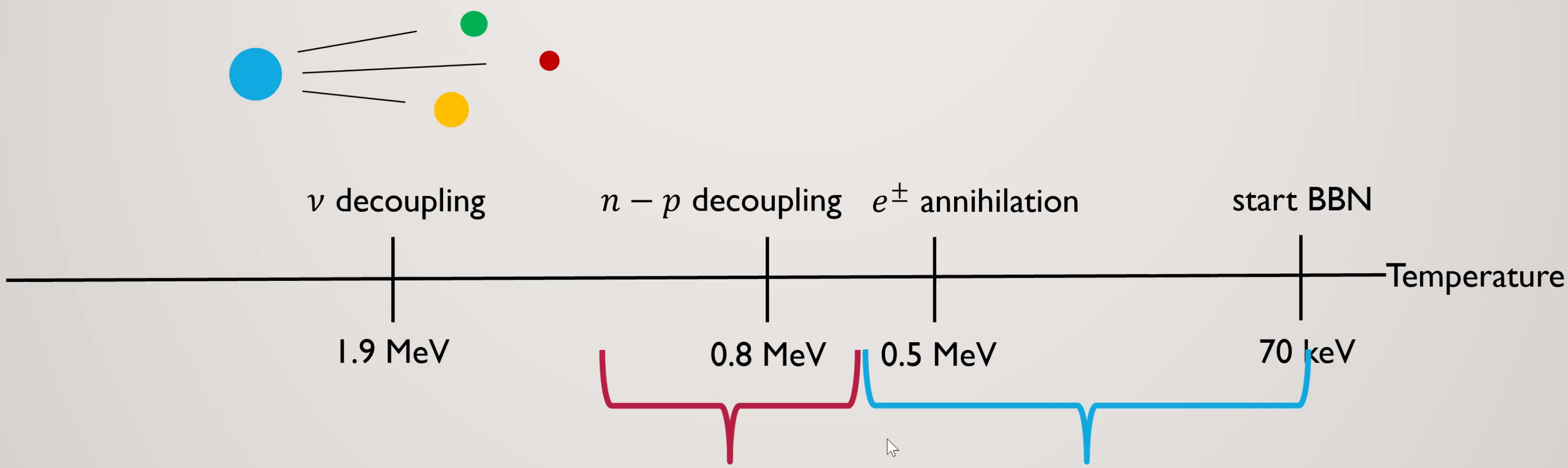
What happens if a SN decays before ν decoupling?



→ obtain back SM BBN



What happens if a SN decays during ν decoupling?



$$n + \nu_e \leftrightarrow p + e^- \qquad n \rightarrow p + e^- + \bar{\nu}_e$$

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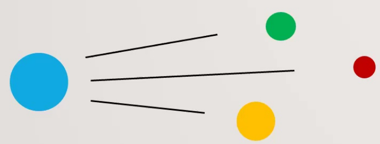

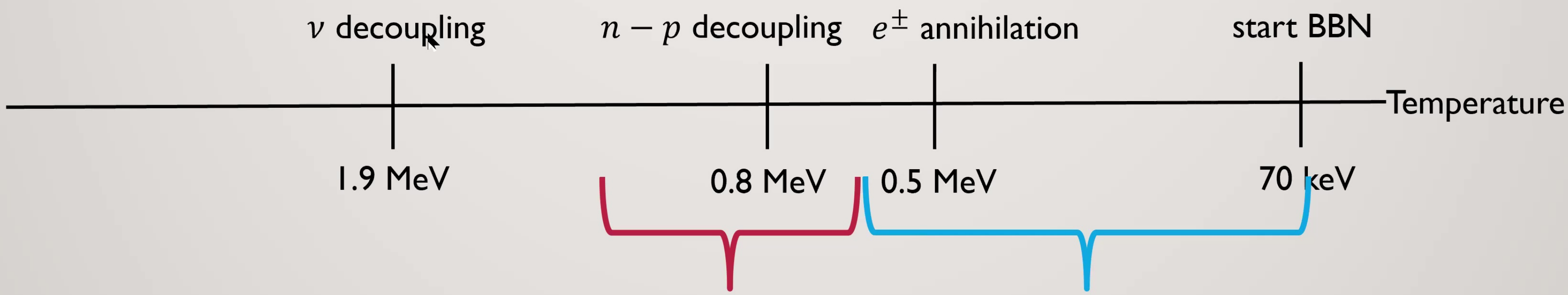

$n + \nu_e \leftrightarrow p + e^-$ $\quad$ $n \rightarrow p + e^- + \bar{\nu}_e$

