Origins of (neutrino-ish) Dark Matter in the Matter Power Spectrum

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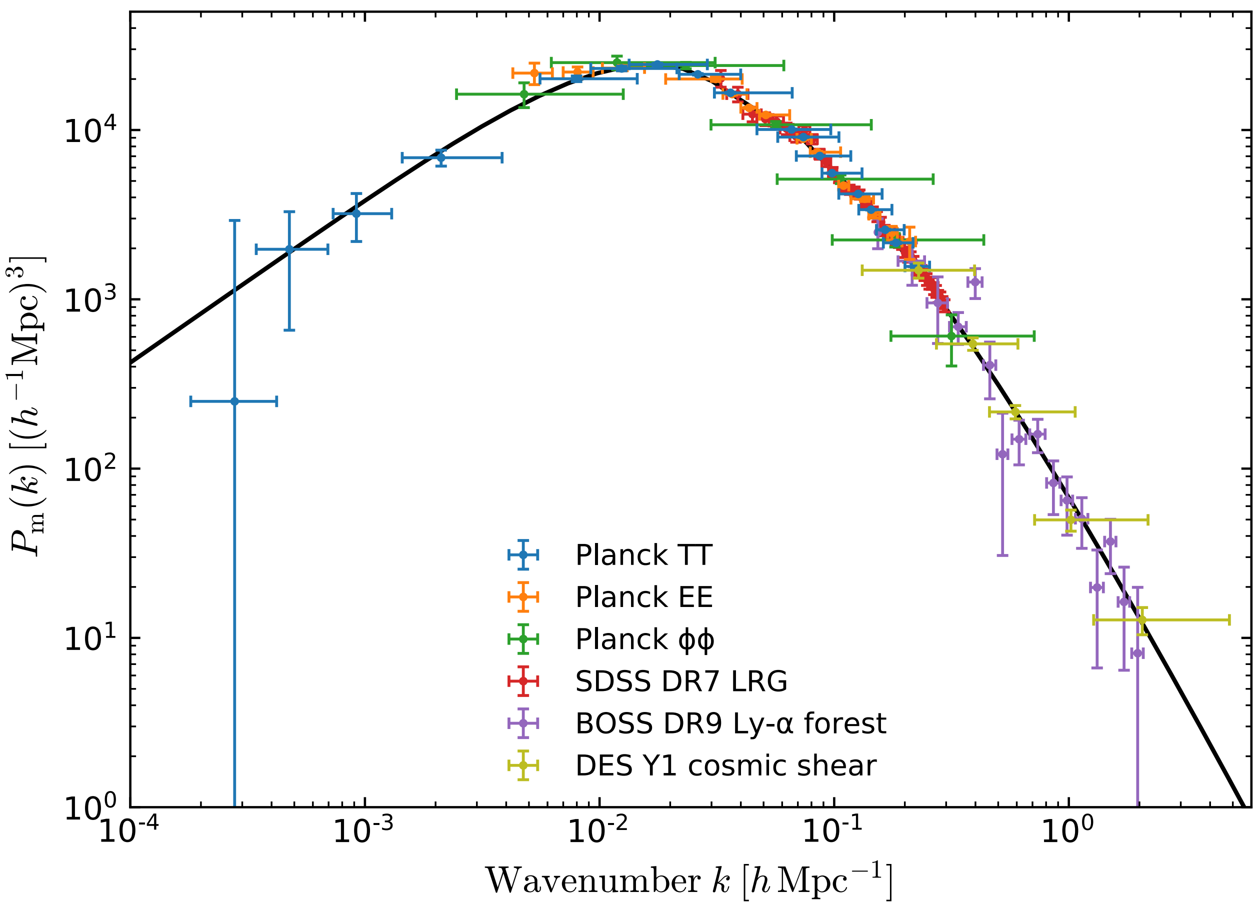
Carleton University

Neutrinos in Cosmology and Astrophysics

TRIUMF, March 2024

This talk is about

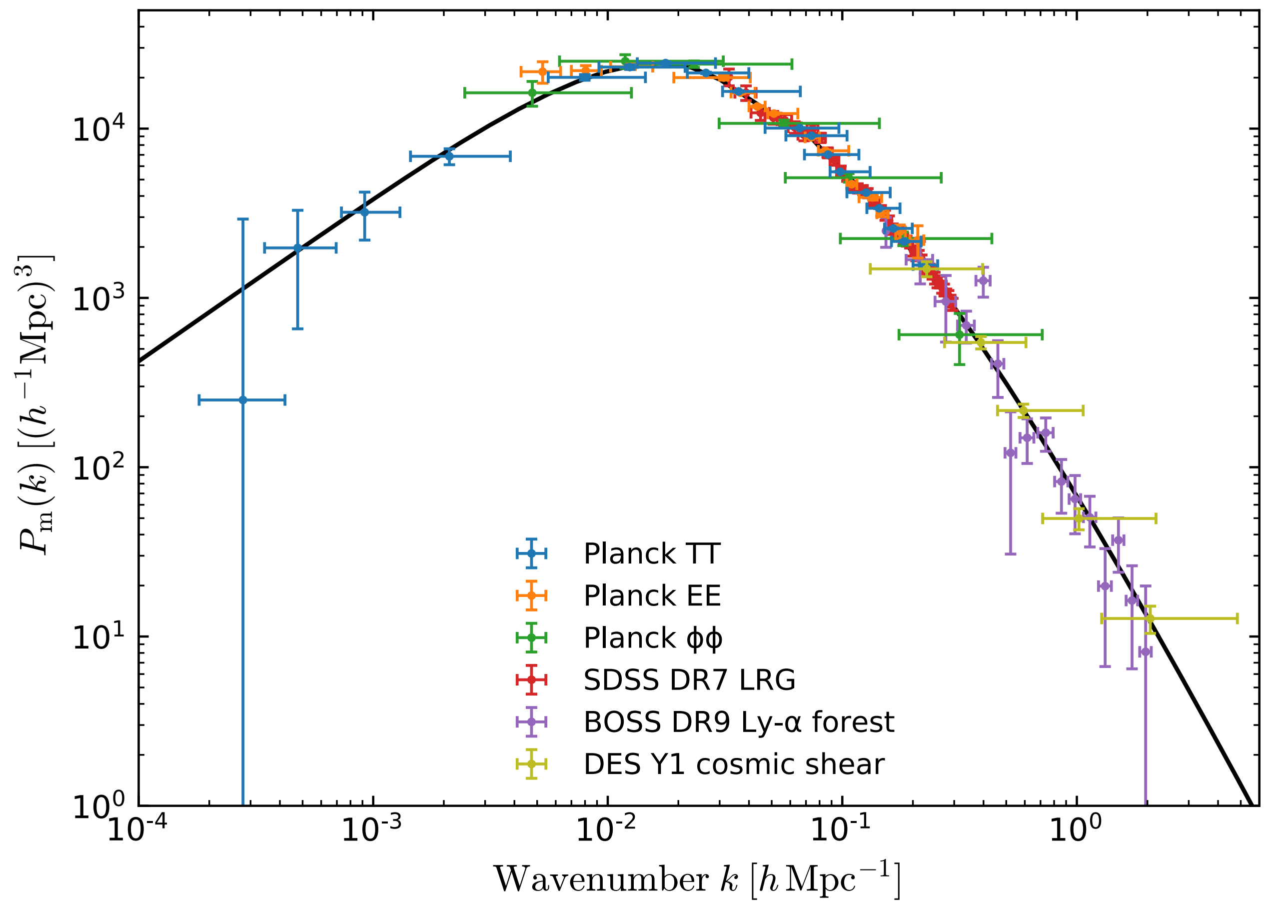


$\longrightarrow$ $\mathcal{L}_{\mathrm{DM}}$

Cosmological observations

Fundamental physics

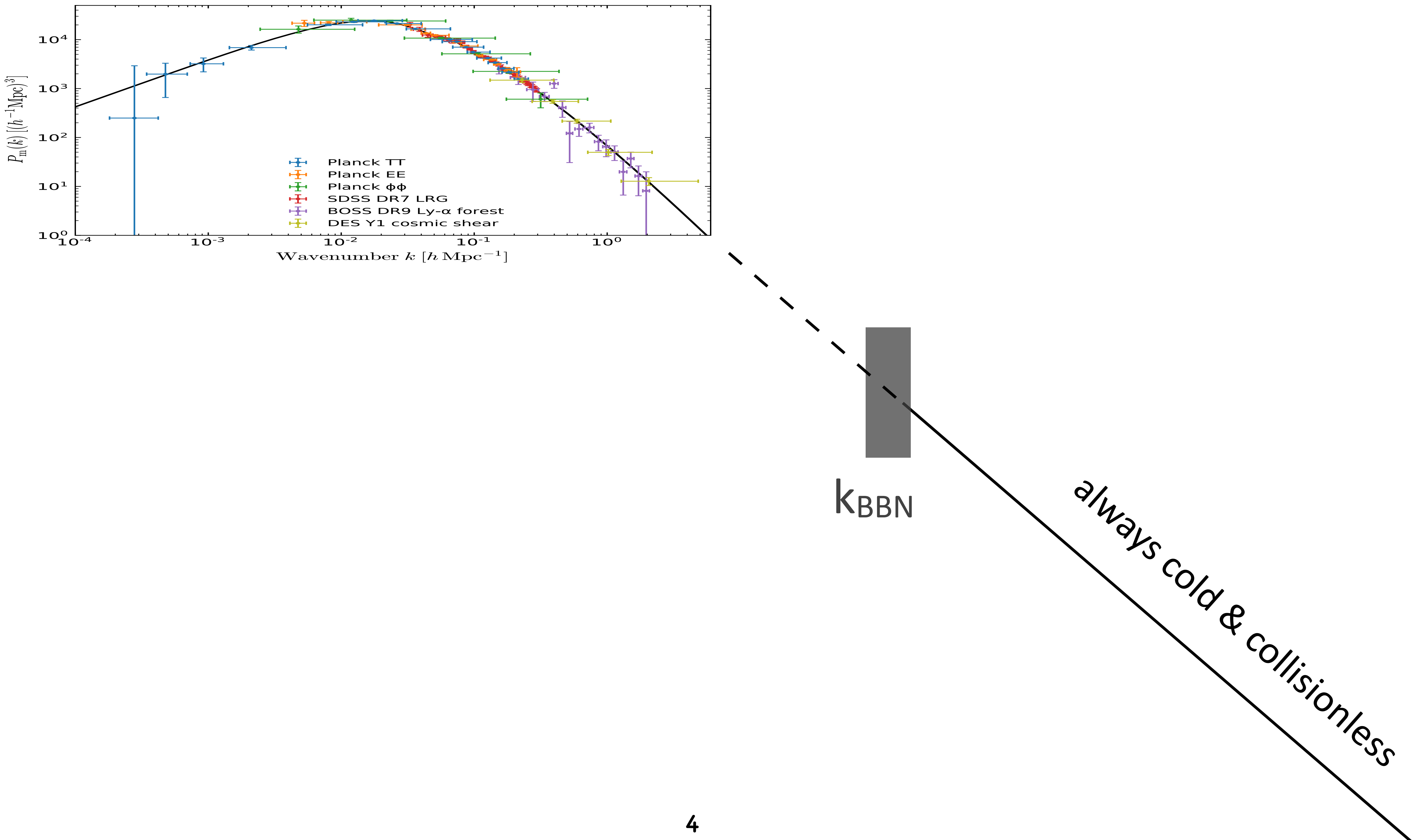
Linear Matter Power Spectrum



PLANCK IMAGE GALLERY (2018)

- Dark matter cold and collisionless throughout entire history.
- Log (linear) growth during radiation (matter) dominated era.
- Peak: matter-radiation equality.
- Linearly evolve primordial fluctuations till today.

Dark Matter Model Predictions



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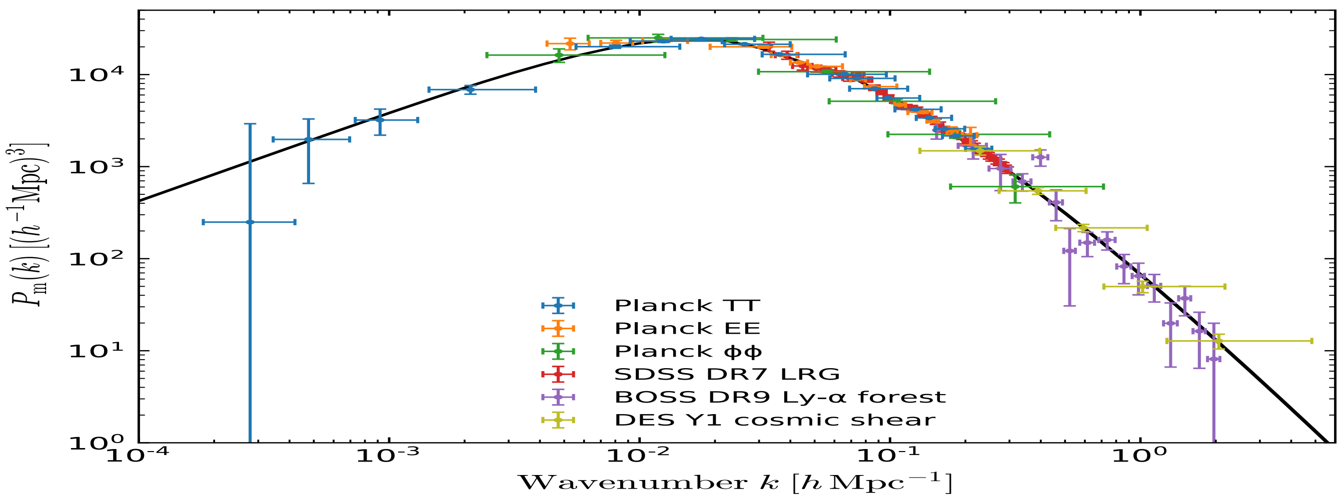
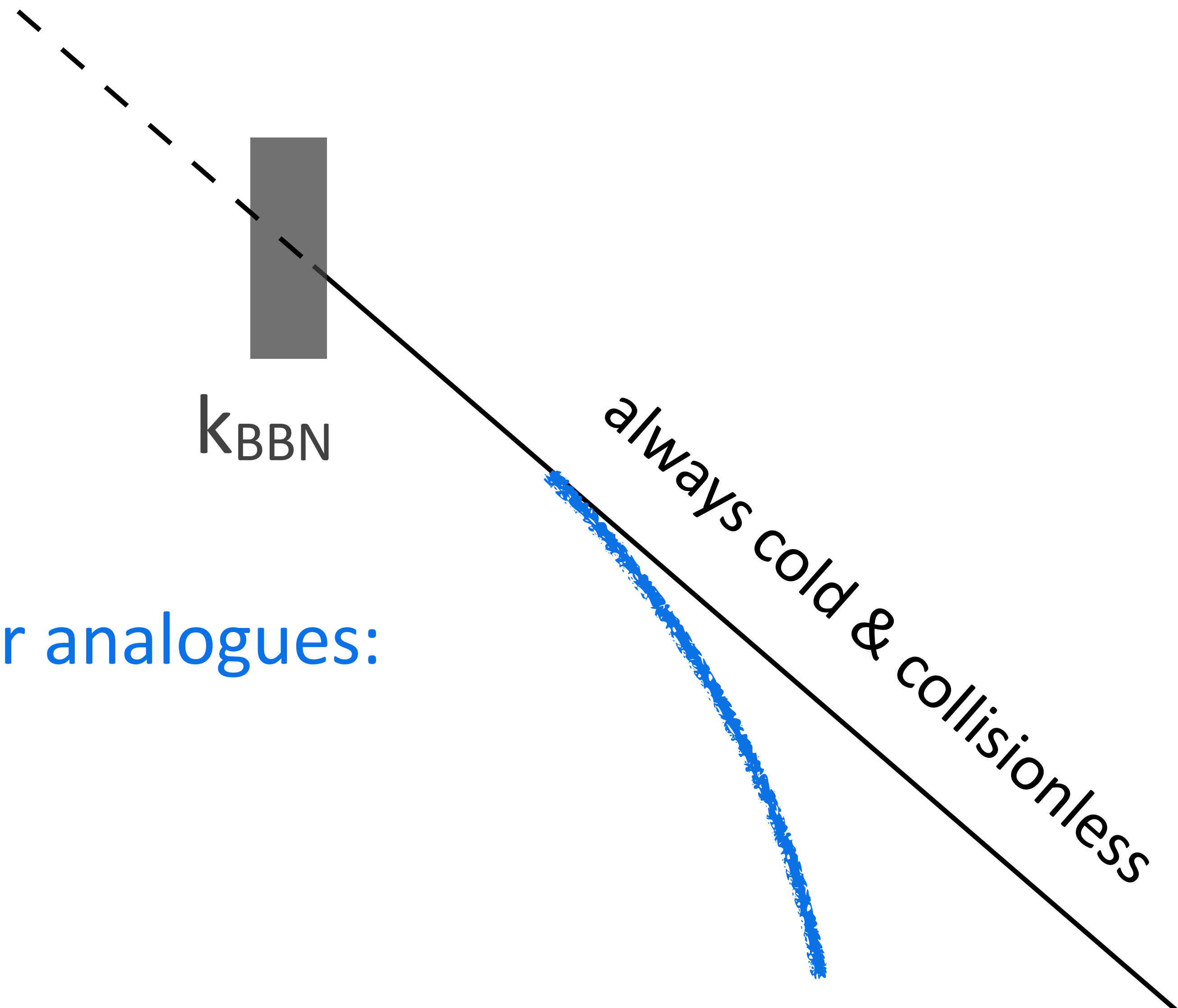


