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

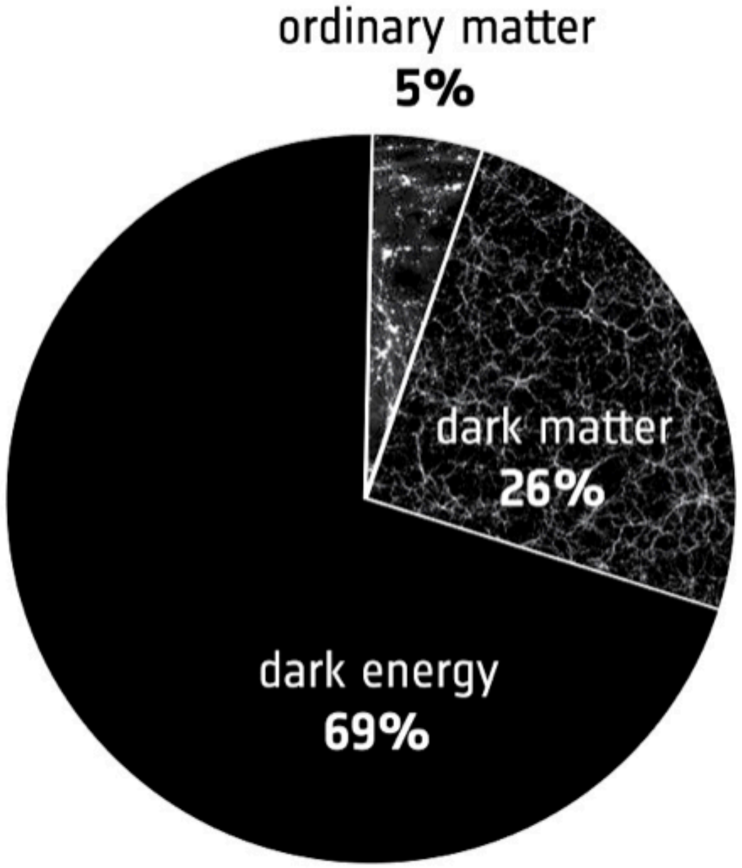
**Yue Zhang**

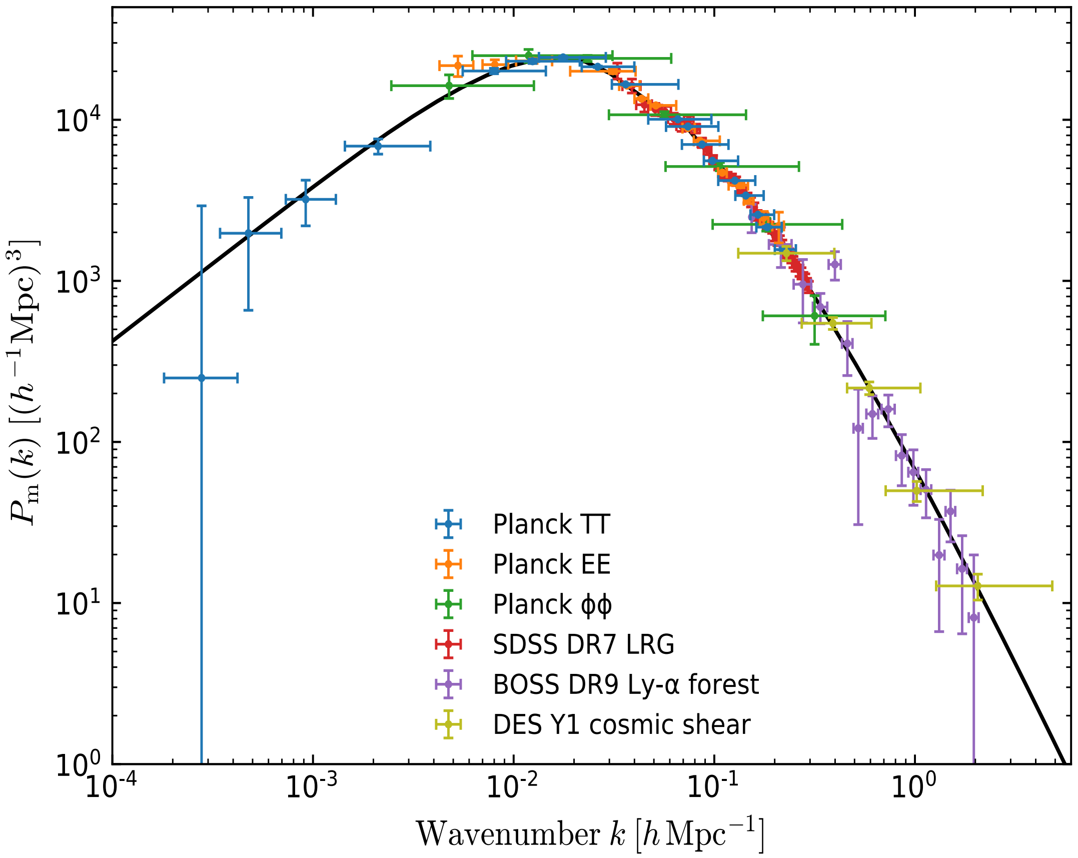
Carleton University

CAP Congress 2024, Dark Matter and Neutrinos Symposium

Western University, London Ontario

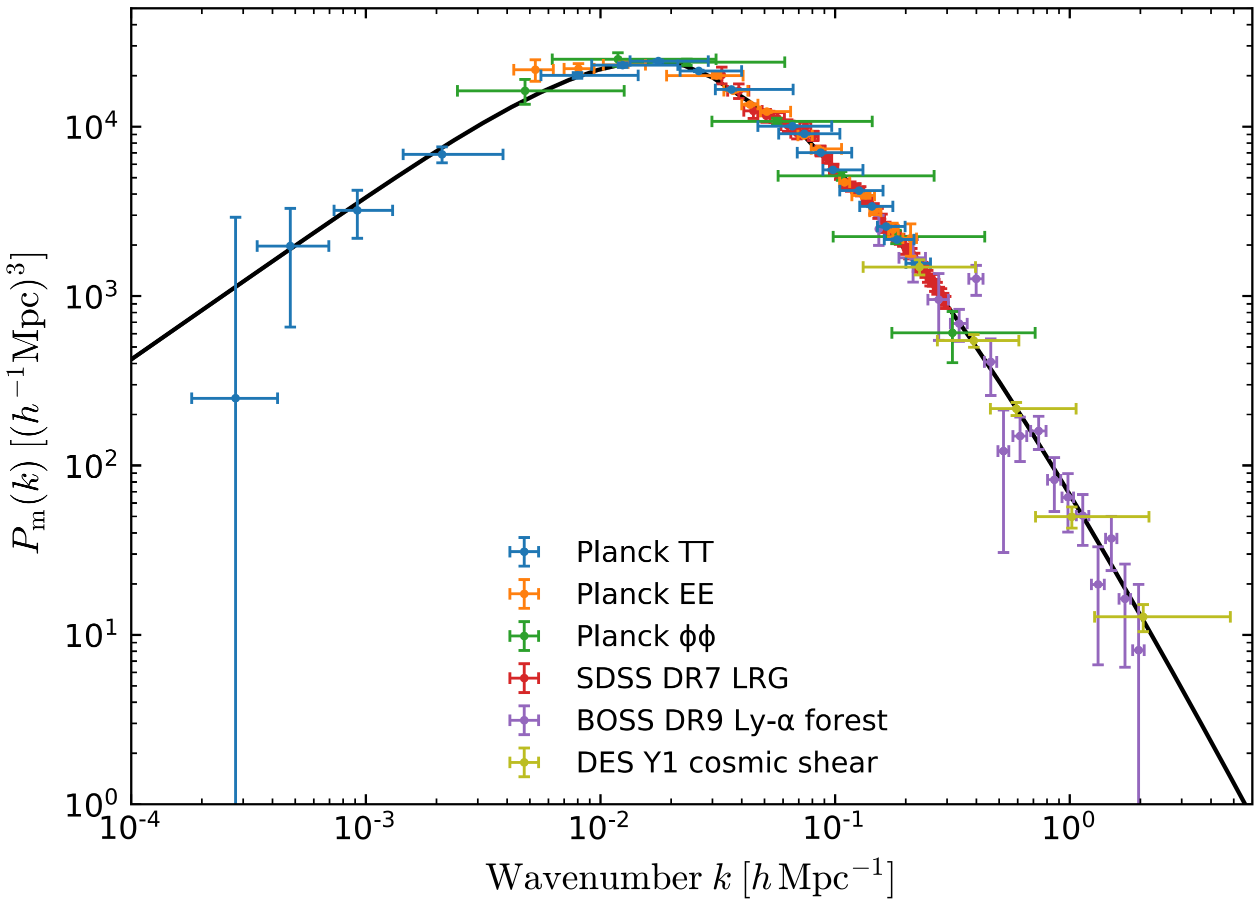
# This talk is about





ΛCDM model: dark matter relic density as guiding principle.

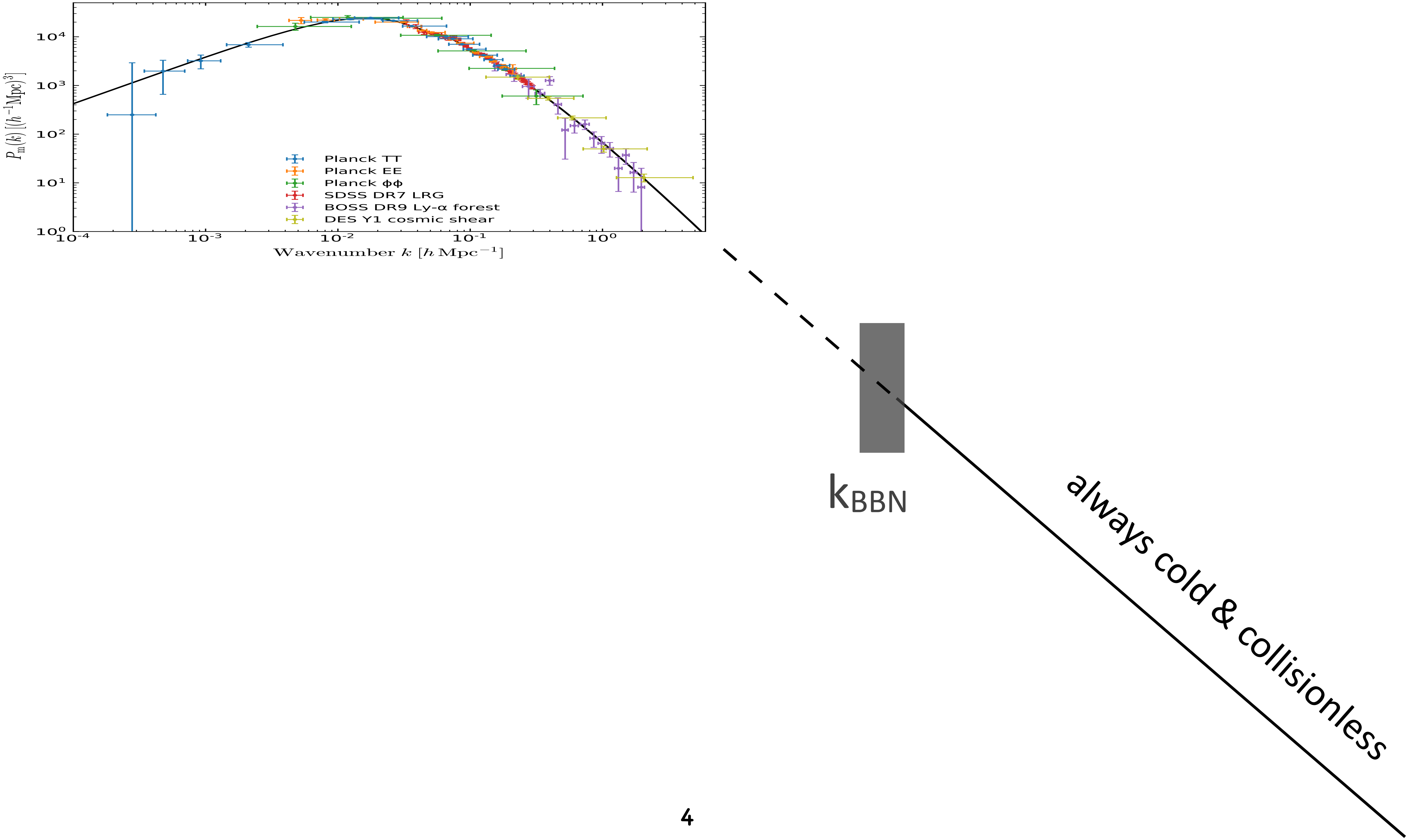
# Linear Matter Power Spectrum



PLANCK IMAGE GALLERY (2018)

- Nearly scale invariant primordial spectrum. Peak: MR equality.
- Log (linear) growth during radiation (matter) dominated era.
- Cold and collisionless dark matter consistent with data.