$n + e^+ \leftrightarrow p + \bar{\nu}_e$

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

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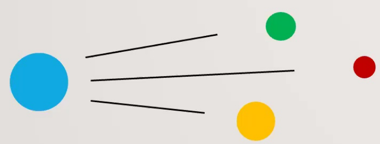

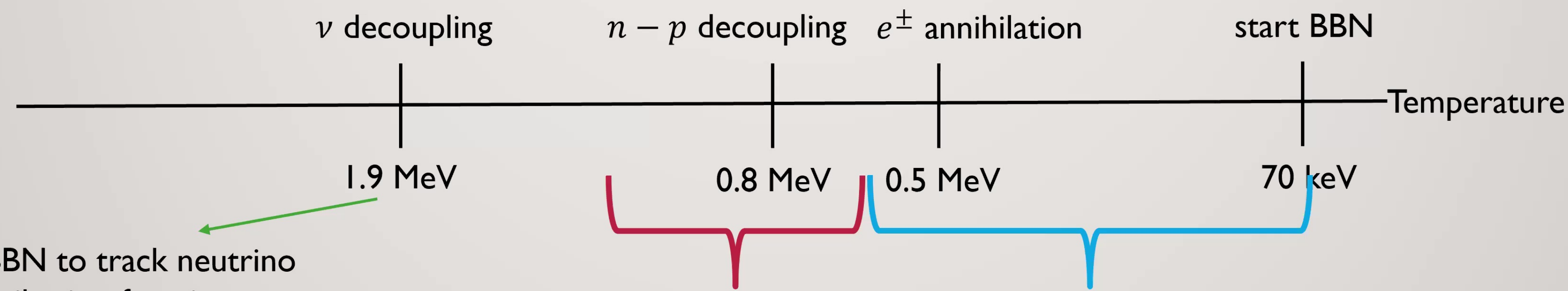

pyBBN to track neutrino distribution function

$$n + \nu_e \leftrightarrow p + e^- \quad n \to p + e^- + \bar{\nu}_e$$

$$n + e^+ \leftrightarrow p + \bar{\nu}_e$$

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

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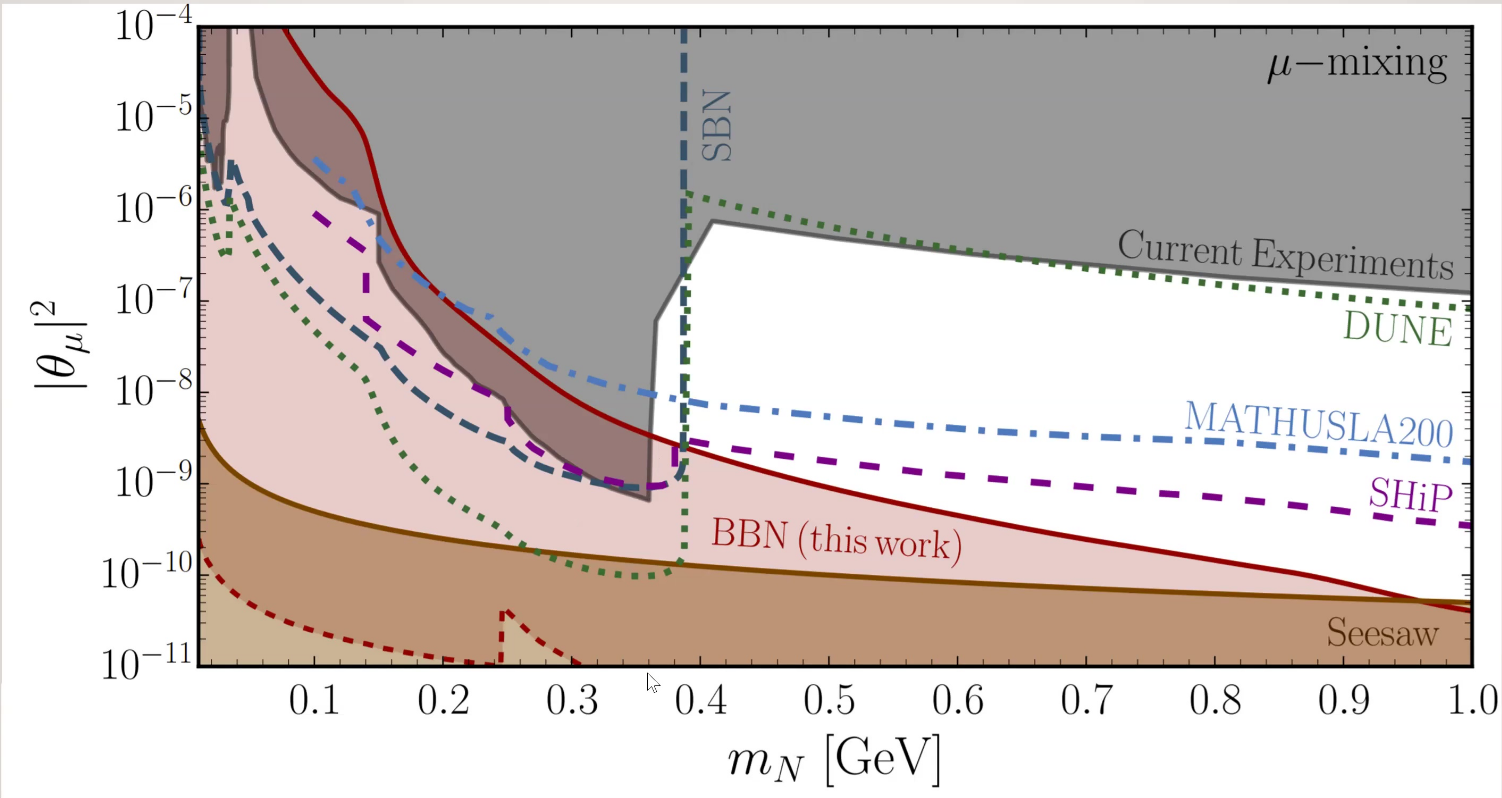

