Astrophysical Constraints on Dark Matter

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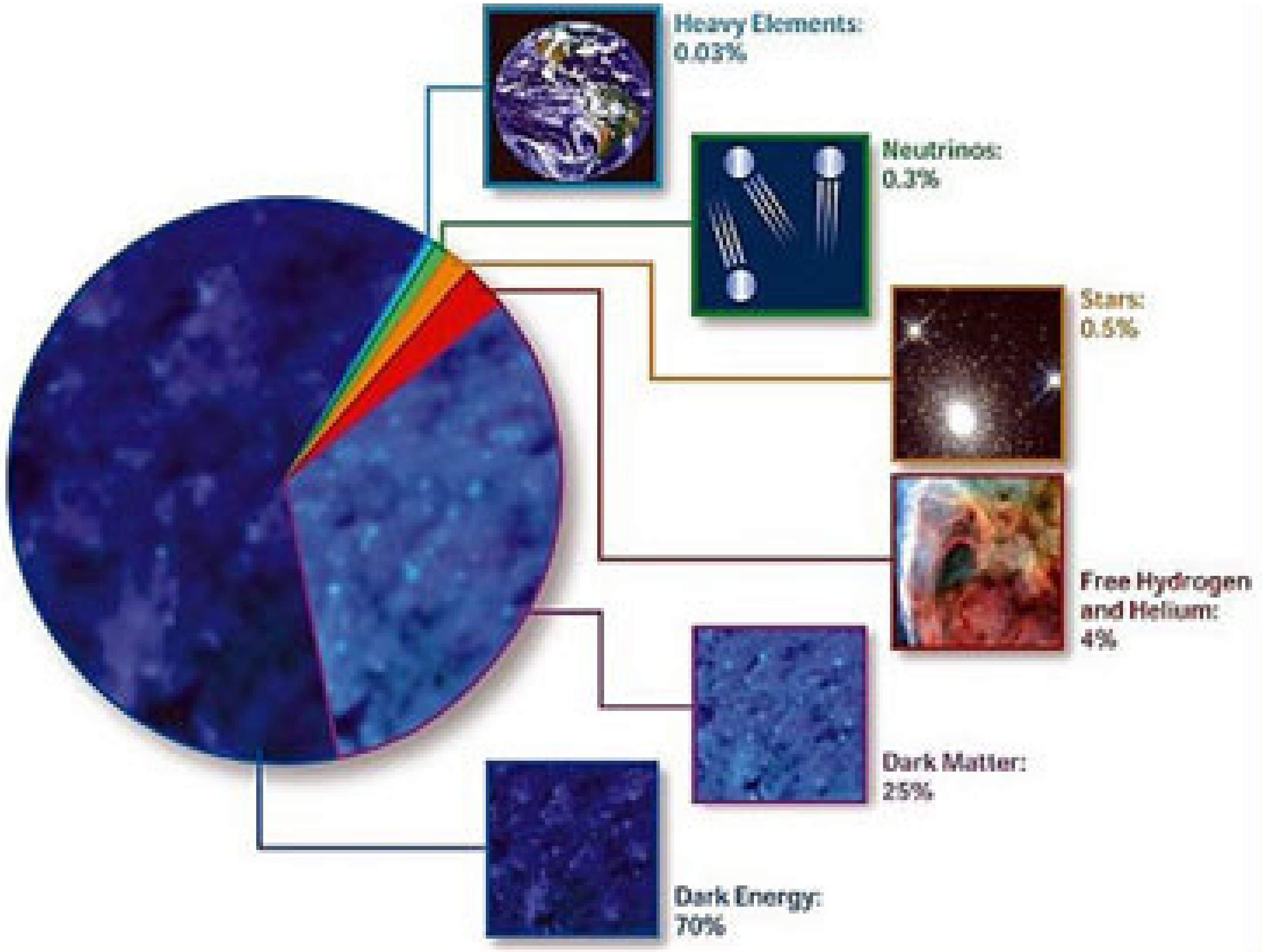
Cygnus workshop, Aussois, June 2011

A mysterious Dark Universe (DM+DE)!

Concordance Model ΛCDM

What we know is only
4%
of the energy density of the Universe

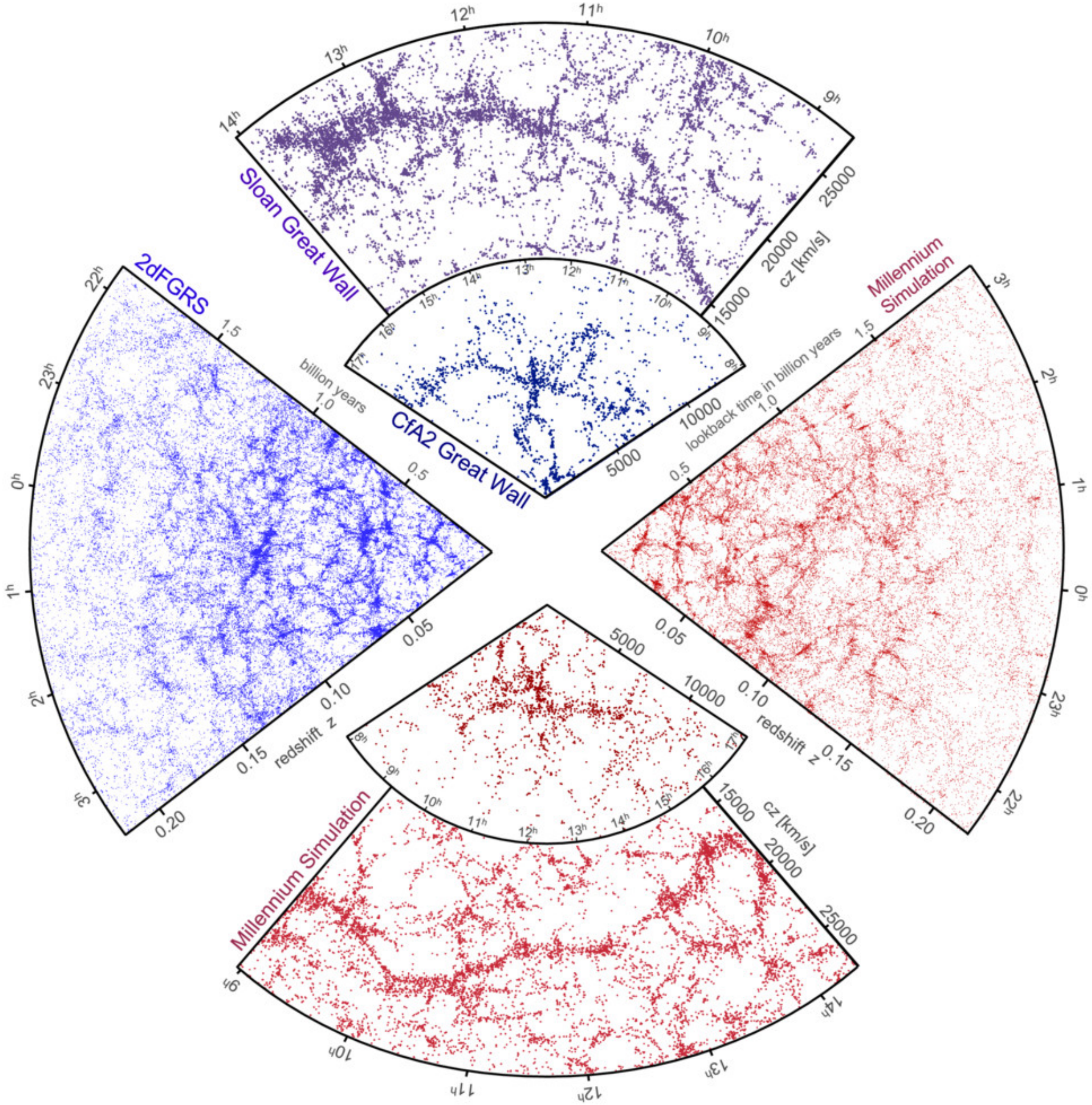
We measure with precision the amount of our ignorance!



Graph source: Wikipedia

Definition: $\Omega=\rho/\rho_c$

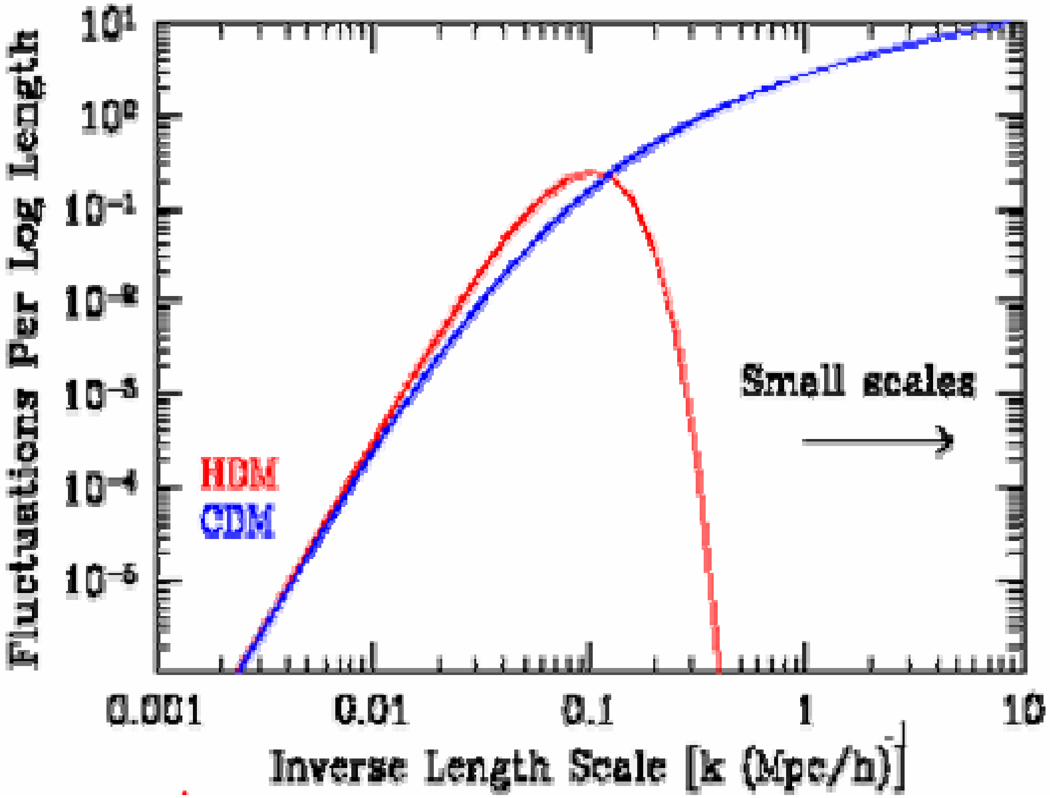
LSS structures



Nature of DM
Hot or Cold?

CDM is non-relativistic at decoupling, forms structures in a hierarchical, bottom-up scenario.

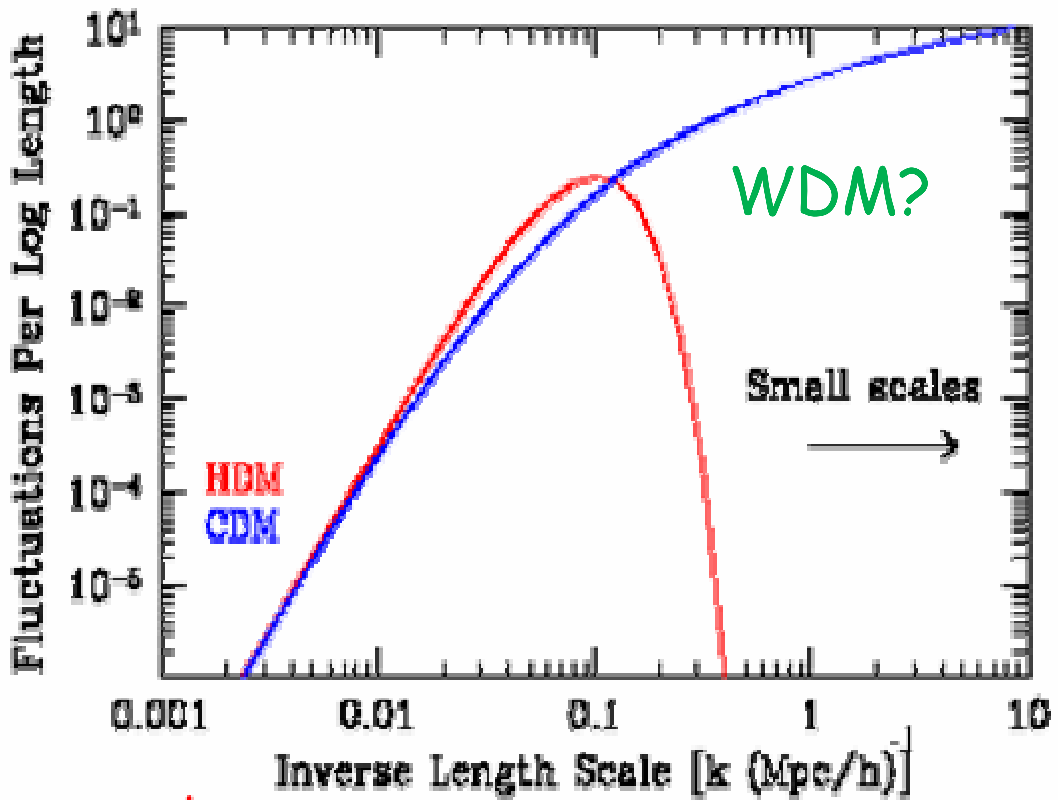
HDM is tightly bound by observations and LSS formation



Nature of DM
Hot or Cold, or Warm?

CDM is non-relativistic at decoupling, forms structures in a hierarchical, bottom-up scenario.

