The Dark and Light Side of Galaxy Formation

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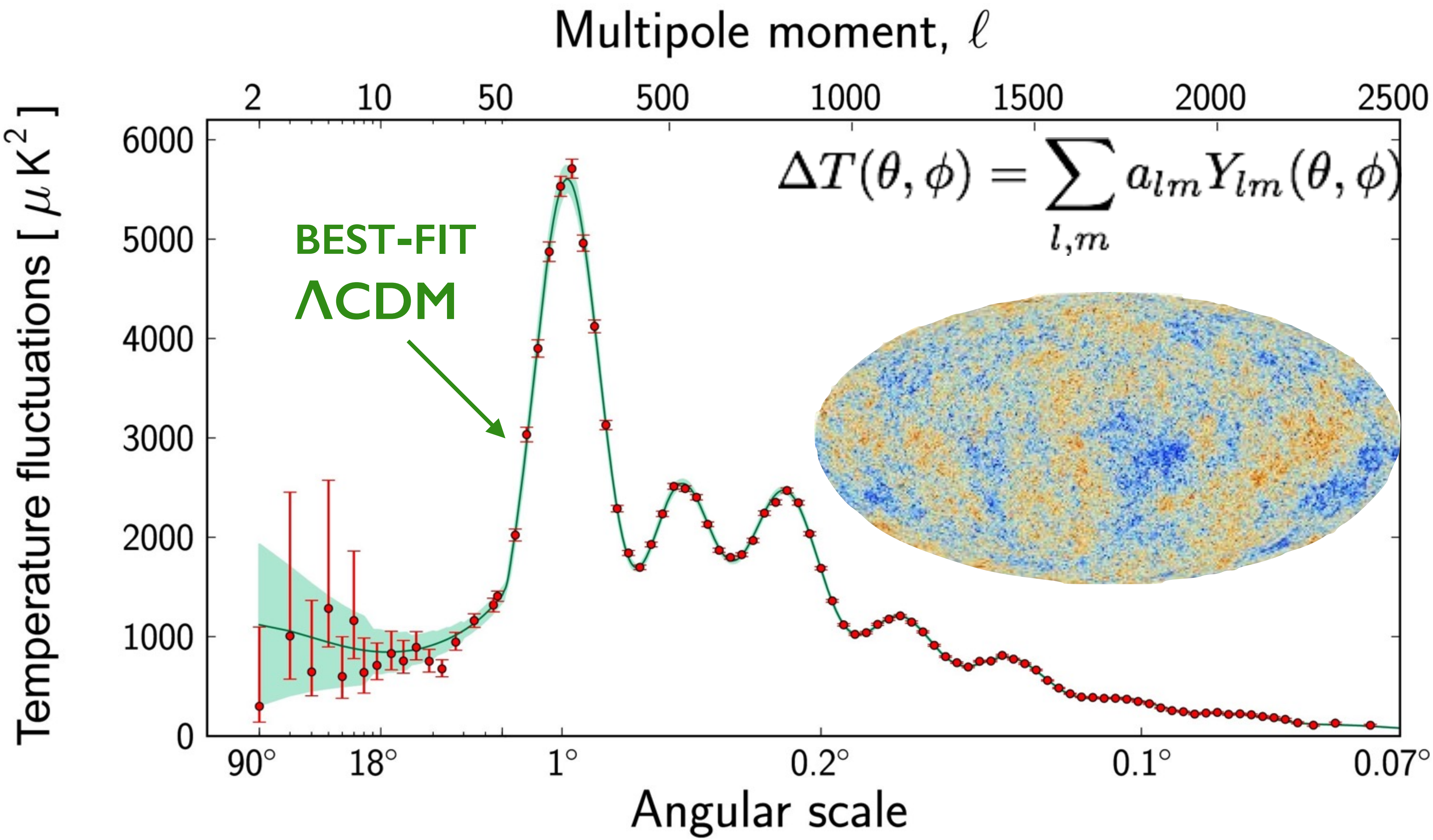
Bologna 2015

From Quantum Foam to Galaxies

Galaxy Formation is the dot-com of Astrophysics. **It is about nothing less than the origin and** ***14*** **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 grandiose 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).***

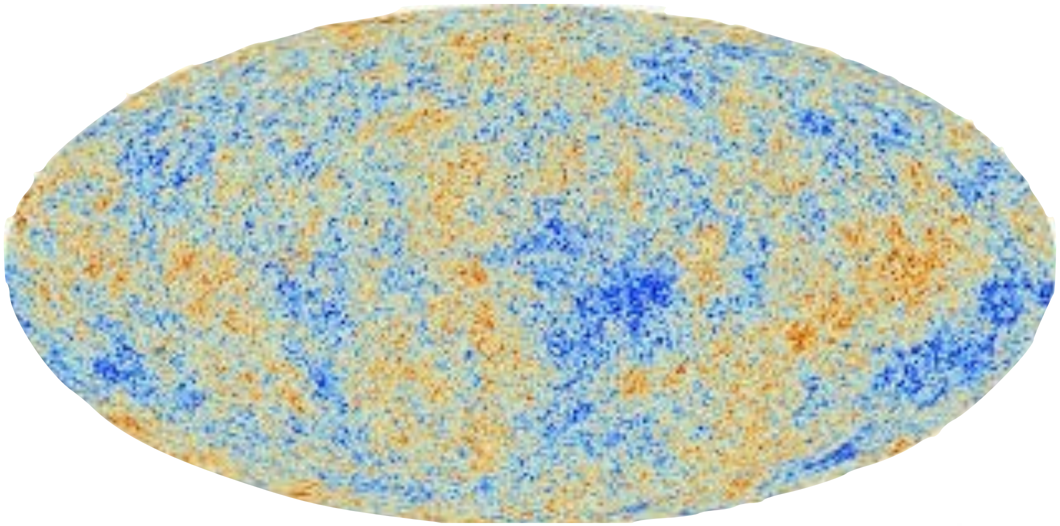
A Nearly Perfect Universe



Angular power spectrum: variance of the brightness of the "spots" in the CMB map vs. the size of the spot.

JUST SIX NUMBERS (FLAT ΛCDM)

