Dark Matter

ISYA 2018, Socorro, Colombia

Octavio Valenzuela

A Brief History of Dark Matter

no negligible compared with light

1930s - Discovery that cluster $\sigma_V \sim 1000$ km/s

1970s - Discovery of flat galaxy rotation curves

1980s - Most astronomers are convinced that dark matter exists around galaxies and clusters **Are you??**

1980-84 - short life of Hot Dark Matter theory

1983-84 - Cold Dark Matter (CDM) theory proposed

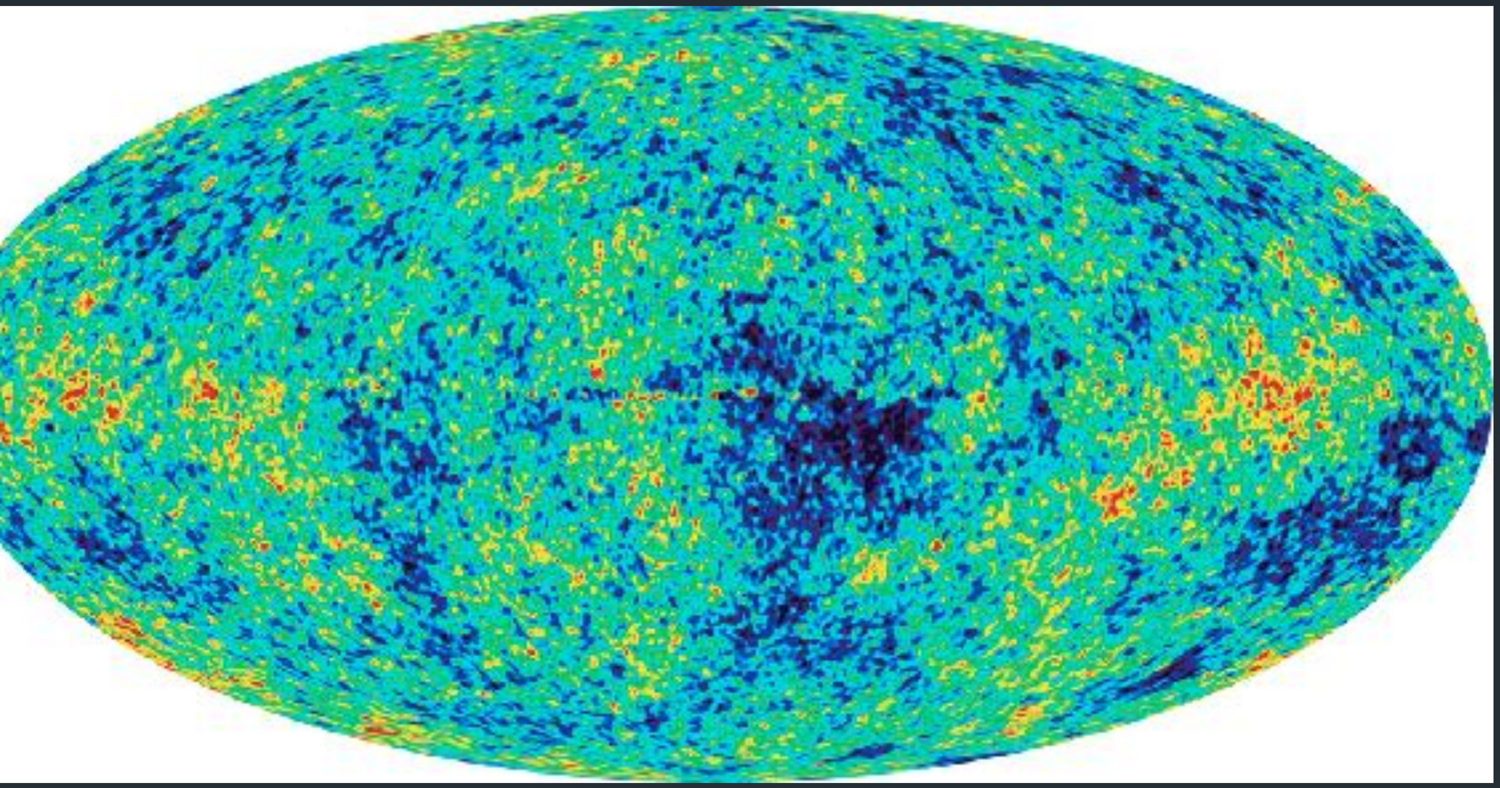
1992 - COBE discovers CMB fluctuations as predicted by CDM; CHDM and ΛCDM are favored CDM variants **for crisis**

1998 - SN Ia and other evidence of Dark Energy

2000 - ΛCDM is the Standard Cosmological Model

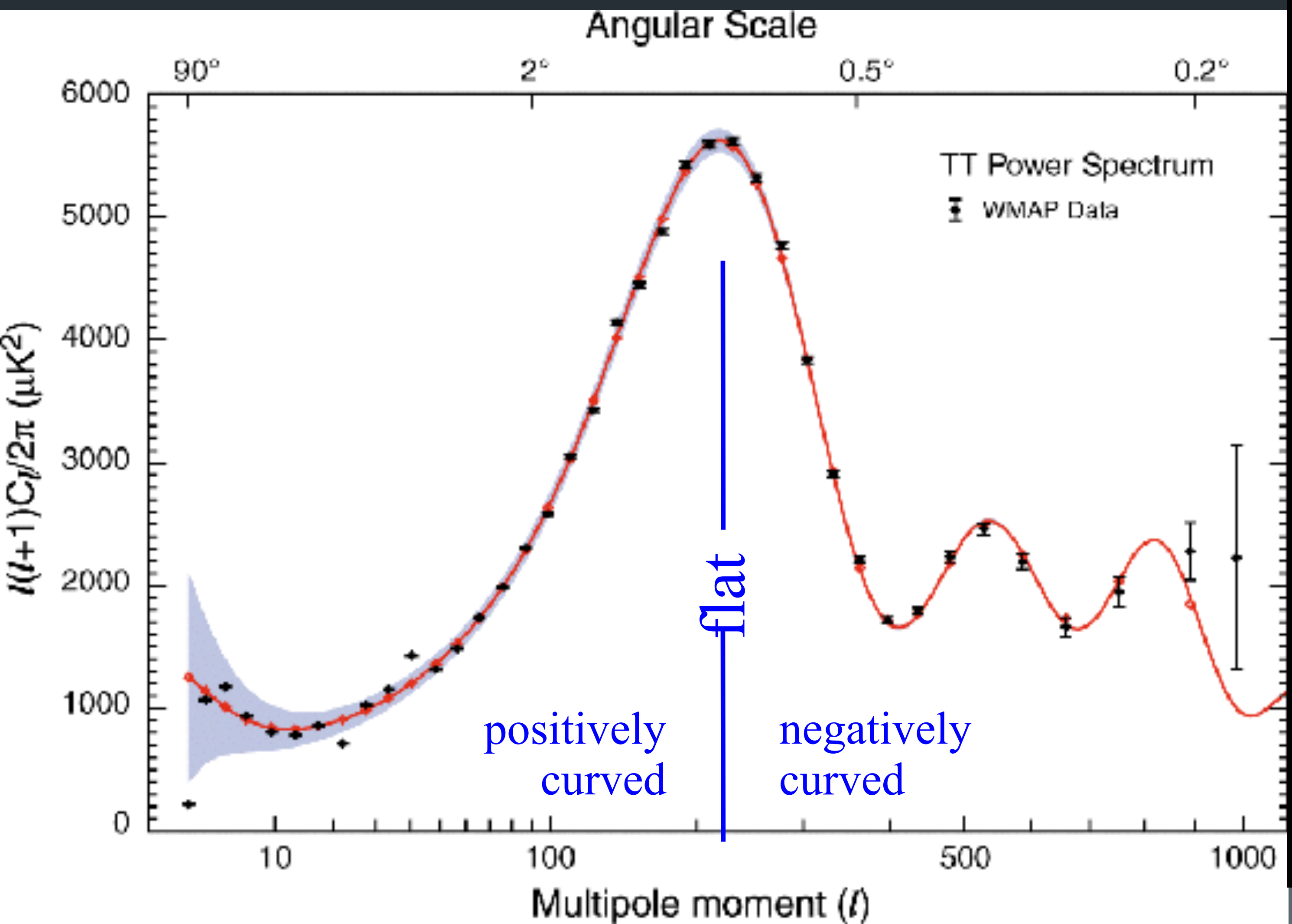
2003-12 - WMAP, Planck, and LSS confirm ΛCDM predictions

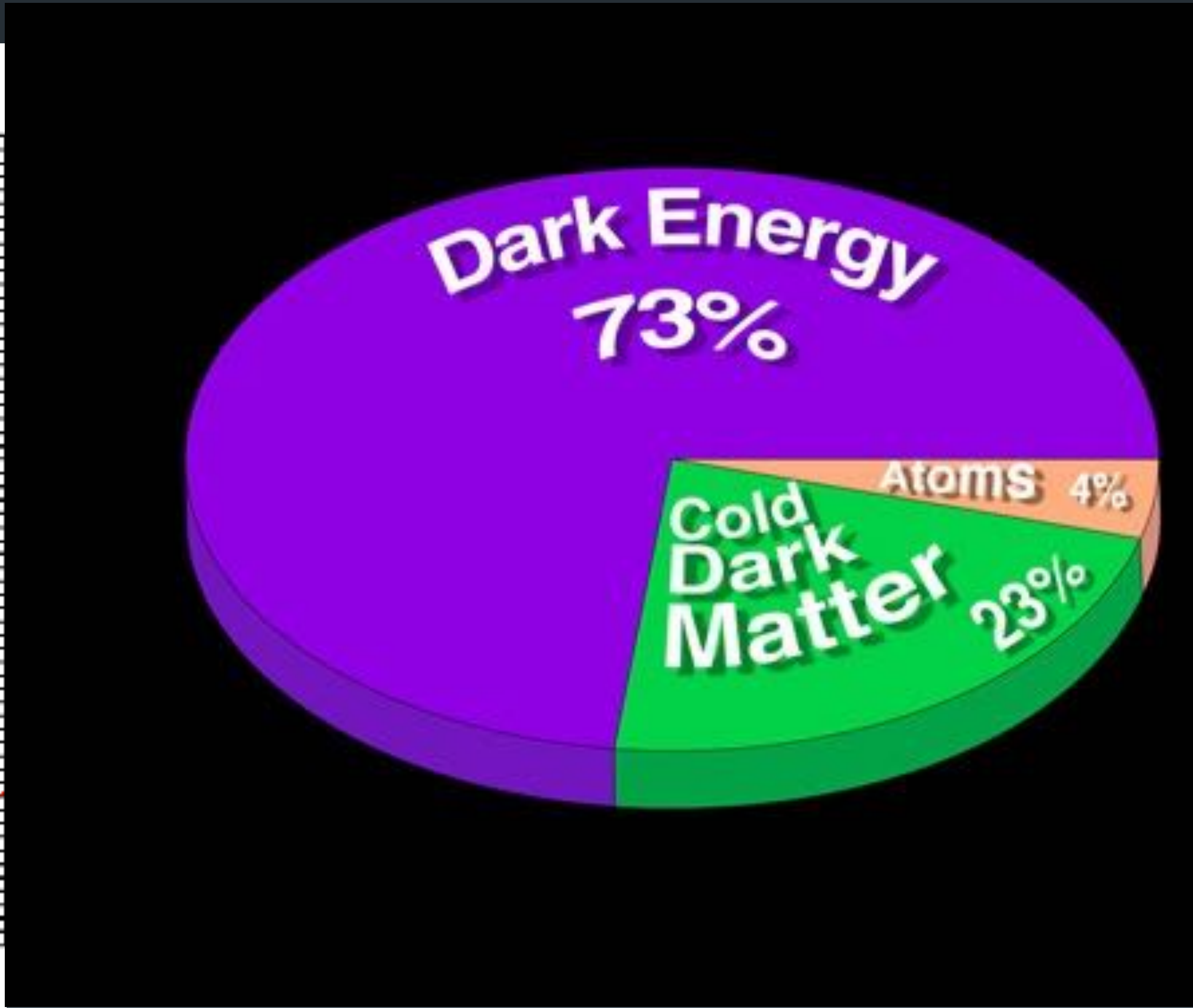
2016-2018 - Planck, eBOSS/SDSS consistent with ΛCDM



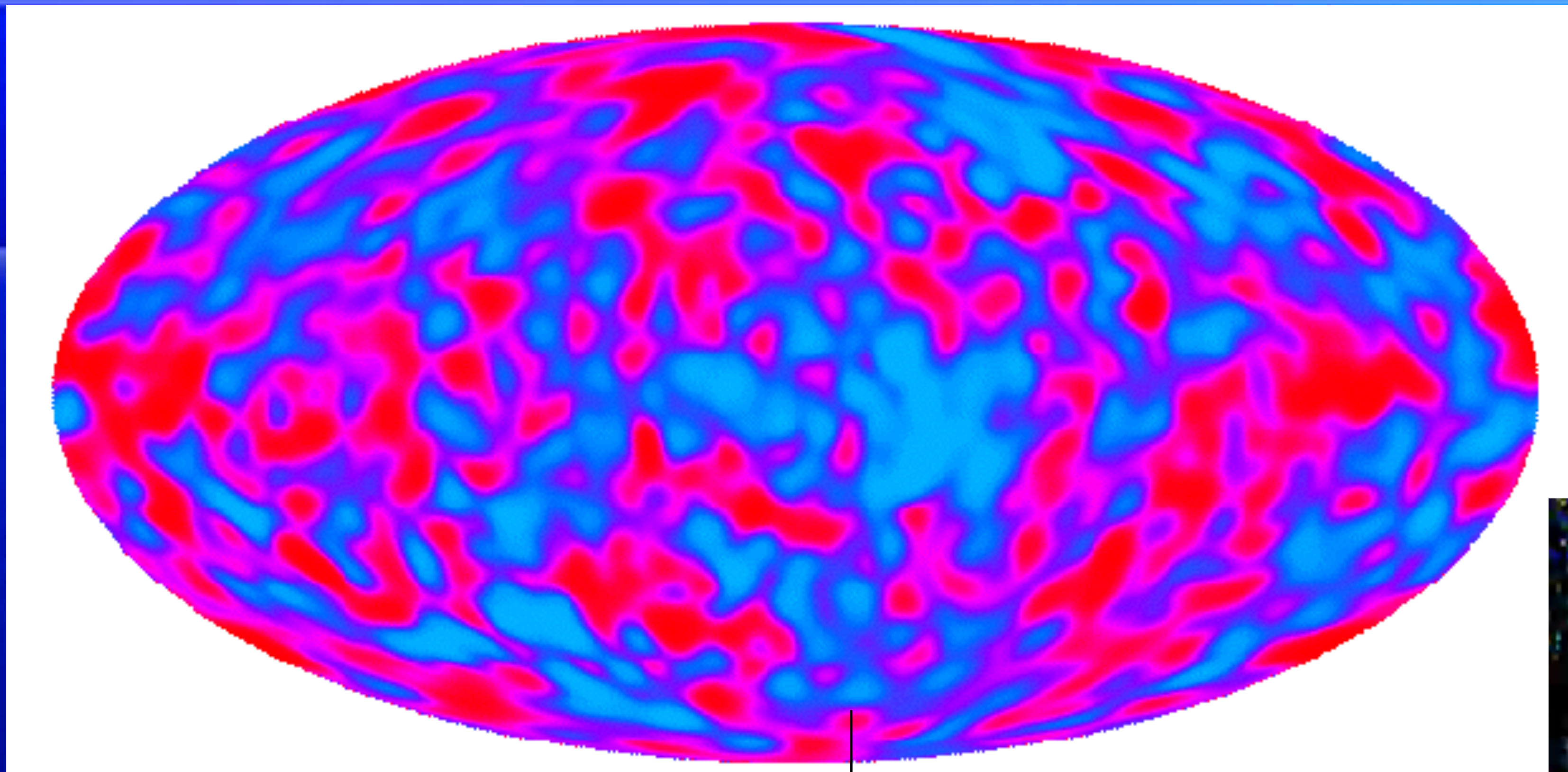
Seeds for the Universe Structure

Problem:
particles (protons electrons)
scape out
of fluctuaciones because interaction with
radition, damping fluctuations
(Silk Damping): **Dark Matter that does not interact with radiation is required to have galaxies**





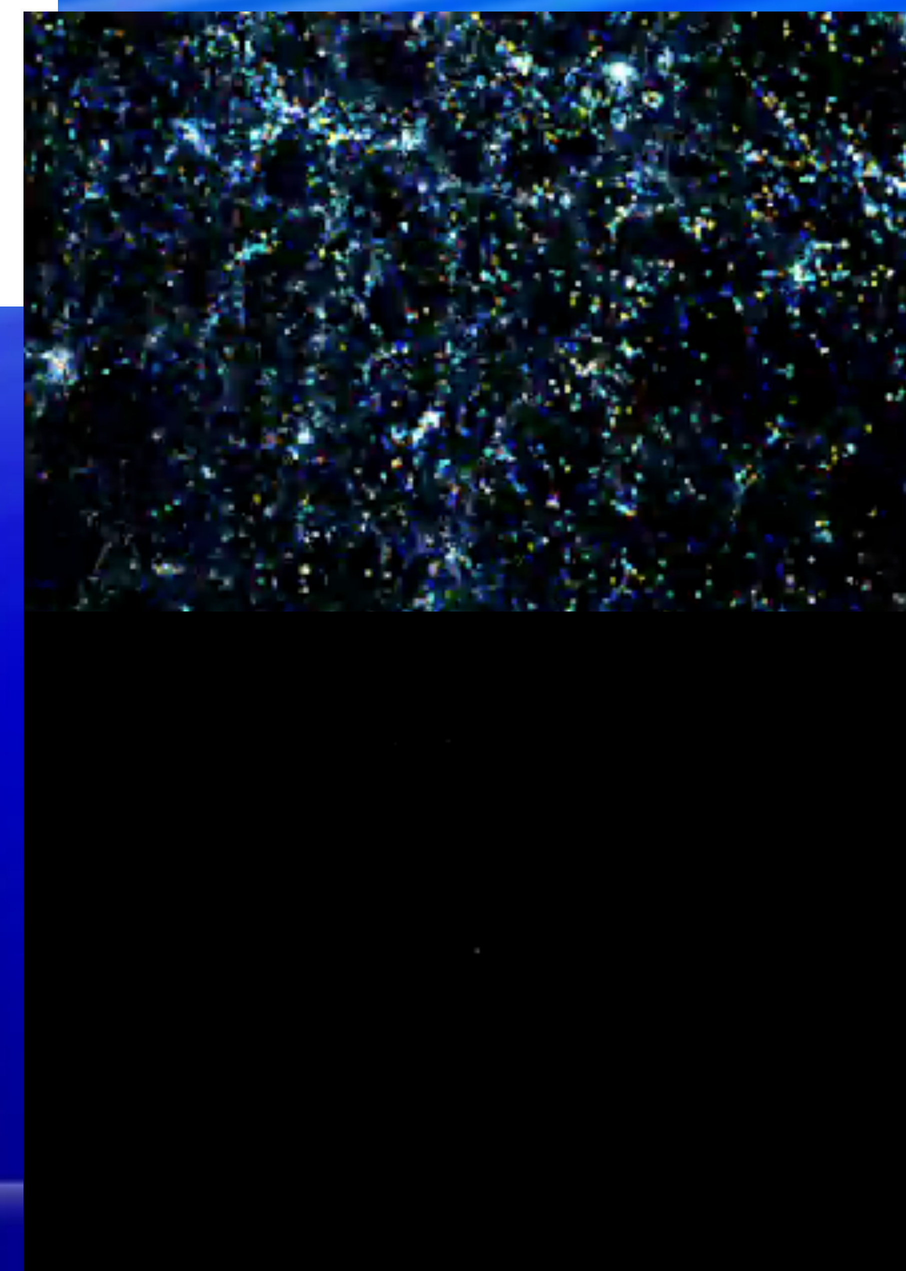
Primordial fluctuations detected (Origin?)



Nobel Prize 2006
Detected
inhomogeneities

COBE experiment

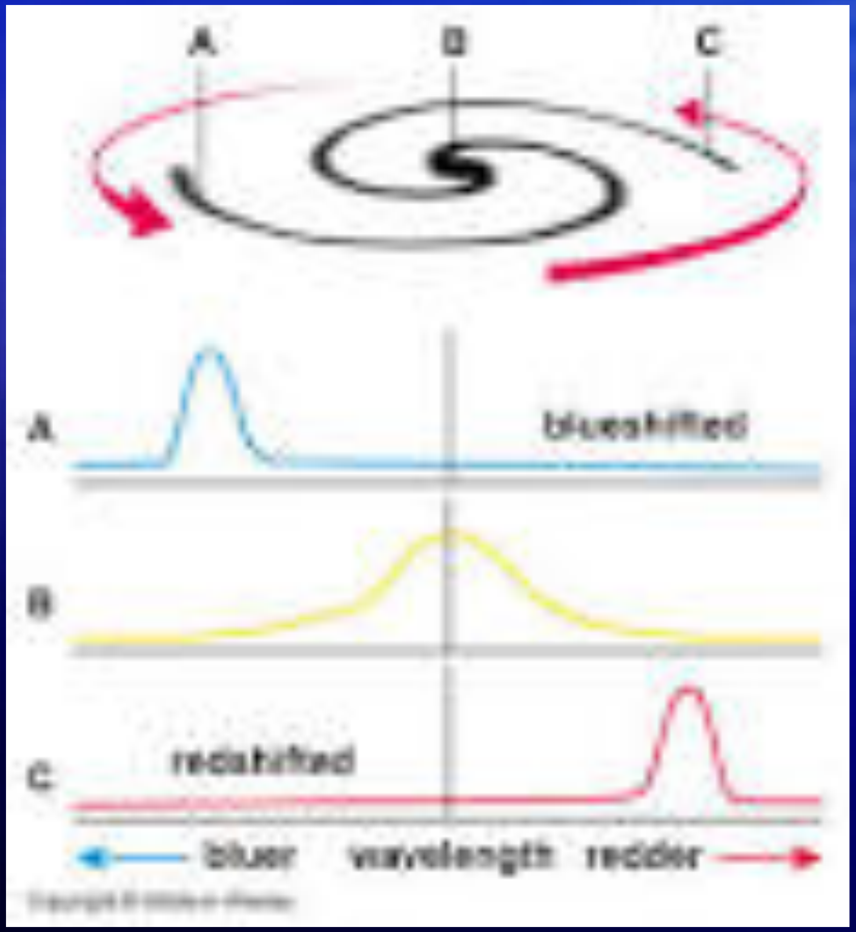
All physics
Non-linear
Simulations Bolshoi Klypin et al



SDSS galaxies
M Aragón-Calvo

LCDM grossly reproduce
Current Observed Universe..
SDSS survey

How do we know that spiral galaxies rotate? Doppler Effect from stellar/gas light



How to weight a galaxy?

Count how many stars and gas do they have analyzing its light: Gustavo´s Lectures

As more luminous a galaxy is, more massive in stars it is

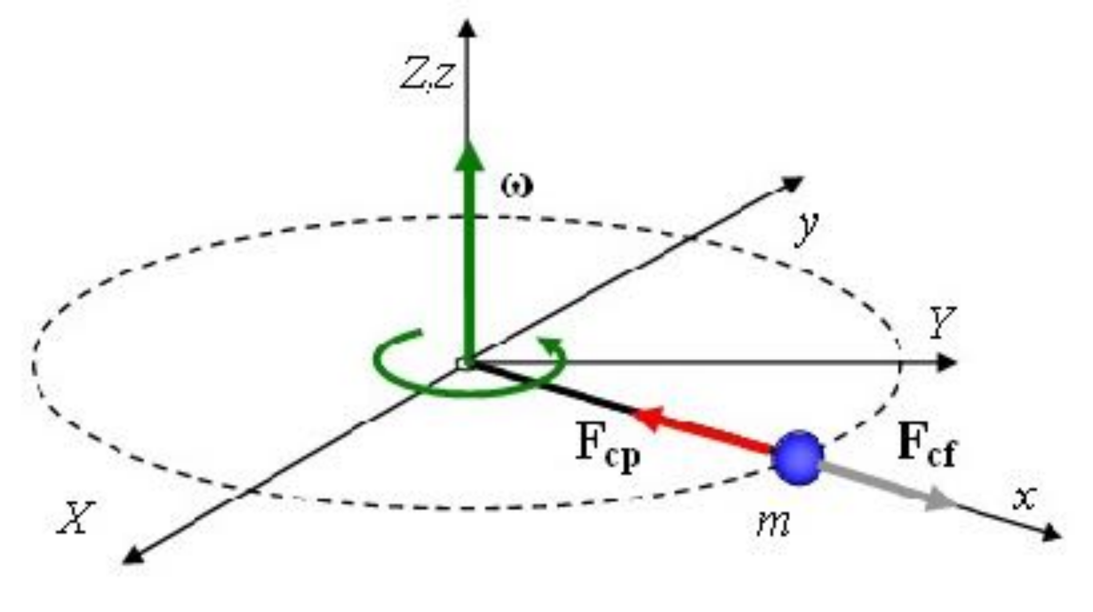
How to weight a galaxy?

Force Internal Spring=
Person weight

How to weight a galaxy?

- centrípetal and centrífugas forces?

As faster stars and gas move, more massive a galaxy is



$$GM/r^2 \approx v^2/r$$

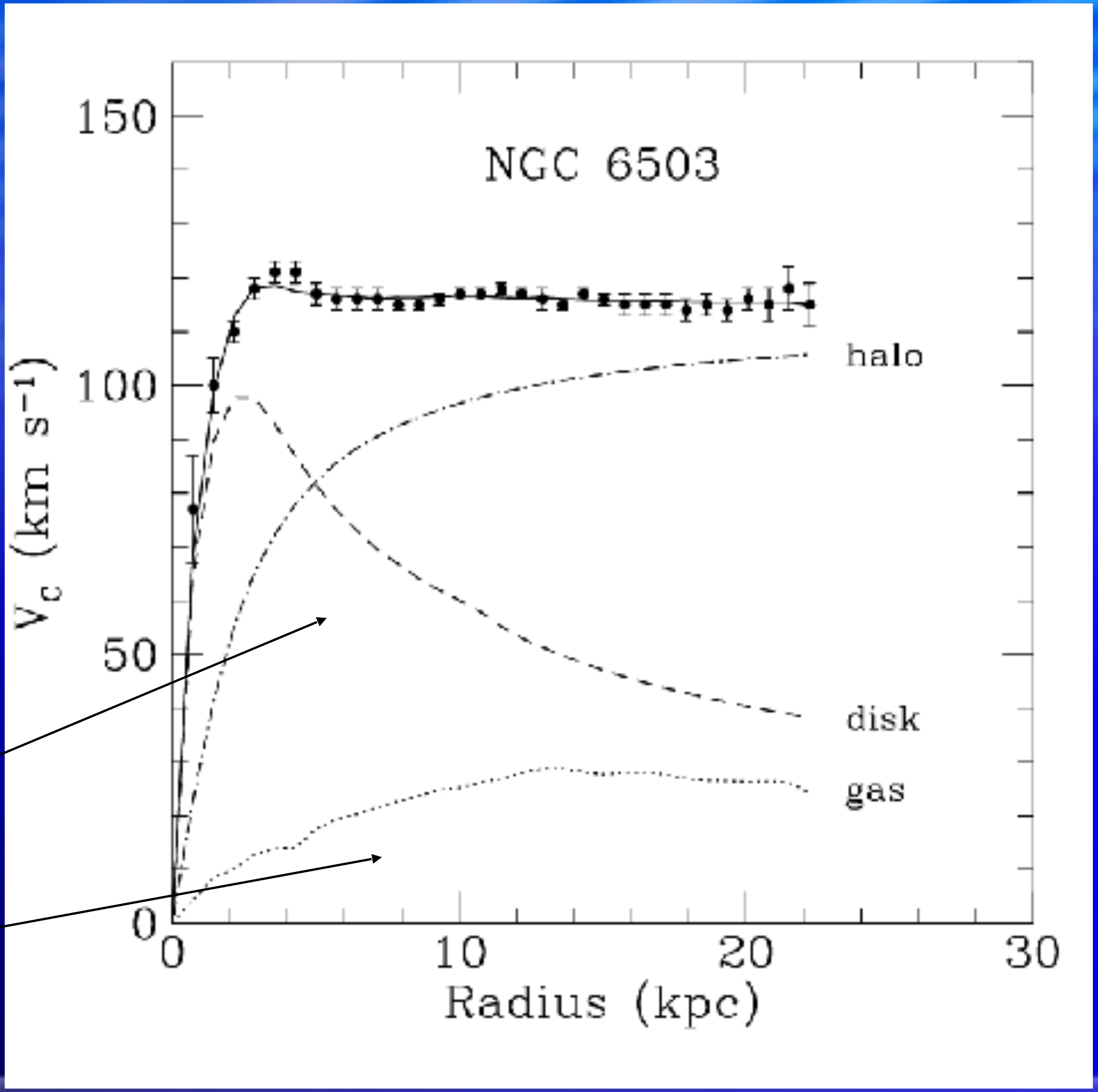
$$M \approx v^2 r/G$$

For spheroidal/elliptical galaxies and clusters instead of rotation use velocity dispersion

Masses estimated with rotation/v dispersion and using light (from stars and gas) are very different. Is there mass not emitting light? Dark Matter? Weird Geodesics?

$$\frac{GM(<r)}{r^2} = \frac{v^2}{r}$$

Stars
and gas



Historical Works

Fritz Zwicky

1937 ApJ 86, 217

ON THE MASSES OF NEBULAE AND OF CLUSTERS OF NEBULAE

F. ZWICKY

The Coma cluster contains about one thousand nebulae. The average mass of one of these nebulae is therefore

$$\overline{M} > 9 \times 10^{43} \text{ gr} = 4.5 \times 10^{10} M_\odot . \quad (36)$$

Inasmuch as we have introduced at every step of our argument inequalities which tend to depress the final value of the mass $\mathcal{M}$, the foregoing value (36) should be considered as the lowest estimate for the average mass of nebulae in the Coma cluster. This result is somewhat unexpected, in view of the fact that the luminosity of an average nebula is equal to that of about 8.5×10^7 suns. According to (36), the conversion factor γ from luminosity to mass for nebulae in the Coma cluster would be of the order

$$\text{Mass/Light} = \gamma = 500 , \quad (37)$$

as compared with about $\gamma' = 3$ for the local Kapteyn stellar system.

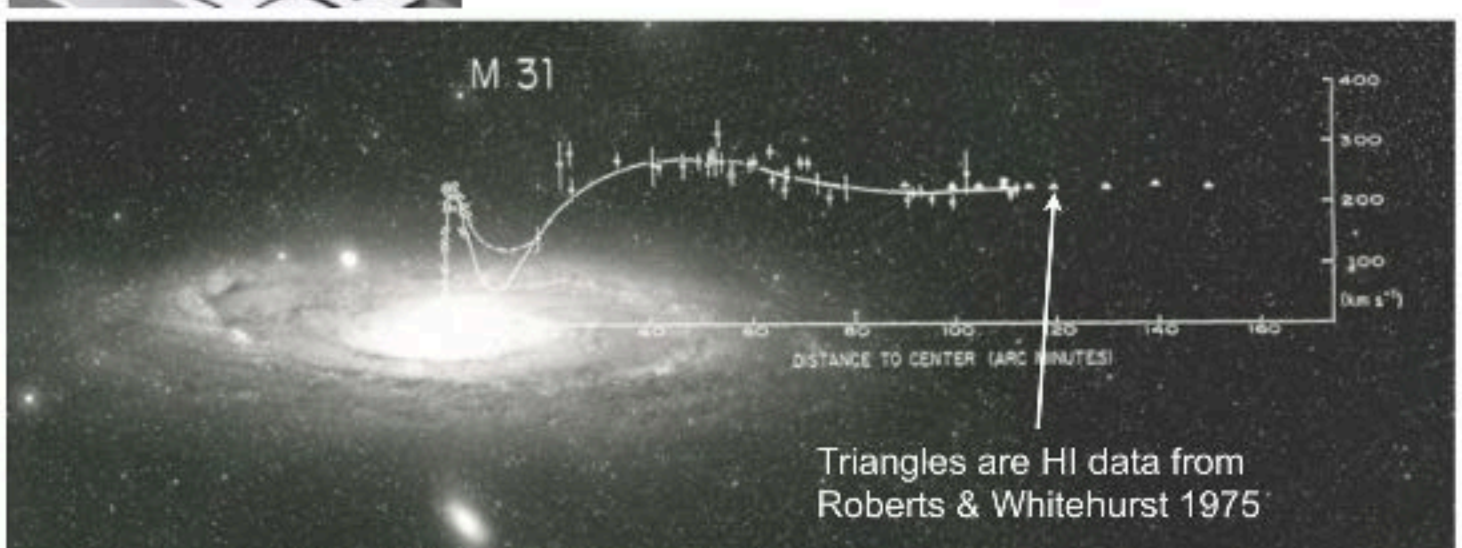
This article also proposed measuring the masses of galaxies by gravitational lensing.

See Rubin's "Reference Frame" in Dec 2006 Physi
article, "A Brief History of Dark Matter," in *The da*
energy and gravity, Proc. STScI Symposium 2001,

1970 ApJ 159, 379

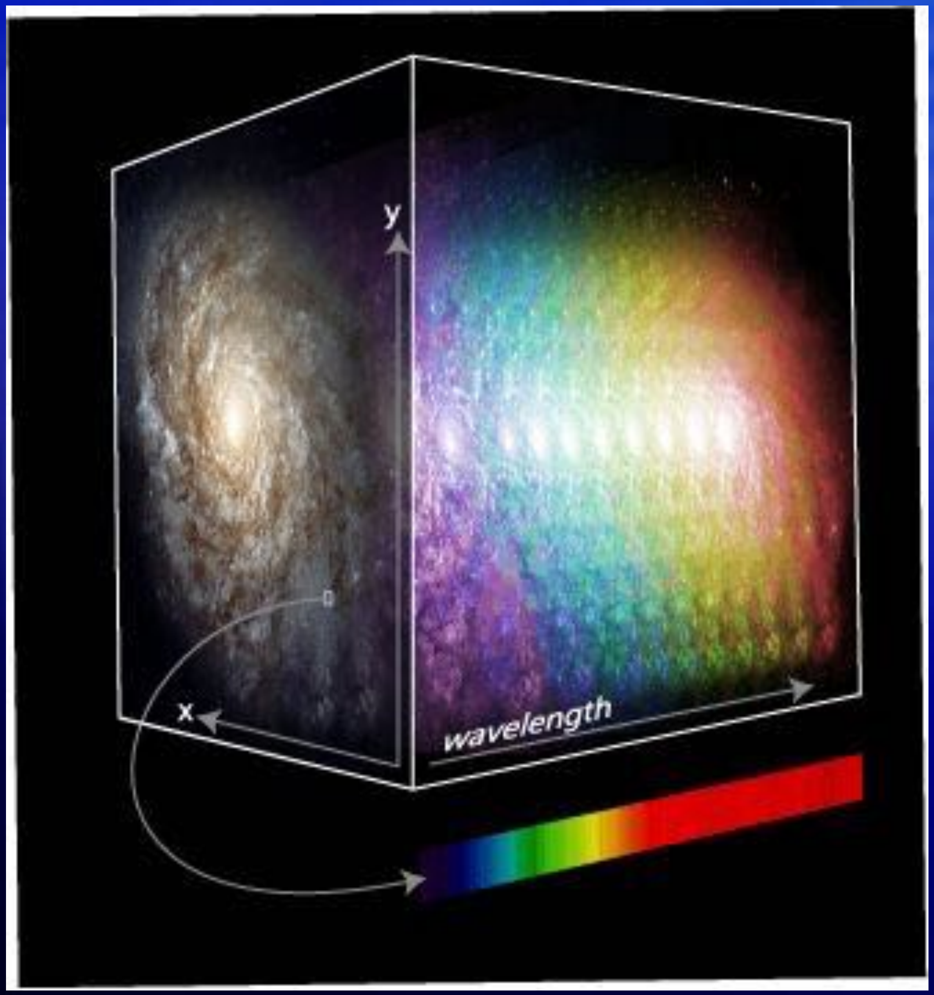
ROTATION OF THE ANDROMEDA NEBULA FROM A SPECTROSCOPIC SURVEY OF EMISSION REGIONS*

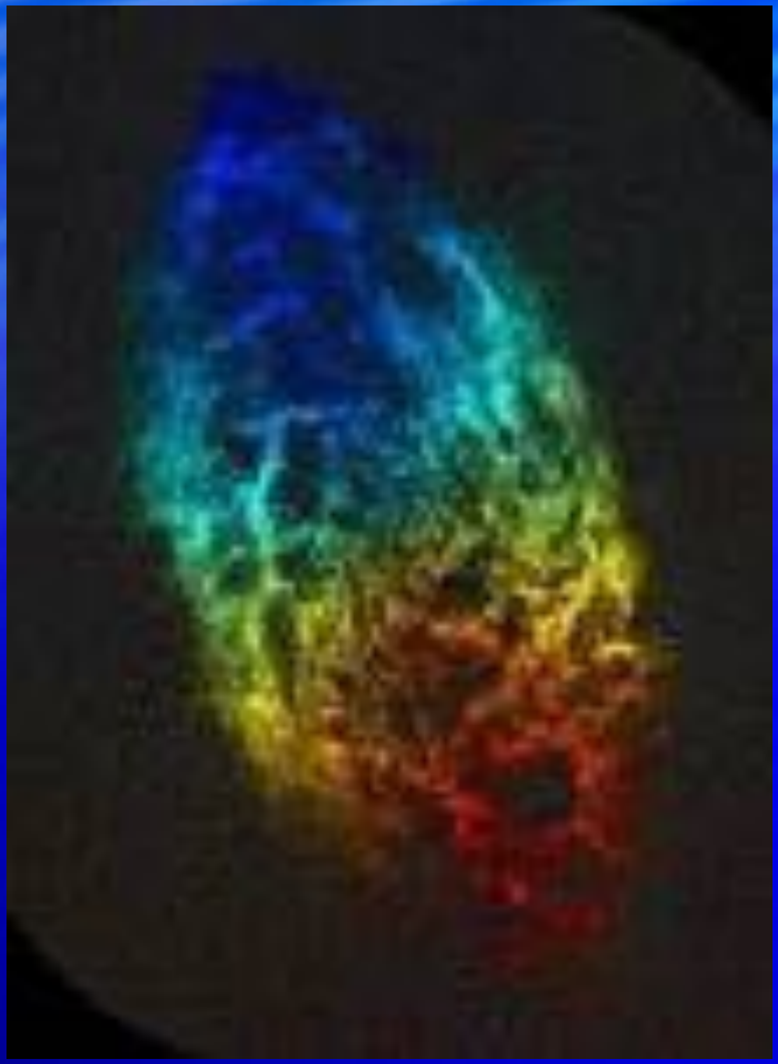
Vera C. Rubin† and W. Kent Ford, Jr.†
Department of Terrestrial Magnetism, Carnegie Institution of Washington and Lowell Observatory, and Kitt Peak National Observatory‡



Galaxies rotation curves and velocity dispersion of galaxies in clusters both suggest that we need more matter than the observed one

Tomography of galaxies: A single spectrum per pixel. No only rotation more accurate models





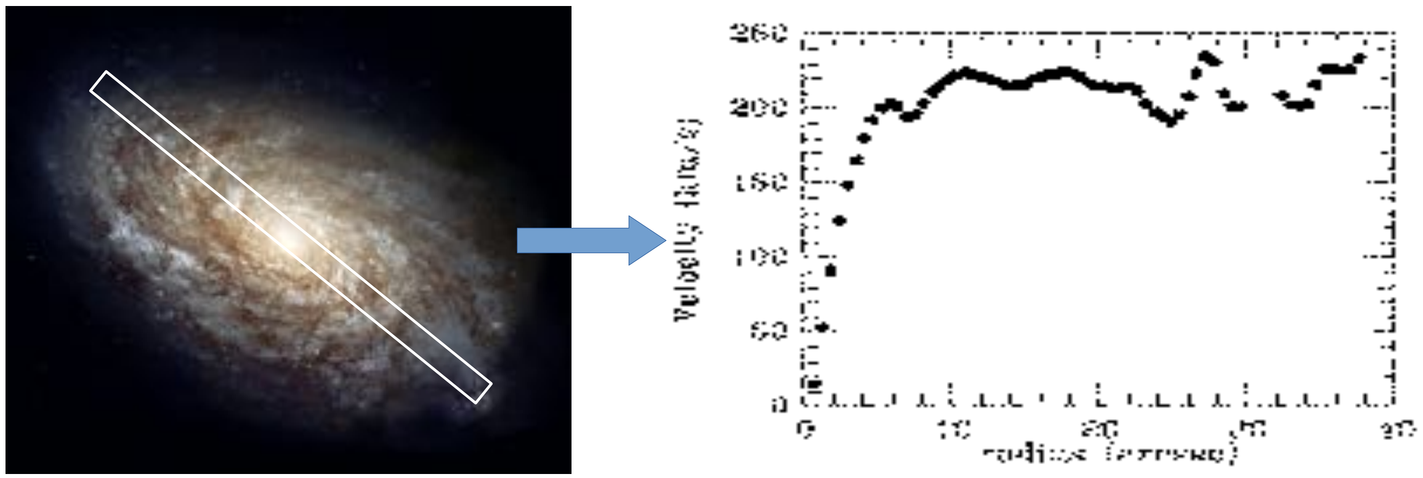
Data: New Generation of Galaxy Surveys

Integral field spectroscopy.

