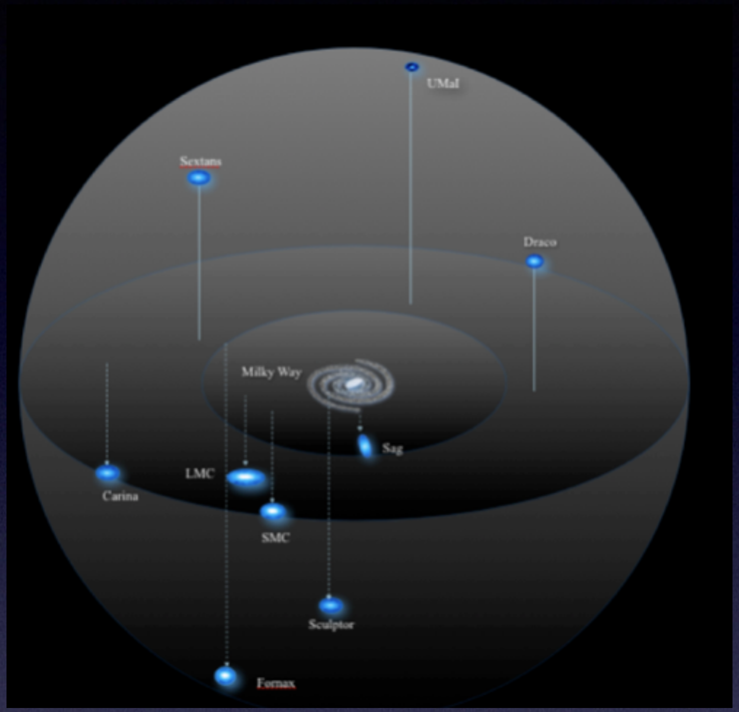
Constraints on particle dark matter from cosmology



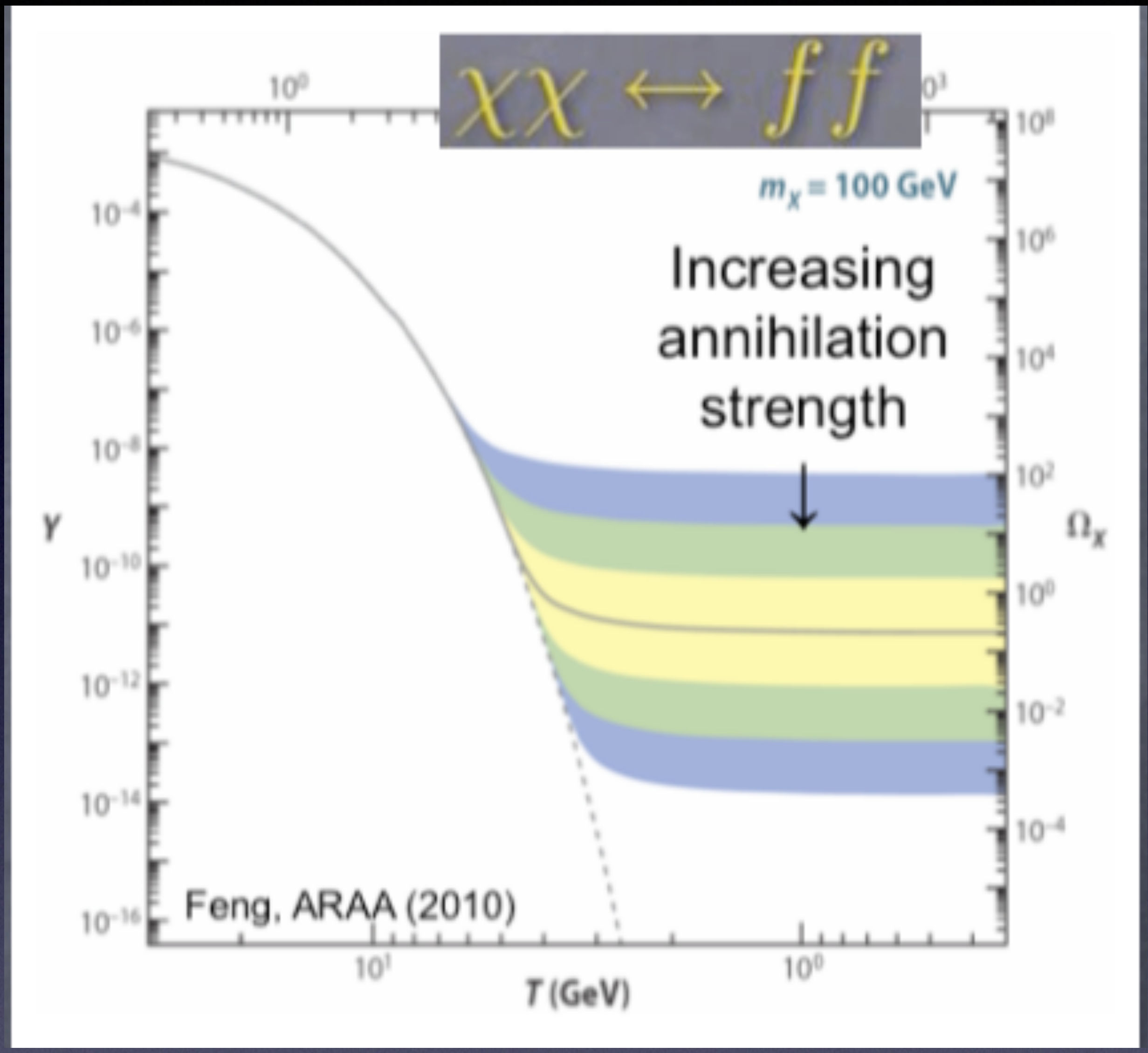
Subinoy Das
Indian Institute of Astrophysics, Bangalore
25/02/2018

Joint astronomy& particles physics meeting
IISER Pune
25/02/2018

Search for Dark matter is
basically finding Lamp Post !

- Need **guess work.** Because we don't know what it interacts with.
- **WIMP Miracle is one such lamp post!** Predicts DM is **cold**(heavy)
- Cosmology puts robust constraints on DM and may even help us design NEW lamp posts if DM is not cold WIMP.

Hubble expansion saves us !



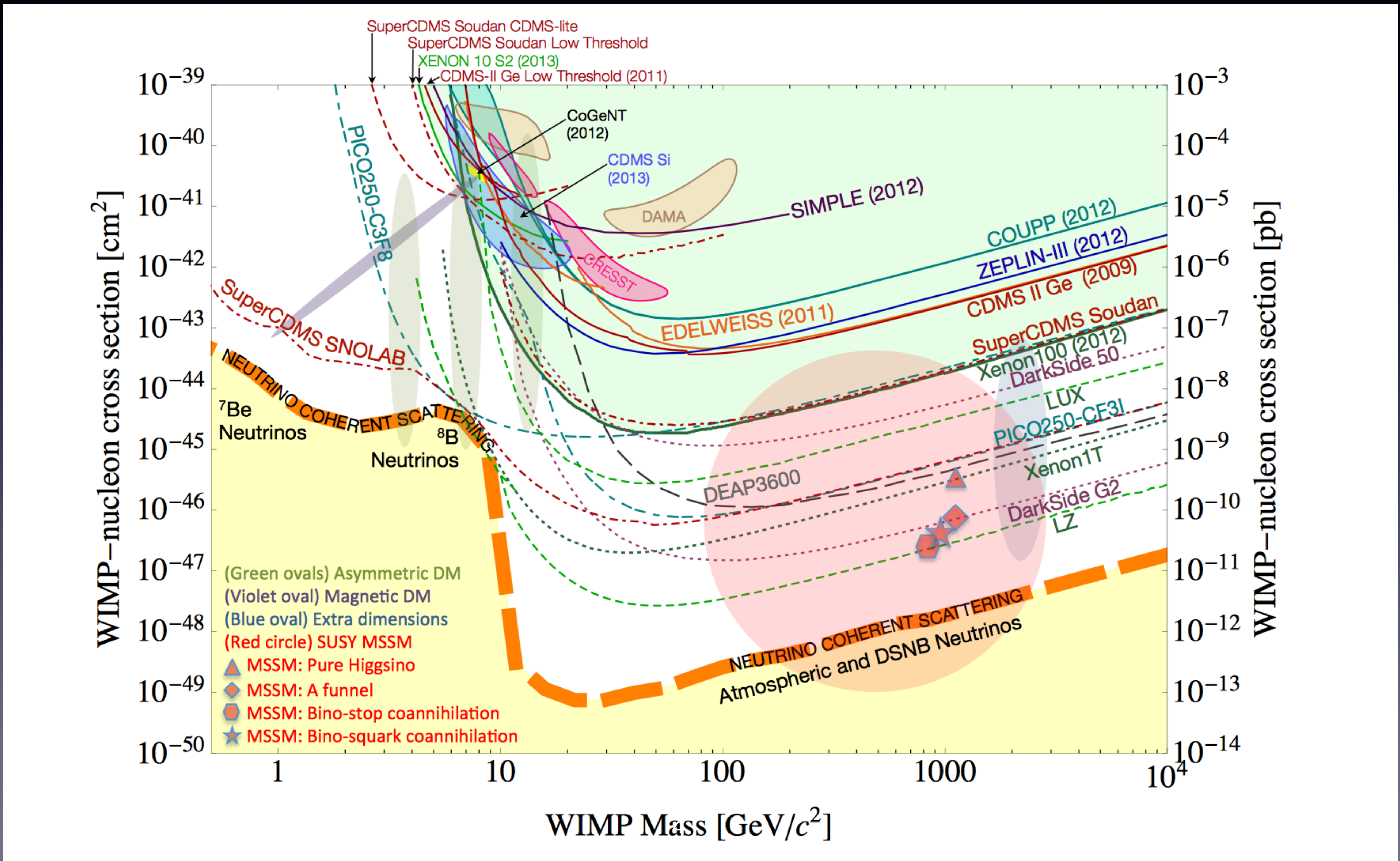
For thermal freeze-out the relation between dark matter relic density and cross-section is remarkably simple

$$\Omega_\chi \propto \frac{1}{< \sigma v >} \sim \frac{m_\chi^2}{g_\chi^4}$$

mass~ 100 GeV
coupling~ 0.6

$\Omega_\chi \simeq 0.1$

STATUS OF WIMP ? (NOT SO GOOD)

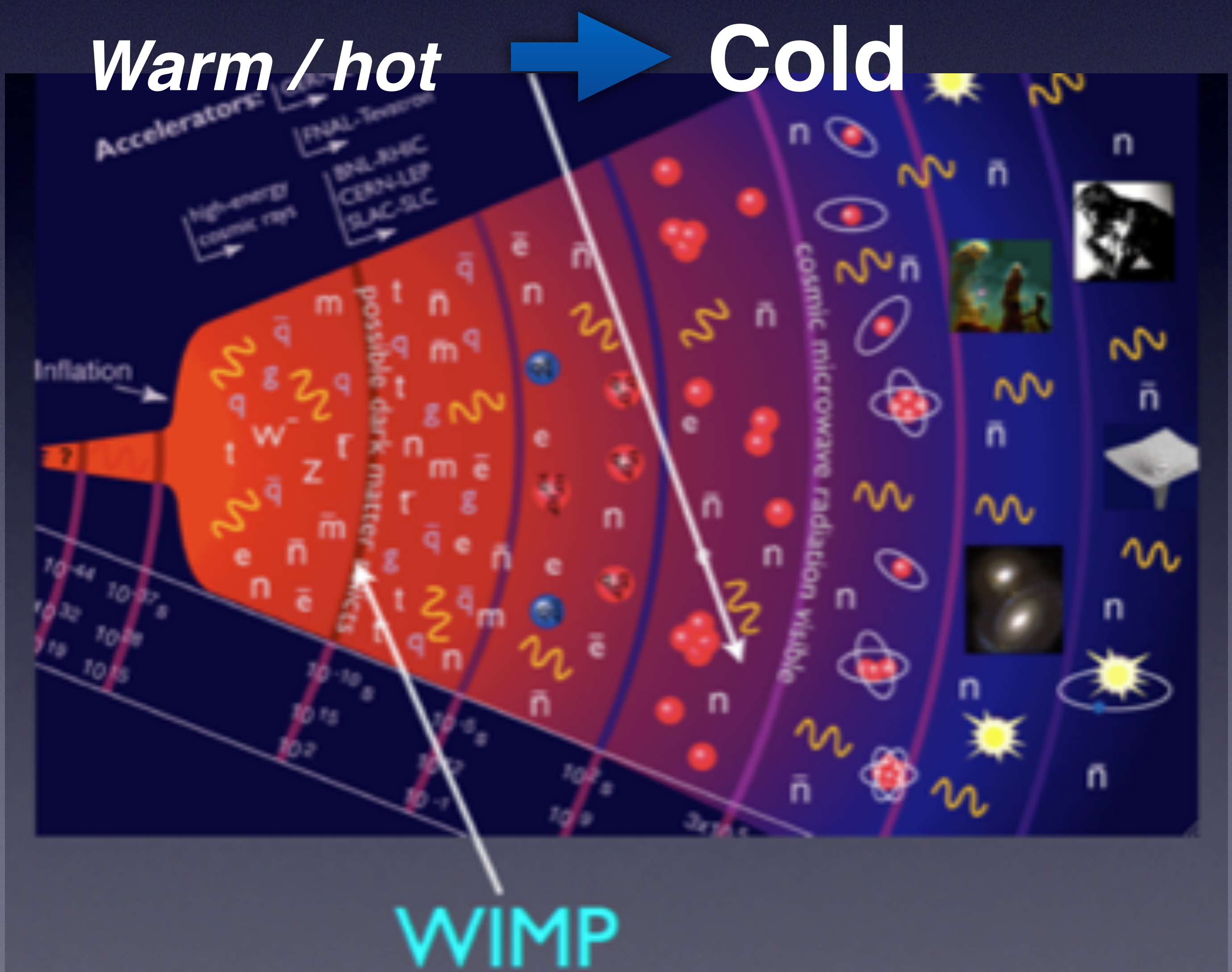


: *Model Independent limits:*

Astrophysical constraints on any DM models

- Free-streaming of Dark matter: Whatever be the DM particle, it's better be *cold* z_f< 10^5 or T~ 25 eV (SDSS), z_f < 9 x 10^5 (Ly-alpha) to T~ 200 eV