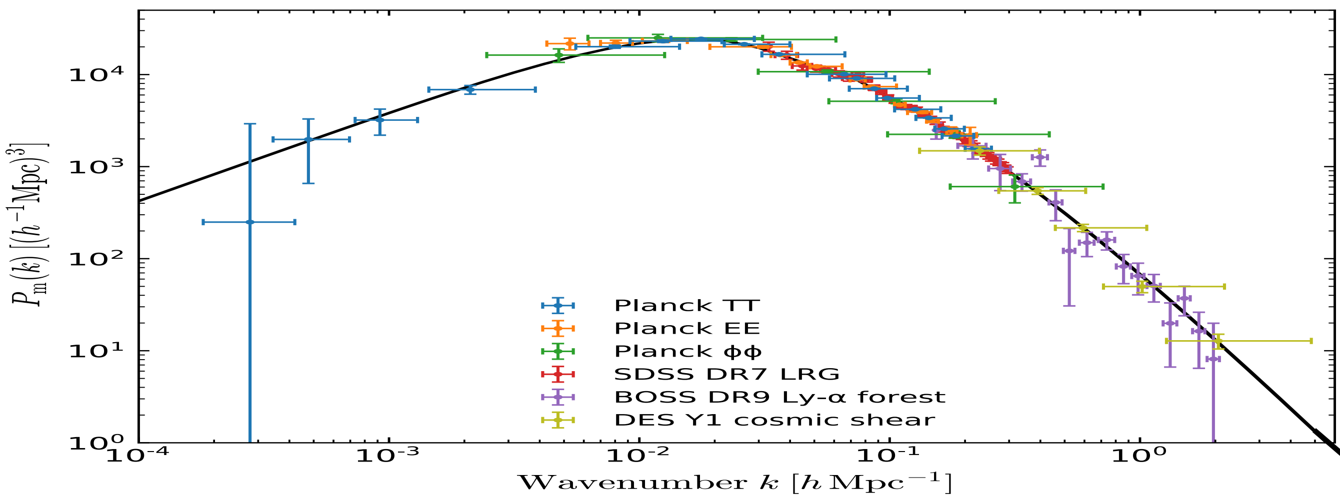
Collisional damping:

$k \sim aH(T_{\mathrm{kinetic\ dec}})$



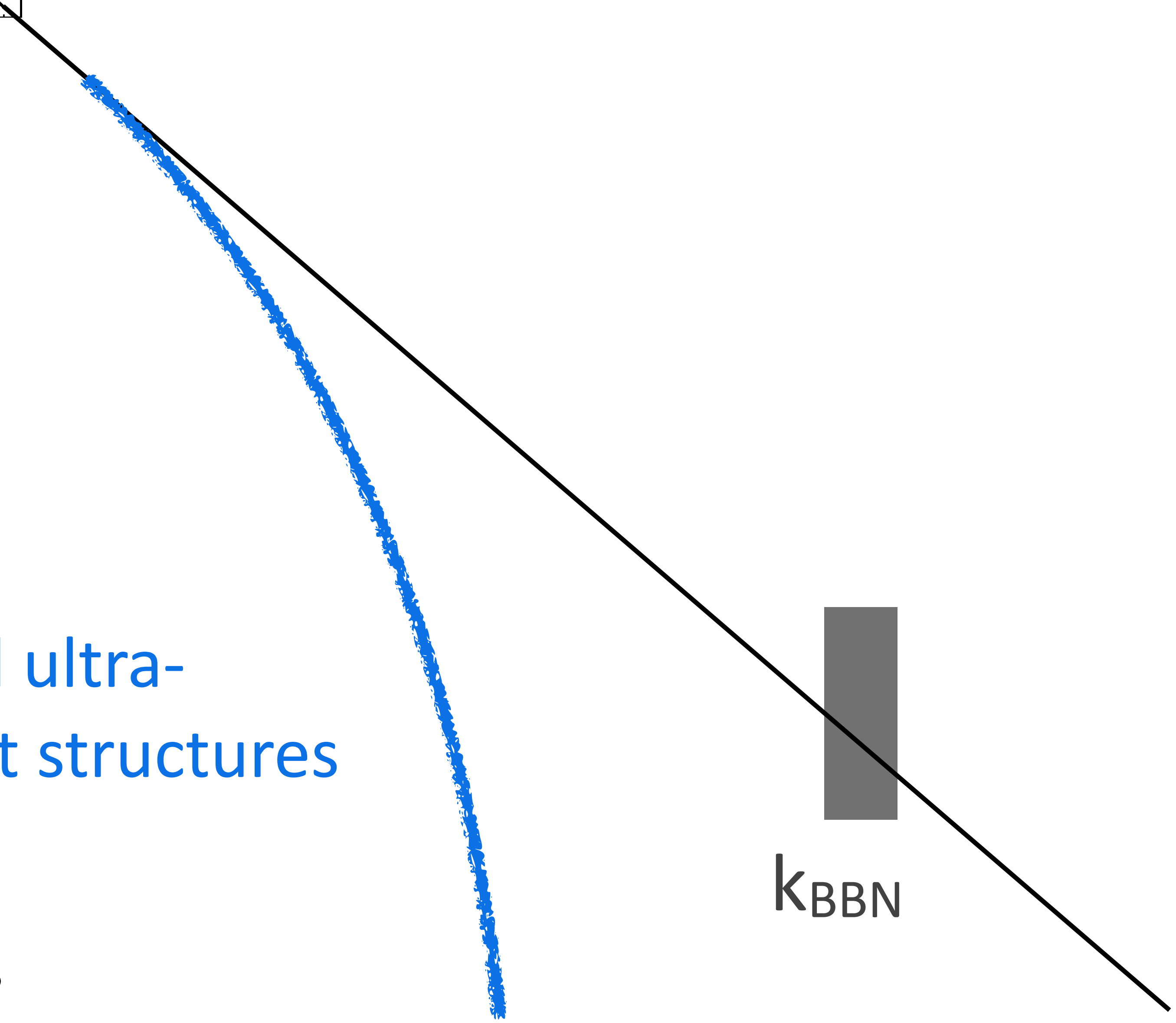
WIMP & dark sector analogues:
thermal freeze-out

Collisionless Damping

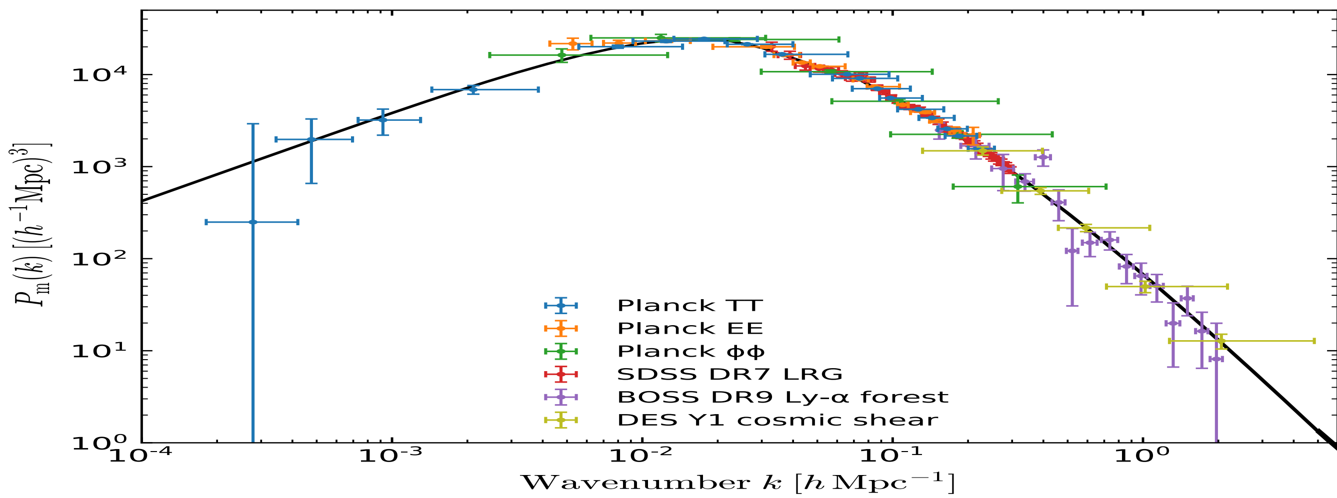


damping due to free streaming: $k \sim aH(T_{NR})$

Lighter dark matter produced ultra-relativistically can smooth out structures

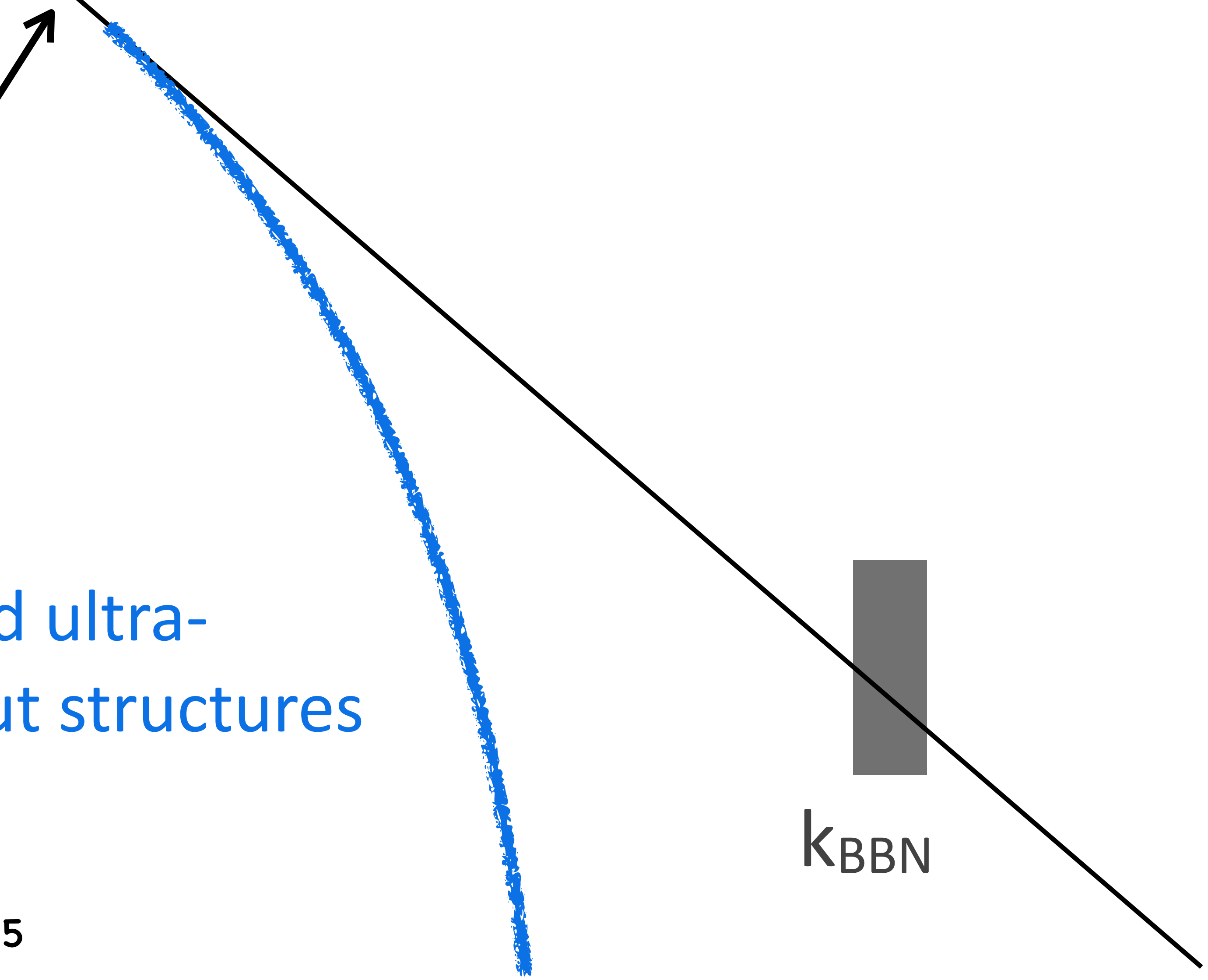


Collisionless Damping



damping due to free streaming: k ~ aH(T_{NR})