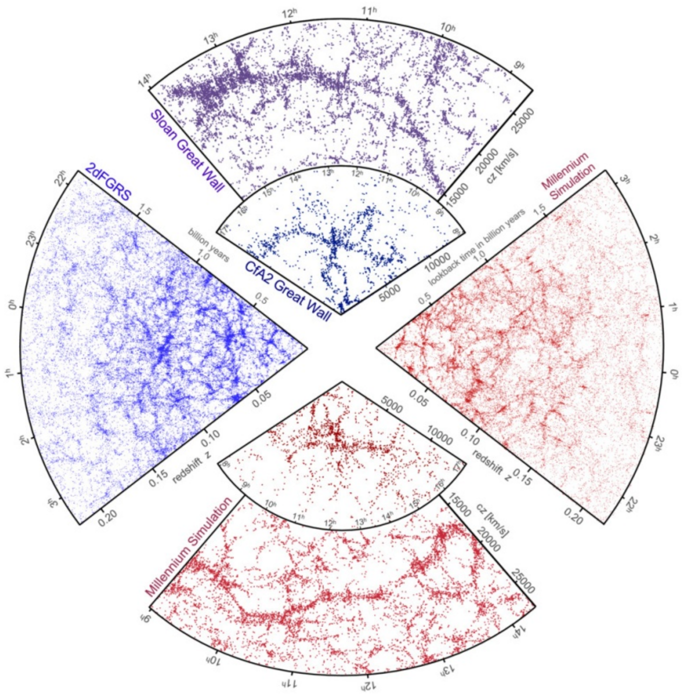
HDM is tightly bound by observations and LSS formation



~2000 :Problems with CDM at small scales

Comparing data with N-body Simulations

- Galactic satellites
- cusp/core at GC

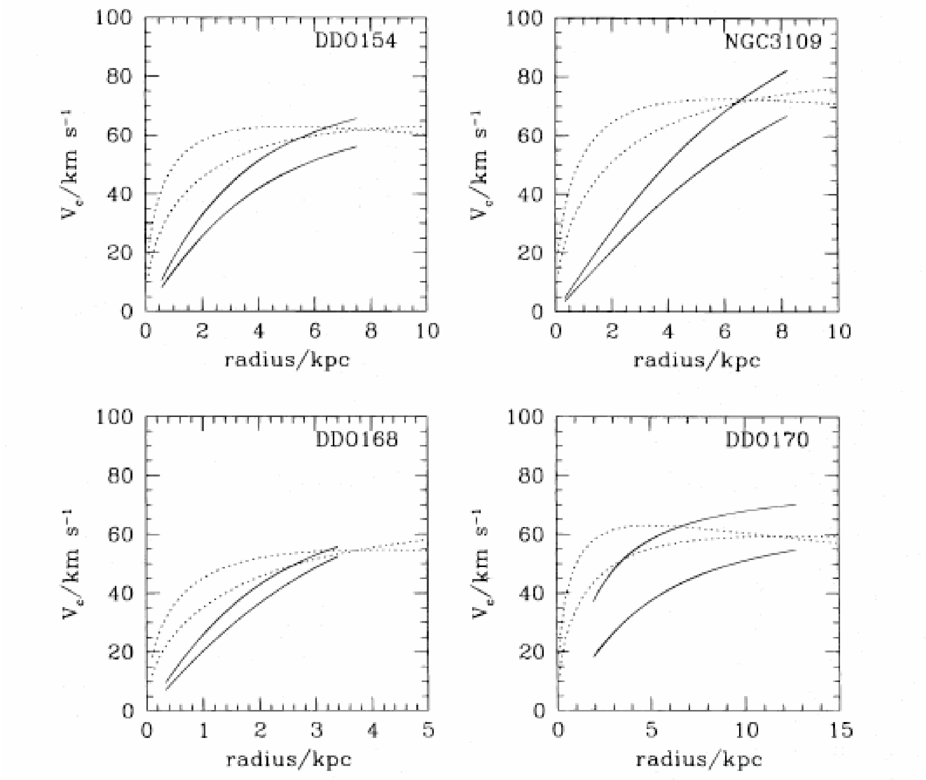


Dark matter halo profile
Cusp-Core problem

CDM Simulations → cusps
(Navarro, Frenk, White 1996):

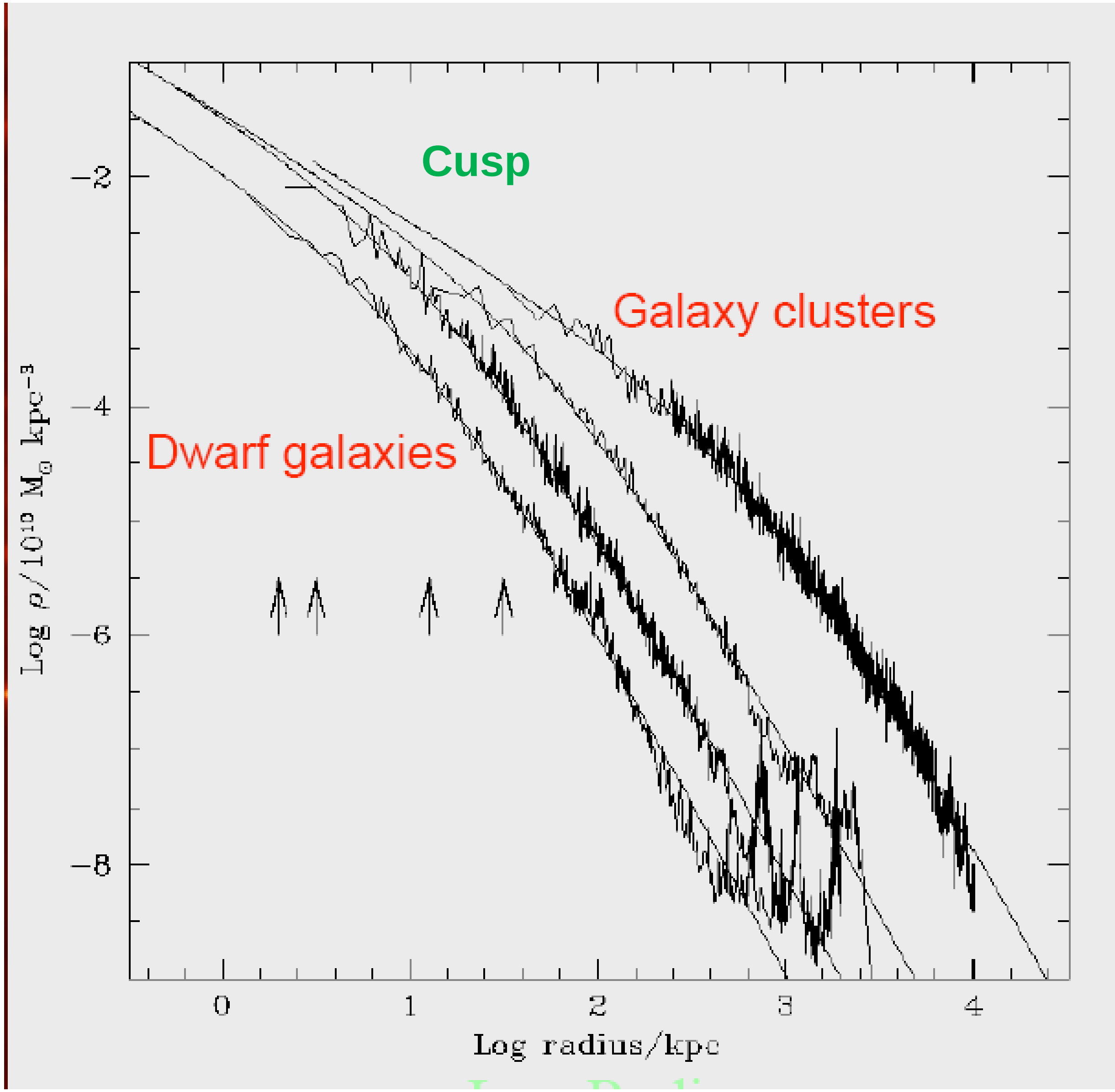
$$\frac{\rho(r)}{\rho_{\rm crit}} = \frac{\delta_c}{(r/r_s)(1 + r/r_s)^2},$$

Observations favour
Core profile (?)



NFW96, rotation curves

Dark matter distribution—Density profiles



Observations of rotation curve favours core profile

Cf talk by A. Baushev

Universal Density Profile

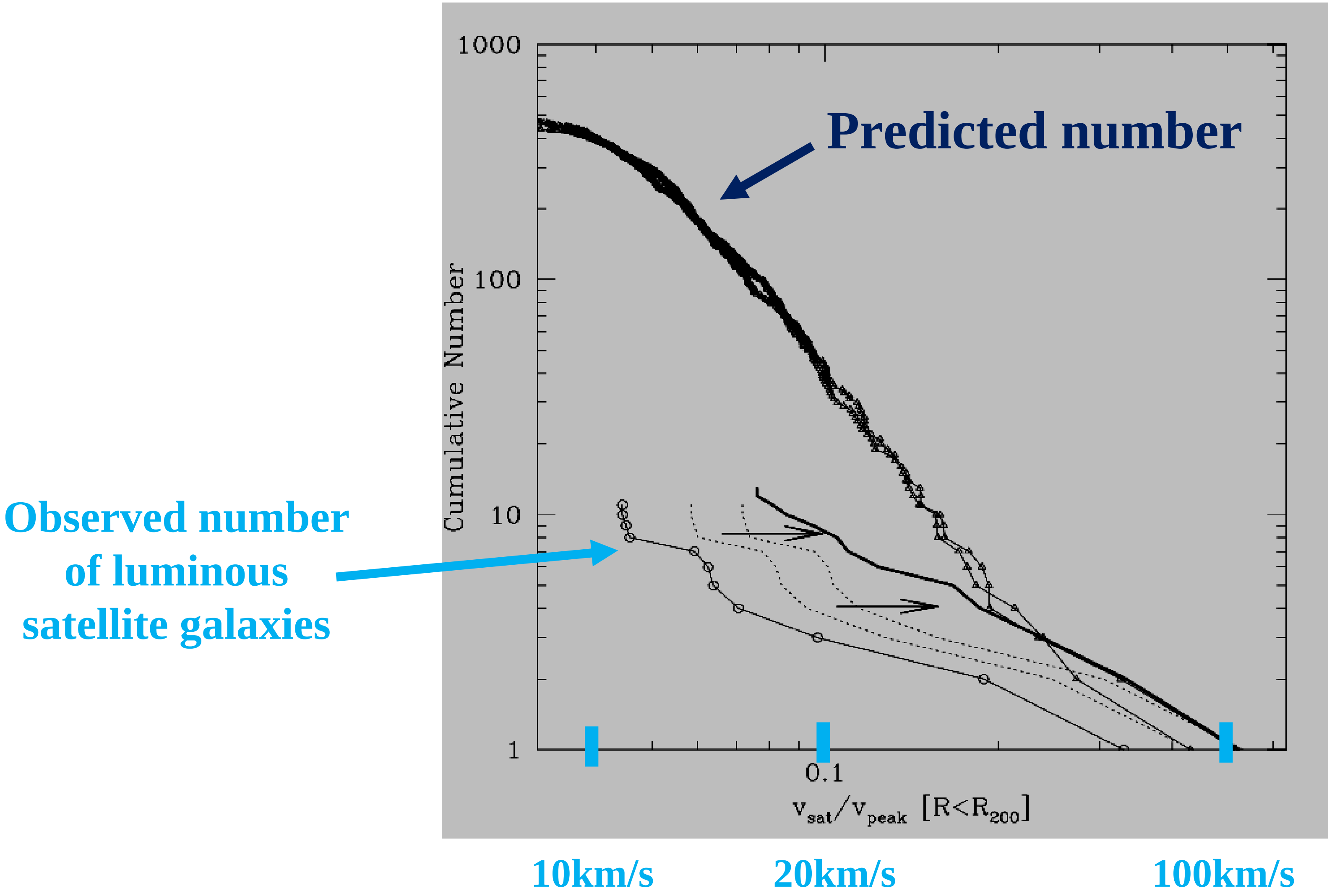
NFW

Navarro, Frenk, White 1996

$$\frac{\rho(r)}{\rho_{crit}} = \frac{\delta_c}{(r/r_s)(1+r/r_s)^2}$$

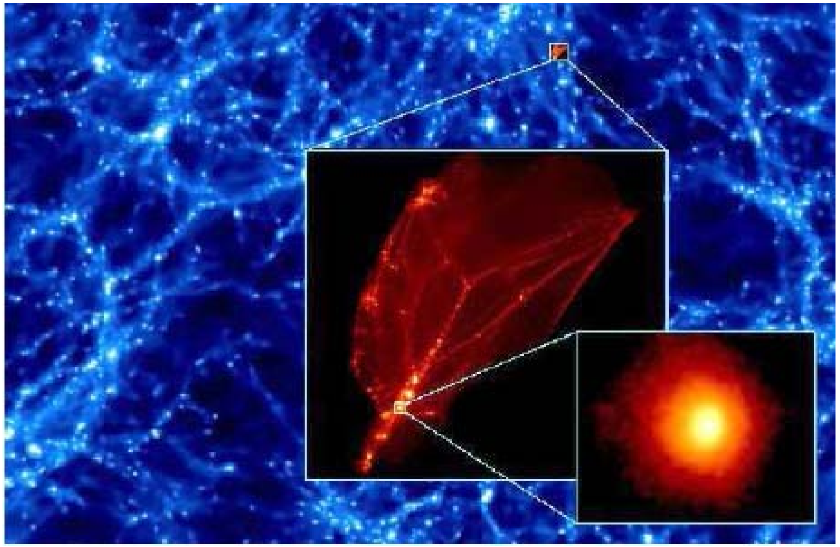
Too low number of visible Satellite galaxies

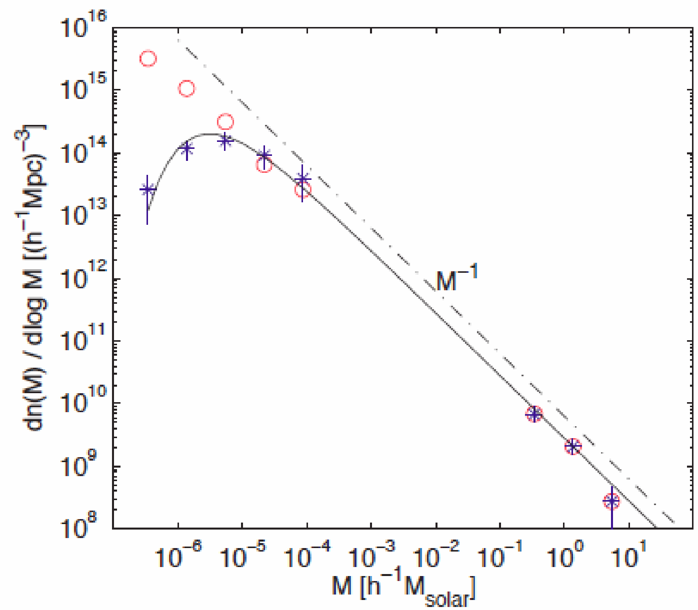
Satellite galaxies are seen in Milky Way, e.g. Saggittarius, MCs



The first dark halos

Diemand, Moore, Stadel 2005

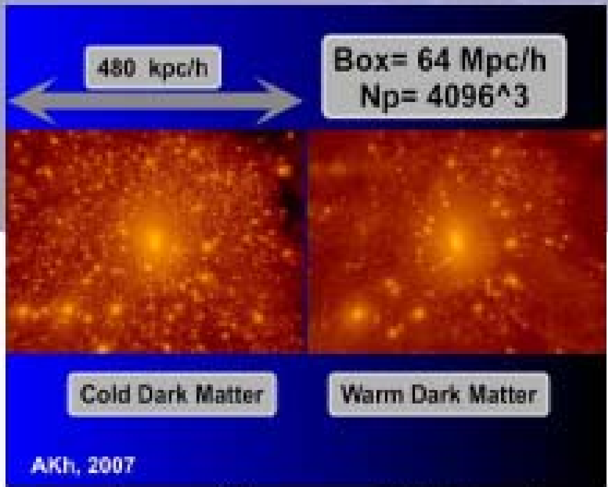




Due to collisional damping and free-streaming, the smallest halo (no sub-structure) is 10^{-6} solar mass (earth mass) for neutralinos.

