The Dark and Light Side of Galaxy Formation

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IAP2015

From Quantum Foam to Galaxies

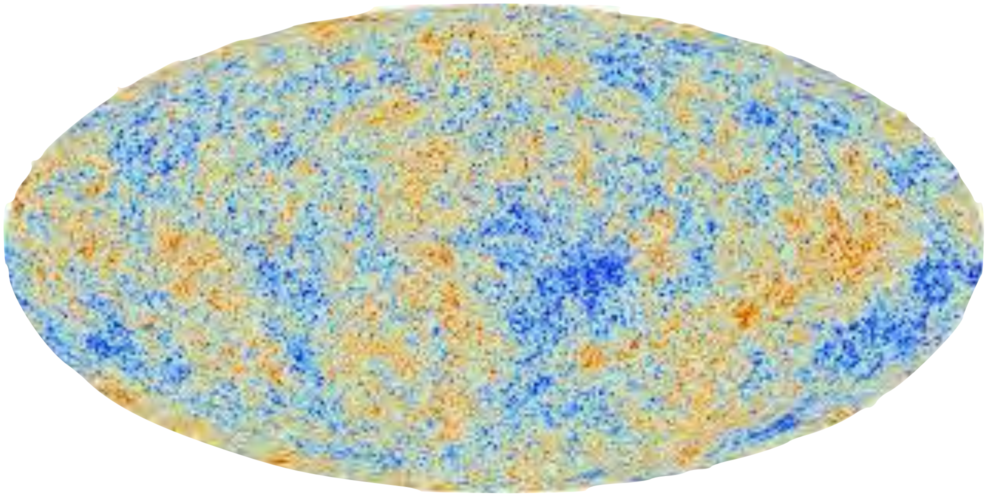
Galaxy Formation is the dot-com of Astrophysics. **It is about nothing less than the origin and *13* Gyr-evolution of the building blocks of our Universe as a result of quantum fluctuations amplified in the aftermath of the Big Bang. "*It is a bold enterprise and not for the faint of heart.*"**

Galaxies are molded by *highly non-linear processes* at work from the "*small*" scales of star formation and accretion onto massive black holes *(where ordinary matter dominates)* up to the very large scales of the "*cosmic web*" *(the realm of non-baryonic dark matter)*.

Just Six Numbers (Flat ΛCDM)

ΛCDM (Planck 2015, TT,TE,EE+lowP+lensing+ext)

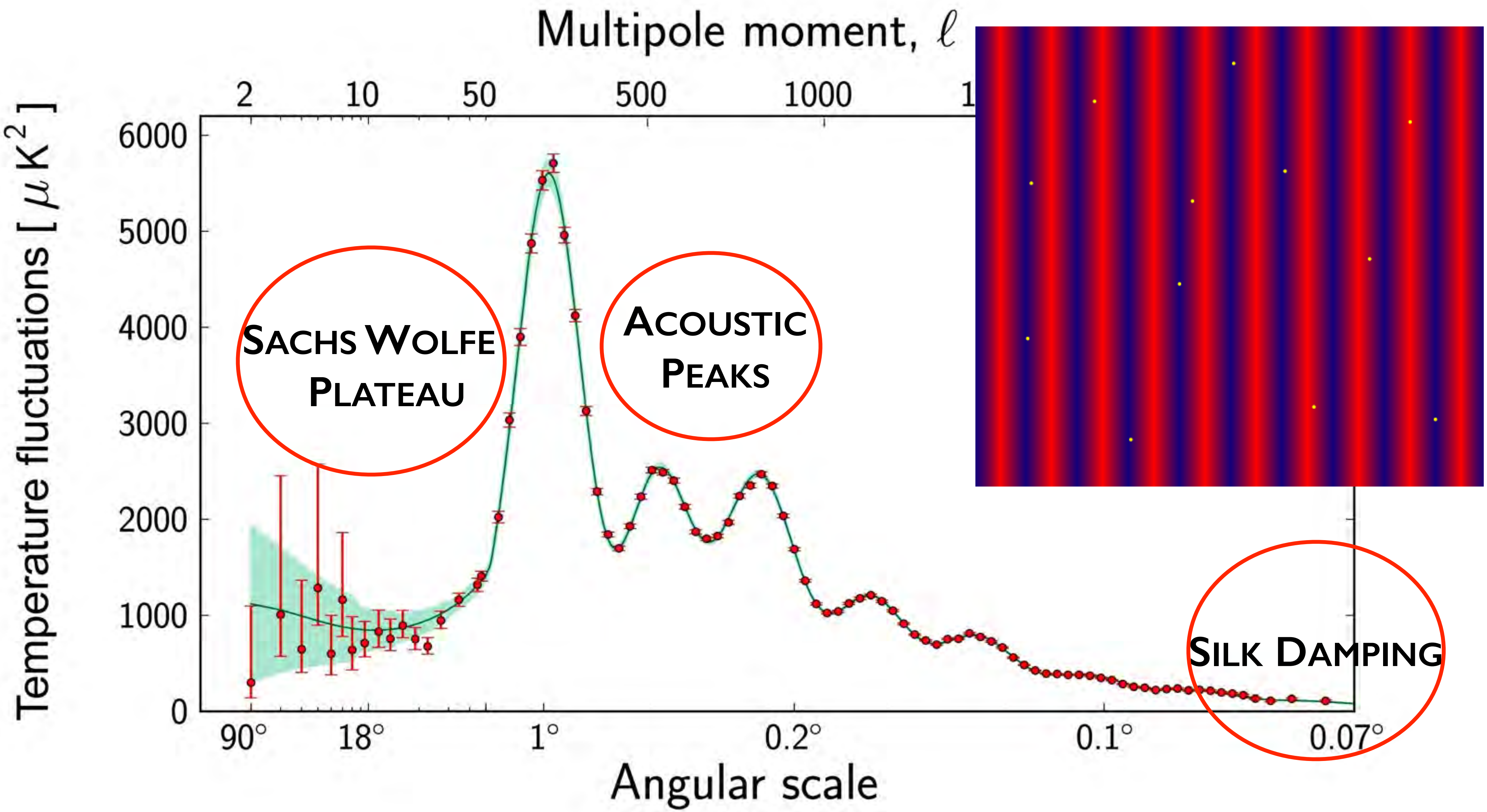
$\Omega_b h^2$	$= 0.02230 \pm 0.00014$
$\Omega_c h^2$	$= 0.1188 \pm 0.0010$
$100\theta_{MC}$	$= 1.04093 \pm 0.00030$
τ	$= 0.066 \pm 0.012$
n_s	$= 0.9667 \pm 0.0040$
σ_8	$= 0.8159 \pm 0.0086$



A *160σ* measurement of the cosmic baryon density and a 120σ detection of non-baryonic DM!

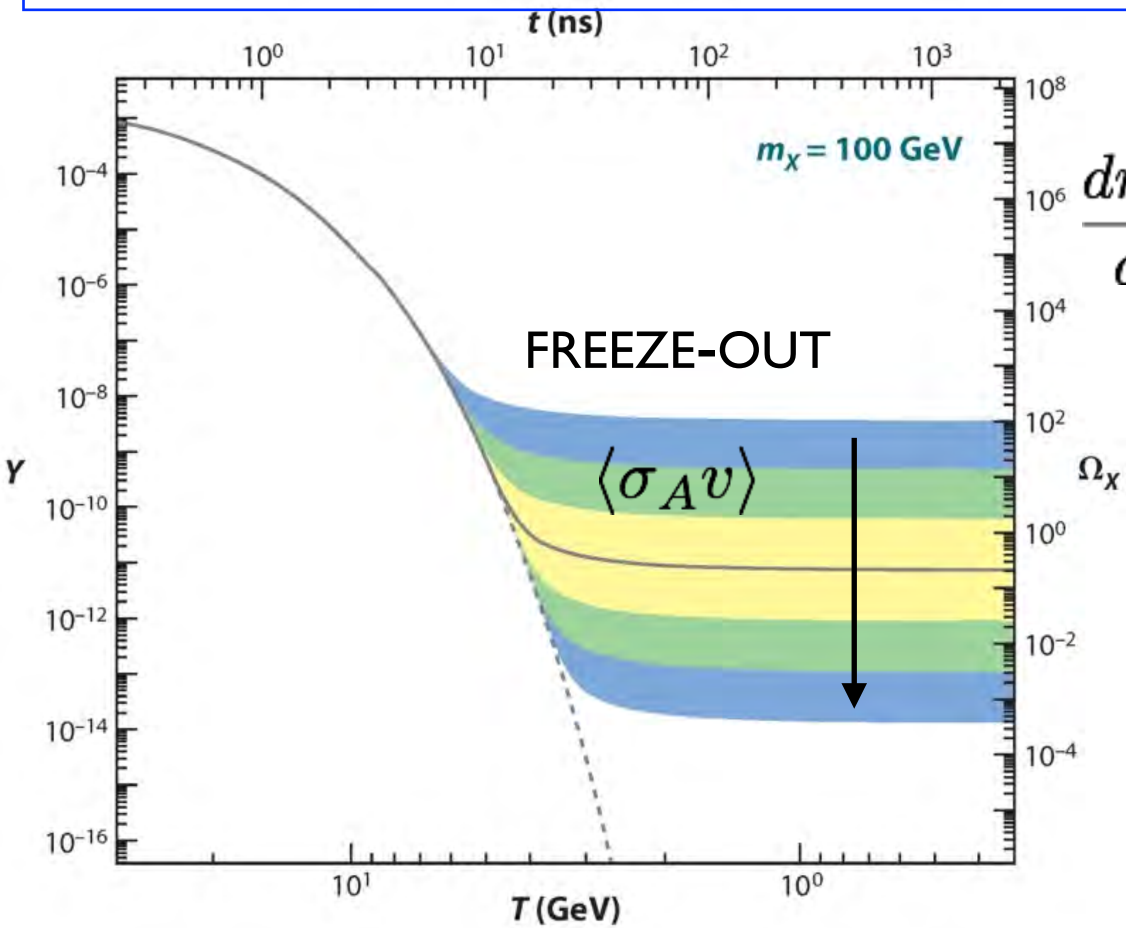
Inflation predicts an initial power spectrum $P_i(k) \propto k^{n_s}$ $\quad n_s \lesssim 1$

Dark Matter is Our Friend



Thermal Relics?

In the "standard" cosmological model a *cold* WIMP dictates the formation of cosmic structure….



$$\frac{dn_X}{dt} = -3Hn_X - \langle \sigma_A v \rangle (n_X^2 - n_{X,eq}^2)$$

Boltzmann Eq.

Decoupling

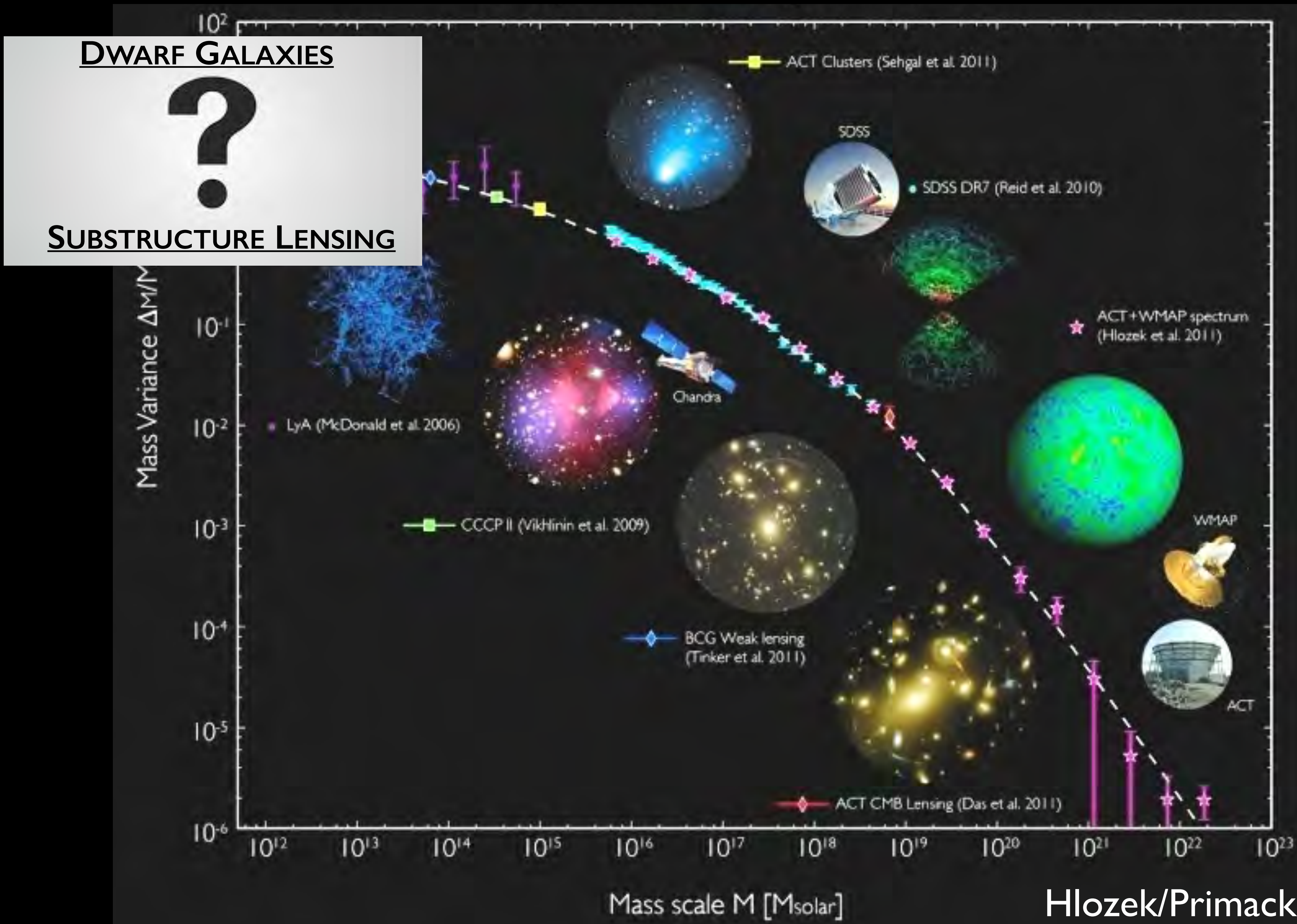
$$\Gamma = n_X \langle \sigma_A v \rangle < H$$

WIMP Miracle!

$$\Omega_\chi h^2 \simeq \frac{3 \times 10^{-27}\,\mathrm{cm}^3\mathrm{s}^{-1}}{\langle \sigma_A v \rangle} \qquad \Omega_\chi h^2 \simeq 0.11$$

$$\langle \sigma_A v \rangle \simeq 3 \times 10^{-26}\,\mathrm{cm}^3\mathrm{s}^{-1} \quad \sigma_W \sim \alpha^2 / m_W^2$$

Density Fluctuations Data Agree with ΛCDM!