# Dark Matter Model Predictions



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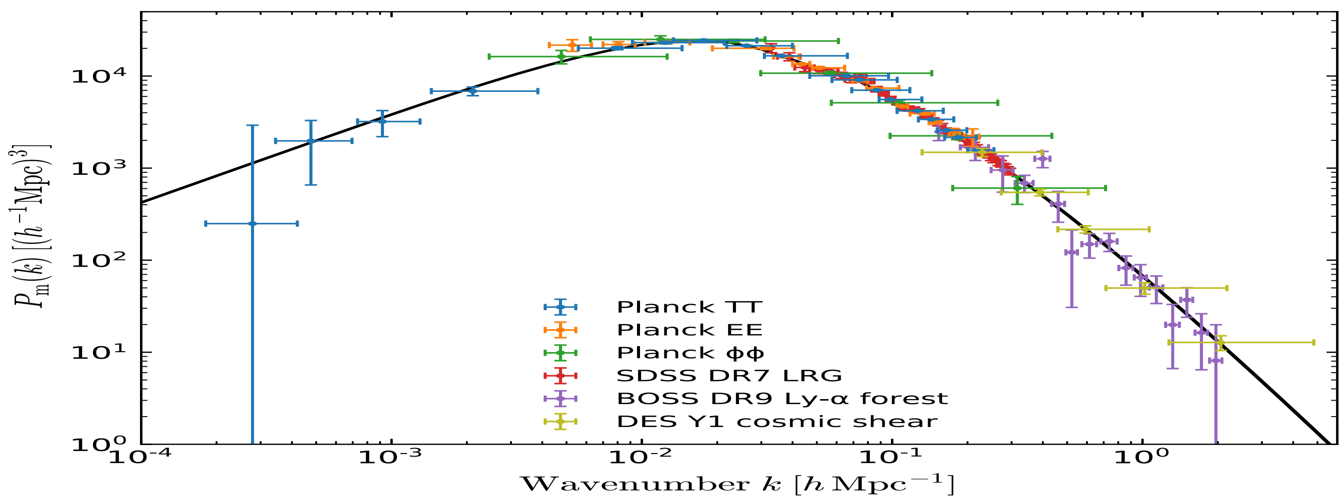
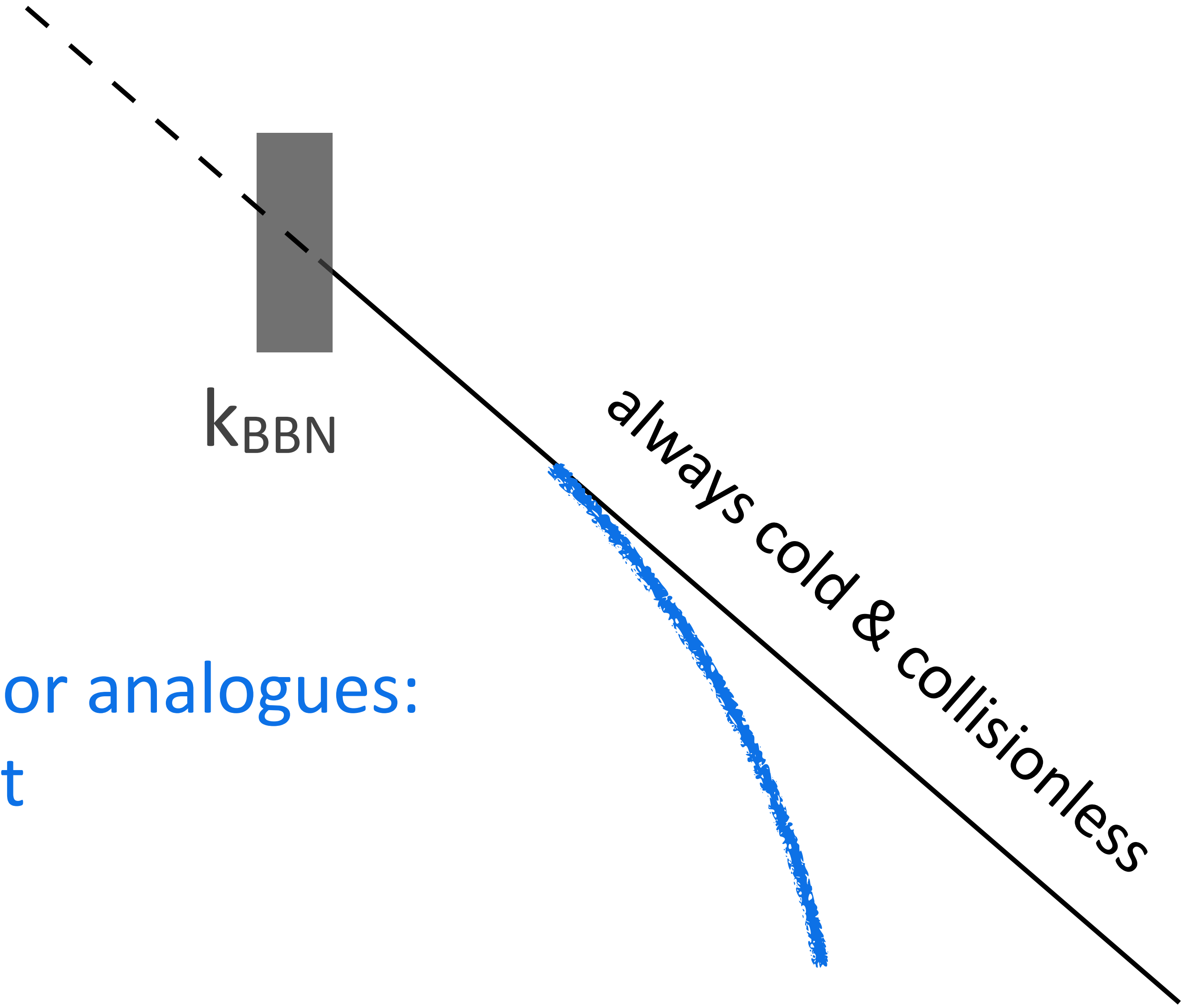


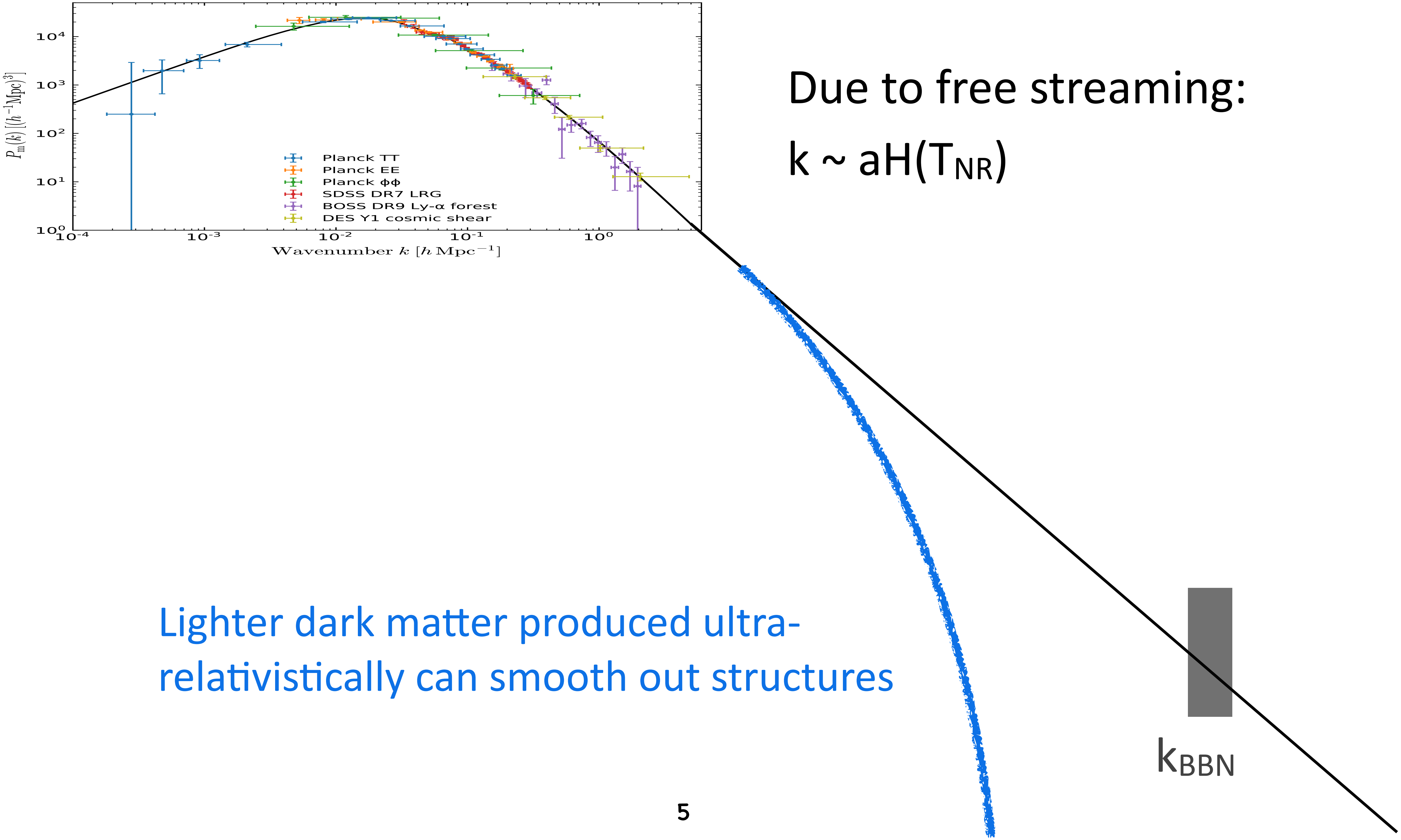
Collisional damping:

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



WIMP & dark sector analogues:
thermal freeze-out

# Collisionless Damping

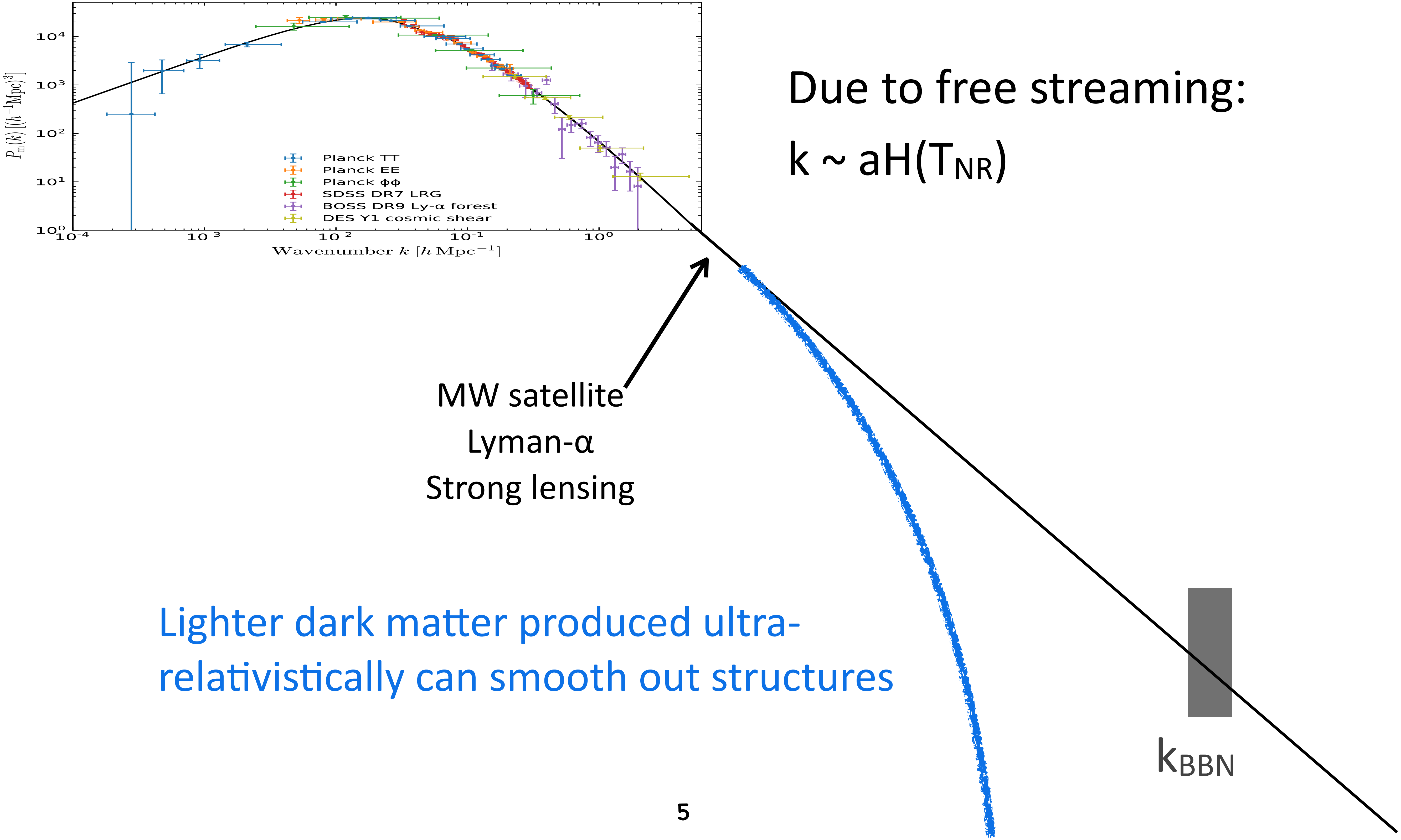


Due to free streaming:

$k \sim aH(T_{NR})$

Lighter dark matter produced ultra-relativistically can smooth out structures

# Collisionless Damping



Due to free streaming:

$k \sim aH(T_{NR})$

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)

