Light Dark Matter and bounds on its properties

Oleg Ruchayskiy

École Politechnique Fédérale de Lausanne

Alexey Boyarsky

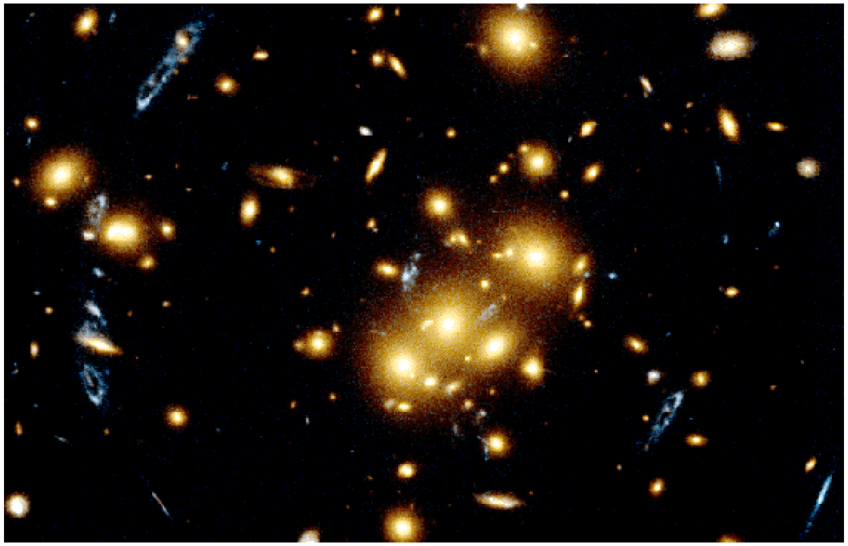
ETH Zürich & CERN

DM at the crossroads

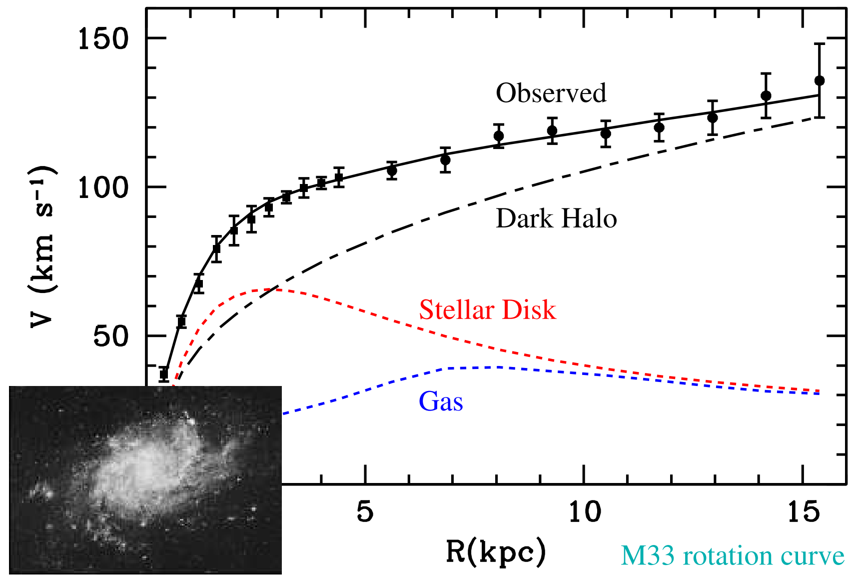
DESY. October 01, 2008

Dark Matter in the Universe

Extensive astrophysical and cosmological evidence for the presence of the dark non-baryonic matter in the Universe



Galaxy cluster CL0024+1654 as a gravitational lense (*Courtesy of HST*)



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

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?

WIMPs: particle physics motivation

- DM is not a Standard Model particle.
- What is the guiding principle to extend the Standard Model?
- If a model contains particles with the mass above electroweak scale (M_W), their quantum corrections to the Higgs mass should be extremely fine-tunned to provide a Higgs with the mass $m_H \sim 10^2$ GeV – **hierarchy problem**.
- Need a special symmetry to ensure such a fine-tunning.
- One example – supersymmetry (boson-fermion symmetry). Additional *R-symmetry* makes **lightest supersymmetric particle** stable – neutralino (generic SUSY DM candidate)
- Other possibilities include: lightest KK states, sneutrino, . . .

Alternatives?

- What if $M_{\text{DM}} \ll 10^2$ GeV? Need **super**-weak interaction! (recall: $\sigma_{ann} \lesssim M_{\text{DM}}^{-2}$)
- WIMPs could not decay. Their interaction strength with matter $\sim G_F$ would lead to the life-time shorter that that of a neutron in β-decay
- Super-WIMP interaction strength $\sim \theta \cdot G_F$ with $\theta \lll 1$.
  $\tau_{decay} \sim 1/\theta^2$ can be longer than the life-time of the Universe
- Scale of the DM particles is **below** EW scale. No hierarchy problem.
- What is the guiding principle for building a theory of super-WIMPs?
- Other problems beyond the scope of the Standard Model?
  - Neutrino oscillations
  - Baryon asymmetry of the Universe

How light can be super-WIMPs?

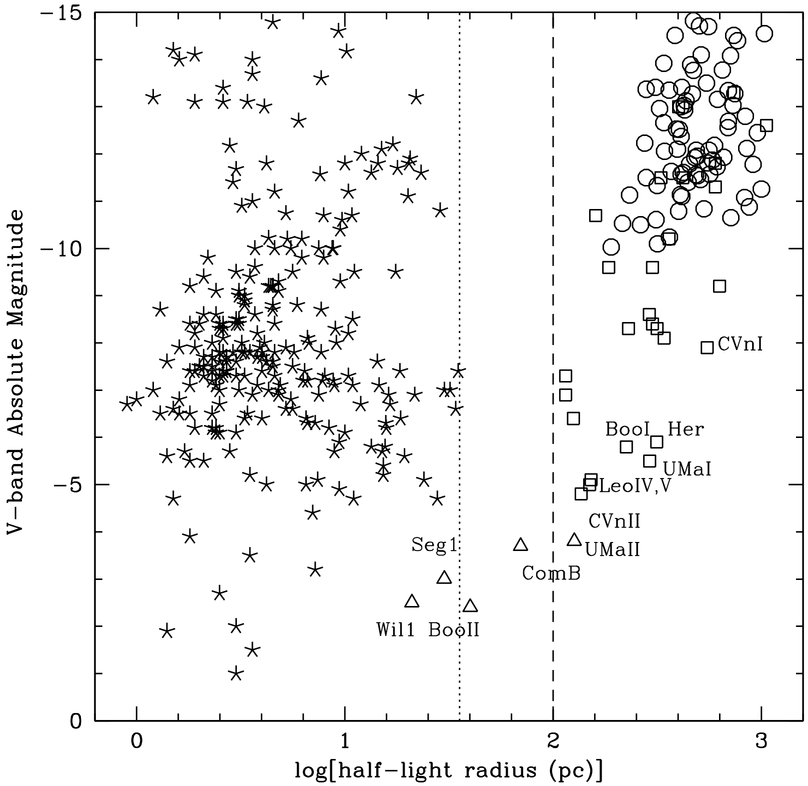
Universal DM bound

- 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 $Q_{obs} = 10^4 - 10^5\ M_\odot\ \text{kpc}^{-3}[\text{km s}^{-1}]^{-3}$.

- Bound on any fermionic DM improved to become $m_{\text{DM}} > 0.41$ **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

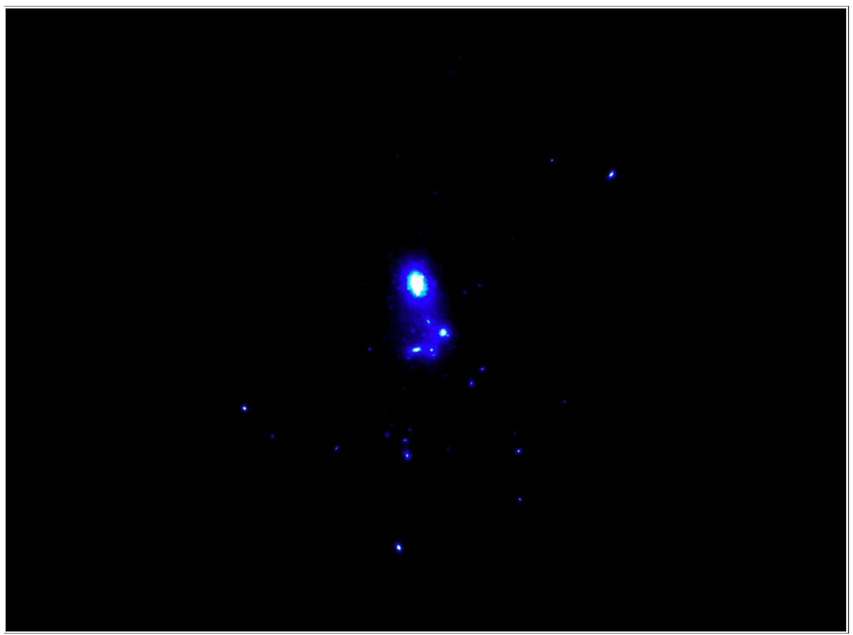
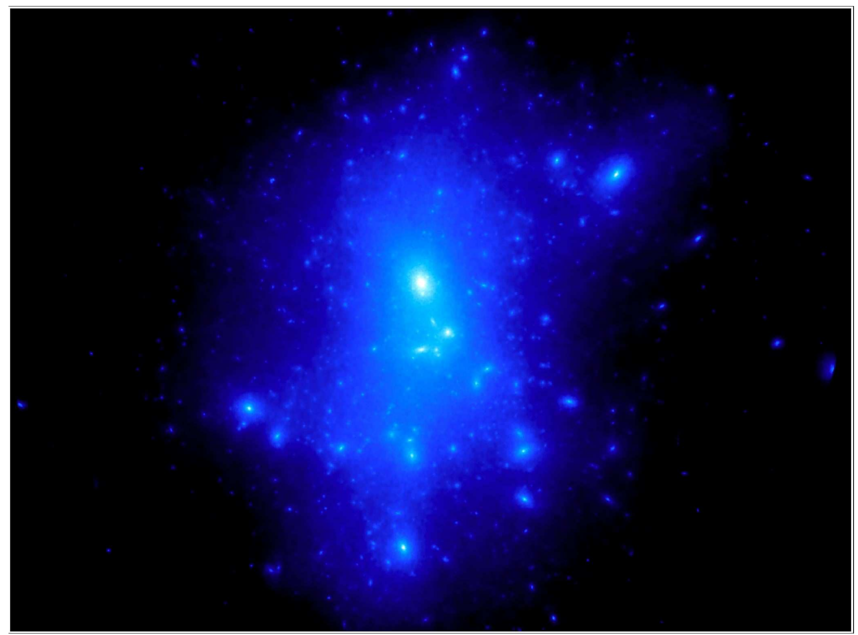
- Liouville theorem for Q?

