



# Dark Matter

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University of California, Irvine



Grenoble  
January 21-22, 2016

# Outline of the Lectures

- Lecture I : Evidence for Dark Matter
- Lecture II : Particle Physics of Dark Matter
  - Supersymmetry
  - Beyond SUSY
- Lecture III : Self-Interacting Dark Matter?



# Dark Matter: Evidence

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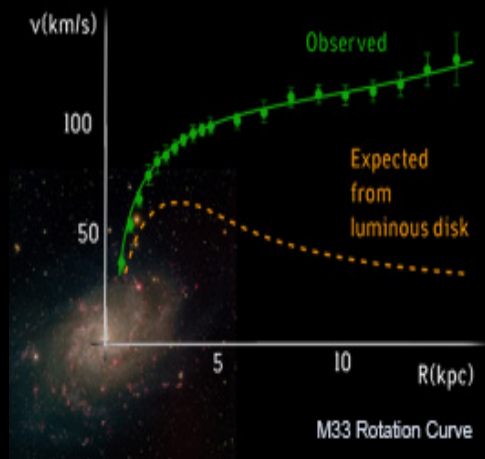


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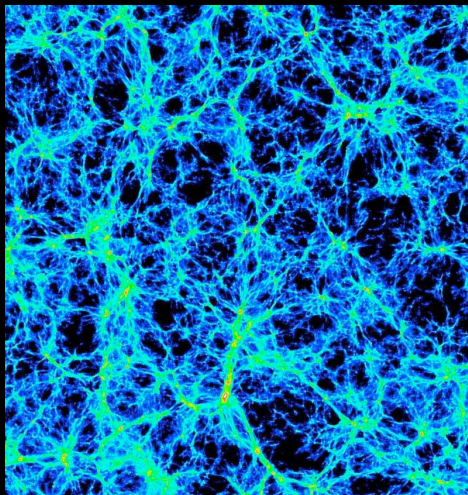
With thanks to Simona Murgia for  
the basis of these lecture notes!

# Outline of Lecture I

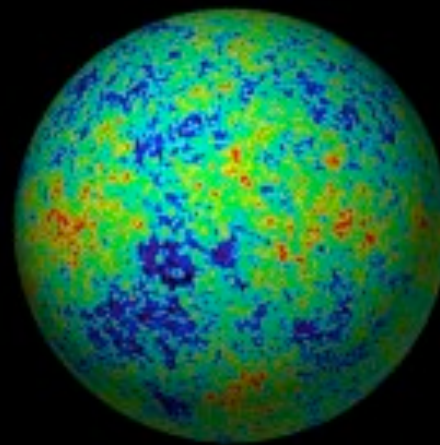
Rotation Curves



Lensing

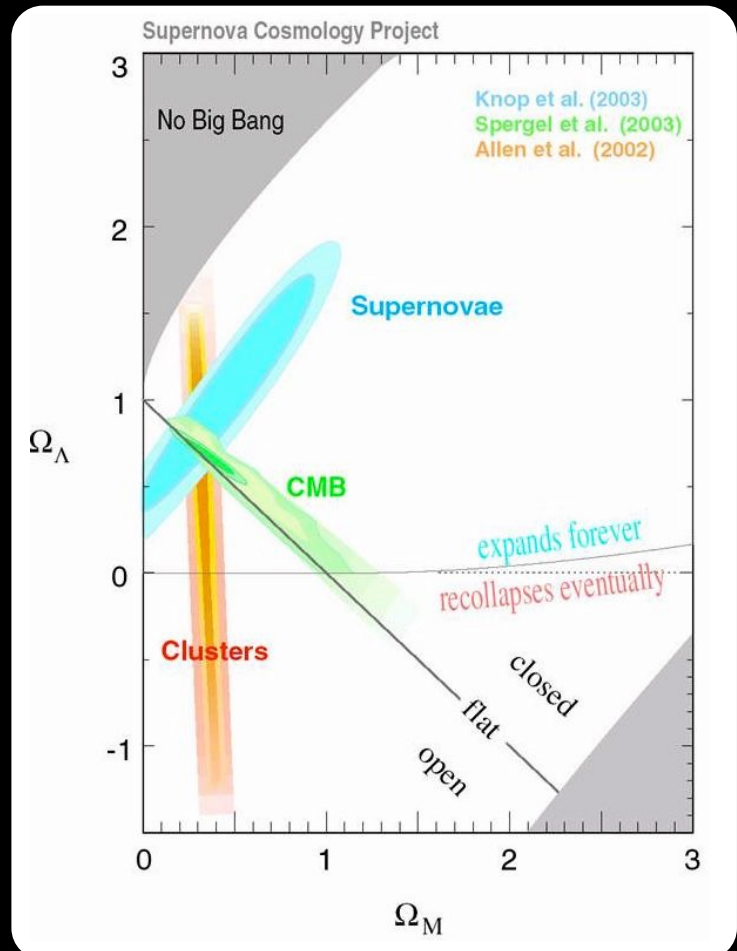
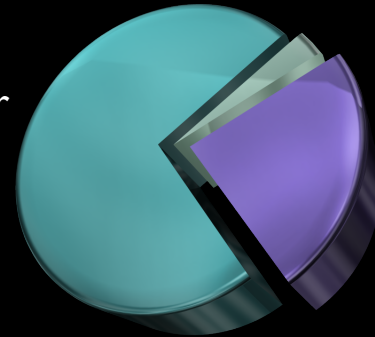


Structure



CMB

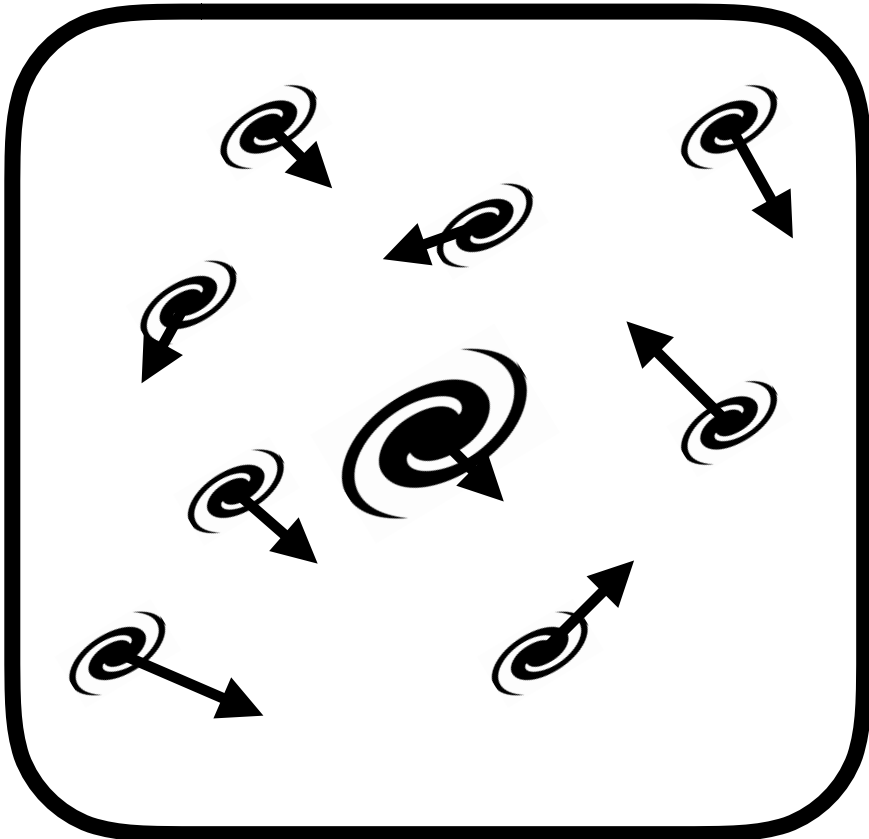
- Ordinary Matter
- Dark Matter
- Dark Energy





# Zwicky and the Coma Cluster

- The existence of dark matter was postulated by Zwicky in the 1930's to explain the dynamics of galaxies in the Coma galaxy cluster.
- (Clusters of galaxies are the largest gravitationally bound systems known in the Universe, containing ~10s to 1000s of galaxies.)
- Because of their very large size, one expects clusters to have roughly the same proportion of ordinary (mostly gas) and dark matter as the Universe itself.



# Zwicky and the Coma Cluster

- For systems in dynamical equilibrium and held together by gravity, the virial theorem says:

$$\frac{1}{2}m(3\sigma^2) \quad \swarrow \quad \nwarrow \quad G \frac{M_{tot}(r)m}{r}$$

$$2\langle T \rangle = -\langle V \rangle$$

Velocities  $\sim 1000$  km/s  
 $R \sim$  Mpcs  
 Distance  $\sim 100$  Mpc  
 (1 pc = 3.26 light yrs)

- By measuring the velocity (dispersion) of the galaxies in the Coma cluster, Zwicky could infer its total mass.
- However, the luminous mass (the galaxies in the cluster) was far smaller!

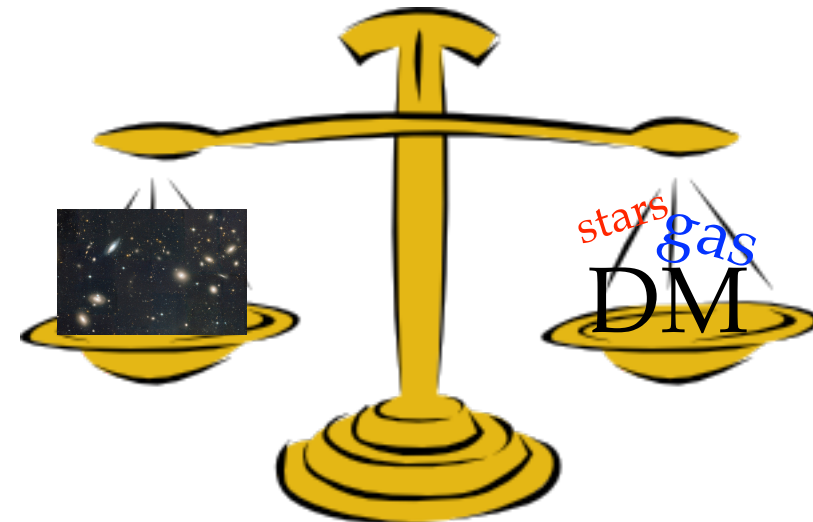
F. Zwicky, *Astrophysical Journal*, vol. 86, p.217 (1937):

$$M > 9 \times 10^{16} \text{ gr.} \quad (35)$$

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

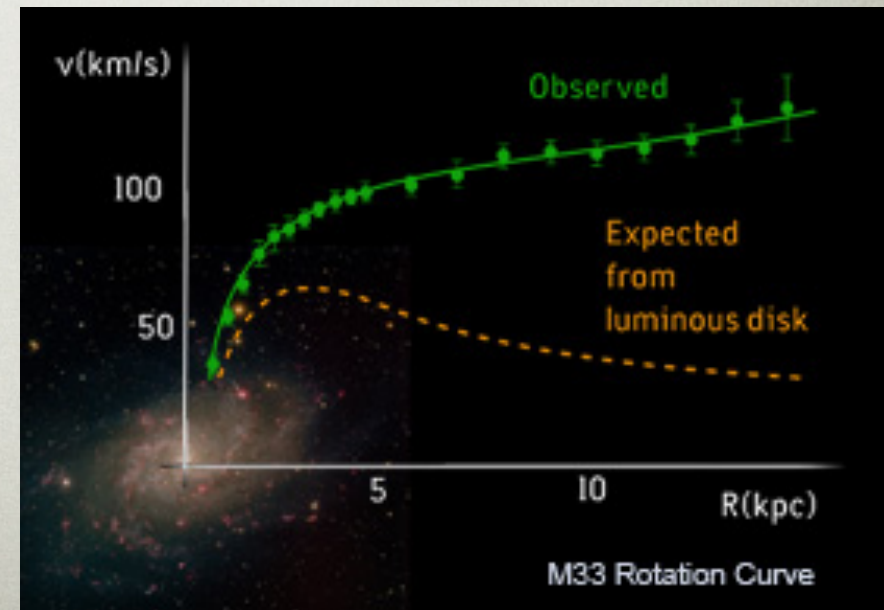
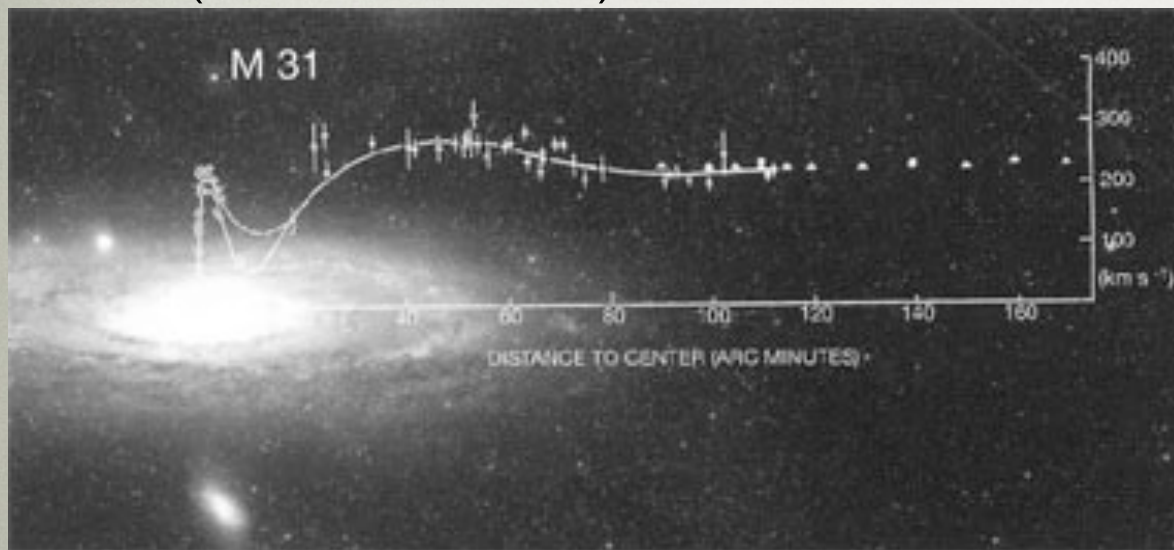
$$\bar{M} > 9 \times 10^{13} \text{ gr} = 4.5 \times 10^{10} M_{\odot}. \quad (36)$$

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  $8.5 \times 10^7$  suns. According



# ROTATION CURVES OF GALAXIES

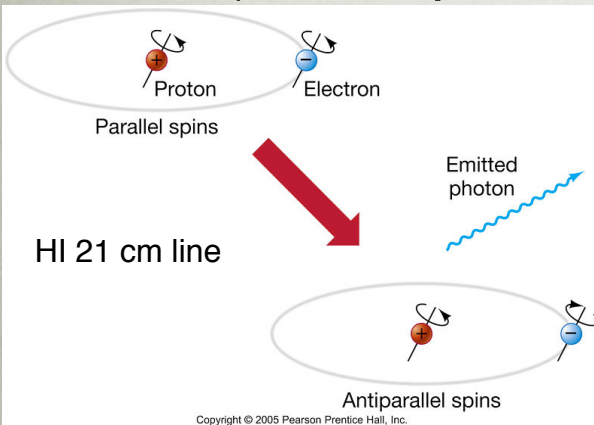
- Departures from the predictions of newtonian gravity became apparent also at galactic scales with the measurement of rotation curves of galaxies (Rubin et al, 1970)



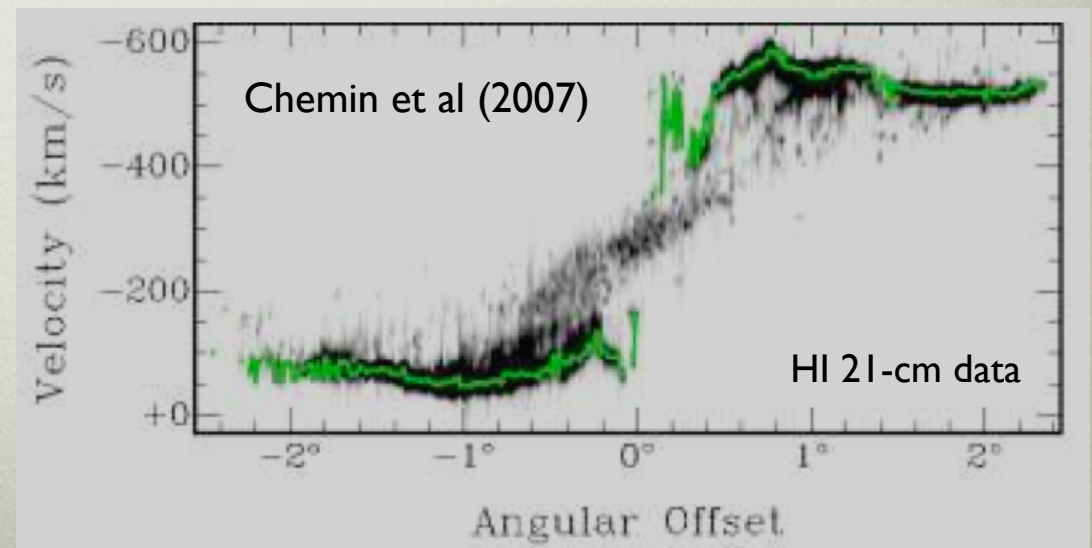
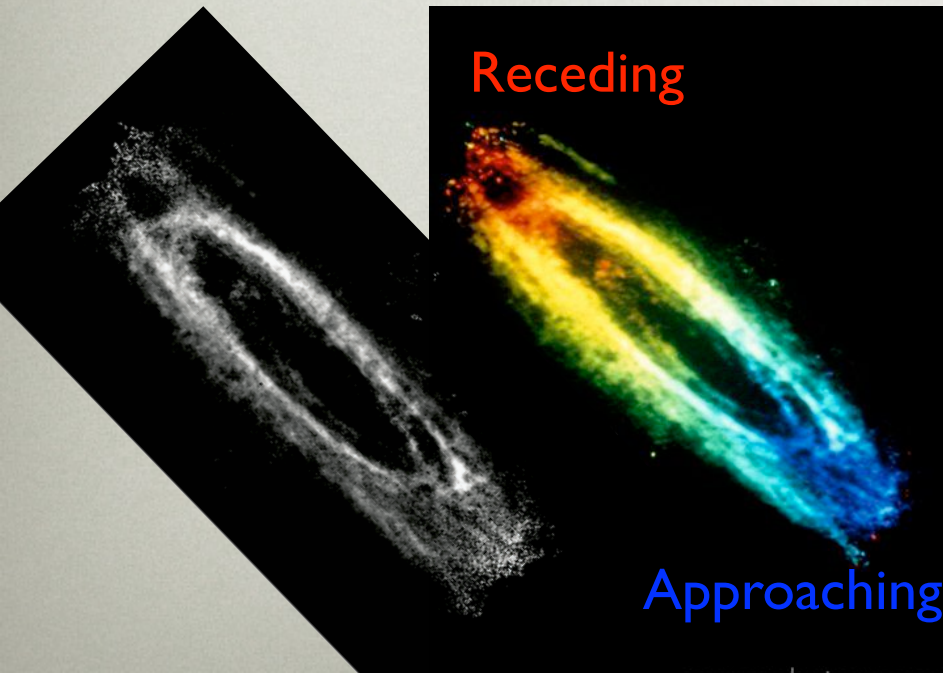


# ROTATION CURVES OF GALAXIES

- Measure line of sight velocity of stars and gas via doppler shift ( $H\alpha$  in optical and HI 21 cm line in radio)