Sarkar, SD, Sethi JCAP



: ***Model Independent limits:***

For Decaying DM

- stability: if a fraction of dark matter is decaying over cosmological time scale

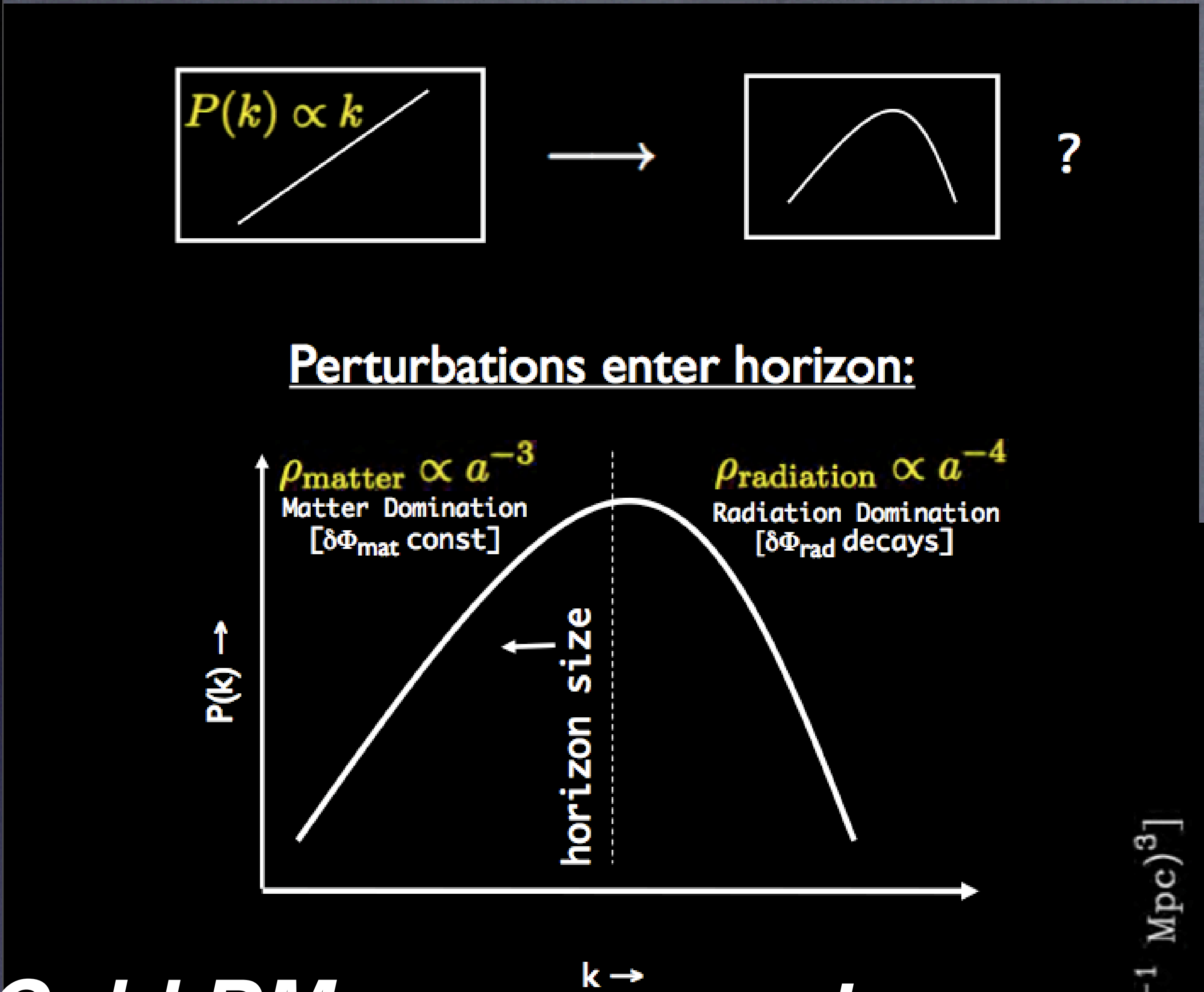
$f_{DM} \times \Gamma_D M \leq 0.086/\tau_U$ *1606.02073 (From CMB alone) J. Lesgourgues et al.*

1605.03928 (CMB + reionization) D. Schwarz et al.

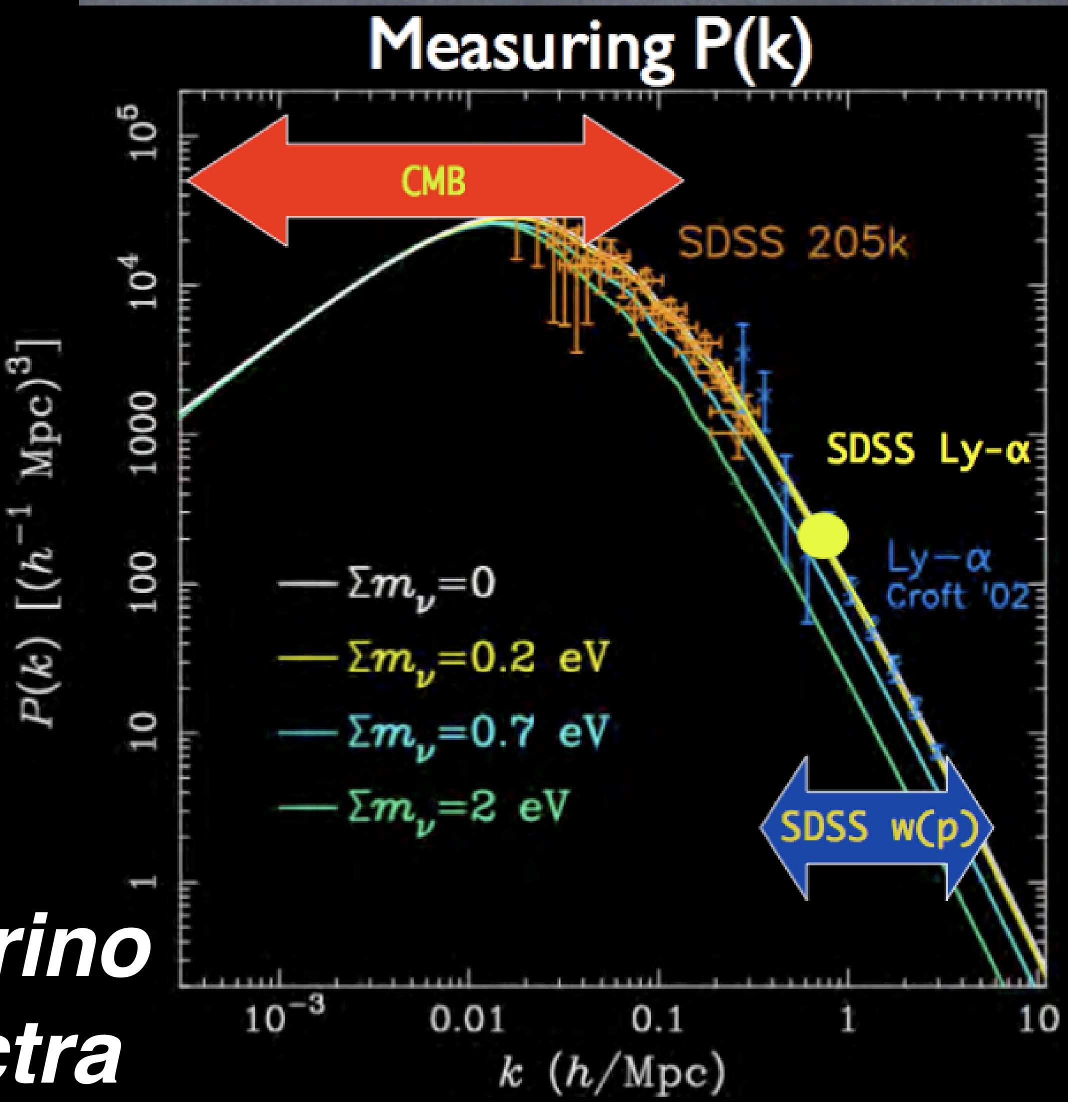
For DM having extra interaction in dark sector

- For long range dark force (violation of **equivalence principle**) disruption of dSpH galaxies in Milkyway[7] : *strength of the force < 0.2 of grav*
  (Kesden + Kamionkoswki et al.)

