Cosmological and astrophysical bounds on the keV mass dark matter

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CERN. February 5, 2009

Weakly Interacting Massive Particles

- Original idea : the particle with the mass $m_\chi \sim m_W$ and the annihilation cross-section $\sim G_F$ (**WIMP**) produces $\Omega_\chi \sim 1$
- Produced through annihilation of SM particles: non-relativistic "freeze-out": $\dot{n} + 3Hn = -\langle \sigma v \rangle (n^2 - n_{eq}^2)$
- Annihilation cross-section $\sigma \lesssim \frac{1}{m_\chi^2}$ (unitarity bound)
- Leads to the mass range $m_\chi \sim 10 - 10^3$ GeV
- Decouples from primeval plasma at $T_{\text{dec}} \sim$ MeV.
- At decoupling has $\langle p \rangle \sim (MT_{\text{dec}})^{1/2}$ – decouples **non-relativistic**

Lower mass alternatives?

General properties of a DM candidate

- Any DM candidate must be
  - Produced in the early Universe and have correct relic abundance
  - Very weakly interacting with electromagnetic radiation ("dark", most probably neutral)
  - Stable or cosmologically long-lived
- DM is **not** baryonic
- DM is **not** a SM particle (neutrinos *could be* but see below)

DM is the physics beyond the Standard Model

How light can be a DM particle?

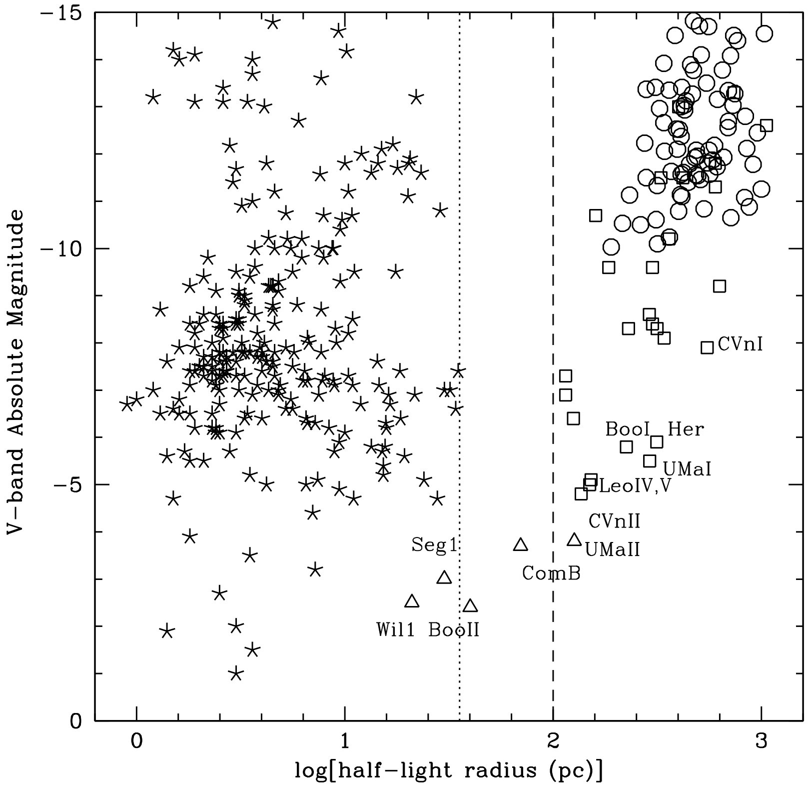
Universal DM bound

- The model-independent lower limit on the mass of **fermionic** DM

Tremaine, Gunn (1979)

- The smaller is the DM mass – the bigger is the number of particles in an object with some velocity dispersion σ
- For fermions there is a **maximal** phase-space density (degenerate Fermi gas) $\Rightarrow$ observed phase-space density restricts number of fermions
- Objects with highest phase-space density – dwarf spheroidal galaxies – lead to the lower bound on the DM mass $m \gtrsim 300$ eV
- Active neutrinos with $m \sim 300$ eV have **primordial** phase-space density $Q \sim Q_{obs}$.
- Neutrino DM abundance $\Omega_\nu h^2 = \frac{m_\nu}{94\ \textbf{eV}}$ $\Rightarrow$ Active neutrinos cannot constitute 100% of DM

Universal DM bound 2008



- Since 1979 a number of known dwarf spheroidal galaxies more than doubled. Gilmore et al. 2007-2008
- New dSph's are very dense $Q_{obs} = 10^4 - 10^5\ M_\odot\ \mathrm{kpc}^{-3}[\mathrm{km\ s}^{-1}]^{-3}$.
- Bound on any fermionic DM improved to become $m_{\mathbf{DM}} > 0.41$ **keV** Boyarsky, Ruchayskiy, Iakubovskyi'08

- Can this bound be further improved?

Yes!

Dynamics of DF

- DM particles are collisionless $\Rightarrow$ their phase-space distribution function (DF) is conserved in time (*Liouville's theorem*):

$$\frac{df(t,x,p)}{dt} \equiv \frac{\partial f}{\partial t} + \frac{p}{m}\frac{\partial f}{\partial x} - \frac{\partial U}{\partial x}\frac{\partial f}{\partial p} = 0$$

- The primordial (initial) phase-space DF **depends on the production mechanism**: (WIMPs – Boltzmann, neutrino – Fermi-Dirac, other super-WIMPs – non-universal DF)
- The final DF – hard to compute from astronomical data
- "Popular" phase-space DF estimator: $Q = \rho/\langle v^2\rangle^{3/2}$. Easy to compute for the initial and final states.

Hogan, Dalcanton 2000

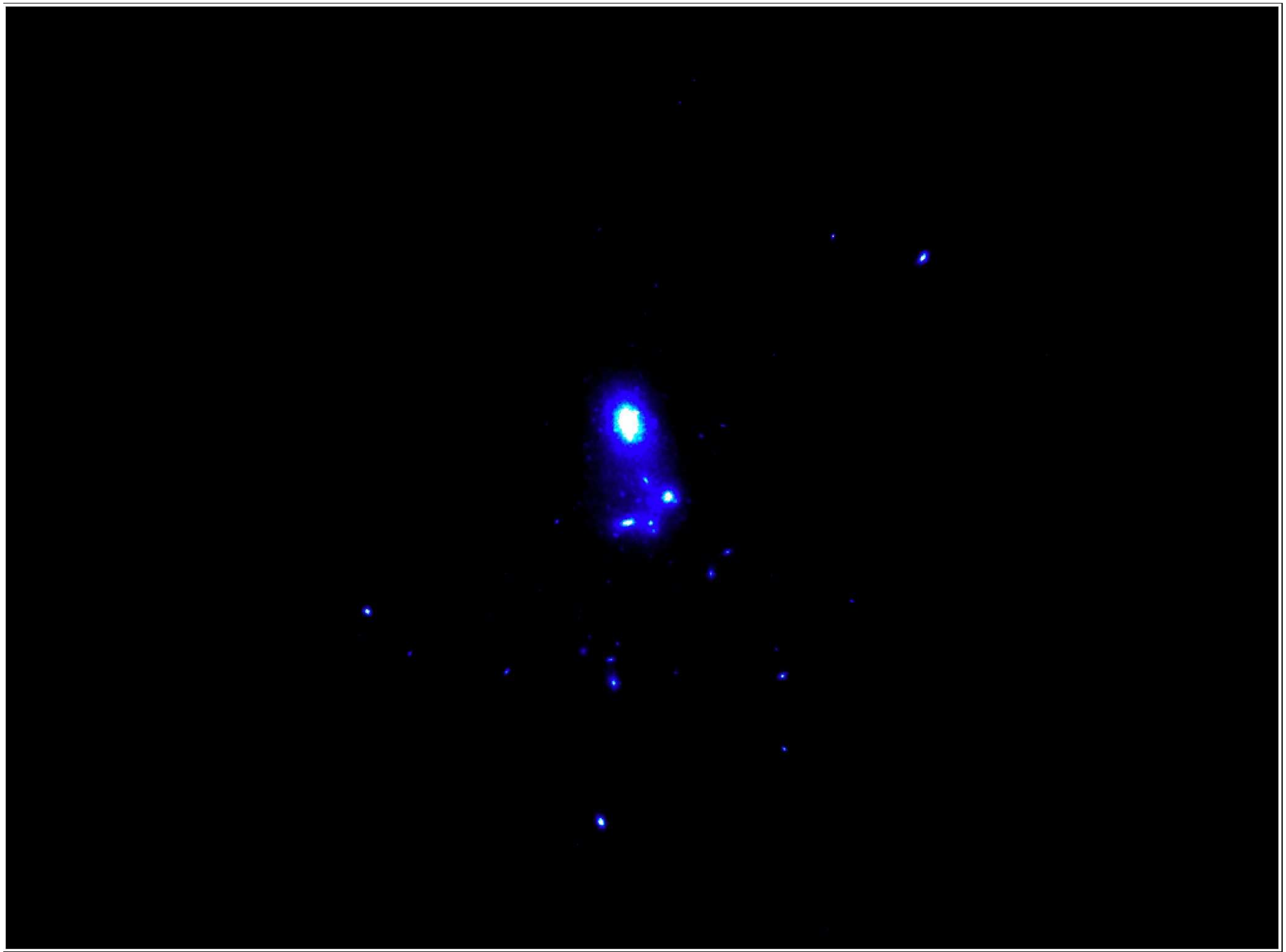
- Liouville theorem for Q?
- In some cases (e.g. Boltzmann DF) Q is related to entropy or to the DF $\Rightarrow Q_{ini} > Q_{fin}$. In general **this is not true**.

