Cosmological bounds on warm dark matter and astrophysical bounds on decaying dark matter

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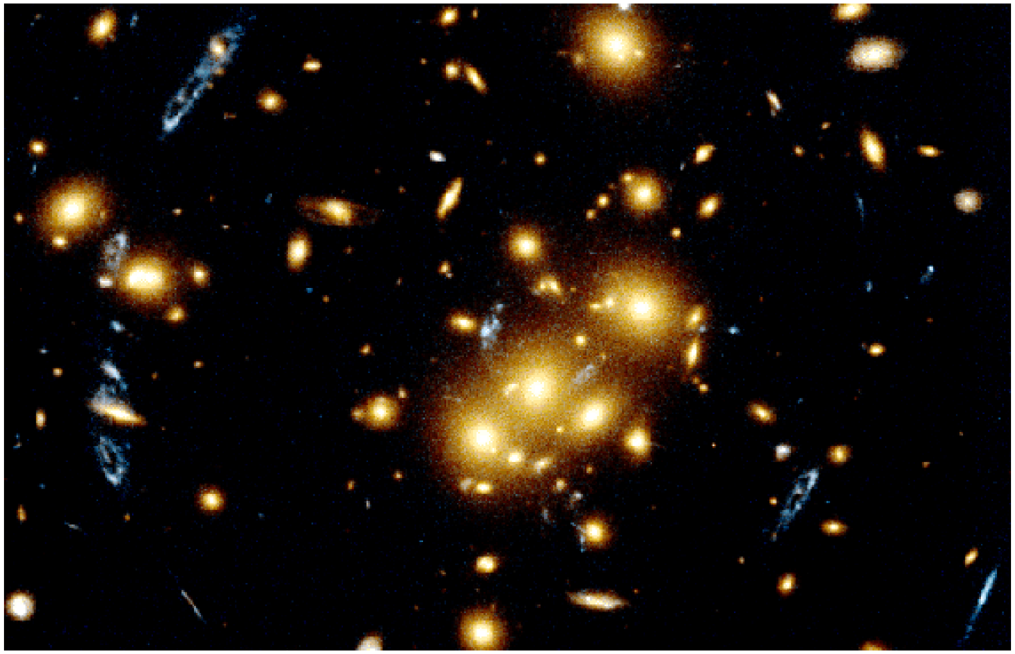
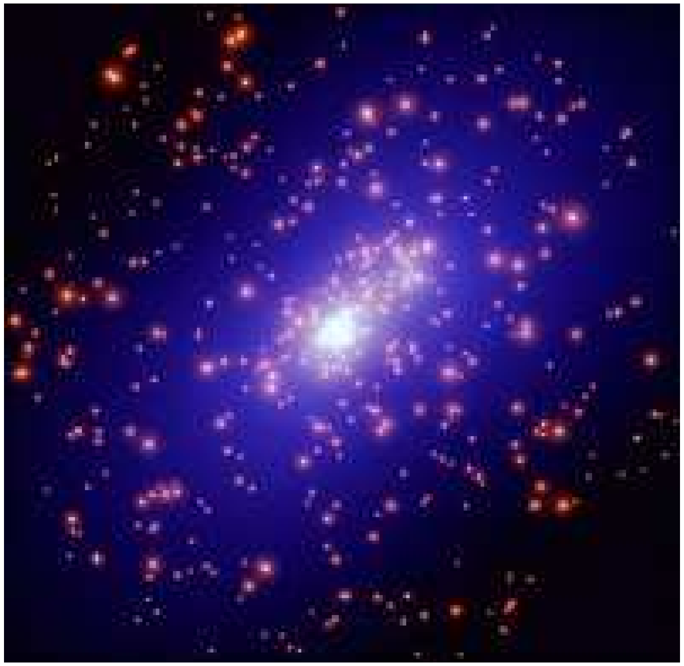
DESY. June 18, 2008

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 (X-ray bright) *intracluster gas*
- Gravitational lensing data





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

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

What is known about DM?

- 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
- What can be the mass of DM?

What can be the DM mass?

- The model-independent lower limit on mass for **fermionic** DM:

Tremaine, Gunn (1979)
Dalcanton, Hogan (1990)

- The smaller is the DM mass – the bigger is the number of particles in a given DM-dominated object.
- For fermions there is a **maximal** phase-space density (degenerate Fermi gas). Hence, maximal number of fermions
- Objects with highest phase-space density: dwarf spheroidal galaxies $Q_{obs} = 10^4 - 10^5\ M_\odot\ \mathrm{kpc}^{-3}[\mathrm{km\ s}^{-1}]^{-3}$.
- Leads to the **lower bound** on the DM mass $m \gtrsim 300 - 500$ eV
- Active neutrinos with $m \sim 300$ eV have **primordial** phase-space density $Q \sim Q_{obs}$. But $\Omega_{\mathrm{DM}} h^2 = \frac{m_\nu}{94\ \mathrm{eV}} \Rightarrow$ Active neutrinos **cannot** constitute 100% of DM

Phase-space density evolution

- Collisionless disipationless dynamics can only lead to the **decrease** of the coarse-grained phase-space density
- N-body simulations show decrease of phase-space density during the collapse by $\mathcal{O}(10^2 - 10^3)$
- WIMPs with $M \sim 100$ GeV and decoupling temperature $T_d \sim 10$ MeV have primordial phase-space density $Q \sim 10^{21} Q_{obs}$
- Can phase-space density decrease by **21** order during the gravitational collapse? **Yes!**
- N-body simulations measure the change of phase-space density between start of simulations $z \sim 10^2$ and today $z = 0$.
- Start of the simulations: particles have peculiar (Zeldovich) velocities $\sigma_i \sim 10 - 30$ km/sec.
- End of the simulations: particles have virial velocities $\sigma_f \sim 100$ km/sec. $(\sigma_f/\sigma_i)^3 \sim 10^2 - 10^3$.

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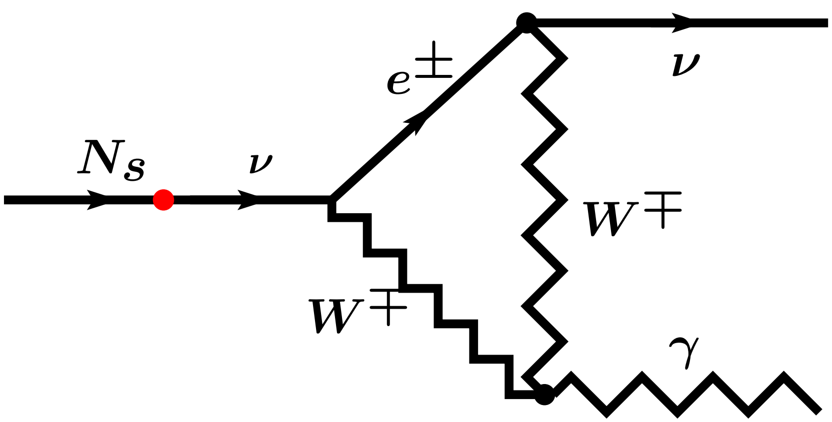
  - Be stable or cosmologically long-lived
- For fermionic DM mass $\gtrsim 300$ eV
- Possible interactions with SM matter?
- **Pessimistic scenario:** DM interacts only in the early (very) hot Universe (e.g. produced in inflaton decays)
- **Optimistic scenario:** DM interact with ordinary matter
  - Annihilation
  - Decay

