Cosmological and astrophysical bounds on super-weakly interacting dark matter

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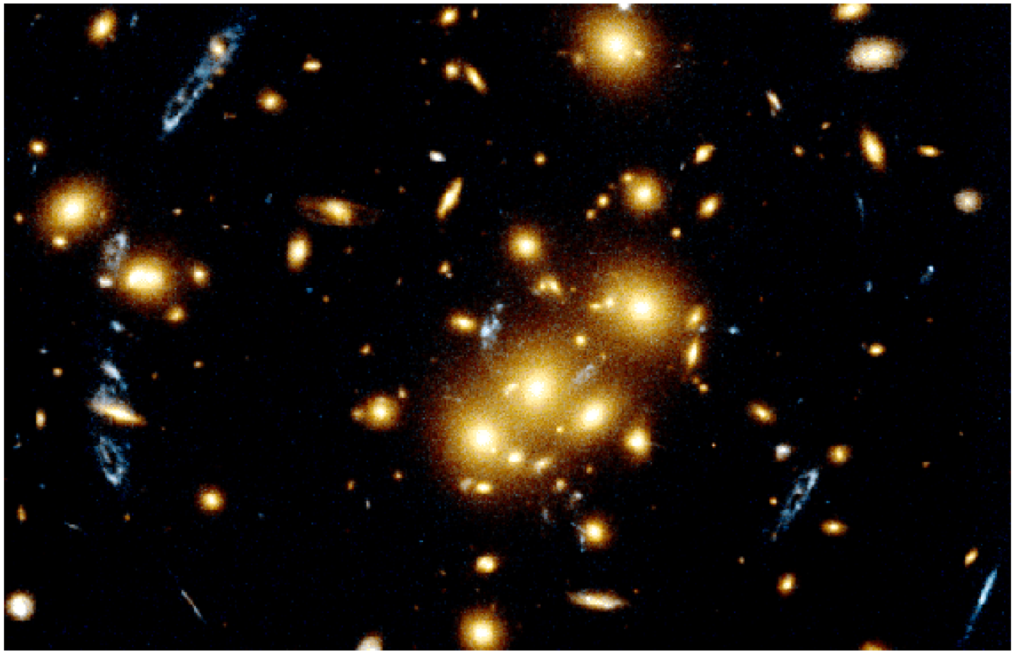
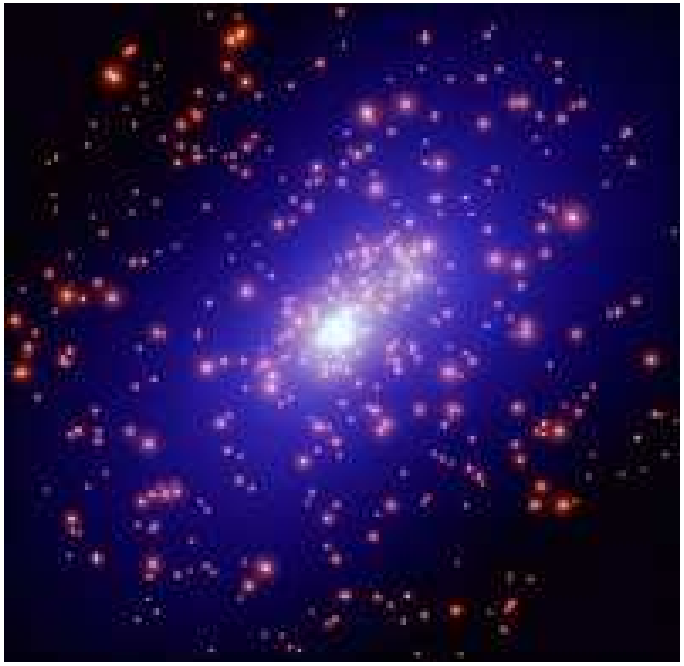
Dark Matter in the Universe

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

- ***Rotation curves*** of stars in galaxies and of galaxies in clusters
- Distribution of ***intracluster gas***
- ***Gravitational lensing data***





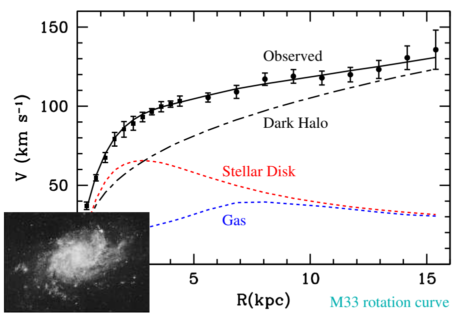
Galaxy cluster CL0024+1654 $(z = 0.39)$
Courtesy of ESA-NASA

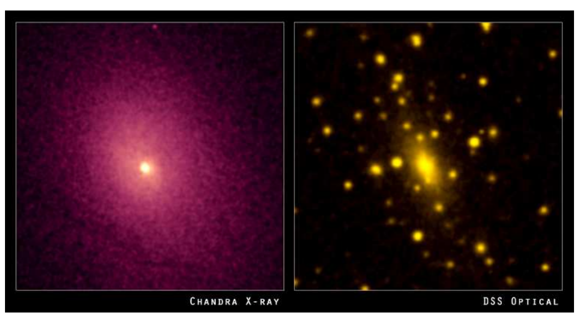
Left: Galaxy cluster CL0024+1654 as a gravitational lens
Courtesy of HST

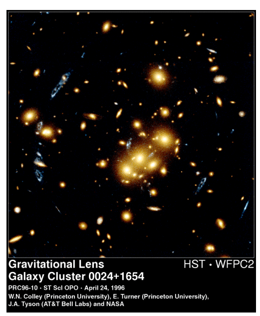
Dark Matter in the Universe

- Rotation curves of stars in galaxies and of galaxies in clusters
- Distribution of intracluster gas
- Gravitational lensing data

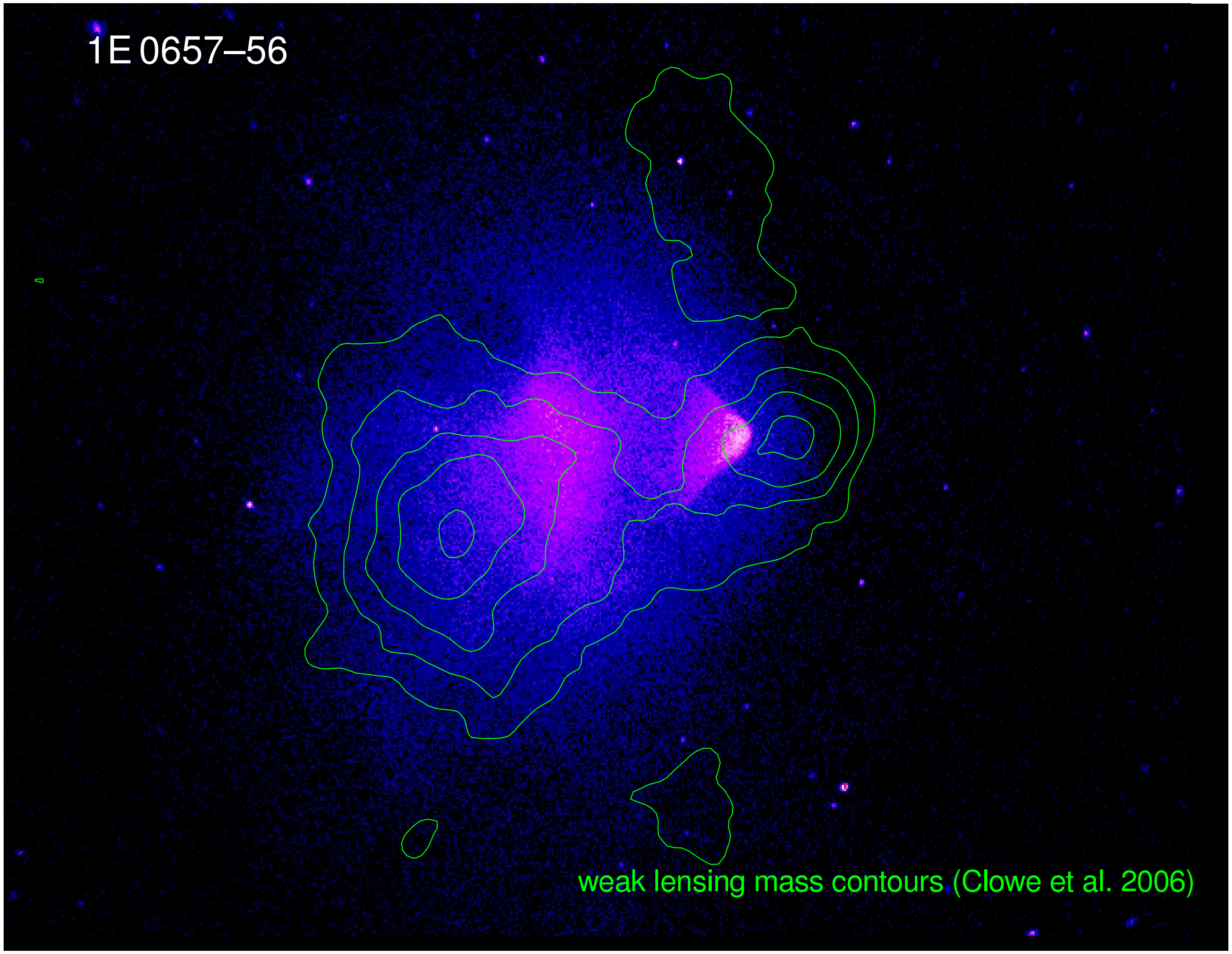
These phenomena are **independent tracers** of gravitational potentials in astrophysical systems. They all show that dynamics is dominated by a matter that is not observed in any part of electromagnetic spectrum.





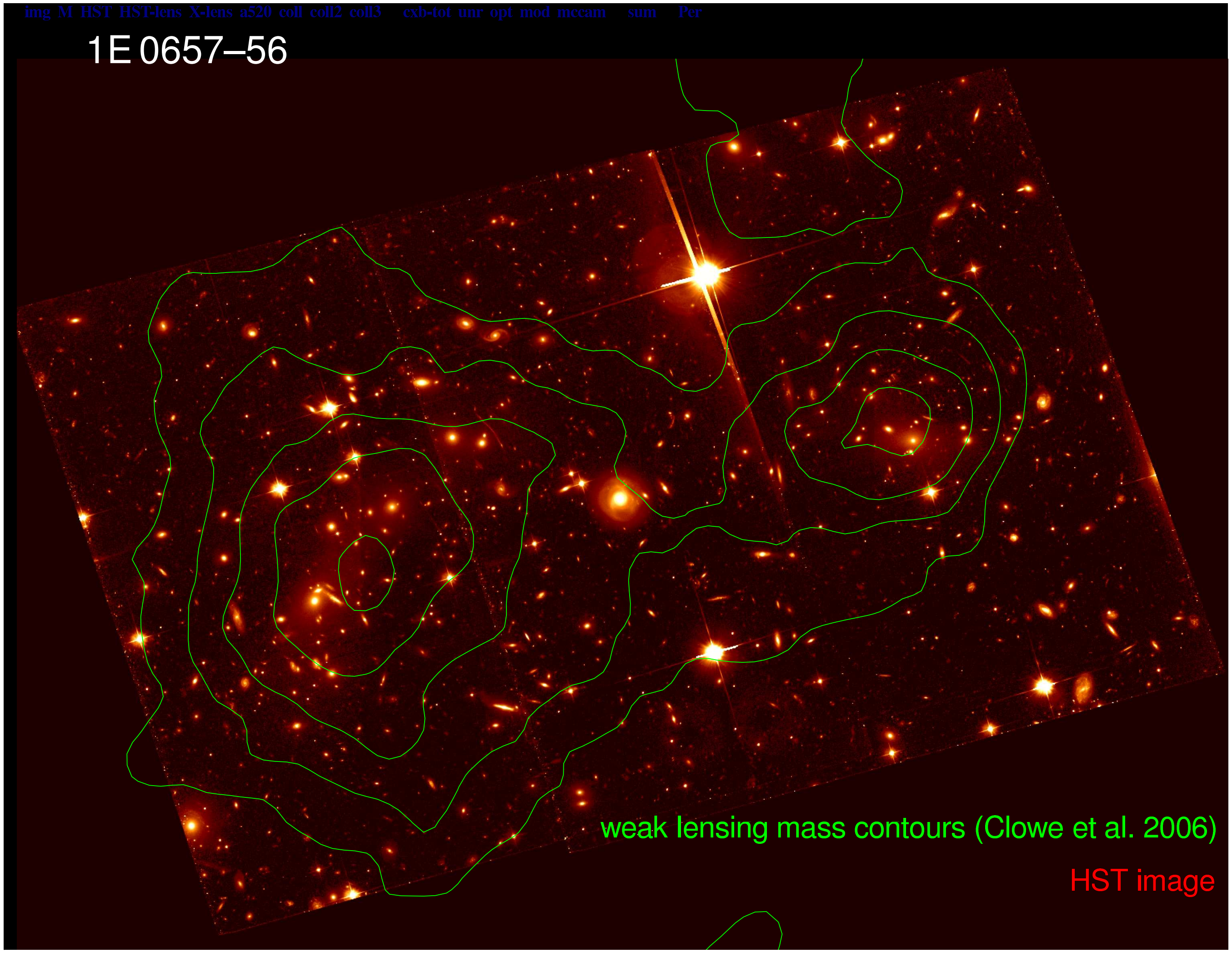


"Bullet" cluster



- ⋆ Subcluster passed through the center of the main cluster.
- ⋆ DM and galaxies are collisionless.
- ⋆ Gas has been stripped away (shock wave, Mach number $M = 3.2$ and $T_{\rm shock} \sim 30$ keV)

Mass determined via gravitational lensing

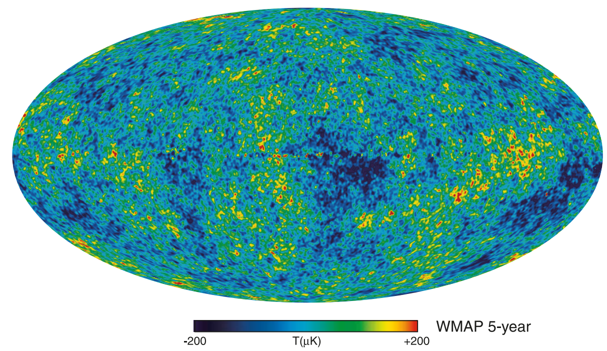


⋆ Comparing the weak gravitational lensing data with velocity distribution for galaxies

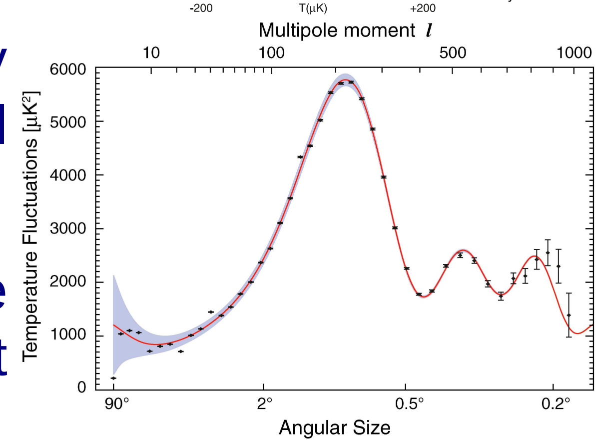
Cosmological evidence for dark matter

- Universe at large scales is not completely homogeneous

- We see the structures today and 13.7 billions years ago, when the Universe was 380 000 years old (encoded in anisotropies of the temperature of cosmic microwave background)



- All the structure is produced from tiny density fluctuations due to gravitational Jeans instability



- In the hot early Universe before recombination photons smeared out all the fluctuations

- To explain the observed anisotropies **we need DM particles** that started to cluster *before* recombination.

What do we know about DM: a summary

- **Is evidence for DM convincing?**
  Yes

- **Is DM made up of particles?**
  Plausible assumption but no hard evidence.

  More exotic possibilities such as primordial black holes or MACHOs are not completely ruled out

- We will study the scenario of **dark matter particle** and its consequences for particle physics.

Properties of a DM candidate

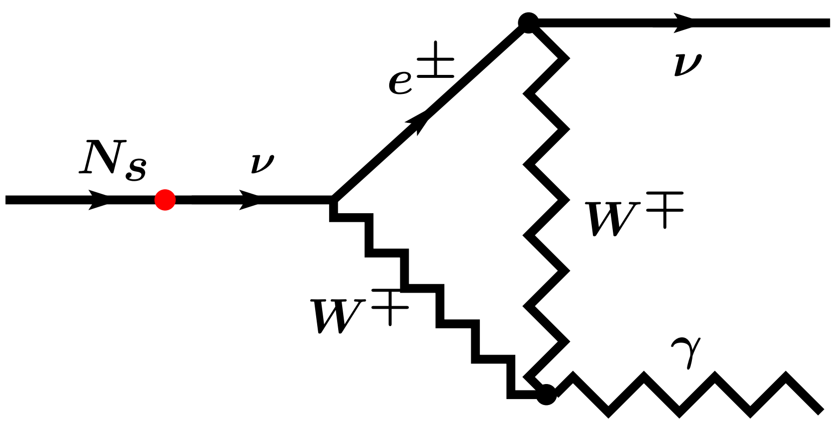
- DM is **not** baryonic
- DM is **not** a SM particle (neutrinos **could be but . . .)**
- Any DM candidate must be
  - Produced in the early Universe and have correct relic abundance
  - Very weakly interacting with electromagnetic radiation ("dark")
  - Be stable or cosmologically long-lived
- There are plenty of ***non-SM candidates***

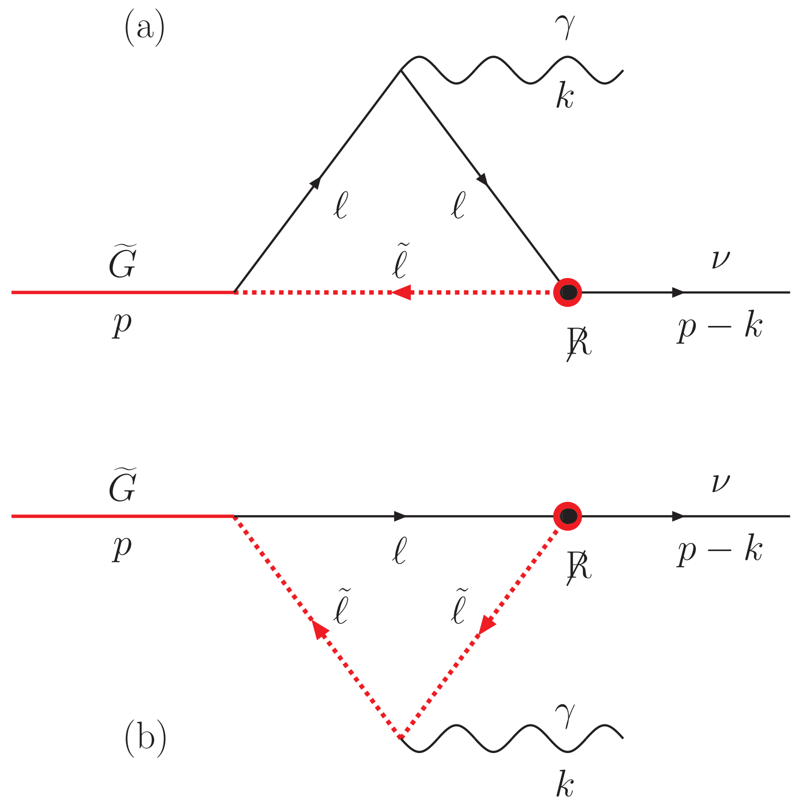
Interactions of a DM candidate

- DM interacts with the rest of the matter gravitationally
- Other possible interactions?
- It is possible that DM particles interact only in the early (very) hot Universe with some unknown particles
- To be produced from the SM matter the DM particles should interact
- It may be absolutely stable and interact with SM particles via annihilation only: $\boxed{\text{DM+DM}\to\text{SM}\ldots}$
- It may decay with very small rate, ensuring cosmologically long life-time: $\boxed{\text{DM}\to\text{SM}\ldots}$

DECAYING DARK MATTER

DM with **radiative signatures:** DM $\to \gamma + \nu,\ \gamma + \gamma,\ e^+ + e^- \ldots$





Appears in many models:

Right-handed neutrino
Dodelson & Widrow'93;
Asaka, Shaposhnikov et al.'05

Gravitino with broken R-parity
Takayama & Yamaguchi'00
Buchmüller'07

Volume Modulus
Quevedo'07

Properties of decaying DM

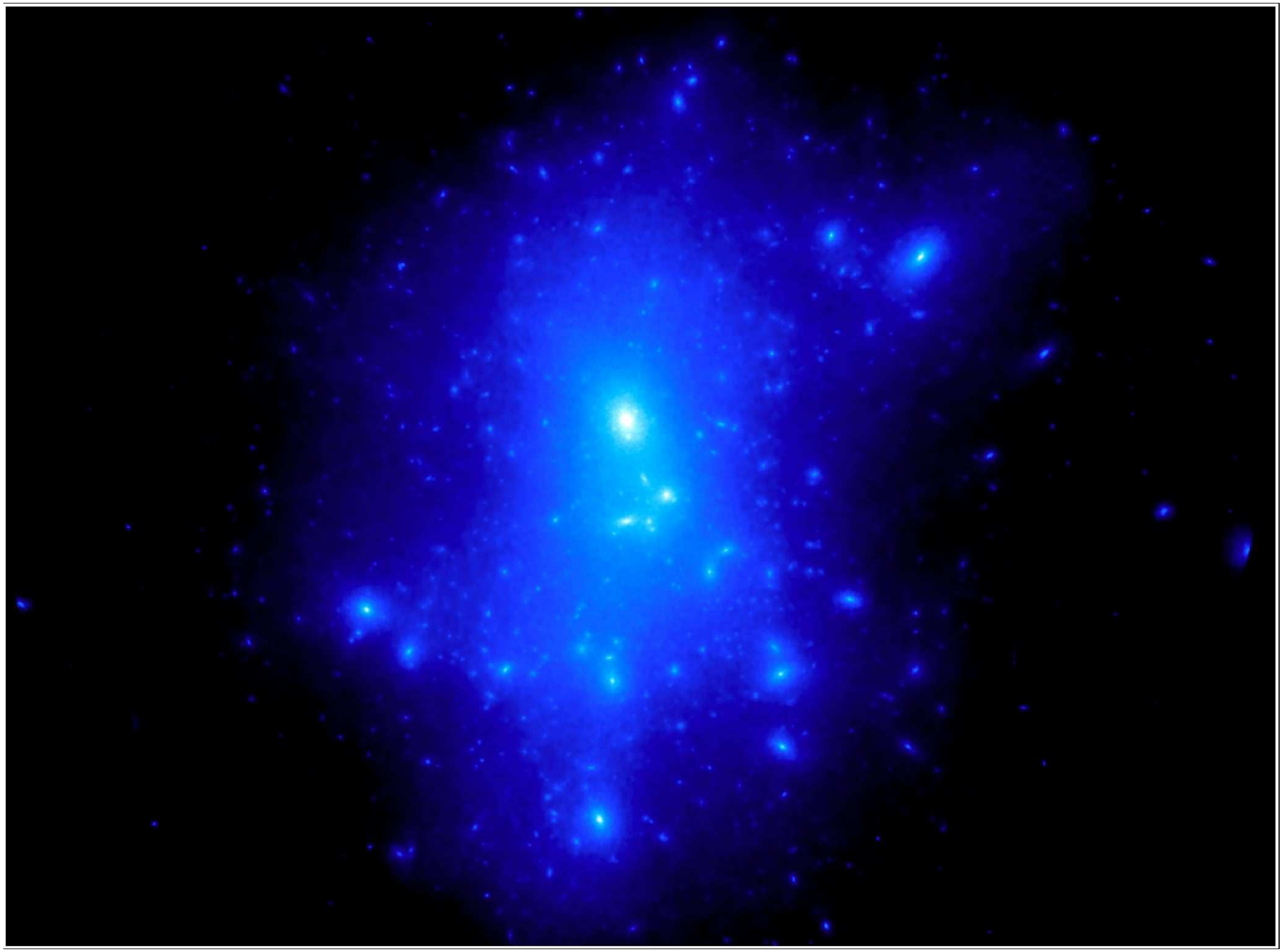
- WIMPs cannot decay. Their interaction strength with matter is $\sim G_F$ as in β-decay: $n \to p + e + \bar{\nu}_e$.
- Decaying DM should interact **superweakly** $\sim \theta \cdot G_F$ and $\theta \lll 1$
- Radiative decay channel : DM $\to \gamma + \nu$
- Photon energy $E_\gamma = \frac{m_{\text{DM}}}{2}$
- Decay width Γ
- Life-time $\tau = 1/\Gamma \gg$ life-time of the Universe
- Flux from DM decay:

$$F_{\text{DM}} = \frac{E_\gamma}{m_{\text{DM}}} \frac{\Gamma \mathcal{M}_{\text{DM}}^{\text{fov}}}{4\pi D_L^2} \approx \frac{\Gamma \Omega_{\text{fov}}}{8\pi} \int \rho_{\text{DM}}(r) dr \quad (z \ll 1, \quad \Omega_{\text{fov}} \ll 1)$$

line of sight

- $\int \rho_{\text{DM}}(r) dr$ is roughly equal for a large class of objects

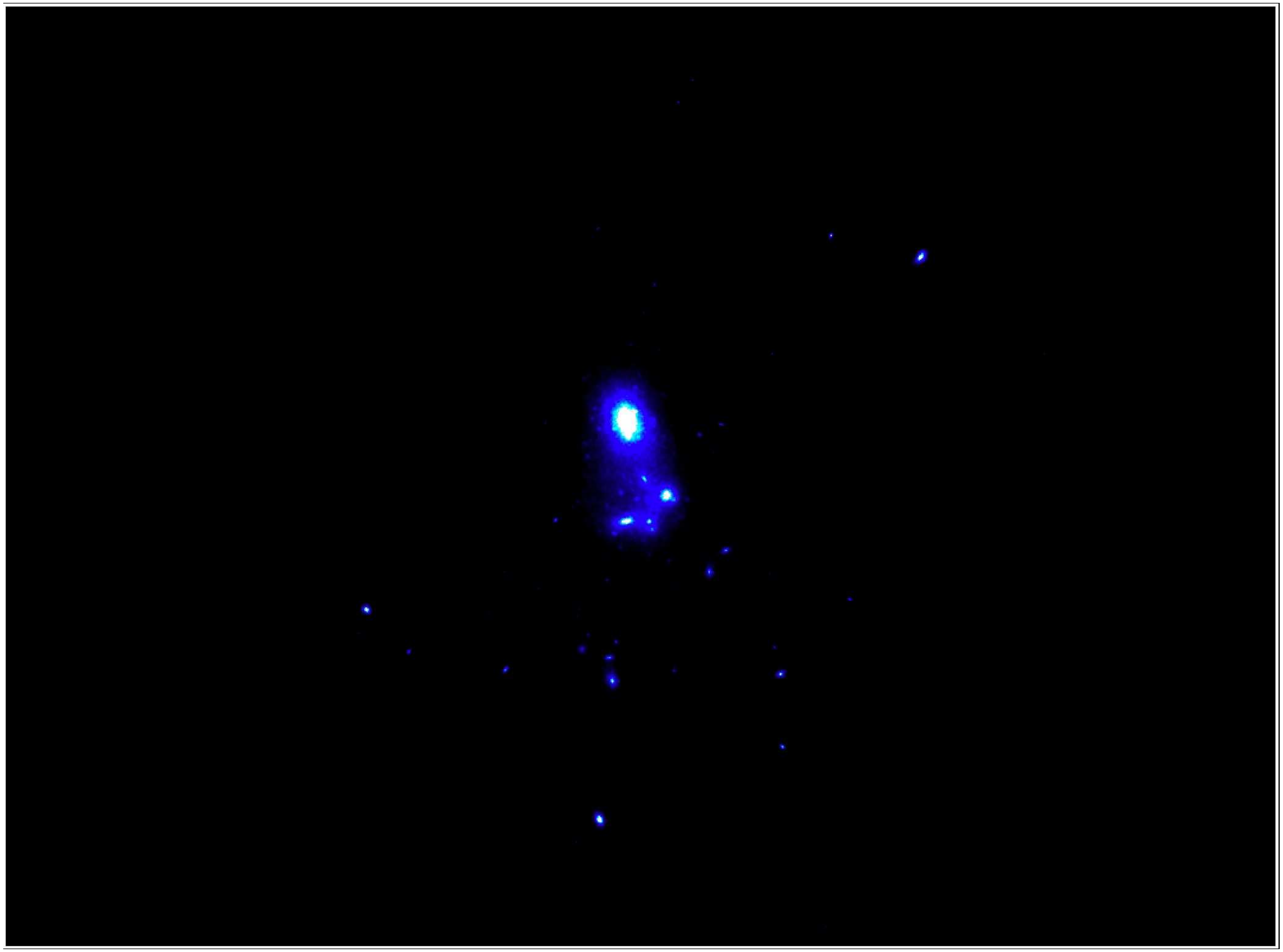
Decay signal from MW-sized galaxy



Moore et al. 2005

$$\int \rho_{\rm DM}(r)dr$$

Annihilation signal from MW-sized galaxy

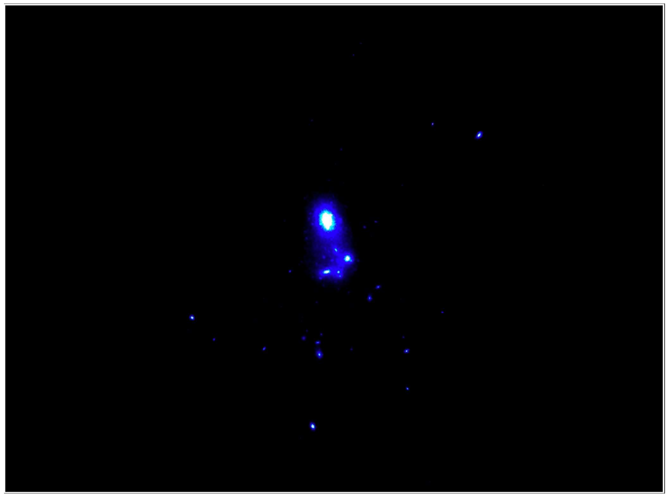


Moore et al. 2005

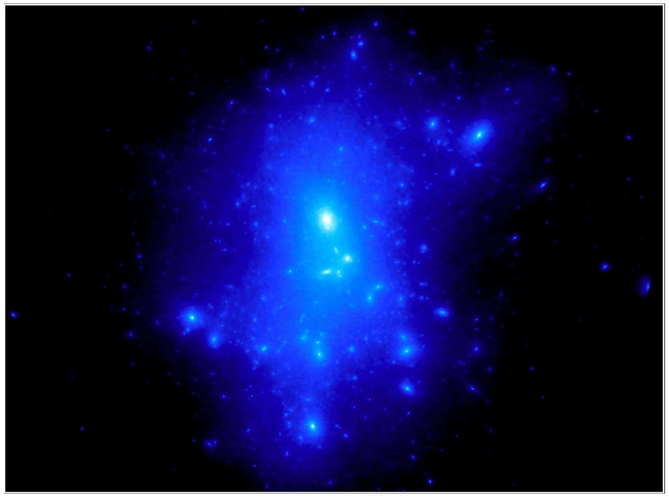
$$\int \rho^2_{\text{DM}}(r)dr$$

Decay vs. annihilation

- In the case of decaying Dark Matter the signal, if detected, is easy to distinguish from astrophysical backgrounds

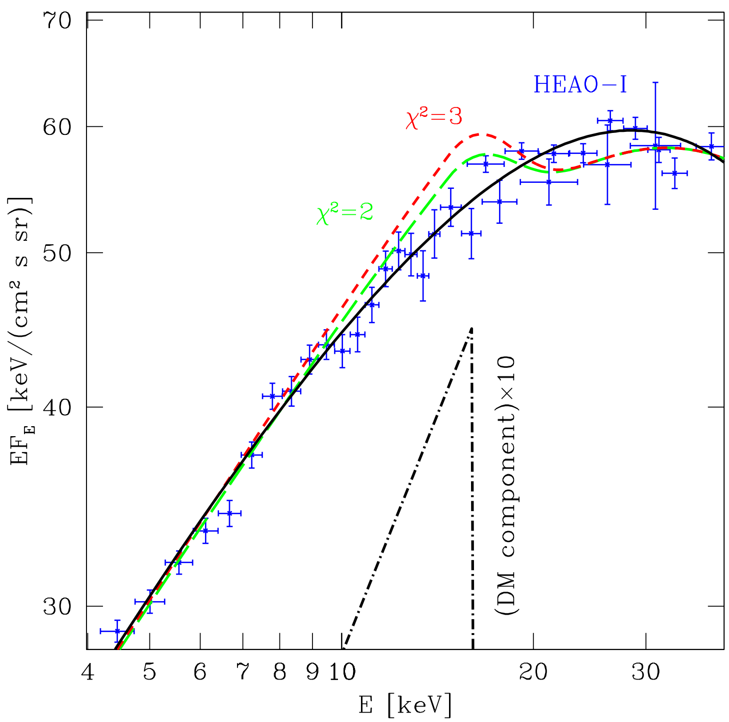


- We have a lot of freedom in choosing observation targets and, therefore, can unambiguously check DM origin of a suspicious signal.

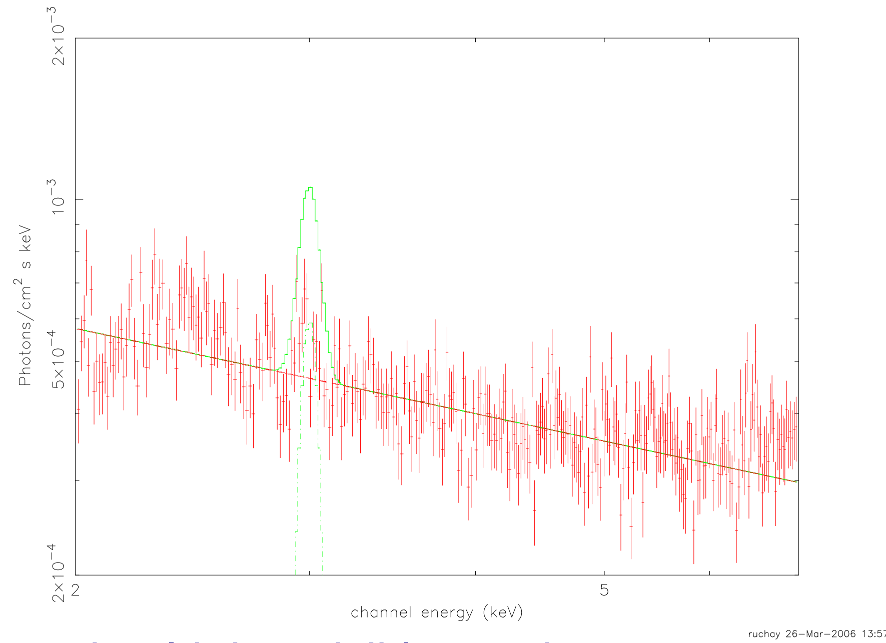


For decaying DM "indirect" search becomes "direct" !

Constraints from X-ray observations

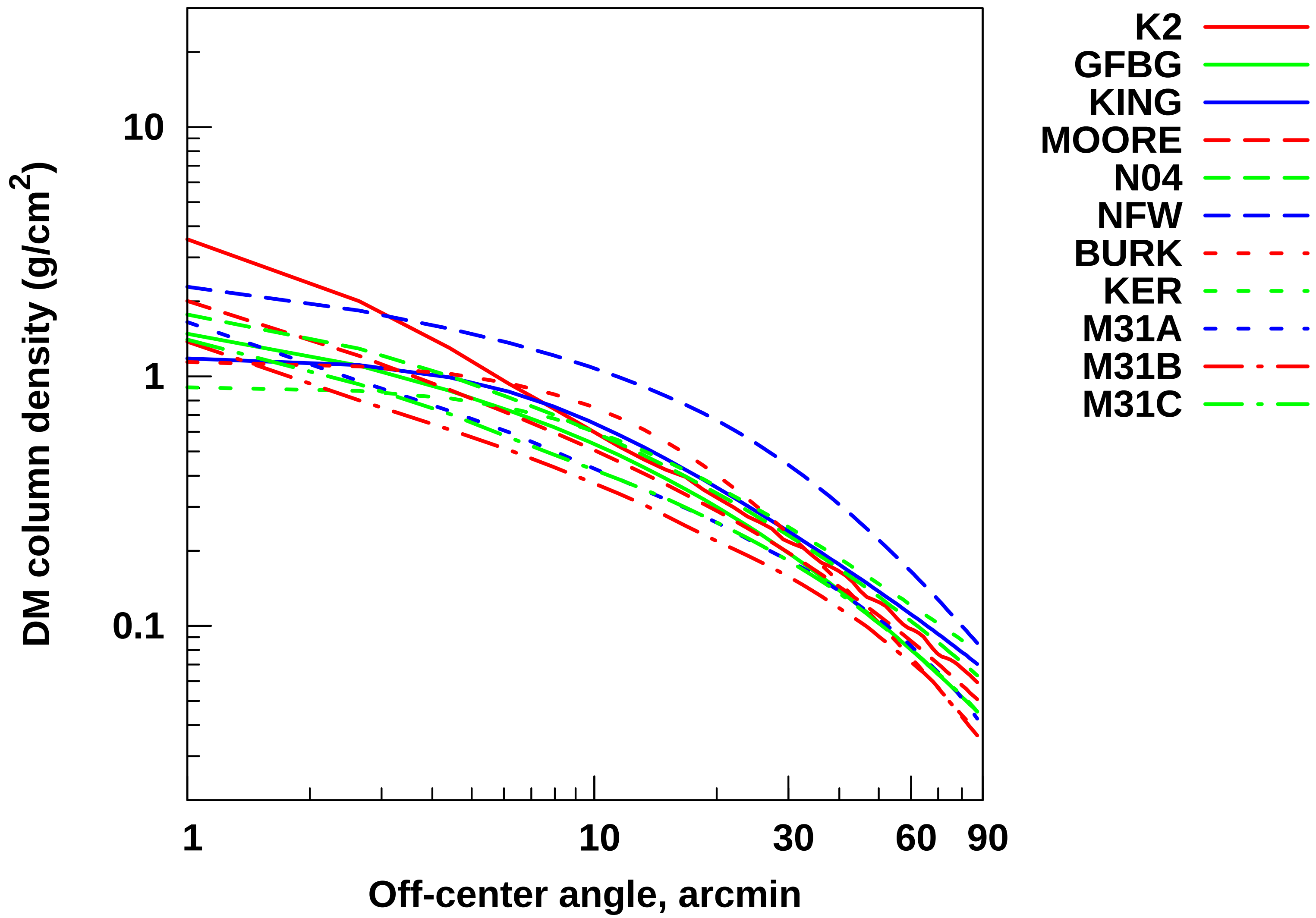


DM decay should produce a line in X-ray spectra of various objects.

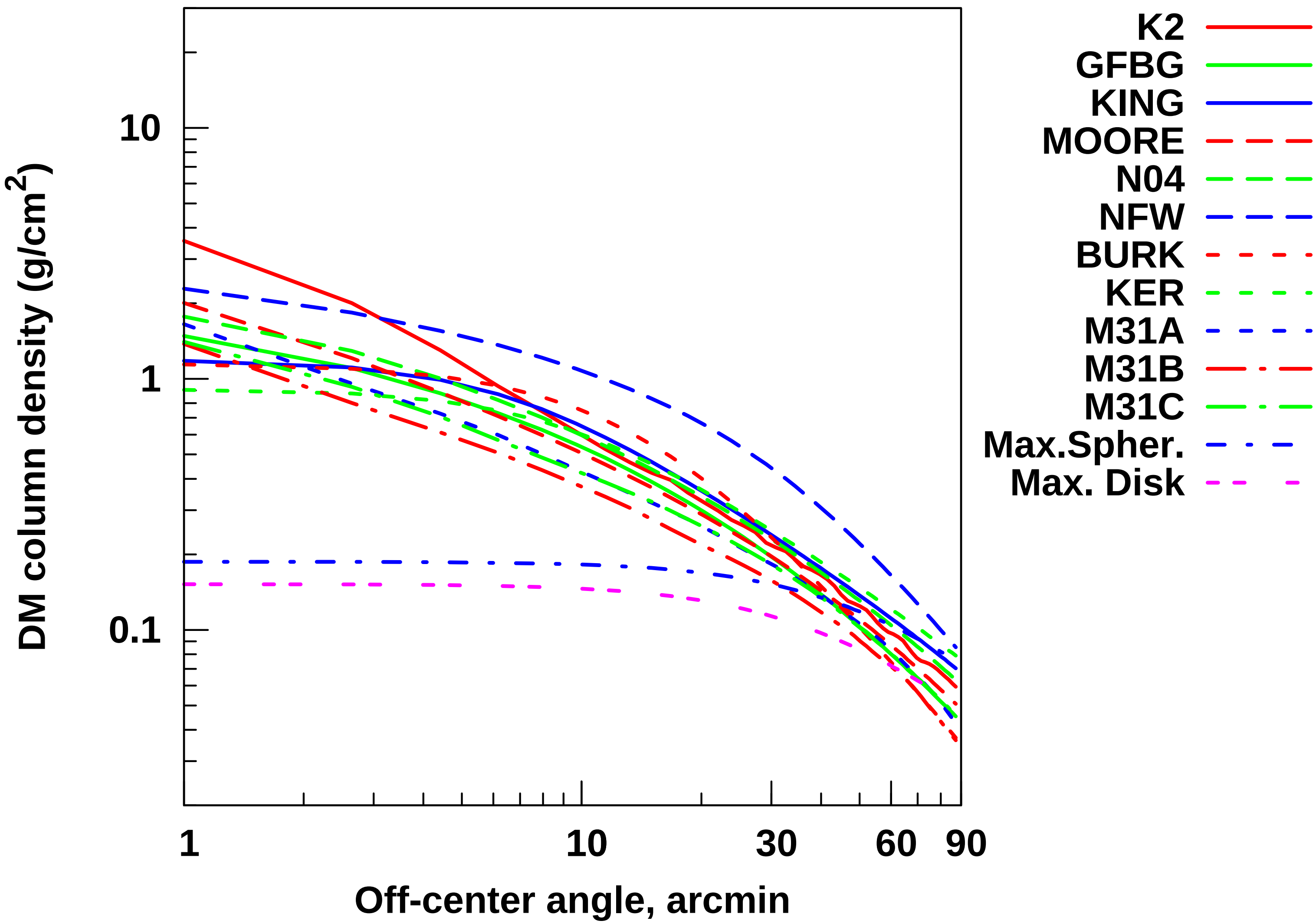


It should be visible against e.g power law spectrum of diffuse extragalactic background.