M31 (Andromeda)

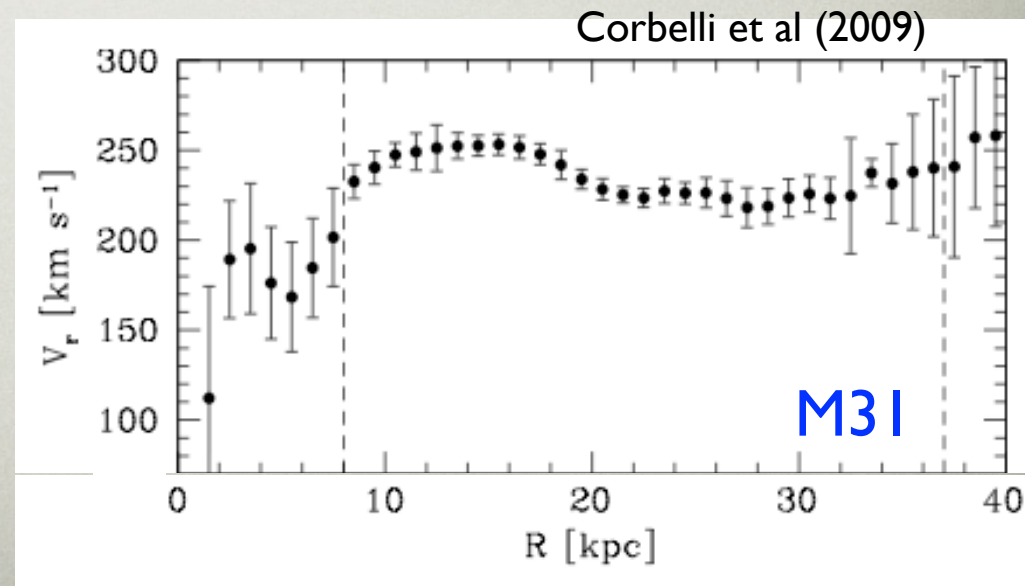
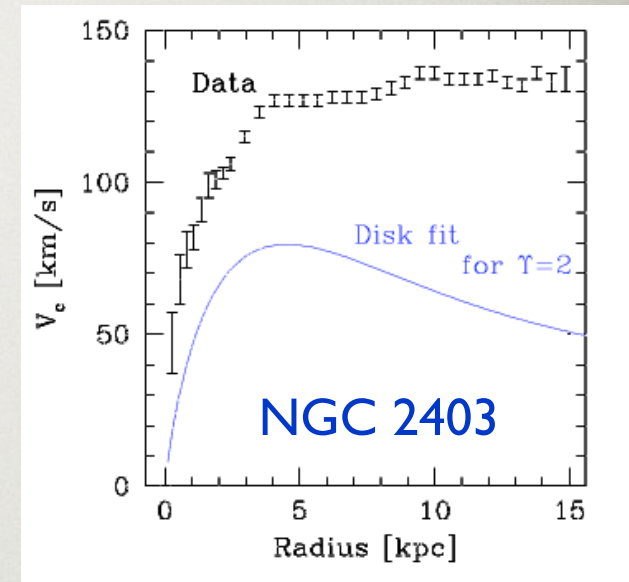
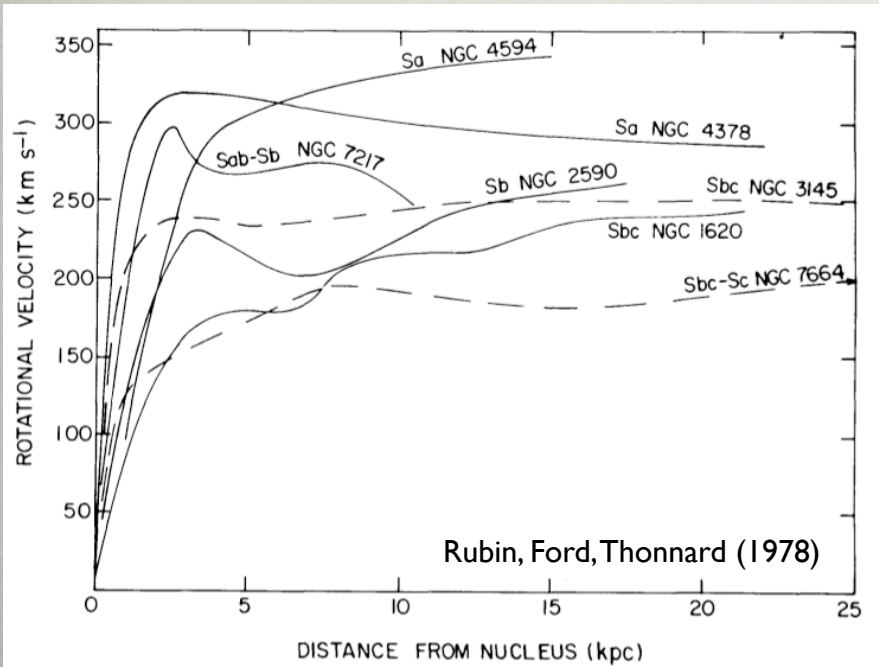


# ROTATION CURVES OF GALAXIES

From newtonian dynamics:

$$F = \frac{mv^2}{r} = G \frac{mM}{r^2}$$

$$v(r) \propto r^{-1/2}$$



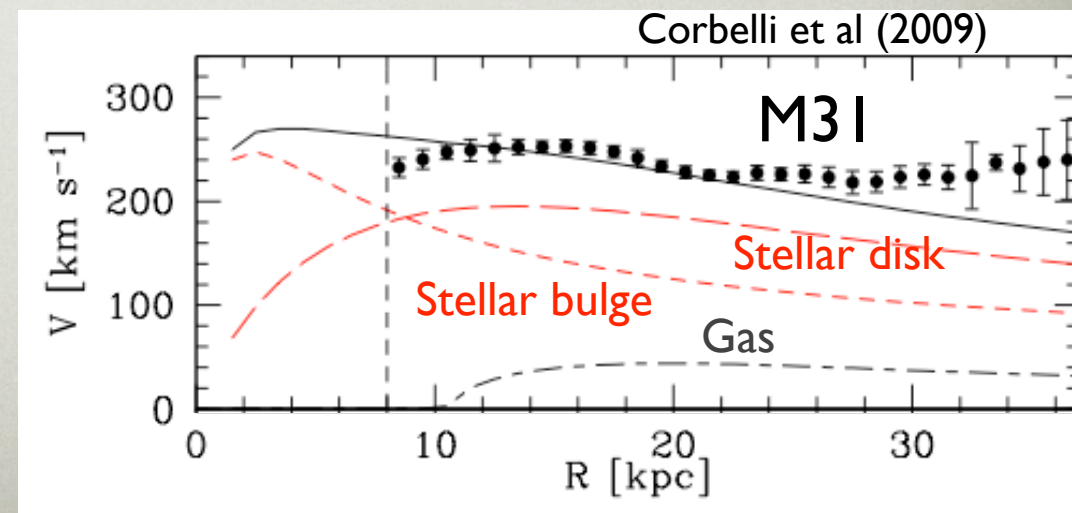
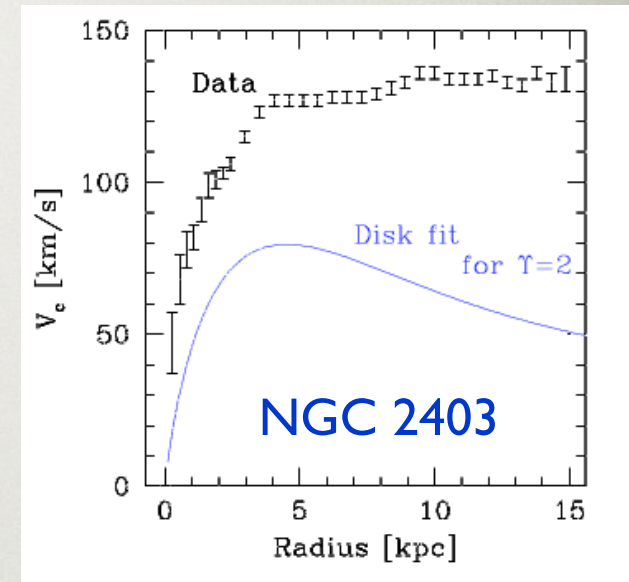


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- From newtonian dynamics:

$$F = \frac{mv^2}{r} = G \frac{mM}{r^2}$$

$$v(r) \propto r^{-1/2}$$

- For constant v:

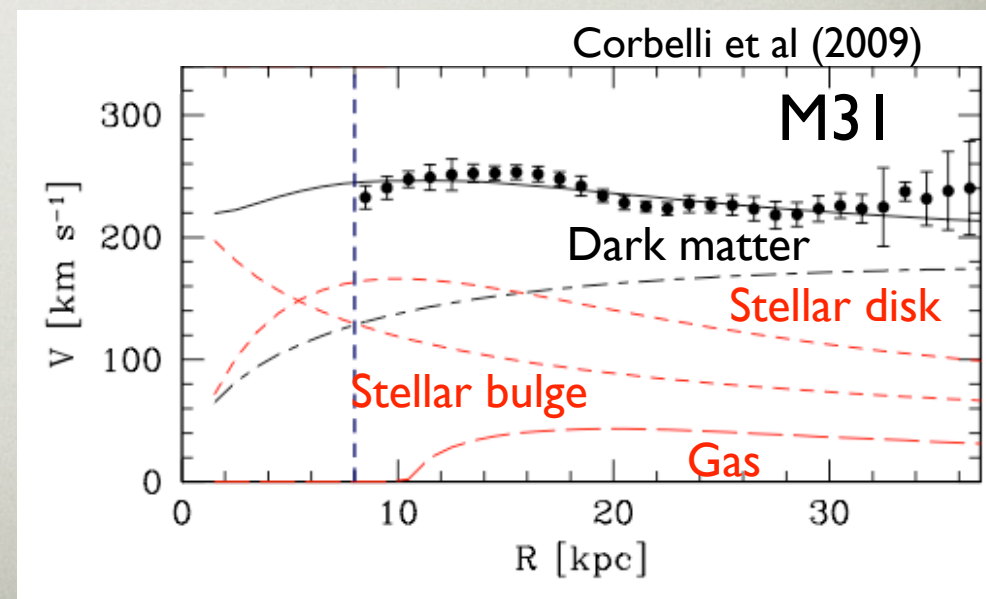
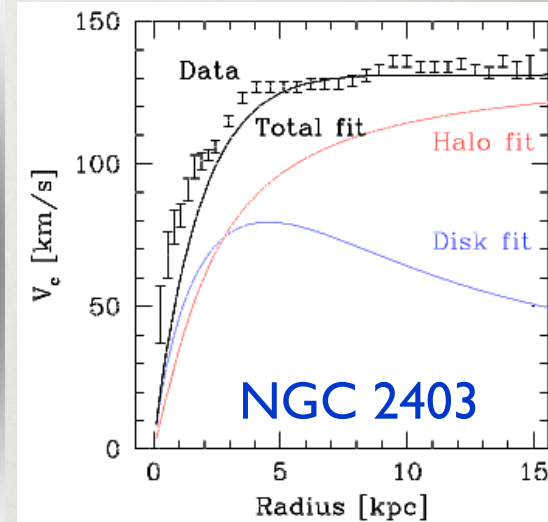
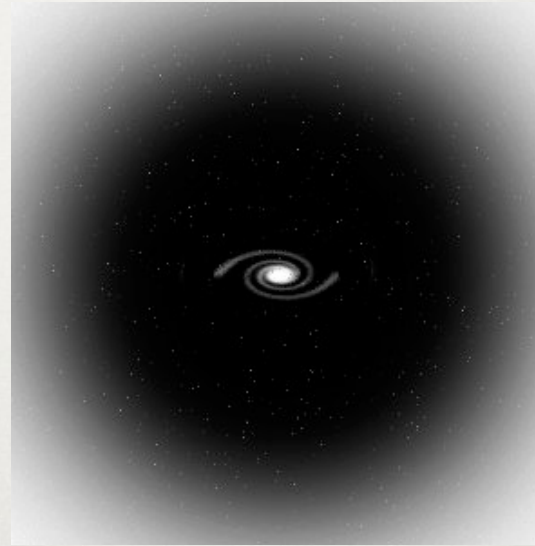
$$M(r) \propto r \quad \rho(r) \propto r^{-2}$$

Mass density not as steeply falling as star density (exponential)!

➔ By adding extended dark matter halo get good fit to the data.

Similar exercise for the Milky Way yields local DM density:

$$\rho(8.5 \text{ kpc}) \sim 0.2\text{-}0.5 \text{ GeV/cm}^3$$



# ROTATION CURVES OF GALAXIES

From newtonian dynamics:

$$F = \frac{mv^2}{r} = G \frac{mM}{r^2}$$

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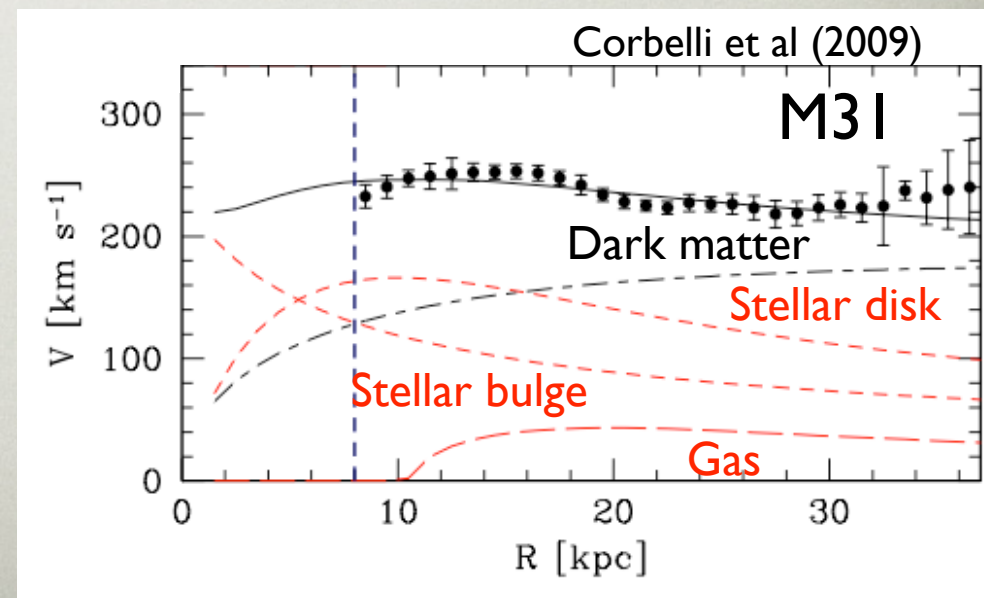
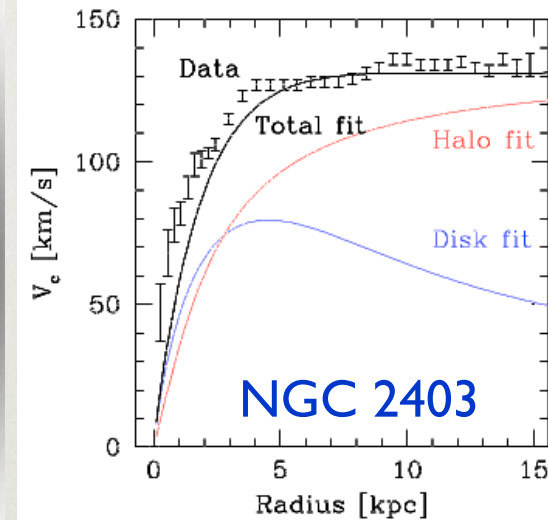
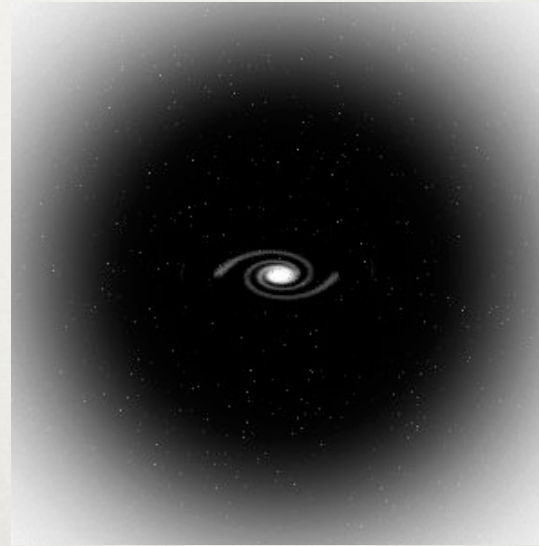
Mass density not as steeply falling as star density (exponential)!

➡ By adding extended dark matter halo get good fit to the data.

$L_{\odot}$ : Stars+gas:  $1.4 \times 10^{11} M_{\odot}$

$M_{\odot}$ : Total mass:  $1.3 \times 10^{12} M_{\odot}$

➡  $M_{\odot}/L_{\odot} \sim 10$

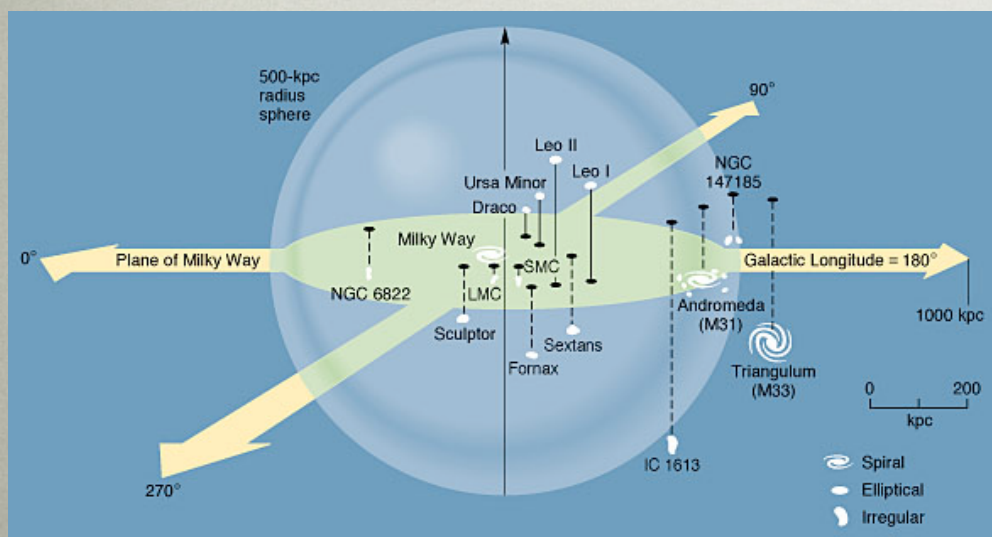




# MASSES OF M31 AND THE MILKY WAY

- By exploiting line of sight velocities and proper motion of satellite galaxies can determine the galactic halo mass out to large radii
- Halo mass within 300 kpc (stat error only! Also, these estimates assume Leo I for MW and And XII and And XIV for M31 are bound satellites):
  - Andromeda:  $1.5 \pm 0.4 \times 10^{12} M_{\odot}$
  - Milky Way:  $2.7 \pm 0.5 \times 10^{12} M_{\odot}$

Watkins et al, 2011



**Table 1.** Data table for the satellites of the Milky Way. Listed are Galactic coordinates ( $l, b$ ) in degrees, Galactocentric distance  $r$  in kpc and corrected line-of-sight velocity in  $\text{km s}^{-1}$ .