Hlozek/Primack

Although LCDM has had great success in explaining the observed large-scale distribution of mass in the universe, the nature of the dark matter particle is best tested on small scales, where its physical characteristics manifest themselves by modifying the structure of galaxy halos and their lumpiness.

It is on these scale that detailed comparisons between observations and theory have revealed several discrepancies and challenged our understanding of the mapping between dark matter halos and their baryonic components.

The CDM Small-Scale Crisis

Universe in a Box: *N*-Body Simulations in ΛCDM

• *N*-body simulations have routinely been used to study the growth of nonlinear structures in an expanding universe.

• assume all Ω_M is in cold particles that interacts only gravitationally, and sample it with $N \sim 10^9$ particles.

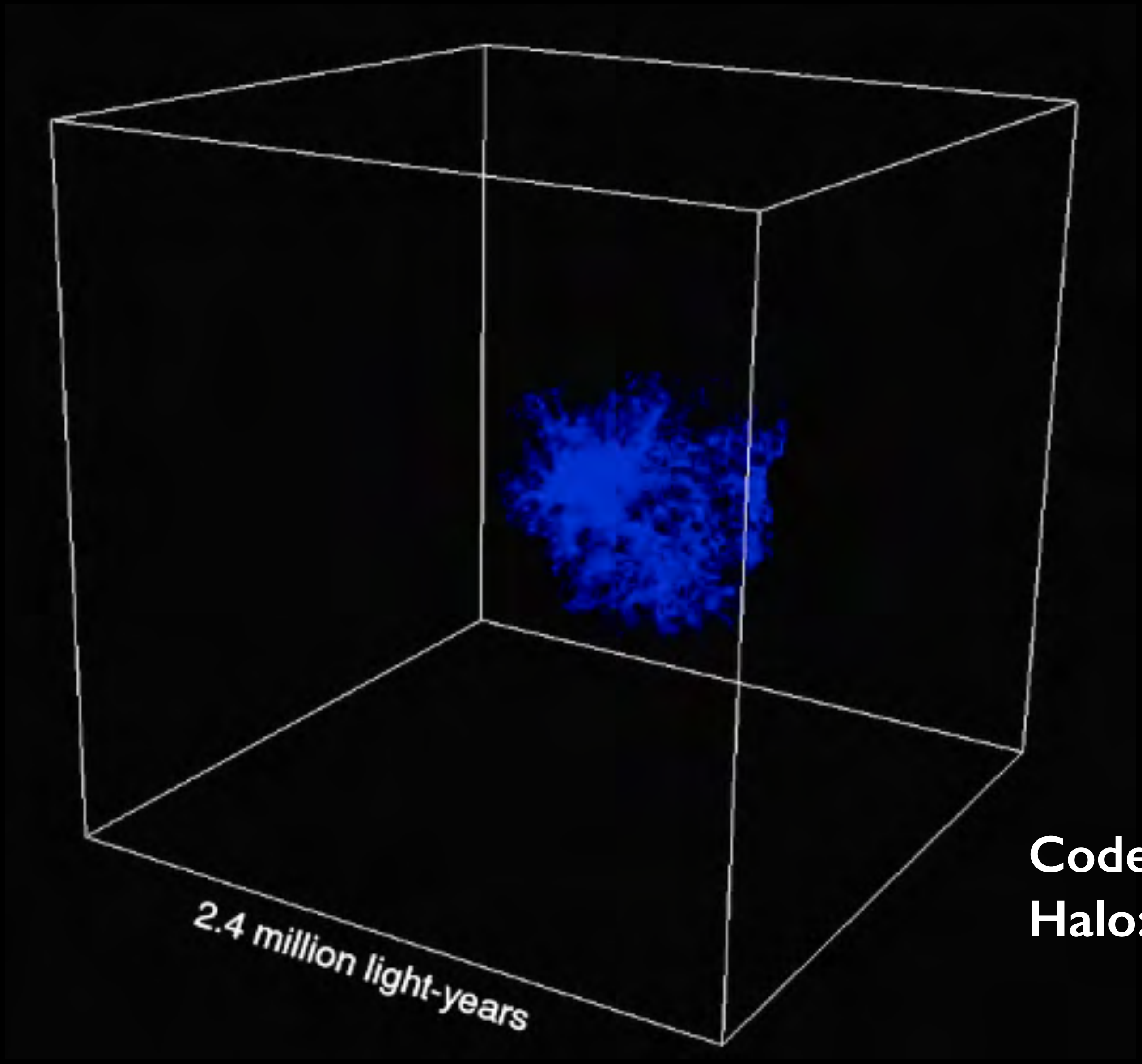
• bad approximation in the center of a massive galaxy where baryons dominate, OK for *faint dwarfs* ($M/L \lesssim 1000$).

• simple physics (just gravity) & good CPU scaling ⇨ high spatial and temporal resolution.

• no free parameters (ICs known from CMB and LSS)