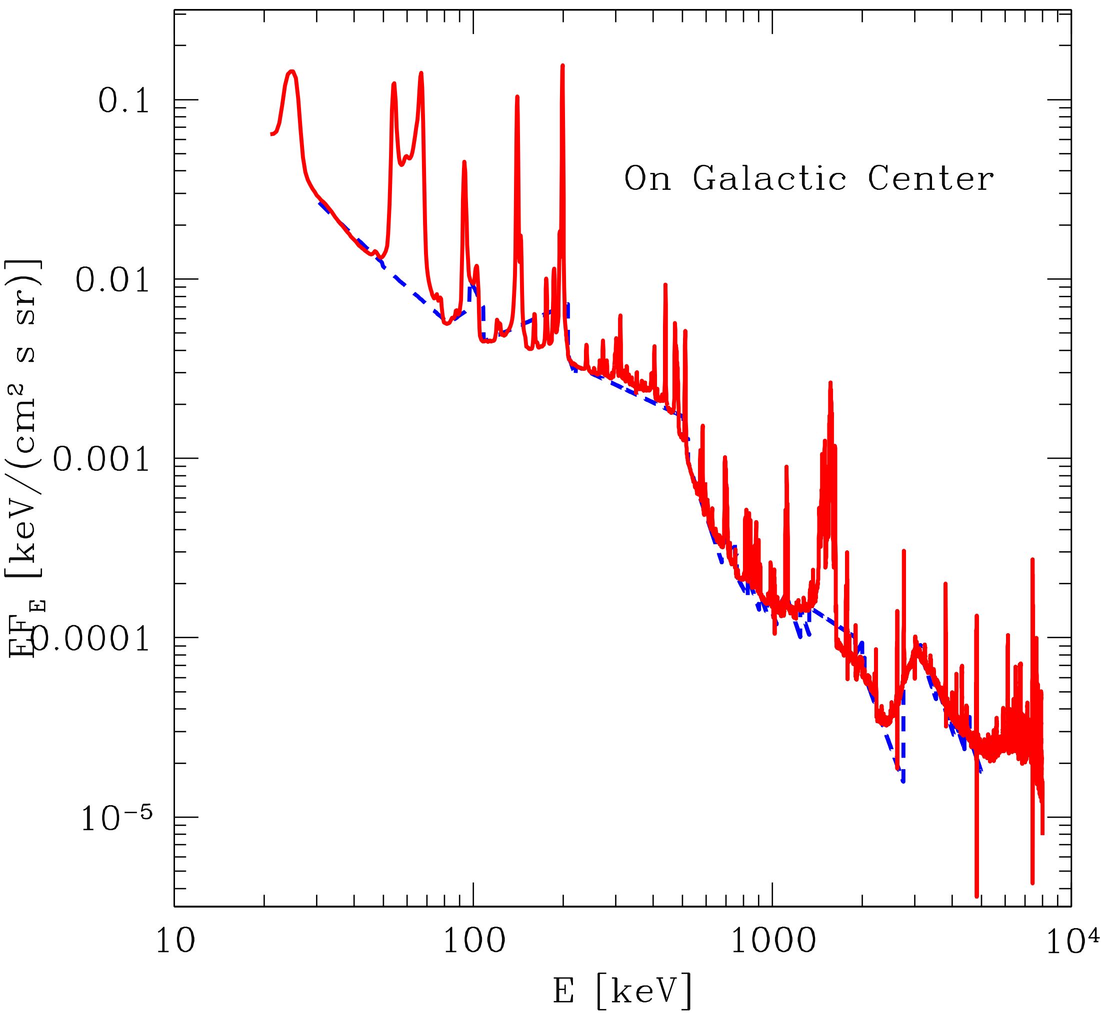
How much DM do we have?



Extreme case



SPI (INTEGRAL) : 20 keV - 8 MeV

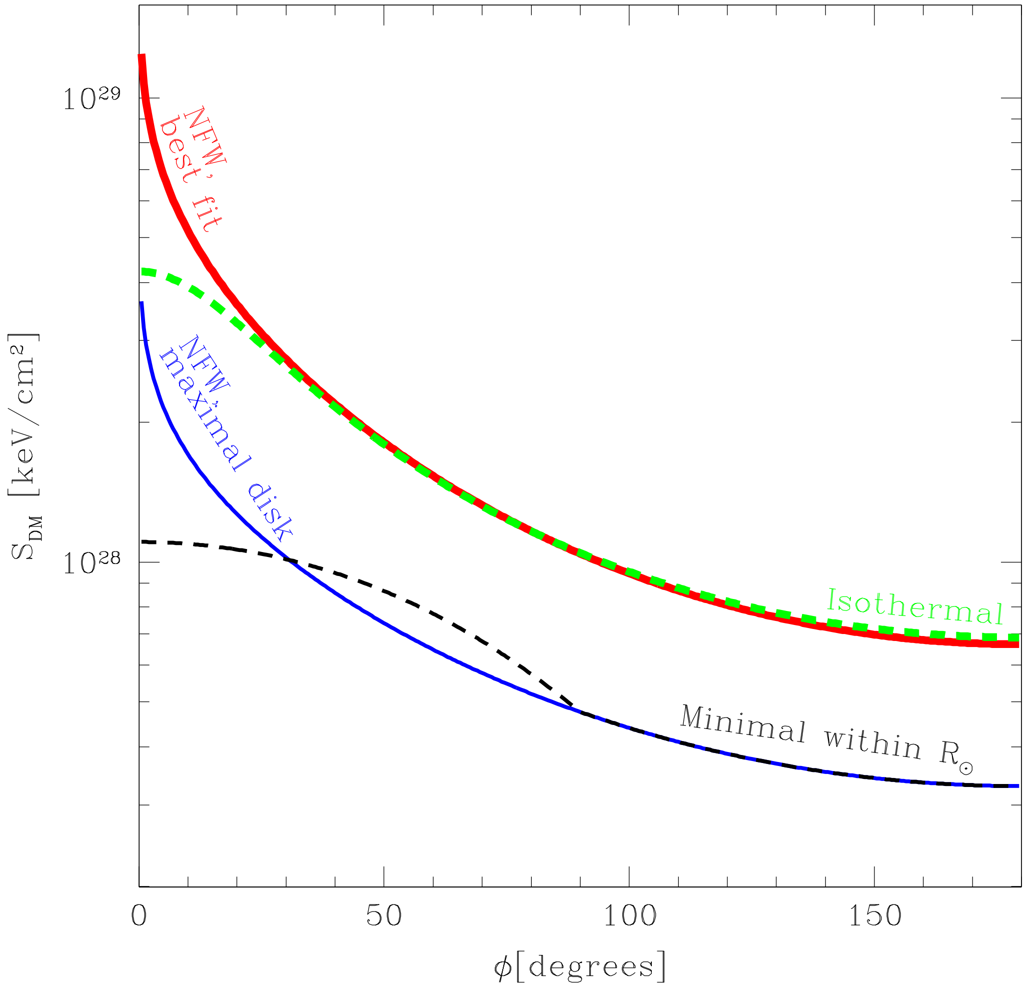


- Required spectral resolution $\Delta E/E \sim 10^{-3}$

Yuksel et al.'07; Boyarsky et al.'07

- Large FoV ($\sim 34°$)
- Nuclear lines: very ubiquitous, less studied than atomic
- Strong instrumental background, *variable in time*
- Not all lines identified
- **Can DM be hiding in this line forest?**

All-sky source



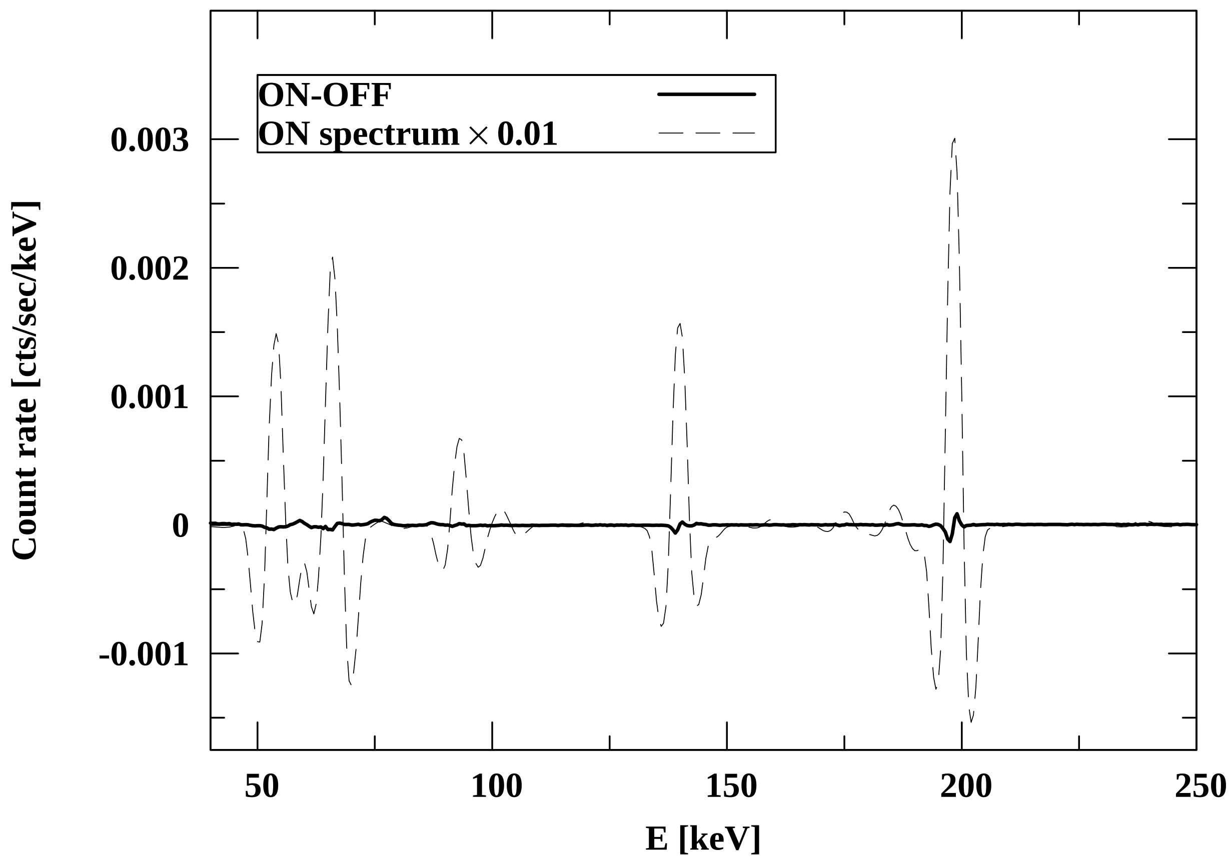
- DM is an all-sky source
- Its variability over the sky can be as low as factor of 3

DM line could be confused with an instrumental line as always present in the spectrum with $\approx$ the same intensity

SPI background subtraction

- Find observation off-GC "close in time"
- Normalize by count rate of 198 keV (strong instrumental line)

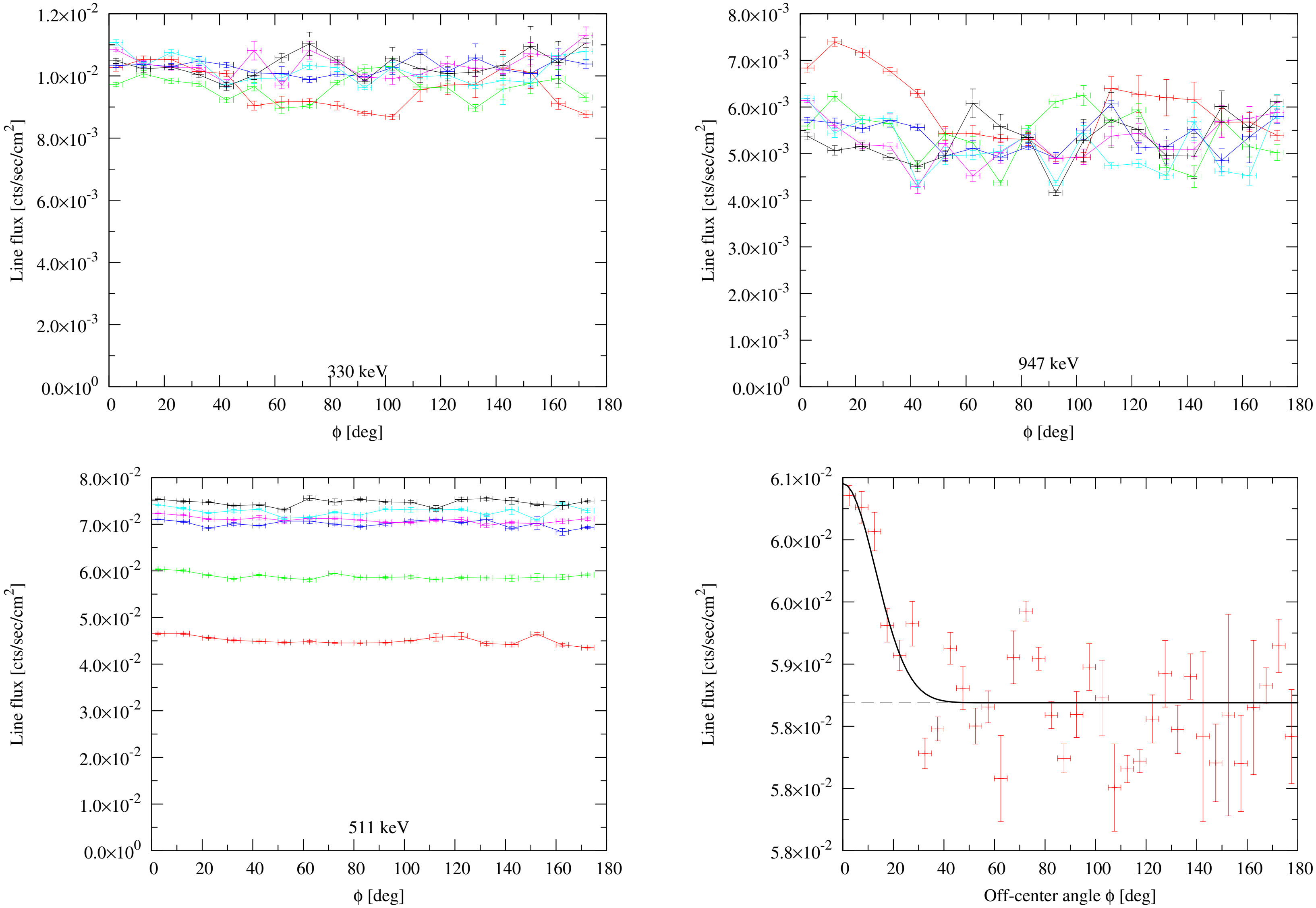
Teegarden
Watanabe
2006



- Hundreds of lines cancel better than 1% by fixing only **one number**
- Line at 511 keV remains
- No other lines above $3-4\sigma$

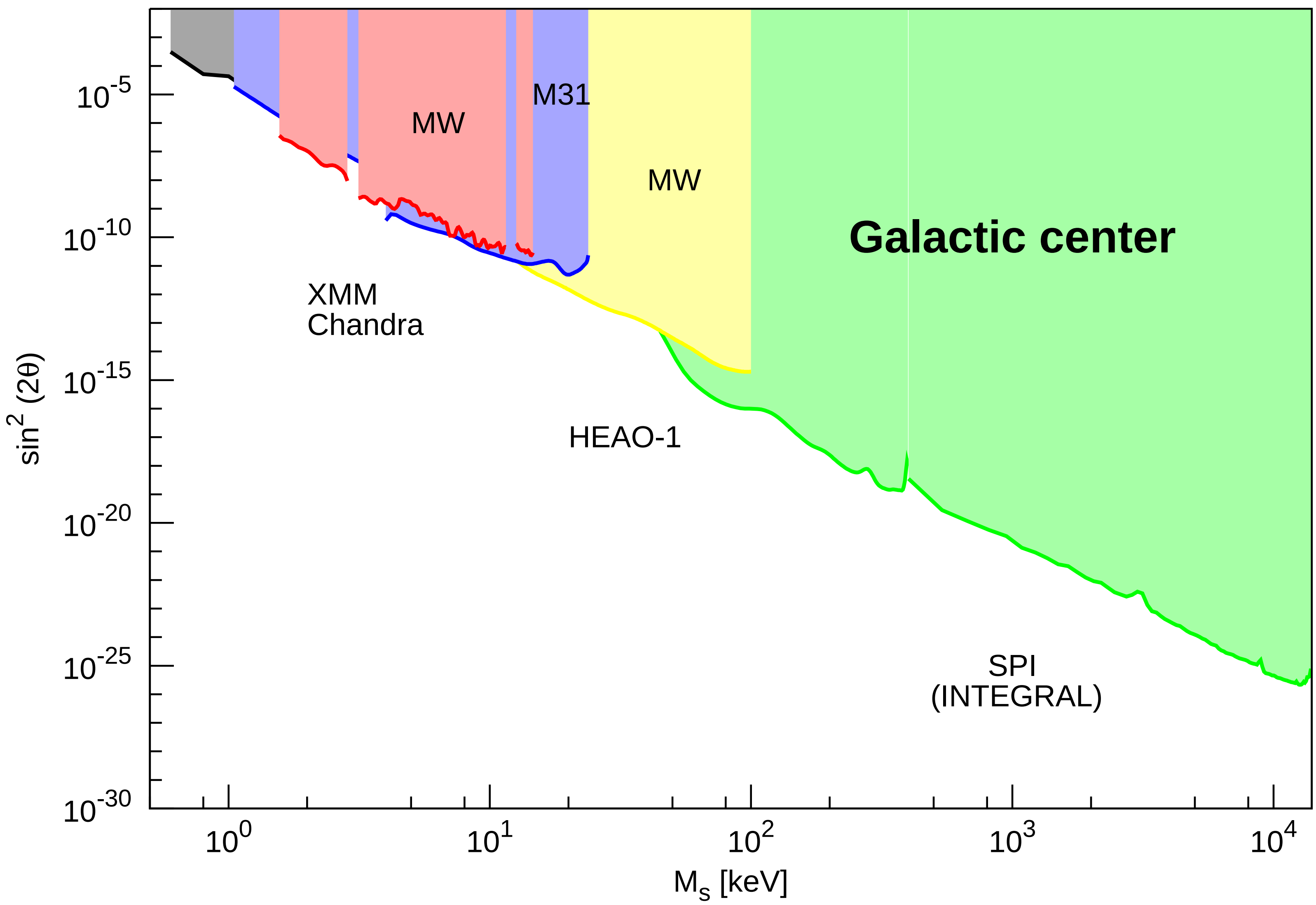
- We can control complicated background of this instrument

SPI: spatial profile of lines

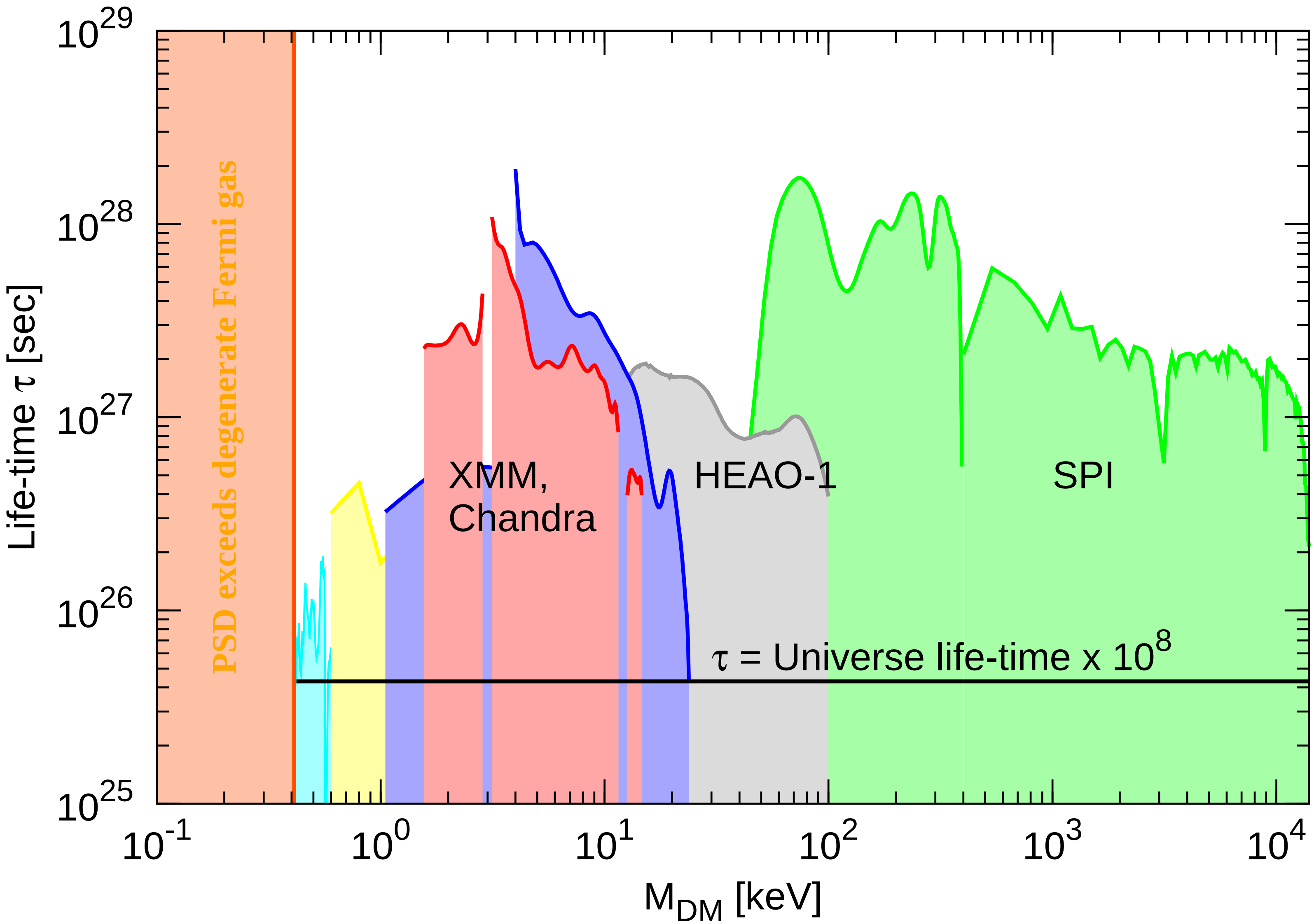


Restrictions on sterile neutrino DM

Boyarsky et al
MNRAS-2008



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

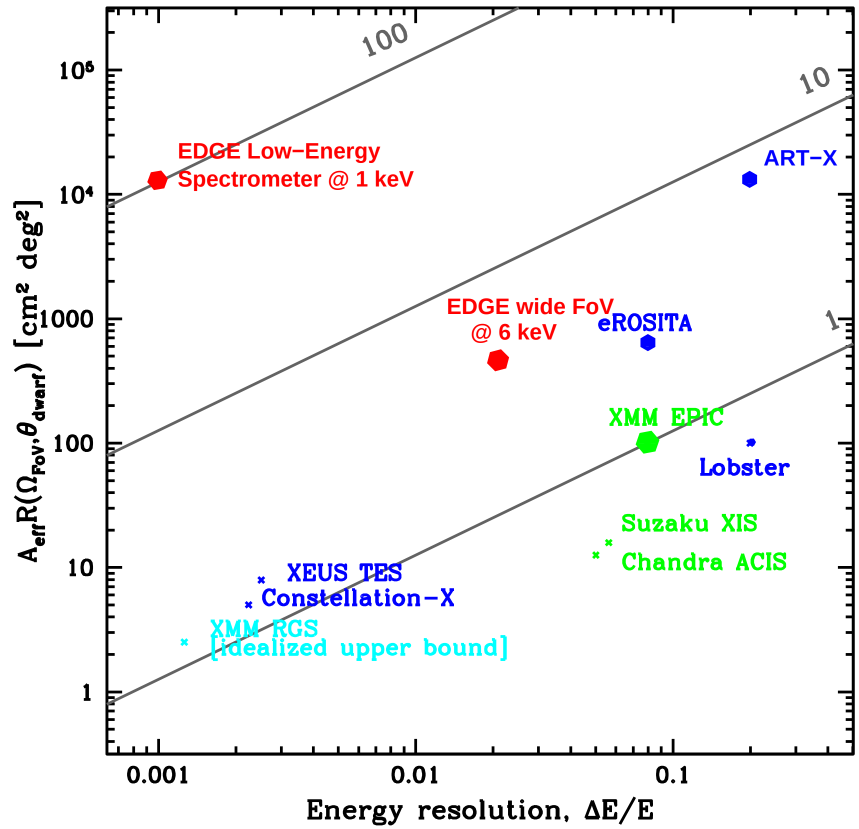
MW (Chandra) Riemer-Sørensen et al.; Abazajian et al.