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

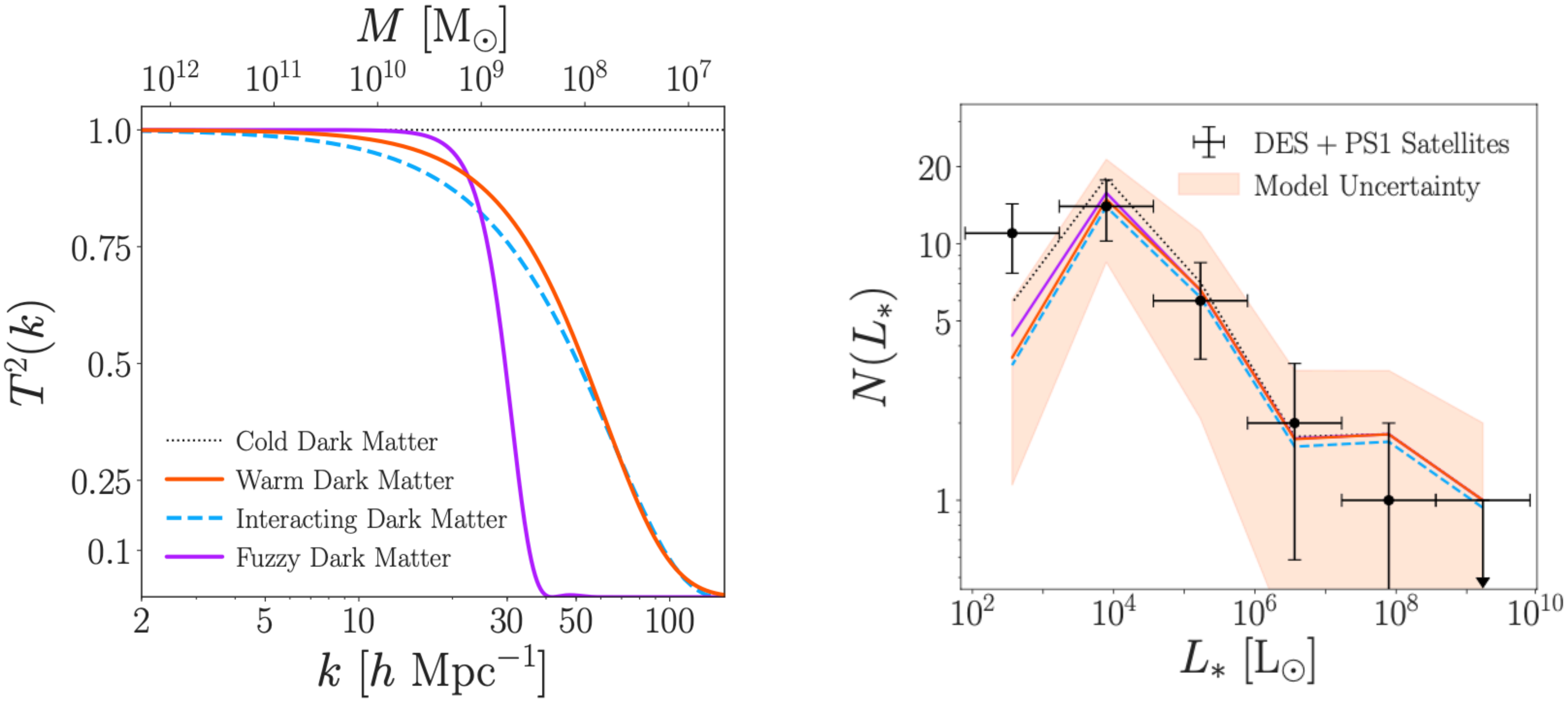
To comprise 100% of dark matter we need

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

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

Substantially cooler than CMB photons, or CvB.

# DES limit: ultra-faint MW dwarfs



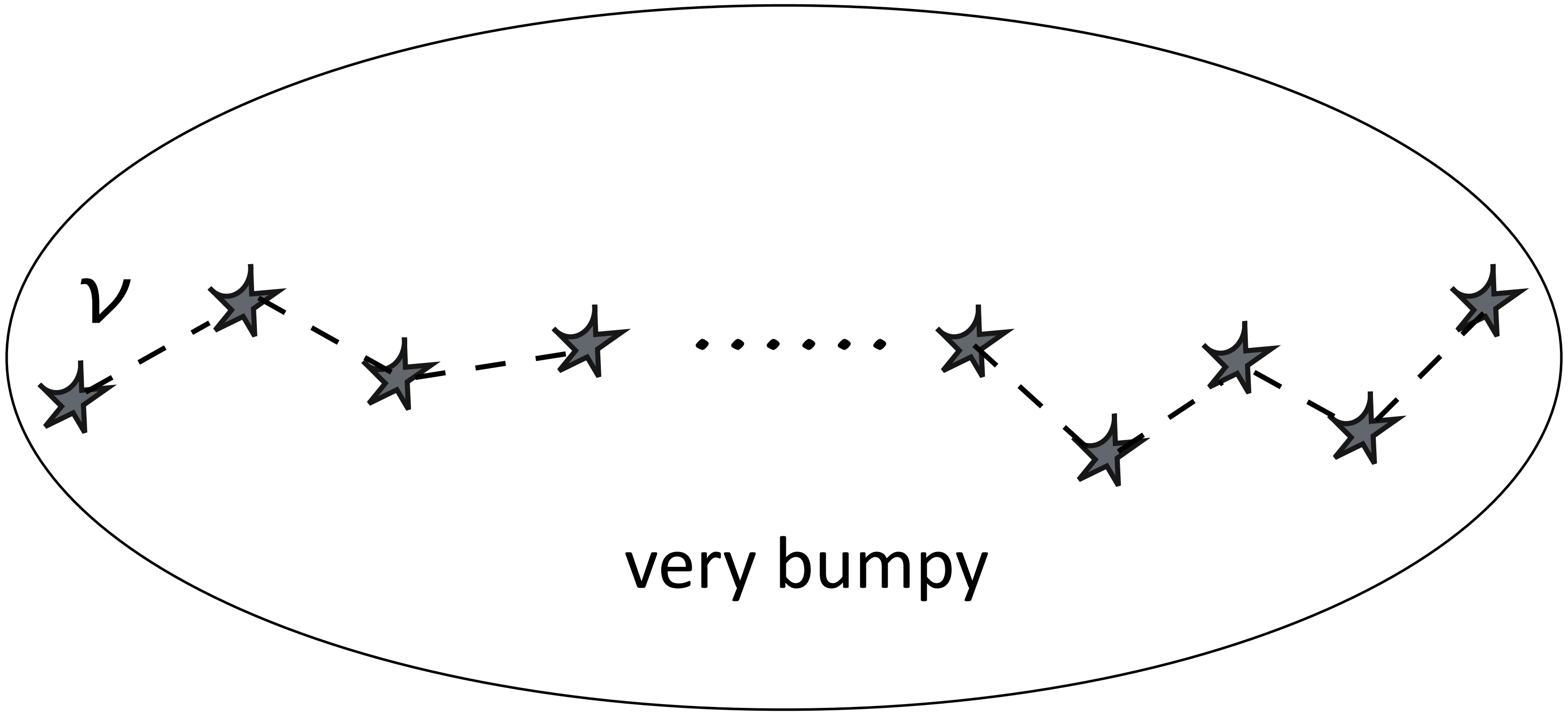
Mapping primordial PSD to P(k), and to subhalo mass function

Nadler et al, DES collaboration (PRL 2021)

# Warmer than WDM

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

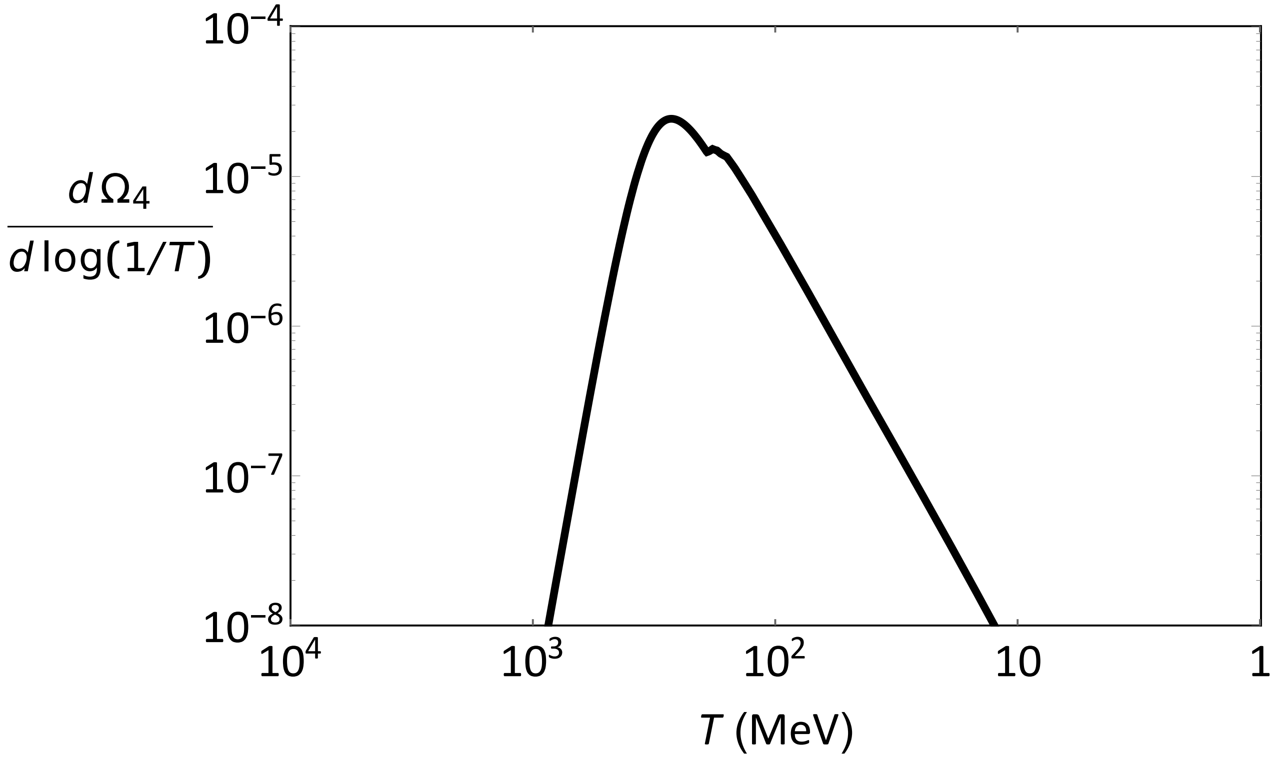
$$T \sim 100\,\mathrm{MeV}, \quad H^{-1} \sim 100\,\mathrm{km}, \quad l_{\text{mean free path}} < 1\,\mathrm{m}$$



Dodelson, Widrow (PRL 1994)

# Collisional Oscillation

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



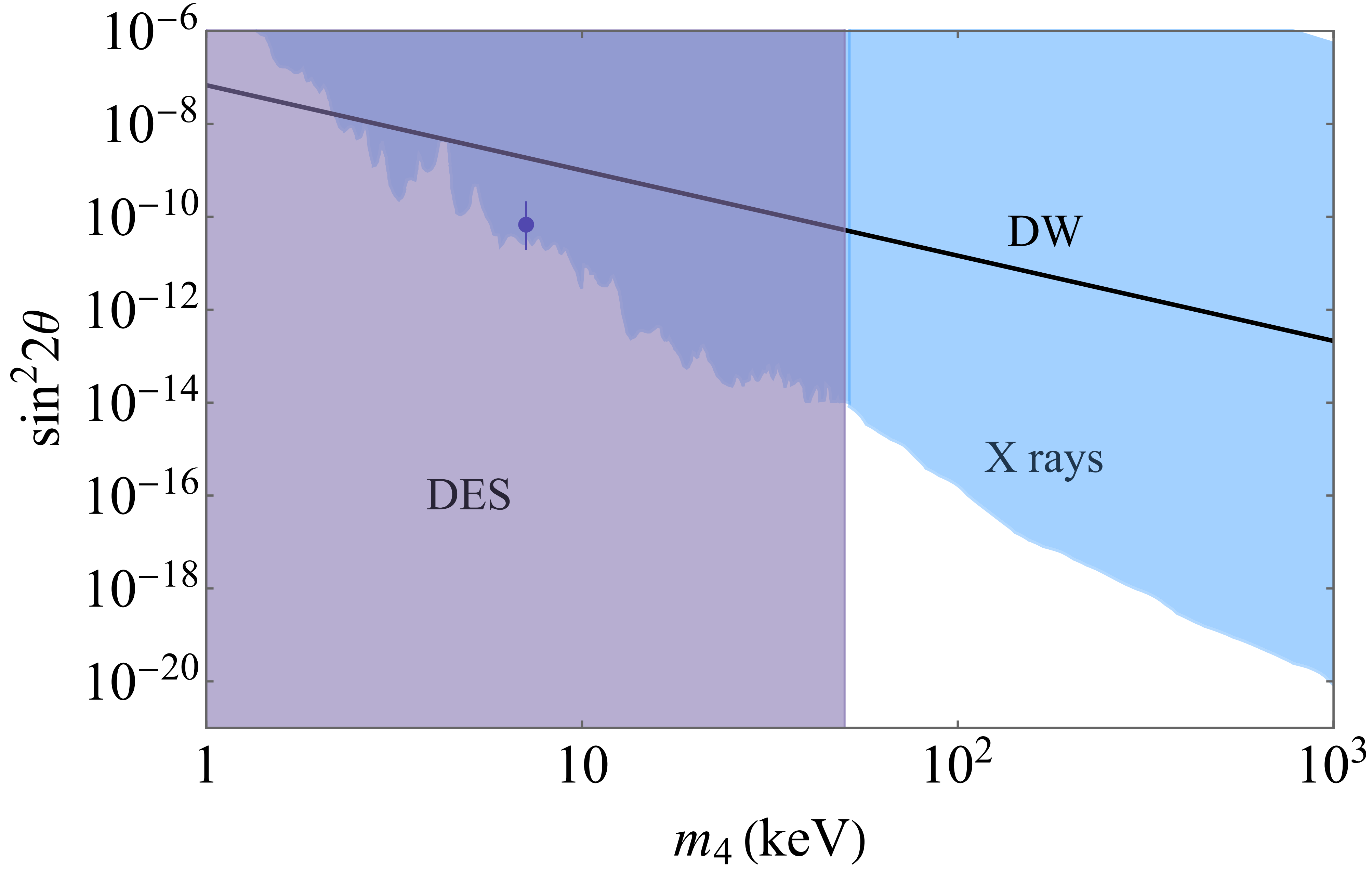
Resulting PSD function:

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

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

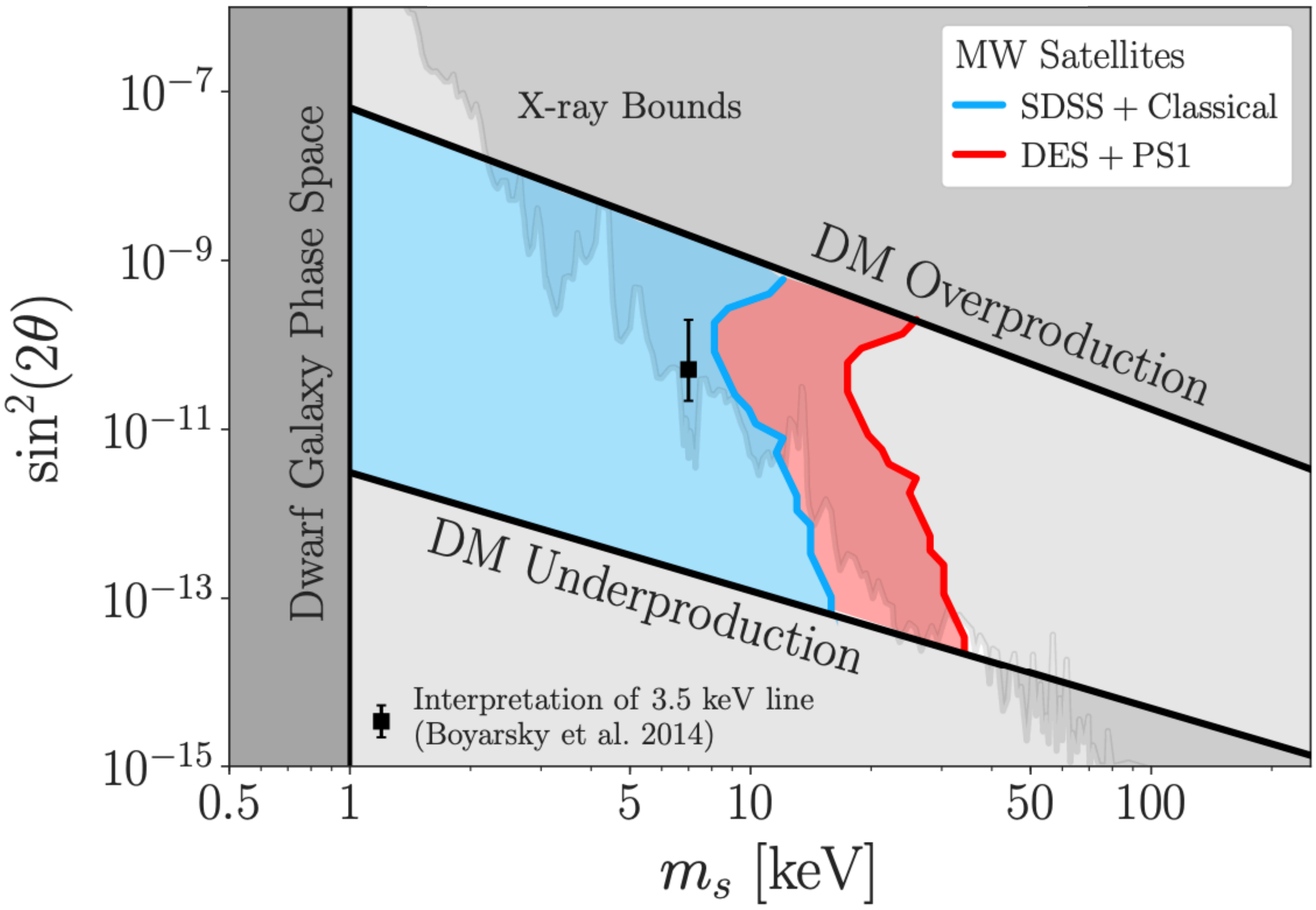
**DES result** implies m > 50 keV for DW produced sterile neutrino DM.

# DW Mechanism is Firmly Excluded



See also Zelko et al (PRL 2022): $m_4 > 92$ keV, combined w. Lyman-α and lensing

# Lepton Asymmetric Option also Excluded



Shi, Fuller (PRL 1999)
Nadler et al, DES collaboration (PRL 2021)

# Neutrino Self-interaction Can Rescue

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

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

→ more oscillation baselines
not more X-rays

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

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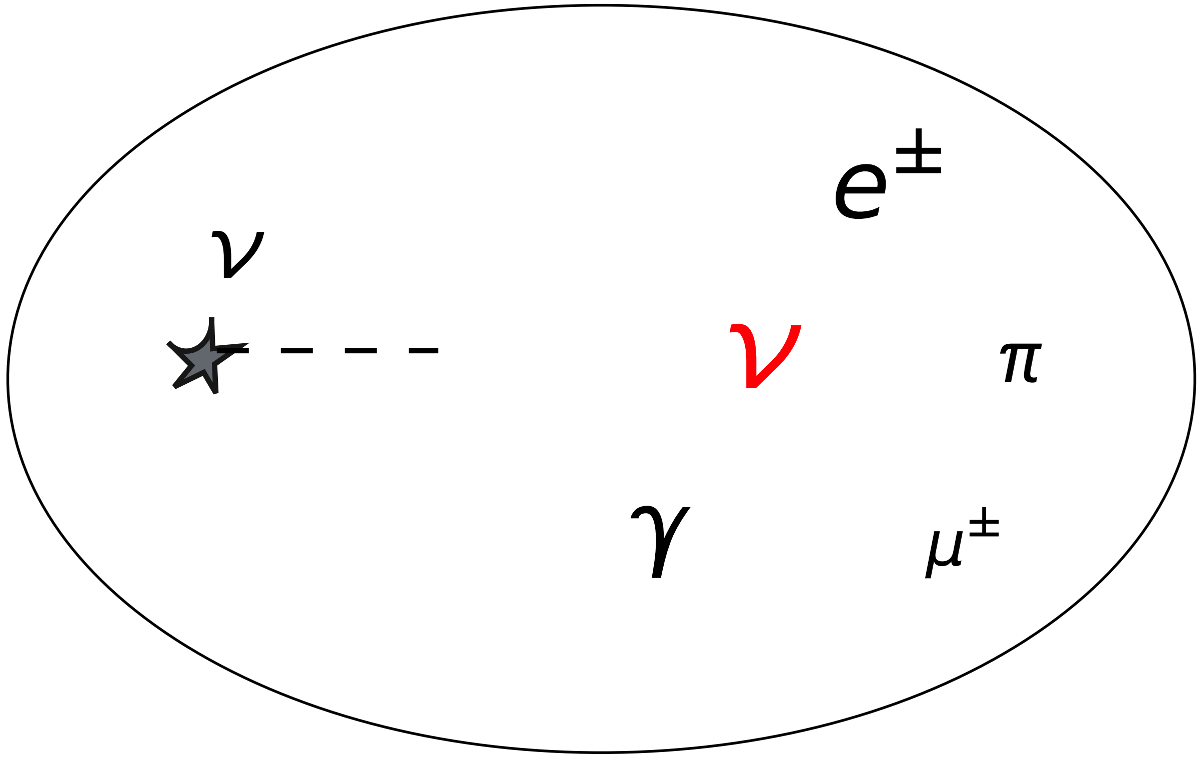

Universe@ T ~ 100 MeV

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

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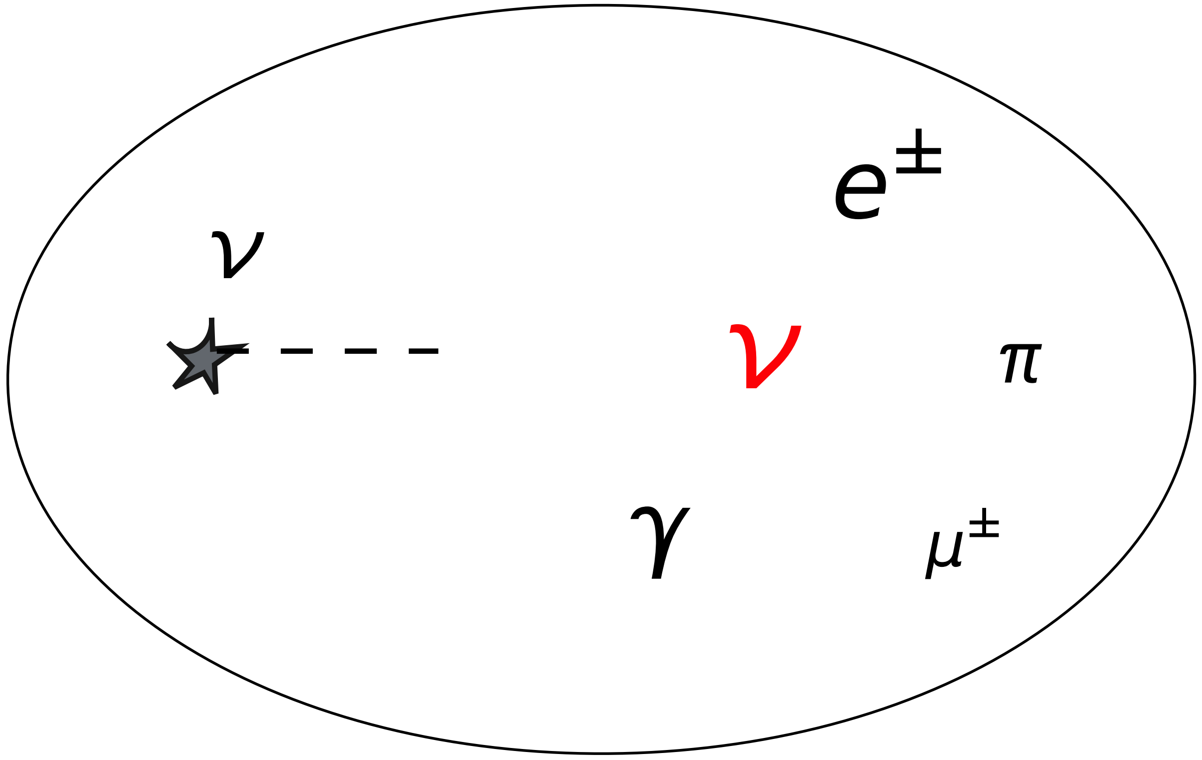

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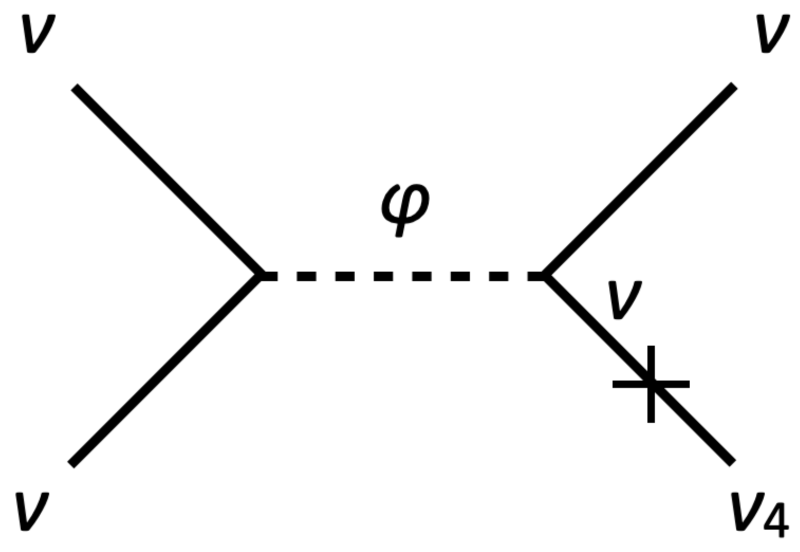
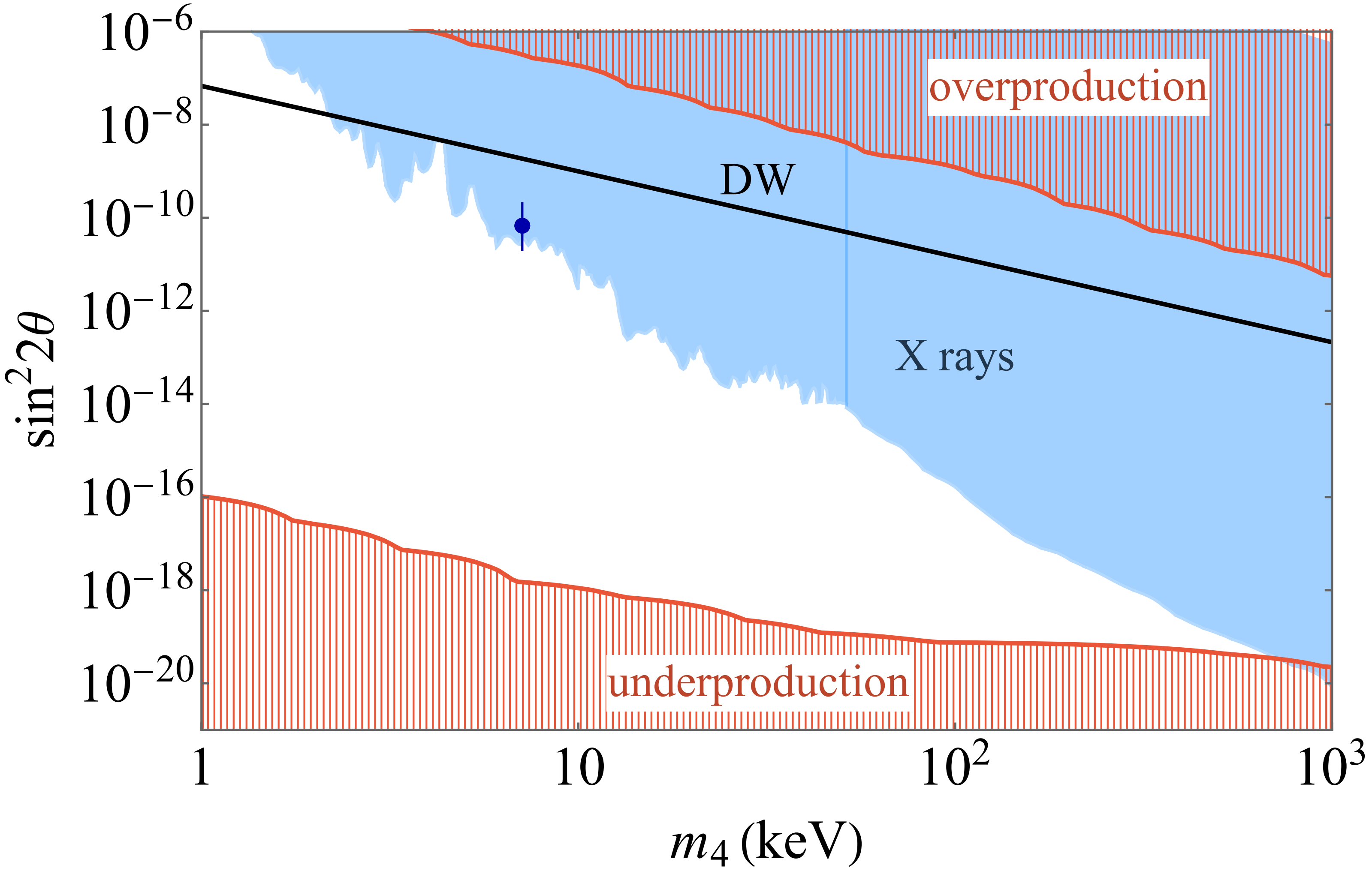
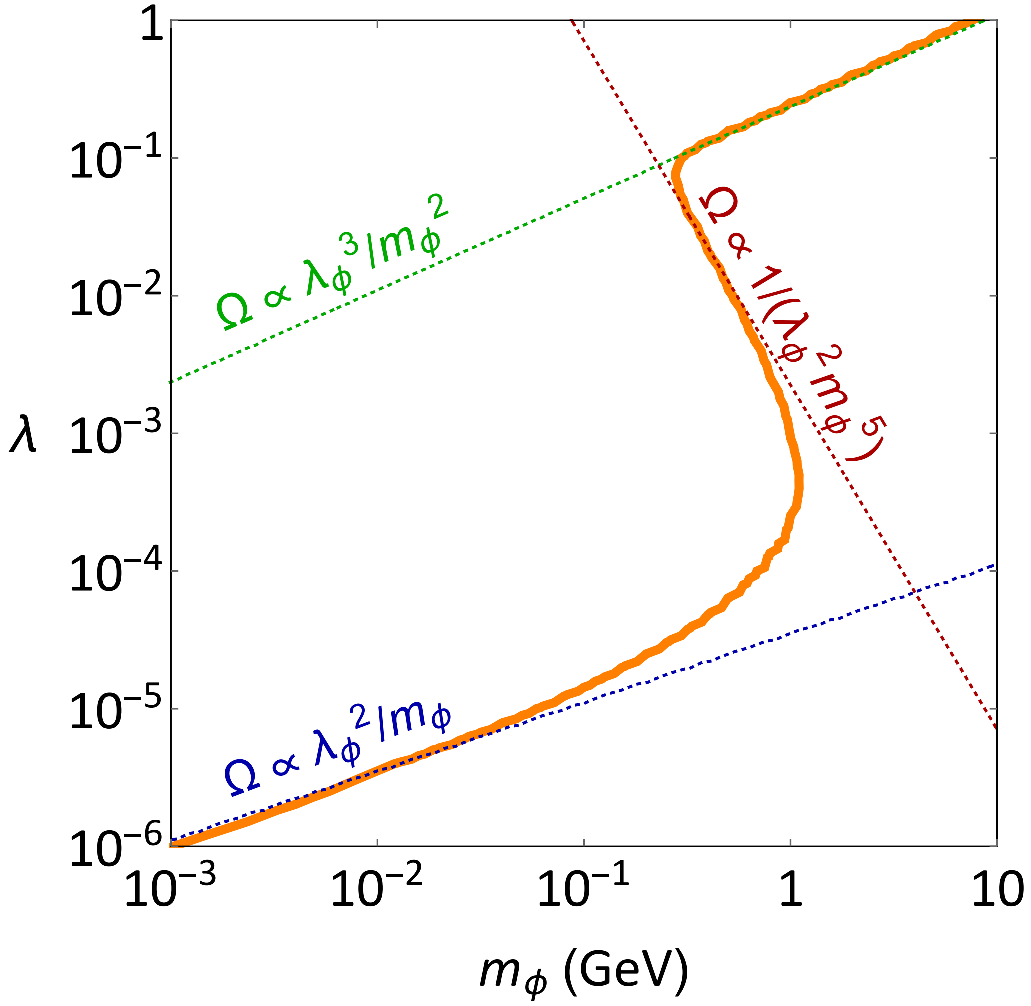