- 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 super-WIMPs

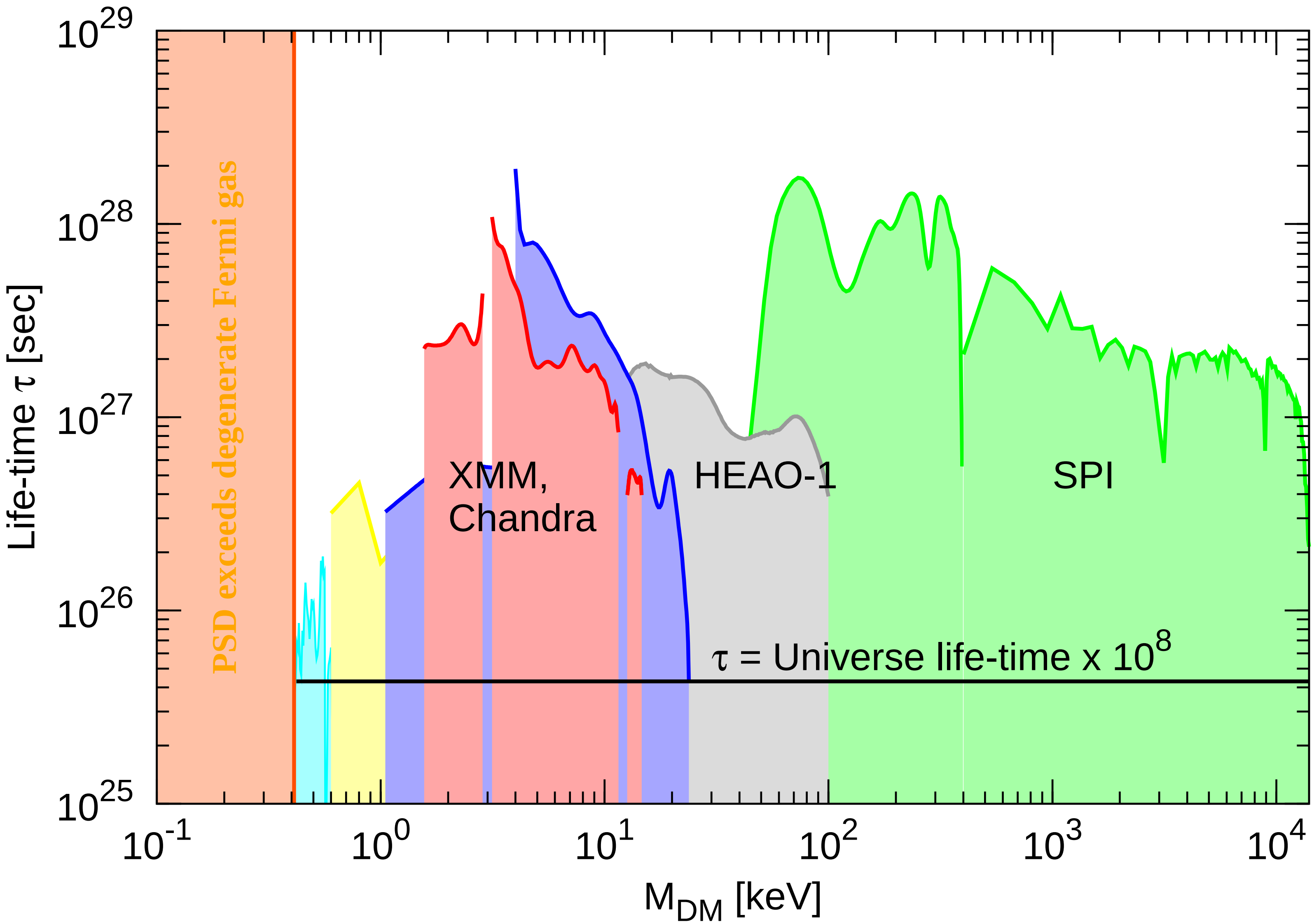
- Mass can be in keV–GeV range (cannot be smaller than ~ 0.4 keV)
- Two-body decay channel: DM $\to \gamma + \nu, \gamma + \gamma$ produces monochromatic decay line
- All-sky signal

Astrophysical search for decaying DM

- Decay signal $\propto \int \rho_{\rm DM}(r)dr$ and not to the $\int \rho^2_{\rm DM}(r)dr$
- Variety of astrophysical objects would produce roughly the same decay signal
- Freedom of choice of observational targets: galaxies, cluster, dwarf spheroidal galaxies, Milky Way, extragalactic background.
- Avoid complicated astrophysical backgrounds, does not have to look at the GC
- 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**.

Restrictions on life-time of decaying DM



MW (HEAO-1) Boyarsky et al 2005

Bullet cluster Boyarsky et al 2006

LMC+MW(XMM) 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?

- What happens if the DM mass gets lower?

- A weakly interacting particle decouples from primeval plasma at $T_{\text{dec}} \sim$ MeV

  – Particle with $M \sim 100$ GeV has $\langle p \rangle \sim (MT_{\text{dec}})^{1/2}$:
  decouples **non-relativistic**

  – Particle with $M \sim 1$ eV has $\langle p \rangle \sim T_{\text{dec}}$
  decouples **ultra-relativistic**

- Can we experimentally distinguish between these possibilities?

Yes!

Free-streaming DM and structure formation

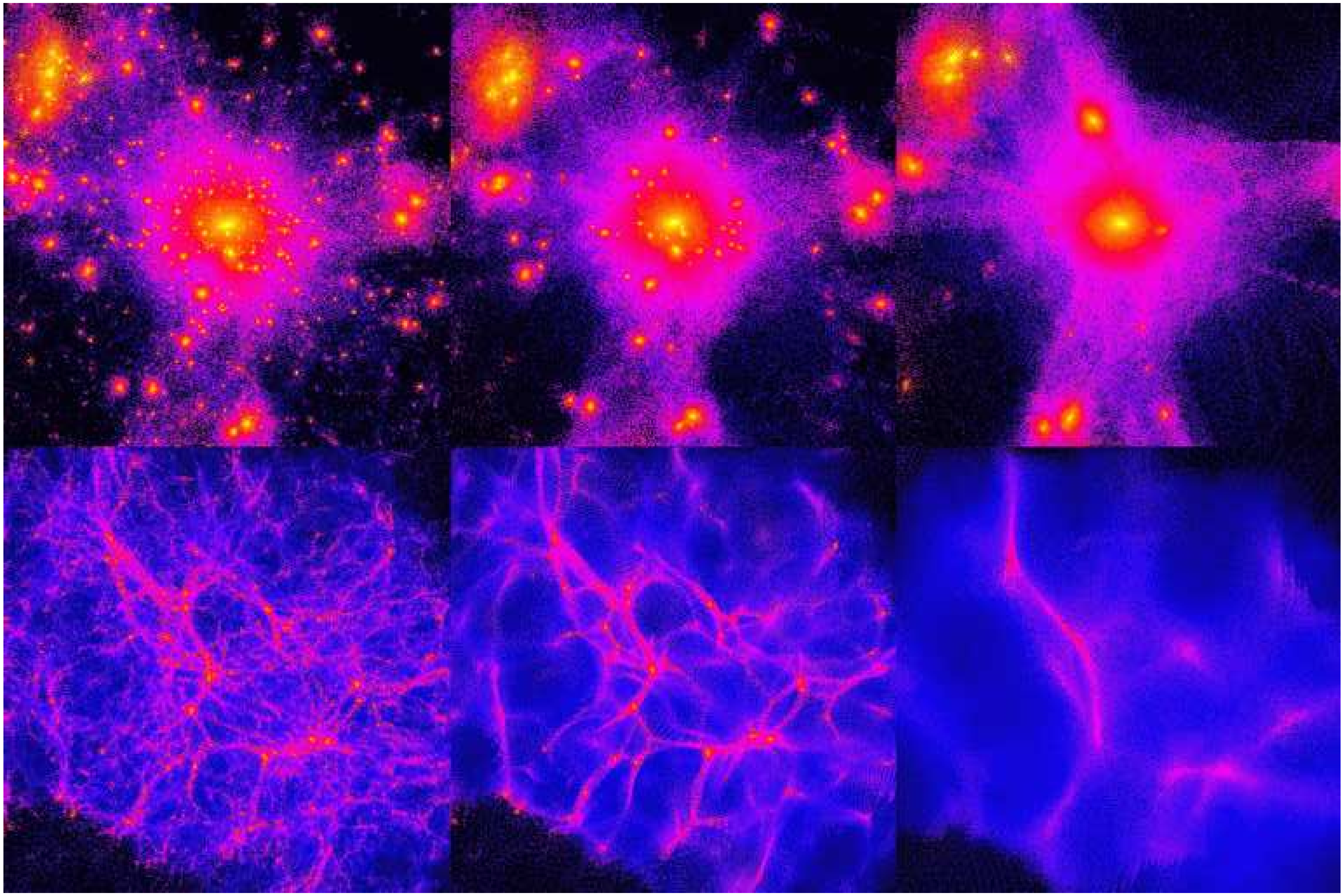
- DM particles erase primordial spectrum of density perturbations on scales up to the DM particle horizon – **free-streaming length**

$$\lambda_{\text{FS}}^{co} = \int_0^t \frac{v(t')dt'}{a(t')}$$

- All DM models are thus divided into 3 groups:
  - **CDM** : free streaming is negligible (particles decouple non-relativistic)
  - **WDM** : free streaming at galaxy scales, particles decouple (ultra)-relativistic at the radiation-dominated epoch: $t_{nr} \ll t_{eq}$
  - **HDM** : free streaming at cosmological scales, particles decouple (ultra)-relativistic at the matter-dominated epoch: $t_{nr} \gg t_{eq}$

- HDM (e.g. active neutrinos with the mass ~ 1 eV) is ruled out. Gives **wrong large scale structure**