Boyarsky, Ruchayskiy, Iakubovskyi'08

Decaying DM

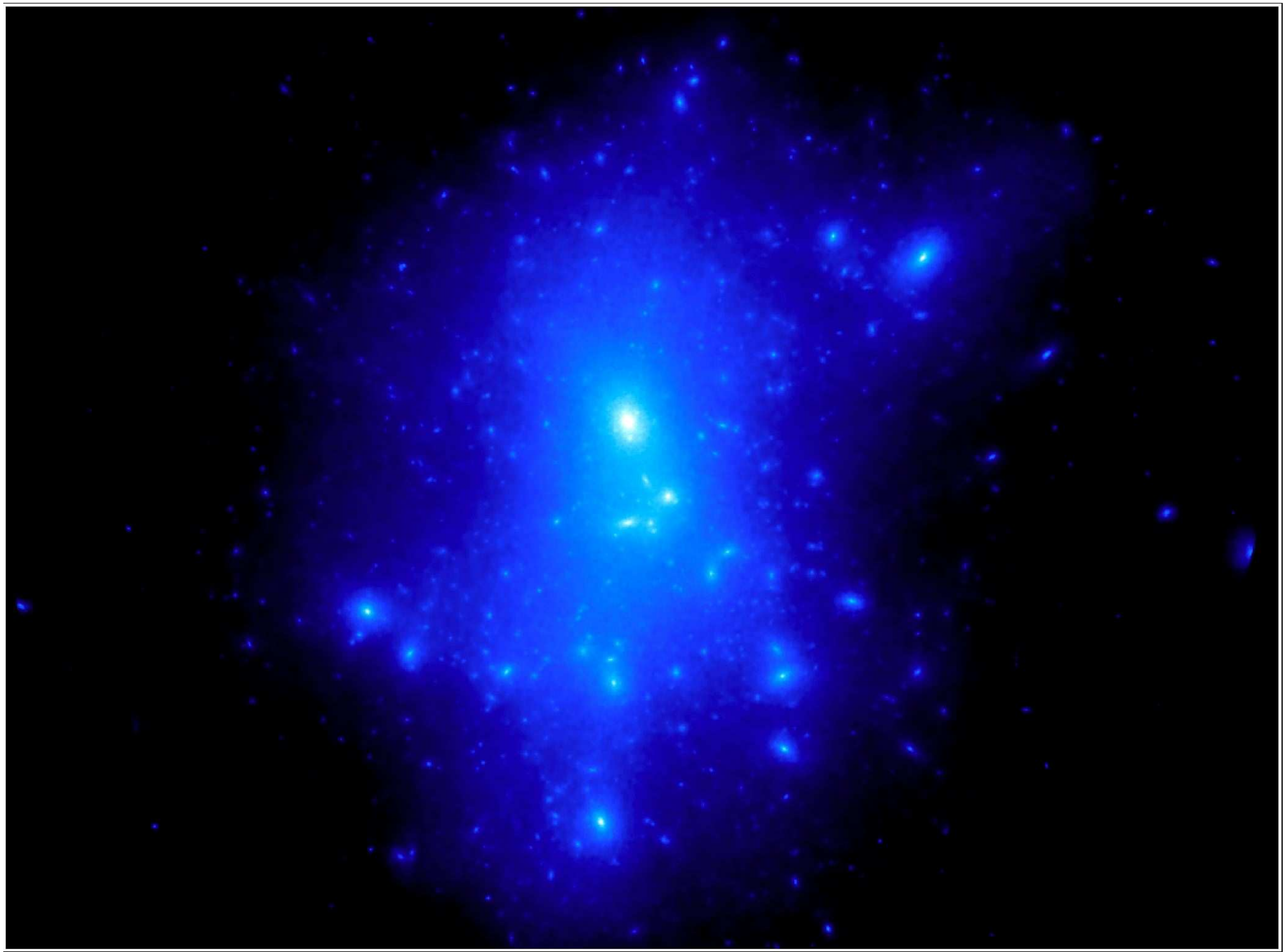
- Mass can be in keV–GeV range (cannot be smaller than ~ 0.4 keV)
- Two-body decay channel: DM $\rightarrow \gamma + \nu, \gamma + \gamma$ produces monochromatic decay line
- All-sky signal
- if a candidate line is found, its surface brightness profile may be measured (differs from that of astrophysical lines), and compared among several objects with the same expected signal.
- The astrophysical search for decaying DM is **another type of a direct detection experiment**.

Annihilation signal from MW-sized galaxy



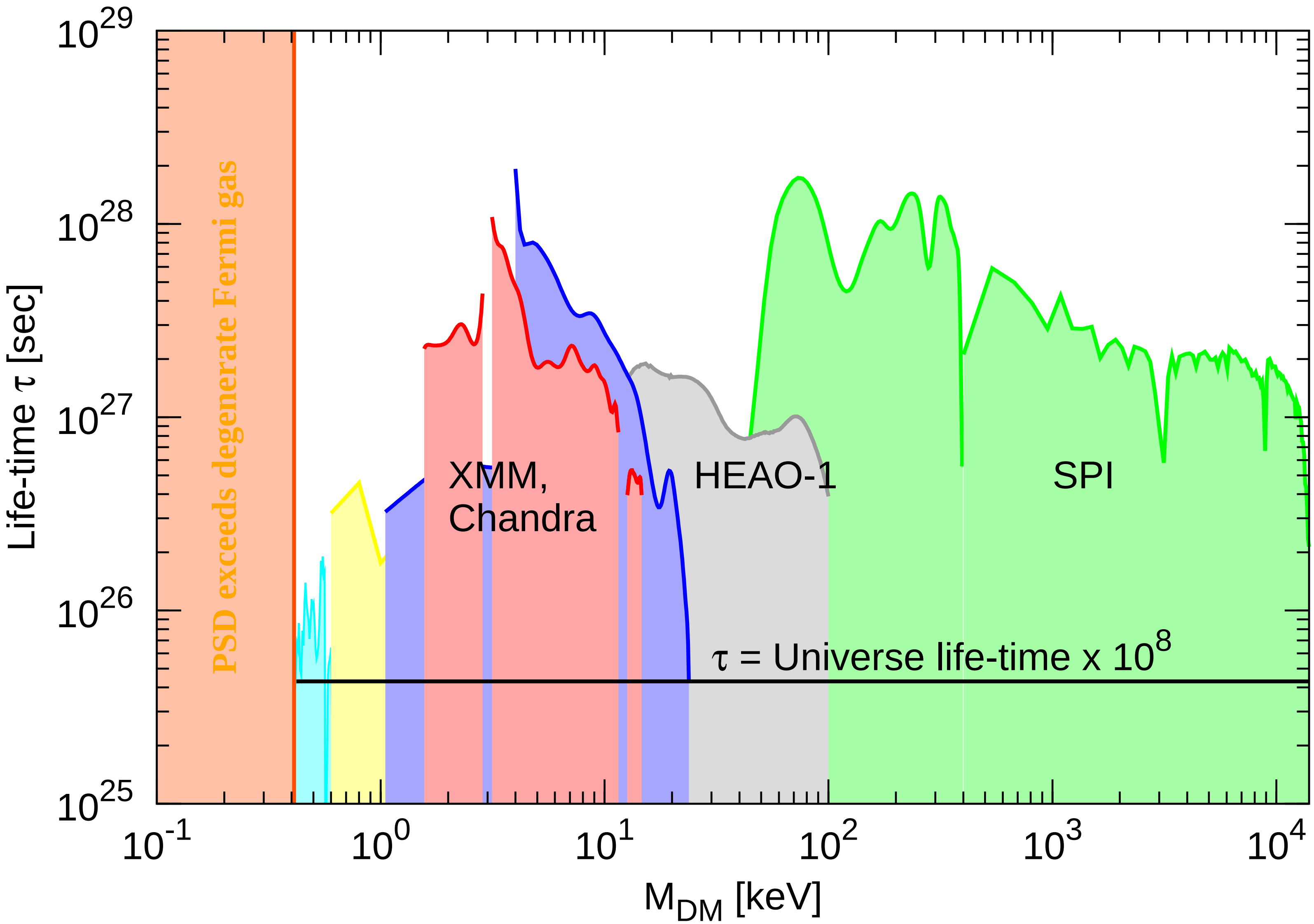
Moore et al. 2005

Decay signal from MW-sized galaxy



Moore et al. 2005

Restrictions on life-time of decaying DM



MW (HEAO-1) Boyarsky et al 2005

Bullet cluster Boyarsky et al 2006

LMC+MW(XM Boyarsky et al 2006

MW (Chandra) Riemer-Sørensen et al.; Abazajian et al.

