Bob in Late Universe Darkness

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Suzaku 2011, SLAC, Jul 22, 2011

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Outline

- Dark Matter (standard view)
- Dark Matter w/o theoretical prejudice
- Decaying Dark Matter and Suzaku
- Dark Energy and Big Rip

Dark Matter
(standard view)

Energy Budget of the Universe

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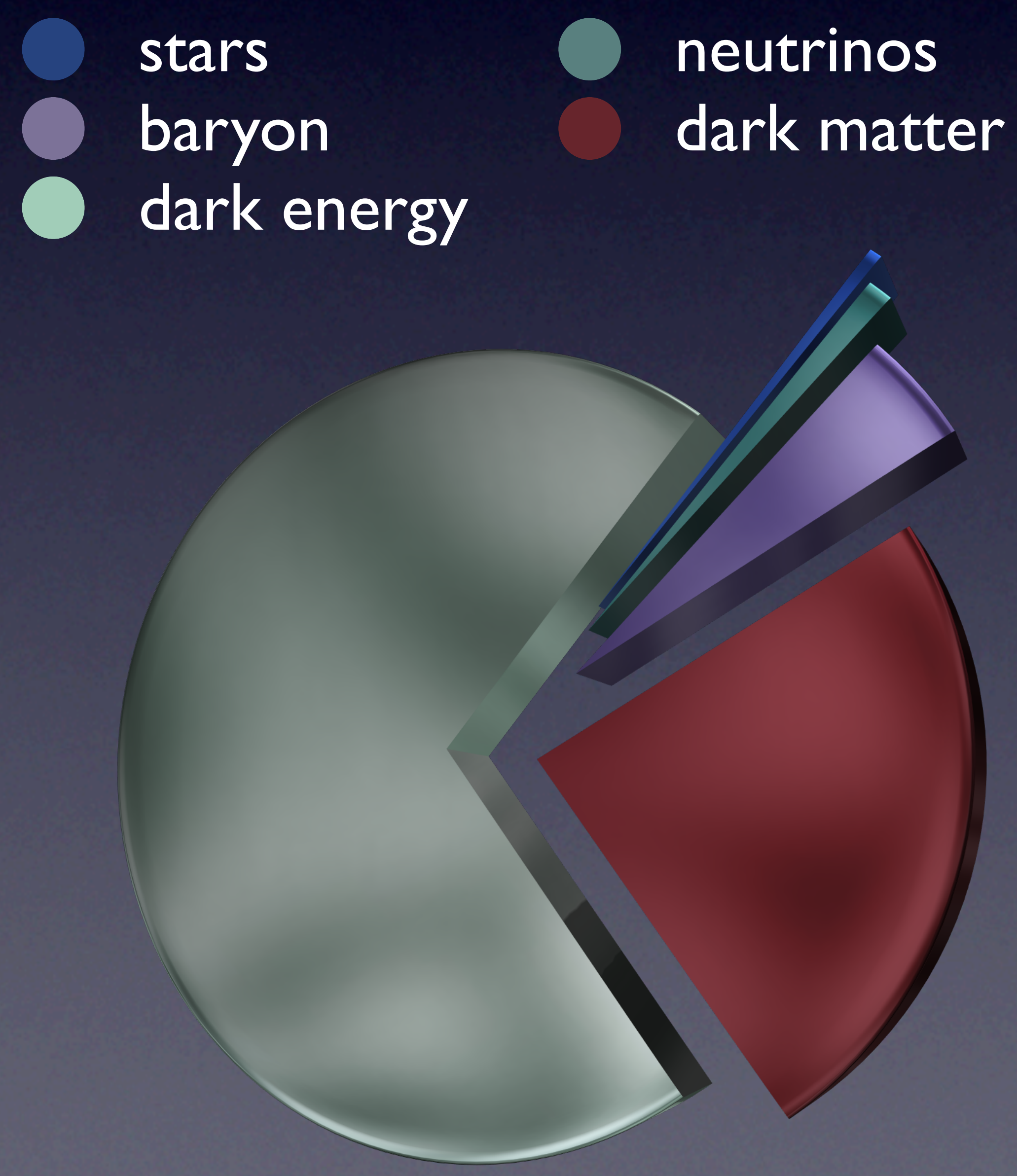
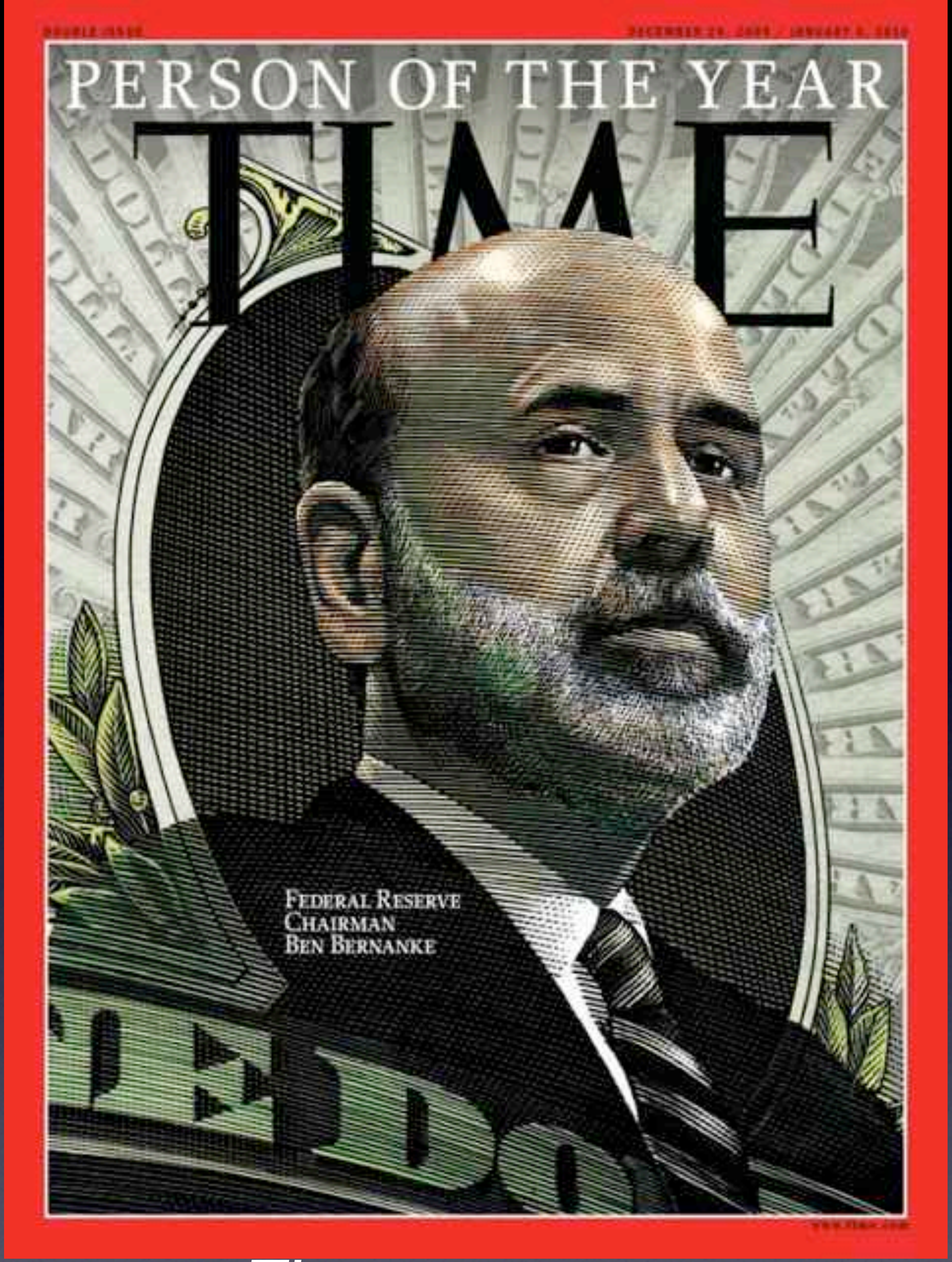
- Stars and galaxies are only ~0.5%
- ν~0.1–1.5%
- Rest of ordinary matter (e, p & n) 4.4%
  Dark Matter 23%
  Dark Energy 73%
- Anti-Matter 0%
- Higgs ~10^{62}%??

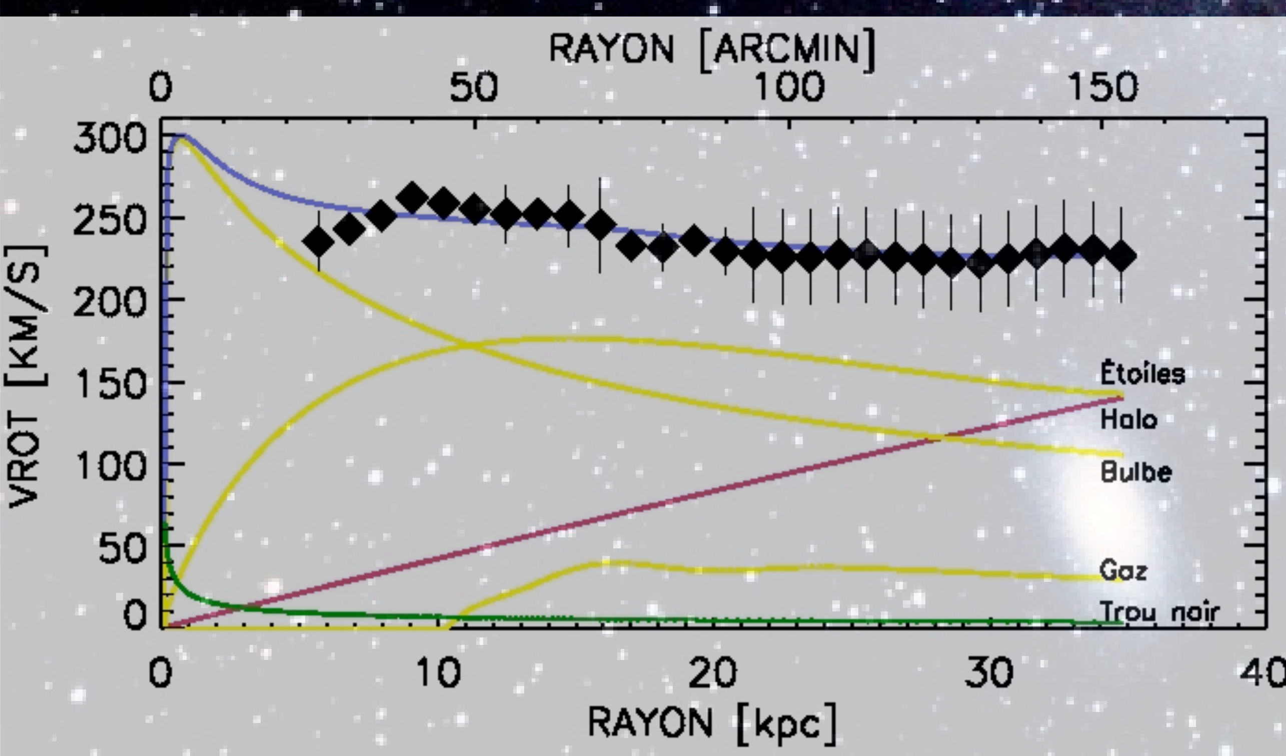
budget deficit!





The prospective
increase in the budget deficit will
place risk at future living standards

Rotation Curves



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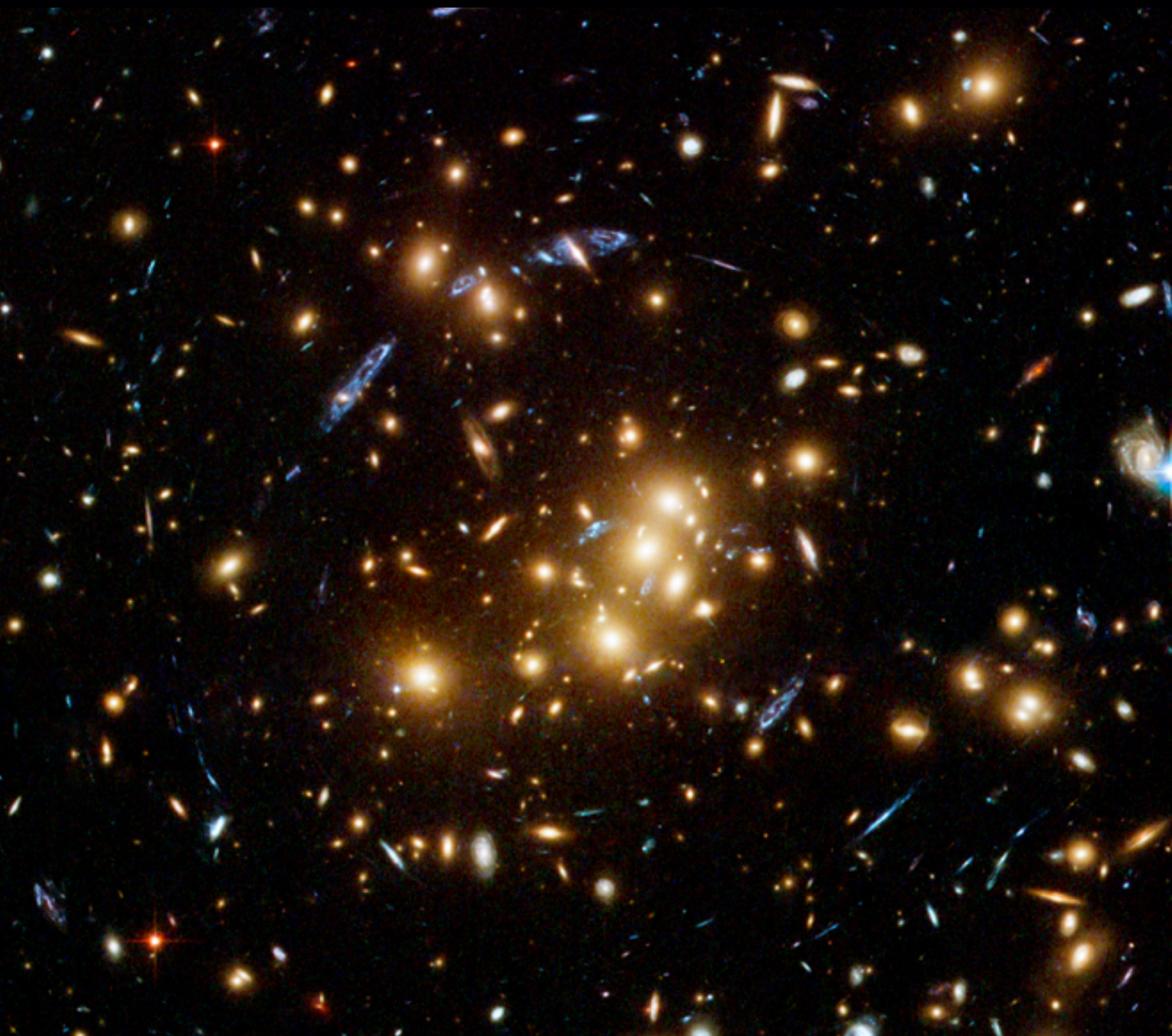
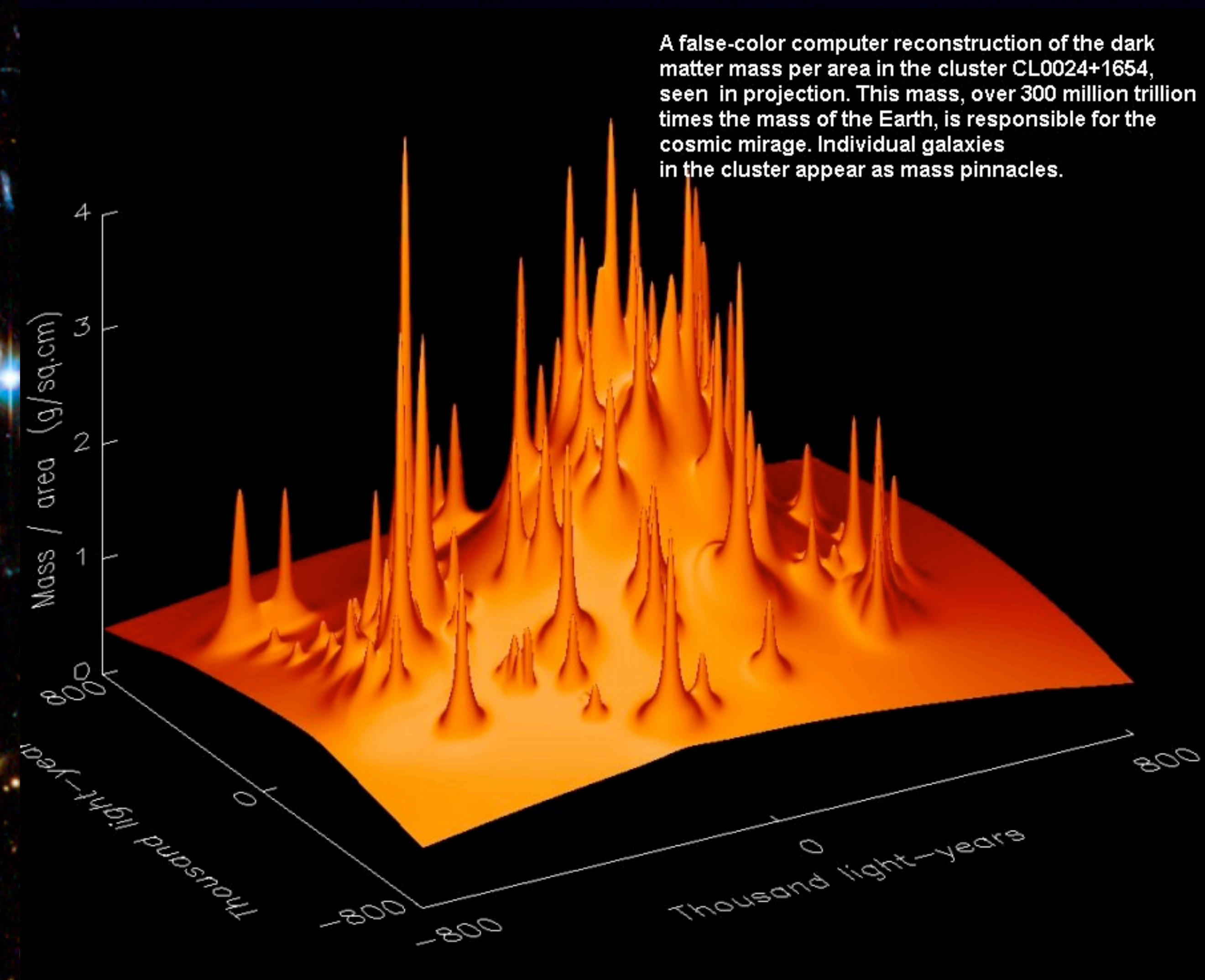
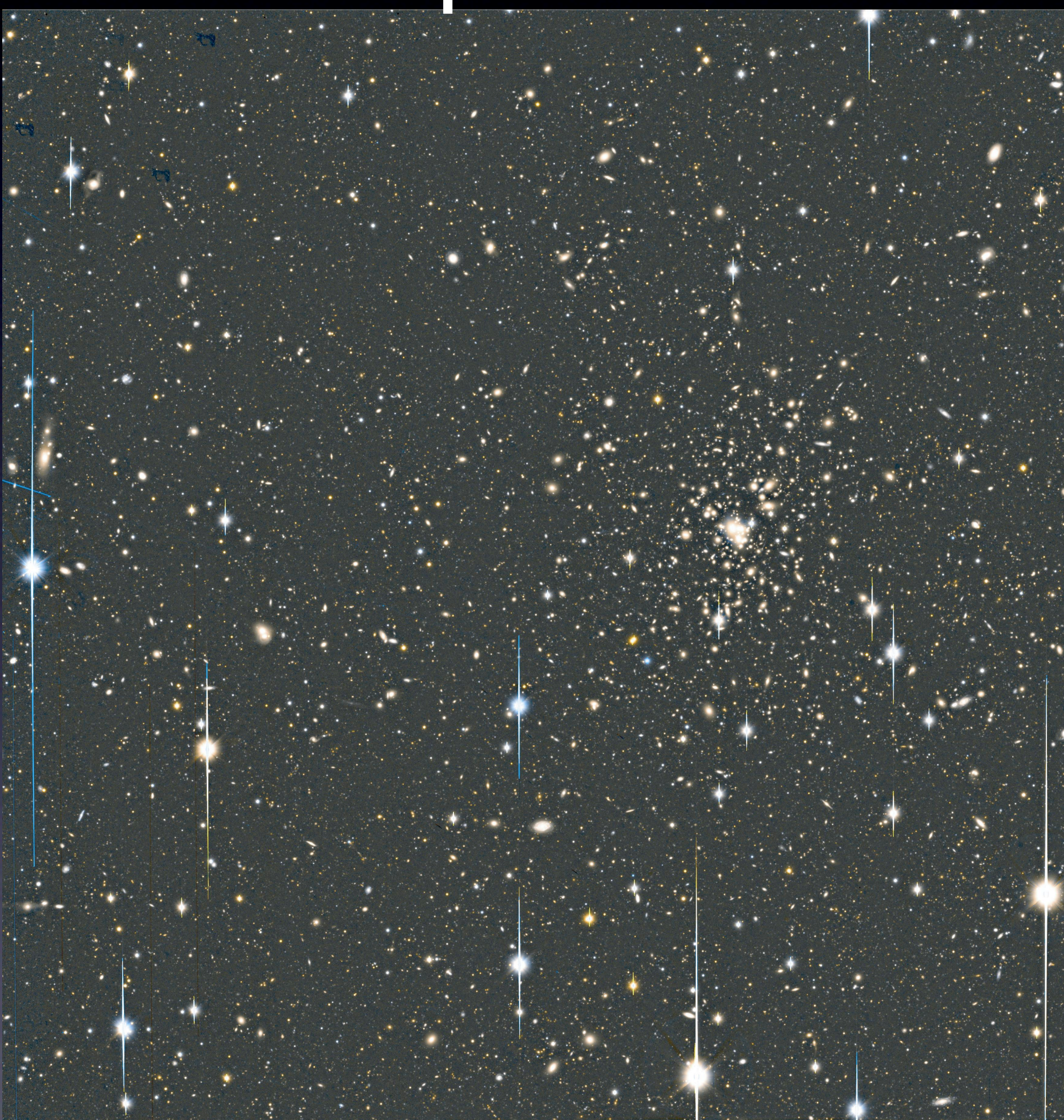
Strong Lensing