de Gouvêa, Sen, Tangarife, YZ (PRL 2020)

# Wide Open Parameter Space





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

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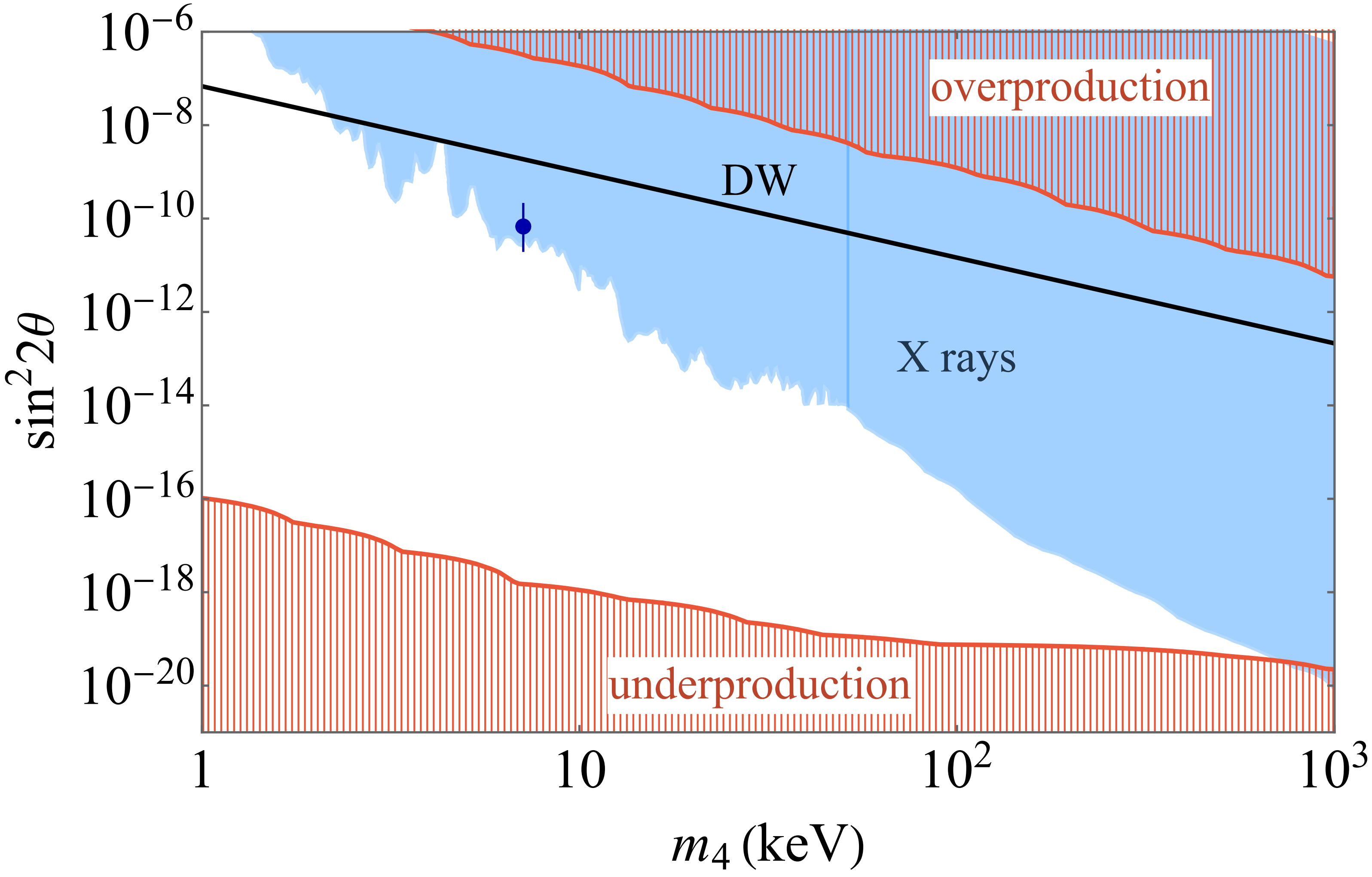
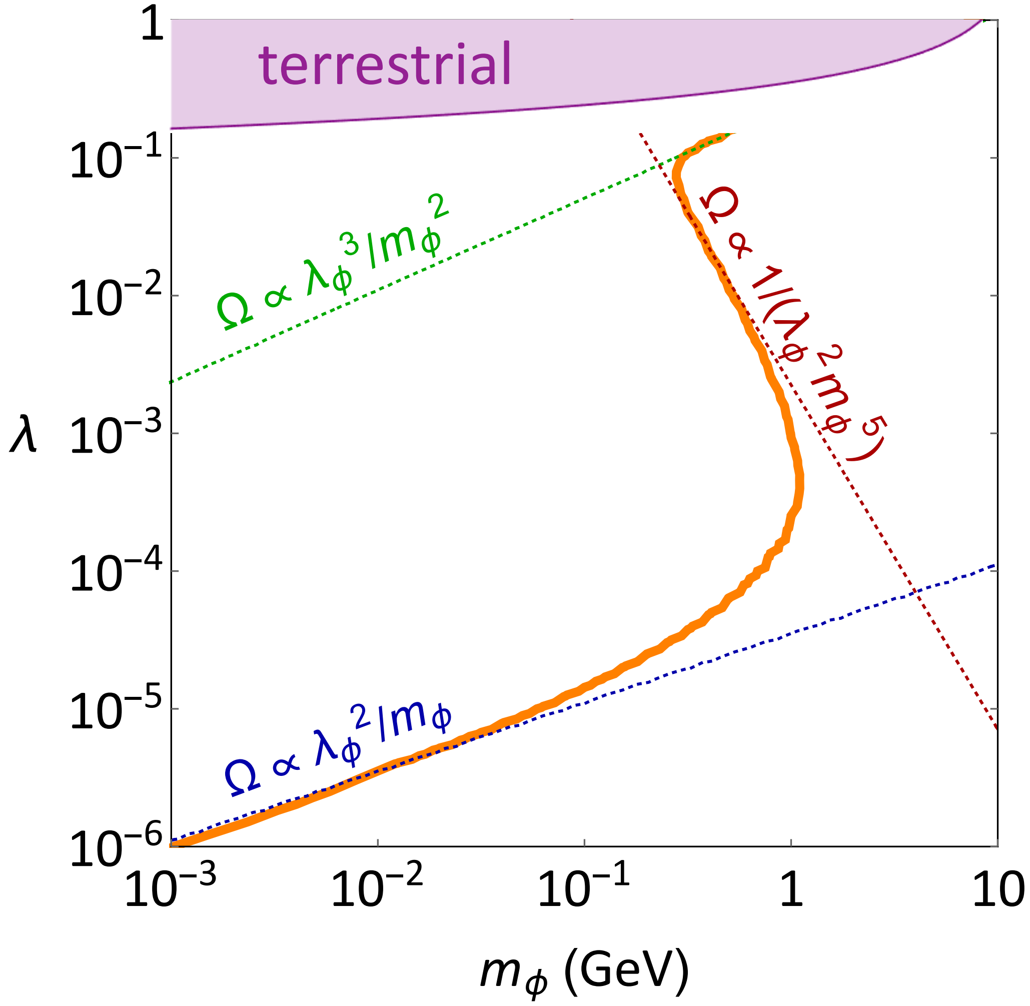
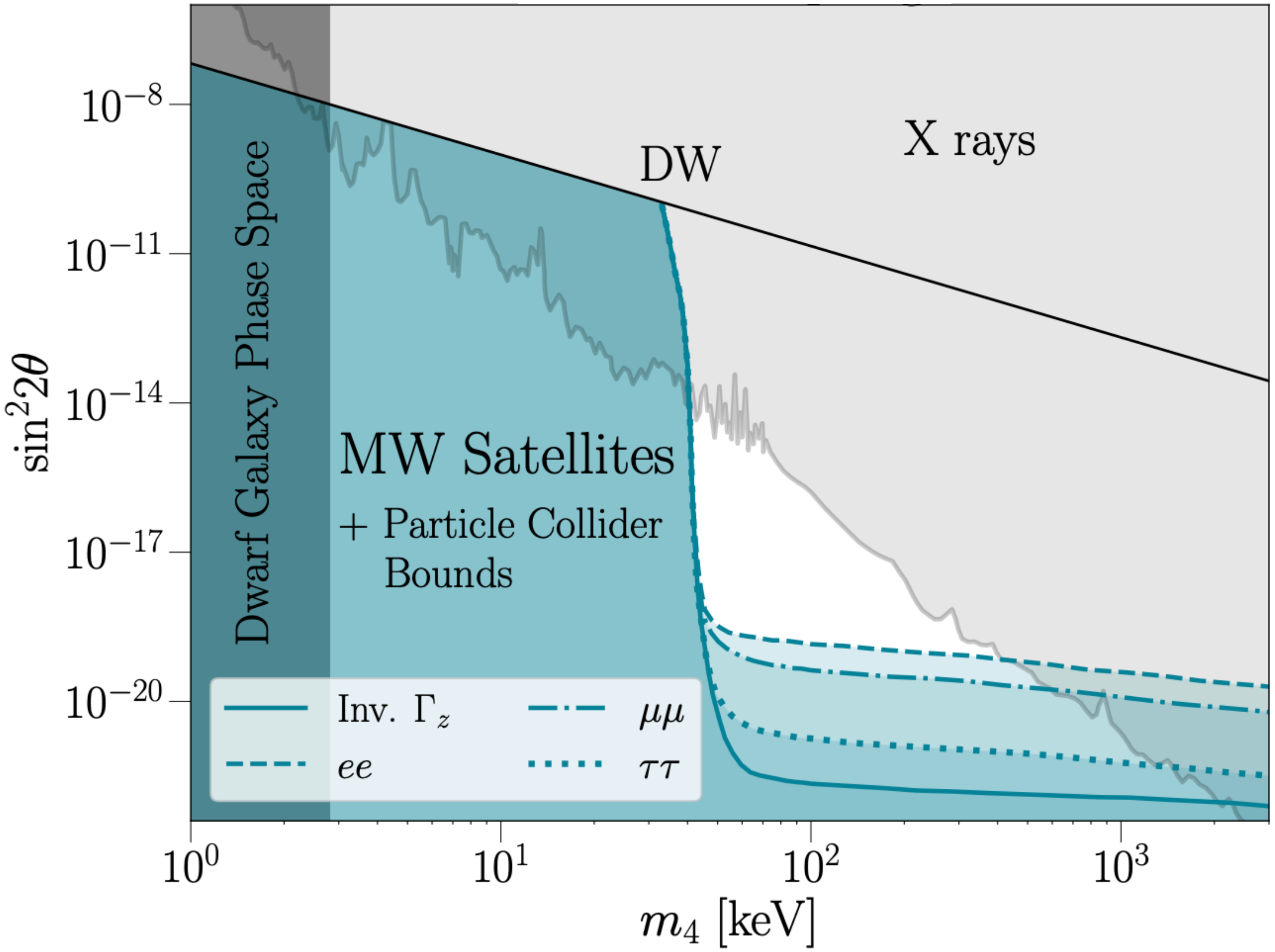




de Gouvêa, Sen, Tangarife, YZ (PRL 2020)