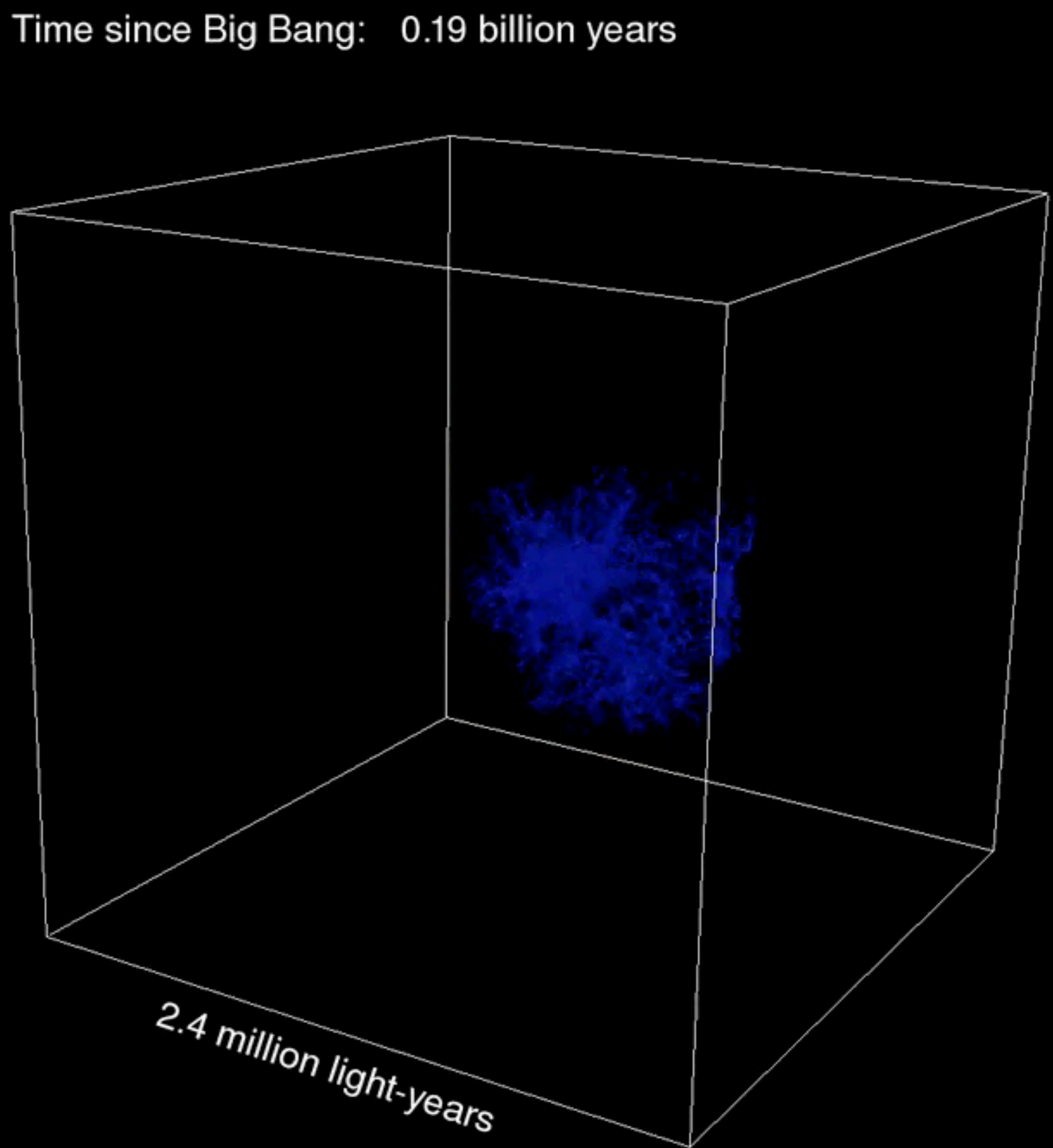
⇨ ACCURATE SOLUTION TO AN IDEALIZED PROBLEM

Substructure: A Unique Prediction of ΛCDM

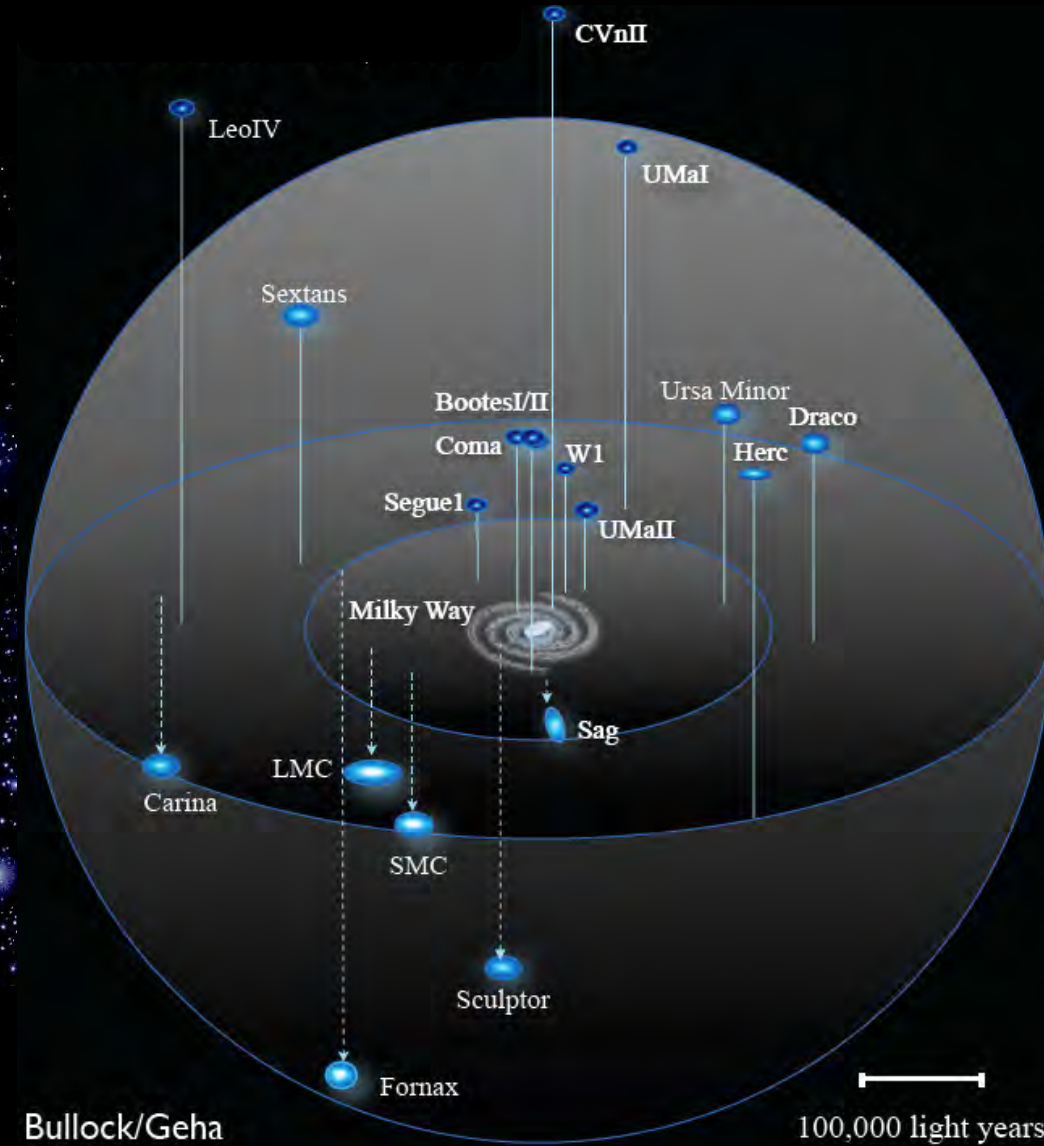


Code: PKDGRAV
Halo: VIA LACTEA II

Diemand et al. 2008



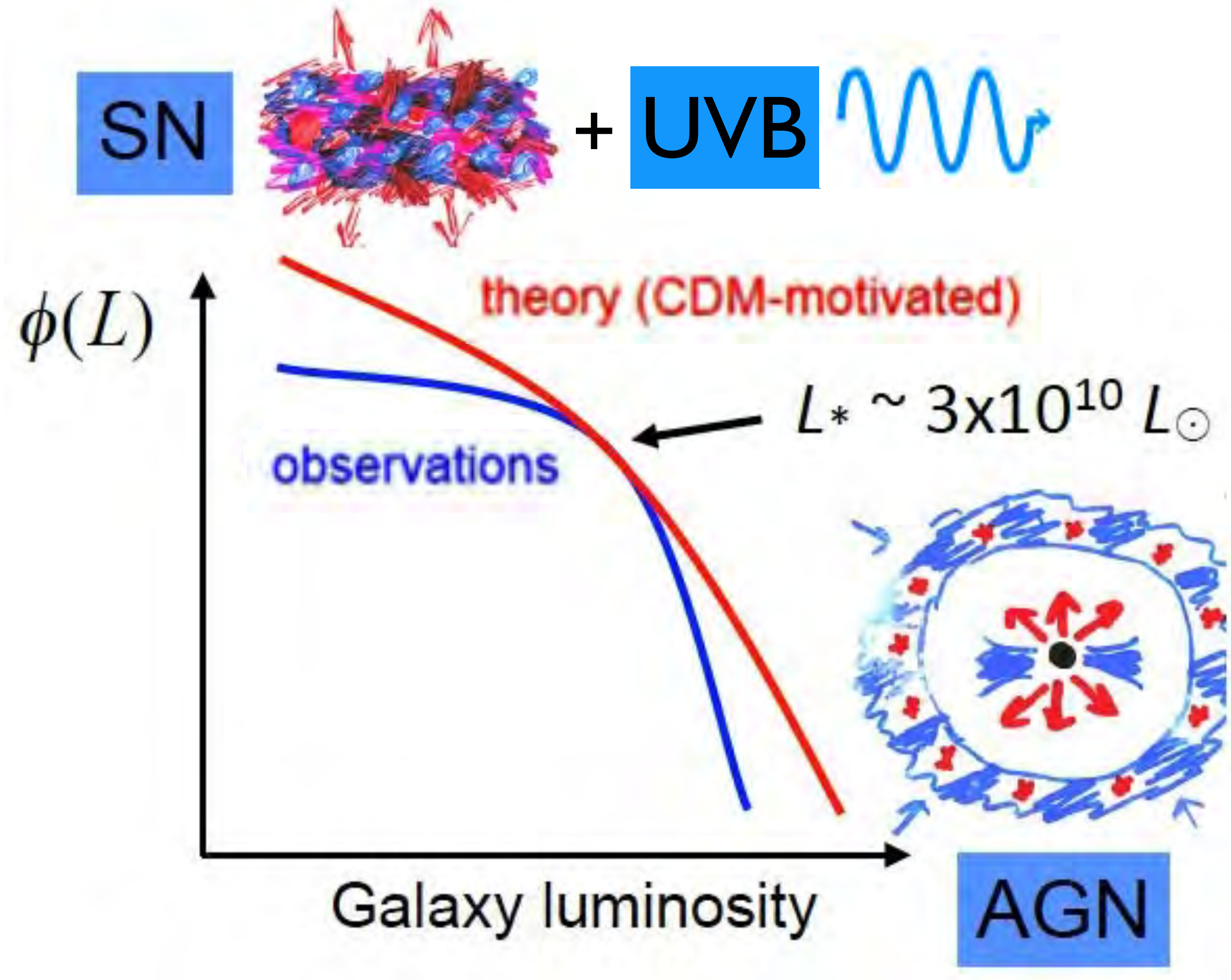
MISSING SATELLITE PROBLEM



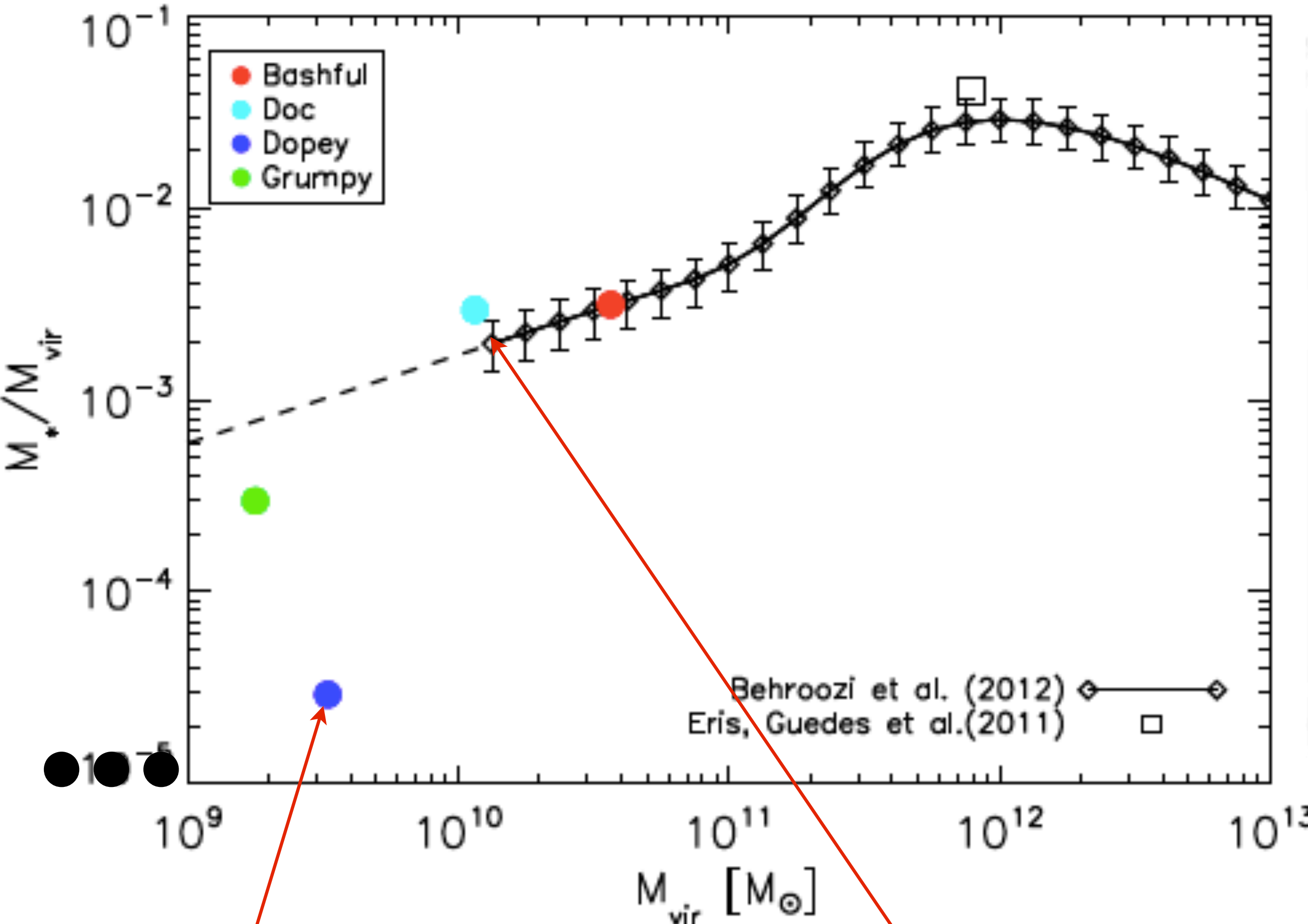
THEORY: $N \approx 1{,}000$
w V_c(infall)$\gtrsim 10$ km/s

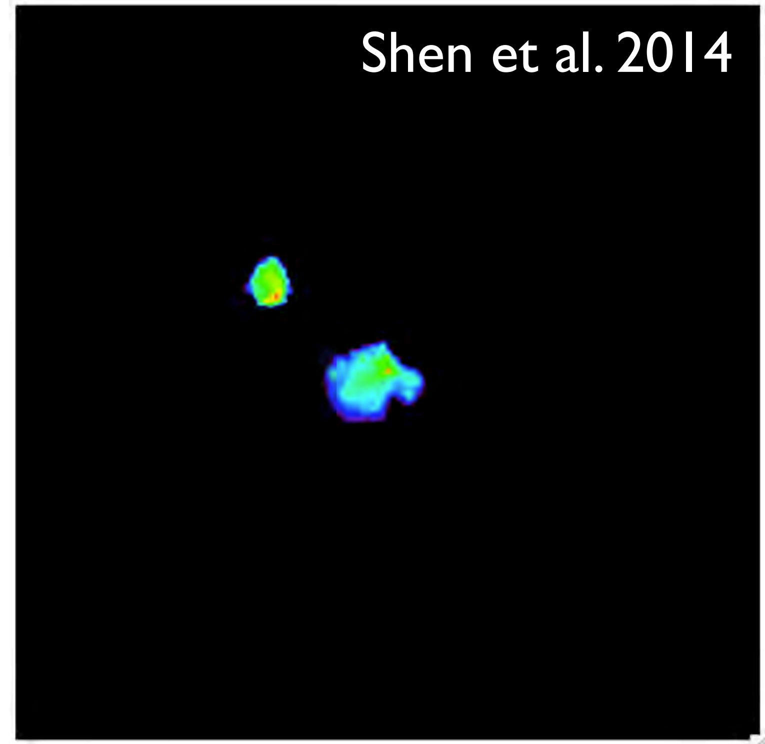
OBSERVATIONS: $N \approx 25$

SOLUTIONS TO THE MSP:



Stellar Mass Fraction of DGs





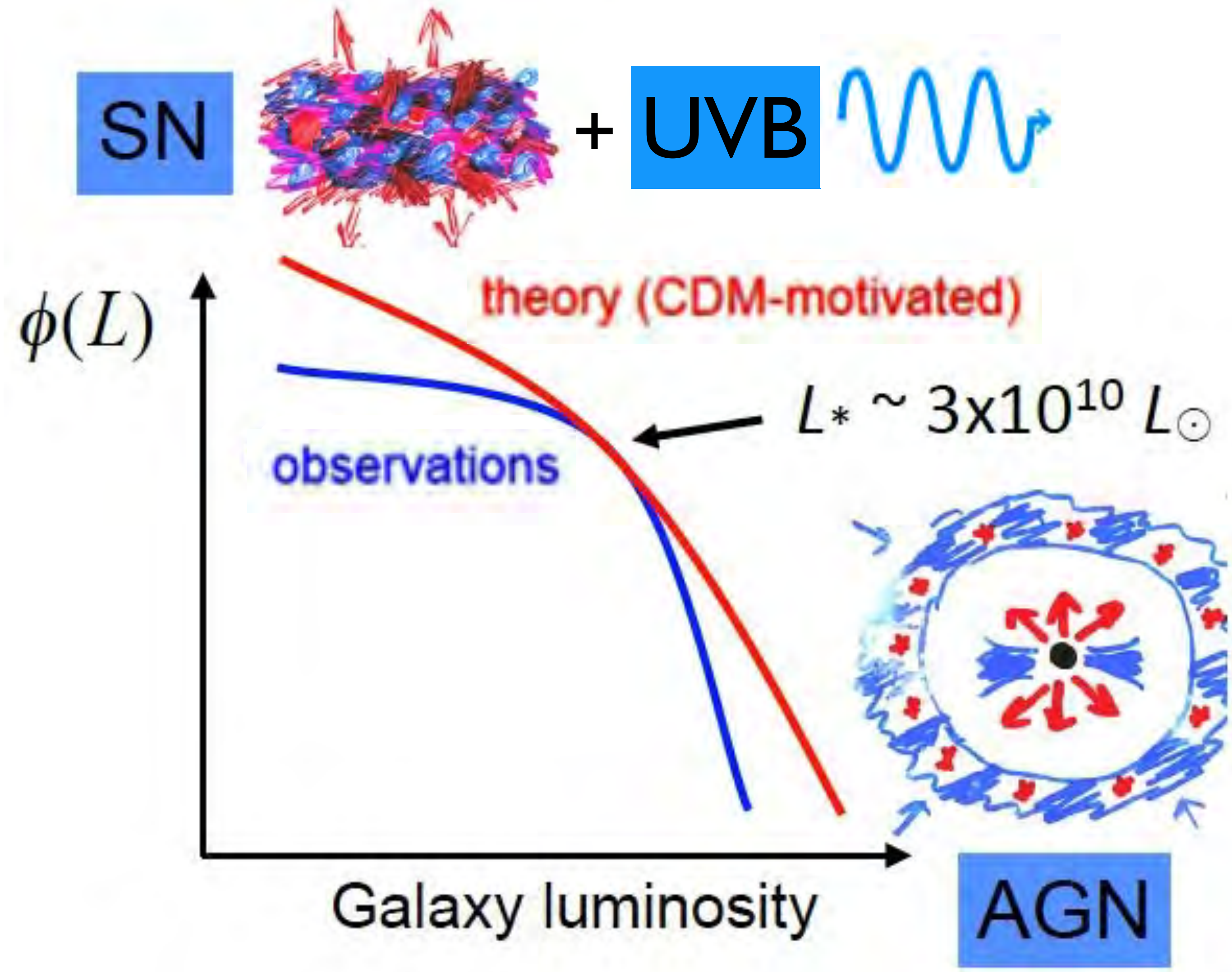
SF Efficiencies Strongly Modulated by the Depth of the Potential Well!