MW (XMM) Boyarsky et al 2007

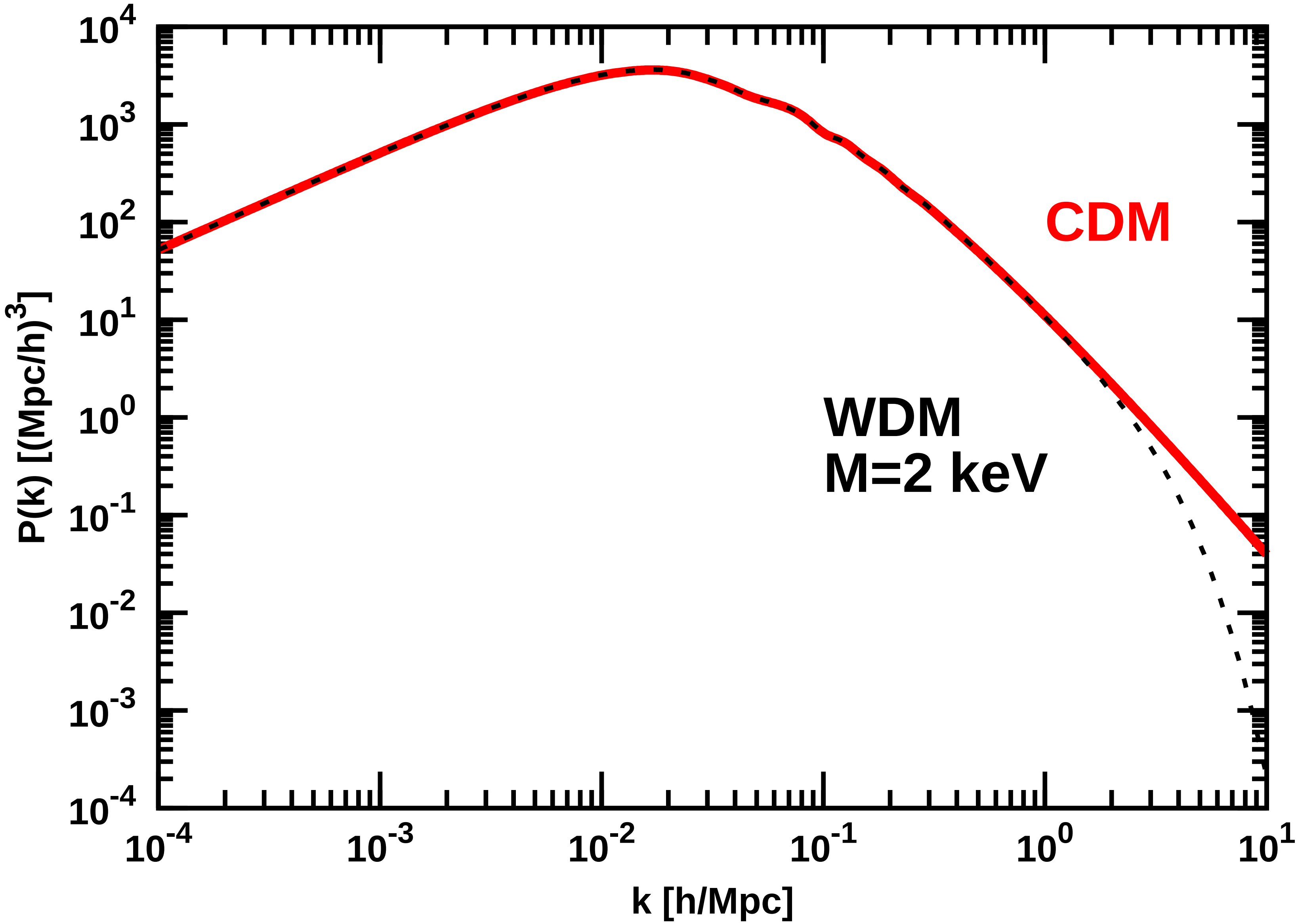
M31 Watson et al. 2006; Boyarsky et al 2007

How fast can be the DM?

- Feeble interaction strength
- A weakly interacting particle decouples from primeval plasma **non-relativistic**
- A super-weakly interacting DM candidate can decouple **relativistic**.
- Relativistic particles erase primordial density perturbations at scales below their **free-streaming**
- Can we experimentally distinguish between these possibilities?

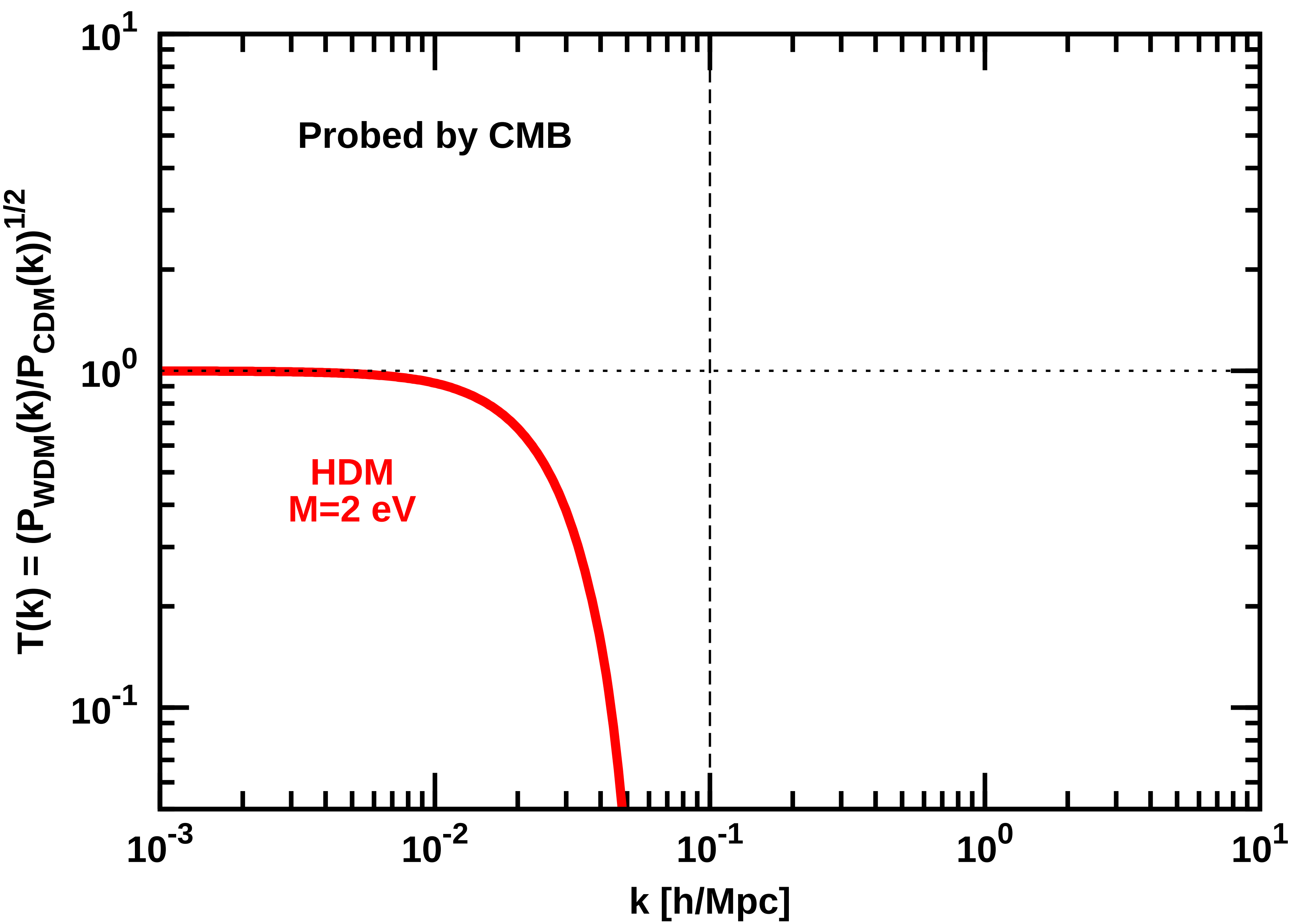
Yes!