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



$\Omega_b h^2$ = 0.02230 ± 0.00014

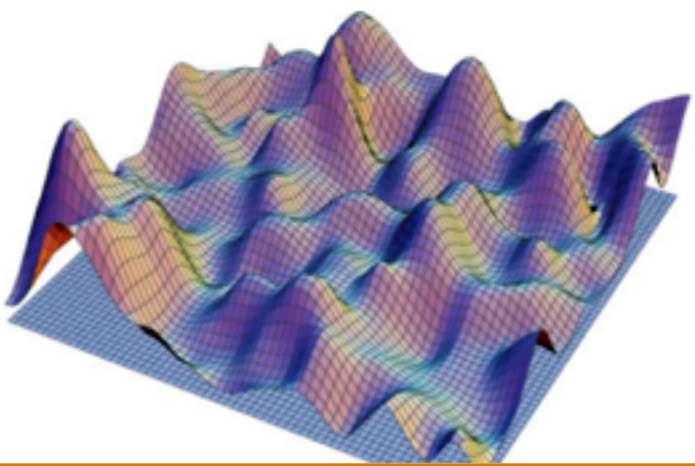
$\Omega_X h^2$ = 0.1188 ± 0.0010

$100\theta_{MC}$ = 1.04093 ± 0.00030

τ = 0.066 ± 0.012

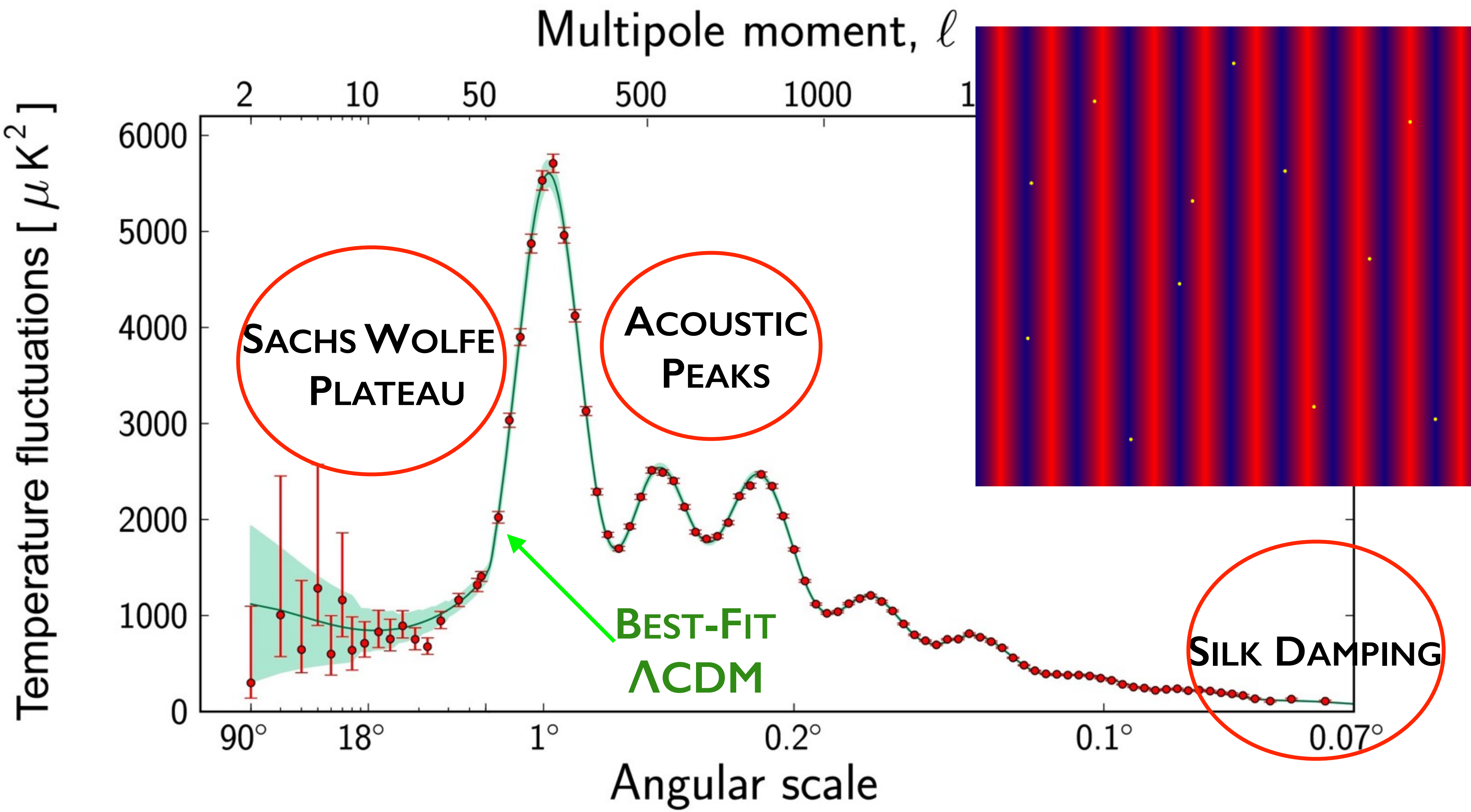
n_s = 0.9667 ± 0.0040

σ_8 = 0.8159 ± 0.0086



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

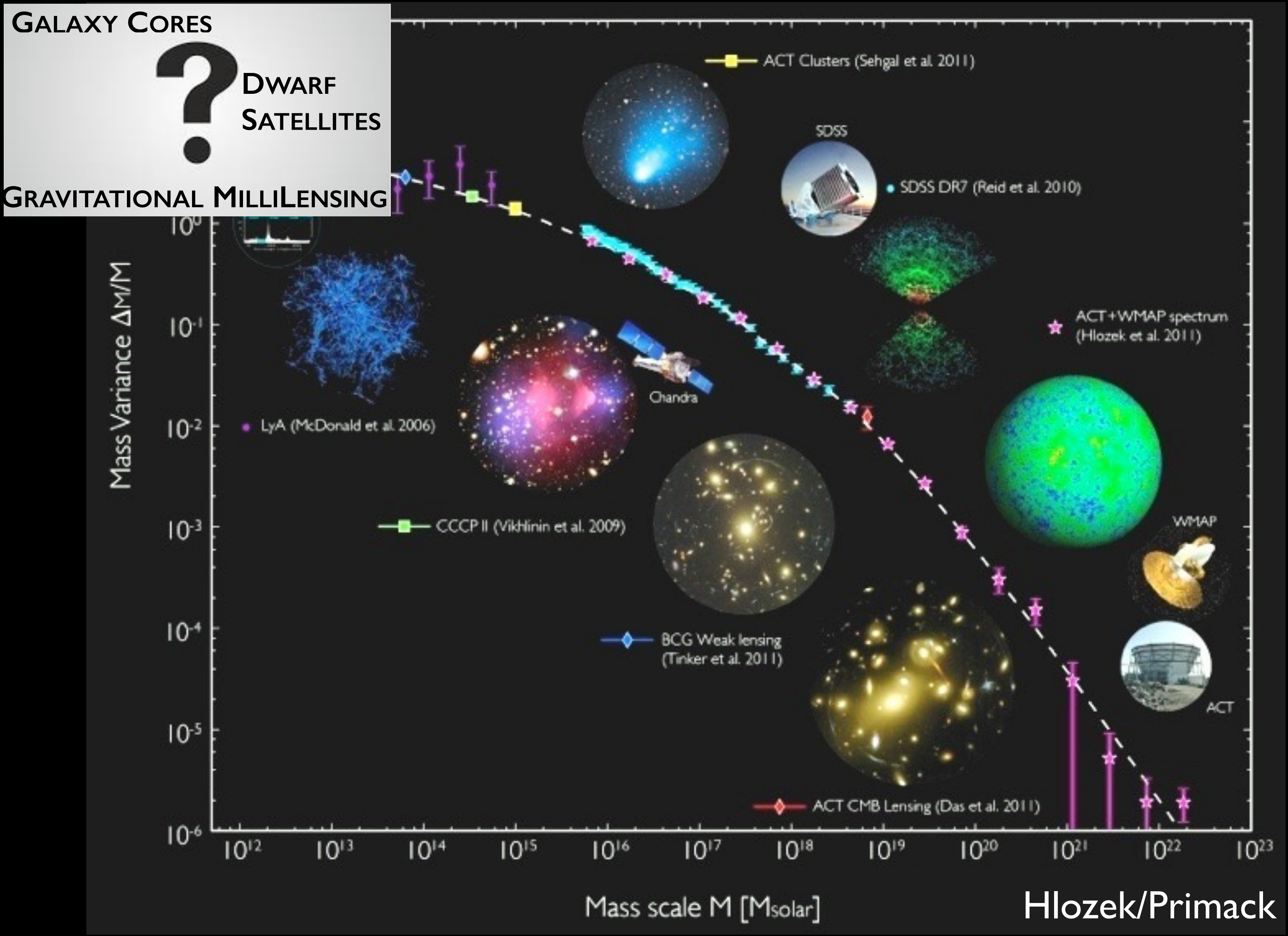
Dark Matter is Our Friend



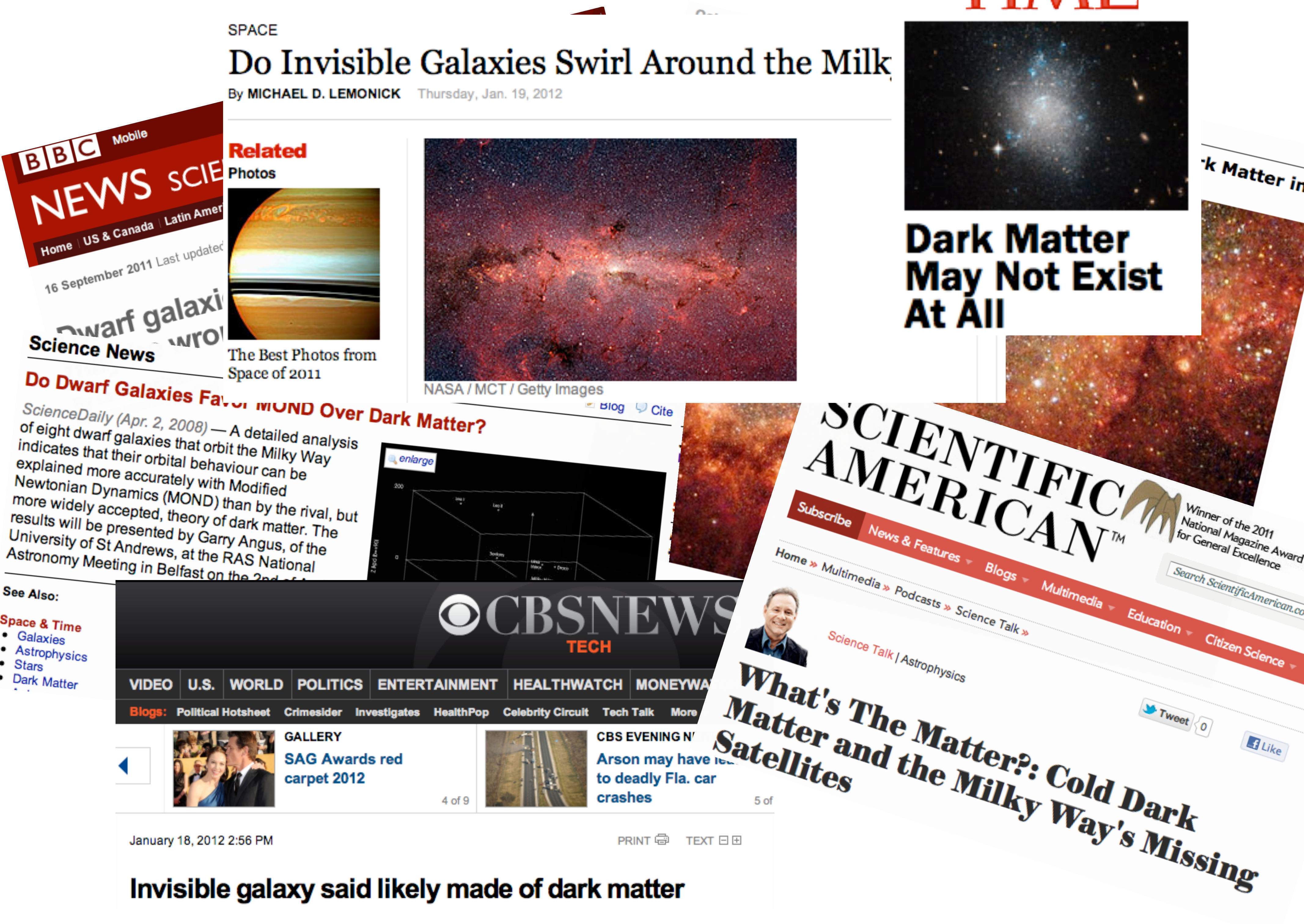
Although ΛCDM has had great success in explaining the observed large-scale distribution of mass in the universe, the nature of the dark matter particle is best tested on small scales, where its physical characteristics manifest themselves by modifying the structure of galaxy halos and their lumpiness.

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.

DENSITY FLUCTUATIONS DATA AGREE WITH ΛCDM!



THE CDM SMALL-SCALE CRISIS



Universe in a Box: *N*-Body Simulations

• ***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

HIERARCHICAL N-BODY TREE CODES

OCTREE gravity calculation
$O(N^2) \Rightarrow O(N \log N)$

Newton's equations of motion in co-moving coordinates

$$\frac{d\vec{x}}{dt} = \vec{v}$$

$$\frac{d\vec{v}}{dt} + 2H(a)\vec{v} = -\frac{1}{a^2}\vec{\nabla}\phi.$$

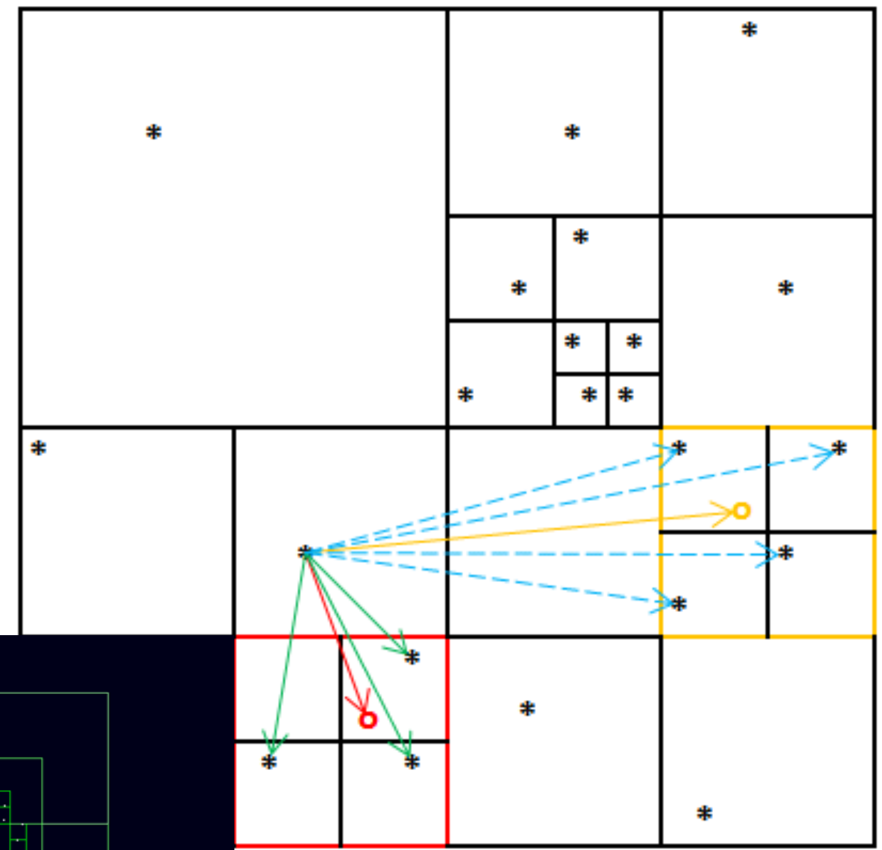
Cosmology, the expansion of the universe

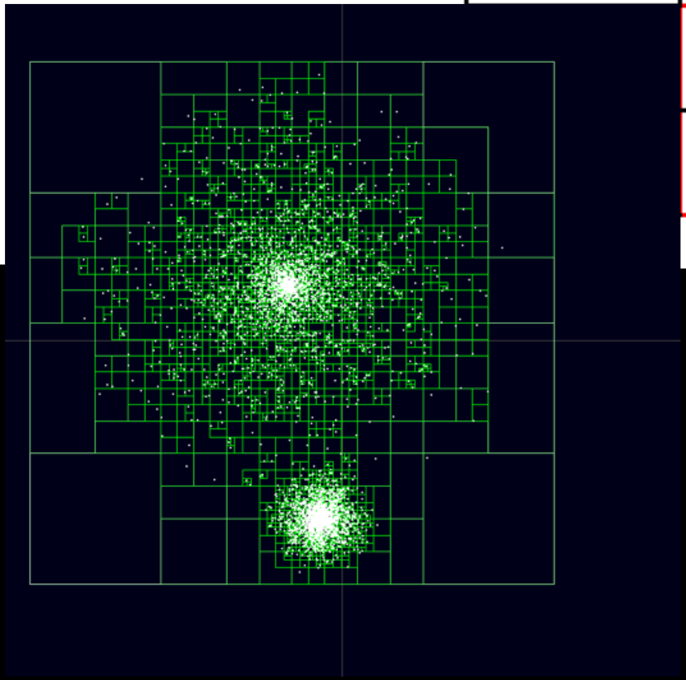
$$H(a) = \dot{a}/a \quad \text{(Hubble constant)}$$

$$\frac{\ddot{a}}{a} = -\frac{4}{3}\pi G\rho_b(t) + \frac{\Lambda}{3} \quad (2^{\text{nd}} \text{ Friedman equation})$$

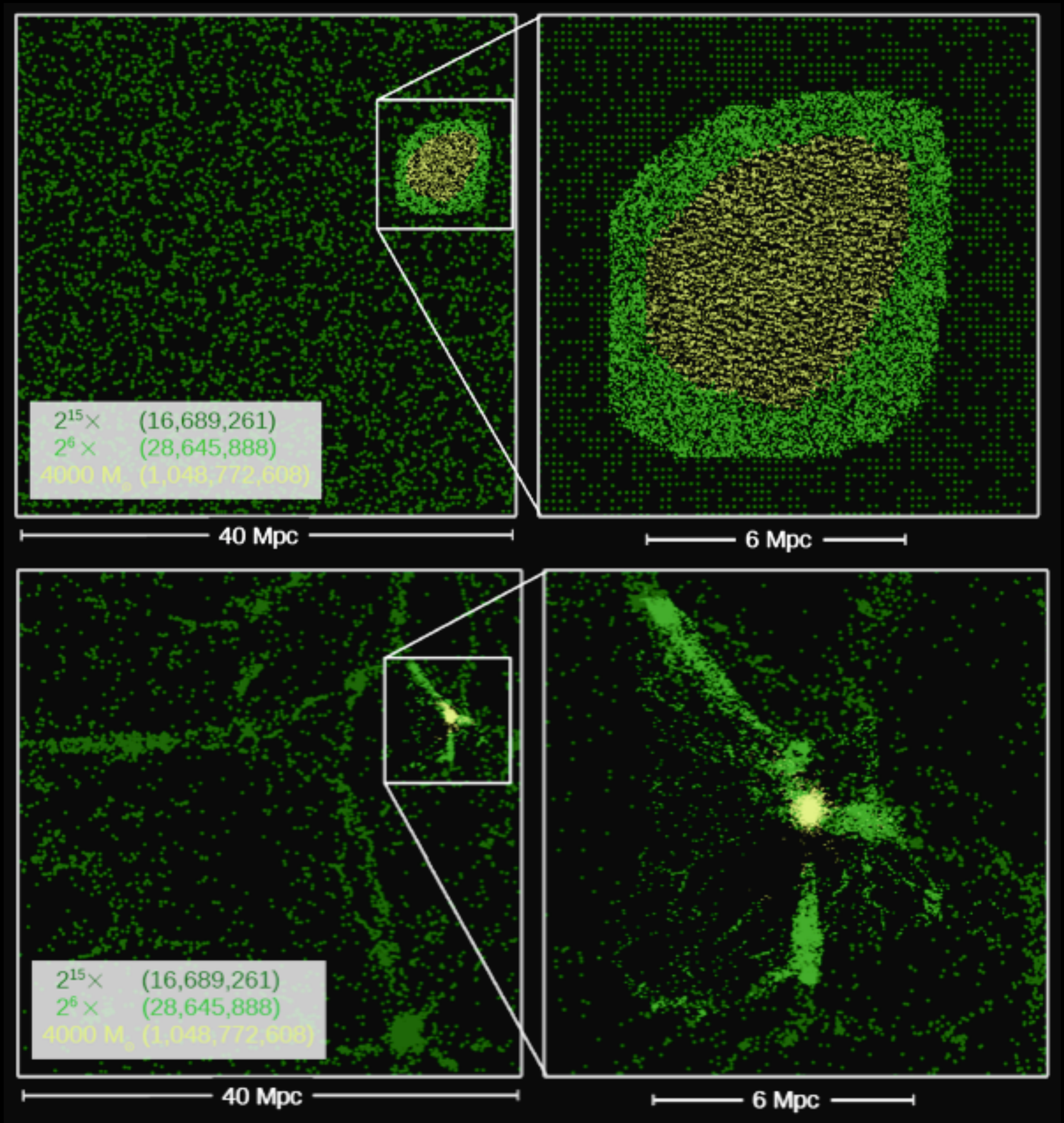
Gravitational potential

$$\nabla^2\phi = 4\pi G\rho a^2 - \Lambda a^2 + 3a\ddot{a}$$
$$= 4\pi G(\rho - \rho_b)a^2$$





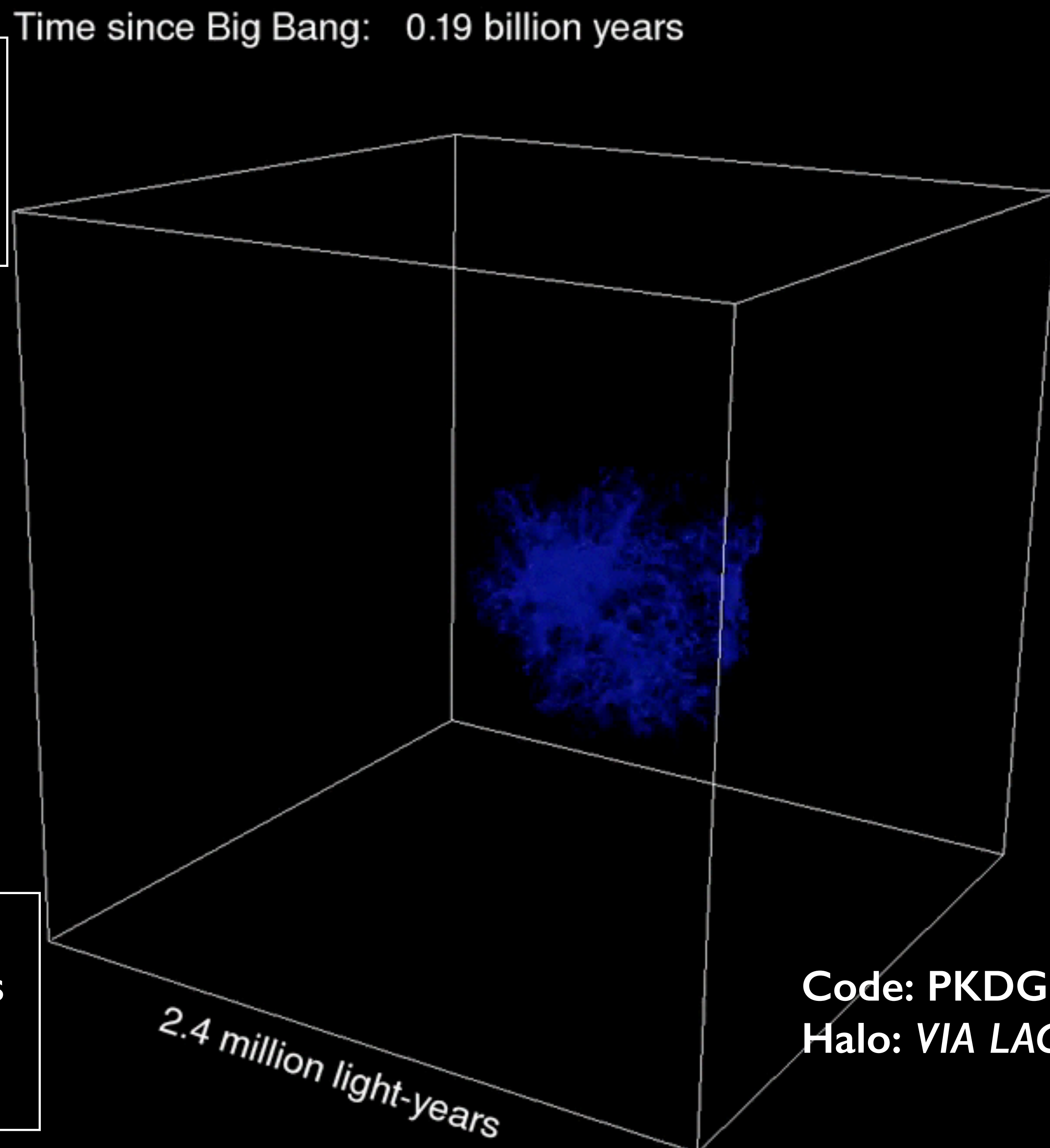
ZOOM-IN



$2^{15}\times$ (16,689,261)
$2^{6}\times$ (28,645,888)
4000 $M_\odot$ (1,048,772,608)
40 Mpc
6 Mpc
$2^{15}\times$ (16,689,261)
$2^{6}\times$ (28,645,888)
4000 $M_\odot$ (1,048,772,608)
40 Mpc
6 Mpc