Name	$l$ (deg)	$b$ (deg)	$r$ (kpc)	$v_{\text{los}}$ ( $\text{km s}^{-1}$ )	Source
Bootes I	358.1	69.6	57	106.6	1,2
Bootes II	353.8	68.8	43	-115.6	3,4
Canes Venatici I	74.3	79.8	219	76.8	5,6
Canes Venatici II	113.6	82.7	150	-96.1	6,7
Carina	260.1	-22.2	102	14.3	8,9
Coma Berenices	241.9	83.6	45	82.6	6,7
Draco	86.4	34.7	92	-104.0	8,10,11
Fornax	237.3	-65.6	140	-33.6	8,12,13
Hercules	28.7	36.9	141	142.9	6,7
LMC	280.5	-32.9	49	73.8	8,14,15
Leo I	226.0	49.1	257	179.0	8,16,17
Leo II	220.2	67.2	235	26.5	8,18,19
Leo IV	265.4	56.5	154	13.9	6,7
Leo T	214.9	43.7	422	-56.0	6,20
Leo V	261.9	58.5	175	62.3	21
SMC	302.8	-44.3	60	9.0	8,22,23
Sagittarius	5.6	-14.1	16	166.3	8,24
Sculptor	287.5	-83.2	87	77.6	8,25,26
Segue 1	220.5	50.4	28	113.5	3,27
Segue 2	149.4	-38.1	41	39.7	28
Sextans	243.5	42.3	89	78.2	8,9,29
Ursa Major I	159.4	54.4	101	-8.8	3,6
Ursa Major II	152.5	37.4	36	-36.5	6,30
Ursa Minor	104.9	44.8	77	-89.8	8,10,11
Willman 1	158.6	56.8	42	33.7	2,3

**Table 2.** Data table for the satellites of M31. Listed are Galactic coordinates ( $l, b$ ) in degrees, actual distance  $r$  from the centre of M31 in kpc, projected distance  $R$  from the centre of M31 in kpc and corrected line-of-sight velocity in  $\text{km s}^{-1}$ .

Name	$l$ (deg)	$b$ (deg)	$r$ (kpc)	$R$ (kpc)	$v_{\text{los}}$ ( $\text{km s}^{-1}$ )	Source
M33	133.6	-31.3	809	206	74	1,2
M32	121.1	-22.0	785	5	95	2,3
IC 10	119.0	-3.3	660	261	-29	2,3,4
NGC 205	120.7	-21.1	824	39	58	1,2
NGC 185	120.8	-14.5	616	189	106	1,2
IC 1613	129.8	-60.6	715	510	-56	2,3,5
NGC 147	119.8	-14.2	675	144	117	1,2
Pegasus	94.8	-43.6	919	473	85	1,2
Pisces	126.7	-40.9	769	268	-37	1,2
And I	121.7	-24.8	745	59	-84	1,2
And II	128.9	-29.2	652	185	83	1,2
And III	119.4	-26.3	749	75	-57	1,2
And V	126.2	-15.1	774	109	-107	1,2
And VI	106.0	-36.3	775	267	-64	1,2
And VII	109.5	-9.9	763	218	21	1,2
And IX	123.2	-19.7	765	41	94	1,6,7
And X	125.8	-18.0	702	110	130	8,9
And XI	121.7	-29.1	785	102	-140	7,10
And XII	122.0	-28.5	830	107	-268	7,10,11
And XIII	123.0	-29.9	785	115	64	7,10
And XIV	123.0	-33.2	740	161	-204	12
And XV	127.9	-24.5	770	94	-57	13,14
And XVI	124.9	-30.5	525	280	-106	13,14
And XVII	120.2	-18.5	794	45	15	
And XVIII	113.9	-16.9	1355	589	16	
And XIX	115.6	-27.4	933	187	16	
And XX	112.9	-26.9	802	128	16	
And XXI	111.9	-19.2	859	148	17	
And XXII	132.6	-34.1	794	220	17	



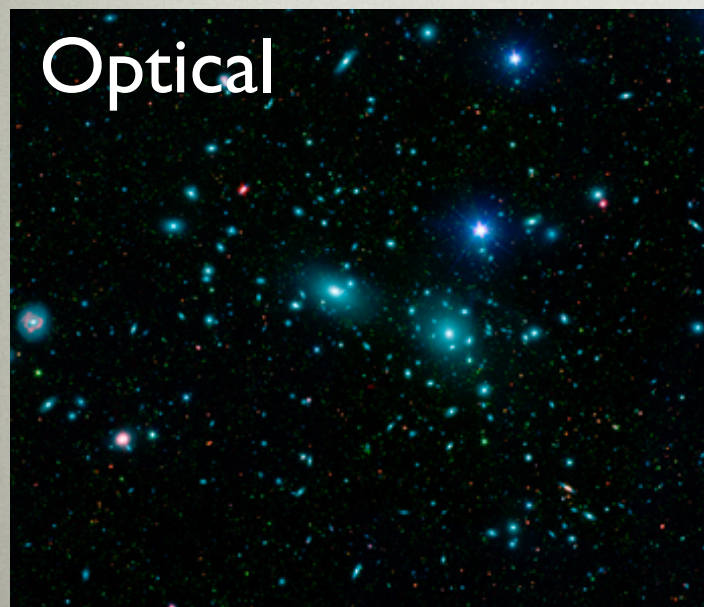
# GALAXY CLUSTERS (REVISITED)

- X-rays emitted by very hot intra-cluster gas ( $10^7$ - $10^8$  K) through bremsstrahlung.
- Gas mass and total mass in galaxy clusters measured by X-rays (assuming thermal equilibrium), as well as lensing
- Mass determination consistent with clusters being dark matter dominated

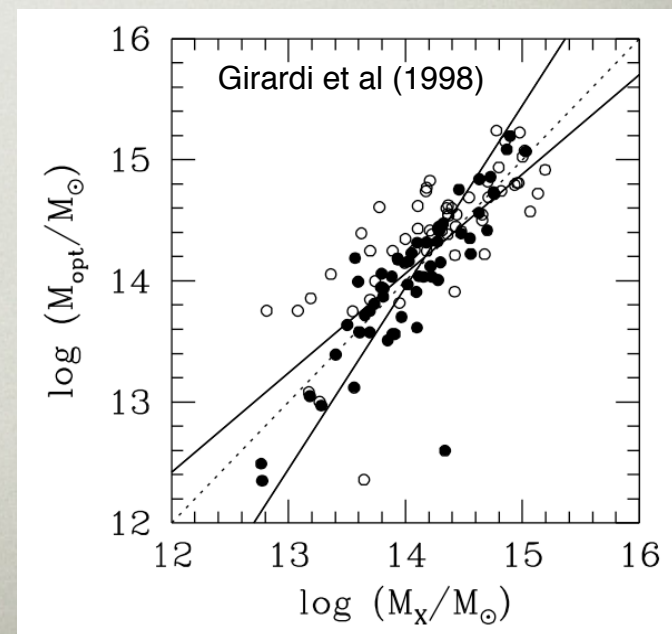
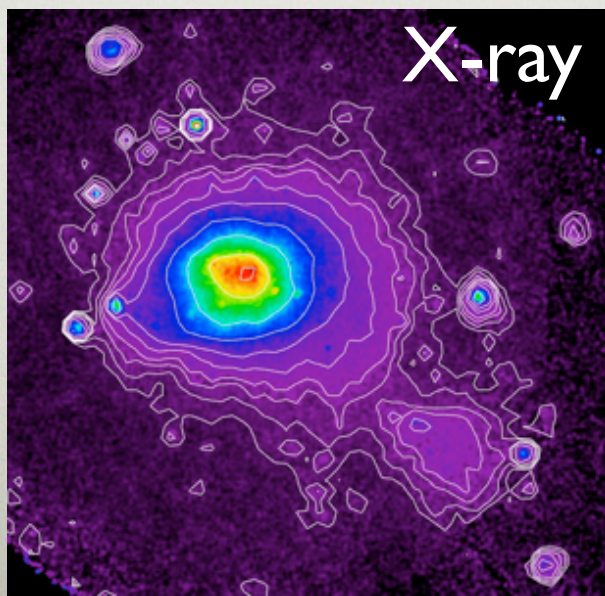
A Typical Galaxy cluster:  
~1-2% stars, ~5-15% gas, **remainder is dark matter**

## Coma galaxy cluster

Optical



X-ray

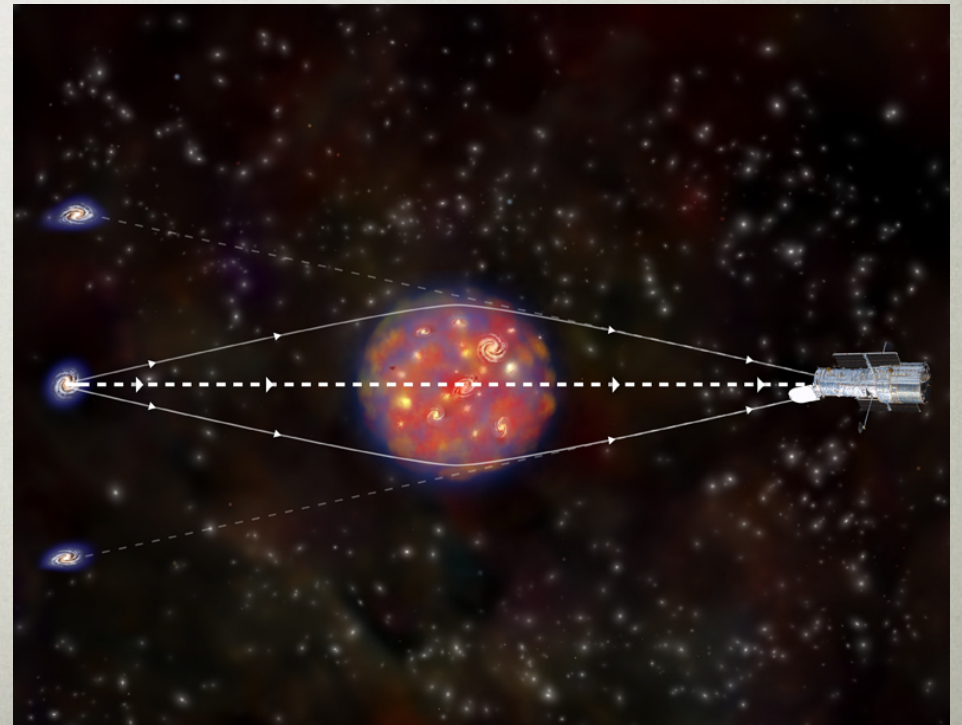
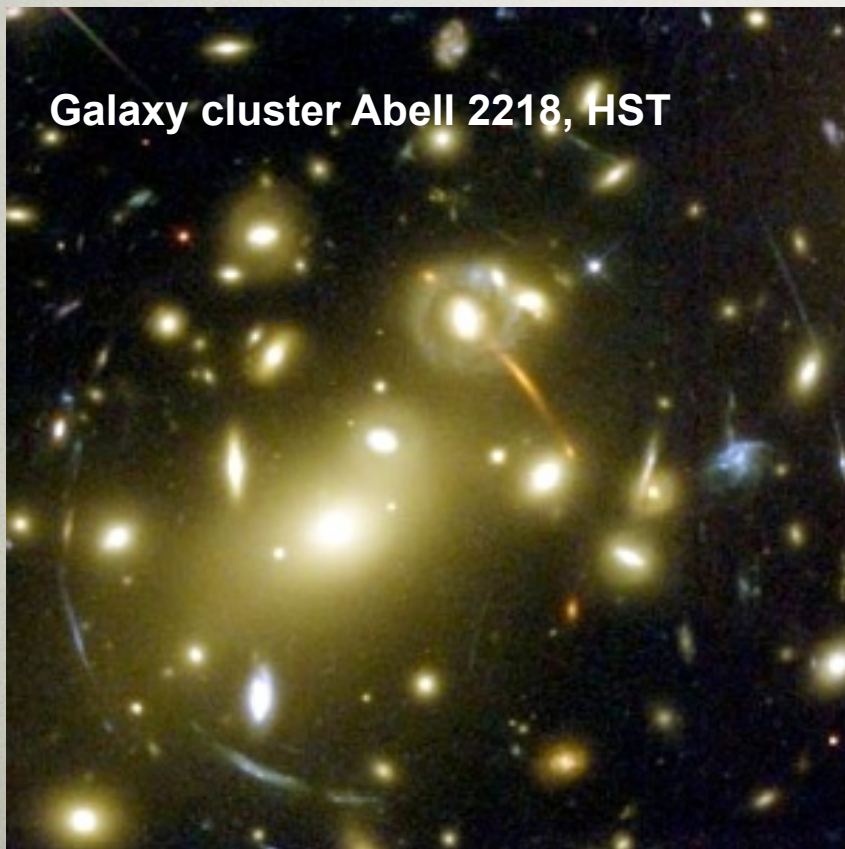




# GRAVITATIONAL LENSING

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- Image distortion caused by intervening gravitational potential
- Sensitive to total mass





# GRAVITATIONAL LENSING

- Image distortion caused by intervening gravitational potential
- Sensitive to total mass
- From general relativity:

Deflection

$$\hat{\alpha} = \frac{4GM}{c^2 \xi}$$

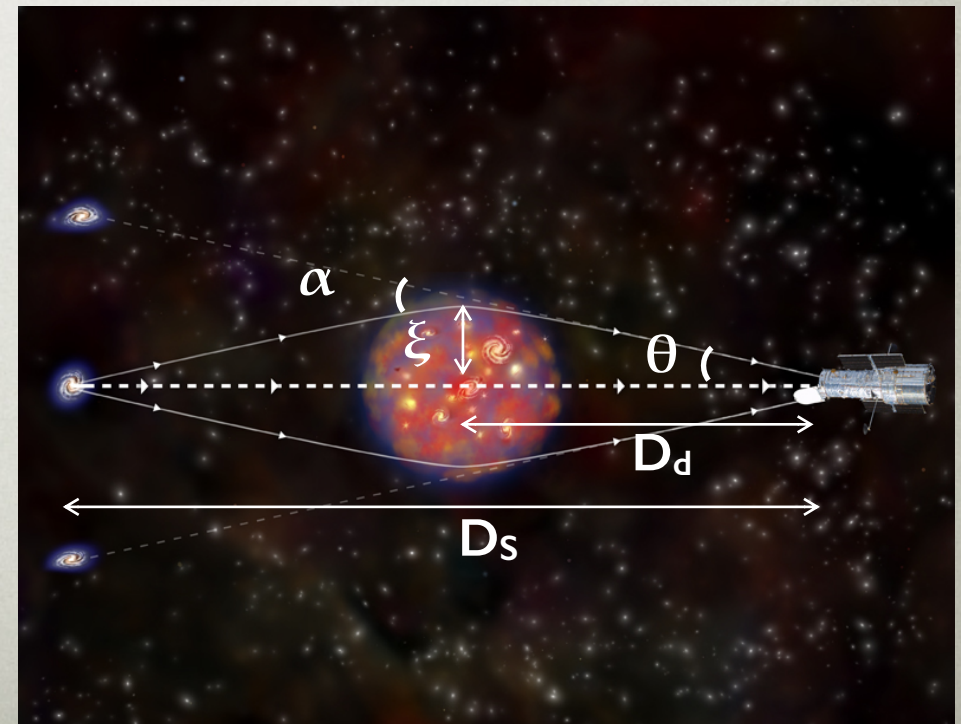
Lens mass

Impact parameter

$$\theta_E = \left( \frac{4GM}{c^2} \frac{D_{ds}}{D_d D_s} \right)^{1/2}$$

$$\sin(\hat{\alpha}) \approx \tan(\hat{\alpha}) \approx \hat{\alpha}$$

- Image separation proportional to  $\sqrt{M}$





# GRAVITATIONAL LENSING

- Image distortion caused by intervening gravitational potential
- Sensitive to total mass
- From general relativity:

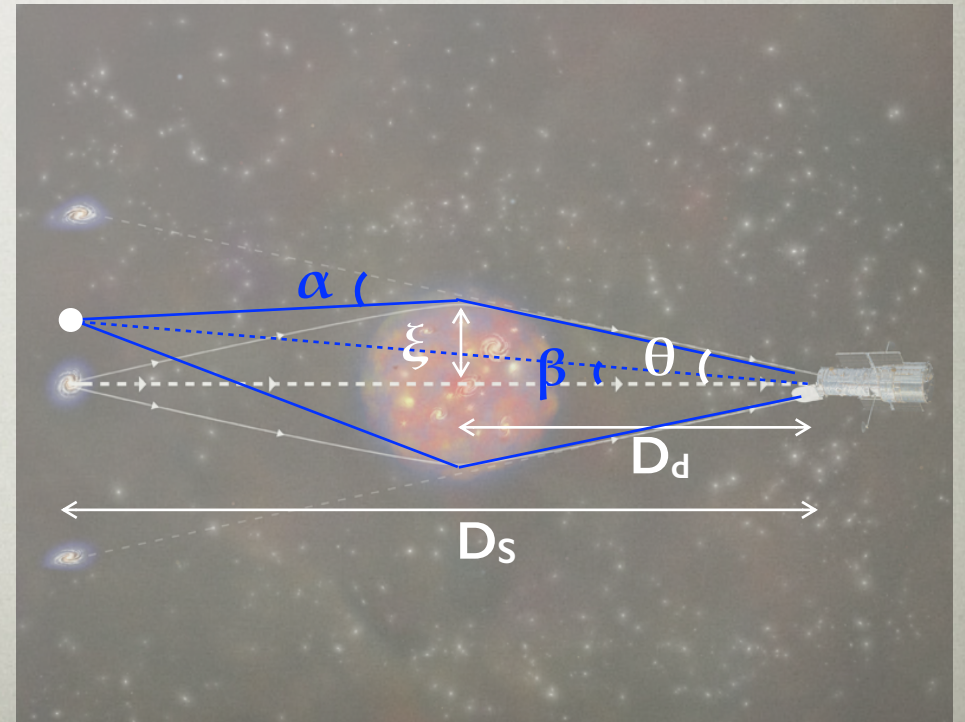
Lens mass

$$\text{Deflection } \hat{\alpha} = \frac{4GM}{c^2 \xi}$$
Impact parameter

$$\theta_E = \left( \frac{4GM}{c^2} \frac{D_{ds}}{D_d D_s} \right)^{1/2}$$

$$\sin(\hat{\alpha}) \approx \tan(\hat{\alpha}) \approx \hat{\alpha}$$

$$\theta - \beta = \frac{\theta_E^2}{\theta}$$





# GRAVITATIONAL LENSING

- Strong (multiple images, rings, ..),
- weak (distortions observed statistically),  
microlensing

$$\theta_E = \left( \frac{4GM}{c^2} \frac{D_{ds}}{D_d D_s} \right)^{1/2}$$

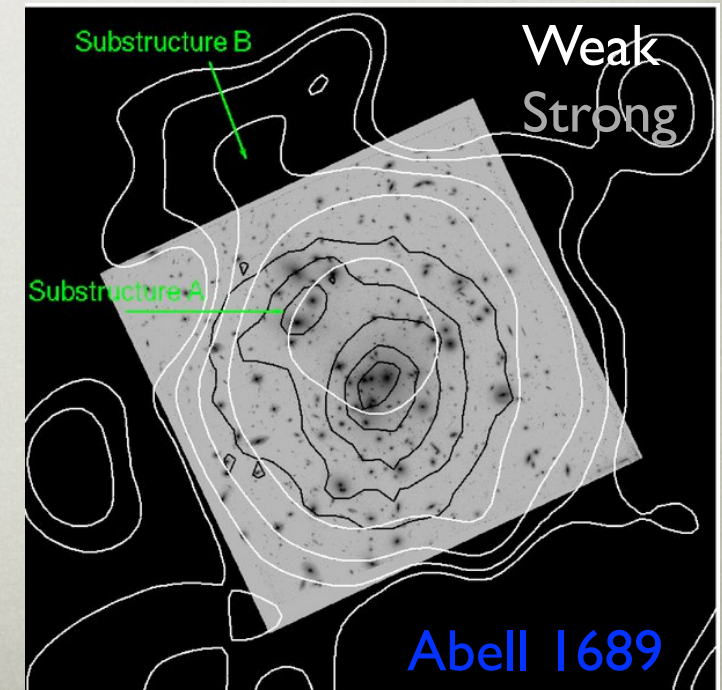
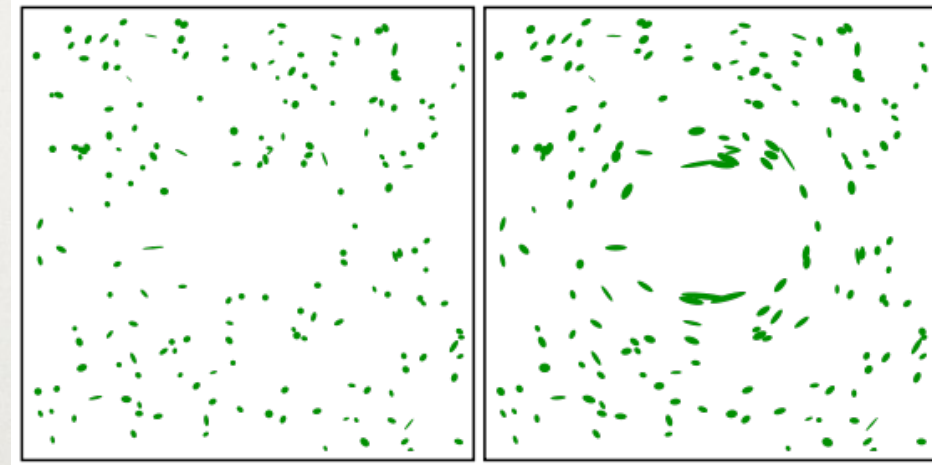
$M \sim 10^{15} M_\odot, D \sim \text{Gpc} \Rightarrow \theta \sim 100 \text{ arcsec}$