2006.07387

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Detour:

How do SNs that decay mostly into active neutrinos affect N_{eff} ?

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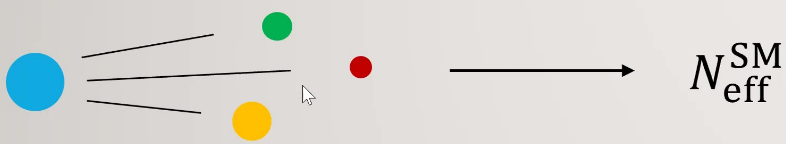
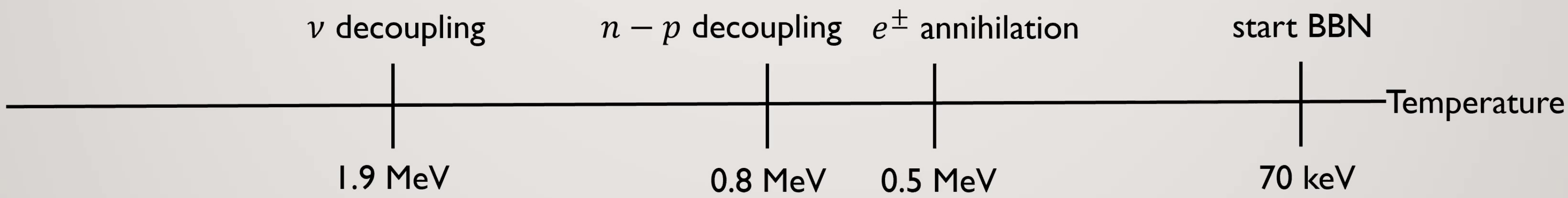
What happens if a FIMP decays into ν before ν decoupling?