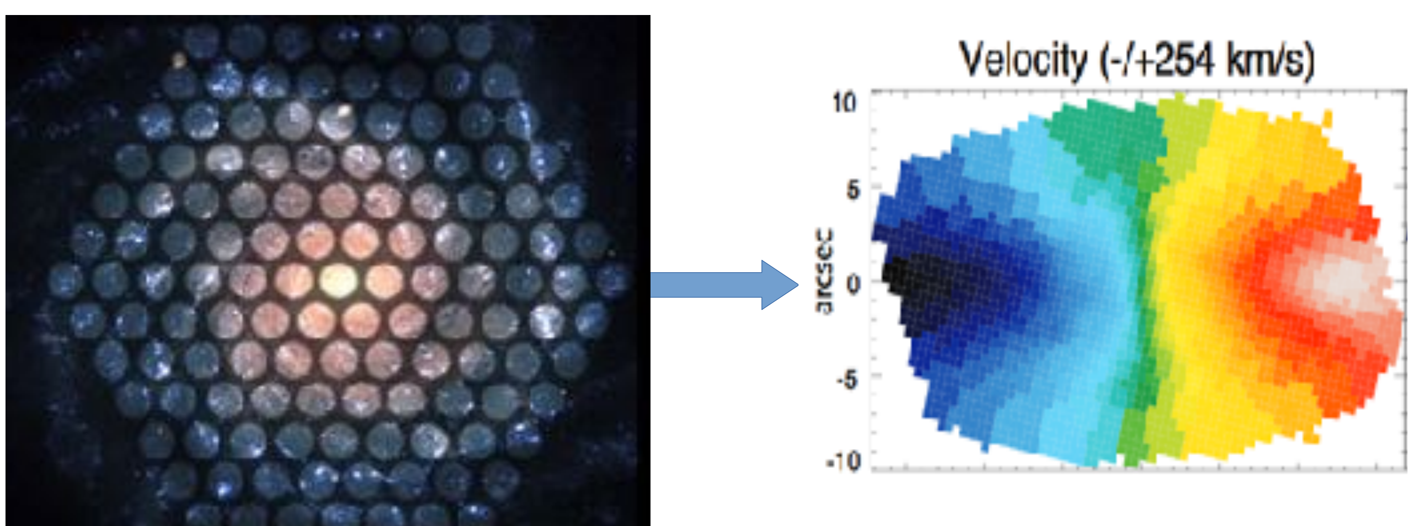
Aquino, Valenzuela,Sanchez et al 2018

Data products from Pipe3D (Sanchez et al. 2016)

Geometrical assumptions

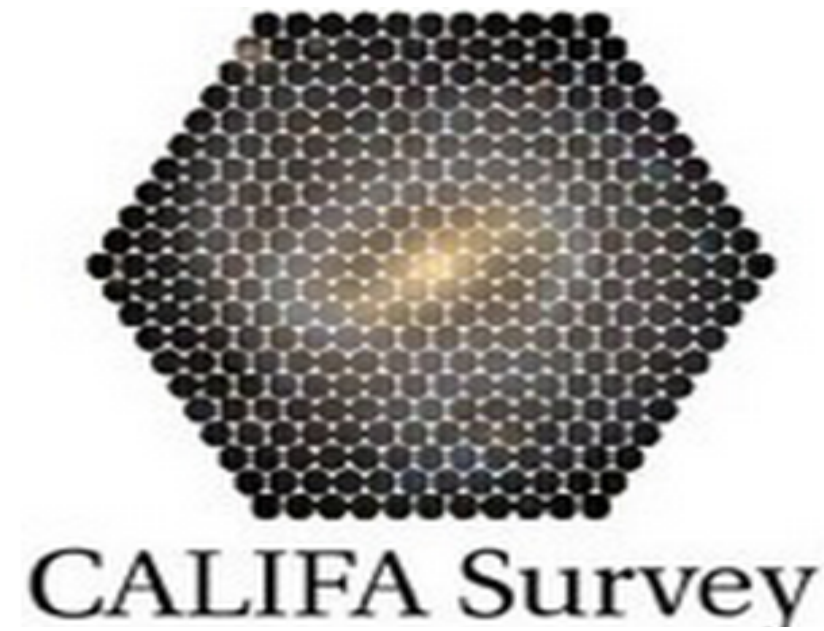


Long slit spectroscopy.



Integral field spectroscopy.

667 galaxies.

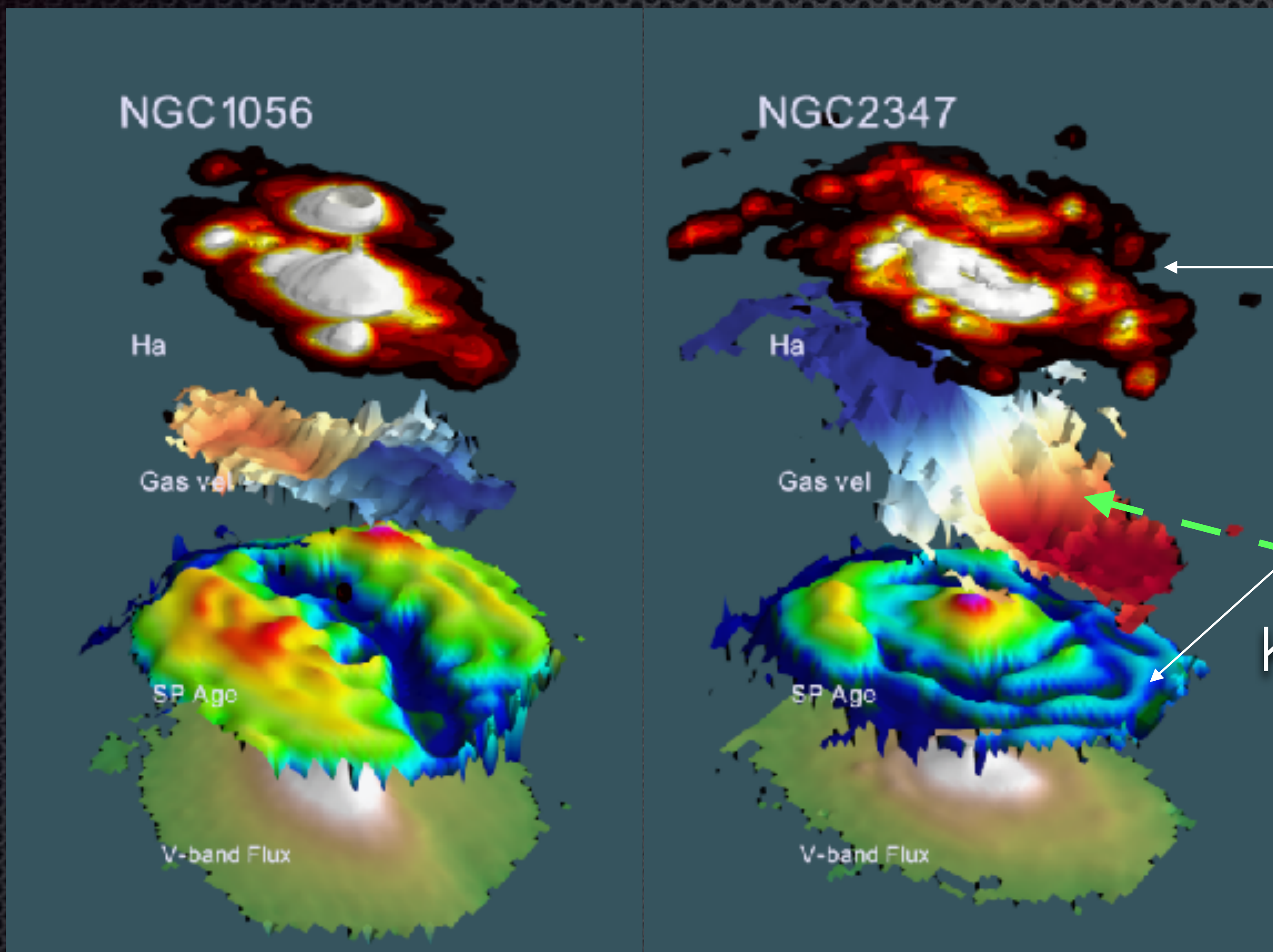


~ 10,000 galaxies SDSS

~ 400 galaxies VLT

muse
multi unit spectroscopic explorer

Tomography of Galaxies IFU´s



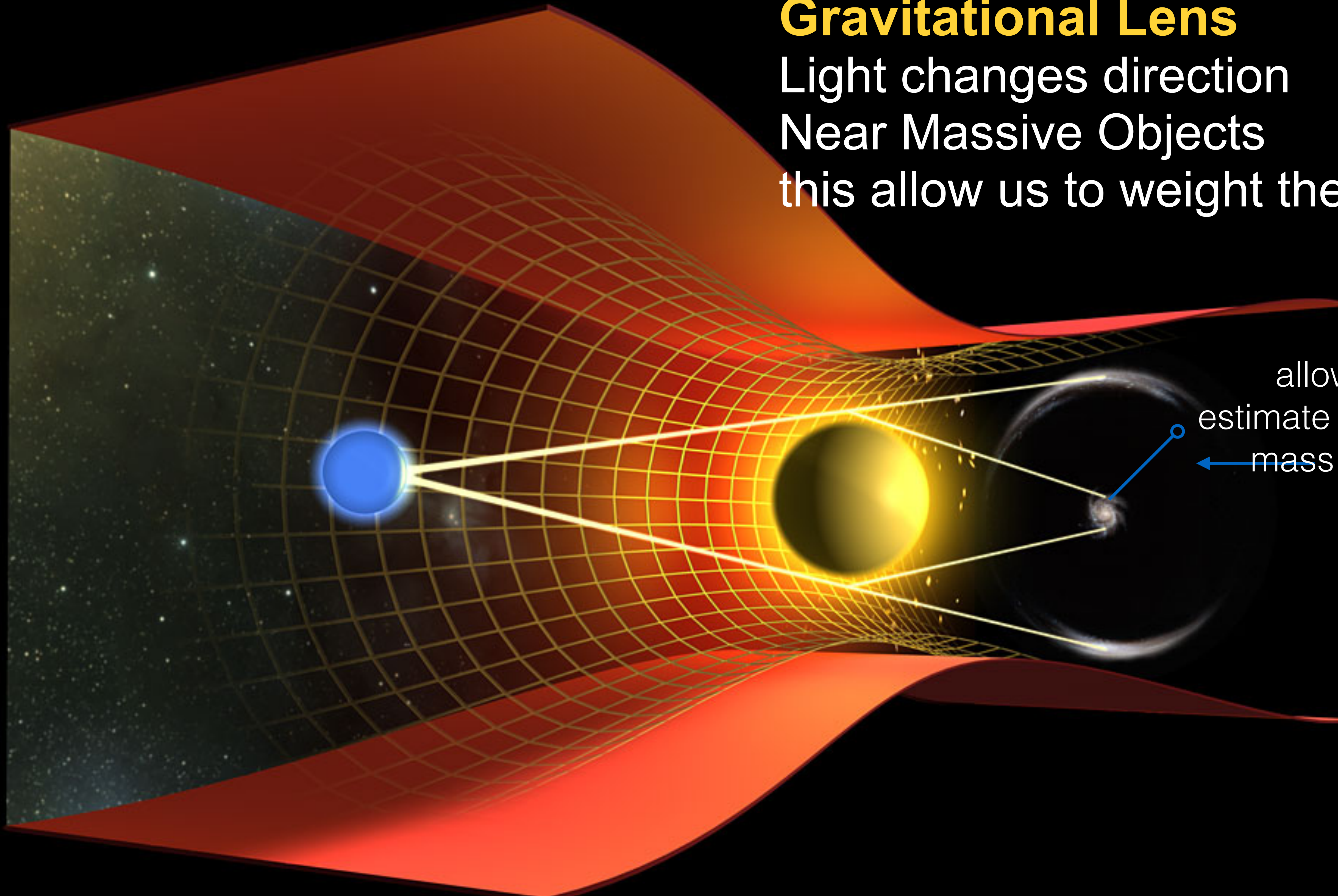
Baryons
Mass, History, feedback

Kinematics: Gas and stars, asymmetries

CALIFA survey, see also MaNGA, SAMI, MUSE

Gravitational Lens

Light changes direction
Near Massive Objects
this allow us to weight them



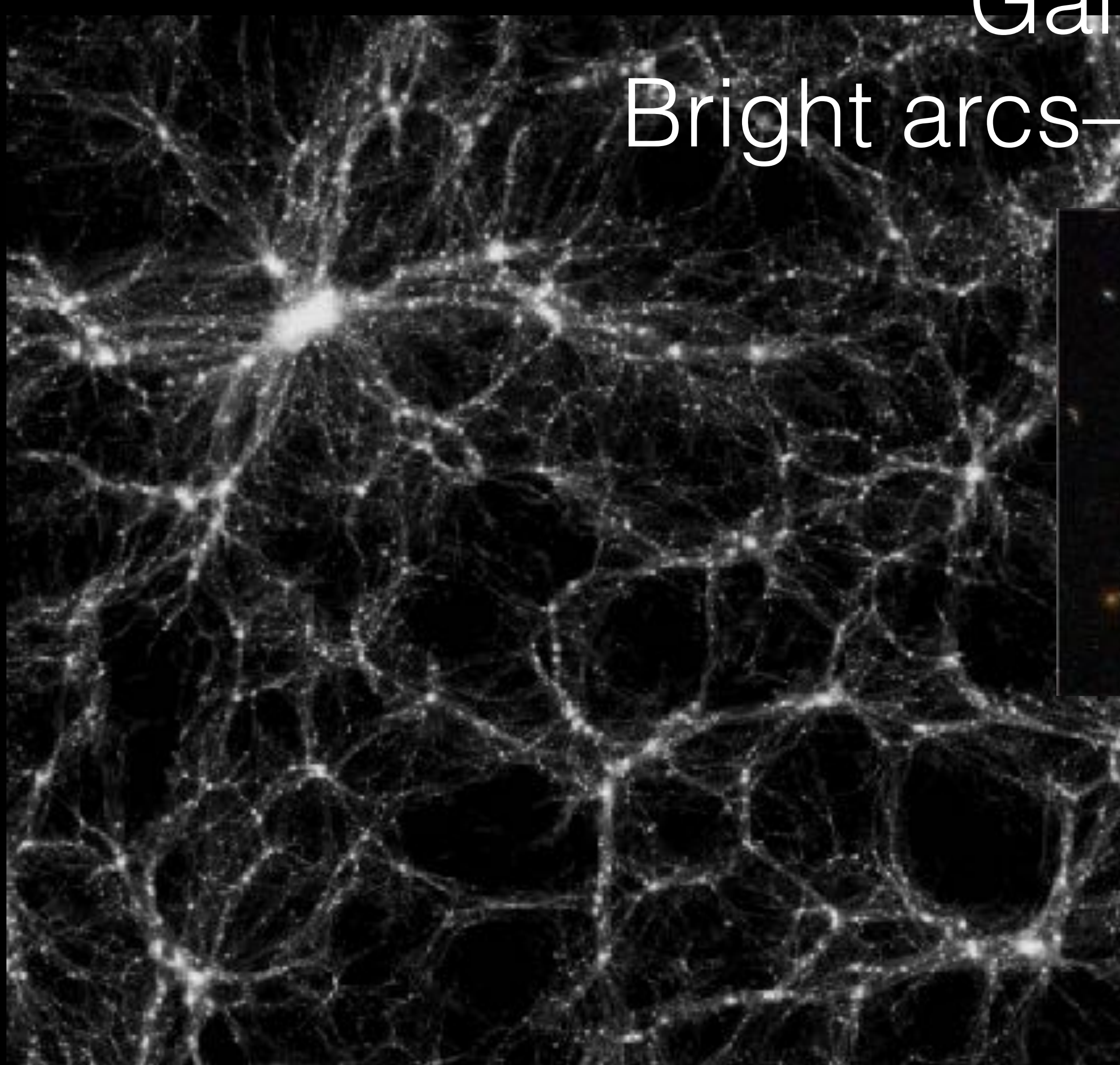
Prediction from GR

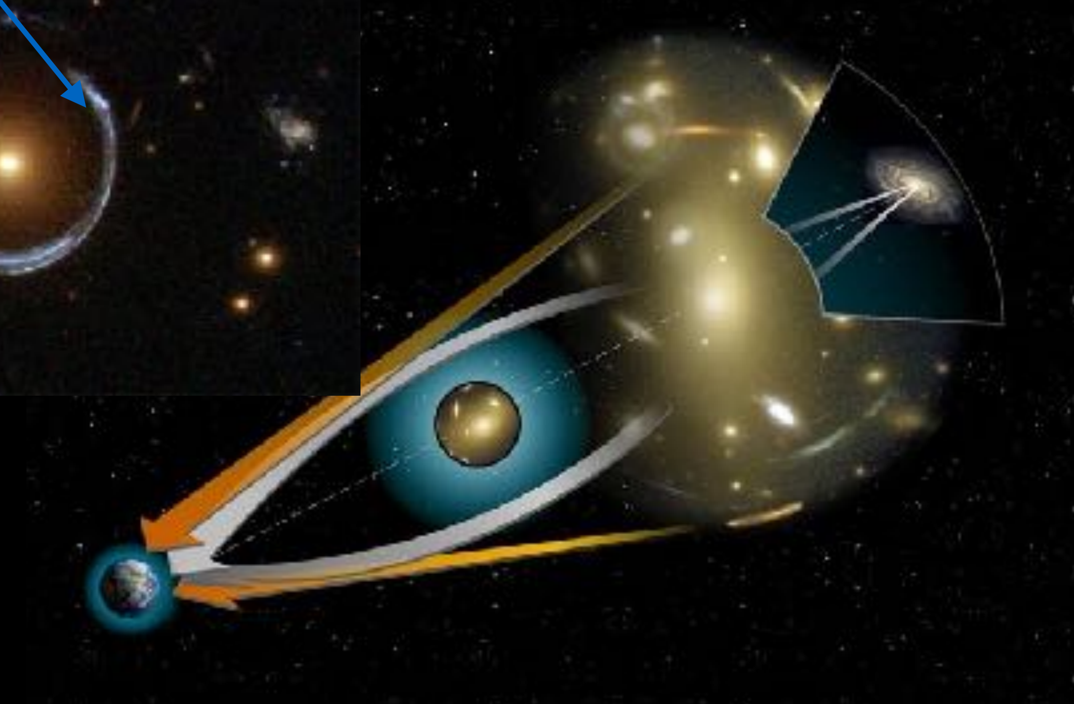
Null Geodesics

Visible like
bright arcs

Galaxy Clusters

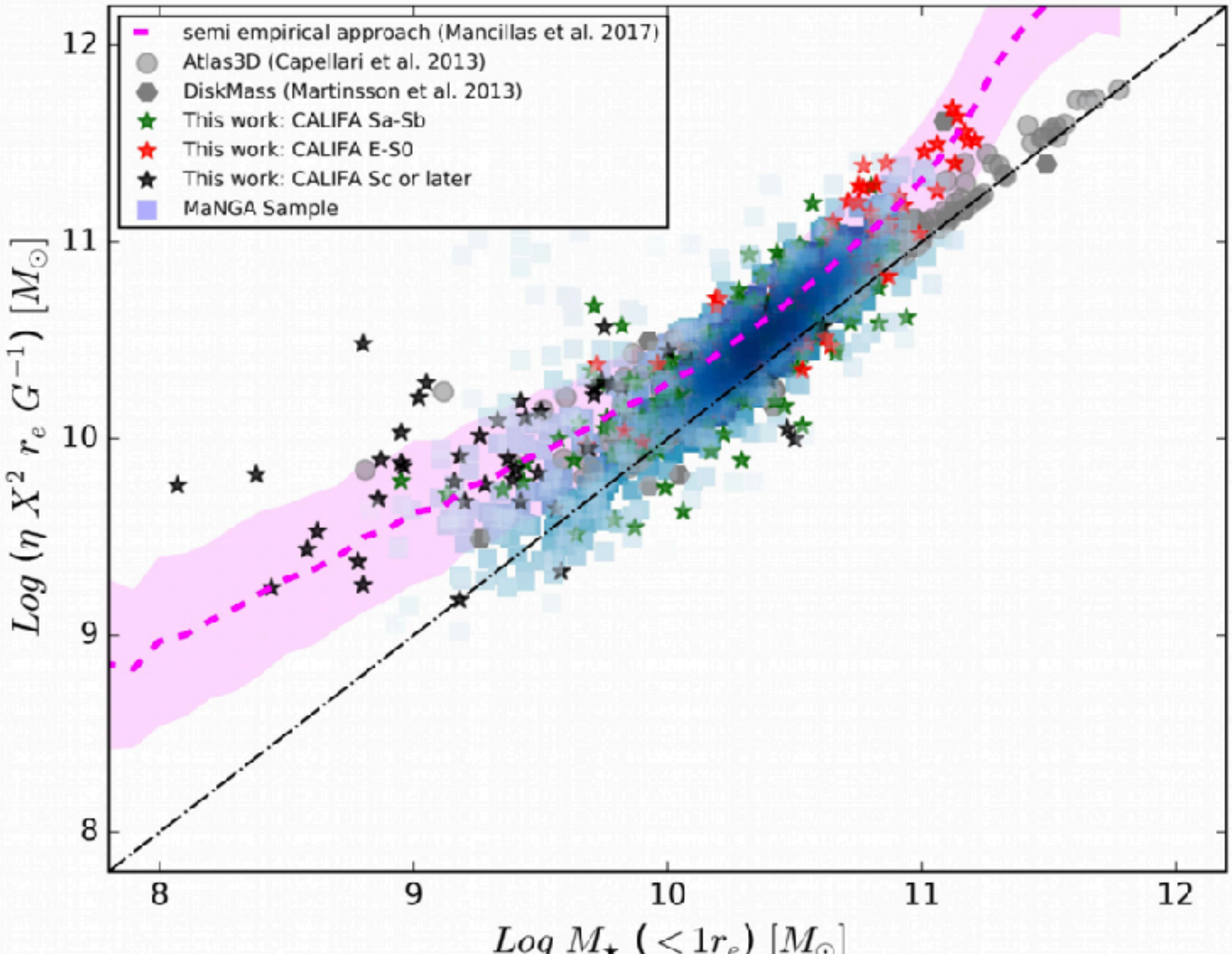
Bright arcs—> gravitational lens





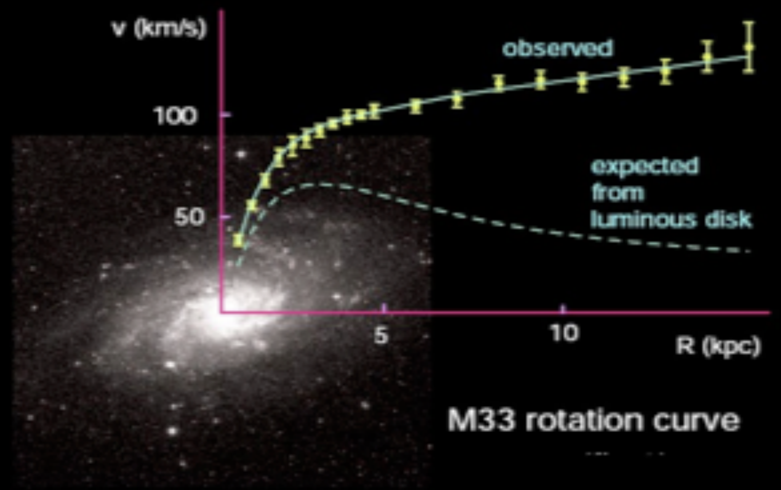
Apparently all galaxies have extra acceleration (dif methods)

Aquino, Valenzuela, Sanchez et al 2018
central dynamical mass vs central stellar mass, acceleration excess

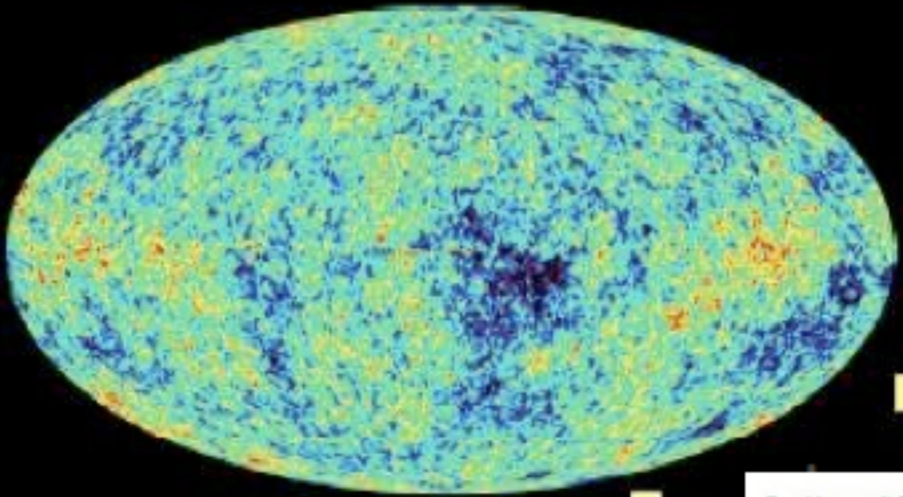


Bullet Cluster Strong Test

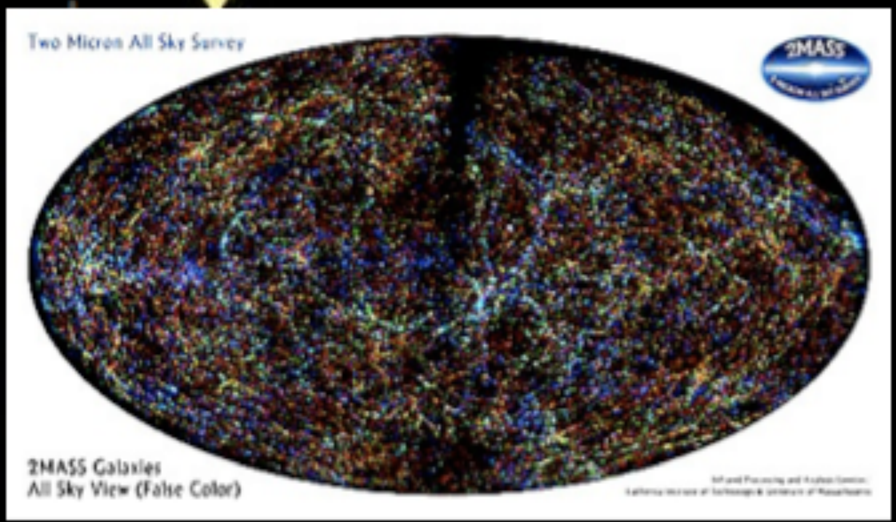
Gravity center does not coincide with the visible density center
There is something else producing gravity



From many astrophysical observations one's conclude (General Relativity behind) that



Dark Matter



Is needed

How is it distributed?

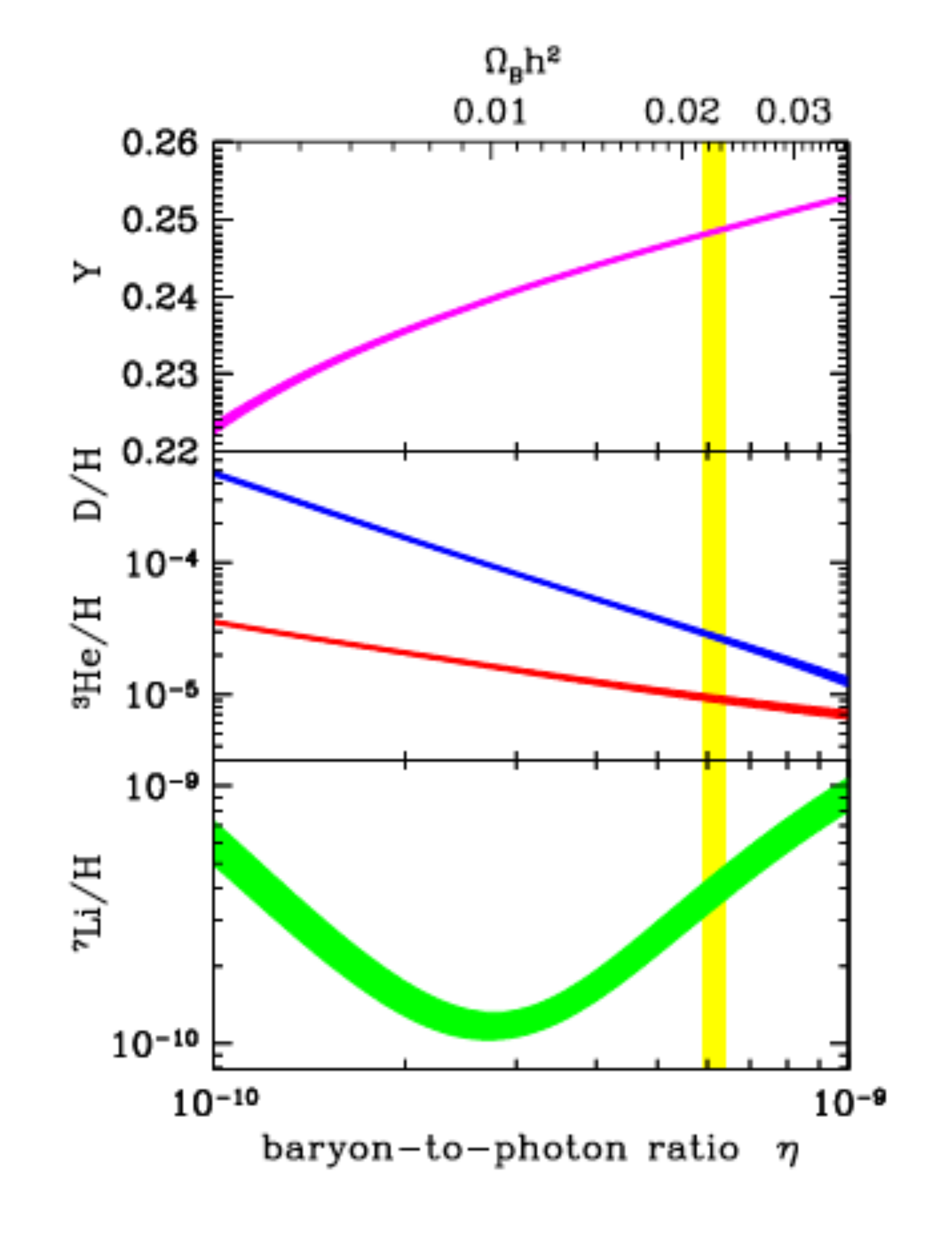
Is there all the predicted structure at galactic and subgalactic scales?

What is dark matter made of?

We know it is not barionic, CMB and Deuterium.

Can DM be baryons? No.
Then New physics!!!

If all DM is baryonic, it is in conflict with Big Bang Nucleonsynthesis and Cosmic Microwave Background anisotropy.
D abundance would be too low compared to observations
and CMB would be smooth



Dark Matter Ultimate Definition

— Excess of gravitational acceleration (curvature) in galaxies/clusters with respect to the acceleration that luminous matter will create if Newton and Einstein theories were correct.

— Delay on Silk damping of primordial fluctuacions

— Most of the mass in galaxies and the Universe does not emit light.

— Alternative??

Is there something wrong? Debate

Observational/ Experimental Problem?

What do we do?

Cosmologist are suspicious?? Dynamicists??

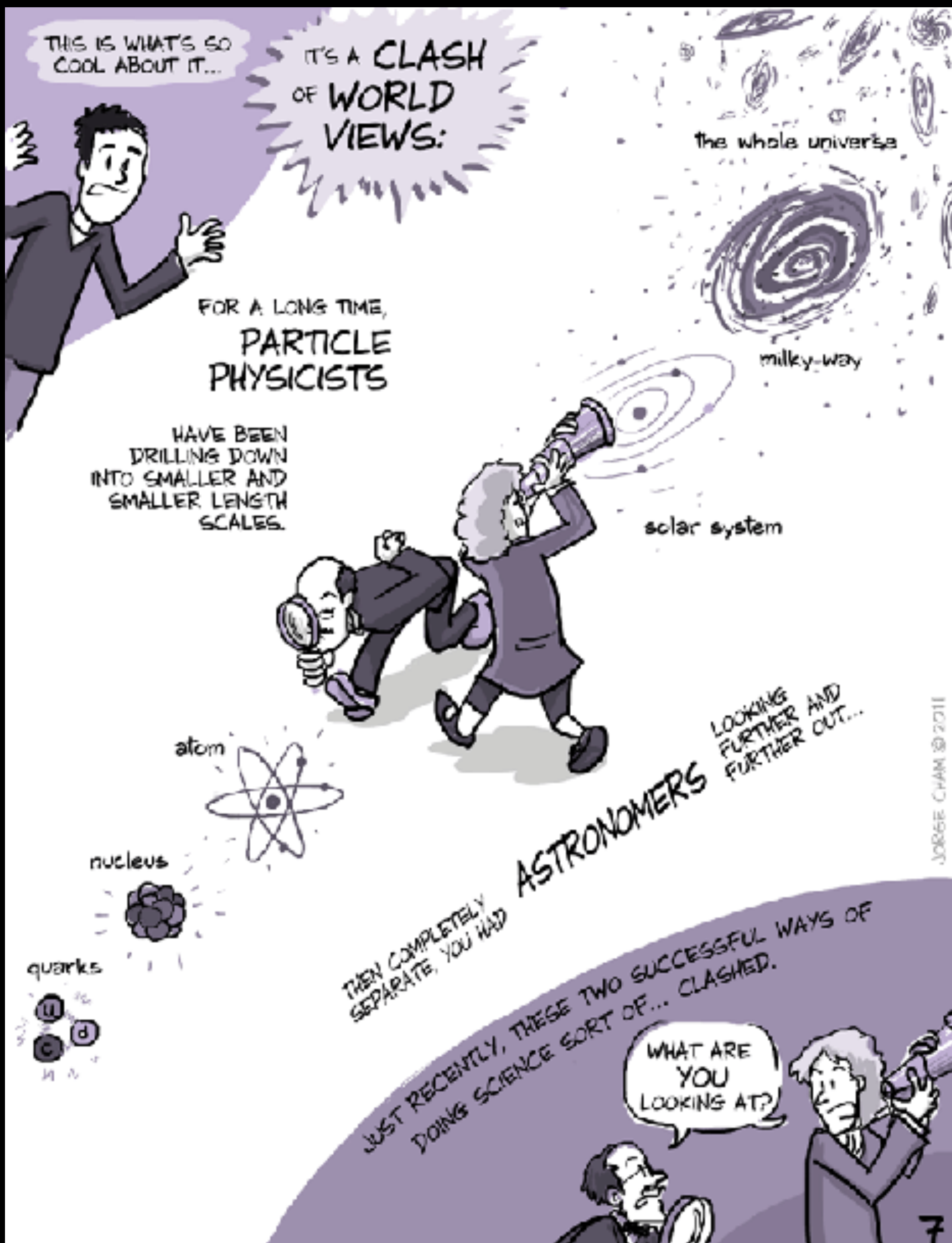
Too good/ugly to be true

Your proposal here…

PhD TV

WWW.PHDCOMICS.COM/TV

Astrophysics indicates that dark matter phenomenology and requires new physics



Where to look for Dark Matter Candidates ...

The Standard Model of particles

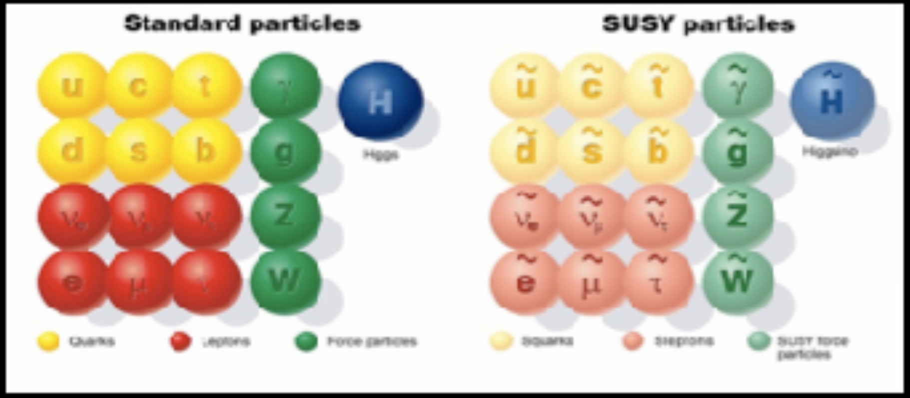
✔ Describes very accurately elementary particles and their interactions.

✔Confirmed experimentally by high precision measurements. Up some energy threshold...

One posible Solution is to extend the model

Eg. supersymmetry ⇒ symmetry relating bosons and fermions

At higher energies,,,



✗ Does not have explain the mass of the neutrinos.

✗ Origin of CP violation unknown.

Any extension implies new particles

Hierarchy problem: Theory not viable perturbatively ~ O(1TeV).