$M \sim M_\odot, D \sim \text{kpc} \Rightarrow \theta \sim 10^{-3} \text{ arcsec}$

Strong lensing



Weak lensing





# GRAVITATIONAL LENSING

- Strong (multiple images, rings, ..),
- weak (distortions observed statistically),  
microlensing

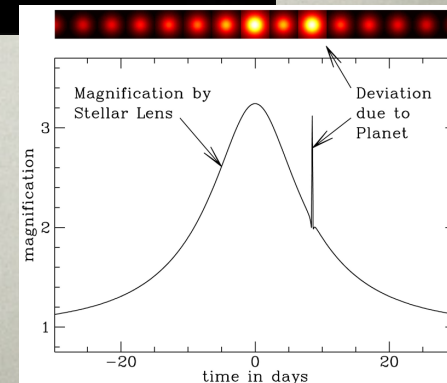
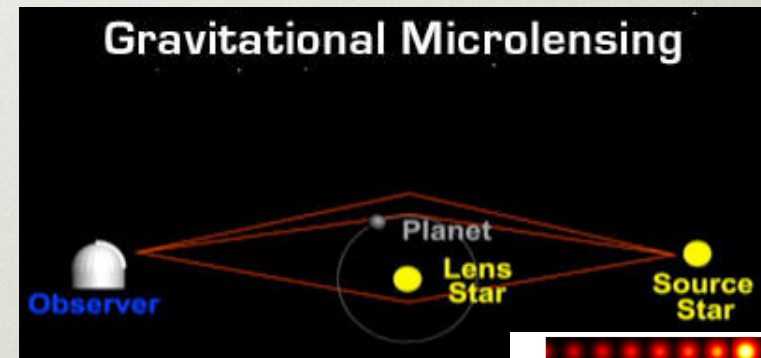
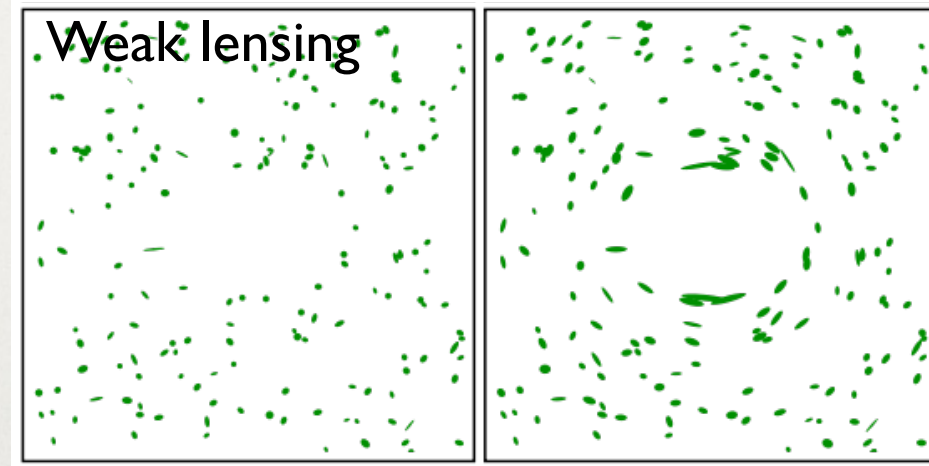
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$M \sim M_\odot, D \sim \text{kpc} \Rightarrow \theta \sim 10^{-3} \text{ arcsec}$



Strong lensing

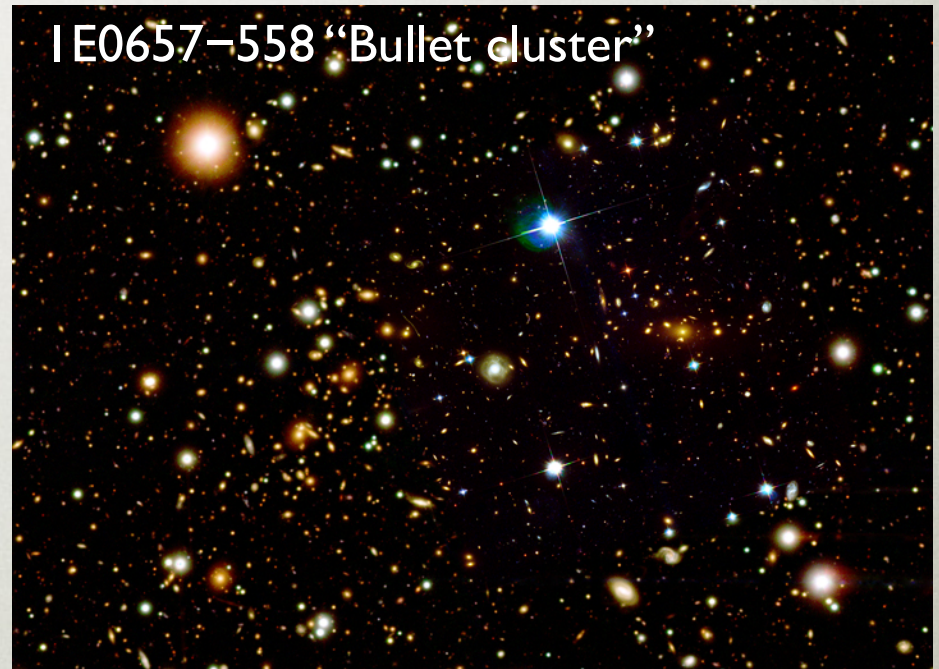




# COSMIC SUPERCOLLIDERS

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- Systems where the presence of dark matter can be inferred and it is not positionally coincident with ordinary matter strongly endorse the dark matter hypothesis
- Galaxy cluster mergers





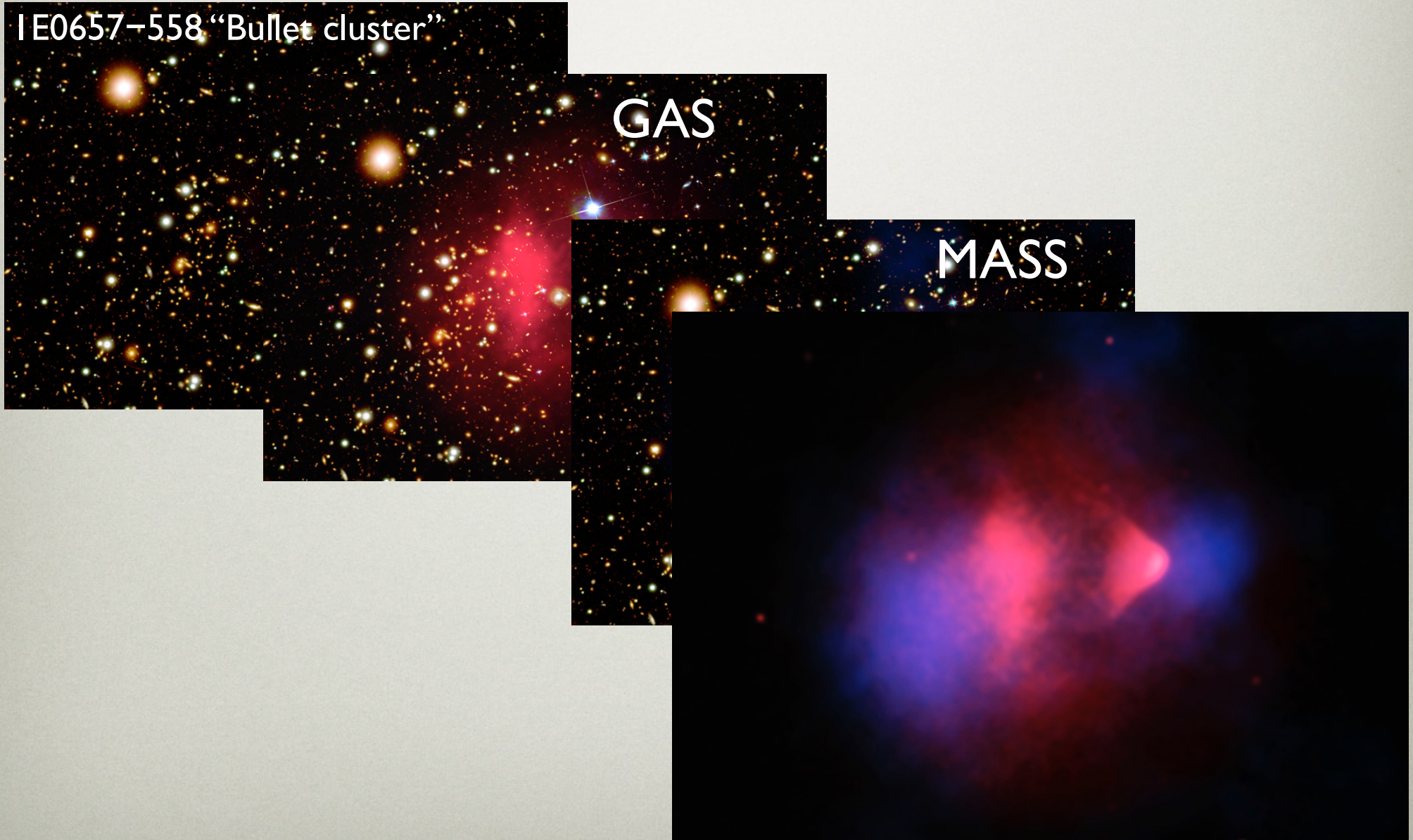
# COSMIC SUPERCOLLIDERS

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IE0657-558 "Bullet cluster"

GAS

MASS



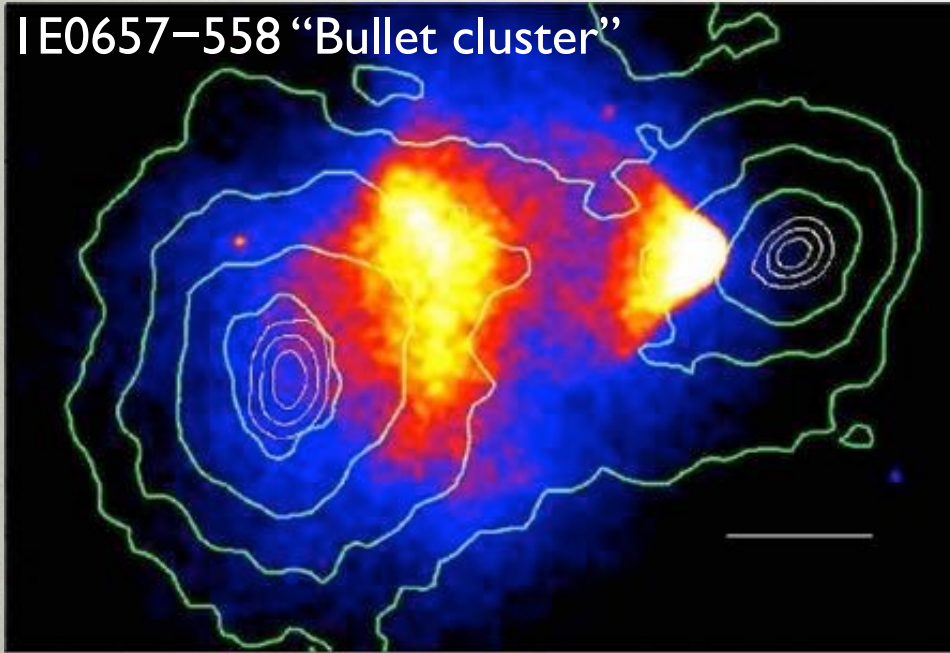


# COSMIC SUPERCOLLIDERS

## Weak lensing

Clowe et al 2006

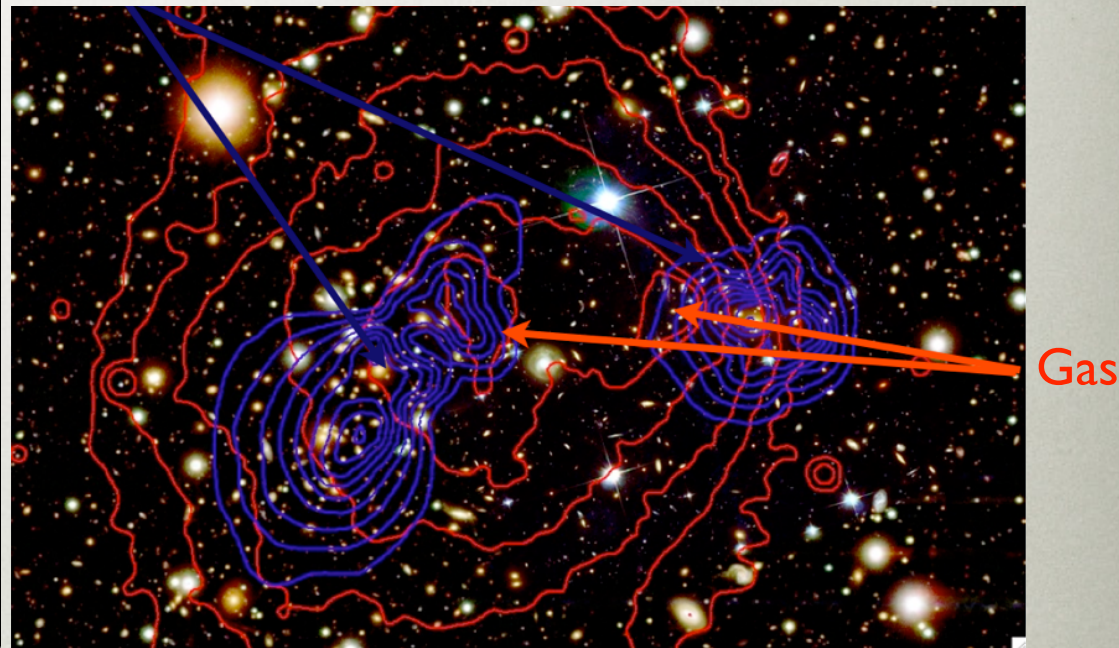
IE0657-558 "Bullet cluster"



## Weak and strong lensing

Bradac et al 2006

Total mass



Most of the matter in the system is collisionless\* and dark

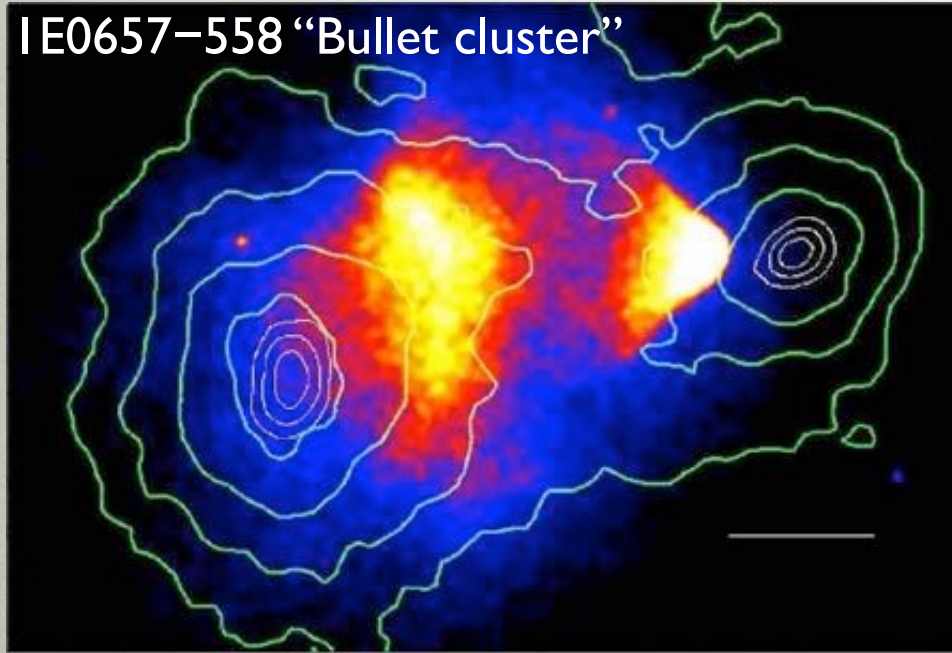


# COSMIC SUPERCOLLIDERS

## Weak lensing

Clowe et al 2006

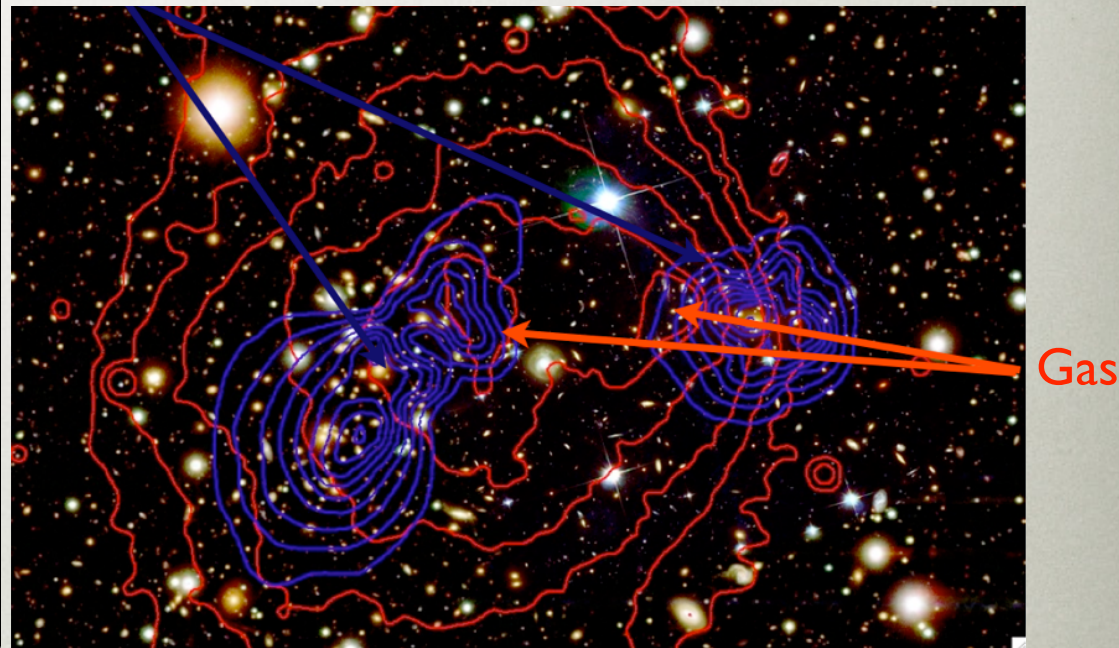
1E0657-558 “Bullet cluster”