Detection of such haloes may probe the nature of DM.
Cf lensing measurements

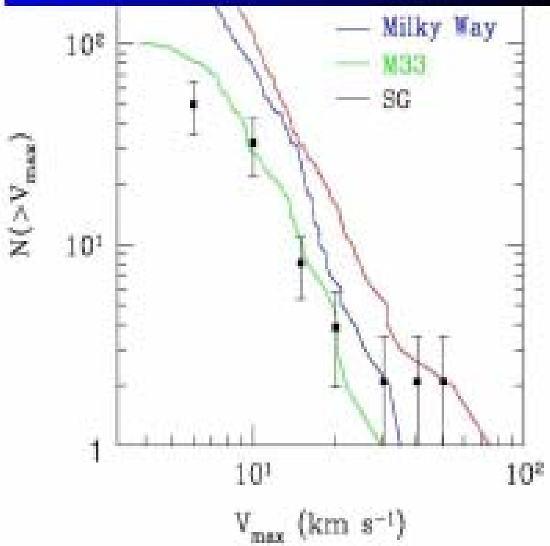
THE MISSING SATTELITE PROBLEM
ΛCDM vs ΛWDM



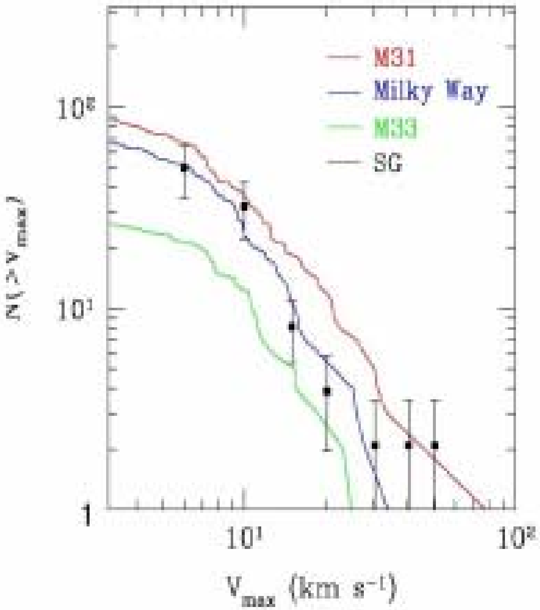
Resimulated Local Group with very high resolution:

Equivalent to 4096^3 particles in 64 Mpc box

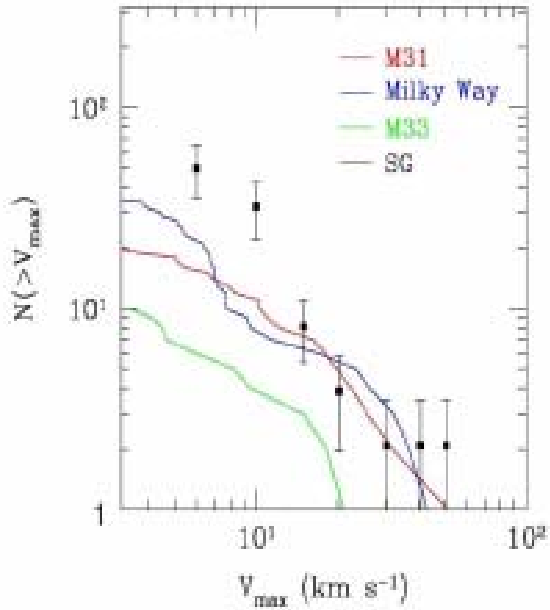
$M_{dm} = 2.5 \times 10^5 M_\odot$



ΛCDM



ΛWDM 3keV



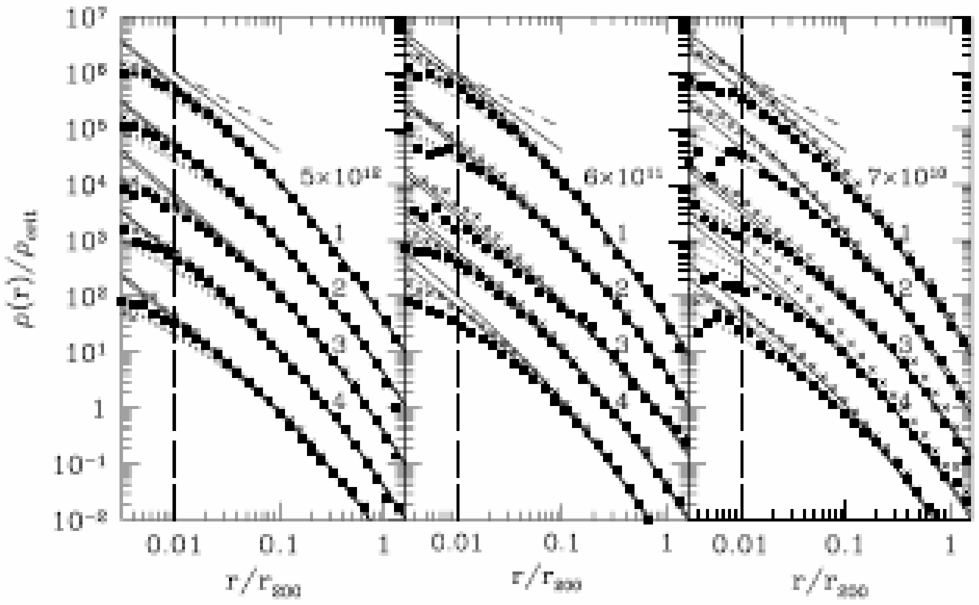
ΛWDM 1keV

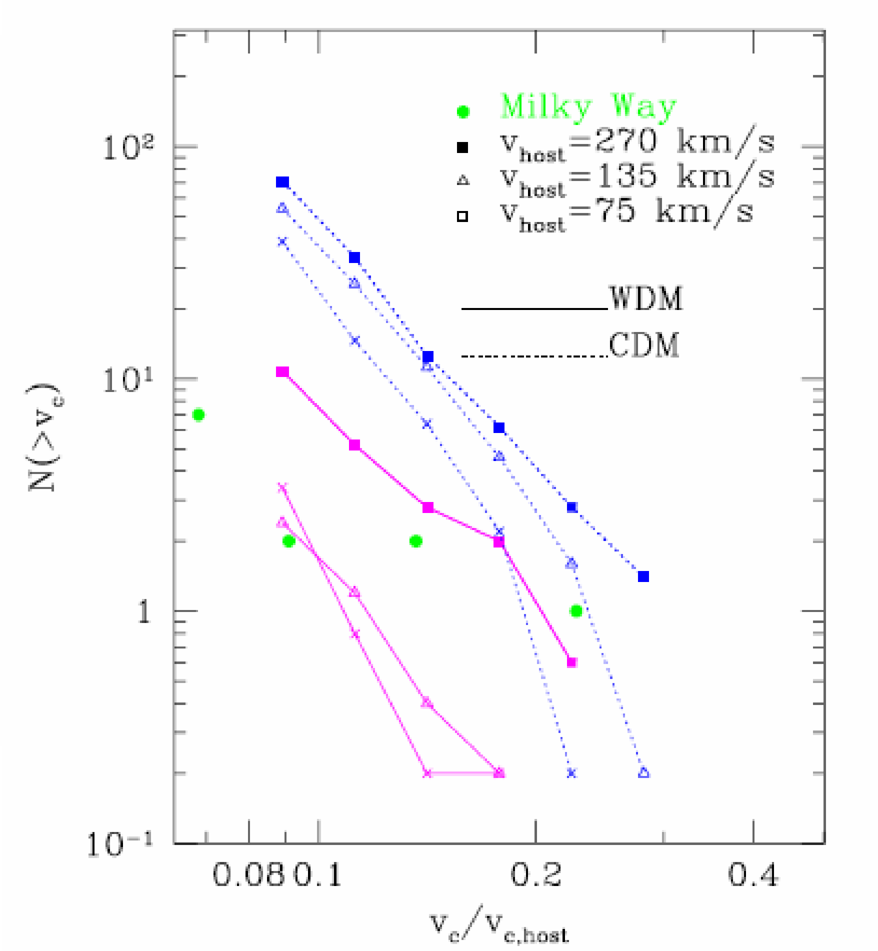
CLUES simulations, Yepes, 2010

WDM vs CDM

Velocity function

Density profile





From Jing 2000

Nature of dark matter or astrophysics process?

REPORTS

Stellar Feedback in Dwarf Galaxy Formation

Sergey Mashchenko,[*] James Wadsley, H. M. P. Couchman

Dwarf galaxies pose substantial challenges for cosmological models. In particular, current models predict a dark-matter density that is divergent at the center, which is in sharp contrast with observations that indicate a core of roughly constant density. Energy feedback, from supernova explosions and stellar winds, has been proposed as a major factor shaping the evolution of dwarf galaxies. We present detailed cosmological simulations with sufficient resolution both to model the relevant physical processes and to directly assess the impact of stellar feedback on observable properties of dwarf galaxies. We show that feedback drives large-scale, bulk motions of the interstellar gas, resulting in substantial gravitational potential fluctuations and a consequent reduction in the central matter density, bringing the theoretical predictions in agreement with observations.

Missing satellites: CDM way out

- satellites do exist, but star formation suppressed (after reionization?)

- satellites orbit do not bring them to close interaction with disk, so they will not heat up the disk.

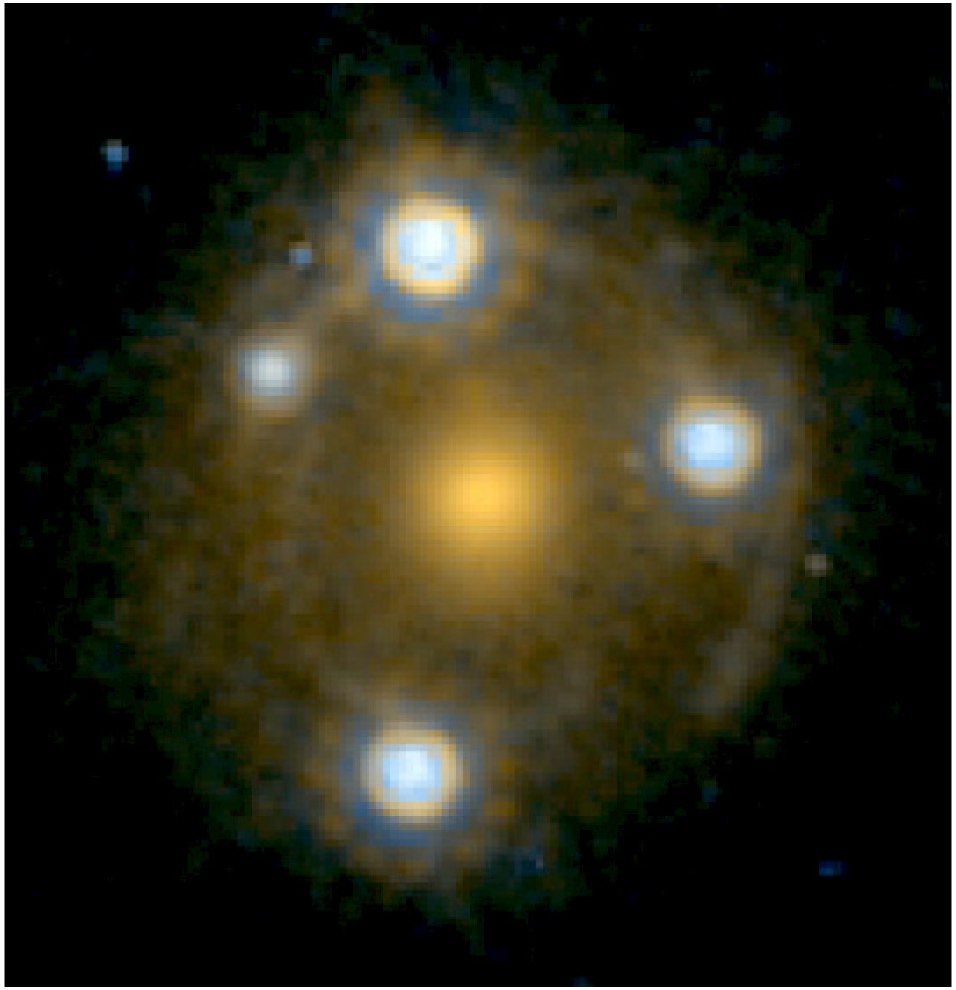
- Local Group dwarf velocity dispersion underestimated

- Galaxies may not follow dwarves

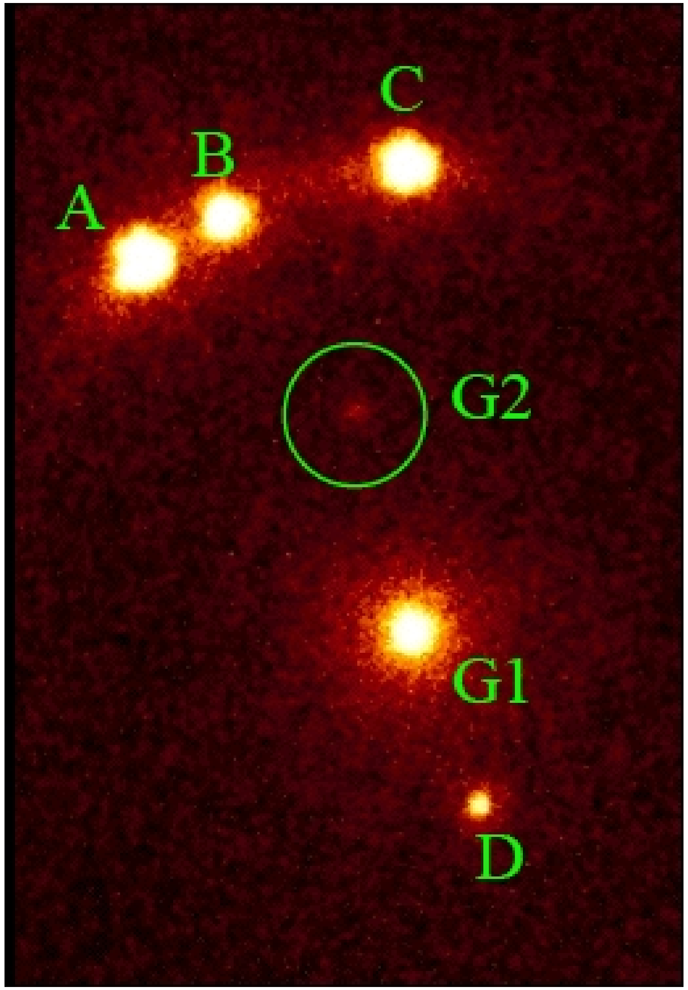
•Halo substructures may be probed by
-Lensing
-local Milky Way structures

DM Substructures from Strong Lensing flux anomalies

Accurate lens model needed for H_0 and dark energy measurements.