Evolution of density fluctuation

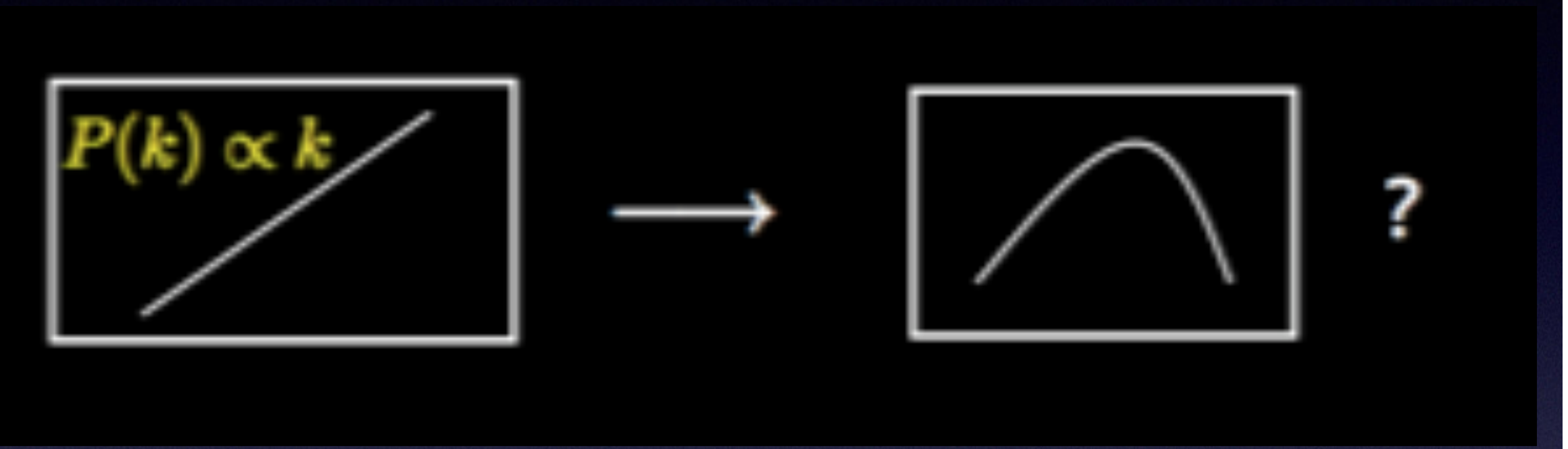


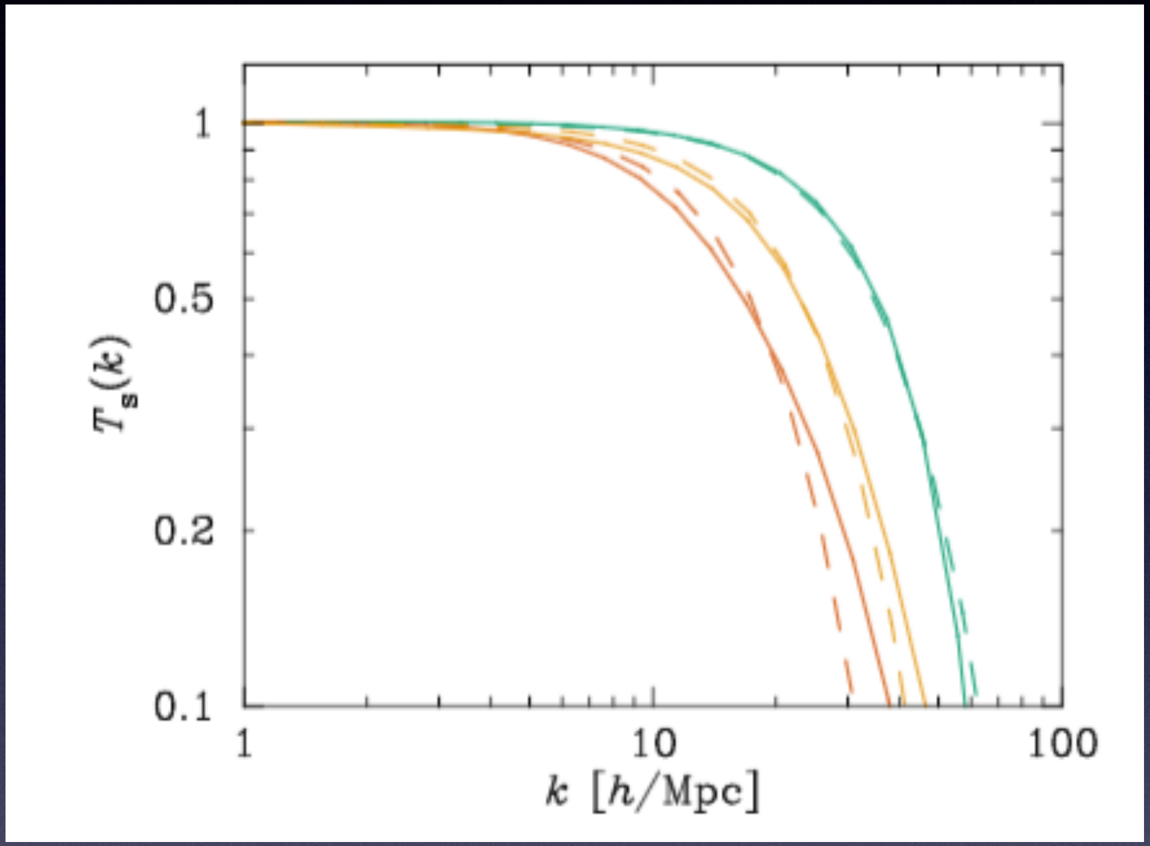
Cold DM power spectra



CDM + neutrino power spectra

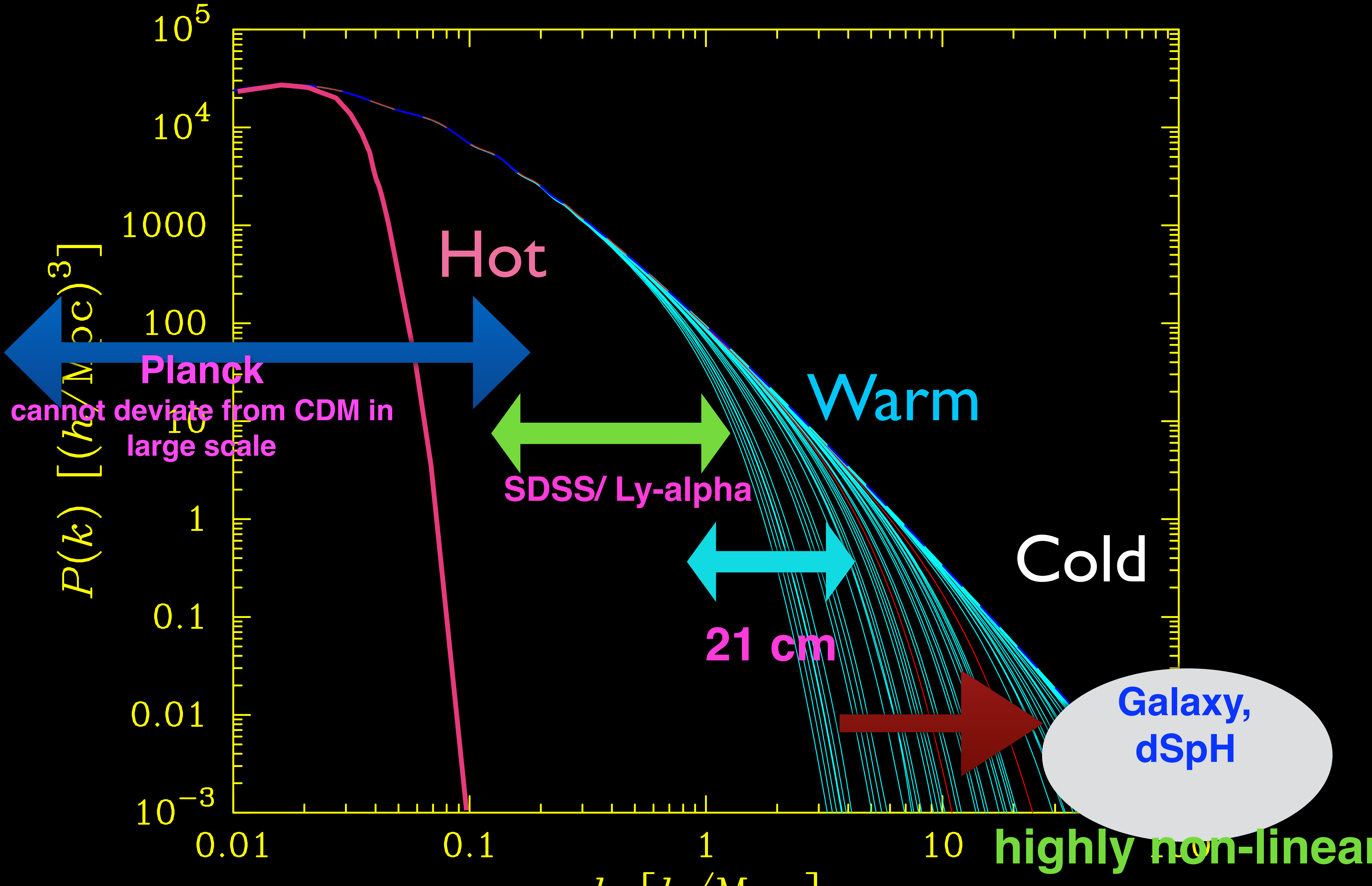
Transfer function T(k): contains same information as P(k)



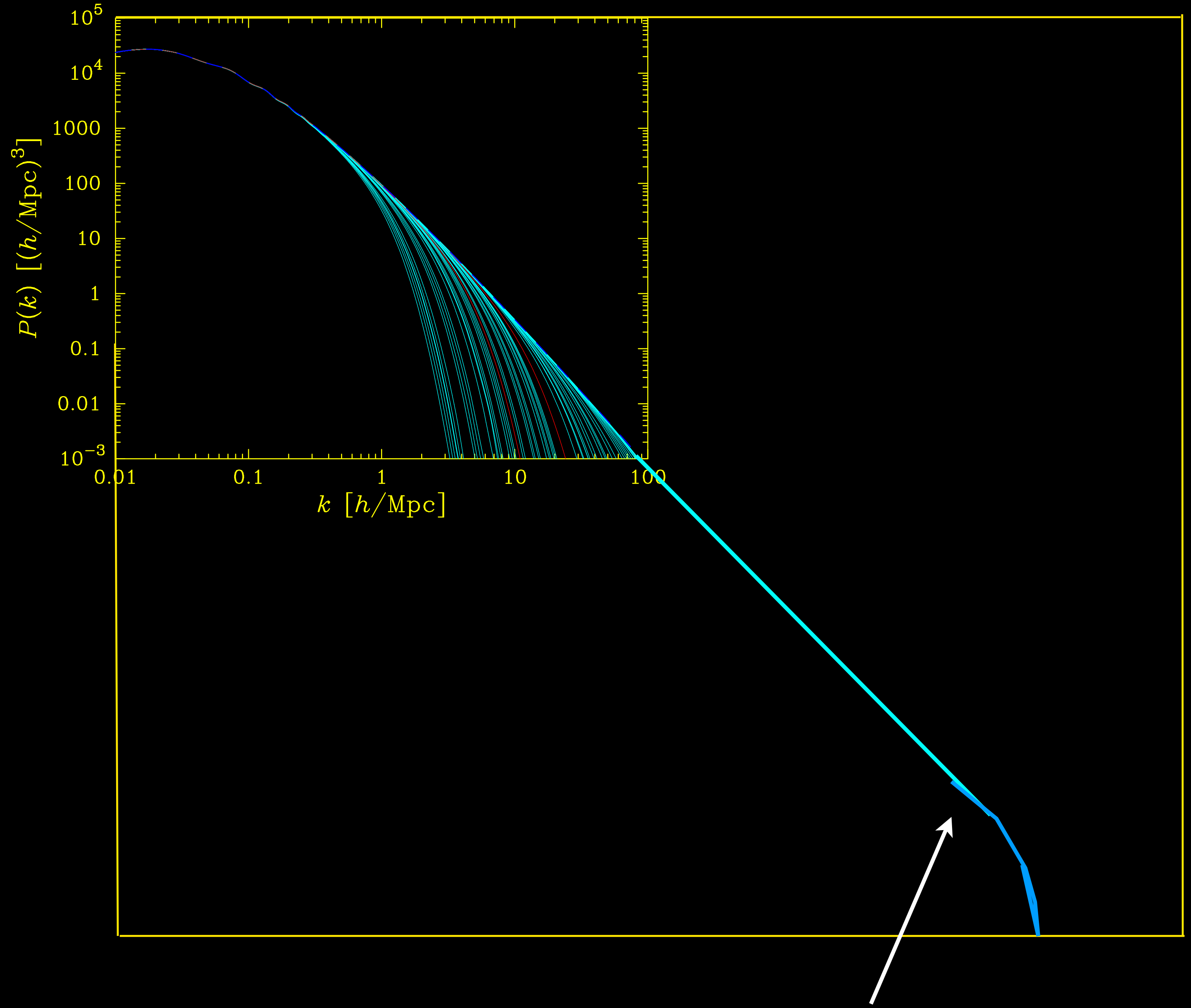


Smaller scales

What is the clustering behavior of dark matter to the smallest scales?



Canonical Cold Dark Matter



WIMP CDM

$k_c \sim 10^6\ h\,/\mathrm{Mpc}$

(Zaldarriaga & Loeb 2006)

Transition from hot / warm to CDM

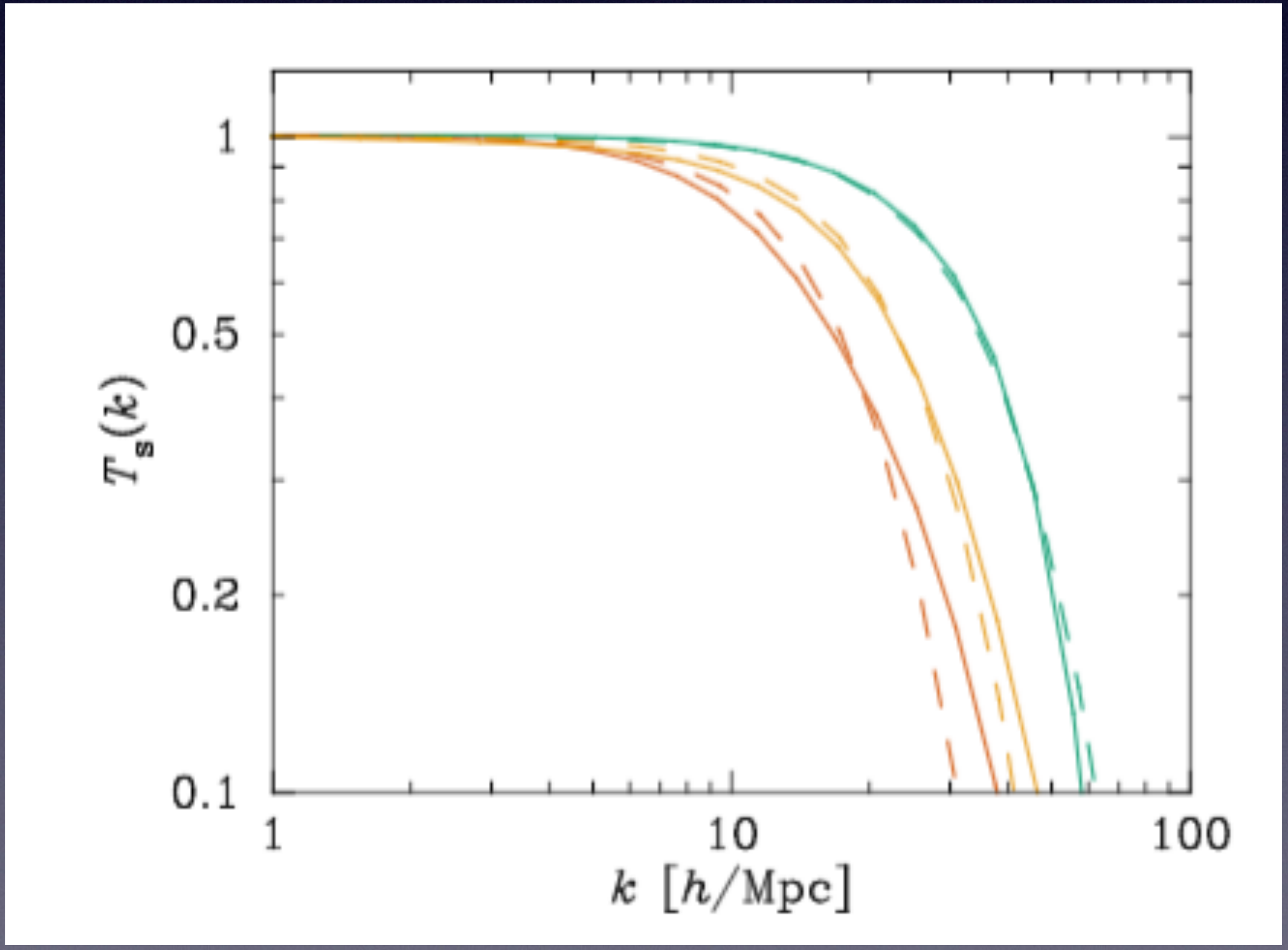
- Can be controlled by mass m ~ T.
  This is case of well known **keV WDM**