SOLUTIONS TO THE MSP:

1) BLAME GASTROPHYSICS

2) BLAME CDM

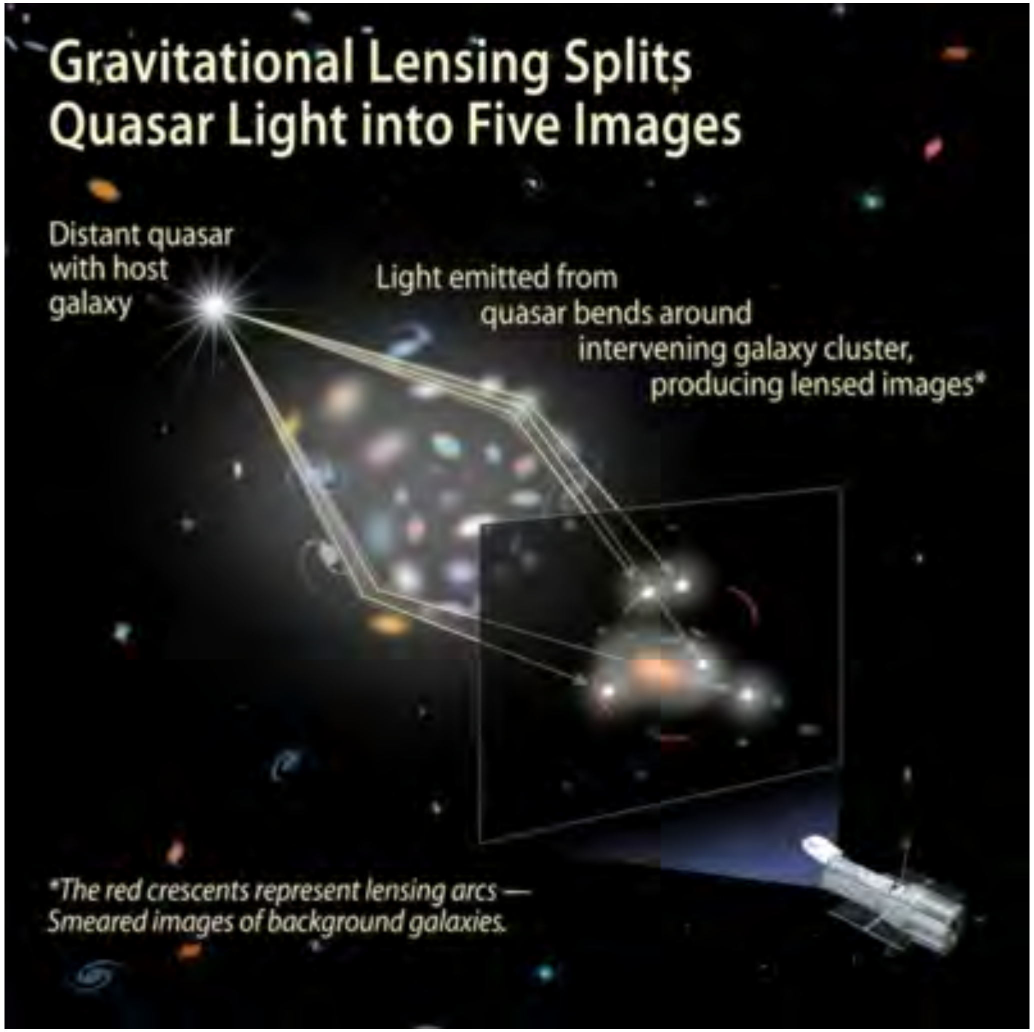
3) BLAME OBSERVATIONS!



1)+3) ➪Q: ARE GALAXIES REALLY SO LUMPY IN DM?

Substructure Lensing

Potential perturbations by **DM substructure** produce *anomalies* (compared to a simple smooth mass profile) in the relative magnifications of gravitational lenses. **Effect is sensitive to subhalo surface mass density in the inner 5-10 kpc of lens.**

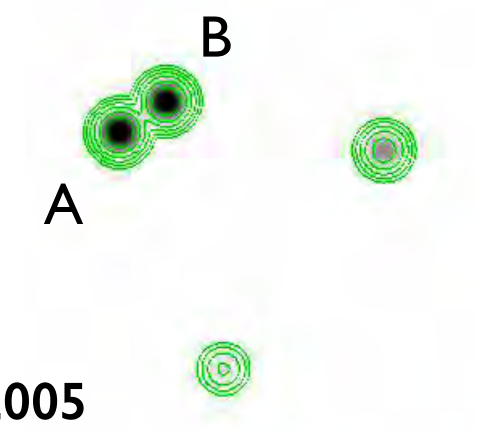


Metcalf & Madau 2001; Chiba 2001; Mao & Schneider 1998; Xu+ 2009

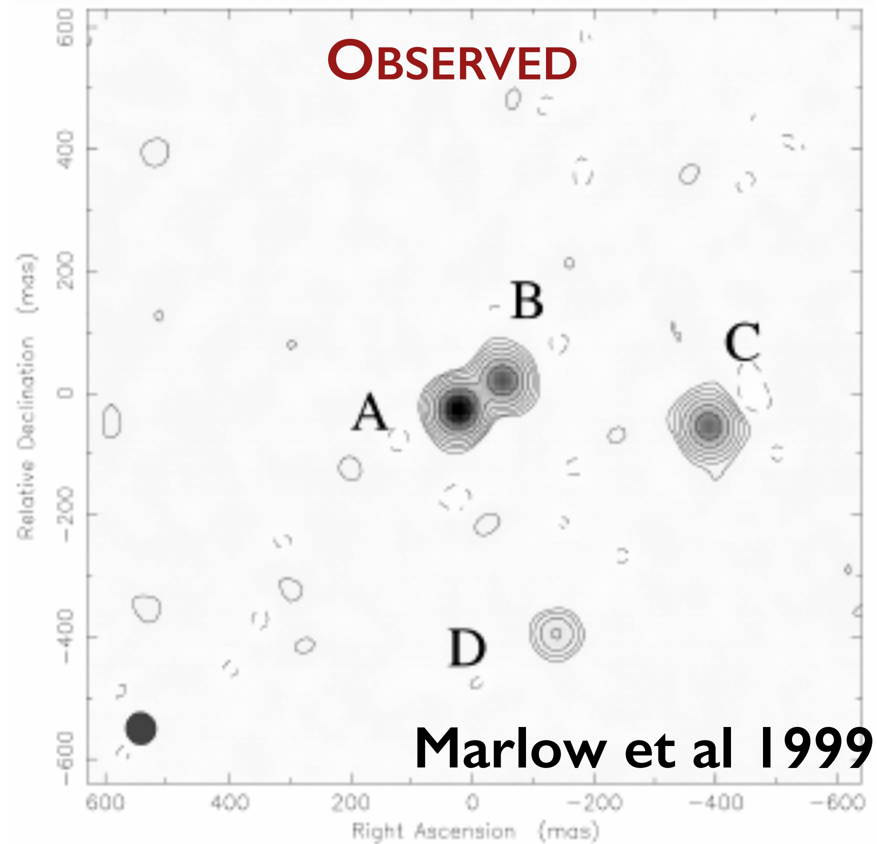
$$\mathrm{M} = \left(\frac{\partial u}{\partial x}\right)^{-1} = \begin{bmatrix} 1-\phi_{xx} & -\phi_{xy} \\ -\phi_{xy} & 1-\phi_{yy} \end{bmatrix}^{-1}$$

CLASS B1555+375 Expected

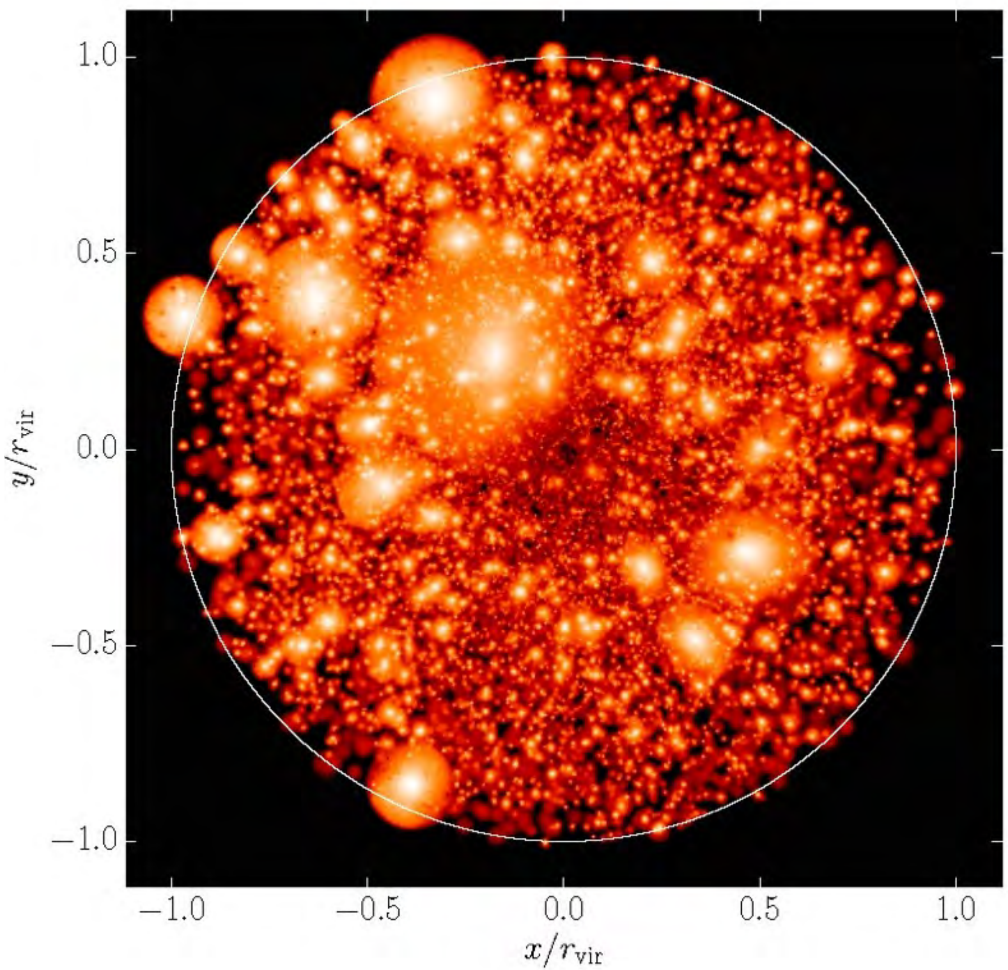
A−B≈0



Keeton et al 2005



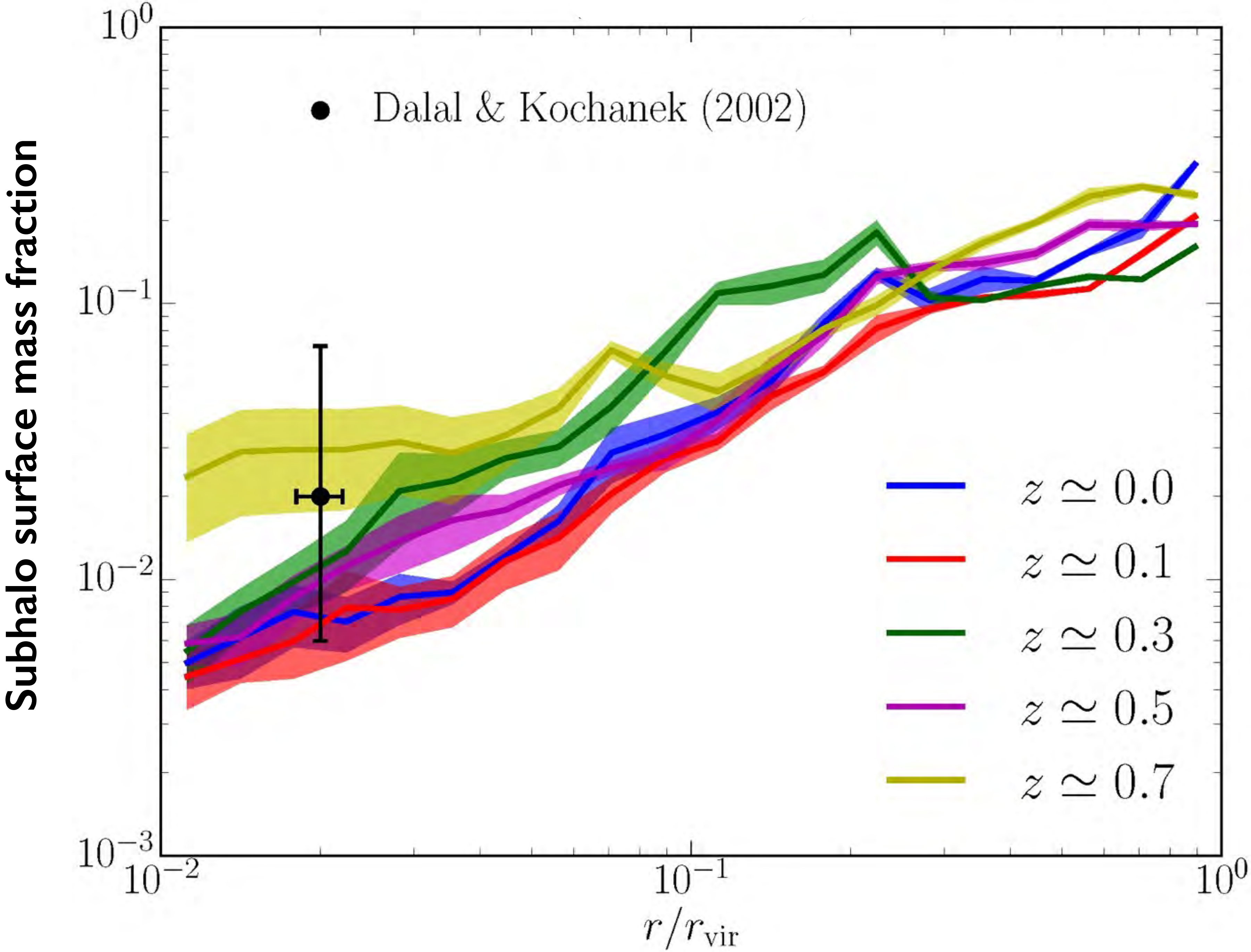
Marlow et al 1999



Dalal & Kochanek (2002)