HST image of SDSS J0924+0219



Keck adaptive optics image of B2045+265

Alternatives to CDM

- Self-Interacting Dark Matter (Spergel & Steinhardt 2000)
- Strongly Interacting Massive Particle
- Annihilating DM
- Decaying DM
- Fuzzy DM

- WDM: reduce the small scale power

SIDM

DM strongly interact with itself, but no EM

interaction can create a core in hierachical scenario (eventually core collapse -> isothermal profile)

Interaction strength: comparable to neutron-neutron

$$\sigma_{XX} = 8.1 \times 10^{-25}\,\mathrm{cm}^2 \left(\frac{m_x}{\mathrm{GeV}}\right)\left(\frac{\lambda}{1\mathrm{Mpc}}\right)^{-1},$$

Difficulty: make spherical clusters: against lensing

SIMP

Motivation:

- SIDM may have QCD interaction but not EM
- Not detectable in WIMP search. (Some window open?)

$$8 \times 10^{-25} < \frac{\sigma/\mathrm{cm}^2}{m/\mathrm{GeV}} < 10^{-23}.$$

CMB & LSS constraint:

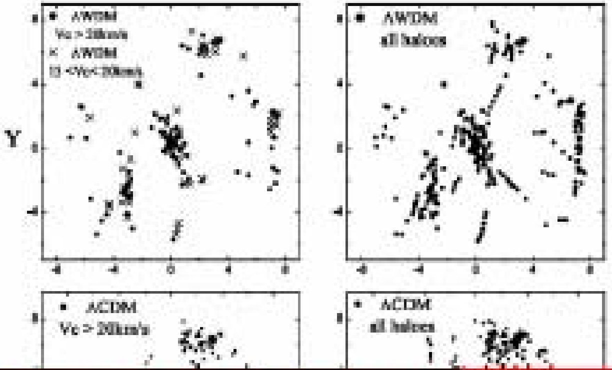
Before decoupling, photons and baryons are tightly coupled, interaction with baryon will cause additional damping of perturbation

“Evidence” for WDM

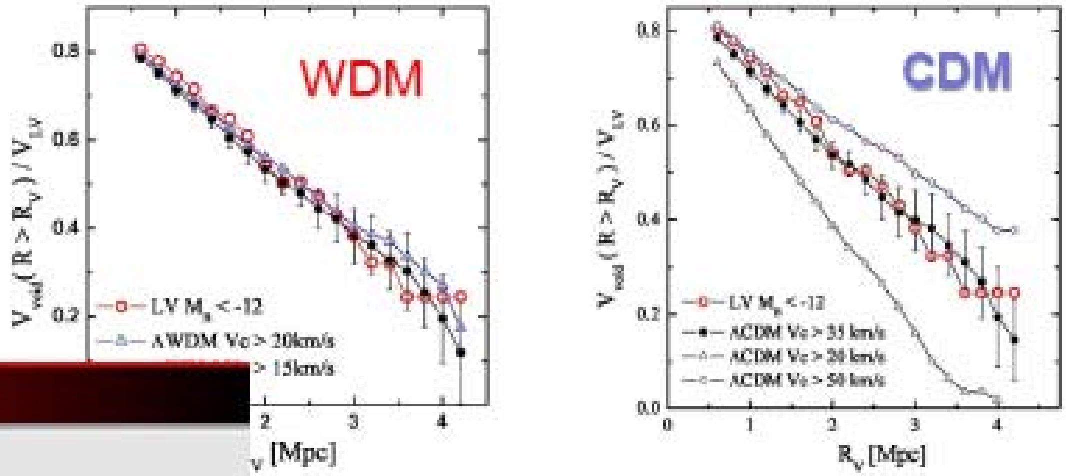
- "missing satellite problem",
- "cusp-core problem",
- ….

VOIDS IN THE LOCAL UNIVERSE: ΛWDM vs ΛCDM

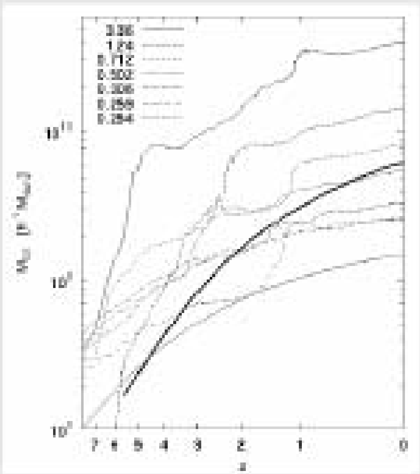
Tikhonov, Gottlöber, Yepes, Hoffman, MNRAS 399,1611, 2009 , astro-ph/0904.0175



Volume filling fraction of voids



Critical mass M_c of star formation



Hoeft et al. (2006)

- uniform UV-background (Haardt, Madau 1996)
- critical mass $M_c(z)$ for halos with low gas fraction (thick solid line)
- mass accretion history of seven halos (mass in $10^{10}h^{-1}M_\odot$)
- mean mass accretion history of a $1.4 \times 10^9 h^{-1} M_\odot$ halo

no star formation right of the thick solid line

Conclusions: For WDM, only halos with Vc < 20 km/s would not have to host galaxies.

Better in agreement with data: there are galaxies as low as V_c=20 km/s observed. Need to do galaxy formation simulations for a self consistent picture.

CDM vs WDM: HI velocity functions Virgo and Anti Virgo directions

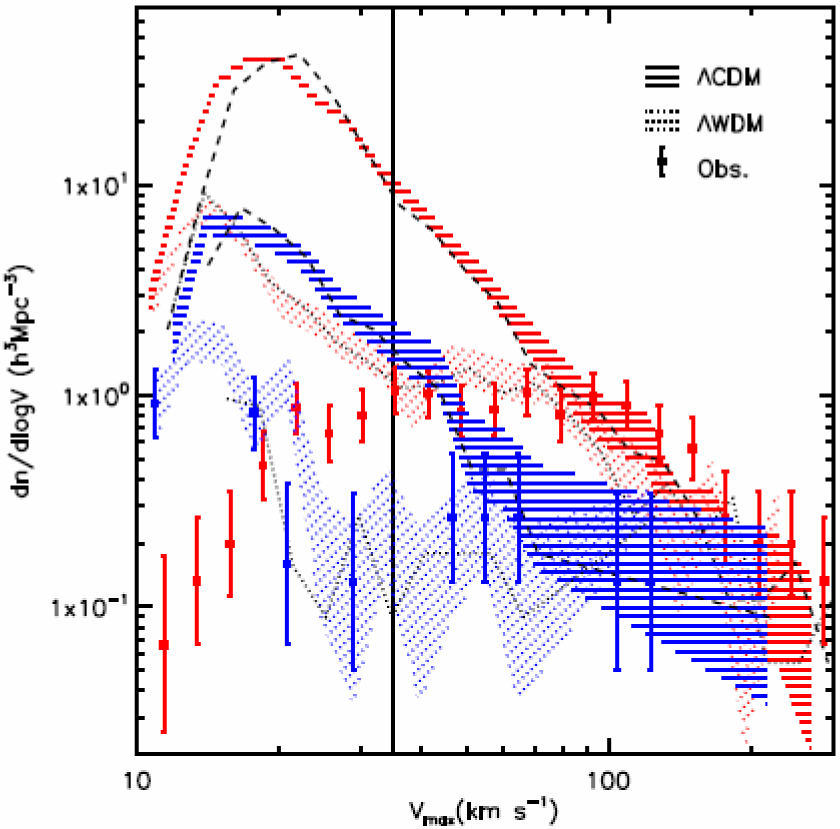


Fig. 5 Velocity function for the sample of galaxies in the Virgo-direction region taken taken from the ALFALFA catalogs (red square symbols with error bars). Predictions from our constrained simulations for the observed field of view appear as the dashed (ΛCDM) and dotted (ΛWDM) red areas, delimited by Poisson error bars. In blue the same is shown for the anti-Virgo-direction. The vertical solid line marks the value of V_{max} down to which the simulations and observations are both complete.

arXiv:1005.2687: Constrained Local UniversE Simulations (CLUES)
Gottloeber, Hoffman , Yepes

No simple feedback mechanism to explain the factor 10 depletion from CDM

“Evidence” for WDM

•"missing satellite problem",

•"cusp-core problem",

• mini-voids The sizes of mini-voids in the local universe: an argument in favor of a warm dark matter model? Tikhonov et al.

•HI determinations of velocity function profiles
N-Body simulation Comparisons with Virgo results by Arecibo Legacy (ALFALFA)

•New detection of 2.5 keV X-ray from dark dwarf galaxy?

Limits on mass of WDM particles

- Stellar dynamics in MW satellites (Boyanovsky, de Vega, Sanchez 2008; de Vega and Sanchez 2009)
- High-z QSO LF (e.g. Song and Lee 2009)
- Ly-alpha forest to constrain P(k) at small scales and different z's (Most popular method: Narayanan et al 2000; Vielet al 2005;2008)
- Ly-a + SDSS results (Boyarsky et al 2009)
- QSO lensing (Miranda & Maccio 2007)
- Abundance of dwarf satellites of MW (Maccio& Fontanot 2010; Polysensky& Ricotti, 2010)

➔ Mass WDM ~ 1- 5 keV

arXiv:0812.0010v2

Lyman-α constraints on warm and on warm–plus–cold dark matter models

Alexey Boyarsky[a,b], Julien Lesgourgues[c,d,e], Oleg Ruchayskiy[c], Matteo Viel[f,g]

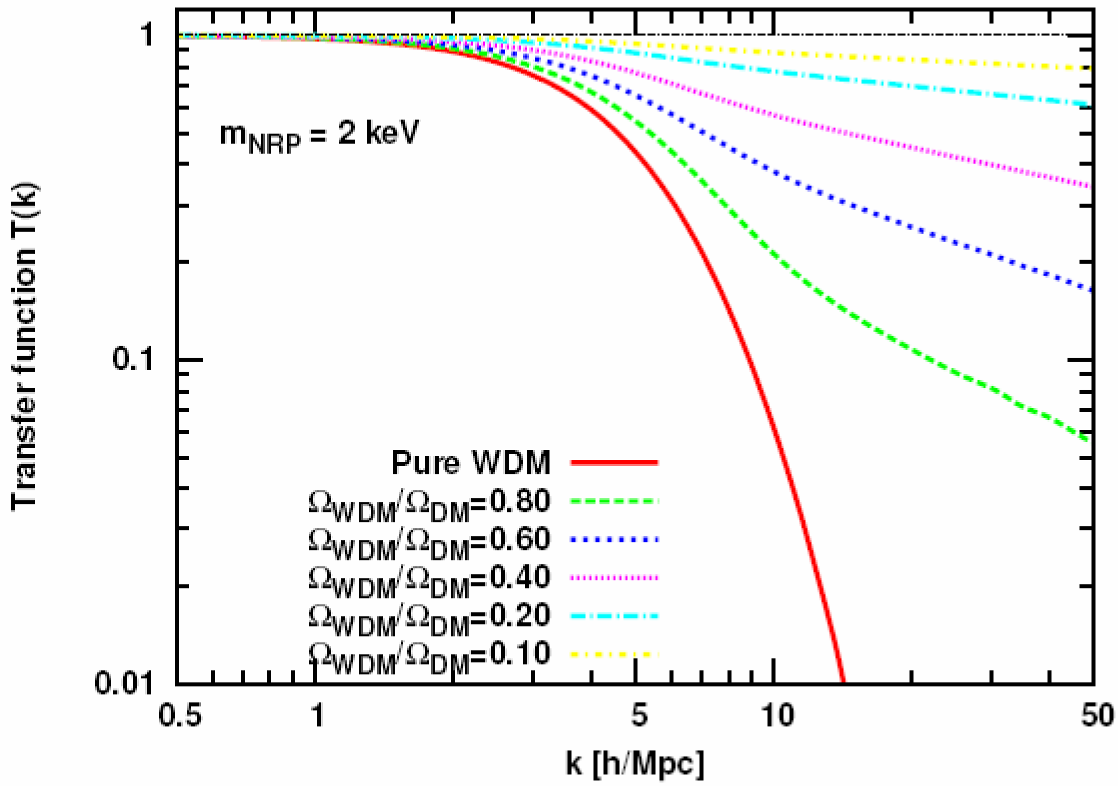


Figure 1: Transfer functions $T(k) \equiv [P_{\Lambda CWDM}(k)/P_{\Lambda CDM}(k)]^{1/2}$ for $m_{NRP} = 2$ keV and different WDM fractions: from left to right, $\Omega_{WDM}/(\Omega_{WDM} + \Omega_{CDM}) = 1, 0.8, 0.6, 0.4, 0.2, 0.1$. Other parameters are fixed to $\Omega_B = 0.05$, $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$, $h = 0.7$.

But doubts on Lyα results by SDSS people!