Substructure: A Unique Prediction of ΛCDM

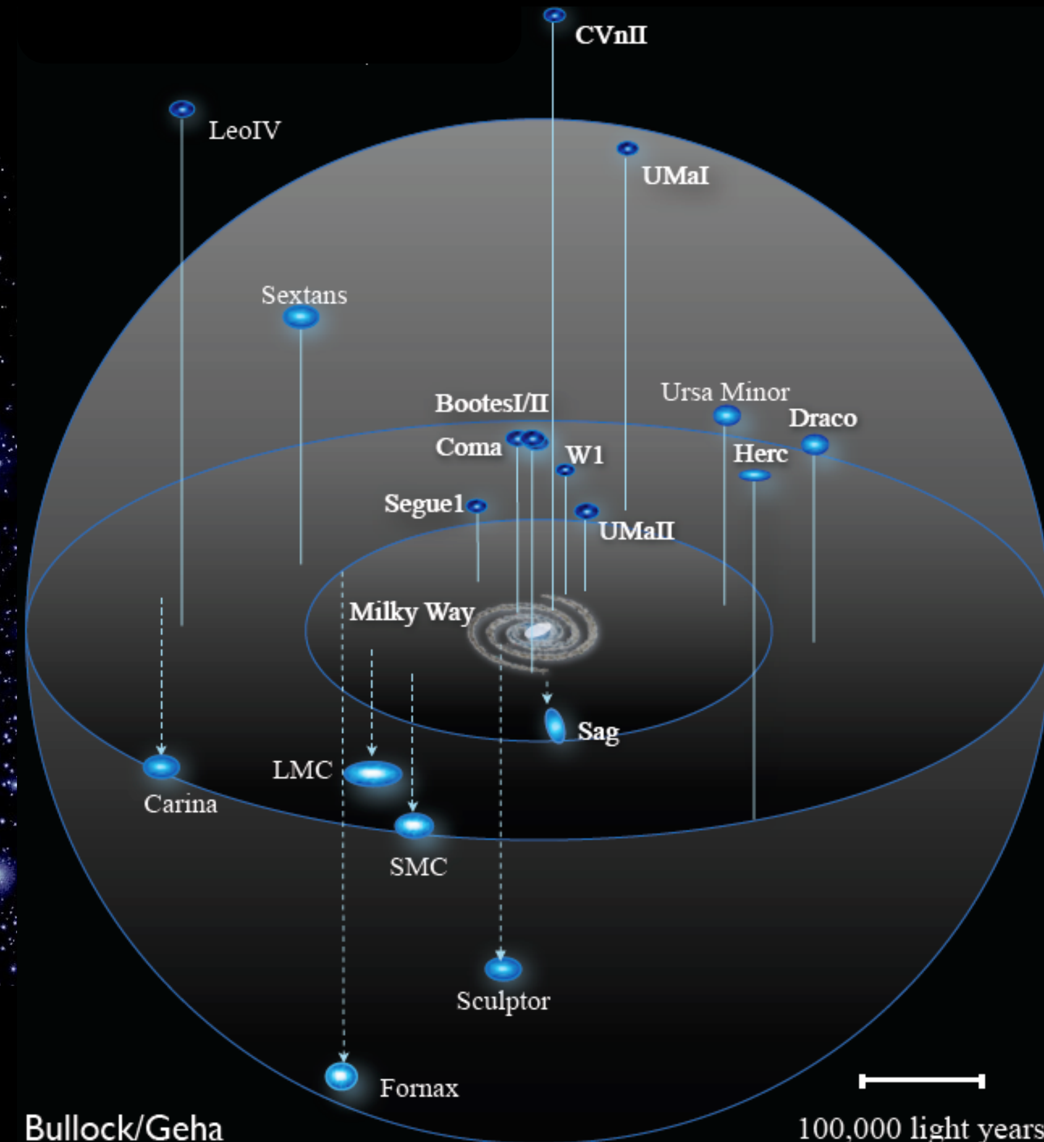
Subhalo differential mass function has slope −1.9 ➪ equal mass per decade of mass



In a MW-sized halo at *z=0*: *5-10%* of host mass locked in self-bound subhalos

Code: PKDGRAV2
Halo: *VIA LACTEA II*

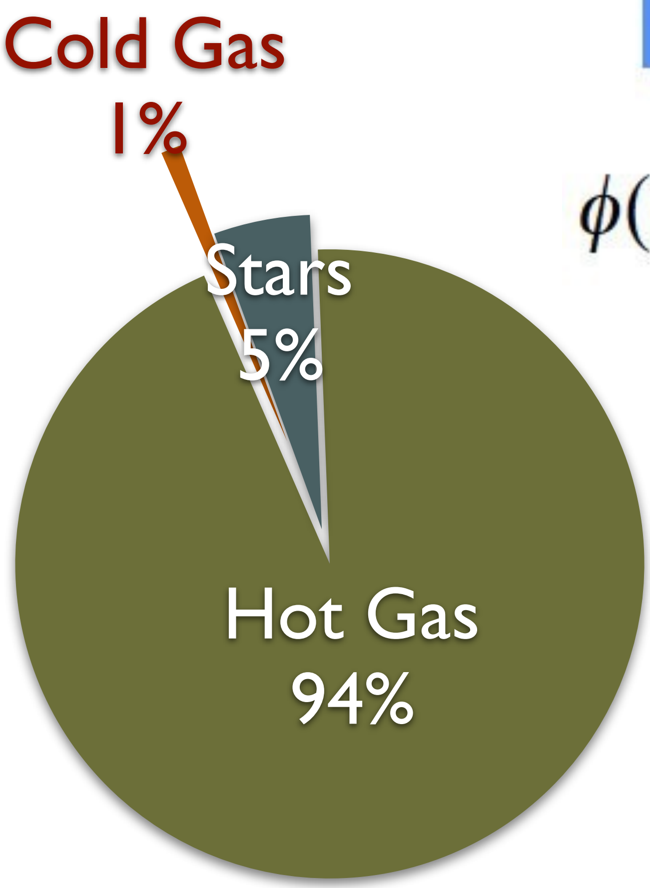
Missing Satellite Problem

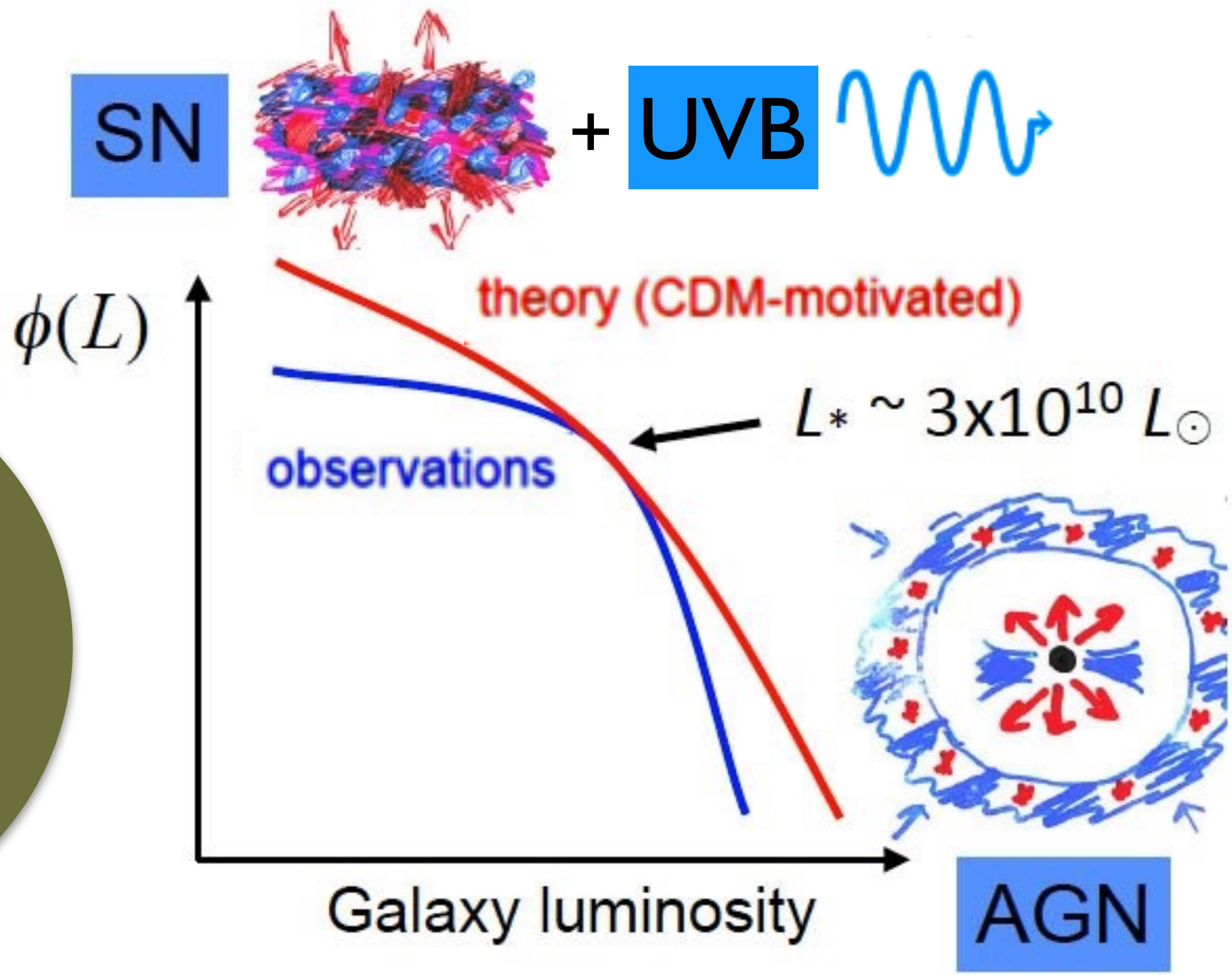


Theory: $N_{sub} \approx 1{,}000$
w V_c(infall)$\gtrsim 10$ km/s

Observations: $N_{sat} \approx 25$

SOLUTIONS TO THE MSP:

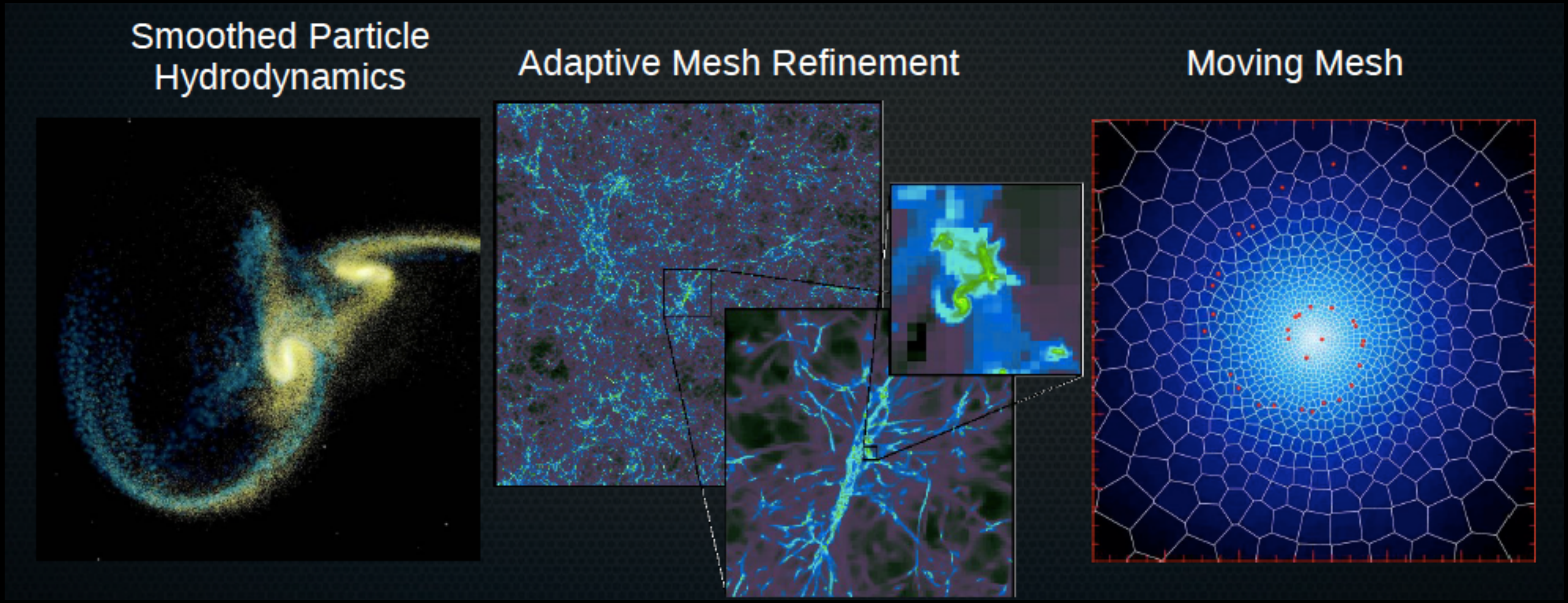




A recipe for Galaxy Formation

Technique for solving in 3D the coupled gravitational dynamics of the dissipationless CDM and the gravitational and radiative hydro of the dissipative baryonic fluid.

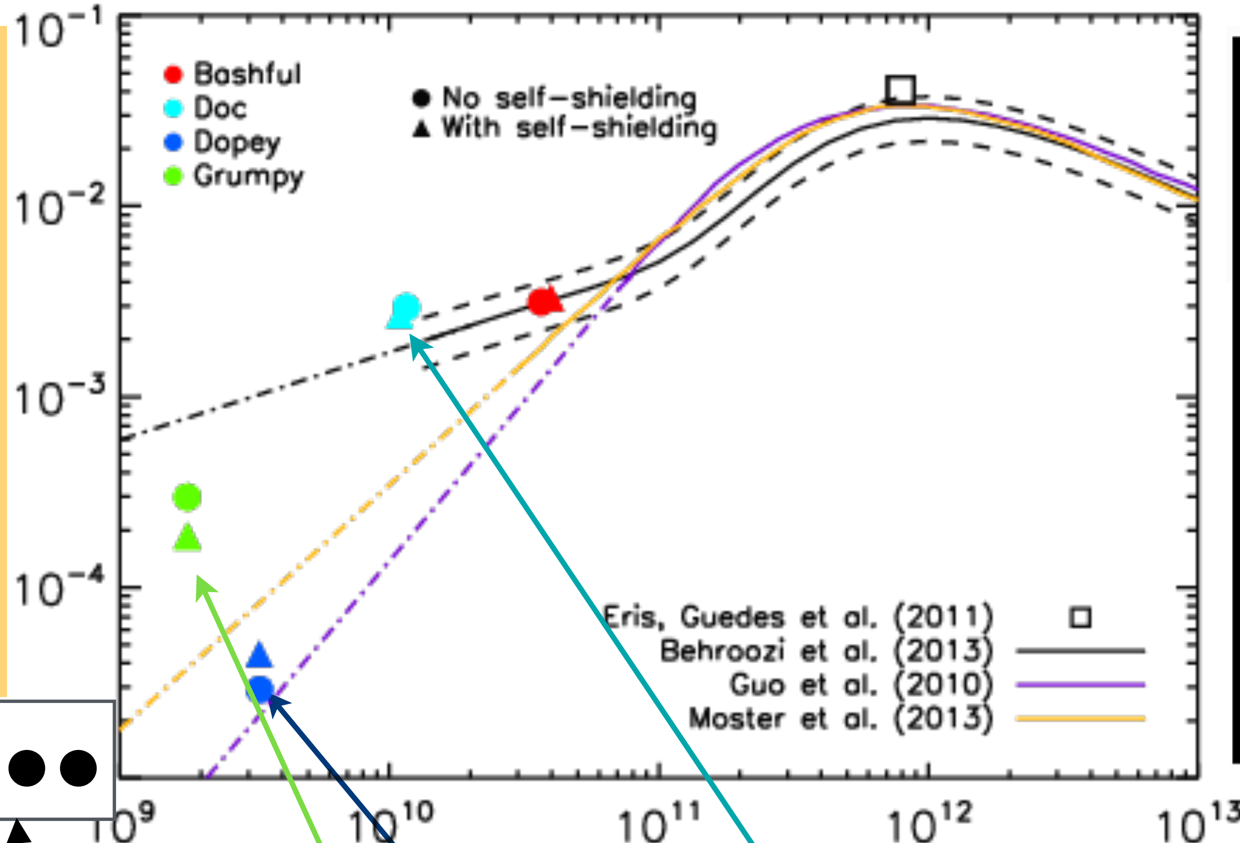
SUB-GRID phenomenological model for star formation to describe the conversion of gas into stars, stellar evolution, SN explosions, and the resulting exchange of energy and metals with the gas phase.