Structure formation in CDM/WDM/HDM

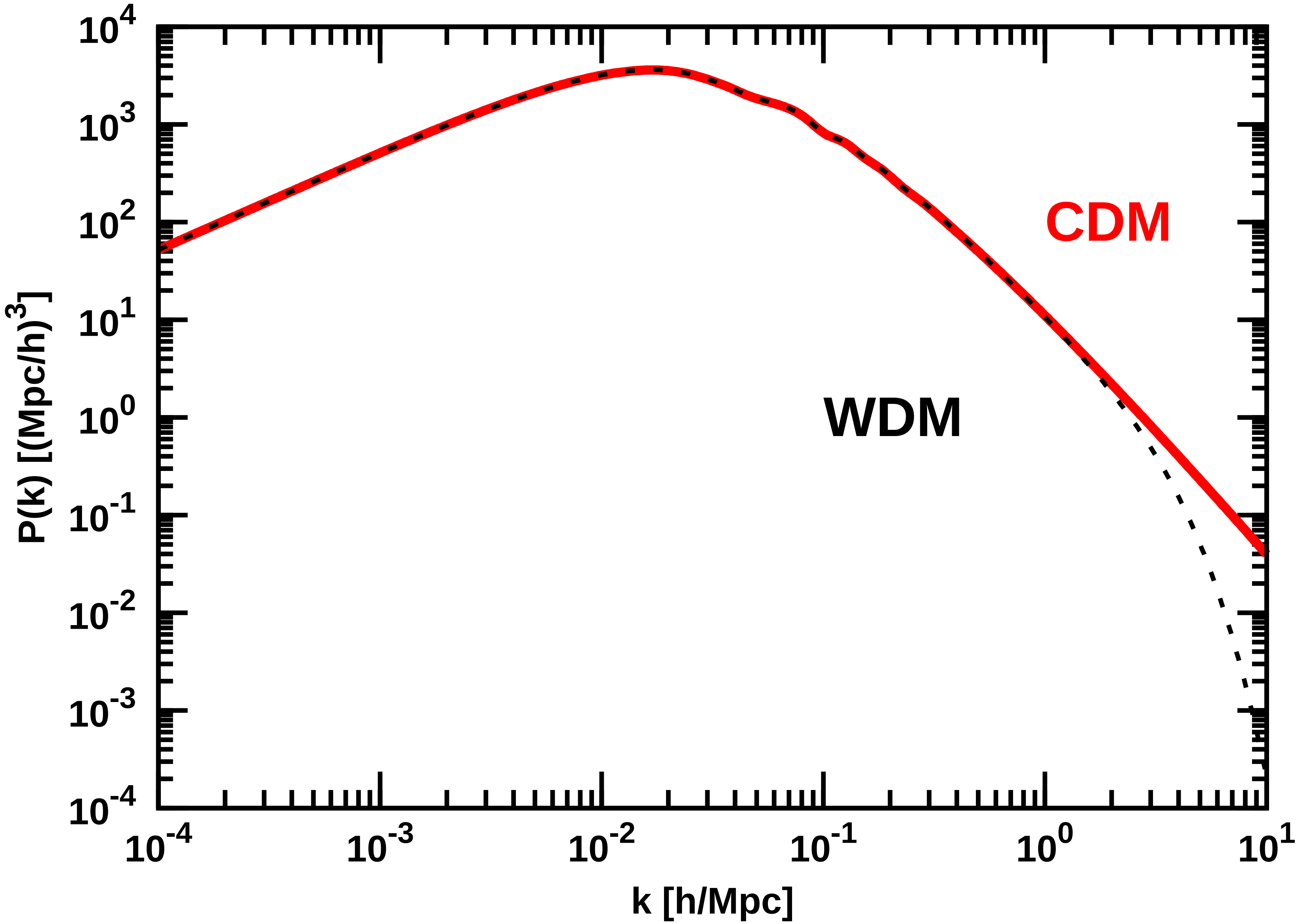


CDM WDM HDM

Courtesy of B.Moore

DM and Structure Formation

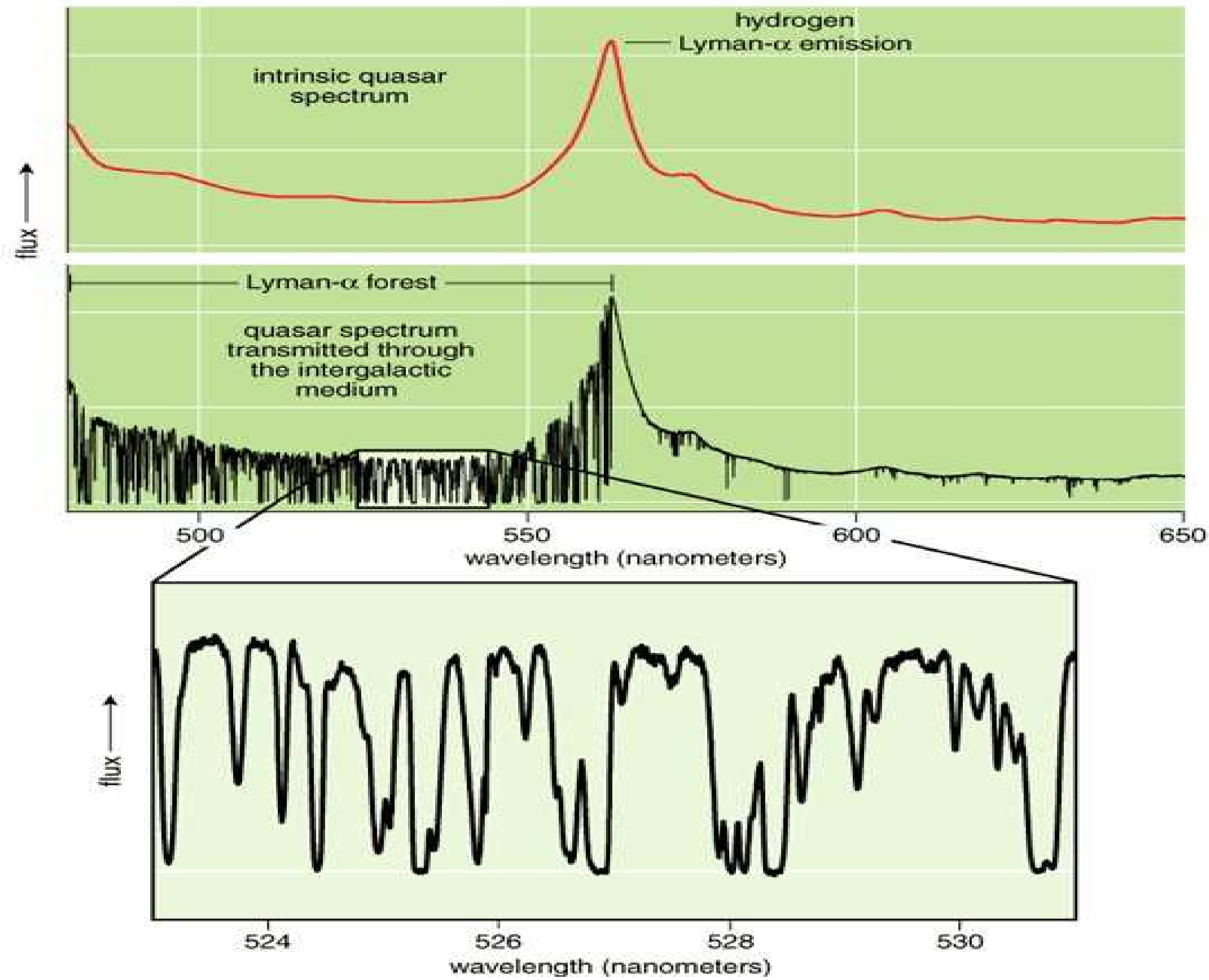
(Linear) powerspectra



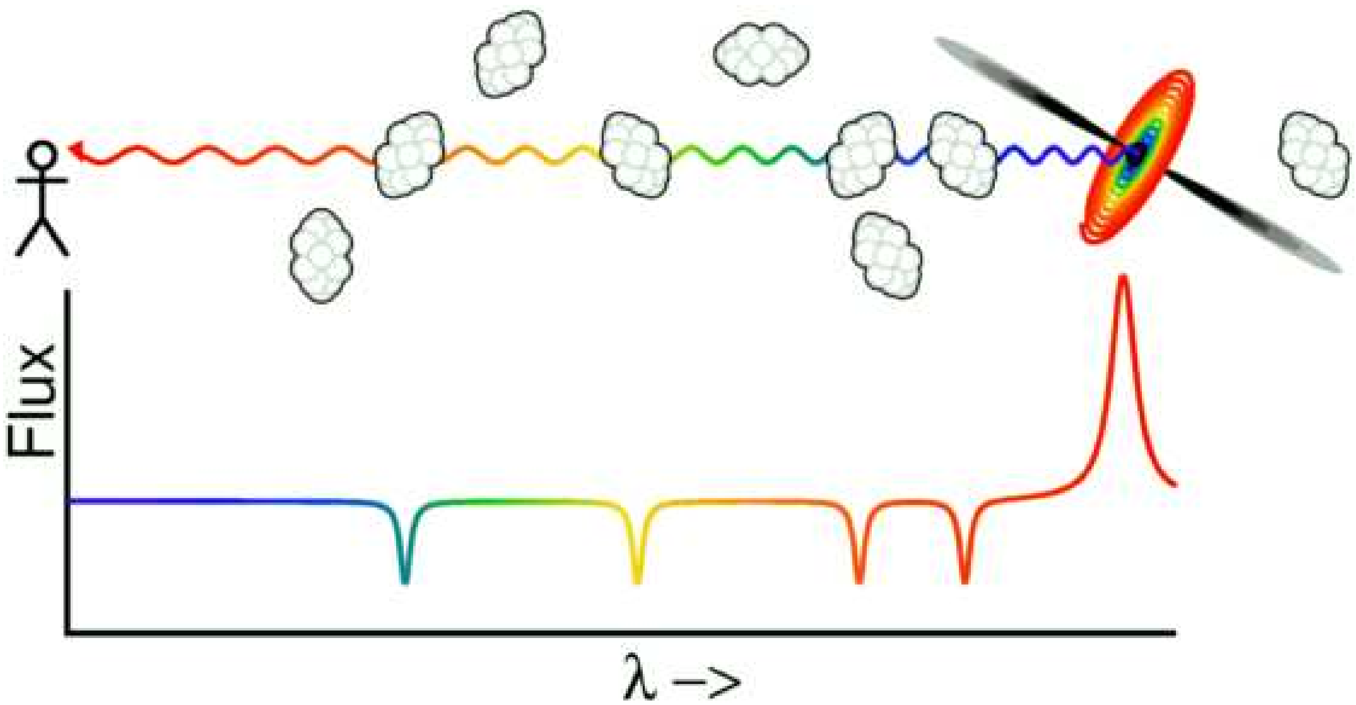
Nonlinear powerspectrum?

Lyman-α forest

What is Lyman-α forest?



What is Lyman-α forest?

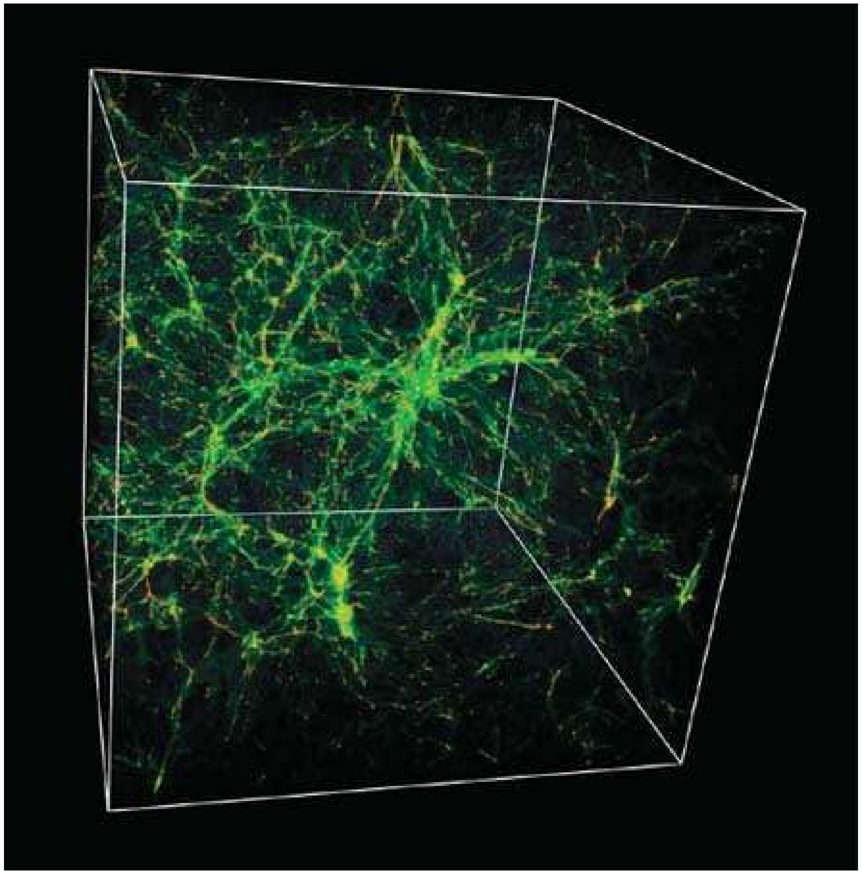


- Neutral hydrogen absorption line at $\lambda = 1215.67\text{Å}$

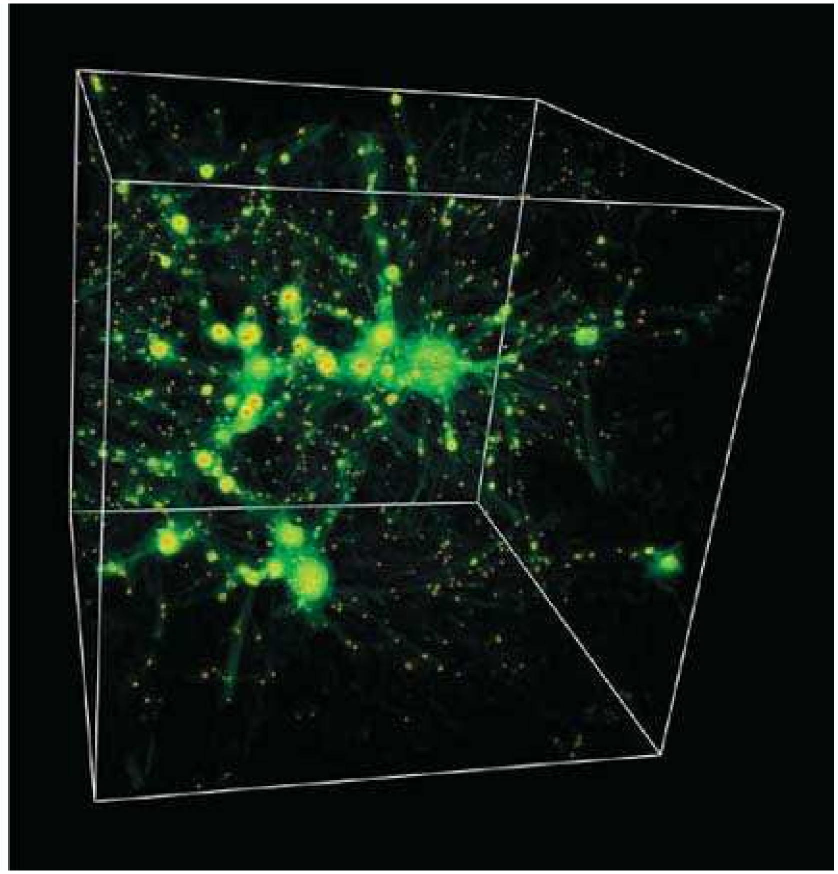
  (Ly-α absorption $1s \to 2p$)
- Absorption occurs at $\lambda = 1215.67\text{Å}$ in the **local reference frame** of hydrogen cloud.
- From the Earth observer point of view we see the forest:

  $$\lambda = (1+z)1215.67\text{Å}$$

Cosmic web

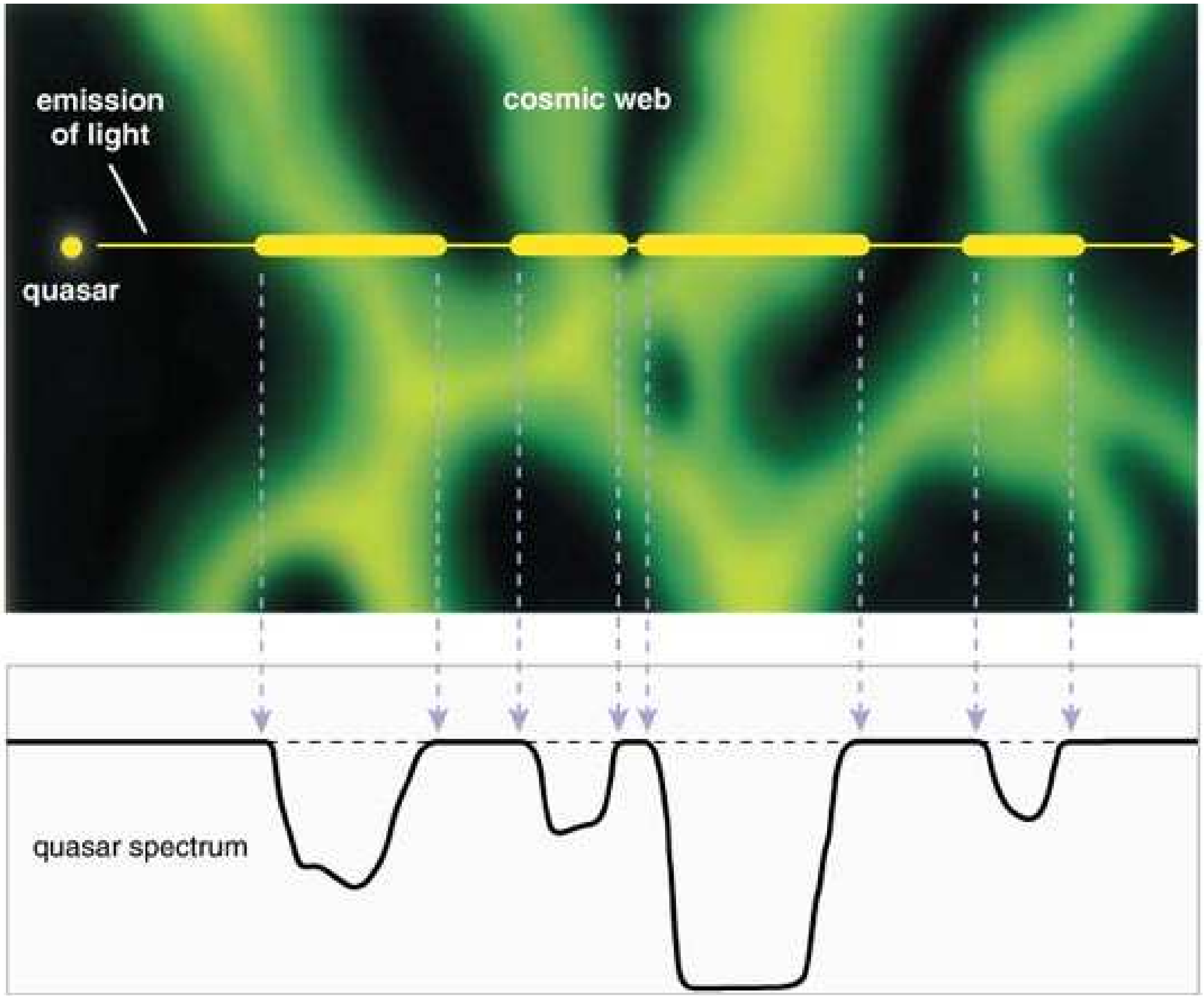


$\tau \approx 2 \times 10^6$ years



$\tau \approx 13 \times 10^6$ years

Lyman-α forest and cosmic web



- Lyman-α allows to measure **non-linear 1D (projected along the line of sight)** $P_F(k)$

$$P_F(k) = \int_k^\infty P_{3D}(k) \frac{kdk}{2\pi}$$

- We can (semi)analytically computed only the **linear** $P_{3D}(k)$ and its dependence on cosmological parameters (including the DM properties)

- In some cases one can reconstruct $P_{3D}(k)$ from measured $P_F(k)$. Reason: within error bars of measurements all the non-linear evolution is encoded into a **bias function**: $P_F(k) = b^2(k)P_{3D}(k)$

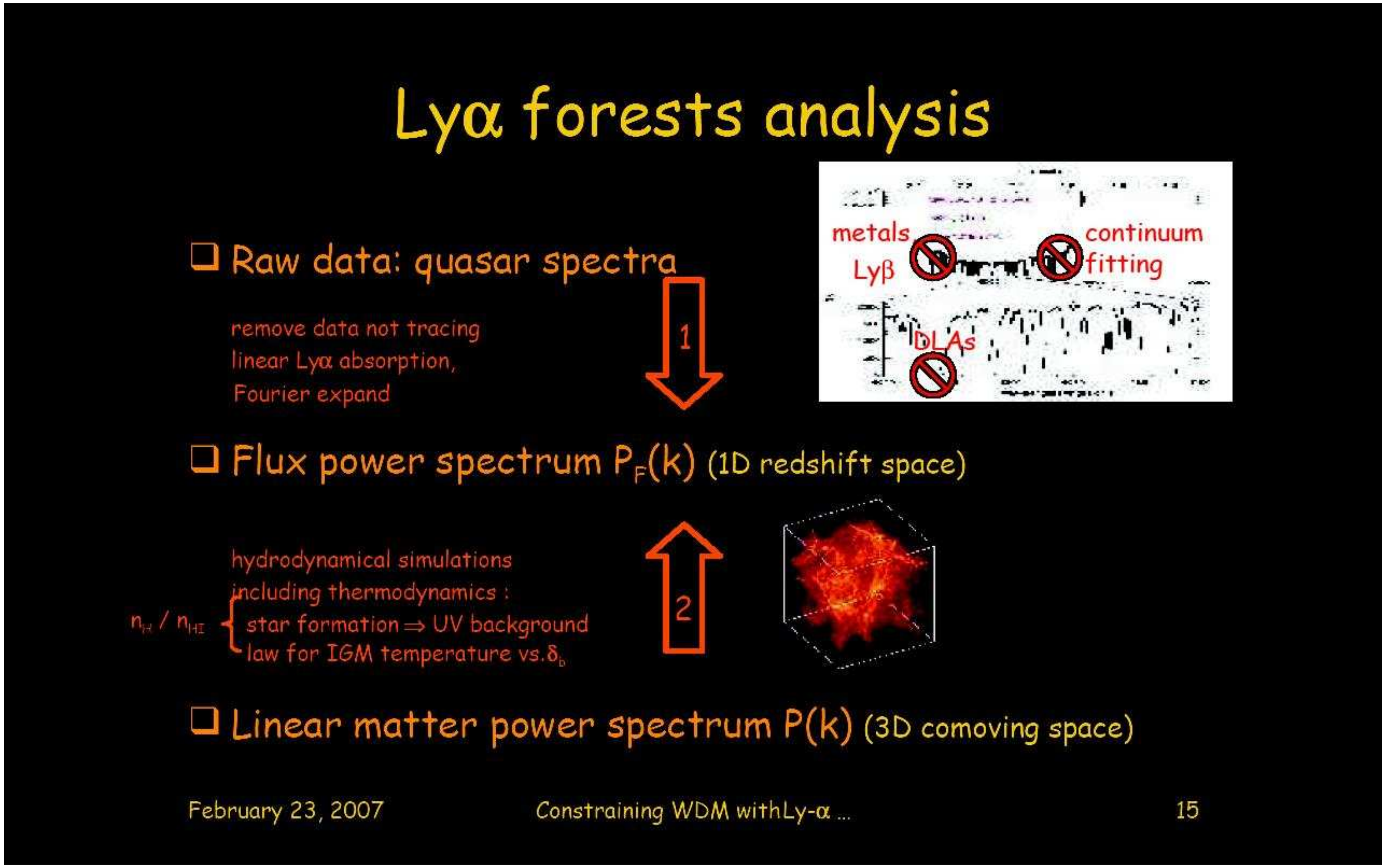
Viel, Haehnelt Springel 2004

- Very poor constraints, comparable with those from PSD

How to improve the results?

Numerical simulations

For Lyman-α datasets with better precision need to perform hydrodynamical simulations for **each set of cosmological parameters**



Borrowed from J.Lesgourgues

Lyman-α forest : challenges

- Simulate (a part of) the Universe (including baryons, star feedback, etc.) and compute in it the statistics of the absorption lines
- Compare the simulated results with the observed.
- Find the combinations of cosmological parameters which fit the data
- Each hydrodynamical simulation takes about 36 hours (optimistic)
- Need to fit **simultaneously** 7+ cosmological parameters (and another $20+$ astrophysical parameters) to the data (Lyman-α, CMB, LSS, . . .).
- To try only **2** values for each parameters one has to explore $\mathbf{10^8}$ models, perform 10^8 simulations which would take $\sim 550\,000$ years

"Honest" processing of Lyman-α data is computationally prohibitive

Initial conditions

- Initial conditions for numerical simulations use linear matter power spectrum at $z_{ini} \sim 100$
- For non-CDM models we should take into account velocity distribution at z_{ini} (Recall J. Lesgourgue's talk yesterday)
- Power-spectra depend on the DM model
- Many super-WIMPs (e.g. gravitino, sterile neutrino) are produced non-thermally, have non-universal initial powerspectra, non-thermal momenta distribution
- Example: mixture of colder and warmer components (gravitino, sterile neutrino)
  - Suppression starts early, at λ_{FS} of warm component.
  - But at smaler scales – like CDM with smaller normalisation.

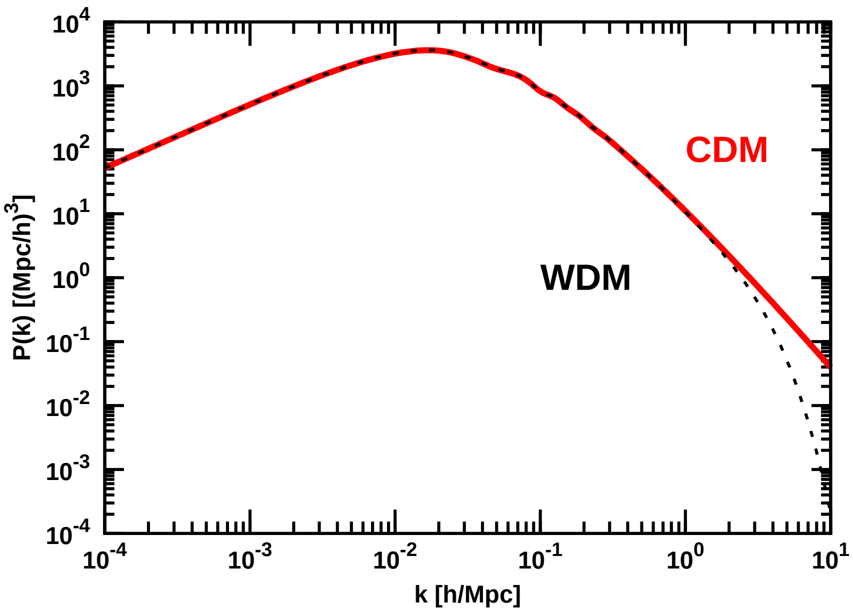
Velocities in initial conditions

- N-body simulations use "particles" (blobs) with mass $10^3 - 10^5 M_\odot$
- Particles are displaced from the uniform grid according to the (random) gravitational field, created by density perturbations and given **Zeldovich** velocities $\mathcal{O}(10)$ km/sec
- Each “blob” would contain $\sim 10^{60} - 10^{70}$ DM particles. Thermal velocity of particles averaged over the blob is **0**!
- Usual choice: assign (at random) velocity of a particle to the whole blob
- Can be true if the size of the blob is much smaller than the scale of interest
- Irrelevant for CDM. Crucial for HDM. Can be relevant for WDM and more complicated models