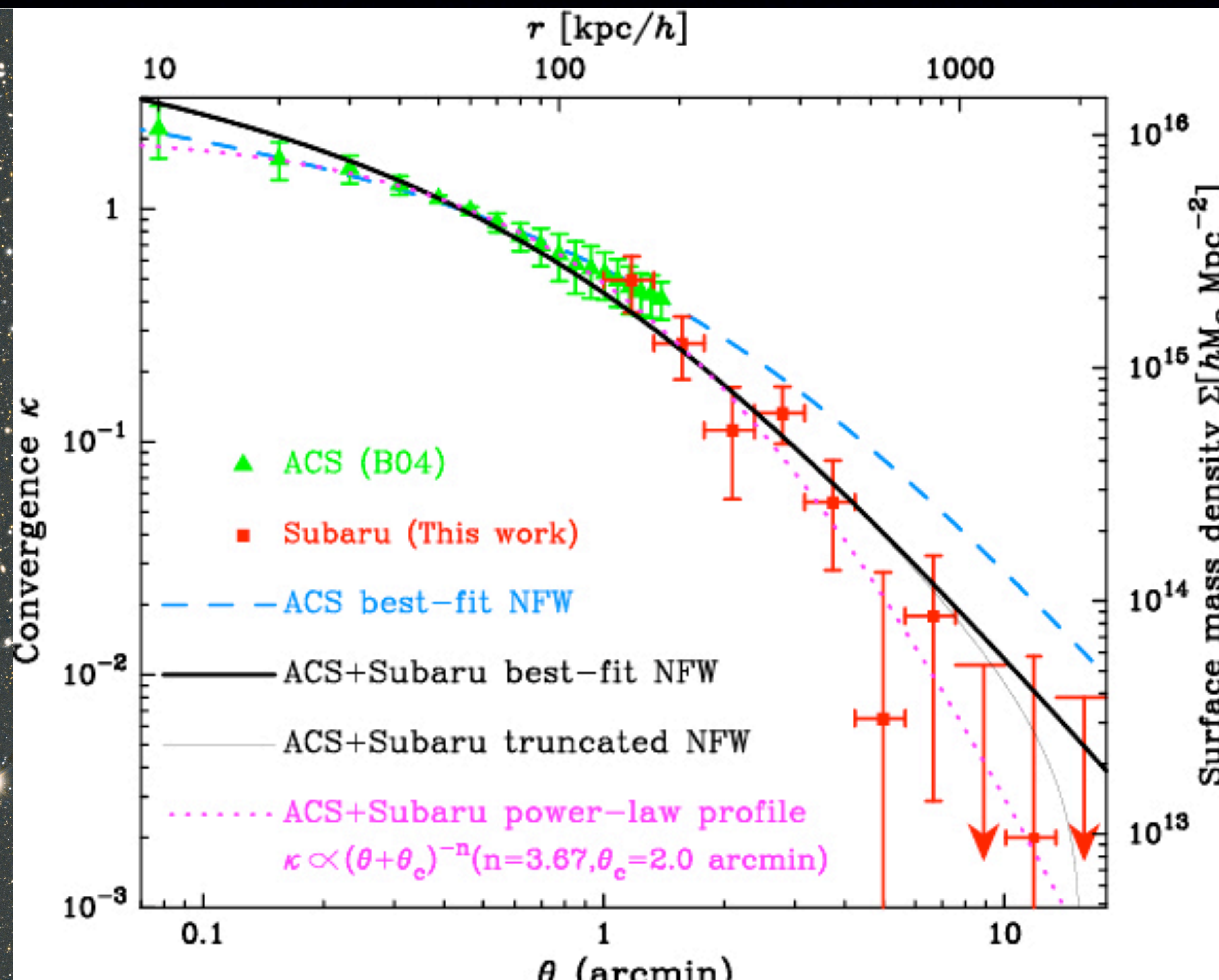




Weak Lensing

3.5x4.4 Mpc/h Subaru

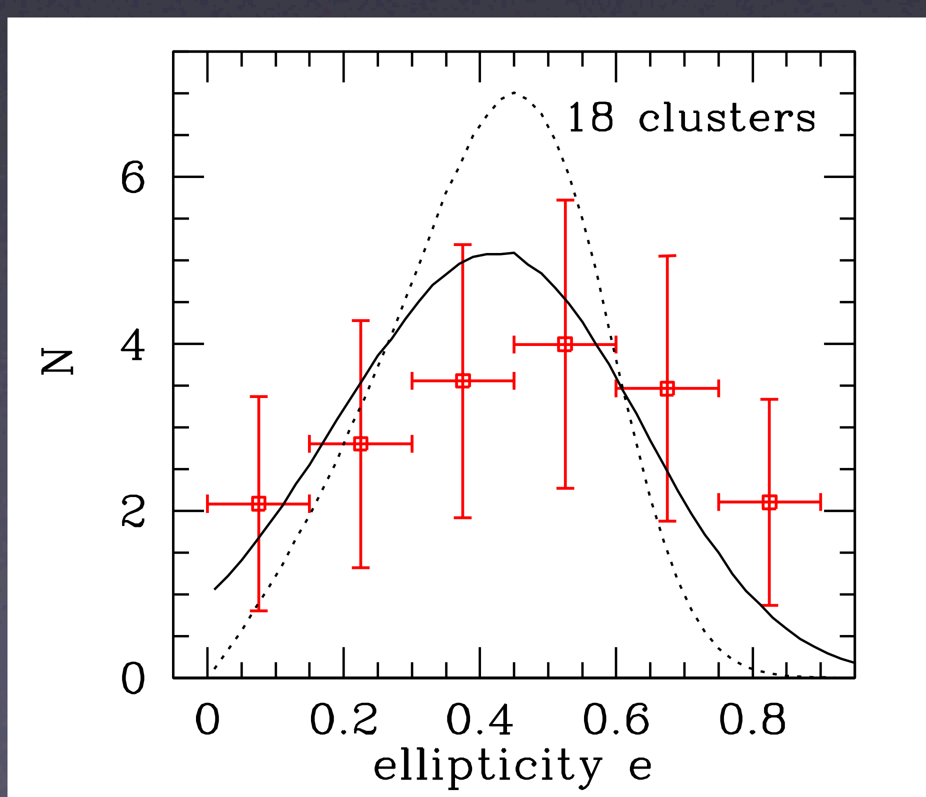


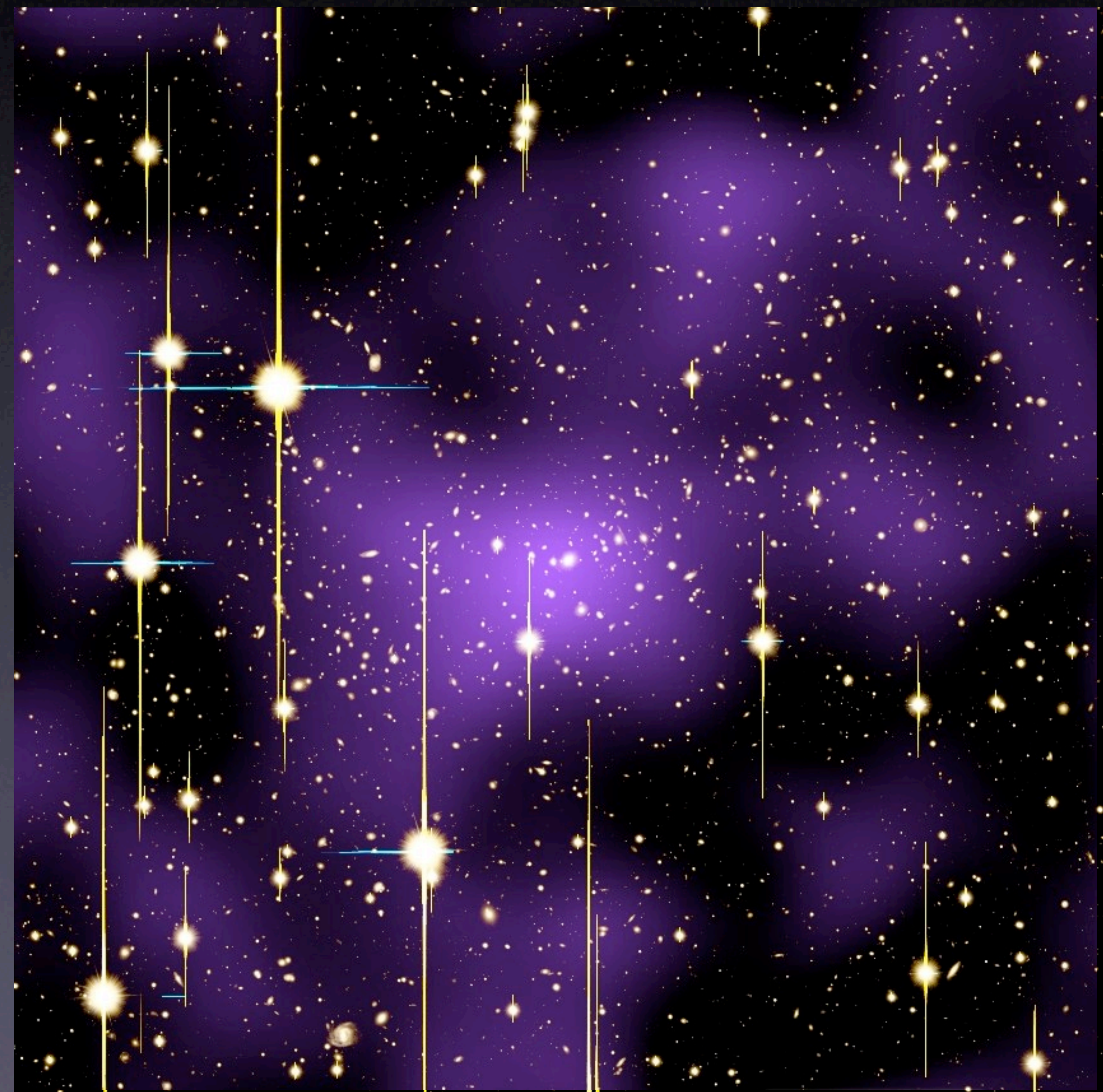


Umetsu, Takada, Broadhurst, astro-ph/0702096

Weak Lensing

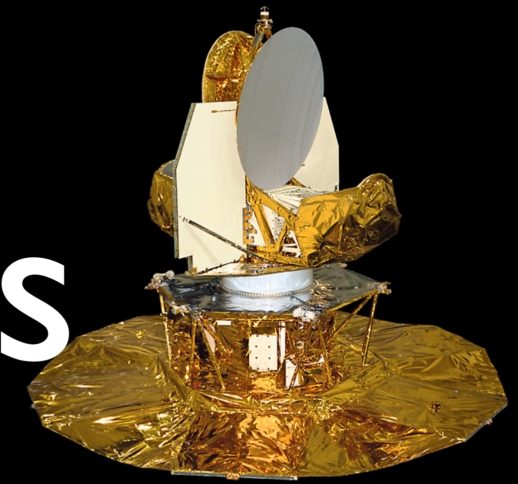
- map out invisible dark matter in clusters
- demonstrated that distribution is *elongated* with meaningful statistics

