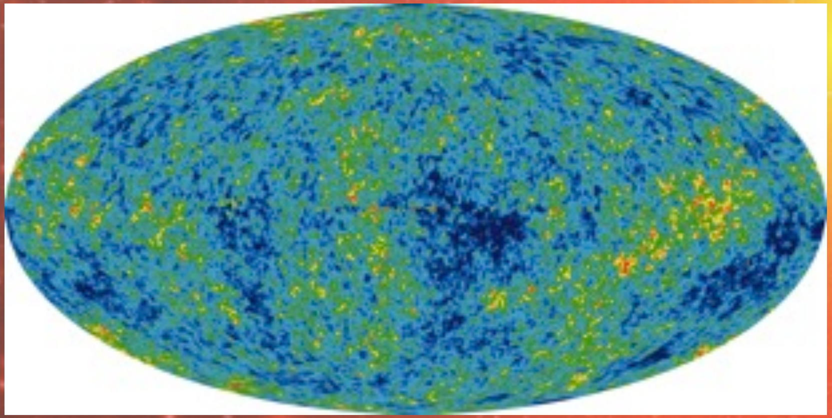
Observational Evidence for Dark Matter

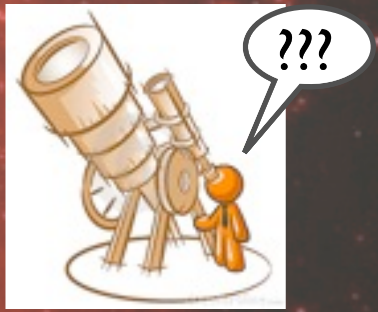
Simona Murgia, SLAC-KIPAC

XXXIX SLAC Summer Institute
28 July 2011

Outline

- Evidence for dark matter at very different scales
  - Galaxies
  - Clusters of galaxies
  - Universe





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 system known in the Universe. They contain ~10s to 1000s of galaxies.)
- Zwicky first inferred the total mass of the cluster by measuring the velocities of its galaxies

Image credit: NASA, ESA, Hubble Heritage (STScI/AURA)

Zwicky and the Coma Cluster

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

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

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

- 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)

$$\mathcal{M} > 9 \times 10^{46}\,\mathrm{gr}\,. \qquad (35)$$

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

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

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 8.5×10^7 suns. According

Zwicky and the Coma Cluster

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

$$G\frac{M_{tot}(r)m}{r}$$

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

Velocities ~ 1000 km/s
R ~ Mpcs
Distance ~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!

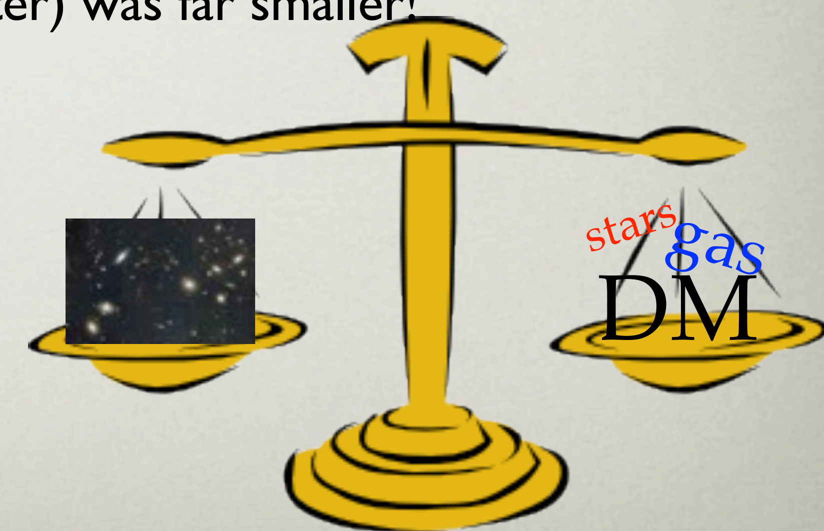
F. Zwicky, Astrophysical Journal, vol. 86, p.217 (1937)

$$\mathcal{M} > 9 \times 10^{46}\,\mathrm{gr}\,. \tag{35}$$

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

$$\overline{M} > 9 \times 10^{43}\,\mathrm{gr} = 4.5 \times 10^{10}\,M_{\odot}\,. \tag{36}$$

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 8.5×10^7 suns. According



Zwicky and the Coma Cluster

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

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

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

Velocities ~ 1000 km/s
R ~ Mpcs
Distance ~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)

$$\mathcal{M} > 9 \times 10^{46}\,\mathrm{gr}. \qquad (35)$$

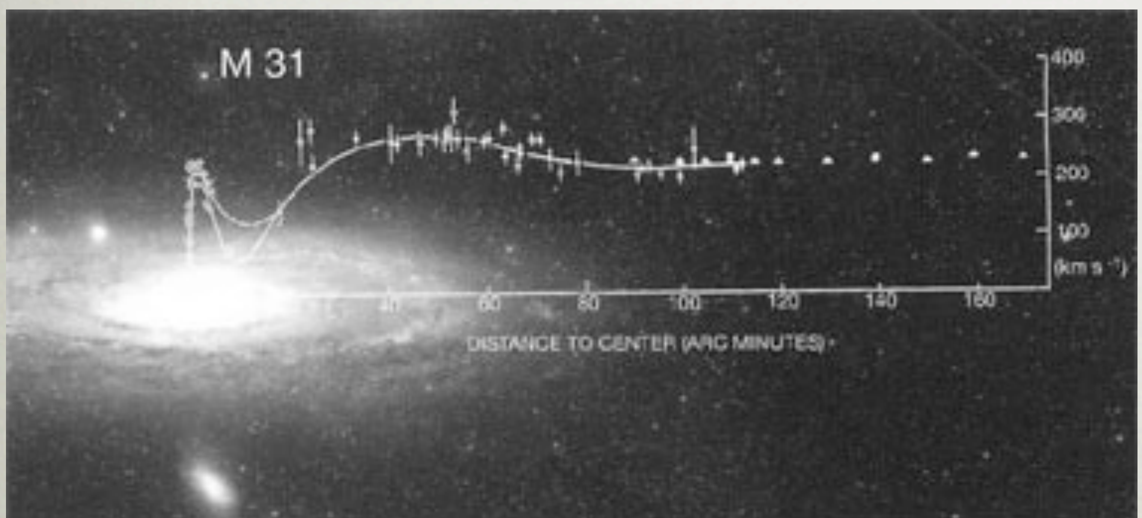
The Coma cluster contains about one thousand nebulae. The average mass of one of these nebulae is therefore