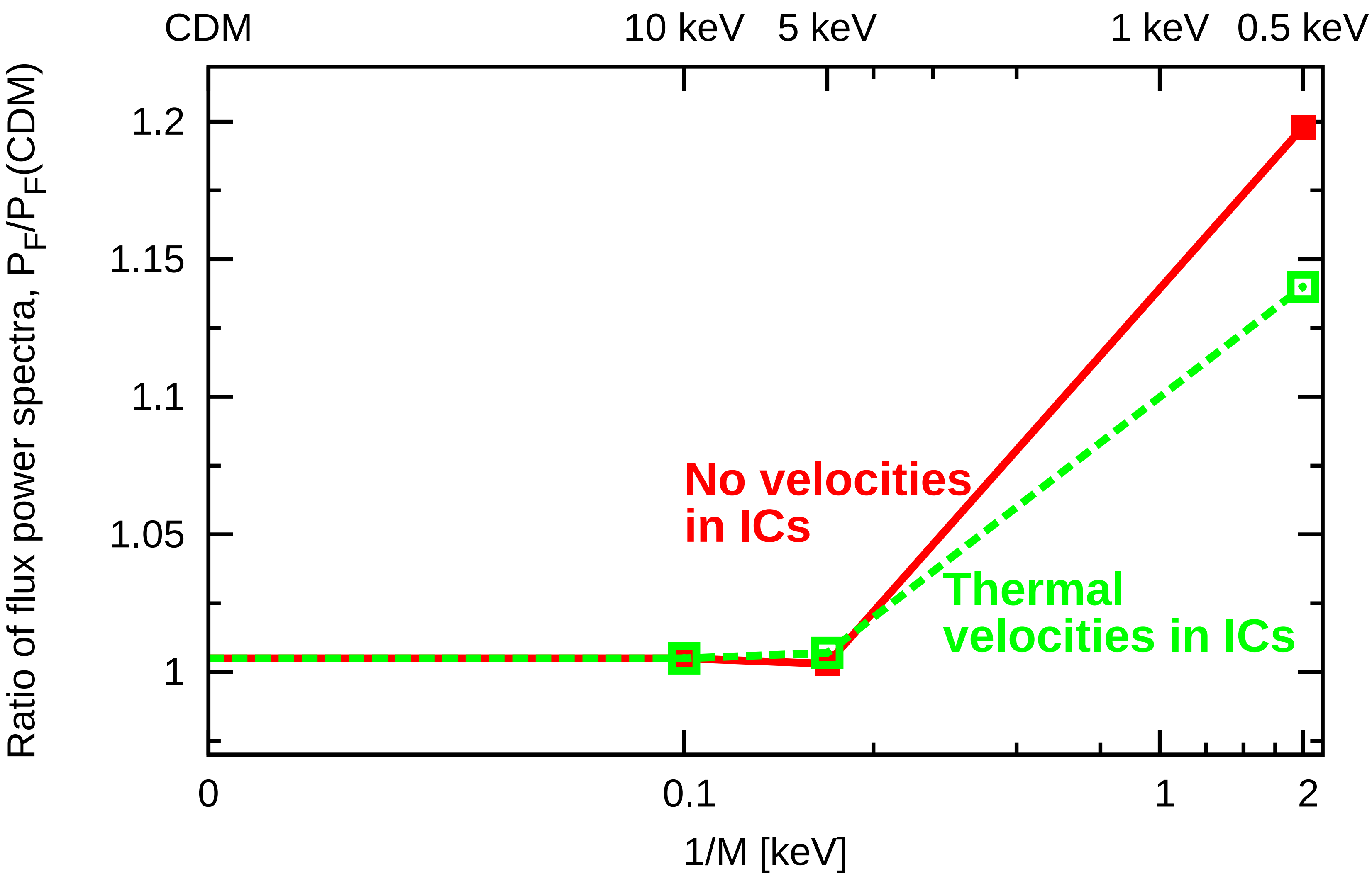
Lyman-α simulations should be perform separately for every DM model

Simplest model: WDM

- Simplest non-CDM model – **pure WDM** contains a power-law cut-off in the linear matter power spectrum
- Position of the cut-off is determine by the free-streaming or DM mass
- Primordial velocity distribution: relativistic Fermi-Dirac



WDM: velocities in ICs



Difference can be as large as $10 - 20\%$ for small (~ 0.5 keV) masses

WDM: velocities in ICs

- Difference in powerspectra propagates into the mass bounds:

ICs with thermal velocities	ICs without thermal velocities
$M_{\text{WDM}} = 12.8$ keV	$M_{\text{WDM}} = 14.0$ keV

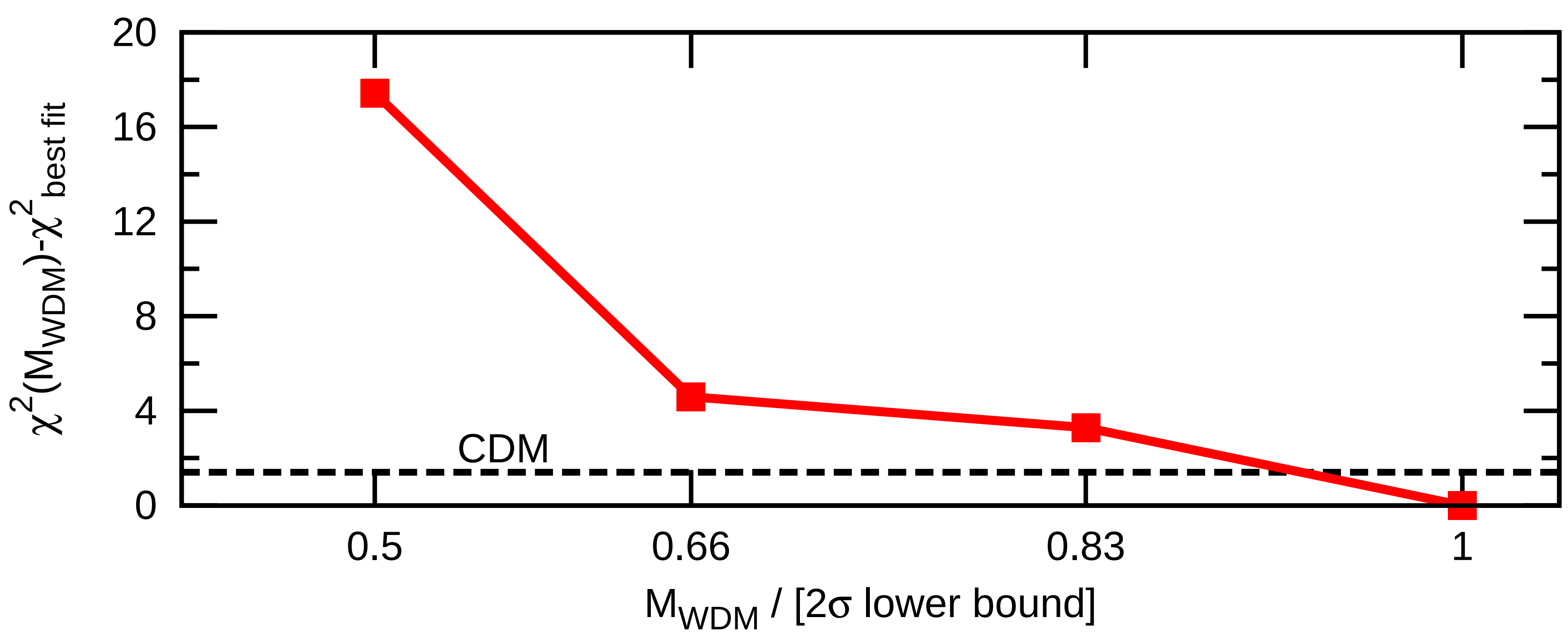
- Why difference at powerspectra at $M_{\text{WDM}} \leq 5$ keV affects bounds above 10 keV?
- Bayesian approach: explore parameter space, build **likelihood function** $\mathcal{L}(M_{\text{WDM}})$ – probability distribution function for M_{WDM}
- 95% CL is defined as the region under the curve $\mathcal{L}(M_{\text{WDM}})$, containing 95% of the area
- Before we explored range from $M_{\text{DM}} = 0.3$ keV to $M_{\text{DM}} = \infty$ (CDM)

Bayesian approach to WDM bounds

- Change the region for $M_{\text{WDM}} \geq 5$ keV. Results agree:

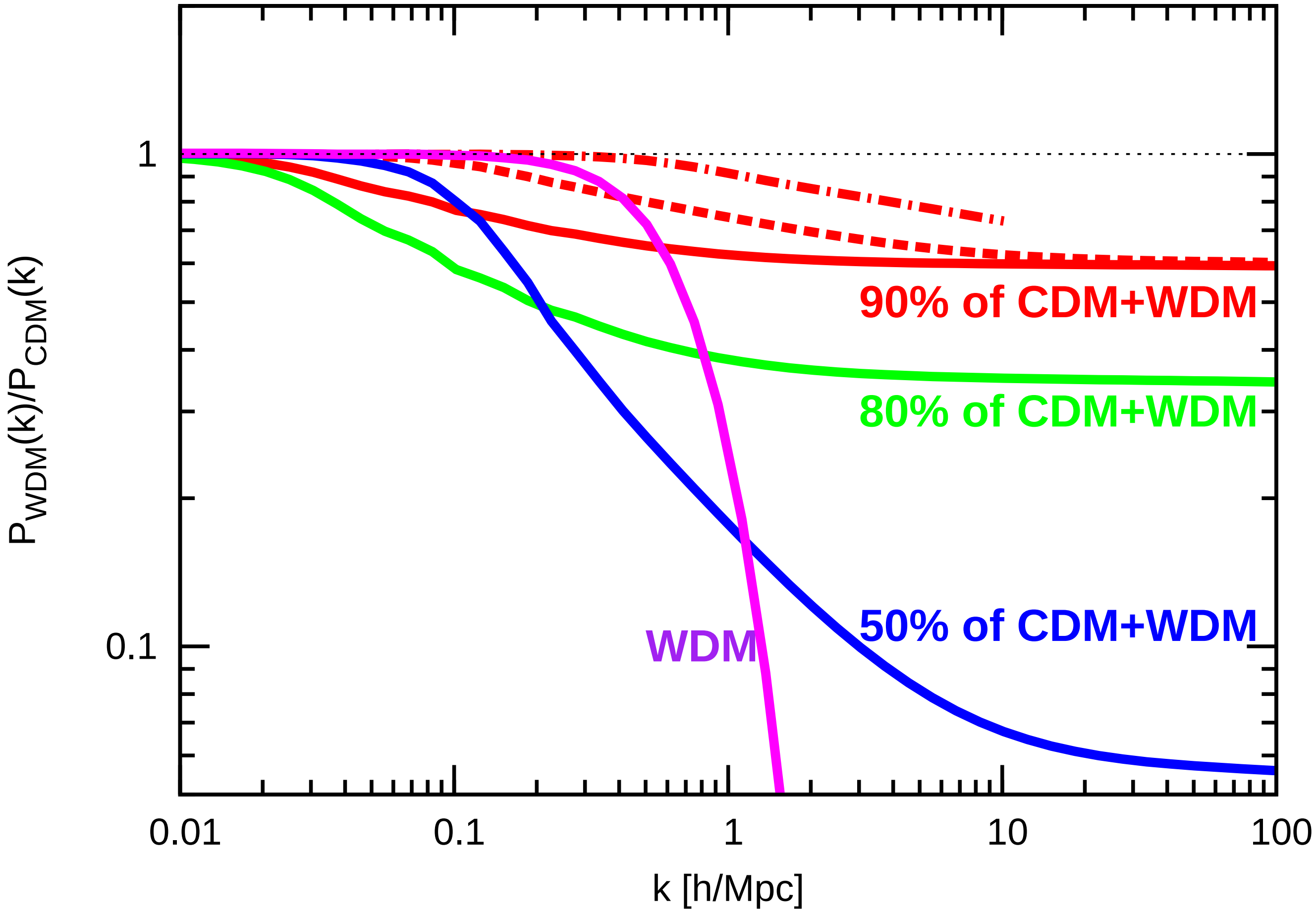
ICs with thermal velocities	ICs without thermal velocities
$M_{\text{WDM}} = 13.5$ keV	$M_{\text{WDM}} = 13.9$ keV

- How robust are these **Bayesian** confidence limits?

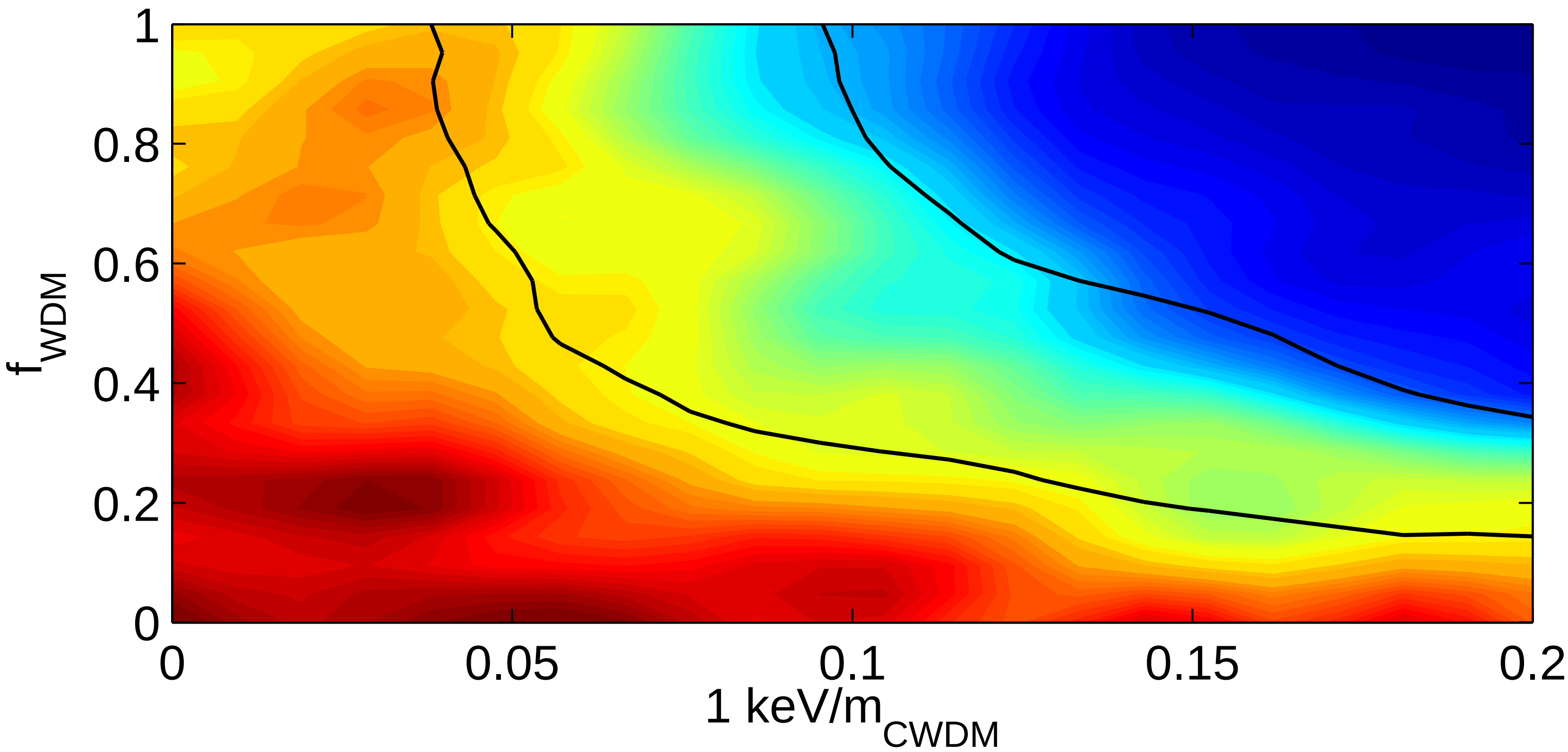


Cold+warm DM model (CWDM)