MW (XMM) Boyarsky et al 2007

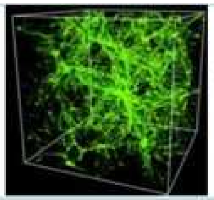
M31 Watson et al. 2006; Boyarsky et al 2007

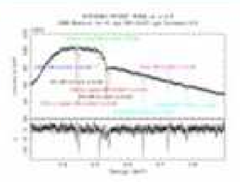
New mission: EDGE/XENIA

- Spectrometers with big FoV and spectral resolution better than 10^{-3} are needed
- Future missions (*XEUS* or *Constellation X*) will have better spectral resolution but very small FoV
- XENIA (former EDGE), proposed for NASA's *Cosmic Origins* by the team from NASA/MSFC, INAF, SRON + ISDC, EPFL,...).



A.Boyarsky, *et al.* (2007)





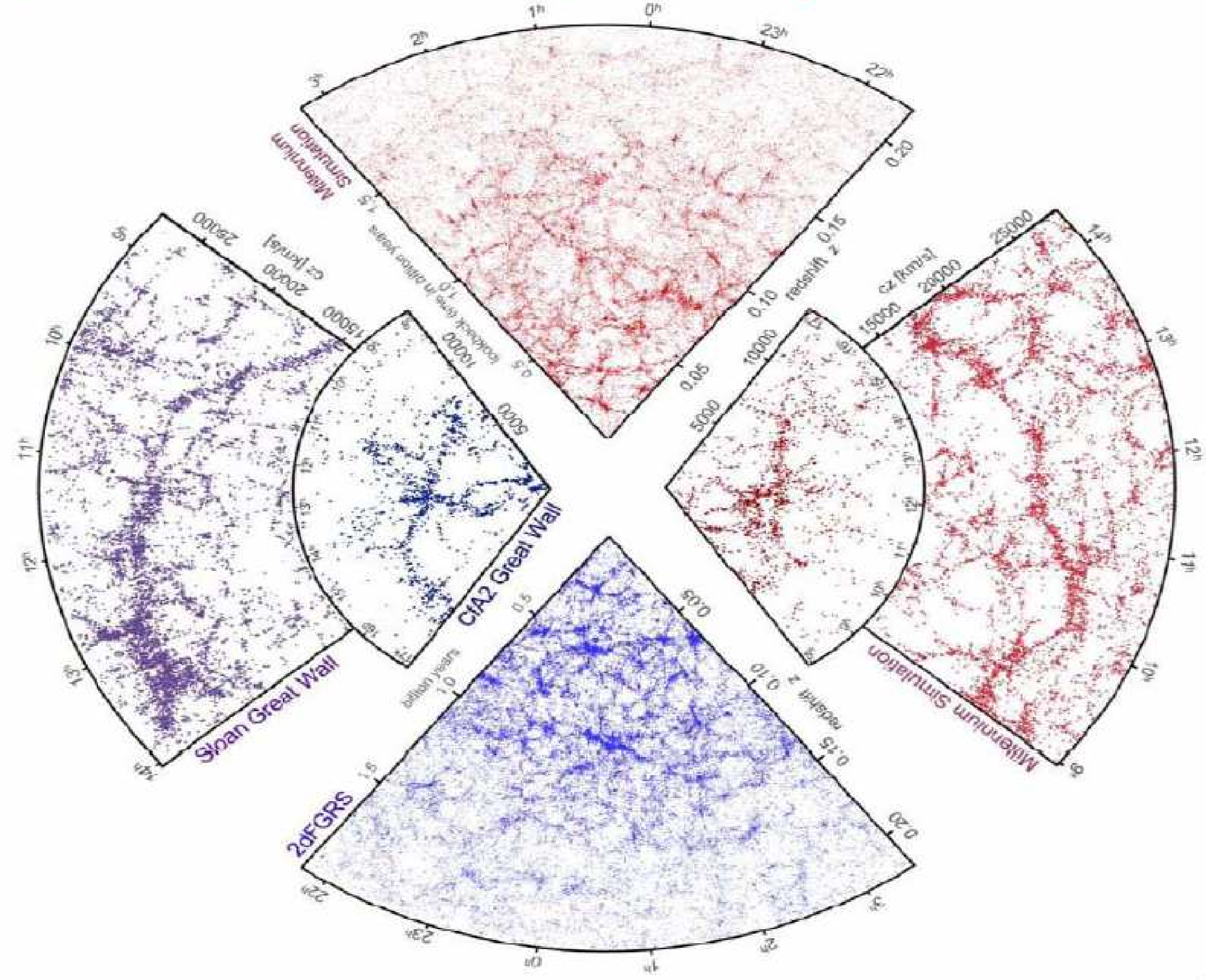
VELOCITIES OF DARK MATTER PARTICLES

Neutrinos

- Data on neutrino oscillations tells that at least one neutrino specimen has mass $m_\nu \gtrsim 0.05$ eV.
- Is neutrino a perfect dark matter candidate (stable, neutral, weakly interacting)?
- No! Neutrinos remain relativistic very late and would homogenize the Universe until baryons start to cluster (after recombination).
- This contradicts to the observed large scale structure and data on CMB anisotropies

LSS: observations vs.simulations

Example : success of CDM to reproduce large scale structures



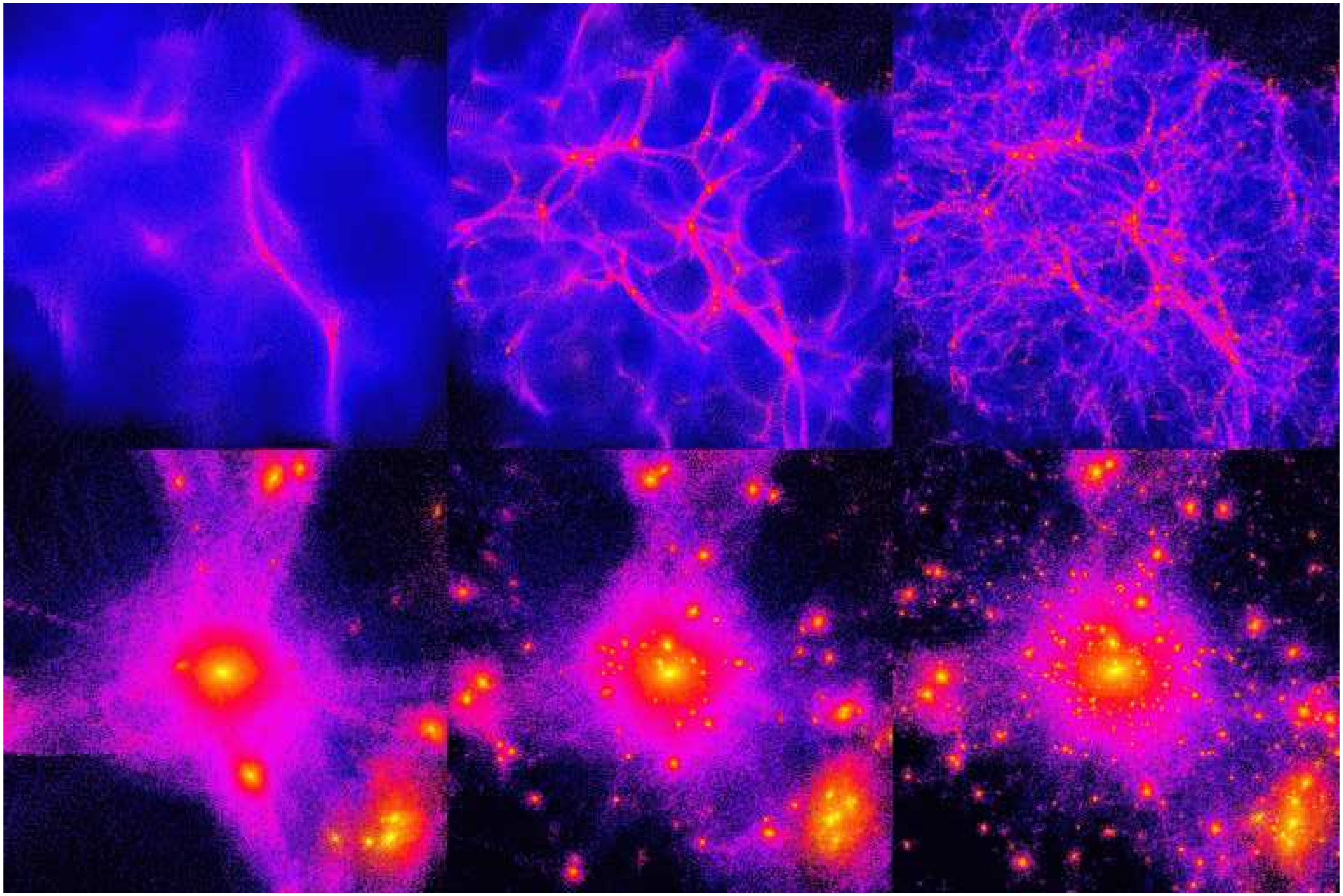
Springel et al. 2006

LSS in neutrino Universe

Moore'05

Neutrino DM

"Cold" heavy DM



DM velocities

- However there is a huge gap between neutrinos and particles, that decouple non-relativistic, like for example weakly interacting massive particles (WIMPs), in particular, DM candidates motivated by SUSY.

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

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

- Comoving free-streaming lengths peaks around $\boldsymbol{t_{nr}}$ when $\boldsymbol{\langle p\rangle \sim m}$

- All DM models are thus divided into 3 groups:
  - **CDM** : free streaming is negligible
  - **WDM** : free streaming at galaxy scales, $t_{nr} \ll t_{eq}$
  - **HDM** : free streaming at cosmological scales $t_{nr} \gg t_{eq}$

Power spectrum of density fluctuations

Field of density fluctuations

$$\delta(x) = \frac{\delta\rho(x)}{\bar{\rho}}$$

Fourier transform

$$\delta_k = \int d^3x\, e^{-ik\cdot x}\,\delta(x)$$

Power spectrum essentially square of Fourier transformation

$$\langle \delta_k \delta_{k'} \rangle = (2\pi)^3 \hat{\delta}(k - k')\, P(k)$$

with $\hat{\delta}$ the δ-function

Power spectrum is Fourier transform of two-point correlation function ($x = x_2 - x_1$)

$$\xi(x) = \langle \delta(x_2)\delta(x_1) \rangle = \int \frac{d^3k}{(2\pi)^3}\, e^{ik\cdot x}\, P(k)$$

$$= \int \frac{d\Omega}{4\pi} \frac{dk}{k}\, e^{ik\cdot x} \underbrace{\frac{k^3 P(k)}{2\pi^2}}_{\Delta^2(k)}$$

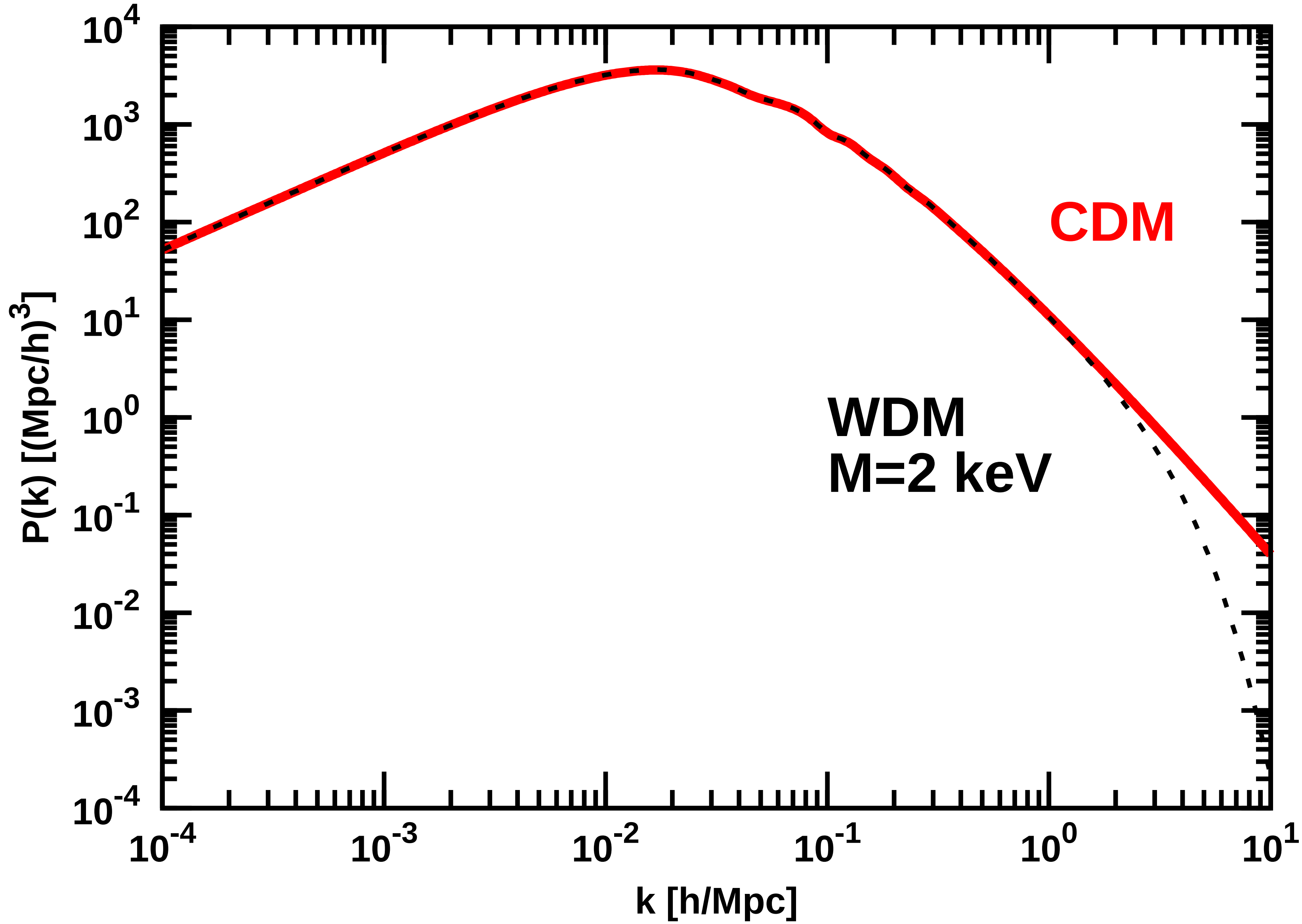
Gaussian random field (phases of Fourier modes δ_k uncorrelated) is fully characterized by the power spectrum

$$P(k) = |\delta_k|^2$$

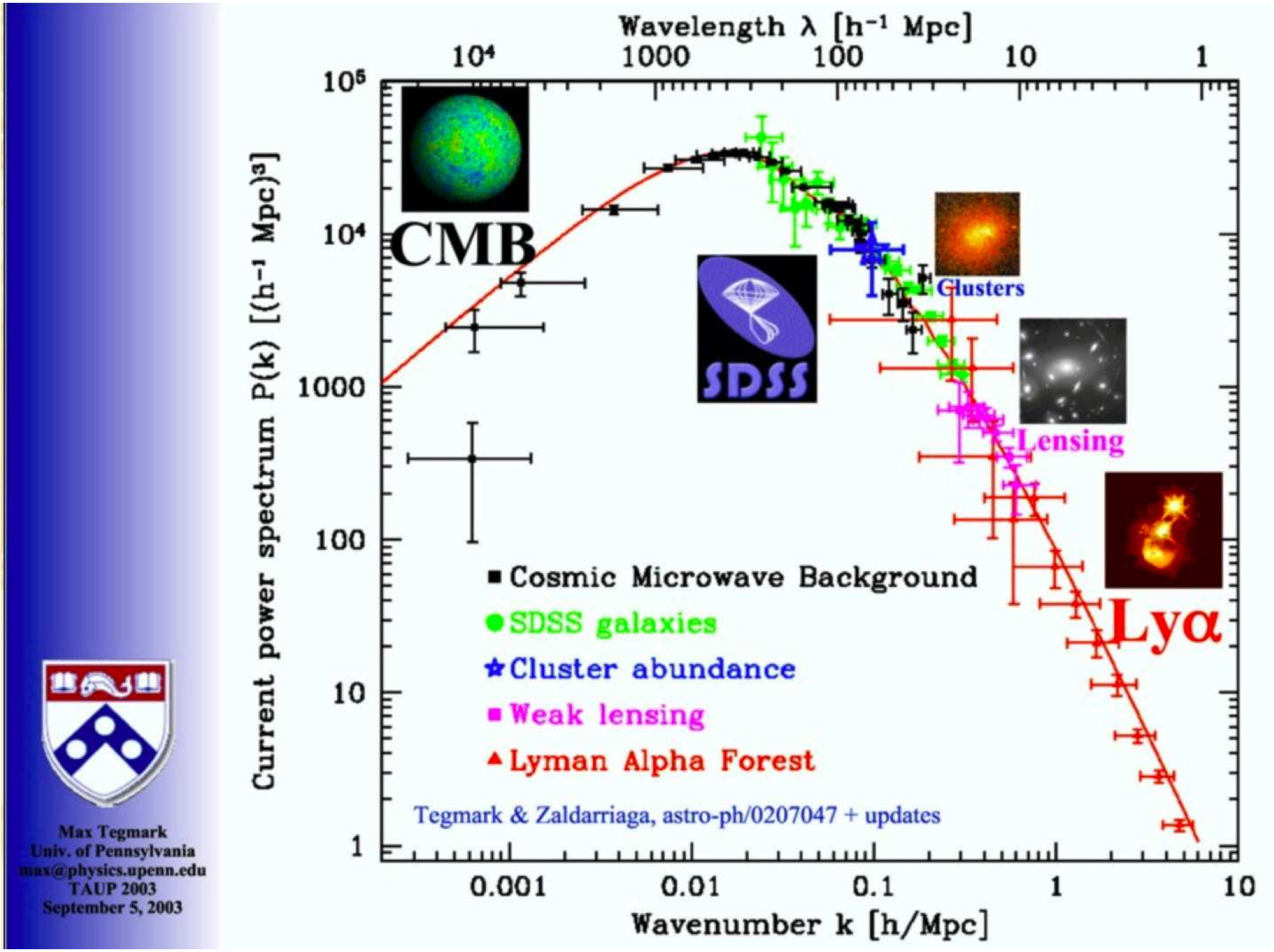
or equivalently by

$$\Delta(k) = \left(\frac{k^3 P(k)}{2\pi^2} \right)^{1/2} = \frac{k^{3/2}|\delta_k|}{\sqrt{2\pi}}$$