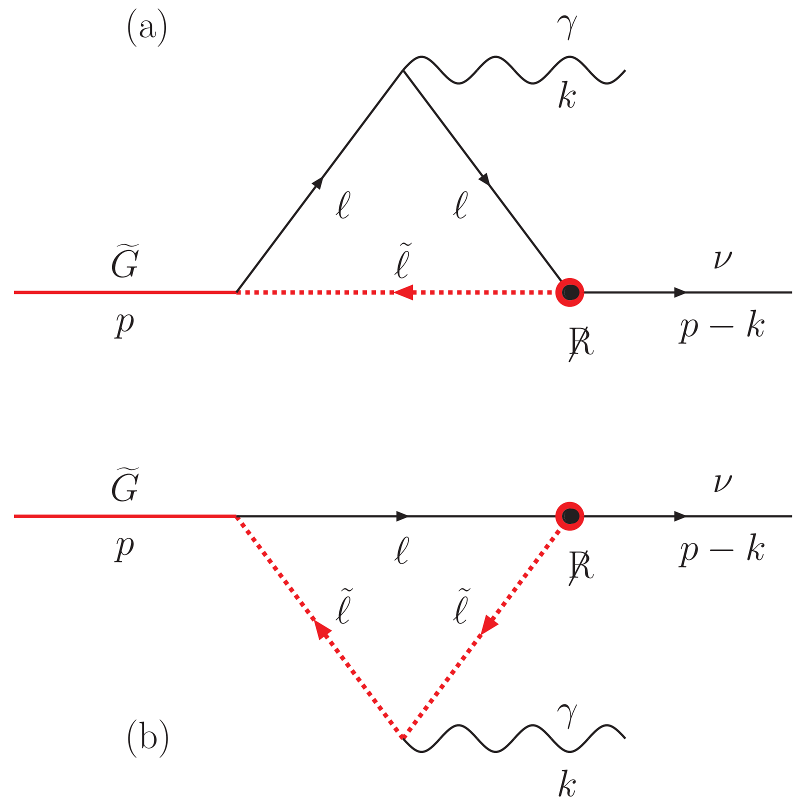
  $\Rightarrow$ possibility of **indirect detection of** DM

Searching for decaying dark matter

Decaying DM

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





Appears in many models:

Sterile neutrino
Dodelson & Widrow'93;
Asaka, Shaposhnikov et al.'05

$\not{R}$ Gravitino
Takayama & Yamaguchi'00
Buchmüller et al.'07

Volume Modulus
Quevedo'07

Decaying Majoron
M. Lattanzi, J.W.F. Valle '07

Properties of decaying DM

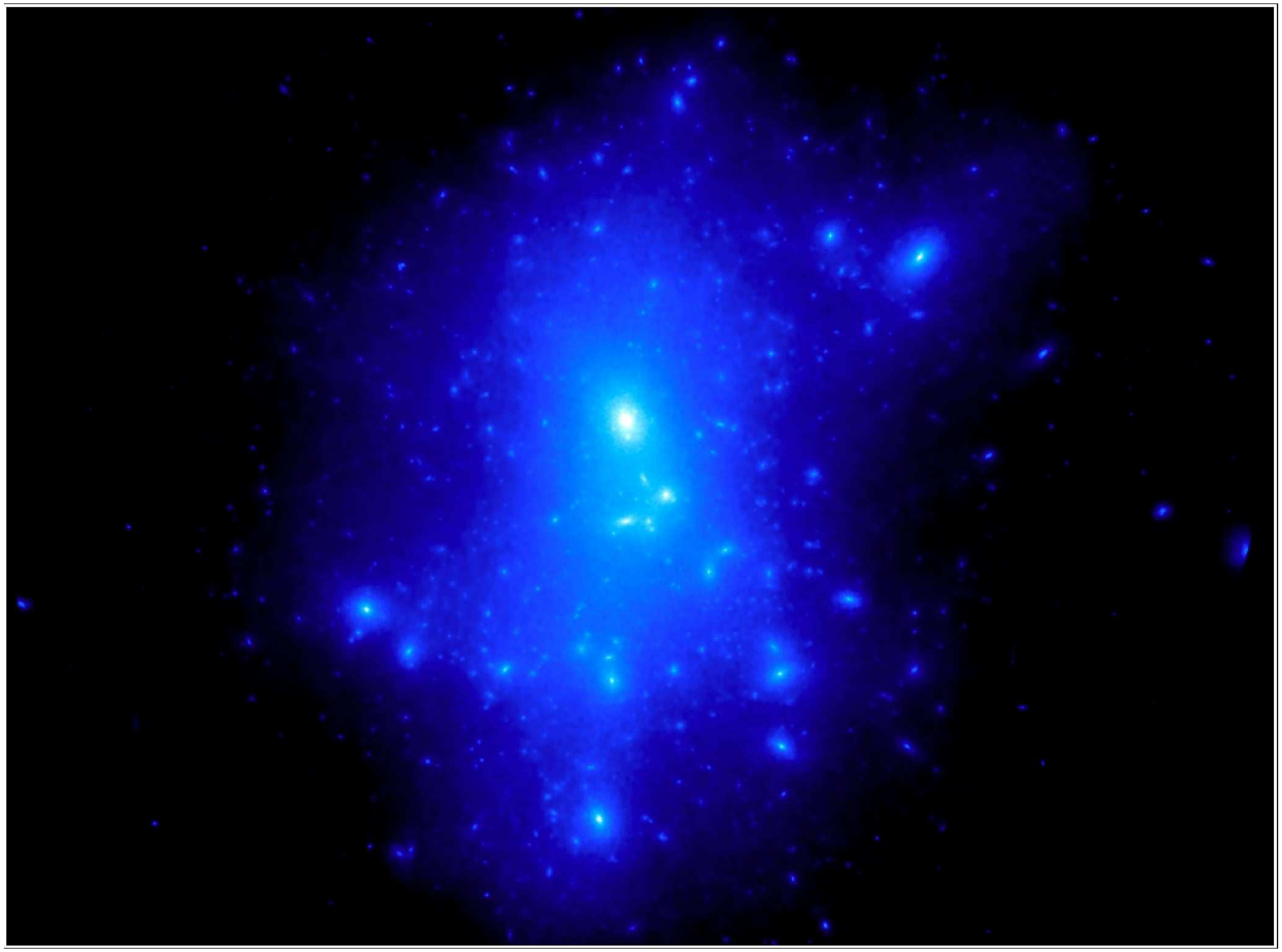
- WIMPs cannot decay. Their interaction strength with matter $\sim G_F$ would lead to life-time of neutron in β-decay: $n \to p + e + \bar{\nu}_e$.
- Decaying DM should interact **superweakly** $\sim \theta \cdot G_F$ and $\theta \lll 1$
- Radiative decay channel : DM $\to \gamma + \nu$
- Photon energy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