MW satellite
Lyman-α
Strong lensing



Lighter dark matter produced ultra-relativistically can smooth out structures

Warm Dark Matter

Primordial phase space distribution (while DM still relativistic)

$$f = \frac{1}{e^{E/T_{\mathrm{WDM}}} + 1}$$

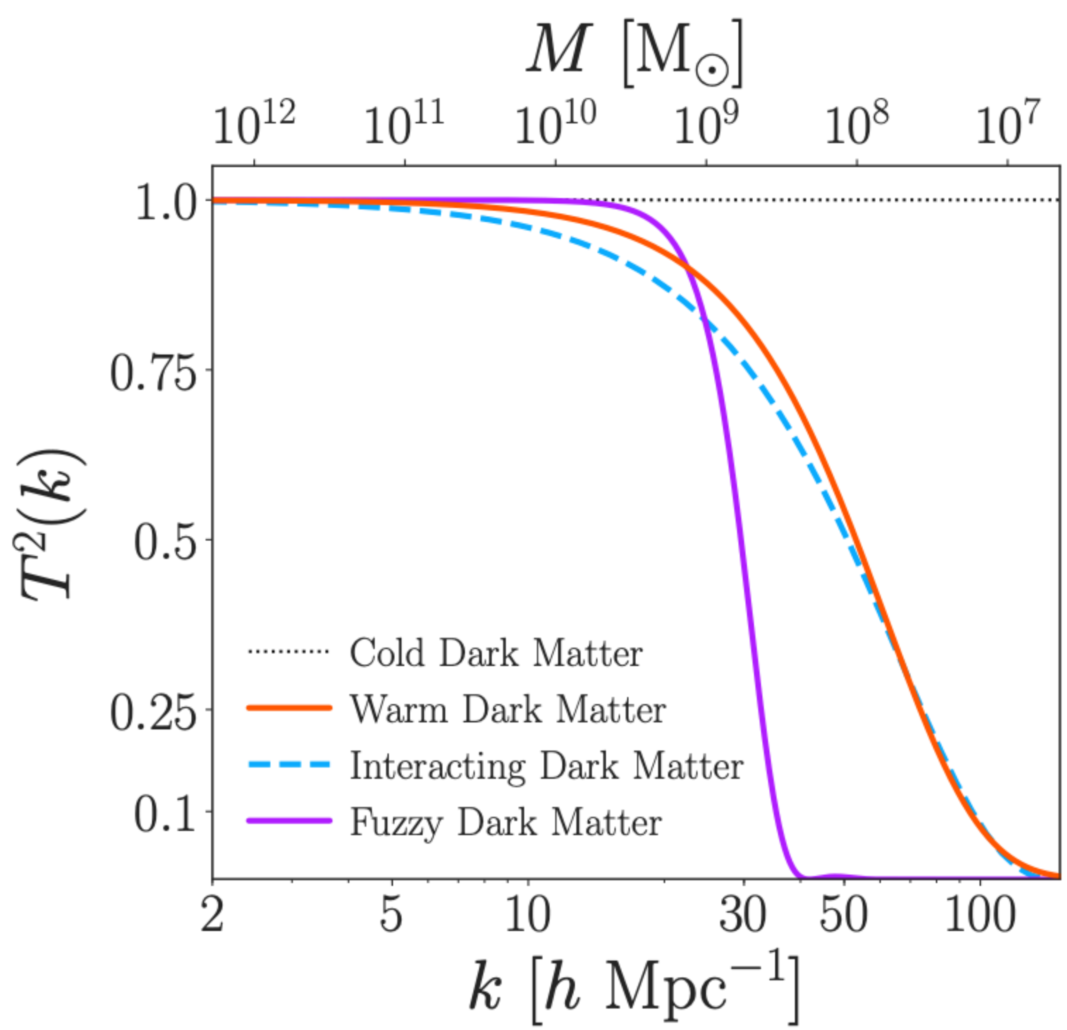
To comprise 100% of dark matter we need

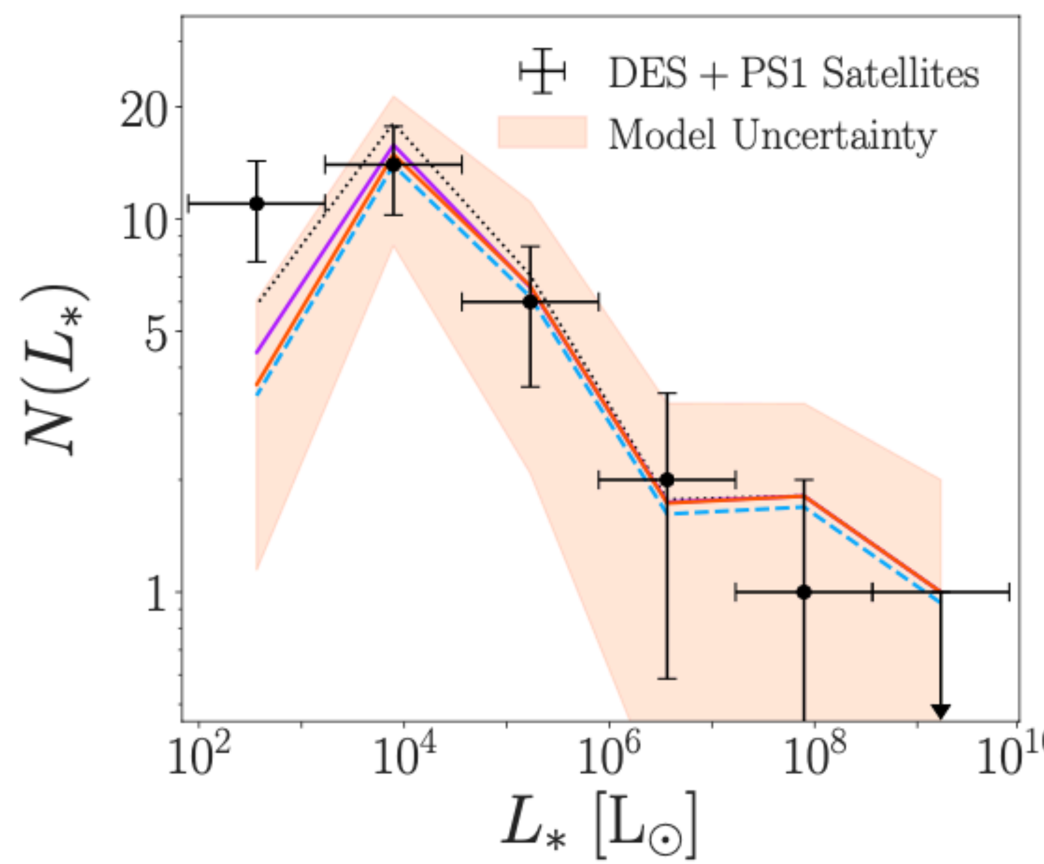
$$T_{\mathrm{WDM}} \simeq 0.086 T_\gamma \left(\frac{6.5\,\mathrm{keV}}{m} \right)^{1/3}$$

Reference mass 6.5 keV is the lower bound on WDM set by DES.

Substantially cooler than CMB photons.

DES limit: ultra-faint MW dwarfs





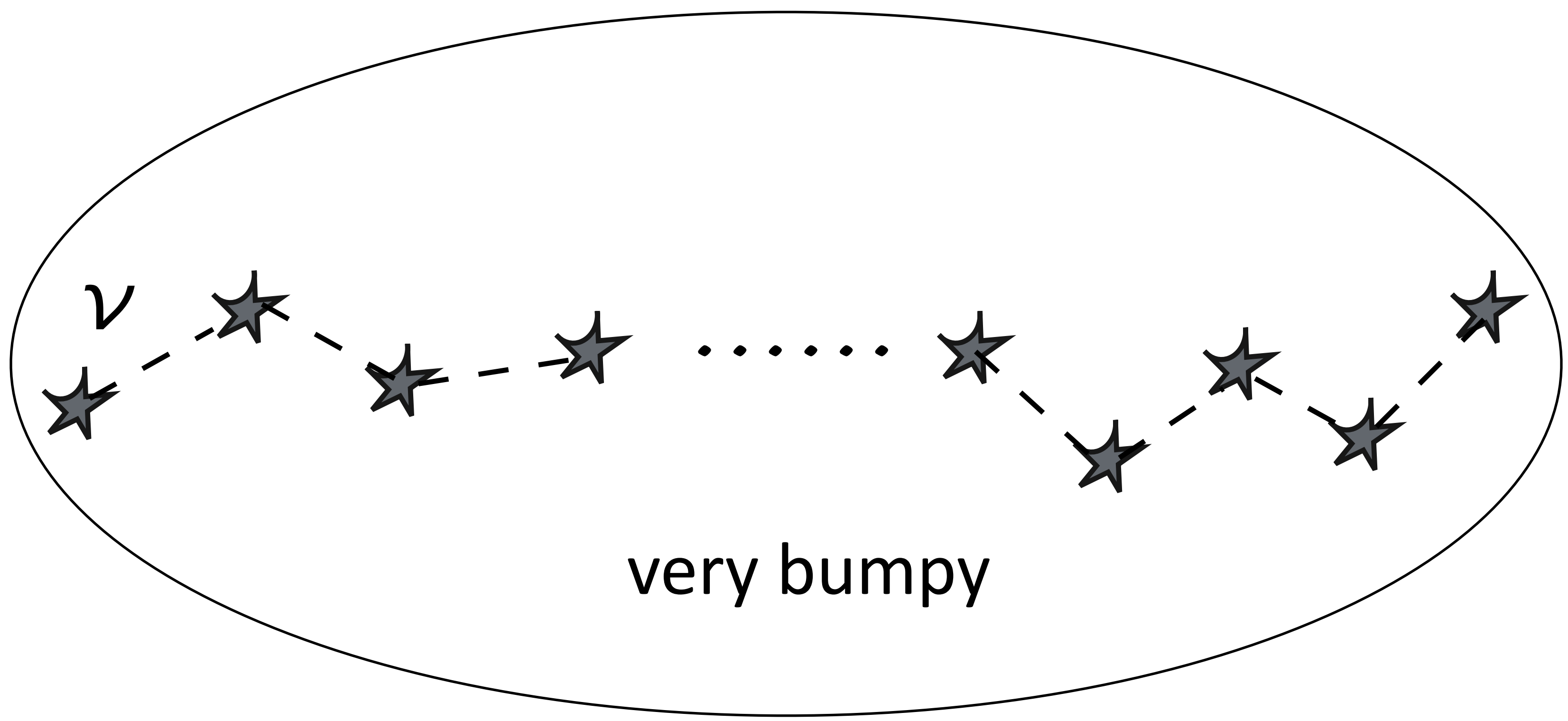
Mapping primordial PSD to P(k), and to subhalo mass function

Nadler et al, DES collaboration (PRL 2021)

Warmer than WDM

Sterile neutrino dark matter $\nu_4 = \nu_s \cos\theta + \nu_a \sin\theta$ produced via neutrino oscillation in early universe.

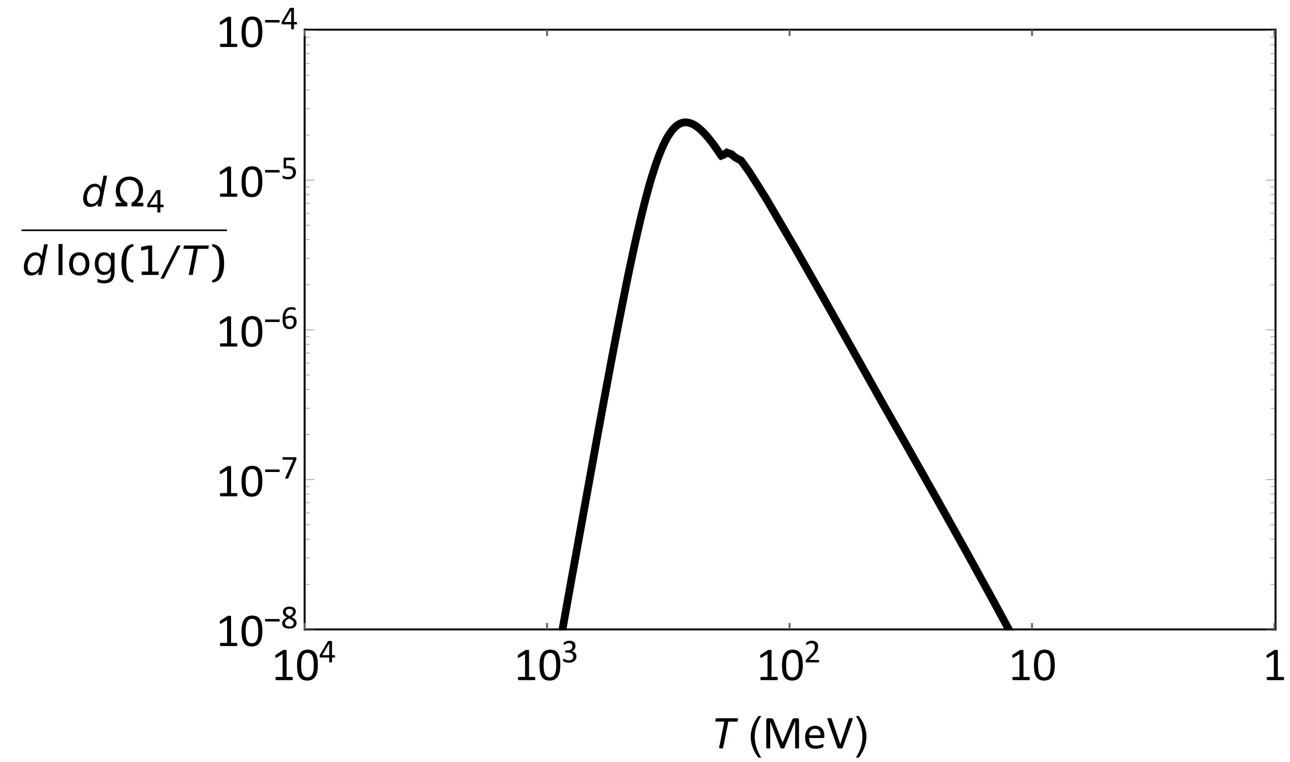
$$T \sim 100\,\mathrm{MeV}, \quad H^{-1} \sim 100\,\mathrm{km}, \quad l_{\text{mean free path}} < 1\,\mathrm{m}$$



Dodelson, Widrow (PRL 1994)

Collisional Oscillation

$$\Omega_4 \sim \int \frac{\Gamma_{\rm weak}}{H} \sin^2\theta_{\rm eff}(T)$$



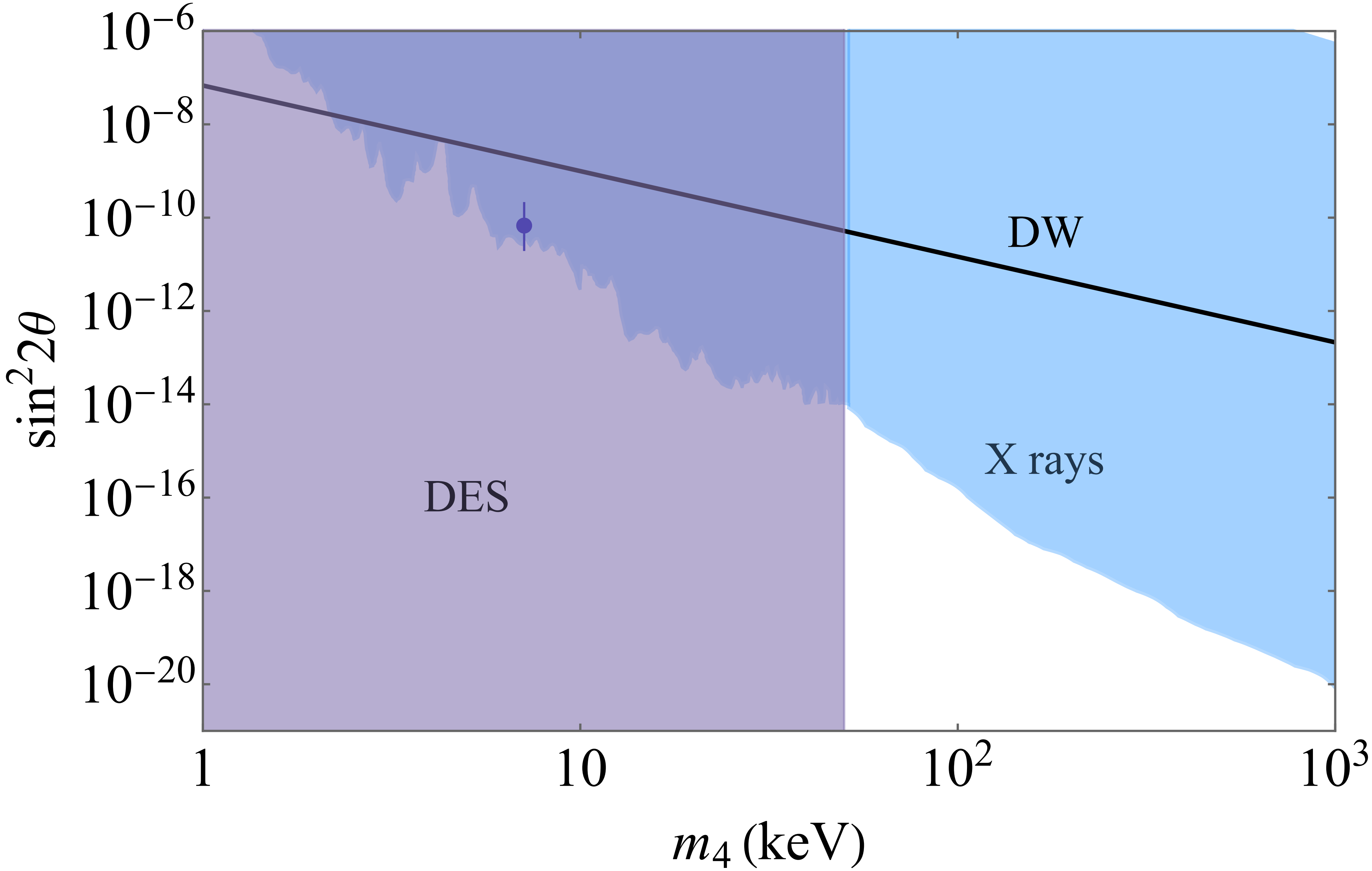
Resulting PSD function:

$$f \simeq \frac{C(\theta)}{e^{E/T_{\nu_4}} + 1}$$

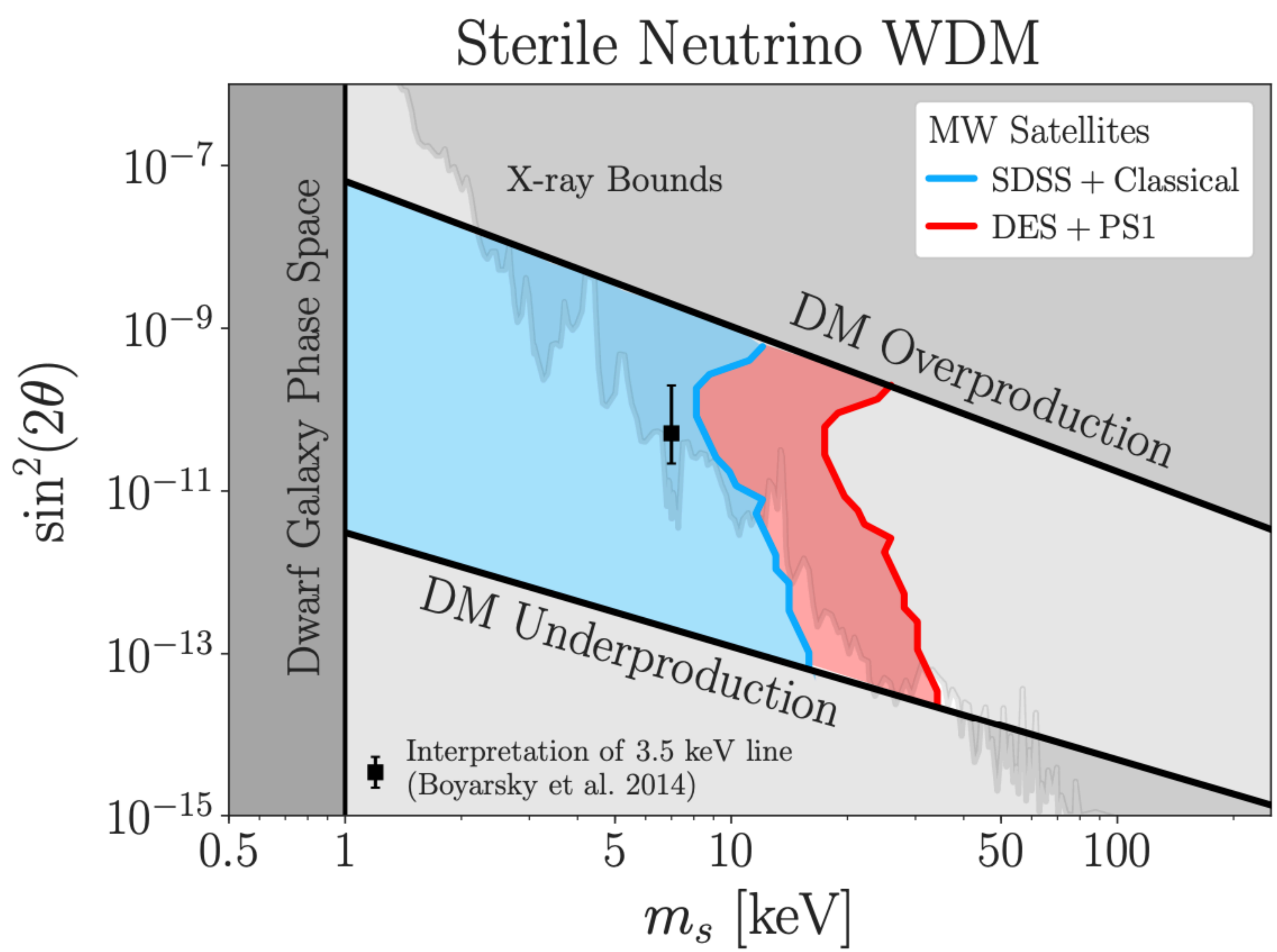
Warmer than WDM $\quad T_{\nu_4} \sim T_\nu \simeq 0.7 T_\gamma \quad C \ll 1$

DES result implies m > 50 keV for DW produced sterile neutrino DM.

DW Mechanism is Firmly Excluded



Shi-Fuller also Excluded by DES



Shi-Fuller: a lepton asymmetry triggers MSW resonant production.

She, Fuller (PRL 1999)

Neutrino Self-interaction Can Rescue

$$\Omega_4 \sim \int \frac{\Gamma_{\text{total}}}{H} \sin^2\theta_{\text{eff}}$$

($\Gamma_{\text{total}} = \Gamma_{\text{weak}}$ + novel interactions)

→ more oscillation baselines
not more X-rays

de Gouvêa, Sen, Tangarife, YZ (PRL 2020)

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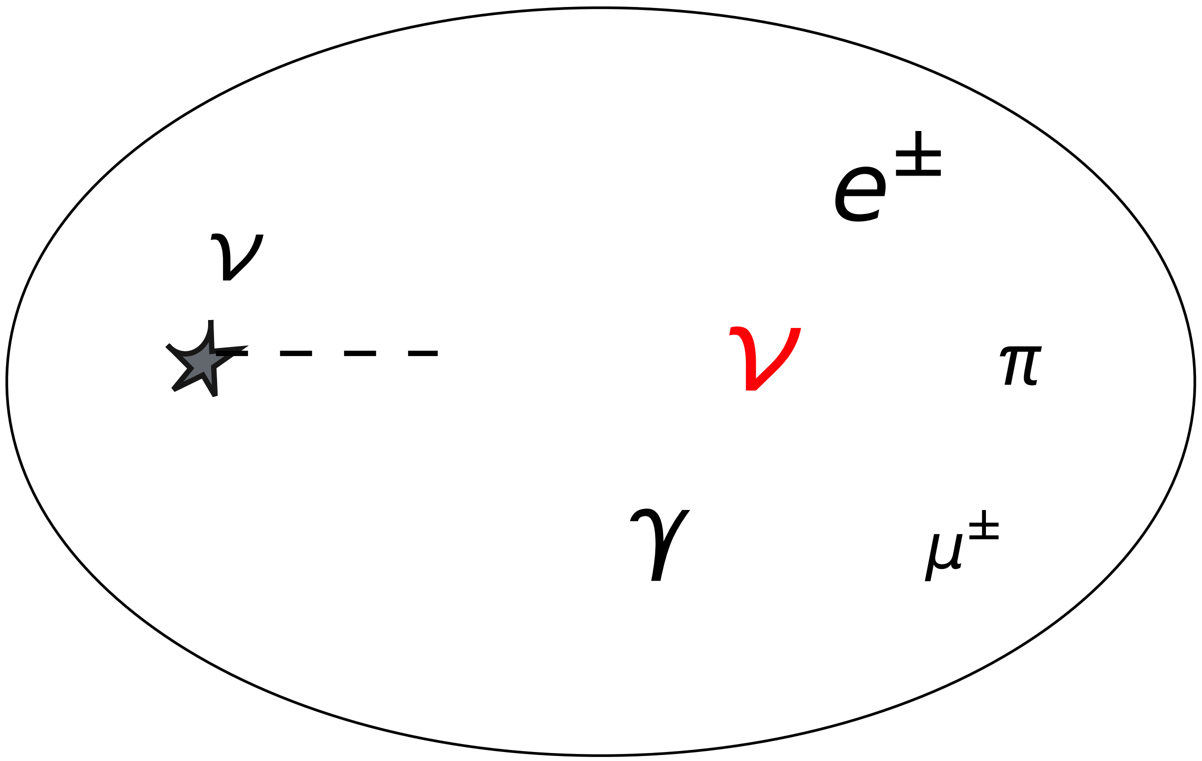

Universe@ T ~ 100 MeV

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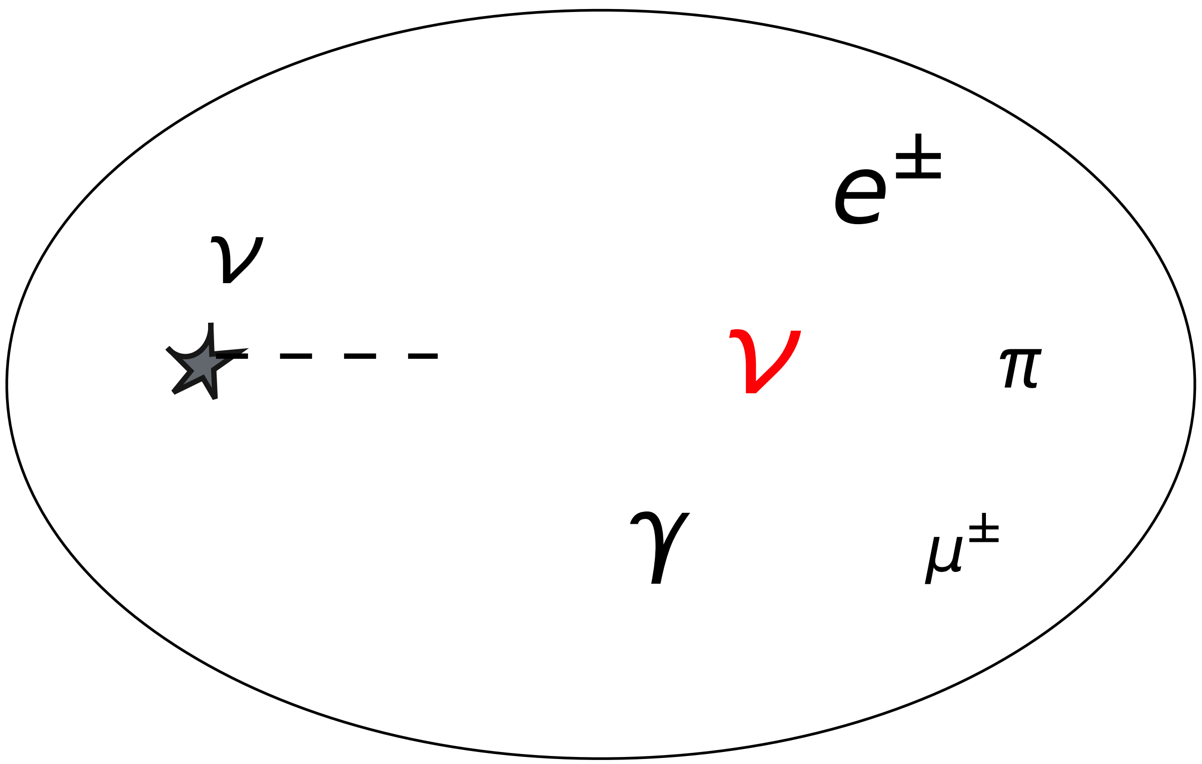