Blinov, Bustamante, Kelly, YZ, et al (PDU 2023) Snowmass 2021 whitepaper

# 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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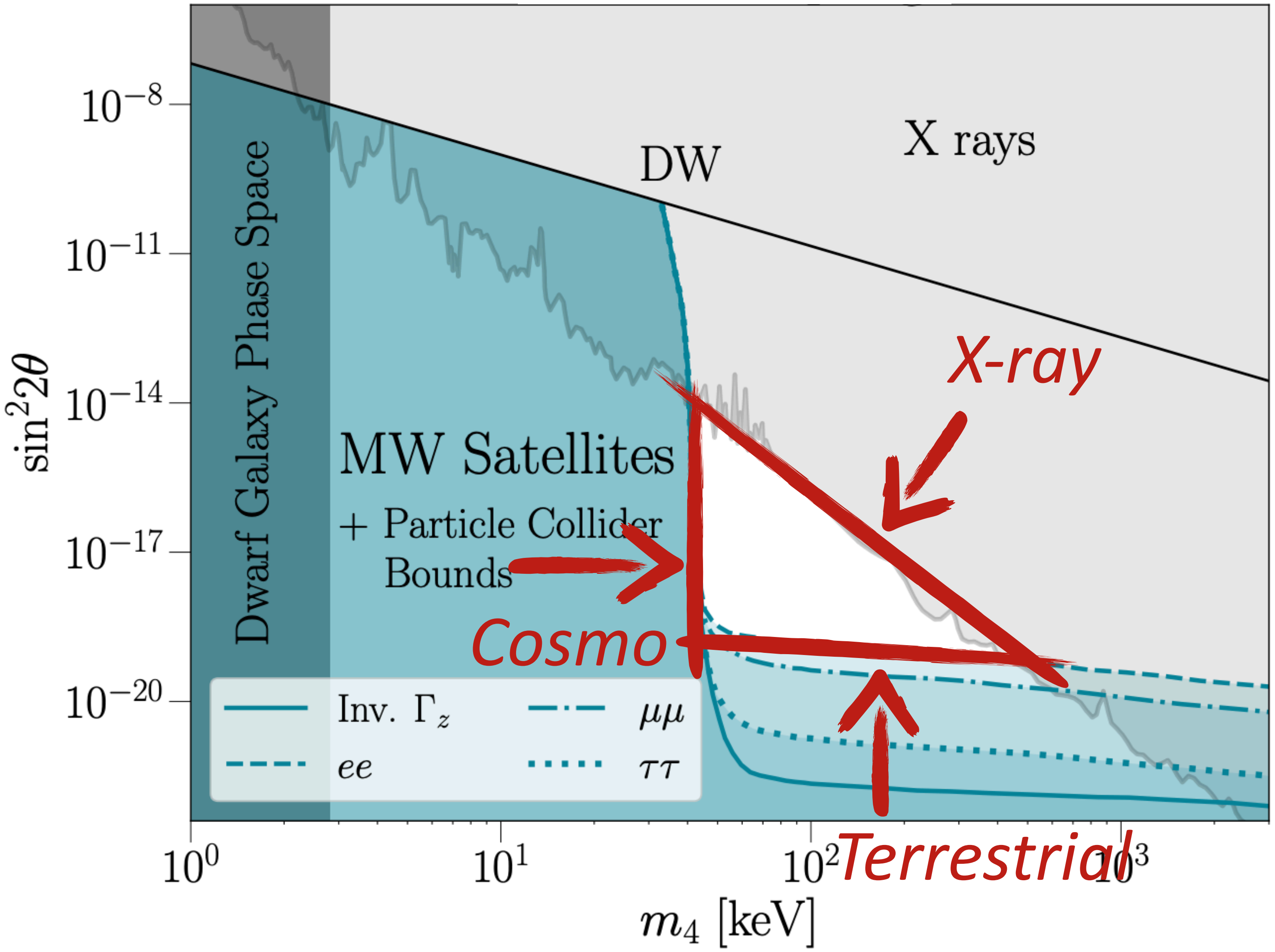

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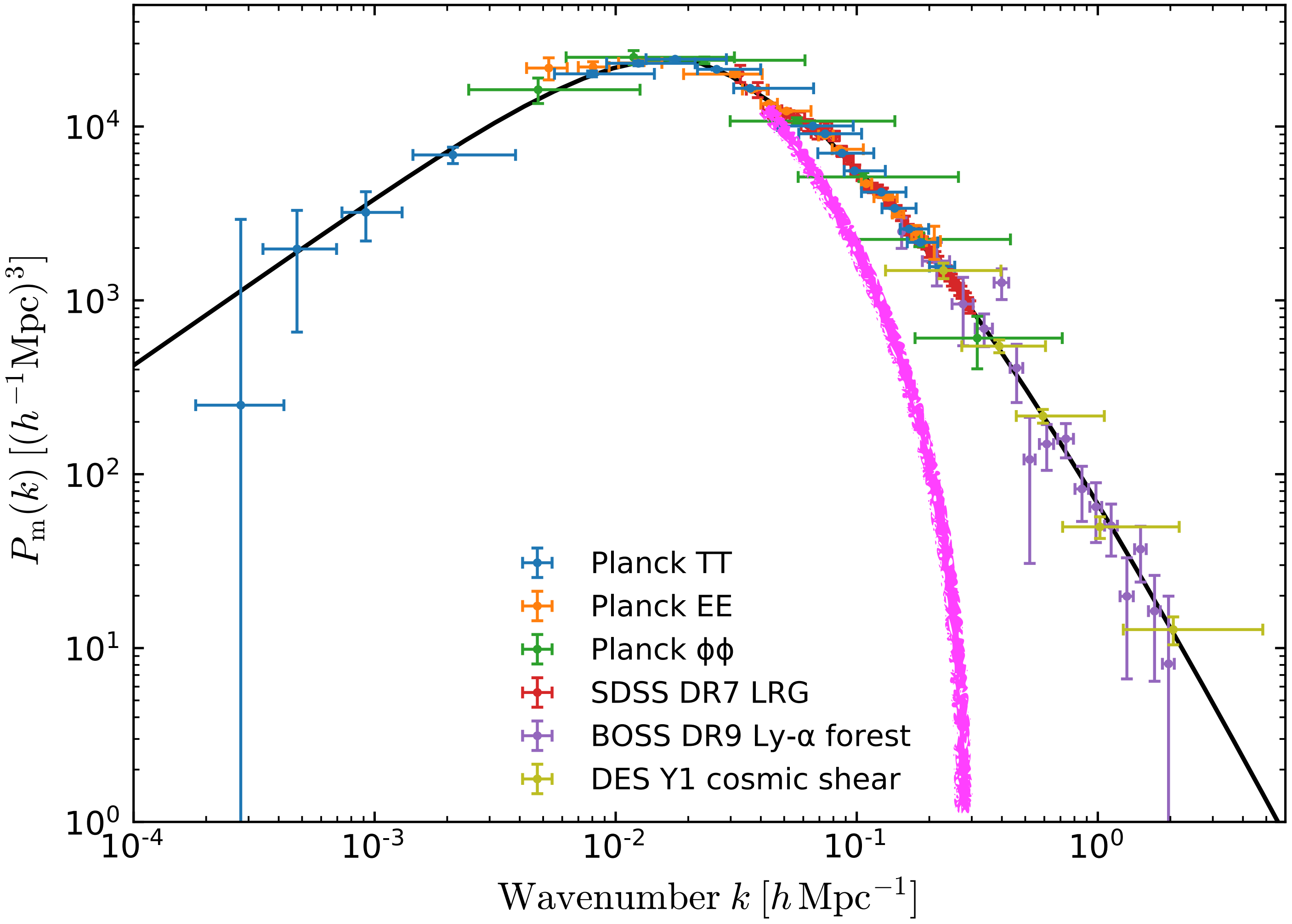
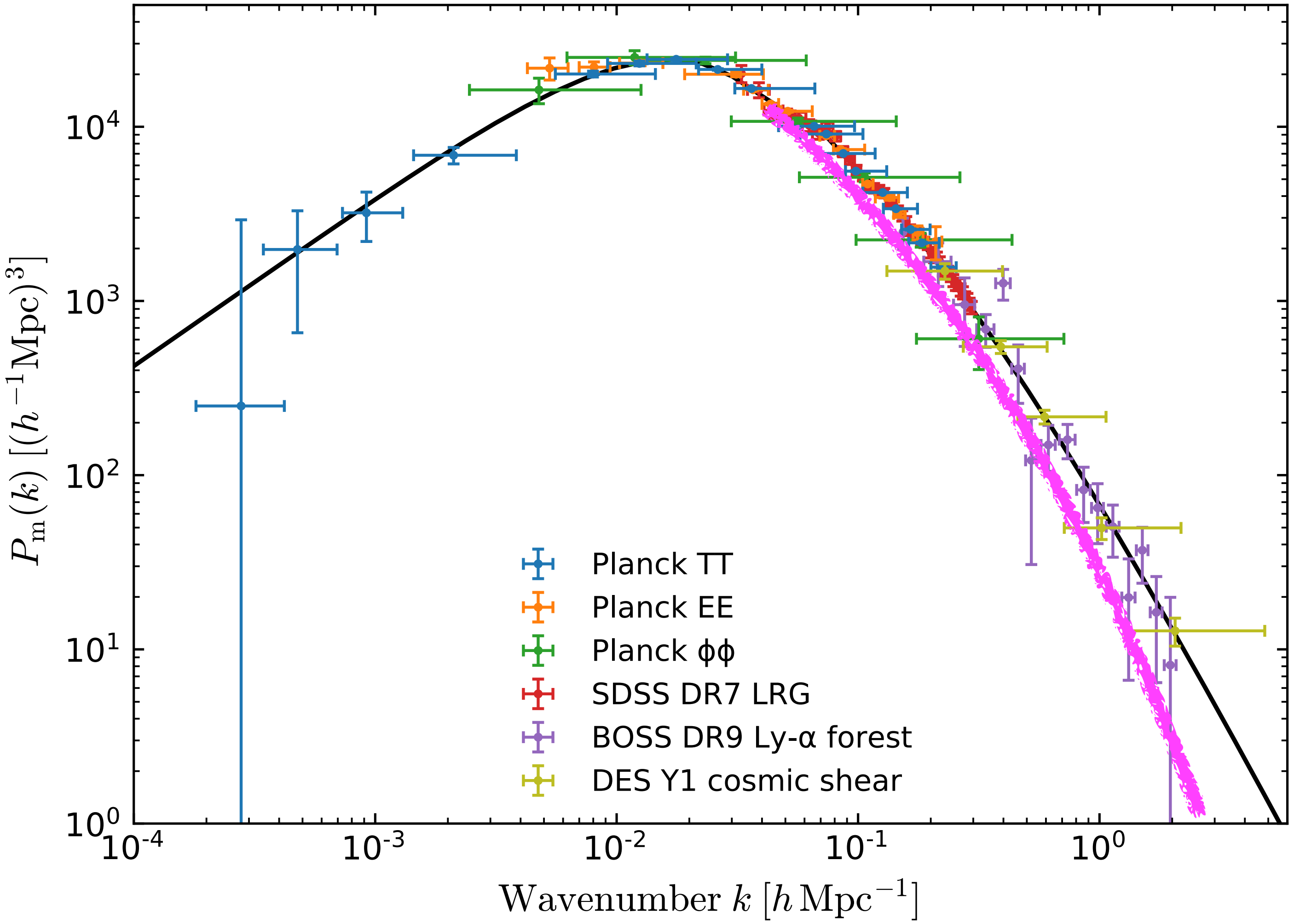