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

line of sight

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

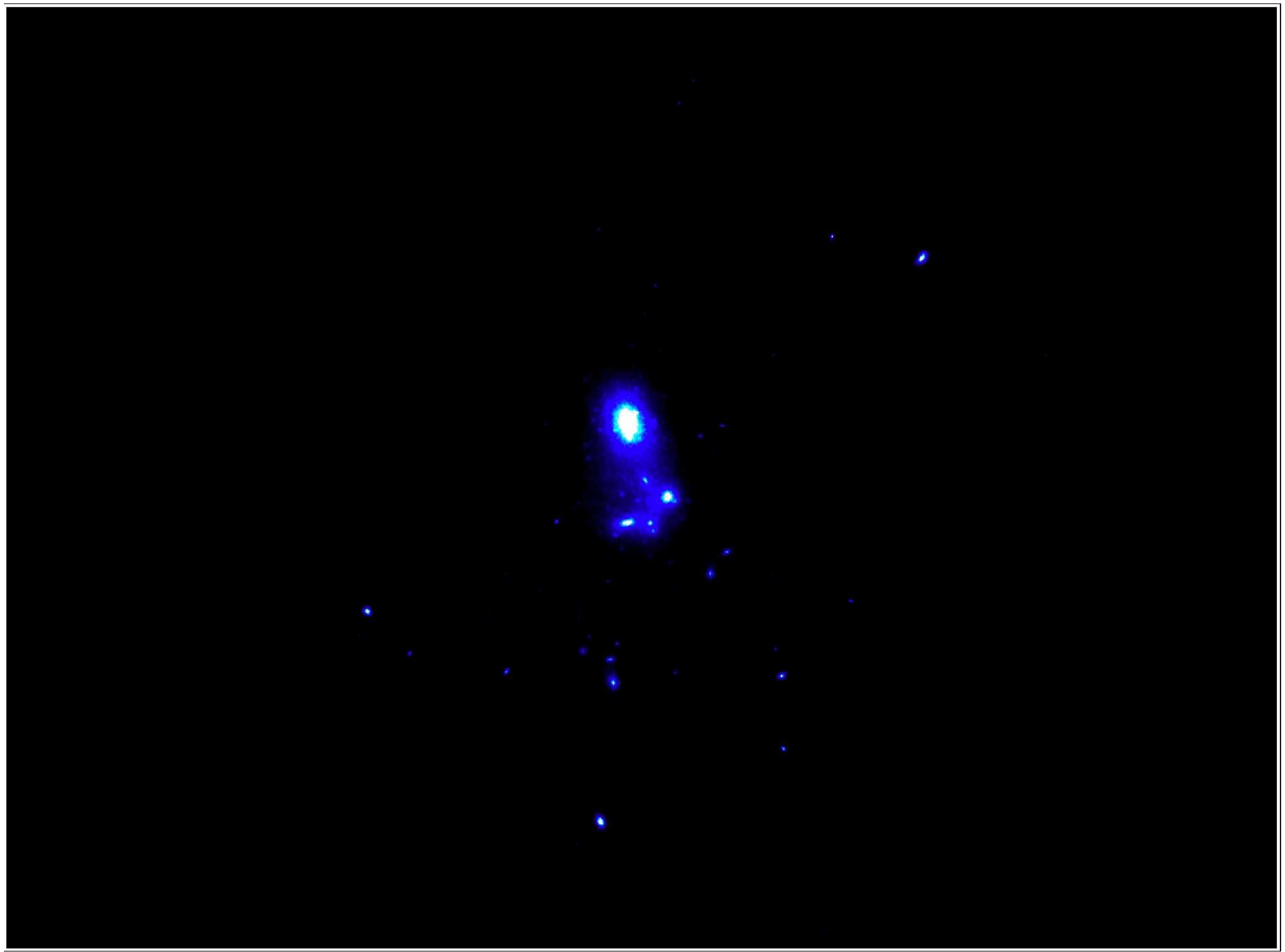
DM decay line search : advantages



Moore et al. 2005

DM decay is an all sky signal

DM decay line search : advantages



Moore et al. 2005

DM annihilation signal is concentrated on GC

DM decay line search : advantages

- Decay signal $\sim \int \rho_{\rm DM}(r)dr$ as compared to $\sim \int \rho^2_{\rm DM}(r)dr$ for annihilation:
- Decay signal is not very sensitive to the precise form of DM profile (difference between cuspy and cored profiles changes signal by a factor of $2-3$)
- For decay signal : freedom of choosing the observational targets (many targets of different nature have comparable signals). Do not need to look at GC
- If a DM decay line candidate is found – can study its surface brightness profile and its distribution over the sky

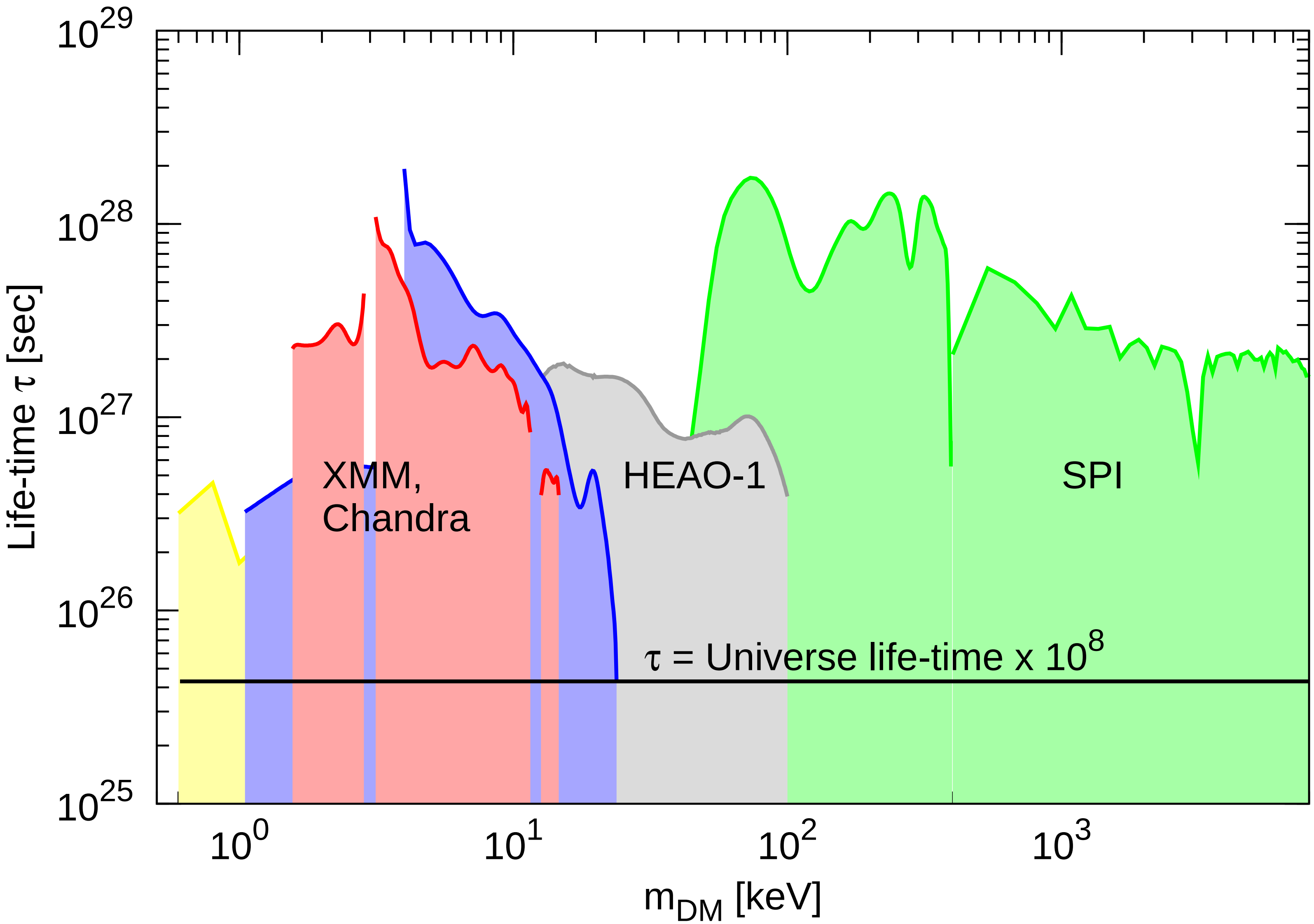
For decaying DM "indirect" search becomes "direct" !

Where to look for DM decay line?

■ Extragalactic diffuse background	Takayama & Yamaguchi, 2000 Dolgov & Hansen, 2000 **Boyarsky, Neronov, O.R., Shaposhnikov, 2005** Buchmüller et al., 2007 Bertone et al., 2007
■ Clusters of galaxies (Coma, Virgo)	Abazajian et al., 2001 **Boyarsky, Neronov, O.R., Shaposhnikov** PRD 74, 2006
■ DM halo of the Milky Way. Signal increases as we increase FoV!	**Boyarsky, Neronov, O.R., Shaposhnikov, Tkachev** PRL 2006 [astro-ph/0603660] Riemer-Sørense et al. ApJL 2006 [astro-ph/0603661] **Boyarsky, Nevalainen, O.R.** A&A 2007 Abazajian et al. [PRD 75, 2007] **Boyarsky, Malyshev, Neronov, O.R., MNRAS 2008**
■ Andromeda galaxy (M31)	Watson et al. PRD 74, 2006 [astro-ph/0605424] **Boyarsky, Iakubovsky, O.R., Savachenko 2007** Bertone et al. 2007
■ "Bullet" cluster 1E 0657-56	**Boyarsky, Markevitch, O.R.** [ApJ 2008]
■ Soft XRB	**Boyarsky, den Herder, Neronov, O.R.** [Astropart.Phys.'07]

Strategy depends on the object, energy range, instrument. . .

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

What else do we know about the DM?