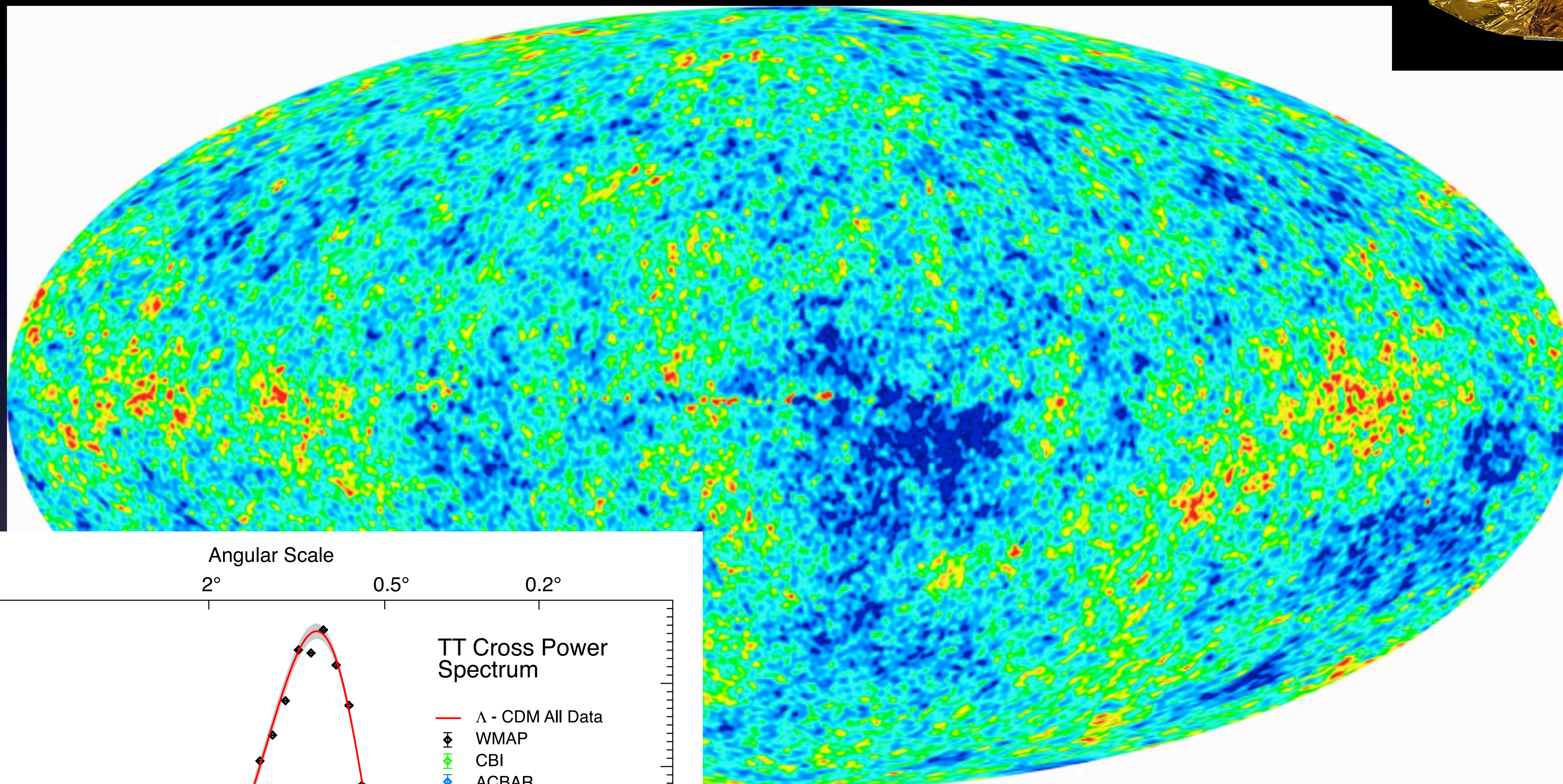


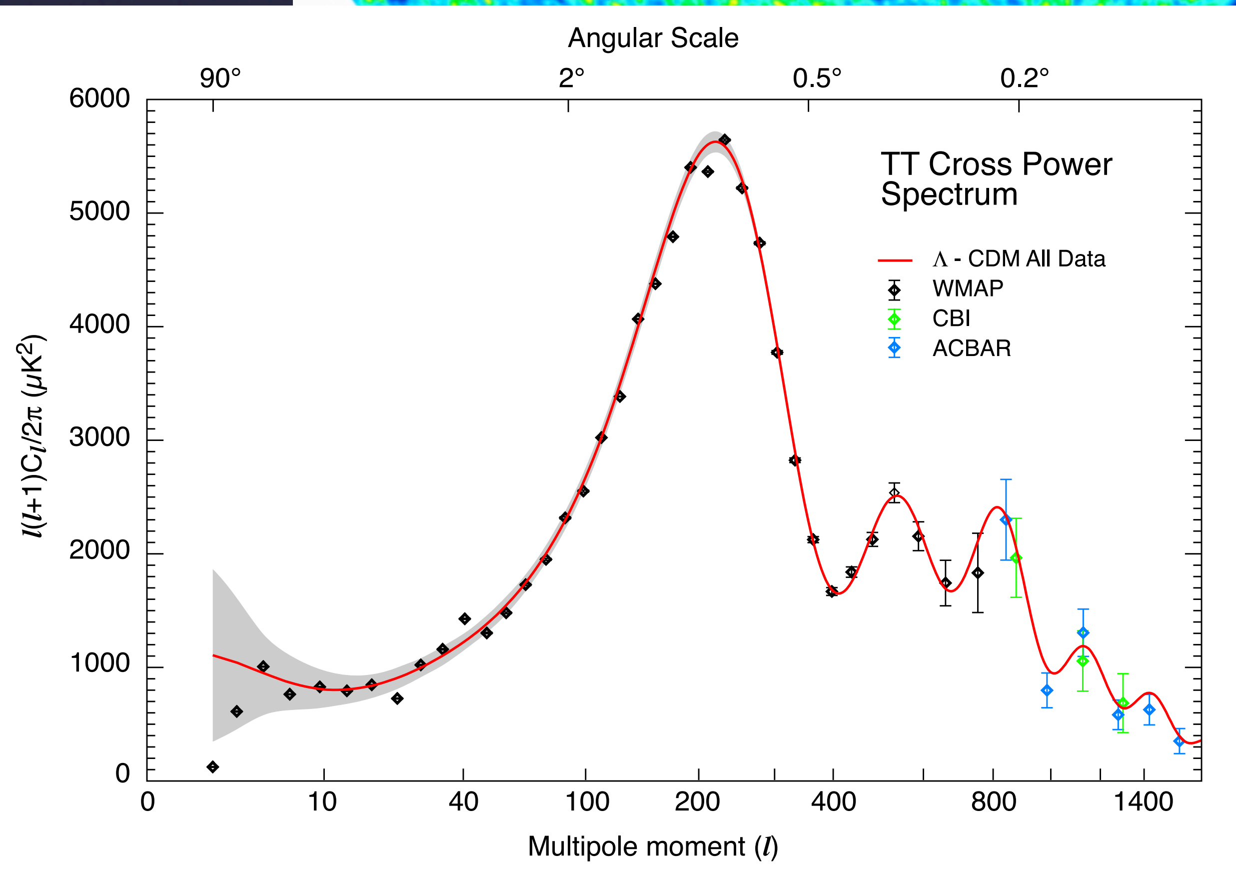


bullet cluster

Cosmological scales

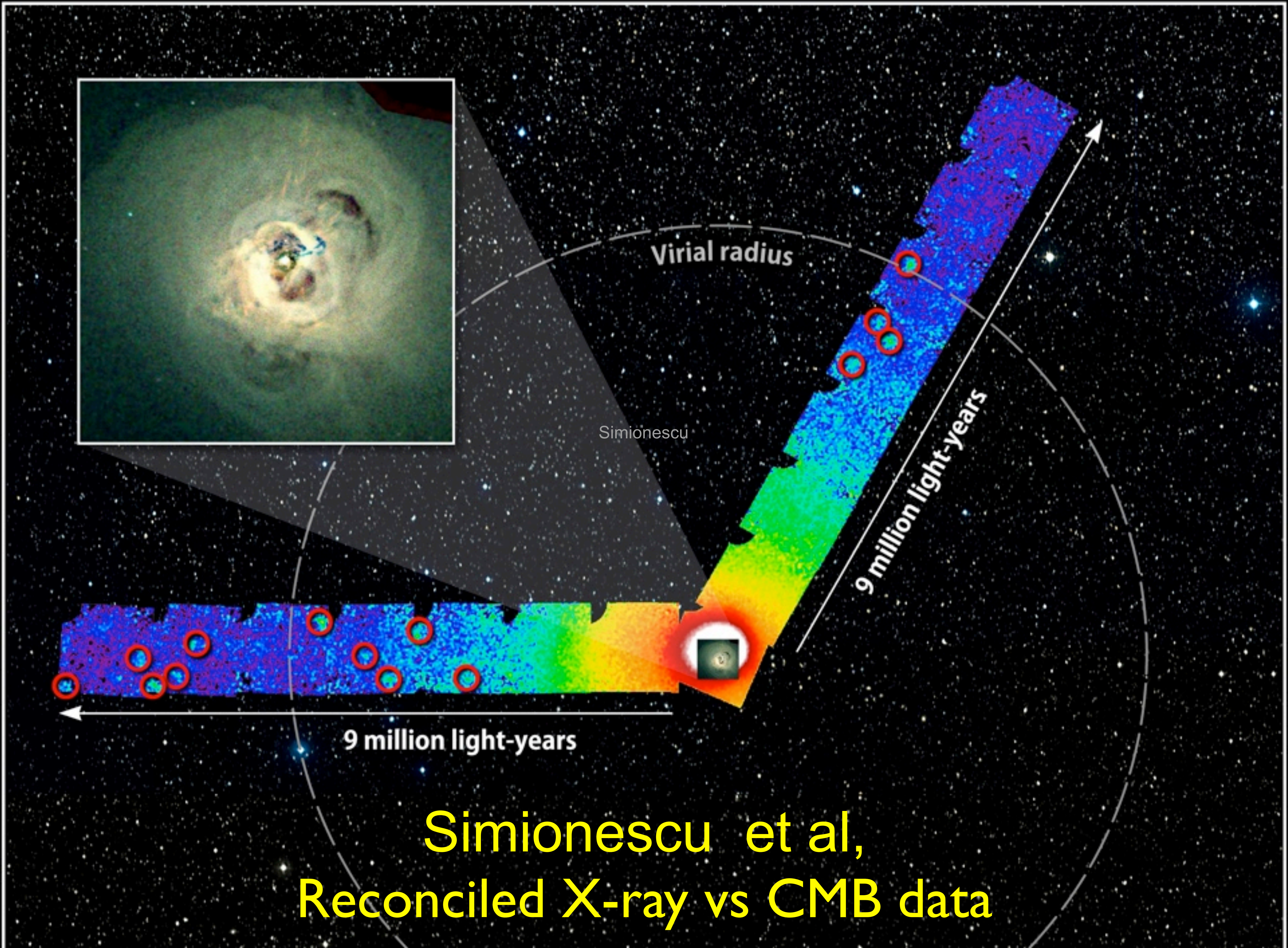






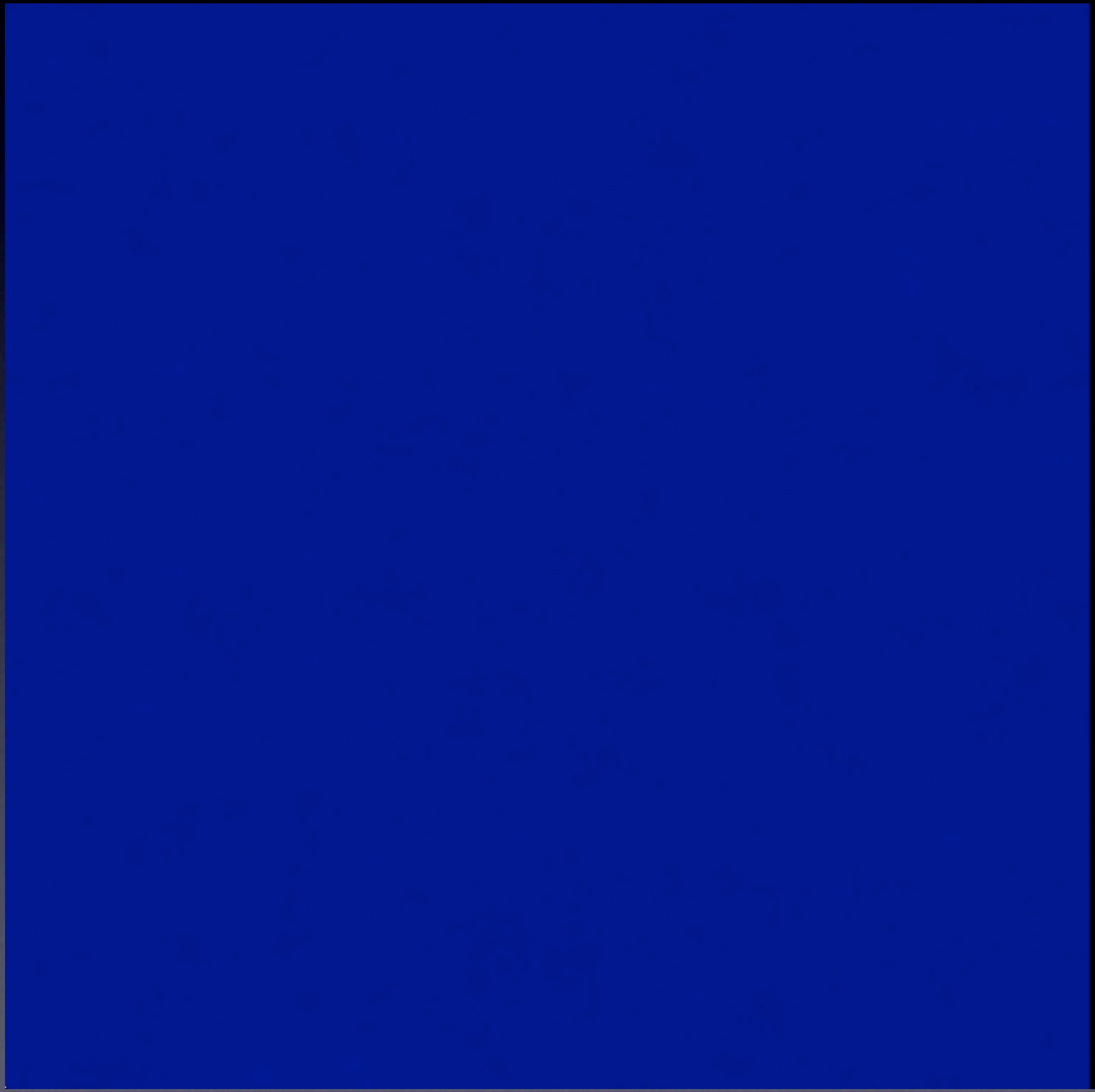
matter/all atoms=6.03±0.03

Suzaku slices through the Perseus Galaxy Cluster

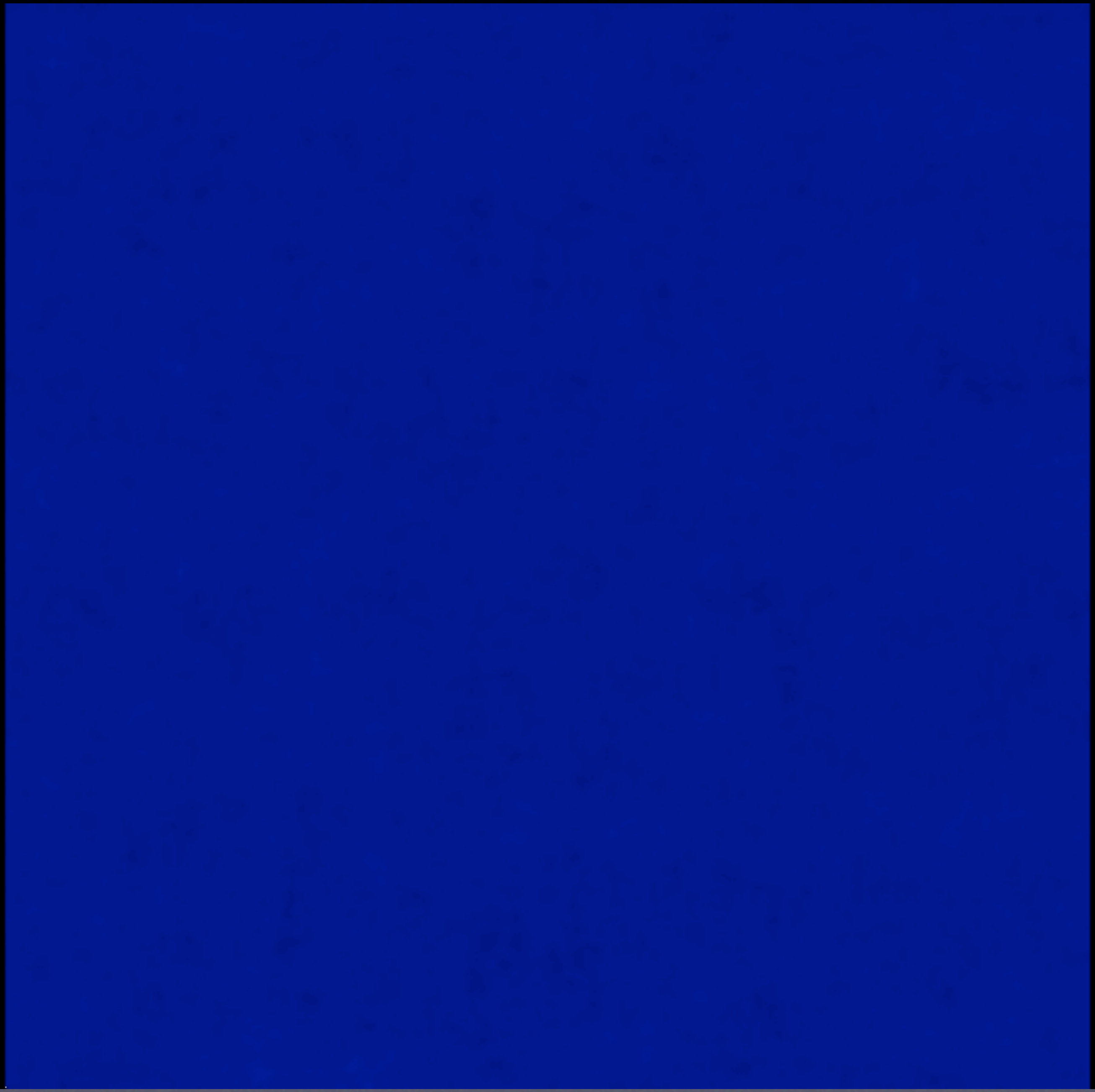


Simionescu et al,
Reconciled X-ray vs CMB data

We wouldn't exist without dark matter



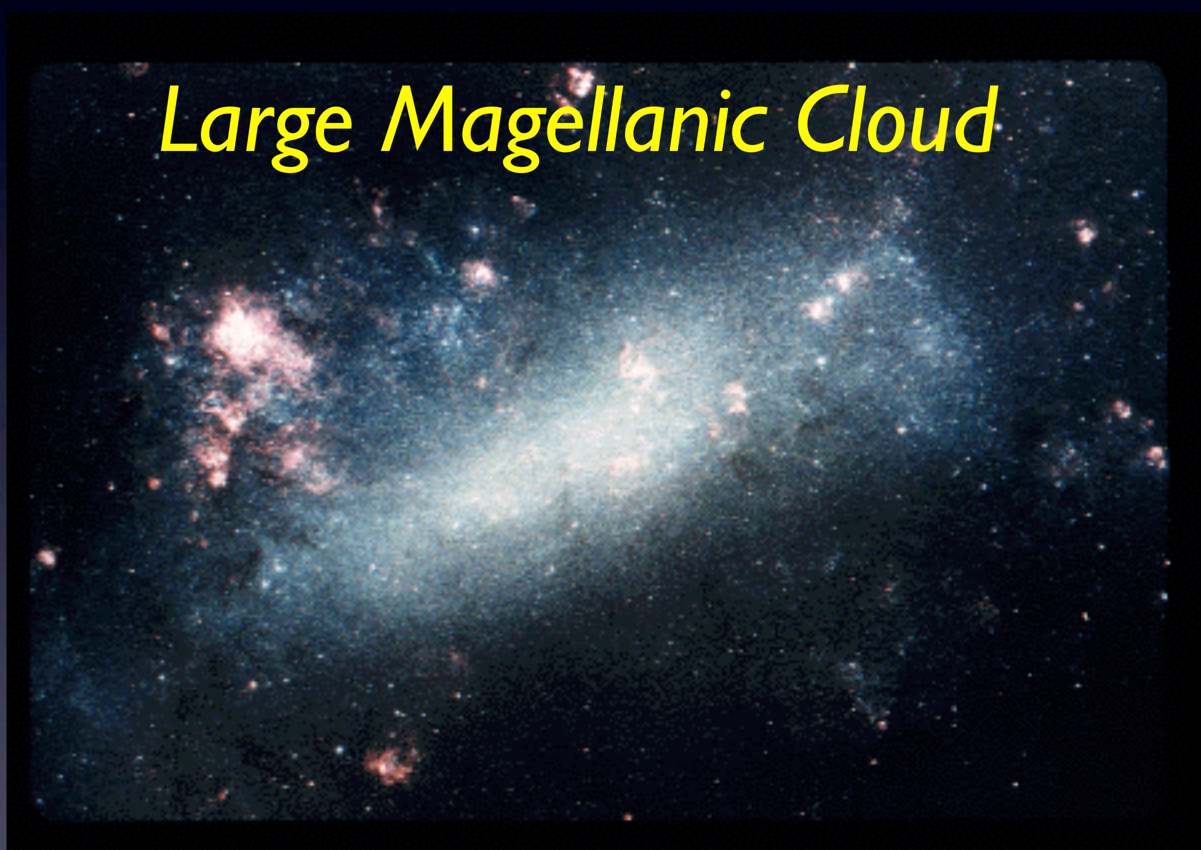
w/o dark matter

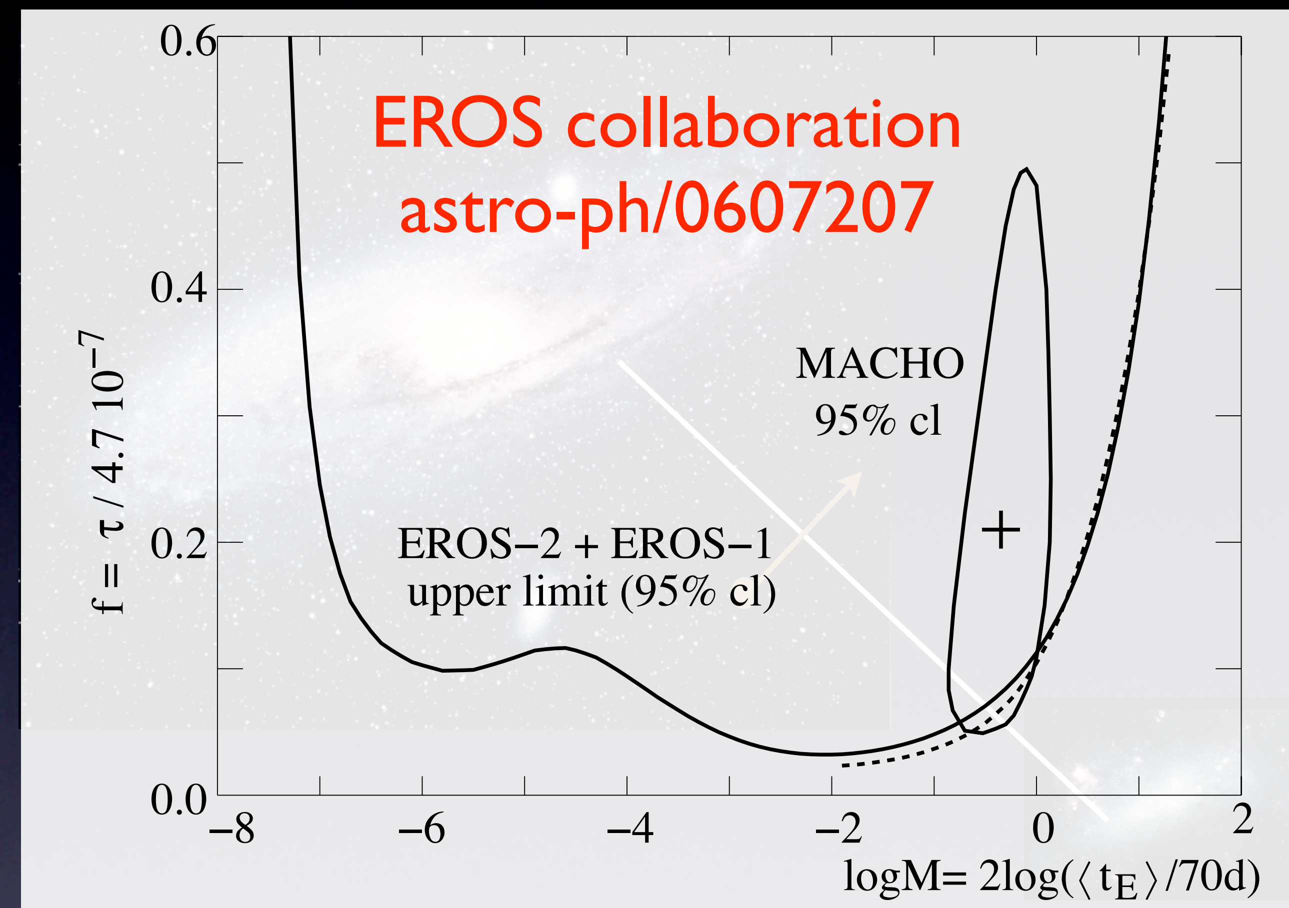


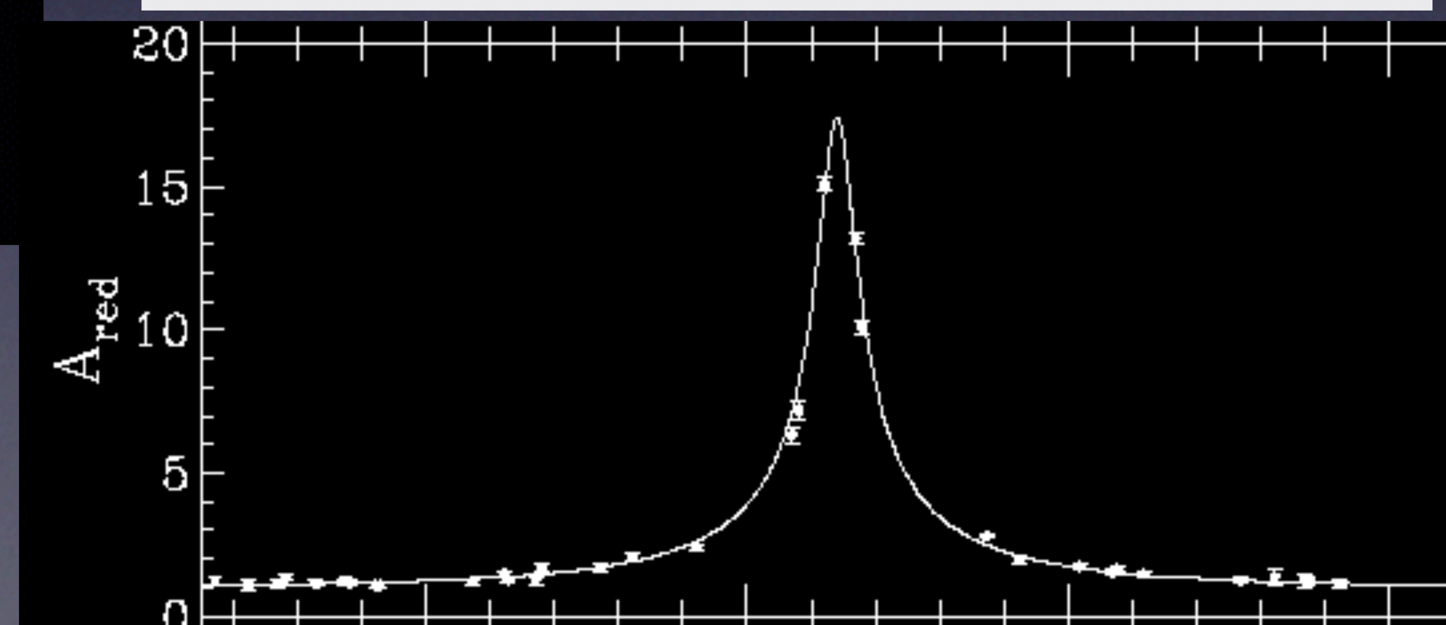
with dark matter

Dim Stars?

Search for MACHOs (Massive Compact Halo Objects)

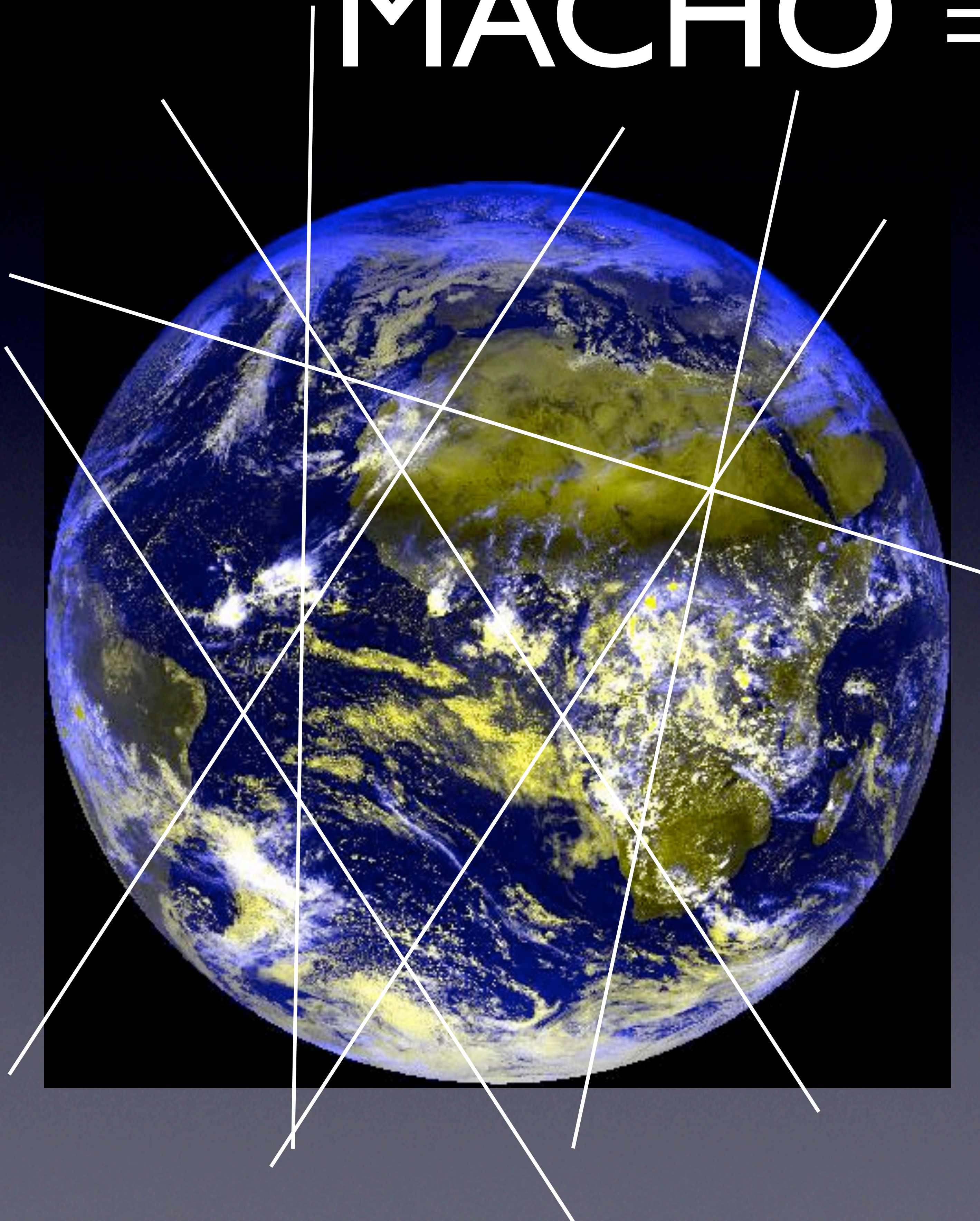






Not enough of them!

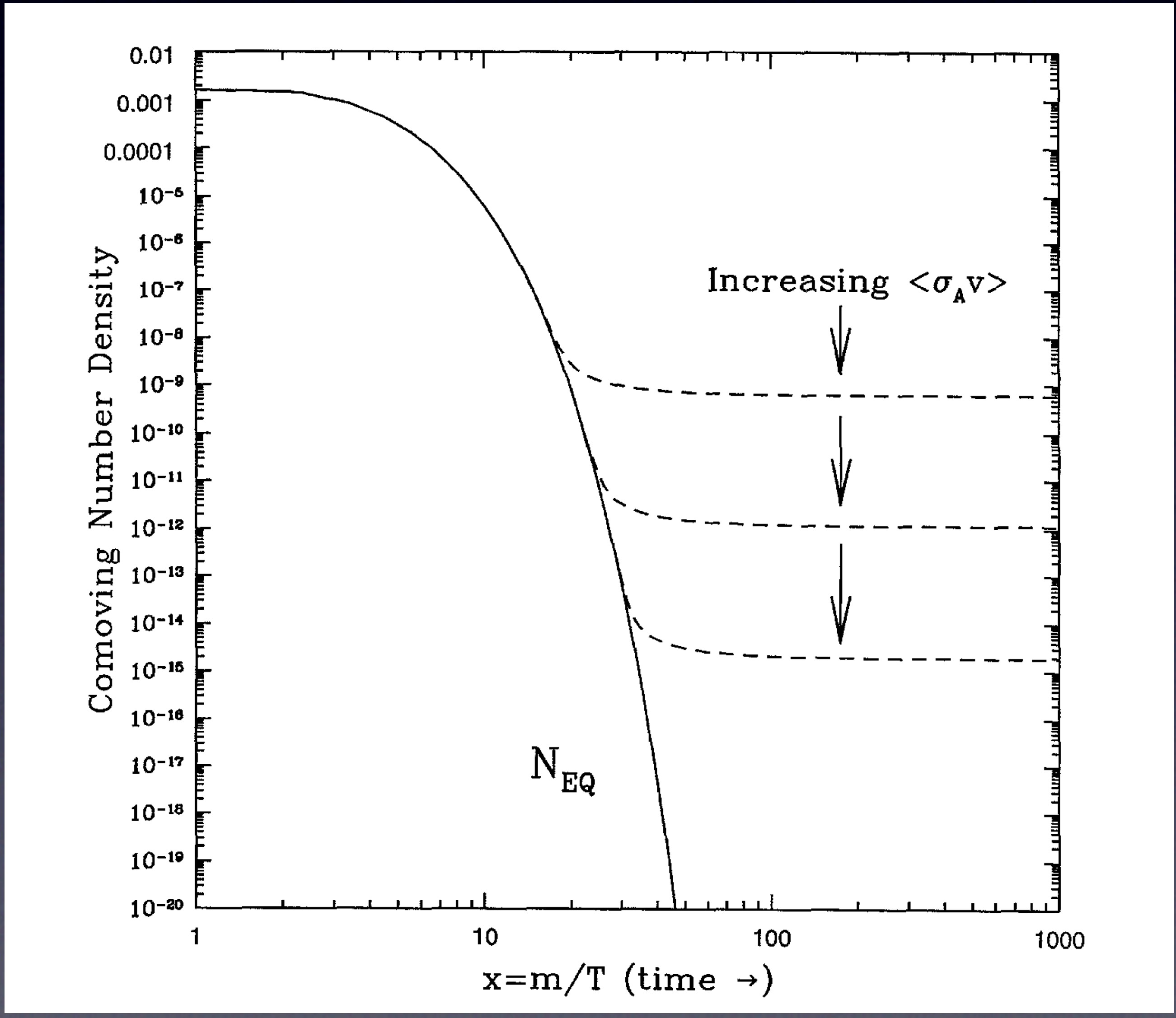
MACHO ⇒ WIMP



- It is probably WIMP (Weakly Interacting Massive Particle)
- Stable heavy particle produced in early Universe, left-over from near-complete annihilation

thermal relic

- thermal equilibrium when $T > m_\chi$
- Once $T < m_\chi$, no more χ created
- if stable, only way to lose them is annihilation
- but universe expands and χ get dilute
- at some point they can't find each other
- their number in comoving volume "frozen"



Order of magnitude

- "Known" Ω_χ=0.23 determines the WIMP annihilation cross section
- simple estimate of the annihilation cross section
- weak-scale mass!!!

$$\Omega_\chi \approx g_*^{-1/2} \frac{x_f}{M_{Pl}^3 \langle \sigma_{\rm ann} v \rangle} \frac{s_0}{H_0^2}$$

$$\langle \sigma_{\rm ann} v \rangle \approx \frac{1.12 \times 10^{-10} {\rm GeV}^{-2} x_f}{g_*^{1/2} \Omega_\chi h^2}$$

$$\sim 10^{-9} {\rm GeV}^{-2}$$

$$\langle \sigma_{\rm ann} v \rangle \approx \frac{\pi \alpha^2}{m_\chi^2}$$

$$m_\chi \approx 300 \text{ GeV}$$

“WIMP Miracle”

- A stable particle at the weak scale with “EM-strength” coupling naturally gives the correct abundance
- This is where we expect new particles because of the hierarchy problem $m_W \ll M_{Pl}$
- Many candidates of this type: supersymmetry, little Higgs with T-parity, Universal Extra Dimensinos, etc
- If so, we may even create dark matter at accelerators

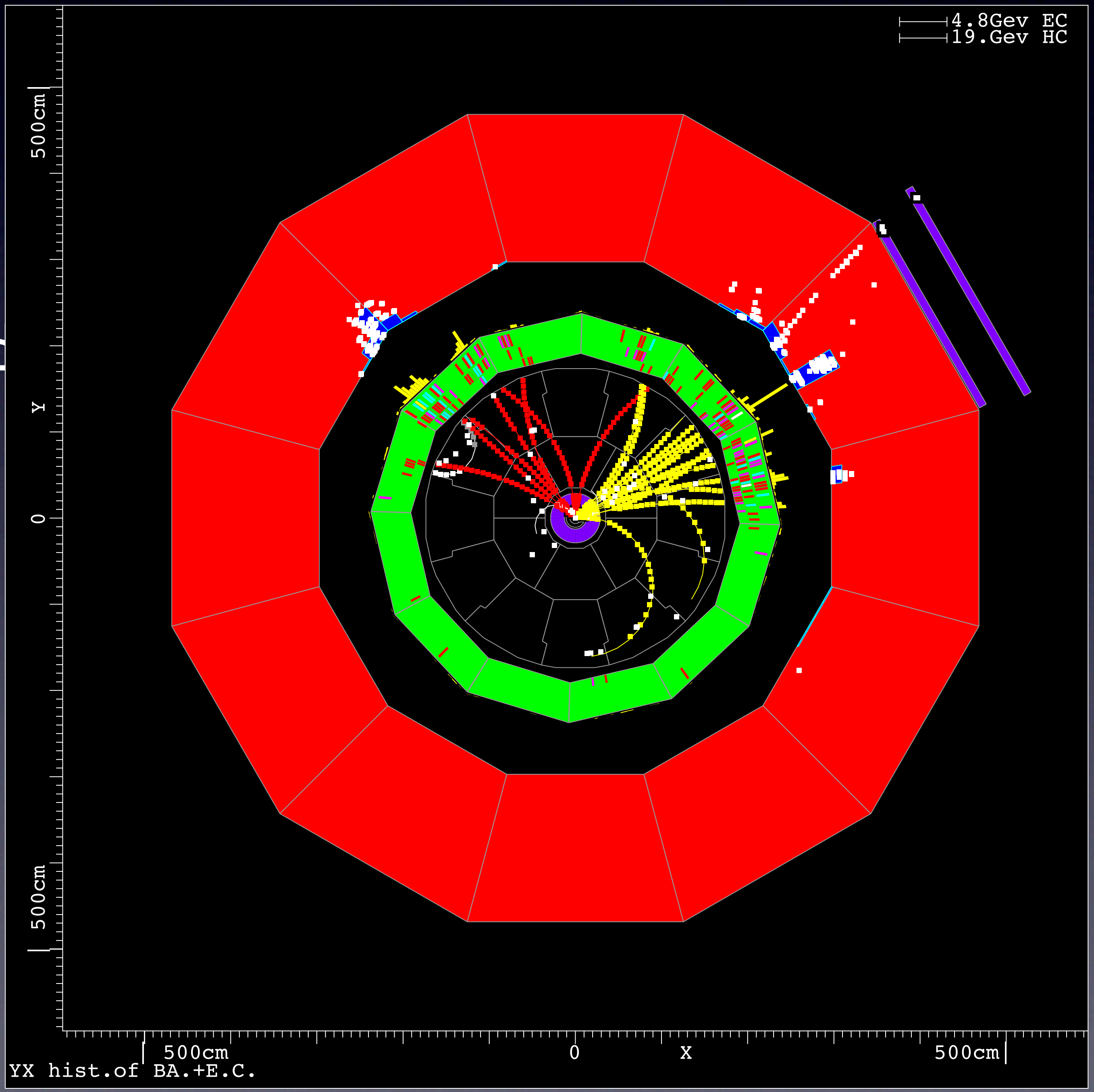
Producing Dark Matter in the laboratory

- Collision of high-energy particles mimic Big Bang
- We hope to create Dark Matter particles in the laboratory
- Look for events where energy and momenta are unbalanced

"missing energy" E_{miss}

- Something is escaping the detector
- electrically neutral, weakly interacting

⇒Dark Matter!?