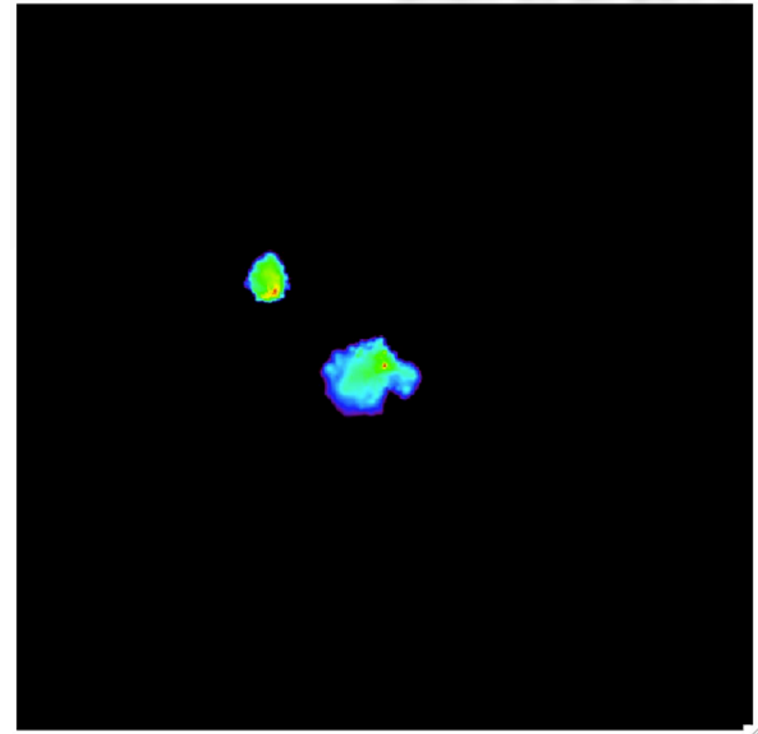


INEFFICIENT SF IN DWARFS?

Shen et al. 2014

Star Formation Efficiency





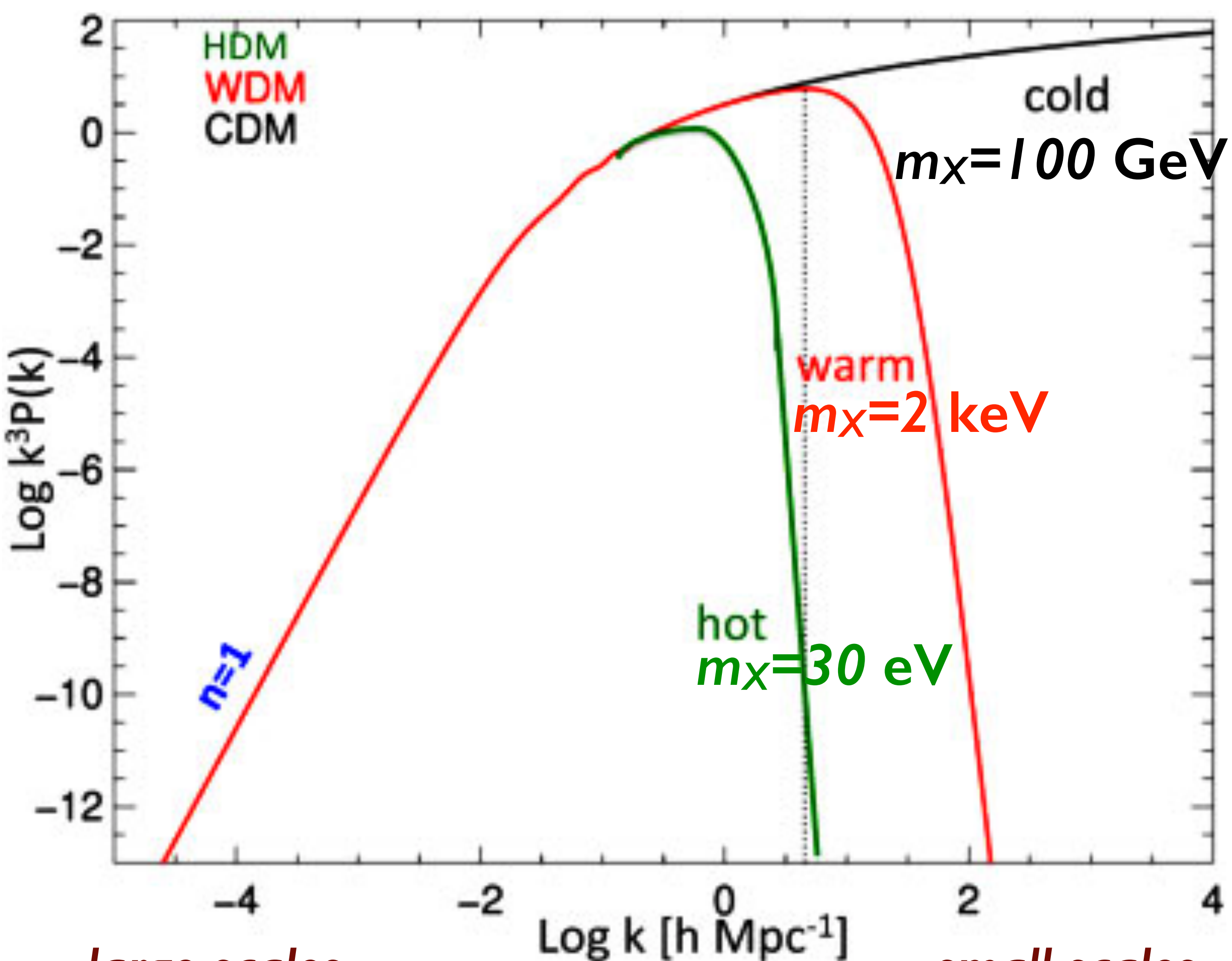
Halo Mass

●●●

V_{max} < 20 km/s are too small to succeed!

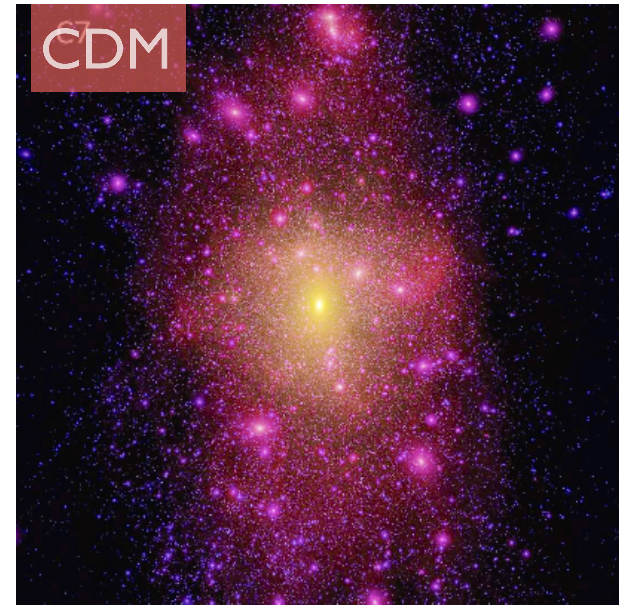
SF efficiencies modulated by potential well!

Solutions to the MSP: 1) Blame Gastrophysics
2) Blame CDM

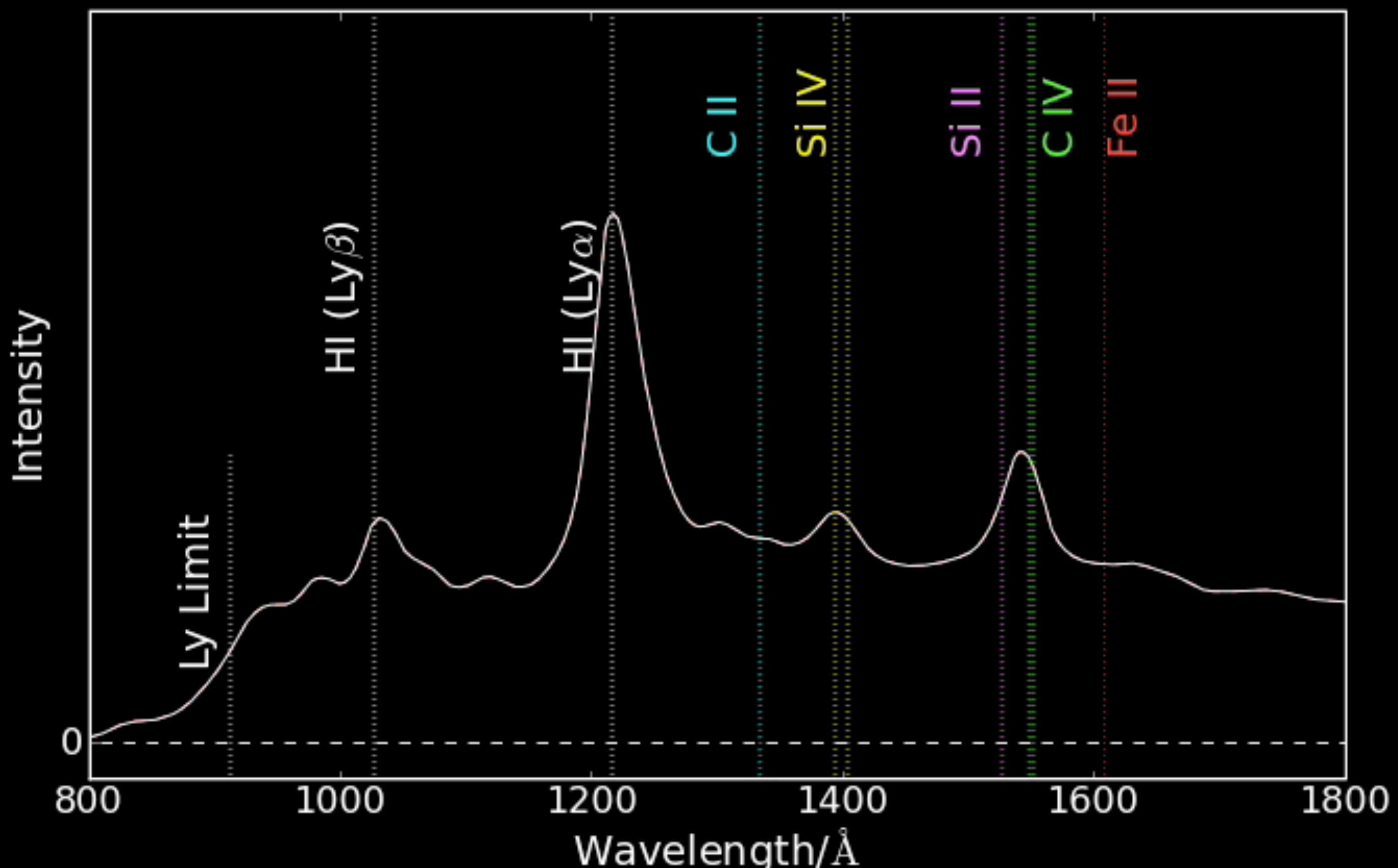


large scales *small scales*

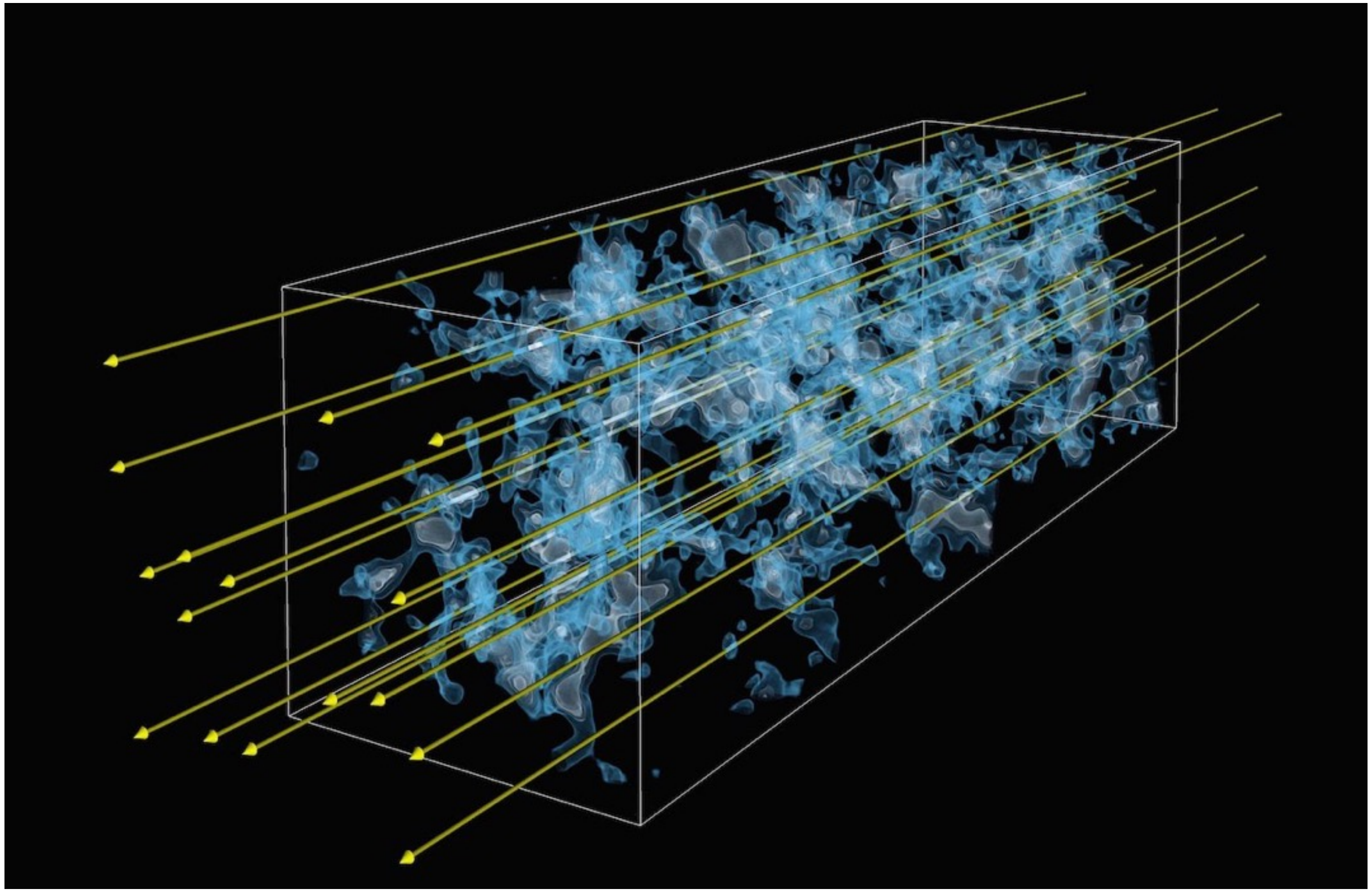
Late-time linear power spectra for density perturbations in universes dominated by hot, warm and cold DM.