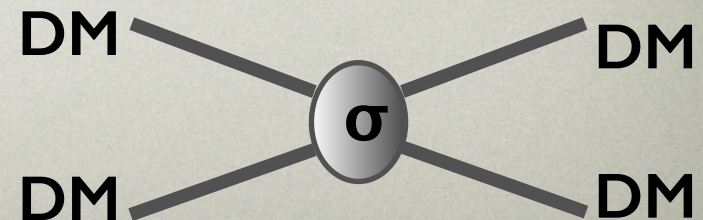
## Weak and strong lensing

Bradac et al 2006

Total mass



(\*) Constraints on the self-interaction cross section:  
 $\sigma/m < 1.3 \text{ barn/GeV}$  (Randall et al 2008)



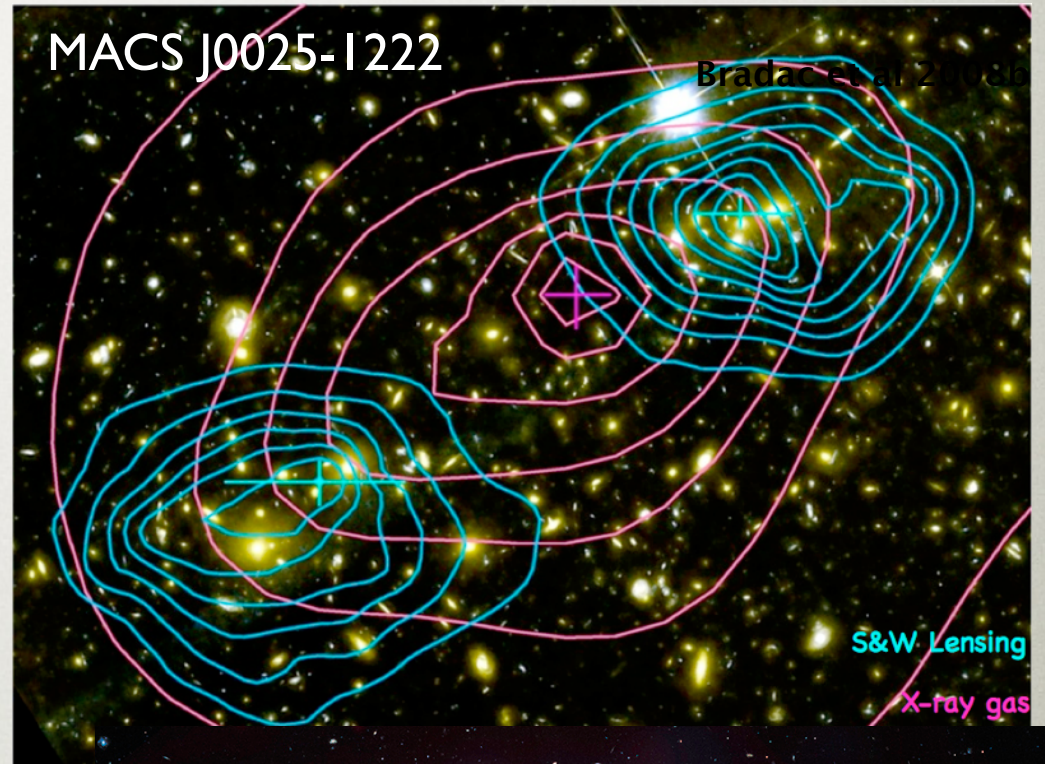


# MORE COSMIC SUPERCOLLIDERS

MACS J0025-1222 “Baby bullet”



MACS J0025-1222



“Musket Ball”



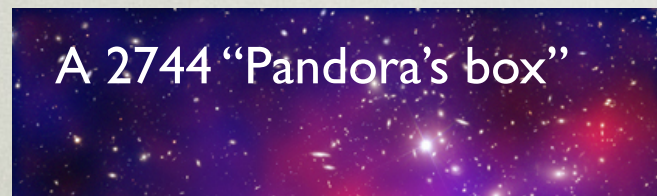
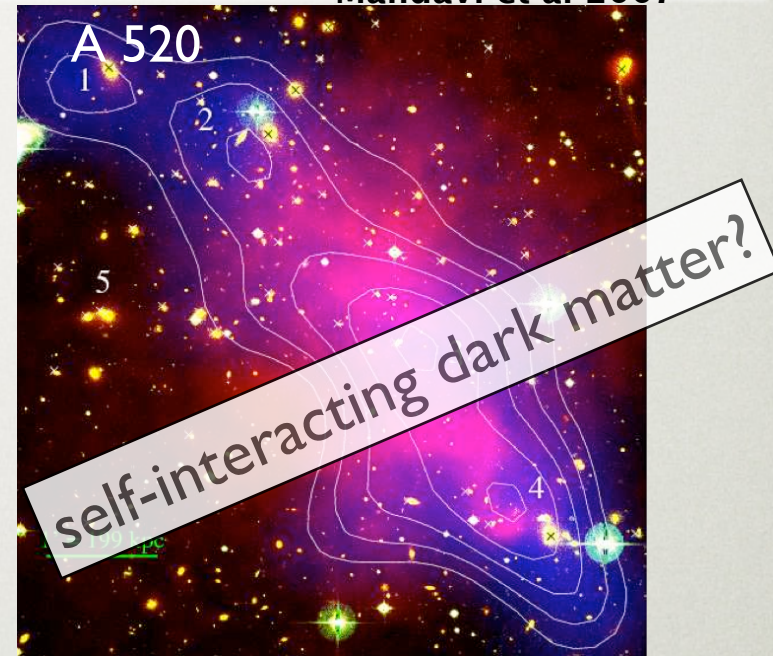
“El Gordo”





# MORE COSMIC SUPERCOLLIDERS

Mahdavi et al 2007



More of these systems have been found...  
As we better understand them, we'll gain better insight on dark matter!



# GALAXY CLUSTERS

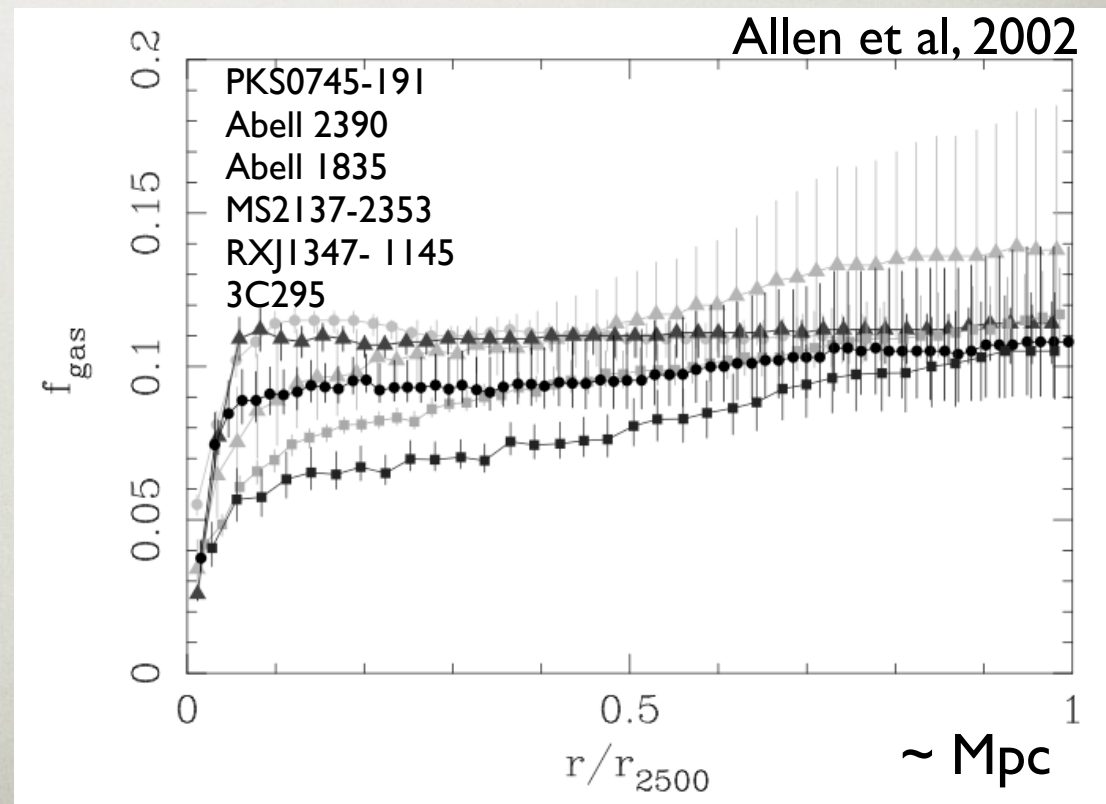
- Gas mass and total mass in galaxy clusters measured by X-ray, lensing
- Assume the matter content in galaxy clusters is representative of the Universe  
 $\Rightarrow$  constrain the Universe total matter density!

Constrain matter density:

$$\Omega_M (\Omega_B \rho_M / \rho_B \sim \Omega_B / f_{\text{gas}}) \sim 0.3$$

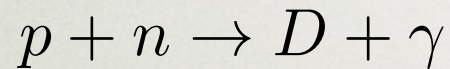
$$\Omega = \frac{\rho}{\rho_c}$$

$\rho_c$ : Critical energy density of the Universe (flat)



# BIG BANG NUCLEOSYNTHESIS

- As the Universe cools down ( $\sim 100$ s sec after Big Bang,  $\sim$  MeV), light elements form (deuterium, helium, lithium). E.g.:



- (Much longer timescales for heavier elements to form, e.g. C, N, O)

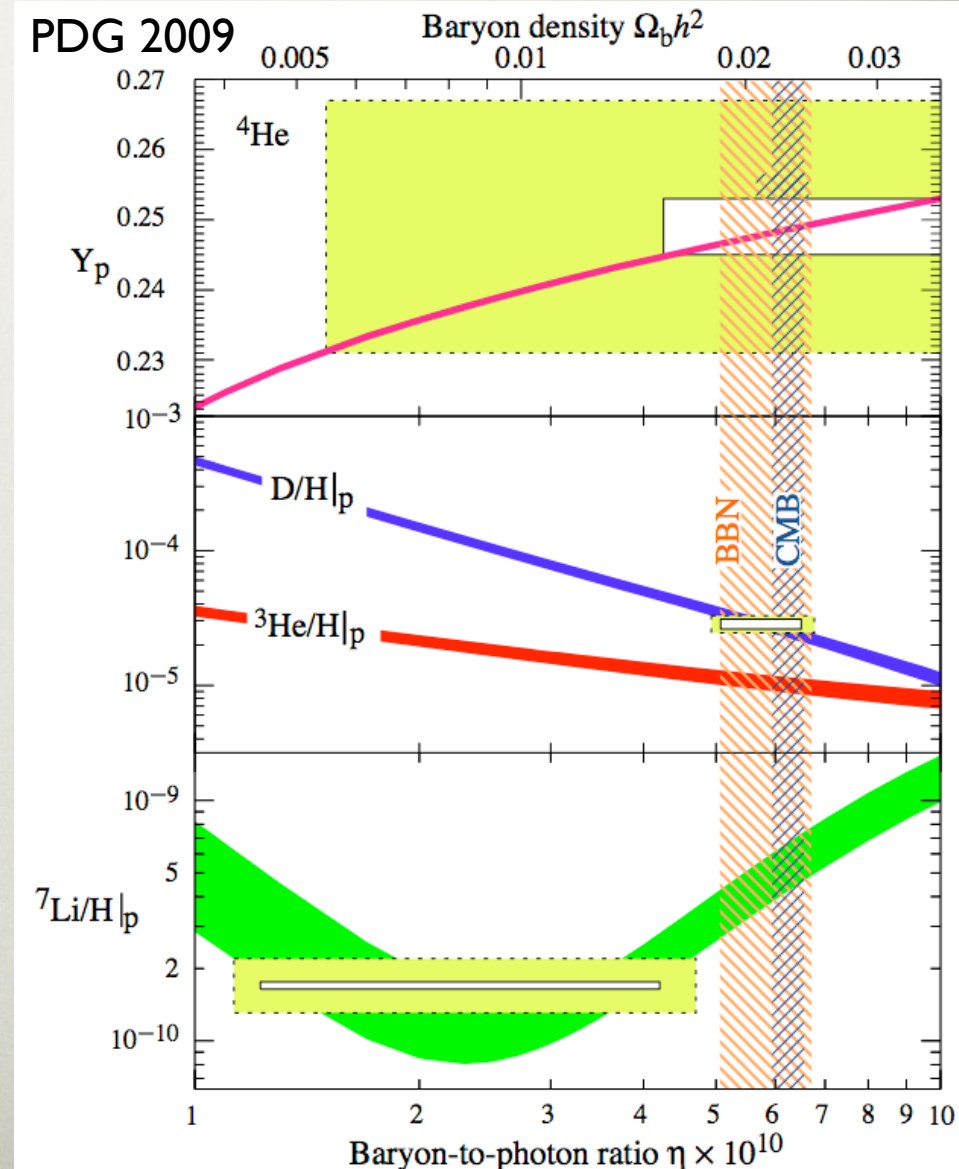
Constrains baryon density:  $\Omega_B \sim$  few %

$$\Omega = \frac{\rho}{\rho_c}$$

$\rho_c$ : Critical energy density of the Universe (flat)

- ➔ Most matter in the Universe is non-baryonic

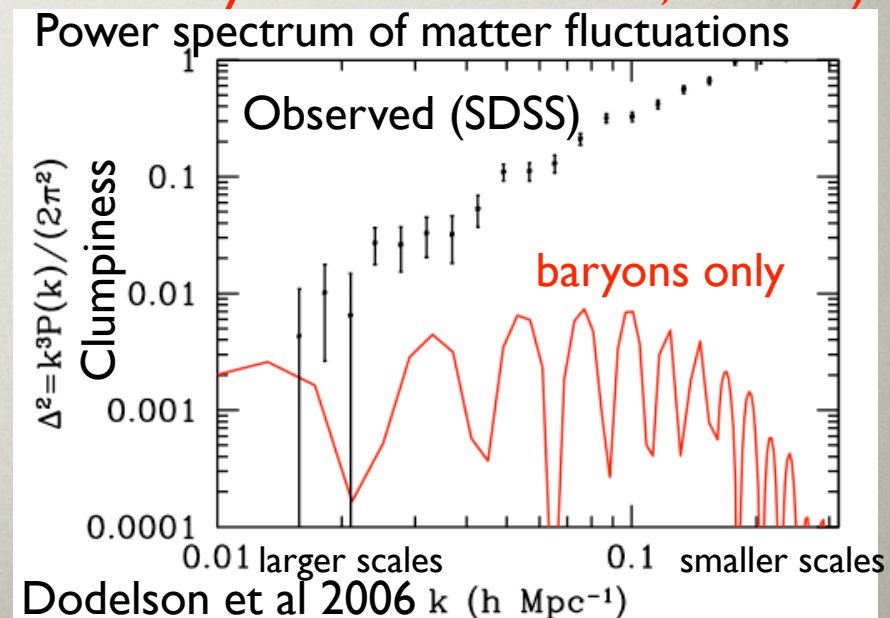
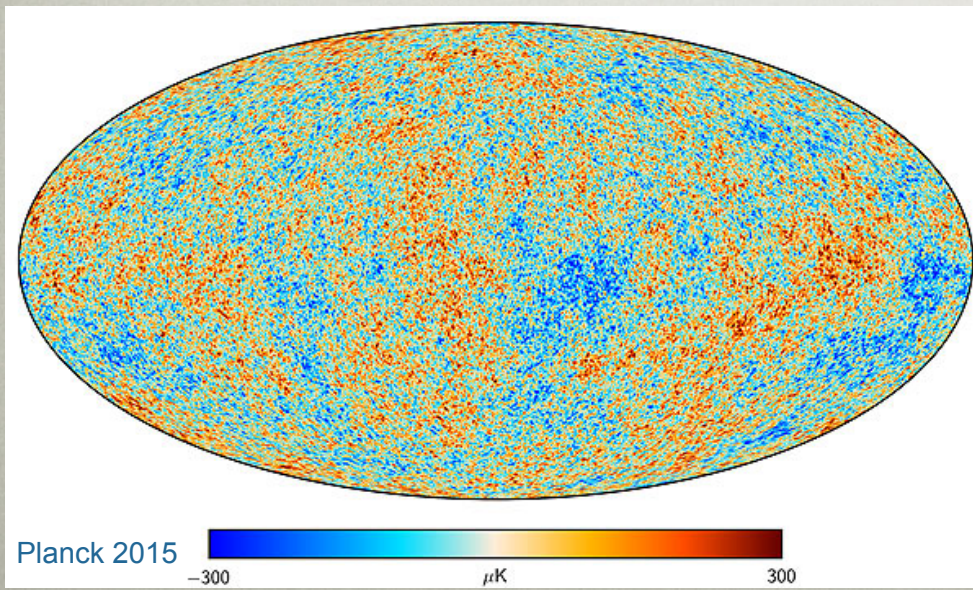
- Remarkable agreement with CMB estimate of baryon density (more next)





# COSMIC MICROWAVE BACKGROUND

- Relic of a time in the early Universe when matter and radiation decoupled (protons and electron form neutral hydrogen and become transparent to photons,  $\sim 100,000$ s years after Big Bang,  $\sim$  eV)
- Universe was isotropic and homogeneous at large scales
- Very small temperature fluctuations, too small to evolve into structure observed today  
 $T = 2.725$  K  $\Rightarrow$  Require additional matter to start forming structure earlier (decoupled from baryons and radiation, neutral)  
 $\Delta T \sim 200$   $\mu$ K