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Not so fast!

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Dark Matter w/o theoretical prejudice

Cold and Neutral

- By the time of matter-radiation equality and until now, dark matter must be non-relativistic and clump together by gravitational attraction
- must be electrically neutral

Mass Limits

"Uncertainty Principle"

- Clumps to form structure
- imagine $V = G_N \frac{Mm}{r}$
- "Bohr radius": $r_B = \frac{\hbar^2}{G_N M m^2}$
- too small m ⇒ won't "fit" in a galaxy!
- m >10^{-22} eV "uncertainty principle" bound
  (modified from Hu, Barkana, Gruzinov, astro-ph/0003365)

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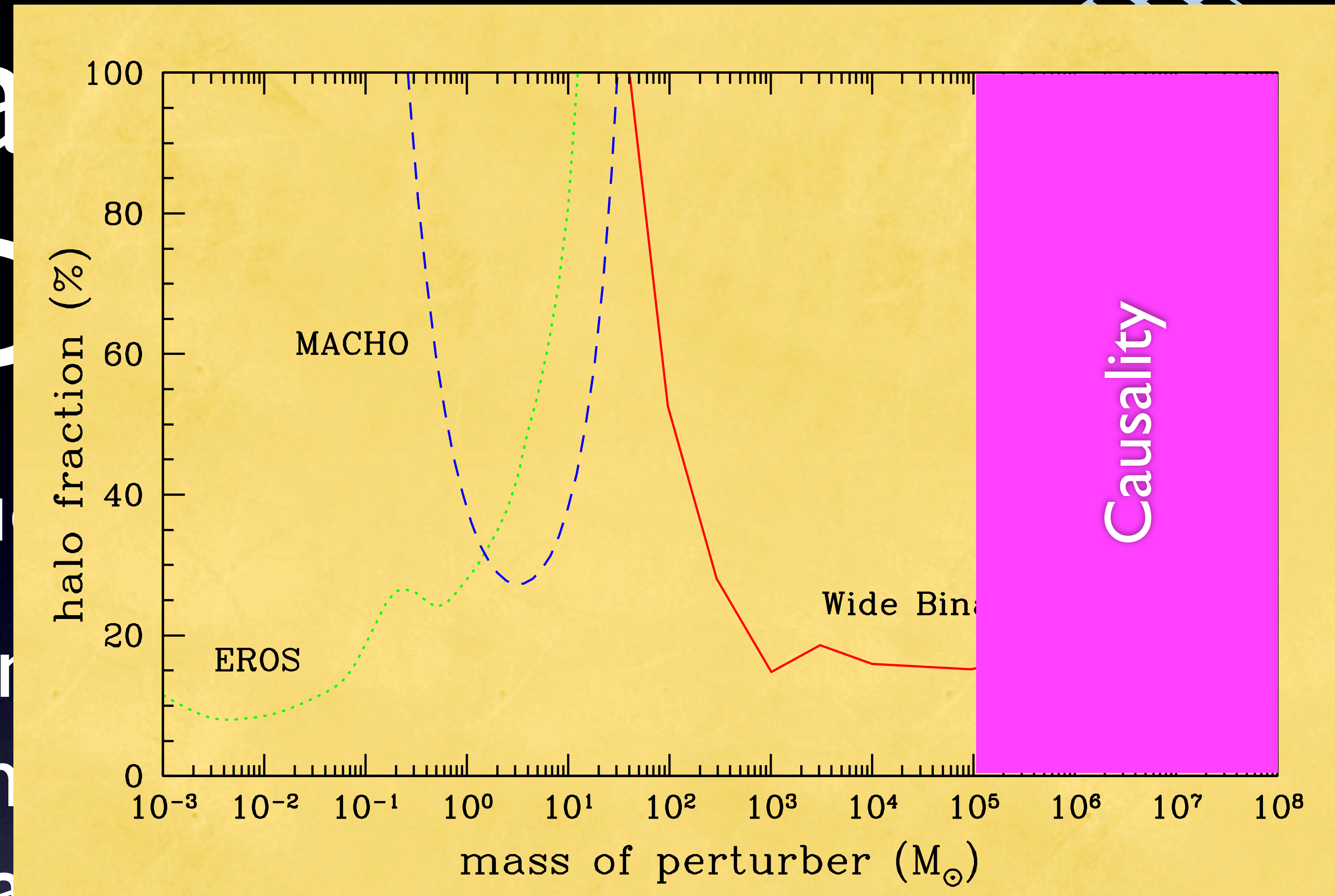
C



- MACHO exclu
- Can't make pri
  normal smooth
- there can't be anything violent since BBN
- maximum mass of PBH is horizon mass@BBN

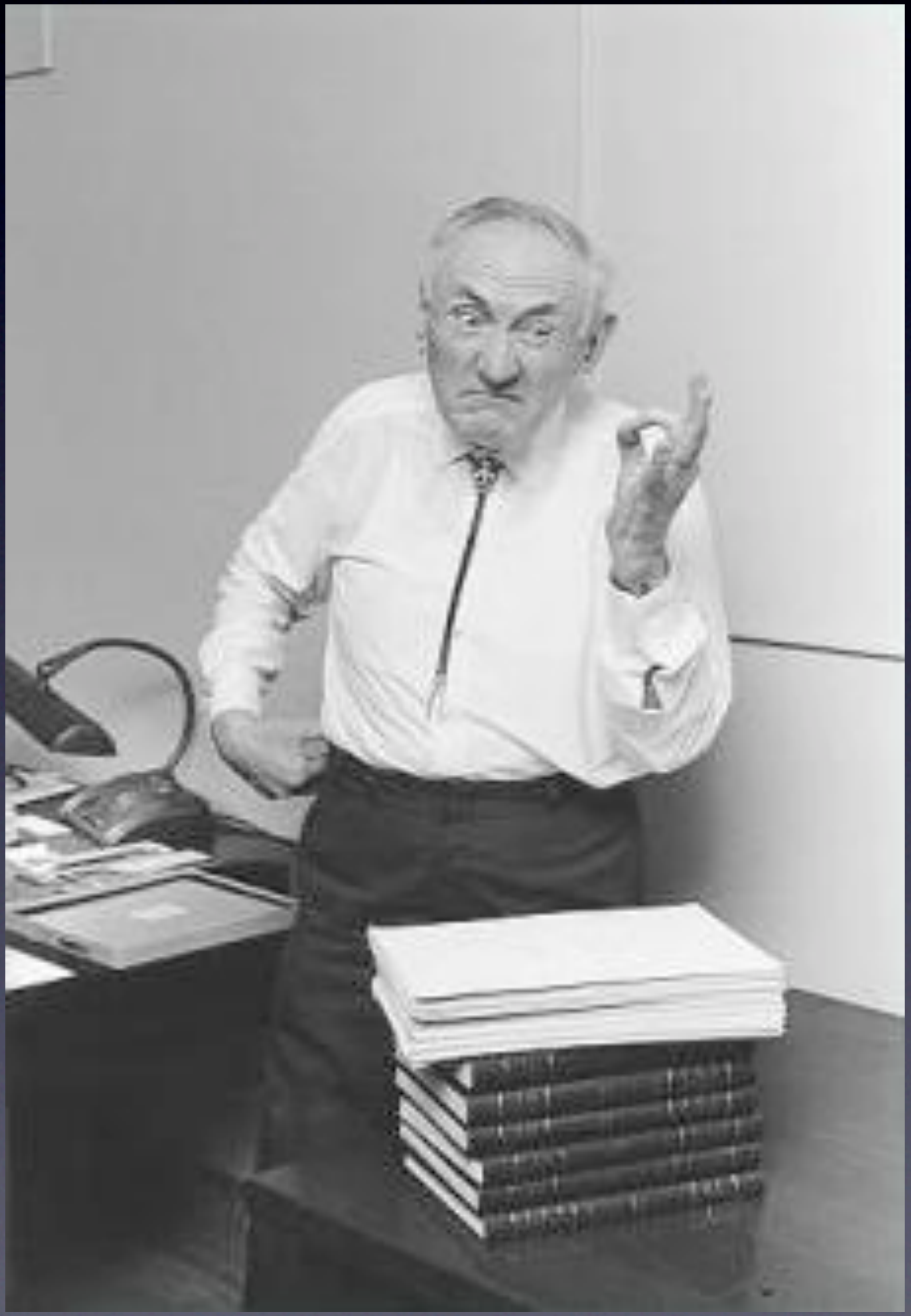
$$M_{\rm horizon} \approx g_* T^4 \left(\frac{M_{Pl}}{g_*^{1/2} T^2} \right)^3 \approx 10^5 M_\odot \left(\frac{\rm MeV}{T} \right)^2$$

- And m < $40M_\odot$ from wide binaries

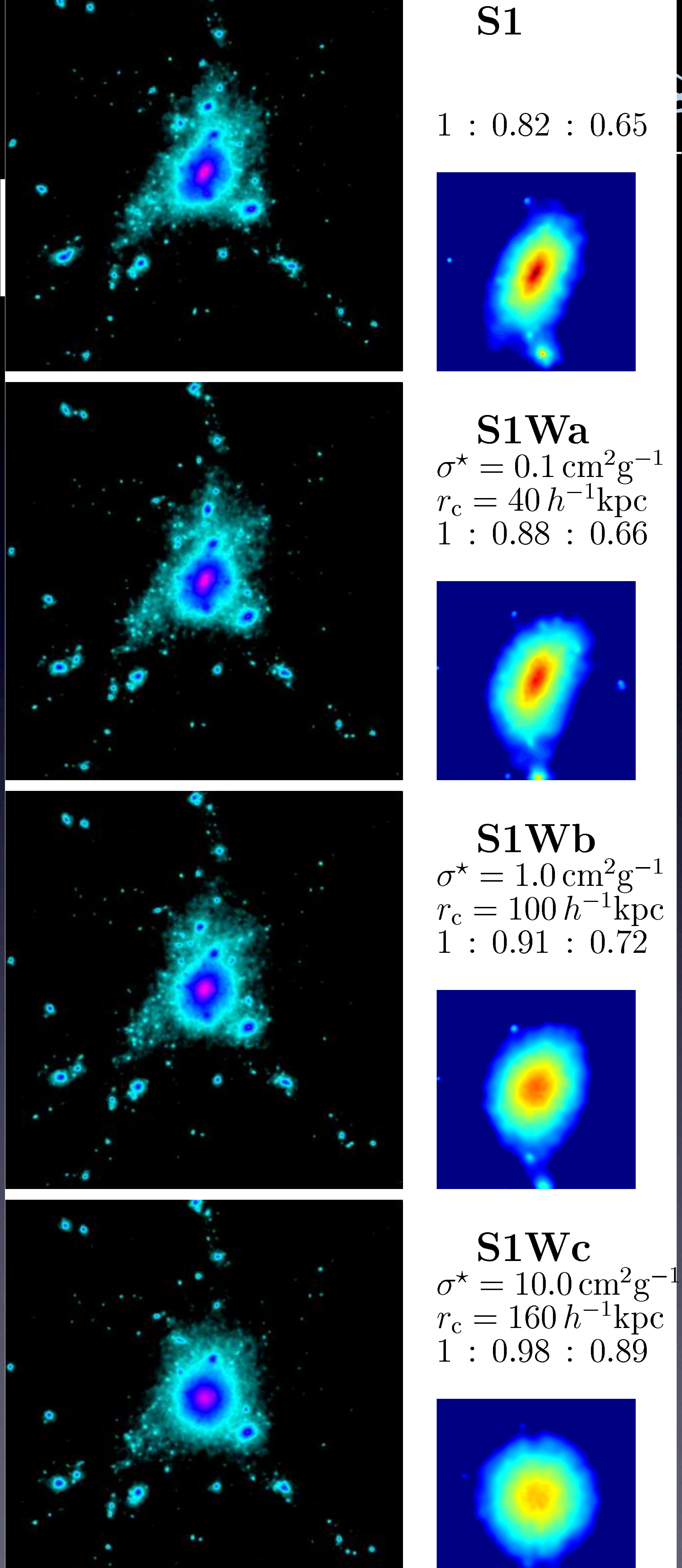
(Yoo, Chaname, Gould, astro-h/0307437)

Summary Mass Limits

- 10^{-31} GeV to 10^{50} GeV
- narrowed it down to within 81 orders of magnitude
- a big progress in 70 years since Zwicky



Self-Coupl



- if self-coupling too big, will "smooth out" cuspy profile at the galactic center
- some people want it

  (Spergel and Steinhardt, astro-ph/9909386)
- need core < 35 kpc/h from data

  $\sigma < 1.7 \times 10^{-25}$ cm^2 (m/GeV)

  (Yoshida, Springel, White, astro-ph/0006134)
- bullet cluster:

  $\sigma < 1.7\times10^{-24}$ cm^2 (m/GeV)
  (Markevitch et al, astro-ph/0309303)

Lifetime

- At least of the order of age of the universe 14Gyr $\approx 4\times10^{17}$sec
- Beyond that, it depends on decay modes, branching fractions, all model-dependent

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Decaying dark matter and Suzaku

keV mass range

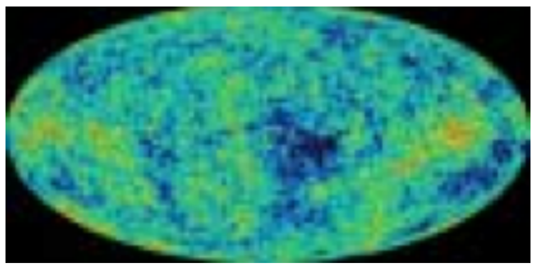
- Two particular motivations for the dark matter in this mass range
  - issues with standard ΛCDM at small scales
  - gauge-mediated supersymmetry breaking

Cold Dark Matter(CDM) and Large Scale Strucuture

CDM : Non-Relativistic @ decoupling
Standard assumption : ΛCDM cosmology

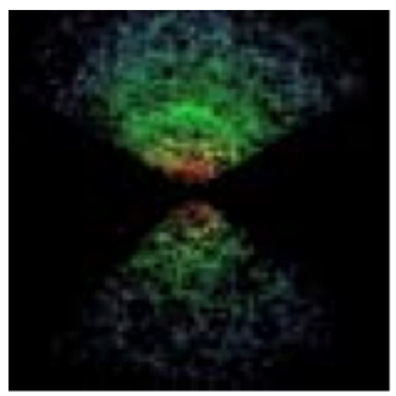
scale

Gpc

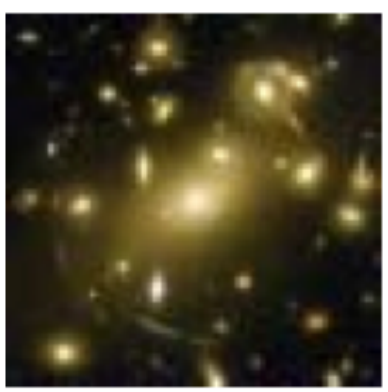


Cosmic Microwave Background

Large Scale Structure (LSS)



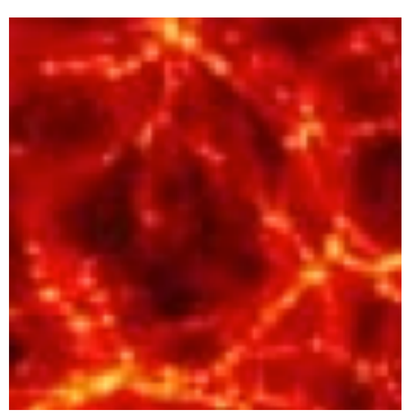
SDSS galaxies
Cluster abundance

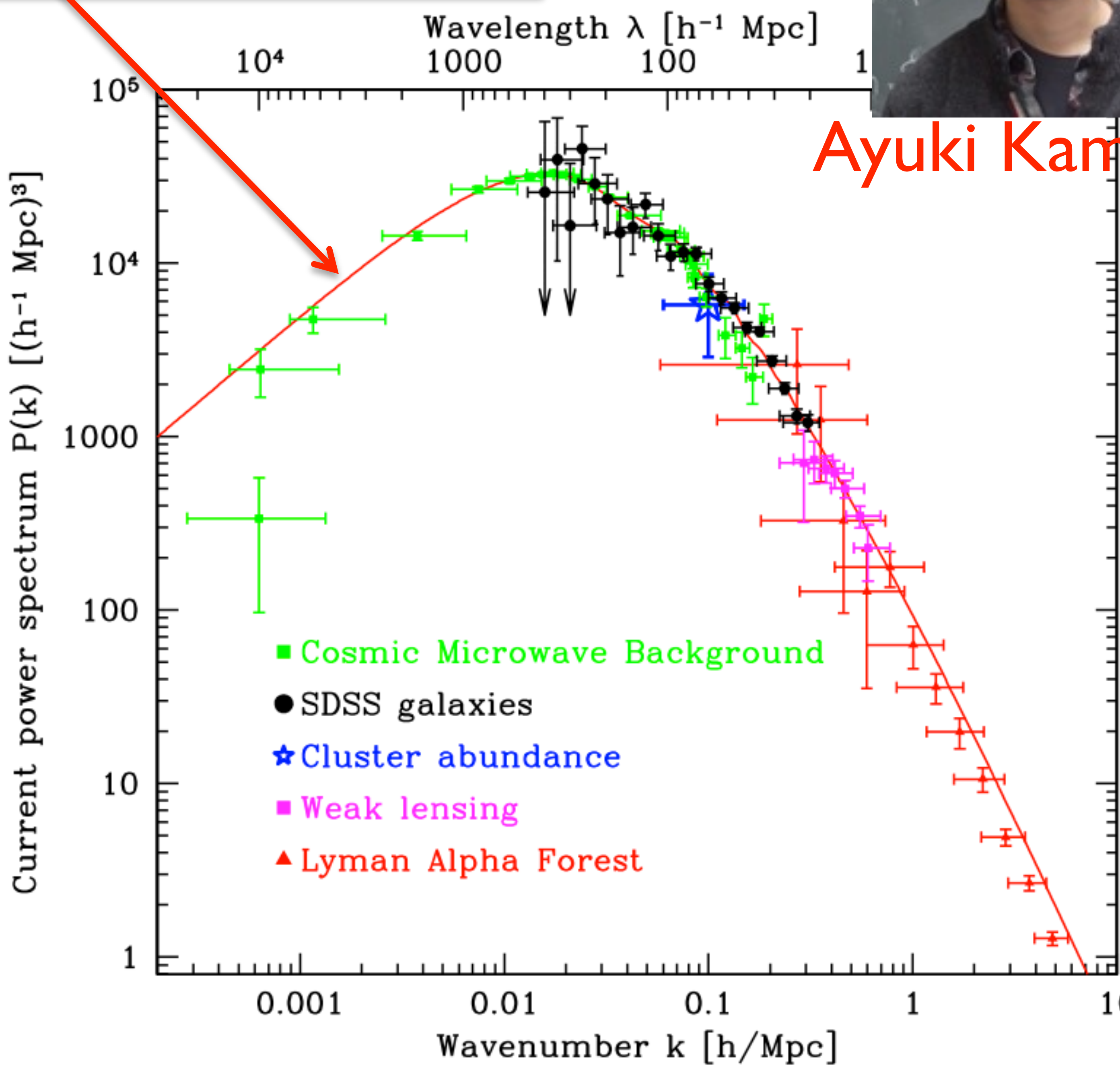


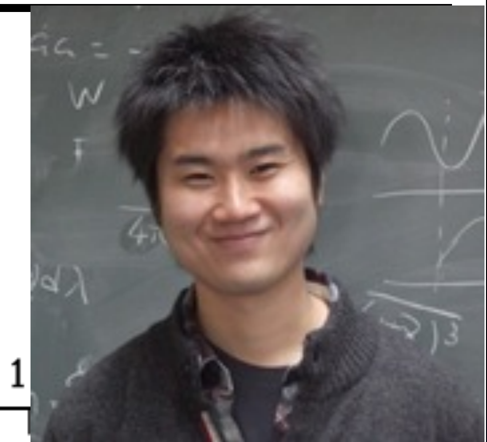
Weak lensing

Mpc

Lyman Alpha Forest







Ayuki Kamada

Tegmark et al. (2004)

CDM agrees with several observations of Large Scale Structure

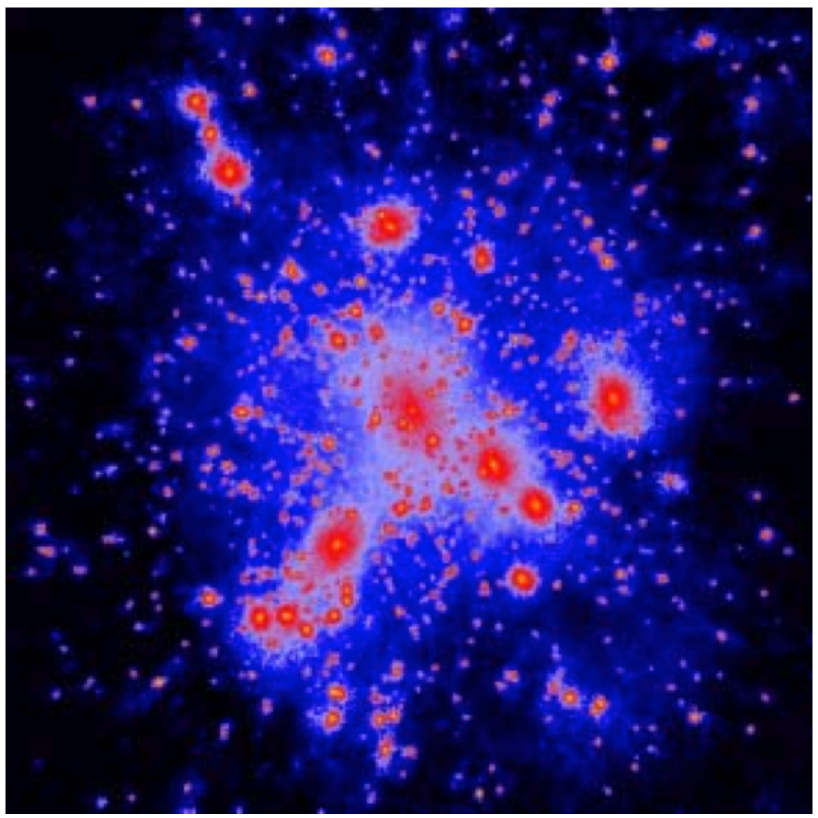
Cold Dark Matter(CDM) and Small Scale Structure