- Can be controlled by New Physics
  between BBN and CMB : **Axion** like particle

- Similar effect on P(k) possible through
  dark acoustic oscillation **DAO** between **CDM** and **DR**

Constraints on Sterile neutrino WDM

- Thermal WDM : keV particle like thermalised neutrino
- Produced later through active -sterile oscillation:
  Dodelson-Widrow / Shi-Fuller mechanism



Mapping between two case

Thermal	Resonant
1.6 keV	4.6 keV
2 keV	7 keV
2.9 keV	8 keV

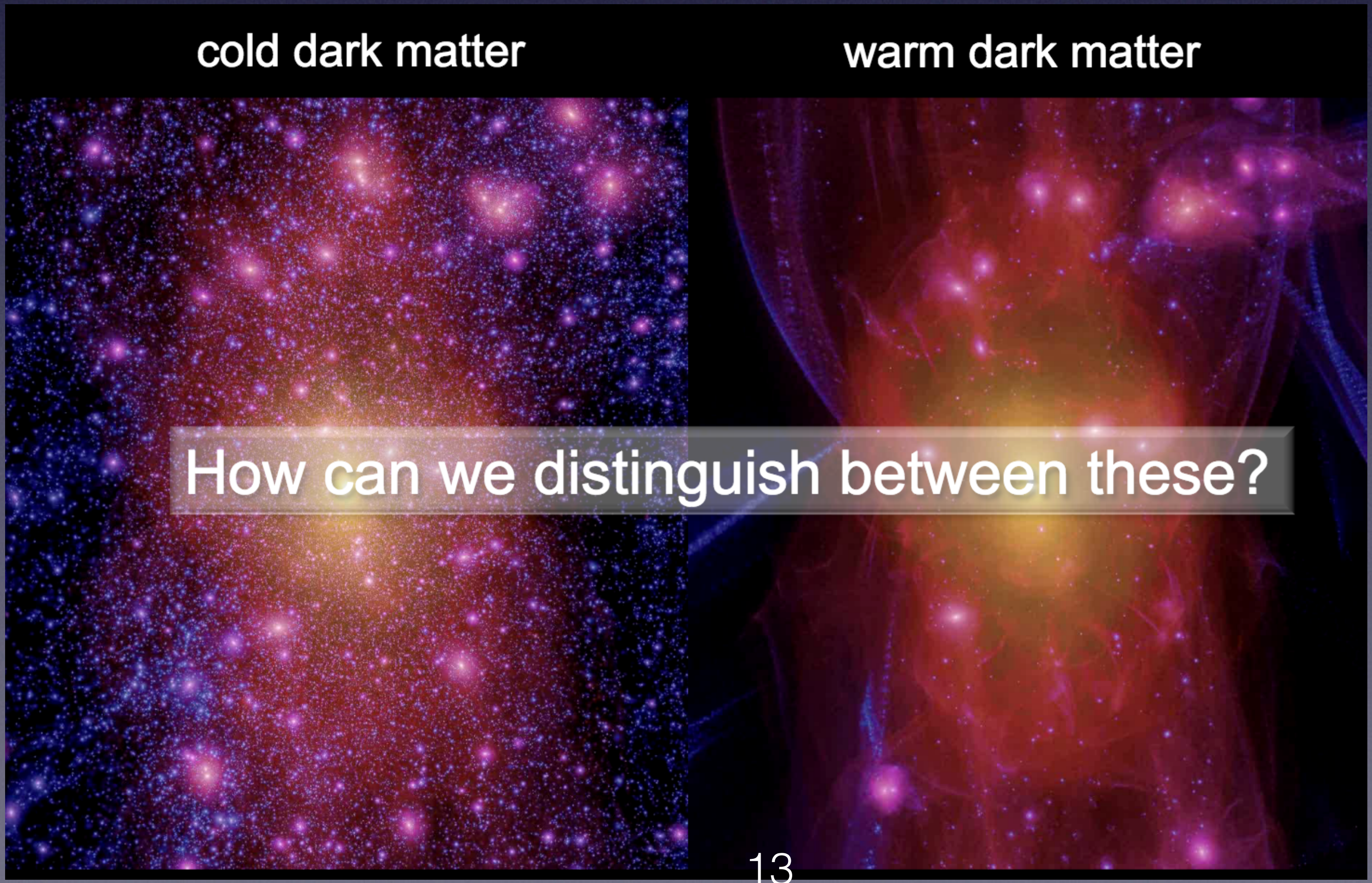
arxiv:1403.0954, PRL by Kevork Abazajian

Mass of DM?

All of these mass below give the same cosmological DM density.

- If DM mass is 100 GeV - 1 particle @ tea cup
- If DM mass is keV - 100 million particle @ tea cup
- If DM mass is neutrino like - 100 billions particle @ tea cup

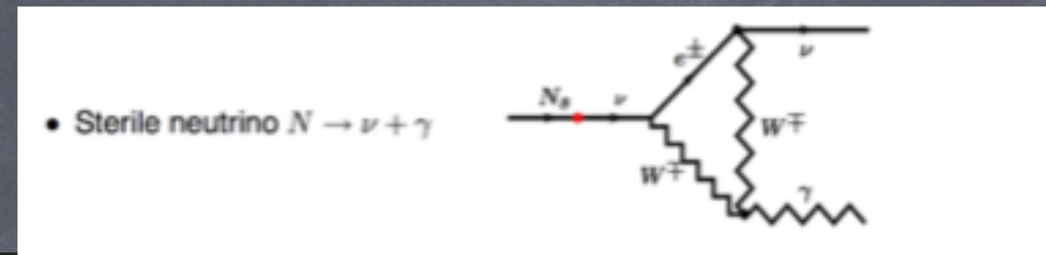
All are ok to give exact DM abundance but …N-body simulation



Some facts about WDM simulation

- N-body Simulation is very sensitive to WDM mass. Eventually , WDM is a too much of a good thing, over suppressing dwarf galaxy scale.
- m_wdm = 0.8 keV ruled out by $10\,\sigma$
  m_wdm = 1.7 keV -2 keV is sweet spot of N-body simulation. But might be in tension with Ly-alpha experiments.
- Cusp vs core may be resolved. But core size is smaller in WDM simulation.

SMOKING GUN



E_x-ray ~ m_N / 2

Has found an un-identified line at 3.5 keV from Andromeda galaxy and persius galaxy cluster.

(Absent in blank sky data set.. but also in Vergo not found)

Sattelite x-ray telescope : XMM-Newton

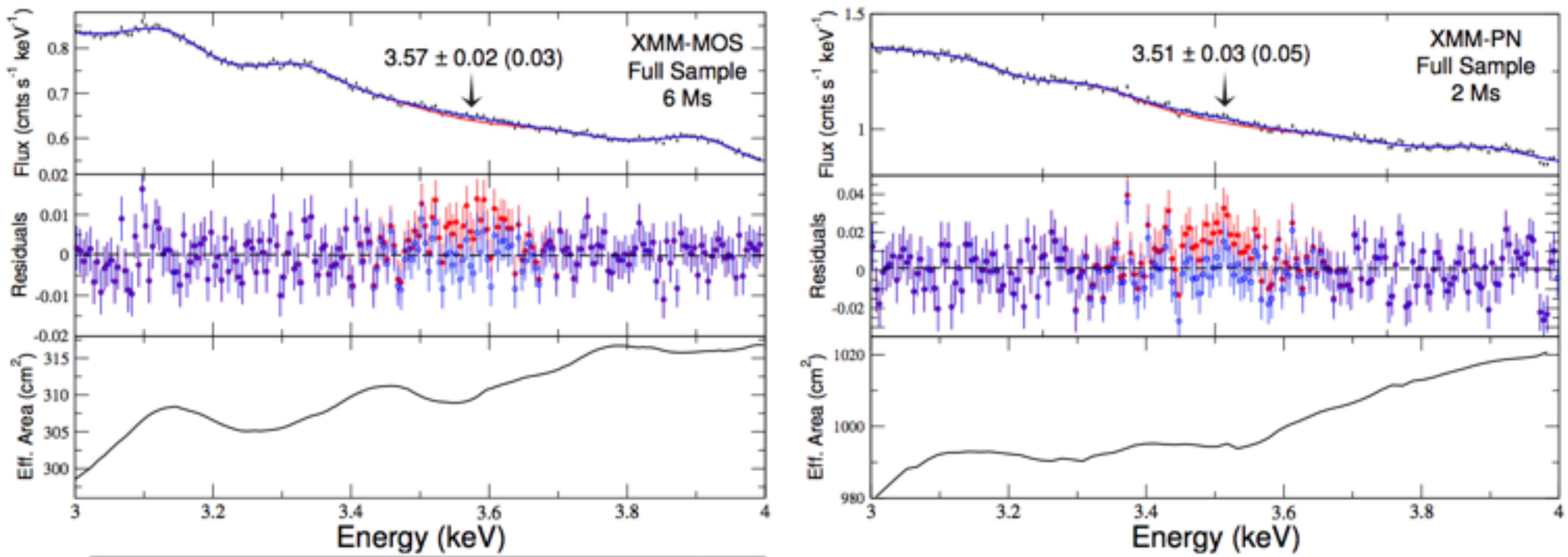
Possible explanation

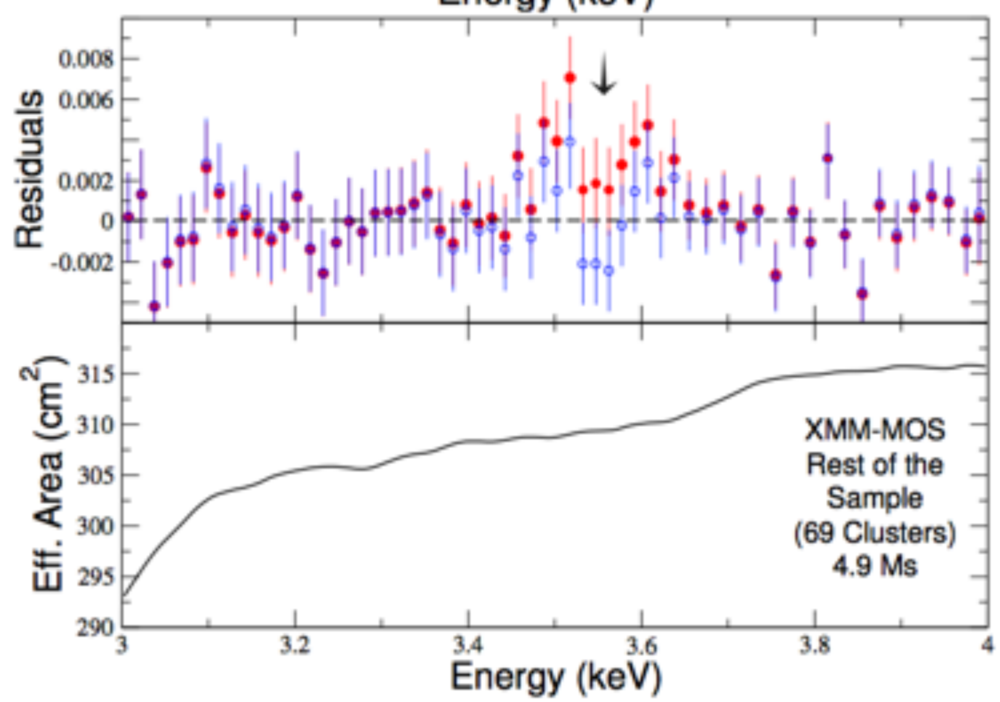
Non-thermal sterile neutrino 7 keV WDM decay to two 3.5 keV xray photon.

arXiv:1403.0954,PRL, Kevork Abzajian

Full stacked spectra

Bulbul et al. [1402.2301]





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- Instrumental background processed similarly and **subtracted**