Cluster constraints on cross sections

4.5 E-7 $(t/E10\ yr)^{-2} < \sigma/m <$ ~1 cm^2/g Bullet cluster

0.02 elliptical core of MS2137-23

Williams et al. 2011

Combine lensing , X ray, and optical cluster measurements

The new fashionable candidate
Sterile neutrinos

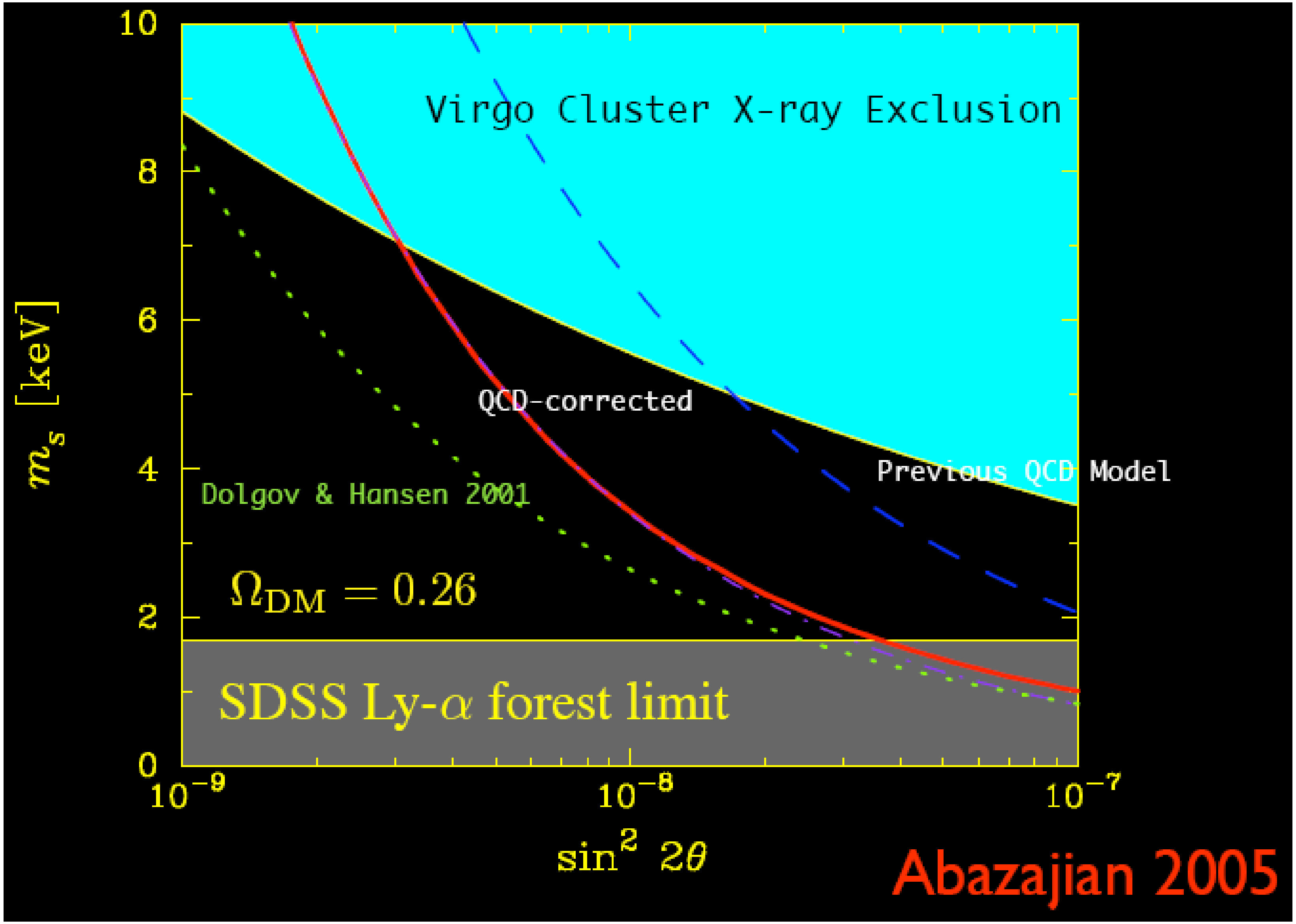
Alexander Kusenko (UCLA) *Dark matter '10*

Sterile neutrinos as dark matter

Can be prouced by the following mechanisms,
color coded by "warmness" vs "coldness",

- Neutrino oscillations off resonance [Dodelson, Widrow] No prerequisites; production determined by the mixing angle alone; no way to turn off this channel, except for low-reheat scenarios [Gelmini et al.]
- Resonant neutrino oscillations [Shi, Fuller]. Pre-requisite: sizeable leptop asymmetry of the universe. (The latter may be generated by heavier sterile neutrinos [Laine and Shaposhnikov])
- Higgs decays [AK, Petrai]. Assumes the Majorana mass is due to Higgs mechanism. Sterile miracle: abundance a "natural" consequence of singlet at the electroweak scale (which itself may not be seen as natural. Also, inflaton decays can also contribute to the population of dark matter [Tkachev,Shaposhnikov]

Constraints on sterile neutrinos



Strong Reliance on N-body simulations

eg Gao et al., Jing et al., Yepes et al.,

WDM and CDM simulations.

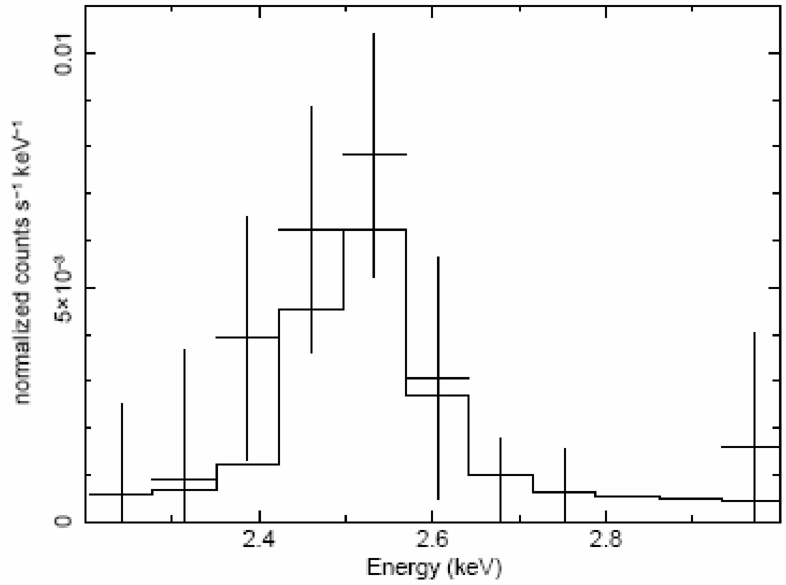
- Non-linear collapse of WDM structures
- A replacement for the NFW model (WDM)
- Effects of Baryonic matter

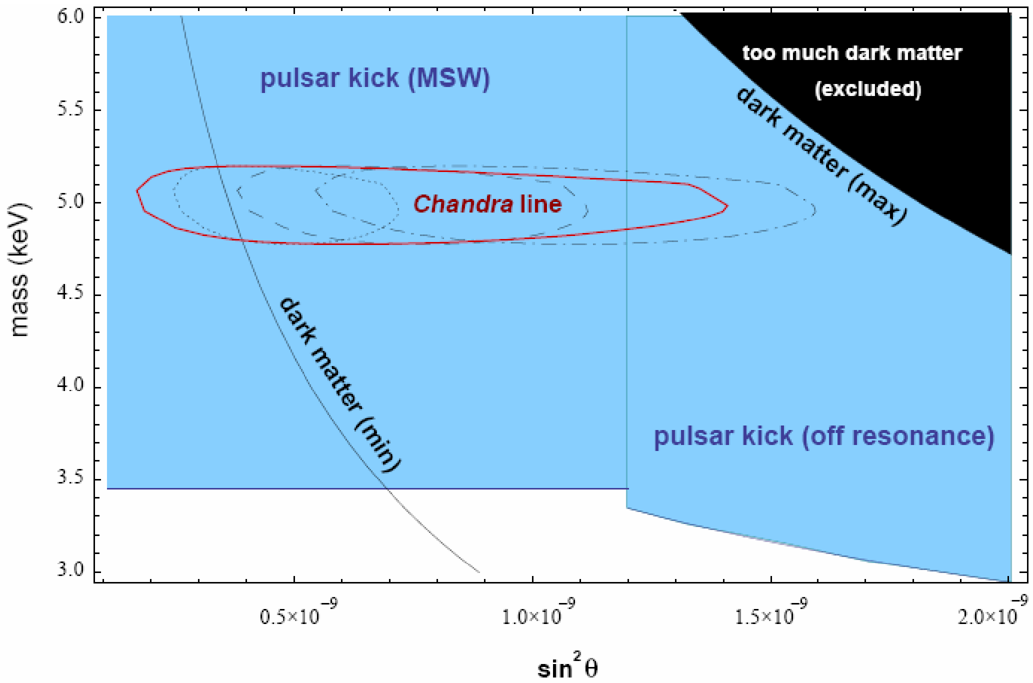
What about Direct observations ?

Dark Matter Search Using *Chandra* Observations of Willman 1, and a Spectral Feature Consistent with a Decay Line of a 5 keV Sterile Neutrino

Michael Loewenstein[1,2], Alexander Kusenko[3,4]

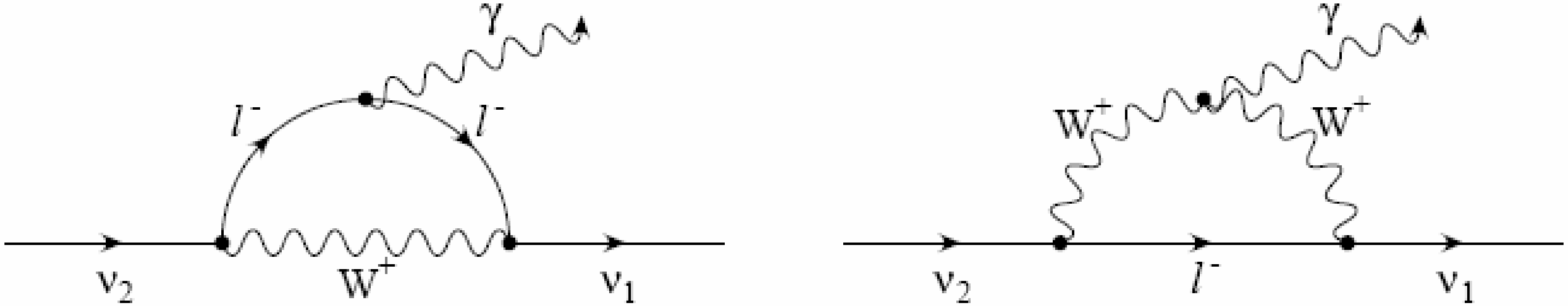
arXiv:0912.0552v3 [astro-ph.HE] 12 May 2010



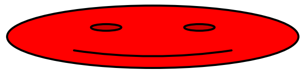
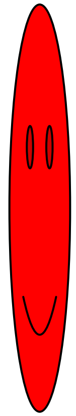


Radiative decay

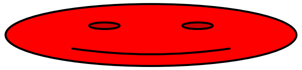
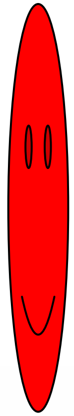
Sterile neutrino in the mass range of interest have lifetimes **longer than the age of the universe**, but they do decay:



Photons have energies $m/2$: X-rays. Concentrations of dark matter emit X-rays. [Abazajian, Fuller, Tucker; Dolgov, Hansen; Shaposhnikov et al.]

Before we get too depressed  or excited  ...

- Do not trust fashion fads !
- How much can one trust N-Body simulations?
- Beware of data analysis bias ! Blind analysis?

Before we get too depressed  or excited  …

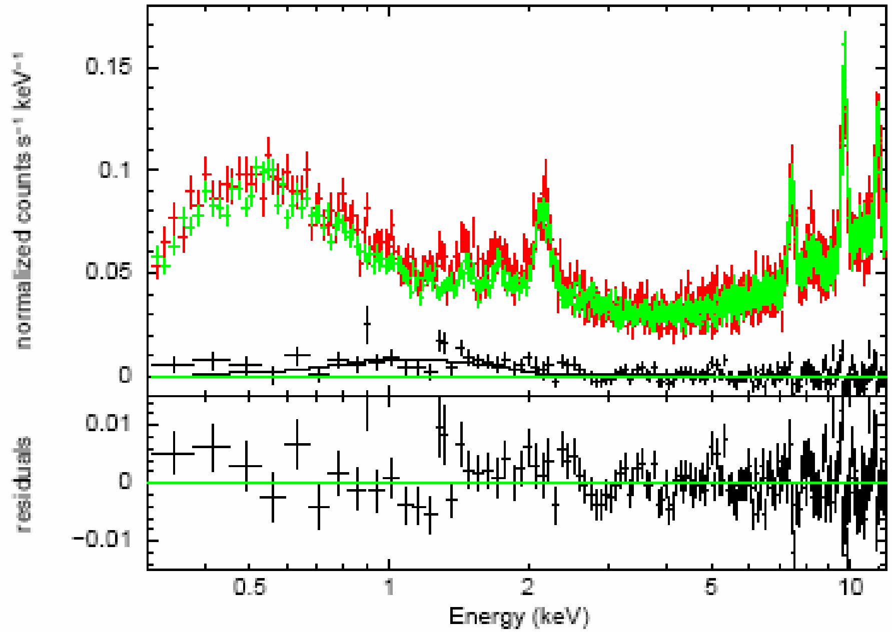


Fig. 1.— (a) **top:** Total (red), PB (green), and source (*i.e.* PB-subtracted; black) spectra. The histogram is the best-fit GXB+CXB model to the source spectrum. (b) **bottom:** Same as **top** with the quiescent-particle-background reduced in the total and PB spectra as explained in the text.

In case there is a signal!
What about other Direct observations ?

Neutrino decay?

Any observation in DD or Directional detectors?

- 2.5 keV X-ray? When background becomes signal!
- Directionality?
- Hierarchy of masses (see saw mechanism?)

Neutrino capture?

arXiv:1009.5870v2

Possible Capture of keV Sterile Neutrino Dark Matter on Radioactive β-decaying Nuclei

Y.F. Li and Zhi-zhong Xing
Institute of High Energy Physics, Chinese Academy of Science, Beijing 100049, China
(Electronic address: liyufeng@ihep.ac.cn, xingzz@ihep.ac.cn)

Conclusions

- Astrophysical observations ➔ existence of non baryonic Dark Matter
- N-Body simulations of LSS ➔ existence of not-hot DM
- Many problems with CDM simulations

  can be solved with O(1keV) WDM

- What can this WDM be? Sterile neutrinos?
- How can O(1keV) WDM be observed?
  - Lensing observations ?

Before despairing about DM DD (and lensing)
More work on N-body simulations needed!
Mixtures of DM masses?