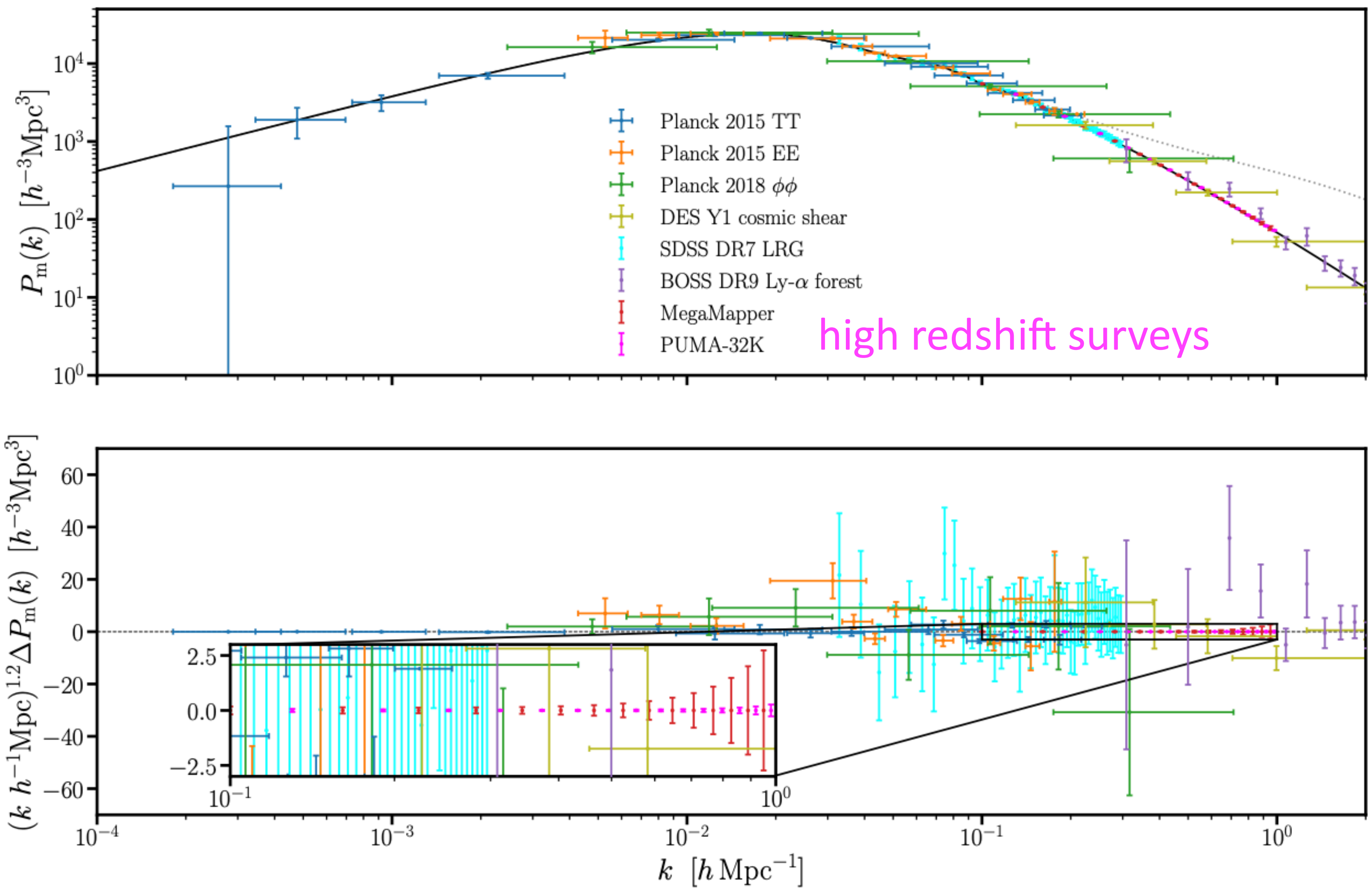
Making all the dark matter hot: clearly not acceptable

# How about Even Larger Scales?



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 is

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

*Over production 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.

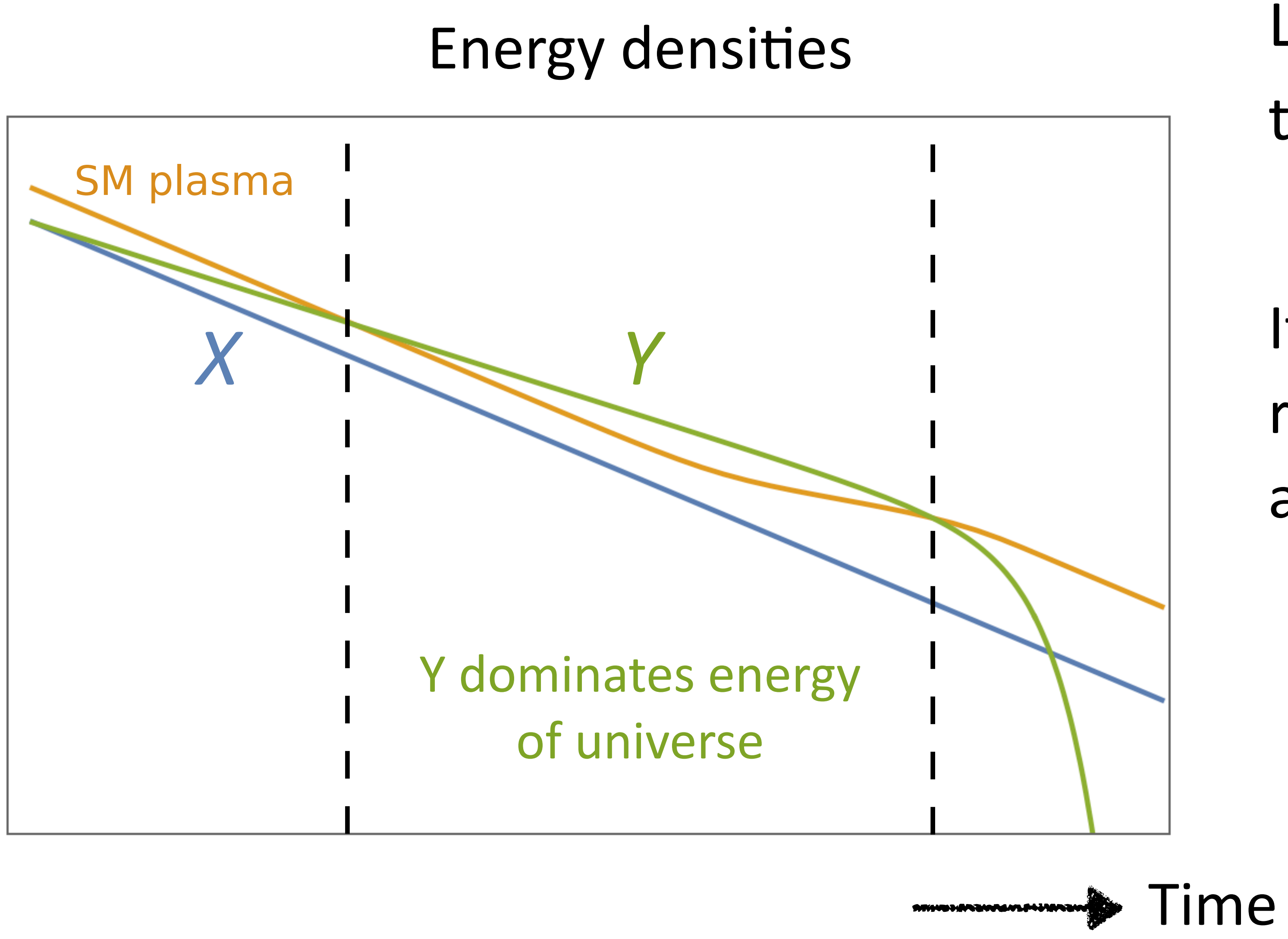
$$\Omega_X h^2 = 650 \times 0.12 \left( \frac{m_X}{6.5\,\mathrm{keV}} \right) \times \frac{1}{\mathcal{S}}$$

Textbook example of dilution via temperature dependence in $g_*$

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

Hard to imagine an appealing BSM with $g_* > 6500$.

# More Entropy from Late Decay



Long-lived diluting particle *Y*, temporarily matter domination.

If both *X*, *Y* freeze out relativistically, similar initial abundance:

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

Scherrer, Turner (PRD 1985)

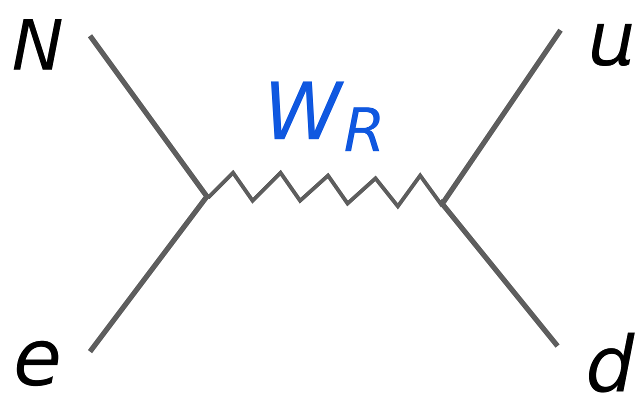
# Gauge Extensions to SM

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.

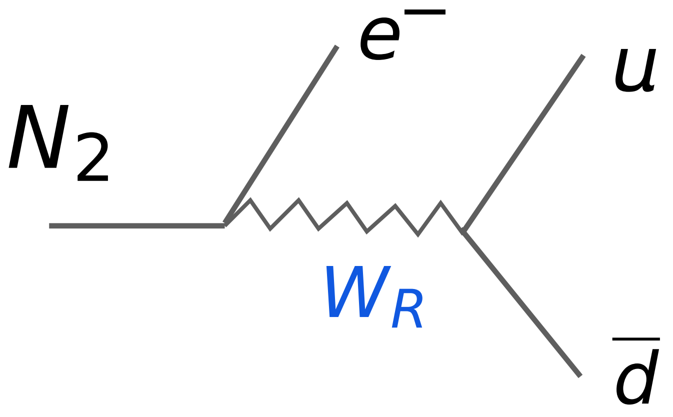
Dark matter $X = N_1$, dilutor $Y = N_2$.

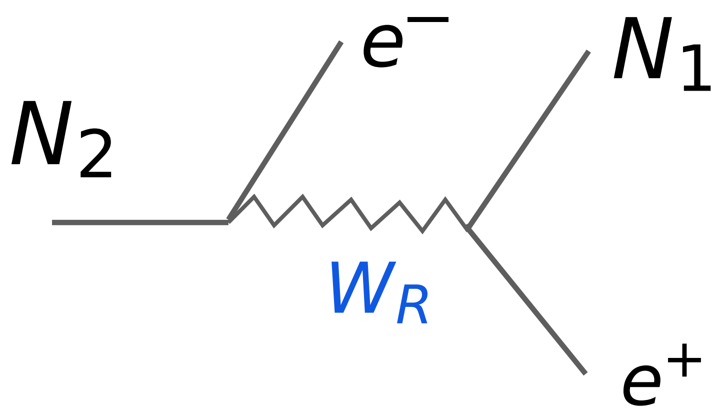


Bezrukov, Hettmansperger, Lindner (PRD 2010)

# 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,



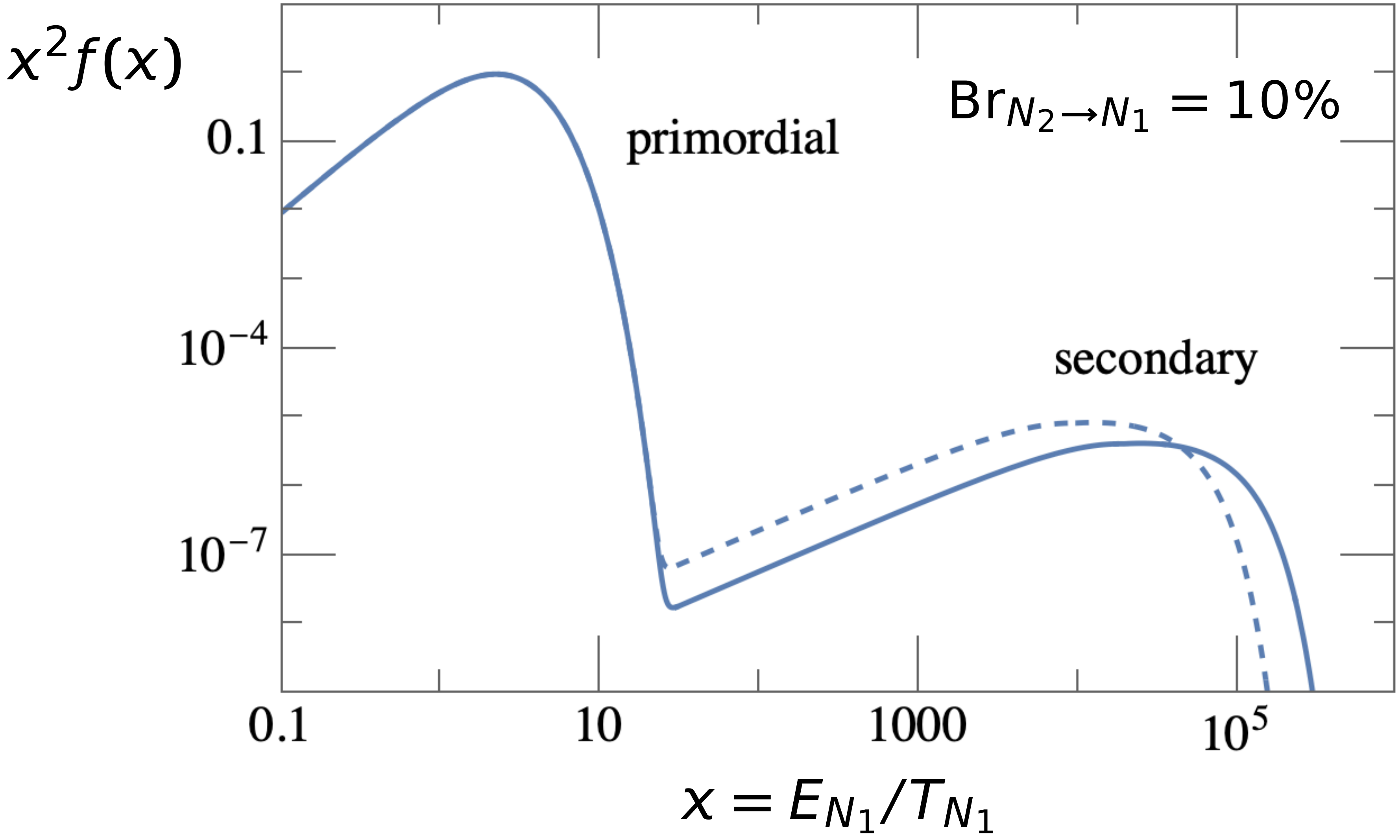


If this is the entire story, $\mathrm{Br}_{N_2 \to N_1} \geq 10\%$

This fraction of DM is energetic (hot). Relic requires $M_{N_2} > 10^6 M_{N_1}$

# 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* | $\sim M_{N_1}$ | $T_{\rm NR} \sim T_{\rm RH}\dfrac{M_{N_1}}{M_{N_2}}$ |