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**

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

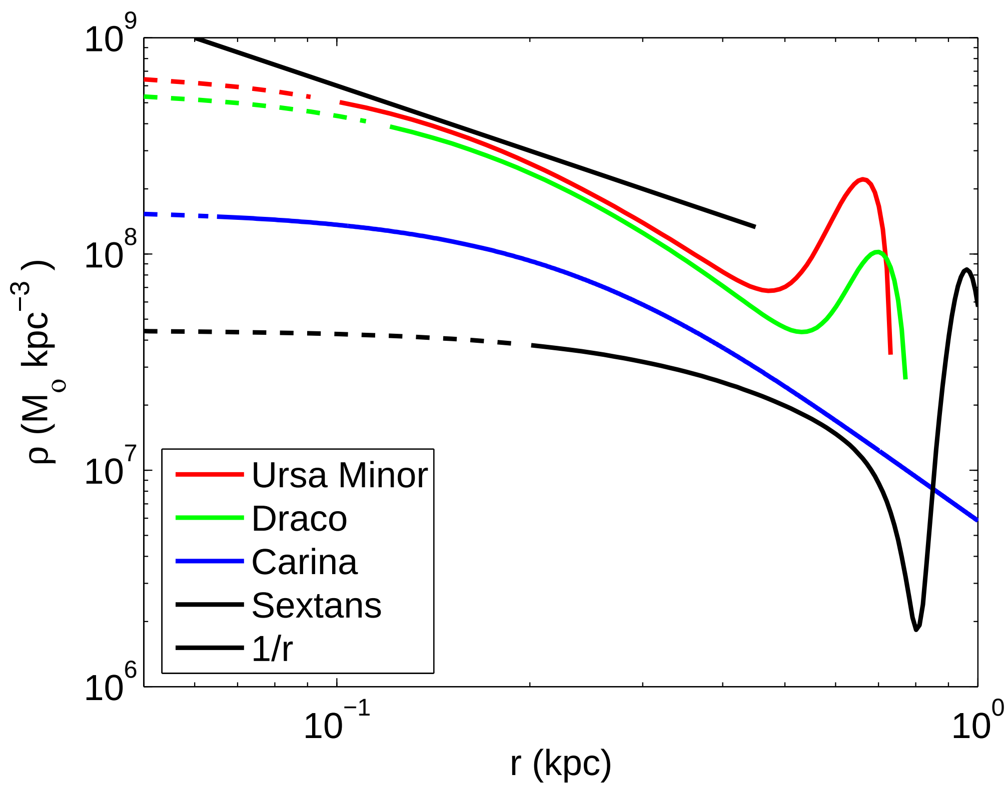
- Comoving free-streaming lengths peaks around t_{nr} when $\langle p\rangle \sim m$

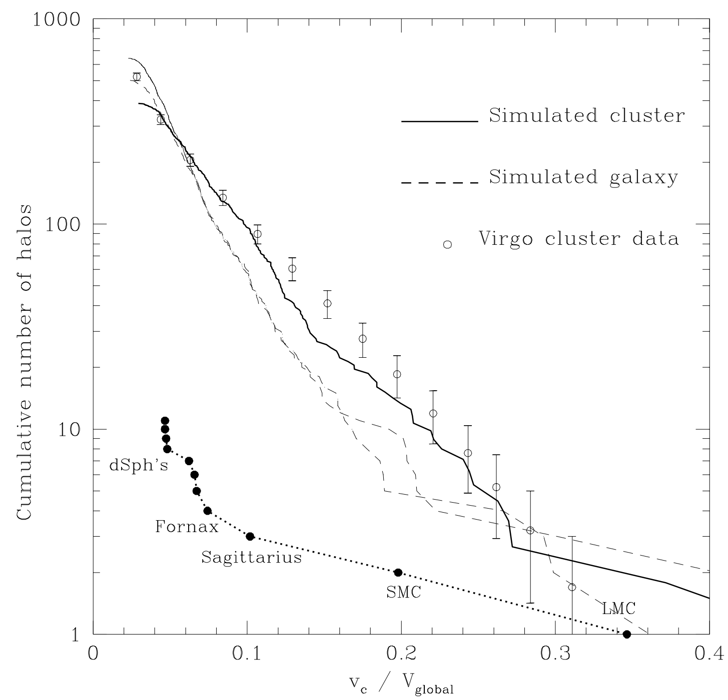
- All DM models are thus divided into 3 groups:
  - **CDM** : free streaming is negligible
  - **WDM** : free streaming at galaxy scales, $t_{nr} \ll t_{eq}$
  - **HDM** : free streaming at cosmological scales $t_{nr} \gg t_{eq}$

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

- CDM and WDM work equally well at large scales (CMB, SDSS, 2dFG). ΛCDM model could have been called "ΛWDM"

Cold or warm?





CDM : success at large scales

At galaxy scale predicts:

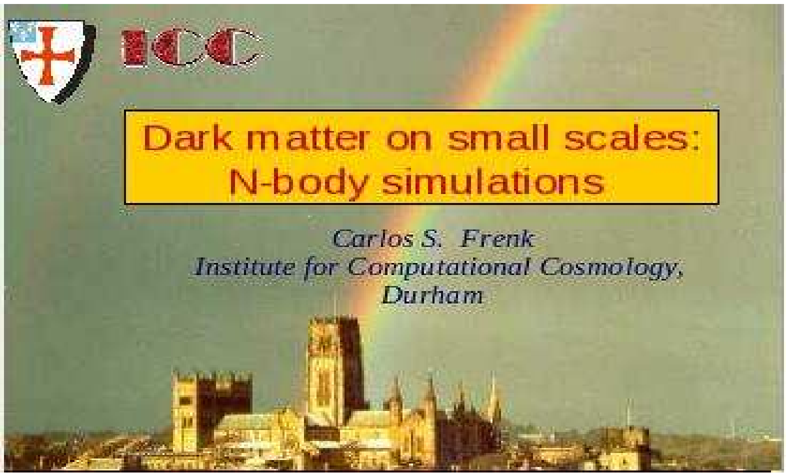
– Cuspy profiles. (cores observed?)

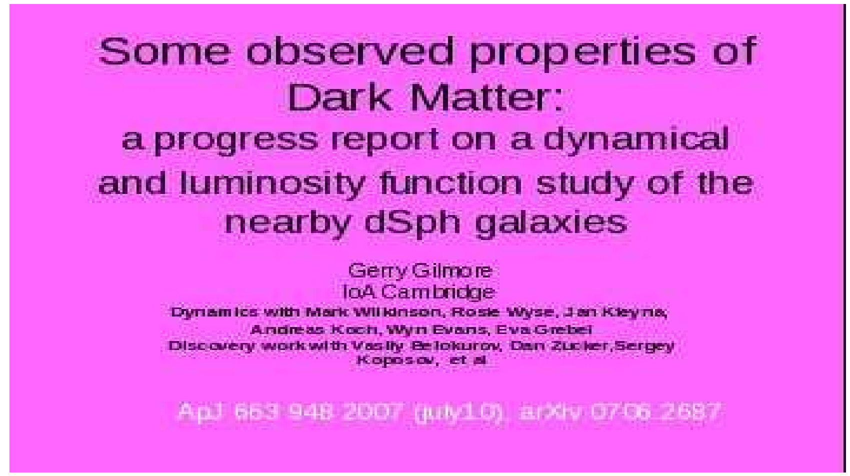
– Many satellites. (few detected?)

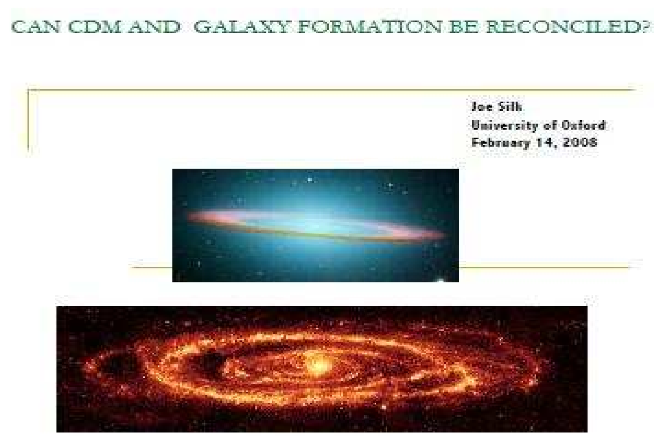
WDM : shares success of CDM at large scales

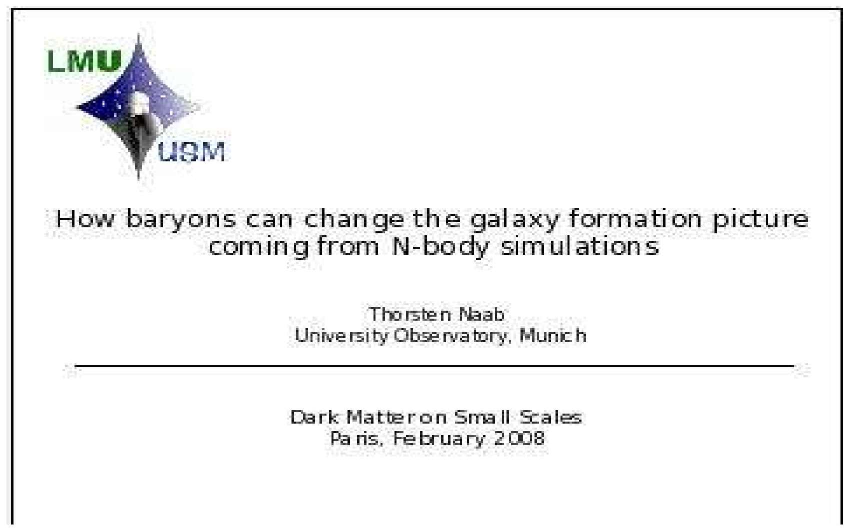
Qualitatively explains small scale structure

DM at small scales. Paris, Feb.13-15









Scientific organizers: A. Boyarsky, O. Ruchayskiy, J. Lesgourgues

CDM or WDM? A summary

1) Does CDM predictions contradict observations?