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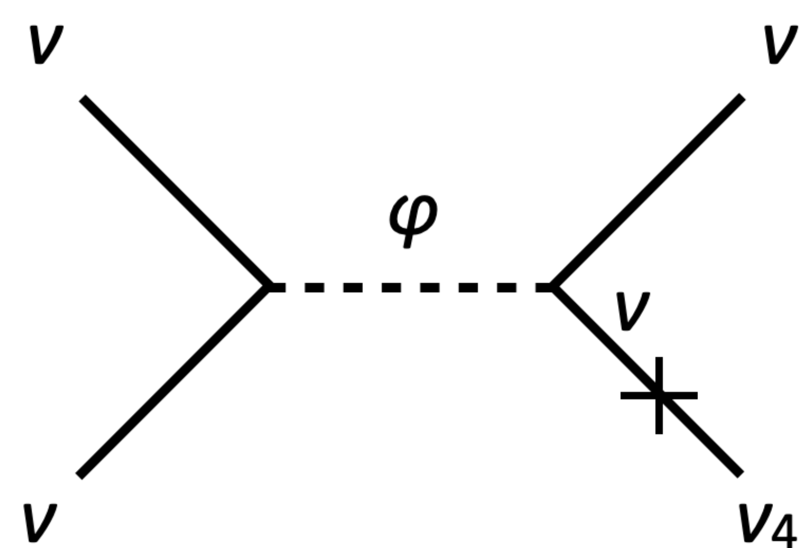
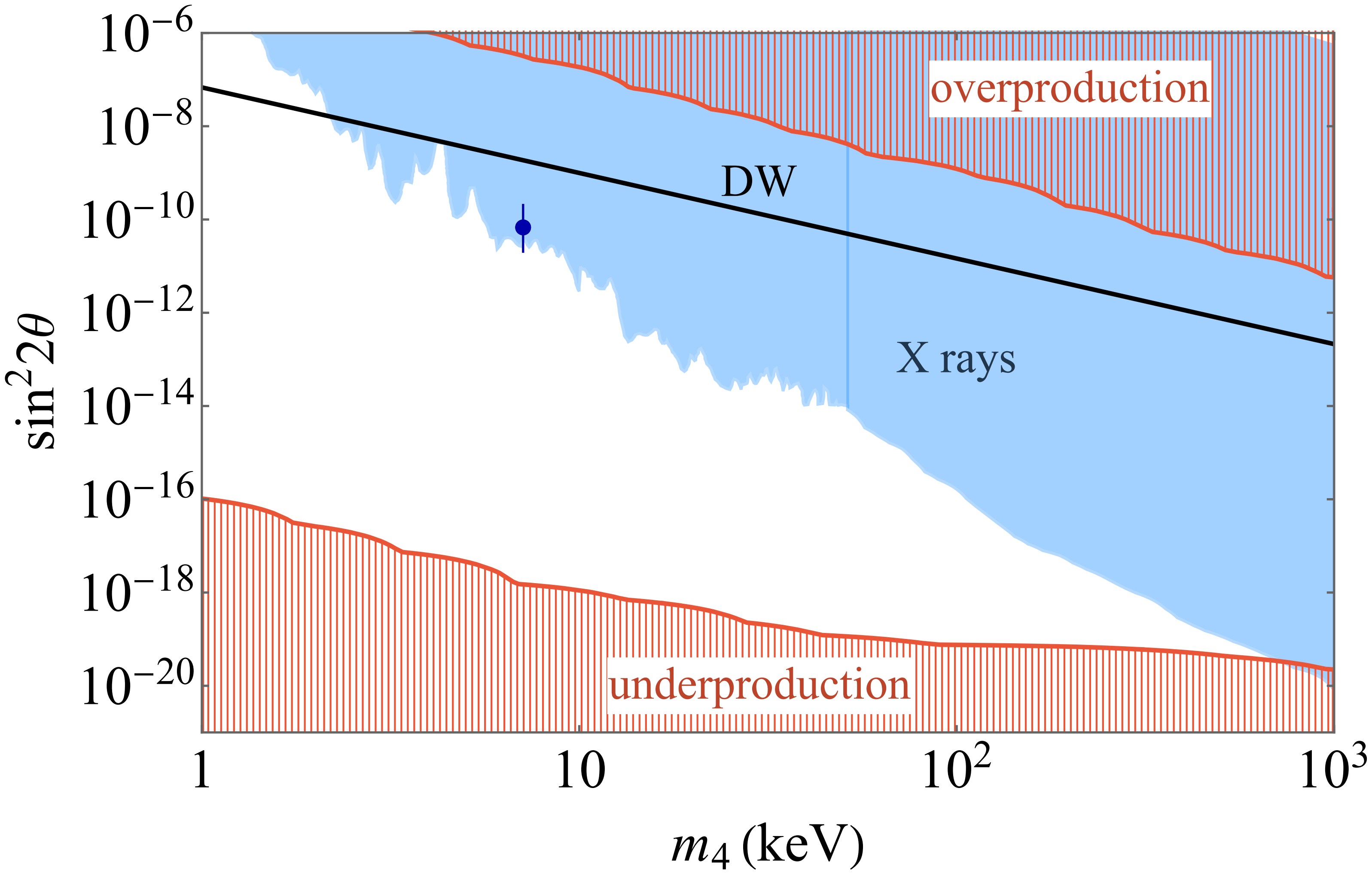
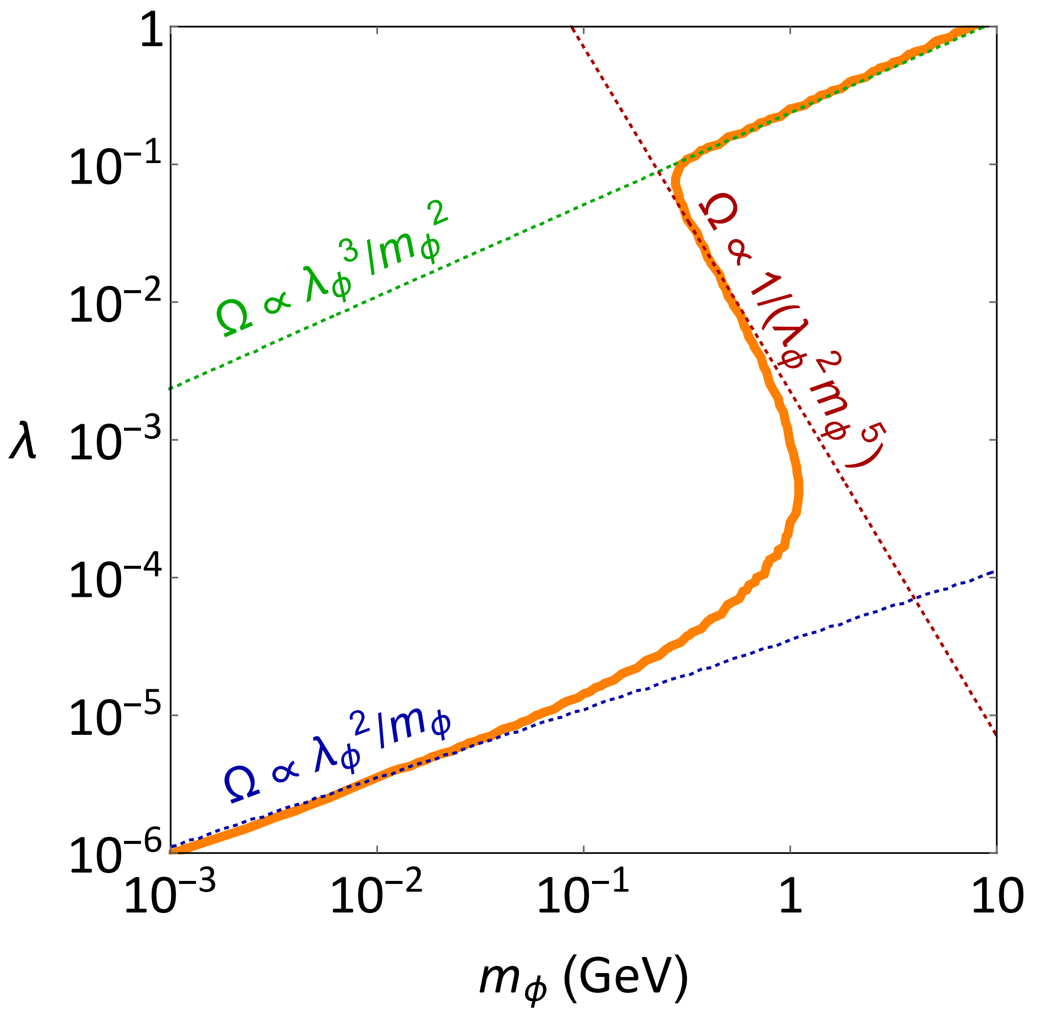


de Gouvêa, Sen, Tangarife, YZ (PRL 2020)

Wide Open Parameter Space





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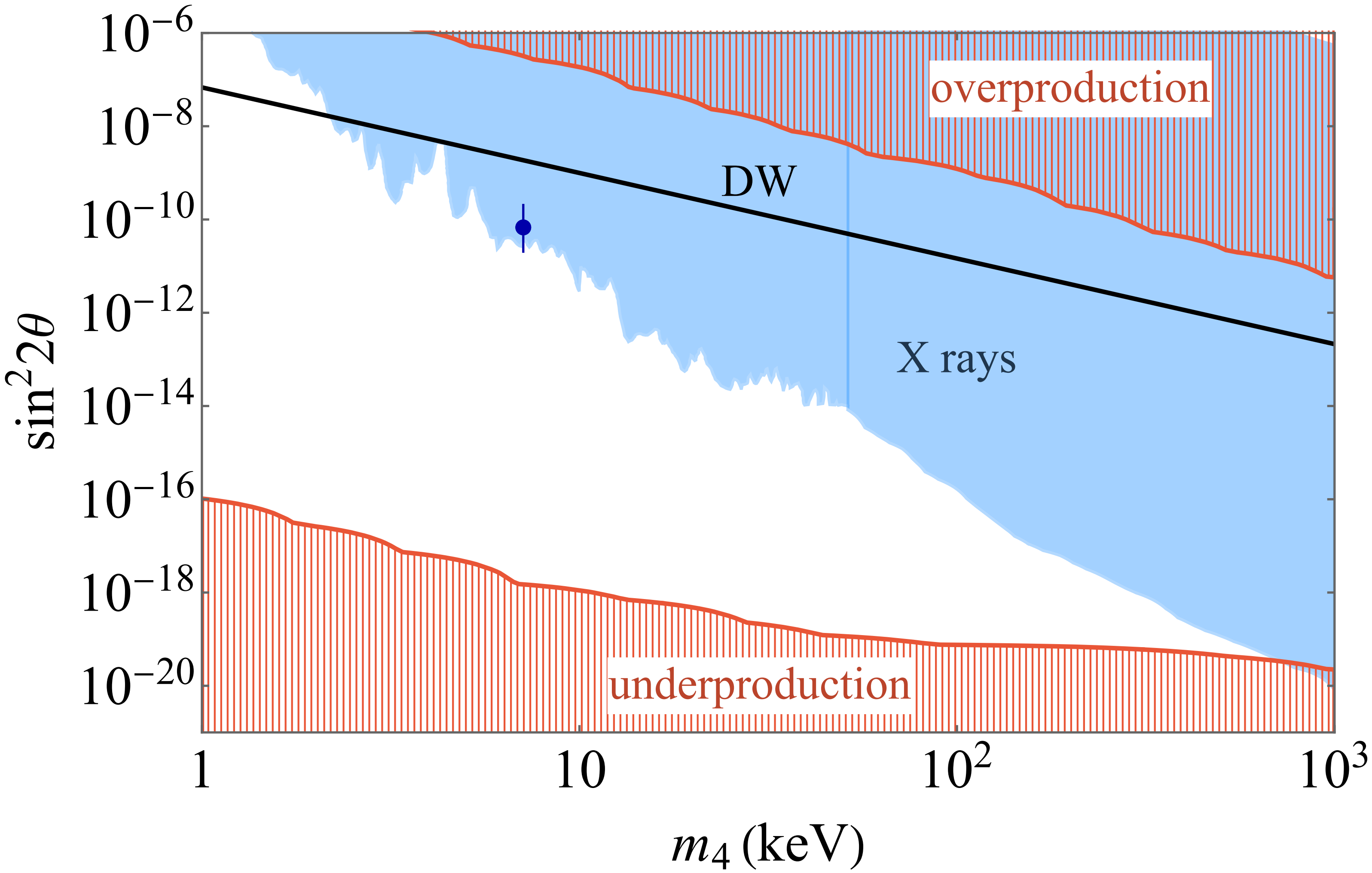
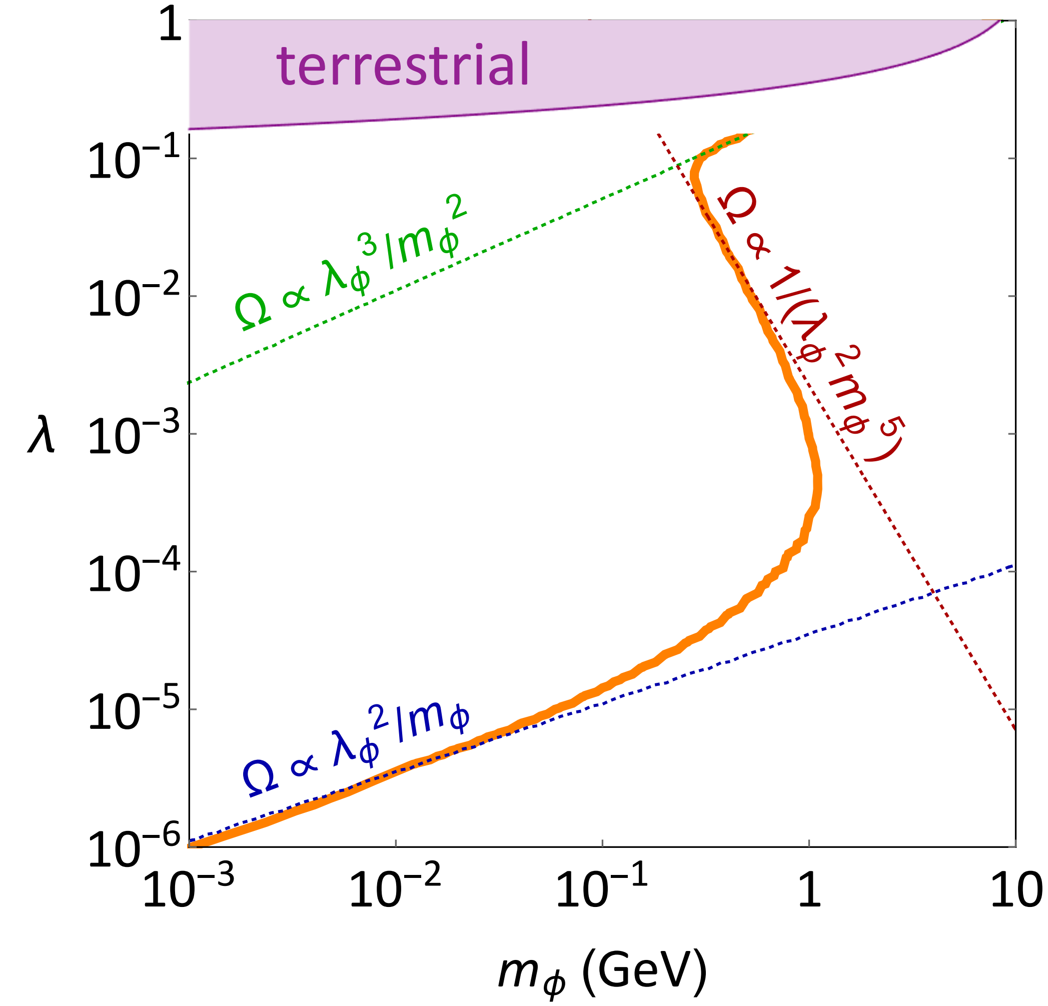
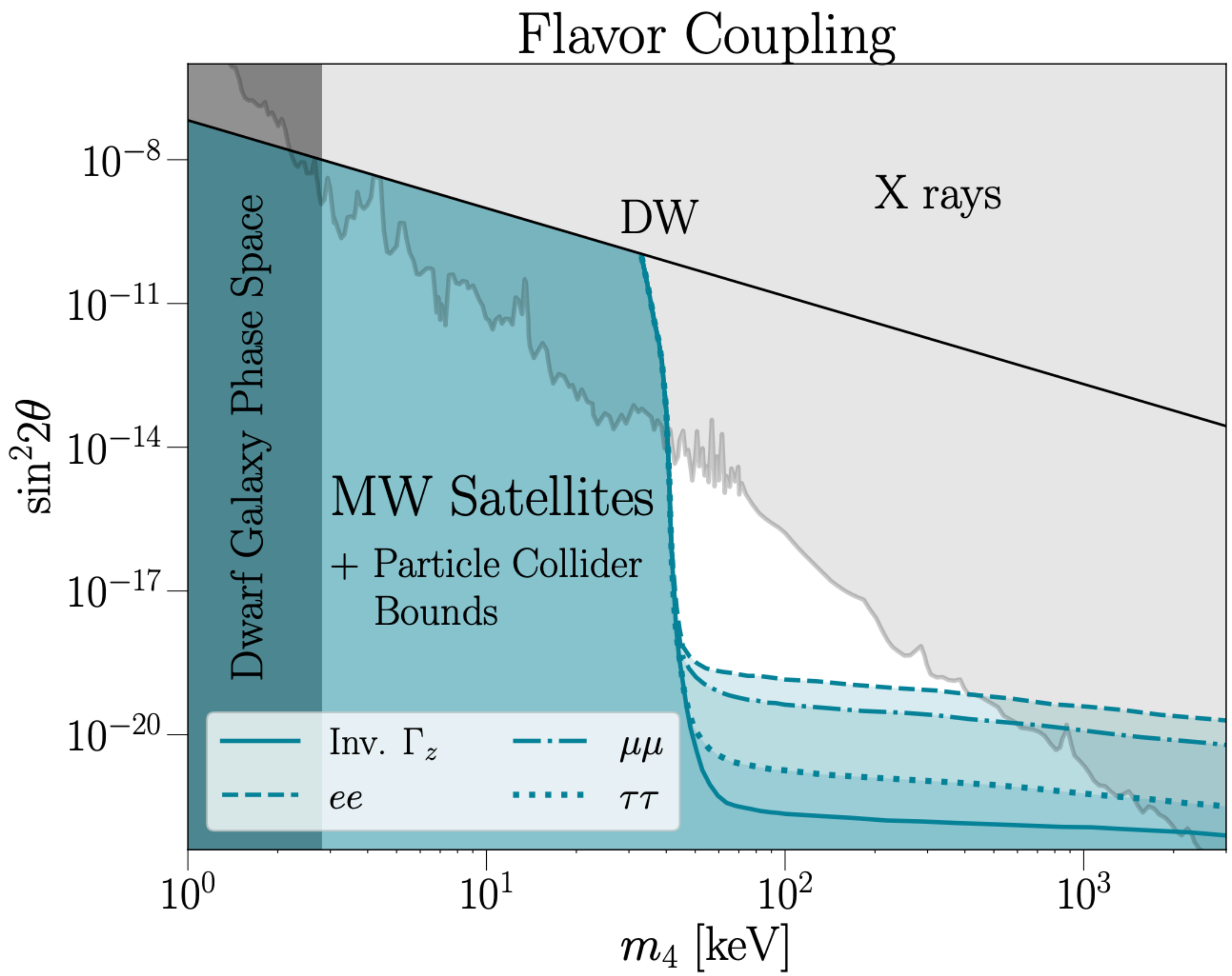