Interplay between theory, experiemnts and astrphysical observations

Challenges Particle and Fields Physics

- Hierarchy
- Neutrino Oscillation….
- CP violation
- Quantum Scalar fields
- Every solution involves new particles

Hierarchy Problem

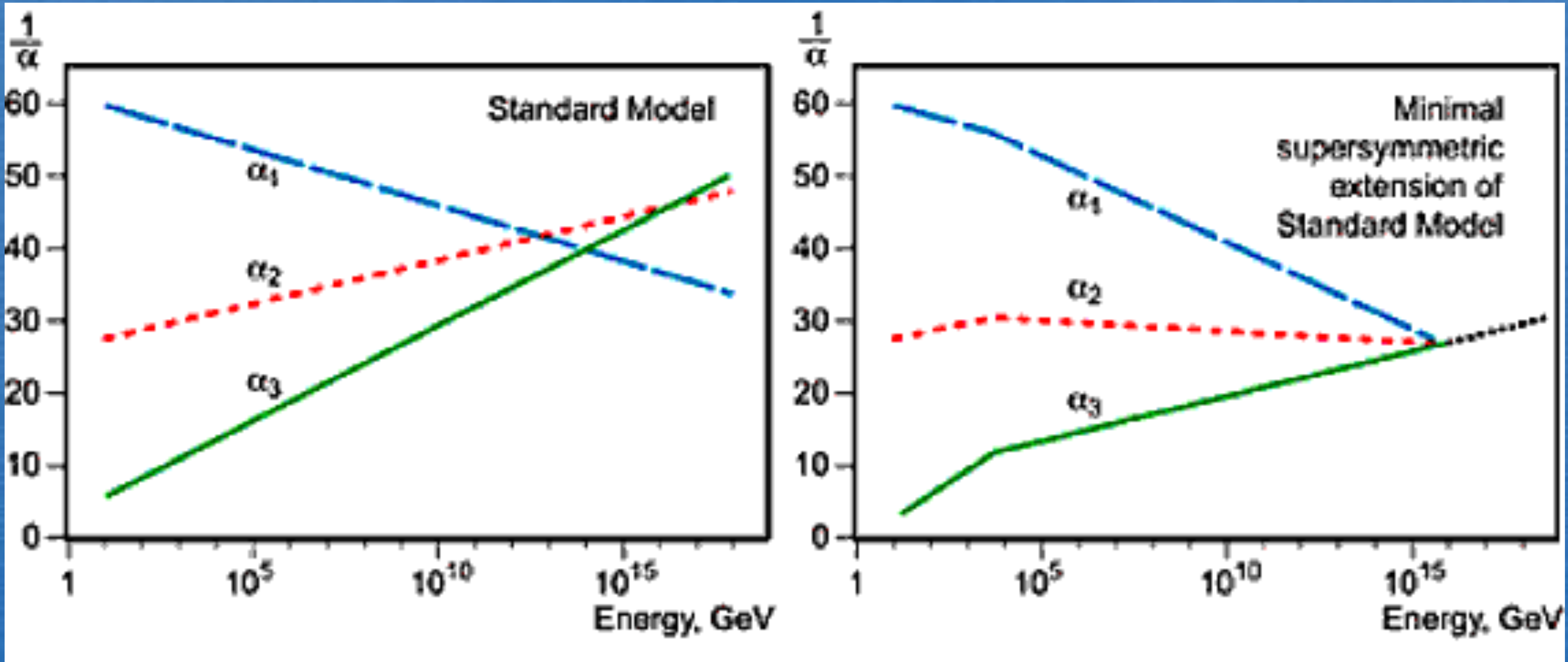
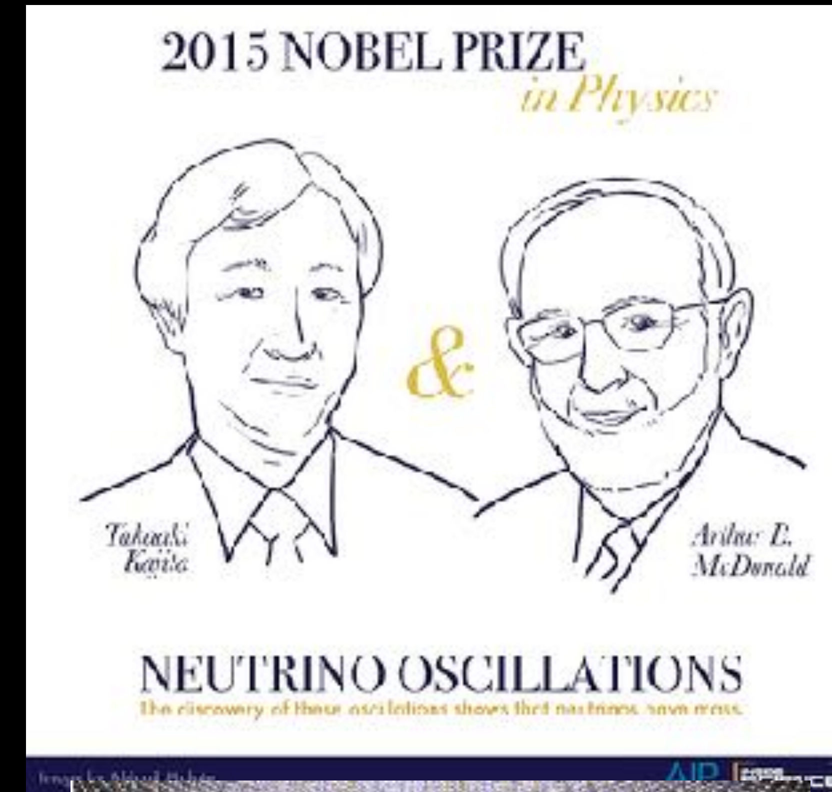
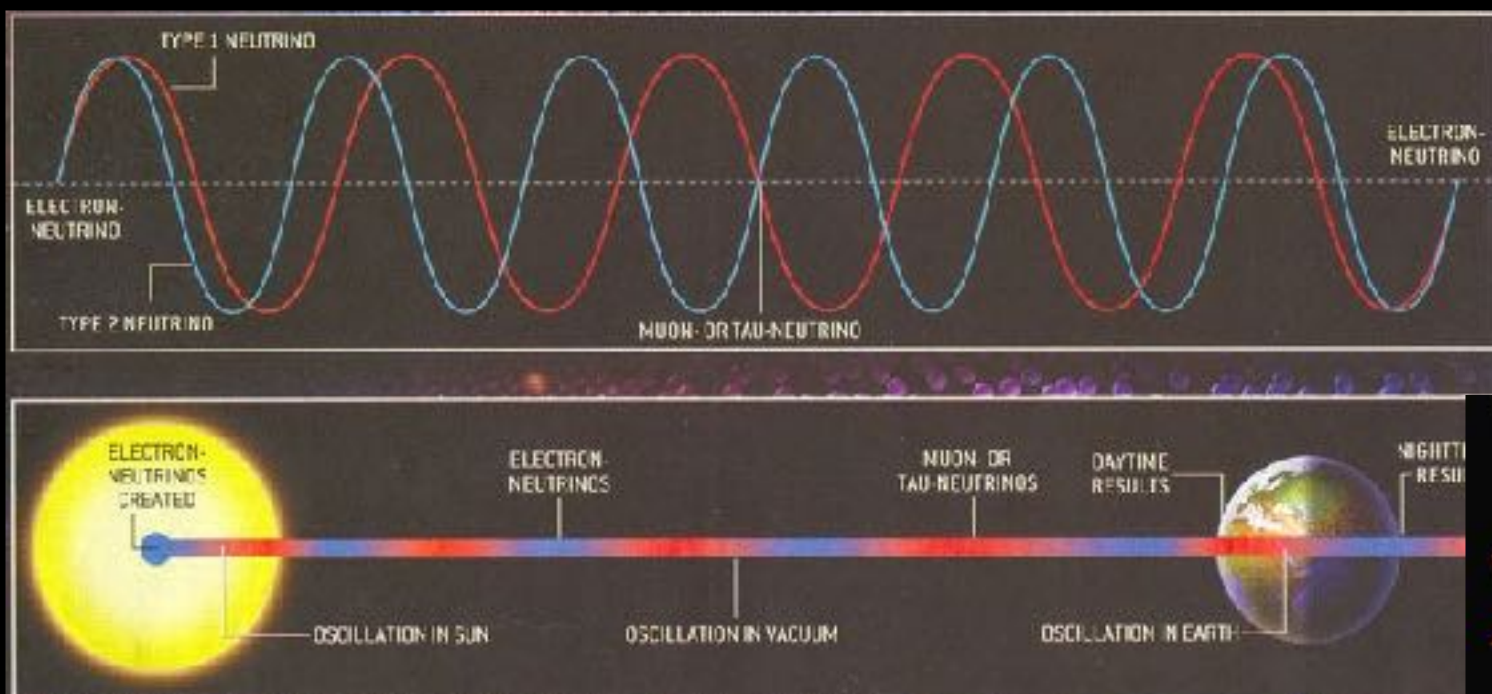


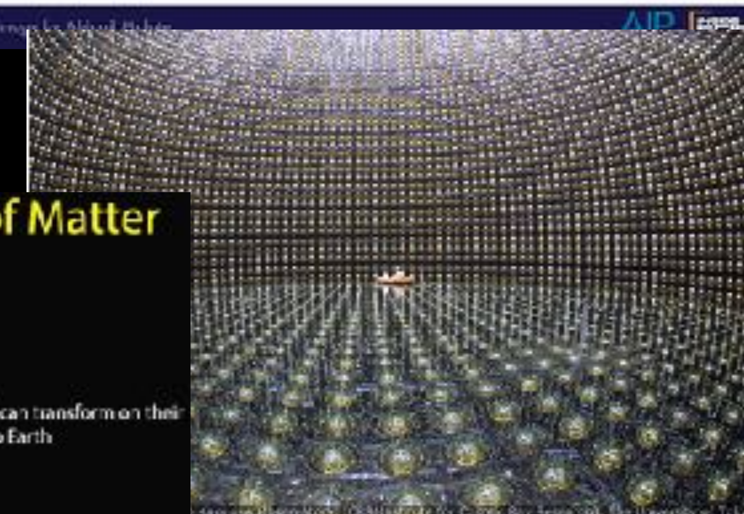
FIG. 8: Unification of interactions helped by SUSY

Supersymmetry? Neutralino Lightest stable particle, Gravitino?

Neutrino Oscillation—> massive
2015 Nobel Prize

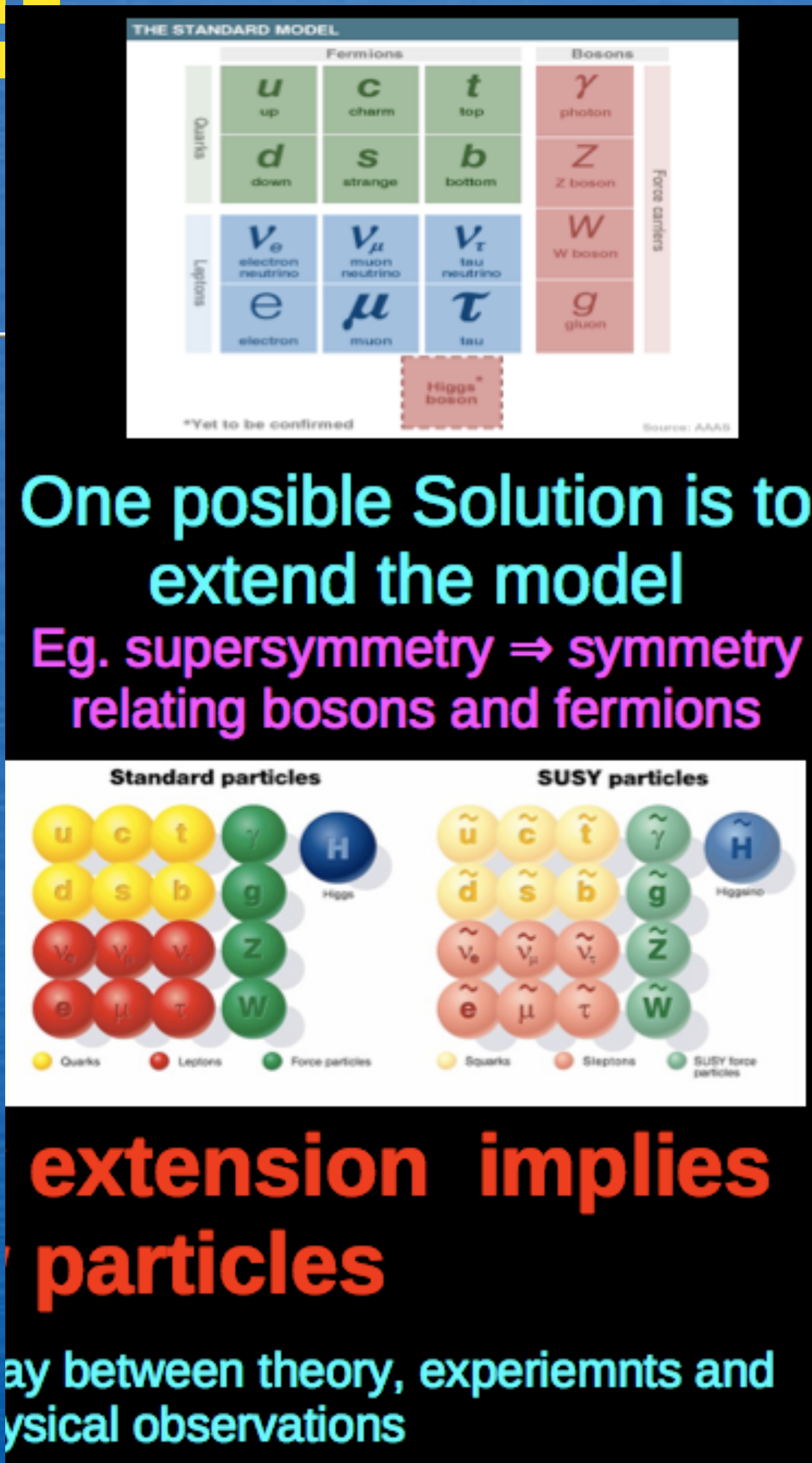






Sterile Neutrino: Makes standard neutrinos to oscillate?

What can Dark Matter be?



New elementary particles:

New theory of particles and fields?

Higher dimensions

Kaluza klein, Strings?

New particles

microscopic motivation

Dark Sector?

- Motivation
- Particle Physics
- Q. Field Physics

- Gravity Physics

- Clusters,Galaxies
- Sneutrino, ..
- Scalar Field, BoseEinsteinCondensate

- MOND,TEVES,f(R), DGP, GALILEONS

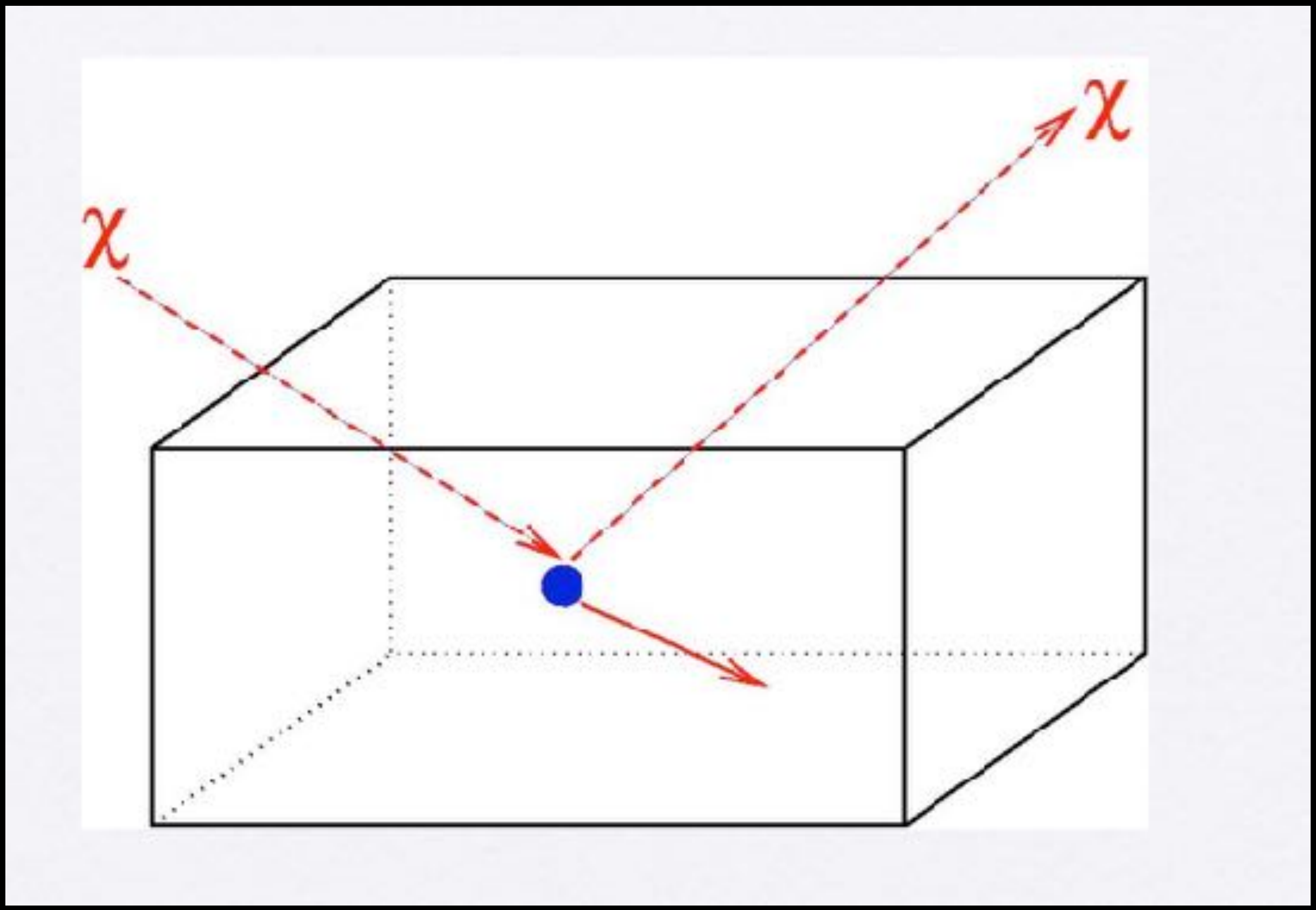
Some DM Particle Candidates

- Neutralino
- Axion: No gamma-ray, radio
- KK particles
- Wave/Axion like dark matter
- SNeutrino

- Majorana Particle: Selfanihilation into gamma rays. Mass Gevs
- Mass in Tevs
- Mass much less than 0.1 ev
- X rays

¿How to search/constrain for dark matter?

- Direct detection
- Accelerator
- In the sky: at least 2 strategies
-



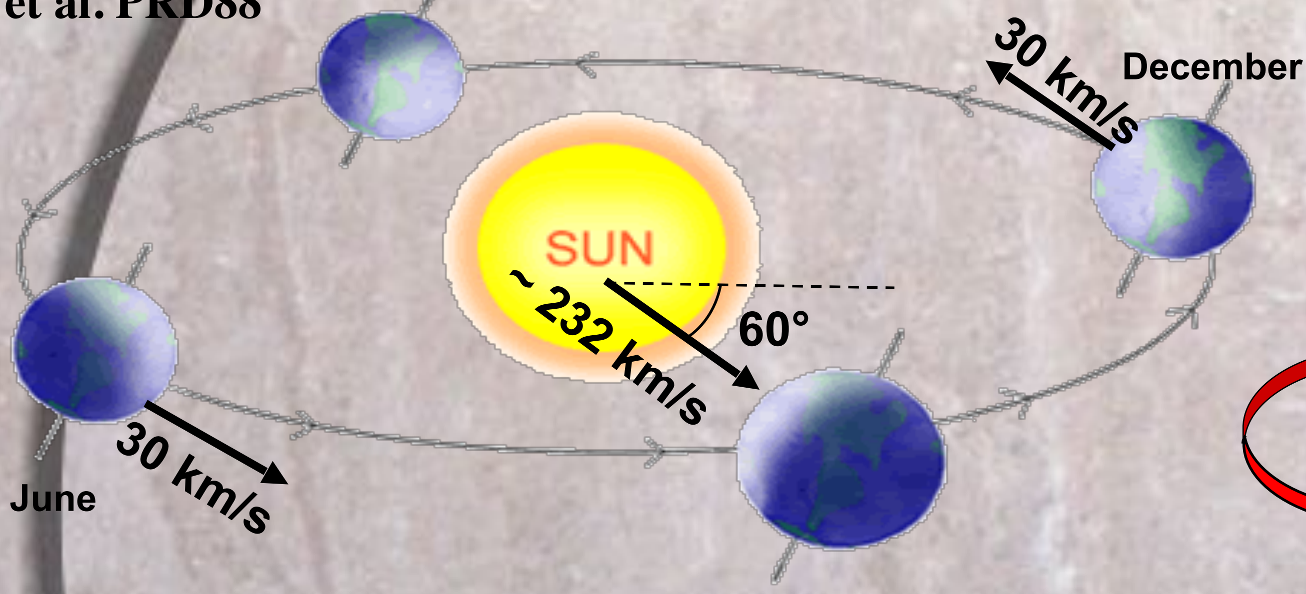
Direct detection
Collision with dark matter triggers
Nuclei recoil that emits light
low cross σ section and particle mas
requires
large amount of material

The annual modulation: a model independent signature for the investigation of Dark Matter particles component in the galactic halo

With the present technology, the annual modulation is the main model independent signature for the DM signal. Although the modulation effect is expected to be relatively small **a suitable large-mass, low-radioactive set-up with an efficient control of the running conditions would point out its presence.**

Bernabel 2008
Drukier, Freese, Spergel PRD86
Freese et al. PRD88

DAMA_LIBRA



- v_{sun} ~ 232 km/s (Sun velocity in the halo)
- v_{orb} = 30 km/s (Earth velocity around the Sun)
- $\gamma = \pi/3$
- $\omega = 2\pi/T$ T = 1 year
- $t_0 = 2^{nd}$ June (when $v_\oplus$ is maximum)

$$v_\oplus(t) = v_{sun} + v_{orb} \cos\gamma \cos[\omega(t-t_0)]$$

$$S_k[\eta(t)] = \int_{\Delta E_k} \frac{dR}{dE_R} dE_R \cong S_{0,k} + S_{m,k} \cos[\omega(t-t_0)]$$

Expected rate in given energy bin changes because the annual motion of the Earth around the Sun moving in the Galaxy

Requirements of the annual modulation

1) Modulated rate according cosine
2) In a definite low energy range
3) With a proper period (1 year)
4) With proper phase (about 2 June)
5) For single hit events in a multi-detector set-up
6) With modulation amplitude in the region of maximal sensitivity must be <7% for usually adopted halo distributions, but it can be larger in case of some possible scenarios

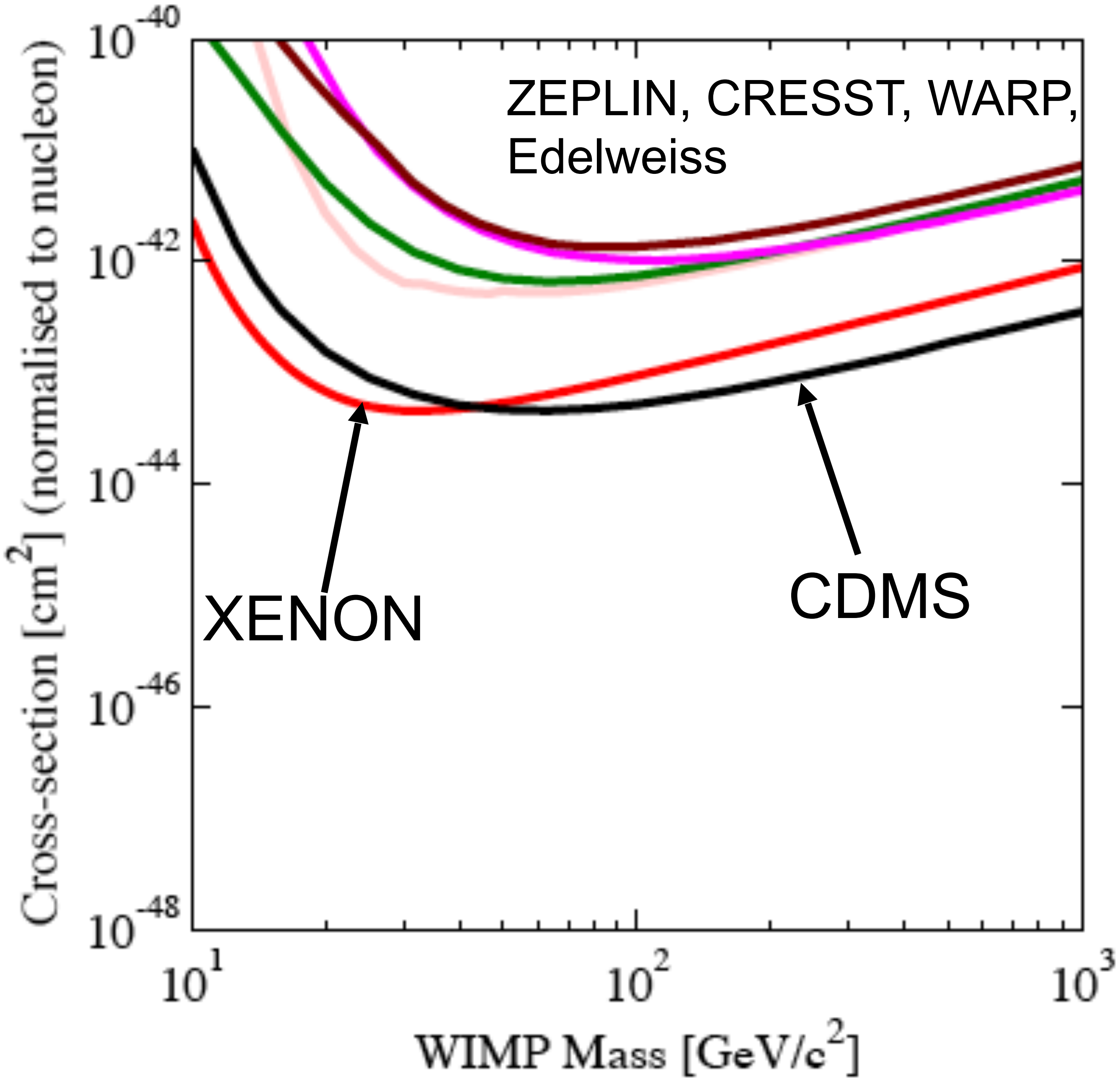
To mimic this signature, spurious effects and side reactions must not only - obviously - be able to account for the whole observed modulation amplitude, but also to satisfy contemporaneously all the requirements

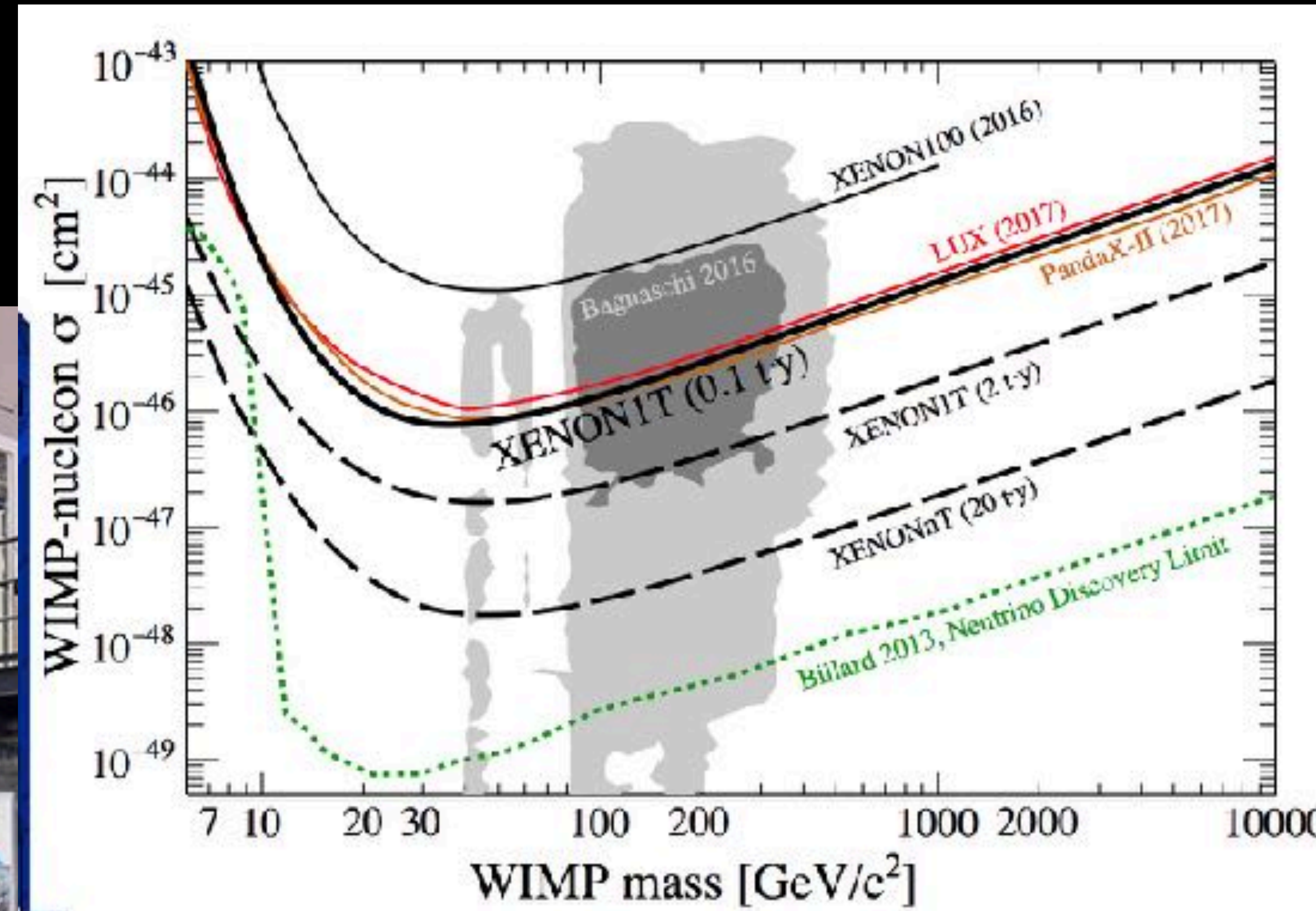
Direct Detection Experiments

- Elastic scattering between WIMPs and target nuclei

- In the past years, we have seen an order of magnitude improvement in sensitivity

Current Status

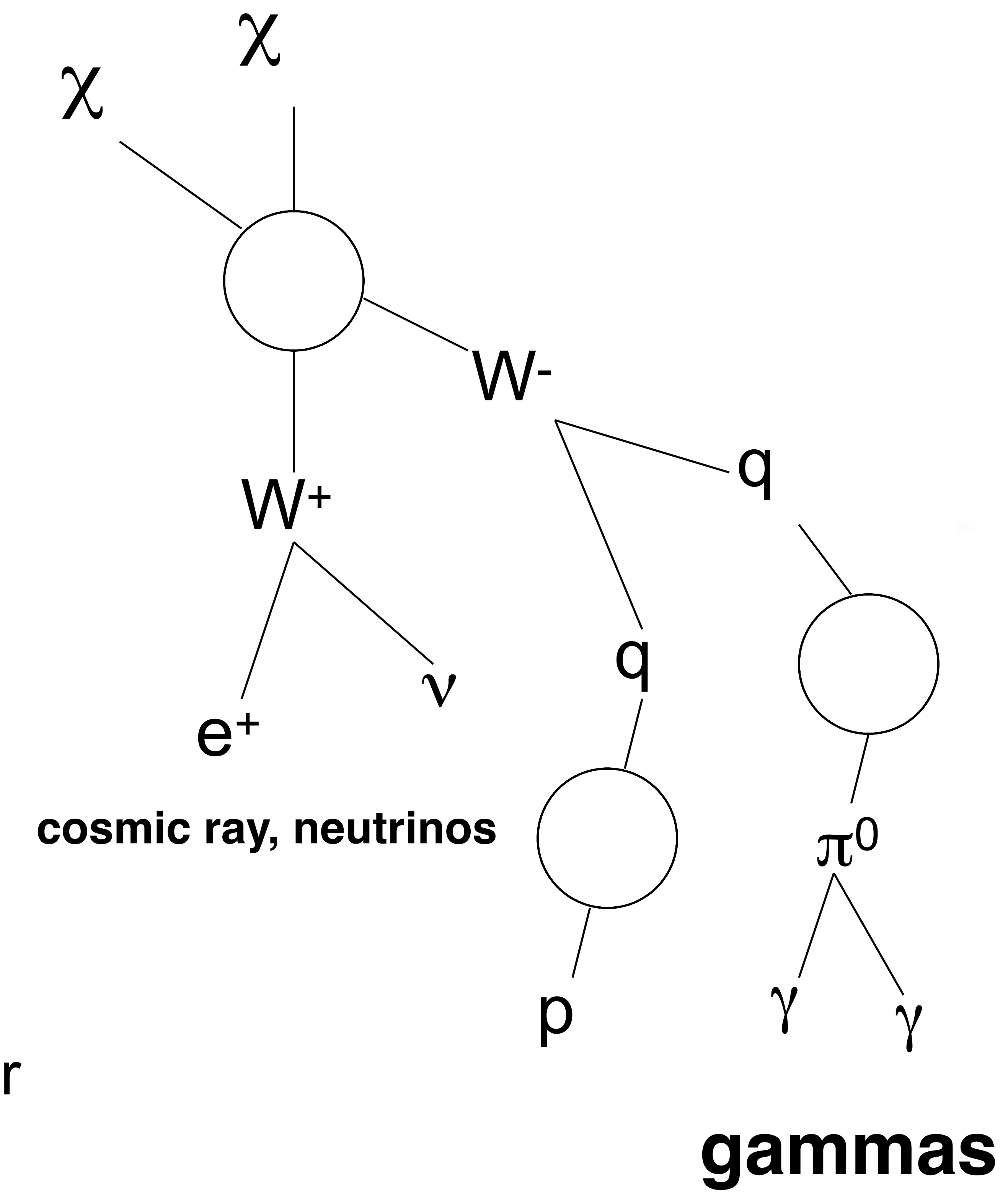




Next years

Also DAMA Libra is being reproduced by independent groups

The Indirect Detection of Dark Matter



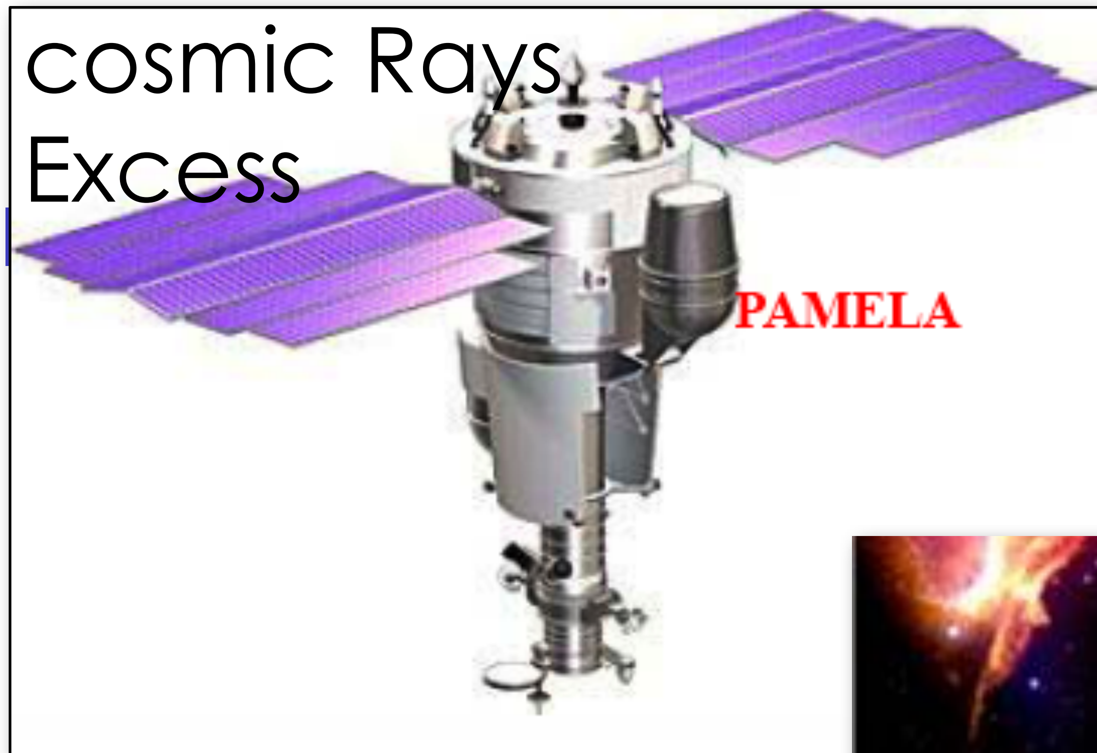
1. **WIMP Annihilation**
   Typical final states include heavy fermions, gauge or Higgs bosons

2. **Fragmentation/Decay**
   Annihilation products decay and/or fragment into combinations of electrons, protons, deuterium, neutrinos and gamma-rays

New Indirect Detection Results!

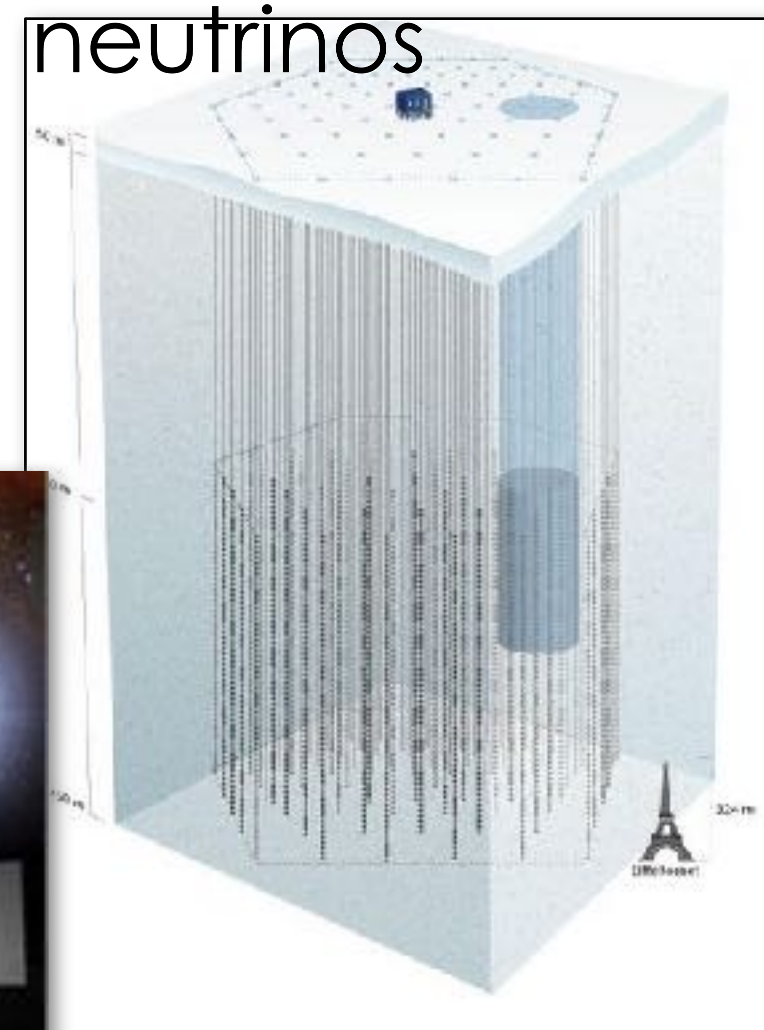
(When it rains it pours)

Pamela, cosmic Rays Excess



Fermi/Glast

IceCube, neutrinos



Indirect Detection Neutralino: Spectrum and Flux

The γ-ray flux [photons•cm^{-2} •s^{-1} •sr^{-1}] above a threshold energy E_0 is thus calculated:

$$\Phi_\gamma(\Psi, E > E_0) = \frac{N_\gamma \langle \sigma v \rangle}{8\pi m_\chi^2} \cdot \frac{1}{\Delta\Omega} \int_{\Delta\Omega} d\Omega \cdot \int_{los} \rho^2[r(s)] ds$$

Pointing angle

Telescope angular acceptance

FLUX uncertainties:

- Astrophysical: strong dependence on the spatial distribution of the amplification region → Modelization of the dark matter radial profile and its evolution necessary
- Particle Physics: cross section and branching ratios

Several sources of uncertainties, of several order of magnitude! Distance to the source plays a big role for detectability

Candidates for observation

High M/L dwarf spheroid galaxies

Draco

Uma:Ultra Faint Dwarfs

Globular Clusters

Mini-spike Model

Unidentified EGRET SOURCES

High galactic latitude

Dwarf spheroidal galaxies

Two possible candidates:

- Draco
- (Ursa Major)

Galaxies with

- high mass, low luminosity (M/L)
- low stellar gas, dust content
- have large DM content
  → good candidates for DM search
- CLEAN from other astrophysical emitters
  → reduced background

More concentrated Substructure the same Density profile

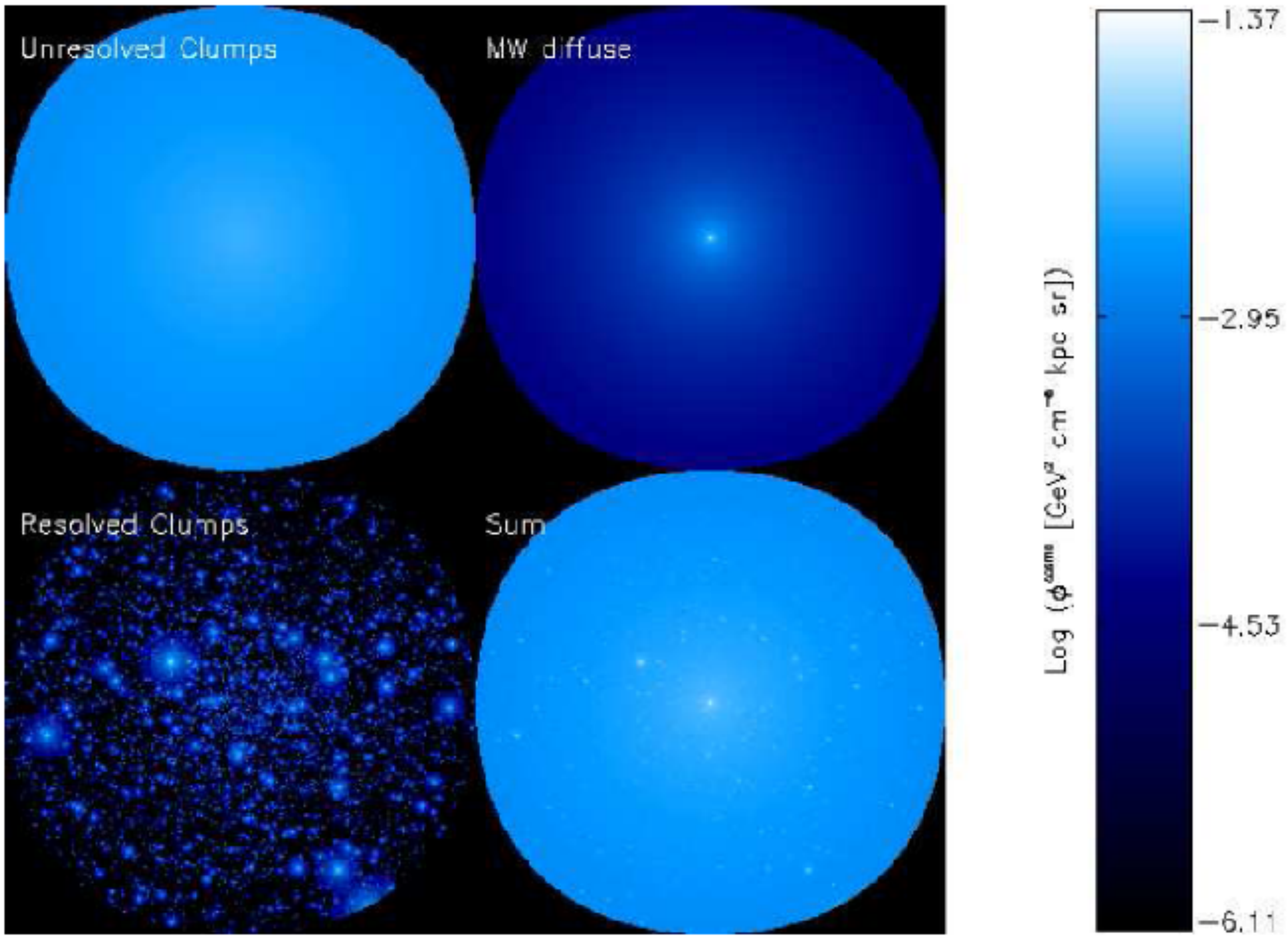
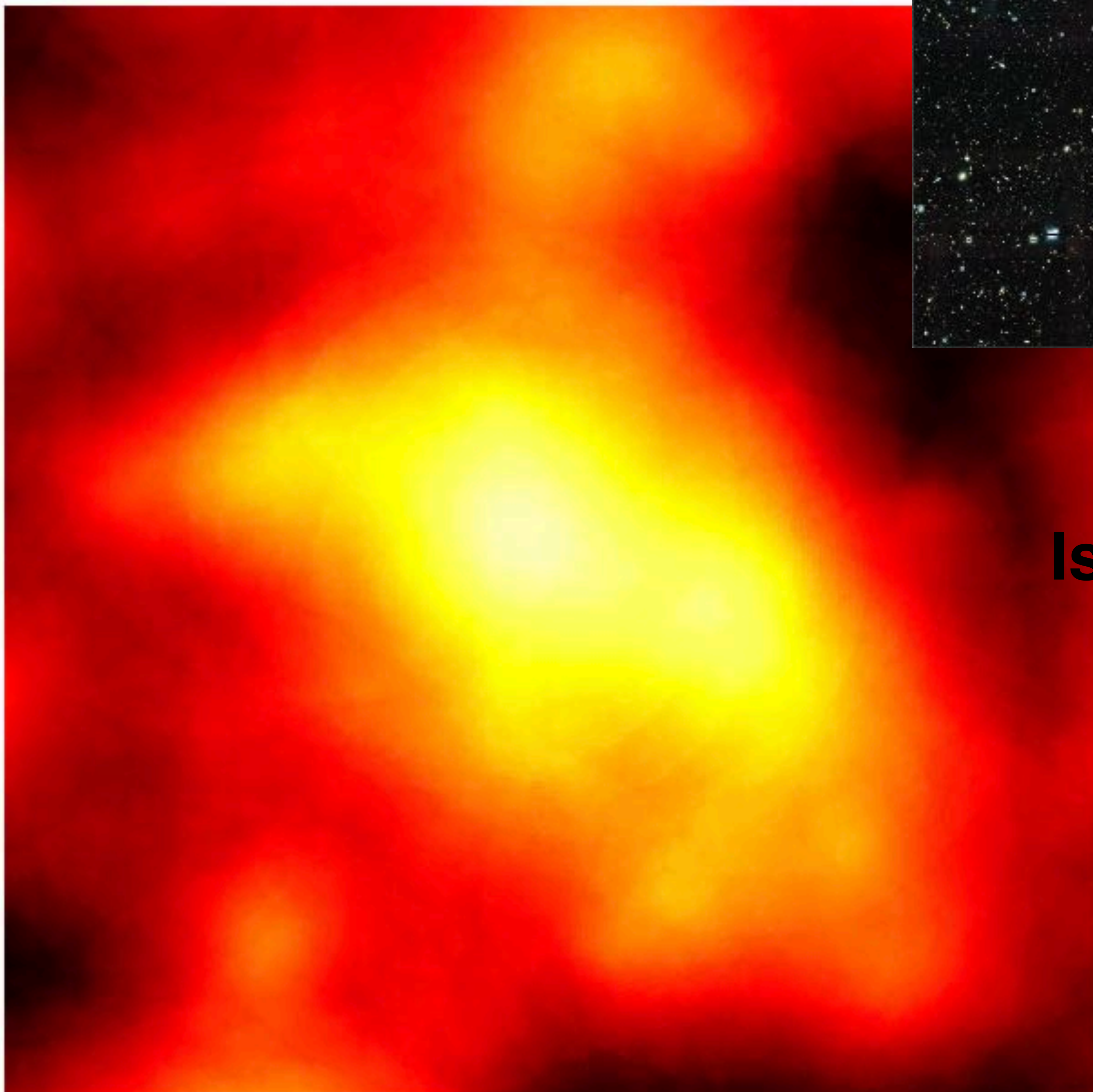


Figure 6. Map of Φ^{cosmo} (proportional to the annihilation signal) for the B_{ref,κ_c} model, in a cone of 50° around the Galactic Center, as seen from the position of the Sun. Upper left: smooth subhalo contribution from unresolved halos. Upper right: MW smooth contribution. Lower left: contribution from resolved halos. Lower right: sum of the three contributions.