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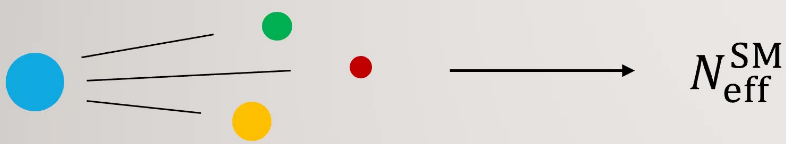
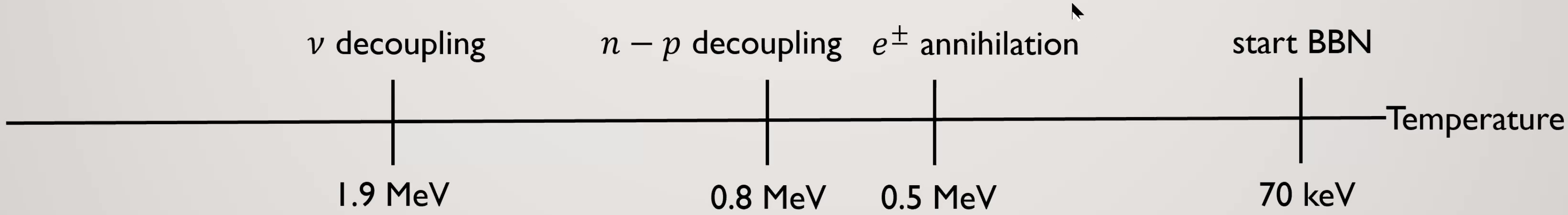
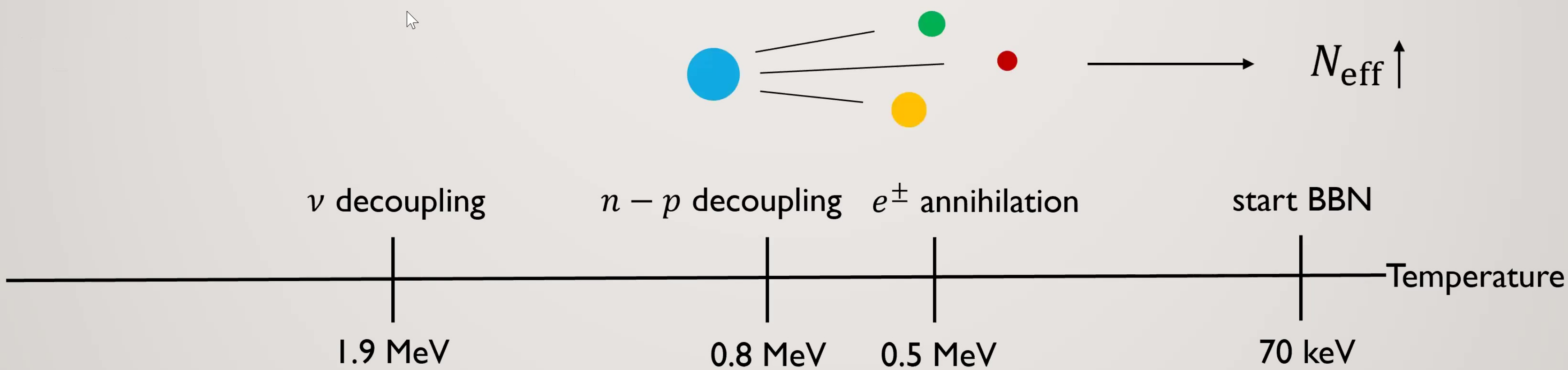
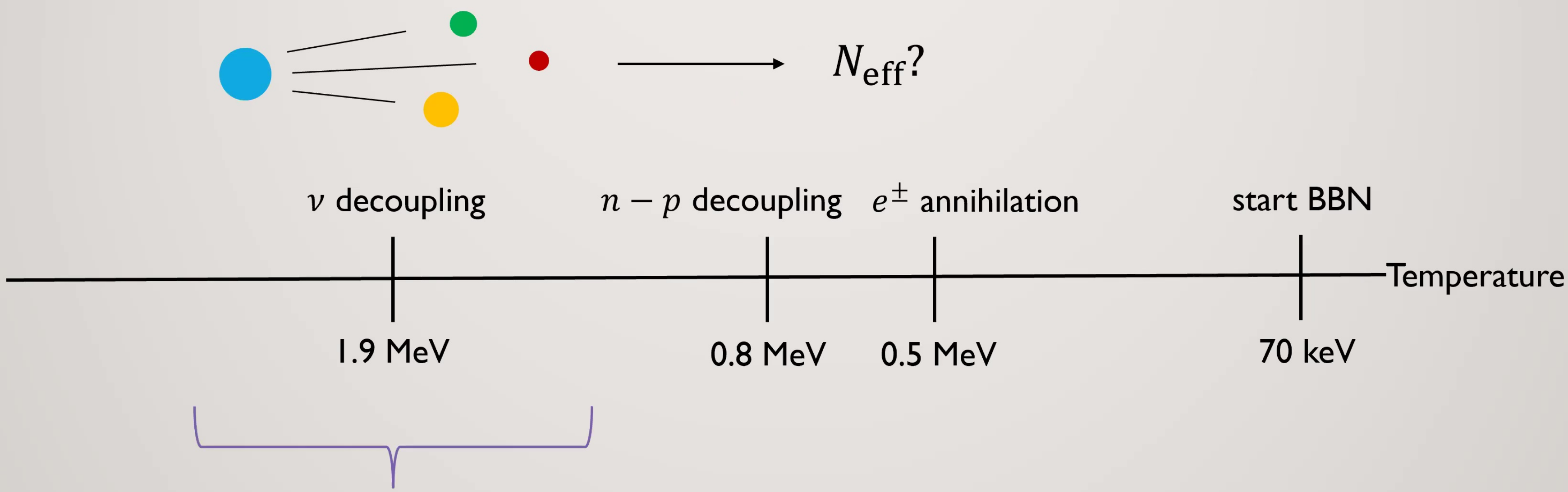




What happens if a FIMP decays into ν after ν decoupling?