(Linear) powerspectra

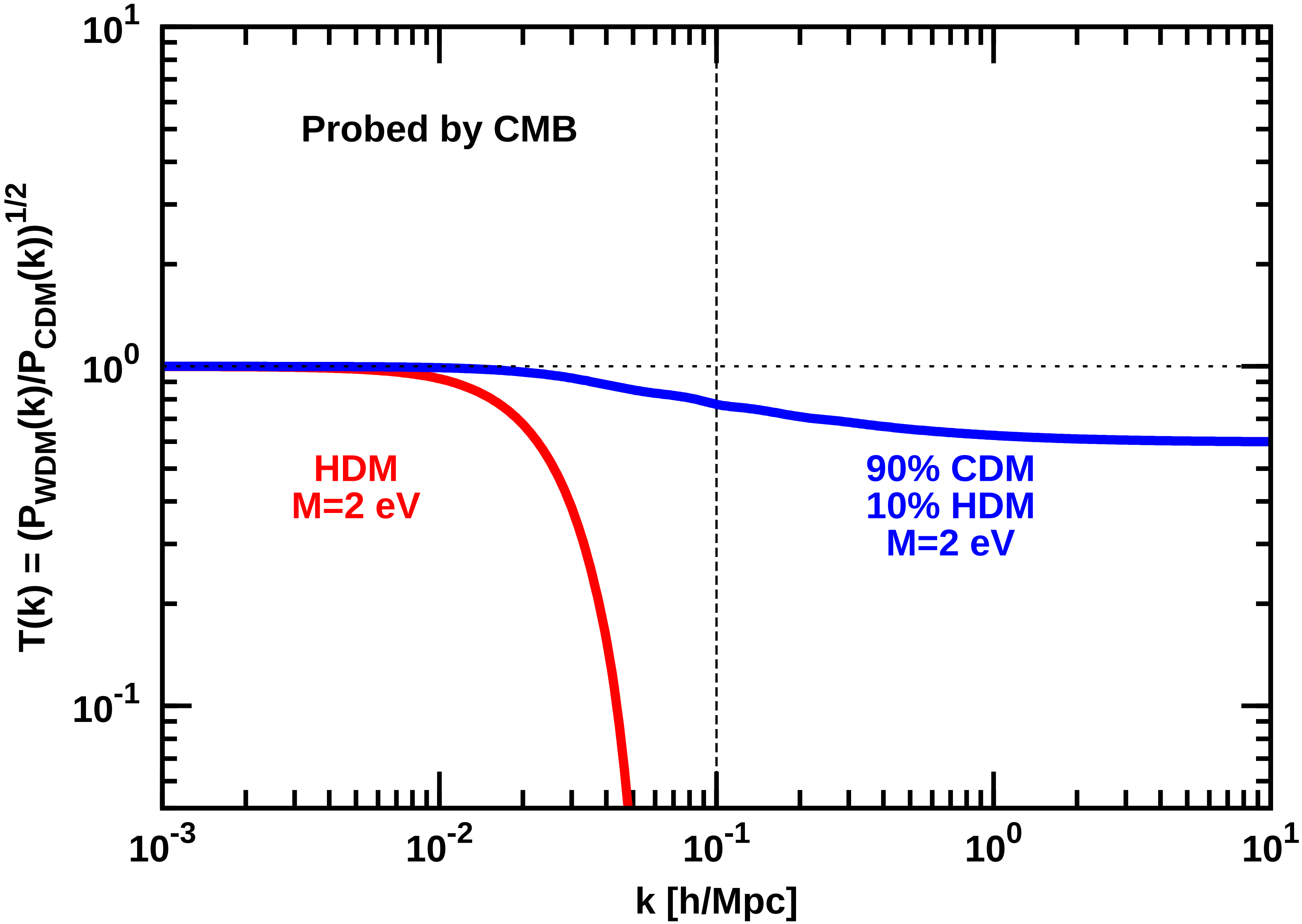


DM and Structure Formation

Transfer function



Transfer function



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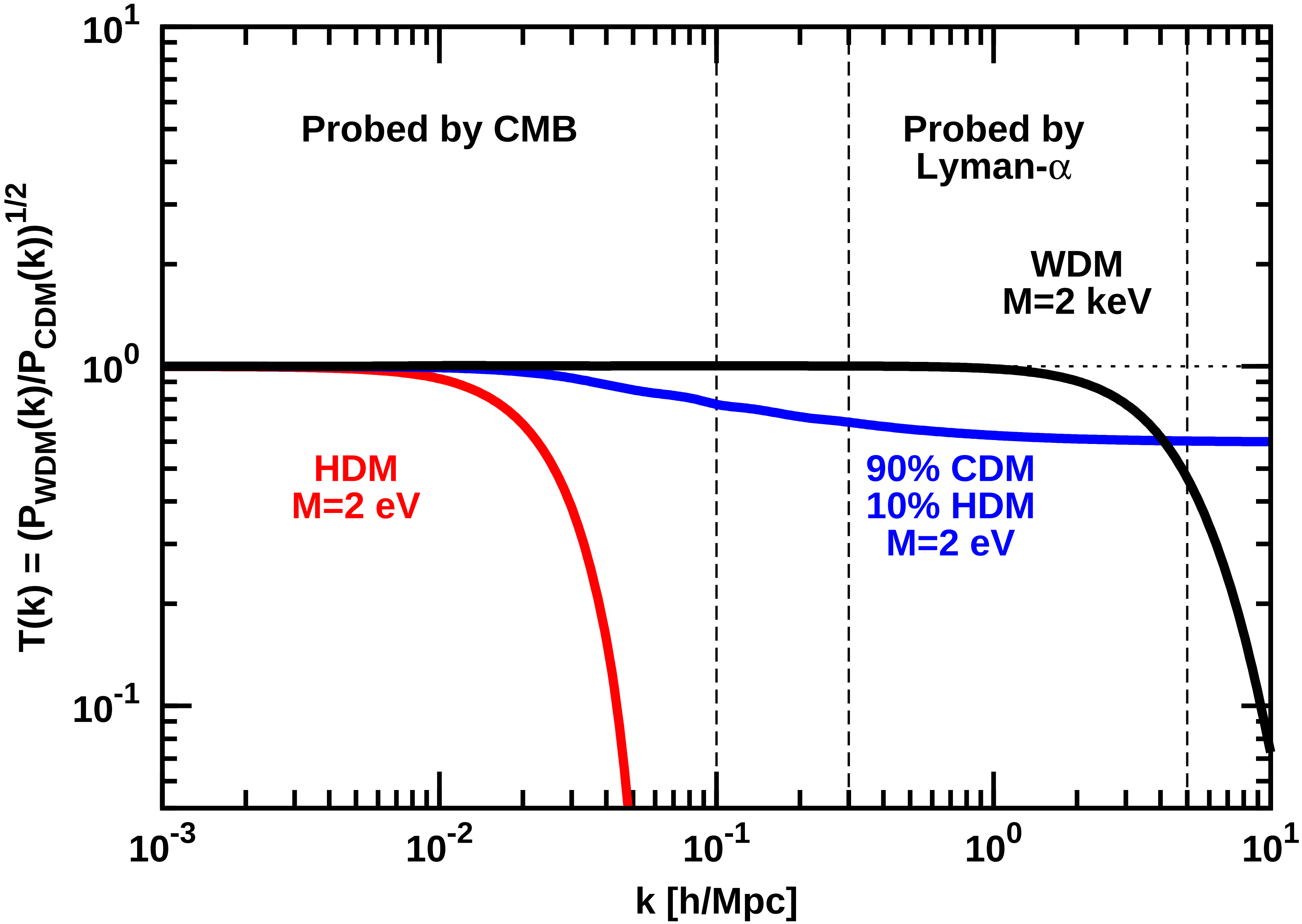
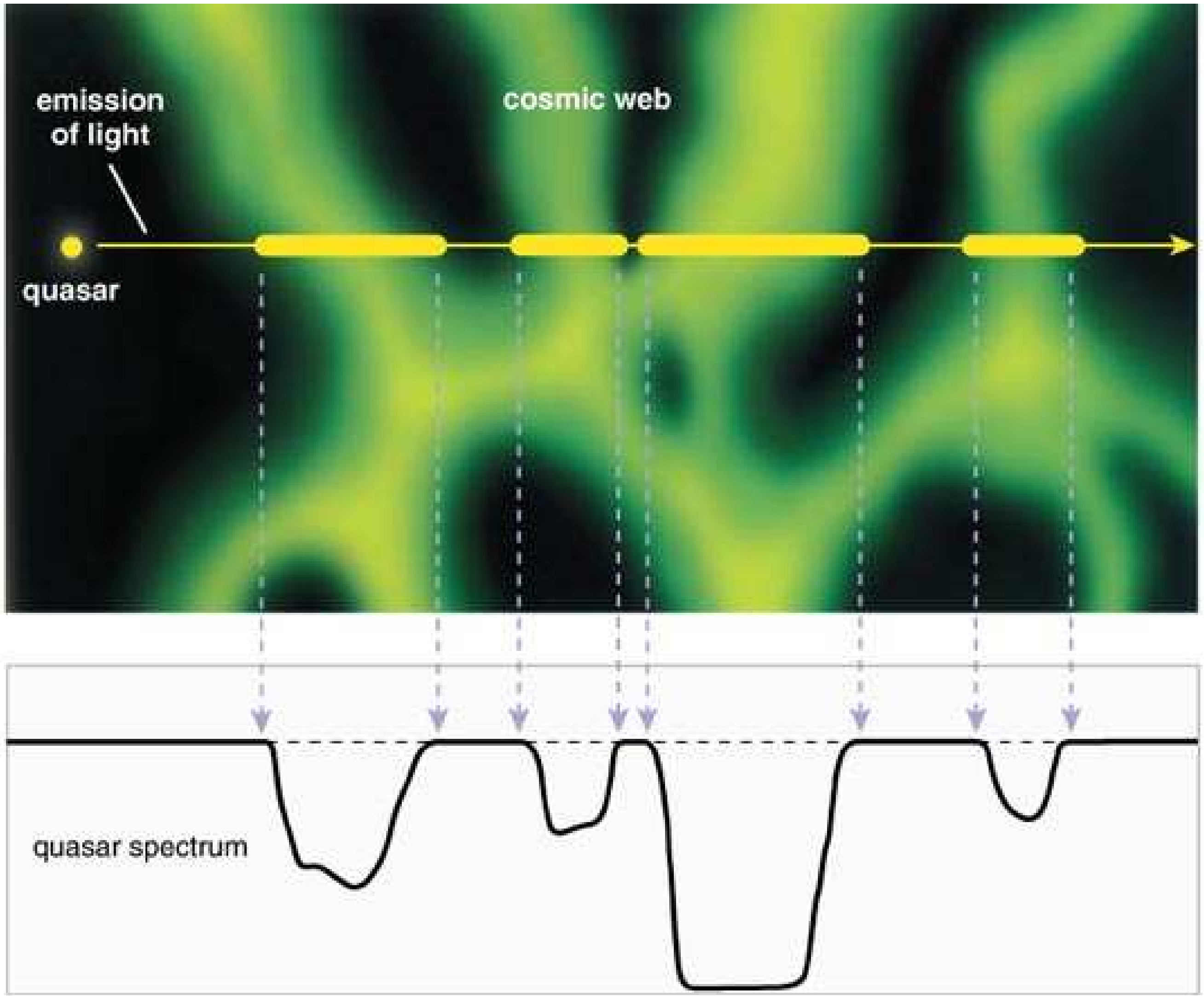


Nonlinear powerspectrum?