Gamma Rays May Be Clue on Dark Matter

The New York Times

Reticulum2



Bright areas indicate gamma rays coming from the direction of the galaxy about 100,000 light-years away. Geringer-Sameth & Walker/Carnegie Mellon University

Is there a galaxy here

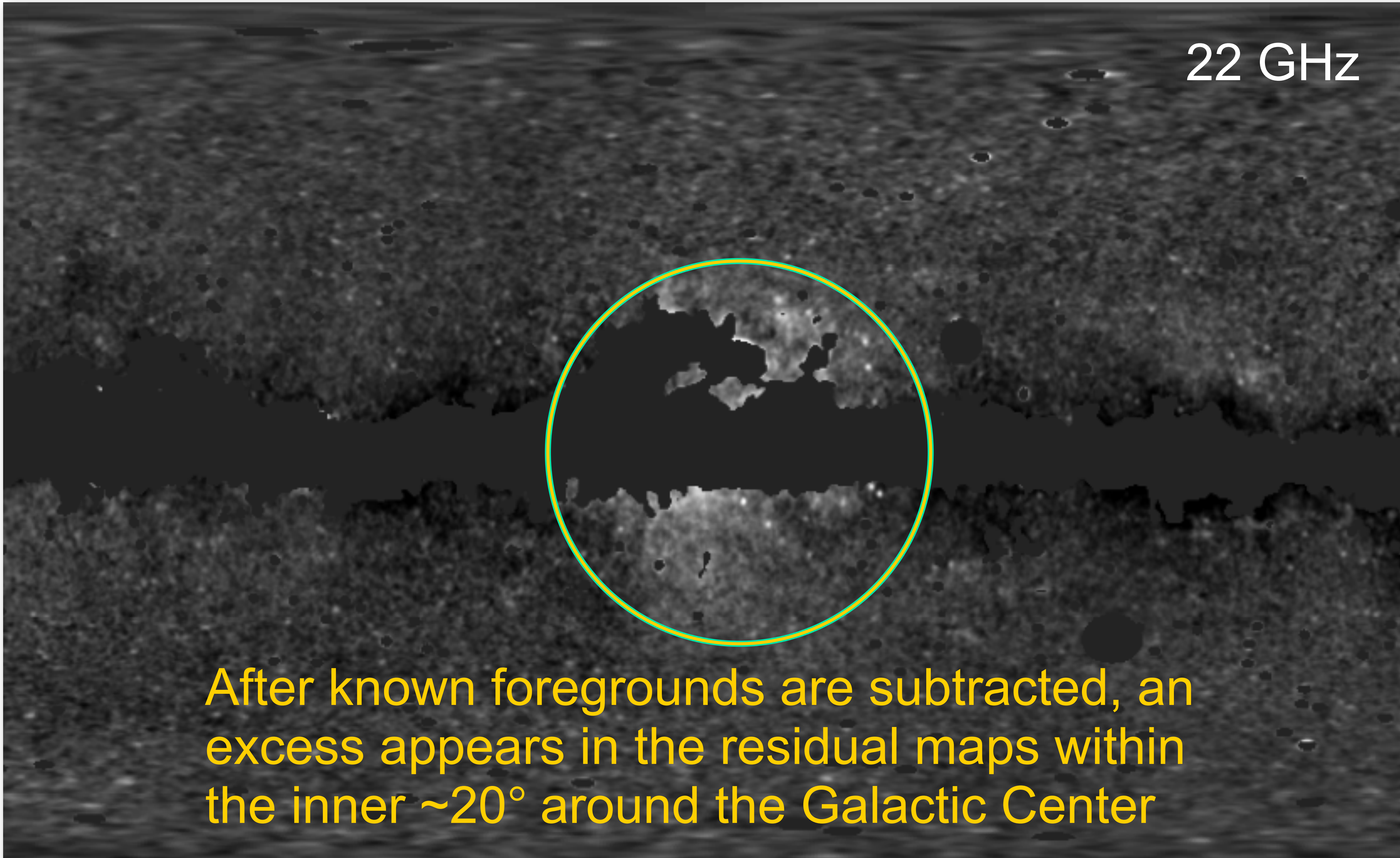
Controversial still

- The most massive globular cluster in the MW
- 5 Kpc from us
- Stellar population suggest is a galaxy¿?
- compact and closer than dsph´s
- Light profile and kinematics may indicate a cusp maybe an IMBH
- **Detected Gamma Ray Excess with no explanation**

- Detecting DM? Milisecond pulsar may mimic the emission. Currently pulsars not found.

with Gonzalez Morales
Oleg Burgueño
Javier Reynoso
S Profumo
A Geringer-Sameth

"The WMAP Haze"




ATTENTION
HAUTE
HIGH
TENSION
DANGER

Difficult task

- Why only 1 particle DM specie?
- Many possibilities
- Sensitivity in experiments
- How DM is distributed inside or around detectors, galaxies??

Using galaxy Astrophysics to constraint DM properties?

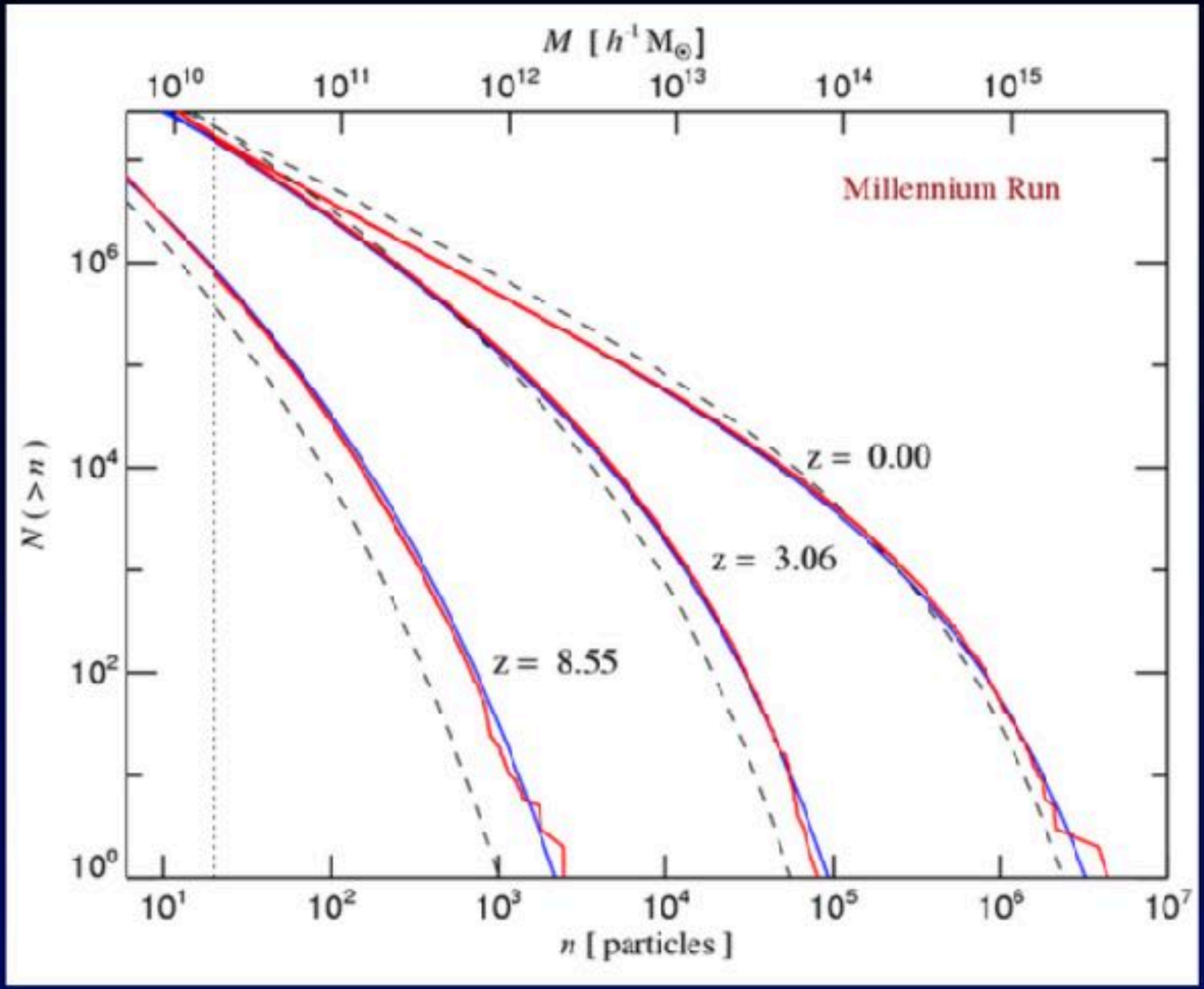
- Halos define galaxies environment and history
- Study halos properties:
- Theory:Simulations, statistical tools
- Observations? Hard
-

1974

Press & Schechter Theory

Halo abundance

- Excellent agreement of theory even with today's state-of-the-art simulations

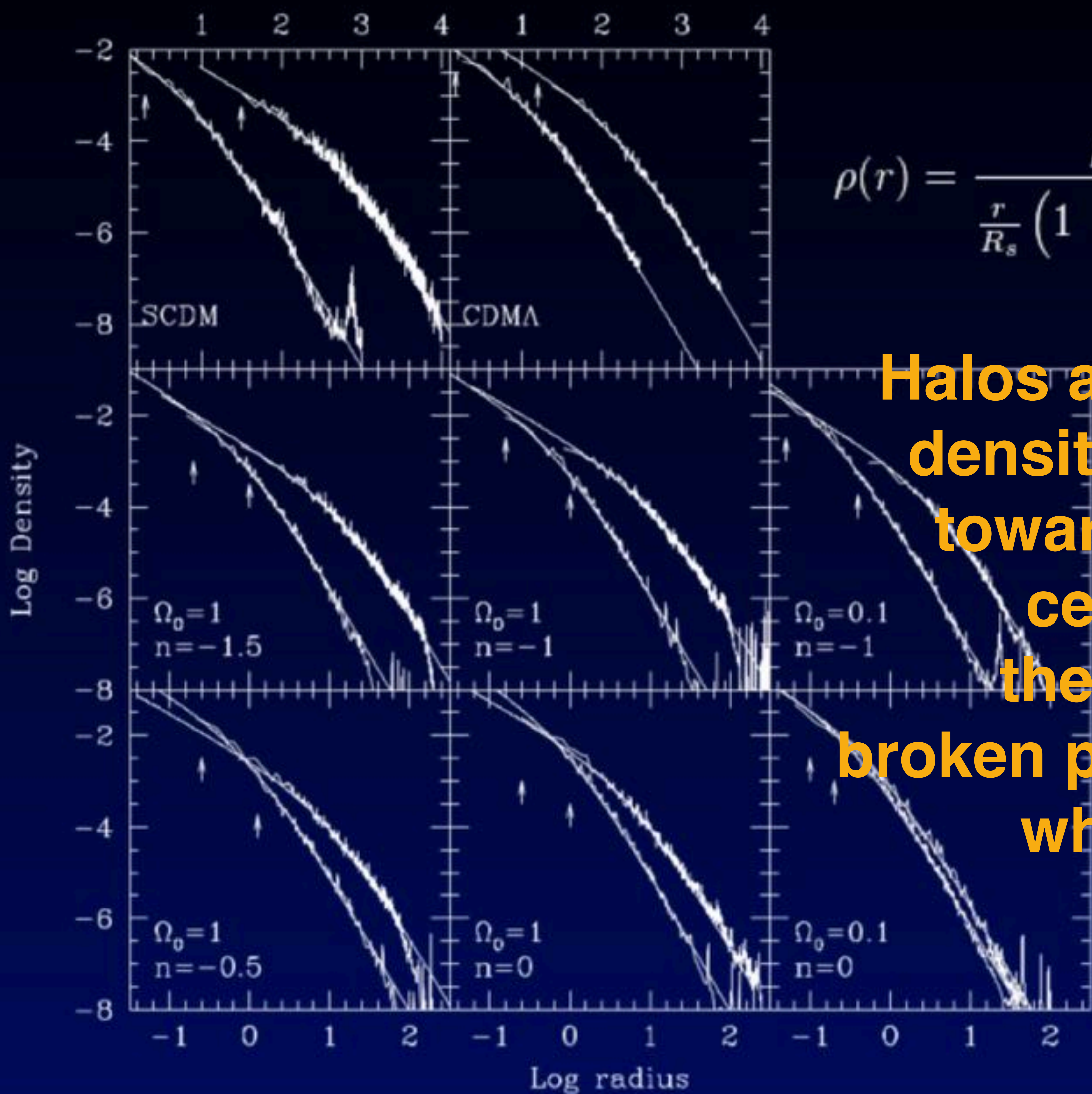


William Press

Paul Schechter

1997

The NFW profile Halo internal structure



$$\rho(r) = \frac{\rho_0}{\frac{r}{R_s}\left(1 + \frac{r}{R_s}\right)^2}$$

Halos are cuspy
density grows towards the center
they are broken power laws
why??


Julio Navarro

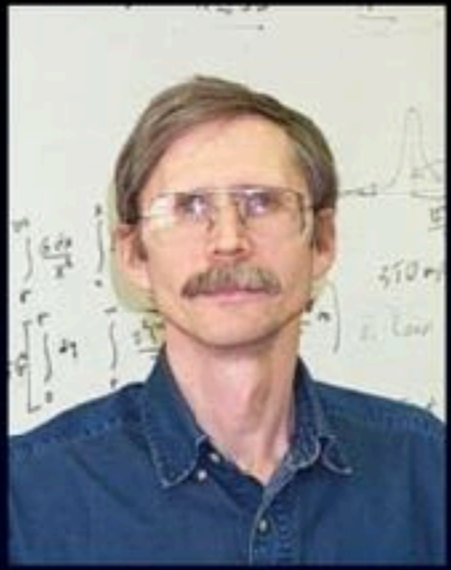

Carlos Frenk


Simon White

1999

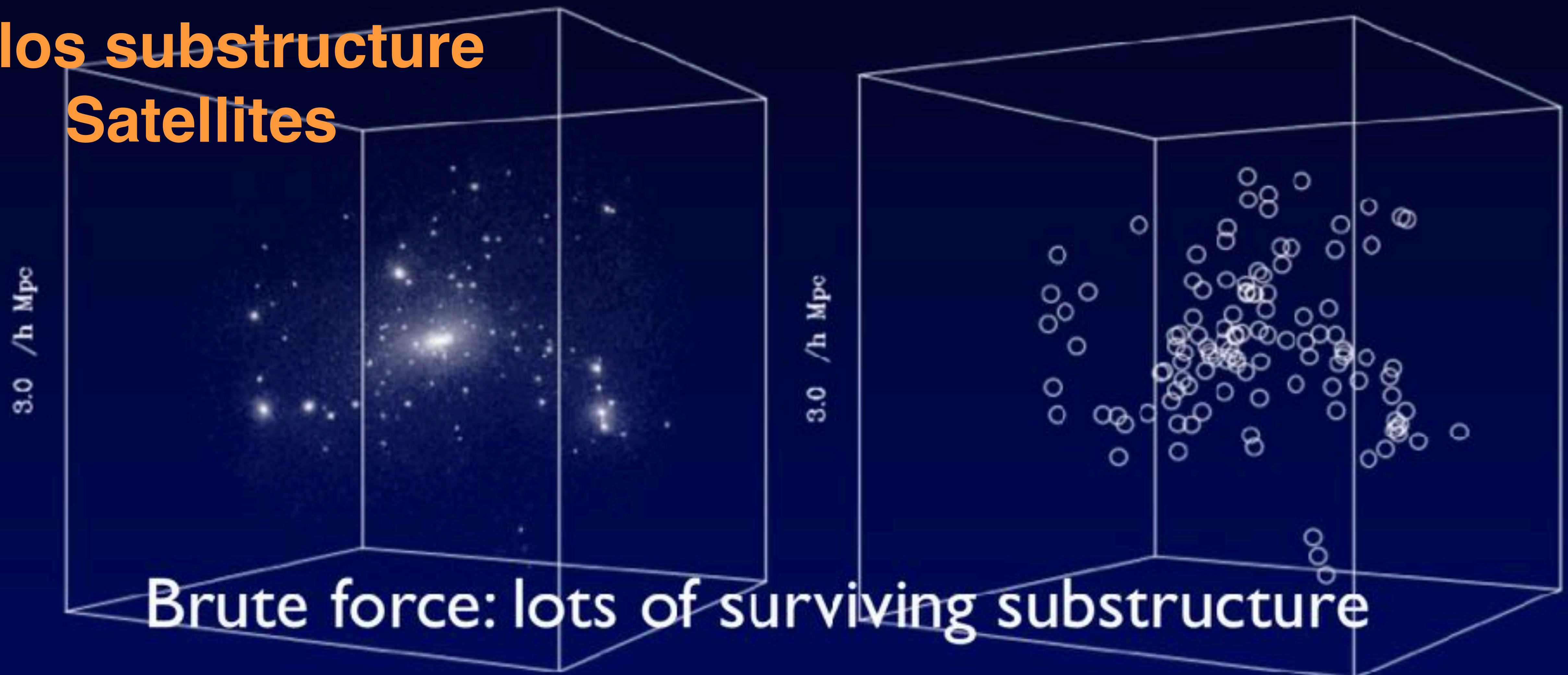
Overmerging vs. resolution

- Extremely high-resolution simulations (~250 000 particles per halo)
- Detailed study of physical vs. numerical effects
- New halo finder introduced (BDM)



Anatoly Klypin

Halos substructure
Satellites



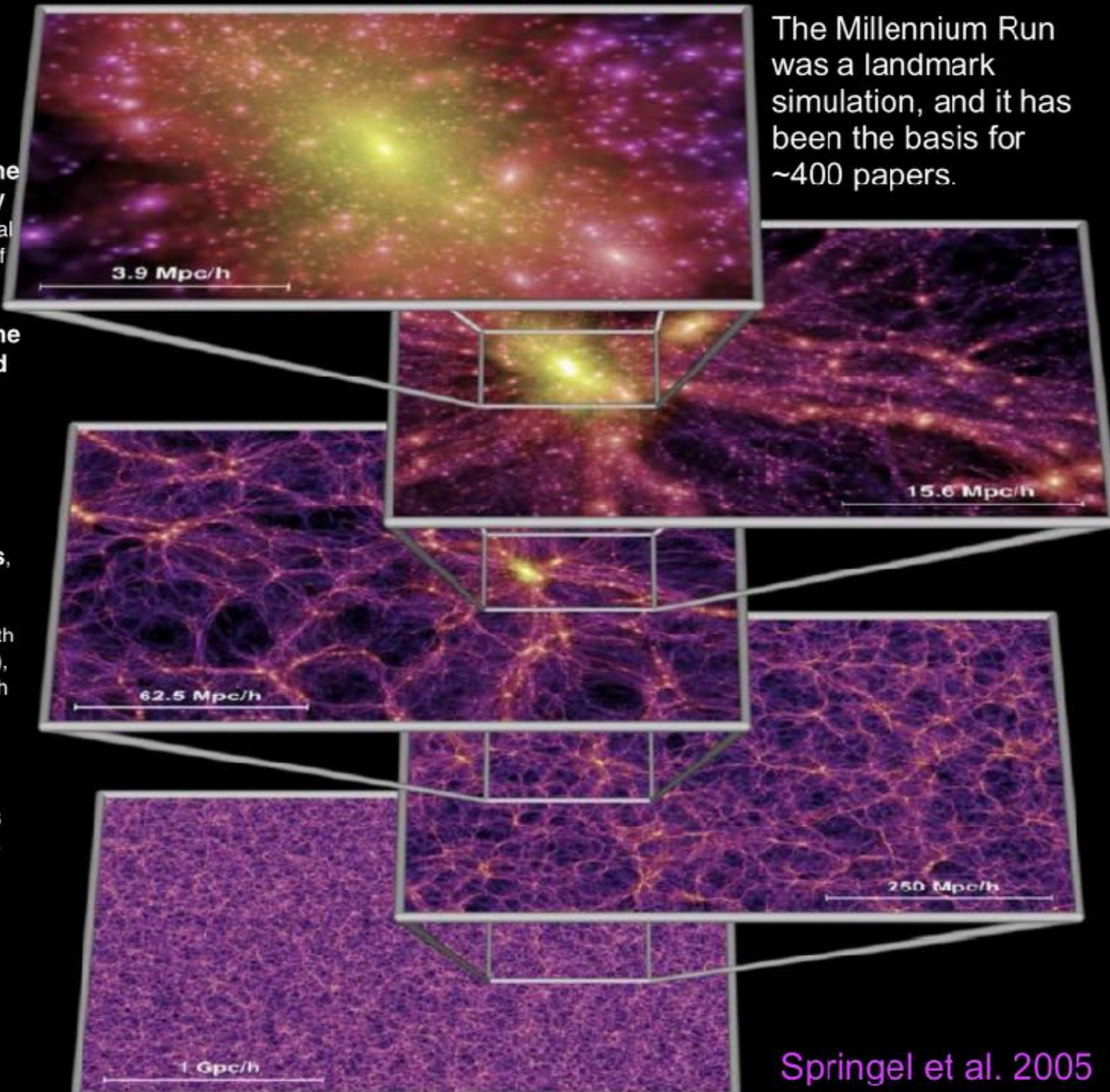
Brute force: lots of surviving substructure

Summary

- Halo internal structure is:
- Cuspy (density grows toward the center), Broken density laws. NFW
- Clumpy they have a number of dark matter clumps inside
- Shape: They are not spherical —>Triaxial
- Two general strategies:
- Numerical simulations (Nbody, hydro): New discovery tool, not only for verification, capture Nonlinear physics/mathematics
- Statistical tools: Mostly synthetic than predictive but highly efficient

The Millennium Run

- **properties of halos** (radial profile, concentration, shapes)
- **evolution of the number density of halos**, essential for normalization of Press-Schechter-type models
- **evolution of the distribution and clustering of halos** in real and redshift space, for comparison with observations
- **accretion history of halos**, assembly bias (variation of large-scale clustering with as- sembly history), and correlation with halo properties including angular momenta and shapes
- **halo statistics** including the mass and velocity functions, angular momentum and shapes, subhalo numbers and distribution, and correlation with environment



The Millennium Run was a landmark simulation, and it has been the basis for ~400 papers.

Springel et al. 2005

- **void statistics**, including sizes and shapes and their evolution, and the orientation of halo spins around voids
- quantitative descriptions of the evolving **cosmic web**, including applications to weak gravitational lensing
- preparation of **mock catalogs**, essential for analyzing SDSS and other survey data, and for preparing for new large surveys for dark energy etc.
- **merger trees**, essential for **semi-analytic modeling** of the evolving galaxy population, including models for the galaxy merger rate, the history of star formation and galaxy colors and morphology, the evolving AGN luminosity function, stellar and AGN feedback, recycling of gas and metals, etc.

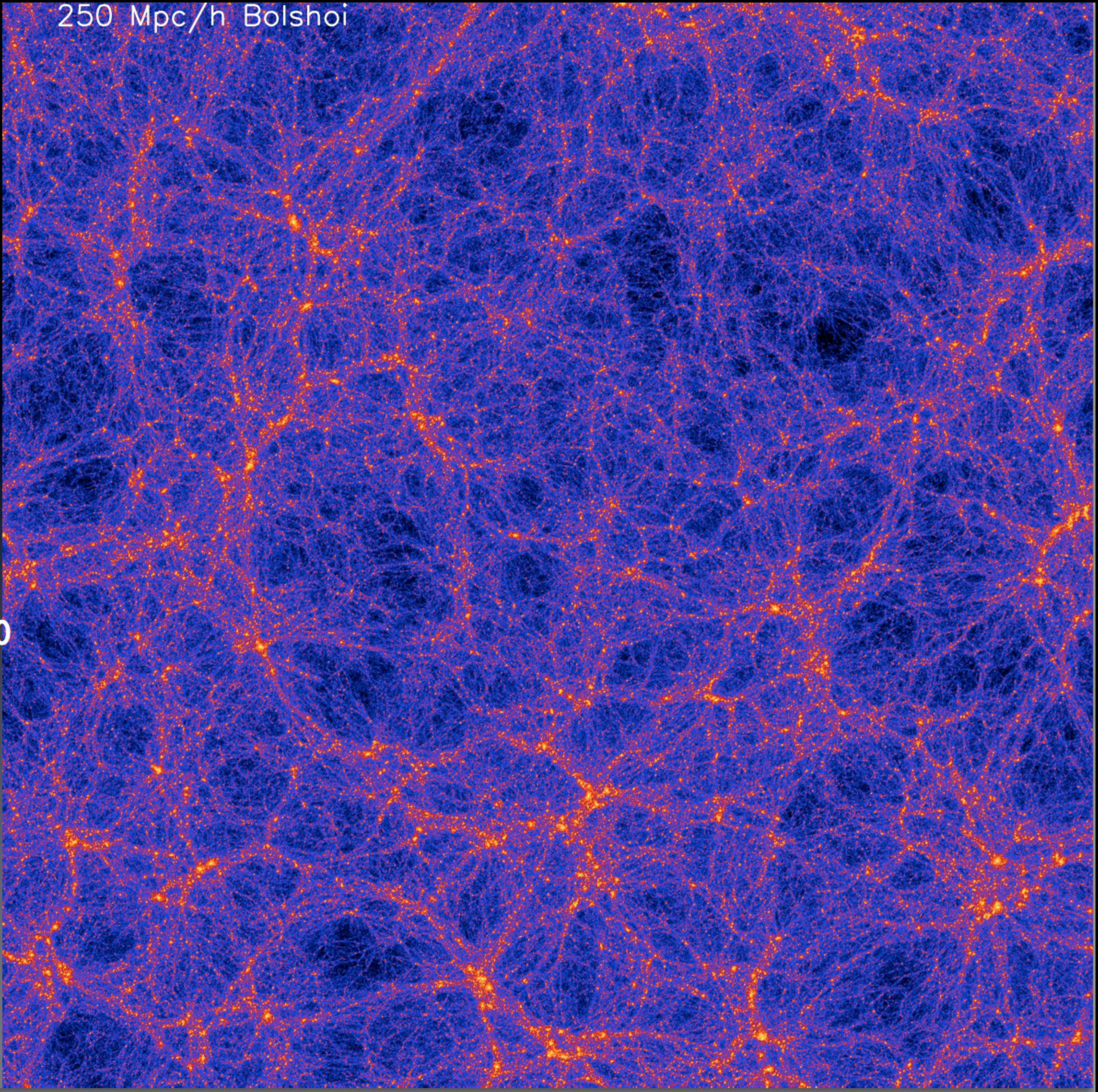
The Bolshoi simulation

ART code

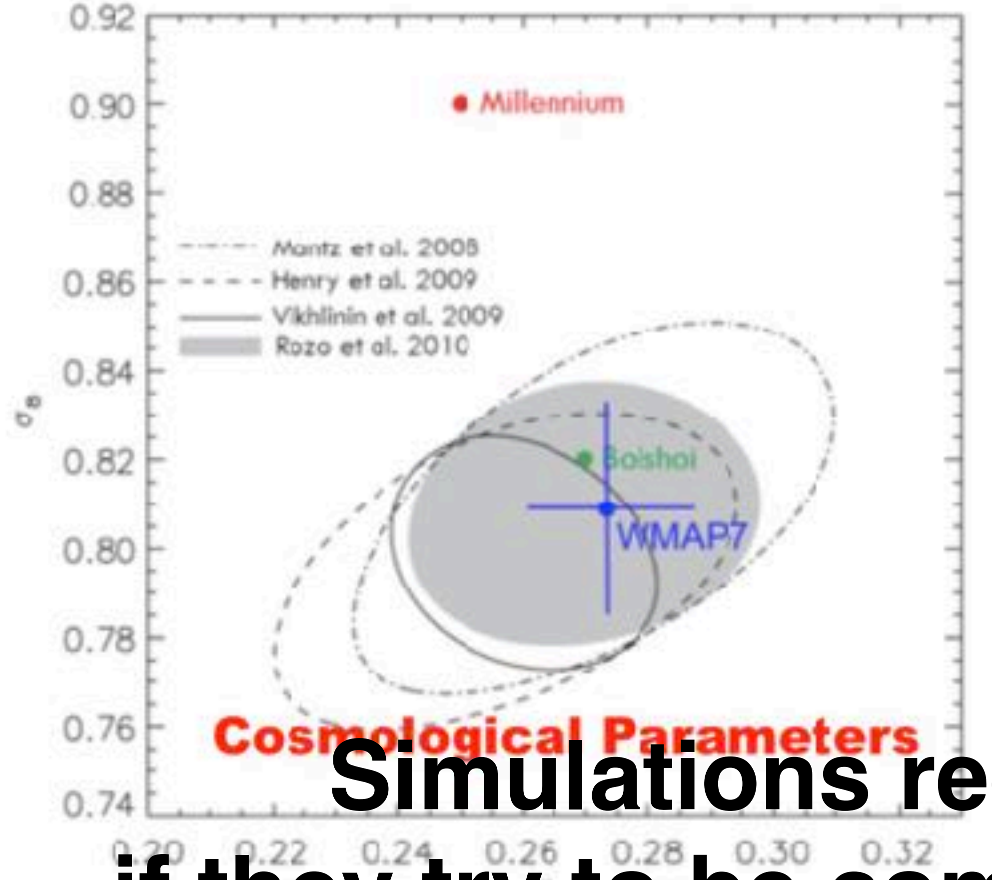
250Mpc/h Box
LCDM
s8 = 0.83
h = 0.73
8G particles
1kpc/h force resolution
1e8 Msun/h mass res

dynamical range 262,000
time-steps = 400,000

NASA AMES
supercomputing center
Pleiades computer
13824 cores
12TB RAM
75TB disk storage
6M cpu hrs
18 days wall-clock time



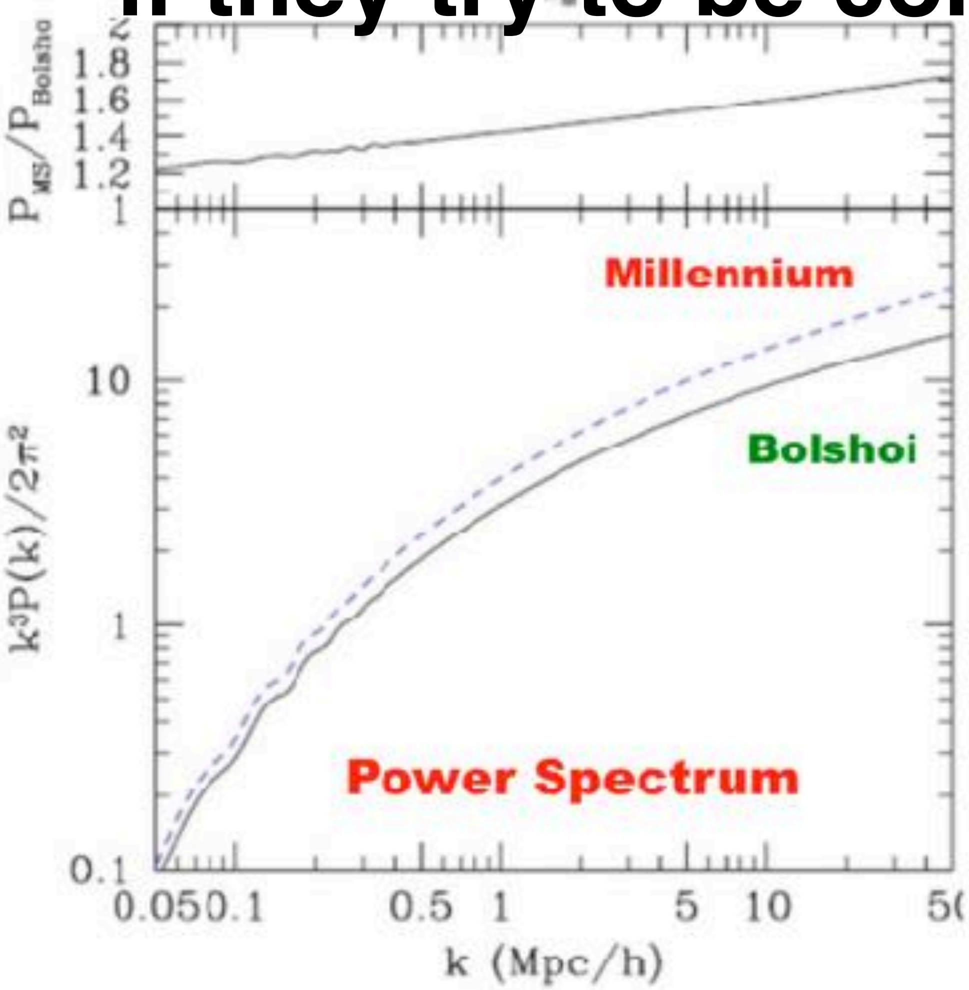
Halos and galaxies: results from the Bolshoi simulation

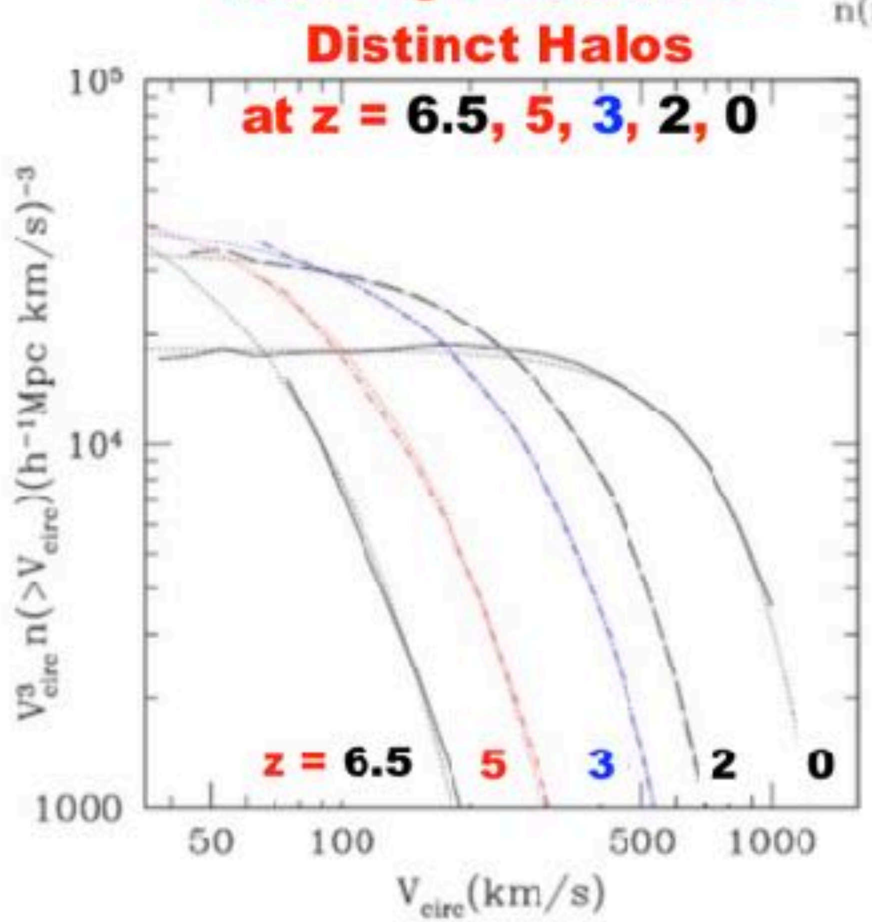


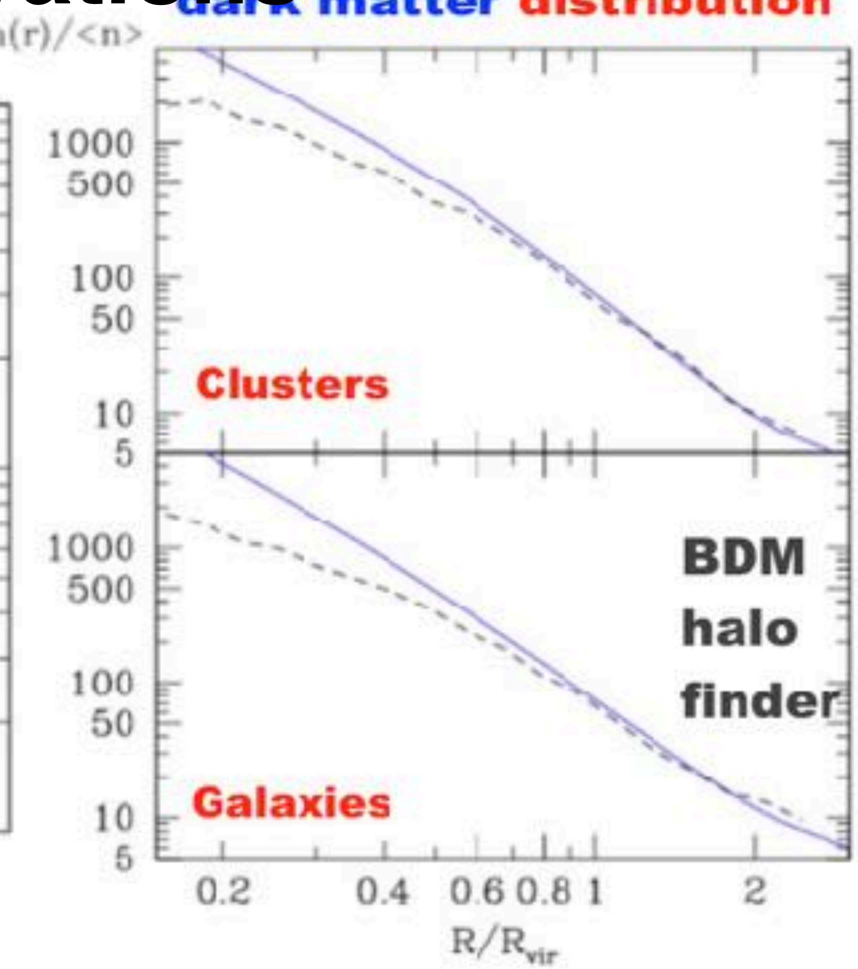
The Millennium Run (Springel+05) was a landmark simulation, and it has been the basis for ~400 papers. However, it and the new Millennium-II and XXL were run using WMAP1 (2003) parameters, and the Millennium-I resolution was inadequate to see many subhalos. The new **Bolshoi** simulation (Klypin, Trujillo & Primack 2011) used the WMAP5 parameters (consistent with WMAP7) and has nearly an order of magnitude better mass and force resolution than Millennium-I. We have now found halos in all 180 stored timesteps, and we have complete merger trees based on Bolshoi.