(Linear) powerspectra



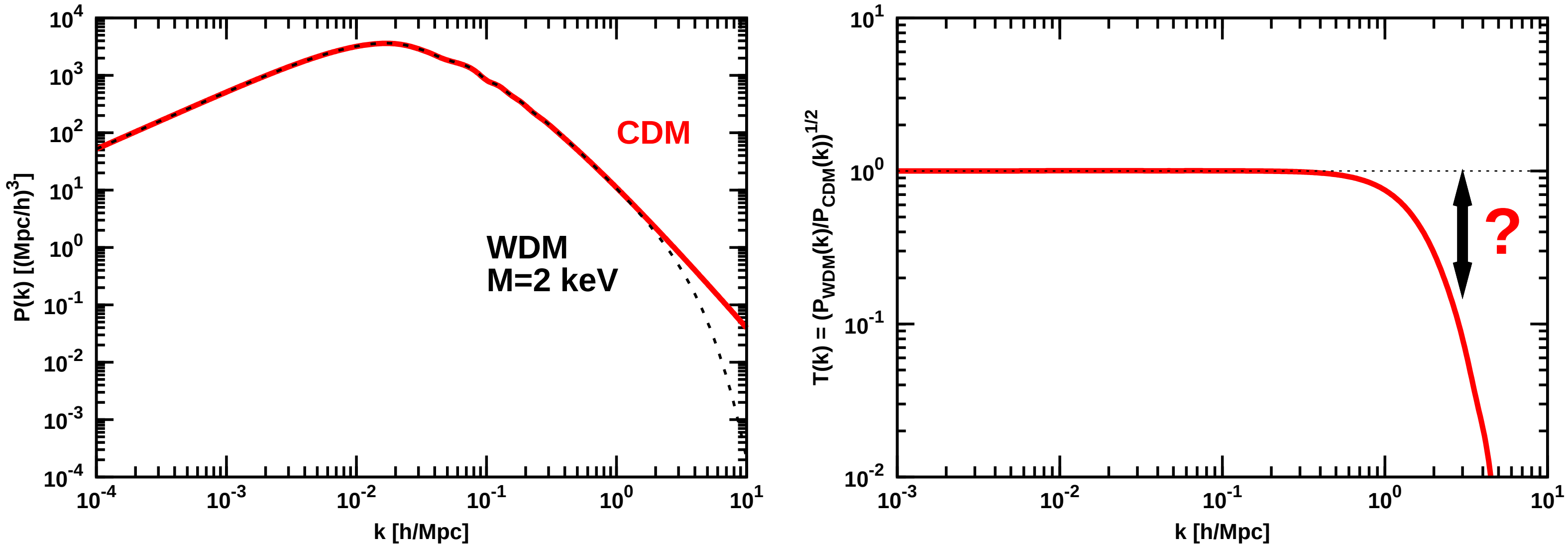
Power spectrum of density fluctuations



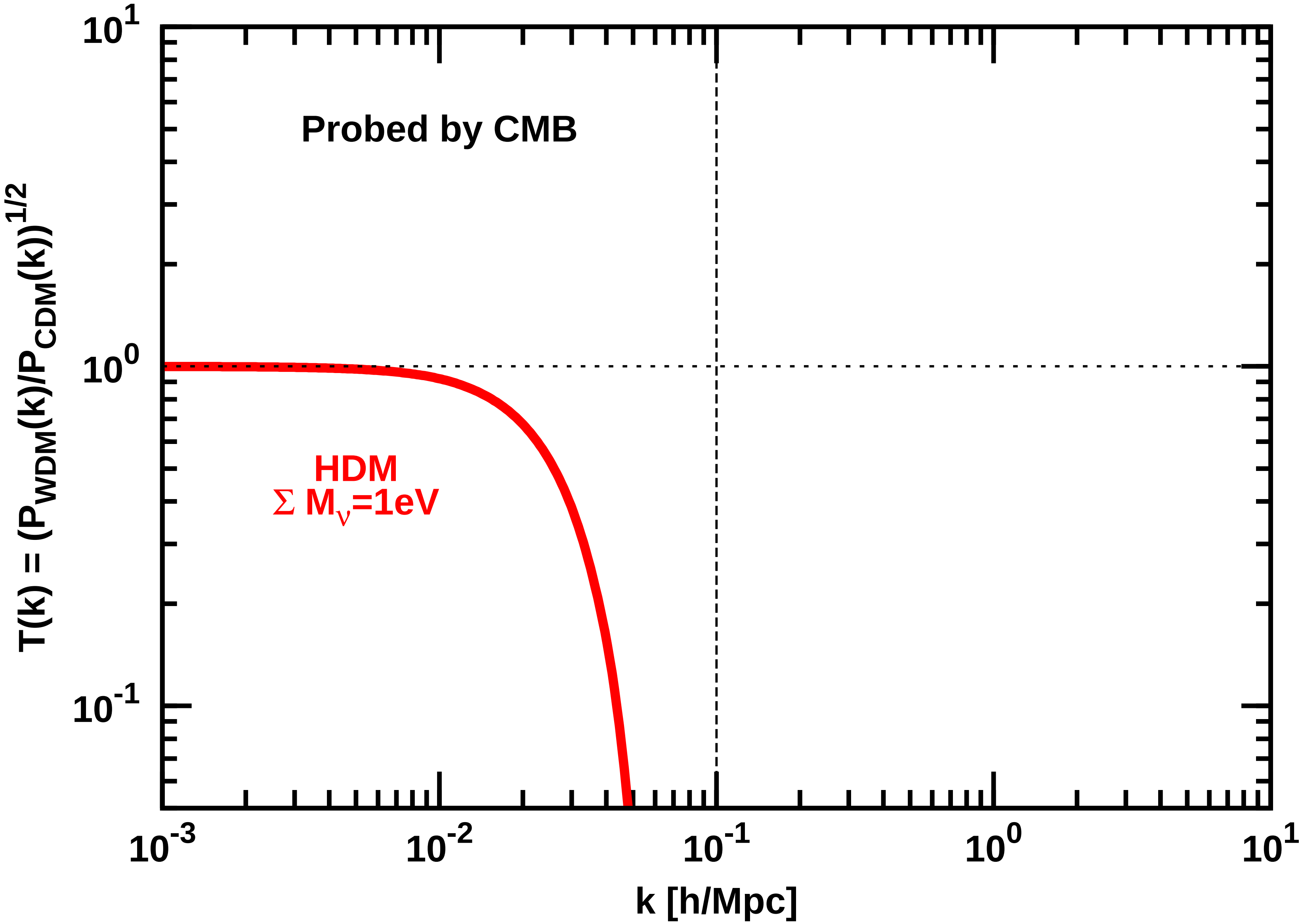
Transfer function

To separate in the powerspectra the influence of primordial velocities from that of other cosmological parameters introduce **transfer function:** $\mathbf{T(k)}$

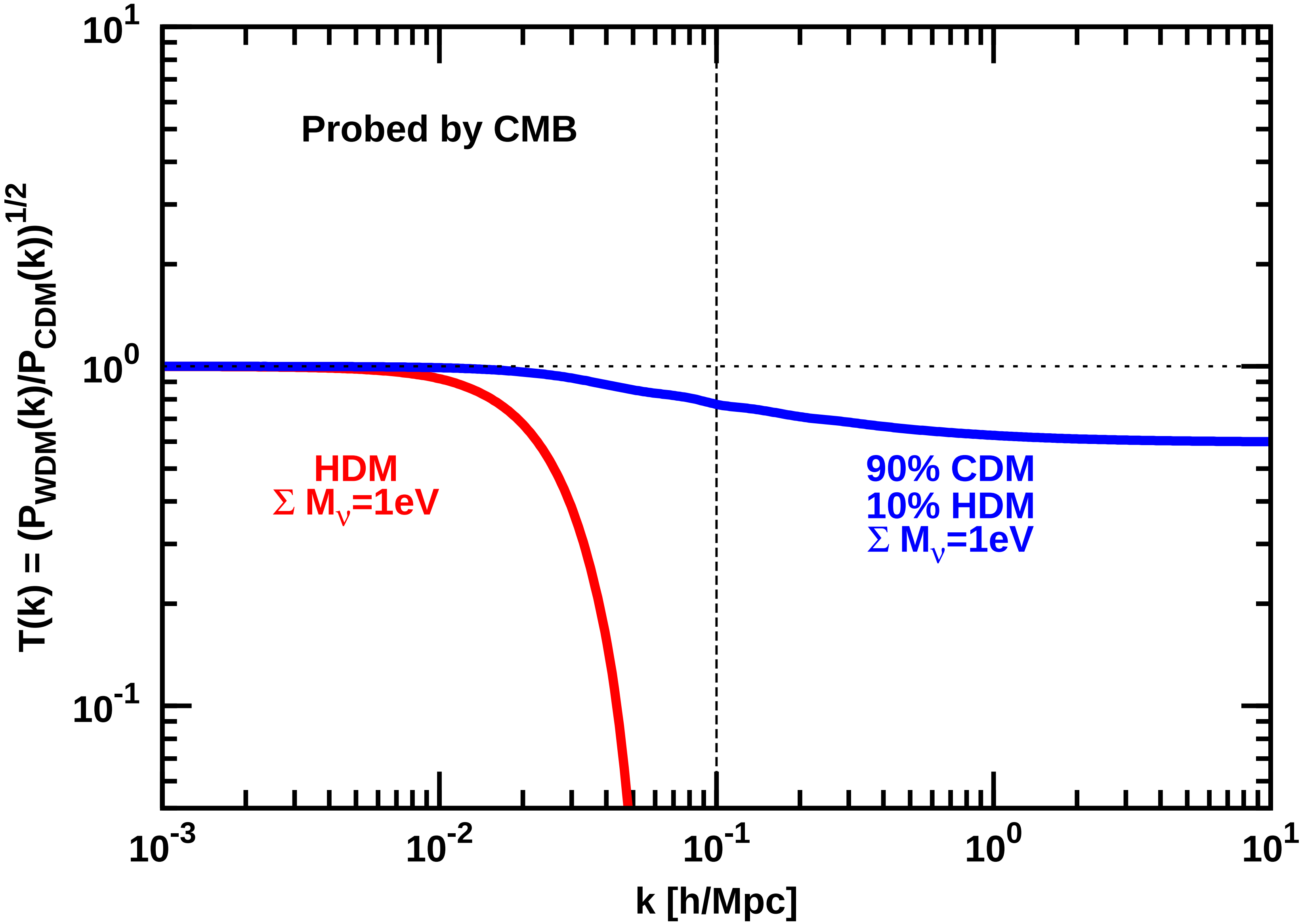
$$T(k) = \sqrt{\frac{P_{WDM}(k)}{P_{CDM}(k)}} \leq 1$$



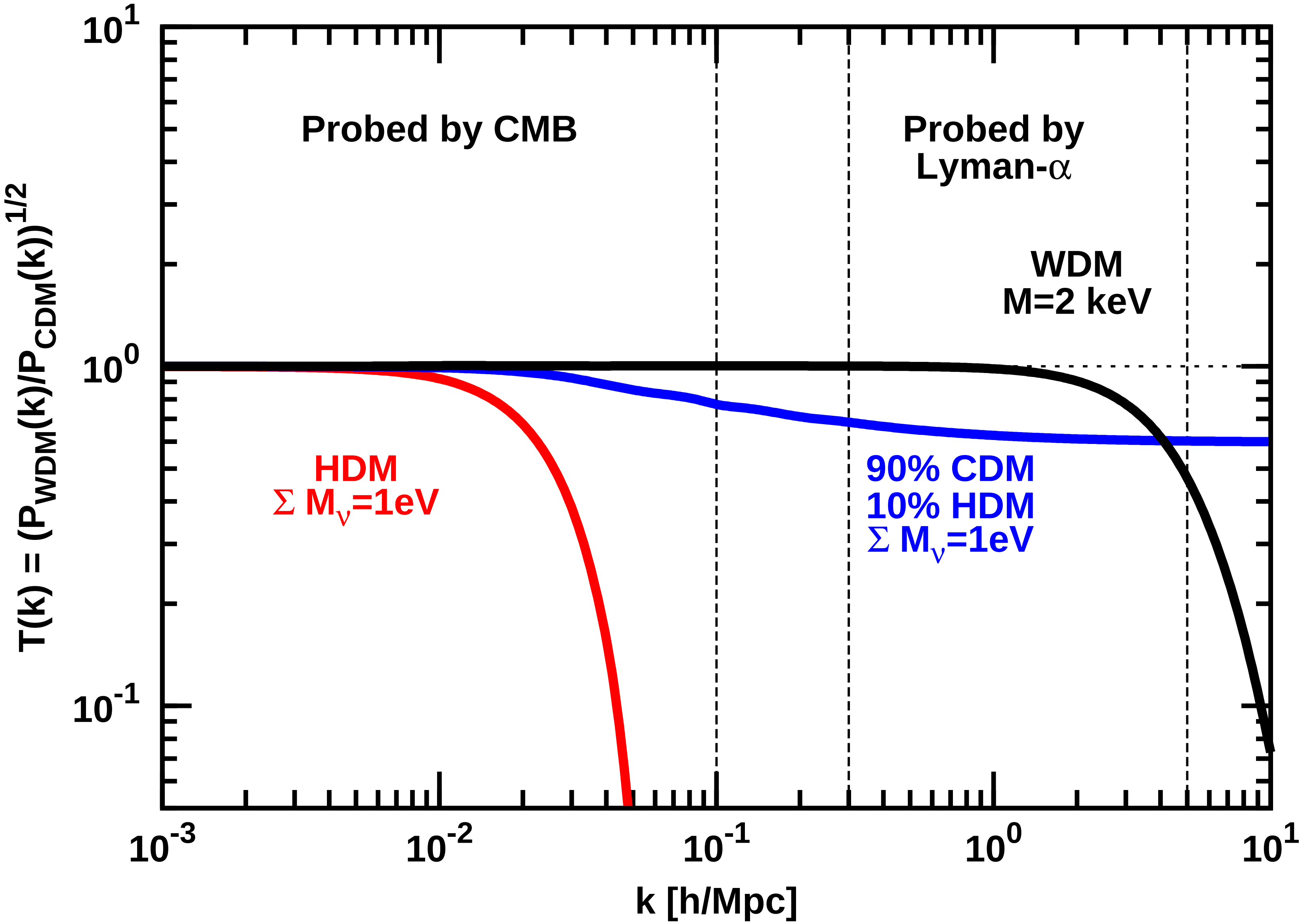
Transfer function



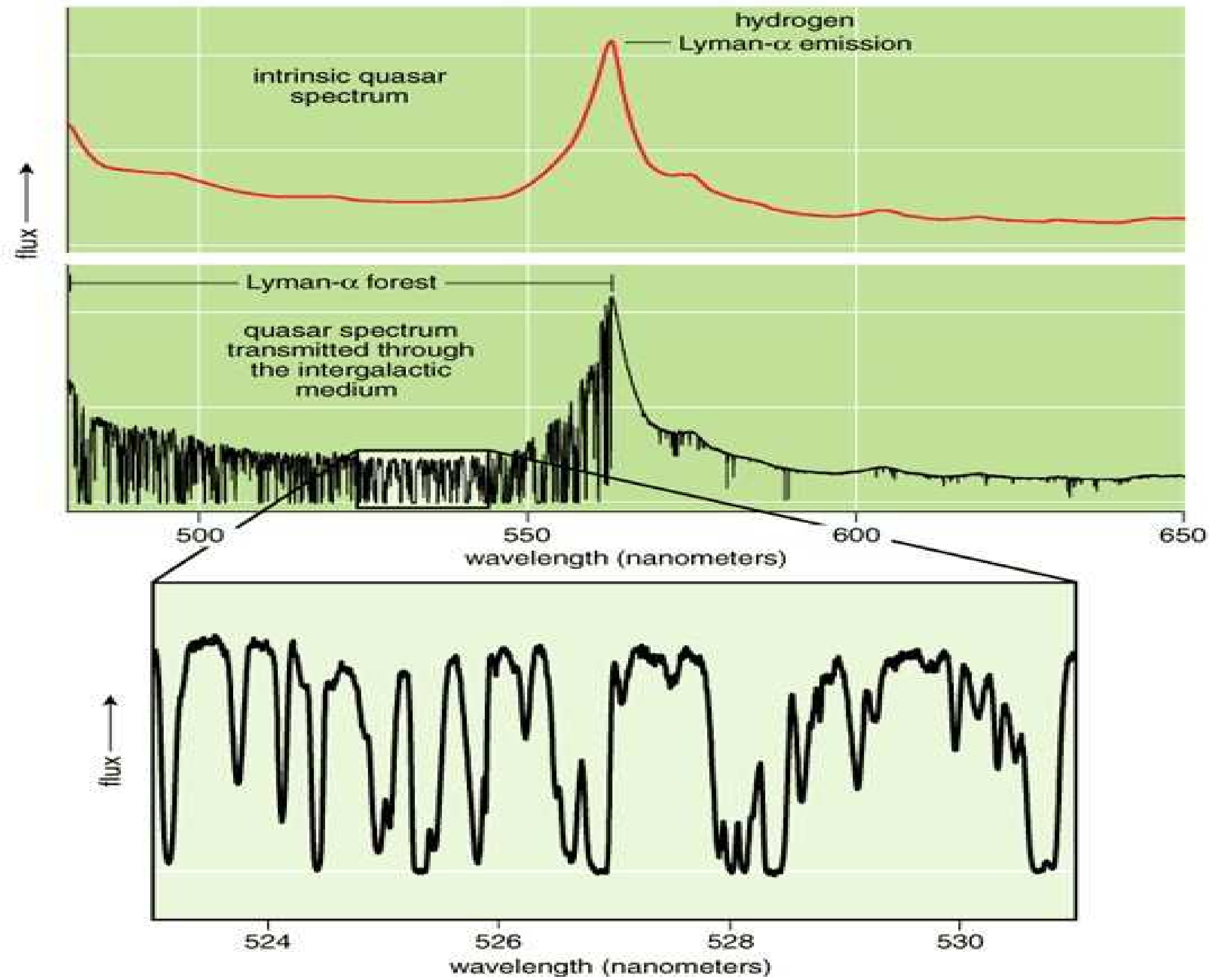
Transfer function



Transfer function



What is Lyman-α forest?



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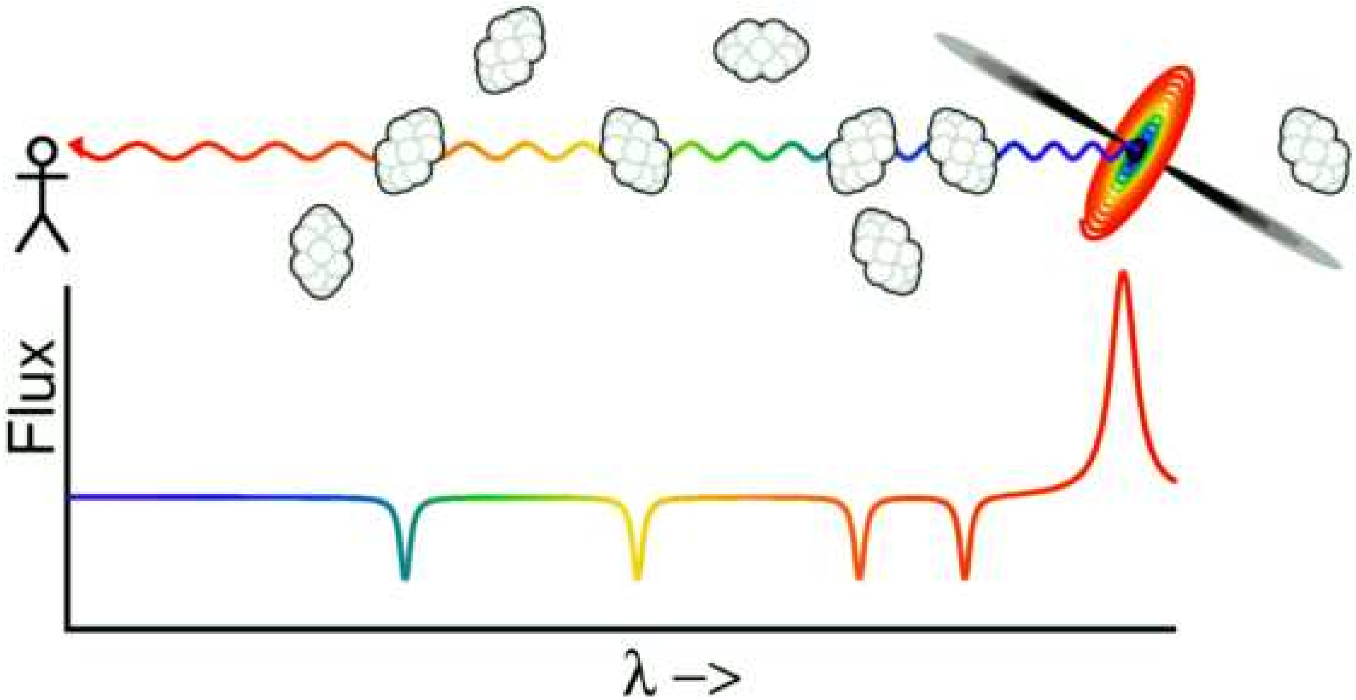
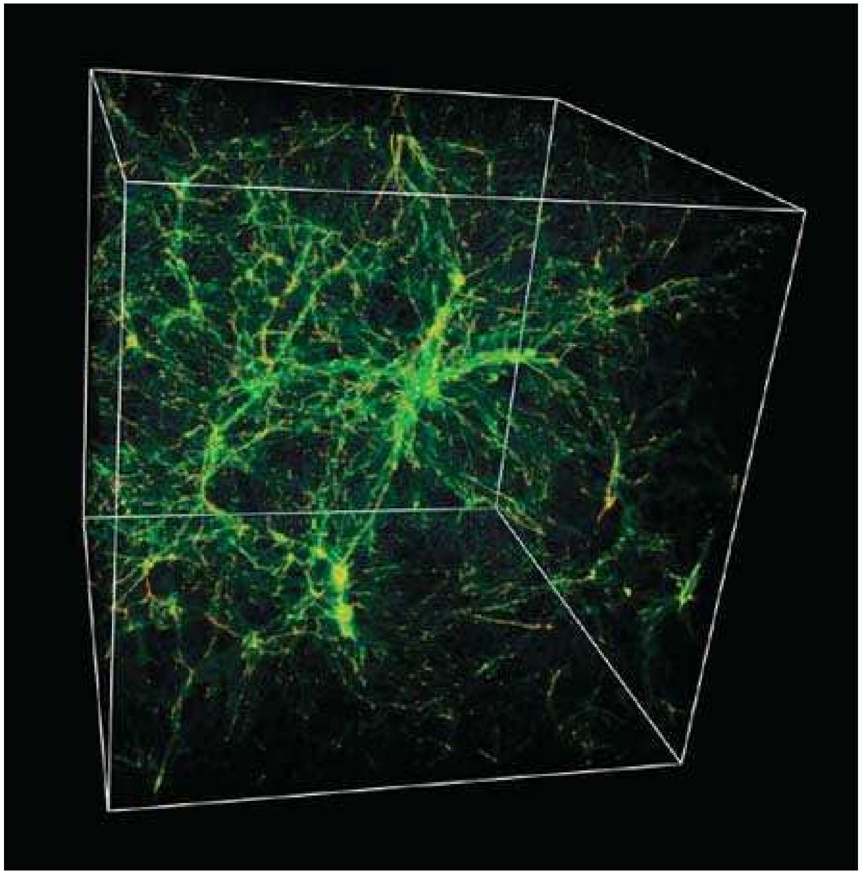