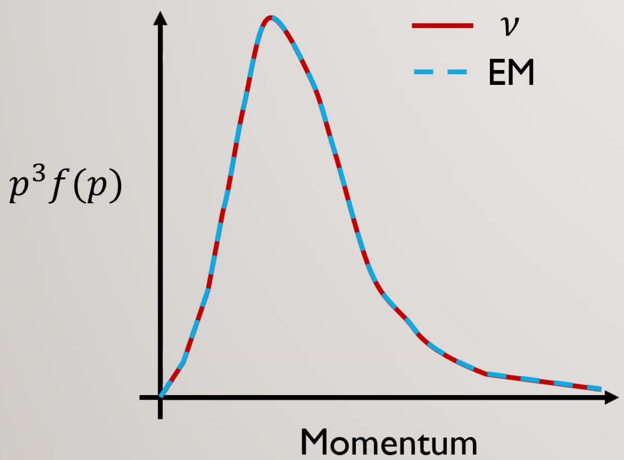
What happens if a FIMP decays into ν during ν decoupling?



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

What is the actual mechanism behind this effect?

Before FIMP decay



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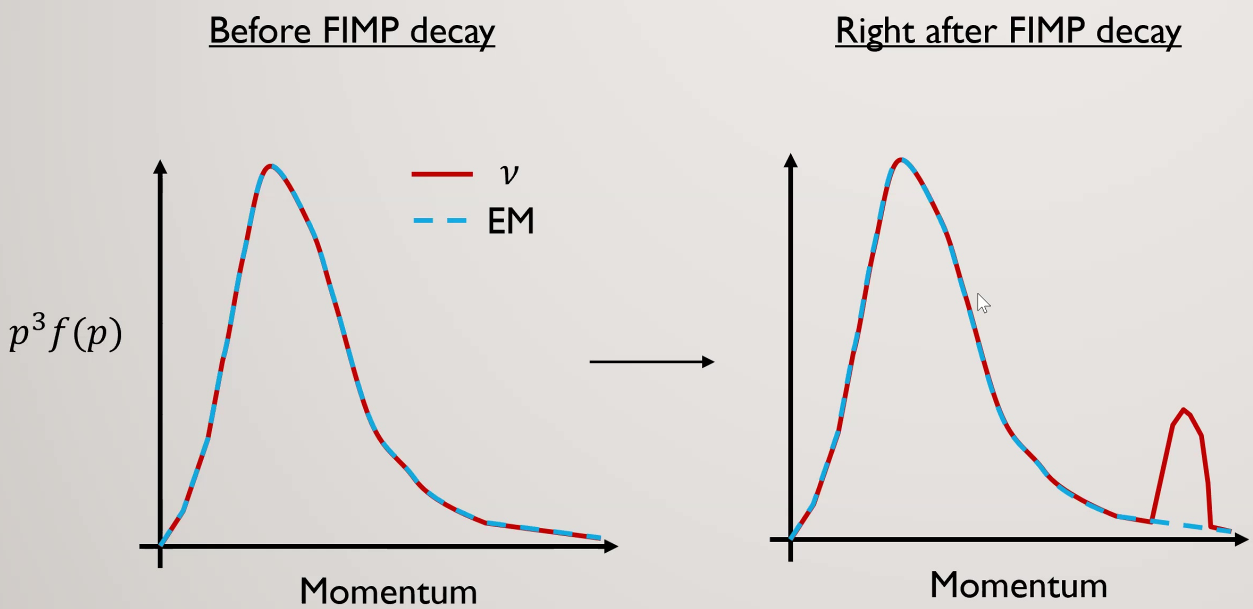
What is the actual mechanism behind this effect?