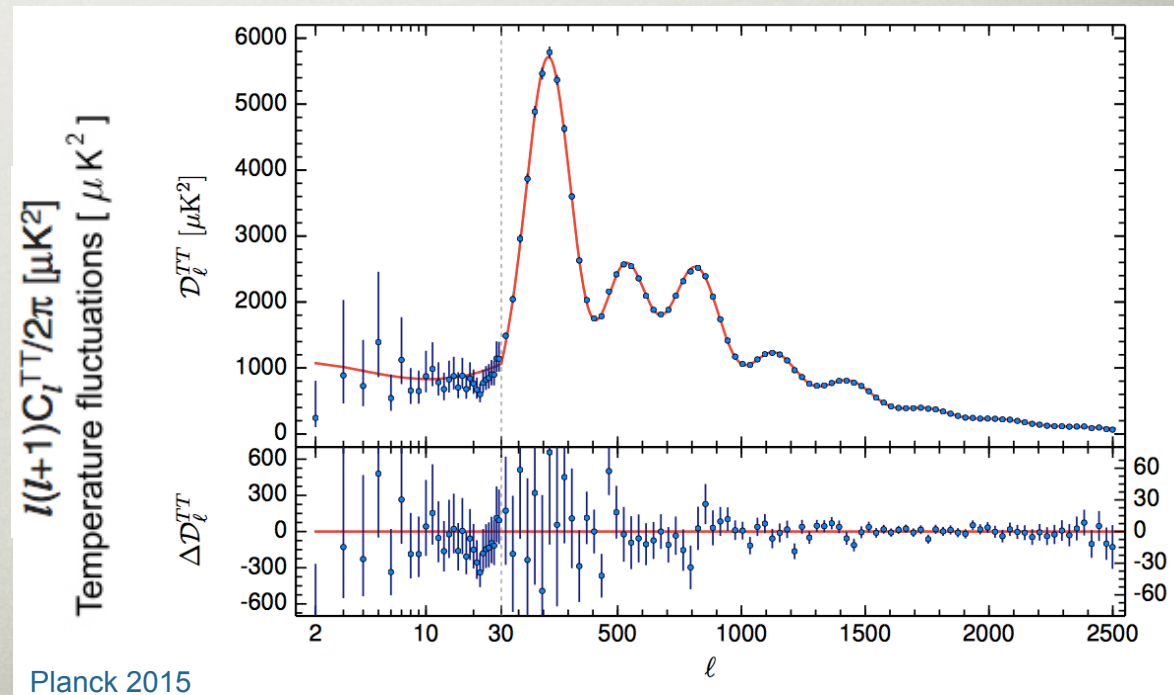


# COSMIC MICROWAVE BACKGROUND

- The CMB angular power spectrum depends on several parameters, including  $\Omega_B, \Omega_M, \Omega_\Lambda$  ( $\Omega_\Lambda$  is the vacuum density)
- Decompose temperature field into spherical harmonics

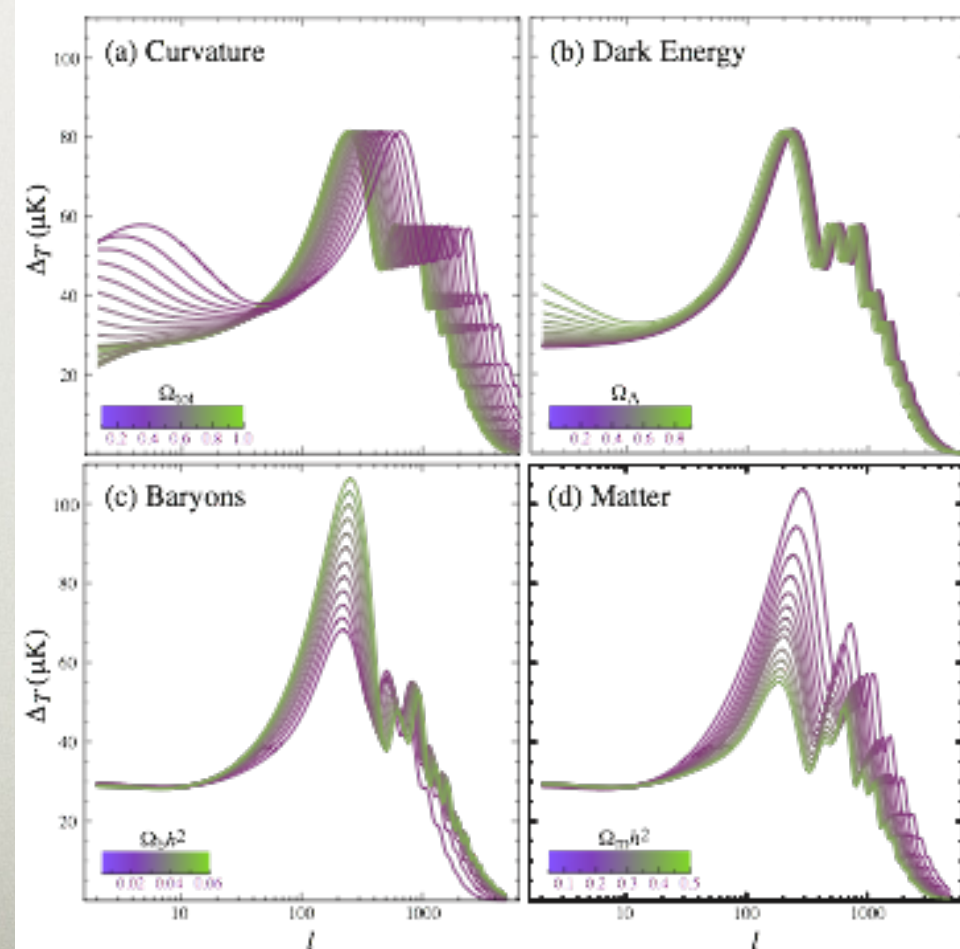
$$T(\hat{n}) = \sum_{l=0}^{\infty} \sum_{m=-l}^l a_{T,lm} Y_{lm}(\hat{n})$$

$$C_l^{TT} = \frac{1}{2l+1} \sum_{m=-l}^l a_{T,lm} a_{T,lm}^*$$



# COSMIC MICROWAVE BACKGROUND

- The CMB angular power spectrum depends on several parameters, including  $\Omega_B, \Omega_M, \Omega_\Lambda$  ( $\Omega_\Lambda$  is the vacuum density)
- Matching location and heights of the peaks constrains these parameters and geometry of the Universe (flat,  $\Omega_{\text{total}}=1$ )





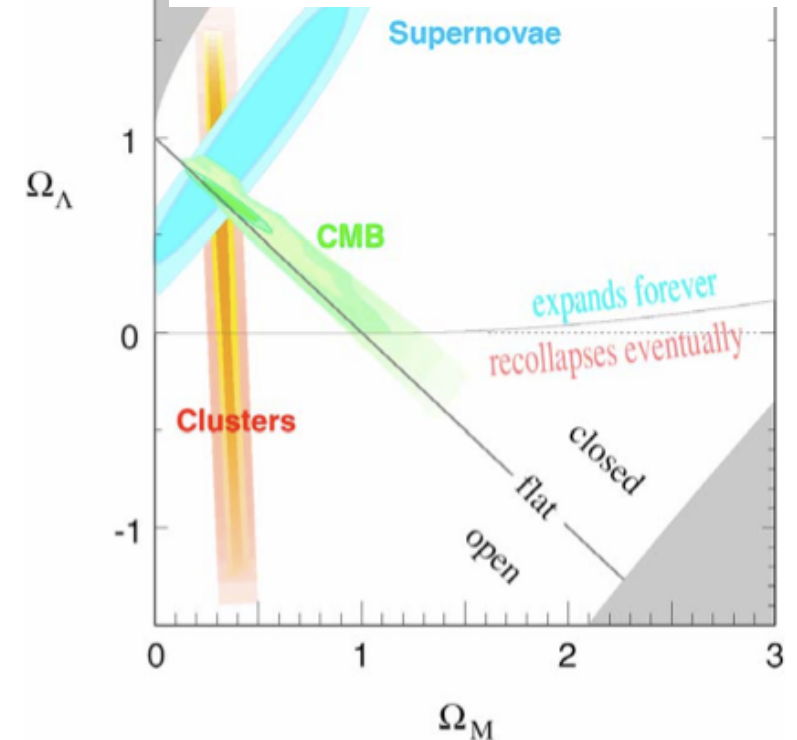
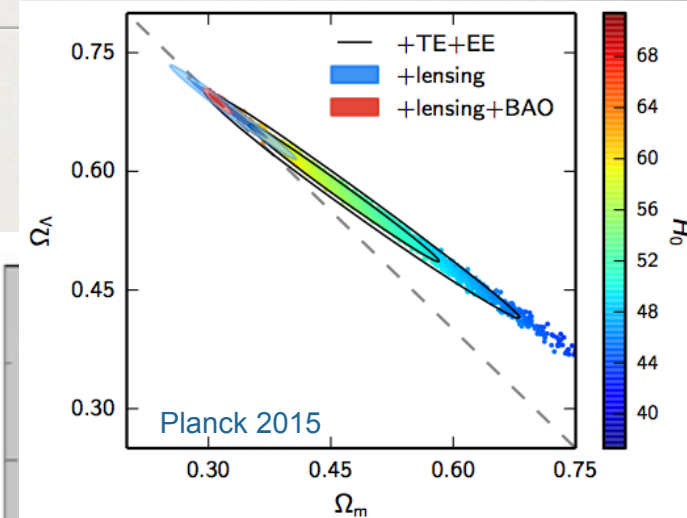
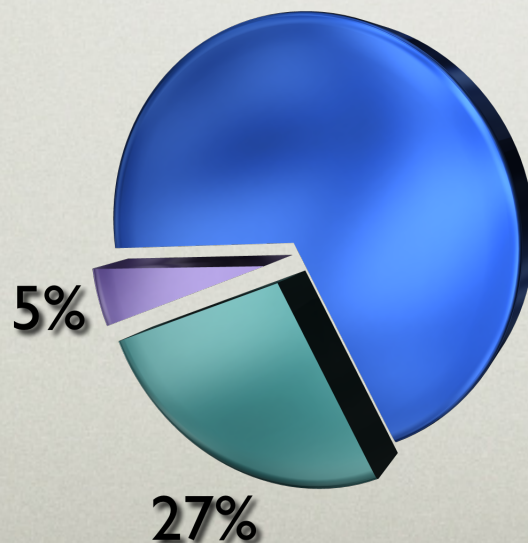
# CONCORDANCE

● Extraordinary agreement in precision cosmology

● Present Universe mostly made out of dark energy, dark matter, and small contribution from baryonic matter

➔  $\Lambda$ CDM (Lambda Cold Dark Matter), standard model of cosmology

● DARK ENERGY  
● DARK MATTER  
● ORDINARY MATTER





# CDM

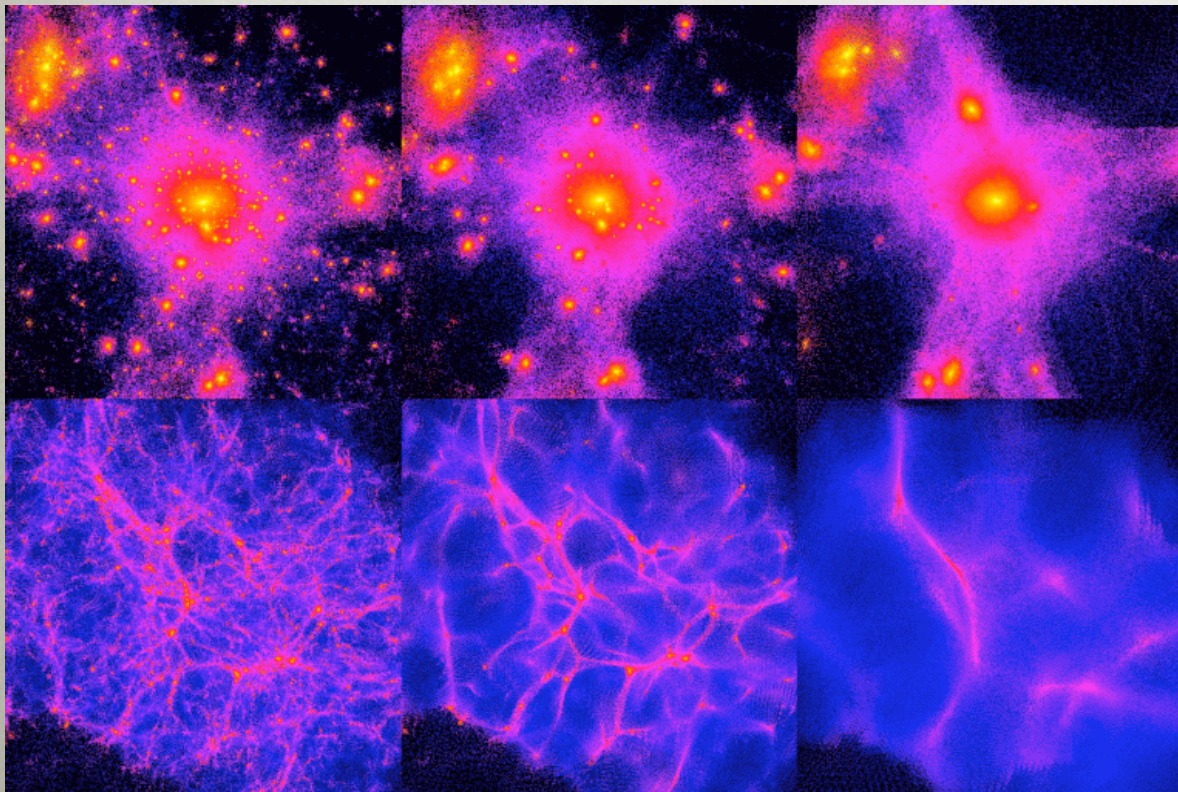
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- CDM (Cold Dark Matter), i.e. non relativistic, consistent with observations
- Hot dark matter excluded (smooths out structure)

COLD

WARM

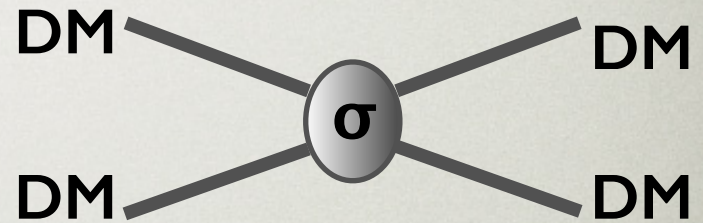
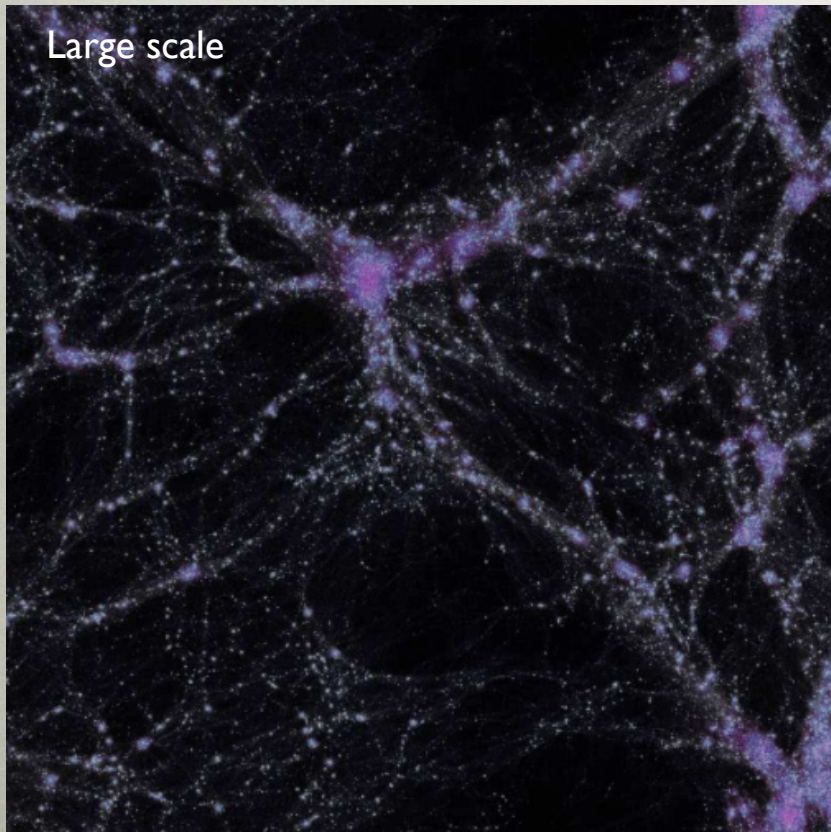
HOT





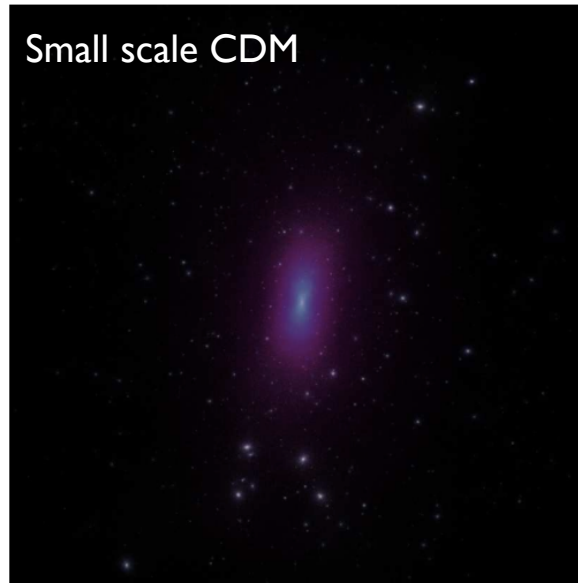
# CDM

- CDM (Cold Dark Matter), i.e. non relativistic, consistent with observations
- Hot dark matter excluded (smooths out structure)
- Self-interactions would also smooth out dense DM regions, though wouldn't significantly affect large scale structure; consistent with observation



Rocha et al. 2012

Small scale CDM



Small scale SIDM

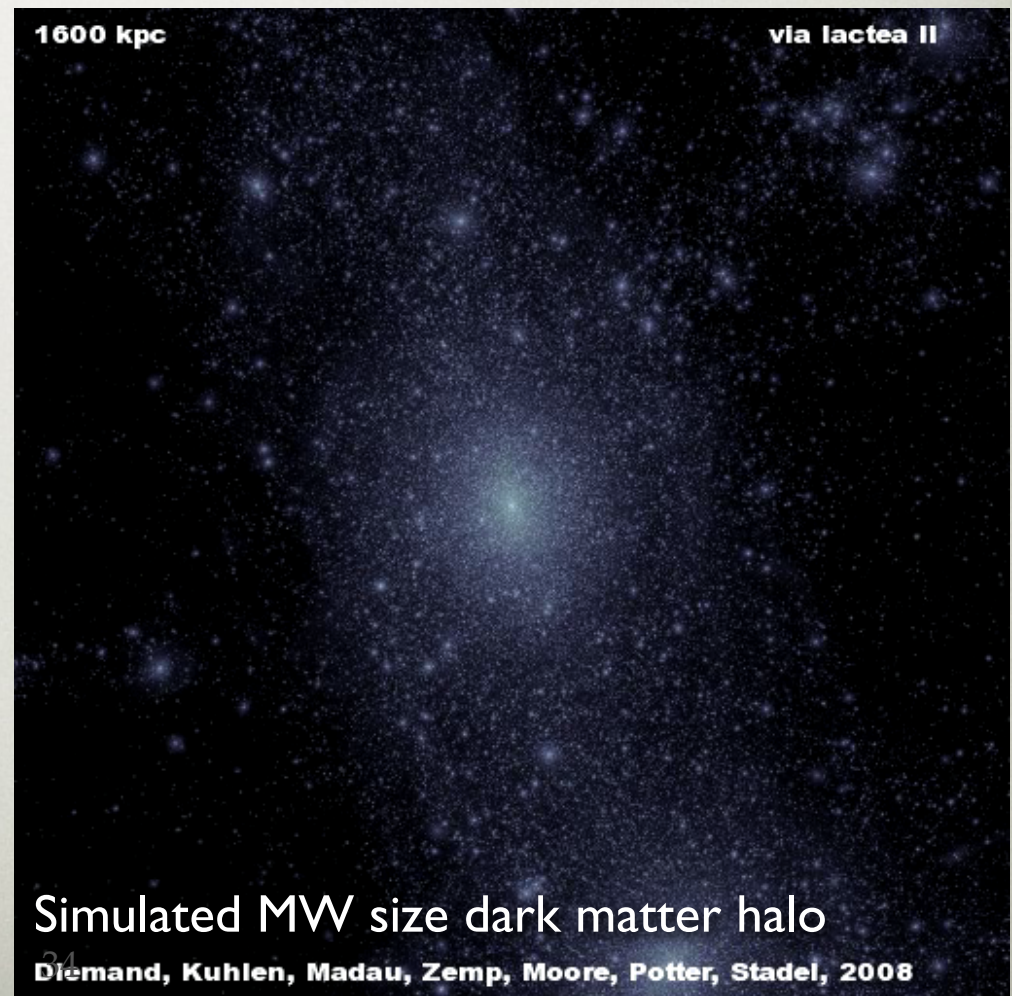
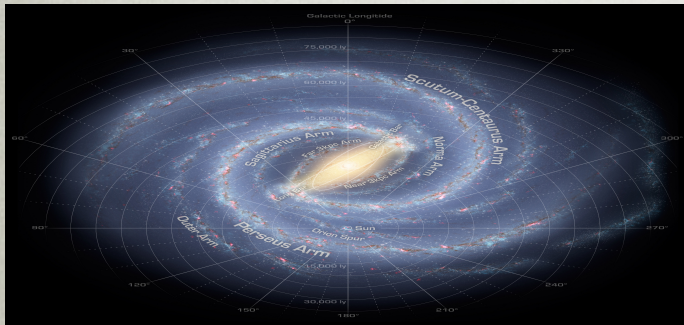