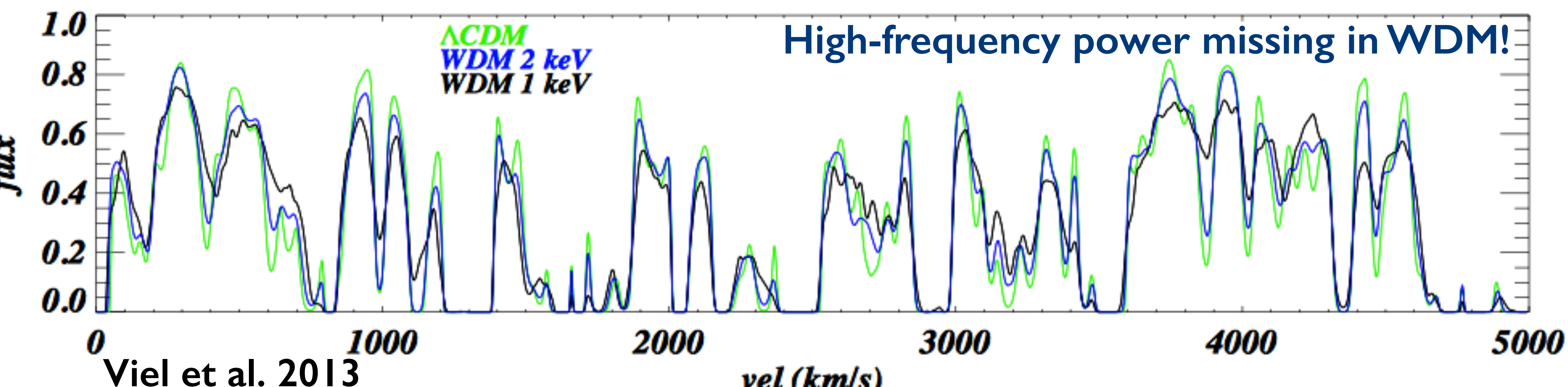


Structure in Intergalactic Gas at High Redshift



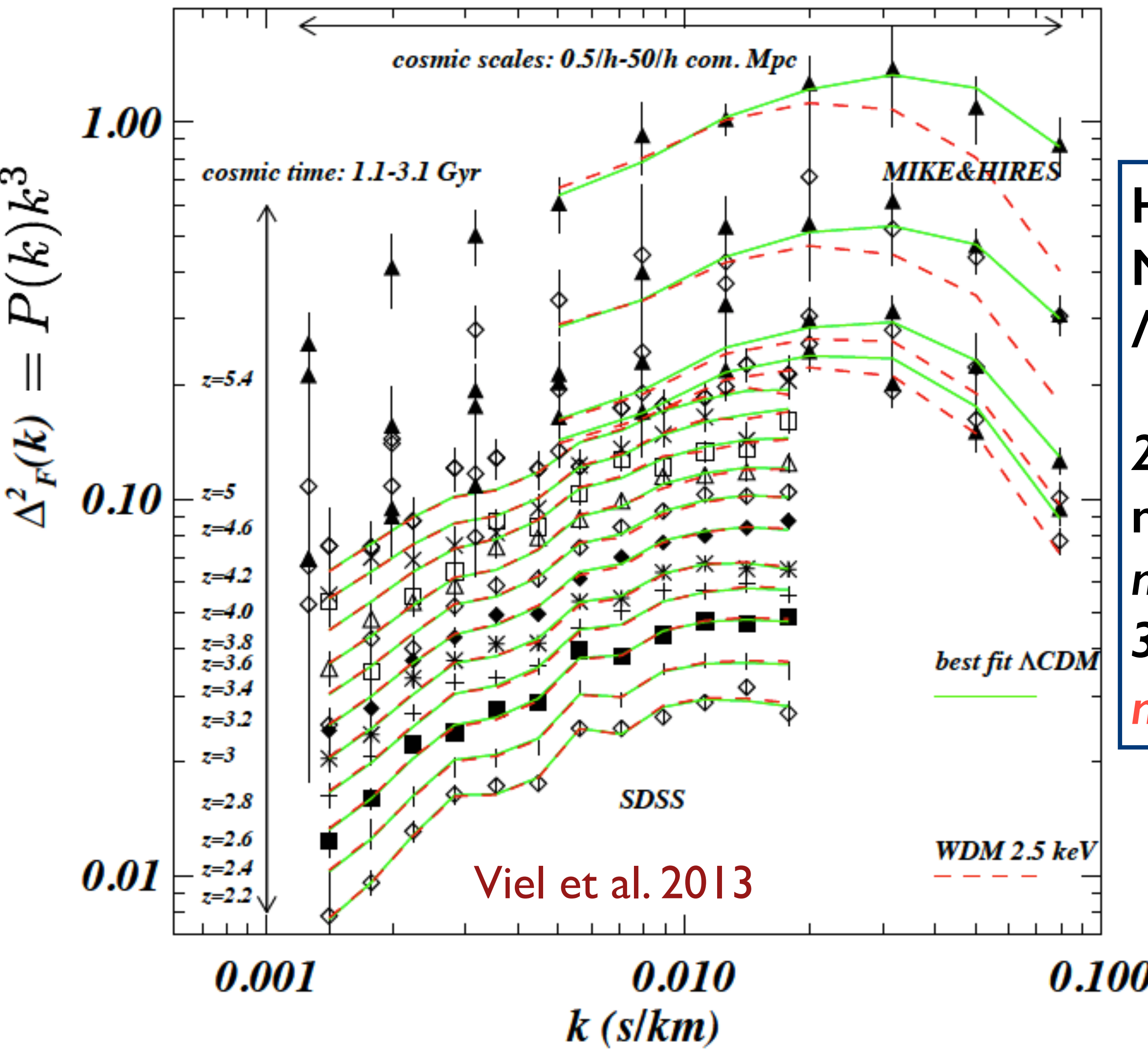
LYMAN-ALPHA FOREST SPECTRA: CDM VS. WDM





Viel et al. 2013

Someone Likes it Cold



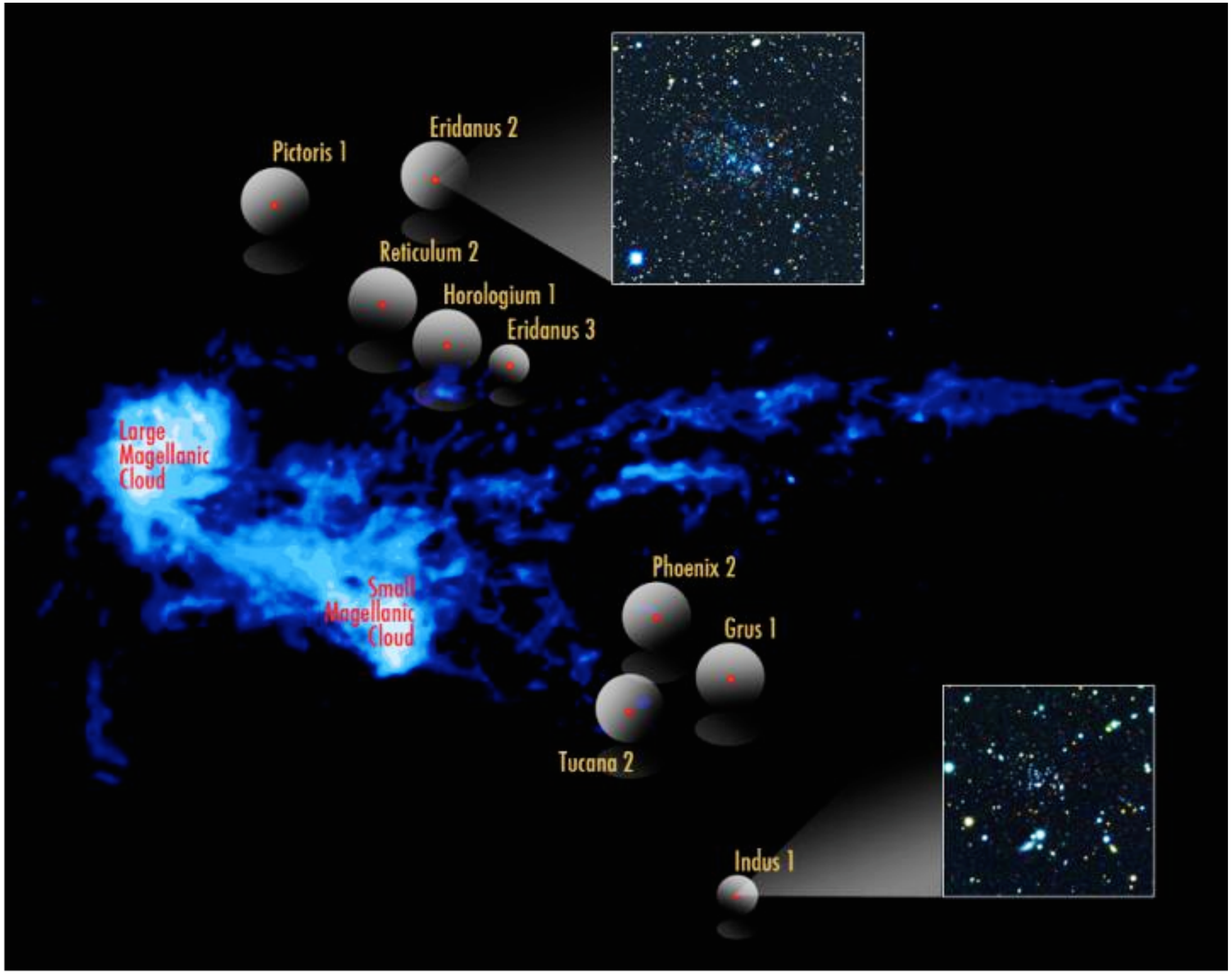
High-resolution Keck and Magellan spectra match ΛCDM up to $z = 5.4$!

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.*~~

Lower limit is too large for WDM to have much effect on the MSP!

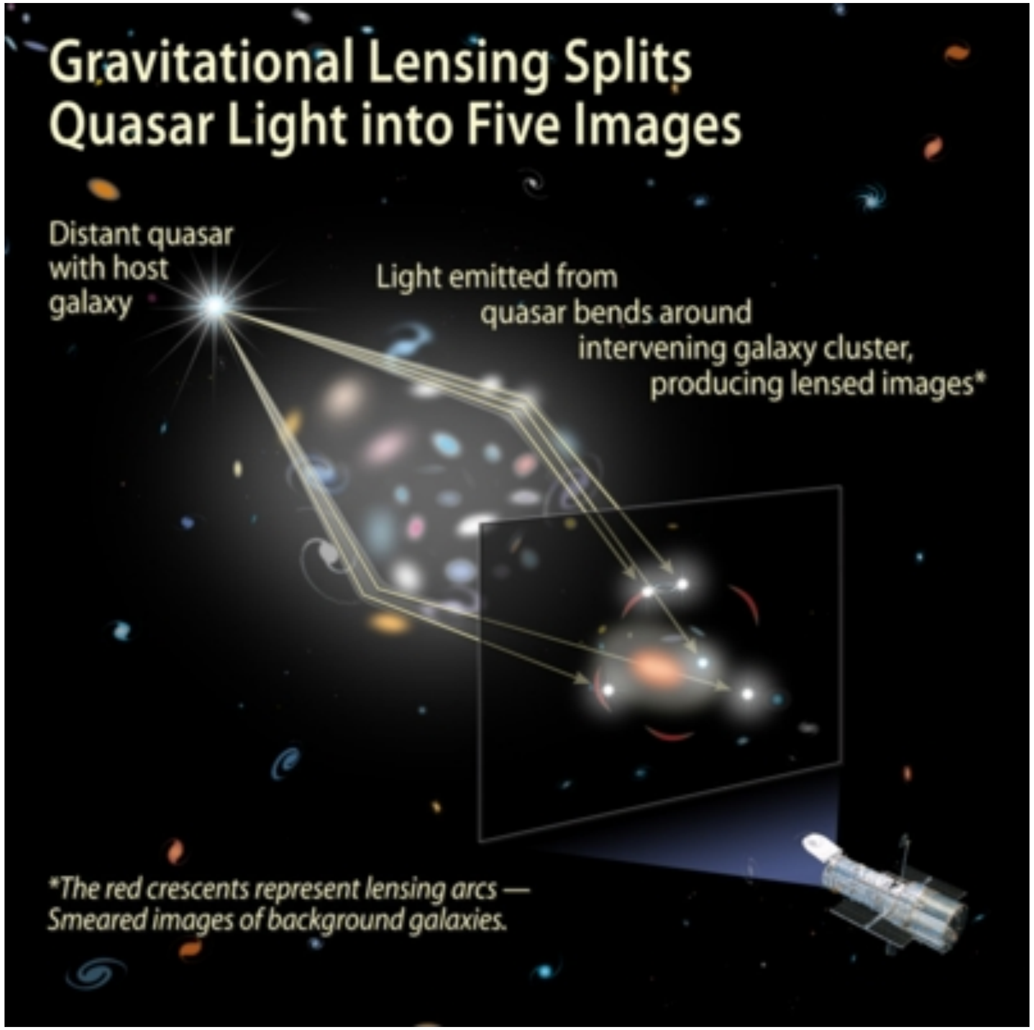
Solutions to the MSP: 1) Blame Gastrophysics
2) Blame CDM
3) Blame Observations!



1)+3) ⇨Q: Are DM Halos Really so Lumpy?

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.**



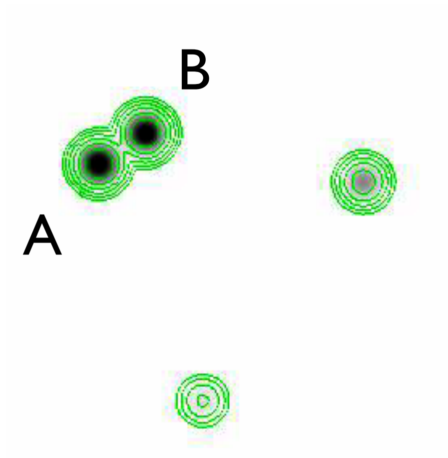
Metcalf & Madau 2001; Chiba 2001; Mao & Schneider 1998; Xu+ 2009

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

EXPECTED

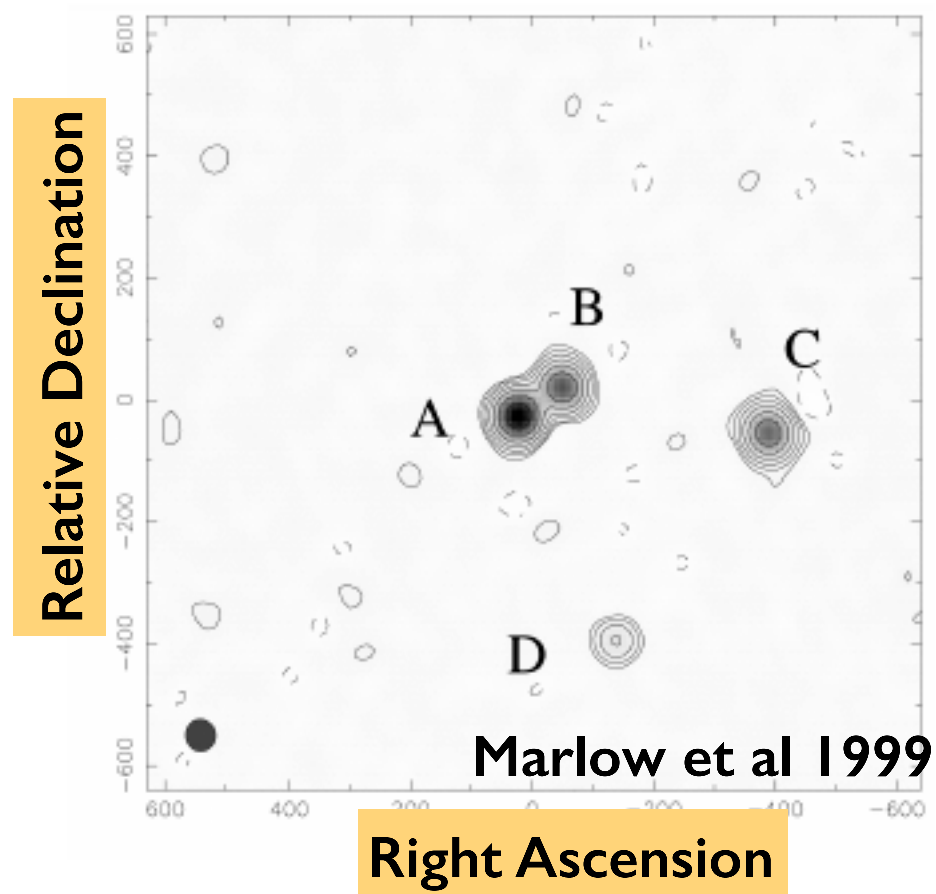
CLASS B1555+375

A−B≈0

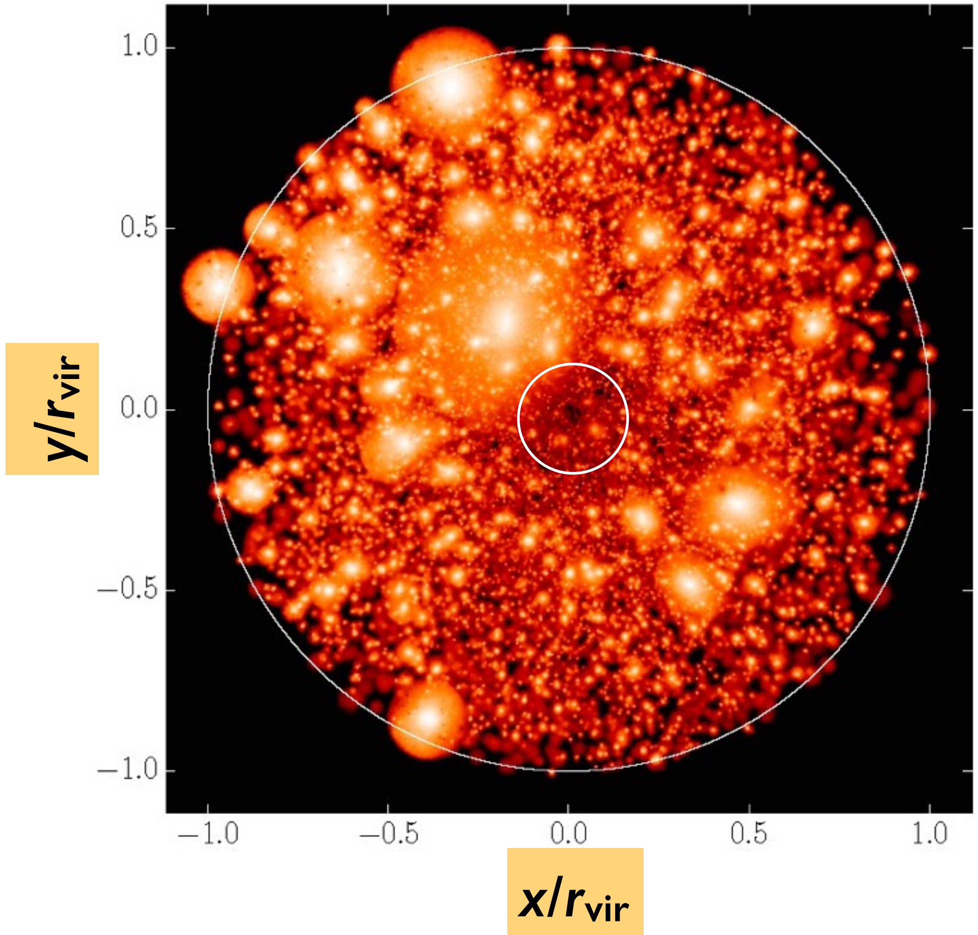


Keeton et al 2005

OBSERVED



Marlow et al 1999



Dalal & Kochanek (2002)