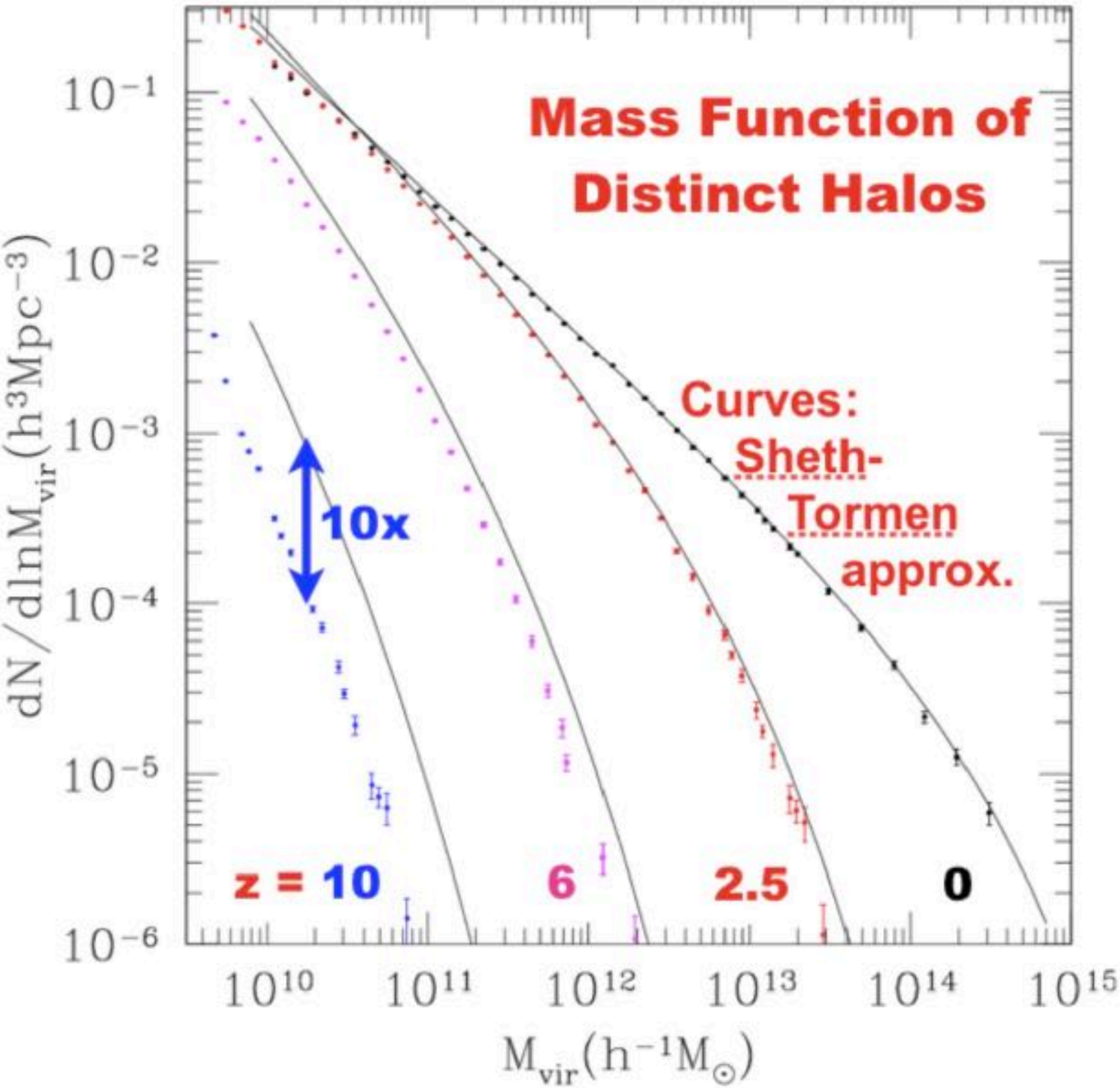
Klypin, Trujillo-Gomez, & Primack, arXiv:1002.3660 ApJ in press

Simulations required improvement if they try to be compared with observations

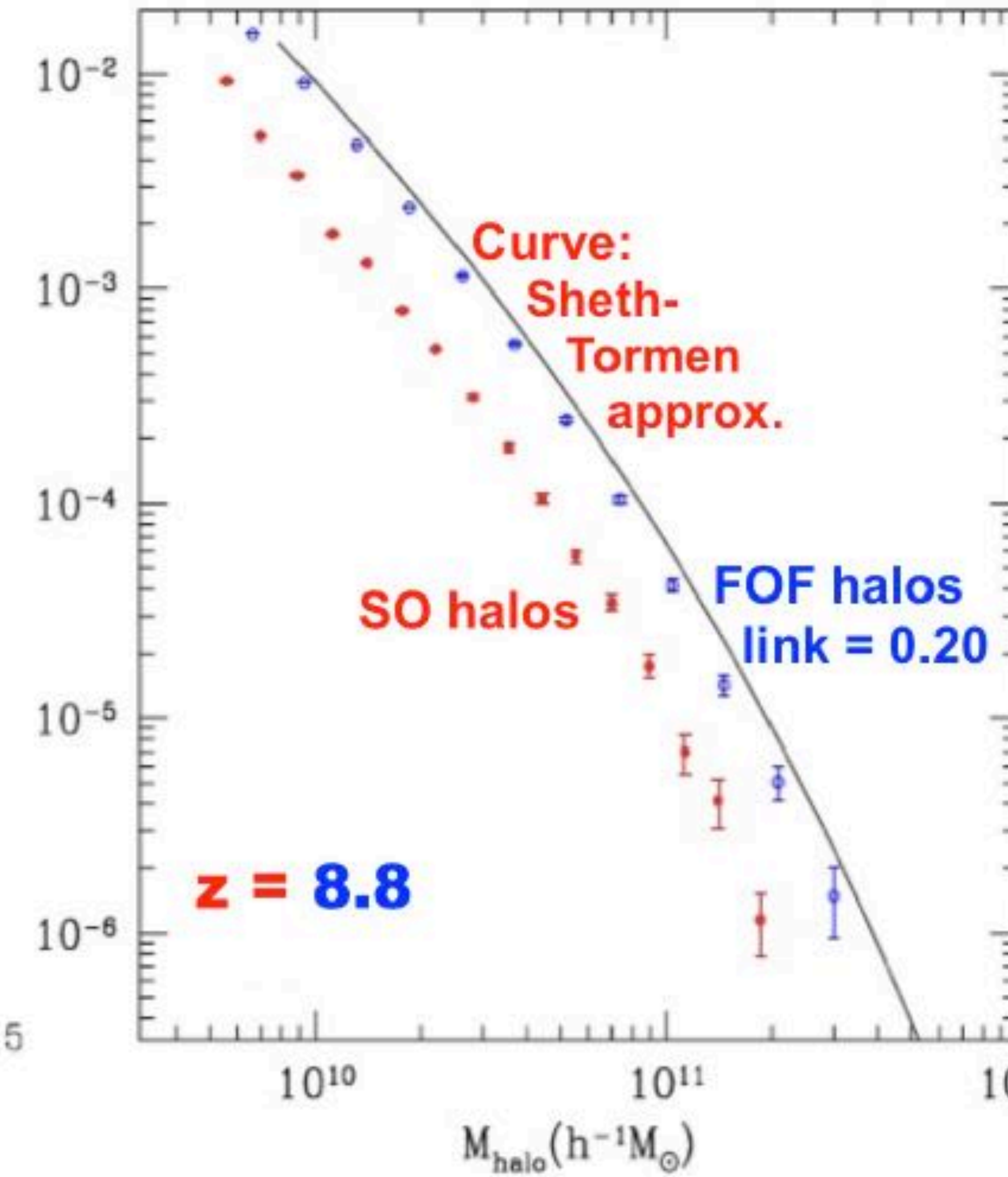








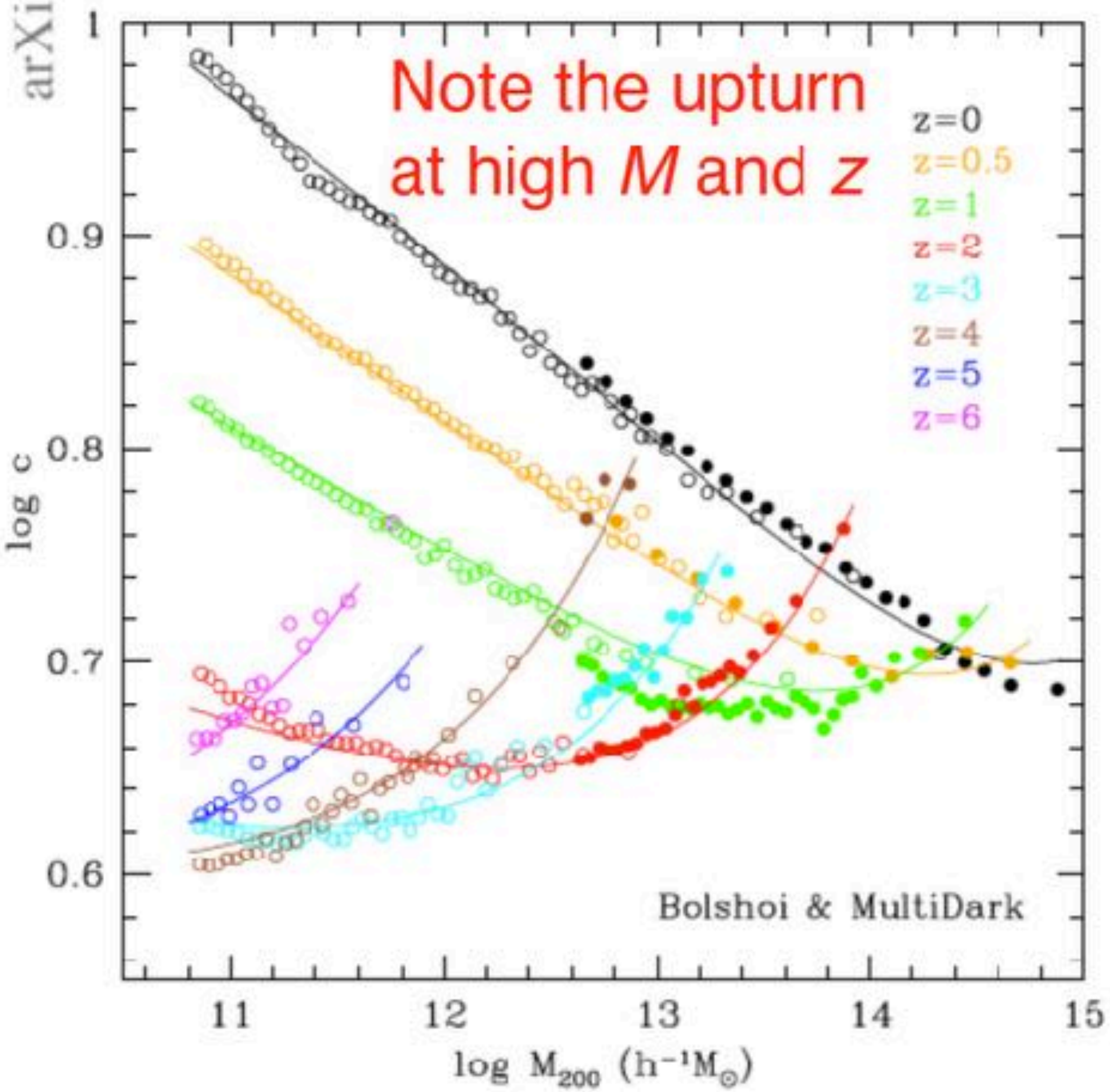
Sheth-Tormen Fails at High Redshifts



The Sheth-Tormen approximation with the same WMAP5 parameters used for the Bolshoi simulation very accurately agrees with abundance of halos at low redshifts, but increasingly overpredicts bound spherical overdensity halo abundance at higher redshifts. ST agrees well with FOF halo abundances, but FOF halos have unrealistically large masses at high *z*.

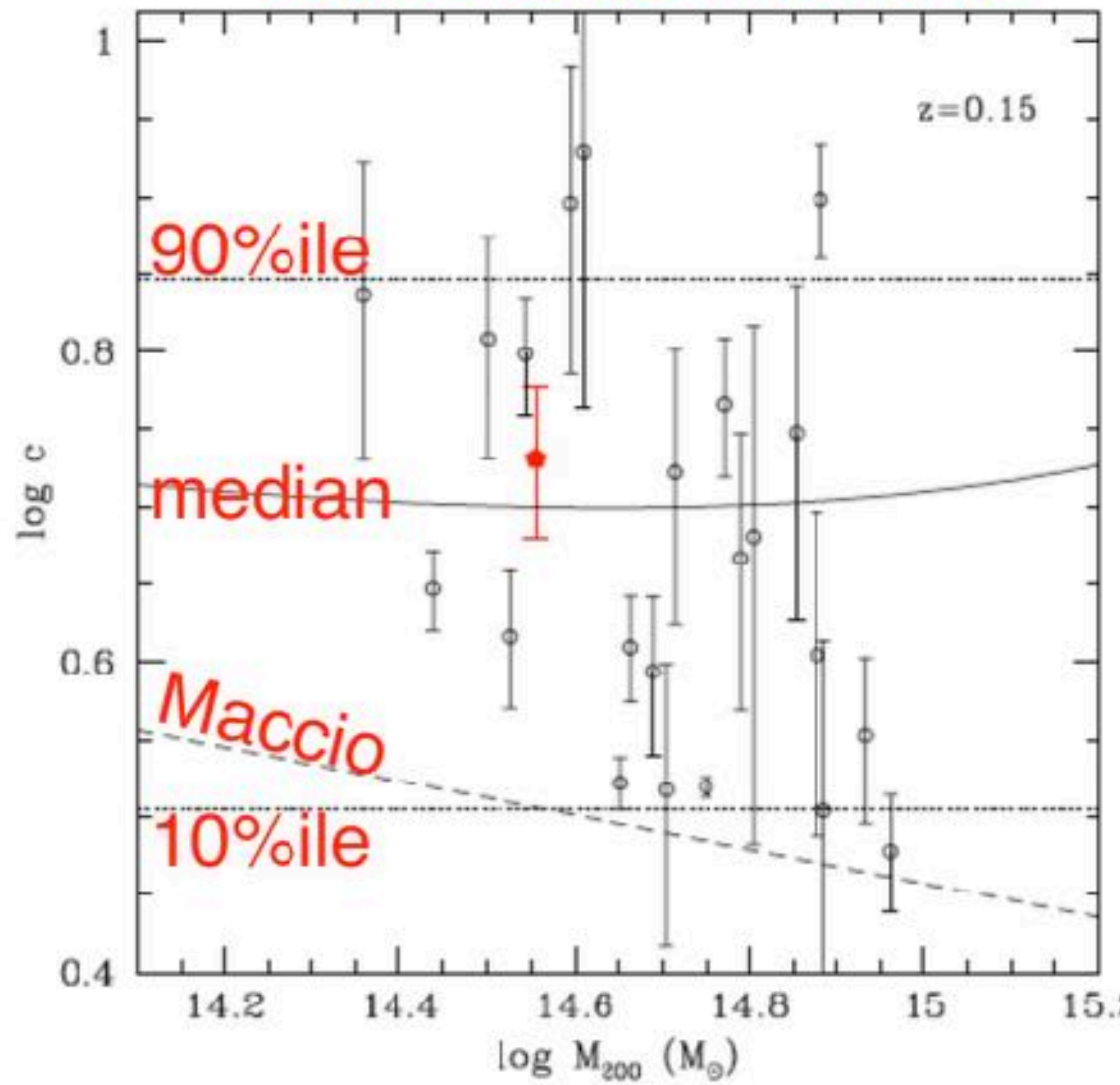
Halo concentrations in the standard CDM cosmology

Francisco Prada, Anatoly A. Klypin, Antonio J. Cuesta, Juan E. Betancort-Rijo, and Joel Primack



Halo mass–concentration relation of distinct halos at different redshifts in the Bolshoi (open symbols) and MultiDark (filled symbols) simulations is compared with an analytical approximation.

Cluster Concentrations



Comparison of observed cluster concentrations (data points with error bars) with the prediction of our model for median halo concentration of cluster-size halos (full curve). Dotted lines show 10% and 90% percentiles. Open circles show results for X-ray luminous galaxy clusters observed with XMMNewton in the redshift range 0.1-0.3 (Ettori et al. 2010). The pentagon presents galaxy kinematic estimate for relaxed clusters by Wojtak & Lokas (2010). The dashed curve shows prediction by Macci`o, Dutton, & van den Bosch (2008), which significantly underestimates the concentrations of clusters.

arXiv:1104.5130

Halo concentrations in the standard CDM cosmology

Francisco Prada, Anatoly A. Klypin, Antonio J. Cuesta, Juan E. Betancort-Rijo, and Joel Primack

V_{max}/V_{200} for Millennium-I,II and Bolshoi/MultiDark

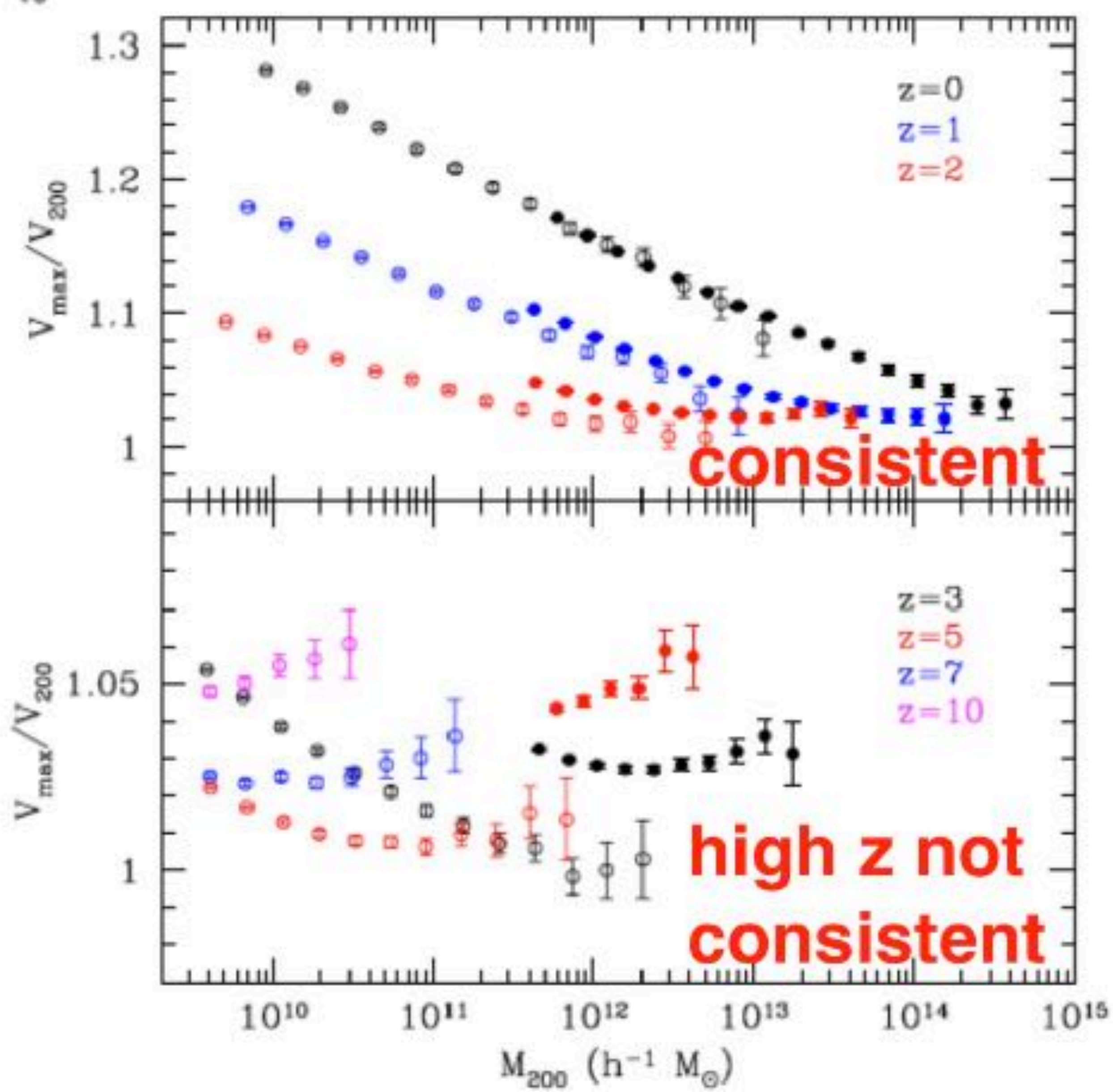


Figure 5. The ratio V_{max}/V_{200} of the maximum circular velocity to the virial velocity as a function of mass M_{200} for distinct halos at different redshifts for MS-I (filled symbols) and MS-II (open symbols) simulations. Error bars are statistical uncertainties. The MS-I and MS-II simulations agree quite well at $z = 0$. At higher redshifts there are noticeable differences between MS-I and MS-II.

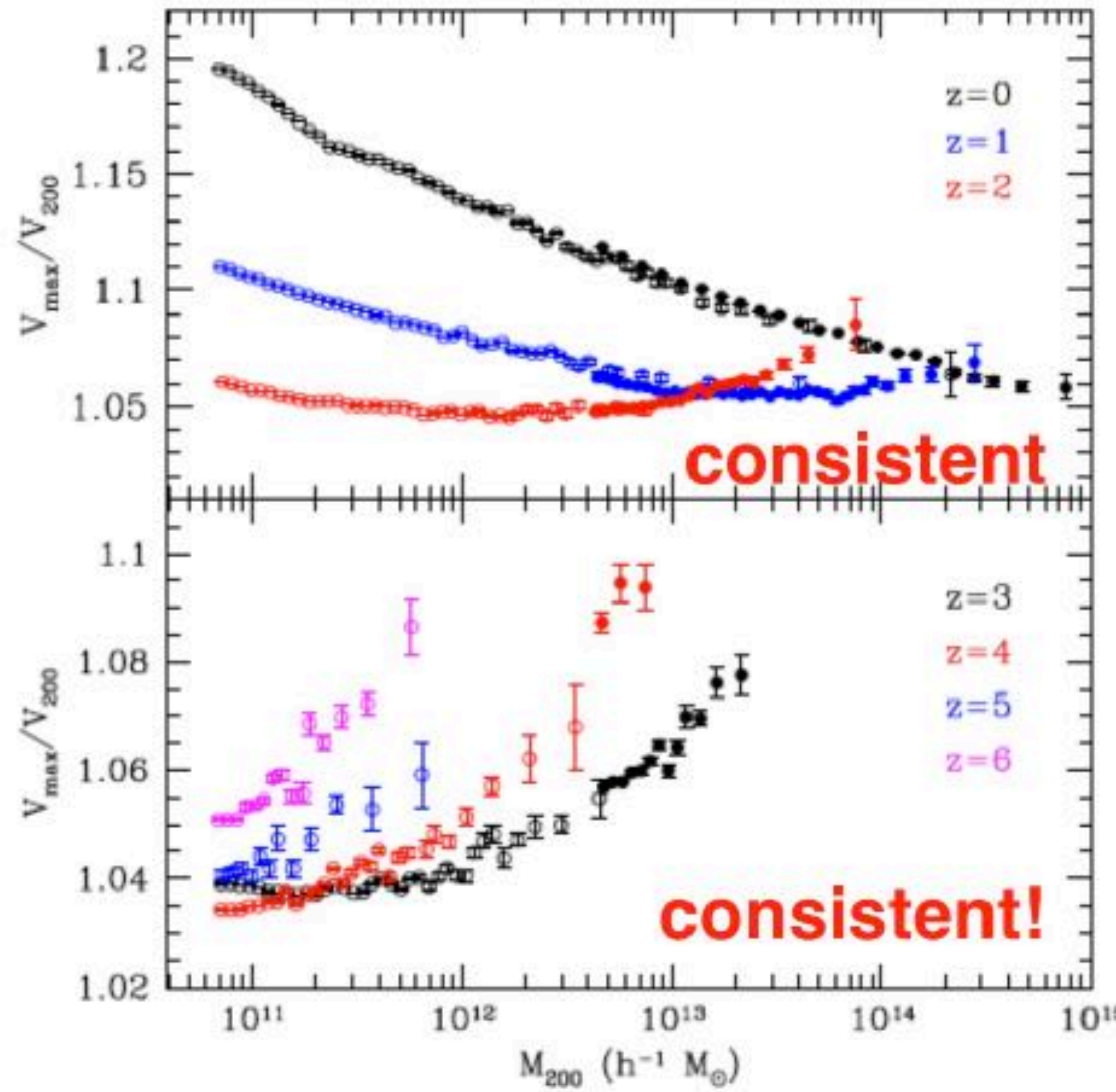


Figure 6. The same as Figure 5 but for Bolshoi (open symbols) and MultiDark (filled symbols) simulations. Both simulations show remarkable agreement at all masses and redshifts.

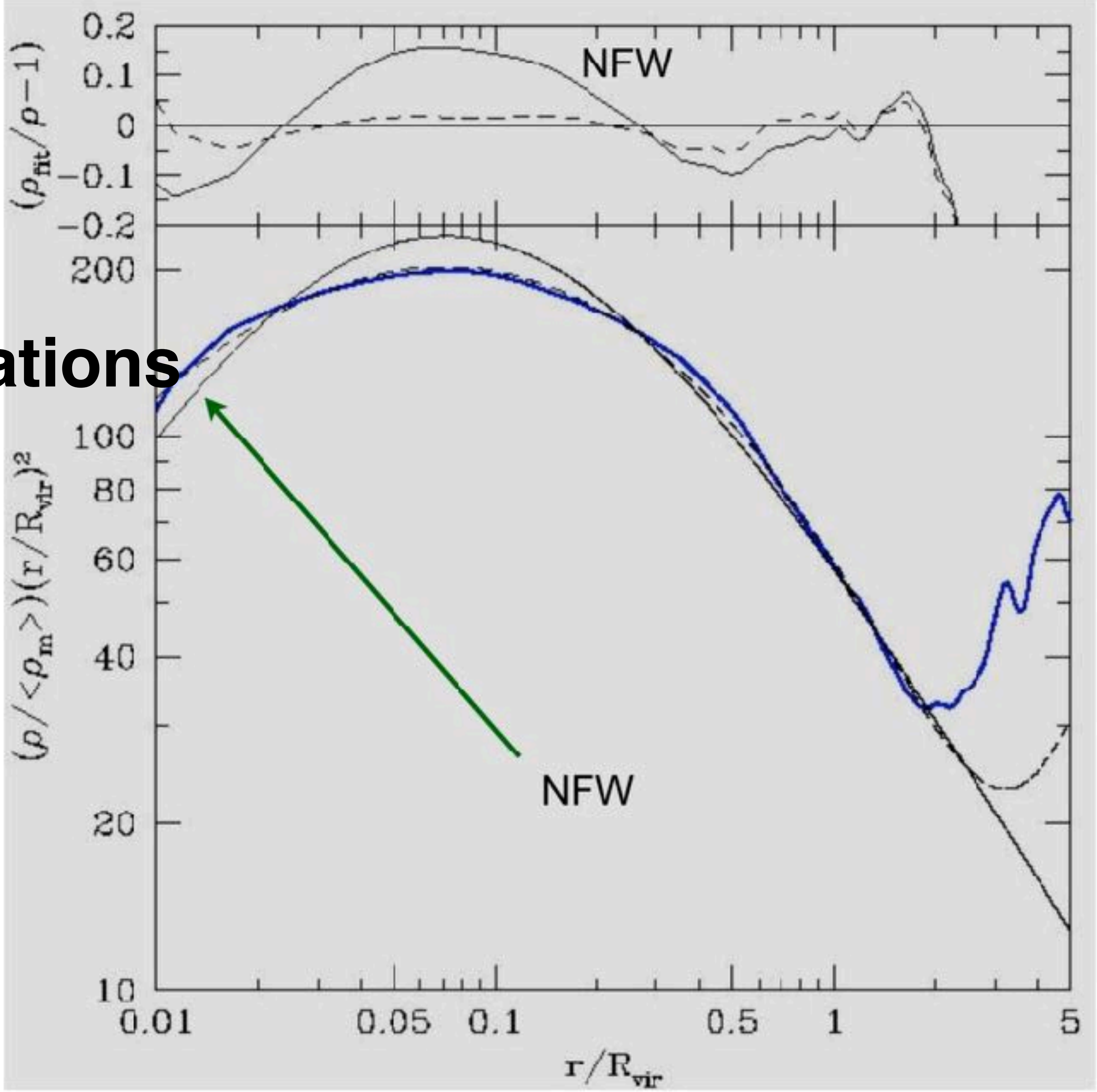
Profiles are NOT NFW

Well …some deviations

$\rho(r)=\rho_o \exp(-2nr^{1/n})+<\rho>$

n=6-8 3D Sersic

Navarro etal 2004
Merritt, Navarro 2004
Prada etal 2005



Fraction of Support by rotation
Spin parameter

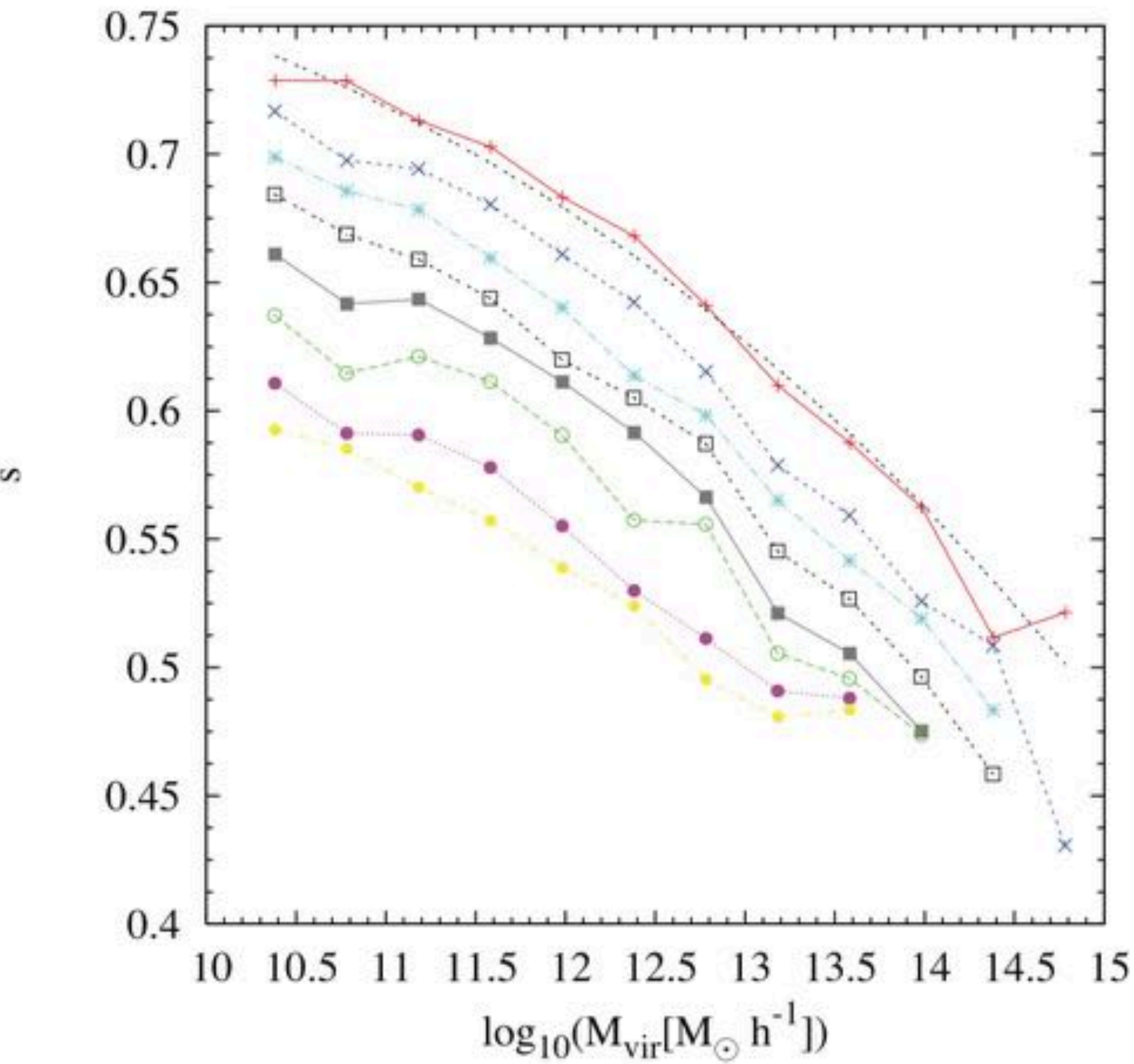


Figure 6. Mass and time evolution of the shape of DM haloes quantified via the $s \equiv a_3/a_1$ ratio. Points represent our data while the dashed line

Elongation:
Massive Halos
are more elongated

Muñoz Cuartas et al

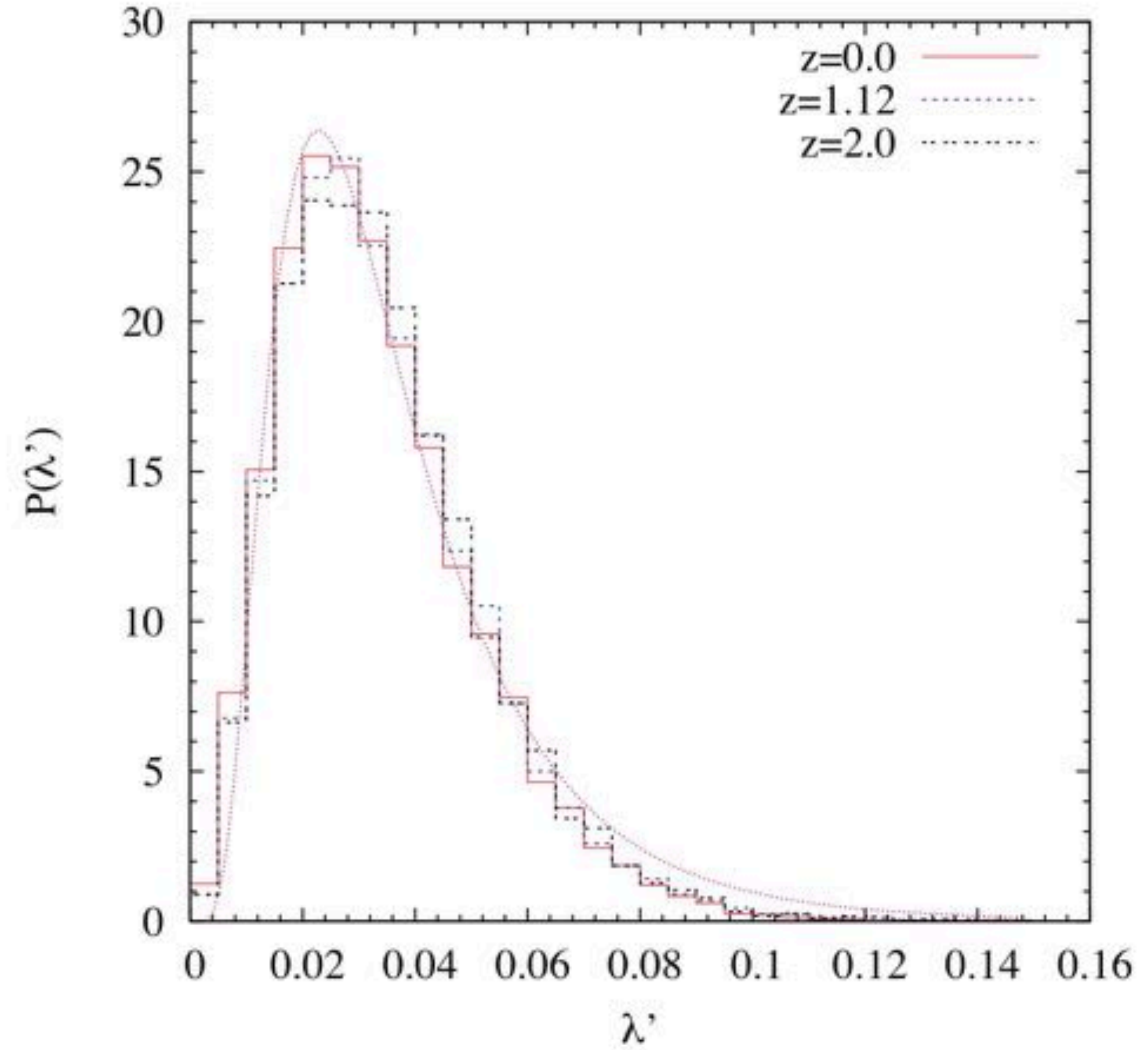
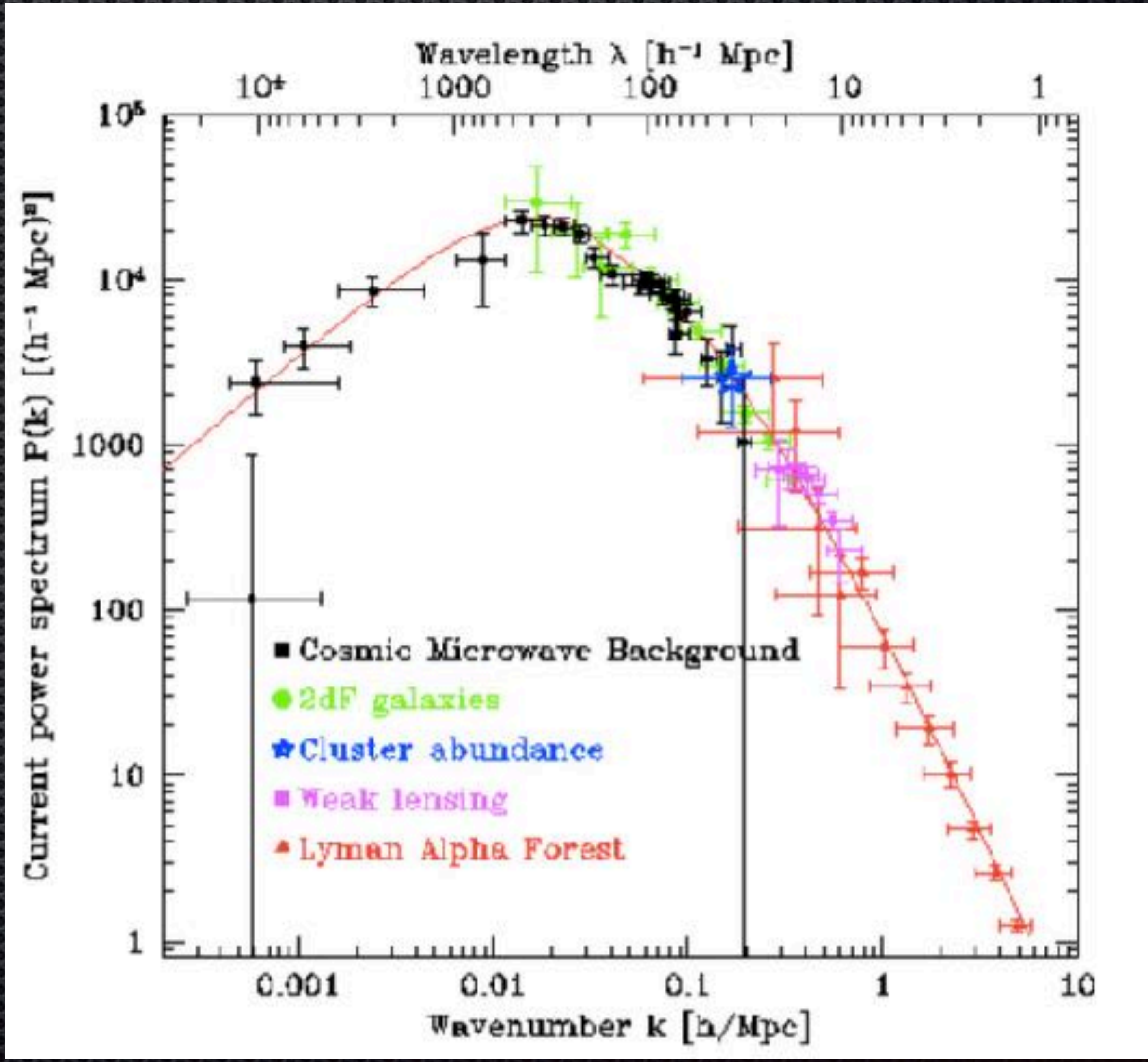


Figure 11. Distribution of the halo spin parameter λ' at redshifts $z = 0$, 1, 2, compared to a lognormal distribution with $\lambda_0' = 0.031$ and $\sigma = 0.57$.