- CDM simulations are **pure DM**. Pure N-body is not enough
- Astronomers observe **luminous** matter.
- Baryonic feedback can be essential
- Example: not all DM halos can acquire baryons

2) Any WDM simulations (N-body or hydrodynamical) should

- properly include primordial velocities of the particles
- use correct power spectrum of initial density perturbations.

3) WDM is ruled out by Lyman-α?

- **No** (discussion follows)

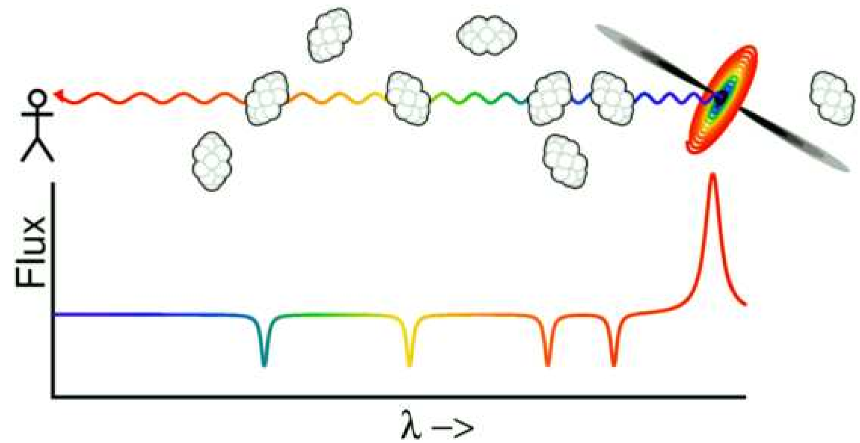
4) DM with keV mass still allowed?

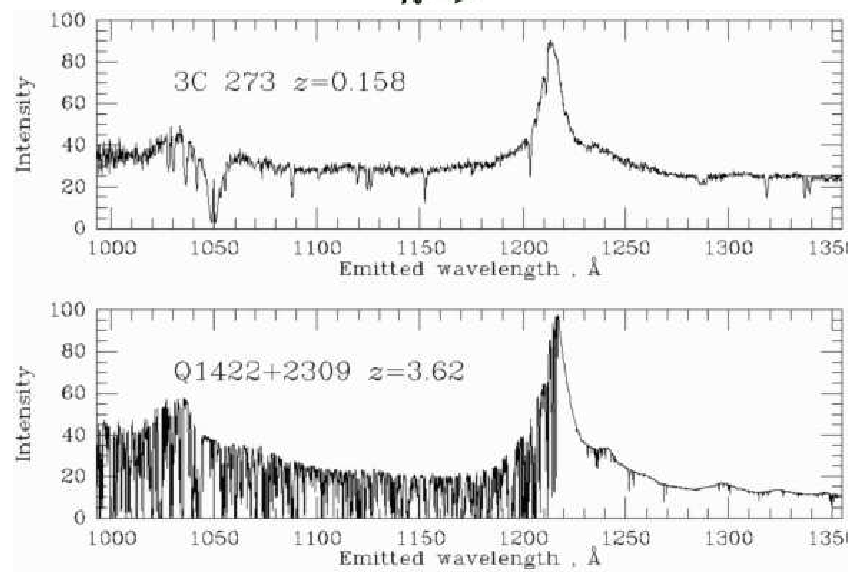
- **Yes**

Lyman-α forest

- To probe the DM properties at small scales one can use **Lyman-α** forest data:
- Red-shifted absorption Lyman-α line in the spectra of distant QSOs
- Neutral hydrogen traces DM distribution at red-shifts $z \sim 2-4$.
- Allows to measure **one-dimensional** non-linear power spectrum:

$$P_{1D} = \int_k^\infty P_{3D}(k) \frac{kdk}{2\pi}$$





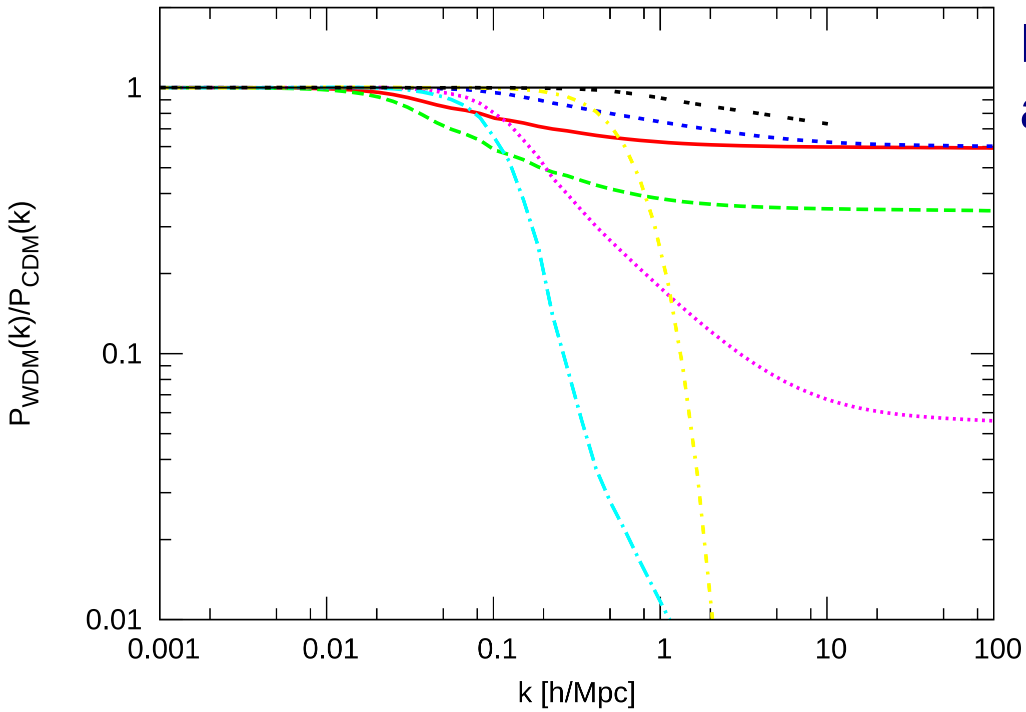
Lyman-α forest : challenges

- Need to compare measured non-linear 1D powerspectrum with the linear 3D power spectrum, predicted by a cosmological model.
- Simulations are needed! Each hydrodynamical simulation takes about 36 hours (optimistic)
- Need to fit **simultaneously** 7+ cosmological parameters plus ~ 20 astrophysical Lyman-α parameters to the data (Lyman-α plus possible other experiments: CMB, 2dFG, SDSS, ...).
- Try **2** values for each parameters. Have 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

Powerspectra of DM models

- Solution? Perform numerical simulations only in a number of points in multi-D parameter space. Interpolate between them
- **But** simulations depend on initial (linear) powerspectrum
- In many WDM models: non-thermal momenta distribution – powerspectra of complicated (non-universal) form