However…, **CDM** disagrees with several observations of Small Scale Structure

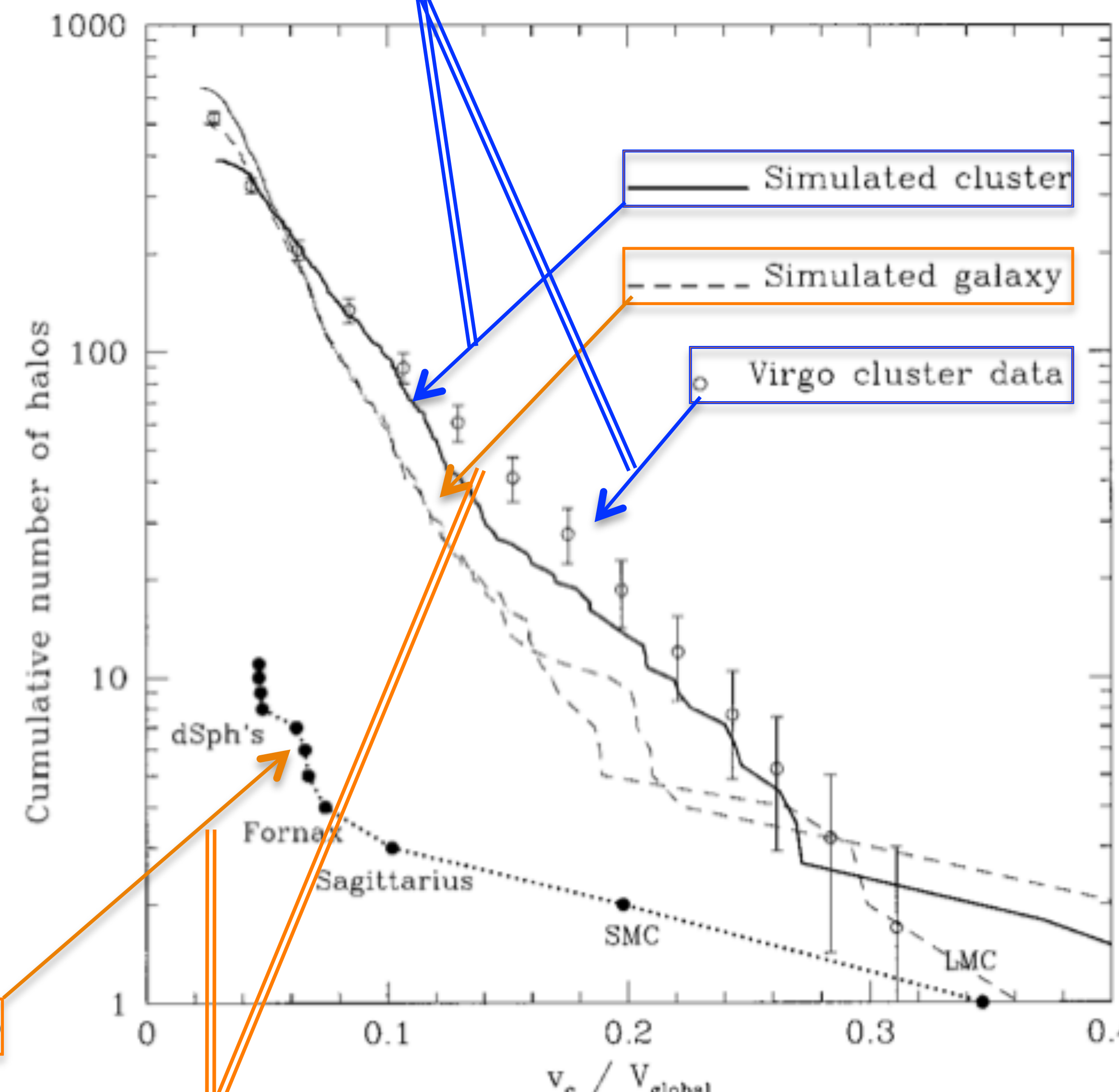
Small Scale Structure (SSS)

kpc

Missing Satellite Problem



Agreement in LSS



Satellites within the Milky Way's halo

Disagreement in SSS

Moore et (1999)

circular velocity

$$v = \sqrt{\frac{Gm}{r}}$$

Cold Dark Matter(CDM) and Small Scale Structure

Small Scale Structure (SSS)

kpc

Cuspy Halo Problem

Density Profile

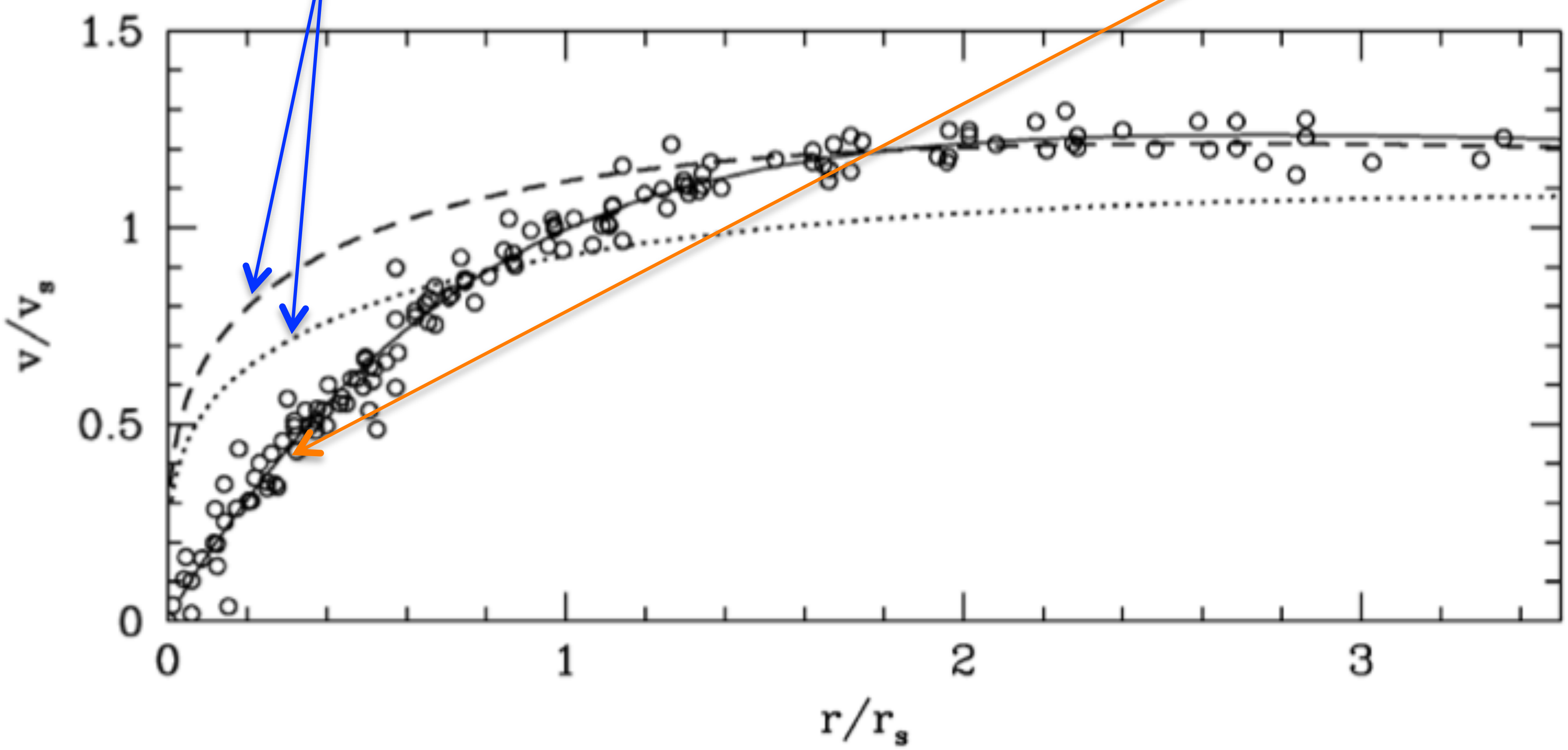
$$\rho(r) = \frac{\rho_0}{(r/r_s)^{\gamma}[1 + (r/r_s)^{\alpha}]^{(\beta-\gamma)/\alpha}}$$

Simulated Profile

$\alpha = 1.5\ \beta = 3.0\ \gamma = 1.5$

Observed Profile

$\alpha = 2.0\ \beta = 3.0\ \gamma = 0.0$



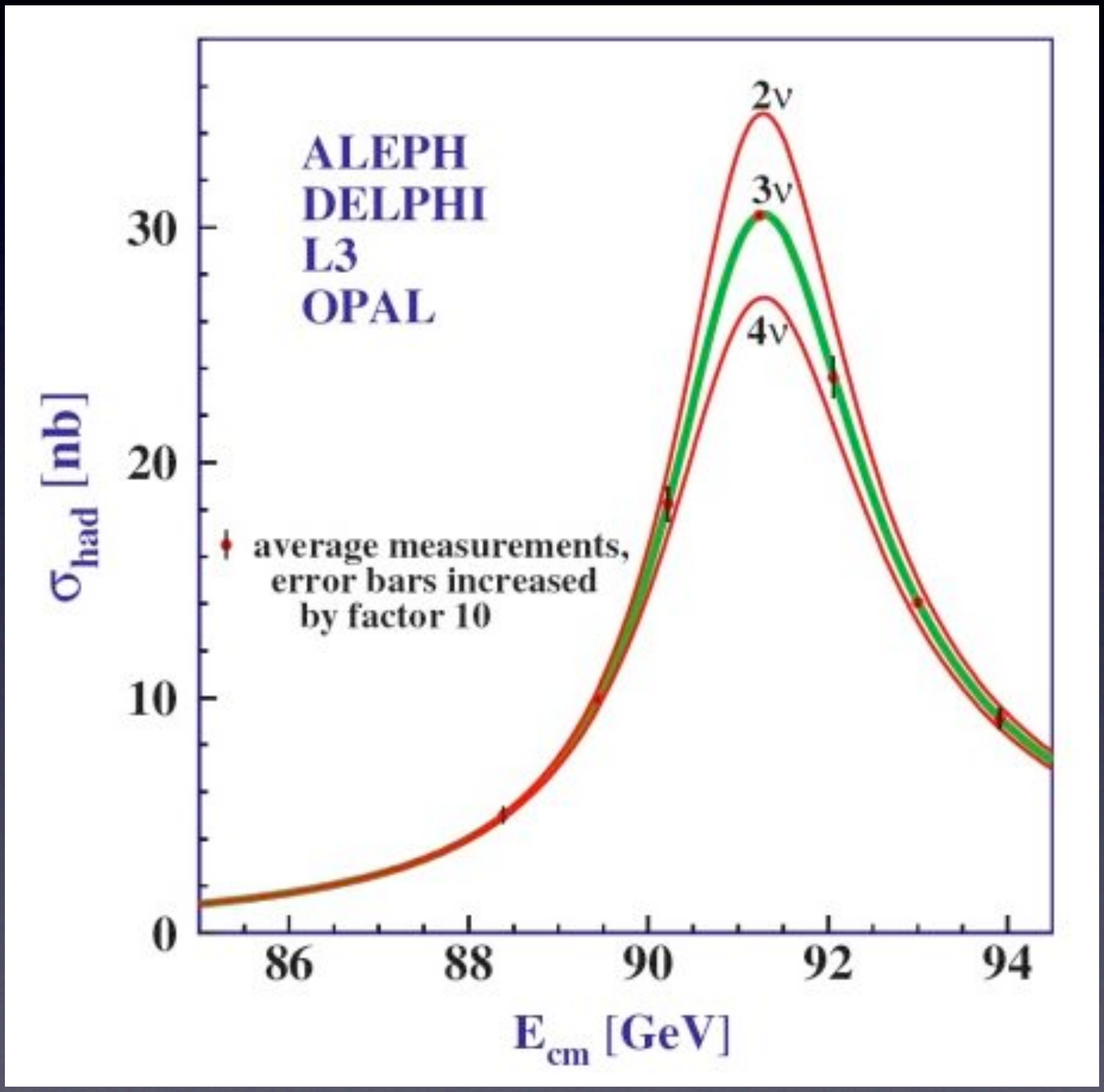
Moore et (1999)

These disagreements in SSS are called **Small Scale Crisis**

Sterile neutrino

$\nu_s \neq 3\nu_a$

- a spin 1/2 fermion
- neutral under *all* gauge interactions, i.e. even no weak interaction
- but gravitates
- and can mix with ordinary neutrinos



LEP e^+e^- collider

Production Mechanism

How ‘sterile’ neutrino was produced

↓

in the thermal history ?

Three ‘Non-thermal’ production mechanisms are considered.

1. Dodelsen & Widrow (DW) Mechanism :

via non-resonant neutrino oscillation

2. Shi & Fuller (SF) Mechanism :

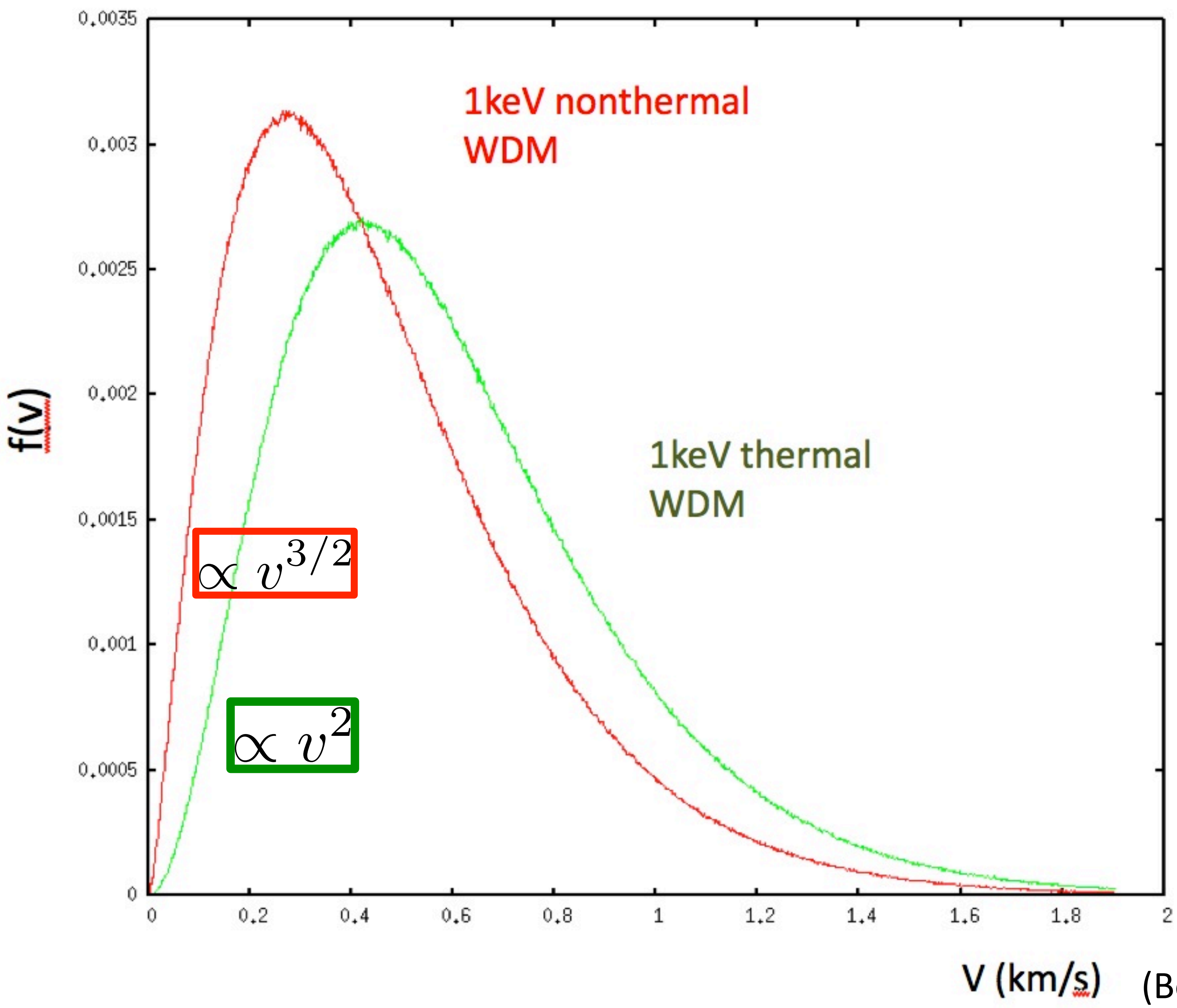
via resonant neutrino oscillation

3. Singlet Higgs Decay :

via Singlet Higgs decay to sterile neutrino

Linear Perturbation Theory

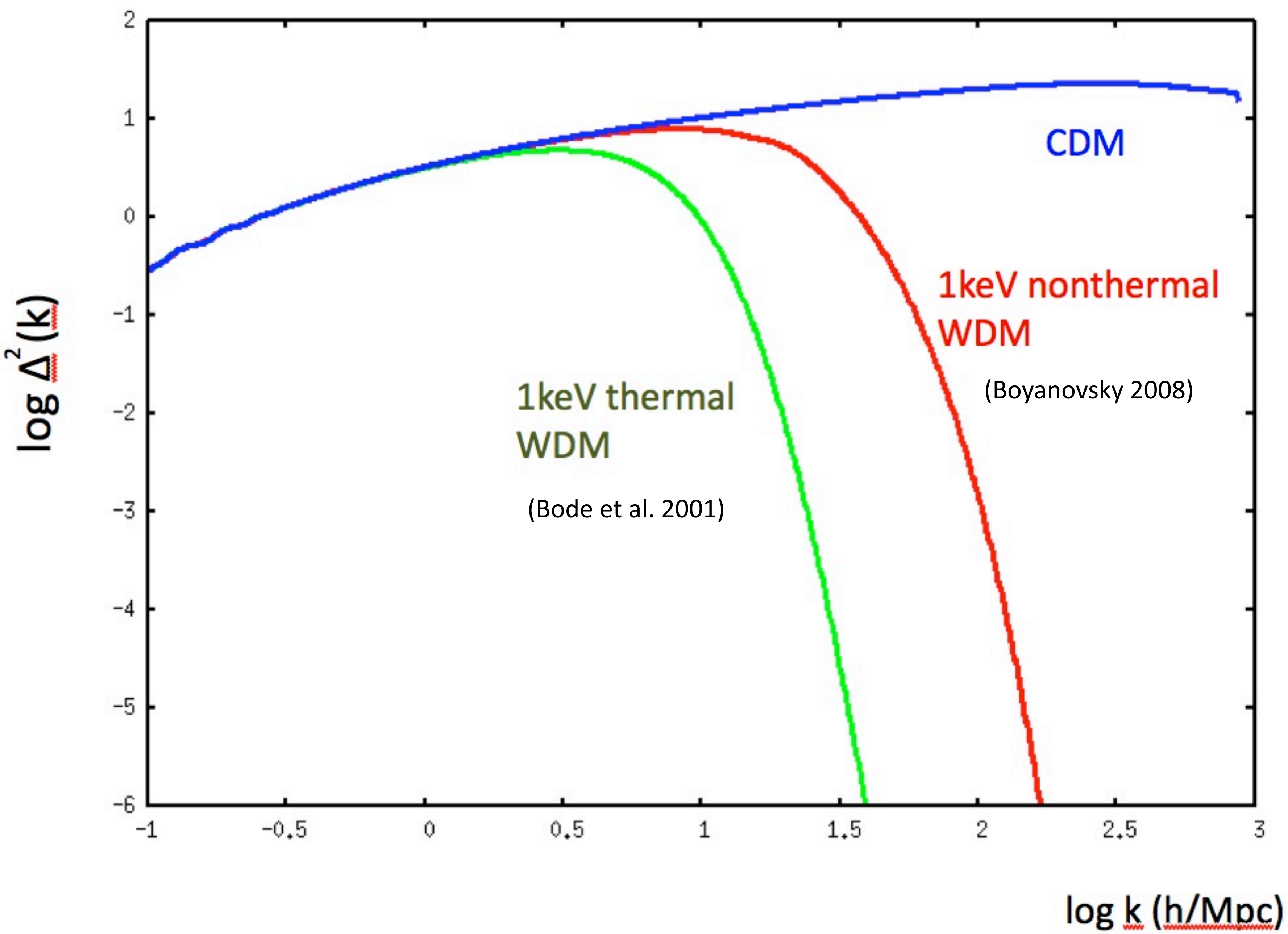
Velocity Distribution @ z=9



(Boyanovsky 2008)