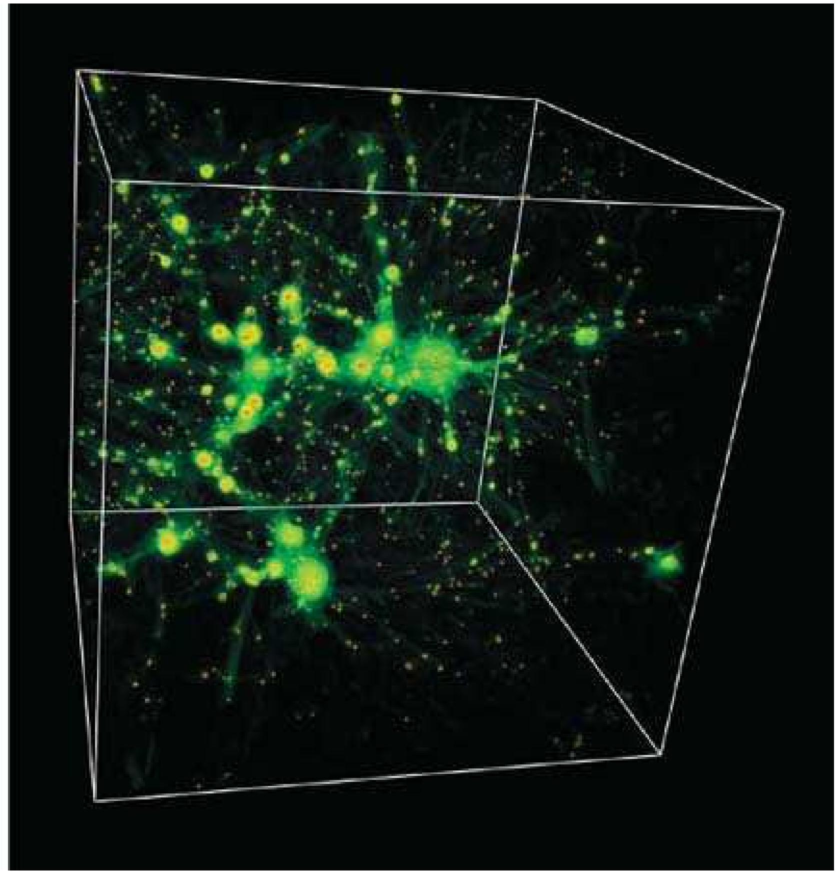
- Neutral hydrogen absorption line at $\lambda = 1215.67\text{Å}$ (Ly-α absorption $1s \to 2p$)
- Absorption occurs at $\lambda = 1215.67\text{Å}$ in the **local reference frame** of hydrogen cloud.
- From the Earth observer point of view we see the forest:

$$\lambda = (1+z)1215.67\text{Å}$$

Cosmic web

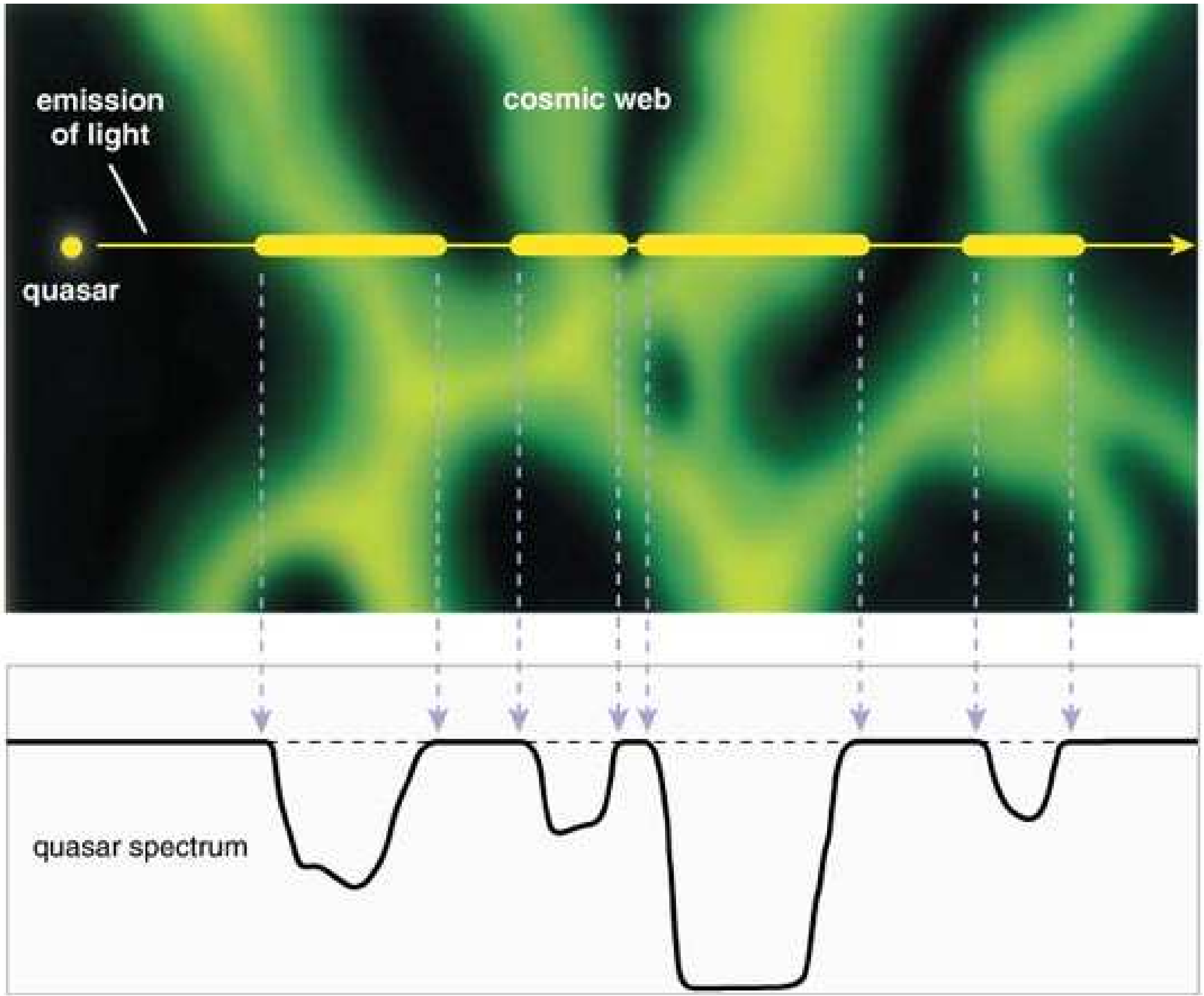


$\tau \approx 2 \times 10^6$ years

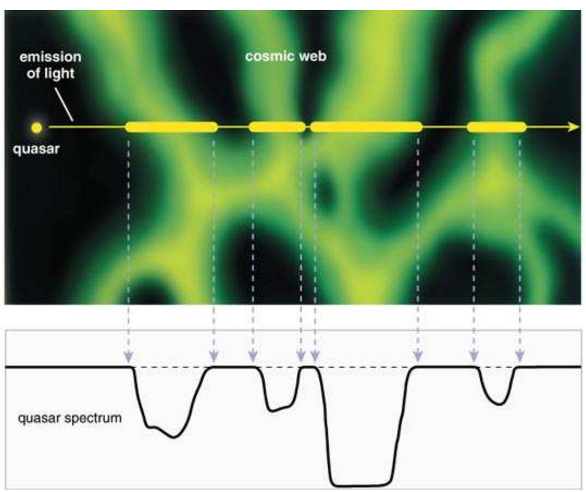


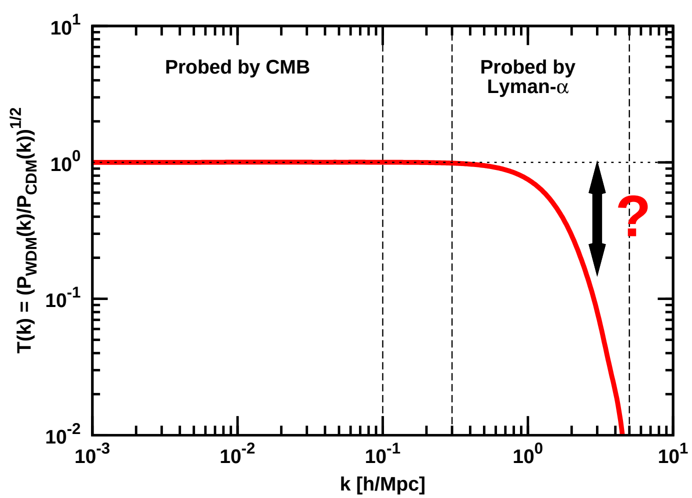
$\tau \approx 13 \times 10^6$ years

Lyman-α forest and cosmic web



- The neutral hydrogen is a part of the warm ($\sim 10^4$ K) and photoionized intergalactic medium (IGM).
- Opacity fluctuations in the spectra arise from fluctuations in the neutral hydrogen density
- From this it is possible to infer fluctuations in the total matter distribution





The Lyman-α method includes

- Astronomical data analysis of quasar spectra
- Astrophysical modeling of hydrogen clouds
- N-body simulations of DM clustering at non-linear stage
- Solving numerically Boltzmann equations for SM in the early Universe
- Finding global fit to the whole set of cosmological data (CMB, LSS, Ly-α), using Monte-Carlo Markov chains

Main challenge: reliable estimate of systematic uncertainties

Flux power spectrum

- For each quasar, the observed spectrum $I(z)$ can be expanded in (one-dimensional) Fourier space.

- The expectation value of the squared Fourier spectrum is called the **flux power spectrum** $P_F(k,z)$

- The Lyman-α data provides an estimate of the flux power spectrum $\boldsymbol{P_F(k,z)}$ at scales $\boldsymbol{k \sim (0.3-5)\, h}$ **Mpc**$^{-1}$ for redshifts $\boldsymbol{z \sim 2-4}$ (for these redshifts light rays of wavelength $\lambda_{obs} = (1+z)1265\text{Å}$ pass through the optical window of the Earth's atmosphere)

- At these redshifts, the density perturbations of such scales already entered into a mildly non-linear stage of gravitational collapse ($\delta\rho/\rho \gtrsim 1$).

Lyman-α forest : methodology

- Simulate (a part of) the Universe (including baryons, star feedback, etc.) and compute in it the statistics of the absorption lines $\to$ simulated $P_F(k,z)$

- Compare the simulated results with the observed.

- In the Lyman-α range the effects of an admixture of WDM might be compensated by a change in other cosmological parameters (σ_8, $\Omega_M h^2$, n_s, etc.) or even astrophysical parameters $\Rightarrow$ perform collective fits to the Lyman-α data and other data sets (e.g. CMB).

- Find the combinations of cosmological parameters ($\Omega_b, \Omega_M, n_s, h, \ldots$) that fit the data

Lyman-α forest : challenges

- Each hydrodynamical simulation (evolution and clustering of DM$+$ baryons in the expanding part of the Universe, ionization feedback from stars, etc. from $z \sim 100$ down to $z \sim 2$) takes about 36 hours with the 142 CPUs of modern supercomputer (optimistic)
- Need to fit **simultaneously** 7+ cosmological parameters
- Astrophysical parameters, describing IGM, are not known and should be fitted as well (another $20+$ parameters)
- The data: Lyman-$\alpha$$+$ CMB $+$ maybe LSS ... (thousands of data points, sometimes correlated)
- To try only **2** values for each parameters one has to explore $\mathbf{10^{11}}$ models. To perform 10^{11} simulations one need $\sim 5 \times 10^8$ years

"HONEST" PROCESSING OF LYMAN-α DATA IS COMPUTATIONALLY PROHIBITIVE

Cosmology with Lyman-α

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

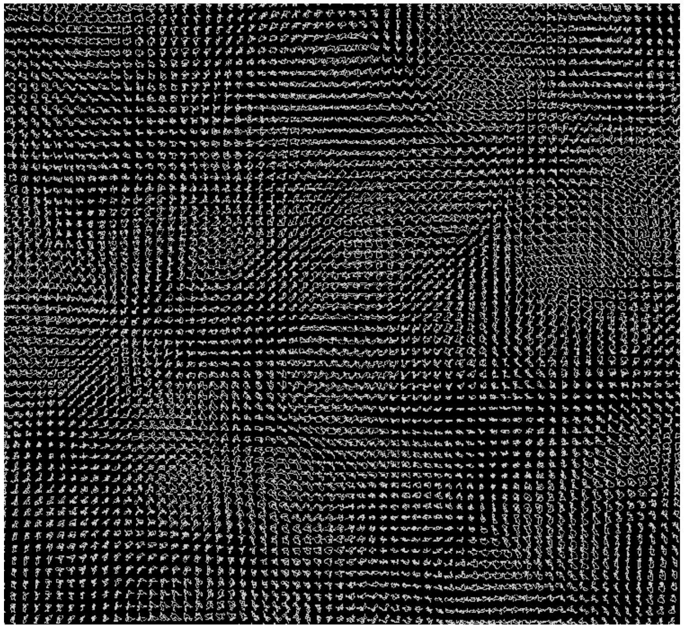
- In some cases one can reconstruct $P_{3D}(k)$ from measured $P_F(k)$.
  Reason: within error bars of measurements all the non-linear evolution is encoded into a **bias function**: $P_F(k) = b^2(k) P_{3D}(k)$

  Viel, Haehnelt Springel 2004

- Very poor constraints, comparable with those from PSD

Initial conditions of numerical simulations

- To perform the numerical simulations one starts by setting **Initial Conditions** (ICs)
- Usually done in **Zel'dovich approximation**:
  - Random displacement of DM particles off the (uniform) grid according to the (linear) matter power spectrum, computed at $z_{ini} \sim 10 - 100$.
  - **Zel'dovich** velocities are functions of position
  - Typical Zel'dovich velocity $v_Z \sim 20$ km/sec



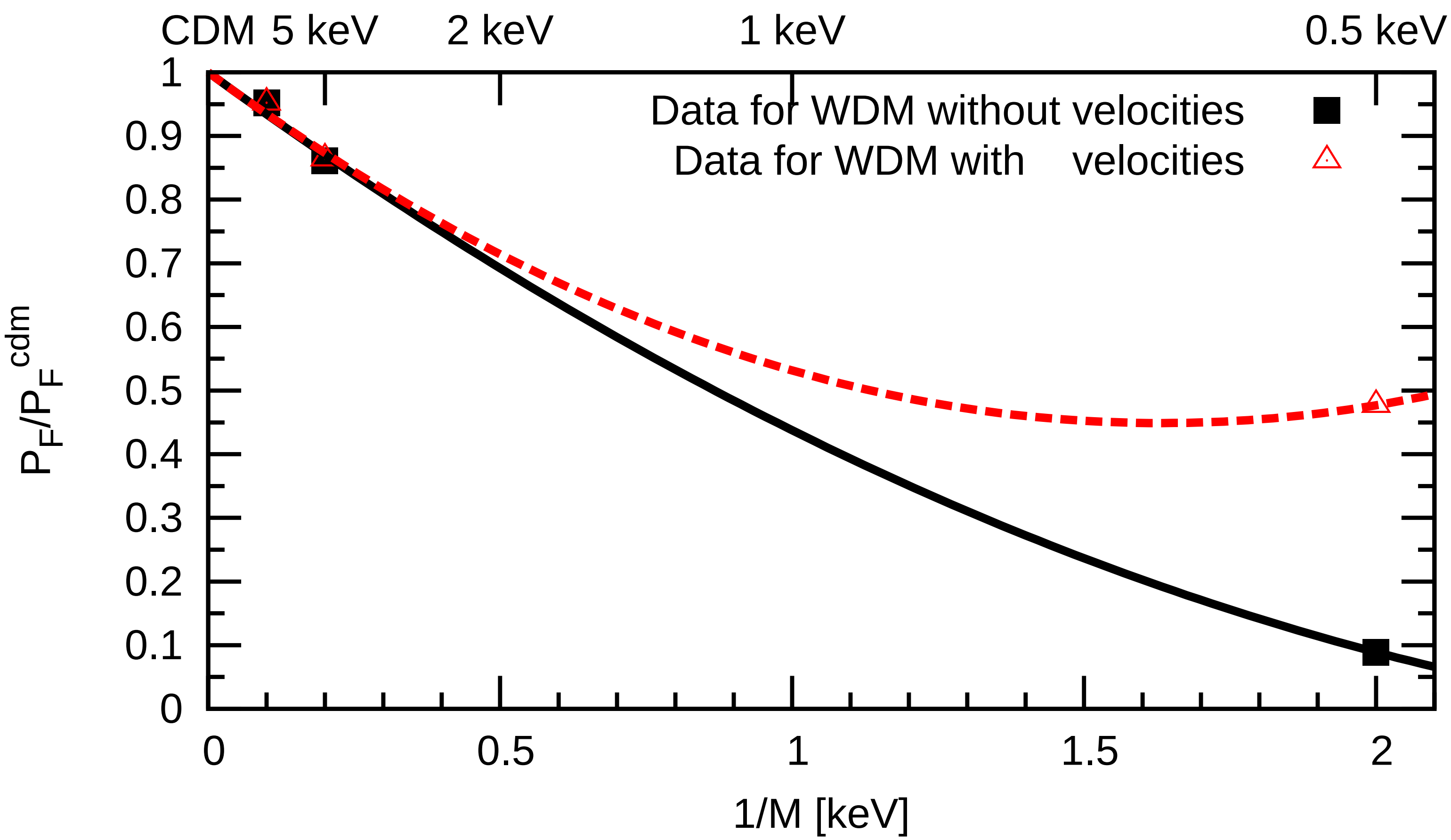
ICs for WDM simulations

- Simplest non-CDM model – **pure WDM**. Primordial velocity distribution is a relativistic Fermi-Dirac
- TF of pure WDM contains a power-law cut-off in the linear matter power spectrum

$$T(k) = \left(1 + \frac{k^{2\nu}}{k_{\text{FSH}}^{2\nu}}\right)^{-5/\nu} \propto k^{-10} \quad \text{for} \quad k \gg k_{\text{FSH}}$$

- Position of the cut-off is determine by the free-streaming or DM mass
- WDM particles have primordial velocities. For masses ~ 1 keV $v_{\text{DM}} \sim v_Z$
- Difficult to take primordial velocities into account in the N-body simulations. Usually this is not taken into account

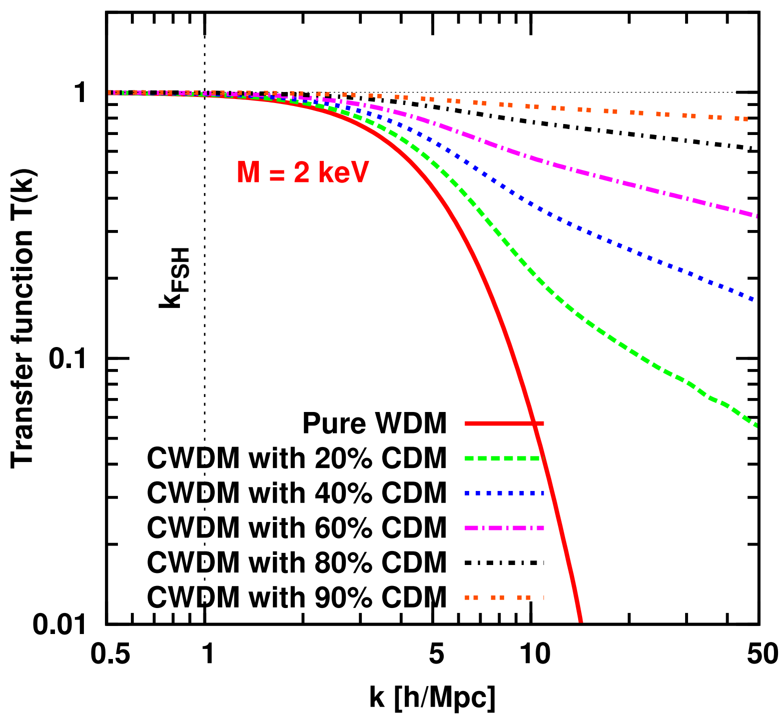
Influence of WDM velocities



Difference can be quite large for small (~ 0.5 keV) masses

Cold+warm DM model (CWDM)