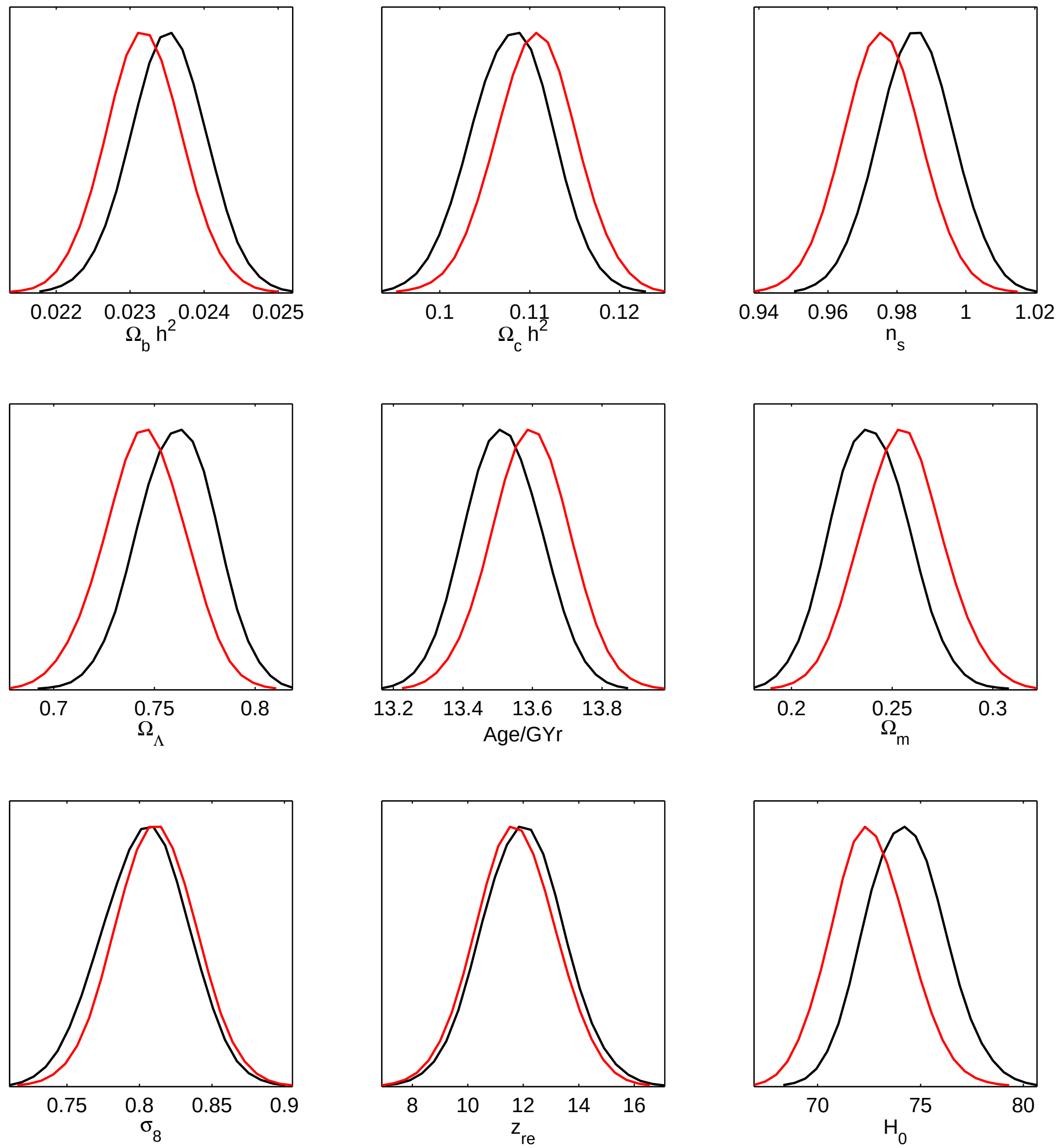
Example: mixture of colder and warmer components

- Suppression starts early, at λ_{FS} of warm component.
- But at smaler scales – like CDM with smaller normalisation.
- This makes Ly-α bounds weaker.

Bayesian approach to WDM bounds

- To explore effectively a vast multi-D parameter space one uses **Bayesian approach**
- **Frequentist approach** (model rejection based on χ^2) can rule out a particular model
- Bayesian approach can tell what model is the "most likely" one
- Bayesian approach determines the **90% confidence limit (CL)** as a region into which 90% of the models would fall
- This leads to the bounds, which are generically weaker than those of frequentist approach

Lower DM mass bound in Bayesian approach



- Example: bayesian analysis gives $m_{\rm DM} \geq 15.3$ keV at 90% CL
- Fixing the parameter of interest at 50% **below** this lower bound (i.e. at 10 keV) gives fit with $\Delta\chi^2 \approx 5$ ($\approx 2.2\sigma$)
- In this case Bayesian 90% CL is weaker by $\approx 50\%$ from the actual (frequentist) one

Summary: Lyman-α bounds on WDM

- Lyman-α analysis of WDM is model-dependent (should be repeated for **each new type of initial power spectrum**)
- Bayesian 2σ bounds on the WDM parameters are *narrower* than the actual (frequentist) ones (i.e. lower bound can be lowered, upper bound can be raised)
- Lyman-α analysis suffers from a systematics which is hard to estimate (due to approximate ways of converting measured to predicted power spectra)
- **Upshot:** Lyman-α allows to probe mildly non-linear stage of structure formation and can be very useful in determining the nature of DM. However, **much more work should be done, until robust bounds are obtained**

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)

$$\mathcal{L}_{\nu MSM} = \mathcal{L}_{MSM} + i\bar{N}^I \partial\!\!\!/ N_I - \left(\bar{L}_\alpha M^D_{\alpha I} N_I + \frac{M_I}{2} \bar{N}^c_I N_I + h.c. \right)$$

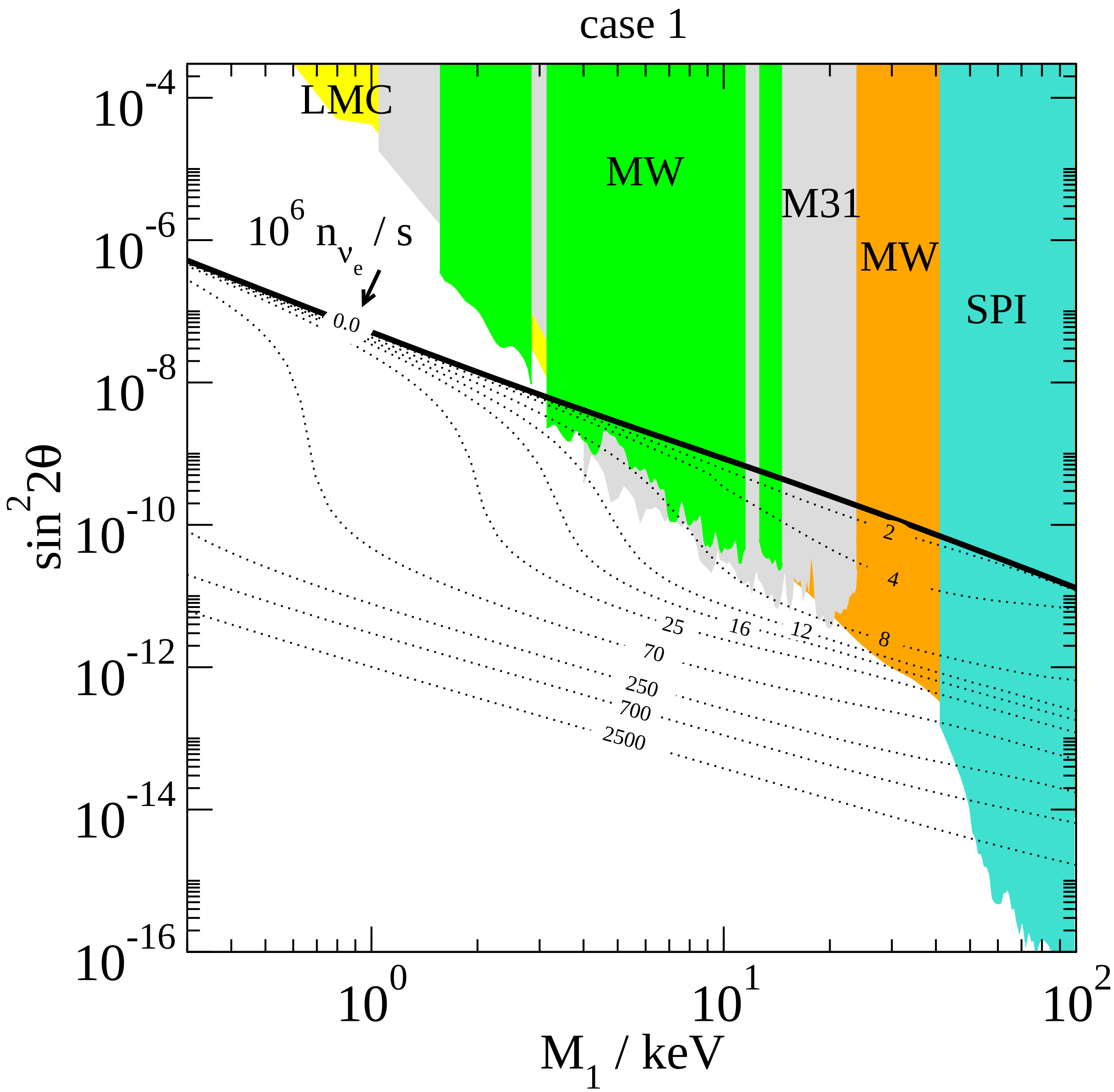
A very modest and simple modification of the SM which can explain **within one consistent framework**