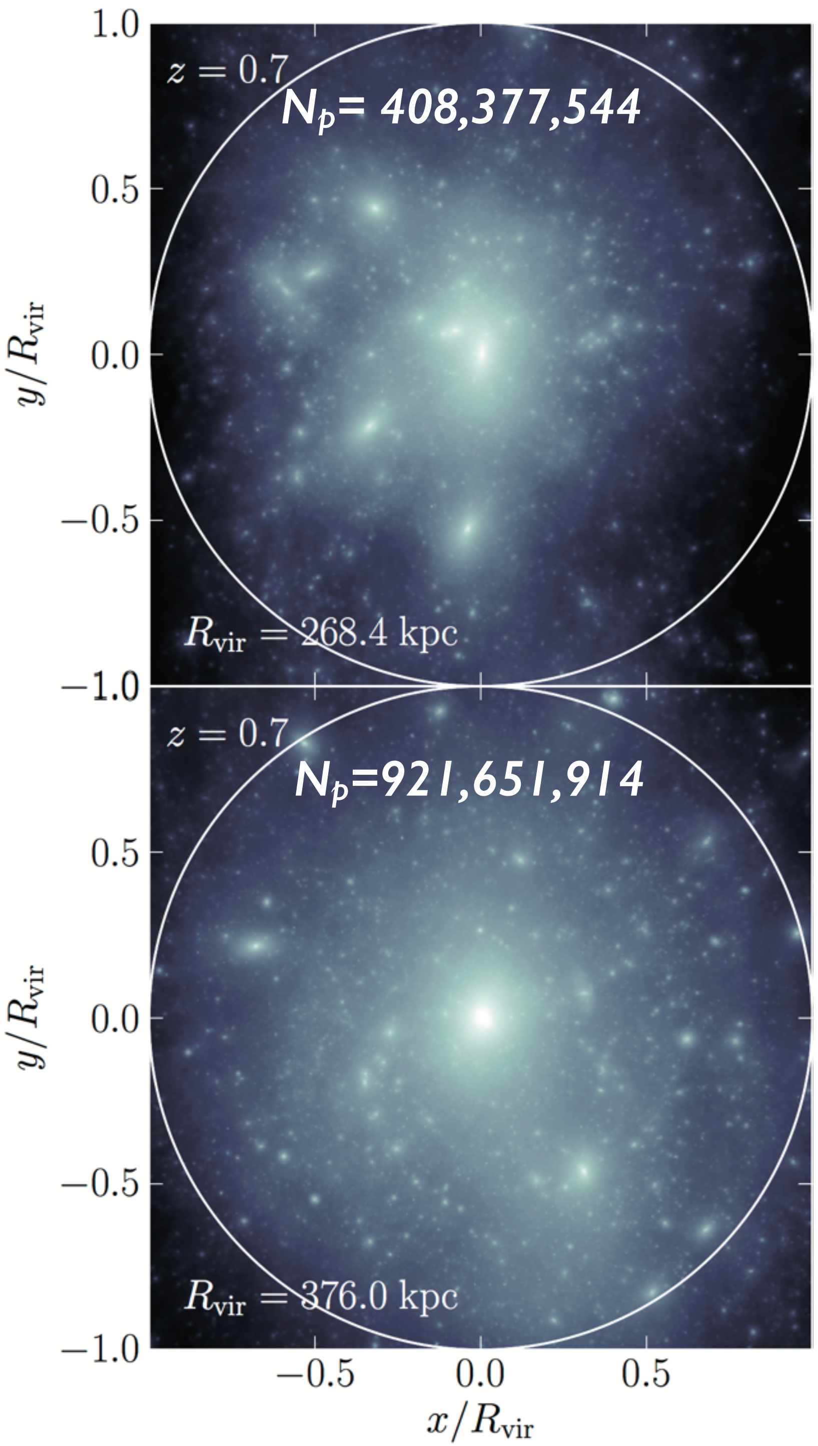
☛ flux ratios in 7 quad lenses

☛ f_{sub}= $2.0^{+5.0}_{-1.4}$ percent

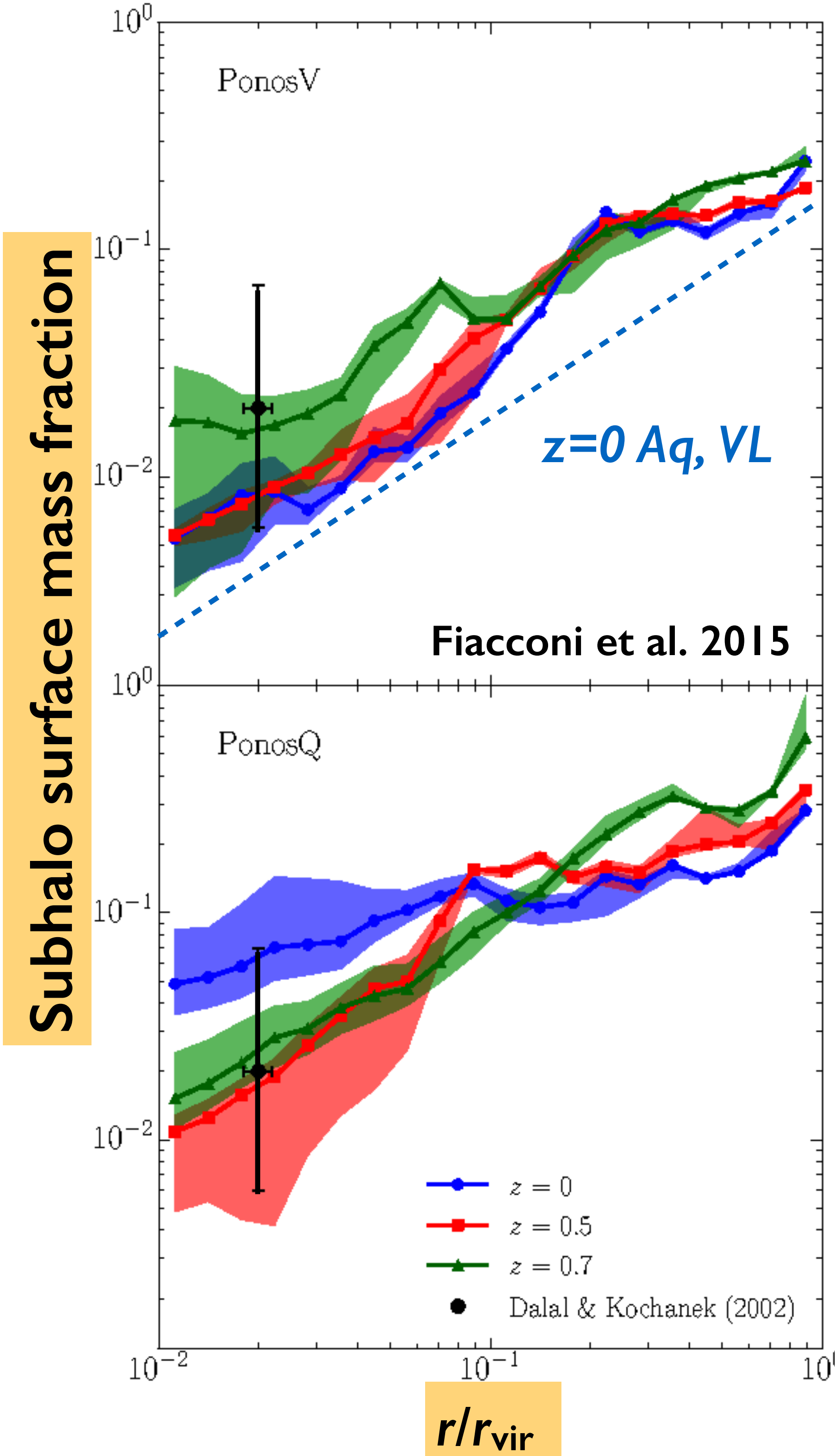
☛ little constraints on clump mass scale

Is there enough substructure in CDM *N*-body simulations to cause the observed flux anomalies? MAYBE

Sensitivity to: ellipticity of lens, intergalactic small-scale structure, baryons, small # of lensed QSOs, etc

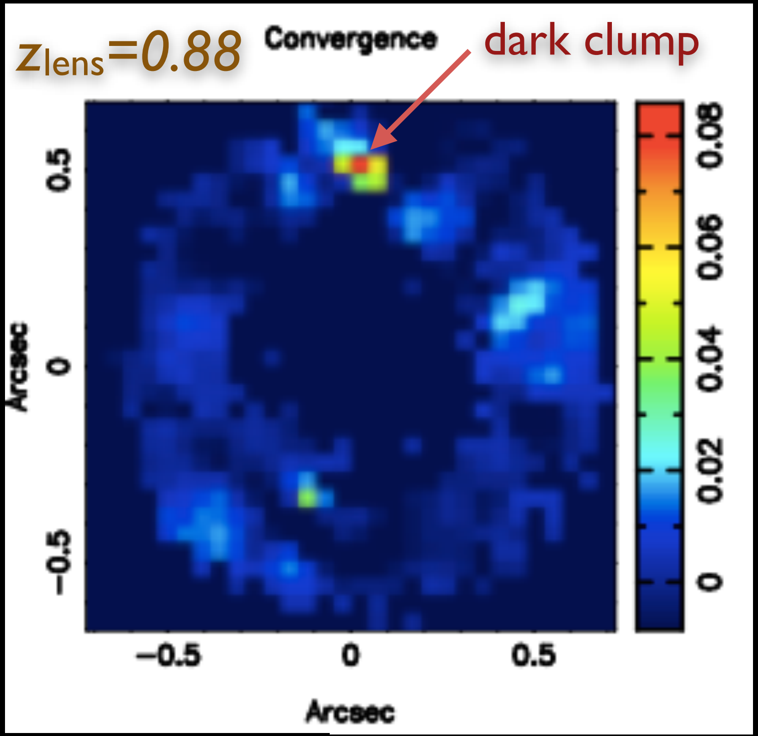


$z = 0.7$
N_p= 408,377,544
$R_{vir} = 268.4$ kpc
$z = 0.7$
N_p=921,651,914
$R_{vir} = 376.0$ kpc
y/R_{vir}
x/R_{vir}

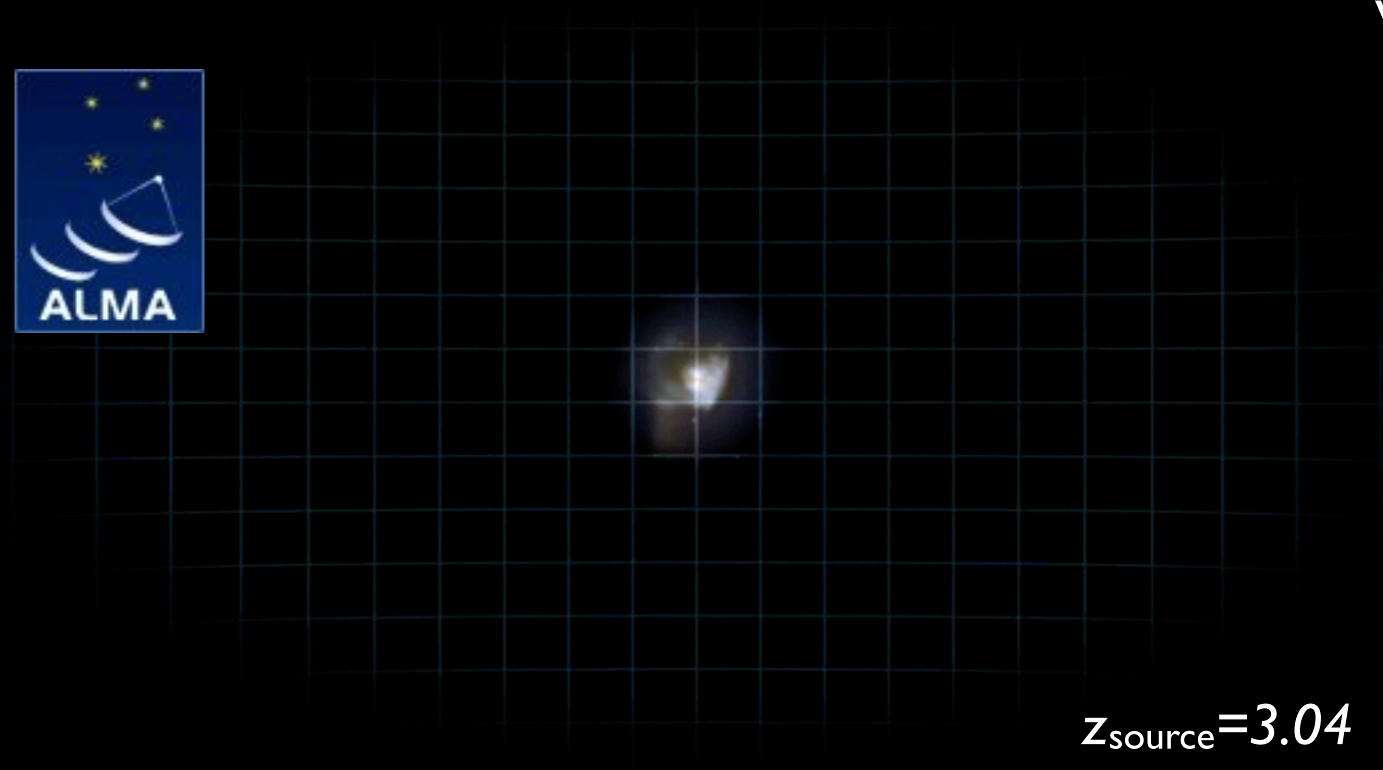


Subhalo surface mass fraction
PonosV
z=0 Aq, VL
Fiacconi et al. 2015
PonosQ
$z = 0$
$z = 0.5$
$z = 0.7$
Dalal & Kochanek (2002)
r/r_{vir}

Another <u>technique</u>: surface brightness anomalies in bright Einstein rings (*direct gravitational imaging of mass substructure*).



Vegetti et al. 2014



$z_{source}=3.04$

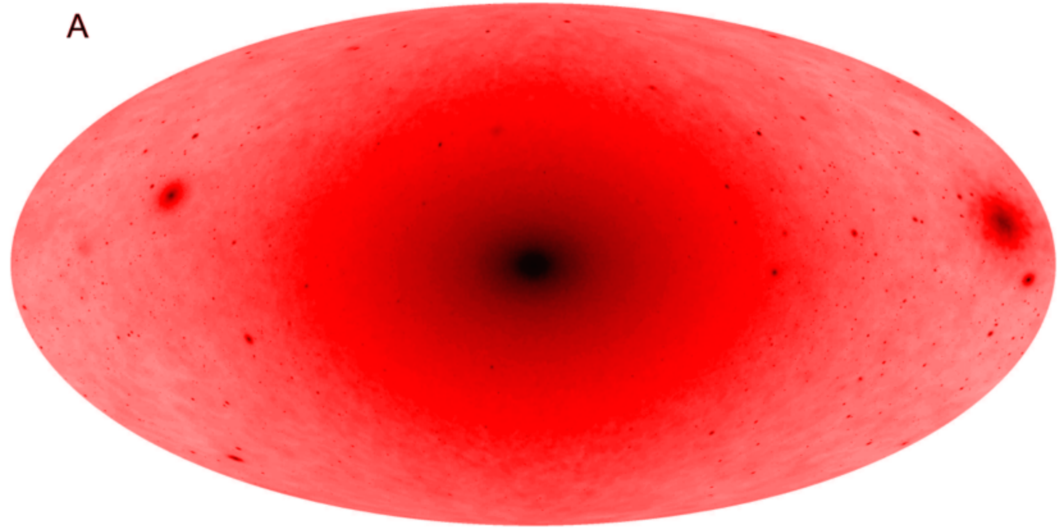
Numbers of Lensed QSOs in Future Wide-Field Optical Surveys.