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



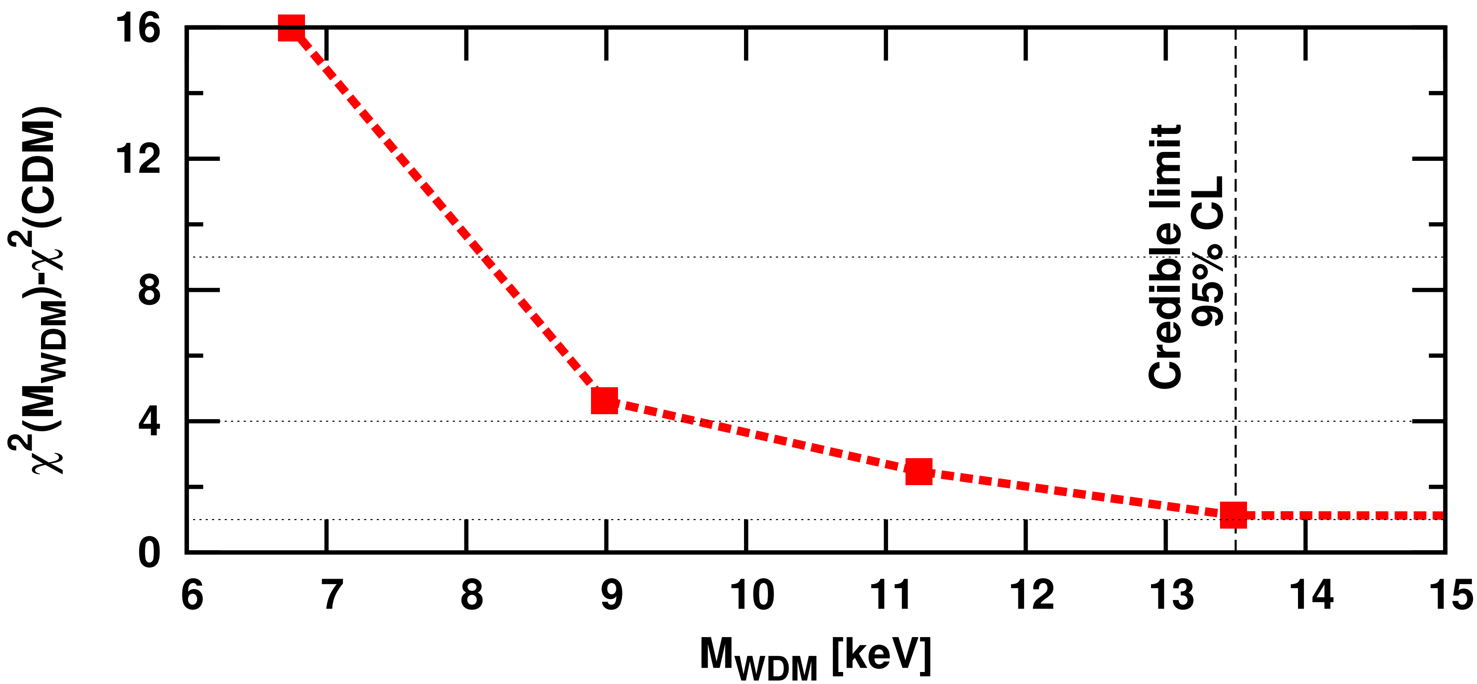
- k_{FSH} depends on mass, does not depend on WDM fraction
- $T(k)$ falls slower if more CDM
- For small WDM fraction $T(k)$ cannot be distinguished from CDM within the precision of the data

Bayesian approach to WDM bounds

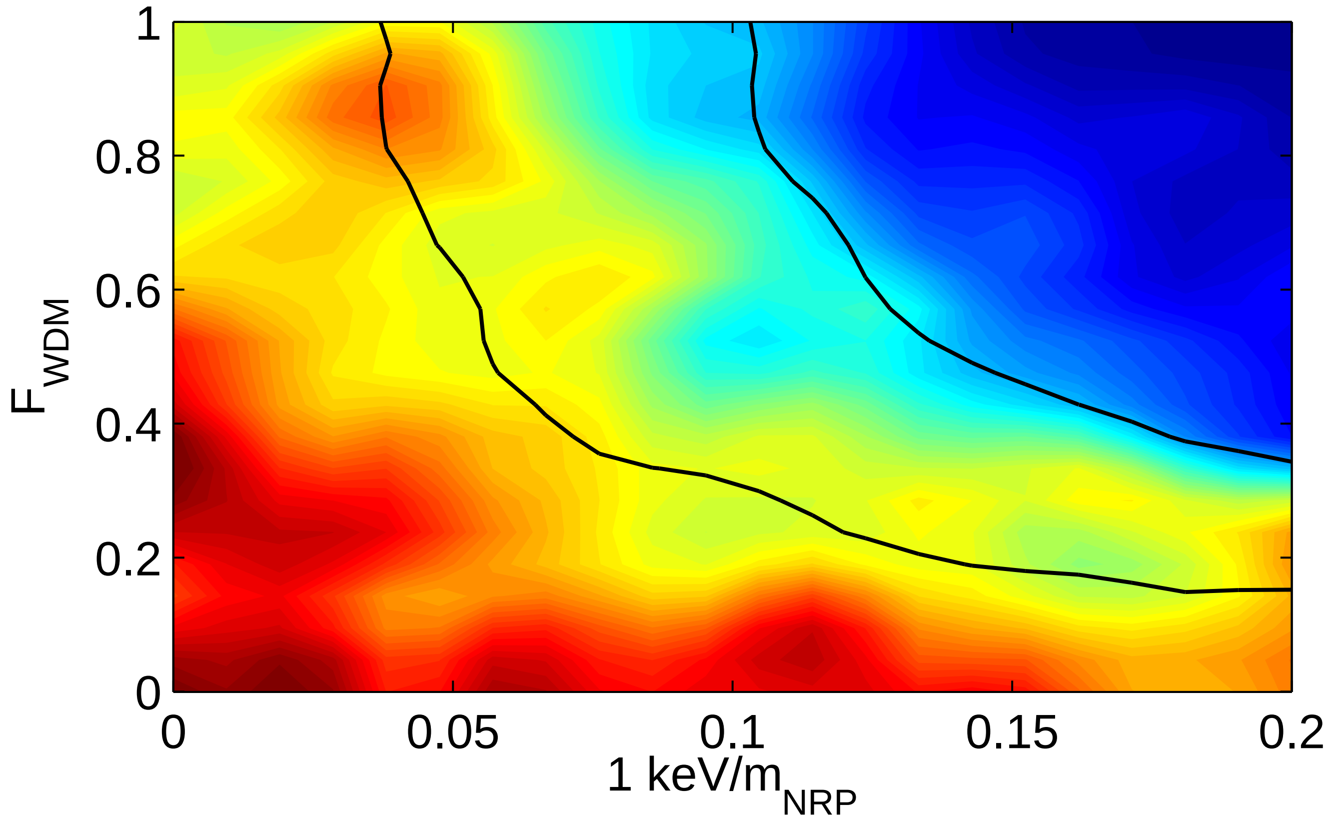
- Change the region for $M_{\rm WDM} \geq 5$ keV. Results agree:

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

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

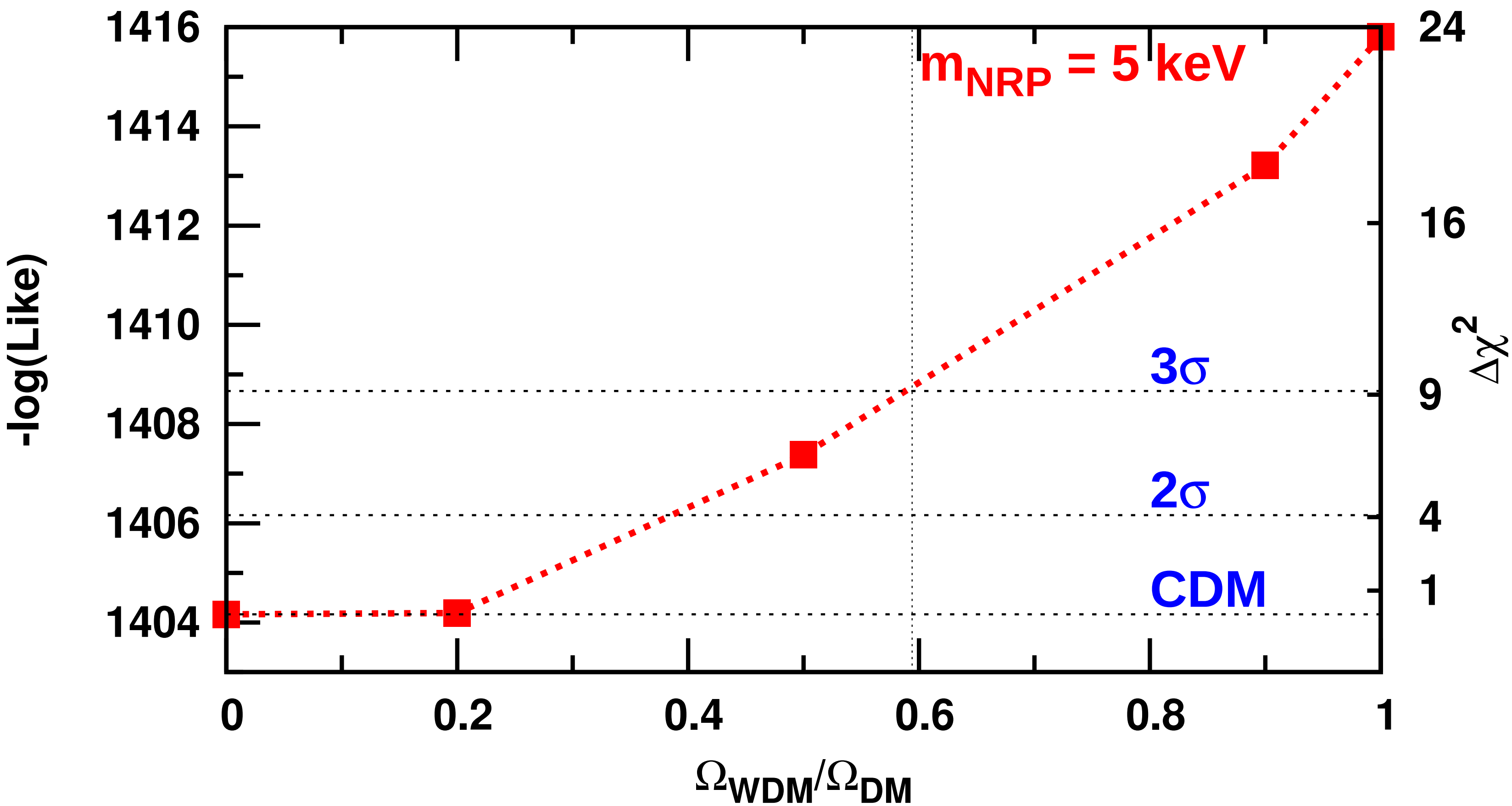


Bayesian bounds on mixture of CDM+WDM



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

Frequentist approach to the CWDM bounds



All models have the same number of degrees of freedom

Sterile neutrinos: a minimal unified model of all observed BSM phenomena.

Neutrino oscillations?

Just add right-handed (sterile) neutrinos N_R^I to the Standard Model

$$\mathcal{L}_{\nu MSM} = \mathcal{L}_{SM} + i\bar{N}_R^I \partial\!\!\!/ N_R^I - \left(\bar{L}_\alpha M_{\alpha I}^D N_R^I + \frac{M_I}{2} (\bar{N}_R^I)^c N_R^I + h.c. \right)$$

- Majorana masses M_I. Dirac mass matrix $M_{\alpha I}^D \equiv F_{\alpha I} \langle \Phi \rangle$, $\alpha = \{e, \mu, \tau\}$ – mixing between left-handed leptons L_α and N_R^I. $M_D \ll M_I$ $F_{\alpha I}$ – Yukawa couplings, Higgs VEV $\langle \Phi \rangle \simeq 174$ GeV.
- Active masses are given via usual **see-saw formula**:

$$(m_\nu) = -M_D \frac{1}{M_I} M_D^T$$

- Parameters of **two** sterile neutrinos are enough to fit the neutrino oscillations data. **Three** sterile neutrinos give even more freedom.
- **The scale of M_I is not fixed!**

The minimal extension?

There is a very simple modification of the SM which can explain **within one consistent framework**

✓ . . . neutrino oscillations

✓ . . . matter-antimatter asymmetry of the Universe

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

Based on this model one can build a theory that

- . . . can incorporate inflation
- . . . can provide a solution to the cosmological constant problem
- . . . treats hierarchy problem differently

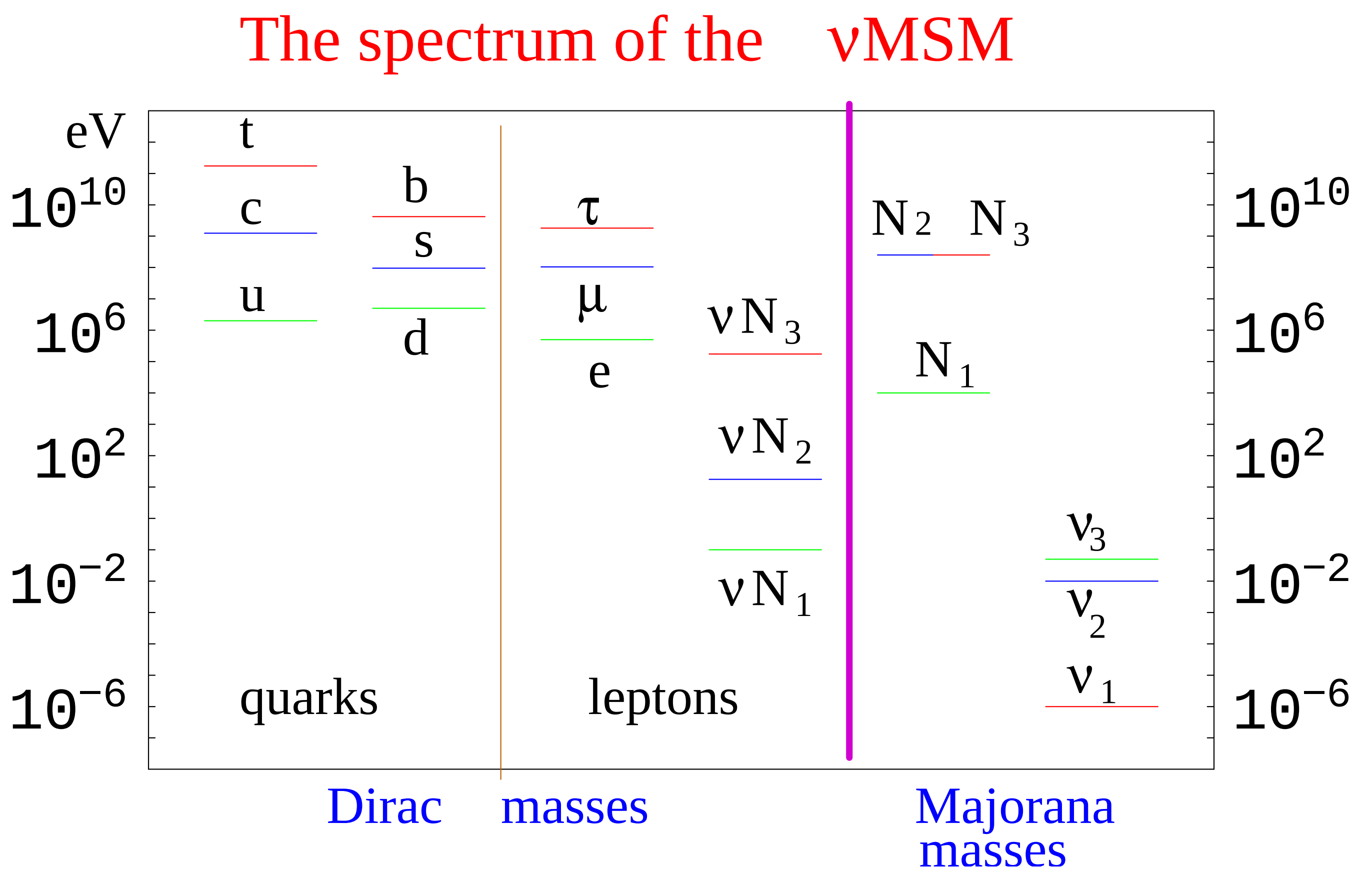
Without a new physics above the EW scale.

νMSM: all masses below electroweak scale

Just add 3 right-handed (sterile) neutrinos N_R^I to MSM:

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

$$\mathcal{L}_{\nu MSM} = \mathcal{L}_{SM} + i\bar{N}_R^I \partial\!\!\!/ N_R^I - \left(\bar{L}_\alpha M_{\alpha I}^D N_R^I + \frac{M_I}{2} (\bar{N}_R^I)^c N_R^I + h.c. \right)$$



Choosing parameters of the νMSM

- Parameters of **two** sterile neutrinos are enough to explain baryogenesis and fit the neutrino 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** neutrino?
- Sterile neutrino interacts with the rest of the SM matter **only** via coupling with active neutrinos, parametrized by $\theta = \frac{m_D}{M}$. Phenomenology is similar to weak interactions but with $\theta \cdot G_F$ (and $\theta \lll 1$)

DM in the νMSM

- 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

Asaka, Laine, Shaposhnikov 07

- Can be produced in the early Universe in the right amount:
  – 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 **singlet scalar** decays. (neutrinos with the mass up to few MeV)

Tkachev, Shaposhnikov (2006)

- Can play the role of (**warm**, **cold** or **mixed**) DM

How sterile neutrino DM is produced?

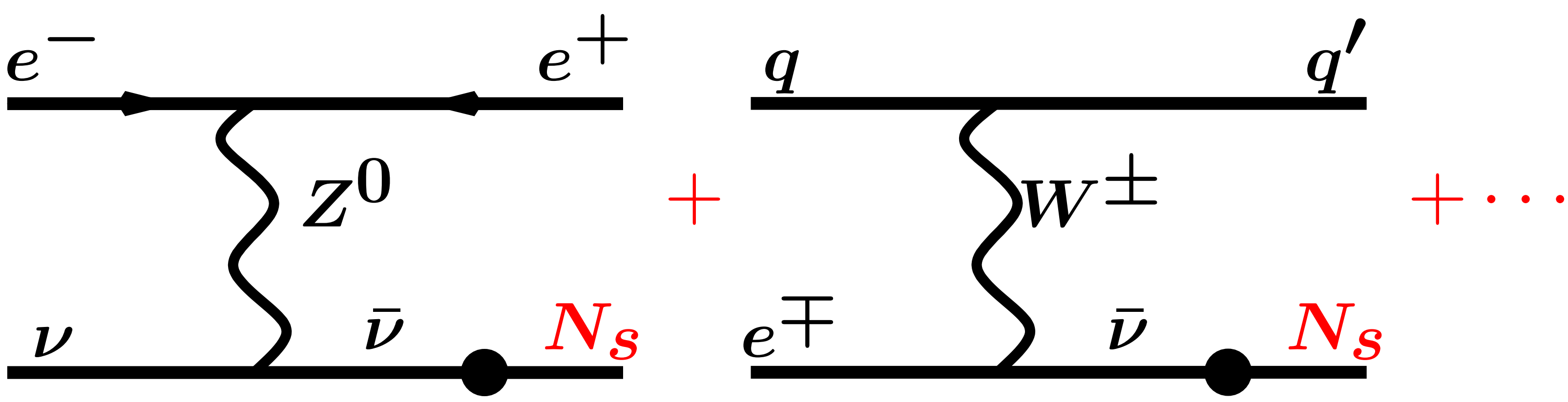
- Sterile neutrino interacts with the rest of the SM matter **only** via coupling with active neutrinos, parametrized by $\theta = \frac{m_D}{M}$

- 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**

- **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



- The presence of lepton asymmetry makes this production much more effective

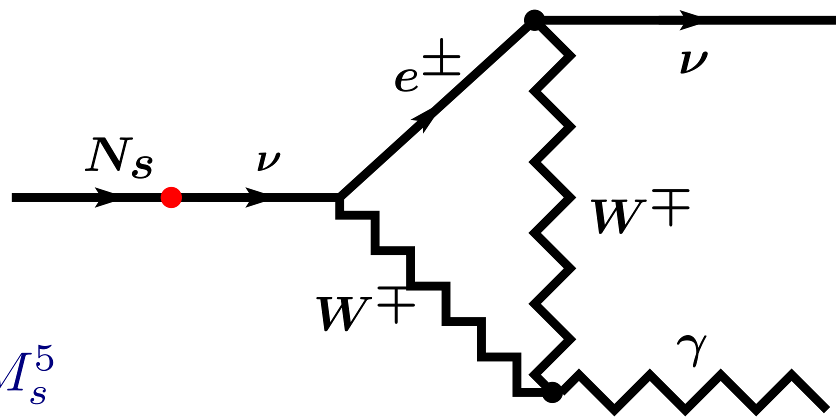
Properties of the lightest sterile neutrino

- Dominant decay channel for sterile neutrino (for $M_s < 1$ MeV) is $N_R \to 3\nu$. Life-time $\tau = 5\times 10^{26}\text{sec}\times\left(\frac{\text{keV}}{M_s}\right)^5\left(\frac{10^{-8}}{\theta^2}\right)^2$

Wolfenshtein Pal (1982)

Barger Phillips Sarkar (1995)

- Subdominant **radiative decay channel**
  - Photon energy: $E_\gamma = \frac{M_s}{2}$



  - Radiative decay width:

$$\Gamma_{\text{rad}} = \frac{9\,\alpha_{\text{EM}}\,G_F^2}{256\cdot 4\pi^4}\,\sin^2(2\theta)\,M_s^5$$