- ☛ flux ratios in 7 quad lenses
- ☛ f_{sub}= $2.0^{+5.0}_{-1.4}$ percent
- ☛ little constraints on clump mass scale

N_p=921,651,914



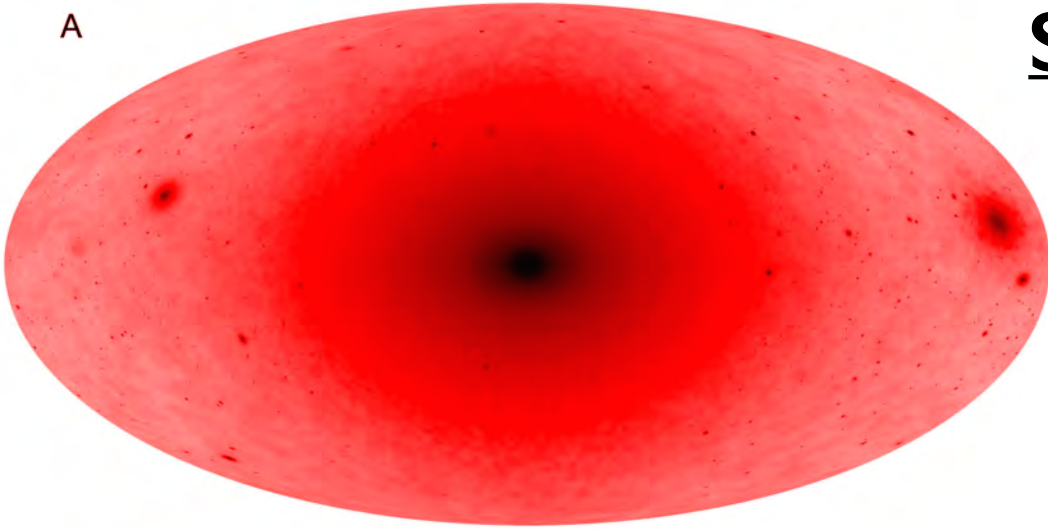
The Future: Expected Numbers of Lensed QSOs in Wide-Field Optical Surveys.

Survey	QSO (detected) $N_{\text{non-lens}}$	N_{lens}
SDSS-II	1.18×10^5	26.3 (15 per cent)
SNLS	9.23×10^3	3.2 (12 per cent)
PS1/3π	7.52×10^6	1963 (16 per cent)
PS1/MDS	9.55×10^4	30.3 (13 per cent)
DES/wide	3.68×10^6	1146 (14 per cent)
DES/deep	1.26×10^4	4.4 (12 per cent)
HSC/wide	1.76×10^6	614 (13 per cent)
HSC/deep	7.96×10^4	29.7 (12 per cent)
JDEM/SNAP	5.00×10^4	21.8 (12 per cent)
LSST	2.35×10^7	8191 (13 per cent)

Oguri & Marshall 2010

Thousands of New Lenses!

SUBSTRUCTURE ANNIHILATION



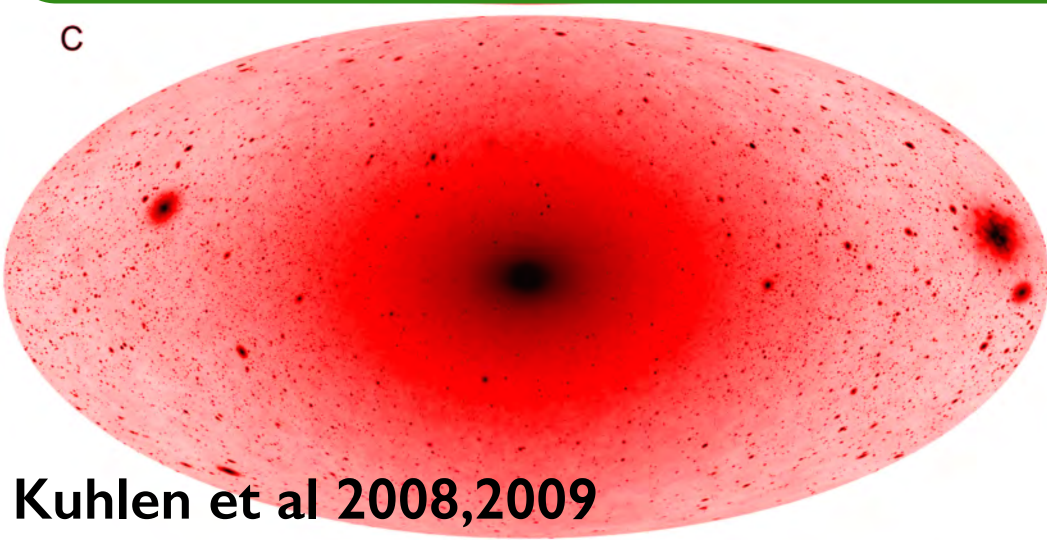
annihilation cross-section

γ-photons produced per annihilation

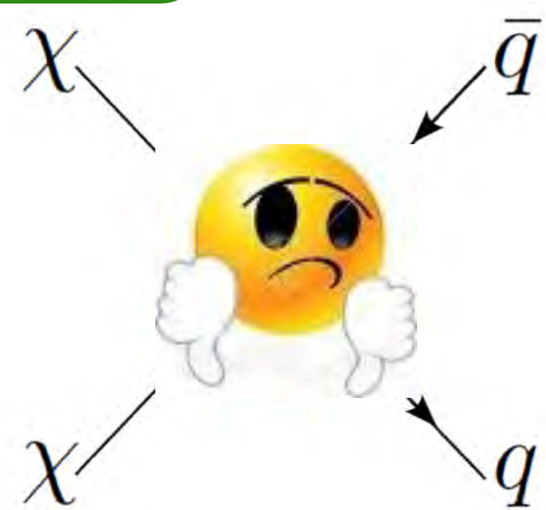
$$\Phi(E_\gamma, \psi) = \frac{\langle \sigma v \rangle}{8\pi m_X^2} \frac{dN_\gamma}{dE_\gamma} \int_{\text{los}} \rho_{\text{DM}}^2 dl$$

mass of DM particle

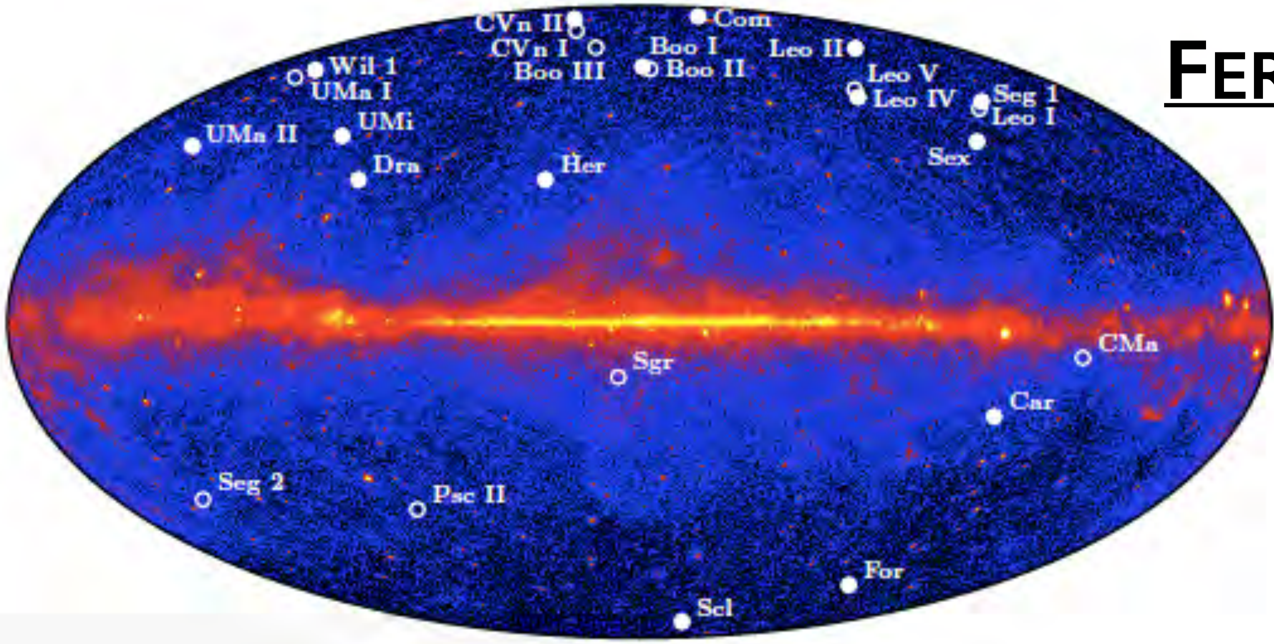
Astrophysics

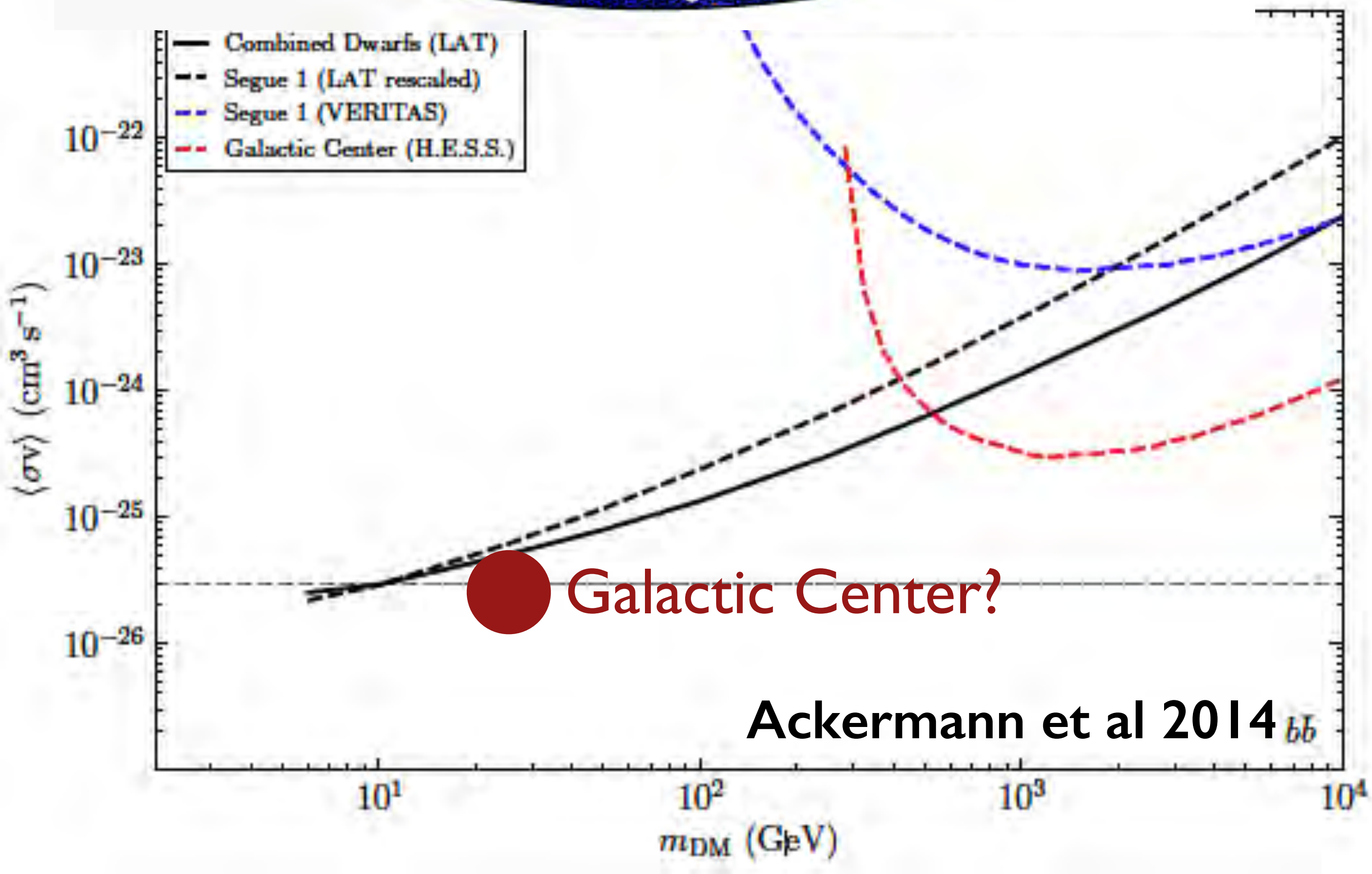


Kuhlen et al 2008,2009



FERMI'S 25 "LUMINOUS" DWARFS





SEEING THE INVISIBLE

Galactic Center produces *more 1–3* GeV *gamma-rays* than can be explained by known sources.