Looking at the sky

Distribution at large scales. DM must look like CDM

- Good agreement from 1Mpc- some Gpc´s
- < 1 Mpc. Signature of Baryons and DM Physics ?



Summary

- Cosmological Nbody simulations showed that galaxies live inside:
- Cuspy, Non-sp of support by r
- Halos abundar compact funct change with th observations.
- Power Spectrum and 2point correlation function of galaxies may be compared with LCDM

Let´s compare with observations

Motivation:

After many tests robust predictions

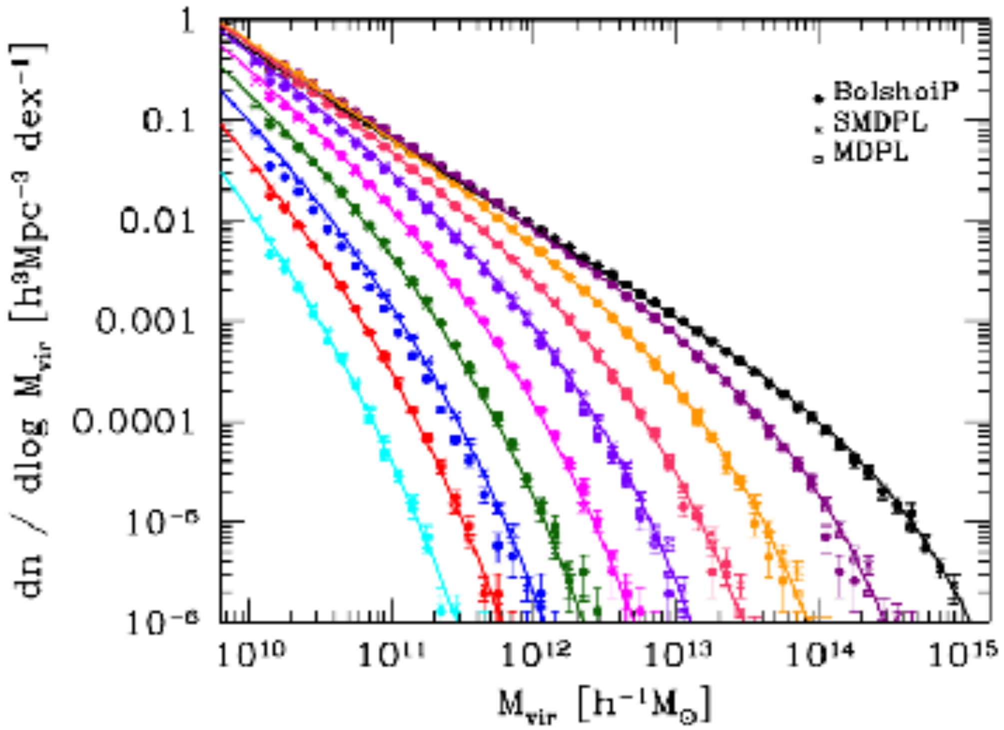
LCDM Robust predictions.

Halo-Galaxy connection.

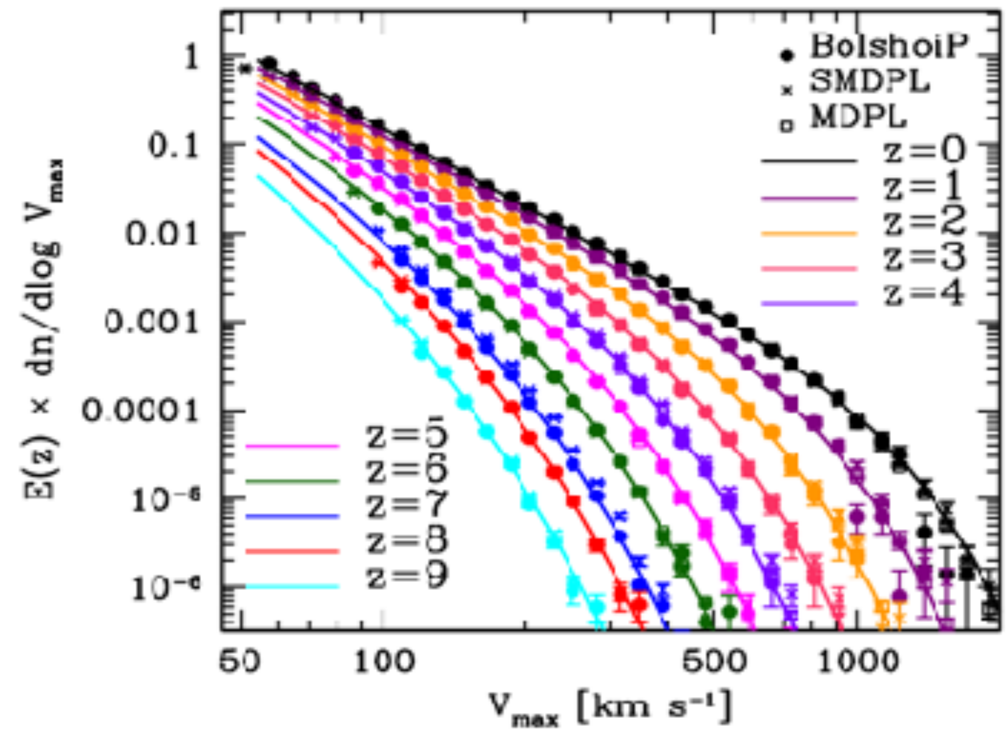
Halo abundance

$$V_c^2 = \sqrt{(GM(R)/R)}$$

Halo mass function.



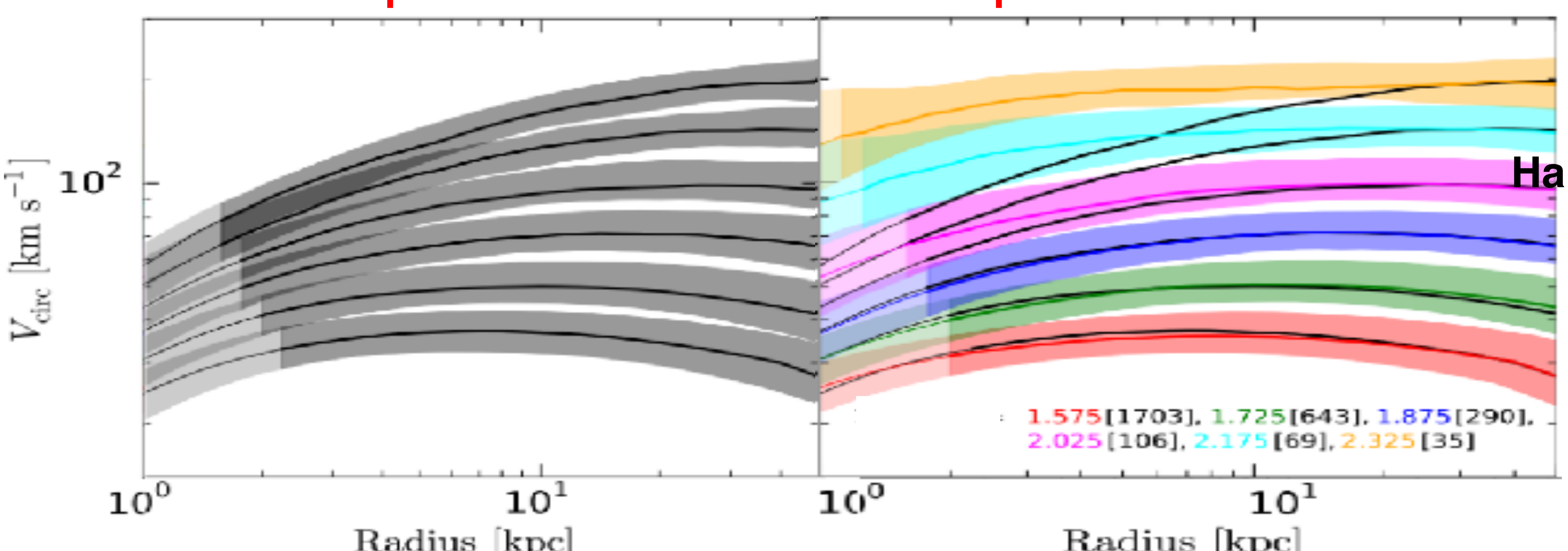
Circular velocity function.



Sensitive to the baryons.

Rodriguez-Puebla et al. 2017

Vc profiles - Halos. **Vc profiles - Halos+Bariones.**

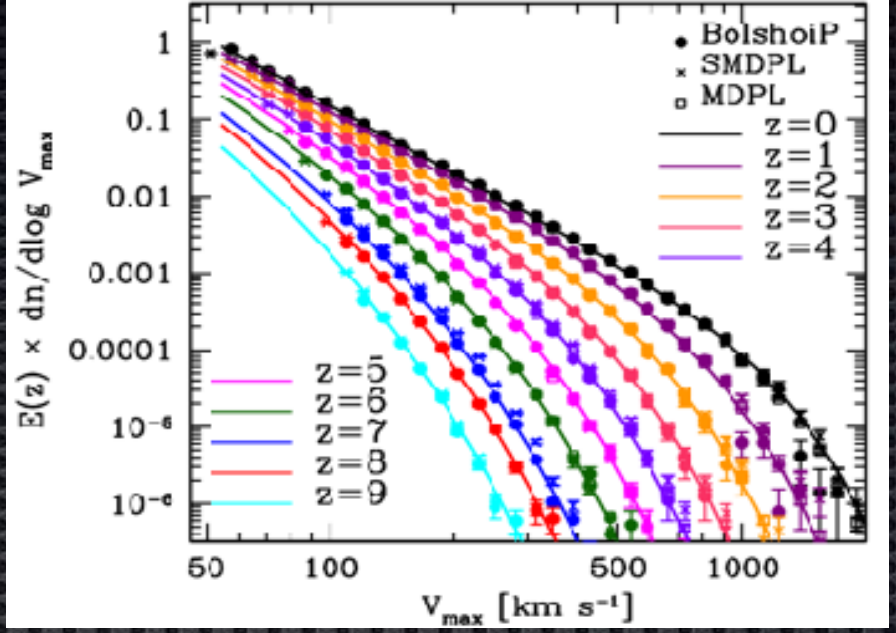


Rotation curve shape

Halo density profile

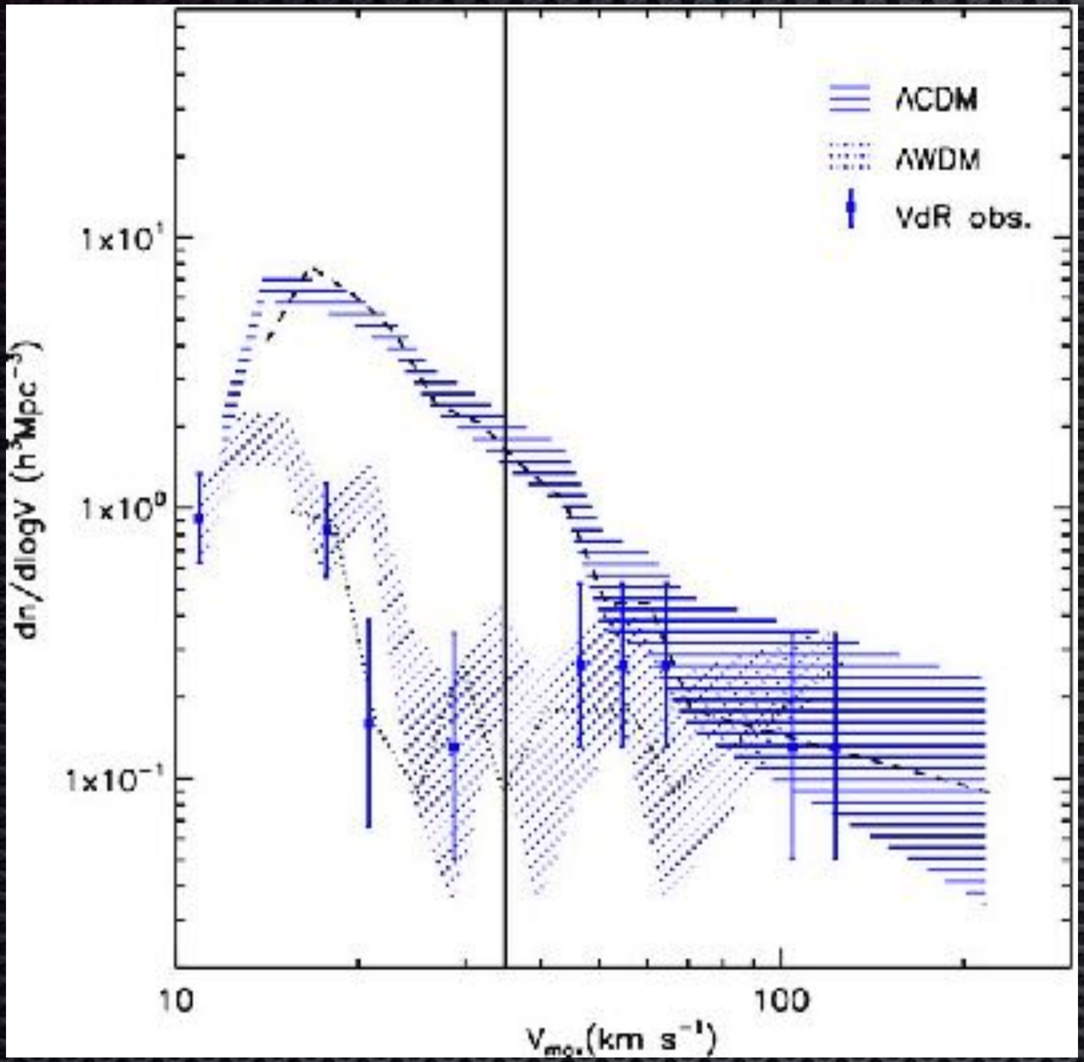
Oman et al. 2015

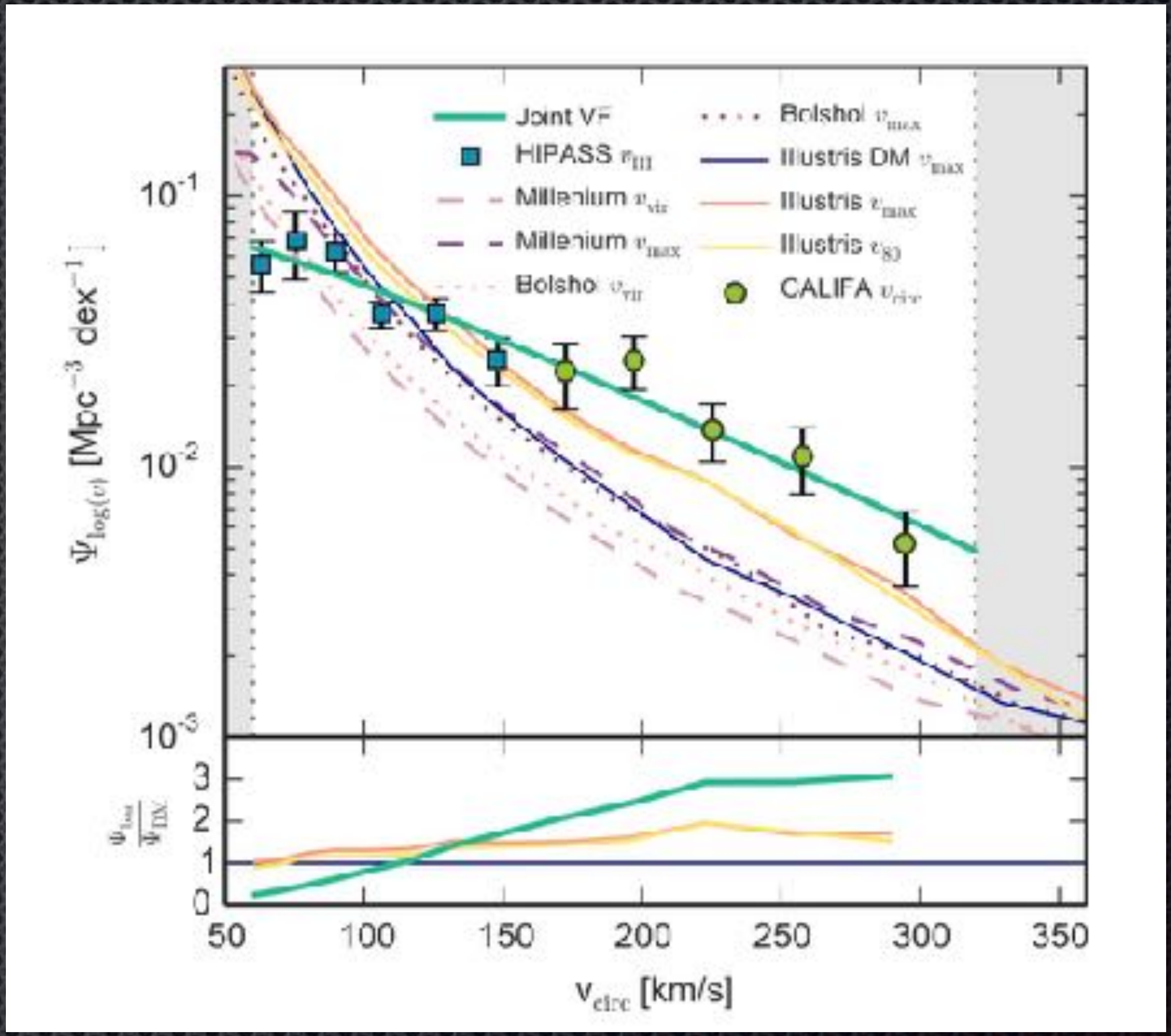
Circular Velocty Function



- One the most robust predictions of Structure Formation Model (Numerical convergence, Cosmic Variance, environment. Sensitive to DM Physics: LCDM, LWDM, Wave Dark Matter-light axion, Gravity Screening…?)
- Presumably Vmax is a more direct comparison than galaxy halo mass (relaxed, axisymmetric system. other degrees of freedom, kinematic tracer?)
- More sensitive to baryons physics than Mh-Ms from gravitational lensing, but pays the price of dynamical complexity, complementary.
- Traditionally HI emission linewidth (ALFALFA, HIPASS) distribution is mapped into V_max function or they start from TF + Stellar Mass Function (Gonzalez et al 2000)

Sensitive to DM and Baryon Physics

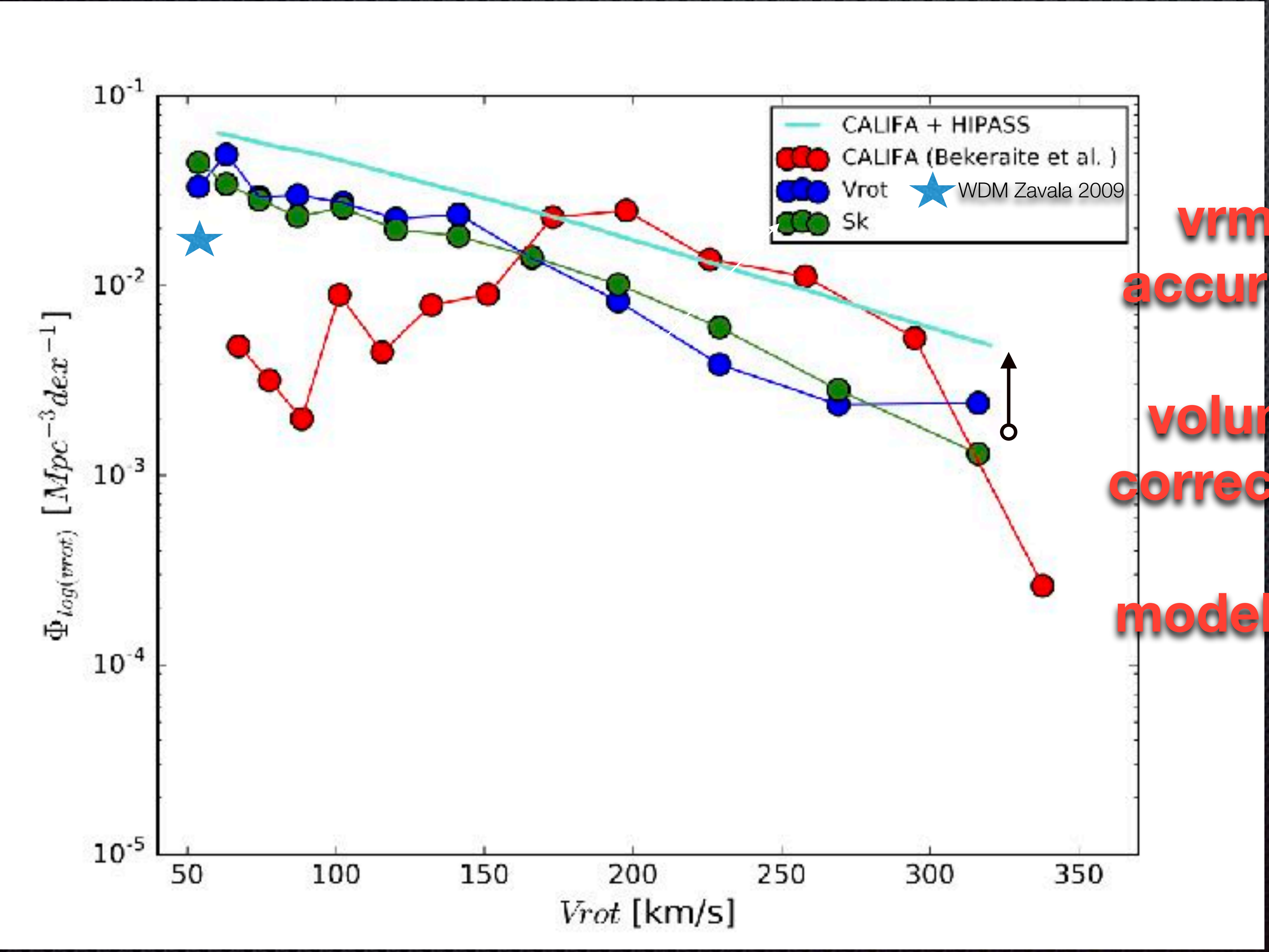




Zavala 2009
emission line width in radio

Bekeraité et al 2017
stellar kinematics, cosmological simulations

Our first attempt using ~4000 galaxies from the survey MaNGA/SDSS, many corrections still to do (instrumental, aperture, dynamics) Is LCDM/WDM compatible?
with UNAM graduate students

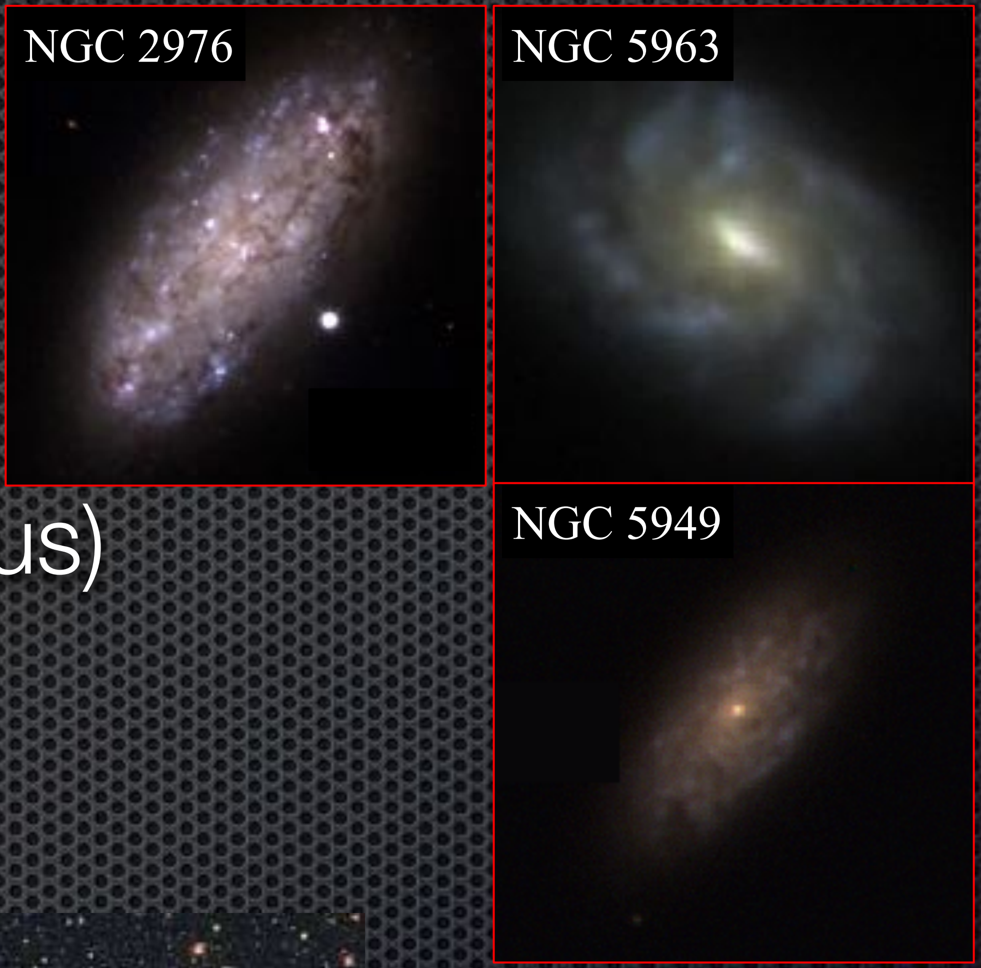


vrms accuracy

volume correction

modelling

From Galaxy Kinematics to Density Profiles



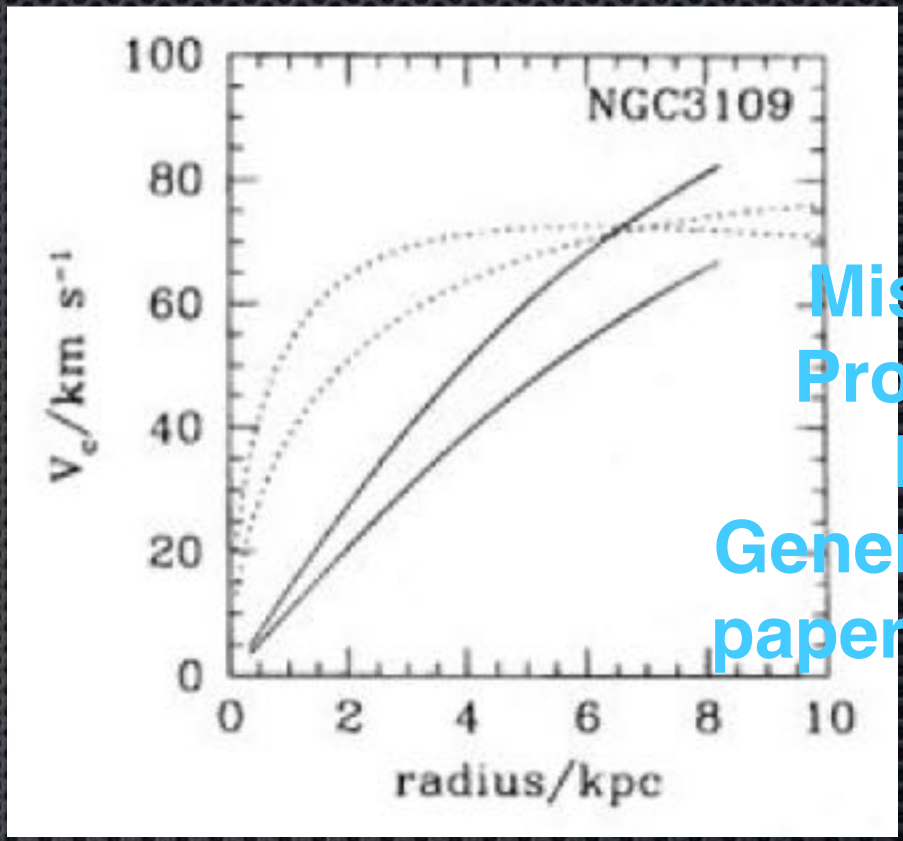
- Bright Dwarfs (Irregular gaseous)
- Classical Dwarf Spheroidal

Irregular Dwarf Galaxies Kinematics

$$V_c^2 = \sqrt{(GM(R)/R)}$$

Moore 1994,
Flores & Primack1994

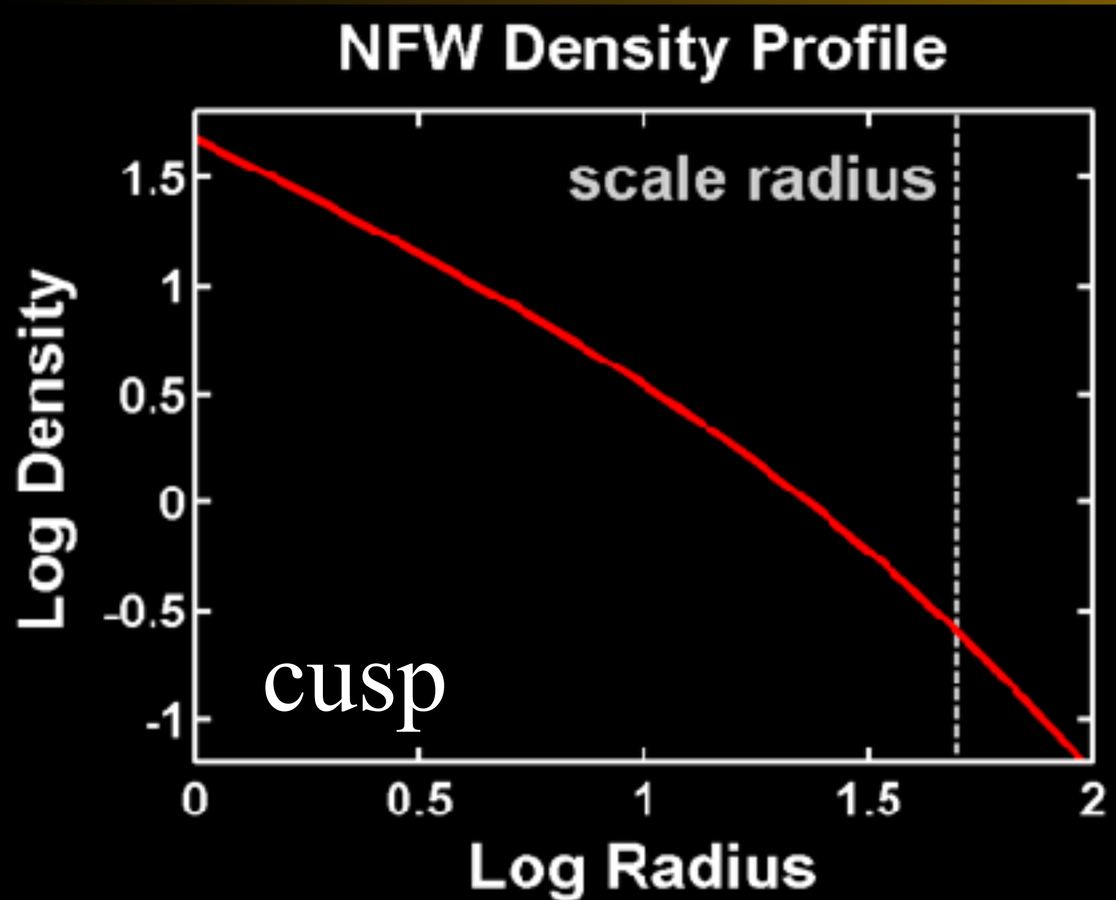
- All started with rotation curves core vs cusp
- Rotation only analysis is consistent with cores in many but not in all cases: suggest a **systematic uncertainty?**
- THINGS/Little THINGS Galaxies: Radio observations 10-20 galaxies. Results are different if we use an optical tracer. Deviations from rotations neglected or filtered out

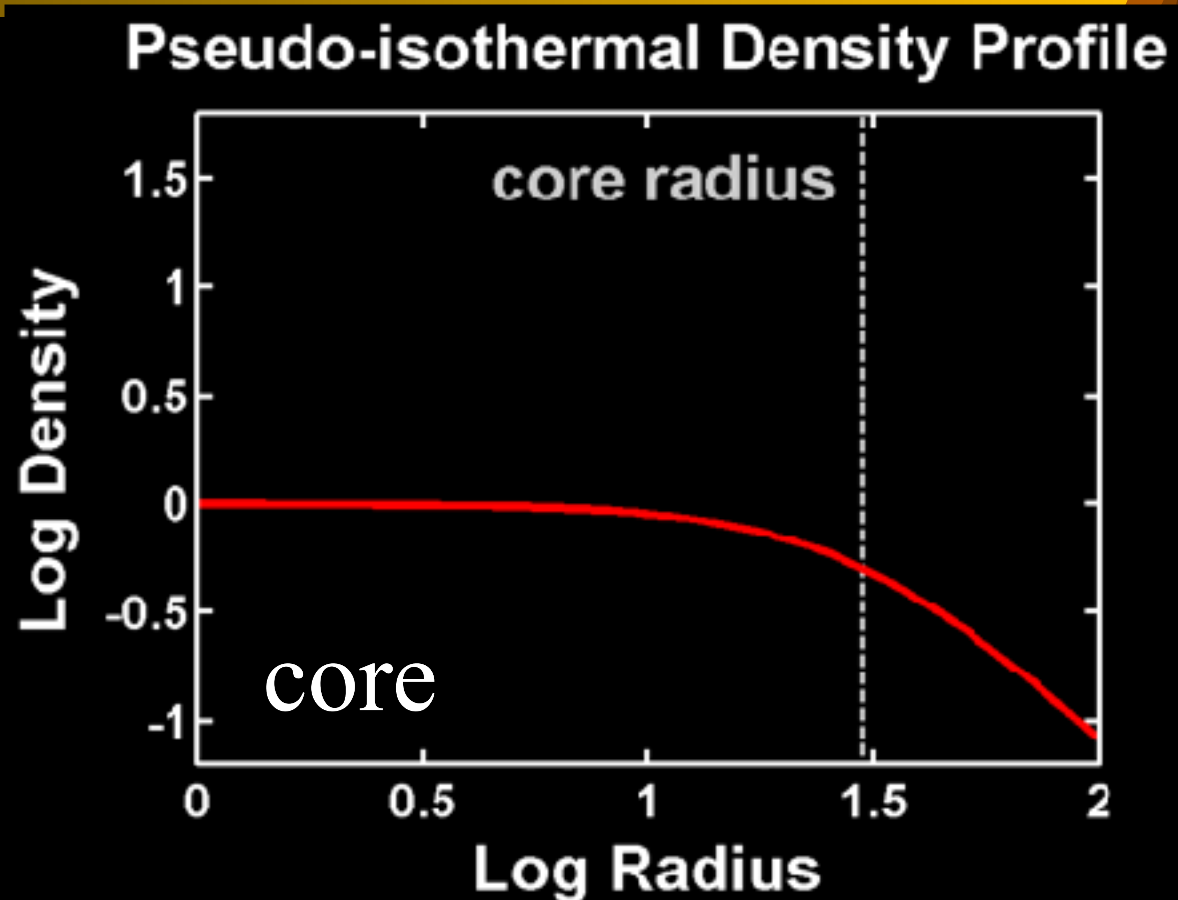


Mismatch? Problem for LCDM Generated many papers by 24 yrs

- Typically 4-10 galaxies per sample. Different instruments. Translating between different instruments non trivial

The Central Density Problem

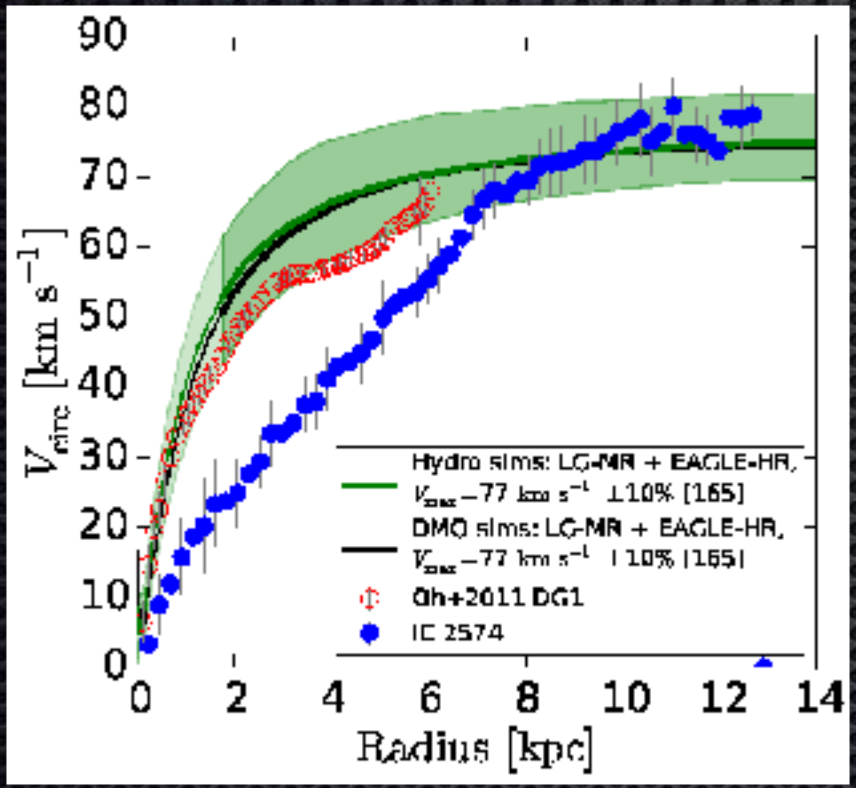




- Parameterize density profile as $\rho(r) \propto r^{-\alpha}$
  - Observations suggest $\alpha \sim 0$ (constant-density core)
  - Simulations predict $1 \leq \alpha \leq 1.5$ (central cusp)
  - Simulations with baryons predict $0.5 \leq \alpha \leq 1$ (shallow cusp)

Irregular Dwarf Galaxies Kinematics

- Oman et al 2015, 2017 PhD thesis, **diversity at the same mass, core importance correlates with non-circular motions**



- Valenzuela et al 2007, Rhee et al 2014. **High res simulated dwarf hydro, SN feedback, inside a cuspy halo: Rotation consistent with a core. Asymmetric Drift like correction may fix things.Thermal Pressure support hard to normalize.**