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



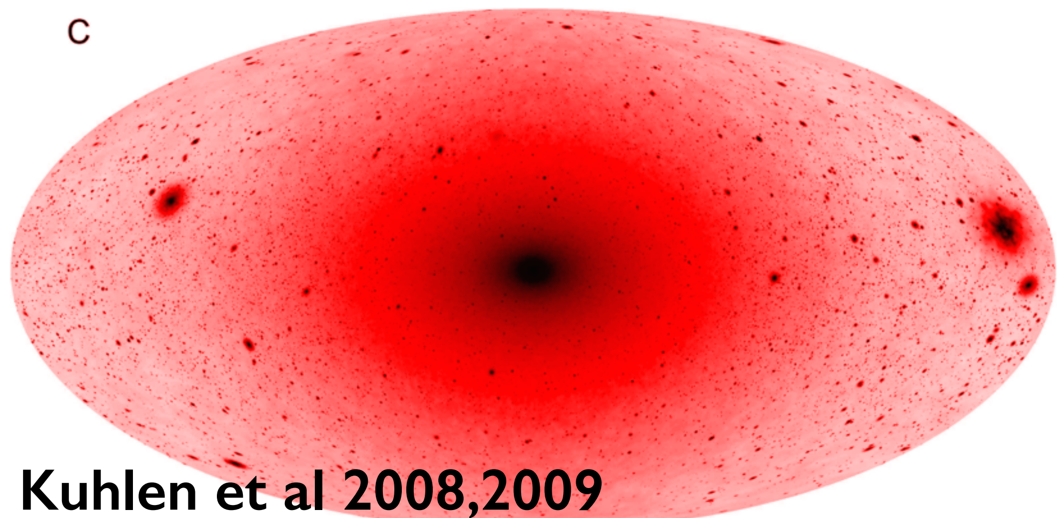
annihilation cross-section

γ-photons produced per annihilation

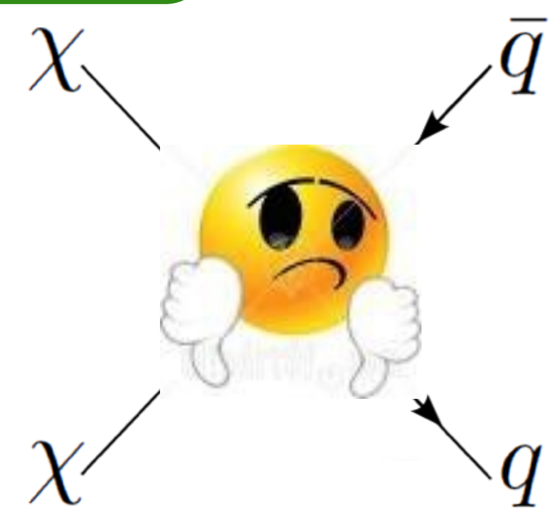
$$\Phi(E_\gamma, \psi) = \frac{\langle \sigma v \rangle}{8\pi m_X^2} \frac{dN_\gamma}{dE_\gamma} \int_{\text{los}} \rho_{\text{DM}}^2 dl$$

mass of DM particle

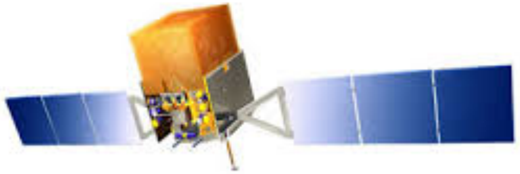
Astrophysics



Kuhlen et al 2008,2009



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 *36–51* GeV *WIMP* annihilating into *quarks* with a thermally-averaged cross-section $\langle\sigma v\rangle = (1.0\text{–}3.0) \times 10^{-26}$ cm^3/s!

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

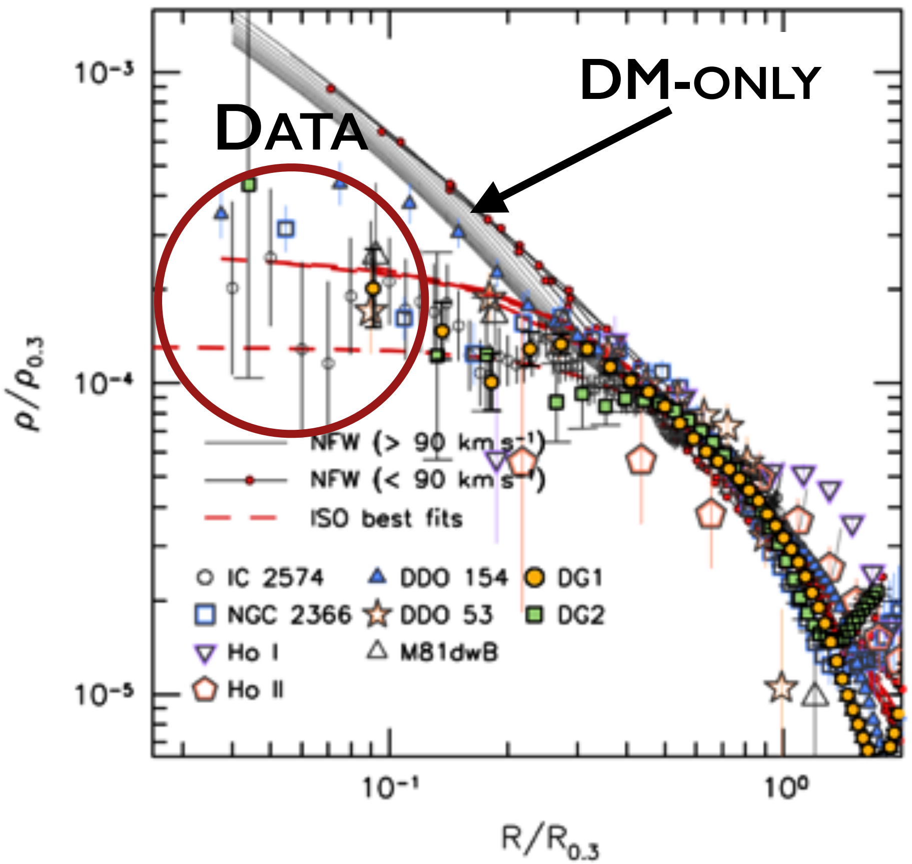
Tansu Daylan,[1] Douglas P. Finkbeiner,[1,2] Dan Hooper,[3,4] Tim Linden,[5]
Stephen K. N. Portillo,[2] Nicholas L. Rodd,[6] and Tracy R. Slatyer[6,7]

Core/Cusp Problem

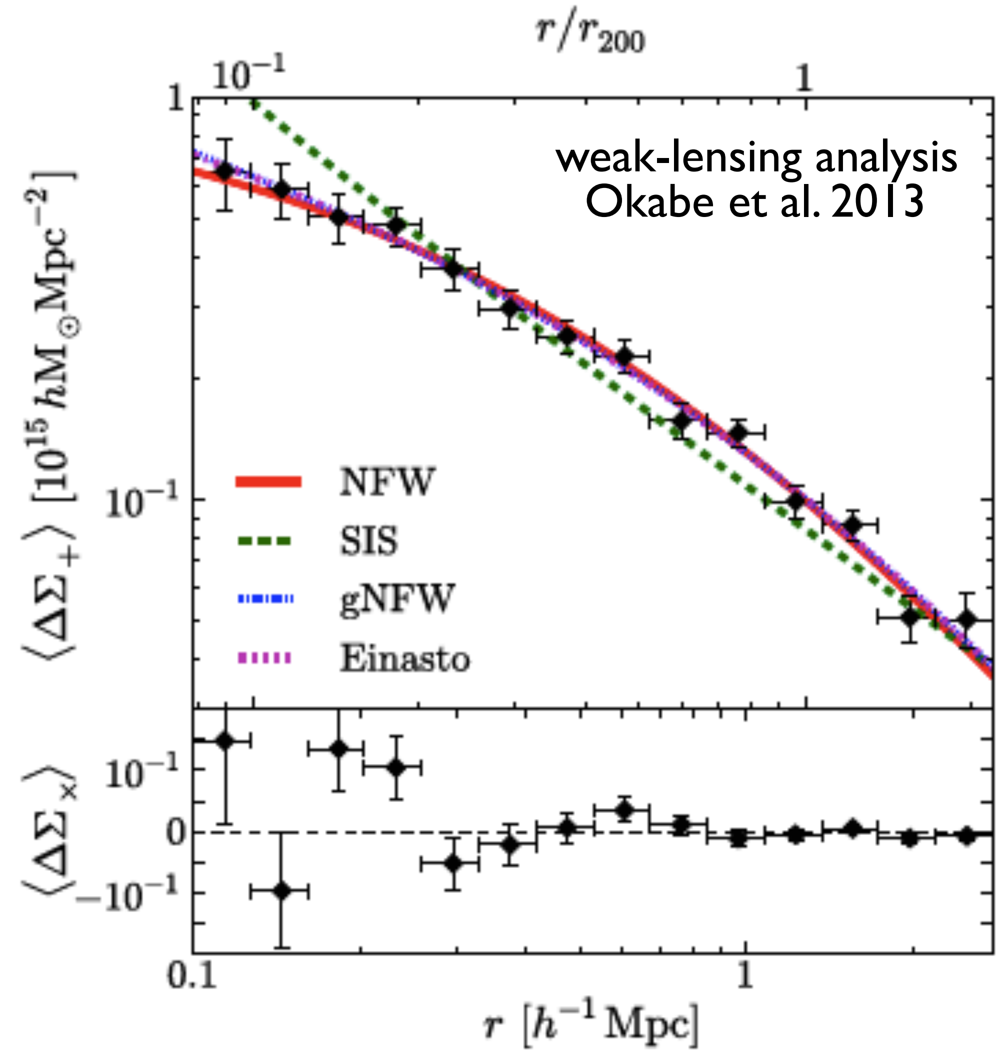
DM-only *N*-body simulations predict cuspy inner density profiles

Observations in dwarf galaxies appear to prefer cores instead!

THINGS

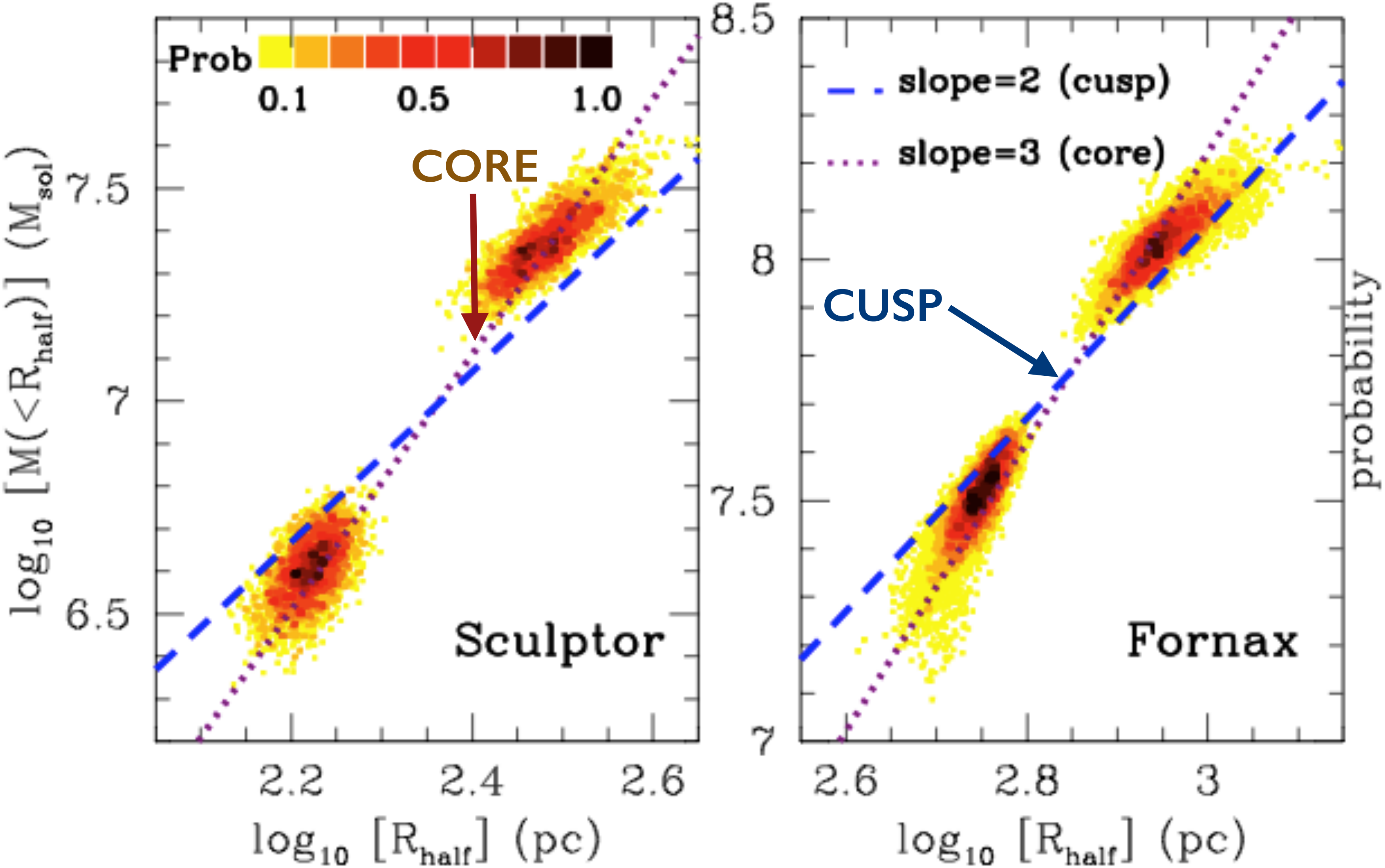


Mean density profile of rich clusters has the predicted ΛCDM shape!



CORES IN MW SATELLITES?