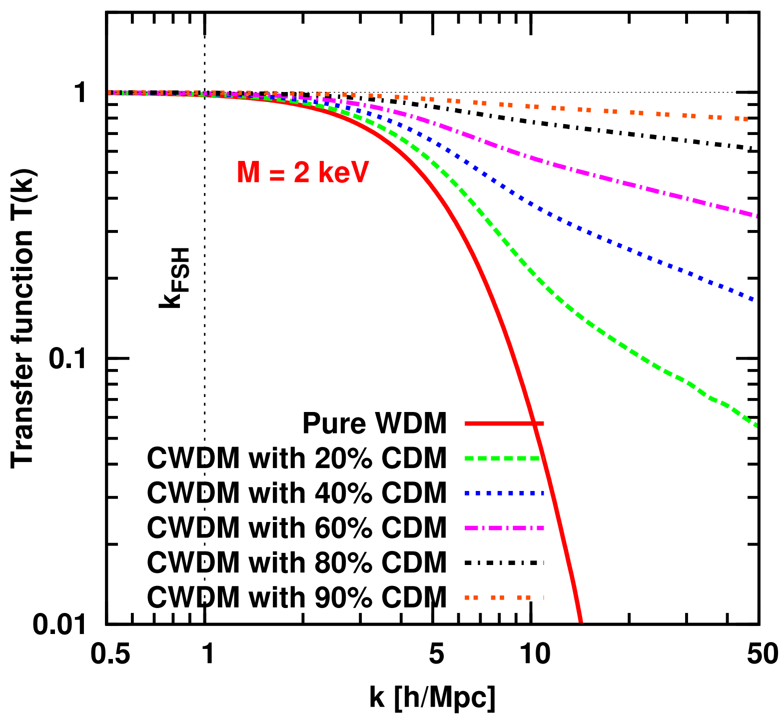
Lyman-α forest

Lyman-α forest and cosmic web



Cold+warm DM model (CWDM)

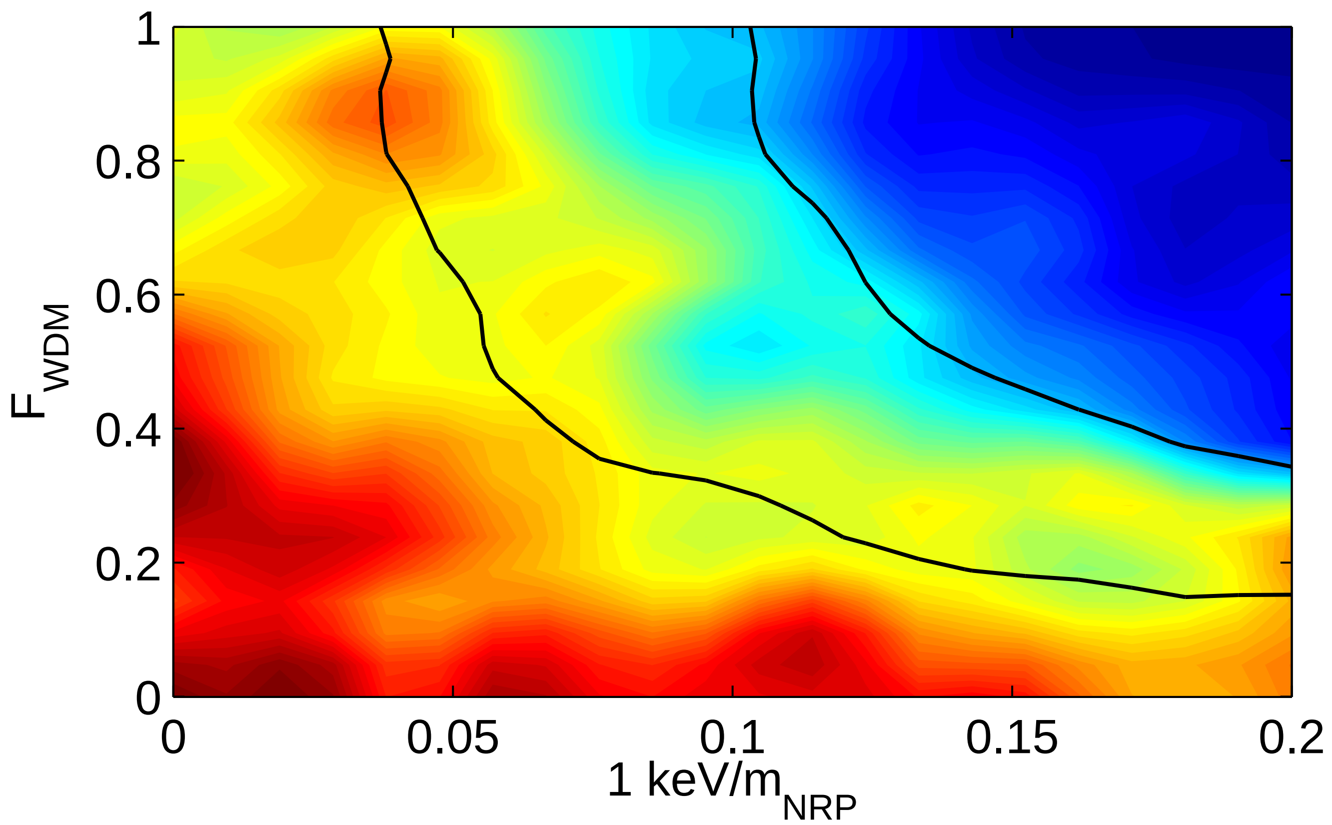
- Models with admixture of cold DM component (relevant for resonantly produced sterile neutrino DM, gravitino DM)



- k_{FSH} depends on mass, does not depend on WDM fraction
- $T(k)$ falls slower if more CDM
- For small WDM fraction $T(k)$ cannot be distinguished from CDM within the precision of the data

Bayesian bounds on mixture of CDM+WDM

Boyarsky, Lesgourgues, Ruchayskiy, Viel'08



$$F_{\text{WDM}} = \frac{\Omega_{\text{WDM}}}{\Omega_{\text{WDM}} + \Omega_{\text{CDM}}}$$

Sterile neutrinos: decaying, (warm) DM and much more

νMSM: all masses below electroweak scale

Just add 3 right-handed (sterile) neutrinos N_I to MSM:

Asaka, Shaposhnikov, PLB **620**, 17 (2005)

$$\mathcal{L}_{\nu MSM} = \mathcal{L}_{MSM} + i\bar{N}^I \not{\partial} N_I - \left(\bar{L}_\alpha M^D_{\alpha I} N_I + \frac{M_I}{2} \bar{N}^c_I N_I + h.c. \right)$$

A very modest and simple modification of the SM which can explain **within one consistent framework**

✓ ... neutrino oscillations

✓ ... baryon asymmetry of the Universe

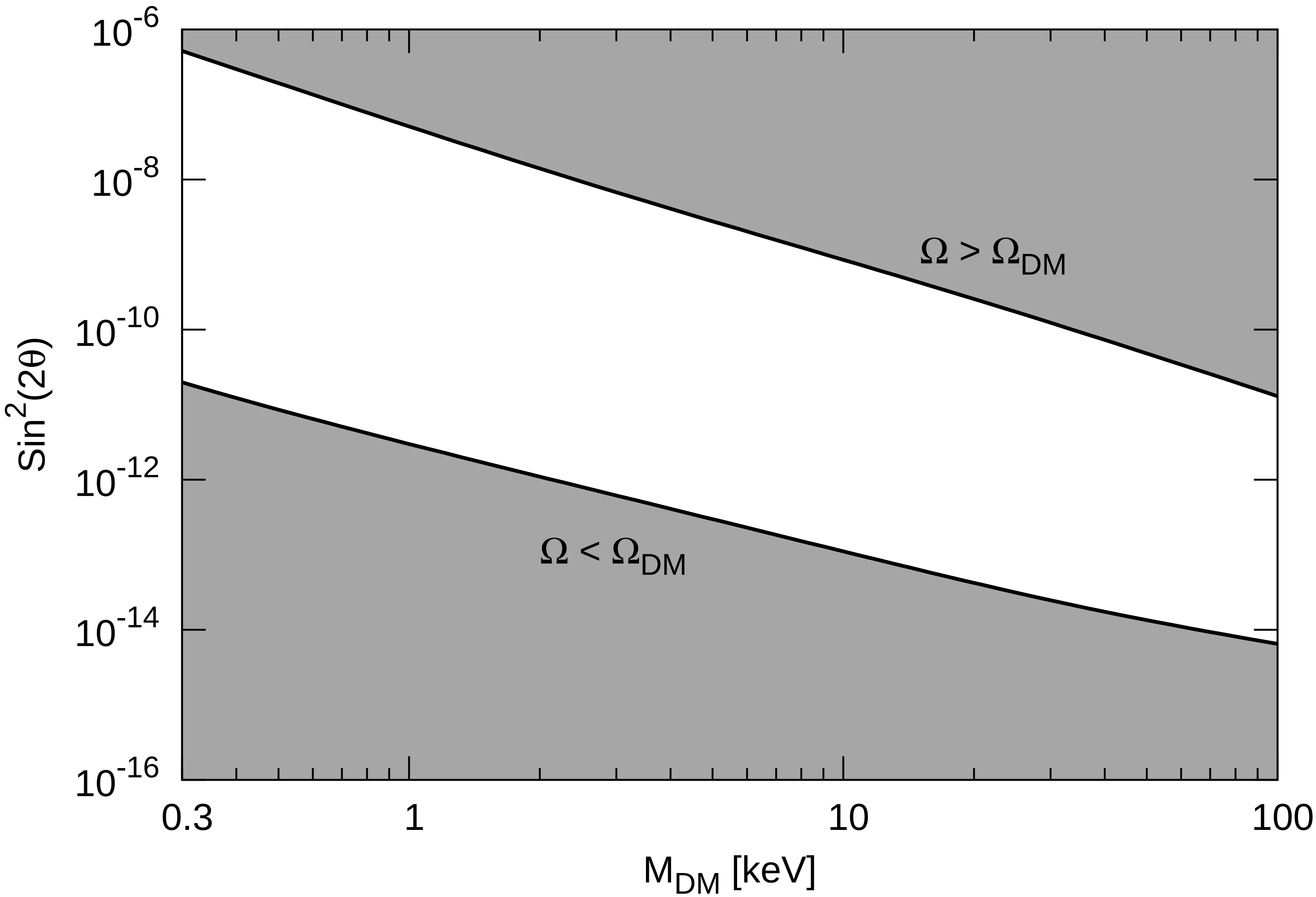
✓ ... provide a viable (warm or cold) dark matter candidate