Are low masses interesting? **Yes**, if we consider models with admixture of cold DM component (relevant for resonantly produced sterile neutrino DM, gravitino DM)

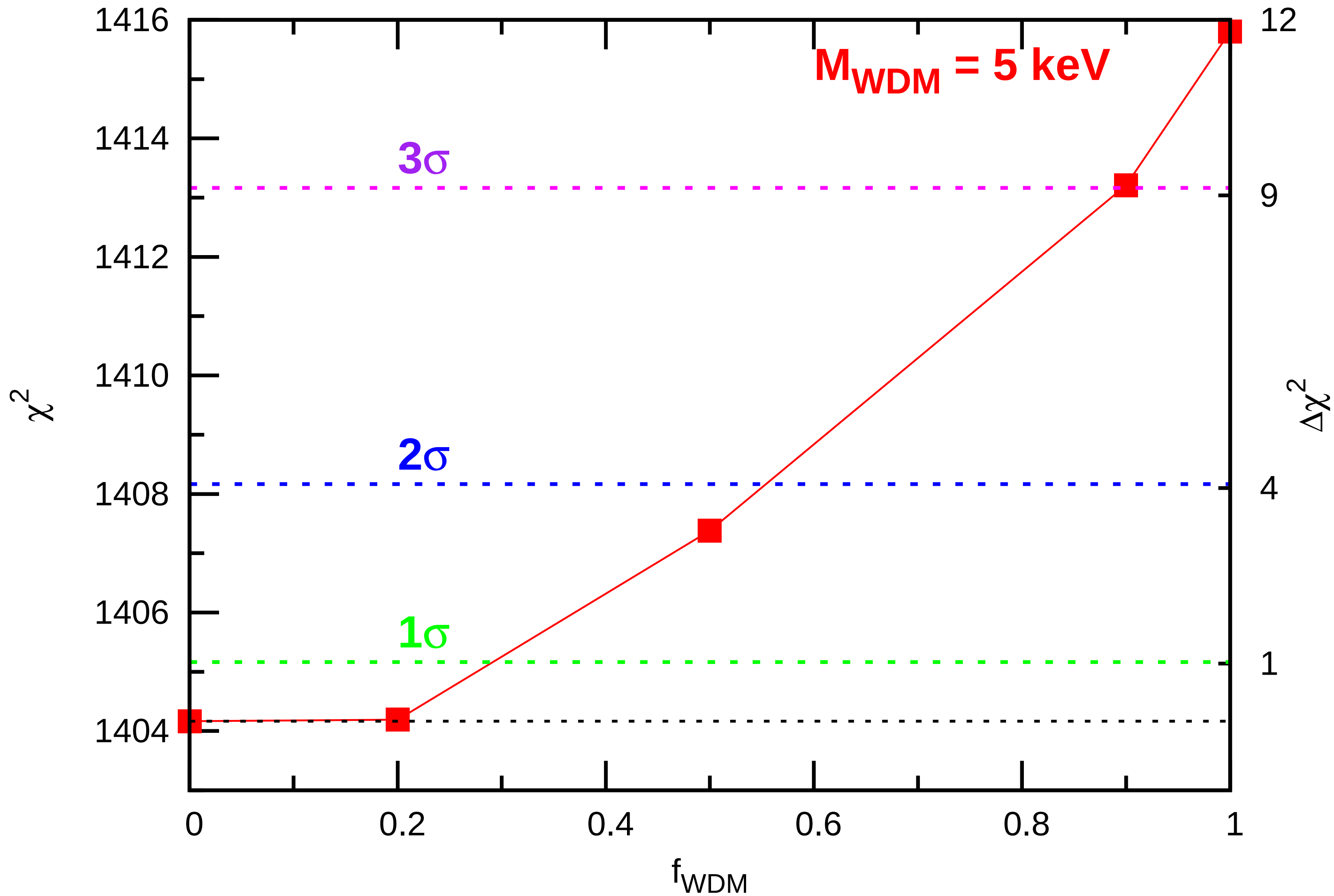


Bayesian bounds on mixture of CDM+WDM



$$f_{\text{WDM}} = \frac{\omega_{\text{WDM}}}{\omega_{\text{WDM}} + \omega_{\text{CDM}}}$$

Frequentist approach to the CWDM bounds



All models have the same number of degrees of freedom

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

Choosing parameters of the νMSM

- Parameters of **two** sterile neutrinos are enough to explain baryogenesis and fit the oscillations data:
  - If $M_{2,3} \sim 150$ **MeV** $- 20$ **GeV** and $\Delta M_{2,3} \ll M_{2,3}$ νMSM explains **baryon asymmetry** of the Universe.
  - Neutrino experiments can be explained within the same choice of parameters. See-saw with masses **below** EW scale.
- The third (lightest) sterile neutrino can have cosmologically long life time $\tau = 5 \times 10^{26}\text{sec} \times \left(\frac{\text{keV}}{M_s}\right)^5 \left(\frac{10^{-8}}{\theta^2}\right)^2$

  Dodelson Widrow'93
- Can be produced in the early Universe in the right amount:

  Asaka, Laine, Shaposhnikov 07
  - Via active-sterile **neutrino oscillations**

  Laine, Shaposhnikov
  - Via **resonant** active-sterile neutrino oscillations in the presence of **lepton asymmetries**. (can produces sterile neutrinos up to $\sim 10^2$ keV.)

  Shi, Fuller'98
  - In **inflaton** decays. (neutrinos with the mass up to few MeV)

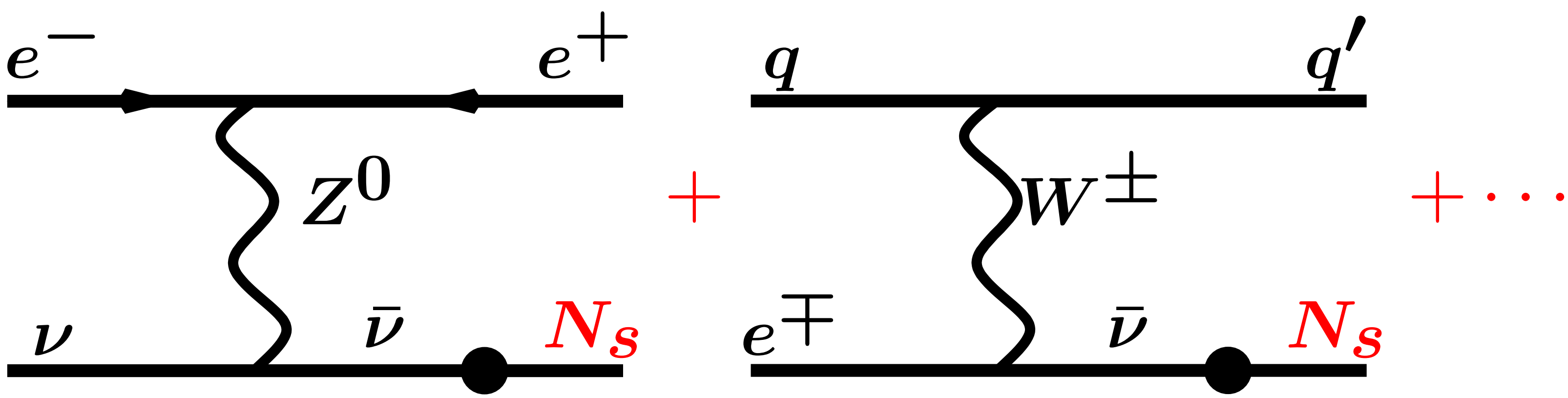
  Tkachev, Shaposhnikov (2006)

How sterile neutrino DM is produced?

- Sterile neutrino interacts with the rest of the SM matter **only** via coupling with active neutrinos, parametrized by $\theta = \frac{m_D}{M}$
- Acceptable θ are so small, that the rate of this interaction Γ is much slower than the expansion rate ($\Gamma \ll H$)
  - $\Rightarrow$ Sterile neutrino are never in **thermal equilibrium**
  - $\Rightarrow$ One must know the **initial conditions** of sterile neutrino at temperatures $T \gtrsim 1$ GeV
- **Simplest scenario:** sterile neutrino in the early Universe interact with the rest of the SM matter via ***neutrino oscillations:***