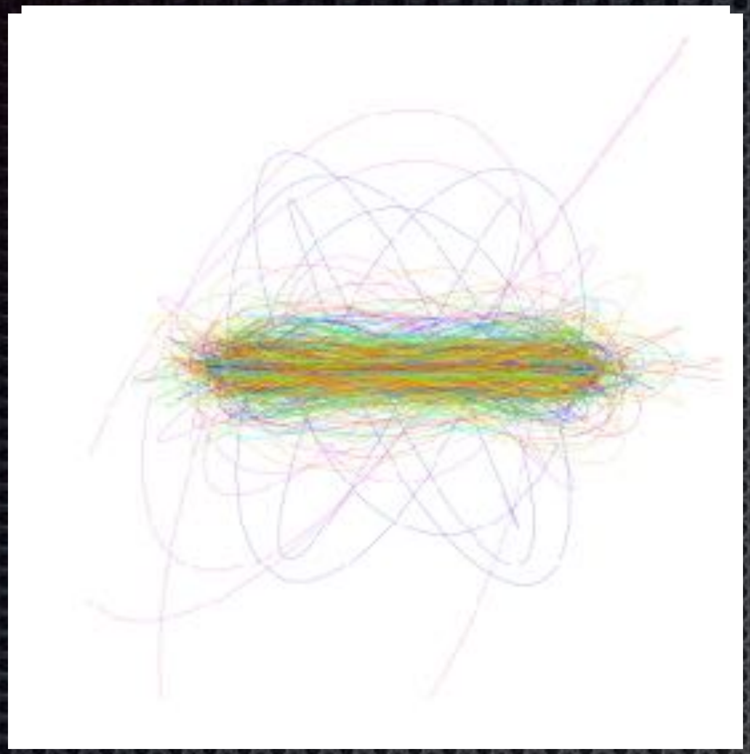
- Oh, Governato et al, high res cosmological simulated hydro SN feedback dwarf inside a cored halo: **Rotation consistent with a core. Idientifies and filtered out non-circular motions**

Five galaxies: α

NGC 2976	0.01
NGC 6689	0.80
NGC 5949	0.88
NGC 4605	0.88
NGC 5963	1.28

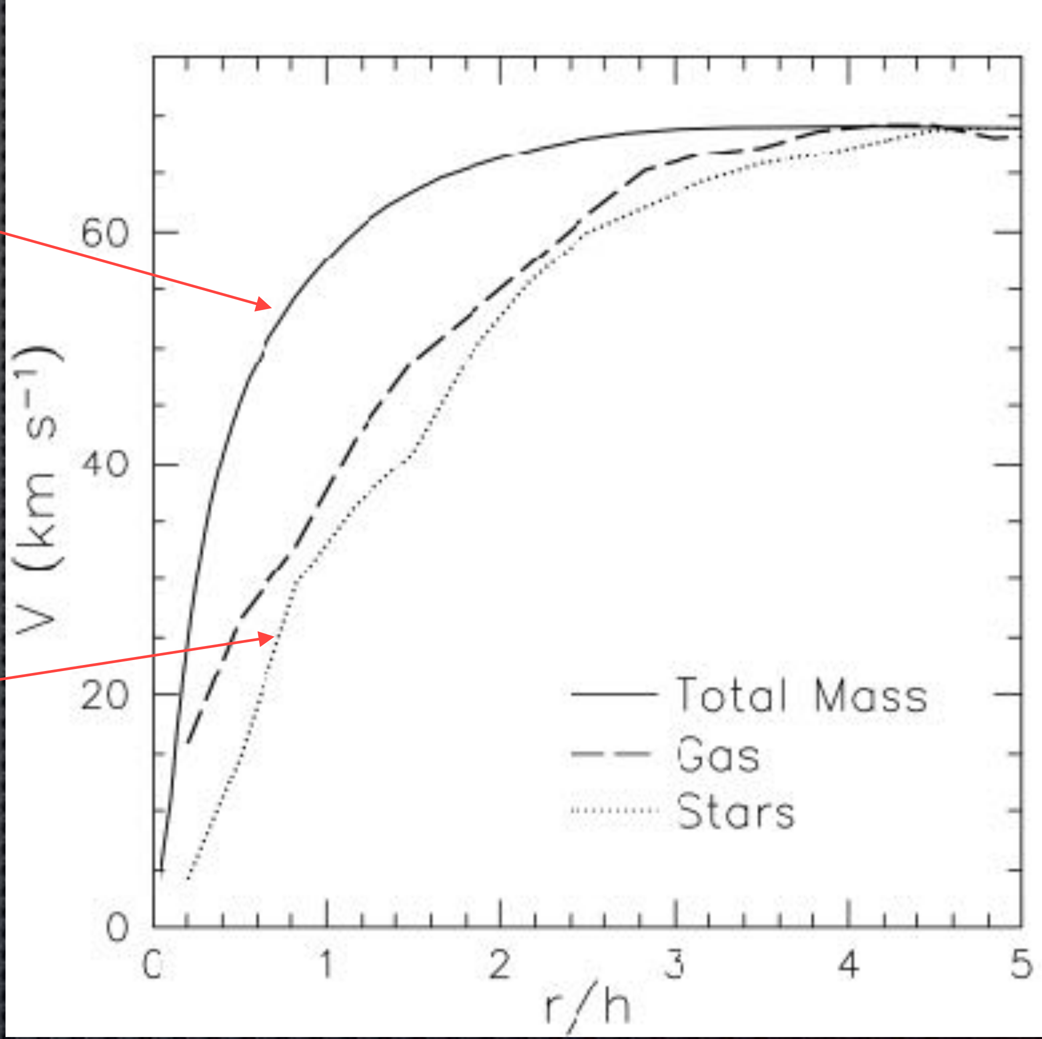
- 0.01 ,1, 0.6 different studies
  - Adams et al 2014 SFH fixes Baryons mass,
  - Simon et al 2005 **non circular motions**

Non circular motions and pressure support force produce differences between Vc -Vrot



Vcirc

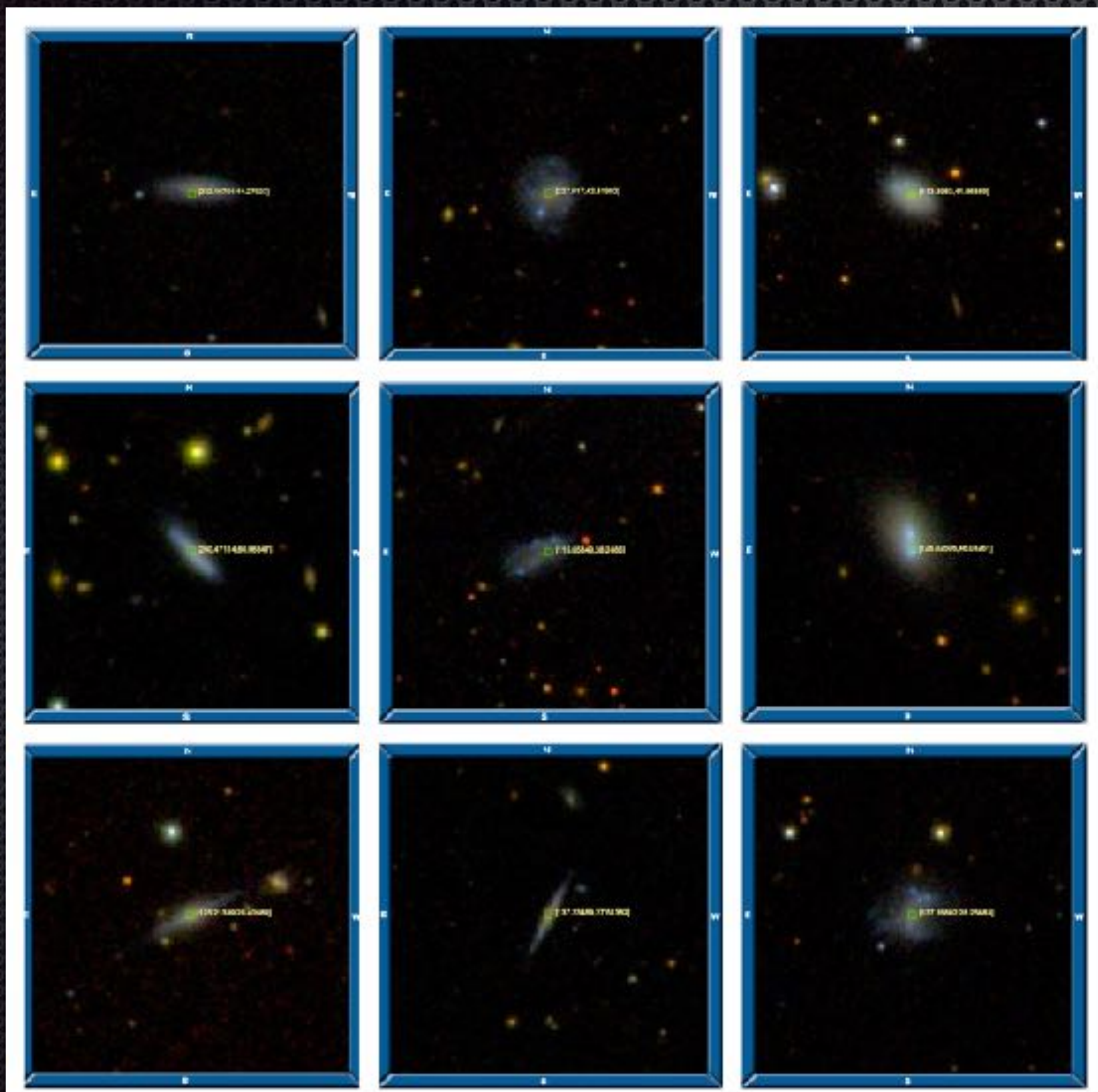
Vrot



Hydro galaxy simulations
Nbody, SF, Feedback

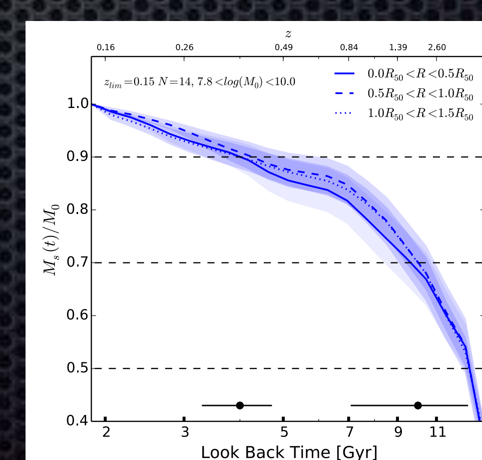
Valenzuela et al 2007, 2014

MaNGA/SDSS Dwarf and Bulgeless Galaxy sample project ongoing

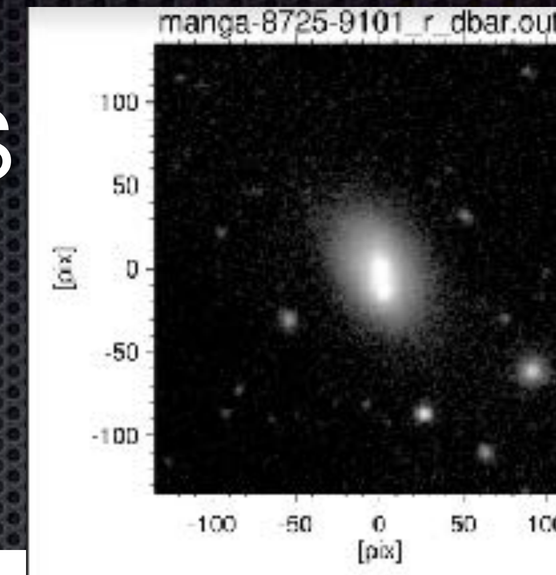


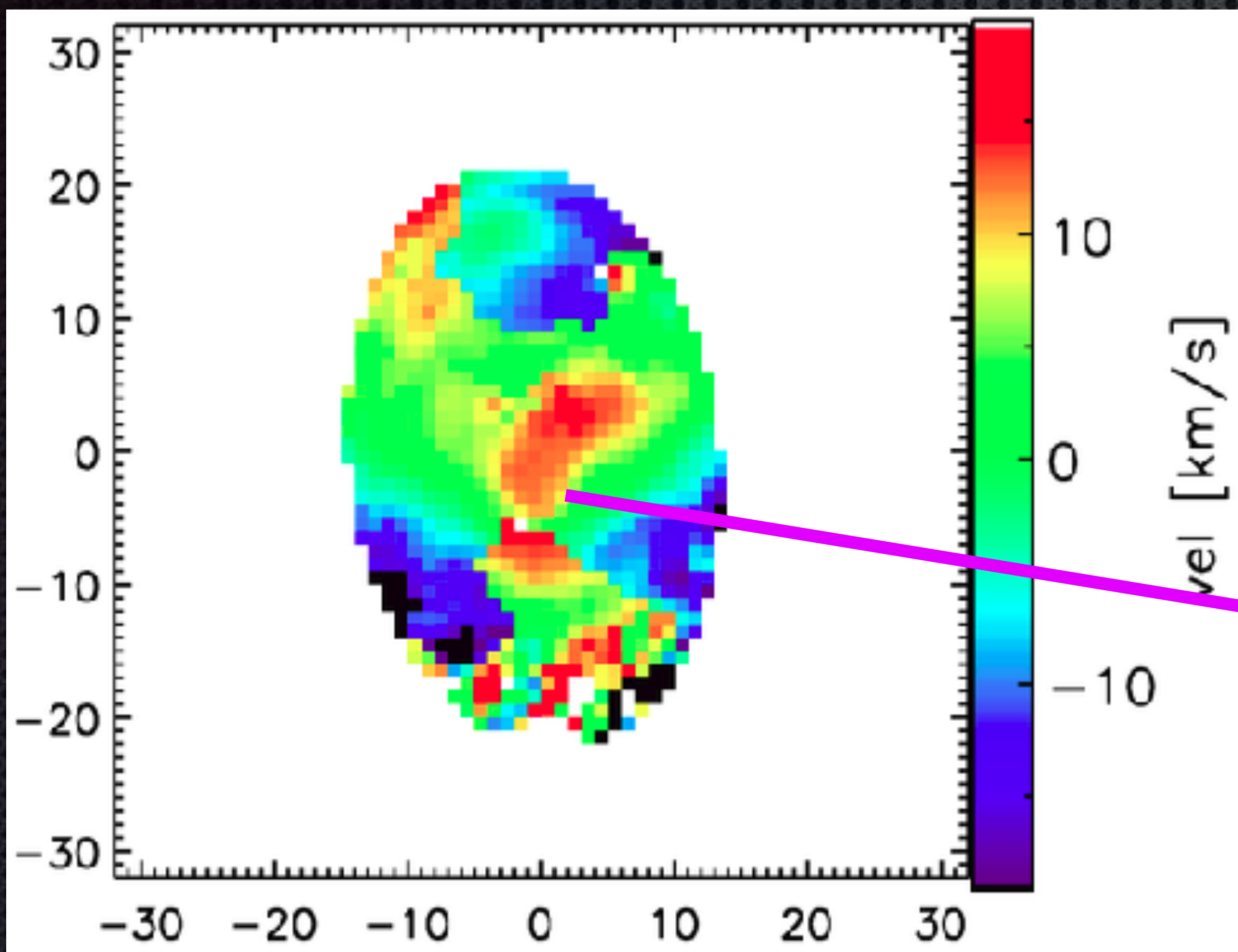
Cano-Díaz, Aquino,Pérez, Pichardo,Velázquez, Sánchez, Ibarra

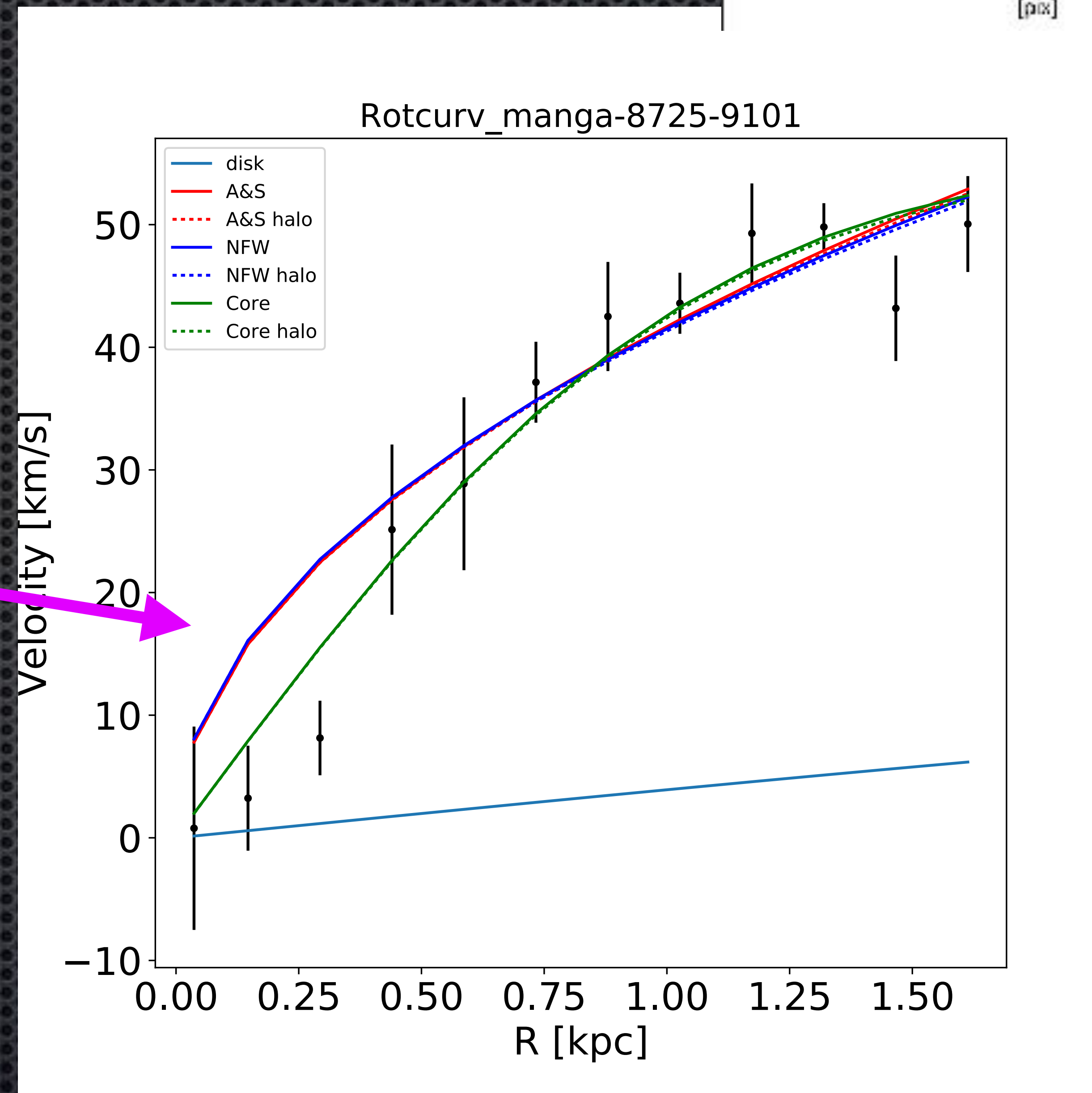
Large sample
Controlling SF history
Feedback



Building 3D self consistent models stability. Using Observed Density, Kinematics Map







Velocity residuals after subtracting rotation. Vmax ~50/km/s

What is the nature of residuals?

Irregular Dwarf Galaxies Kinematics: No trivial way out

- We need to model simultaneously the full velocity and dispersion field, including asymmetries
- We need to estimate from spectroscopy the mass density distribution including asymmetries and the SFH in order to constrain feedback
- Test dynamical stability to break degeneracy

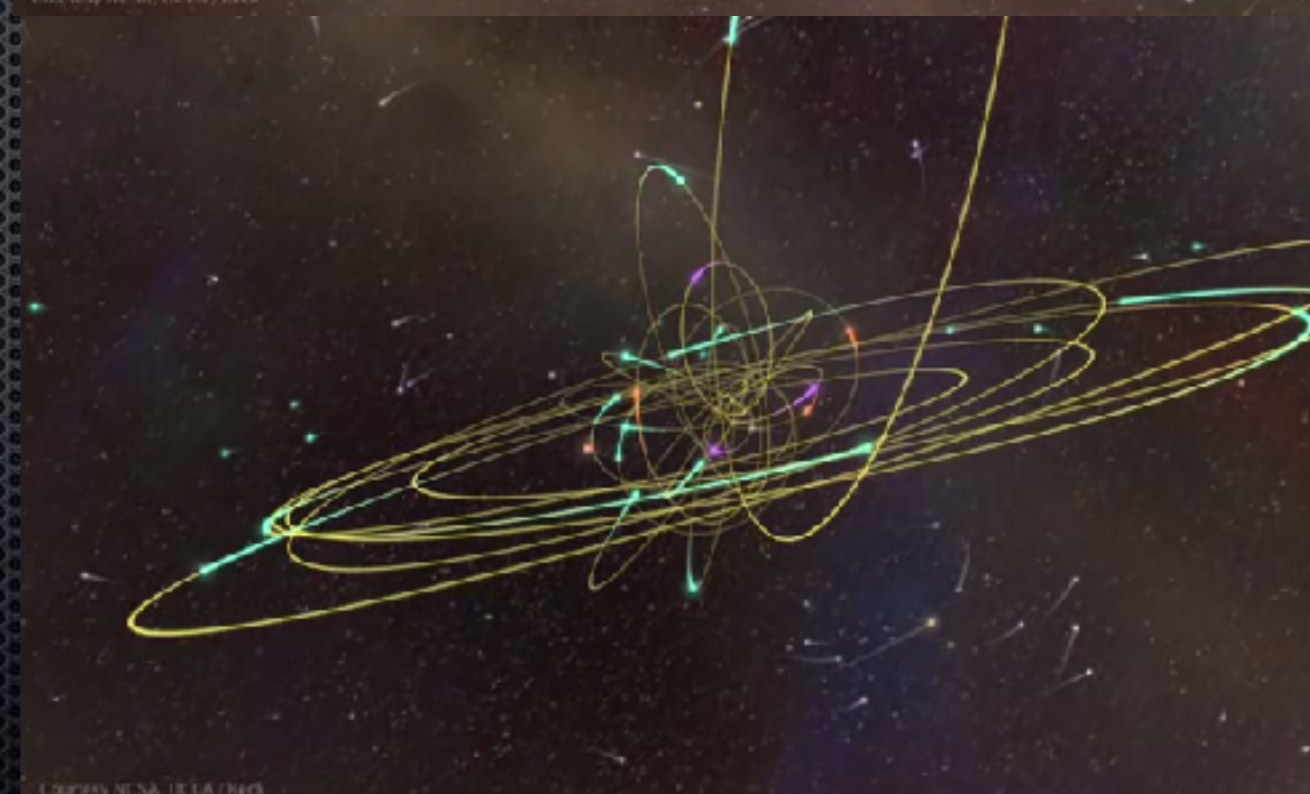
Dwarf Spheroidal´s: Classical

- Central Density Profile from resolved stellar kinematics
-

Dwarf Spheroidal´s: Classical and Ultra Faint Requires galaxy modeling and observations

Main sources of uncertainty: Stellar **kinematics anisotropy, rotation, dynamical equilibrium,**

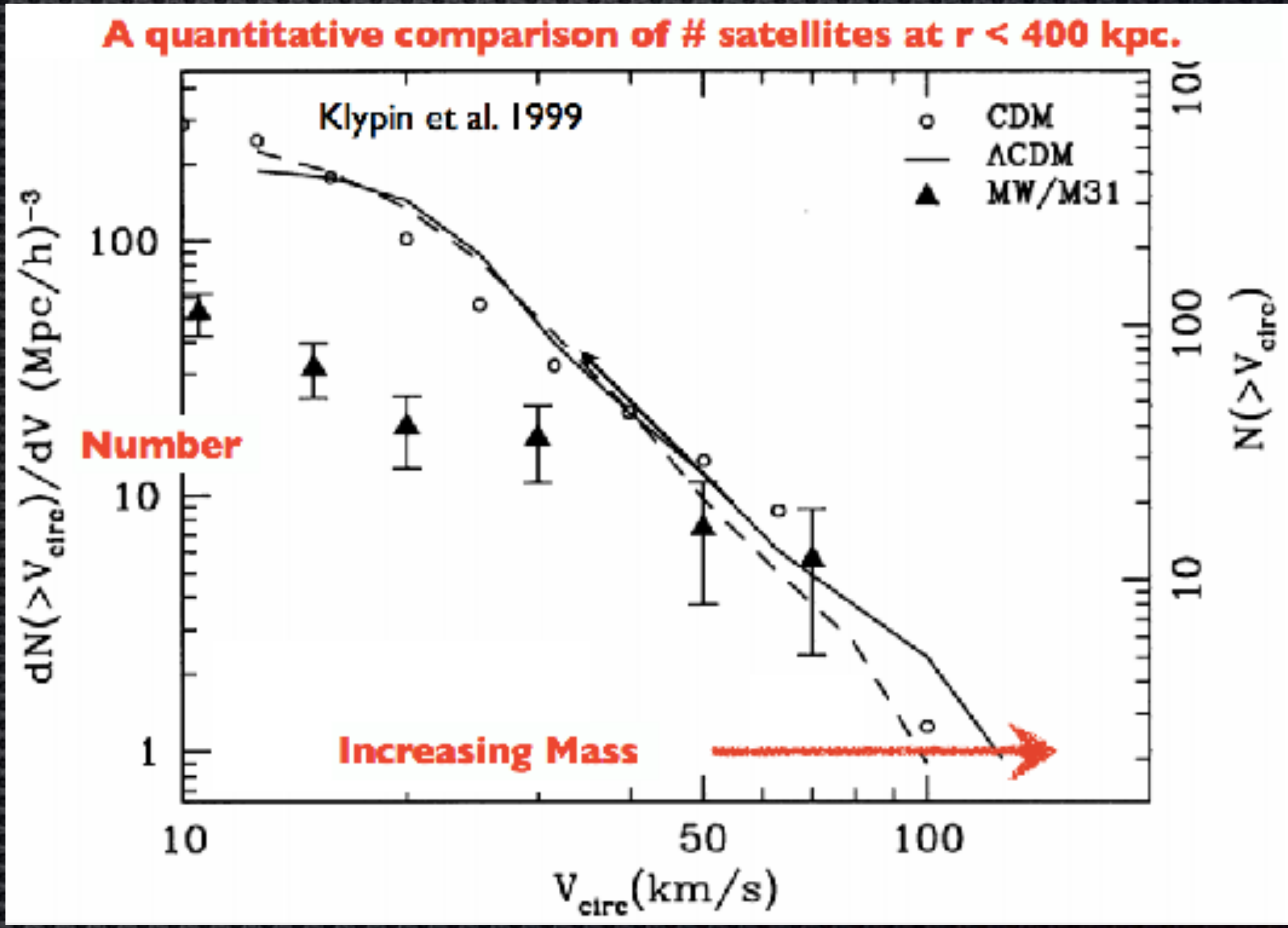
- number of stars with dsph certified membership, shape (stellar, dark matter)
- Common assumption isotropy=core



Missing Satellite Problem:

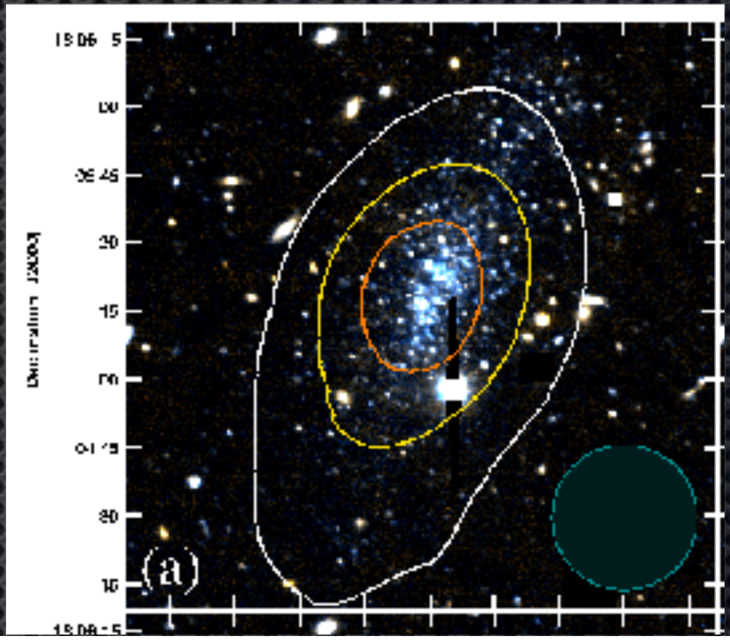
Klypin, Kravtsov, Valenzuela, Prada 1999,
Moore Ginghna, Governato et al 1999,
Kauffman, White, Giderdoni 1993

- CDM Dark matter only simulations predict ~1000´s of dark satellites vs 10ish observed.
- Many may be tiny or even may be void of stars (ALFALFA, HVC)
- No problem with baryons. Smallest Detectable by lensing: 10^7-10^8 Msun

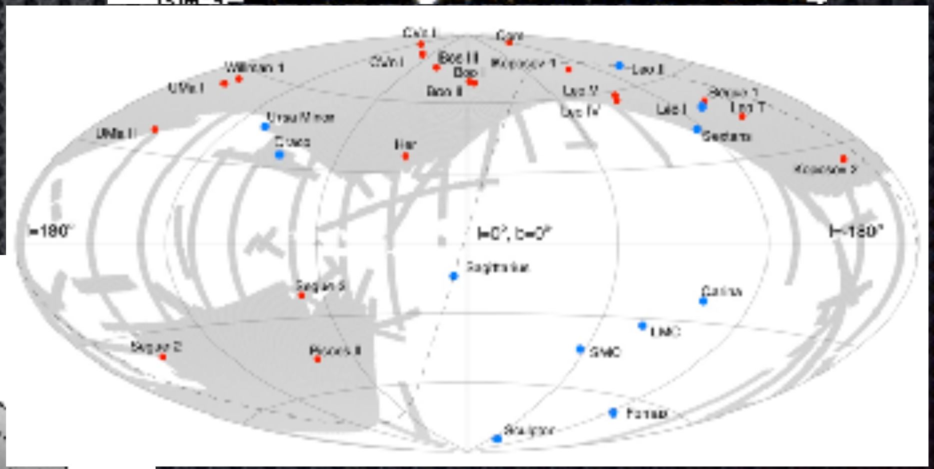


Missing Satellite Problem:

Leo-P, discovered
as a HI cloud HVC

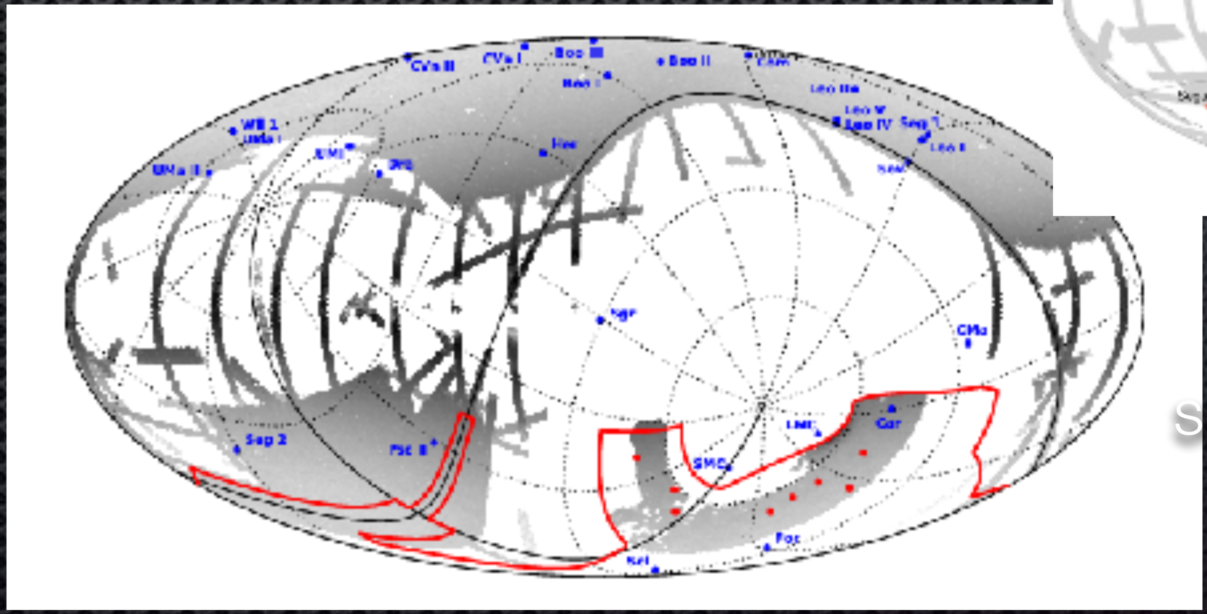


- New searches: SDSS (Willman;Belokurov), DES, HI,GAIA (Antoja et al 2016)
-



SDSS-UFaint´s

smaller than a globular cluster



DES

GAIA Astrometric Mission

10^7 Stars in 6D
x,y,z
vx,vy,vz (bright ones), RAVE, LAMOST, WeaveDESI

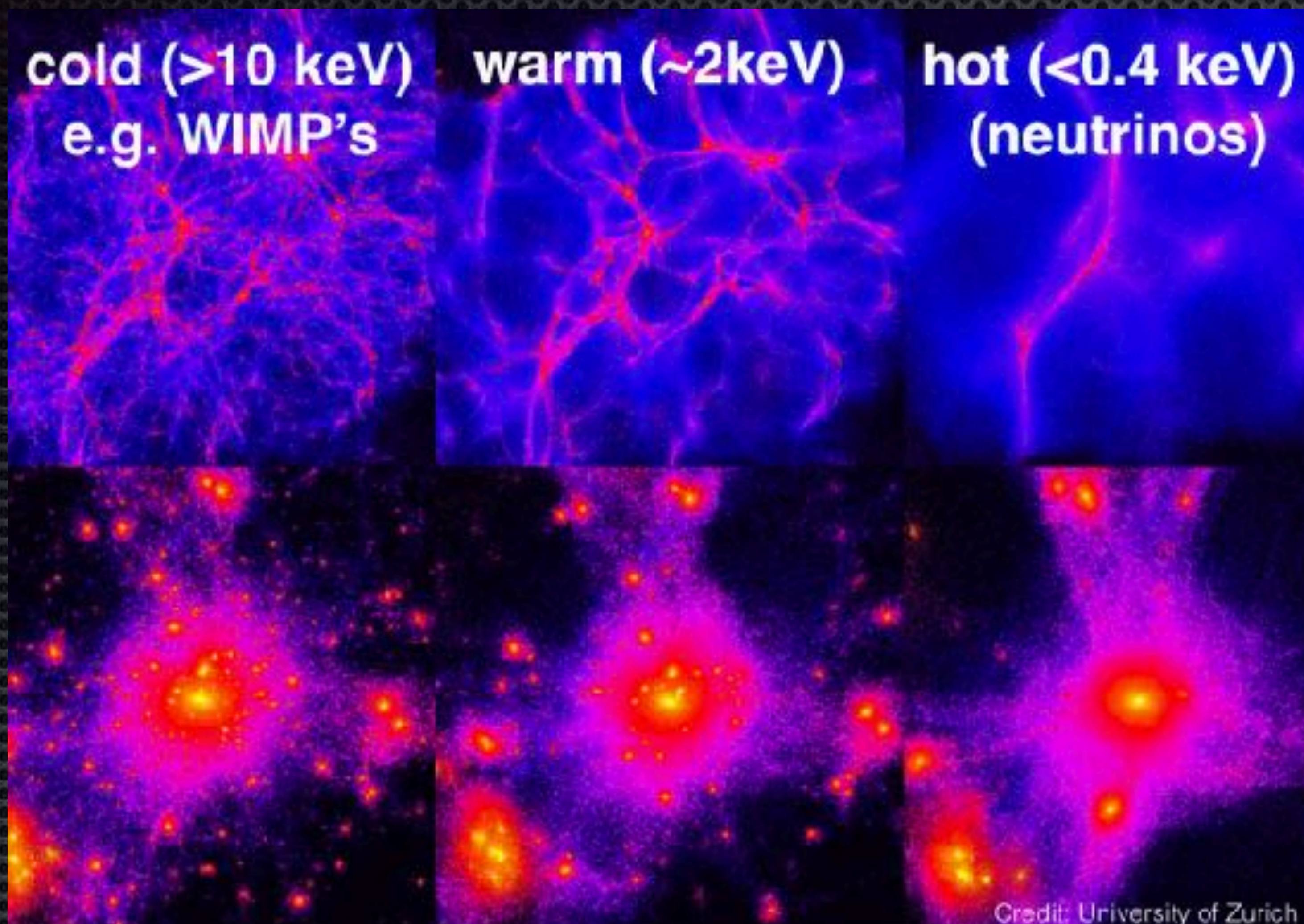
Looking for missing satellites in phase space
Antoja et al 2015, coherent kinematics + stellar over densities, mostly nearby

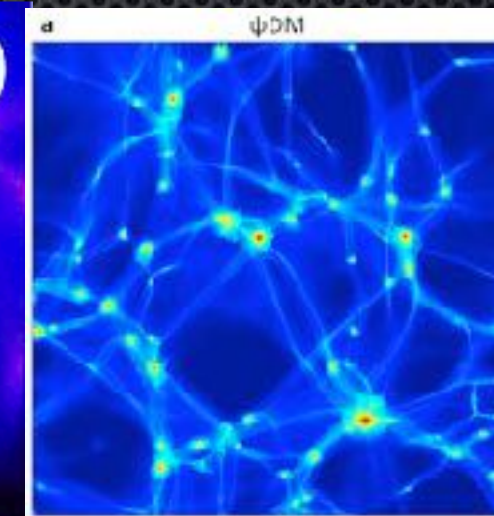
dsph´s anisotropy Massari 2017

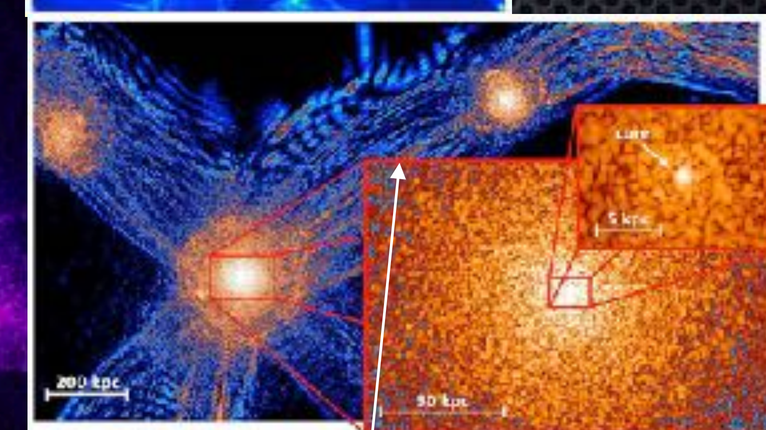
Missing Satellite Problem:

- Dark Matter Physics:
  WDM, Wave Dark Matter
- Reionization and
  feedback

Moore







- WDM
- Self-Interacting DM
- Wave Dark Matter: light axion, scalar field
- Gravity?

Not satellites

Missing Satellite Problem:

Kim, Peter etal 2017

No problem with LCDM? WDM mp > 8kev

All are uncertainties or baryons?