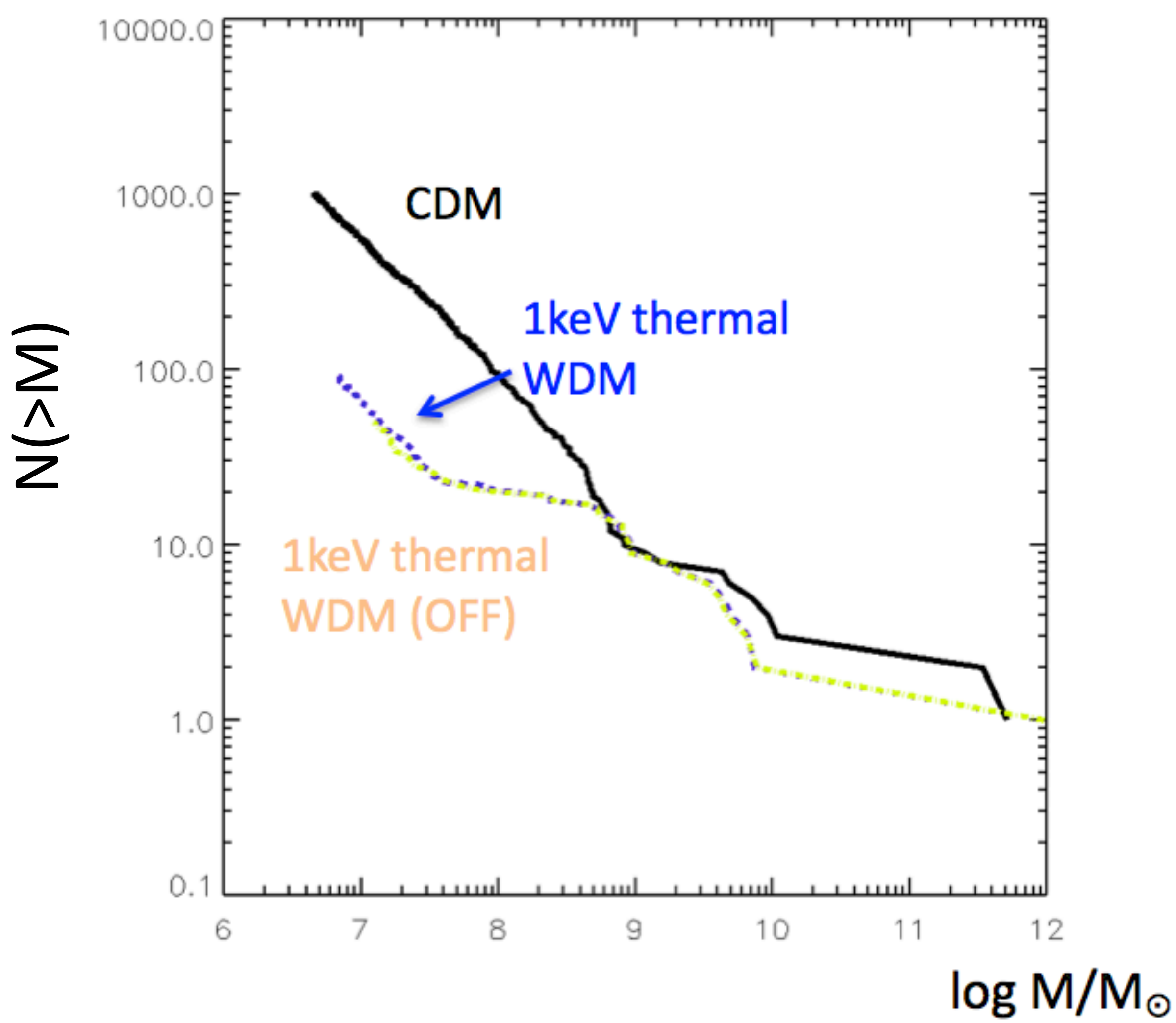
Linear Power Spectrum

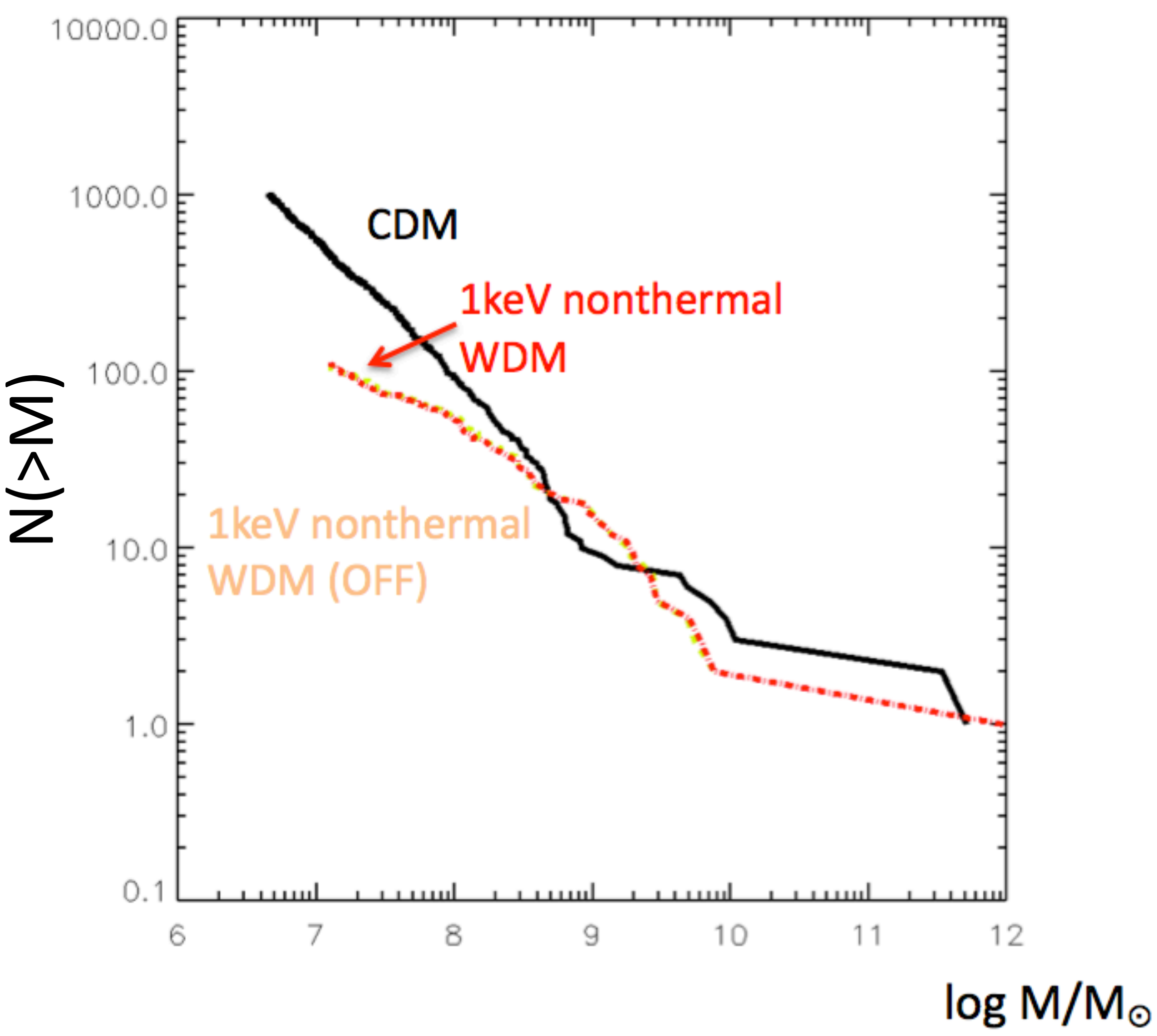
Linear Power Spectrum @z=0



Simulation Result

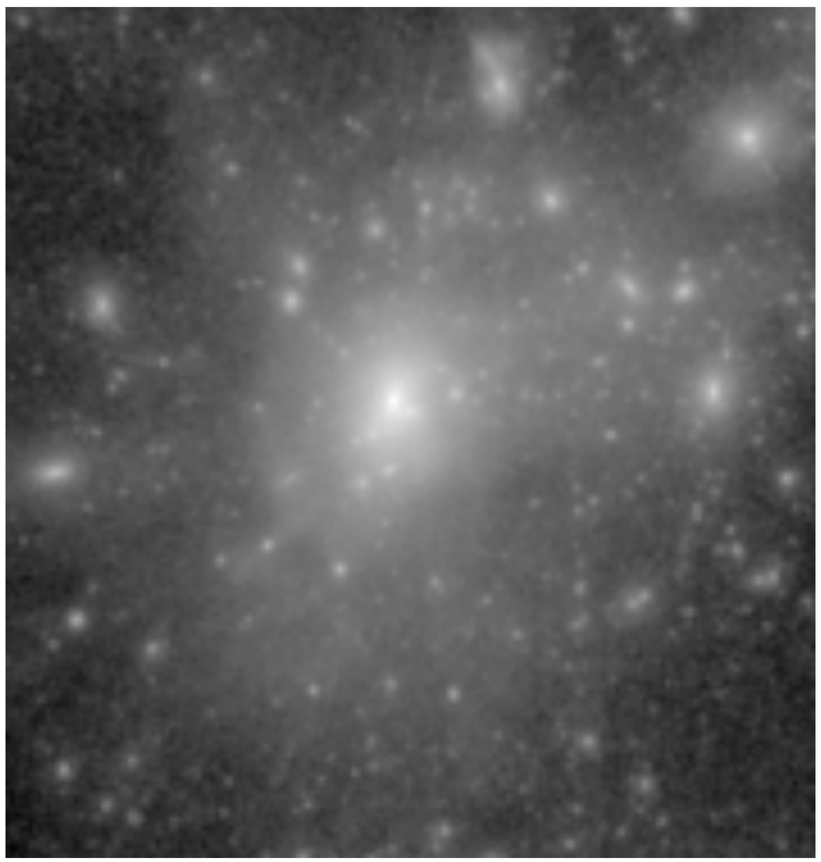
Mass Function of Milky Way like halo

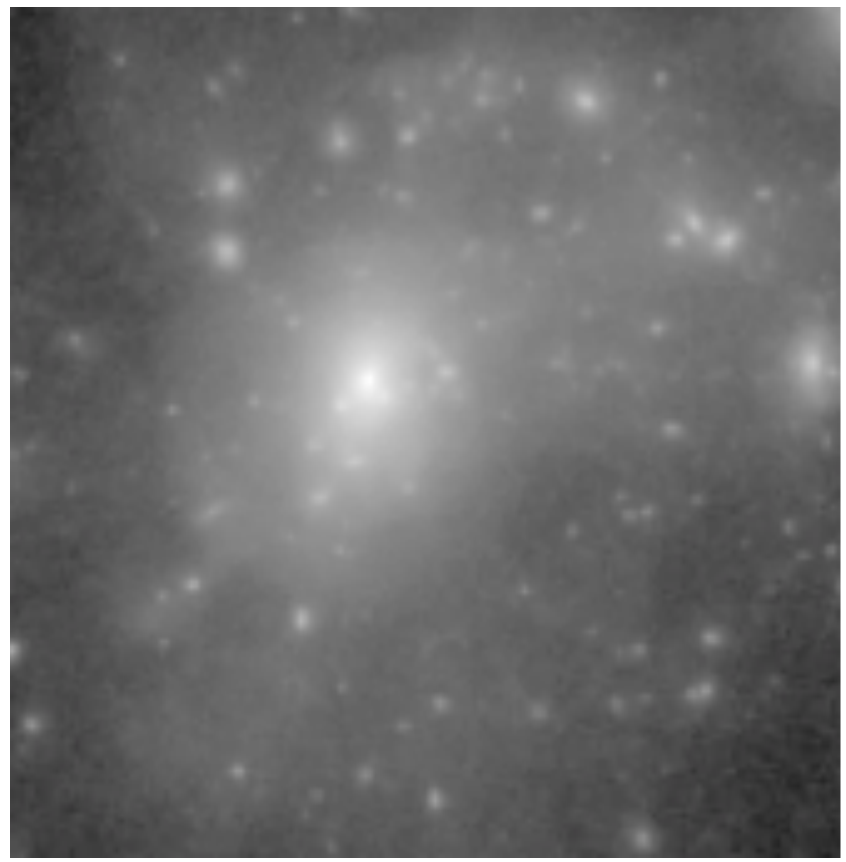


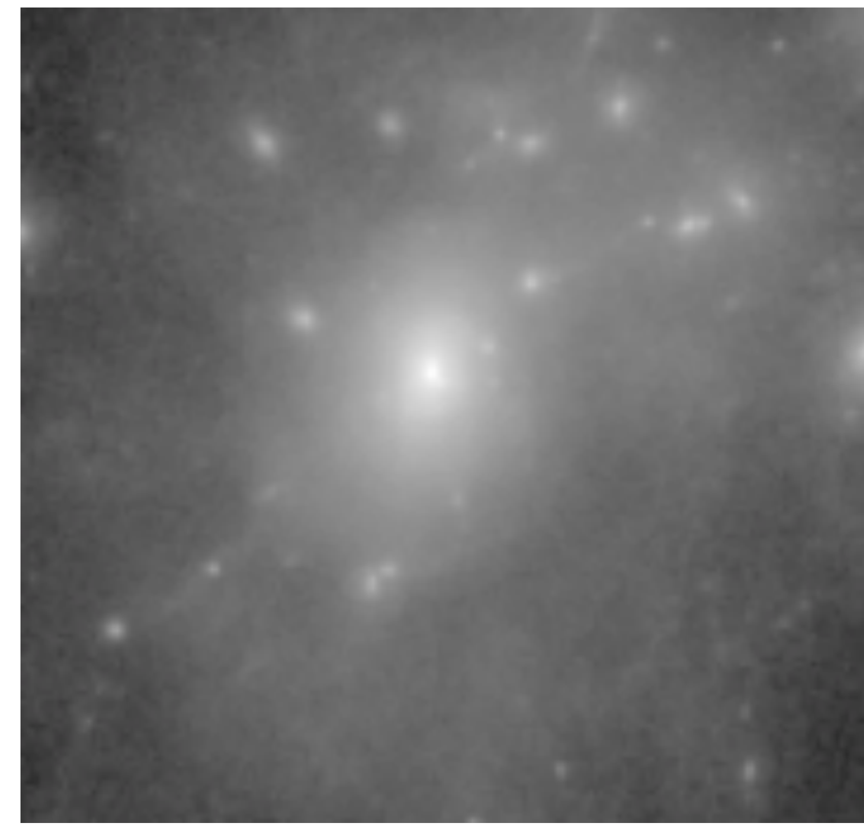


A.K. and Naoki Yoshida (in preparation)

Simulation Result







100 kpc

CDM

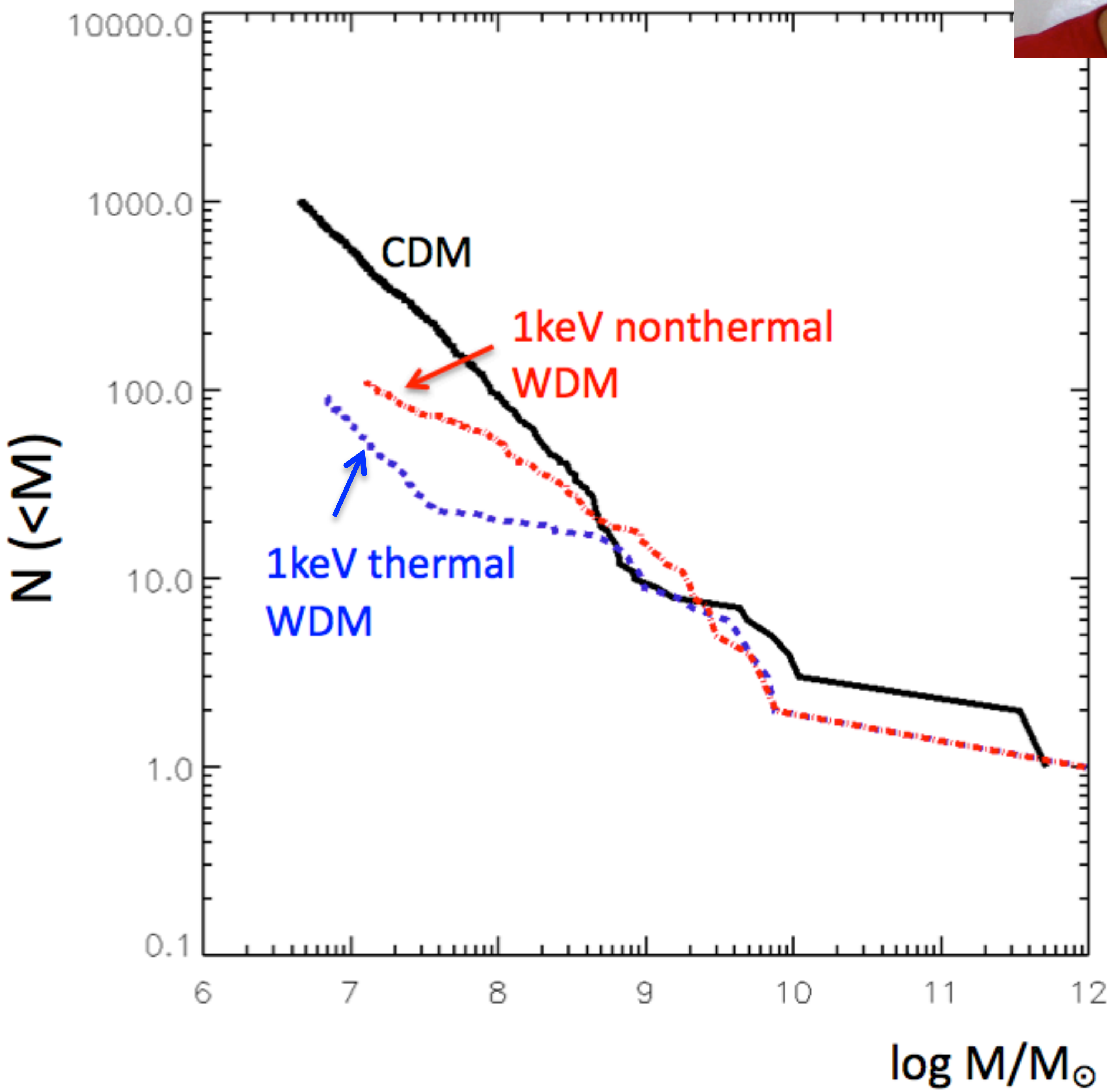
1keV nonthermal WDM

1keV thermal WDM

A.K. and Naoki Yoshida (in preparation)

Simulation Result

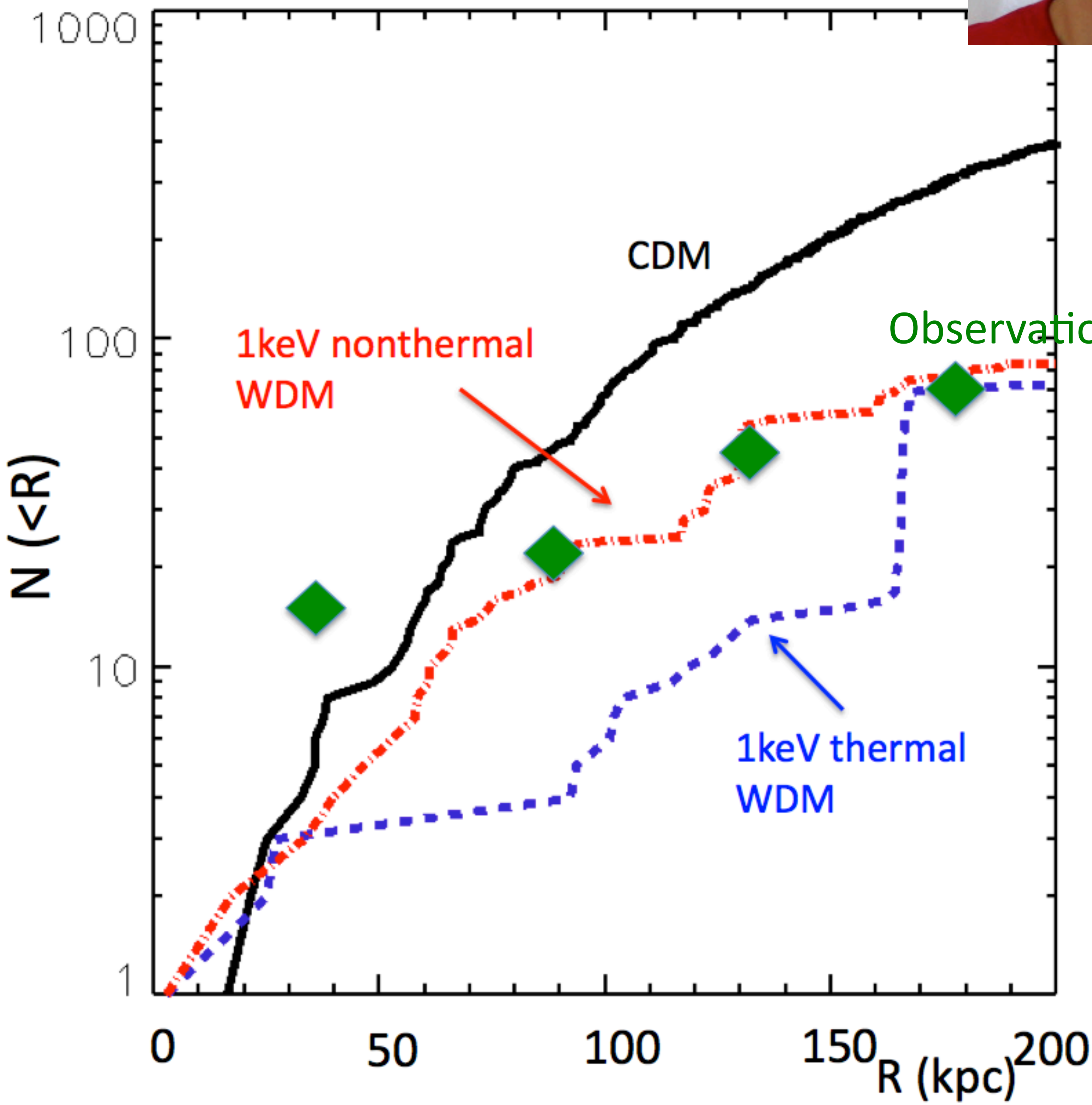
Subhalo Mass Function



A.K. and Naoki Yoshida (in preparation)

Simulation Result

Radial Distribution in Milky Way



Observation (SDSS data normalized to all sky)

A.K. and Naoki Yoshida (in preparation)

$\nu_s \rightarrow \nu_a + \gamma$

THE ASTROPHYSICAL JOURNAL, 700:426–435, 2009 July 20 doi:10.1088/0004-637X/700/1/426

NEW LIMITS ON STERILE NEUTRINOS FROM *SUZAKU* OBSERVATIONS OF THE URSA MINOR DWARF SPHEROIDAL GALAXY

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Received 2008 December 14; accepted 2009 May 19; published 2009 July 2

ABSTRACT

We present results of our search for X-ray line emission associated with the radiative decay of the sterile neutrino, a well motivated dark matter candidate, in *Suzaku* Observatory spectra of the Ursa Minor dwarf spheroidal galaxy. These data represent the first deep observation of one of these extreme mass-to-light systems and the first dedicated dark matter search using an X-ray telescope. No such emission line is positively detected, and we place new constraints on the combination of the sterile neutrino mass, $m_{\rm st}$, and the active-sterile neutrino oscillation mixing angle, θ. Line flux upper limits are derived using a maximum-likelihood-based approach that, along with the lack of intrinsic X-ray emission, enables us to minimize systematics and account for those that remain. The limits we derive match or approach the best previous results over the entire 1–20 keV mass range from a single *Suzaku* observation. These are used to place constraints on the existence of sterile neutrinos with given parameters in the general case and in the case where they are assumed to constitute all of the dark matter. The range allowed implies that sterile neutrinos remain a viable candidate to make up some—or all—of the dark matter and also explain pulsar kicks and various other astrophysical phenomena.

Key words: dark matter – galaxies: dwarf – galaxies: individual (Ursa Minor)

Online-only material: color figures

Loewenstein

Where to Look, What to Look With

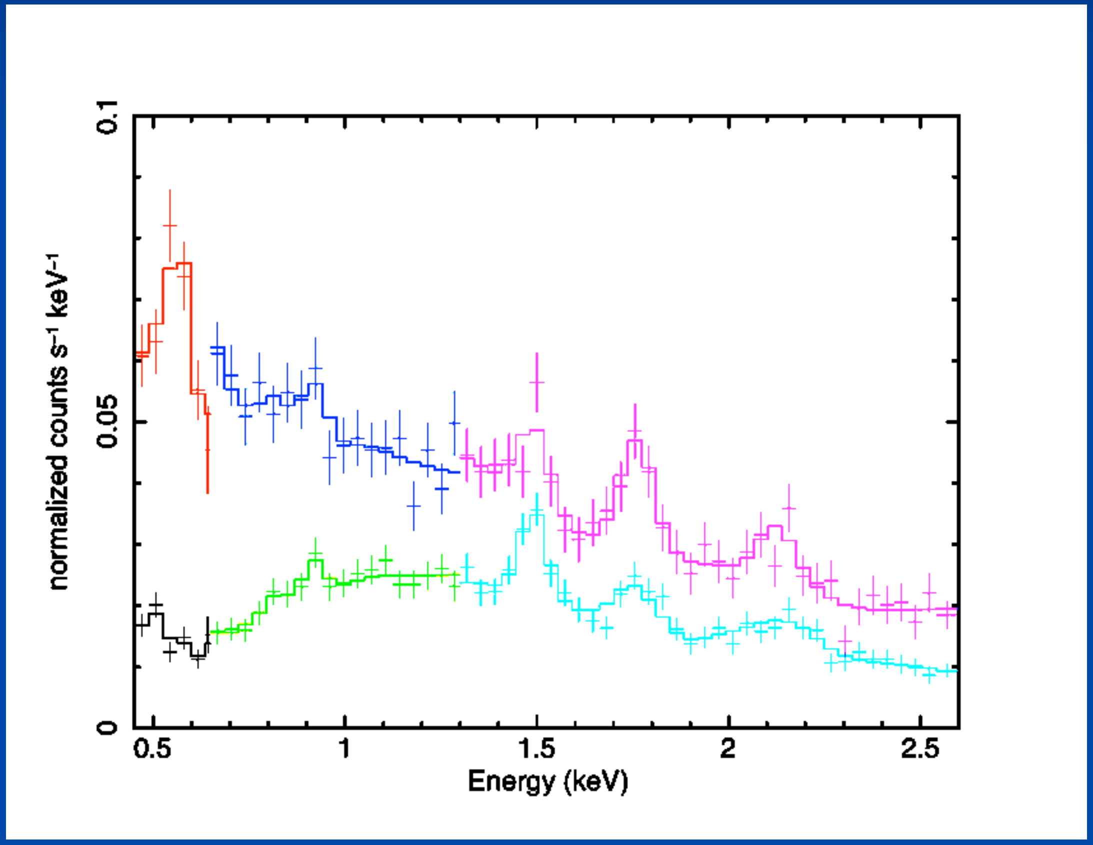
- In our pilot *Suzaku* Cycle 2 program, we observe the Ursa Minor and Draco dwarf spheroidal galaxies for ~ 67 ksec each (200 ksec of data).

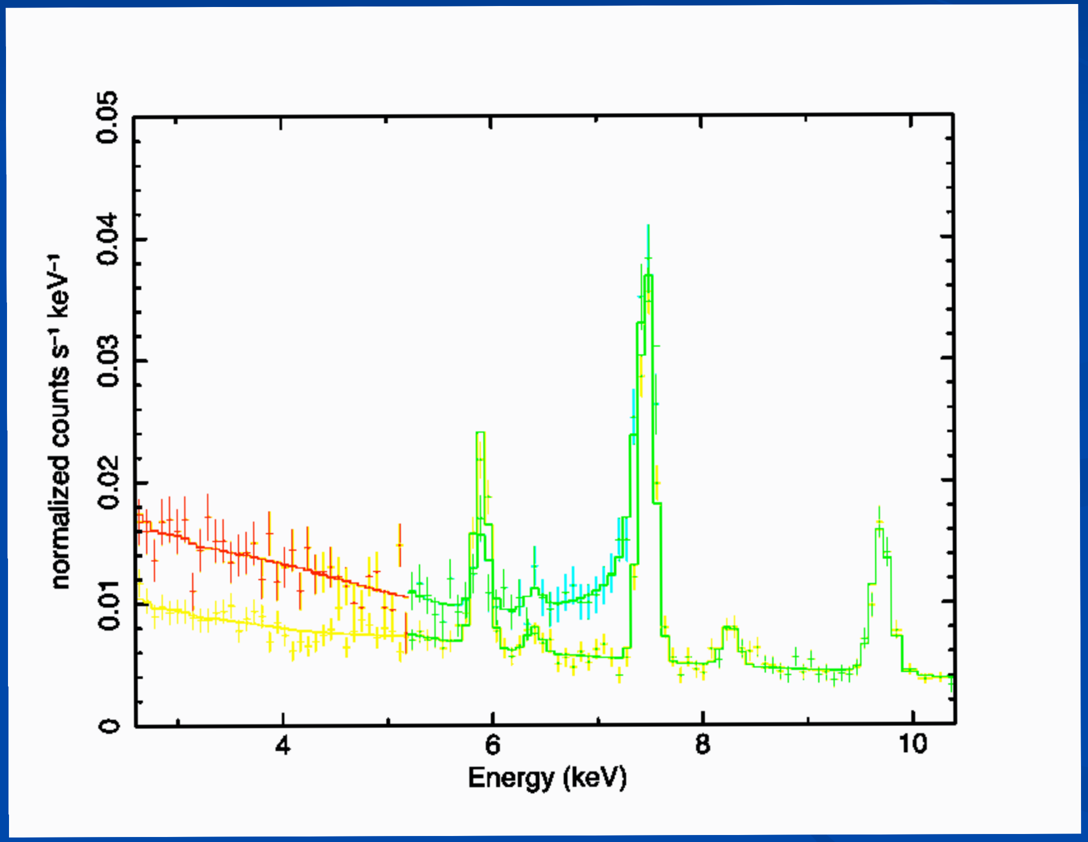
Ursa Minor Dwarf

15' field from the Digital Sky Survey.