Other probes: talks by Douglas, Kevin

de Gouvêa, Sen, Tangarife, YZ (PRL 2020)

Narrowing Down Relic Target



Include small scale structure limit from DES → $m_4 > 37.4$ keV

An, Gluscevic, Nadler, YZ (APJL 2023)

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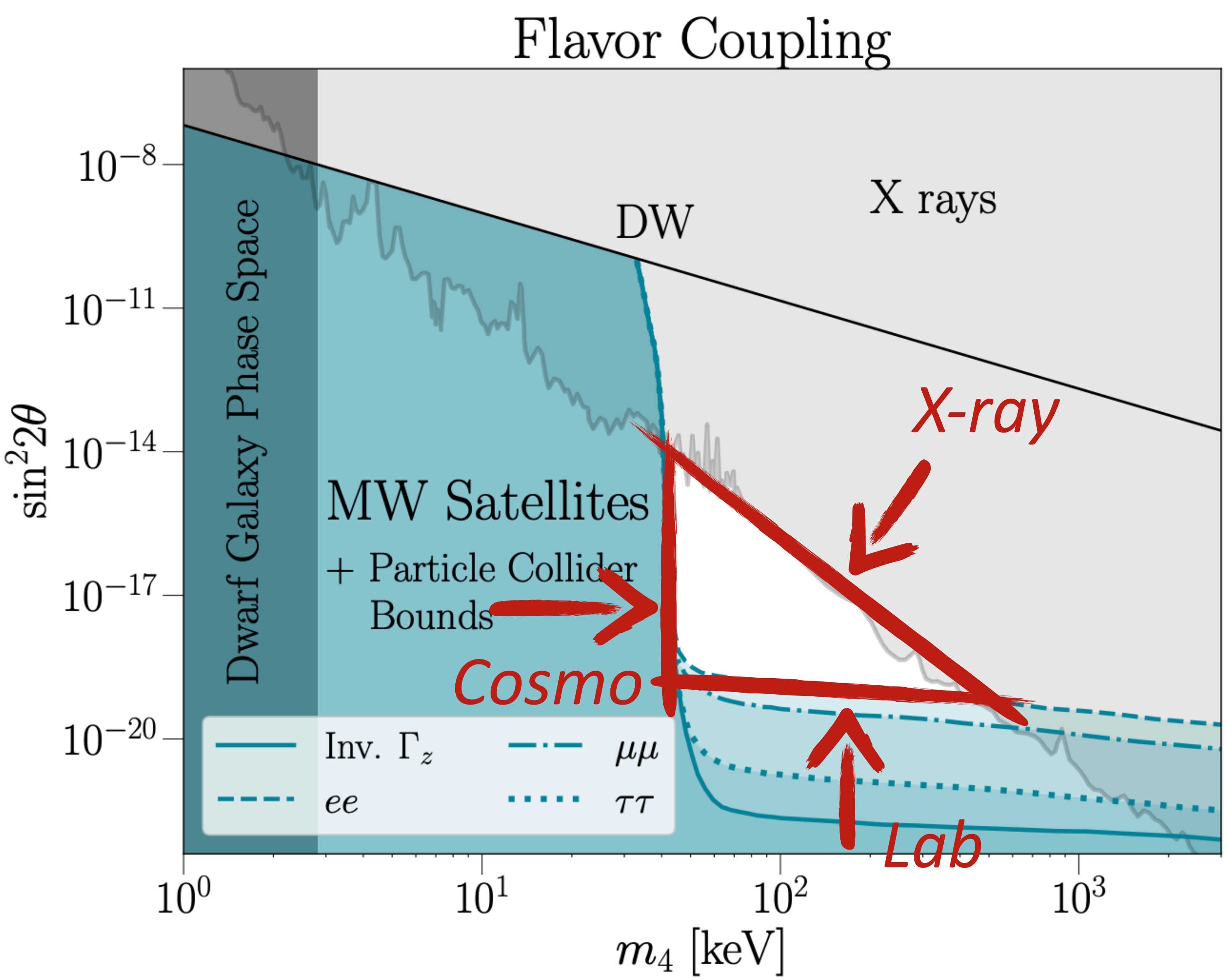

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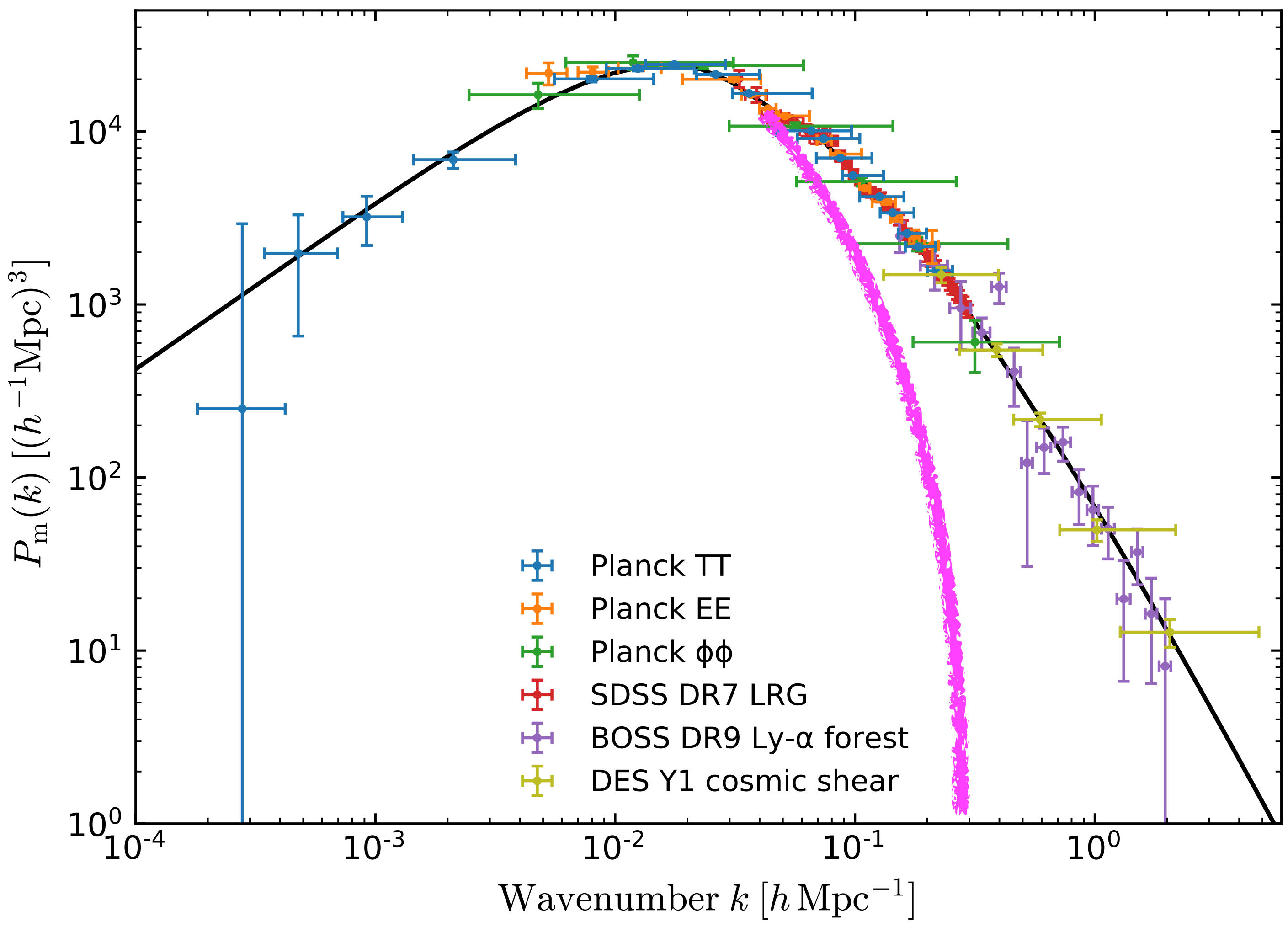
How about Even Larger Scales?



Making all the dark matter hot: clearly not acceptable

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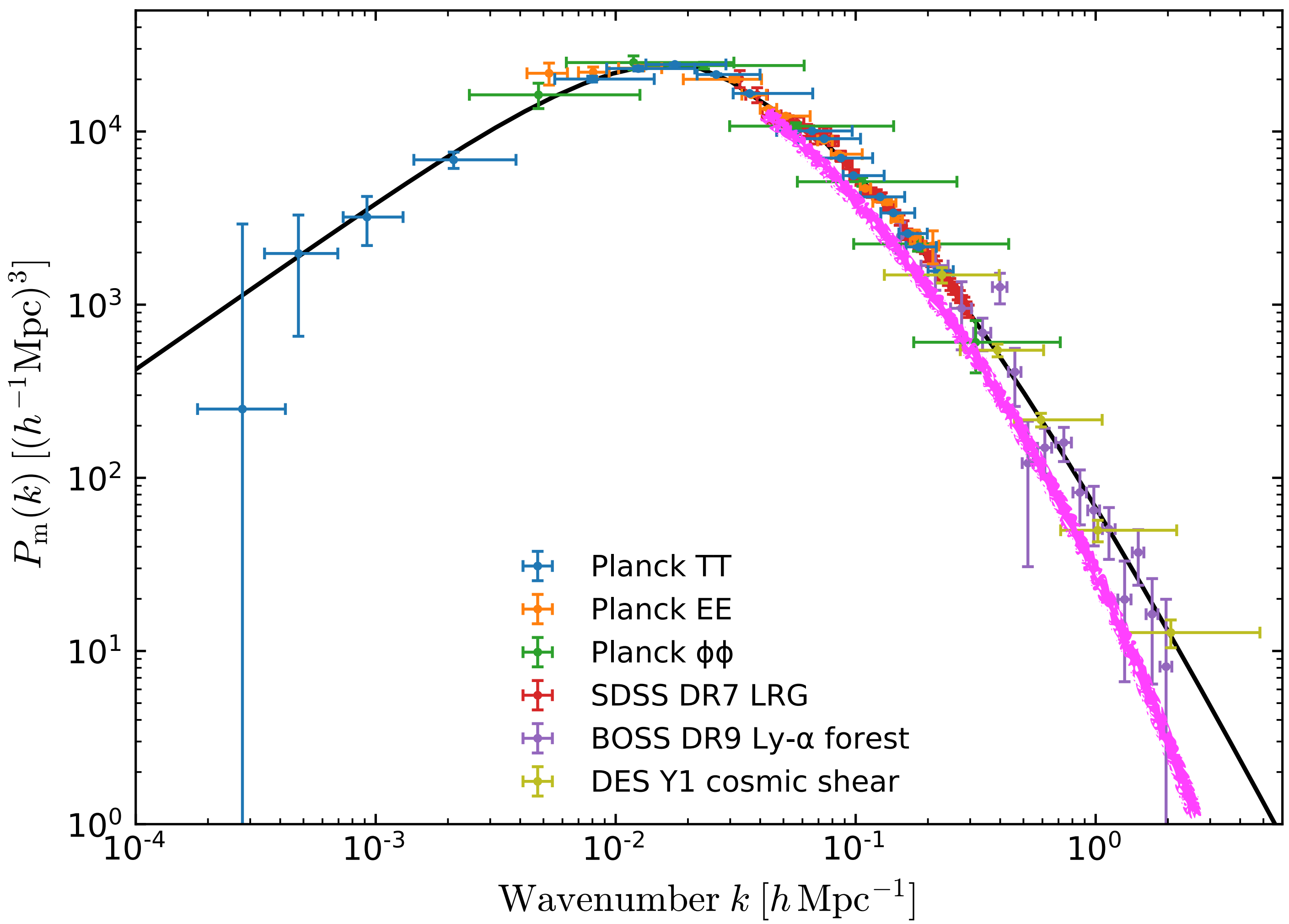
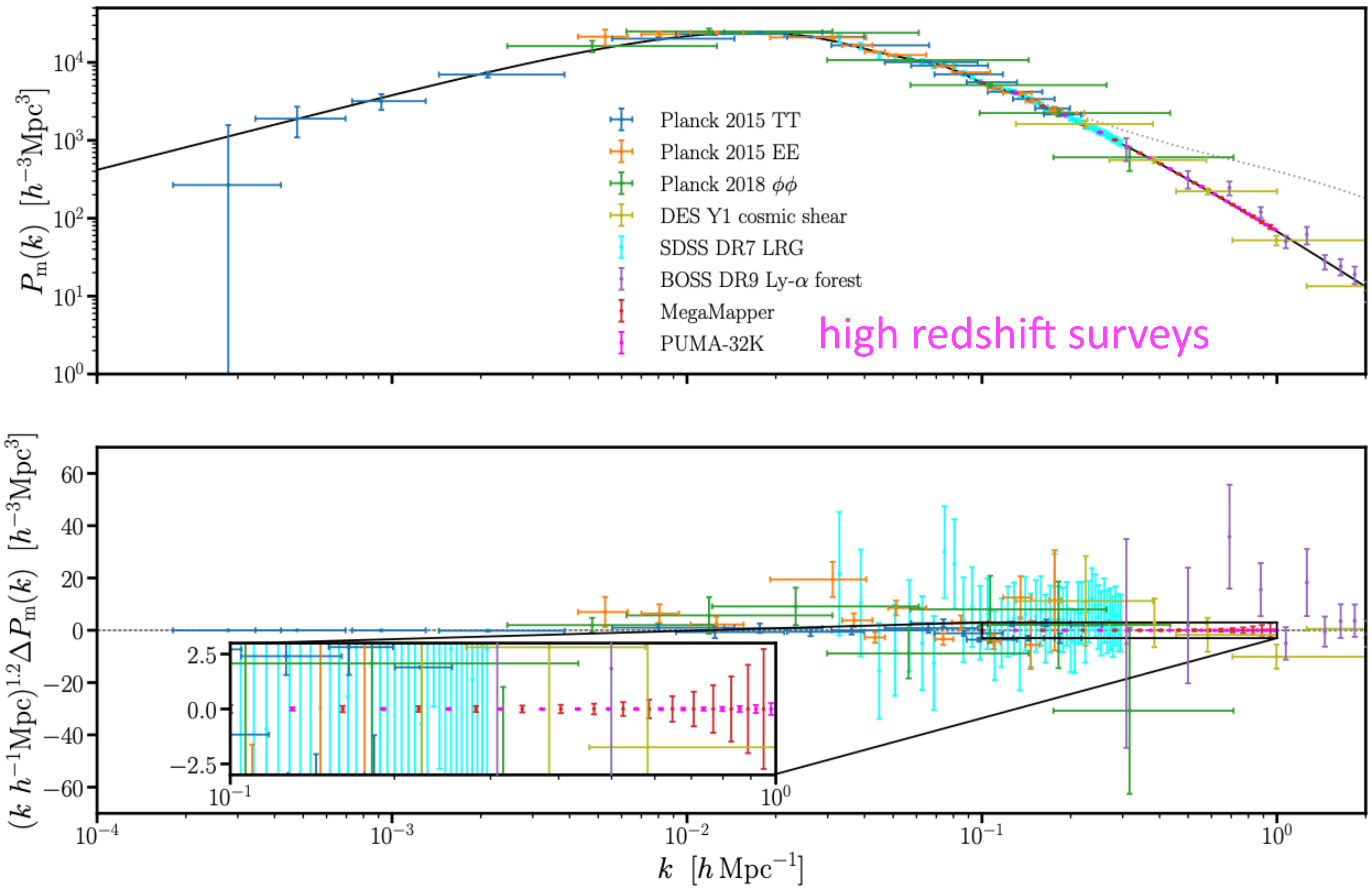


Feasible option: make a *fraction* of dark matter hot

Why Relevant? — Opportunities!