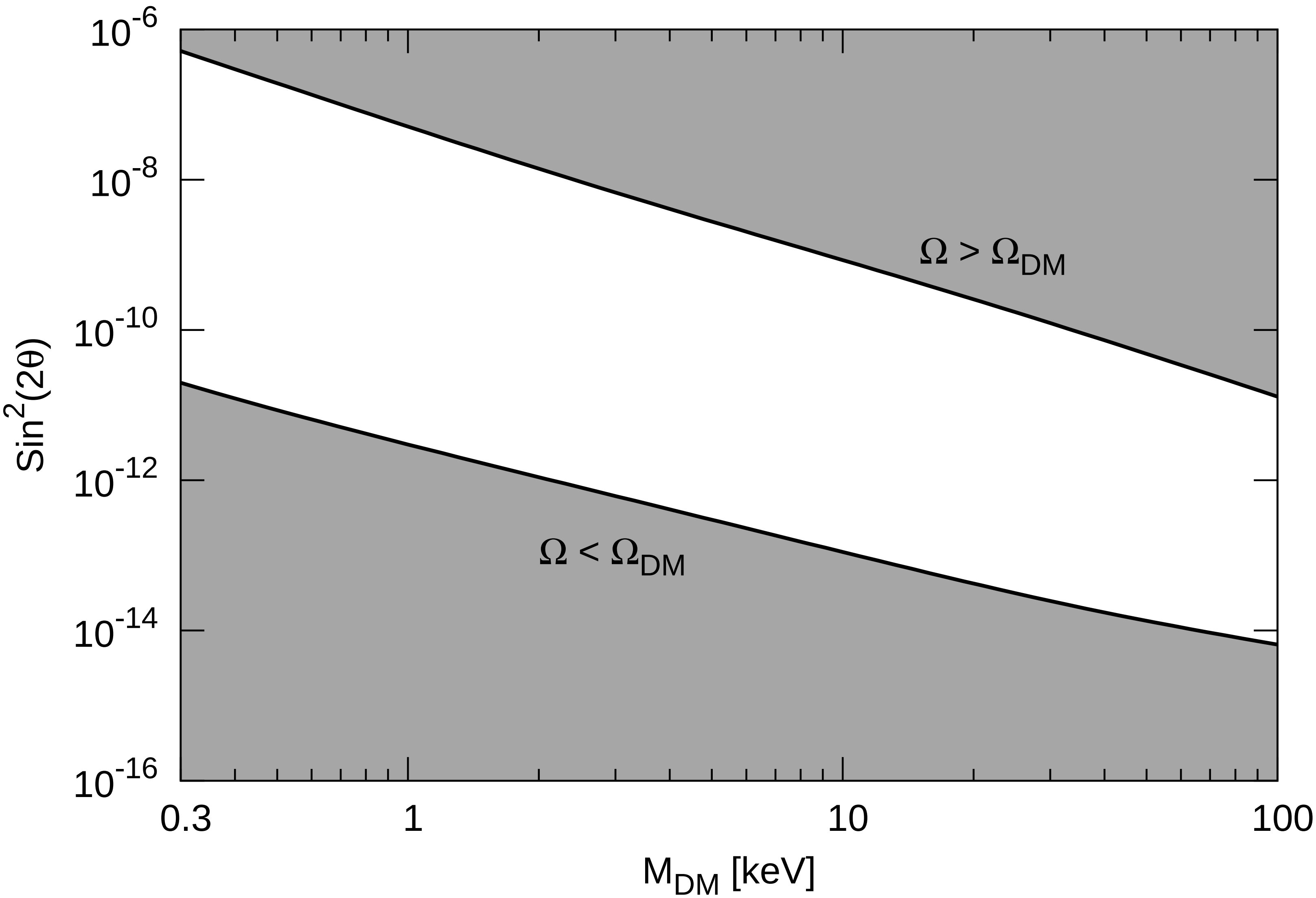
Dodelson Widrow'93

Shi Fuller'98

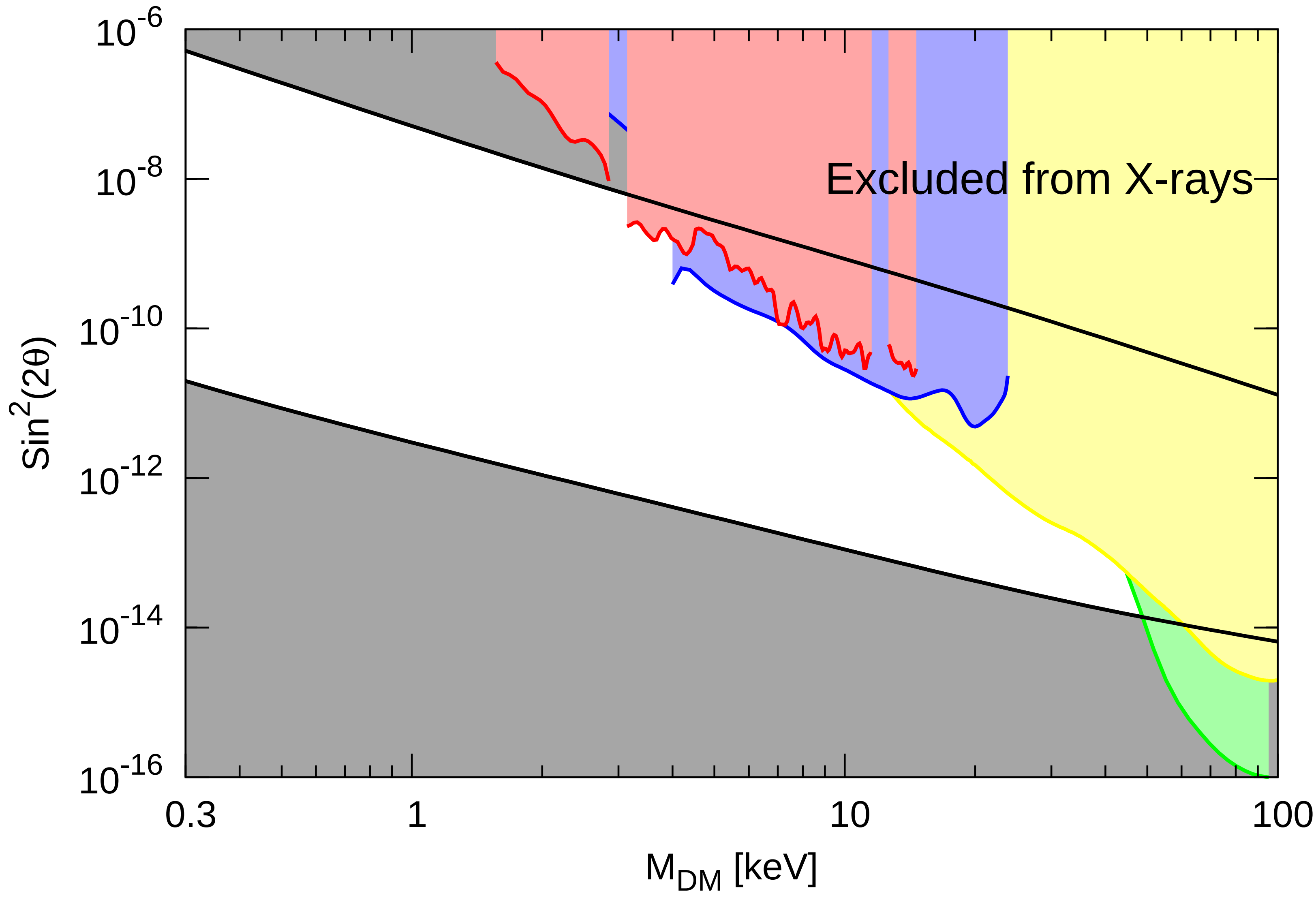


Window of parameters of sterile neutrino DM

Laine, Shaposhnikov



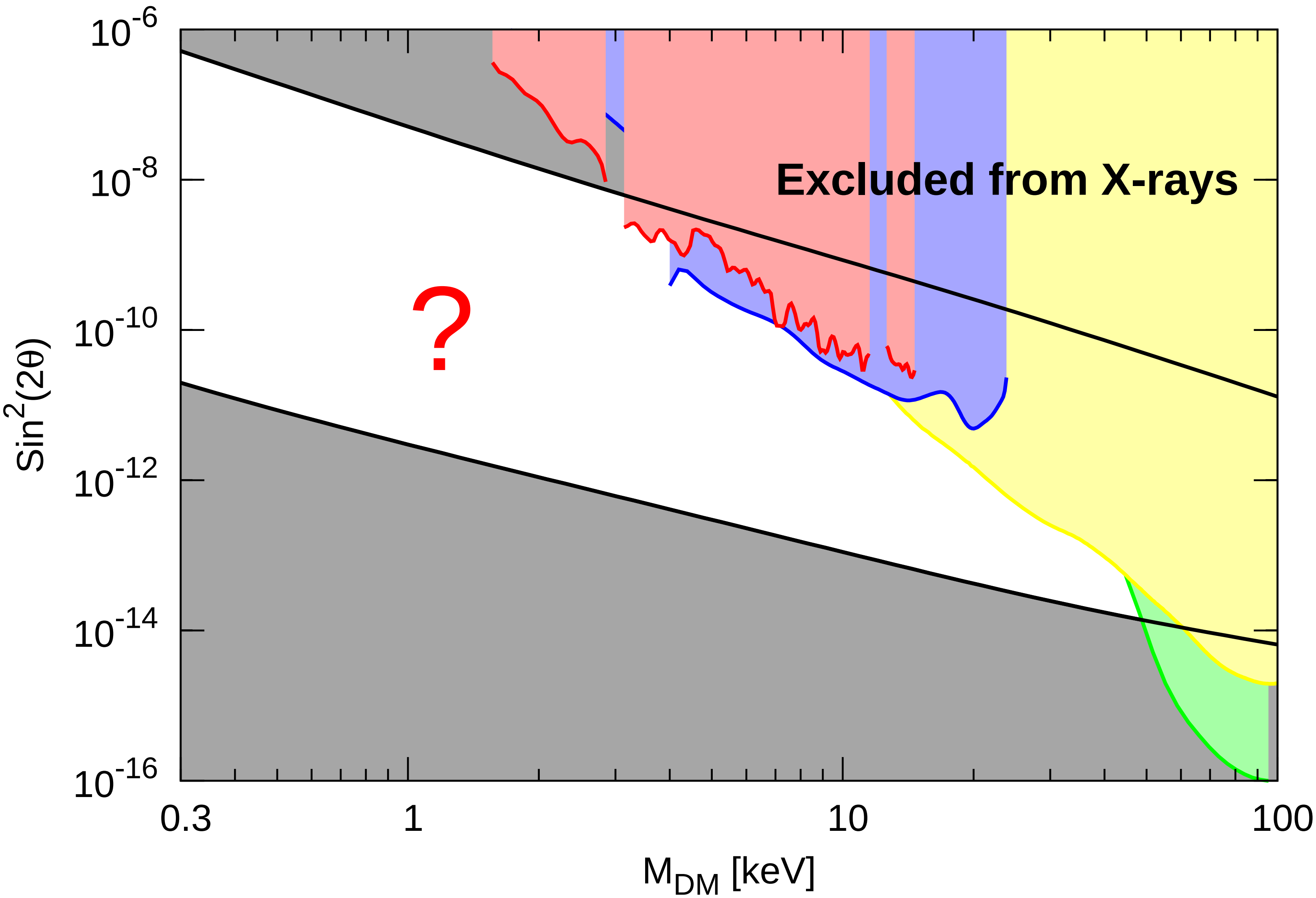
Window of parameters of sterile neutrino DM



Boyarsky, Ruchayskiy et al. 2005-2008

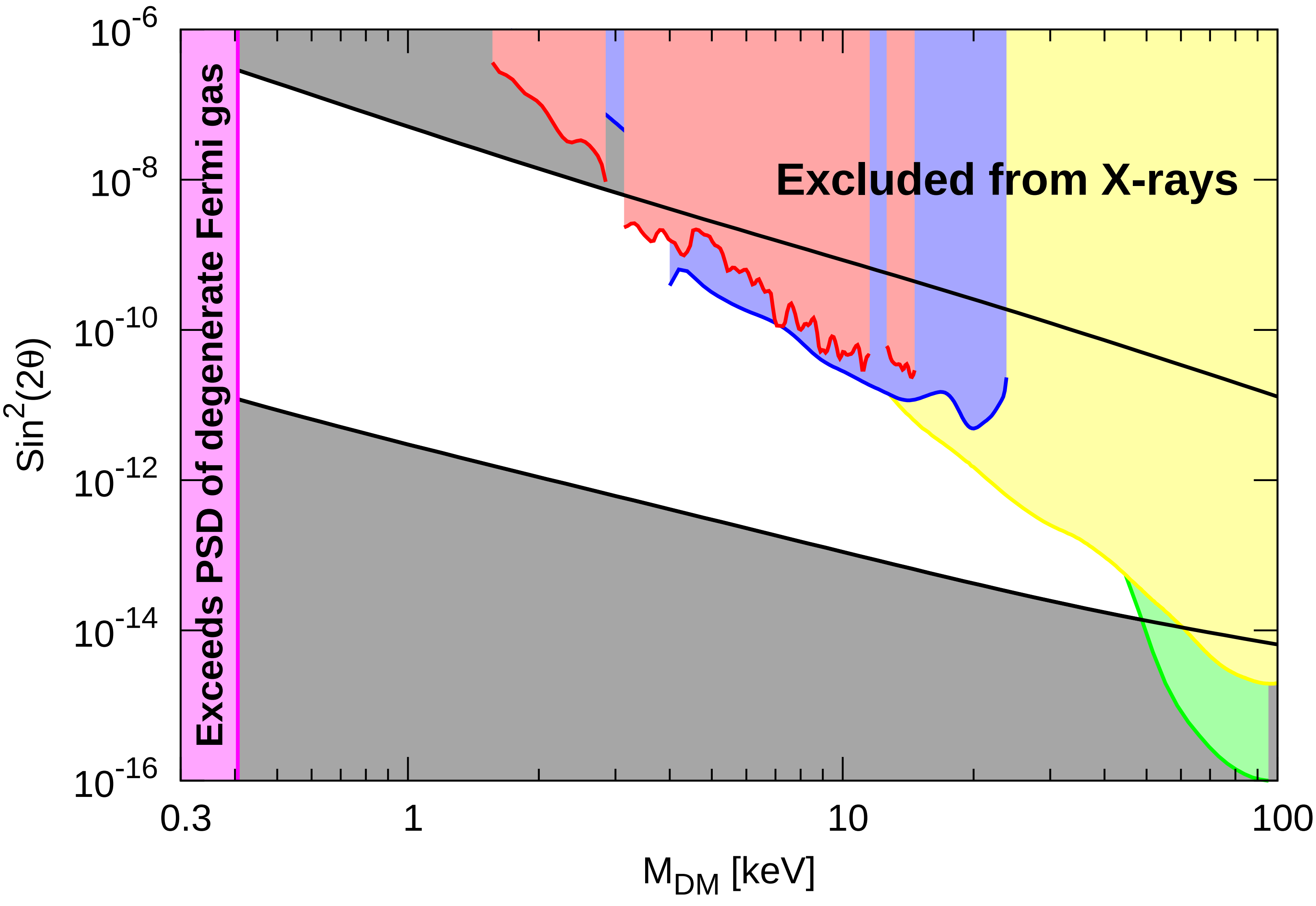
Window of parameters of sterile neutrino DM