- Sterile neutrino DM **is not completely dark**
  - Flux from DM decay:

$$F_{\text{DM}} = \frac{E_\gamma}{M_s}\frac{\Gamma_{\text{rad}} M_{\text{DM}}^{\text{fov}}}{4\pi D_L^2} \approx \frac{\Gamma_{\text{rad}}\Omega_{\text{fov}}}{8\pi}\int \rho_{\text{DM}}(r)dr$$

line of sight

Dolgov Hansen (2000

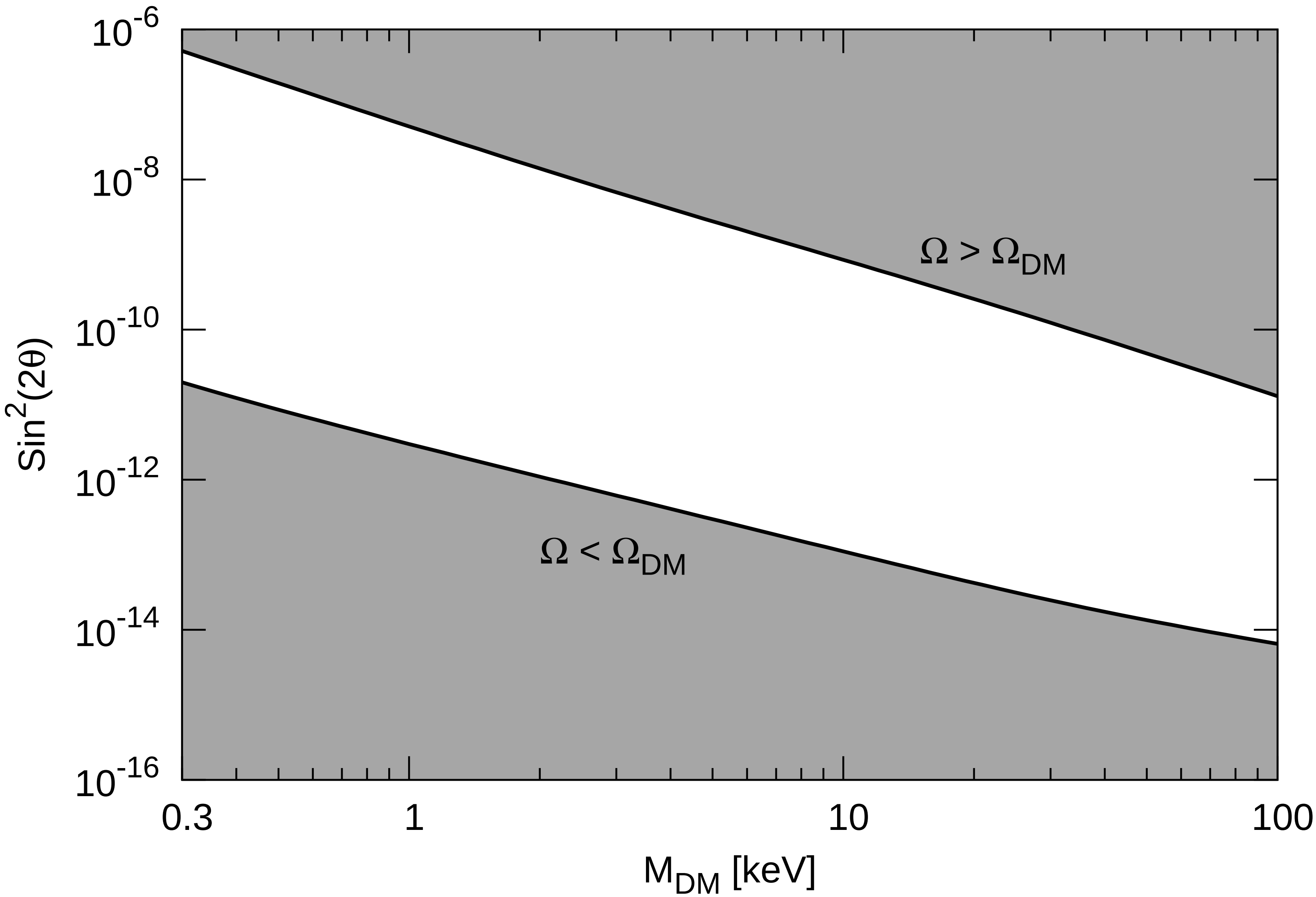
Abazajian Fuller Tucker (2001)

Boyarsky et al (2006)

Window of parameters of sterile neutrino DM

Asaka, Laine, Shaposhnikov

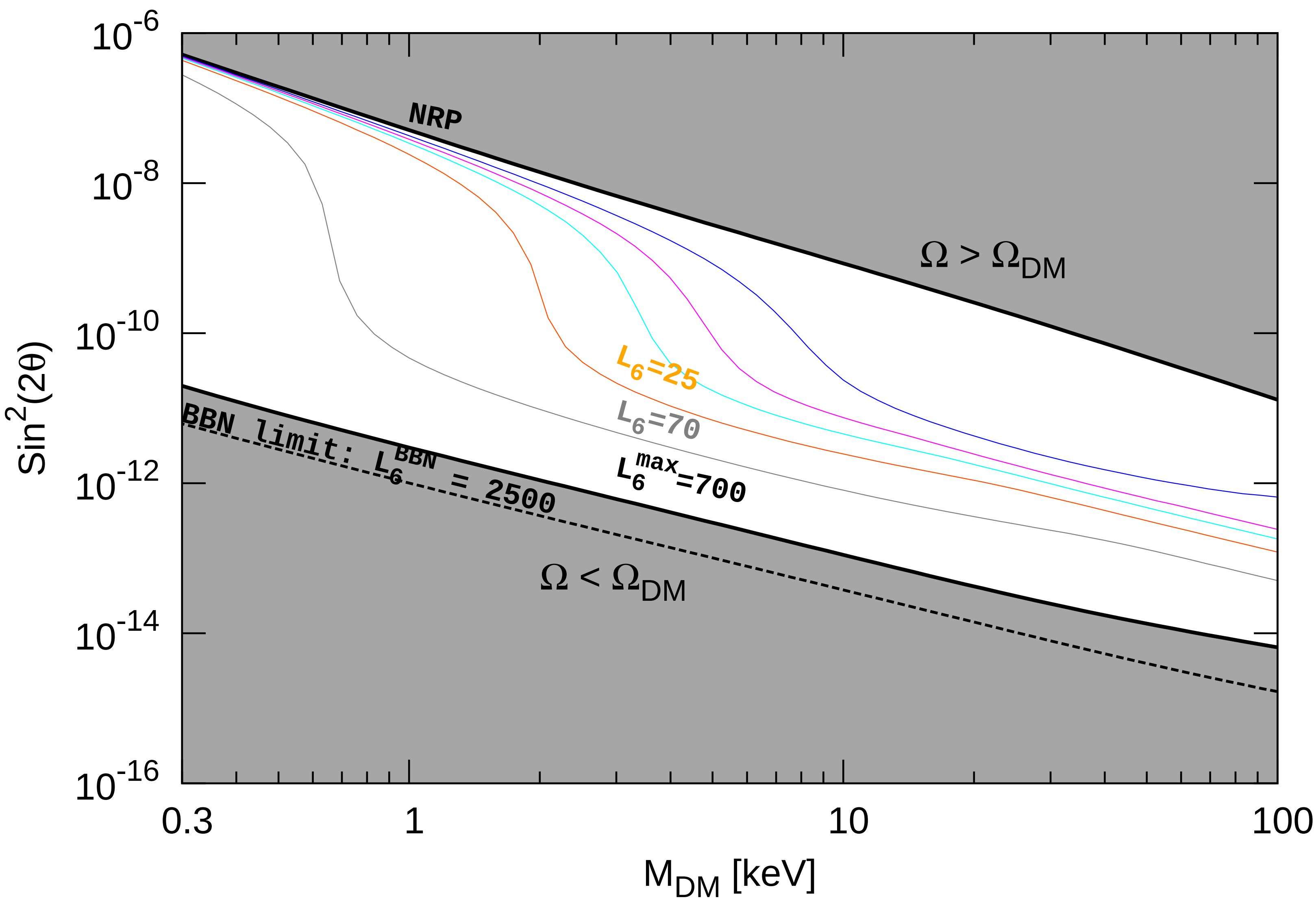
Laine, Shaposhnikov



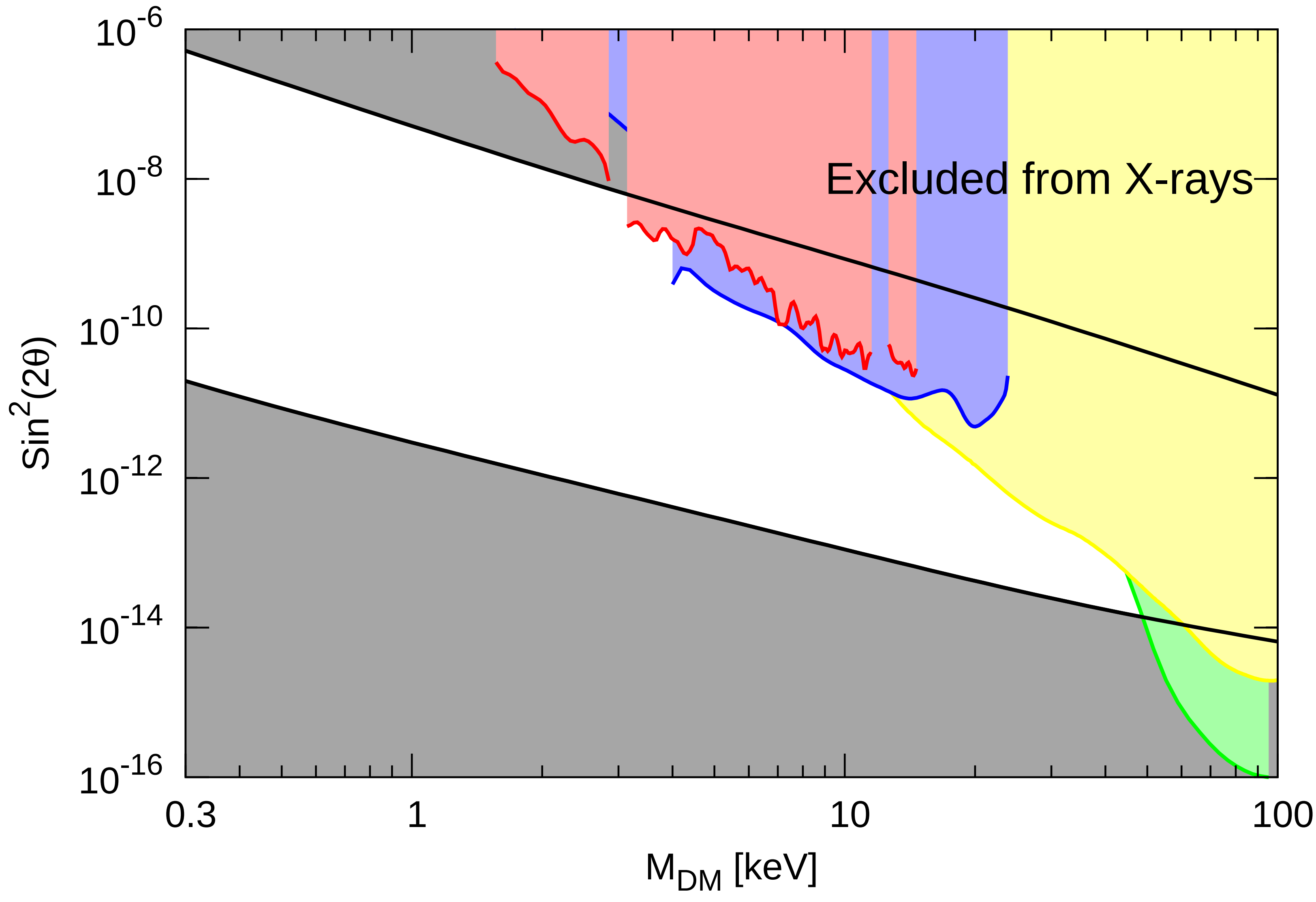
Window of parameters of sterile neutrino DM

Asaka, Laine, Shaposhnikov

Laine, Shaposhnikov



Window of parameters of sterile neutrino DM

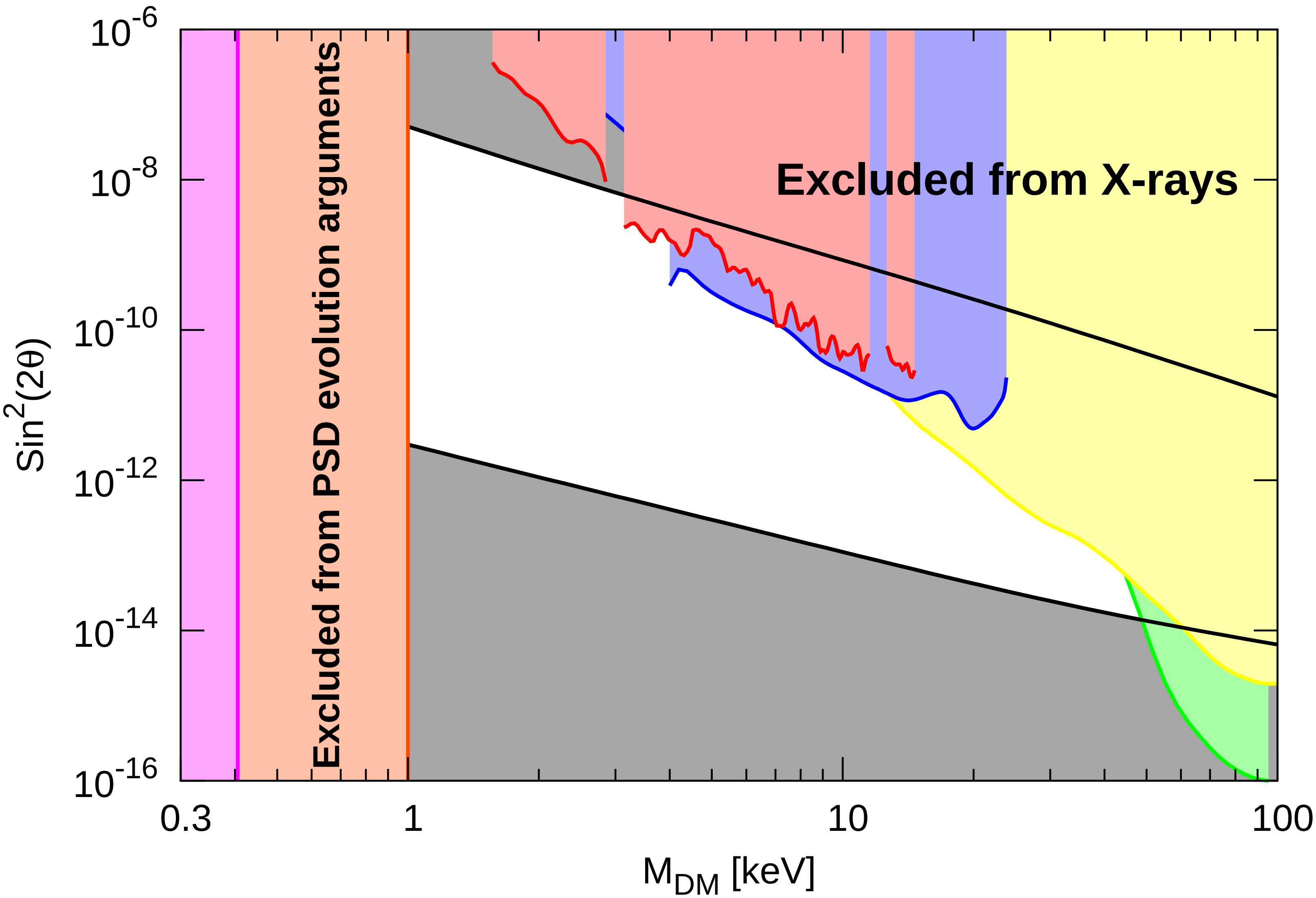


Asaka, Laine, Shaposhnikov

Laine, Shaposhnikov

Boyarsky, Ruchayskiy et al. 2005-2008

Window of parameters of sterile neutrino DM



Asaka, Laine, Shaposhnikov

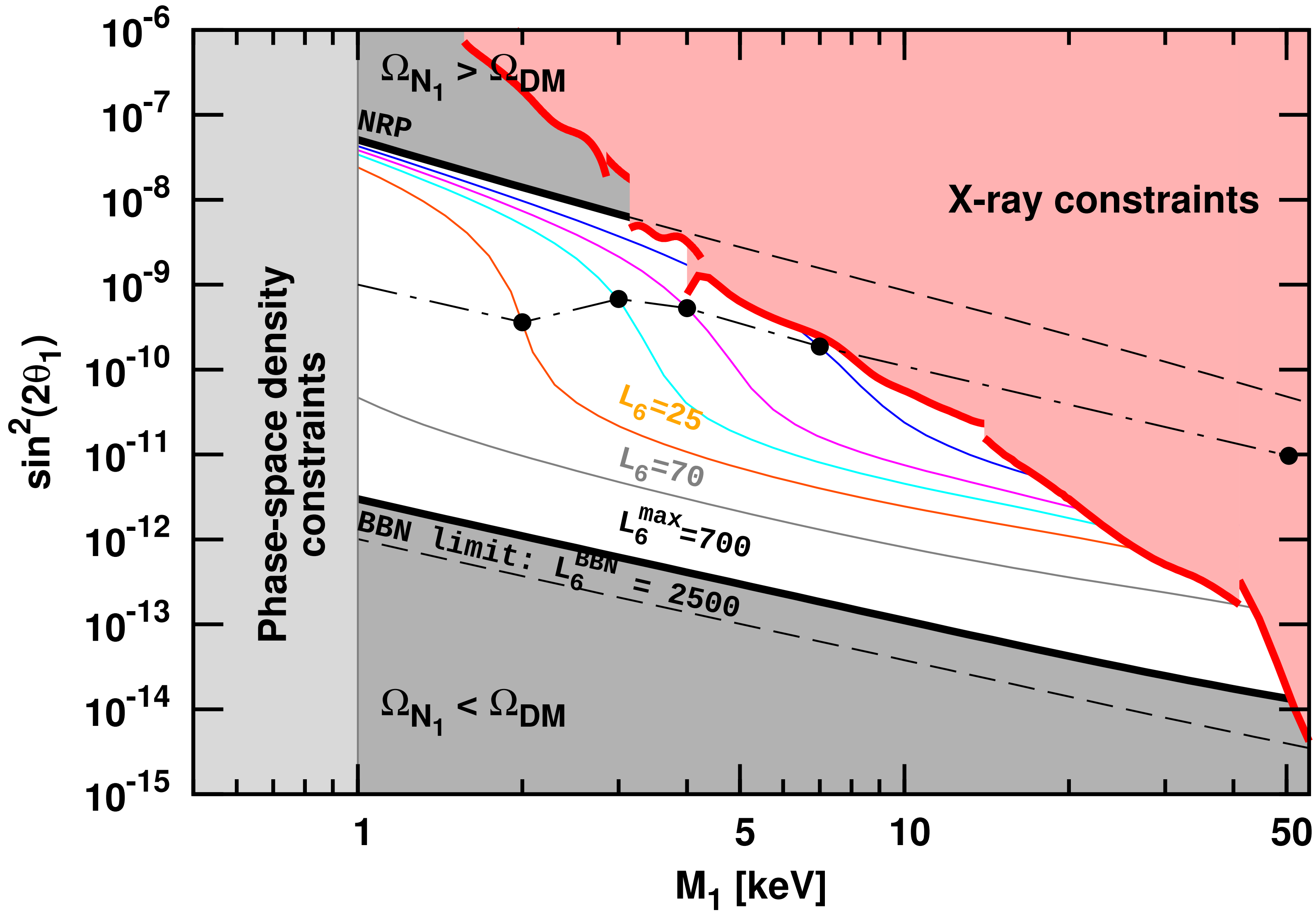
Laine, Shaposhnikov

Boyarsky, Ruchayskiy et al. 2005-2008

Boyarsky, Ruchayskiy, Iakubovskyi, 2008

Gorbunov, Khmelnitsky, Rubakov, 2008

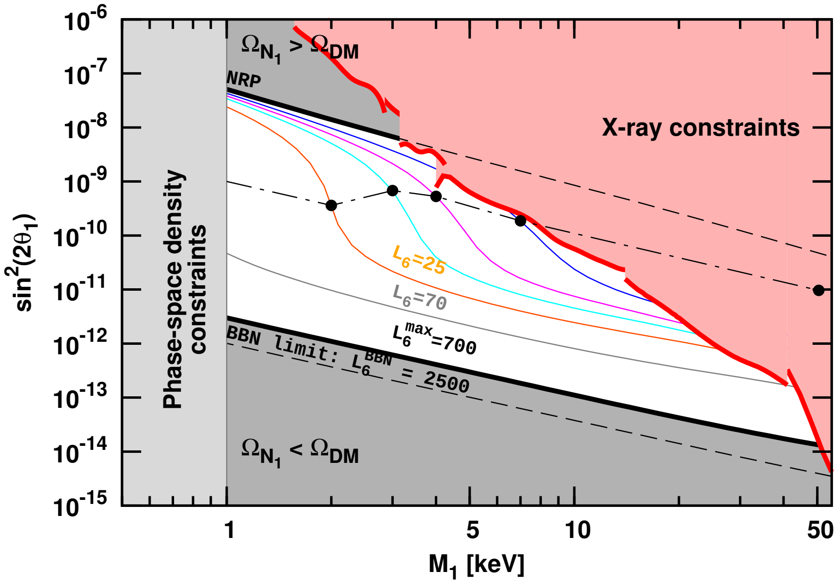
Window of parameters of sterile neutrino DM



Boyarsky, Ruchayskiy, Lesgourgues, Viel [0812.3256]

Boyarsky, Ruchayskiy, Shaposhnikov [0901.0011]

Window of parameters of sterile neutrino DM



Boyarsky, Ruchayskiy, Lesgourgues, Viel [0812.3256]

Boyarsky, Ruchayskiy, Shaposhnikov [0901.0011]

- Sterile neutrino is still viable and very attractive DM candidate. The νMSM should be verified.
- To explore the allowed window, more theoretical efforts, both on **particle physics and astrophysics** sides, and new methods of analysis of the full set of the cosmological and astrophysical data is needed.

THANK YOU FOR YOUR ATTENTION

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