Ferraro, Sailer, Slosar, White (Snowmass white paper 2203.07506)

Why Take this Seriously?

Any sound reasons and predictive models.

Consider a thermal history for the origin of warm dark matter (X).

IF X freezes out relativistically, same population as SM neutrinos ($T_X = T_\nu$), relic density would be overproduced

$$\Omega_X h^2 = 650 \times 0.12 \left(\frac{m_X}{6.5\,\mathrm{keV}} \right)$$

problem needs to be fixed

Entropy Production (dilution)

Reduce the dark matter relic abundance by "heating up" photons in the early universe — more expansions to cool down to 2.7 K.

$$\Omega_X h^2 = 650 \times 0.12 \left(\frac{m_X}{6.5\,\mathrm{keV}} \right) \times \frac{1}{\mathcal{S}}$$

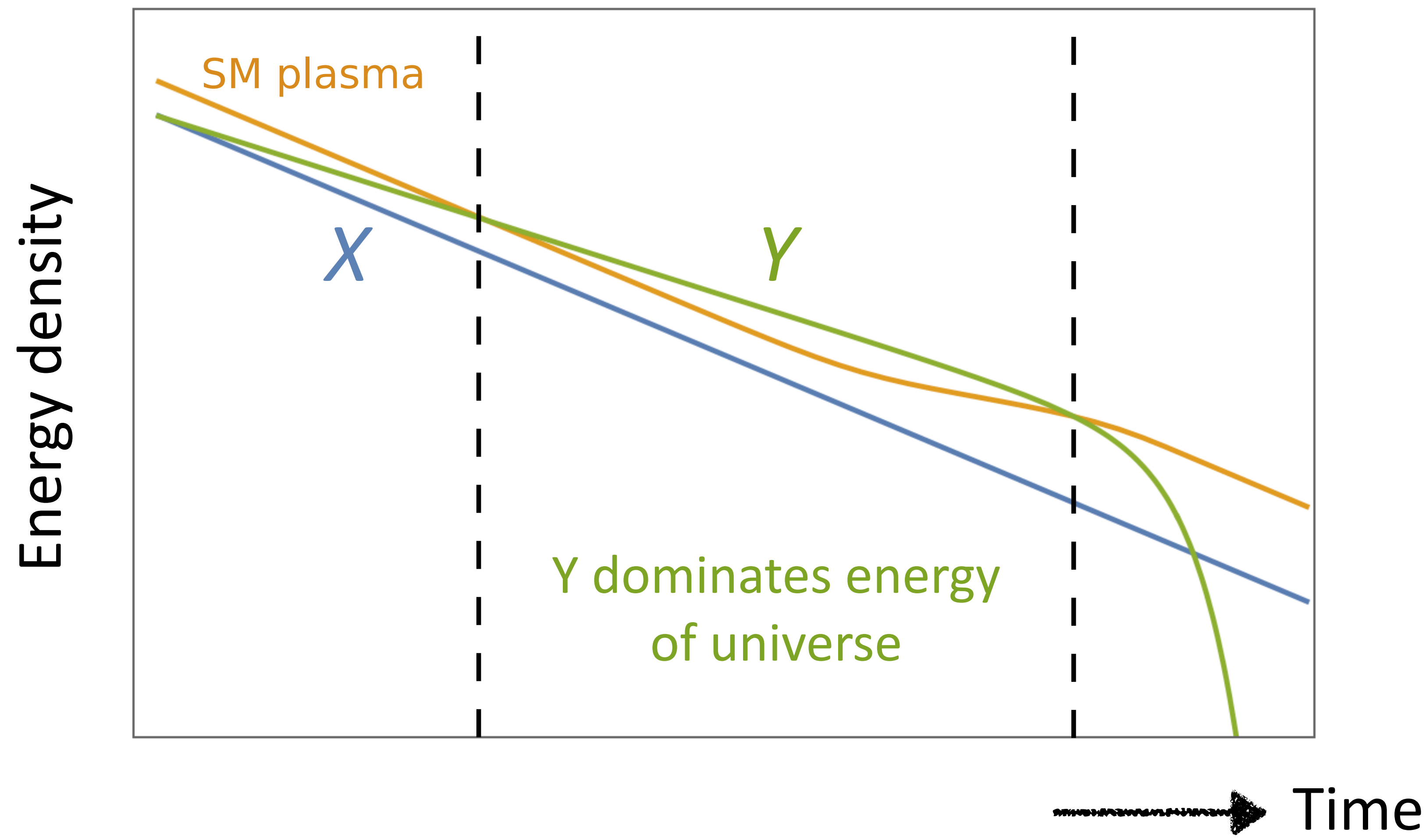
Textbook example of dilution via temperature dependence in g_*

$$\frac{1}{\mathcal{S}} = \left(\frac{10.75}{g_*(T_{\mathrm{dec}})} \right)$$

Hard to imagine an appealing BSM with so many new particles.

Entropy from Late Decay

Introducing a diluting particle *Y*, long-lived, temporarily matter domination before decaying away, into SM particles.



Scherrer, Turner (PRD 1985)

Dilution to Warm Dark Matter

Assuming both X, Y freeze out relativistically, similar initial abundance:

$$\Omega_X h^2 \simeq 0.12 \left(\frac{10^6 m_X}{m_Y} \right) \sqrt{\frac{1\,\mathrm{sec}}{\tau_Y}}$$

Dilutor needs to be at least a million times heavier than DM.

After dilution, $T_X = T_{\mathrm{WDM}}$.

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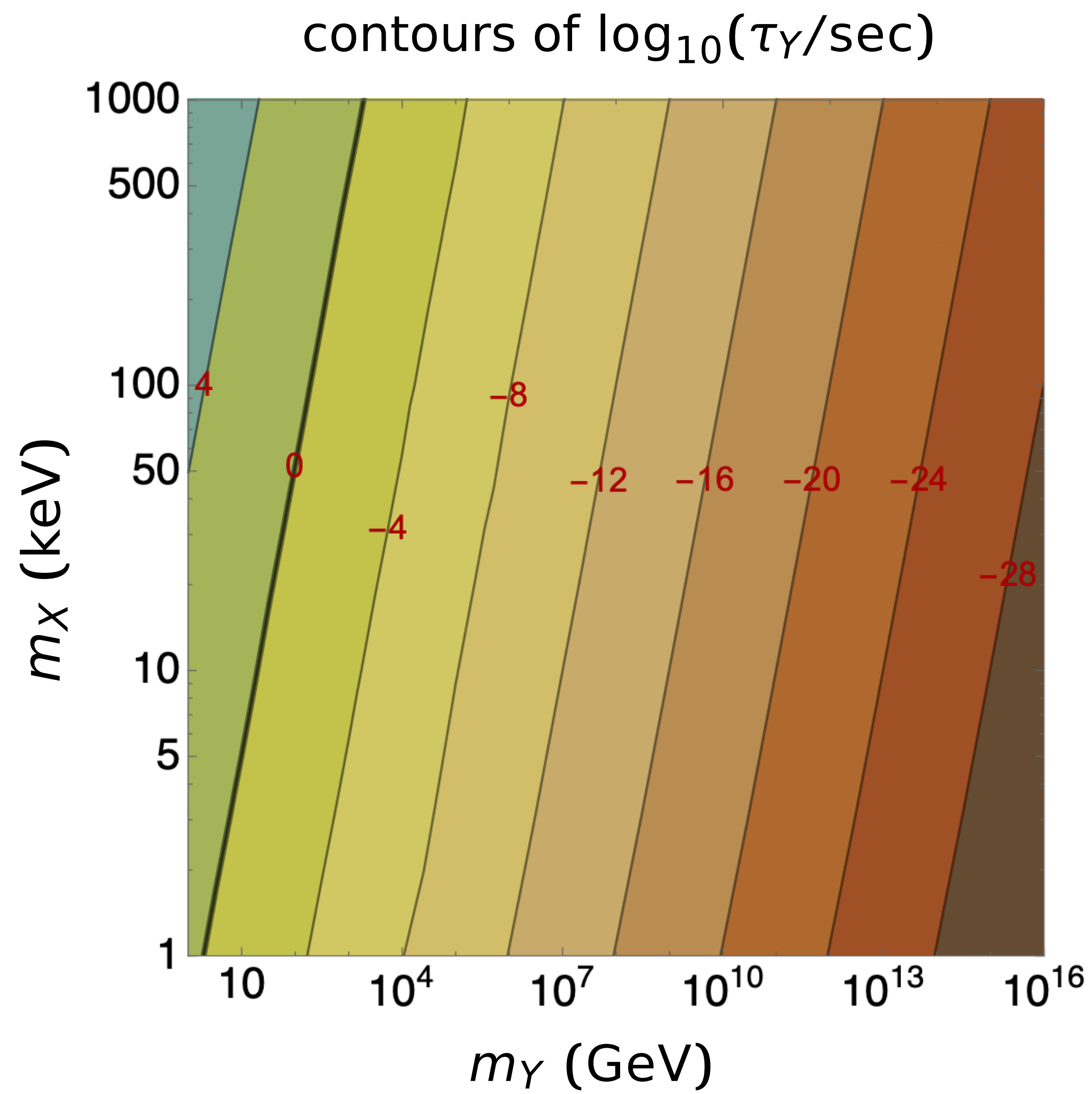


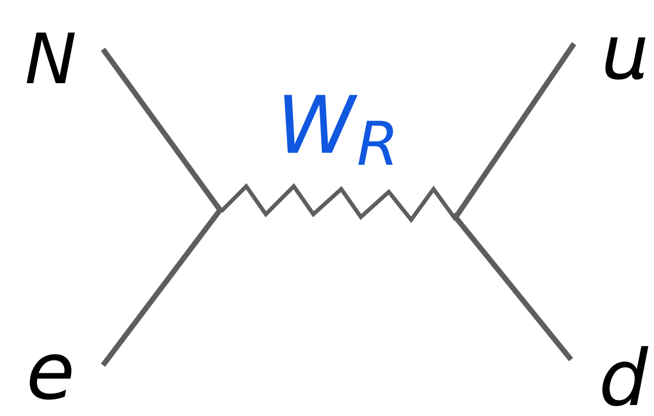
Gauge Extensions to SM

Left-right symmetric model: $SU(3)_c xSU(2)_L xSU(2)_R xU(1)_{B-L}$

Or Pati-Salam model: $SU(2)_L xSU(2)_R xSU(4)_c$

Originally written down for explaining neutrino mass (Seesaw). Introduce three right-handed neutrinos for gauge anomaly cancellation.

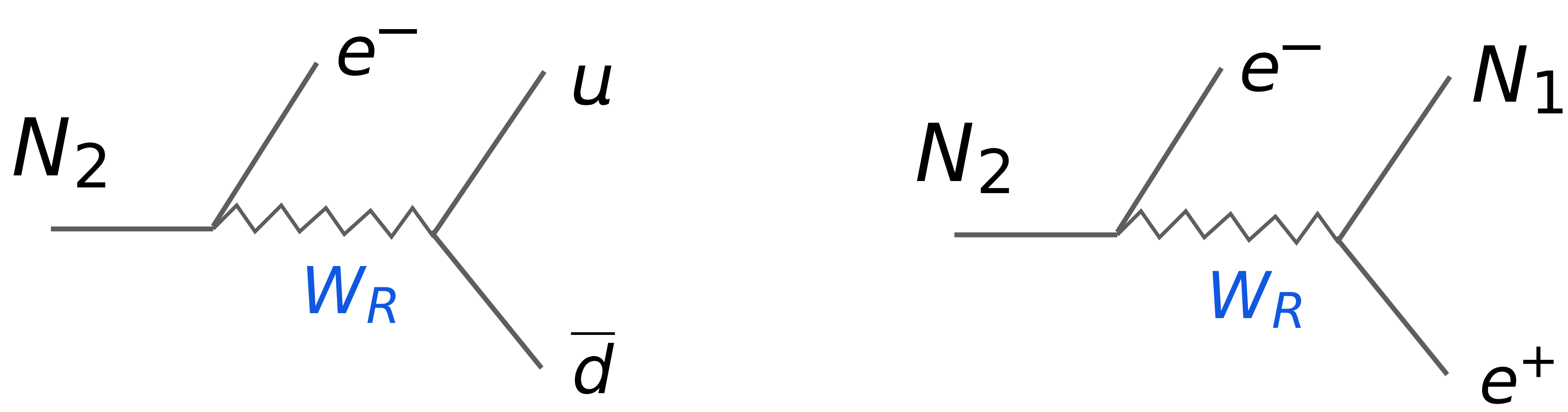
Dark matter $X = N_1$, dilutor $Y = N_2$.



Bezrukov, Hettmansperger, Lindner (PRD 2010)

Dilutor Decay Can Produce DM

Against the goal of dilution, but inevitable in the models with RH current interactions. In analogy to weak decay of tau lepton,

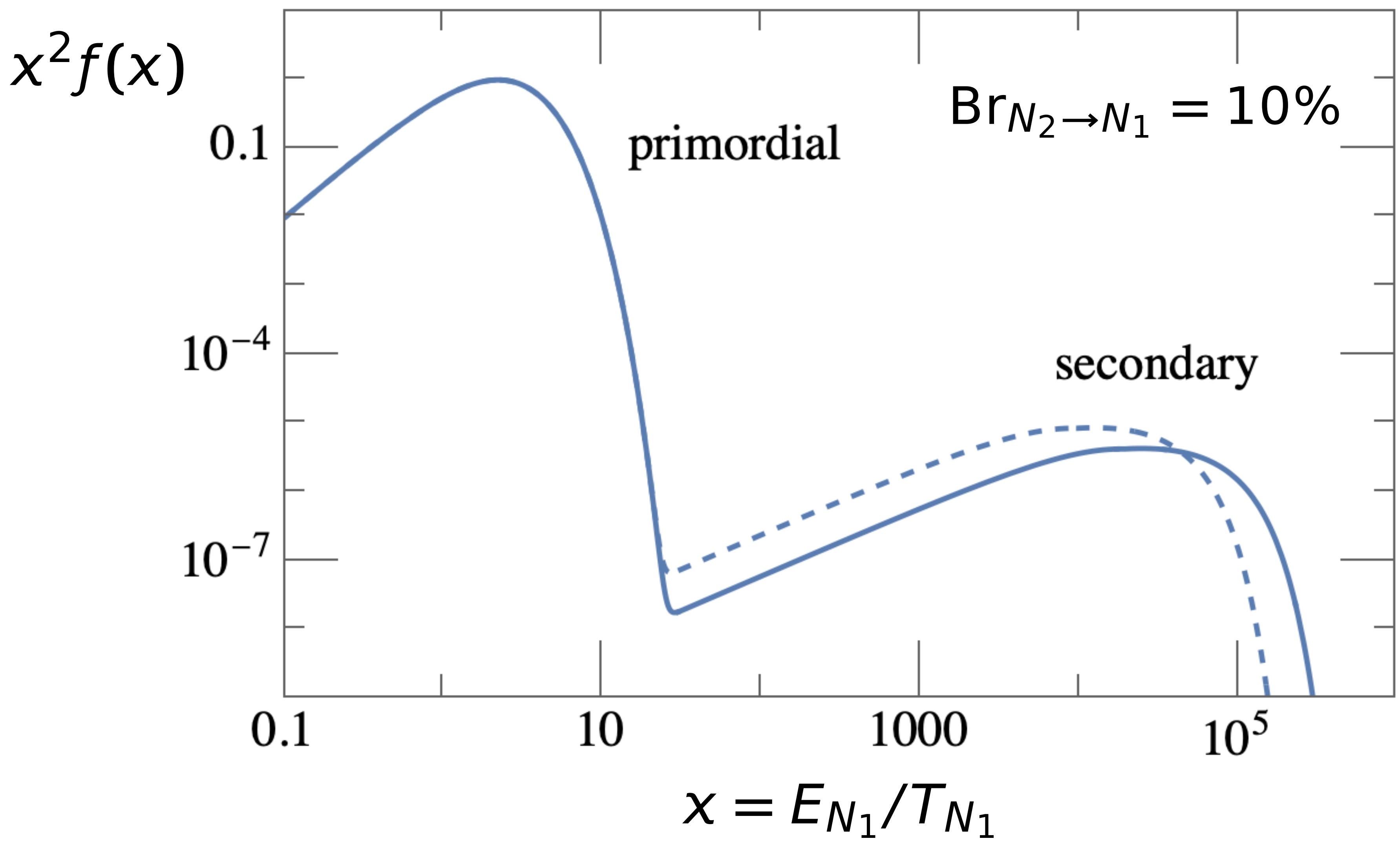


If this is the entire story, $\mathrm{Br}_{N_2 \to N_1} \geq 10\%$

Is it consistent with the observed matter power spectrum?