✓ ... can incorporate inflation

✓ ... can have a number of astrophysical applications

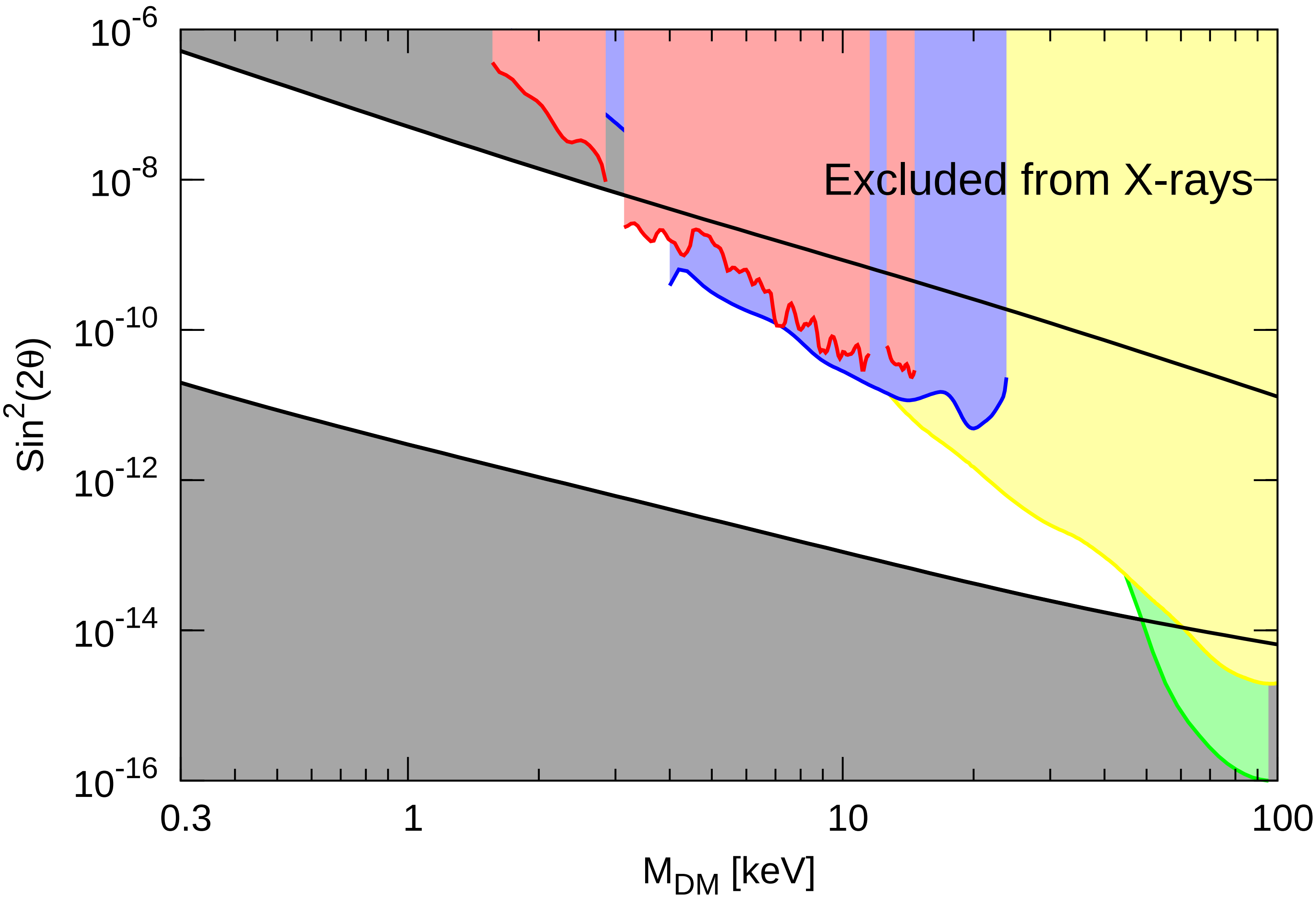
Window of parameters of sterile neutrino DM

Laine, Shaposhnikov



Window of parameters of sterile neutrino DM

Boyarsky, Ruchayskiy et al. 2005-2008



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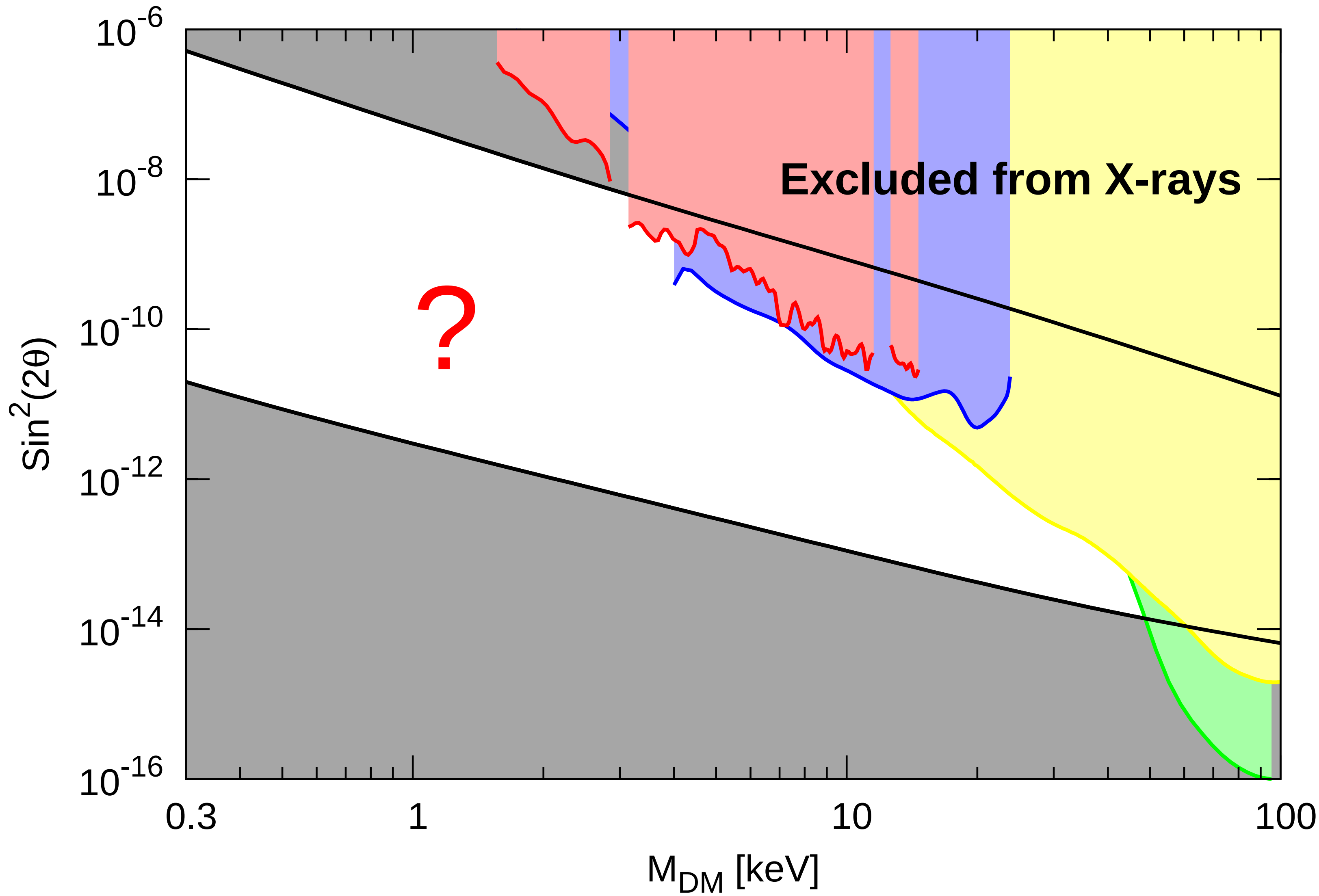