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

Nemevsek, YZ (PRL 2023)

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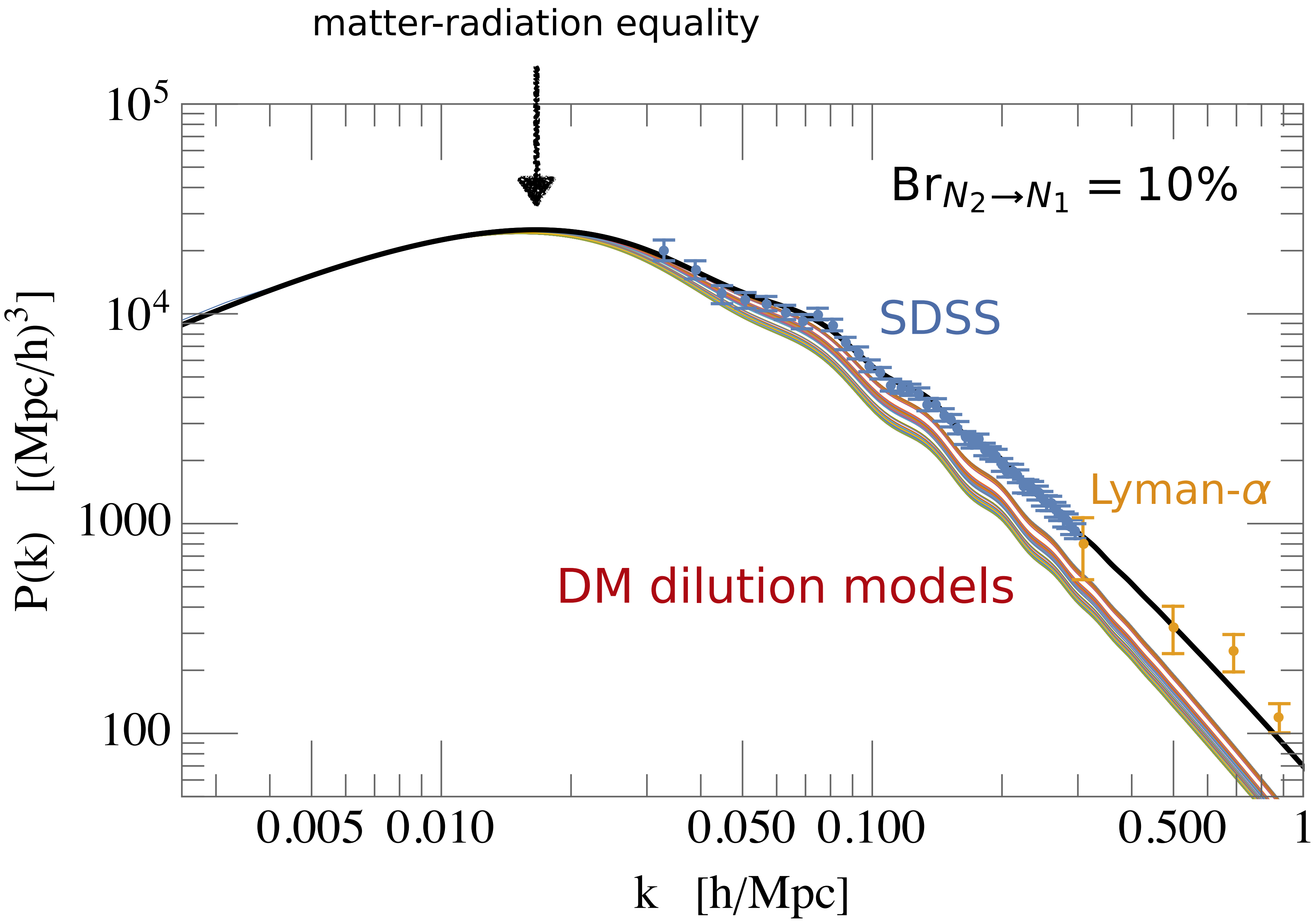
Another look at relic density $\Omega h^2 \simeq 0.12 \left( \dfrac{10^6 M_{N_1}}{M_{N_2}} \right) \left( \dfrac{T_{\rm RH}}{1\,{\rm MeV}} \right)$

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

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

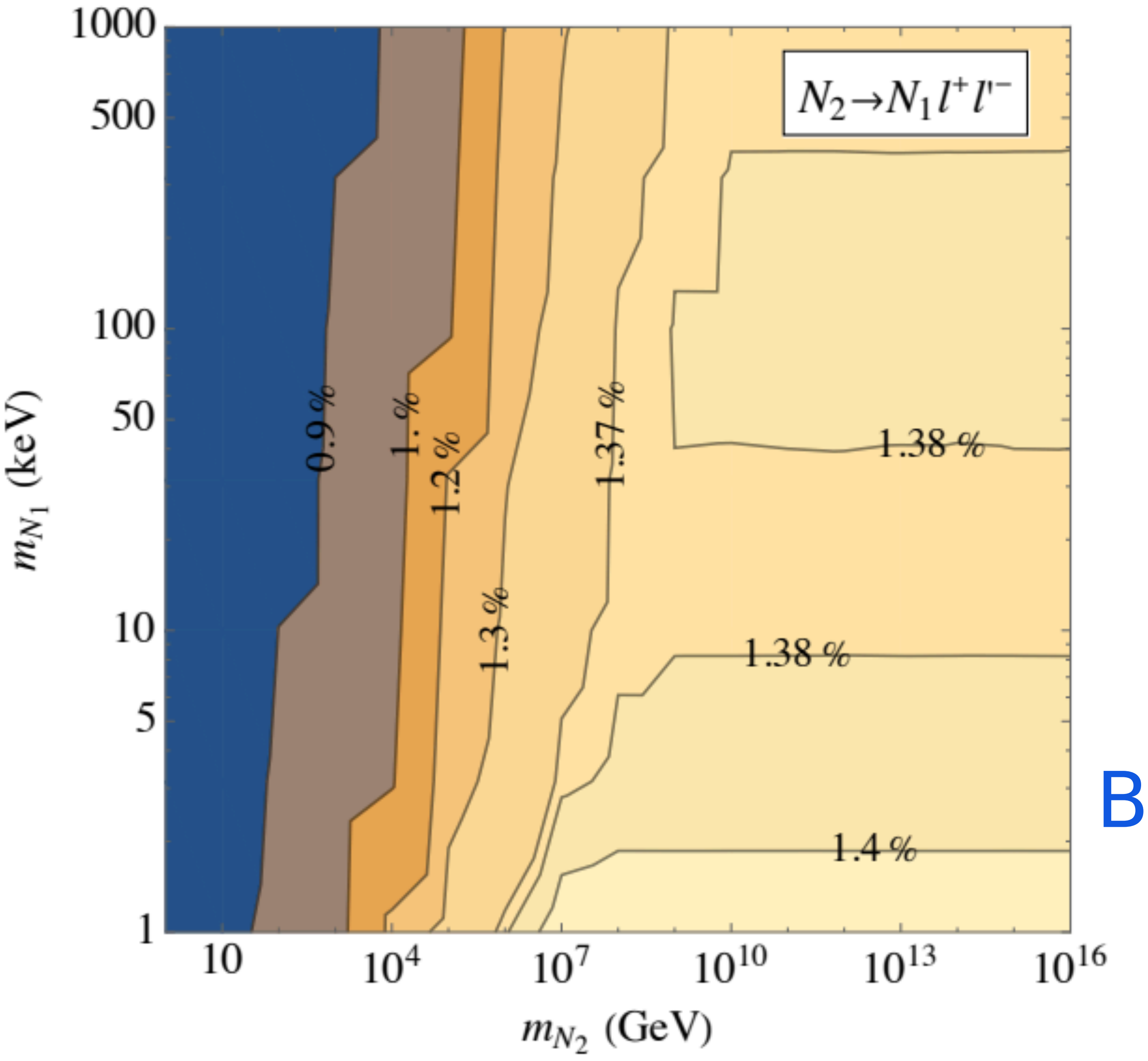
Nemevsek, YZ (PRL 2023)

# Damping Effects in P(k)



Nemevsek, YZ (PRL 2023)

# Large Scale Structure Constraint (SDSS)

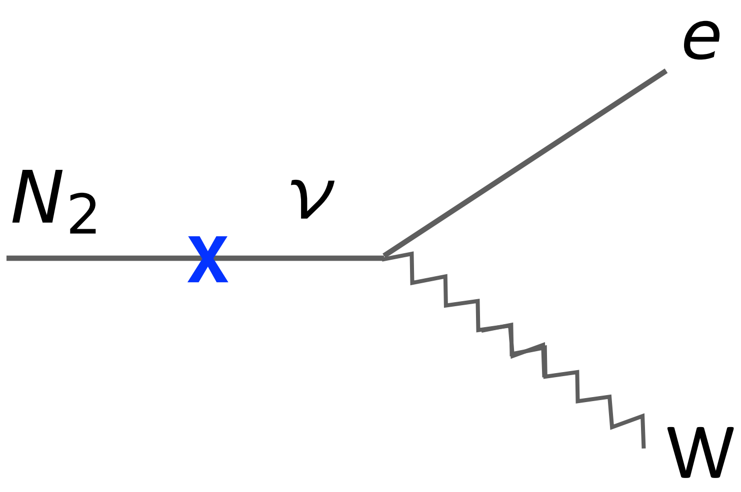


$\mathrm{Br}_{N_2 \to N_1} \lesssim 1\%$

Nemevsek, YZ (PRL 2023)

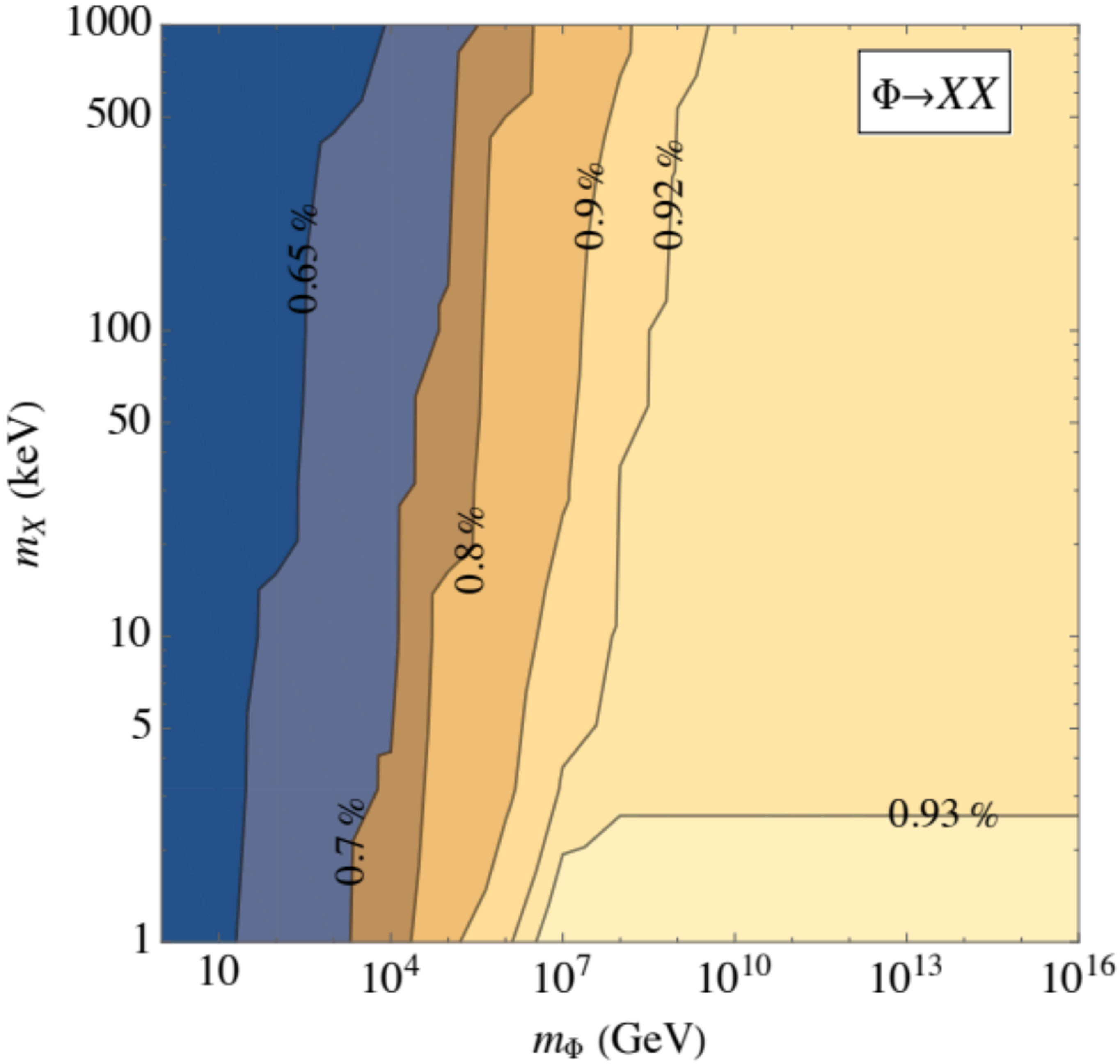
# Implication for Left-Right Model

To evade the LSS constraint, can resort to a N-ν mixing or W-$W_R$ gauge boson mixing → lower limit on mass scale $M_{W_R} > \mathrm{PeV}$ - stronger than any collider and flavour physics probes.



Nemevsek, YZ (PRD 2024)

# Generalization



Robust upper limit (SDSS)

$$\mathrm{Br}_{\mathrm{dilutor}\to\mathrm{DM}} \lesssim 1\%$$

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

Cosmological data can have important imprint about origins of dark matter.

Complementary to terrestrial searches.

Many opportunities for years to come.

Thanks!