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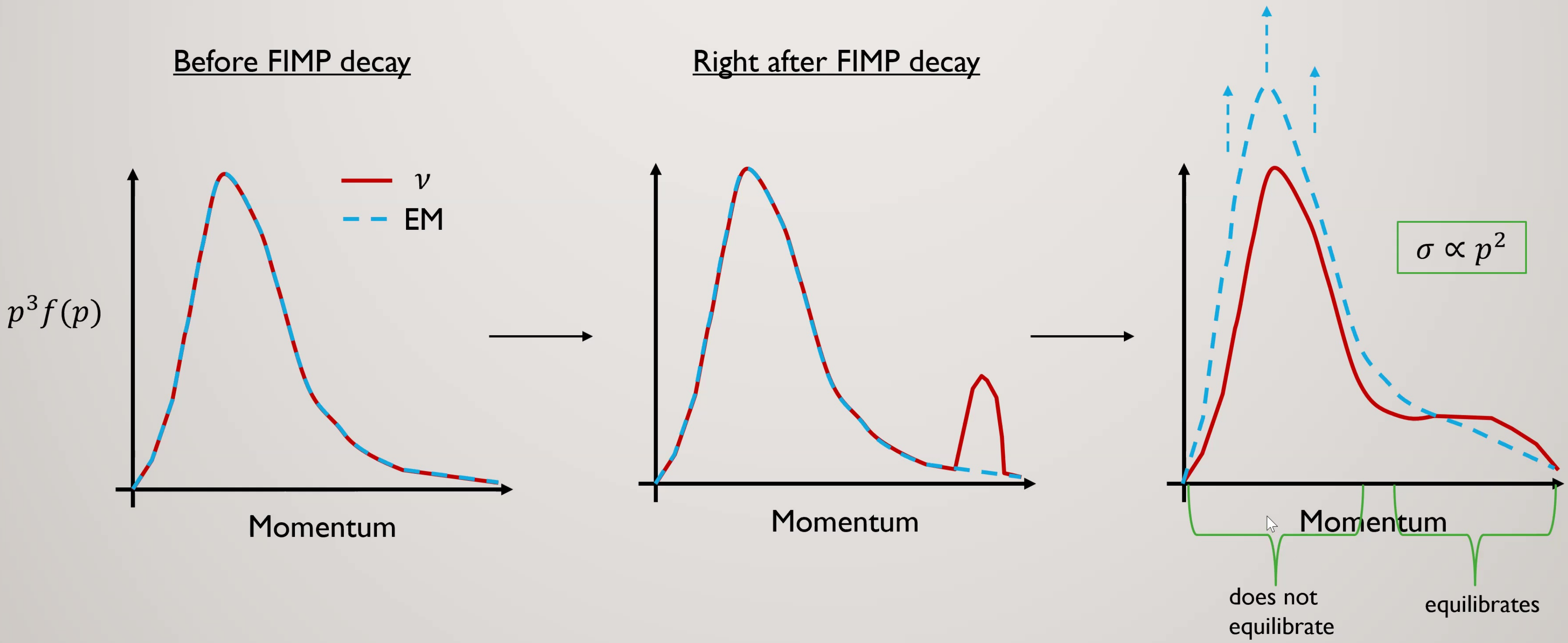

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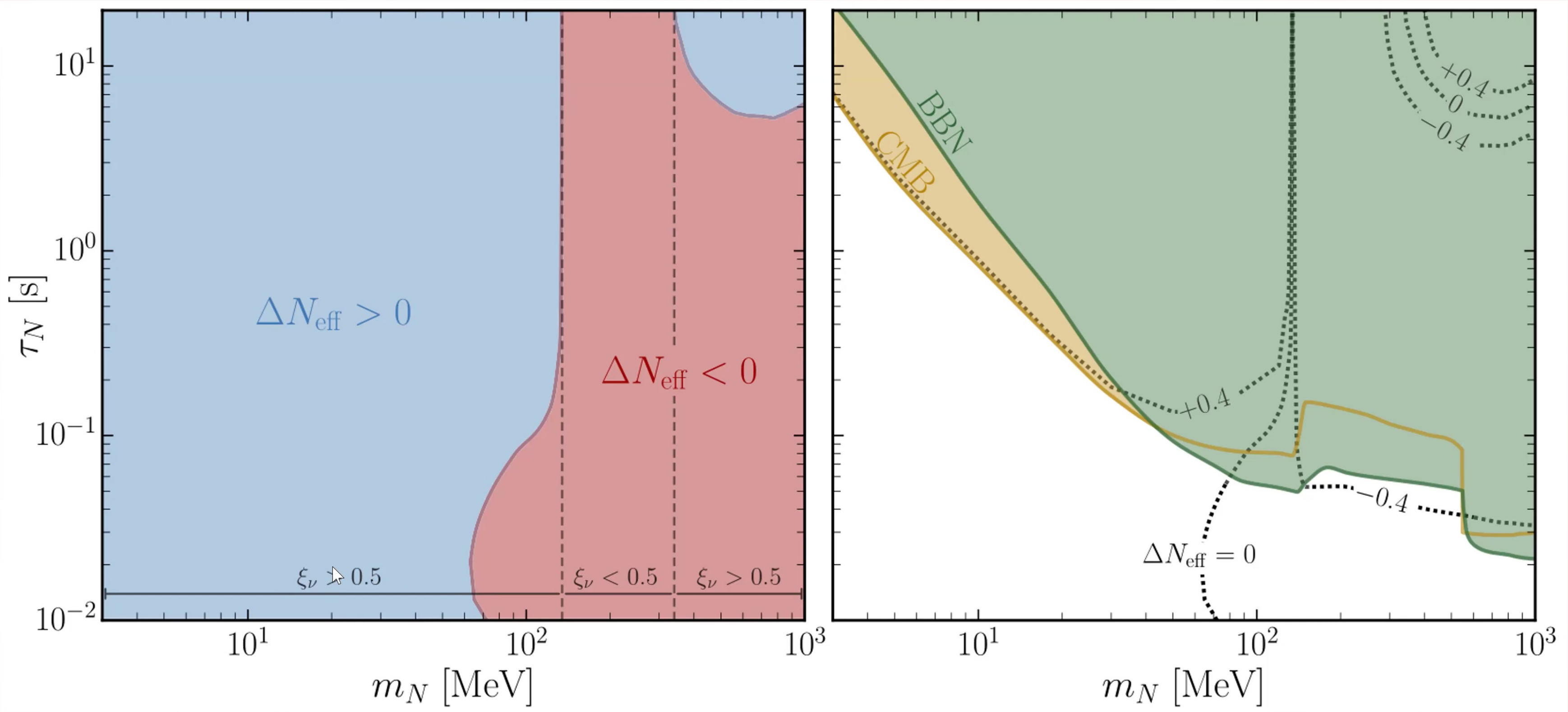