How to Look – Spectral Analysis

✓ Fit total spectrum with NXB+GXB+CXB model using the C-statistic





➢ Derive upper limits to line fluxes corresponding to ΔC that occurred in 1% of Monte Carlo simulations with an extra emission line component

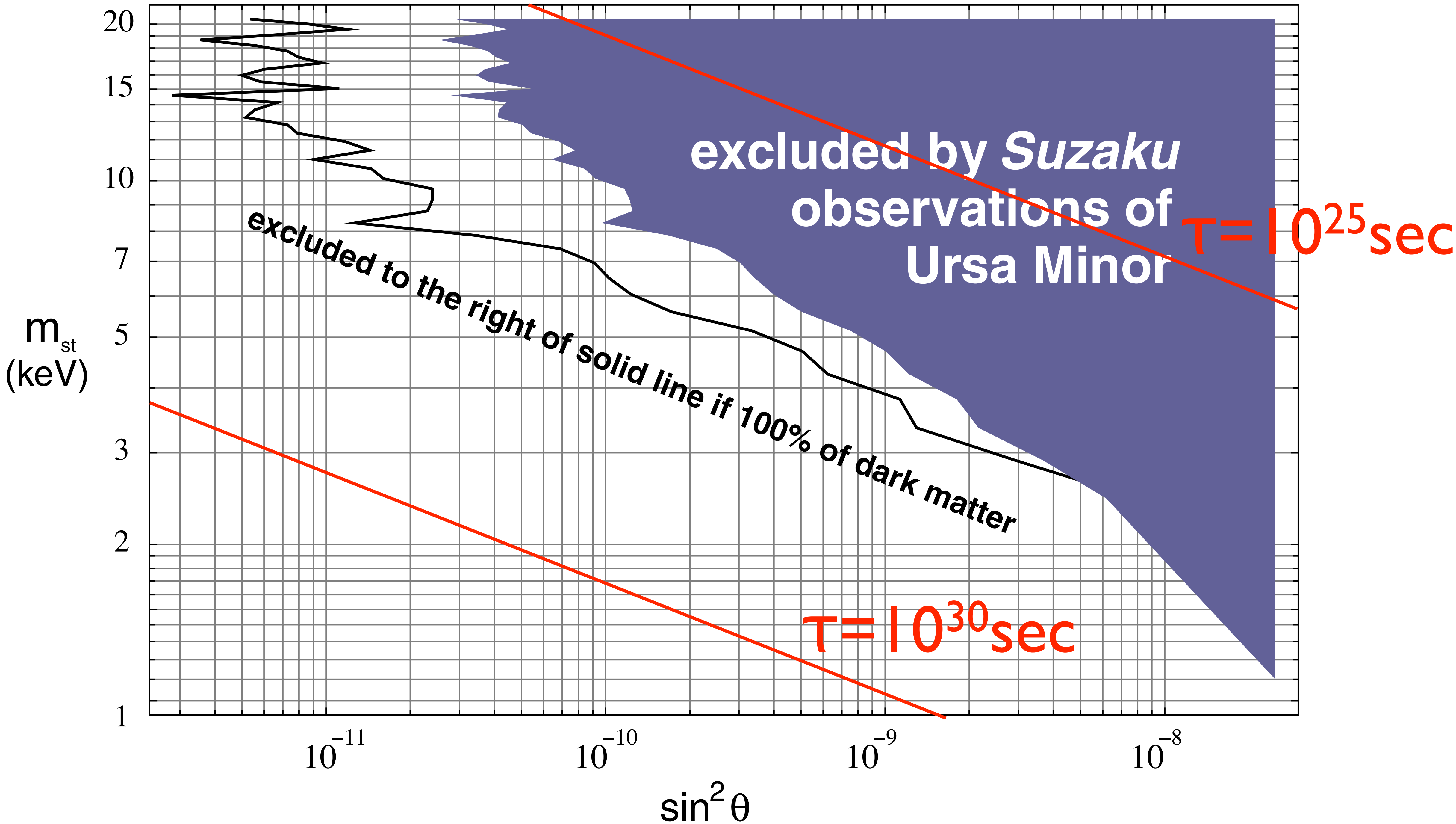
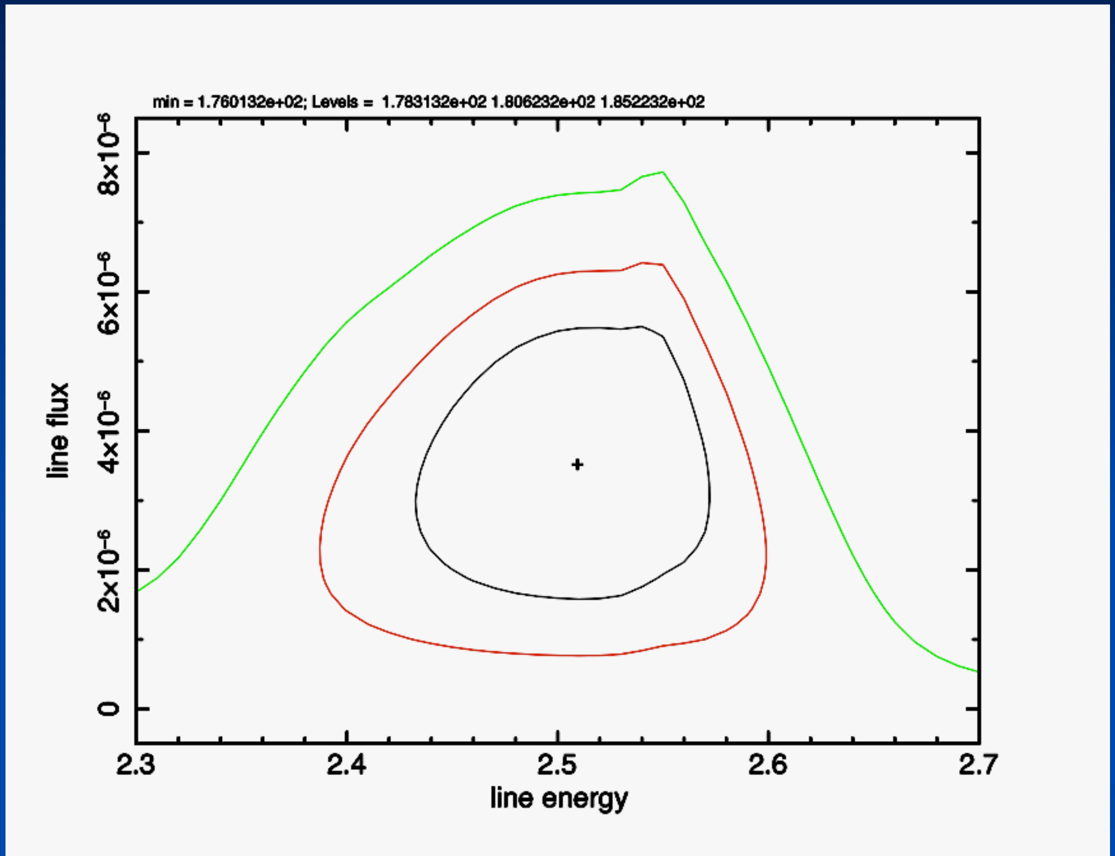


Figure 9. Sterile neutrino parameter space to the right of the solid curve is excluded by the *Suzaku* observation of Ursa Minor if dark matter is solely composed of sterile neutrinos produced by some (unspecified) mechanism. The solid exclusion region is model-independent, based only on the assumption of the standard cosmological history below the temperature of a few hundred MeV, when the DW production by neutrino oscillations takes place.

Loewenstein, Kusenko, Biermann

Chandra observation of Willman 1 dwarf spheroidal
A Candidate Line at 2.5 keV

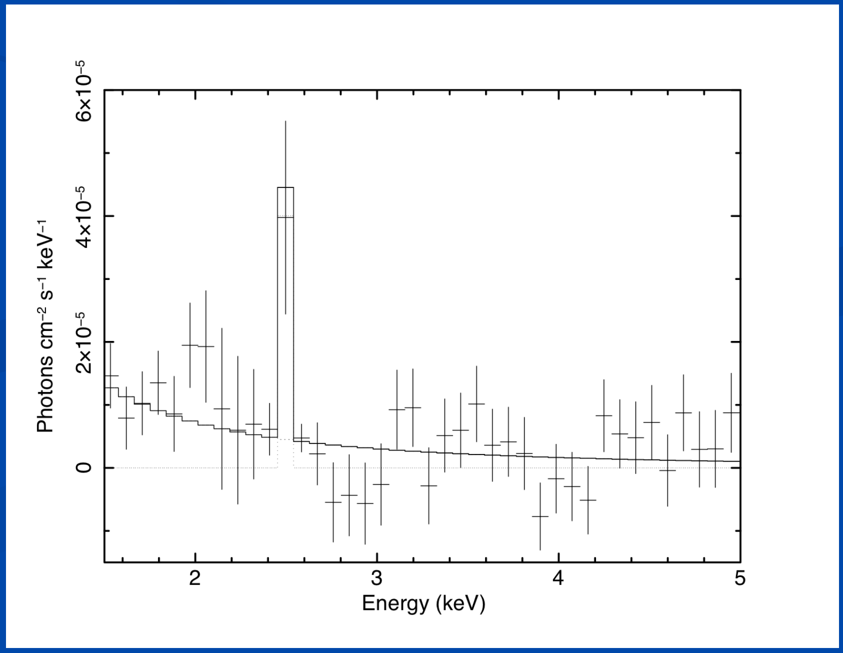
- Energy=2.51±0.11 keV
- Flux=[3.53±2.77] X 10^{-6} photons cm^{-2} s^{-1} (90% confidence)



Consistent with radiative decay of a sterile neutrino with

- $m_{ster\text{-}\nu}$ =5±0.2 keV, and
- $\sin^2 \theta_{mix}$=[7.8±6.1] X 10^{-10} X ($f_{st}\Sigma_{dark}$/210), Σ_{dark} in $M_{\odot}/pc^2$
- f_{st} = fraction of DM in sterile ν's

unfolded spectrum



Loewenstein

gauge mediation of supersymmetry breaking

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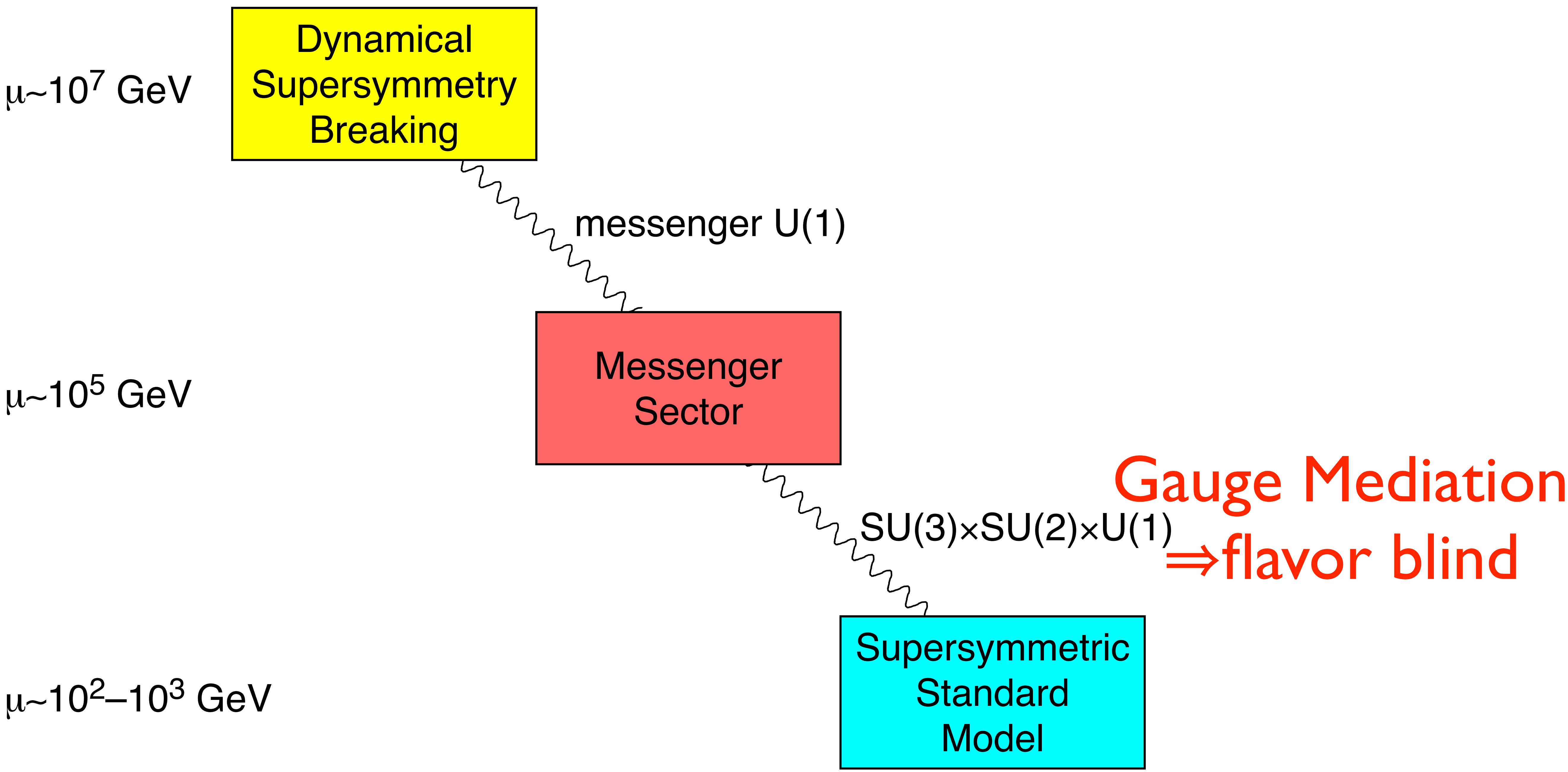
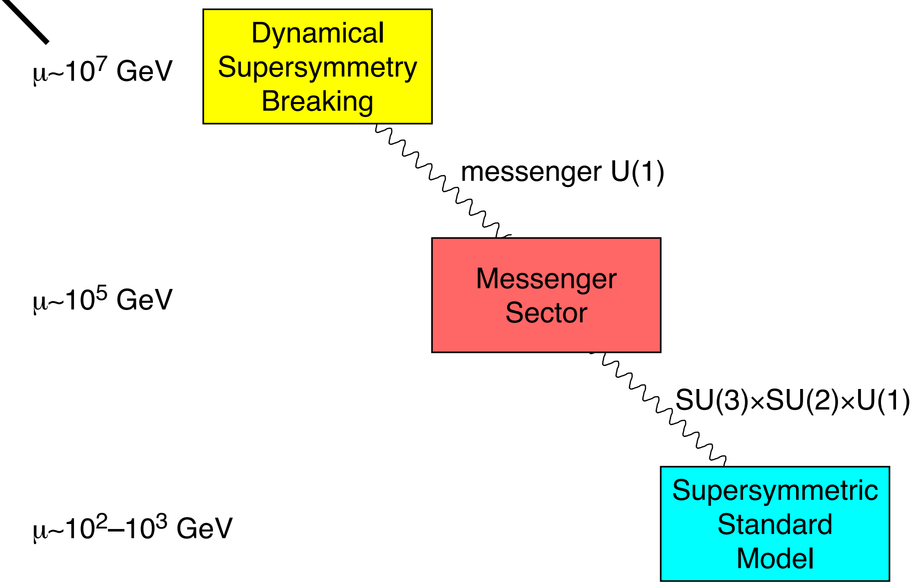


Dine-Nelson-Nir-Shirman

gauge mediation of supersymmetry breaking

$M_{Pl}=2\times10^{18}$GeV Quantum Gravity



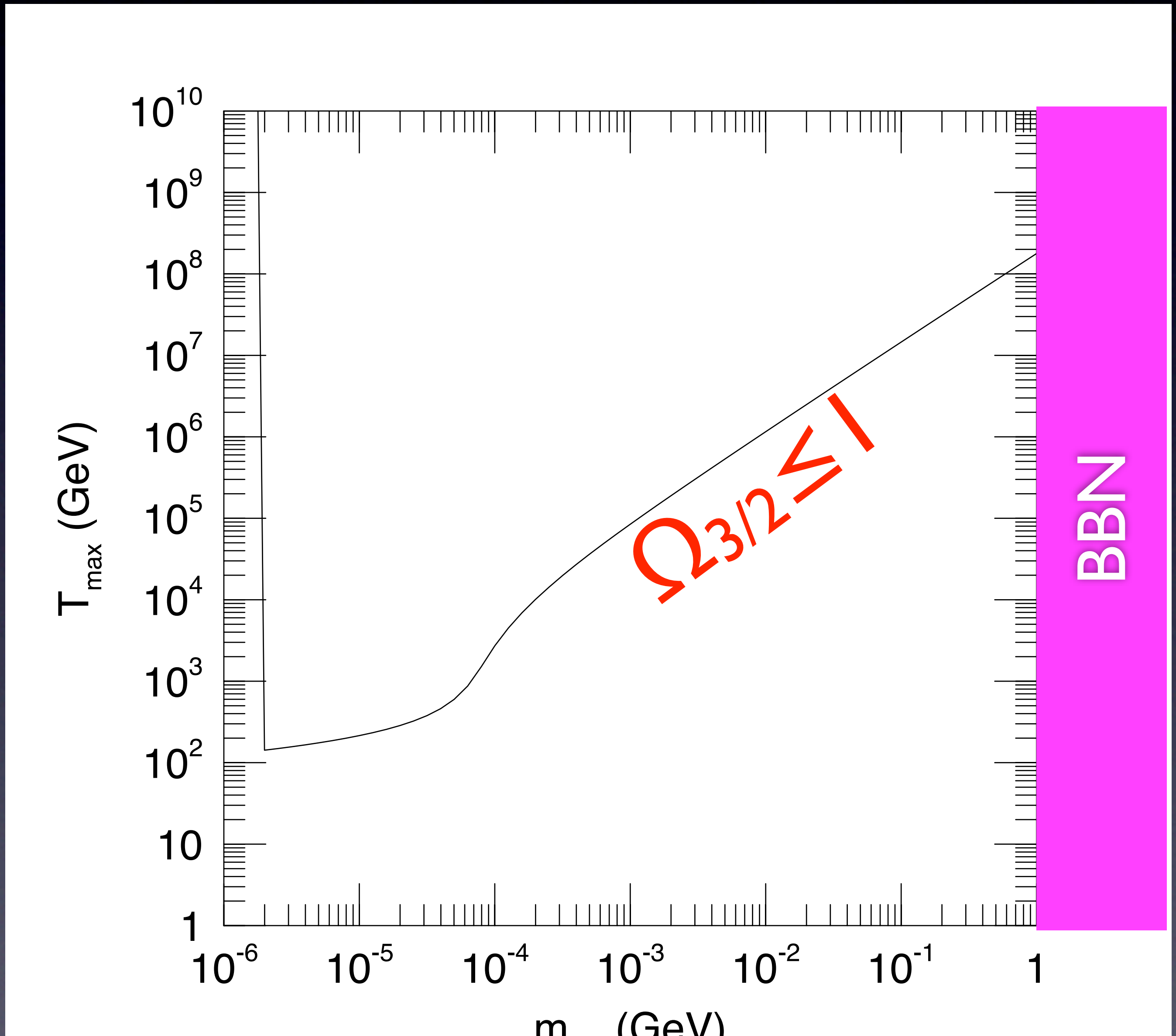
$\mu=(10^7\text{GeV})^2/M_{Pl}$

$\approx$100keV

gravitino dark matter

- usual WIMP neutralino decays into gravitino
- lower the gravitino mass, stronger the coupling
- abundance depends on the reheating temperature
- If warm (m<keV), Lyman alpha says m < 16eV (Viel, Lesgourgues, Haehnelt, Matarrese, Riotto)
- Possible in recent gauge mediation models by HM, Nomura
- can further decay if R-parity violated (lifetime arbitrary)

$$\psi_{3/2} \to \nu_a + \gamma$$



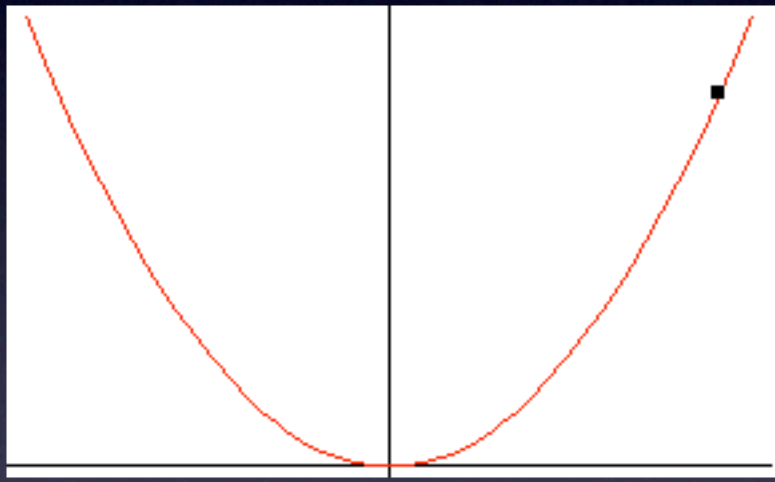
de Gouvêa, Moroi, HM

string theory

- string theory is full of "moduli fields" that characterize the size and shape of the small six dimensions of space
- some of them acquire potential only from supersymmetry breaking
- In gauge mediation,
  - $V(\varphi) \approx (10^7 \mathrm{GeV})^4$
  - $\varphi \approx M_{Pl}$
  - $m_\varphi^2 = V''(\varphi) \approx (10^7 \mathrm{GeV})^4 / M_{Pl}^2 \approx (100 \mathrm{keV})^2$

moduli decays

- oscillating modulus field may be dark matter (de Gouvêa, HM, Moroi)
- the only decay mode $\varphi \rightarrow \gamma\gamma$
- lifetime $\tau \approx 8\pi M_{Pl}^2/m_\varphi^3 \approx 10^{26}$sec
- unfortunately a big "slop" in O(1) factors
- the best limit from Suzaku