Significance

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Bulbul et al. 2014

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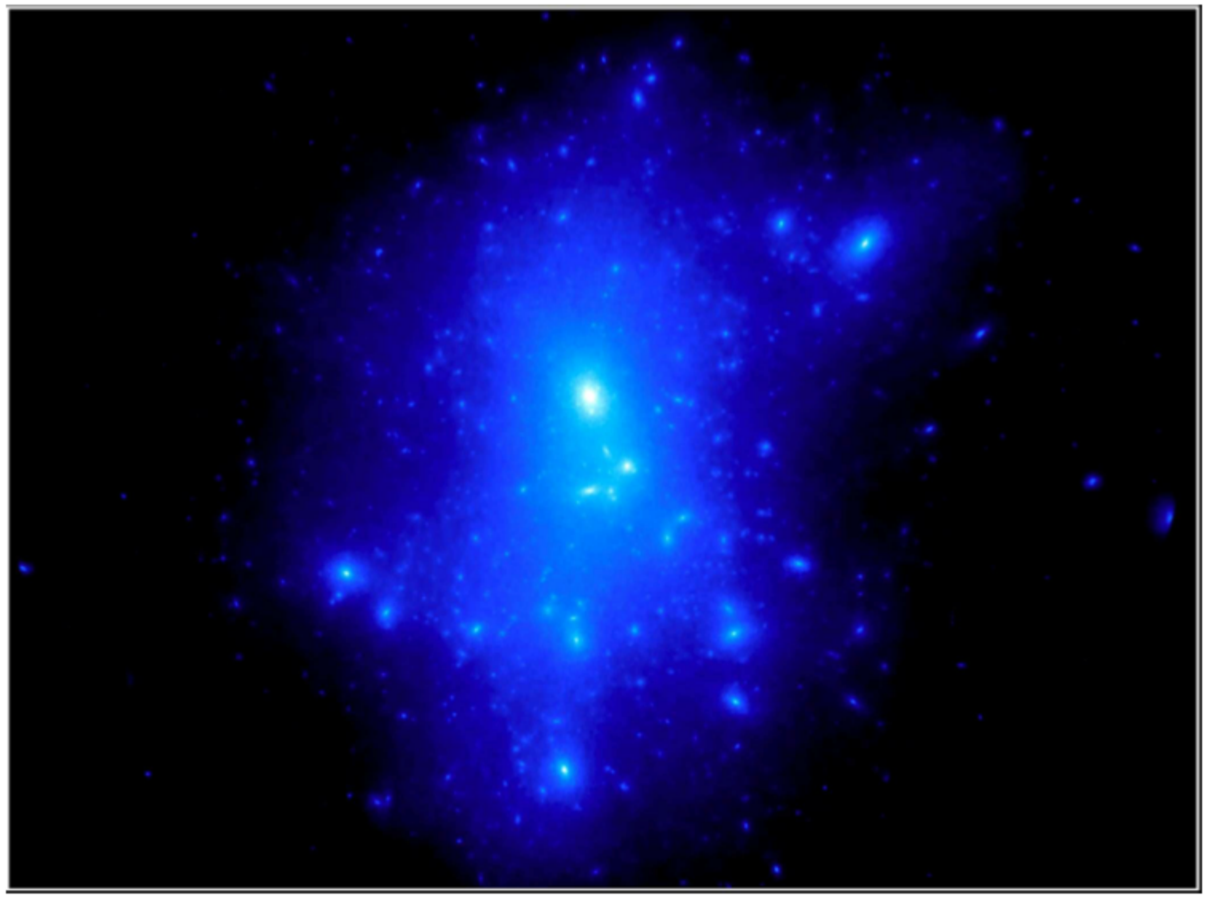
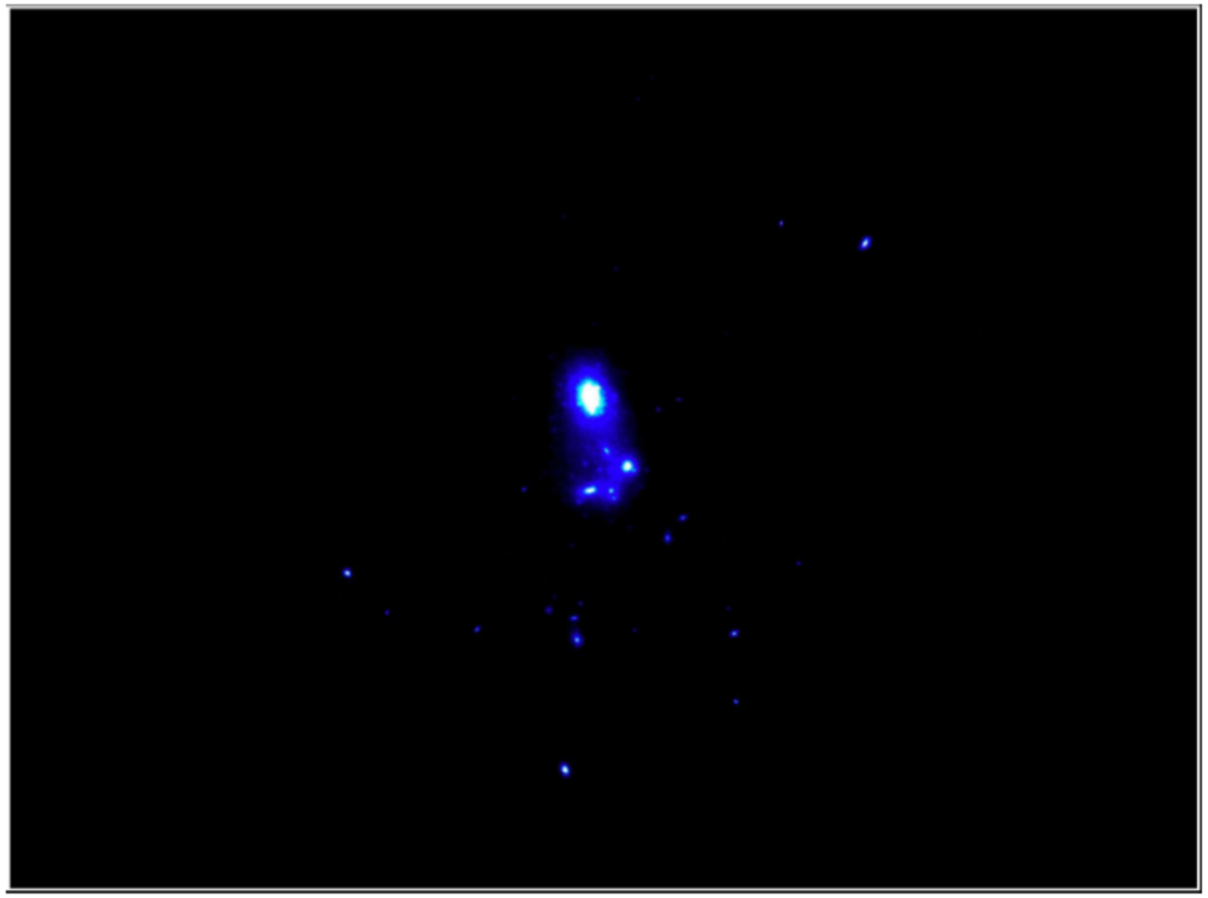
Decay vs annihilation

Decay signal depends on density.
Annihilation depends on density^2

Search for decaying dark matter



DM **decay** signal from a galaxy



DM **annihilation** signal from a galaxy

Transition from hot / warm to CDM

- Can be controlled by mass m ~ T. This is case of well known **keV WDM**

- Can be controlled by New Physics between BBN and CMB : **Axion** like particle / ***Late forming*** DM

- Similar effect on P(k) possible through dark acoustic oscillation **DAO** between **CDM** and **DR**

On the Mass of Dark matter particle !

All of the masses below give correct relic density

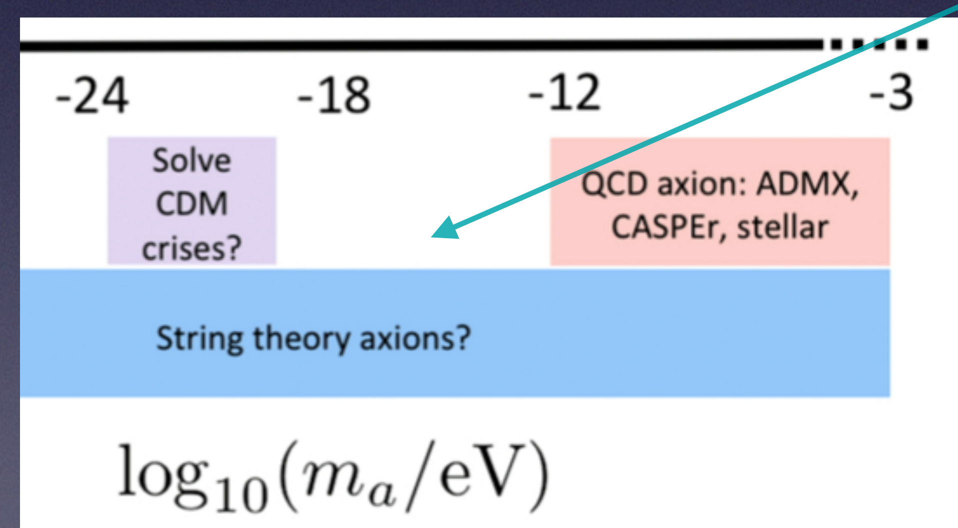
- If DM mass is 100 GeV - 1 particle @ tea cup (challenged by density profile
- If DM mass is keV - 100 million particle @ tea cup (a part got ruled out)
- If DM mass is neutrino like - 100 billions particle @ tea cup (Ruled Out)

Scalar DM (Axion / axion like particle)

$$\ddot{\phi} + \boxed{3H}\dot{\phi} + m_a^2\phi = 0$$

Hubble friction
→ Freezes field

gravity wave+
Spectral distortion



m_a ~ 10^-21 eV (de Broglie wavelength 1 Kpc)

Cold fuzzy DM (Lam Hui , E Witten 2016, M Kamionkowski et al. 2017
SD, S Sethi, A Sarkar, D Marsh 2017)

$H > m_a \Rightarrow w_a \approx -1$

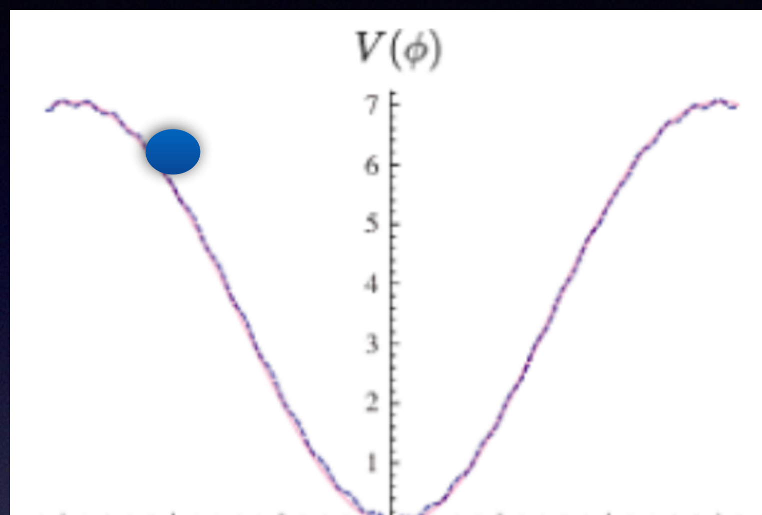
Hubble friction → no clustering.

$\ddot{\phi} + 3H\dot{\phi} + m_a^2\phi = 0$

Hubble friction
→ Freezes field

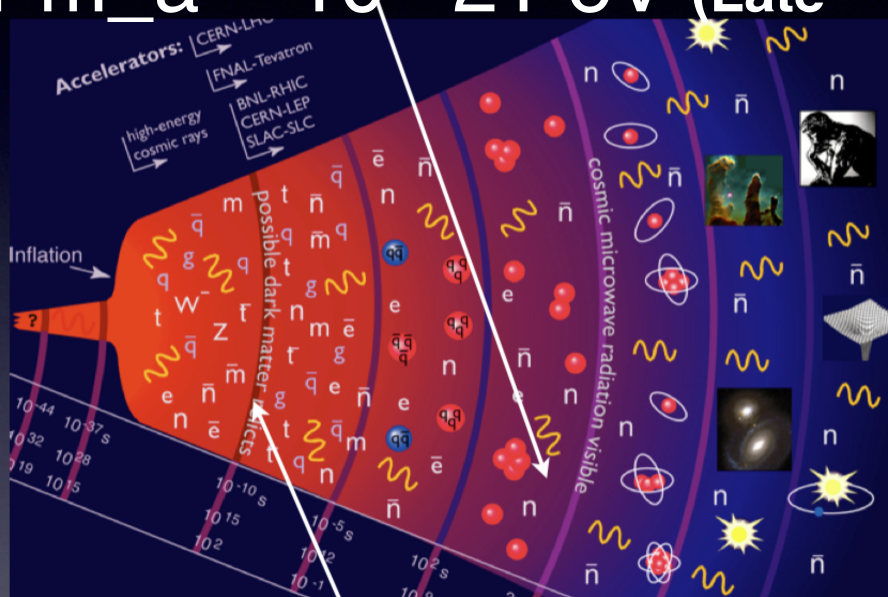
e.g. Svrcek & Witten (2006)
Arvanitaki et al (2010)

@ m_a = 3H , starts to oscillate
Behaves like CDM.