Boyarsky, Ruchayskiy et al. 2005-2008



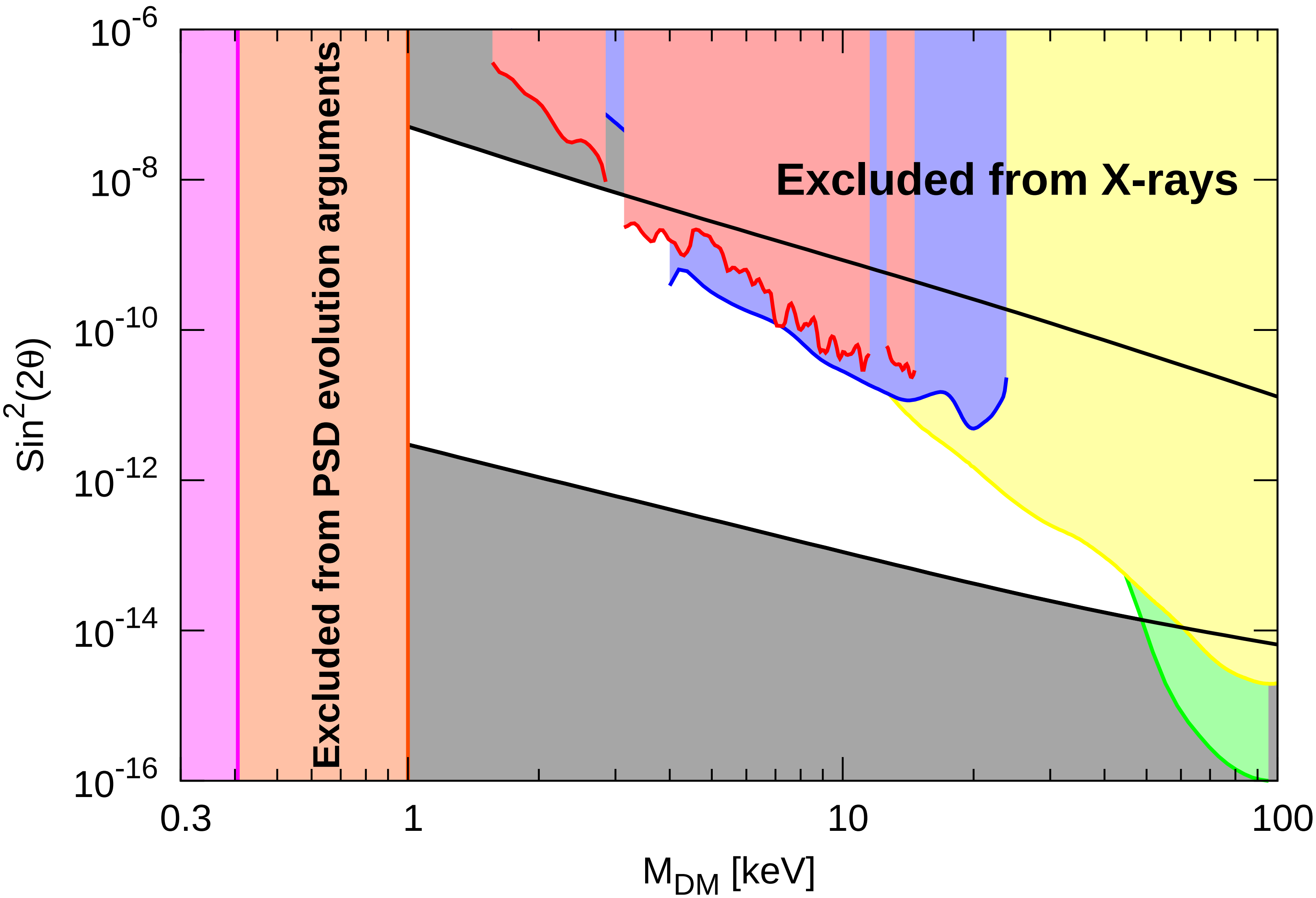
Window of parameters of sterile neutrino DM

Boyarsky, Ruchayskiy et al. 2005-2008



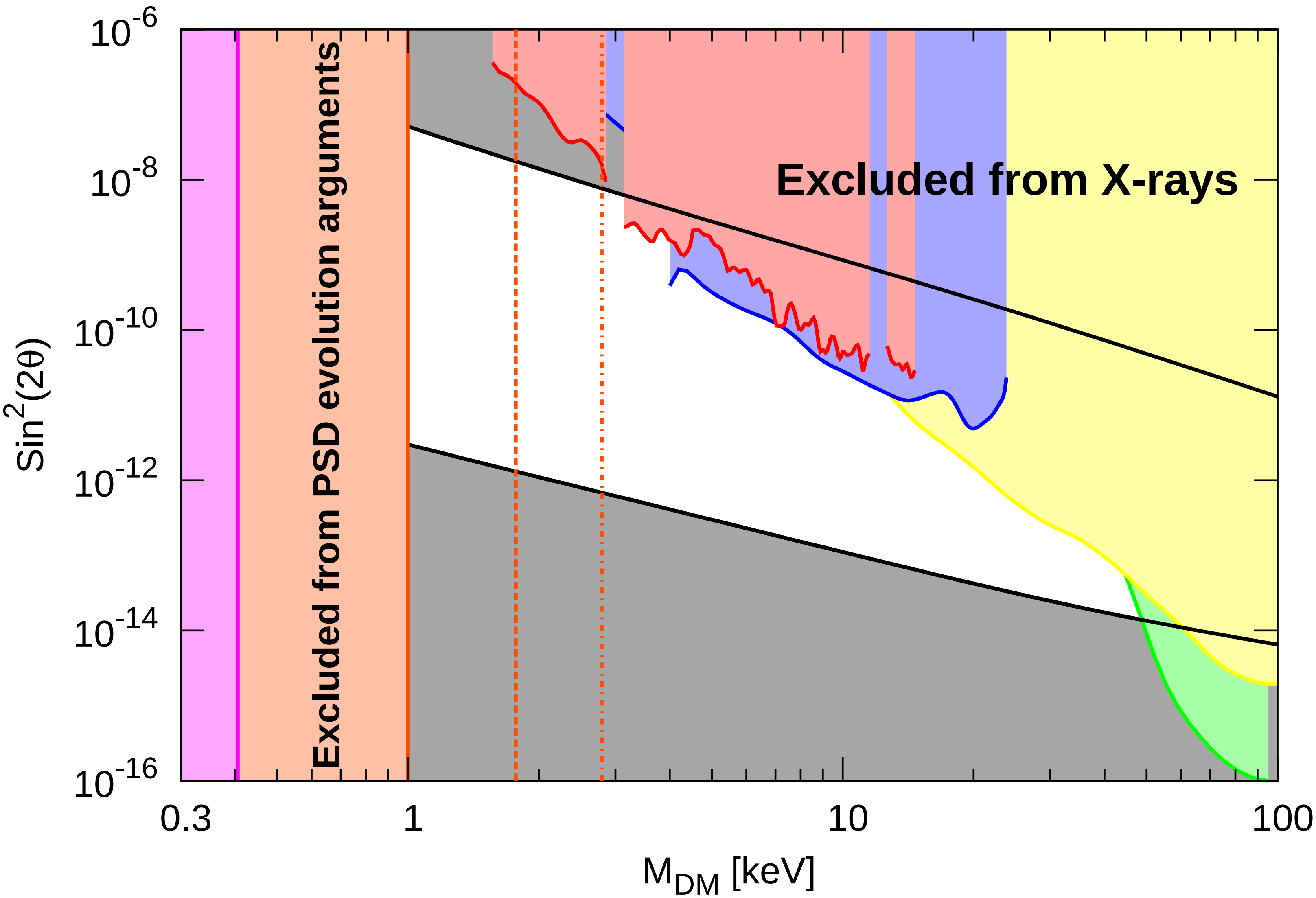
Window of parameters of sterile neutrino DM

Boyarsky, Ruchayskiy et al. 2005-2008

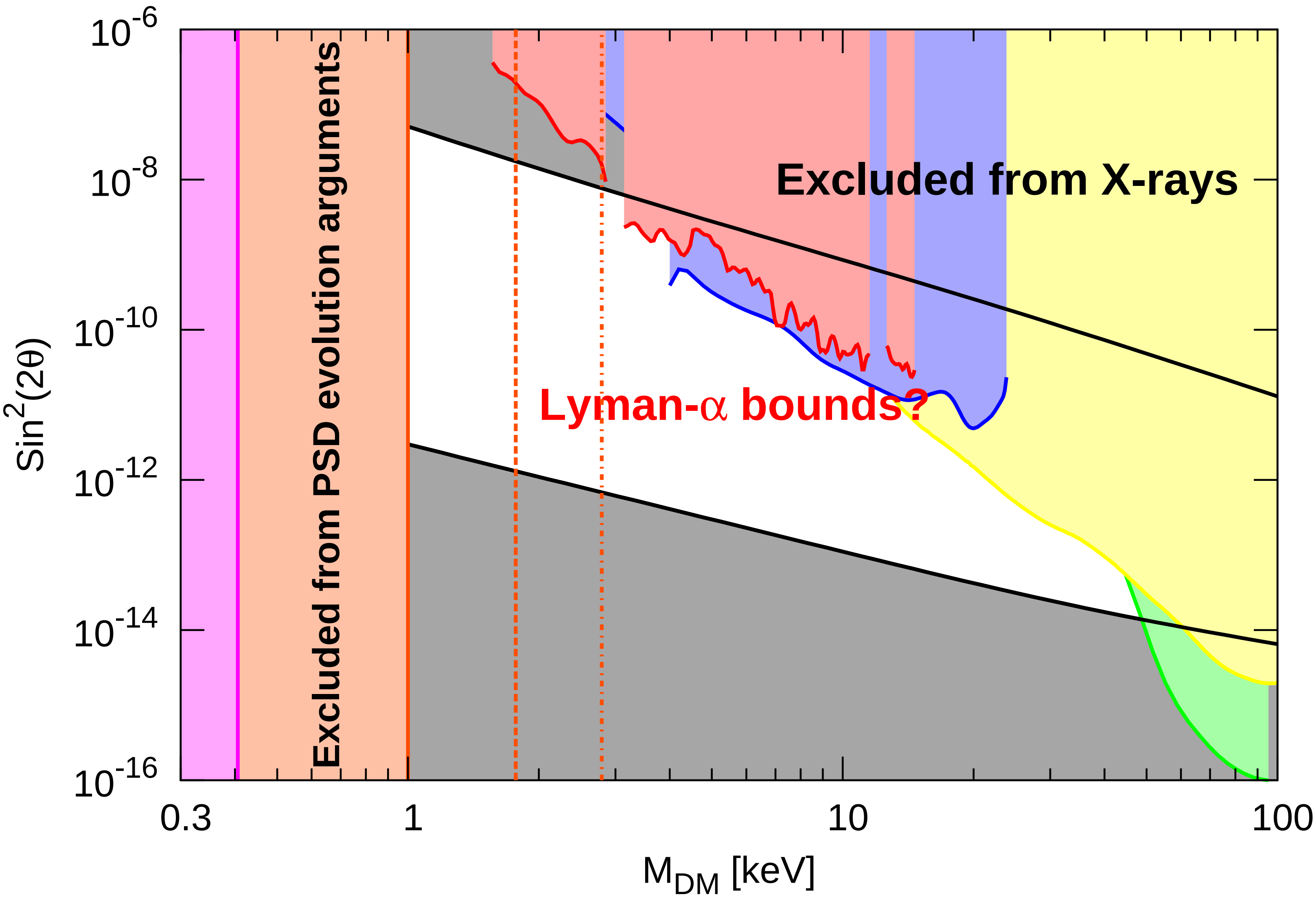


Window of parameters of sterile neutrino DM

Boyarsky, Ruchayskiy et al. 2005-2008



Window of parameters of sterile neutrino DM



Boyarsky, Ruchayskiy, Lesgourgues, Viel 2008

Summary

- A number of models provides **decaying** DM (sterile neutrino, gravitino, Majoron, volume modulus,...). The DM candidates can be light (keV – MeV range)
- Astrophysical search of decaying DM model is an experiment of "direct detection" type (if a line is detected, it can be distinguished from the line of any other origin)
- DM models can be warm (with various velocity distribution functions), this can be probed by the Lyman-α data
- So far the Lyman-α data were obtained only for the models with thermally produced WDM particles. The **Bayesian** (usually quoted) CL bounds should be understood with **at least** $\pm 50\%$ additional uncertainty
- Improving on these results can rule out (or confirm) several interesting extensions of the SM (νMSM, volume moduli)

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)

TOC

TOC

TOC