# DARK MATTER DISTRIBUTION IN THE MILKY WAY

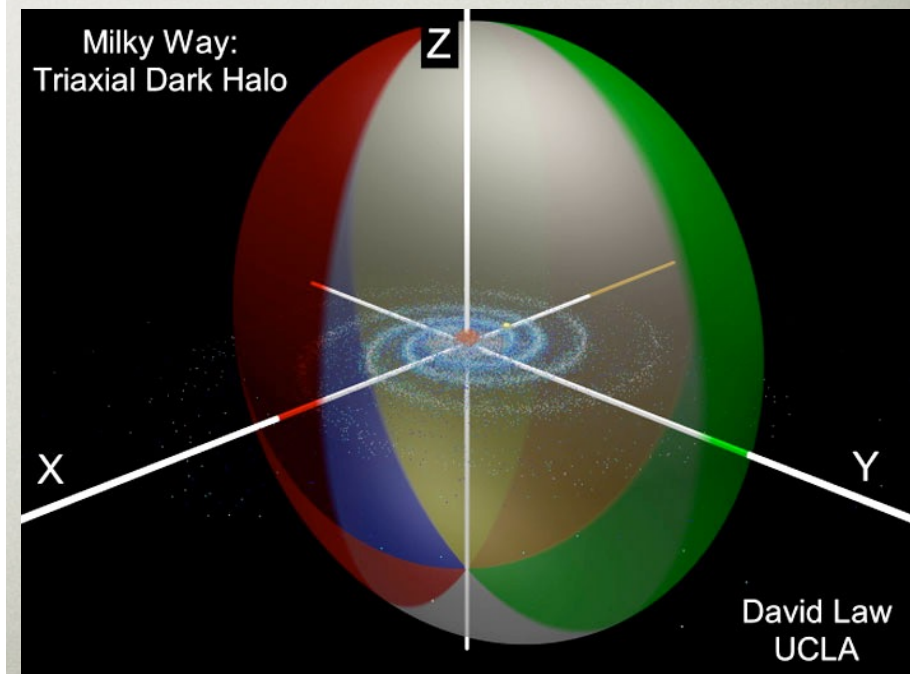
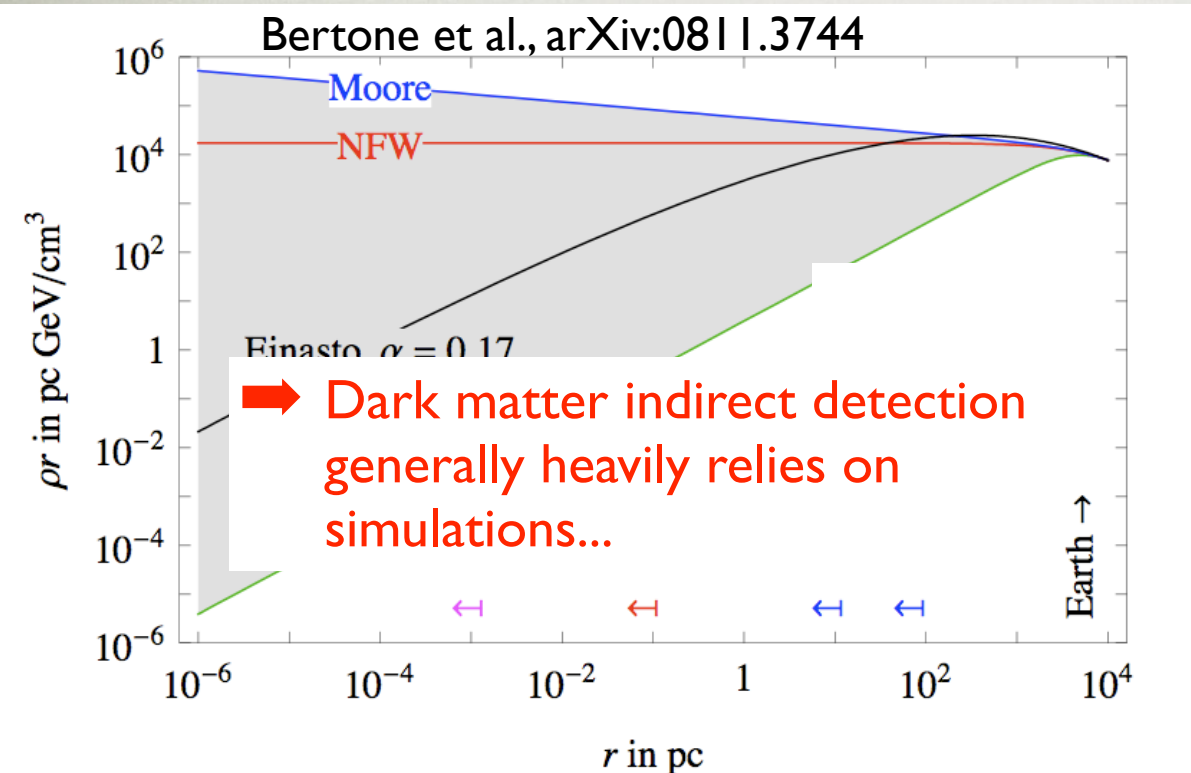
- Milky Way galaxy stellar disk: approx. 30 kpc diameter and 300 pc thick
- The dark matter halo is predicted to extend far past the luminous matter

← 30 kpc →



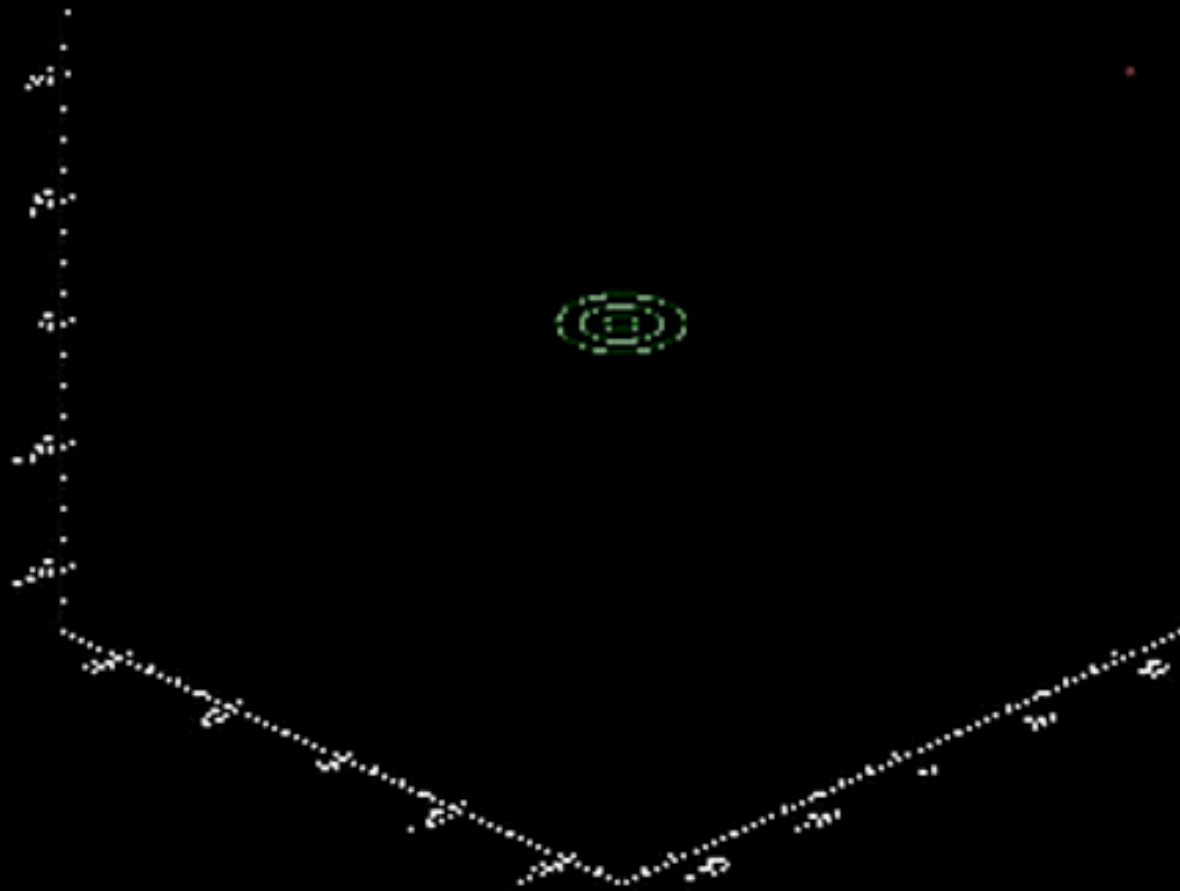
# DARK MATTER DISTRIBUTION

- Strong predictions from  $\Lambda$ CDM on how DM is distributed
- ... but much is still unknown (affects DM indirect searches!), e.g.:
  - core-cusp profile
  - halo shape (spherical, prolate, oblate, triaxial, dark disk, ...)
  - substructure (missing satellites?)

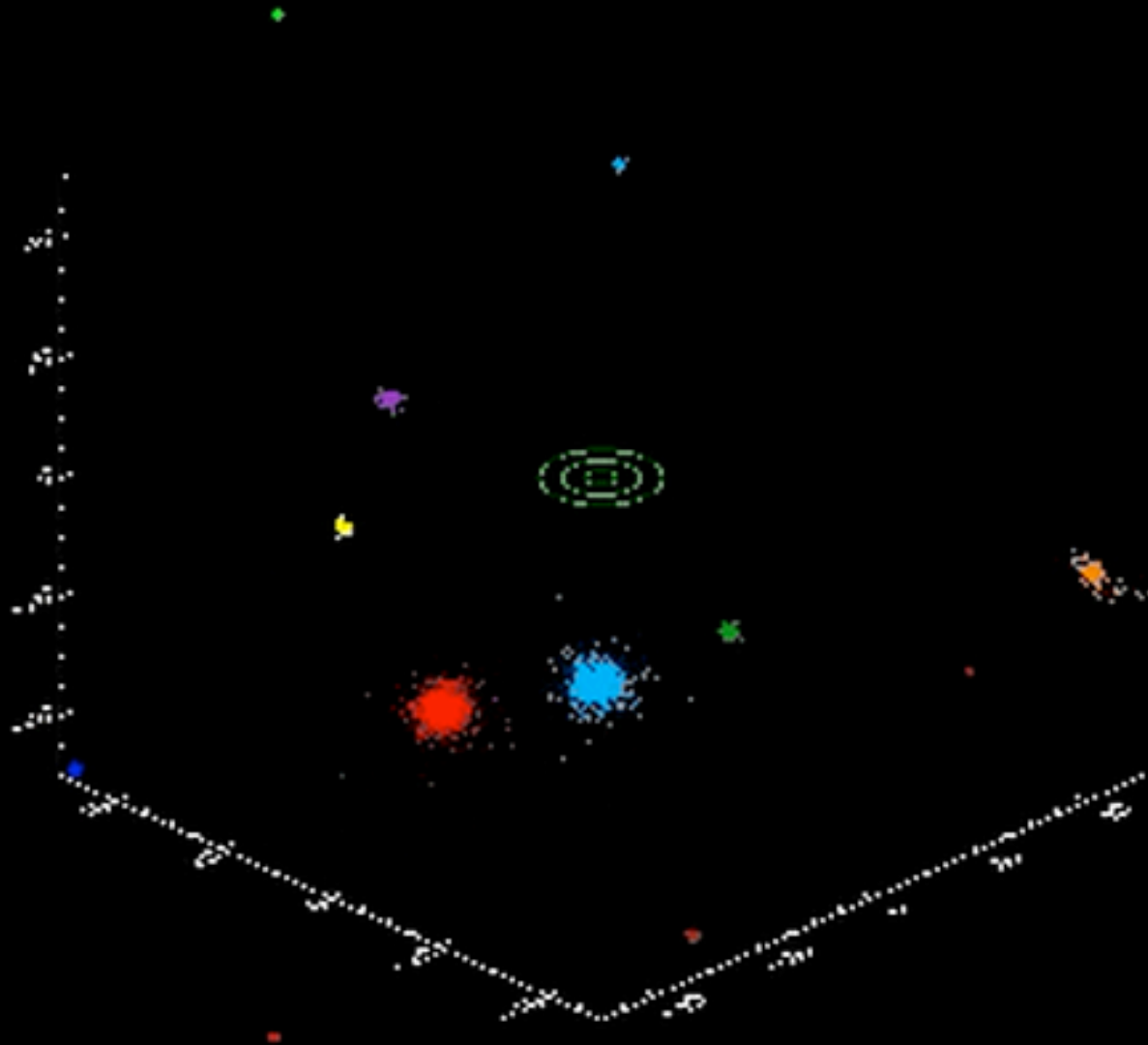




# Galaxy Formation is Messy!



# Galaxy Formation is Messy!





# DM SUBSTRUCTURES

● Optically observed dwarf spheroidal galaxies (dSph): largest clumps predicted by N-body simulation.

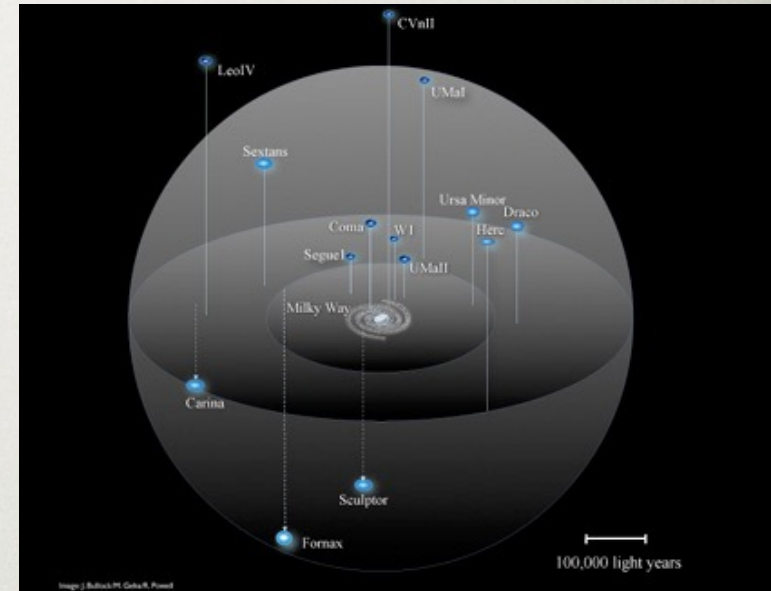
- ▶ Very large M/L ratio: 10 to  $\sim > 1000$  (M/L  $\sim 10$  for Milky Way)

➡ DM density inferred from the stellar data!

● Excellent targets for indirect DM searches!

● Also, never before observed DM substructures:

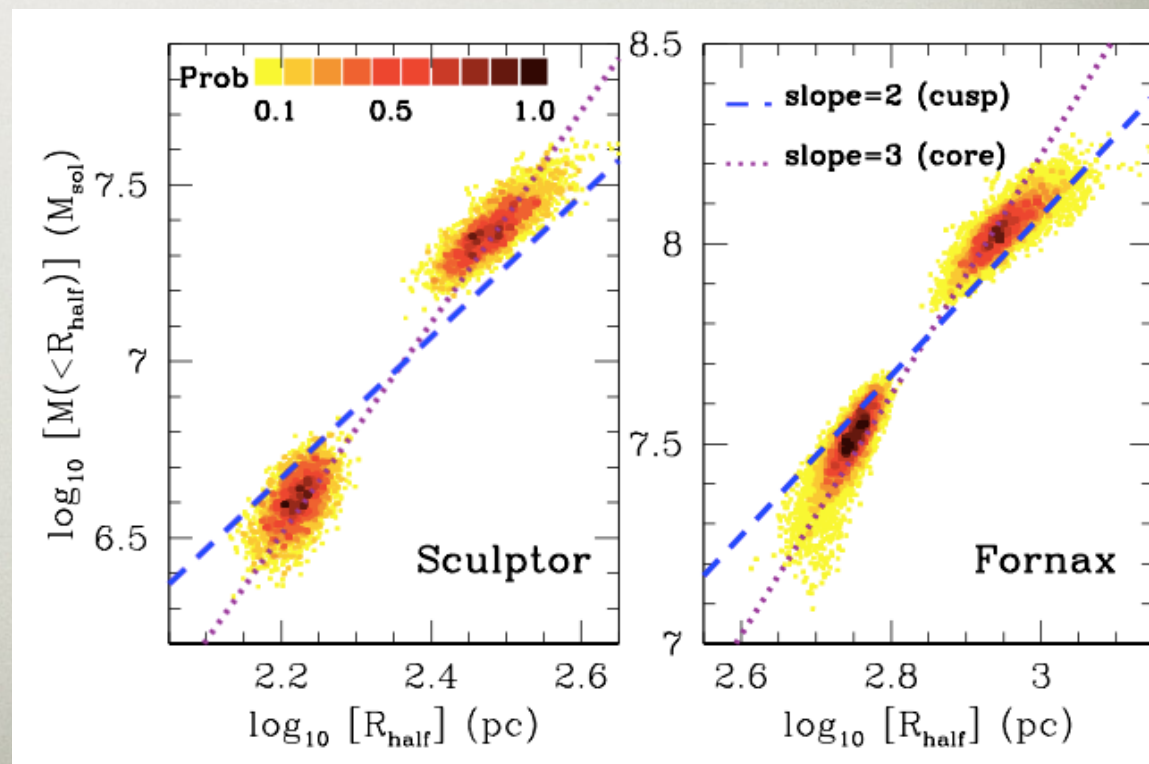
- ▶ Would significantly shine only in radiation produced by DM annihilation/decay
- ▶ But we don't know where they are!