Also solves core-cusp issue due to quantum pressure

For m_a ~ 10^-21 eV **(Late**



WIMP

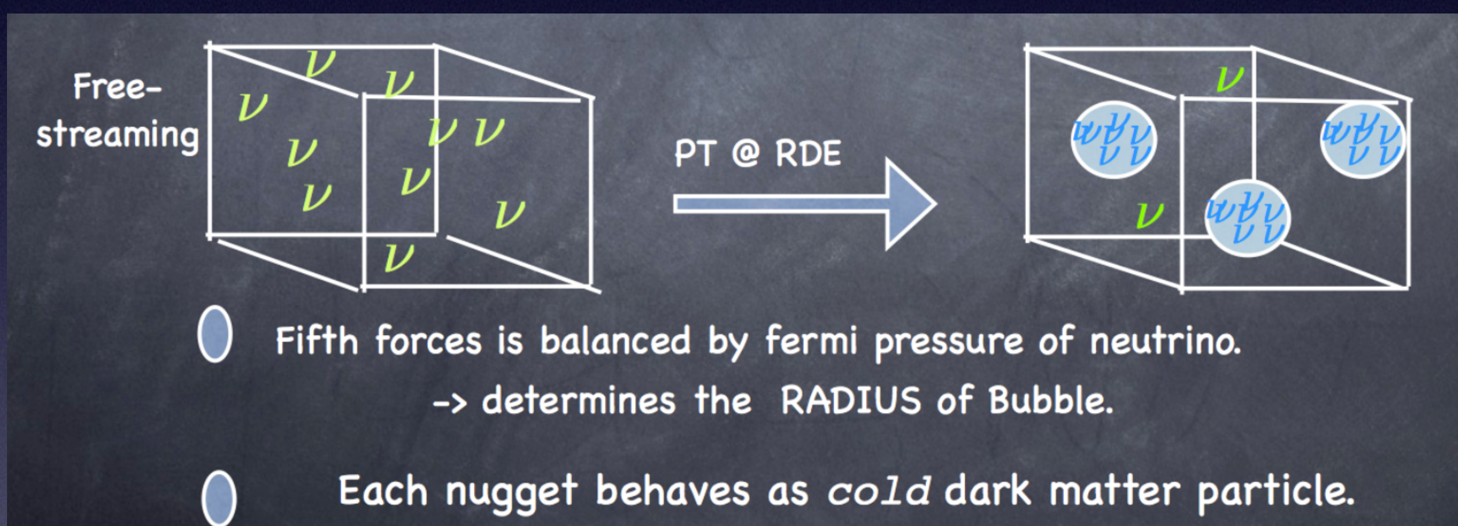
m_a ~ T^2 /m_pl
vs
m_wdm ~ T

Dark matter from light sterile neutrino nuggets

Phase transition in thermalised sterile neutrino
in presence of scalar interaction

SD, K. Sigurdson (UBC)

Radiation to matter transition:



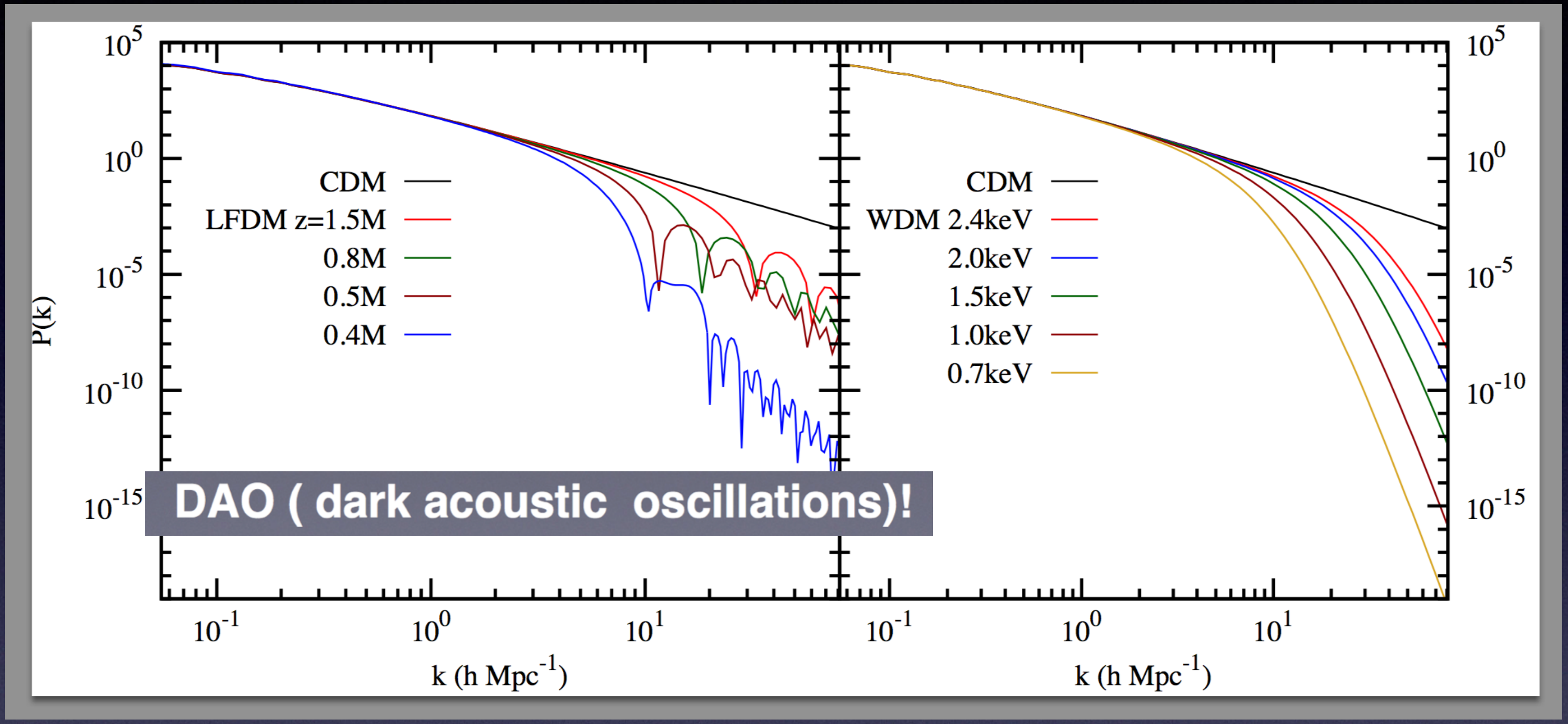
a fractional dark radiation ΔN_{eff}

is enough

eV sterile states can hide
from Planck

Idea: Instability in MaVaN dark energy
(Zaldariaga and afshordi)

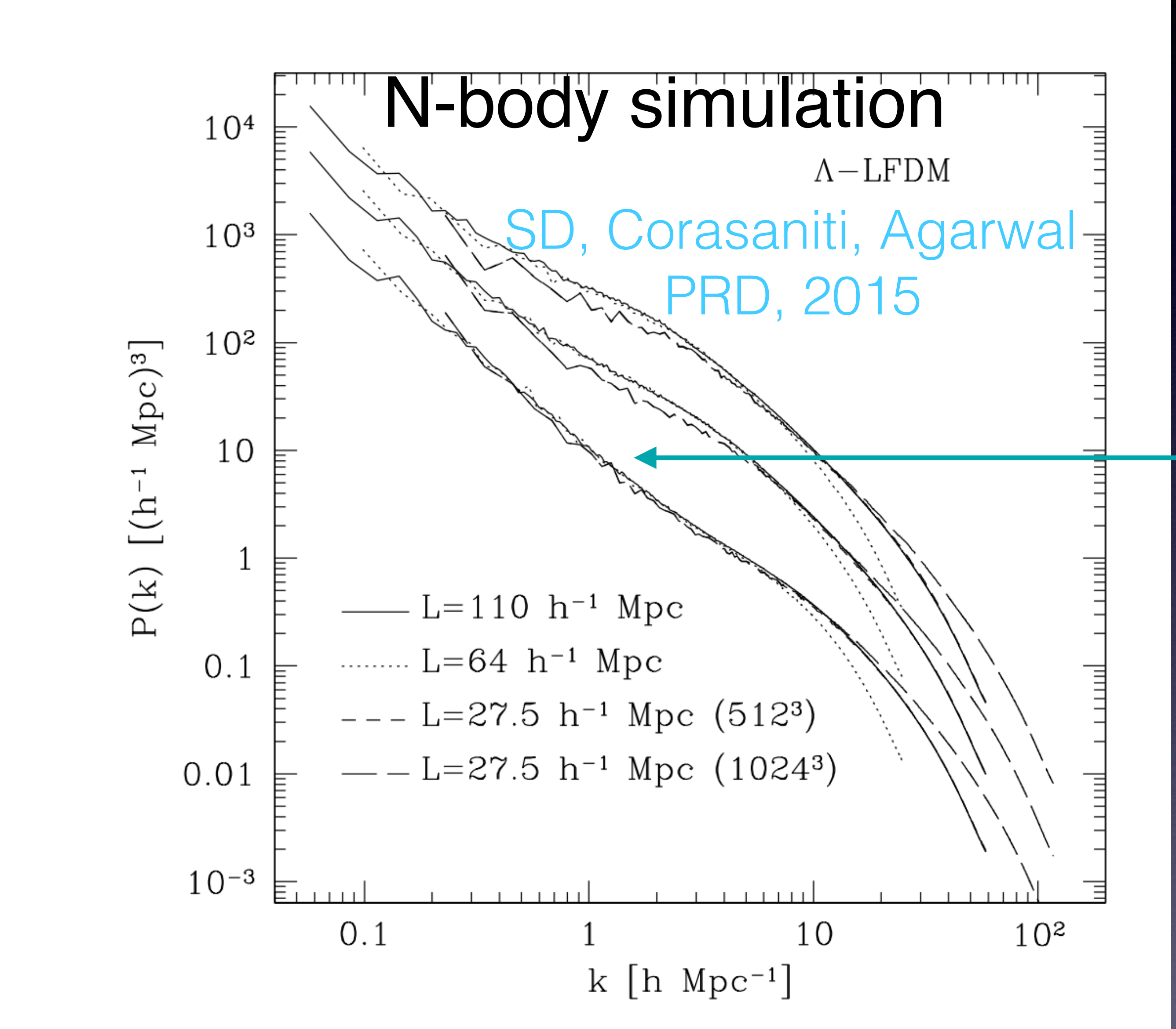
Signature of new physics in p(k)



- If a relativistic fluid (dark radiation) transits to CDM state at redshift z_f (SD, Neal Weiner PRD,2011, M kamionkowski 2008)
- If CDM interacts with dark radiation (B Dasgupta 2015)
- String axiverse (ULA). Controlled by mass m_a ~ H. From C.C to dark matter transition (Avnirtaki, D. Marsh (2016), Lam Hui, Ed. Witten,2016)

Caveat !

Small scales perturbation evolve till today and become highly non-linear from z= 3 or 4 onwards!



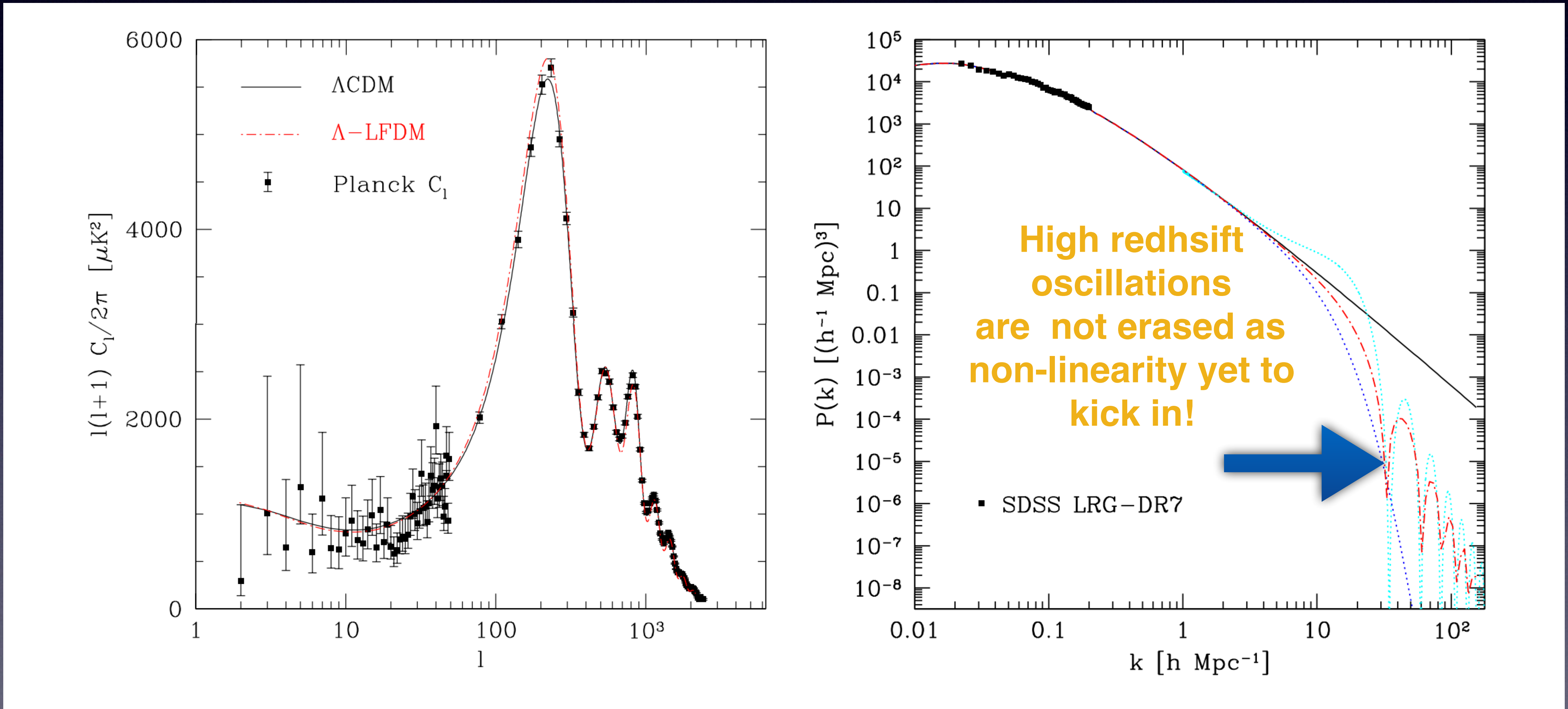
z=0,1,3

Almost all the oscillations are erased due to non-linear effects.

Thats why SDSS at local redshift not effective

BUT (early epoch)High redshift 21 cm signal (z= 7-10) will probe this features with linear power spectra.