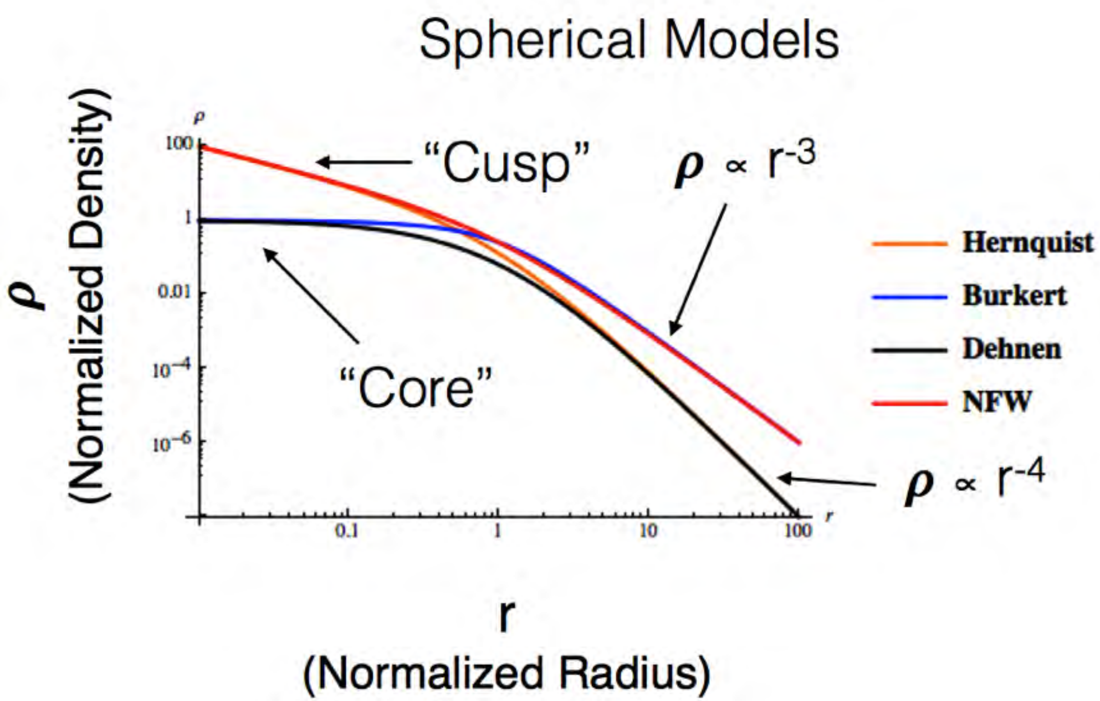
Excess emission is consistent with a *30–40* GeV *WIMP* annihilating into *quarks* with a thermally-averaged cross-section $\langle\sigma v\rangle=(1.4–2.0) \times 10^{-26}$ cm^3/s!

The Characterization of the Gamma-Ray Signal from the Central Milky Way: A Compelling Case for Annihilating Dark Matter

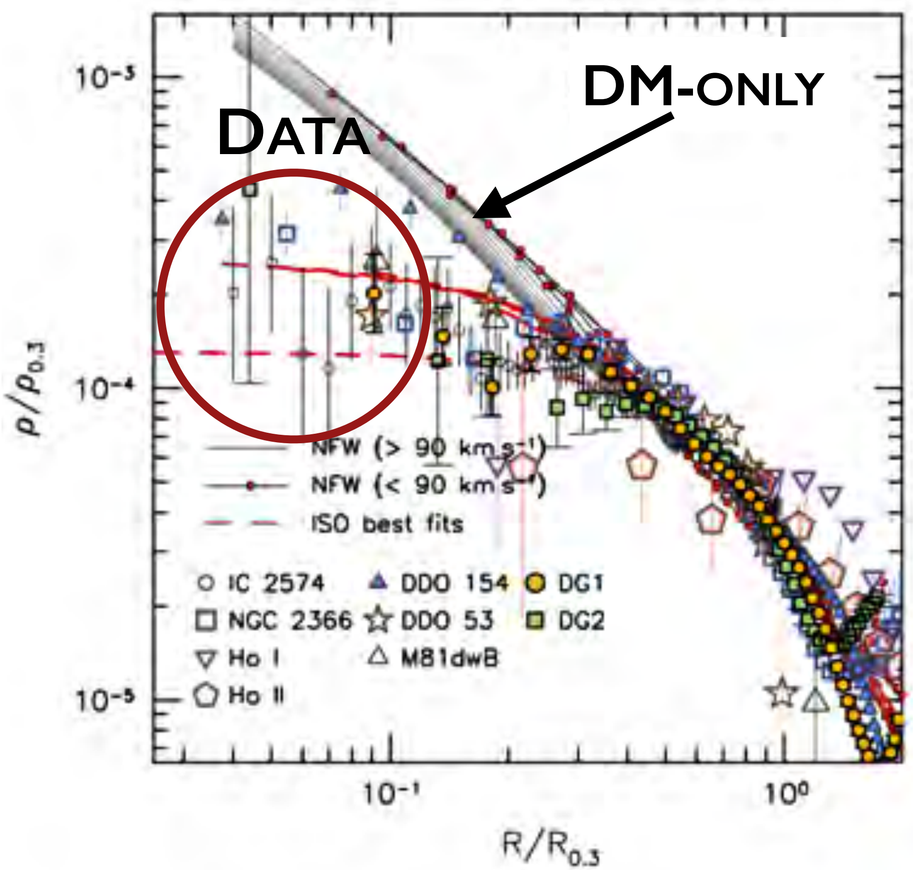
Tansu Daylan,[1] Douglas P. Finkbeiner,[1,2] Dan Hooper,[3,4] Tim Linden,[5] Stephen K. N. Portillo,[2] Nicholas L. Rodd,[6] and Tracy R. Slatyer[6,7]

Core/Cusp Problem

DM-only *N*-body simulations predict cuspy inner density profiles $\alpha \equiv -\frac{d \ln \rho}{d \ln r} \gtrsim 1$



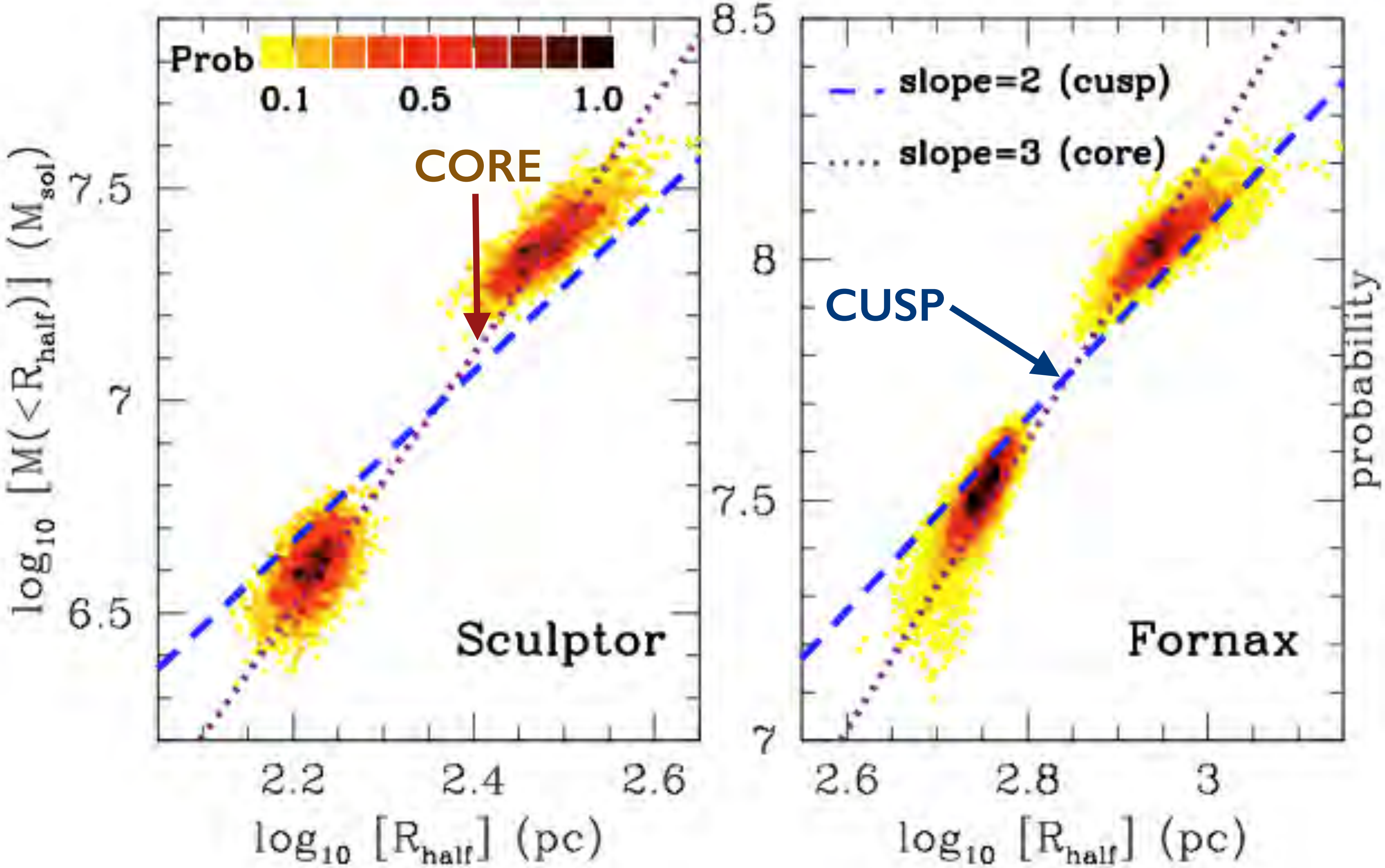
THINGS



Observations in dwarf galaxies appear to prefer cores: $\alpha \equiv -\frac{d \ln \rho}{d \ln r} \sim 0$

Cores in dSphs?

$$M(<r) = \frac{r\sigma_r^2}{G}\left(-\frac{d\ln\rho_*}{d\ln r} - \frac{d\ln\sigma_r^2}{d\ln r} - 2\beta\right)$$



Walker & Penarrubia (2011)

Beyond Cold and Collisionless DM-only Simulations

Change DM Physics:

WDM

Self-Interacting

(SI)DM

just-so solutions to CDM's problems, requiring a particle mass or SI cross-section that are tuned to the particular scale of dwarf galaxy halos.

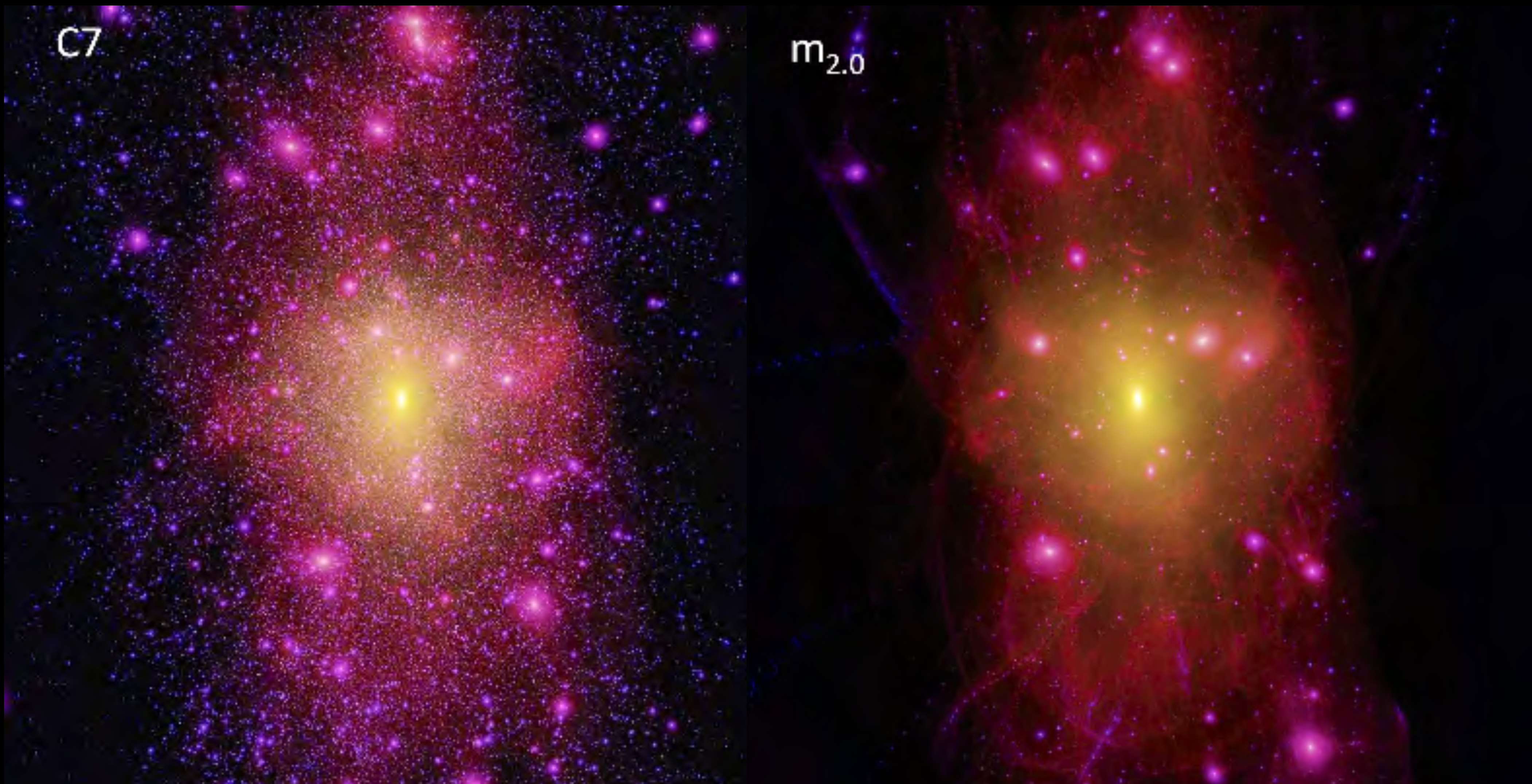
Include Baryonic Physics:

Gas Cooling

Star Formation

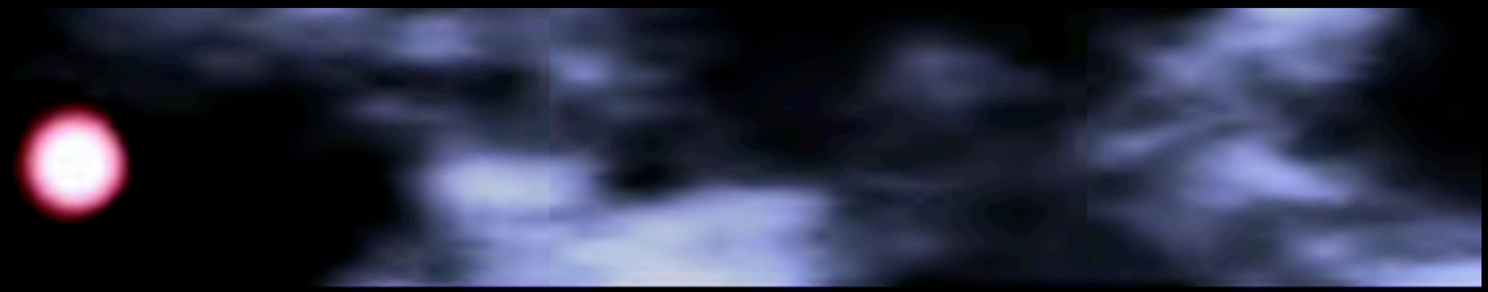
Feedback

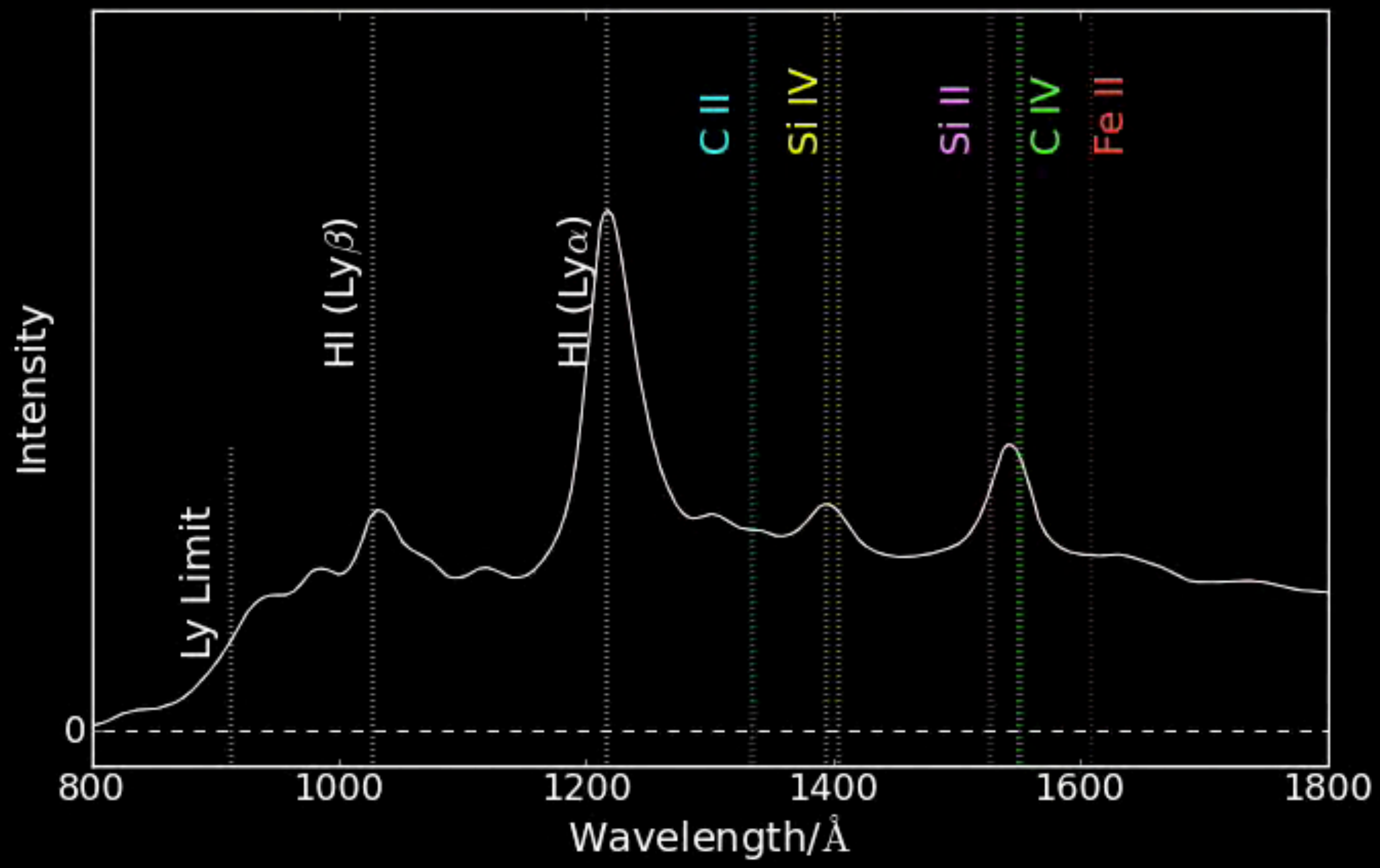
Milky Way CDM   Milky Way WDM

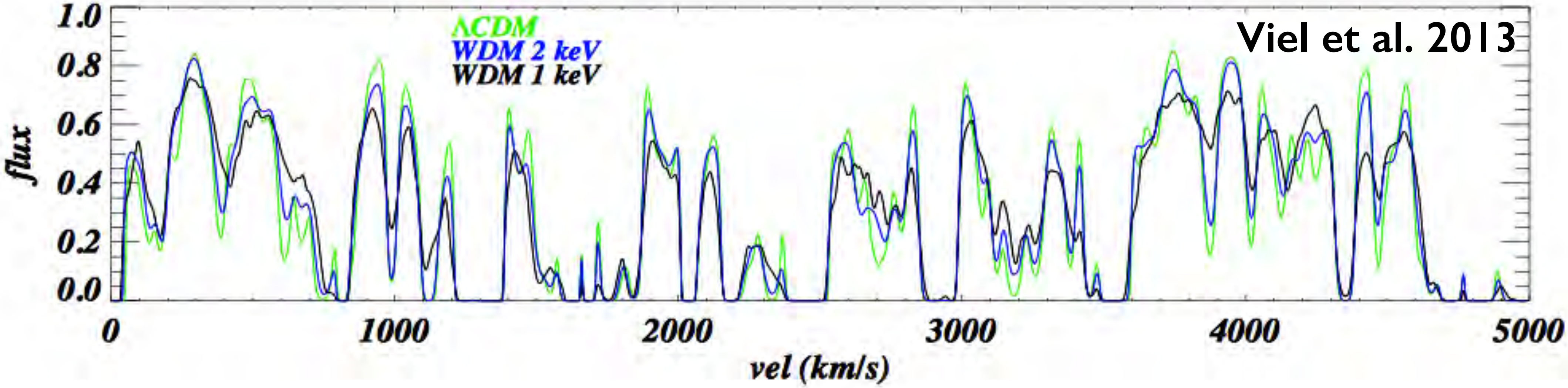


Lovell et al. 2014

STRUCTURE IN INTERGALACTIC GAS AT HIGH REDSHIFT

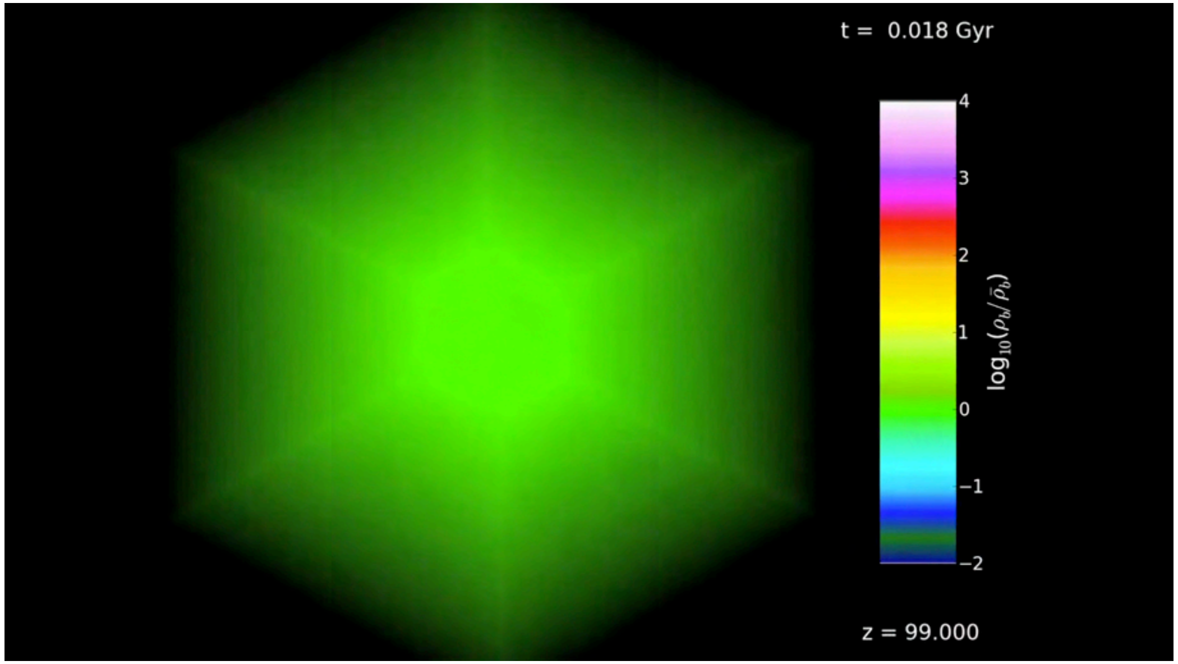




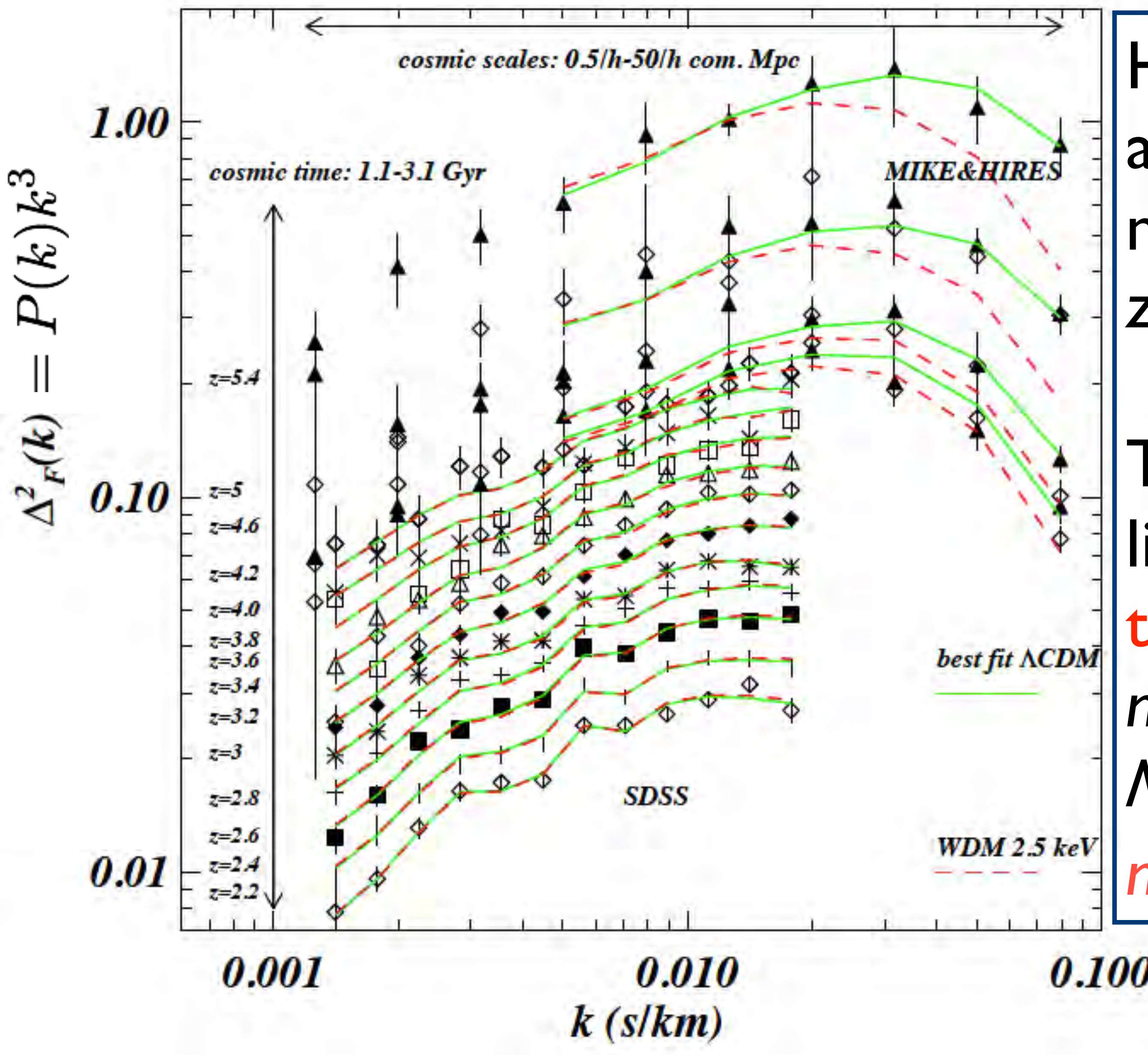


Transmitted quasar flux in hydrodynamic simulations of the early intergalactic medium in ΛCDM and WDM models.