2103.09831

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Signatures at neutrino experiments?

- With current CMB data, we are not able to measure sum of neutrino masses

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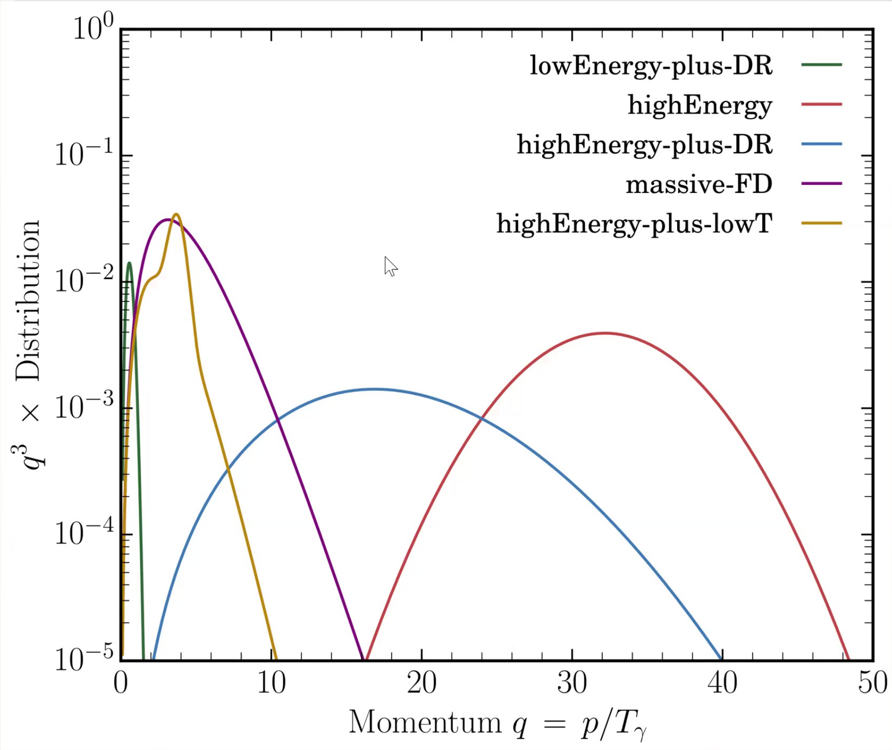

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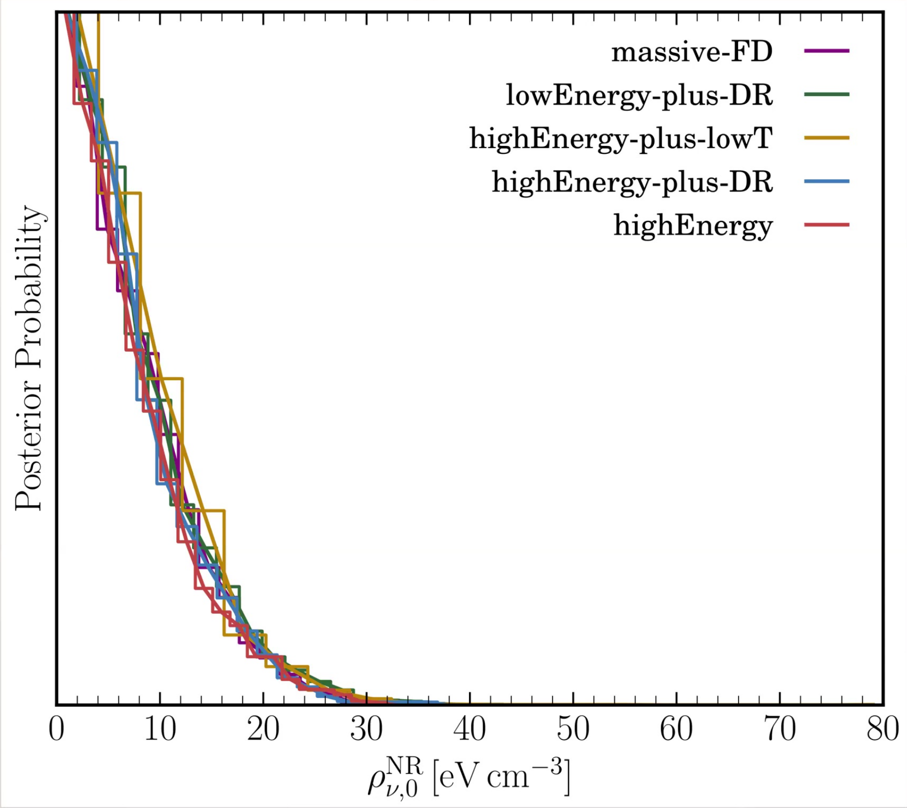
Signatures at neutrino experiments?