Phase Space Distribution

Secondary component of DM from dilutor much more energetic.



Something Remarkable

	Energy of secondary DM (N_1)	Temperature of photon background
Immediately after dilutor (N_2) decay	$\sim M_{N_2}$	$T_{\rm RH}$
Secondary DM turns non-relativistic	$\sim M_{N_1}$	$T_{\rm NR} \sim T_{\rm RH} \frac{M_{N_1}}{M_{N_2}}$

Another look at relic density $\Omega h^2 \simeq 0.12 \left(\frac{10^6 M_{N_1}}{M_{N_2}} \right) \left(\frac{T_{\rm RH}}{1\,\text{MeV}} \right)$

Nemevsek, YZ (PRL 2023)

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→ $T_{\rm NR} \sim 0.3$ **eV** — robust prediction up to a $g_*(T_{\rm RH})^{\frac{1}{12}}$ dependence.

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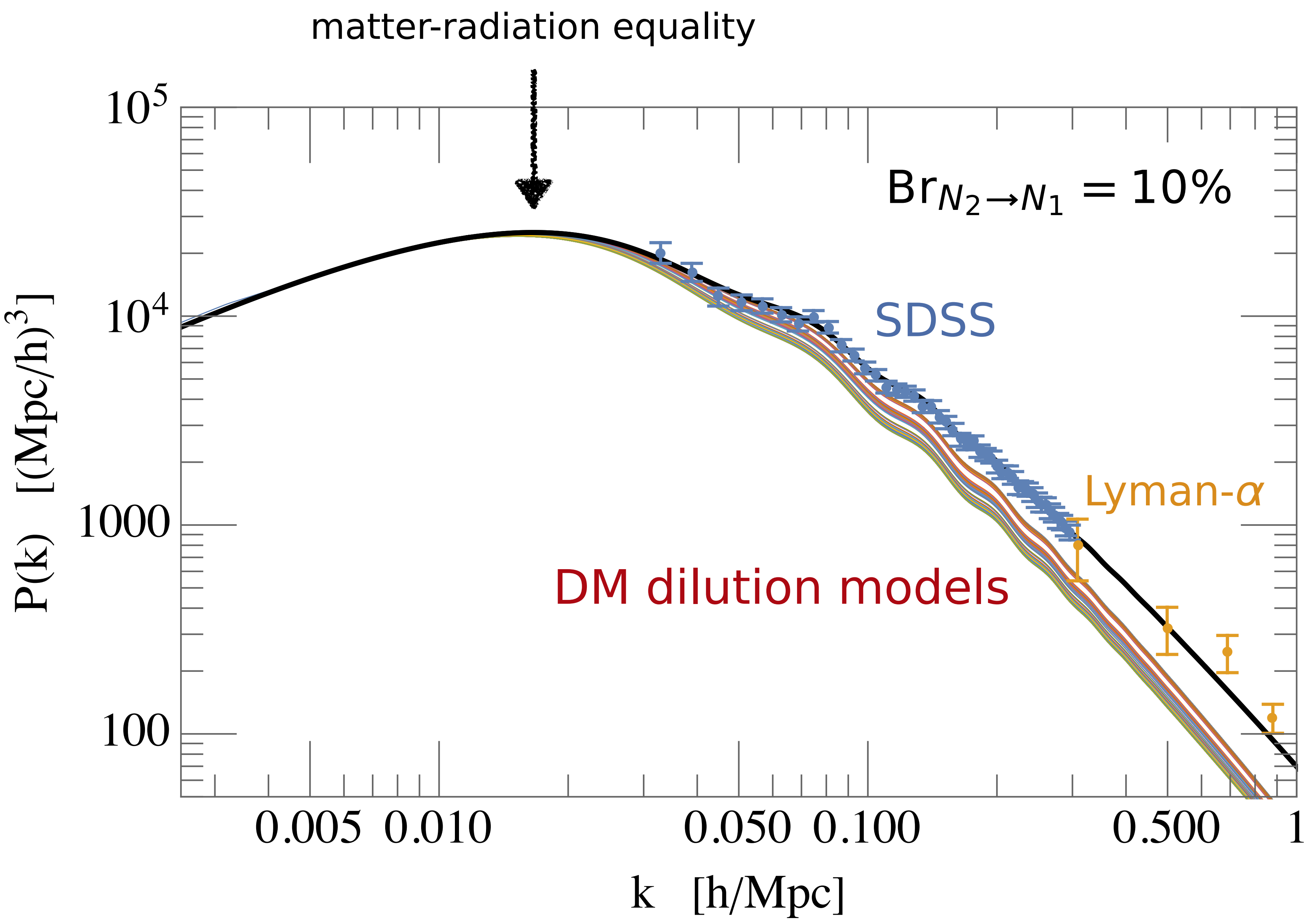
Coincidence: around matter-radiation equality, $T \sim 0.3$ eV.

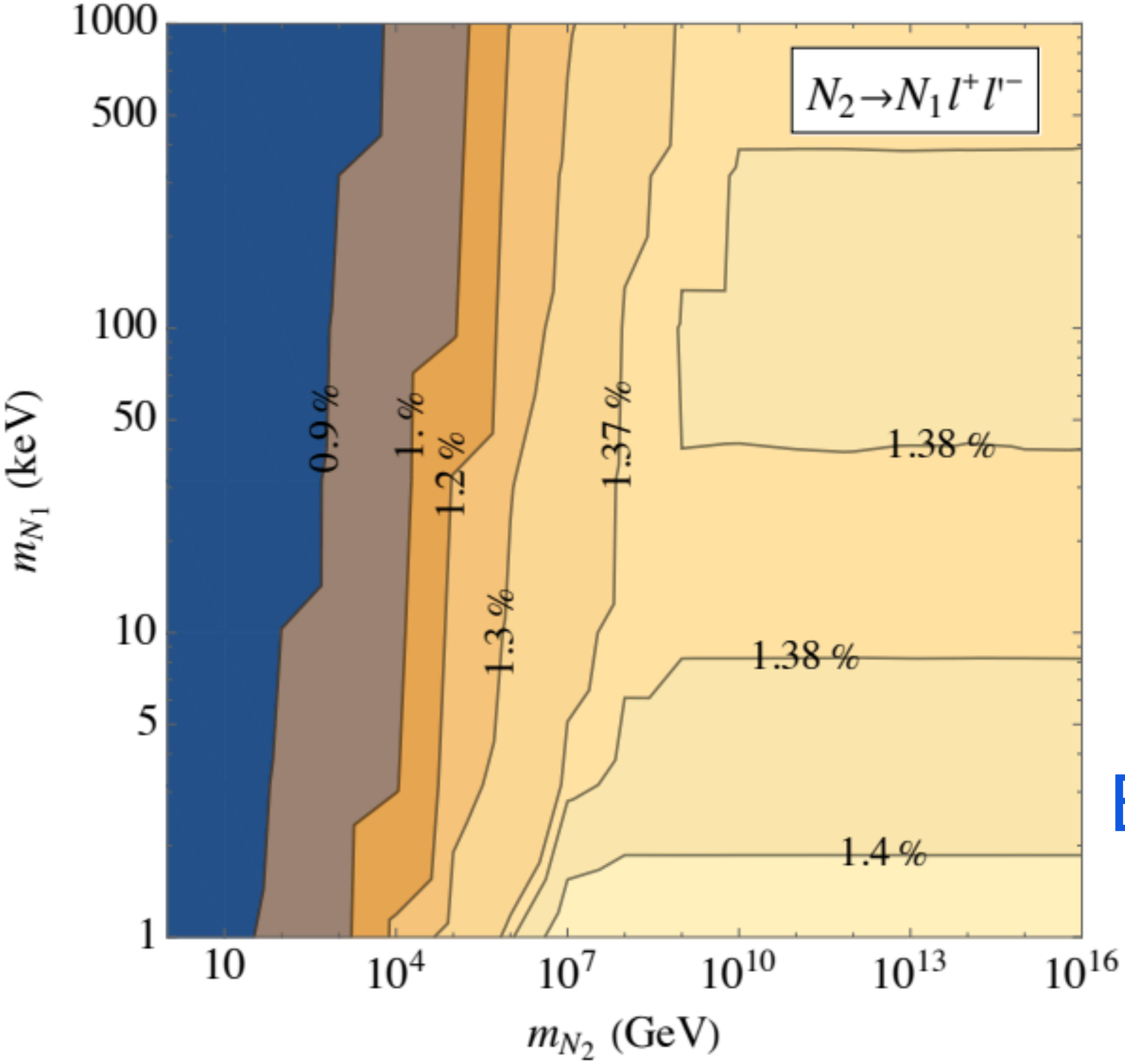
Nemevsek, YZ (PRL 2023)

Damping Effects in P(k)



Nemevsek, YZ (PRL 2023)

Large Scale Structure Constraint (SDSS)

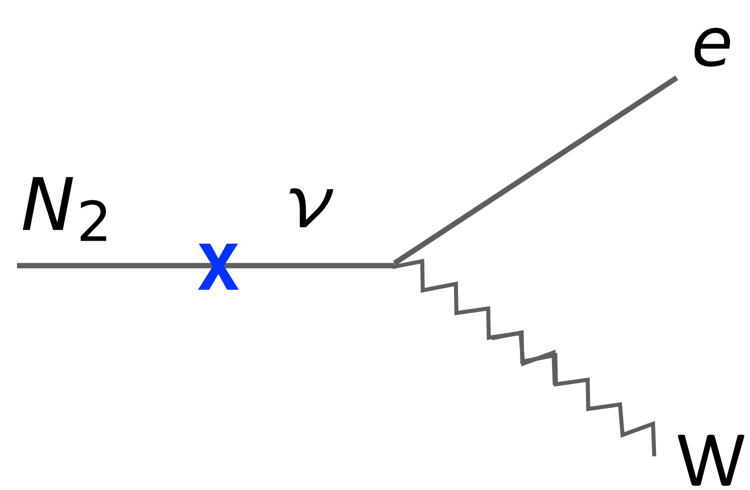


$\mathrm{Br}_{N_2 \to N_1} \lesssim 1\%$

Nemevsek, YZ (PRL 2023)

Implication for Left-Right Model

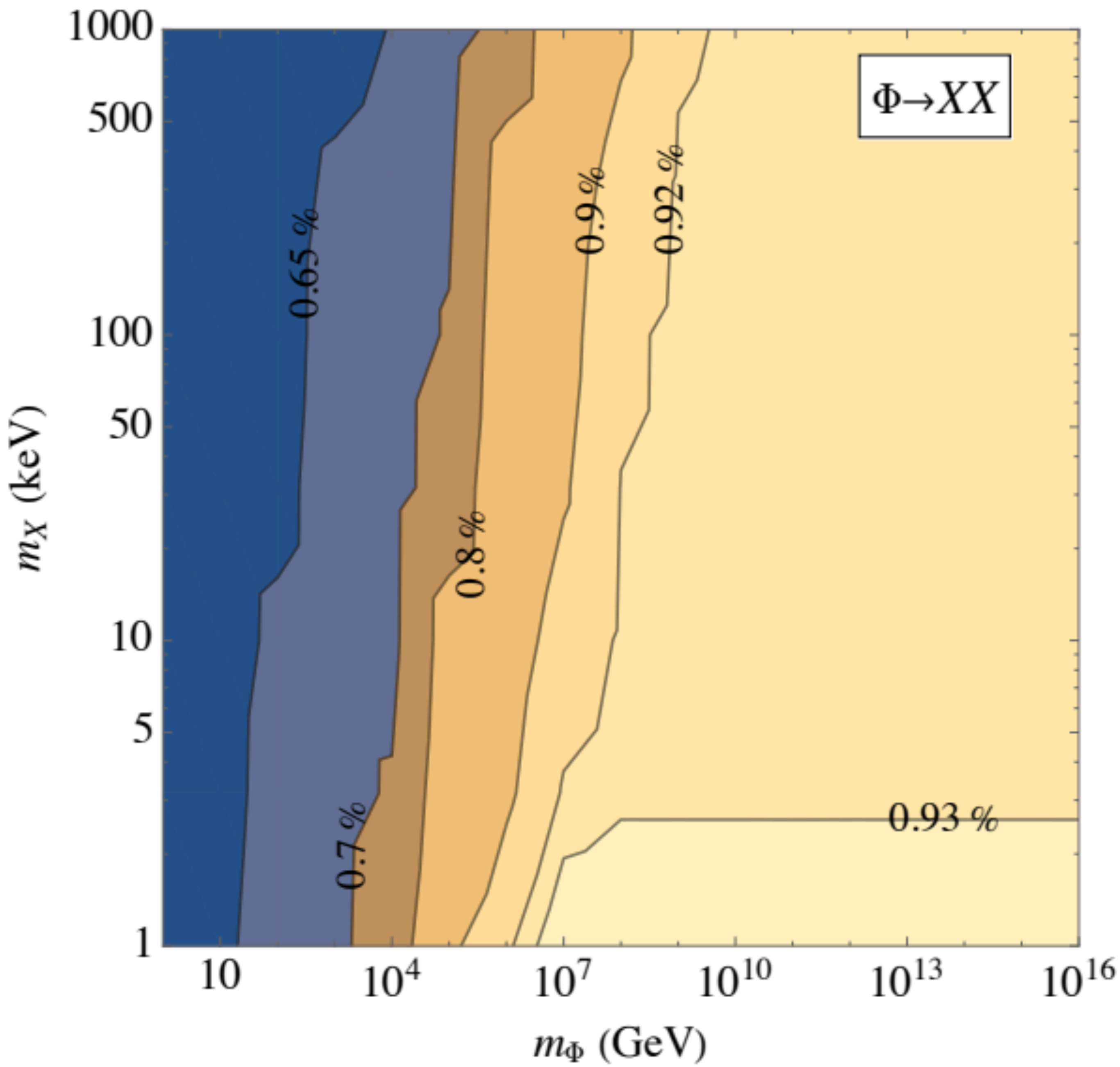
To evade the LSS constraint, resort to a N-ν mixing or W-W_R gauge boson mixing → lower limit on mass scale M_{W_R} > PeV.



For dilution to work, N_2-ν mixing is very small and irrelevant for seesaw mechanism. N_3 alone cannot account for both solar and atmospheric mass differences, additional source needed.

Nemevsek, YZ, 2312.00129, (PRD to appear)

Generalization



Robust upper limit (SDSS)

$$Br_{\text{dilutor}\to\text{DM}} \lesssim 1\%$$

Sub-percent branching ratio will be scrutinized by upcoming experiments.

Other models that resort to dilution: gravitino DM, strongly coupled dark sectors, twin-Higgs, primordial black holes …

Nemevsek, YZ (PRL 2023)

Summary

A lot to learn from cosmological data on origins of dark matter.

Complementary to terrestrial searches.

Many opportunities for years to come.

Thanks!