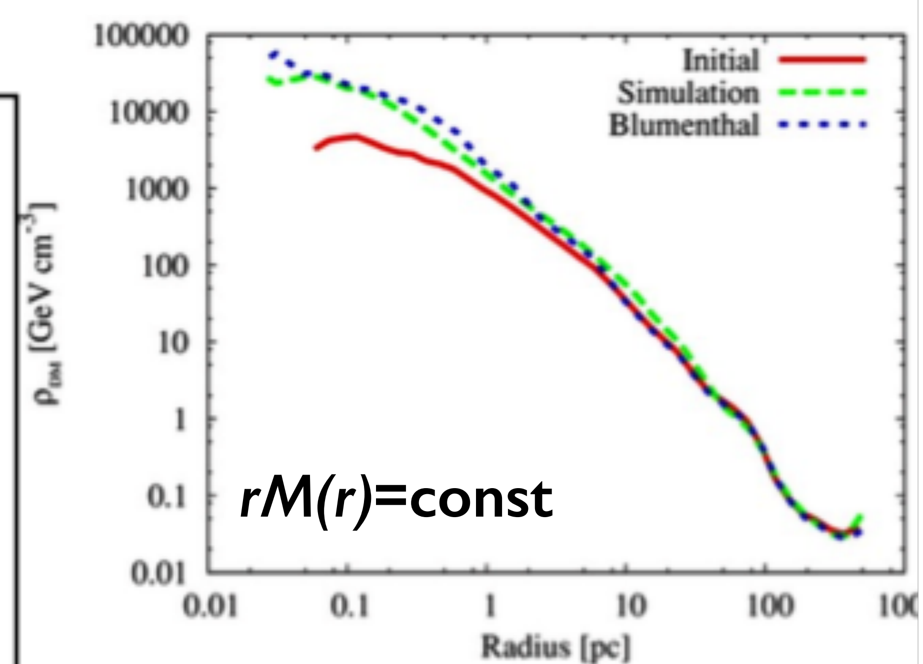
$$M(<r) = \frac{r\sigma_r^2}{G}\left(-\frac{d\ln\rho_*}{d\ln r} - \frac{d\ln\sigma_r^2}{d\ln r} - 2\beta\right)$$



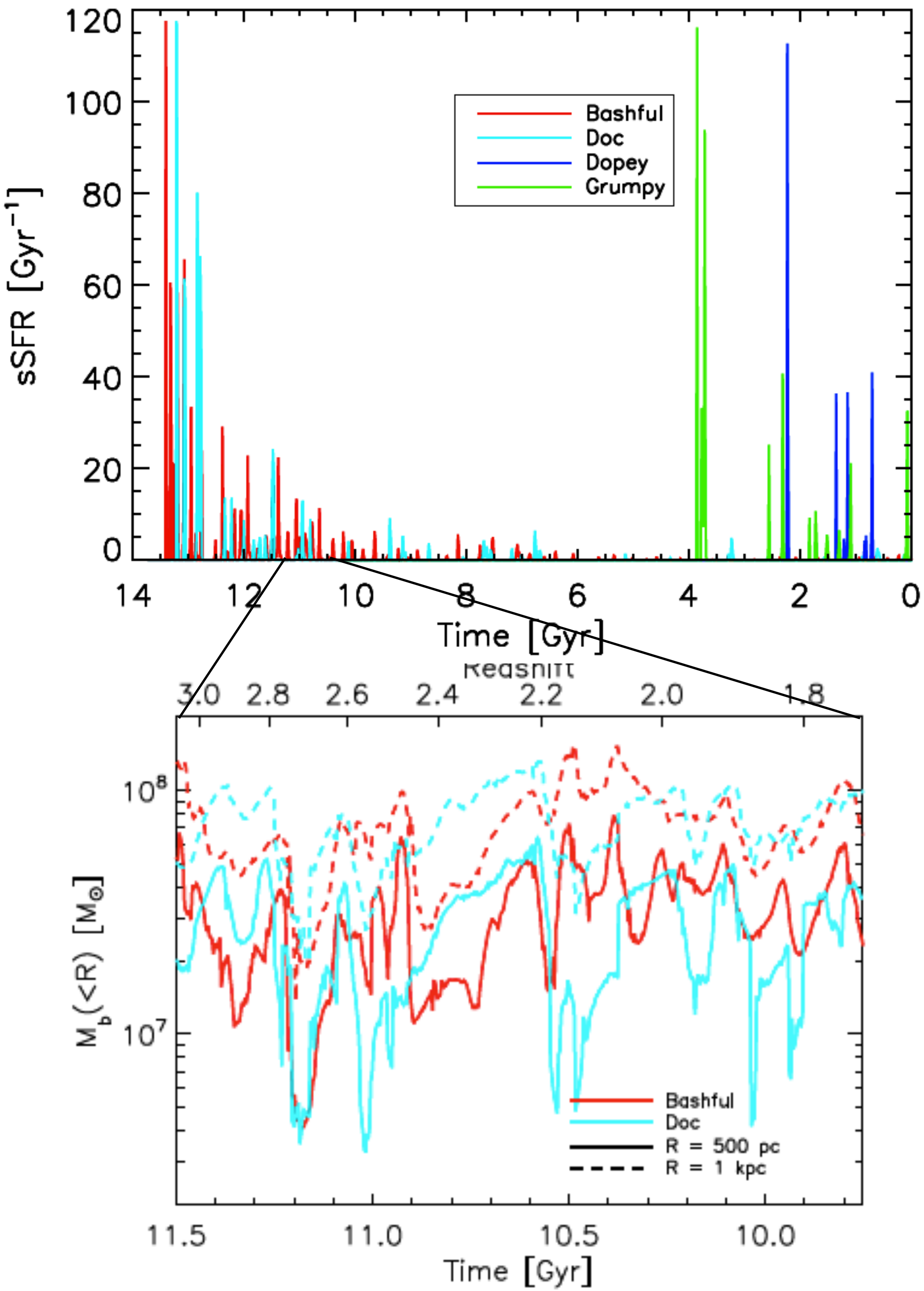
Walker & Penarrubia (2011)

• Until recently any direct effect of the baryonic component on the DM was limited to a minor *adiabatic* correction, i.e. baryonic processes modulate the SFR *without changing the underlying DM scaffolding.*

• This picture has recently been subverted. Spectroscopic observations have revealed the ubiquity of *galaxy-scale outflows*, even in dwarfs with SFR$\ll 1\,M_\odot$/yr. It has been realized that these processes have a *non-adiabatic* impact on the host DM halo.



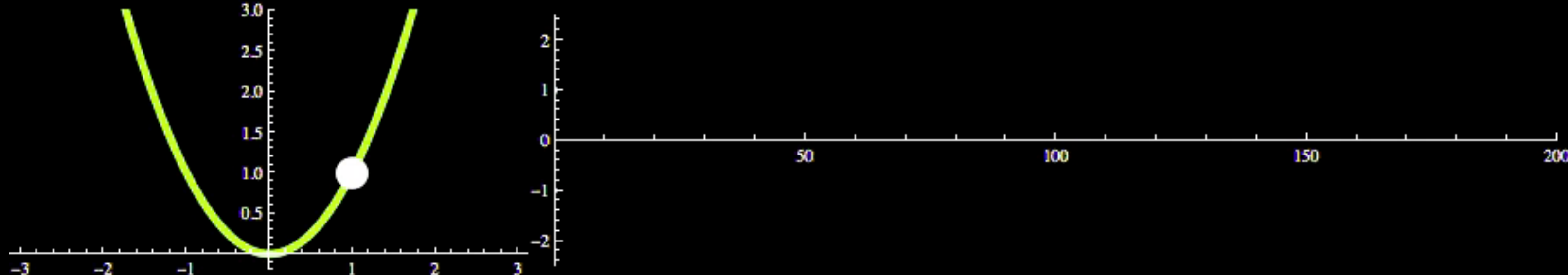
BURSTY STAR FORMATION & POTENTIAL FLUCTUATIONS



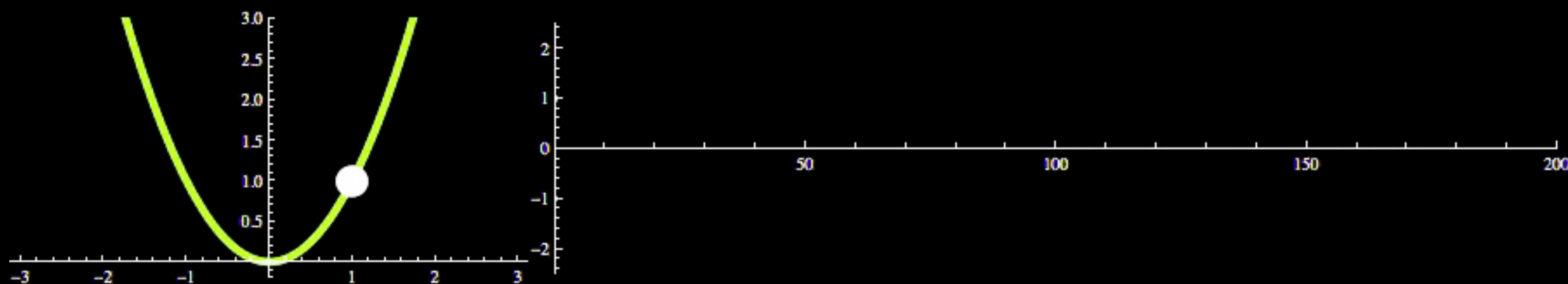
The bursty SF histories of simulated DGs. Bottom left panel: fluctuating baryonic (gas+stars) central masses.

Mechanism for injecting energy into the dark matter orbits illustrated by the exact solution for a time-varying harmonic oscillator potential.

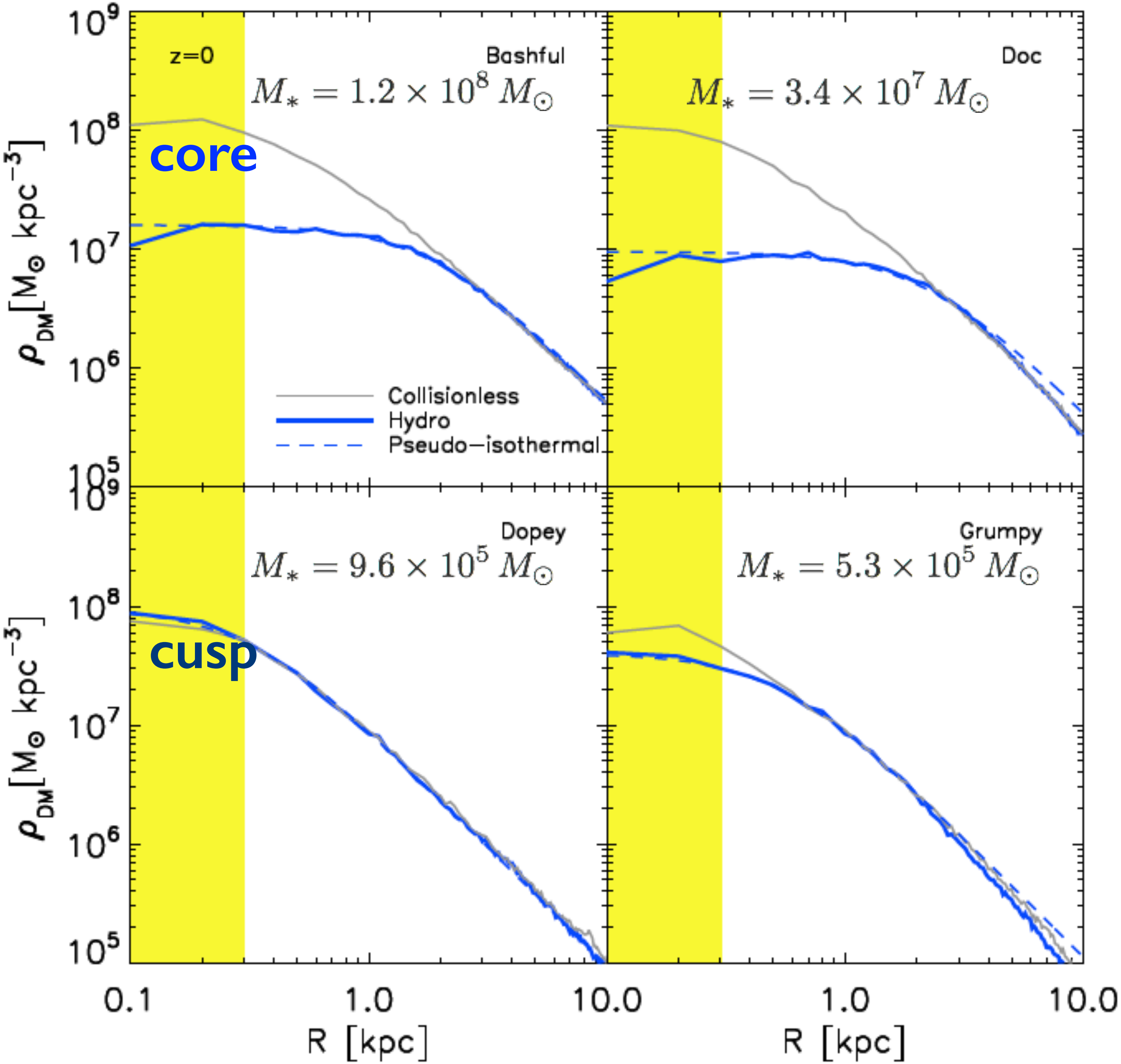
ADIABATIC BLOW-OUT & RECONDENSATION



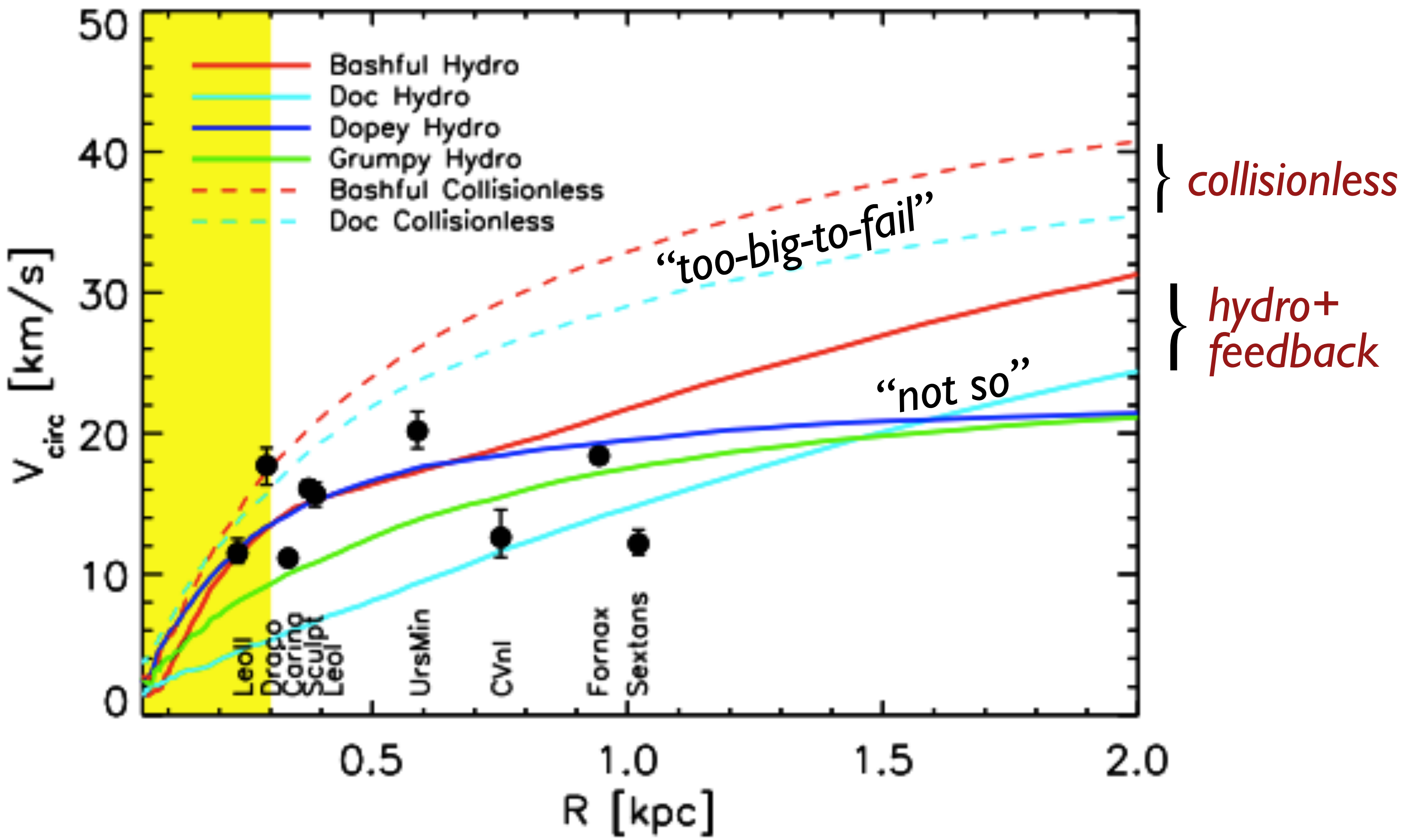
SUDDEN BLOW-OUT, THEN ADIABATIC RECONDENSATION



CDM HEATS UP



Madau et al 2014



Bashful Hydro
Doc Hydro
Dopey Hydro
Grumpy Hydro
Bashful Collisionless
Doc Collisionless
"too-big-to-fail"
"not so"
collisionless
hydro+
feedback
V_{circ} [km/s]
R [kpc]
0
10
20
30
40
50
0.5
1.0
1.5
2.0
LeoII
Draco
Carina
Sculpt
LeoI
UrsMin
CVnI
Fornax
Sextans

We Know Much, Understand Some, Need Help

- Evidence that the Universe conforms to the expectations of the ΛCDM model is *compelling but hardly 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.

- In galaxy centres DM densities appear lower than expected, and small subhalos must be dark. Tensions between CDM predictions and observations may be telling us something about the *fundamental properties of DM* or more likely something about the *complexities of galaxy formation.*

- **Em**erging 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* ➪ *on small scales clearly CDM is not enough…..*

- Still no show-stoppers for ΛCDM. More exotic possibilities like WDM/SIDM may still be viable, but require careful tuning and do not provide any silver bullet. There are great hopes that underground detection experiments, γ-ray observations, or collider experiments will identify the DM particle within the next decade.

- In the meantime, astronomers will continue their decades-long practice of studying the dark sector by observing and modeling the visible. Over the next decade, strong *gravitational lensing* may provide important evidence for CDM substructure.