High-frequency power is missing in the WDM case.



Someone Likes it Cold/Tepid



High-resolution Keck and Magellan spectra match ΛCDM up to *z* = *5.4*

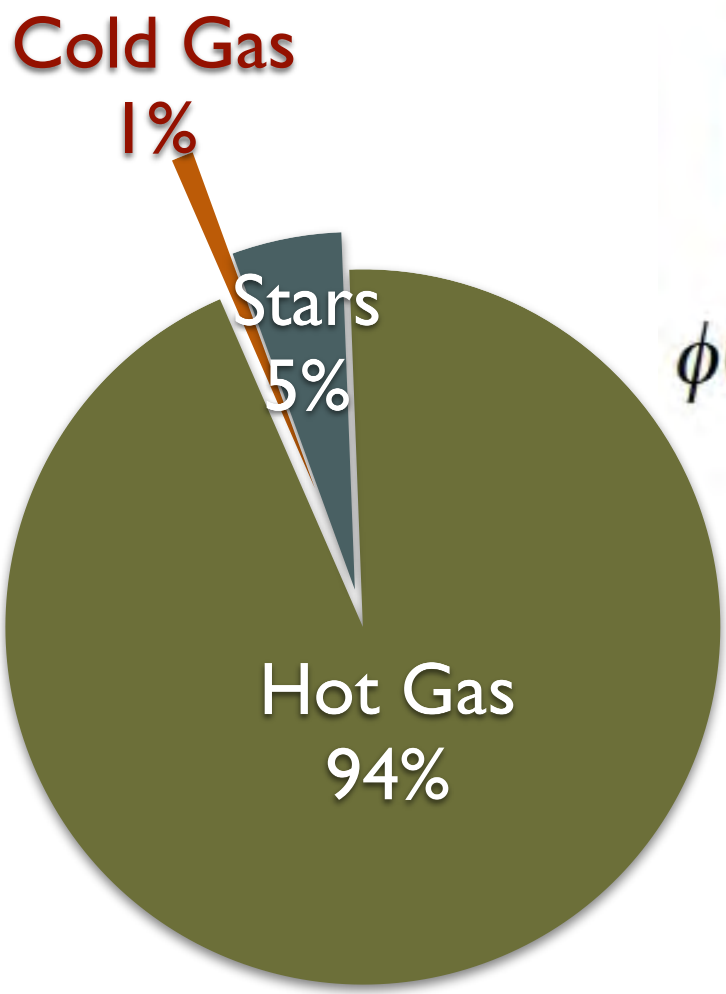
This places a 2σ lower limit on the mass of a thermal relic:

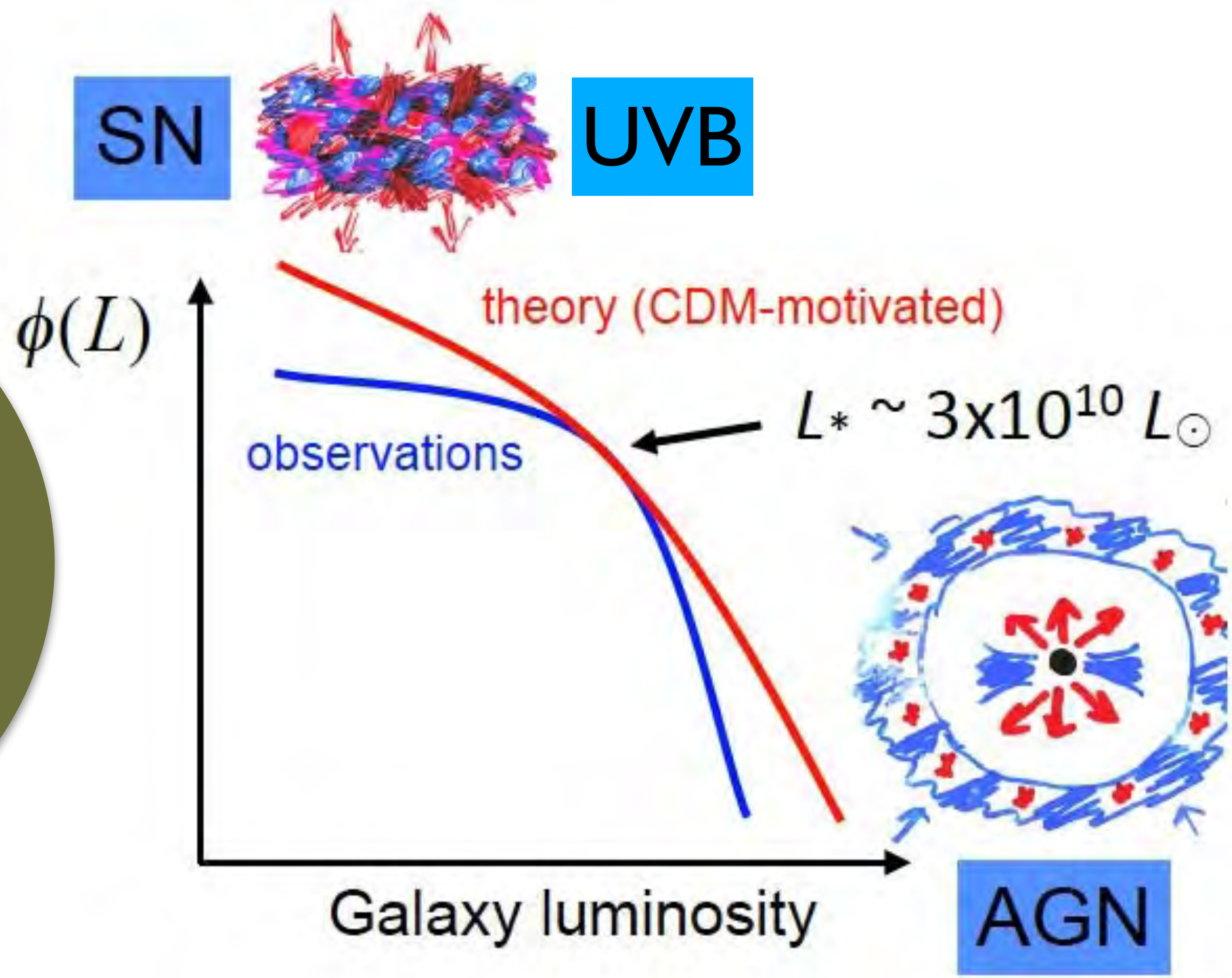
$m_{WDM} > 3.3$ keV ⇨

$M_{FS} < 3\times10^8\ M_\odot$

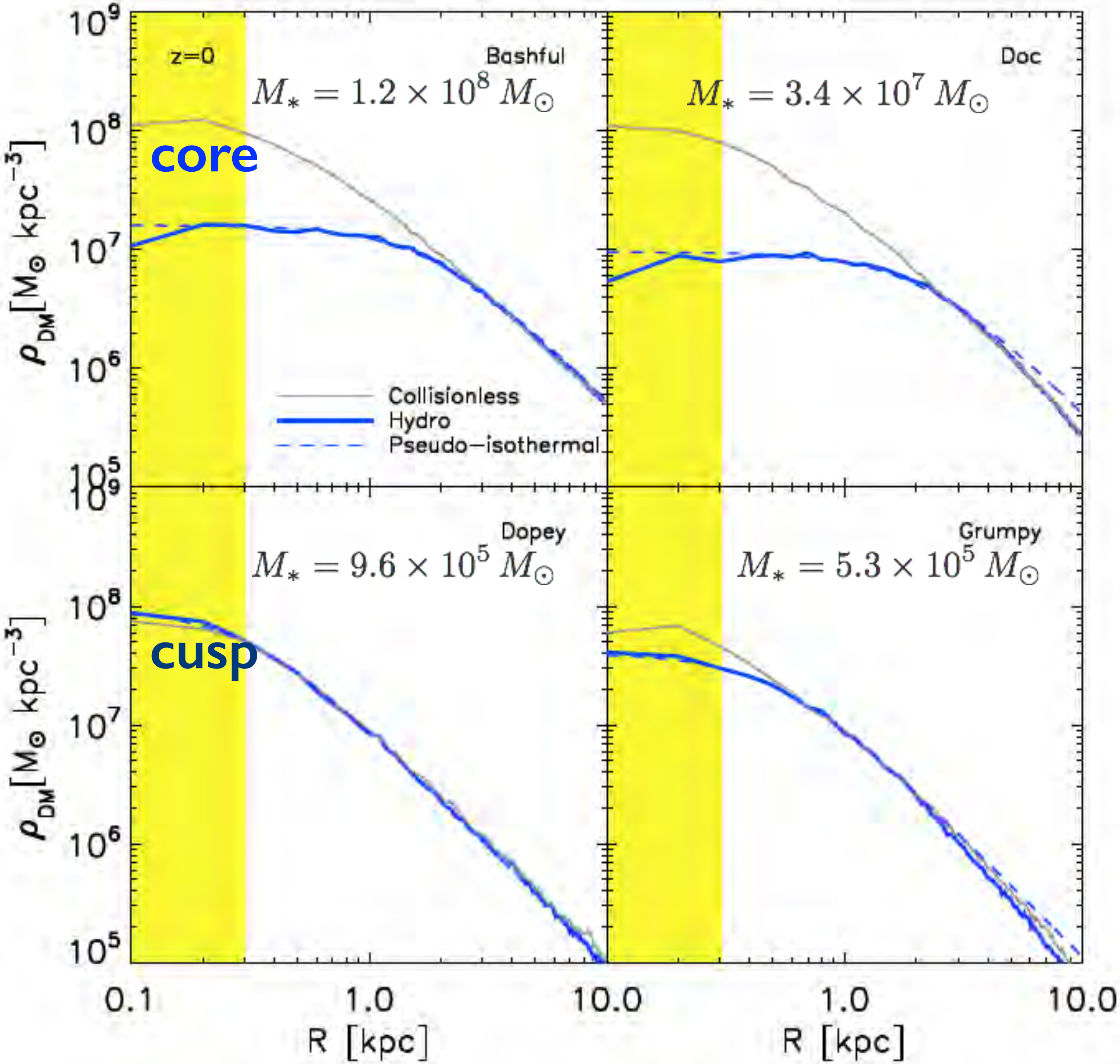
~~m_{WDM}=2 keV at 4σ C.L.~~

Baryons Matter: Feedback





CDM HEATS UP



Madau et al 2014

WE KNOW MUCH, UNDERSTAND SOME, NEED HELP

- Evidence that the Universe conforms to the expectations of the CDM model is ***compelling but not definitive***. Current observational tests span a very wide range of scales, and state-of-the-art simulations are exploring the predictions of the "standard model" with increasingly higher precision.

- Tensions between CDM predictions and observations on the scales of galactic cores and satellite halos may be telling us something about the ***fundamental properties of DM*** or something about the ***complexities of galaxy formation***. After two decades of debate, emerging evidence may suggest that a *poor understanding of the baryonic processes* involved in galaxy formation may be at the origin of these "*small scale controversies*".

- WDM remains a possibility if particles are sufficiently massive to evade the *Lyman-α forest constraints*. More exotic possibilities such as SIDM may also be viable, provided their properties are carefully tuned. *Flux anomalies in gravitational lenses,* however, may be providing important evidence for CDM substructure.

- There are great hopes that underground detection experiments, γ-ray observations, or collider experiments will identify the DM particle within the next decade. *Is this the "DM decade"? If scientific progress is characterized by periods of confusion, which are resolved by neat and tidy models, the current DM-search era is most definitely of the confusion sort.*

- In the meantime, astronomers will continue their decades-long practice of studying the <u>dark sector</u> by observing and modeling the <u>visible.</u>