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Dark Energy and Big Rip


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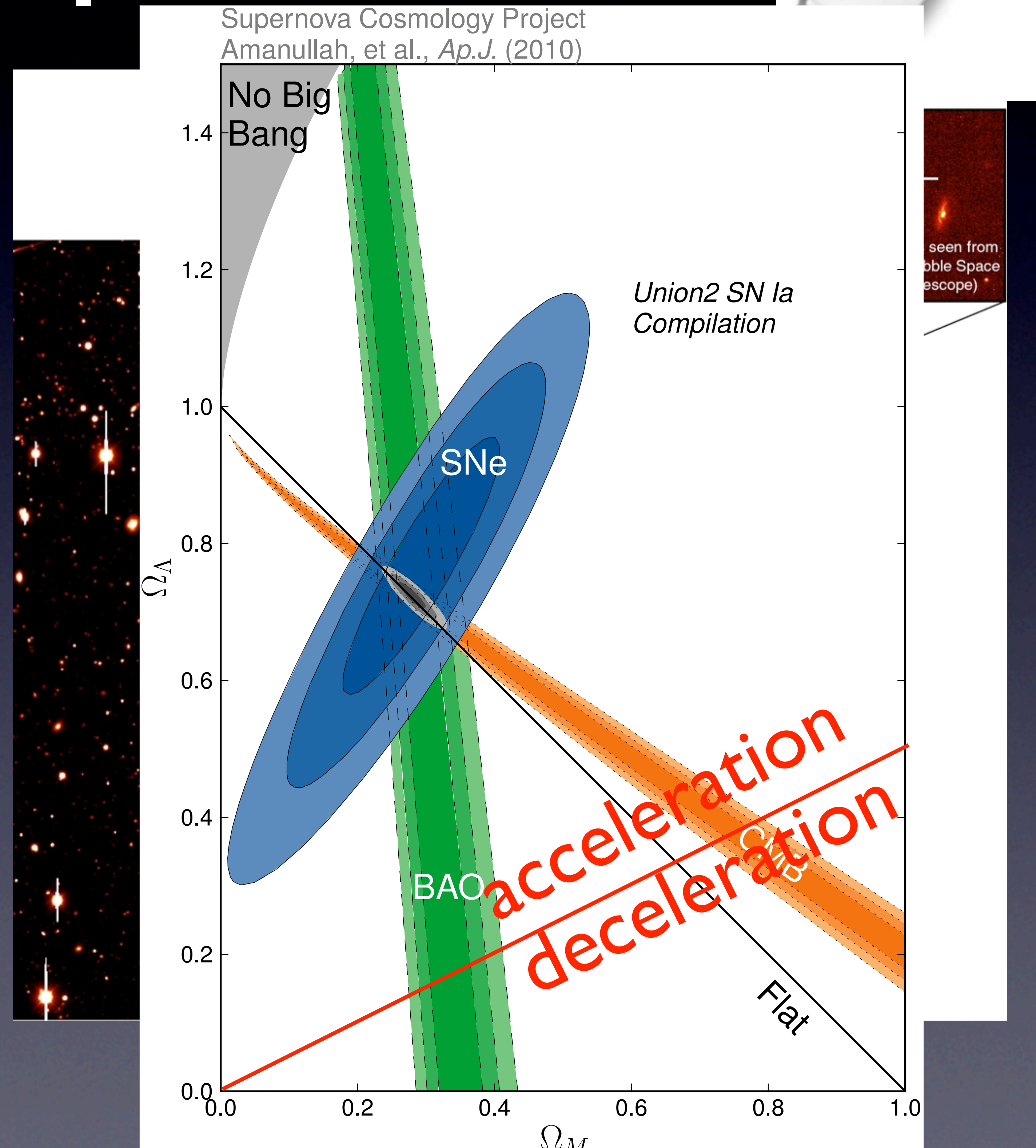
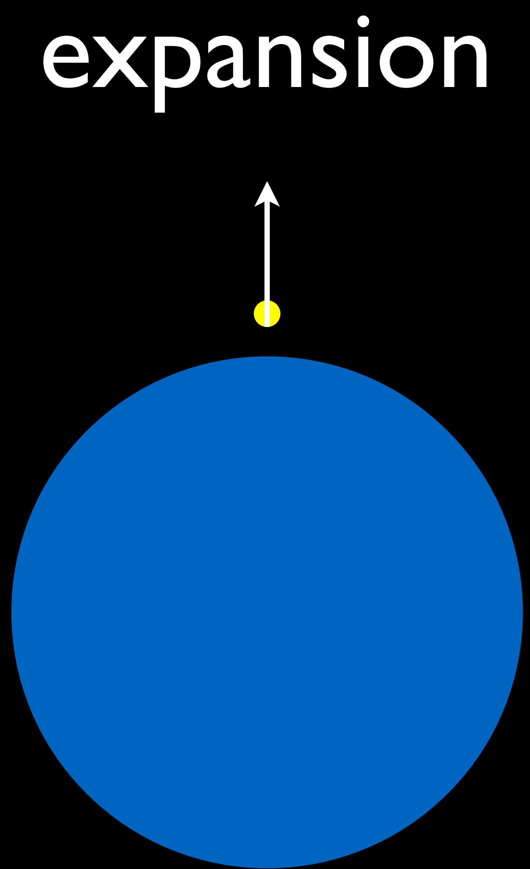
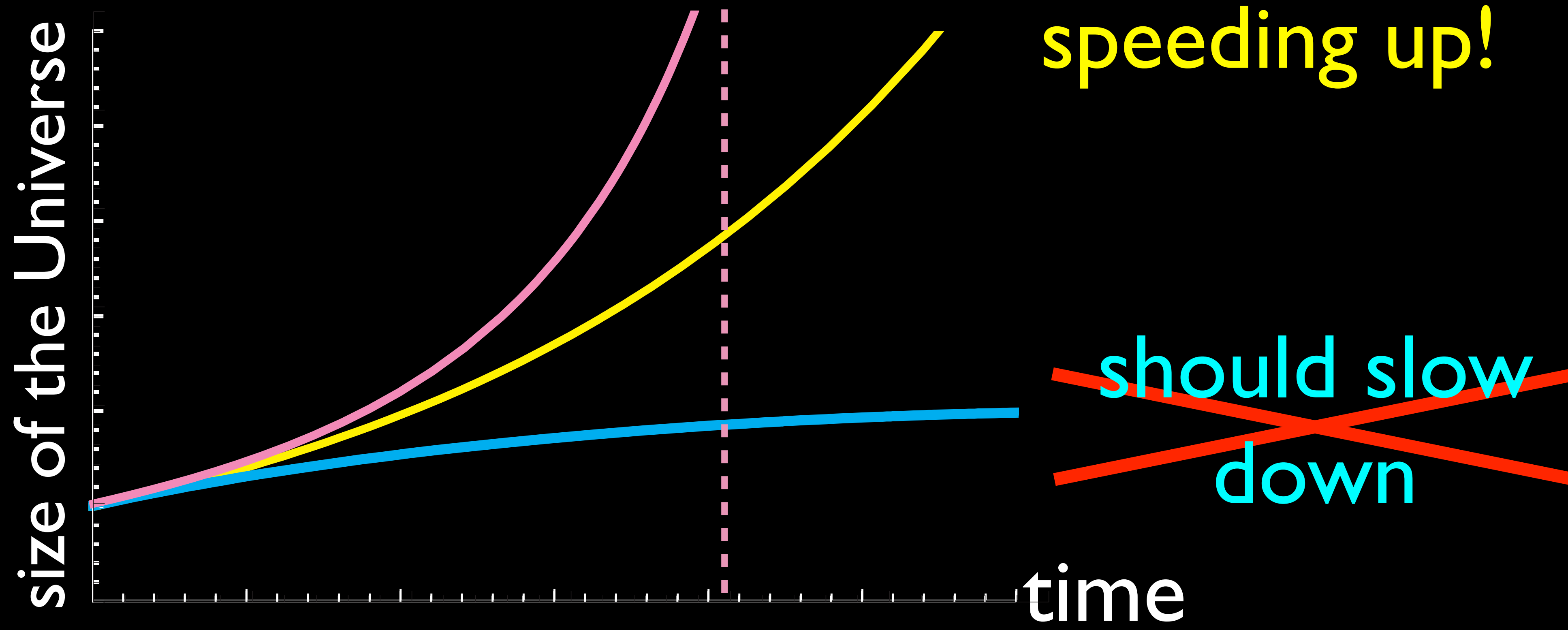
Type-Ia supernovae

- Type-Ia supernova as an approximate “standard candle”
- *apparent luminosity* ⇒ *luminosity distance*

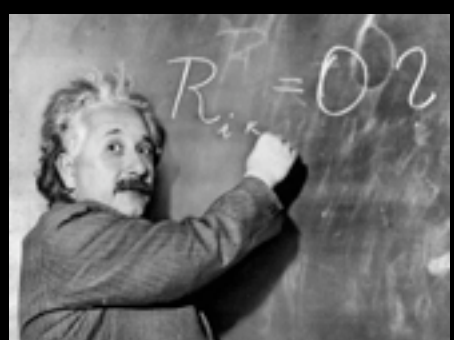
  ⇒ *How far back in time*
- *redshift* ⇒ *How much expansion*
- Expansion of the Universe is accelerating!

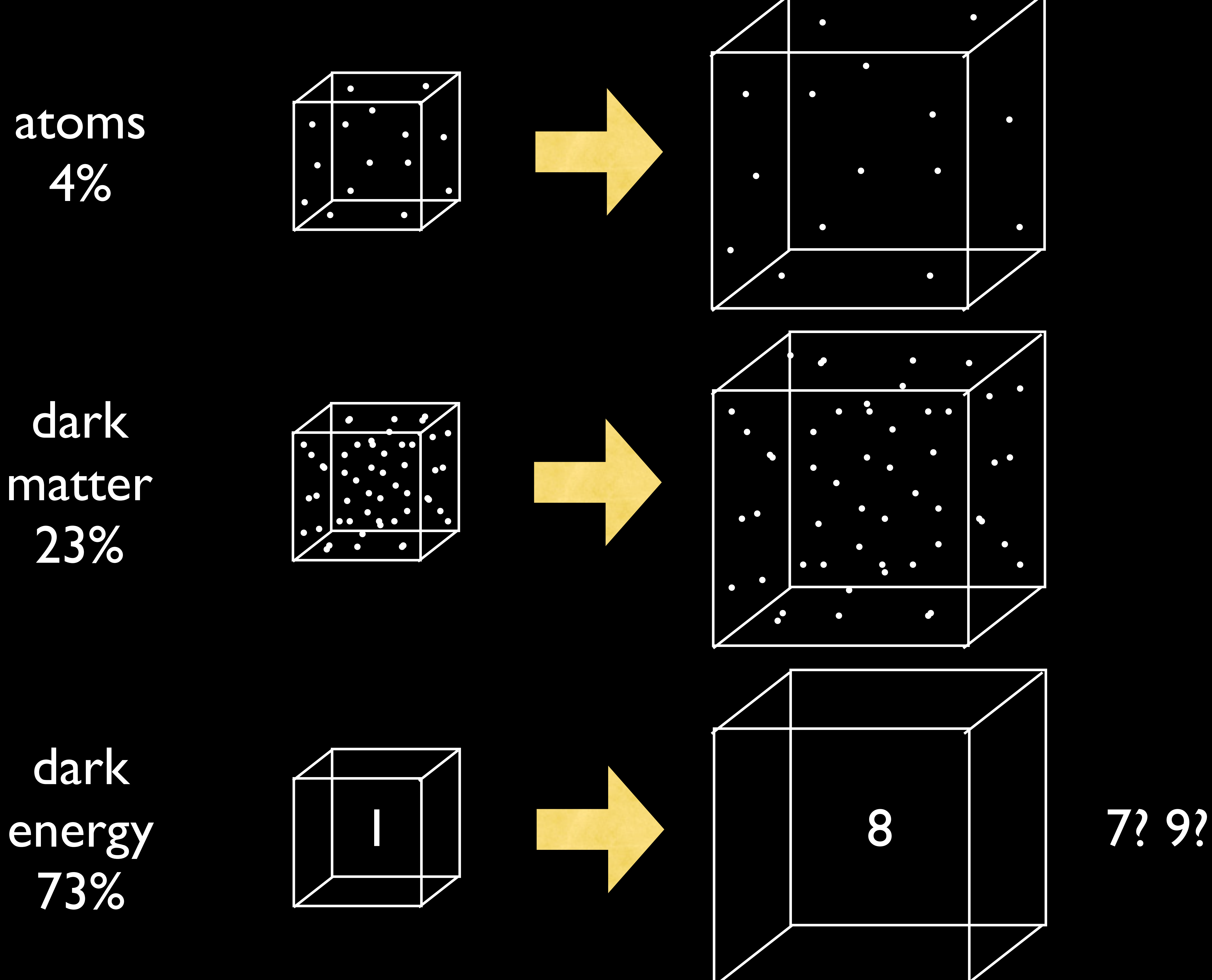






- expansion started to speed up recently (~7Byr)
- energy is increasing!
- infinite source of energy?? dark energy
- Was Einstein wrong?
- new paradigm of the Universe, fundamental laws
- If the rate of energy increase very quick, eventually the expansion becomes infinitely fast
  ⇒ Will the Universe end??
- Need to measure the rate of energy increase!




atoms
4%
dark
matter
23%
dark
energy
73%
1
8
7? 9?

Does the Universe end?

- If $w<-1$, the Universe ends in a Big Rip
- Expansion becomes so fast that galaxies, stars, eventually atoms and even nuclei get ripped apart
- Universe ends with an infinite speed and empty!
- We need to know the equation of state

Caldwell, Kamionkowski, Weinberg

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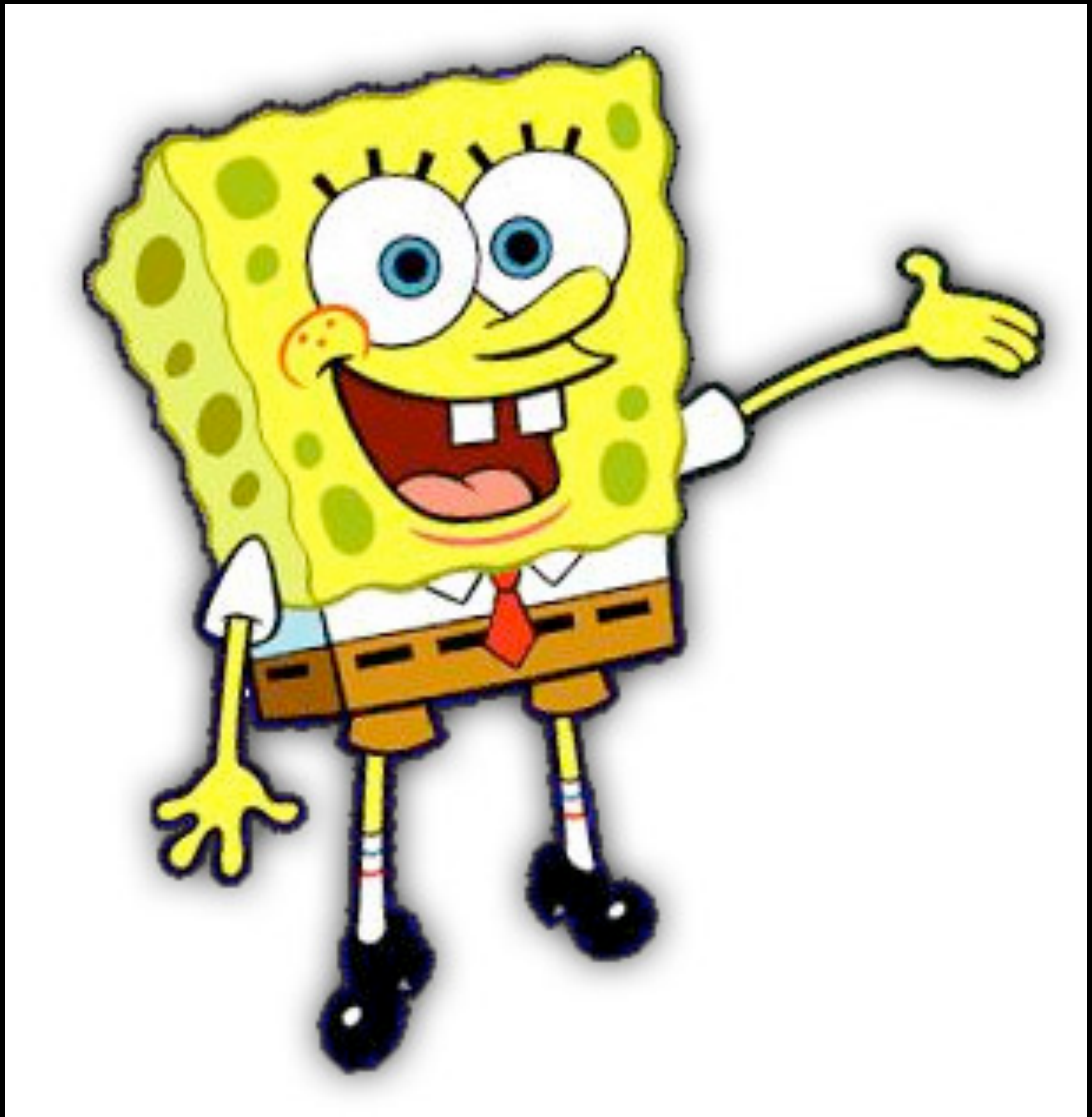
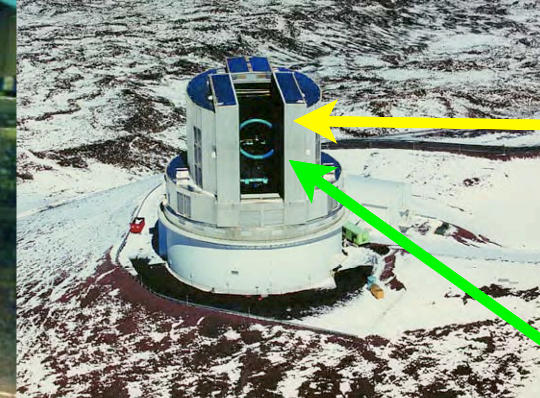
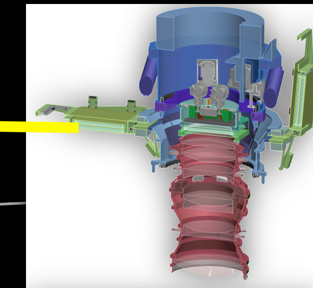


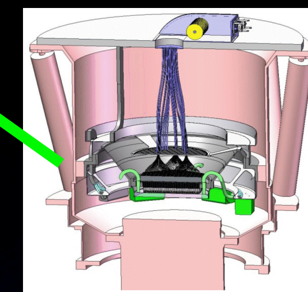
We can study cosmology only now.

Need funding ASAP.



Subaru





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3.2m!

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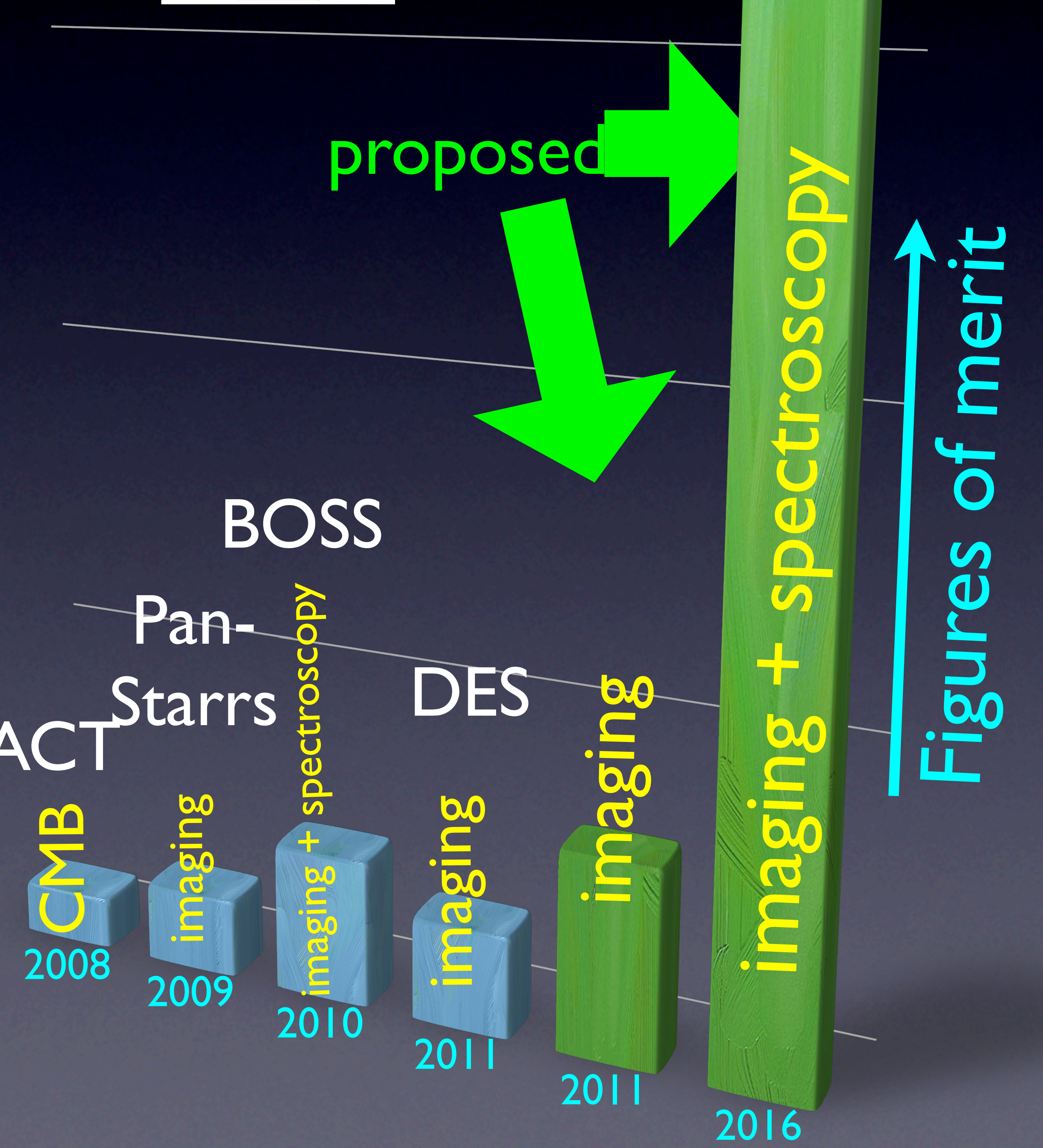
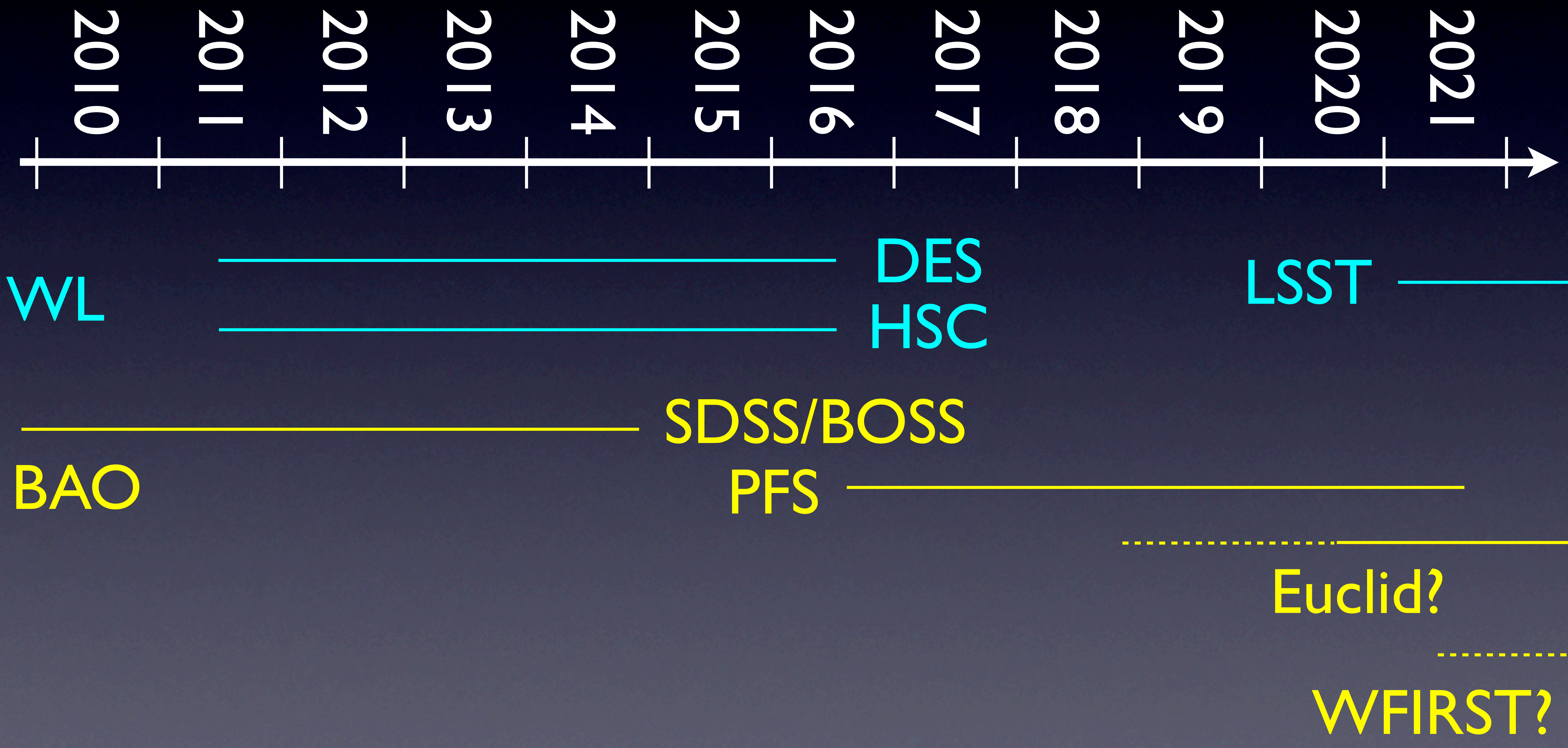


Timeline


2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
WL
DES
HSC
LSST
SDSS/BOSS
BAO
PFS
Euclid?
WFIRST?

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John Hopkins?

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Bob in Late Universe Darkness

- Eventually the dark matter may all decay into relativistic particles and the known structure may disappear
- dark energy may rip the whole Universe down to elementary particles
- Suzaku probes keV-scale dark matter with lifetime range 10^{18}–10^{23} years
- Not to mention that the Universe past the stage of active star formation, and all st will die in about 10^{14} years