# DM SUBSTRUCTURES

- Probing stellar populations with different metallicity in dwarf spheroidal galaxies allows measurements of mass enclosed within two different radii
  - ➔ Can measure slope of mass profile!
- For Sculptor and Fornax, consistent with cored profile for inner  $\sim 100$  pc. Rule out NFW at CL  $> 95\%$
- Baryonic feedback?

Walker & Penarrubia 2011



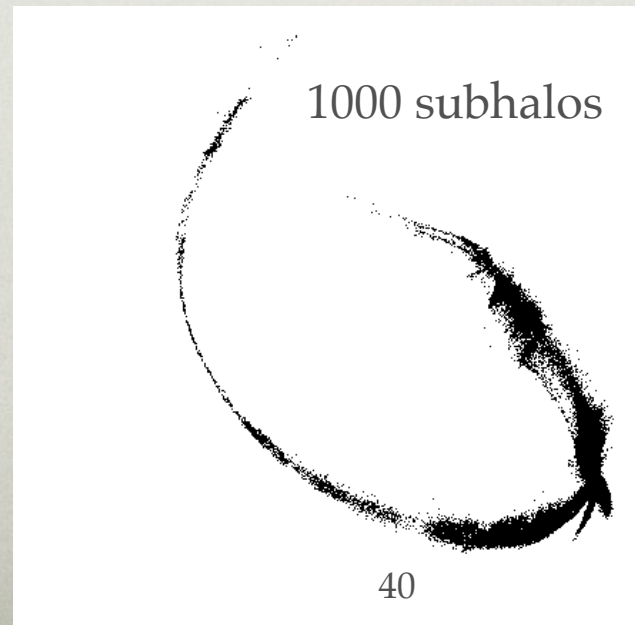


# TESTING DM SUBSTRUCTURES

- Tidal streams cannot remain smooth in CDM
- Are observed streams smooth or have structure?

Measurements seem to be  
consistent with structure/gaps!

Simulated star stream



Star stream north-west  
of M31 (Andromeda)

Carlberg et al, arXiv:1102.3501

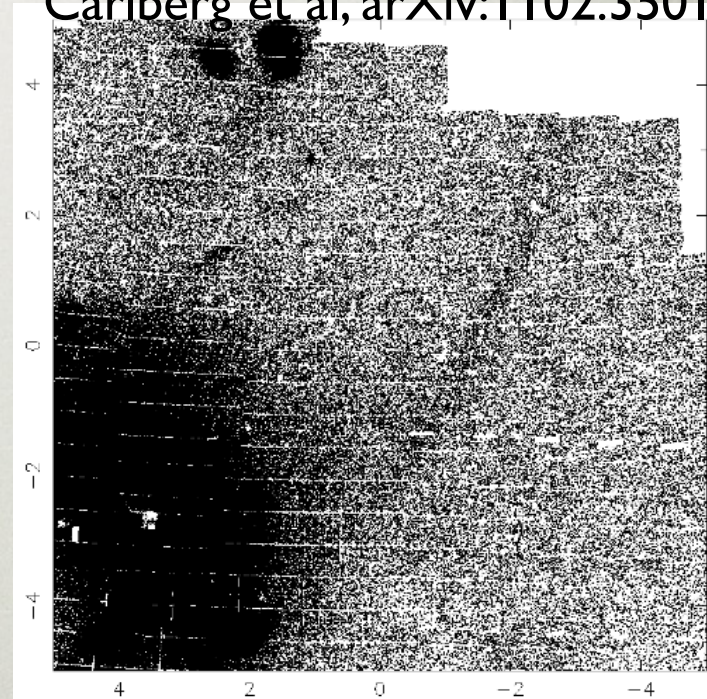


FIG. 1.— The spatial distribution of the  $[\text{Fe}/\text{H}] = [-0.6, -2.4]$  red giant stars in the NW region of M31. A full field version is presented in Richardson et al. (2011). The image is  $10^\circ$  across in the tangent projection co-ordinates, which are centered in the exact middle of this map.

# TESTING DM SUBSTRUCTURES

- Tidal streams cannot remain smooth in CDM
- Are observed streams smooth or have structure?

Pal 5 stream

Measurements seem to be  
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Carlberg, 2012

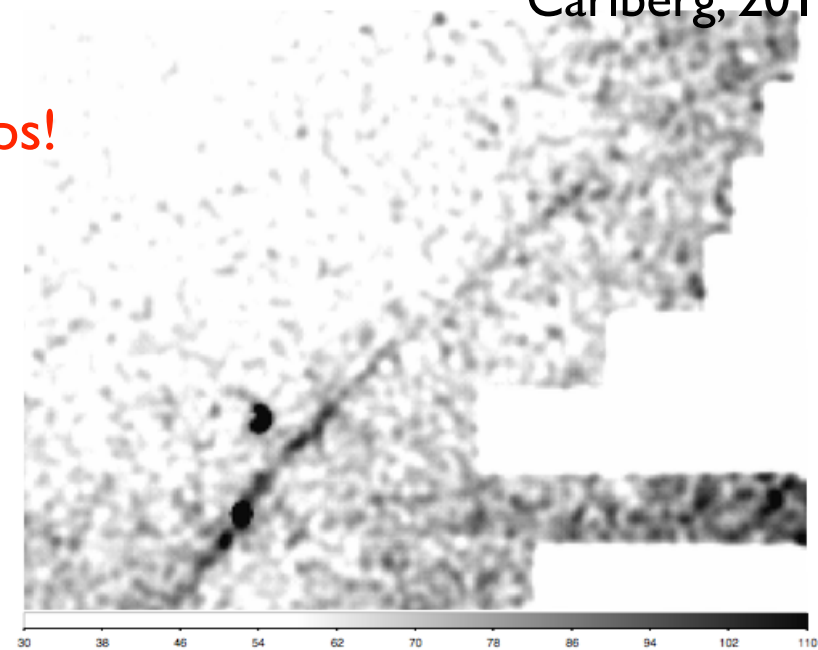
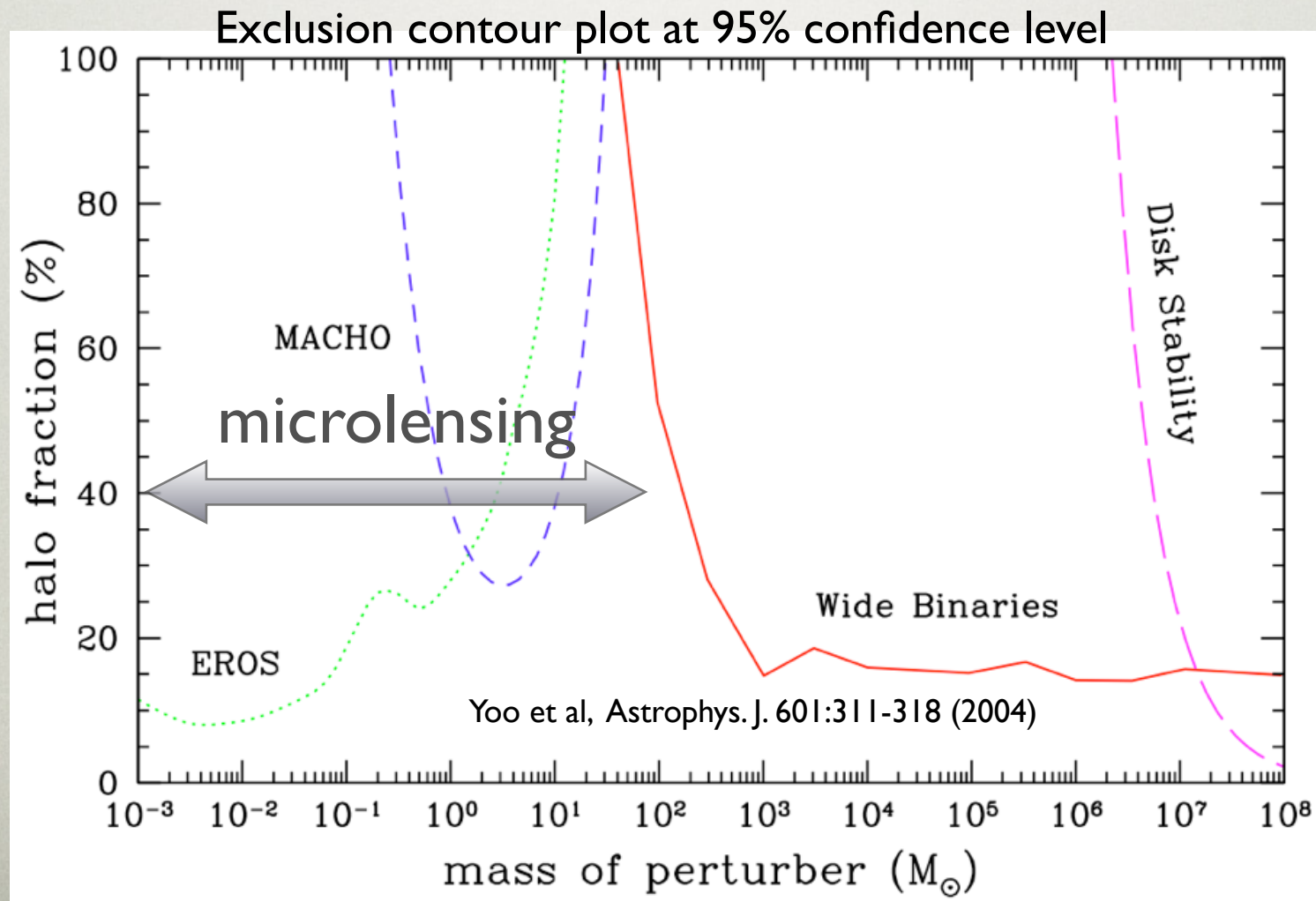


FIG. 1.— The match filtered star densities in the region of the Pal 5 stream in the SDSS  $\lambda$  and  $\eta$  co-ordinate system. The raw image has been smoothed with a 3 pixel Gaussian. The object above the stream is the foreground cluster M5.



# MACHOs

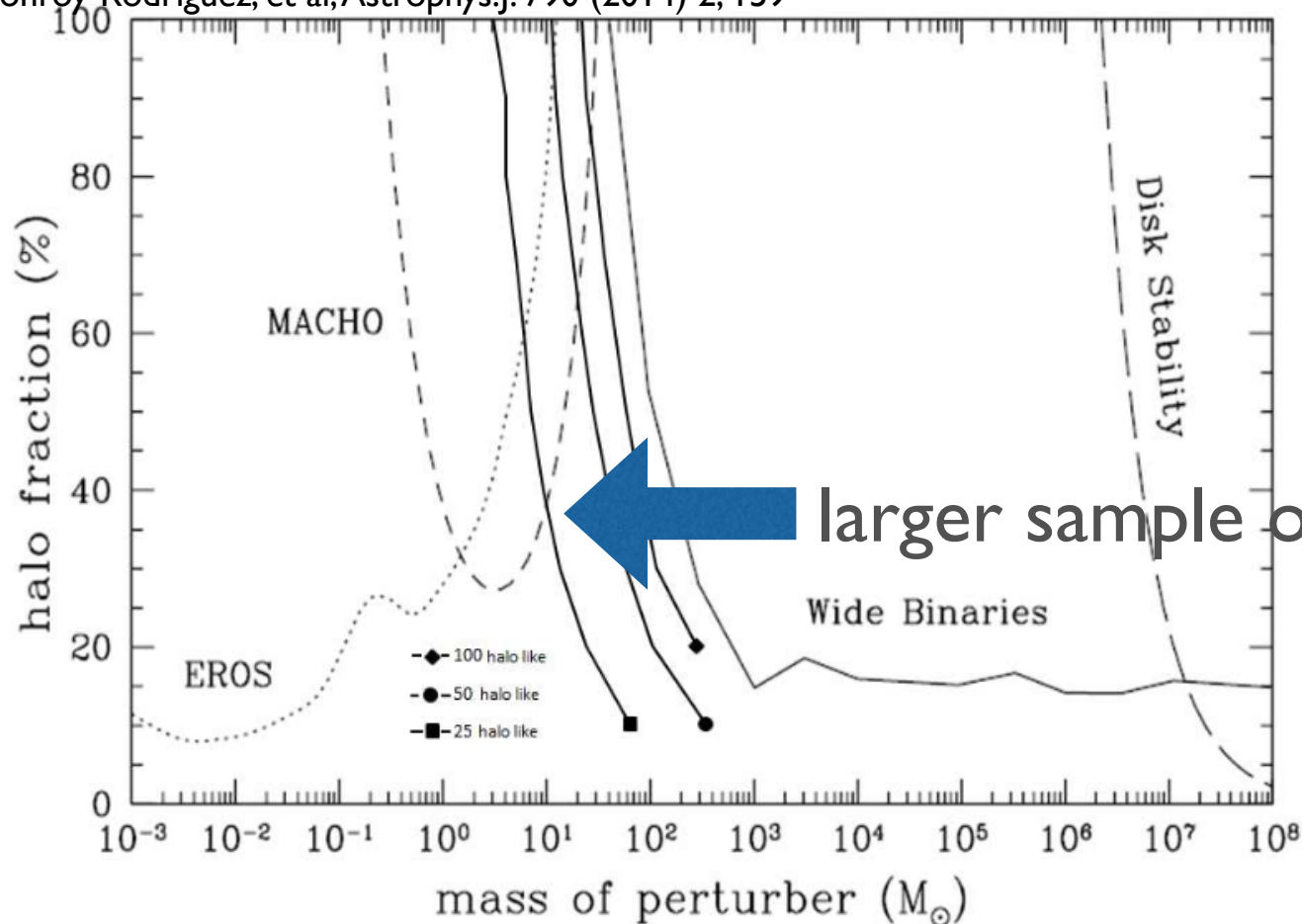
- MACHOs (MASSive Compact Halo Objects) are strongly disfavored as an explanation for dark matter
- E.g. low luminosity stars, planets, black holes



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- E.g. low luminosity stars, planets, black holes

Monroy-Rodriguez, et al, *Astrophys.J.* 790 (2014) 2, 159





# MOND

- Modified Newtonian Dynamics postulates that Newton's law breaks down for very small accelerations
- Proposed to explain rotation curves of galaxies (Milgrom, 1983). Does a very good job! No dark matter necessary.

- Parameter  $a_0$  ( $1.2 \times 10^{-10} \text{ms}^{-2}$ , determined by observations):

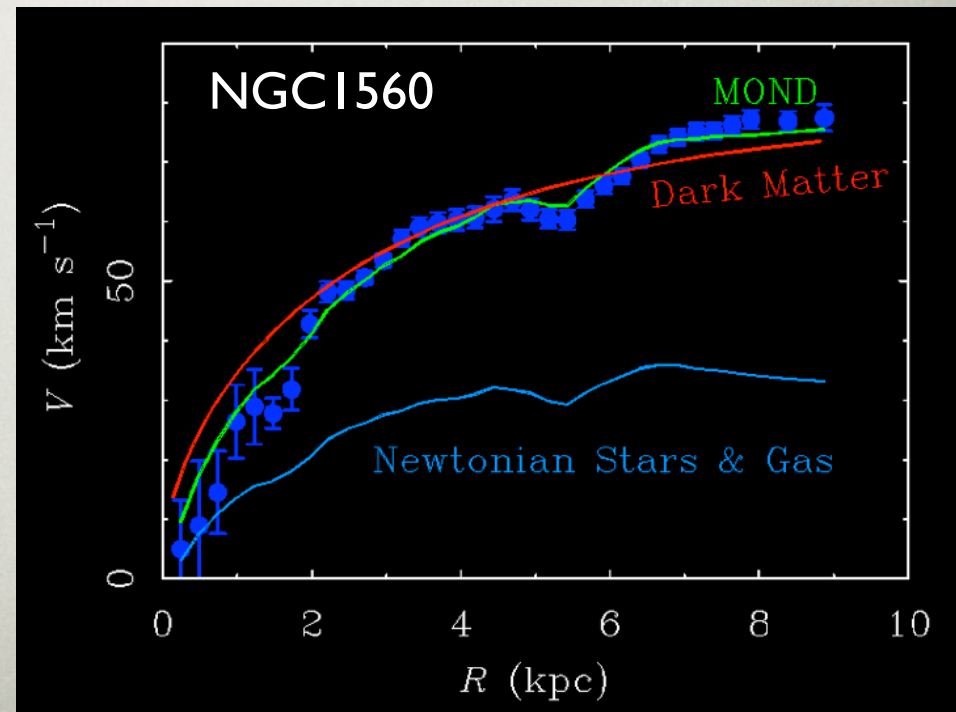
$a \gg a_0$  conventional dynamics  $a = \frac{MG}{r^2}$

$a \ll a_0$  modified dynamics  $\frac{a^2}{a_0} = \frac{MG}{r^2}$

total mass  $\rightarrow$   $a_0 G M_b = V_f^4$   $\leftarrow$  flat rotation velocity

- MOND fails at larger scales, galaxy clusters

Begeman et al 1991  
Sellwood et al 2005



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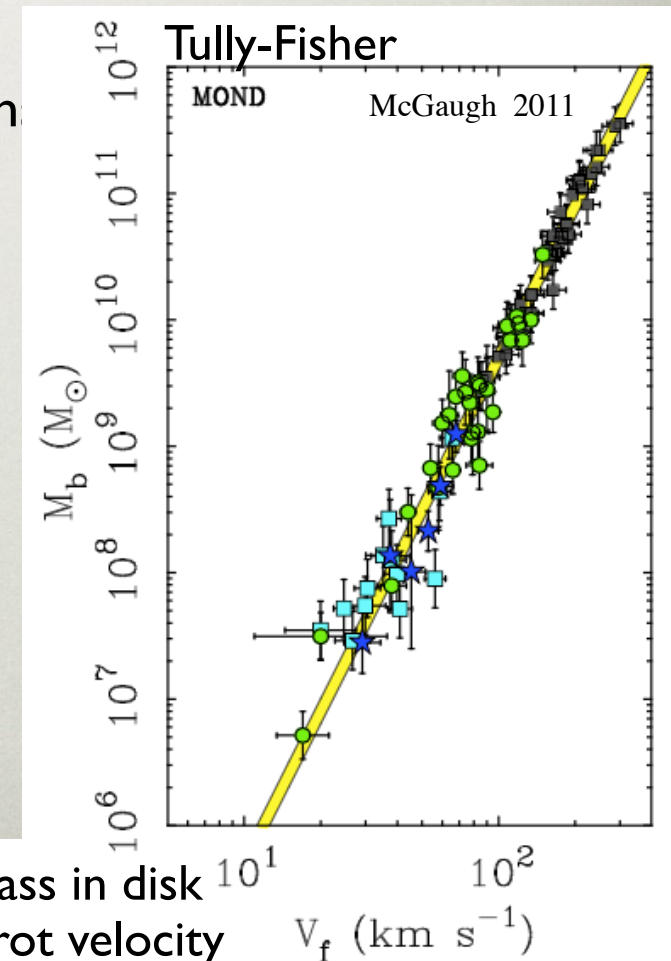
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total mass  $\rightarrow$  flat rotation velocity  $\nwarrow$

$$a_0 G M_b = V_f^4$$

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# SUMMARY OF LECTURE I

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- Evidence for dark matter is overwhelming, e.g.:
  - ▶ Rotation curves
  - ▶ Gravitational lensing
  - ▶ Structure formation
- What data tells us about dark matter:
  - ▶ it makes up almost all of the matter in the Universe
  - ▶ it interacts very weakly, and at least gravitationally, with ordinary matter
  - ▶ it is cold, i.e. non-relativistic
  - ▶ it is neutral
  - ▶ it is stable (or it is very long-lived)

➡ But doesn't tell us what it is...