- ✓ . . . 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

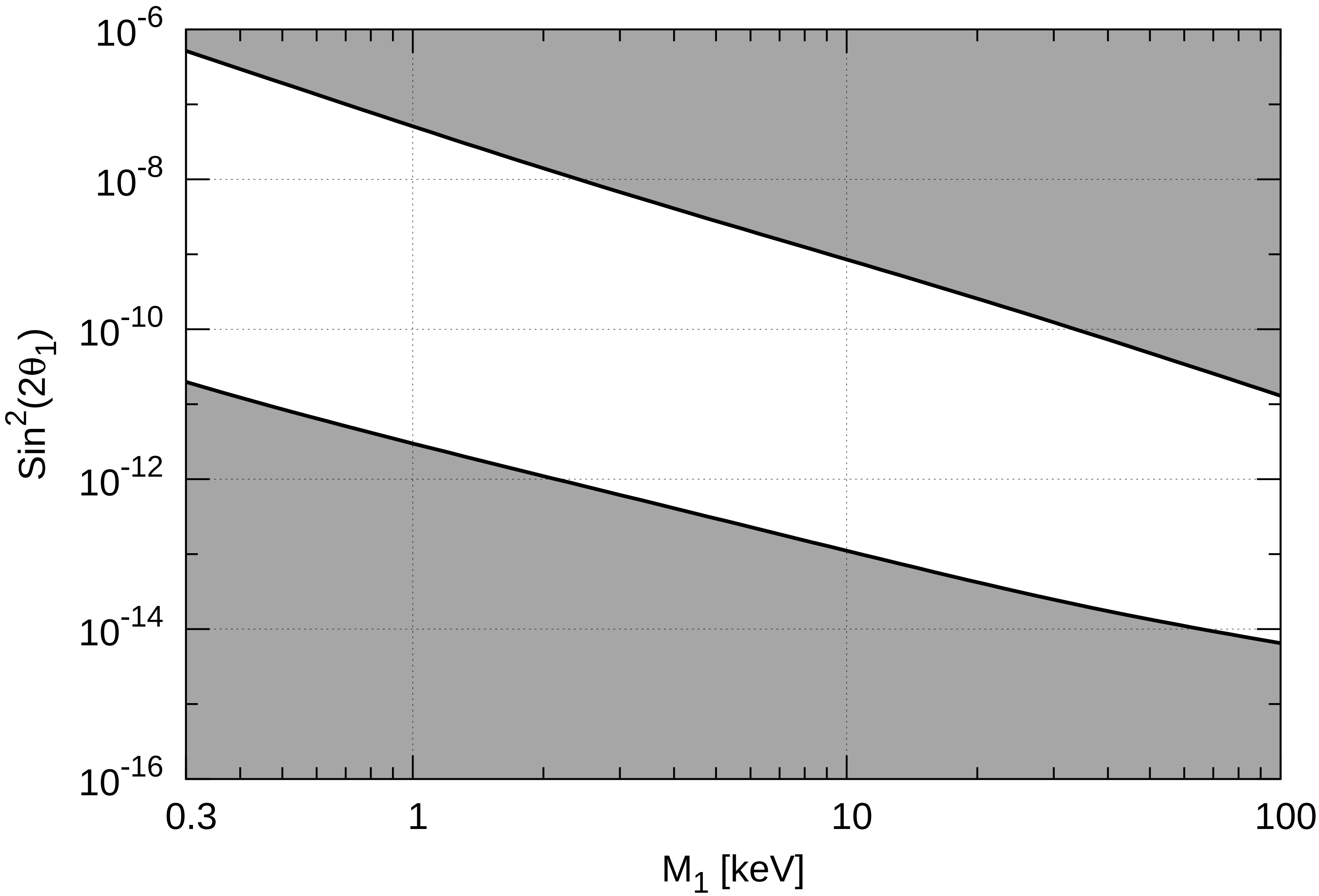
- Parameters of **two** sterile neutrinos are enough to explain baryogenesis and fit the oscillations data:
  - If $M_{2,3} \sim 150$ **MeV** $- 20$ **GeV** and $\Delta M_{2,3} \ll M_{2,3}$ νMSM explains **baryon asymmetry** of the Universe.
  - Neutrino experiments can be explained within the same choice of parameters. See-saw with masses **below** EW scale.
- The third (lightest) sterile neutrino can have cosmologically long life time $\tau = 5 \times 10^{26} \text{sec} \times \left(\frac{\text{keV}}{M_s}\right)^5 \left(\frac{10^{-8}}{\theta^2}\right)^2$
- Can be produced in the early Universe in the right amount:
  - Via active-sterile **neutrino oscillations** — Dodelson Widrow'93
  - Via **resonant** active-sterile neutrino oscillations in the presence of **lepton asymmetries**. (Works well for sterile neutrinos in keV range.) — Asaka, Laine, Shaposhnikov (2006); Shi, Fuller'98
  - In **inflaton** decays. (Can produce sterile neutrinos up to the mass of few MeV) — Tkachev, Shaposhnikov (2006)
- Can play the role of DM (**warm**, **cold** or **mixed**)

Production of sterile neutrino DM



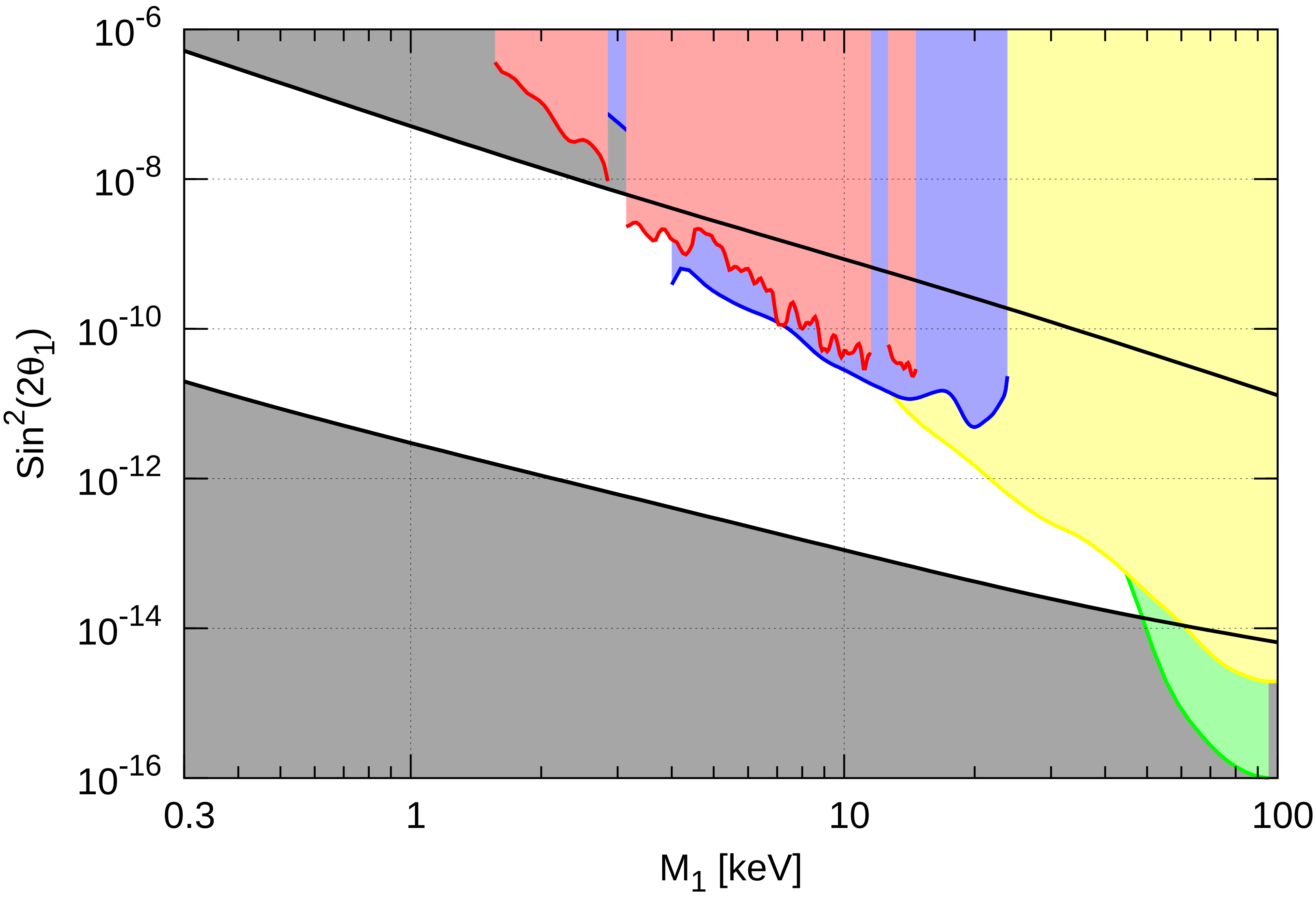
- Sterile neutrino interacts with the rest of the SM matter **only** via coupling with active neutrinos, parametrized by $\theta = \frac{m_D}{M}$
- Interaction is different with and without lepton asymmetry