Importance of SKA for dark matter search!



In collaboration with Marc Kamionkowski (JHU) and Shiv Sethi (RRI) and Adrienne (UNC, Chapel Hill)

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➡ Similar effect on P(k) possible through
dark acoustic oscillation **DAO** between **CDM** and **DR**

Results from Planck (March,2013)

- Planck combined with WMAP polarisation gives

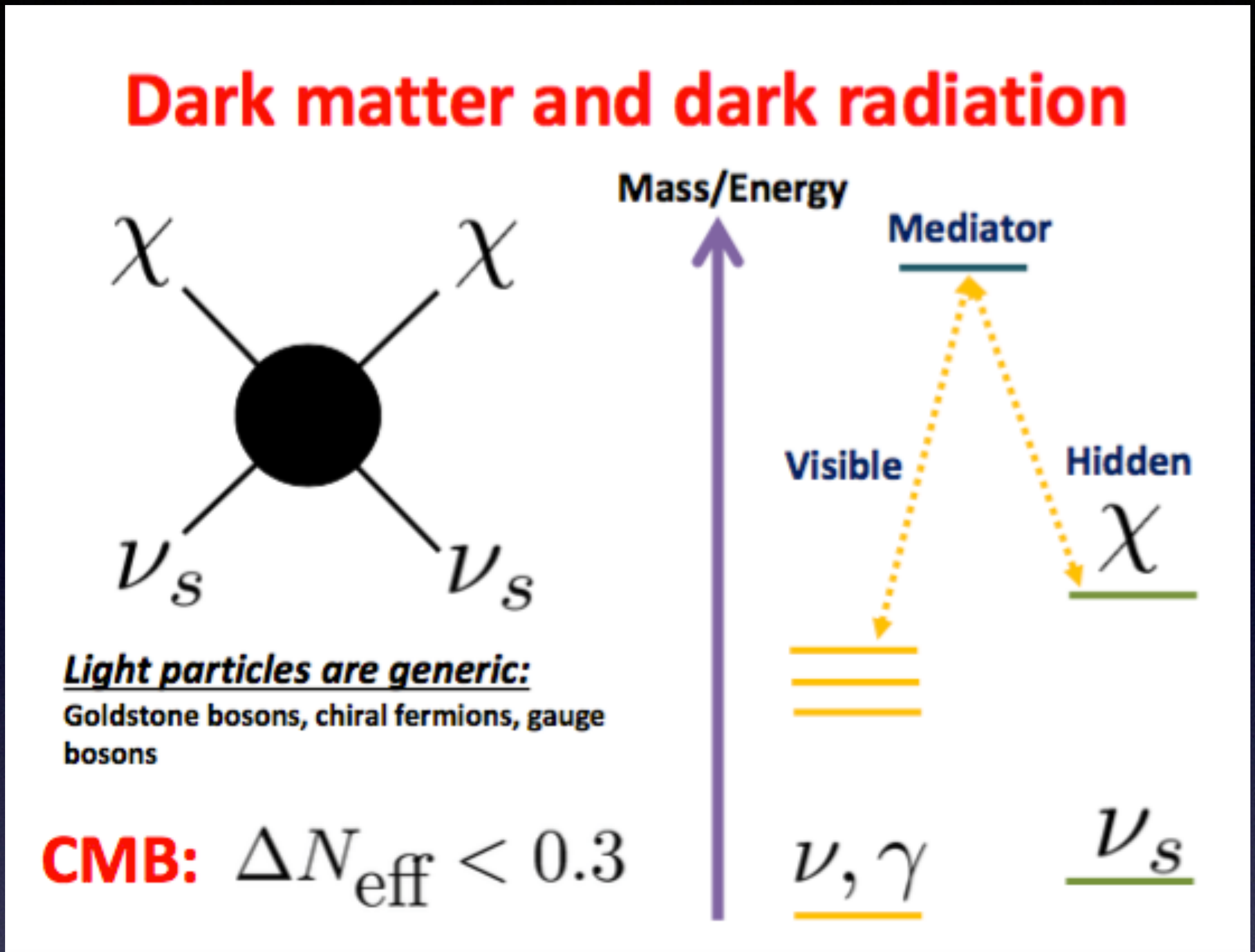
$$N_{\rm eff}^{\rm Planck} = 3.36 \pm 0.34$$

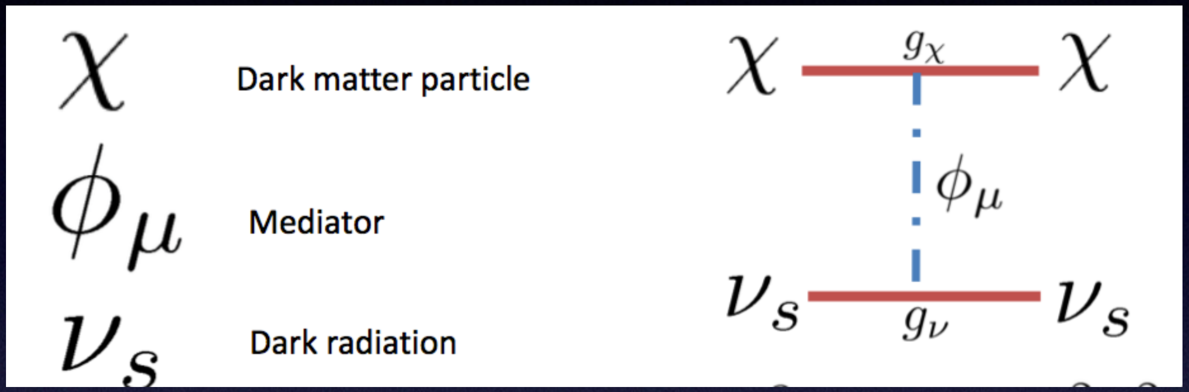
- Planck combined with astrophysical Hubble constant measurement (HST) gives

$$N_{\rm eff}^{\rm Planck} = 3.62 \pm 0.25$$

So, a fractional dark radiation ΔN_{eff} component is not ruled out (highly possible)

- On the other side, anomalies from neutrino oscillation experiments may strongly hint for O(1) ΔN_{eff}





$$n\sigma \sim a_4 T^{4+1} \qquad T \sim (1+z)$$

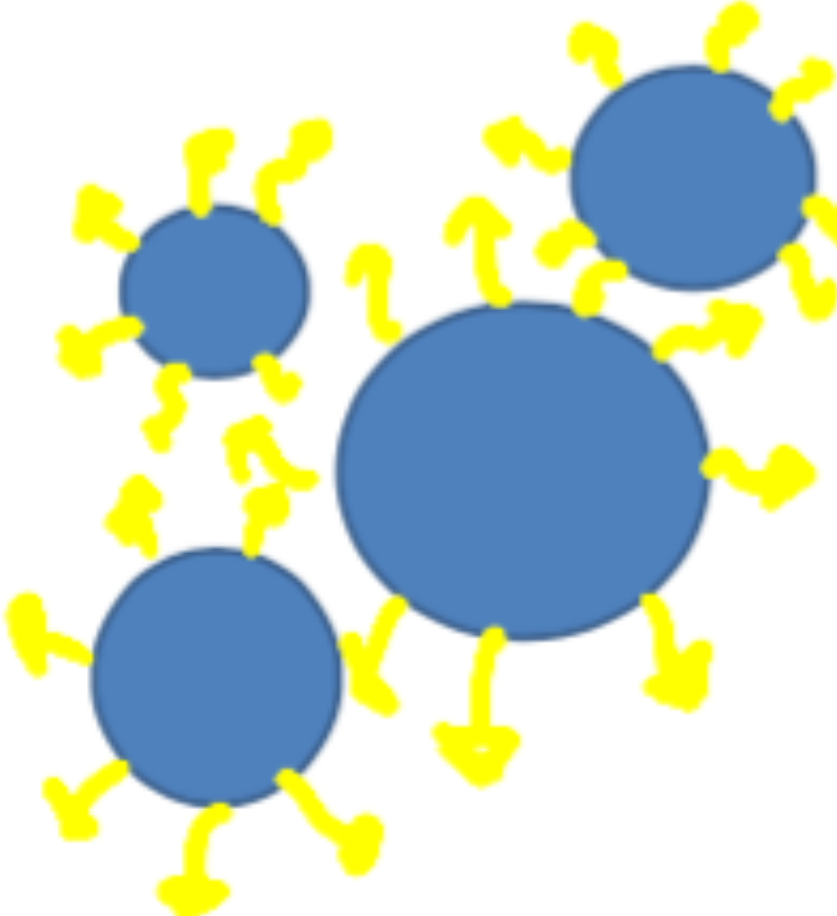
$$a_4 = 0.4 \times 10^5 \left(\frac{g_\chi}{1}\right)^2 \left(\frac{g_\nu}{1}\right)^2 \left(\frac{0.5\ \mathrm{MeV}}{m_\phi}\right)^4 \left(\frac{2\ \mathrm{TeV}}{m_\chi}\right)\ \mathrm{Mpc}^{-1}$$

From structure to reionization

Parameters:

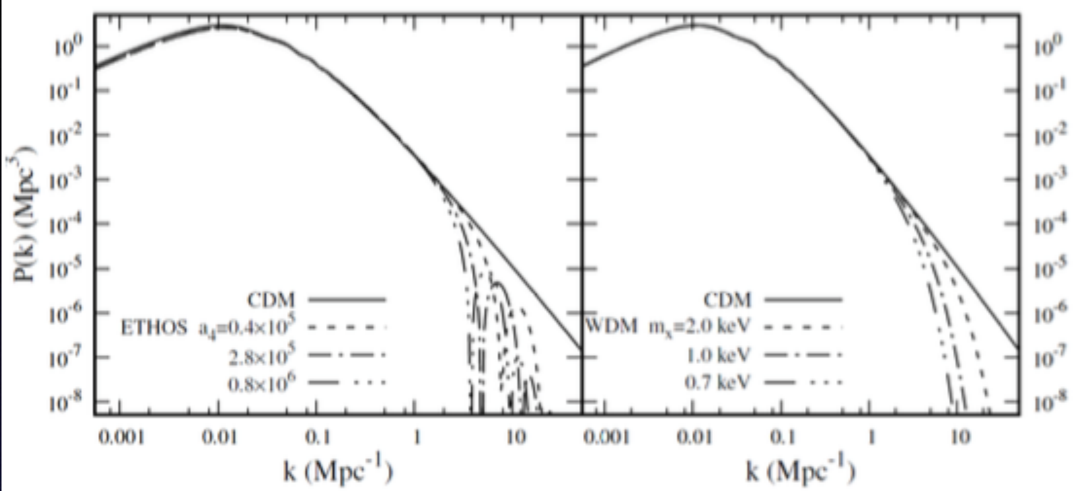
$$N_\gamma^{\rm halo} = N_{\rm ion} \frac{M_{\rm halo}}{m_H}$$

$$N_{\rm ion} = 8 \left(\frac{N_{\rm ion}^{\rm b}}{4000}\right) \left(\frac{M_{\rm b}/M_{\rm halo}}{1/5}\right) \left(\frac{\epsilon_{\rm esc}}{10\%}\right) \left(\frac{\epsilon_{\rm SF}}{10\%}\right)$$

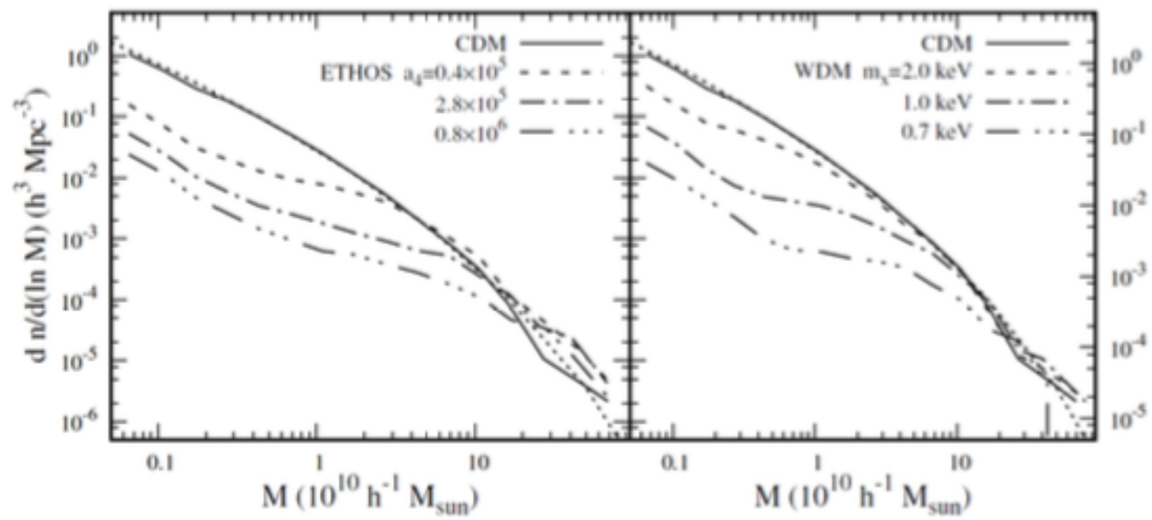


$N_{\rm ion} \leq 500$ **can be safely assumed**

Linear Power Spectrum (z=124)