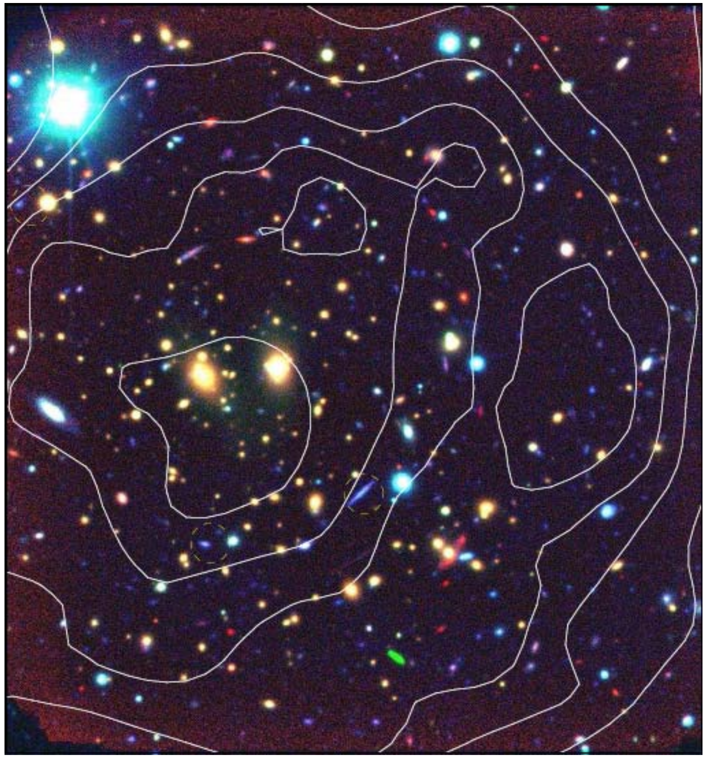
Weak Lensing mass reconstruction

Image ellipticity -> shear->

$$\alpha = \nabla\psi, \qquad \kappa = \frac{1}{2}\nabla^2\psi = \frac{\Sigma}{\Sigma_{cr}}$$

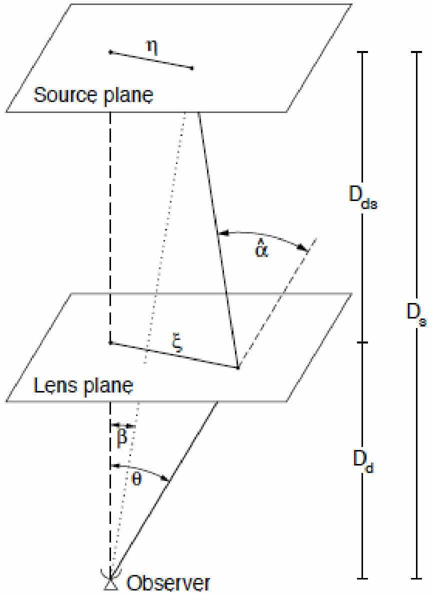
invert the equation

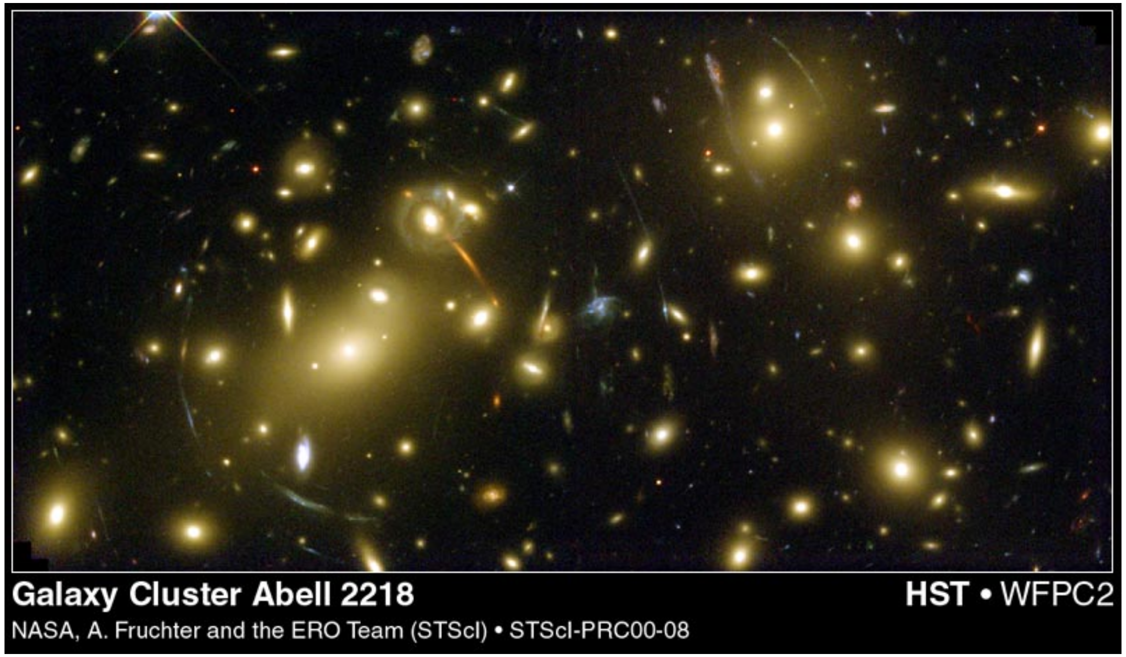
$$\alpha(\boldsymbol{\theta}) = \frac{1}{\pi}\int_{\mathbb{R}^2} \mathrm{d}^2\theta'\,\kappa(\boldsymbol{\theta}')\,\frac{\boldsymbol{\theta}-\boldsymbol{\theta}'}{|\boldsymbol{\theta}-\boldsymbol{\theta}'|^2}$$



RXJ1347.5-1145
(Bradac et al 2005)

Gravitational Lensing





Strong lensing arclets

$$\alpha = \frac{4GM}{c^2\xi} = \frac{4\pi\langle v_{\|}^2\rangle}{c^2}$$

$$\theta_E = \alpha\frac{D_{ds}}{D_s}$$

- Weak lensing
- Flexion
- (Microlensing)

Future Measurements of DM properties with lensing

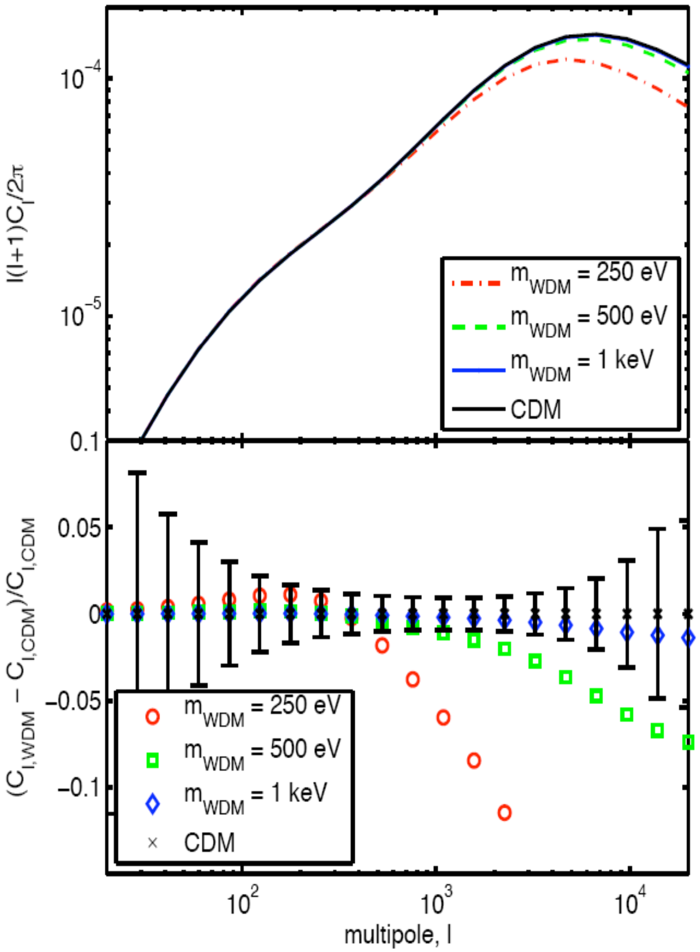
I. Cosmic shear power spectra: Mass constraints?

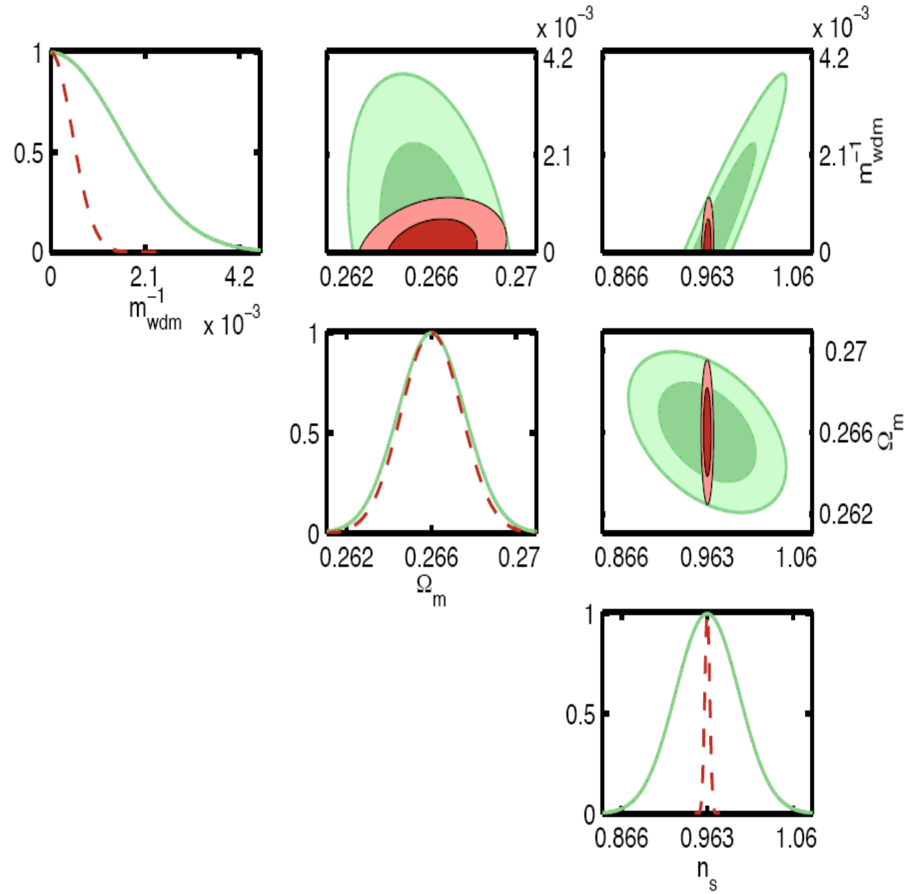
II. Galaxy-scale DM density profiles:
- Galaxy-galaxy lensing
- Magnification

Cosmic shear power spectra

Markovic et al. 2010 Euclid-like DE space survey +Planck:

Integral effects → better than matter power spectrum





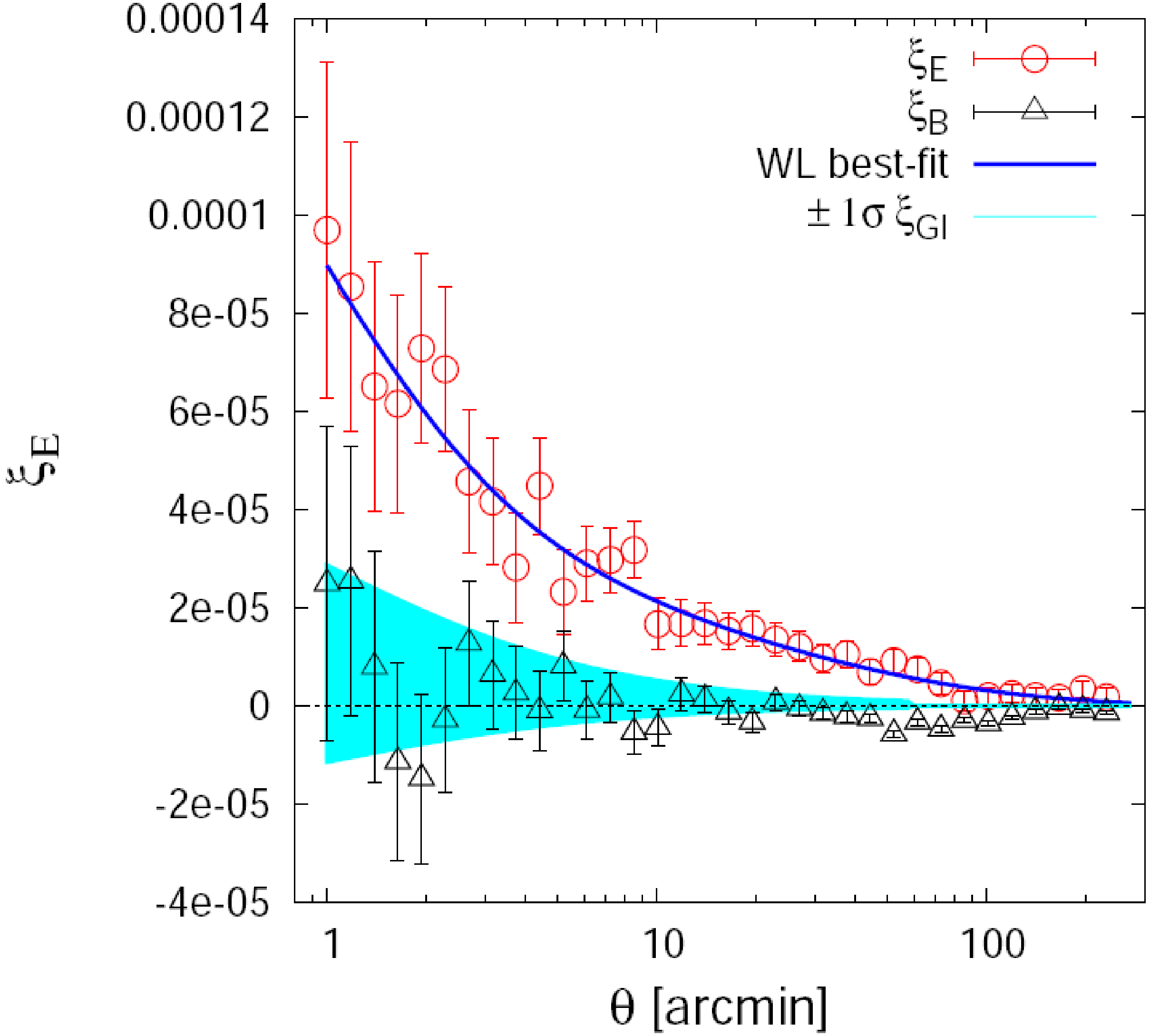
Cosmic shear power spectra

Markovic et al. 2010 Euclid-like DE space survey +Planck:

	Fiducial value	*Halo model*	*Halofit*	
		Shear only	Shear only	Shear + Planck
$m_{\rm WDM}$	CDM	> 935 eV	> 645 eV	> 2500 eV
$m_{\rm WDM}^{-1}$ $[eV^{-1}]$	$10^{-8}(\approx 0)$	$+0.00107$	$+0.00155$	$+0.00040$
$\Omega_{\rm m}$	0.27	±0.0011	±0.0016	±0.0012
$n_{\rm s}$	0.96	±0.031	±0.035	±0.002
$A_{\rm s}$ $[h^{-3}Mpc^3]$	1.3×10^5	$\pm0.119 \times 10^5$	$\pm0.183 \times 10^5$	$\pm0.005 \times 10^5$
Γ	0.18	±0.0090	±0.0123	±0.0005

Table 1: Table of 68 per cent confidence limits for a flat ΛWDM cosmology marginalised over 4 other parameters in each case. The errors on the inverse particle mass, $m_{\rm WDM}^{-1}$, are single tailed limits.