- Corrections to simulated halos abundance assuming tidal stripping, star formation-reionization, detection rates, calibrated using Galaxy Formation Simulations

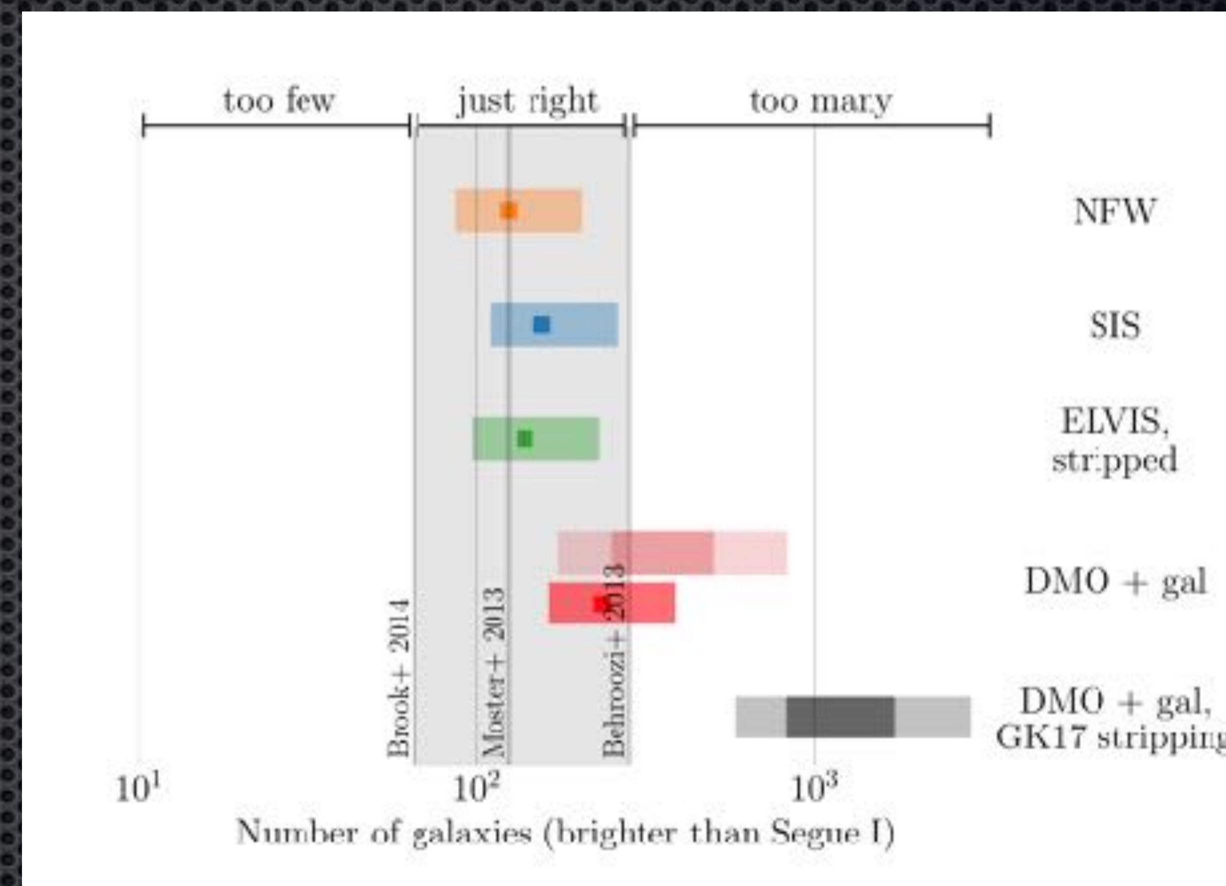
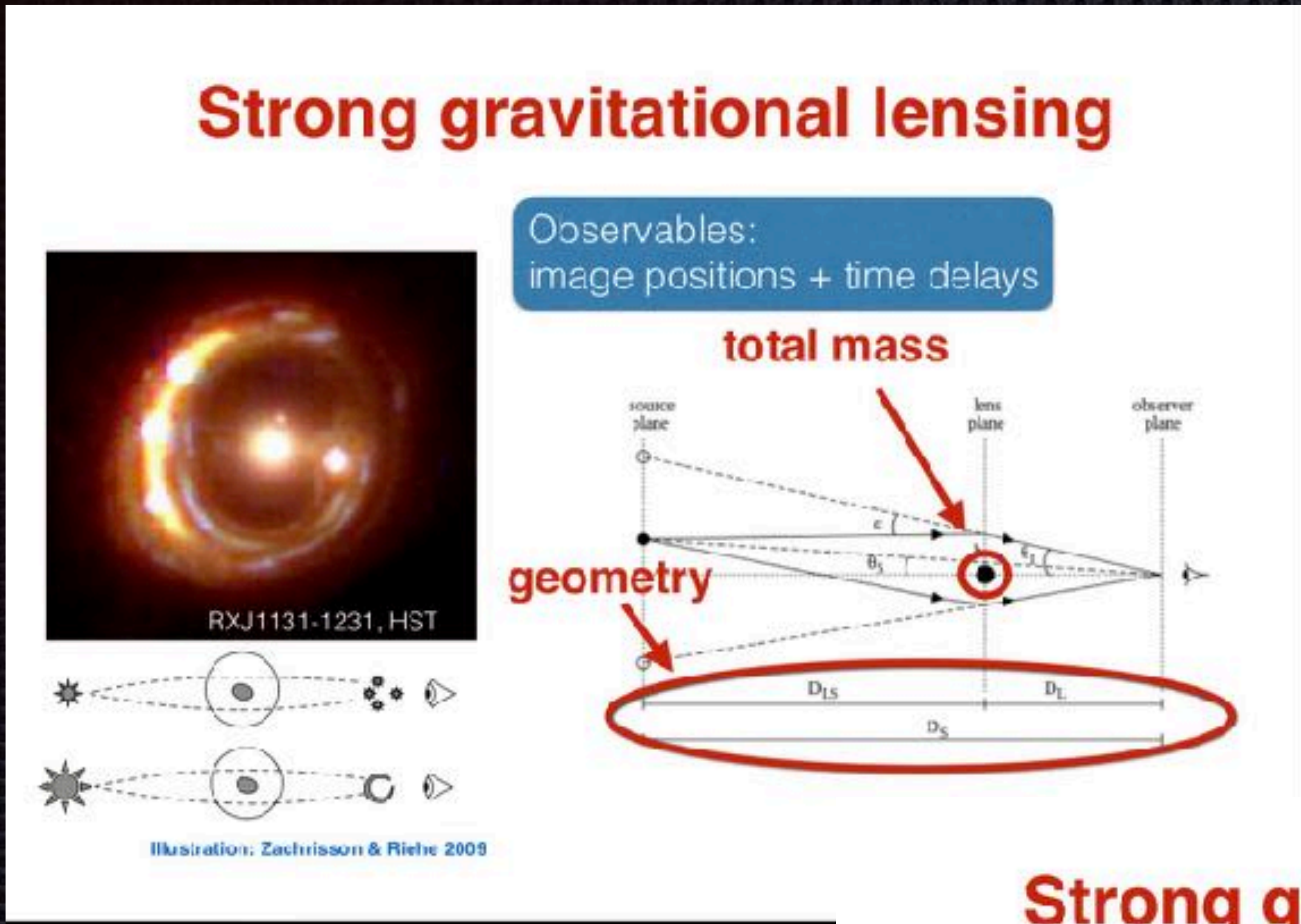


TABLE I. Completeness corrected satellite counts

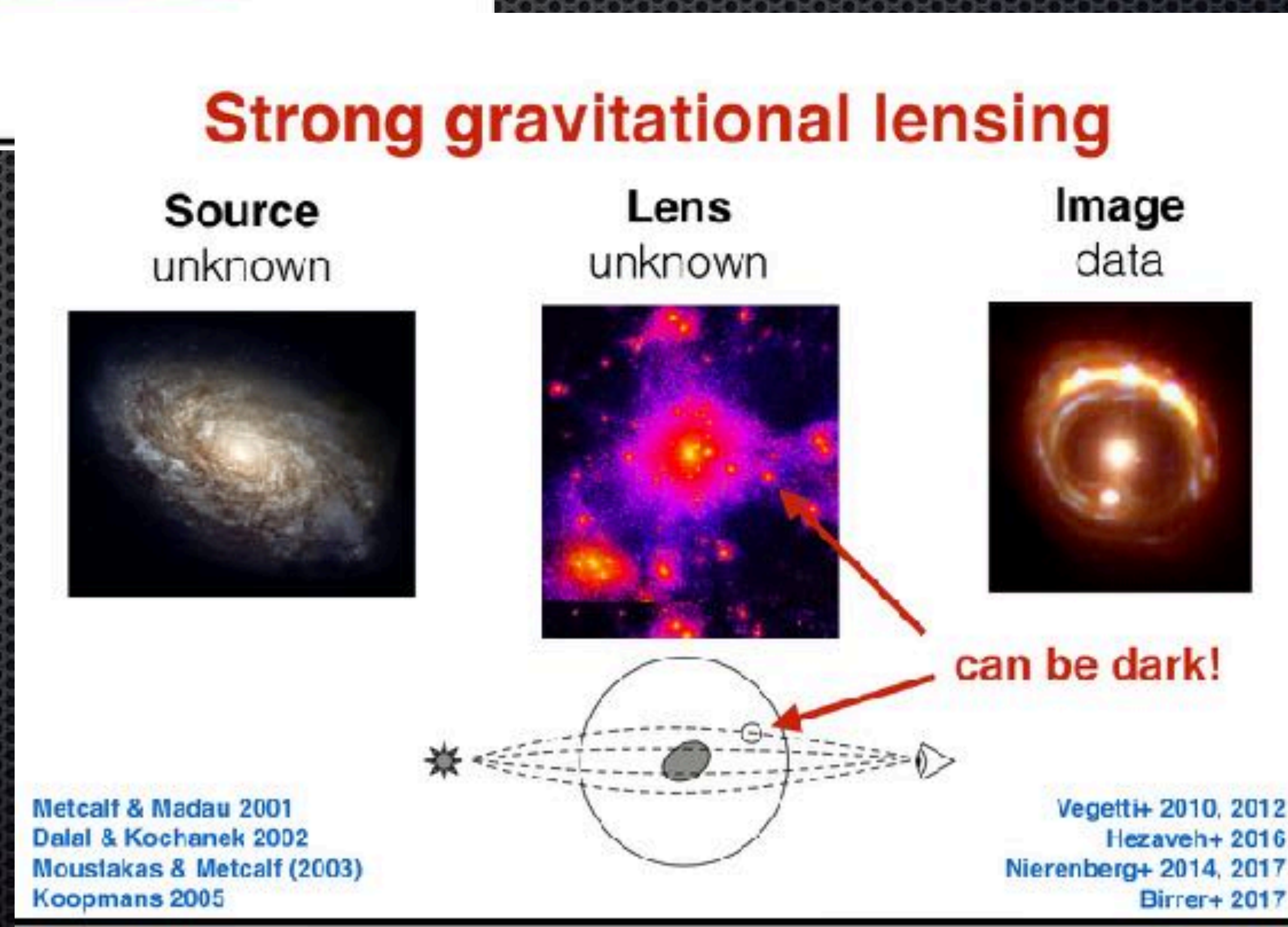
distribution	$r_{1/2}$	Predictions all sky	DES	LSST Year 1
NFW	124 kpc	124	11	38
SIS	150 kpc	157	13	42
ELVIS, stripped	90 kpc	139	13	44
D17	124 kpc	235	18	53
DMO + gal	110-158 kpc	250-503	20-28	56-71
DMO + gal + GK17	130-170 kpc	830-1740	49-69	104-130

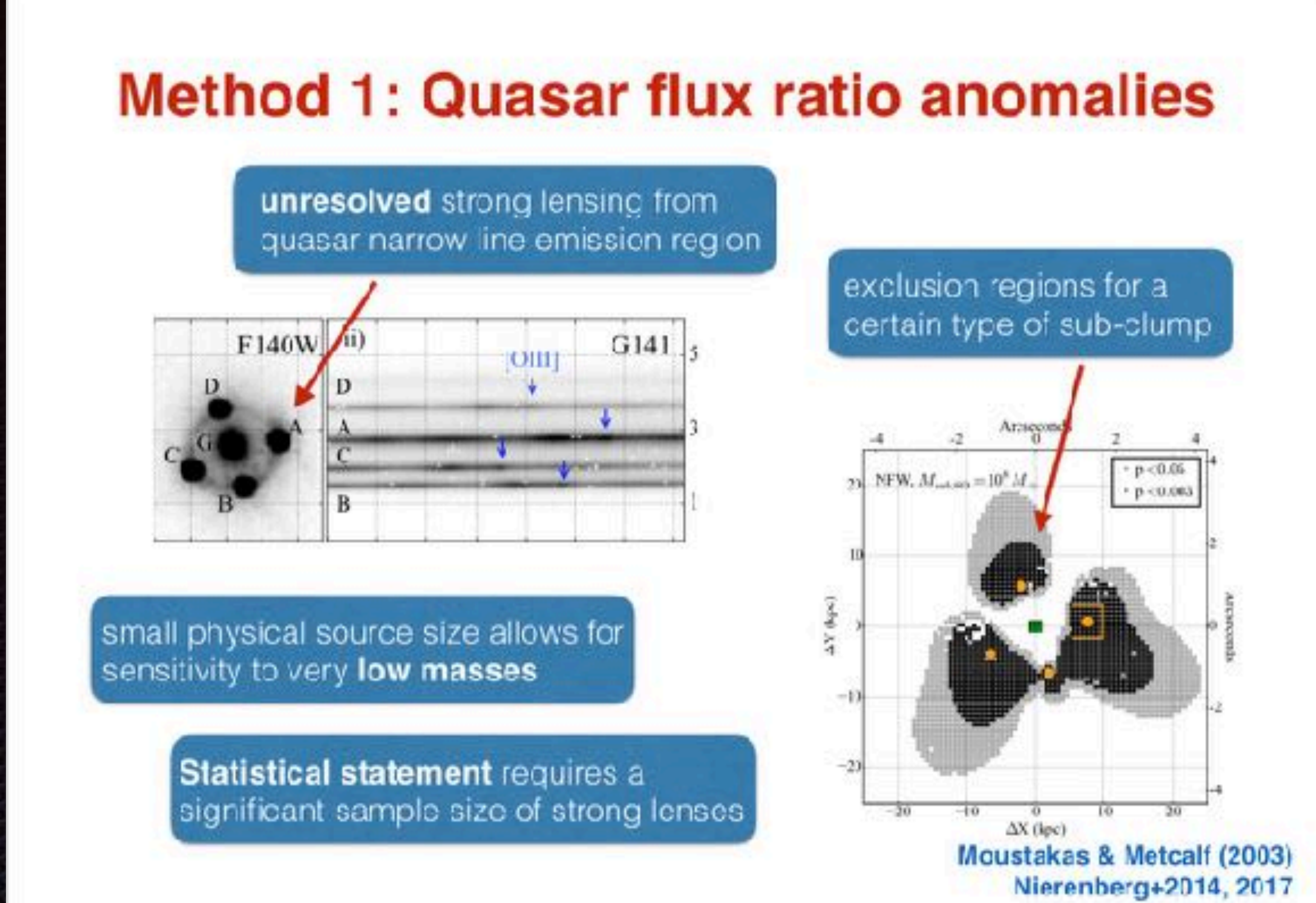
$r_{1/2}$ denotes the radius that encloses half the total satellites. Predictions for DES, when complete after year 5, and sensitive down to apparent magnitudes $V = 24.7$; and for LSST after year 1, down to $V = 23.8$.

Predicted detection rates
Not including GAIA



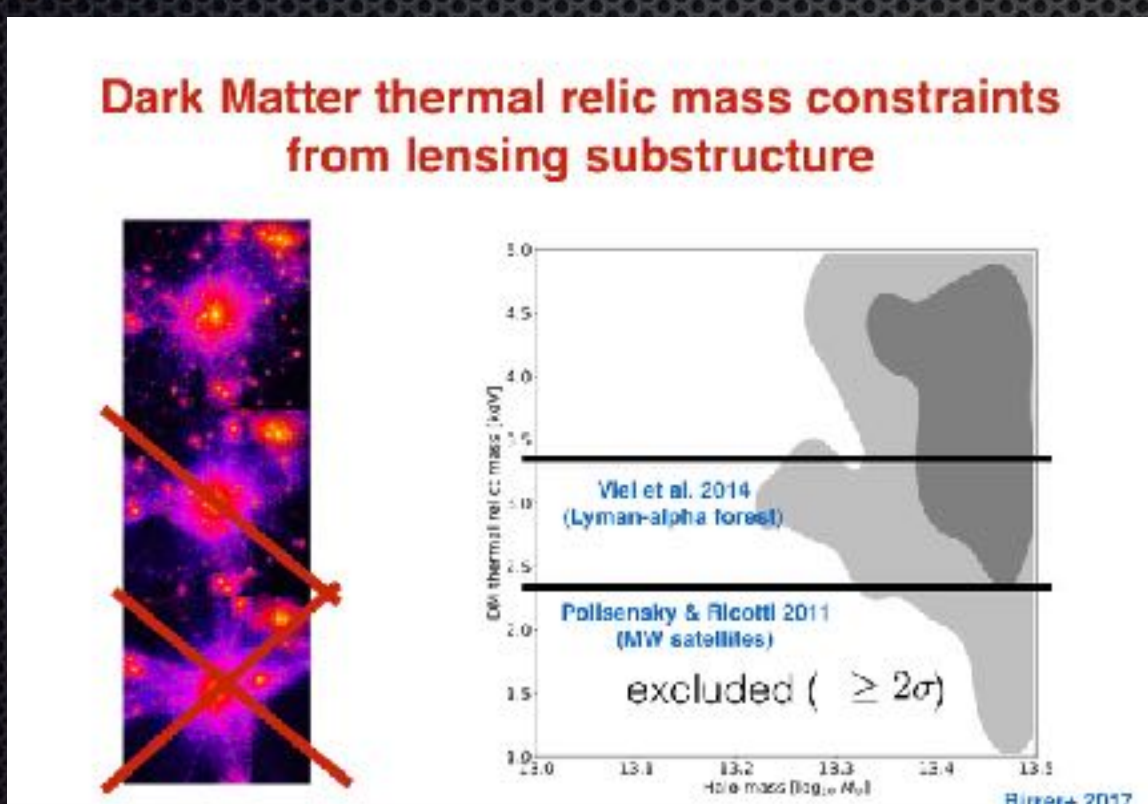
Birrett et al 2017

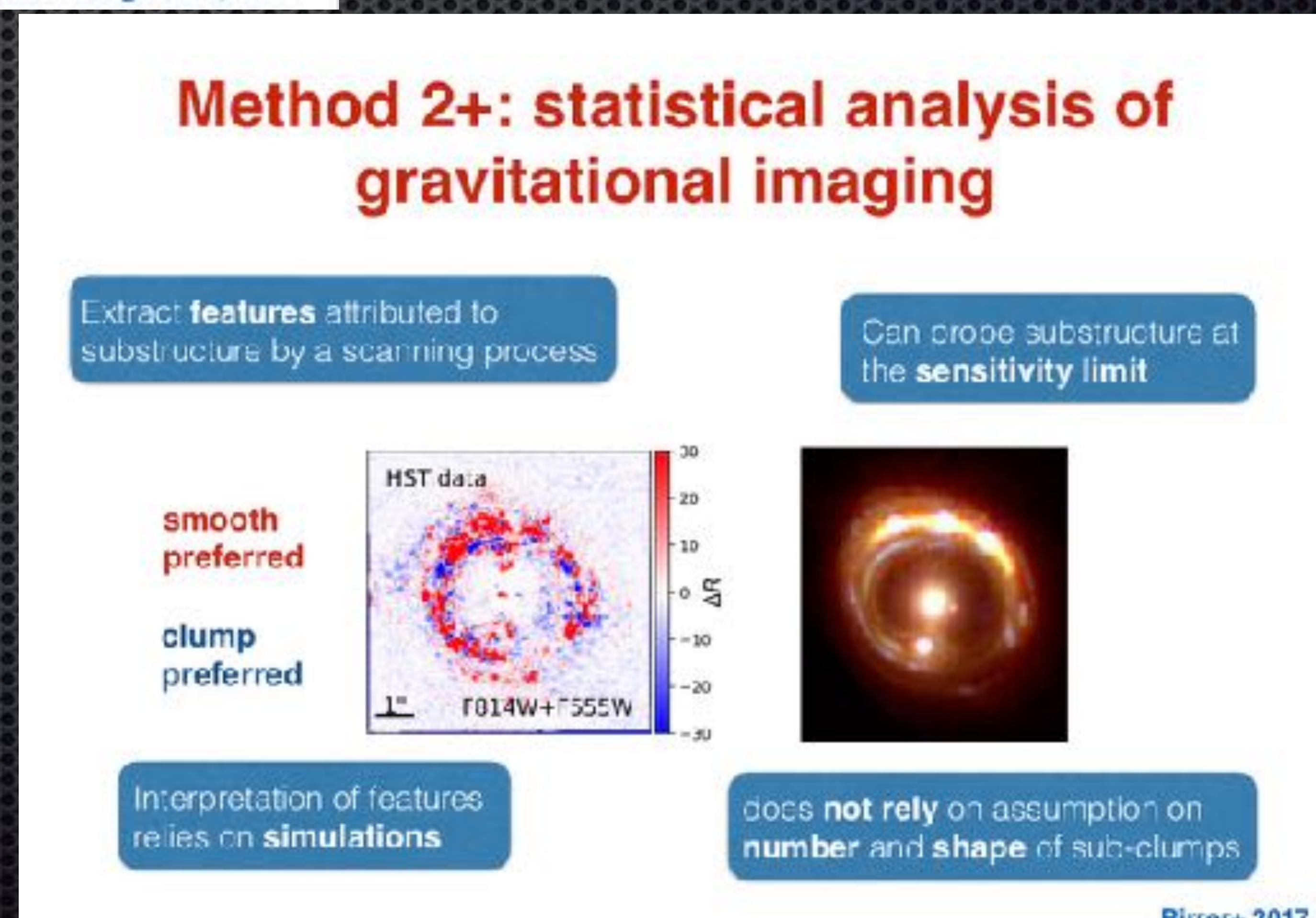




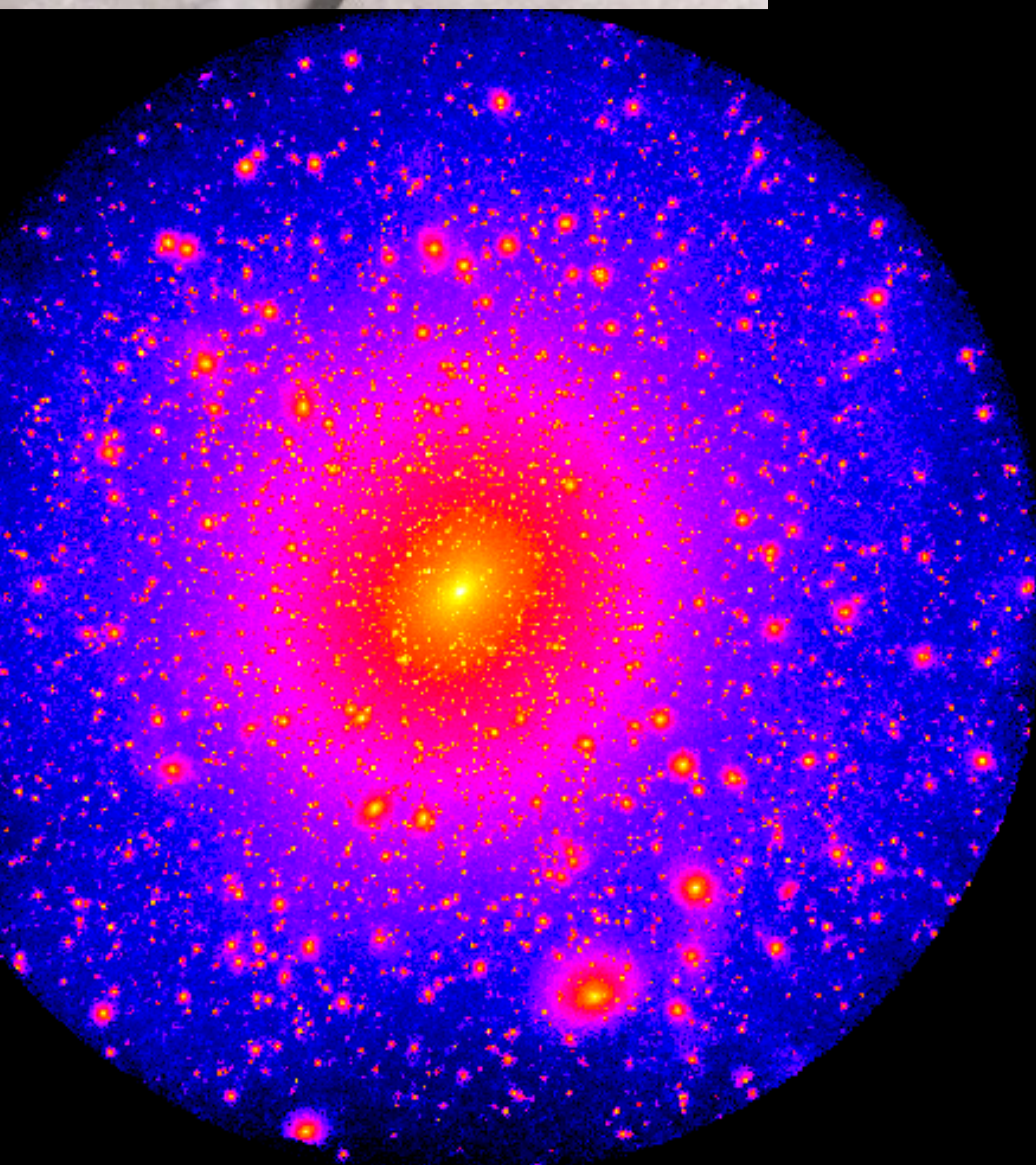
Encouraging but requires many systems to control systematics
Detailed simulations

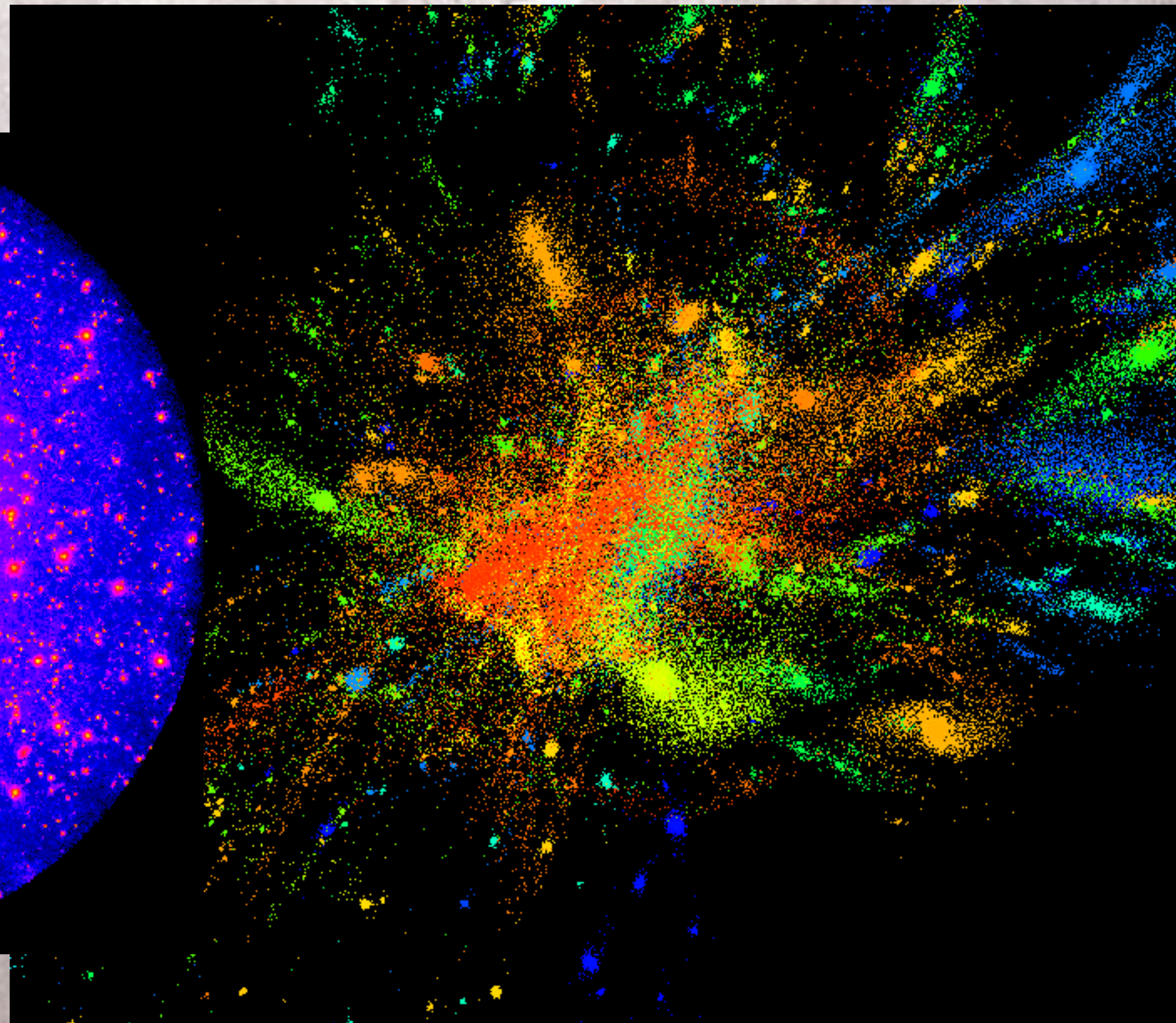
mp >2kev, thermal constraint to WDM





Fine Structure of Galaxies

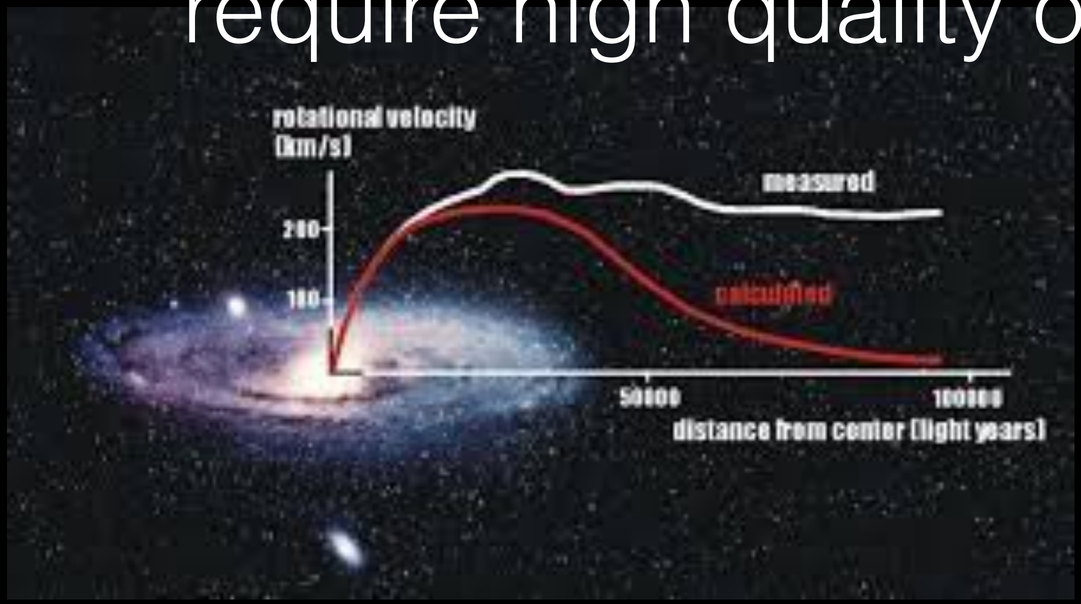


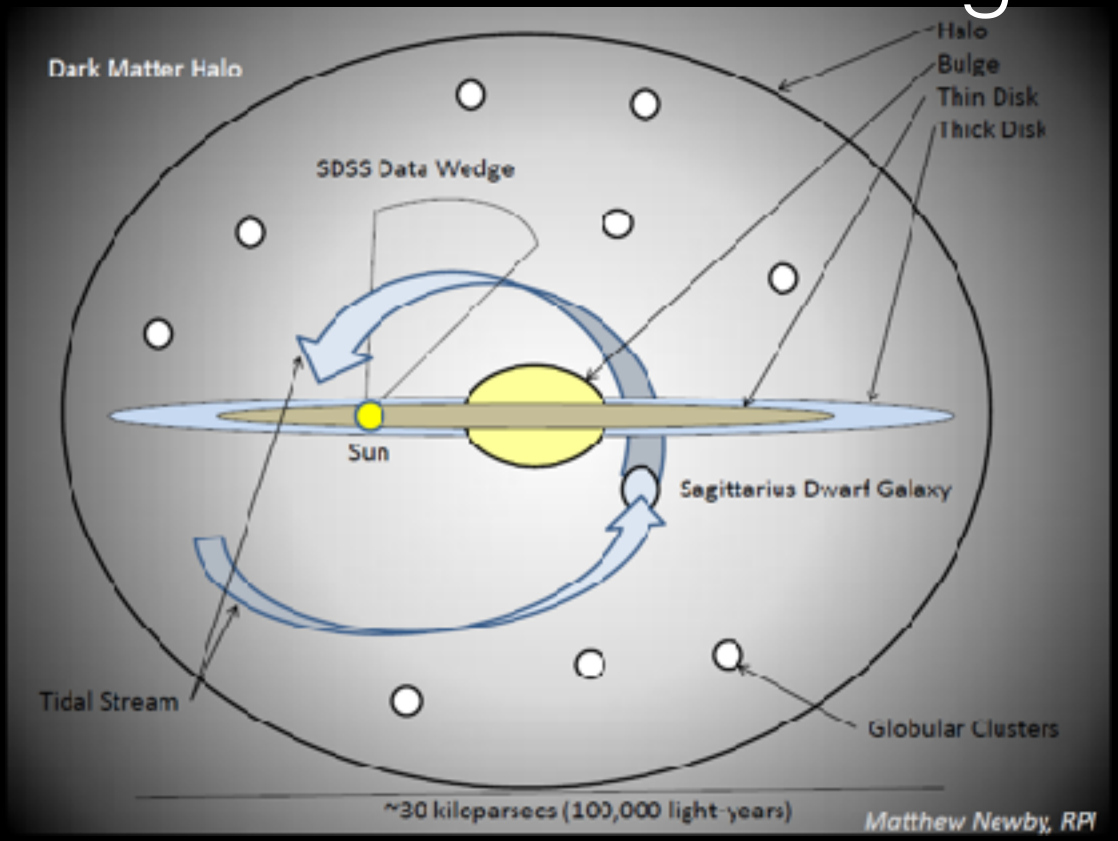


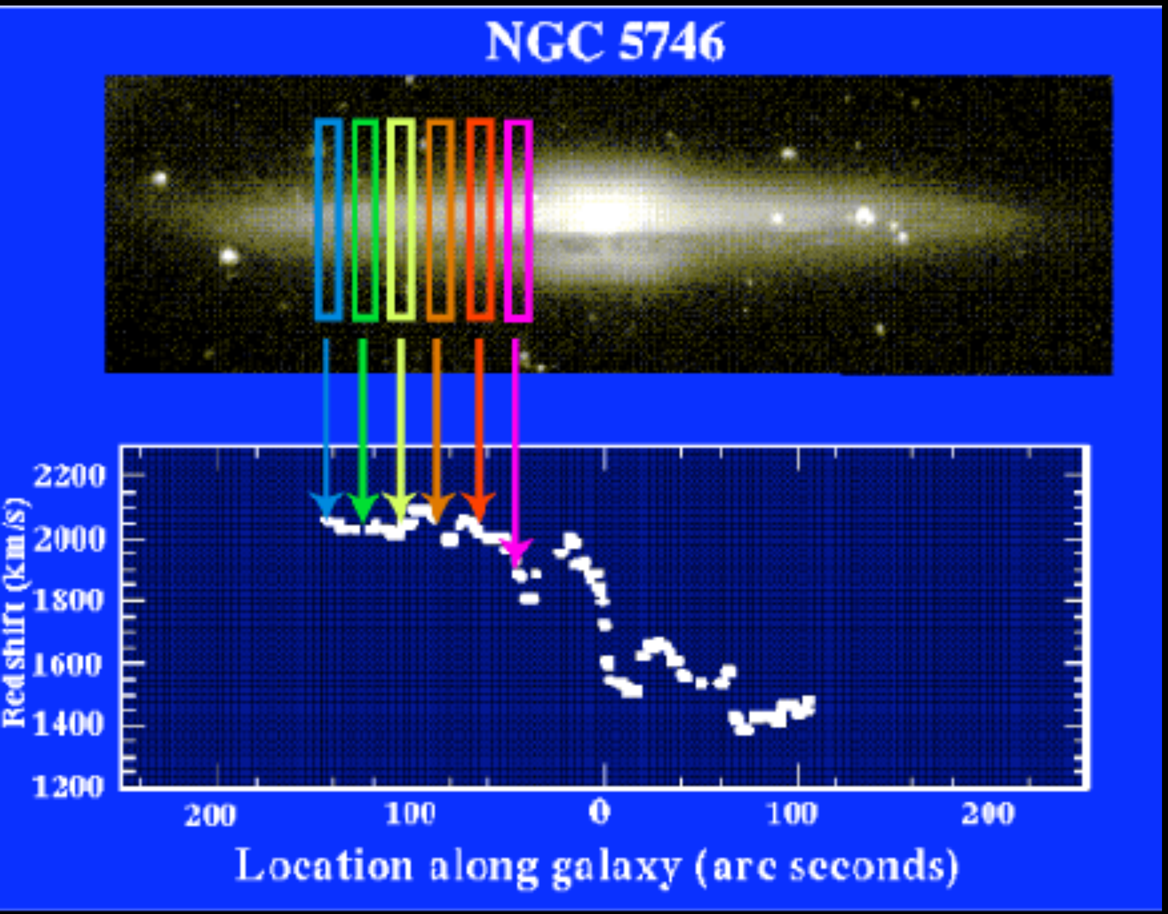
Galaxy structure reacts to the properties of dark matter halo
spirals, bars, asimetries, warps, oval disks?

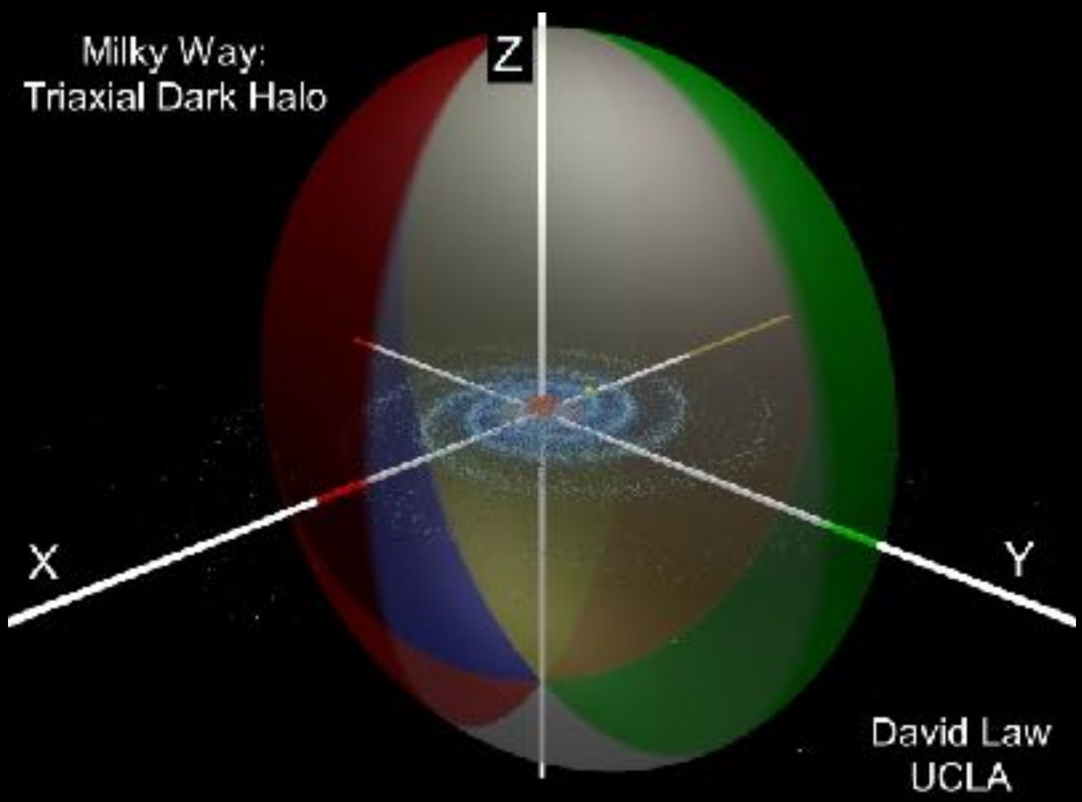
How galaxy disks react to non-spherical, clumpy halos??
Any idea?

Dark Matter in Galaxies may have several signatures that require high quality observations and modeling skills









Dark Matter explanation may require a new gravity theory

Different ways to deform the space-time compared with GR predictions

Interesting Idea but the most simple versions have failed, either require some Dark Matter or they under predict observations or they have theoretical problems (field theory) (MOND, TeVes)

Requires more research and more quantitative observational tests. Room is decreasing.

Conclusions

- **Dark Matter hypothesis** is based on the **acceleration excess in galaxies and clusters**: measured with kinematics, gravitational lensing
- Baryonic undetected matter is ruled out (Deuterium) assuming General Relativity
- Independently of astronomy particle and quantum field theories show evidence of being incomplete (neutrino oscillations, convergence of fundamental interactions at high energy density, etc) **proposals to solutions imply very often new particles that can be dark matter.**
- Dark matter searches in the sky: galaxy properties, anomalous gamma or radio emission or cosmic rays. It is also searched in labs: scintillation or in large accelerators: missing energy
- The answer will modify quantum field and particle **physics (new)**, or **gravity** or both or **something else** we are not thinking yet. **Your suggestion here…**
- Determining dark matter nature is one of the most critical challenges of astronomy and modern physics
- Comparisn with galaxies a very active area, there are challenges but not contundent failure