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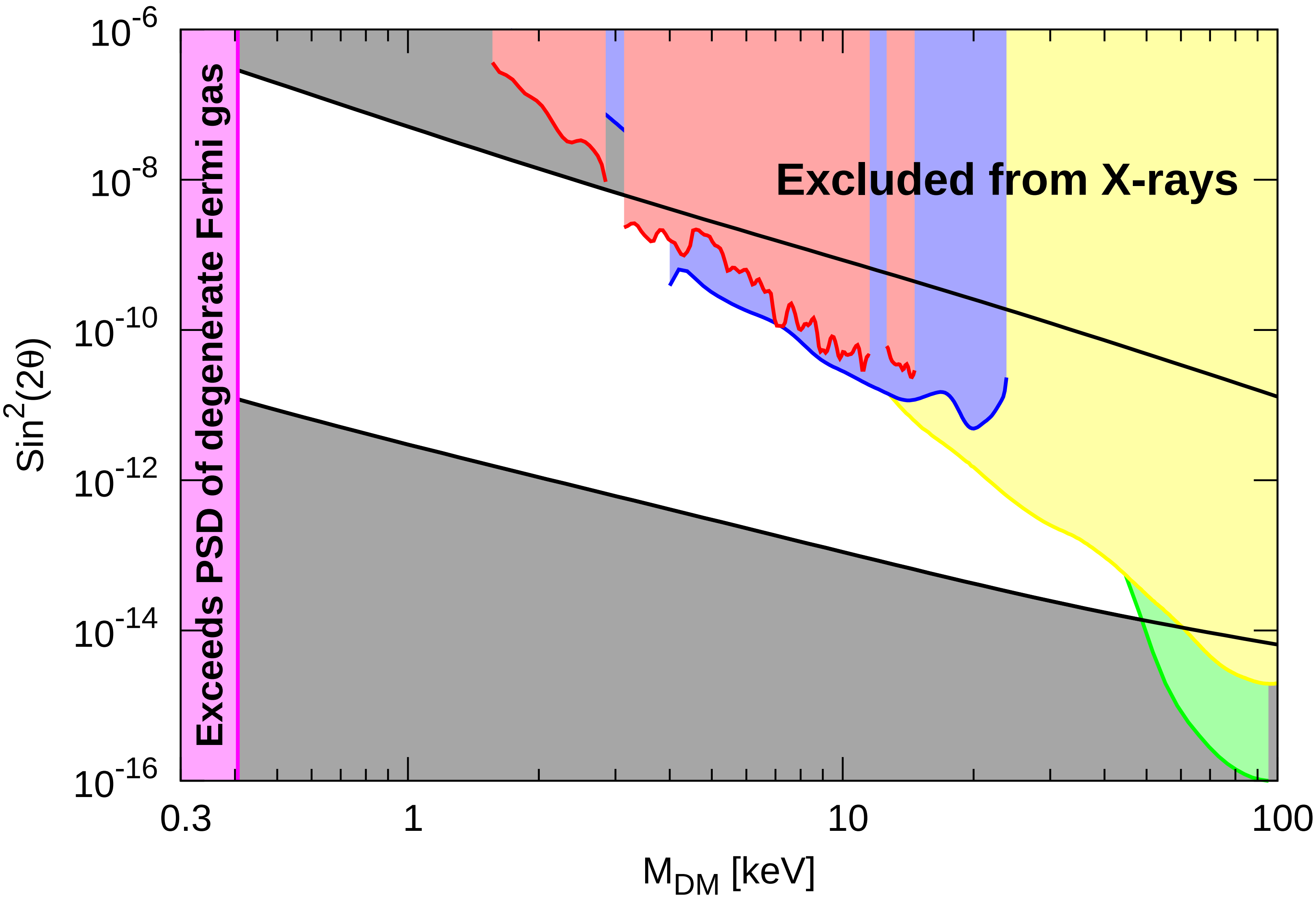

Boyarsky, Ruchayskiy et al. 2005-2008

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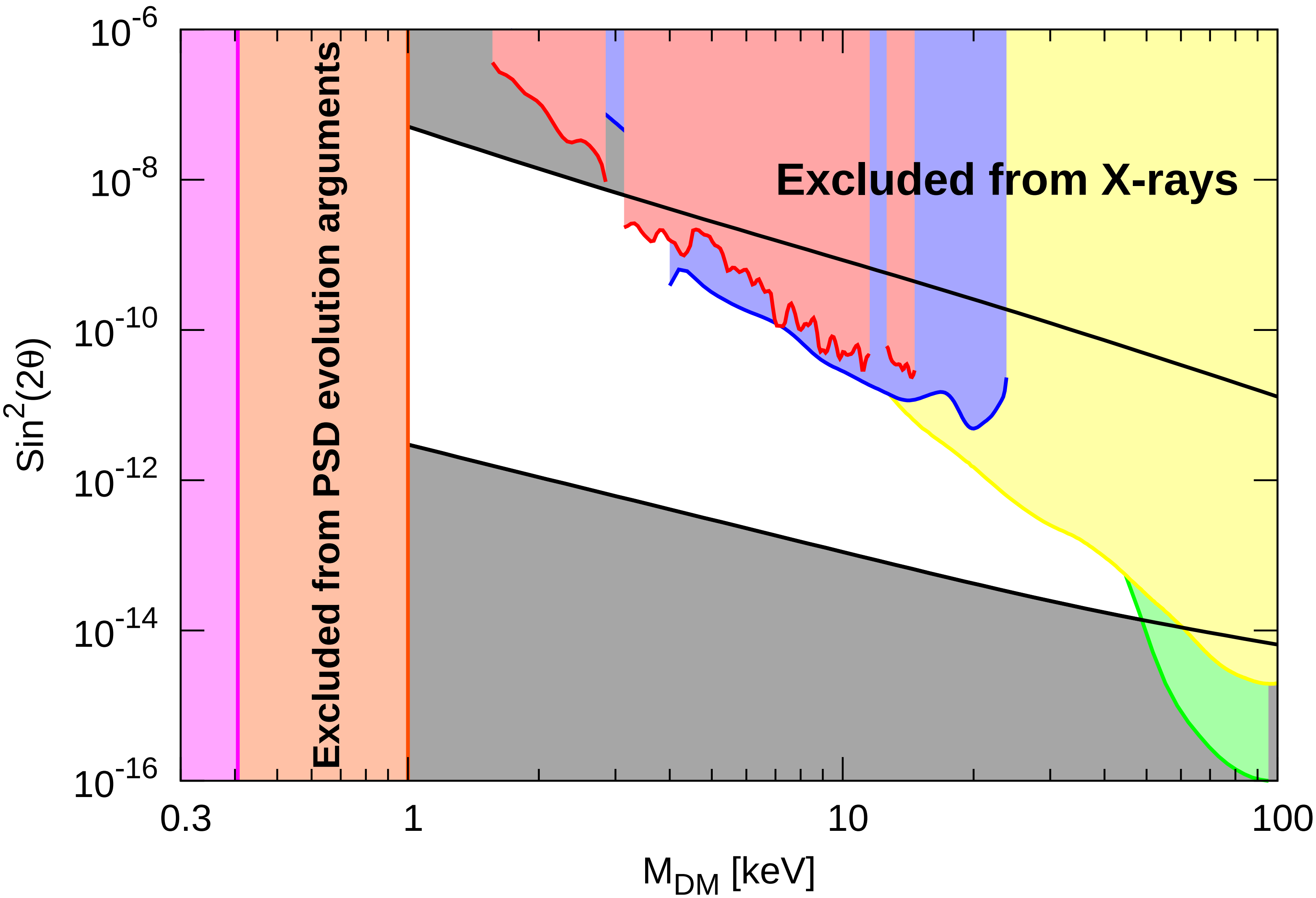