Sensitive to m_WDM < 2.5 keV

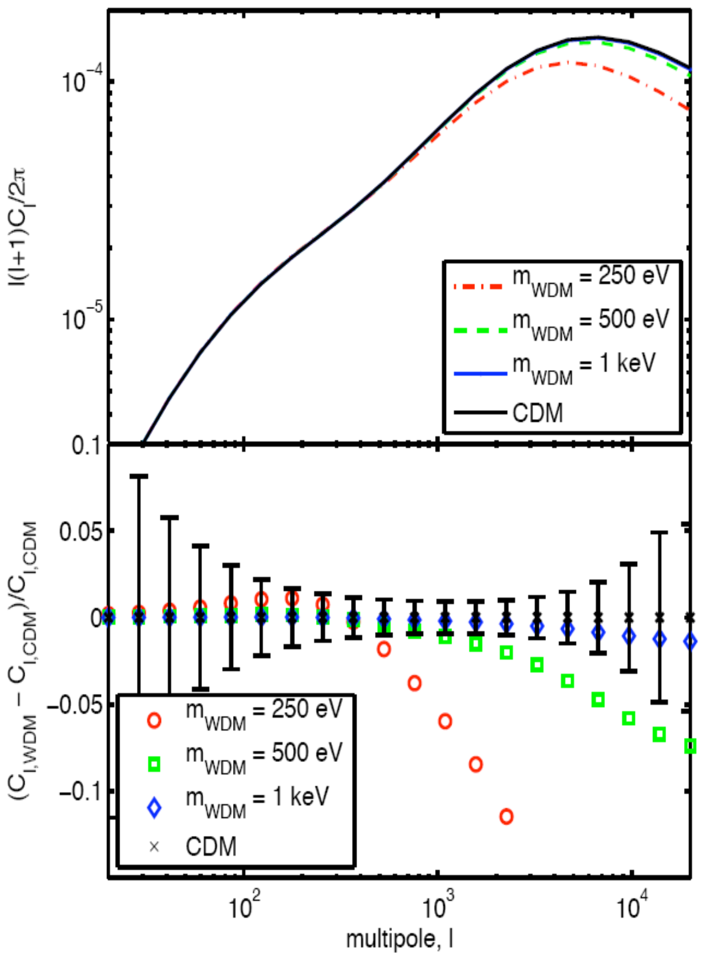


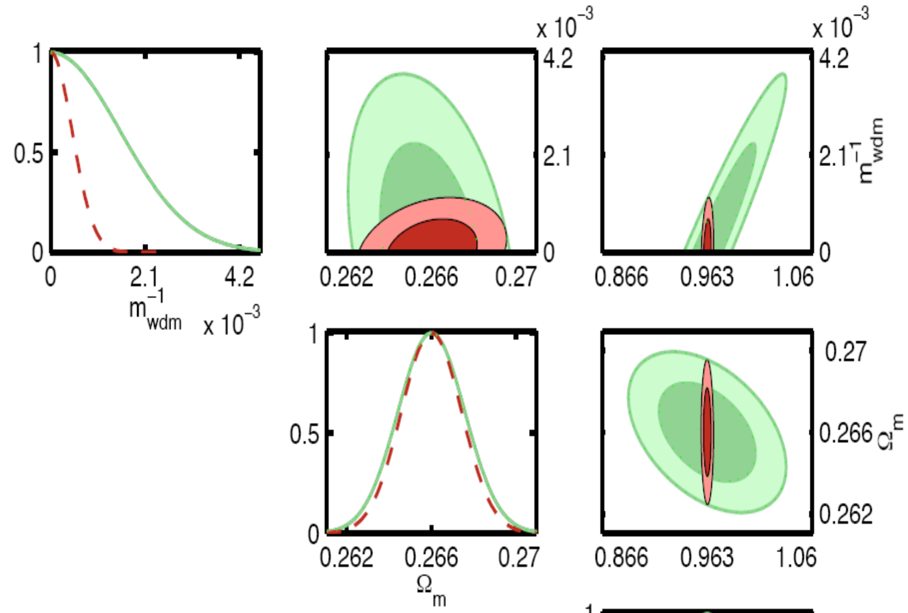
Present cosmic shear correlation functions measurement with CFHTLS T0003 release data by Fu et al. (2008) (57 sq deg)

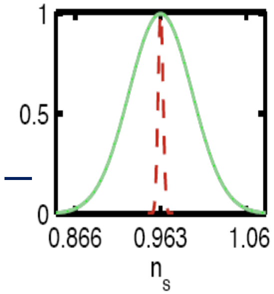
Cosmic shear power spectra

Markovic et al. 2010   Euclid-like DE space survey+Planck:

Sensitive to m_WDM < 2.5 keV







Is that interesting ?
Lyman α constraints
m > 2 or 4 keV or even higher –
But doubts on Lyα results!

Galaxy-scale DM density profile

Generalized NFW model → Dark Matter mass

(Bi et al. 2010)

Sensitivity of detection scales by lensing

Strong lensing: 1-10 kpc

Flexion: 10-100 kpc

Weak lensing: <100 kpc

Galaxy-galaxy lensing

Measure the correlation of shear of the background galaxies with mass of the foreground galaxies

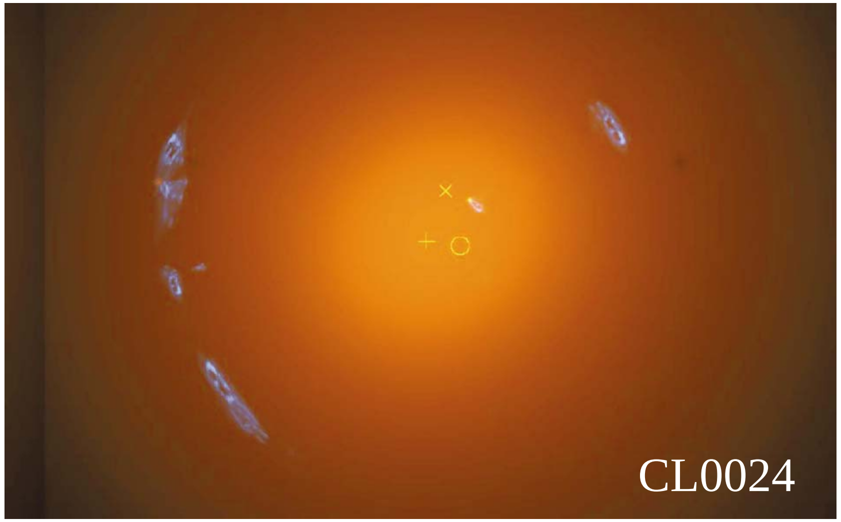
$$\Delta\Sigma(R) \equiv \overline{\Sigma}(< R) - \overline{\Sigma}(R) = \Sigma_{\rm crit} \times \gamma_t(R).$$

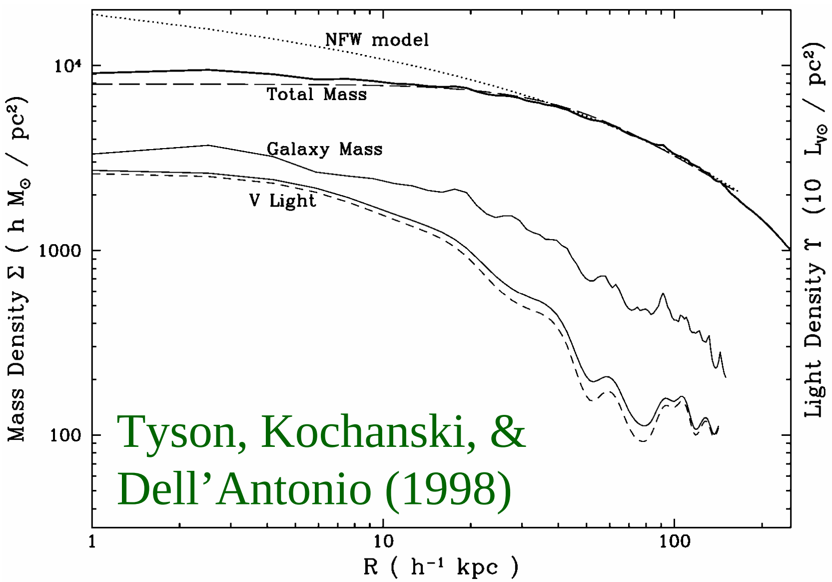
To achieve the galaxy-galaxy lensing signal, we need two important ingredients that we can extract from the data

1)the redshift distribution of the lensed background galaxies

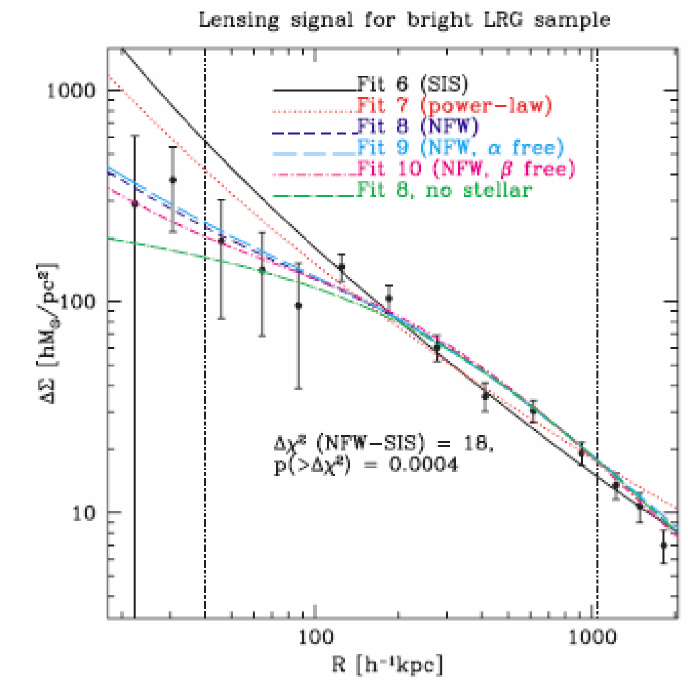
2)the shape of the lensed background galaxies

Probing DM Particle properties





Tyson, Kochanski, & Dell'Antonio (1998)

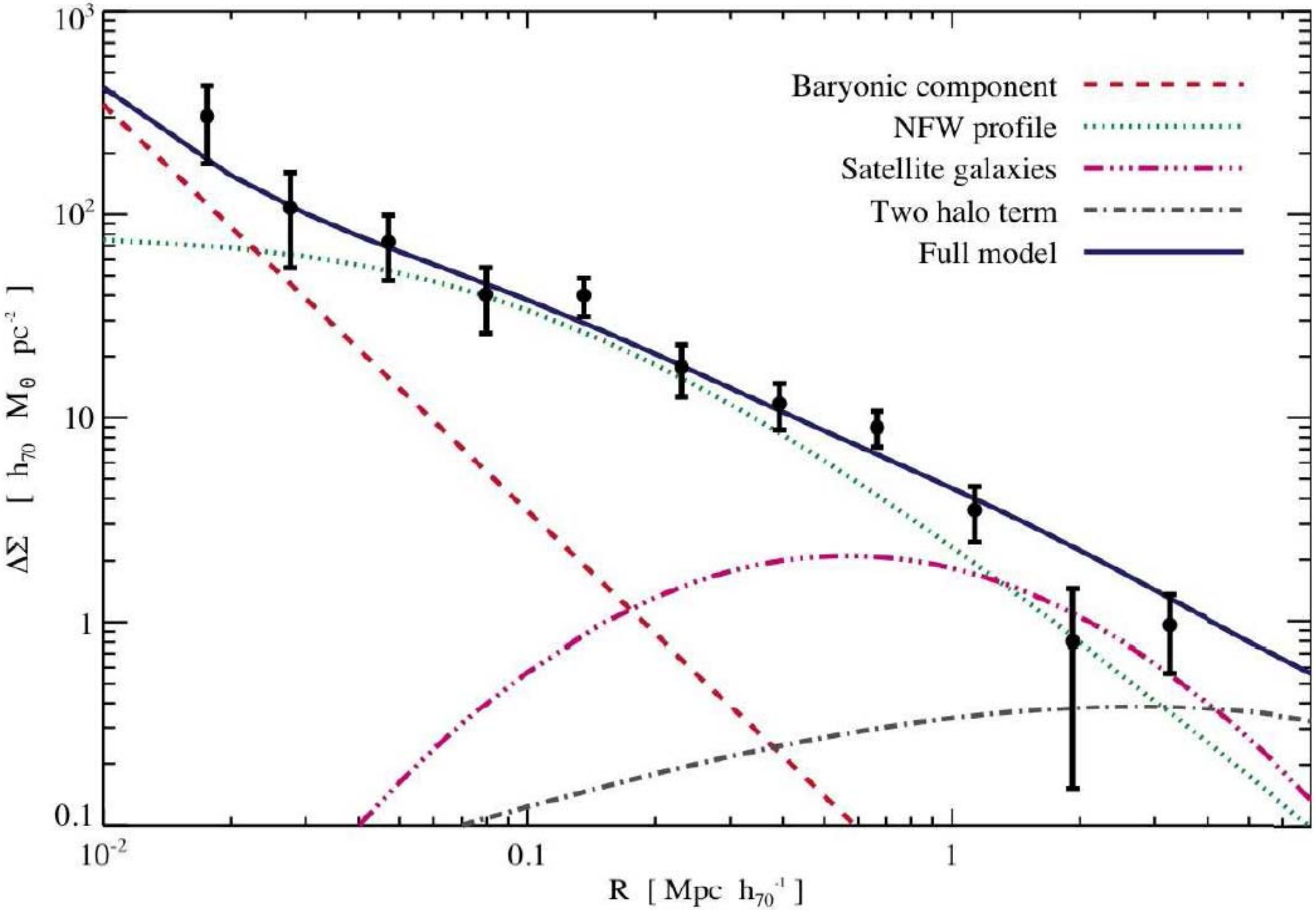


Mandelbaum et al. (2006)

Stacked galaxy—galaxy weak lensing signal fit with various profiles.

Surface density profile measurements obtained from galaxy groups in the COSMOS survey

Leauthaud et al. 2010



Magnification (Van Waerbeke et al. 2010)

An alternative way to determine the galaxy profile, especially for the high redshift galaxies (z>=1).