Window of parameters of sterile neutrino DM

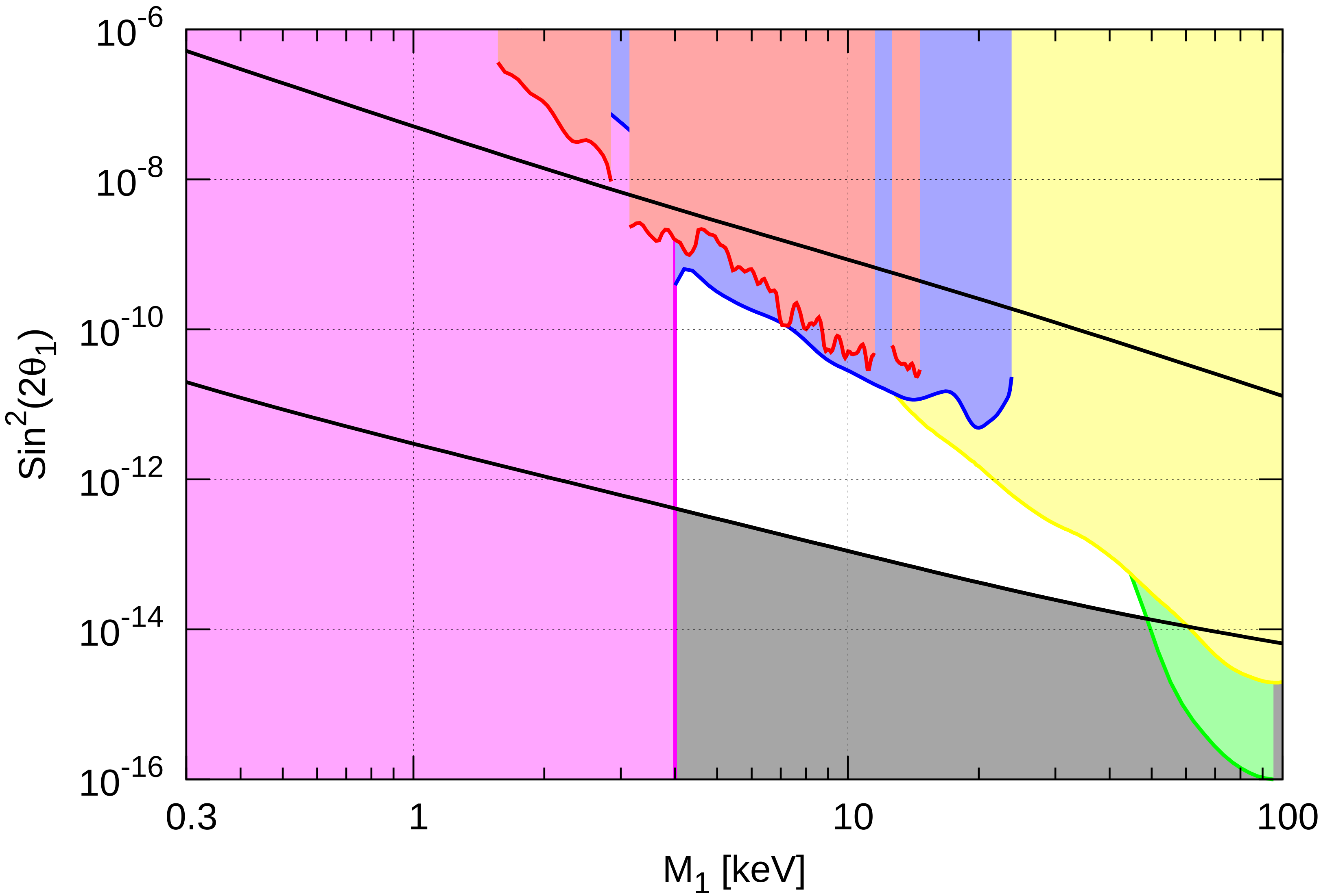


Window of parameters of sterile neutrino DM

Boyarsky, **O.R.** et al. 2008



Window of parameters of sterile neutrino DM



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 “90% 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

How to test this theory?

How to detect heavy sterile neutrinos

- Missing energy signal in $K,\ D$ and B decays (θ^2 effect)
  - $M_N < M_K$: KLOE, NA48, E787
  - $M_N < 1$ GeV : charm and τ factories
  - $1\ \mathrm{GeV} < M_N < M_B$: charm, τ and B-factories (planned luminosity is not enough)

Gorbunov & Shaposhnikov 2007

- Decay processes $N \to \mu^+\mu^-\nu$, etc ("nothing"$\to \mu^+\mu^-$) (θ^4 effect)
  - $M_N < M_K$: Any intense source of K-mesons (e.g. from proton targets of K2K, MiniBooNe or MINOS)
  - $M_N < M_D$: JPARC, MINOS, CNGS beams + very near detector
- $M_N > M_D$: extremely difficult

Laboratory detection of sterile neutrino

- **Creation** and **detection** in the lab: suppressed by θ^4 and hopeless.
- Creation somewhere and **detection** in the lab – θ^2 effect. But the only realistic possibility is to search for radiative decays of sterile neutrino in the DM clouds – not a laboratory experiment.

Bezrukov, Shaposhnikov PRD 2007

- **Creation** in the lab without subsequent detection – the unique option, θ^2 effect.
- Possibilities:
  - Forbidden decays, e.g. $\pi^0 \to N\nu$ – branching ratio is too small. Hopeless.
  - β-decay kinematics: ${}^3H \to {}^3He + e + \bar{\nu}_e$ is not the same as ${}^3H \to {}^3He + e + N$!
- **Full kinematics** event-by-event mass measurement: may work. COLTRIMS technology

νMSM valid up to Planck scale?

- For Higgs masses 129 GeV $< M_H < 189$ GeV νMSM can be consistent quantum field theory up to the Planck scale.

- Thus νMSM describes all particle physics experiments, explains *neutrino oscillations*, provides the *DM candidate* and explains the *baryon asymmetry* of the Universe without introduction of any new scale above the EW scale.

- νMSM (as well as MSM) suffers from the **Landau pole** in the Higgs self-coupling.

- For Higgs mass $M_H < 189$ GeV the Landau pole occurs **above** the Planck scale

- For sufficiently low Higgs masses the νMSM vacuum is unstable. This does not happen (with the cut-off scale $\sim M_{\rm Pl}$) for $M_H > 129$ GeV.

Maiani et al. 1978; Cabibbo et al. 1979

Pirogov & Zenin 1999; Hambye & Riesselmann 1997

Altarelli & Isidori 1994 Casas et al. 1995

νMSM in LHC era

- **If** LHC finds only Higgs boson – the νMSM can be an effective theory up to the Planck scale!
- It introduces no new scale to explain physics $\Rightarrow$ there may be no hierachy problem.
- **If** LHC finds Higgs + new physics — it will not be possible to e.g. to calculate the DM abundance. WDM/CDM/mixed, decaying/annihilating and other properties of the DM still should be tested.
- other aspects of the νMSM should be tested as well
- **If** LHC does not find Higgs – the main predictions of the νMSM are still valid.

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