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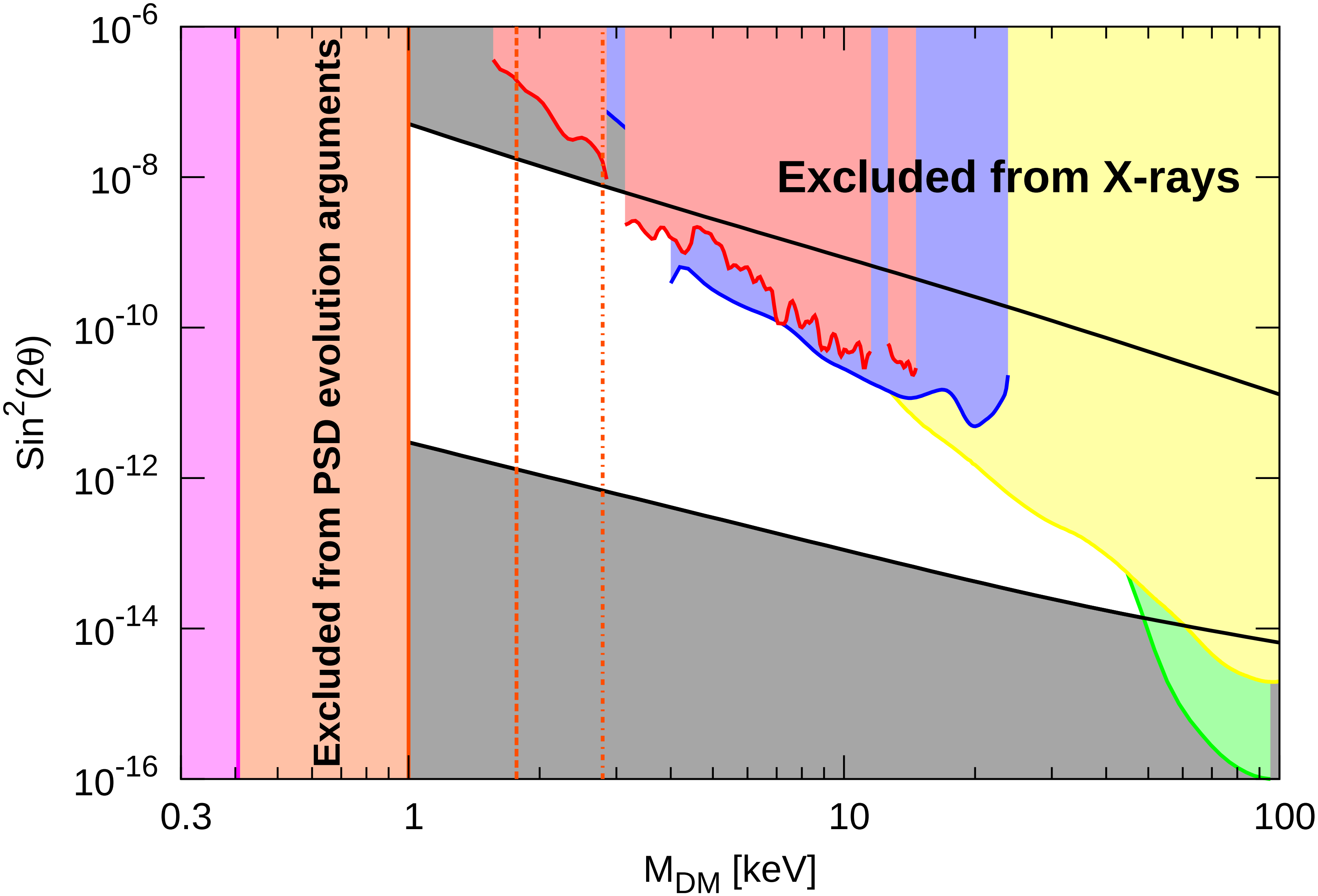
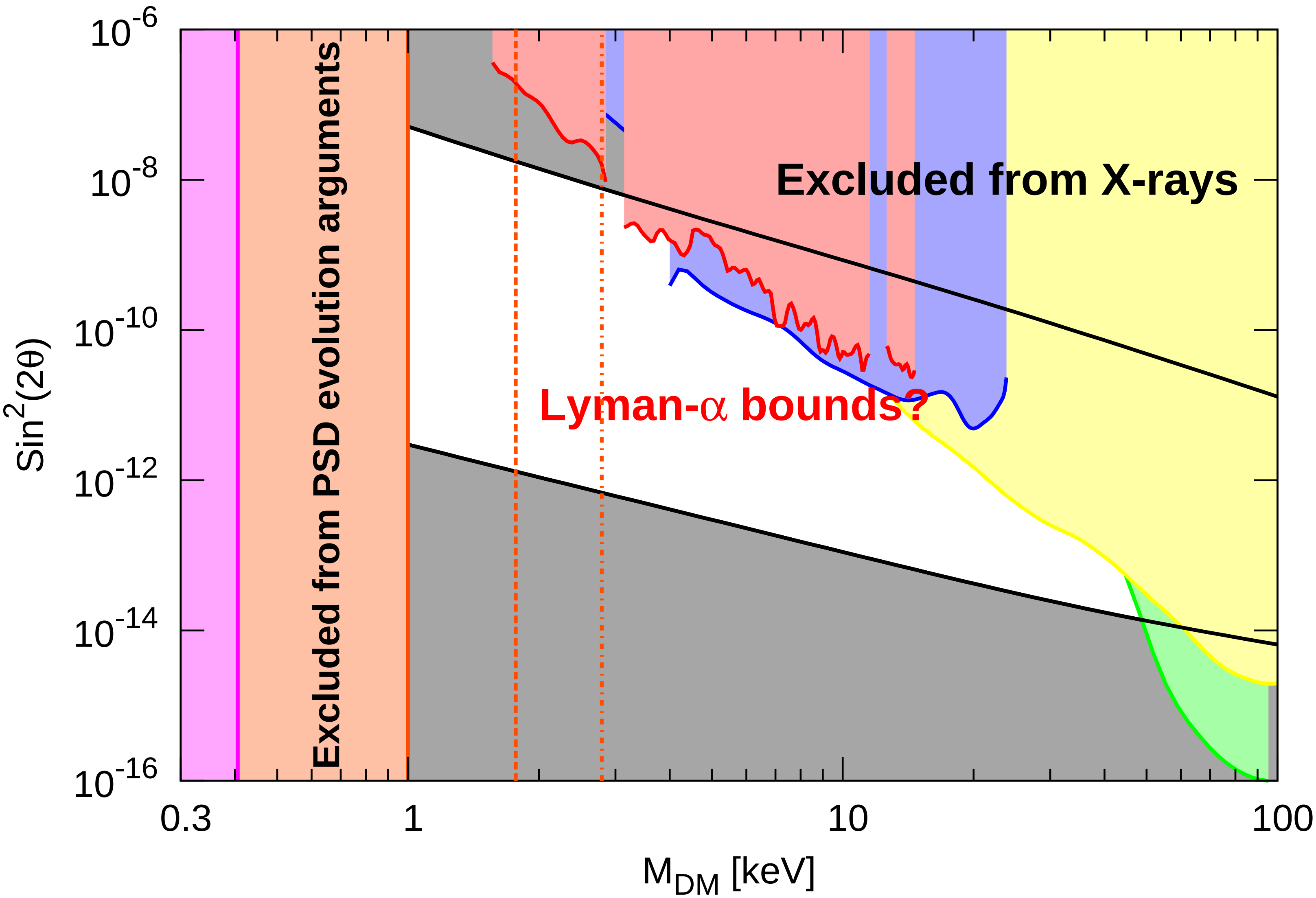
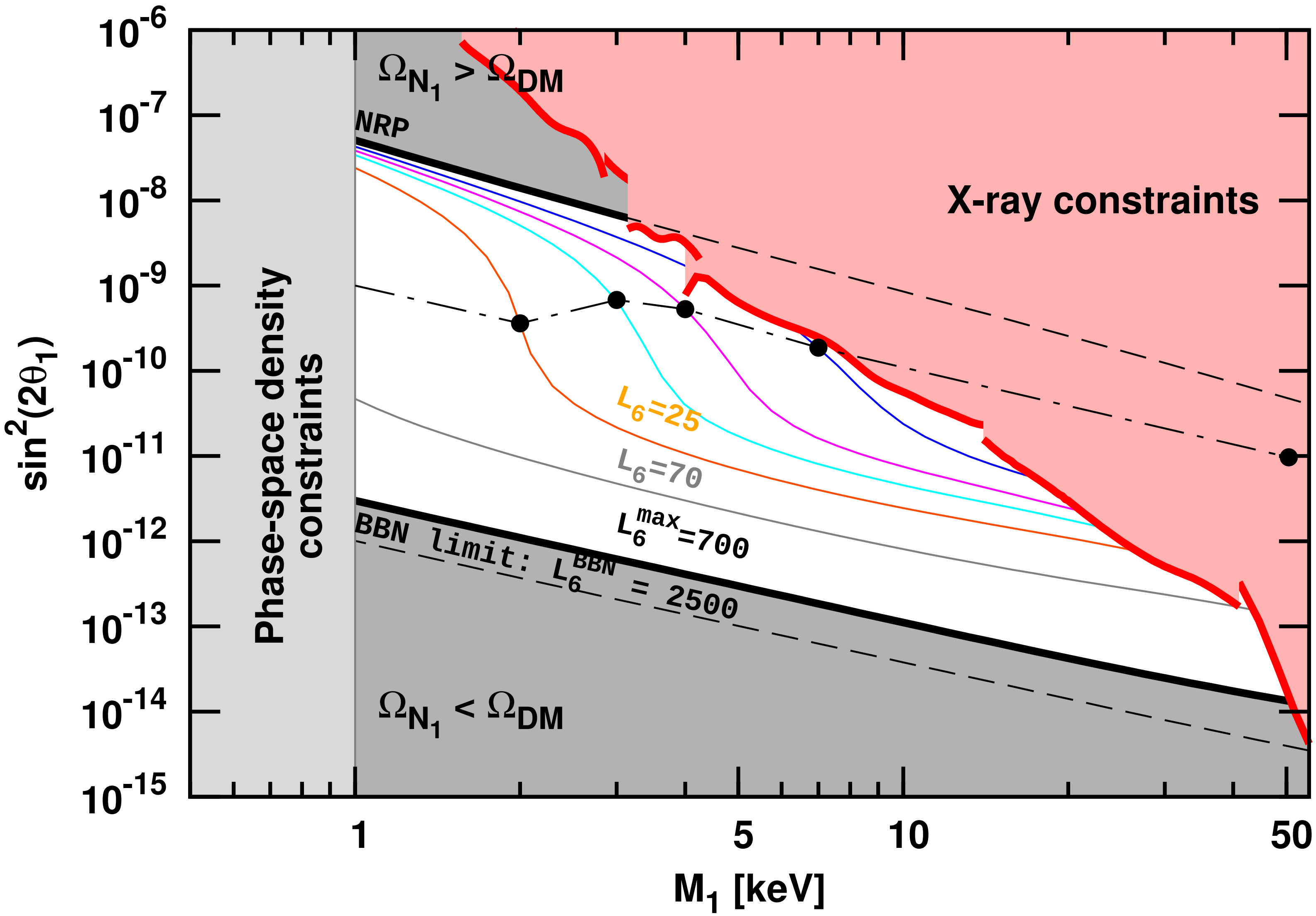


Window of parameters of sterile neutrino DM

Boyarsky, Ruchayskiy, Lesgourgues, Viel 2008



Window of parameters of sterile neutrino DM



Boyarsky, Ruchayskiy, Lesgourgues, Viel [0812.3256]

Boyarsky, Ruchayskiy, Shaposhnikov [0901.0011]

Summary

- Light DM with the mass in the keV–MeV range is an interesting viable possibility
- Such a DM can decay rather than annihilate
- For decaying DM the astrophysical search may become “direct”
- Such a DM may be **cold**, **warm** or **mixed**
- Whether warm of mixed DM can explain structures in the Milky Way halo is an open question
- Sterile neutrino with the keV mass is an interesting DM candidate, explaining also neutrino masses and baryogenesis. This DM candidate is fully consistent with standard cosmology and all available observational data

Thank you for your attention

Physical assumptions beyond Ly-α results

In each point:

- Photon wavelength $\lambda(x)$ = emission wavelength redshifted by Hubble flow + peculiar velocities. Need to disentangle both
- Flux absorption fraction $\propto n_{HI}(x)$ – neutral hydrogen fraction
- δ_{HI} is related to δ_H (photoionization equilibrium in presence of UV background produced by stars at given T)
- $\delta_H = \delta_b = \delta_{\text{DM}}$ – neutral hydrogen traces DM
- $T = T_0(1+\delta_b)^{\gamma-1}$ (balance between UV heating and expansion cooling; T_0, γ depend on reionization history)

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