- Need: precise photometry (but not shape)
- Measure: number density of galaxies

$$\delta_N(\boldsymbol{\theta}) = \frac{N(m, \boldsymbol{\theta}) - N_0(m)}{N_0(m)} = \mu^{2.5s(m)-1} - 1$$

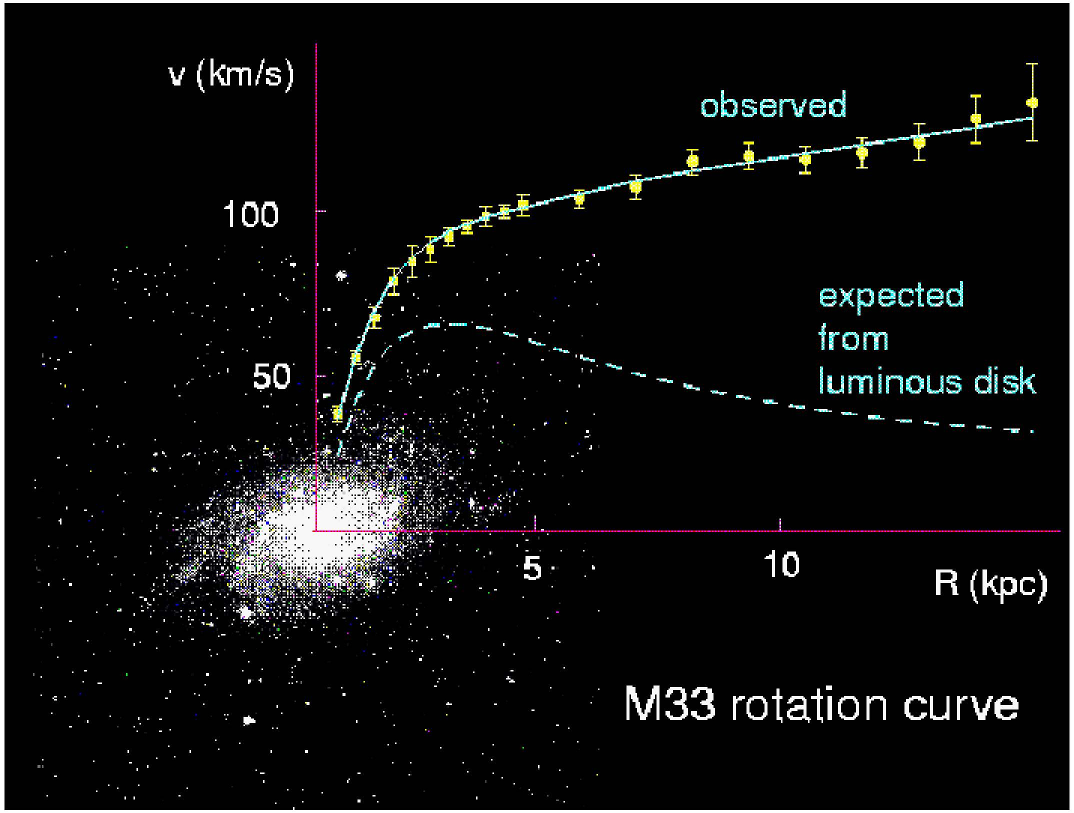
$$\mathcal{L} \propto \exp\left[(\delta_N \theta) - \bar{\delta}_N(\theta))C^{-1}_{\delta_N \delta_N}(\delta_N(\theta) - \bar{\delta}_N(\theta))^{\mathbf{T}}\right]$$

-Noise:

1. Poisson noise
2. galaxy clustering

Evidence for DM

- Galaxy rotation curves



Corbelli & Salucci (2000); Bergstrom (2000)

Kepler's law

$$v_{circ} = \sqrt{\frac{GM(r)}{r}}$$

Dynamics of galaxy clusters

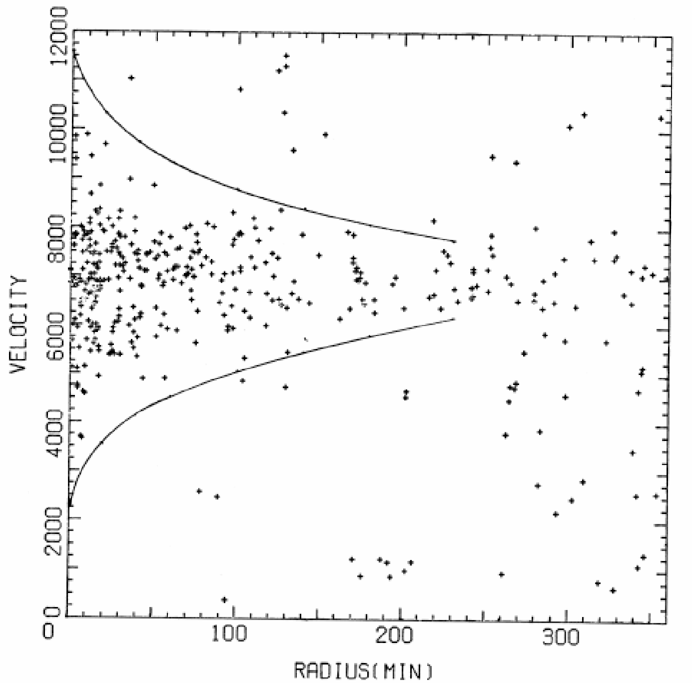
Virial theorem

$U=2K$

$K = \Sigma\, m_i\, v_i^2$

$U \sim GM^2/R$

eg,Coma cluster



Mass to Light ratio

typical cluster: 100/h-300/h Υ_{Sun}

stellar pop: 1-10 Υ_{Sun}

critical: 1390 h (+/- 35%)

X-ray clusters

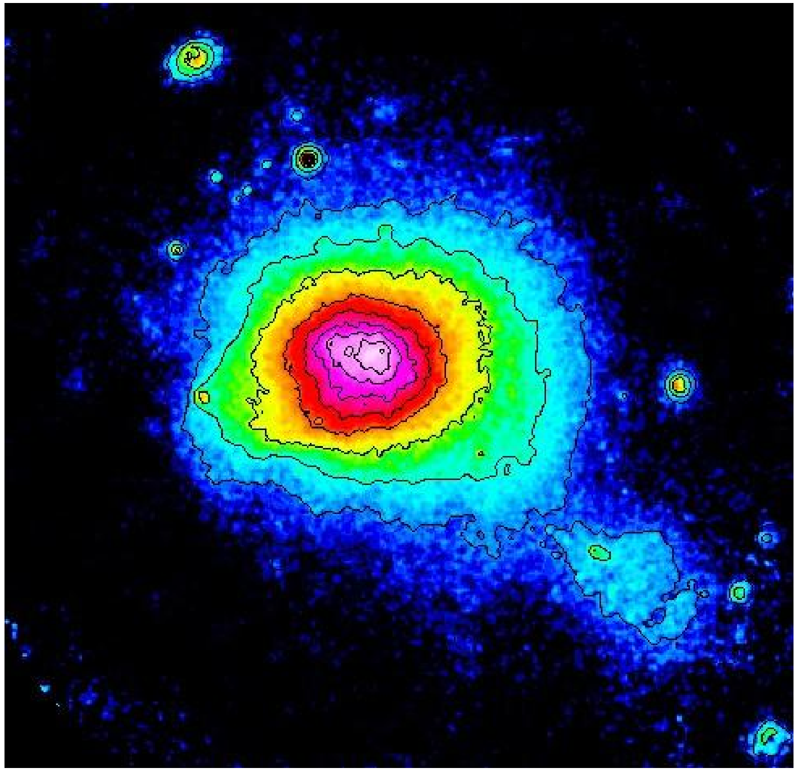
Hydrostatic equilibrium

$$\frac{GM(r)}{r^2} = -\frac{k_B T}{\mu m_H}\left[\frac{d\log\rho}{dr} + \frac{d\log T}{dr}\right]$$

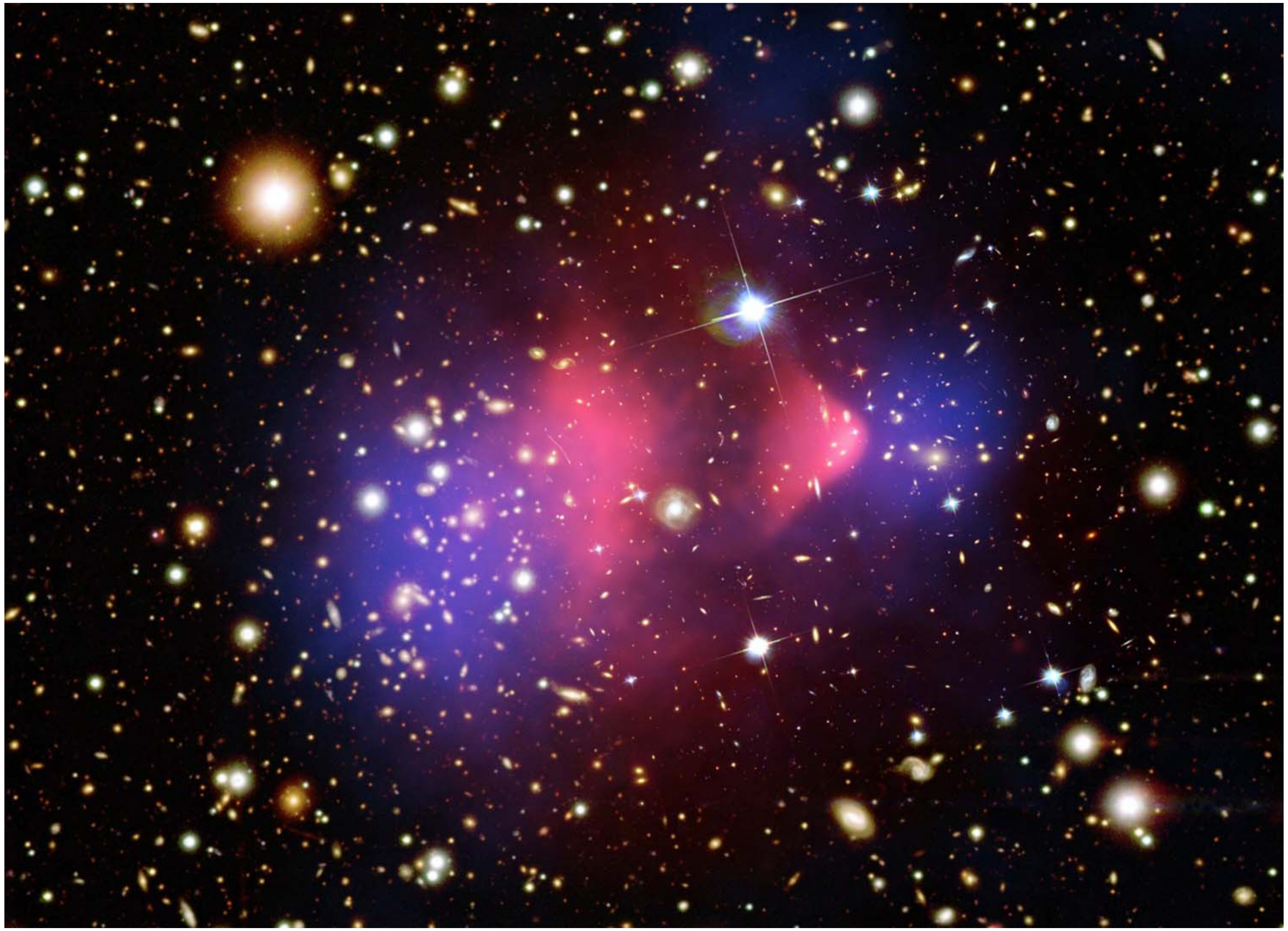
β model:

$$\rho = \rho(0)(1 + r^2/r_c^2)^{-3\beta/2}$$

However, X-ray emission measures the temperature and M/Mvisible=20



Bullet Cluster



Clowe et al. (2006)

CDM scenario with WDM?

- Non-thermally produced decaying DM could reconcile CDM and WDM

  Lin, Huang, Zhang, Brandenberger 2001

- Phenomenology: Bi et al. 2010

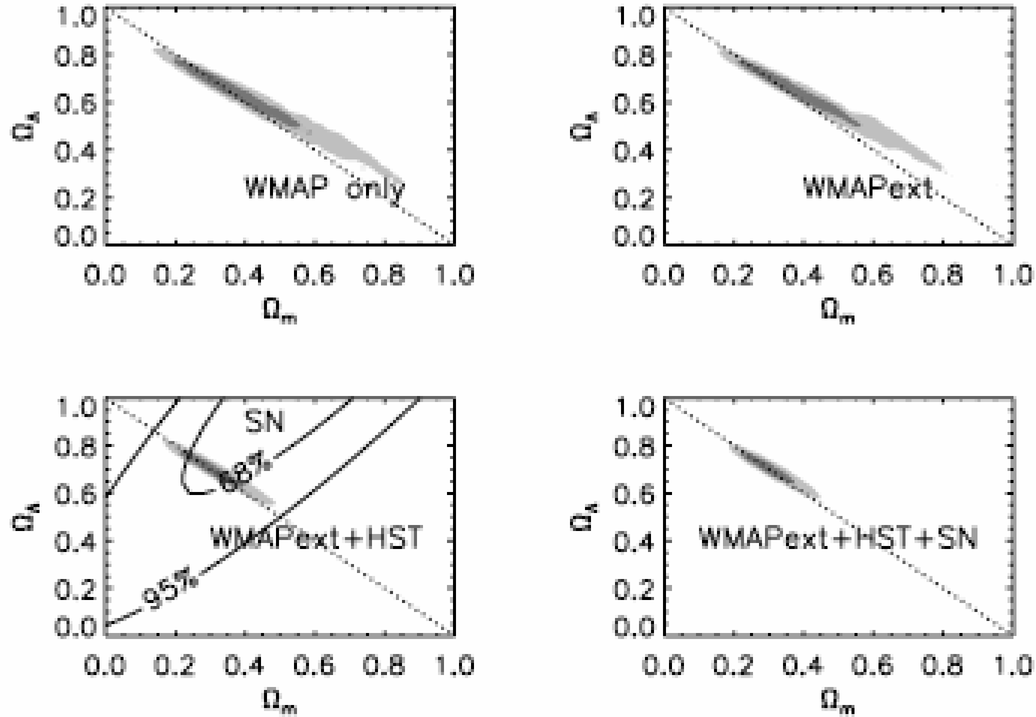
Cosmological constraints: WMAP constraints

WMAP Combined fit:

$\Omega_m h^2 = 0.135 +- 0.009$

$\Omega_m = 0.27 +- 0.04$

Results and errors depend on other probes,eg, Supernovae and Hubble constant data.



Baryonic and Non-baryonic DM

From BBN and CMB,

$\Omega_b h^2 = 0.02 +/- 0.002.$

➔ non-baryonic DM

$\Omega_{DM} h^2 = 0.113 +/- 0.009$