- With current CMB data, we are not able to measure sum of neutrino masses



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)

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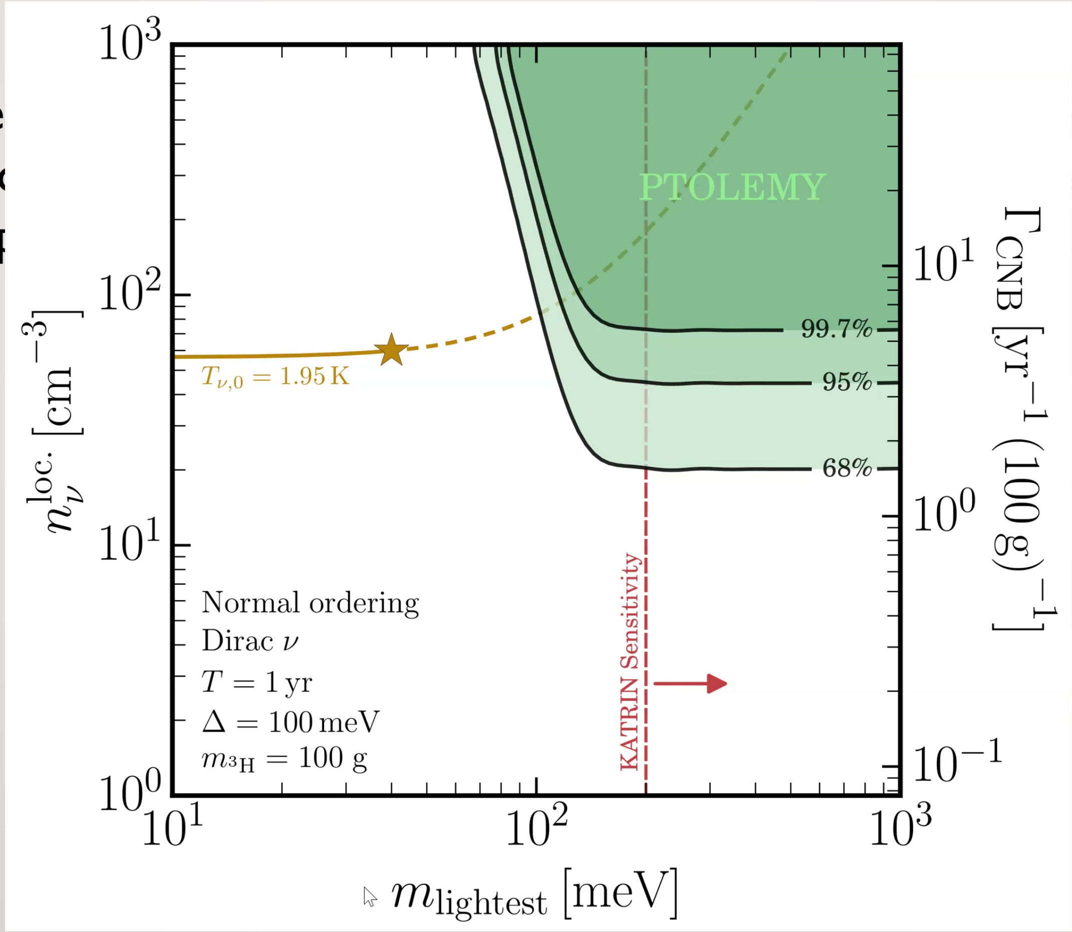
Signatures at neutrino experiments?

- With curre… …utrino masses
- Cosmologi… …y, Lesgourgues et al., to appear)
- Detection … …, PTOLEMY,…



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

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SUMMARY

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

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THANK YOU ☺

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