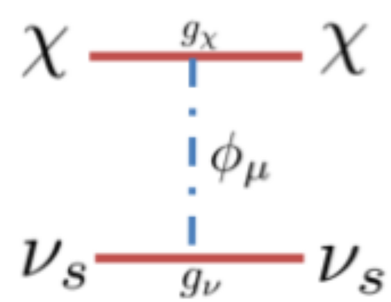


Halo mass distribution (z=8)



Our Result

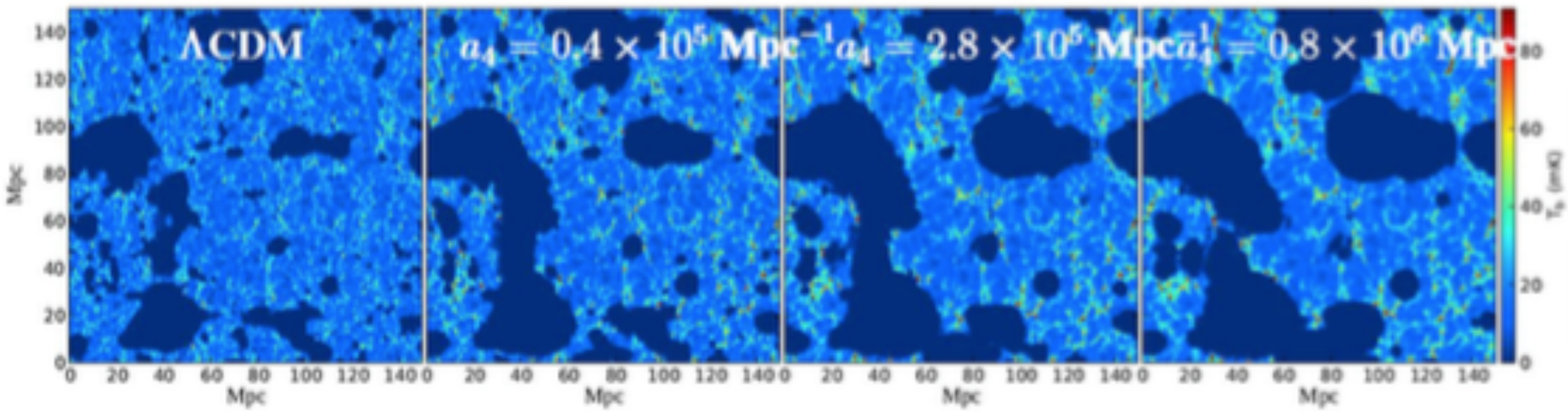
- Constraint on a_4 from demanding consistency with global history of reionization



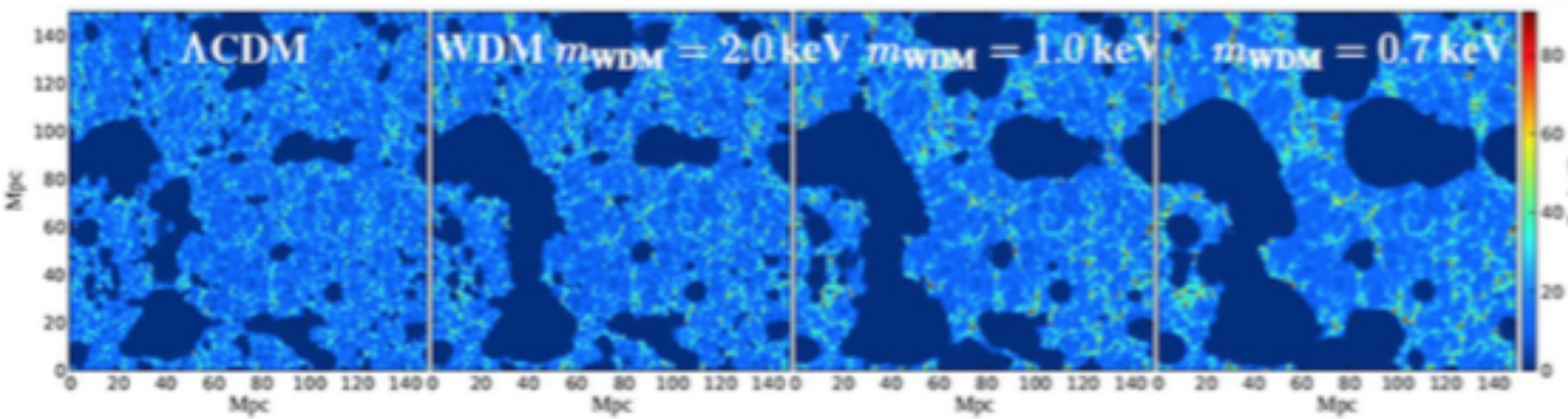
$$a_4 = 0.6 \times 10^5 \left(\frac{g_\chi}{1}\right)^2 \left(\frac{g_\nu}{1}\right)^2 \left(\frac{0.5\ \mathrm{MeV}}{m_\phi}\right)^4 \left(\frac{2\ \mathrm{TeV}}{m_\chi}\right)\ \mathrm{Mpc}^{-1}$$

$$\lesssim 1.2 \times 10^6\ \mathrm{Mpc}^{-1}$$

HI brightness temperature (z = 8)



N_{ion} 23 100 321 721



N_{ion} 23 57 225 861

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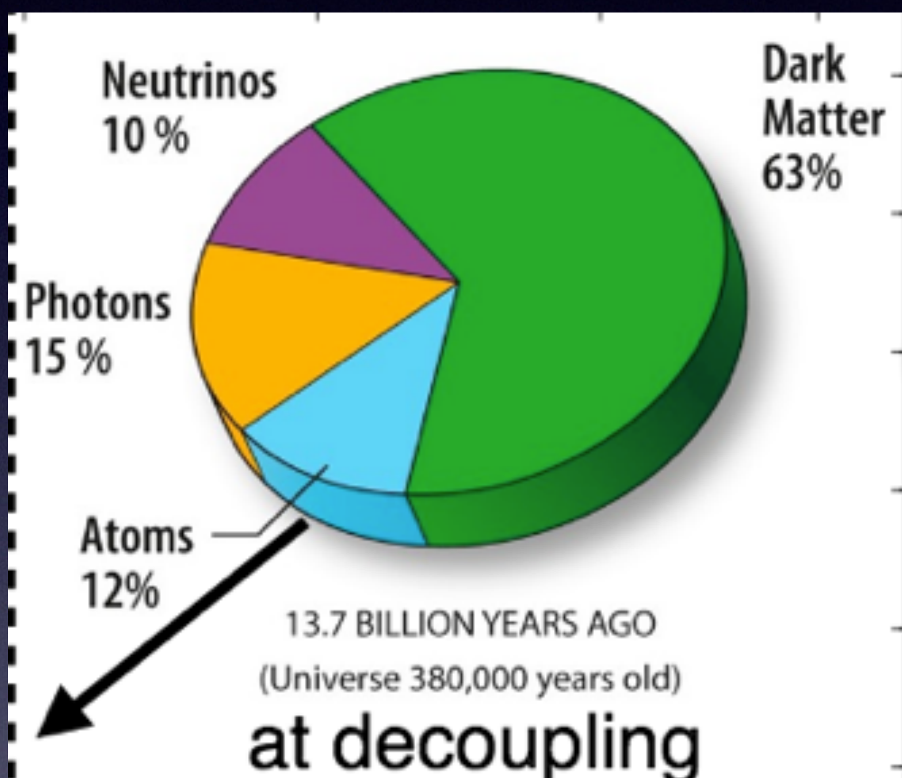
- **Story learnt from visible sector**



DM , DE
may transform
into something !

Axion
DM, DE

FUTURE OF DARK IS BRIGHT !

30 Oct 1998

IS COSMOLOGY SOLVED?
An Astrophysical Cosmologist's Viewpoint

P. J. E. Peebles
Joseph Henry Laboratories, Princeton University,
and Princeton Institute for Advanced Study

ABSTRACT

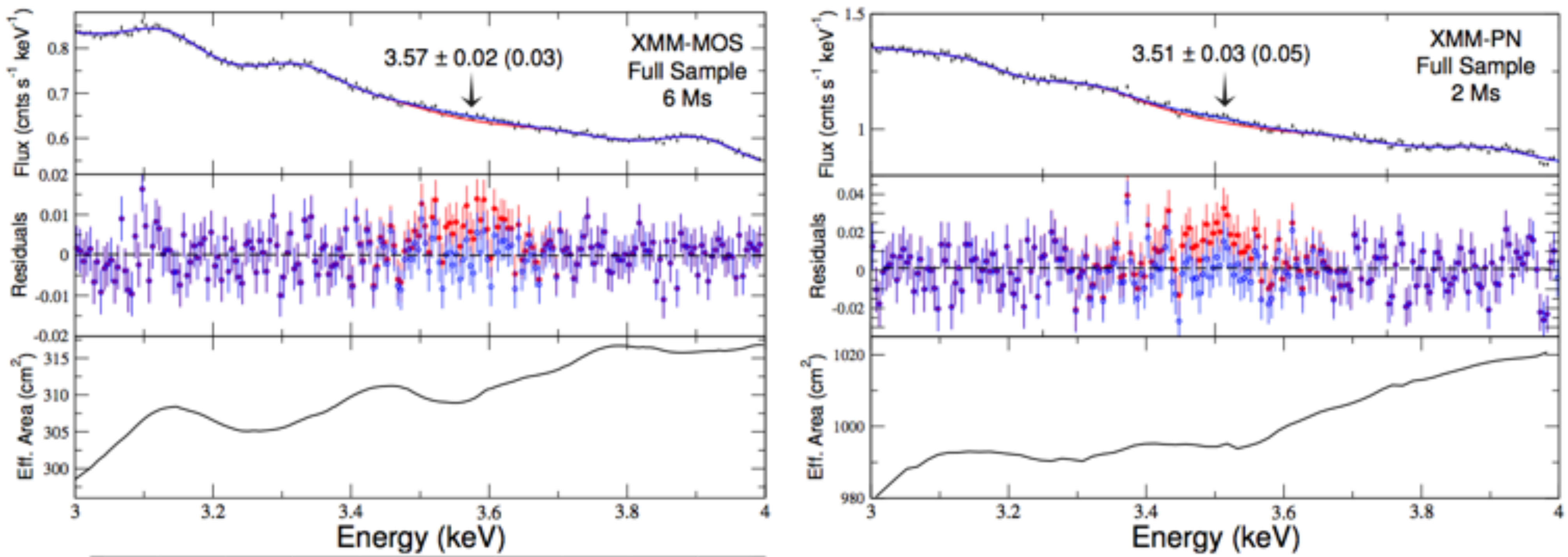
We have fossil evidence from the thermal background radiation that our universe expanded from a considerably hotter denser state. We have a well defined, testable, and so far quite successful theoretical description of the expansion: the relativistic Friedmann-

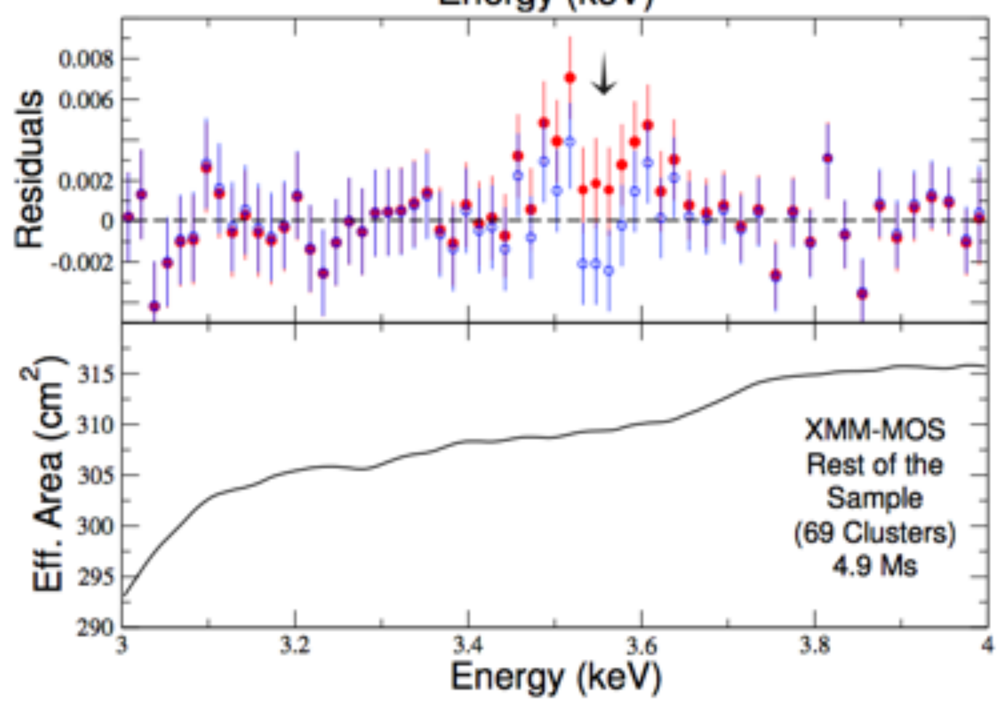
"Does ΛCDM signify completion of the fundamental physics that will be needed in the analysis of ... future generations of observational cosmology? Or might we only have arrived at the simplest approximation we can get away with at the present level of evidence?"

– P. J. E. Peebles

Full stacked spectra

Bulbul et al. [1402.2301]





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Virgo cluster (Chandra, ACIS-I)	No detection	