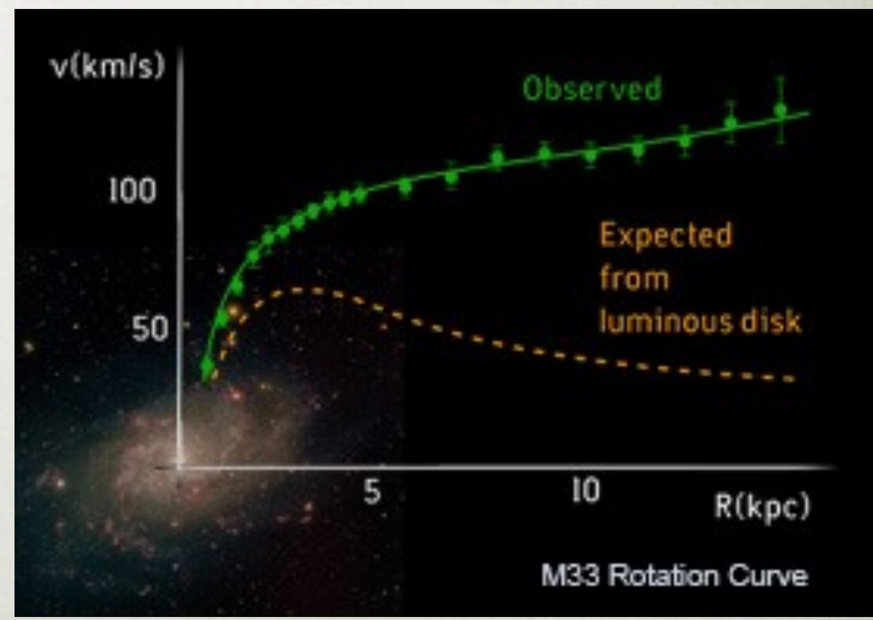
$$\overline{M} > 9 \times 10^{43}\,\mathrm{gr} = 4.5 \times 10^{10}\, M_{\odot}. \qquad (36)$$

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 8.5×10^7 suns. According

Rotation Curves of Galaxies

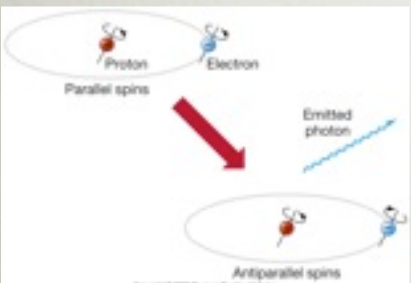
- Departures from the predictions of newtonian gravity became apparent also at galactic scales with the measurement of rotation curves of galaxies (Rubin et al, 1970)



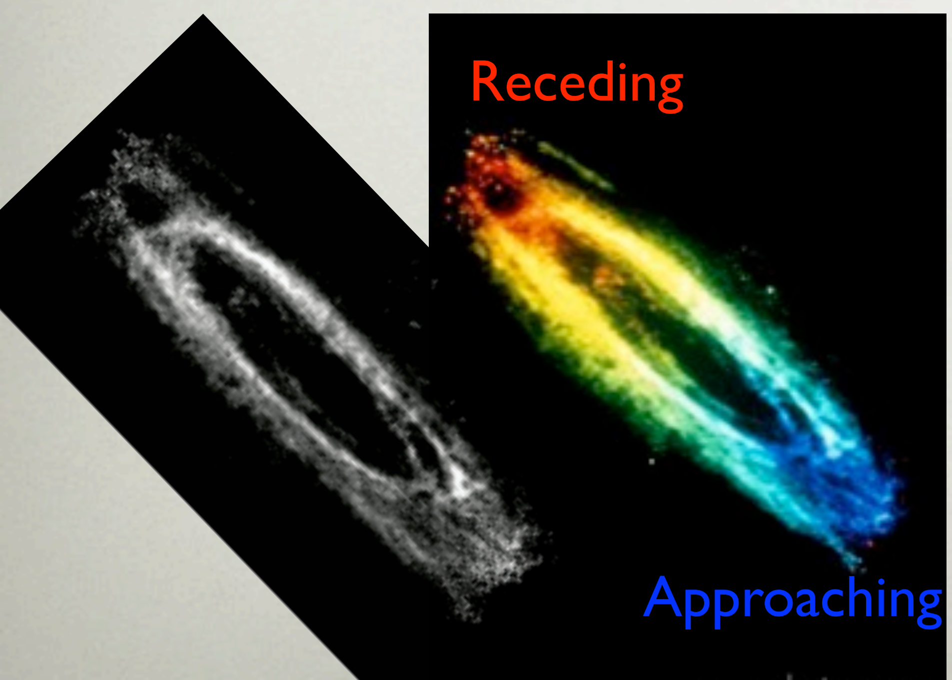


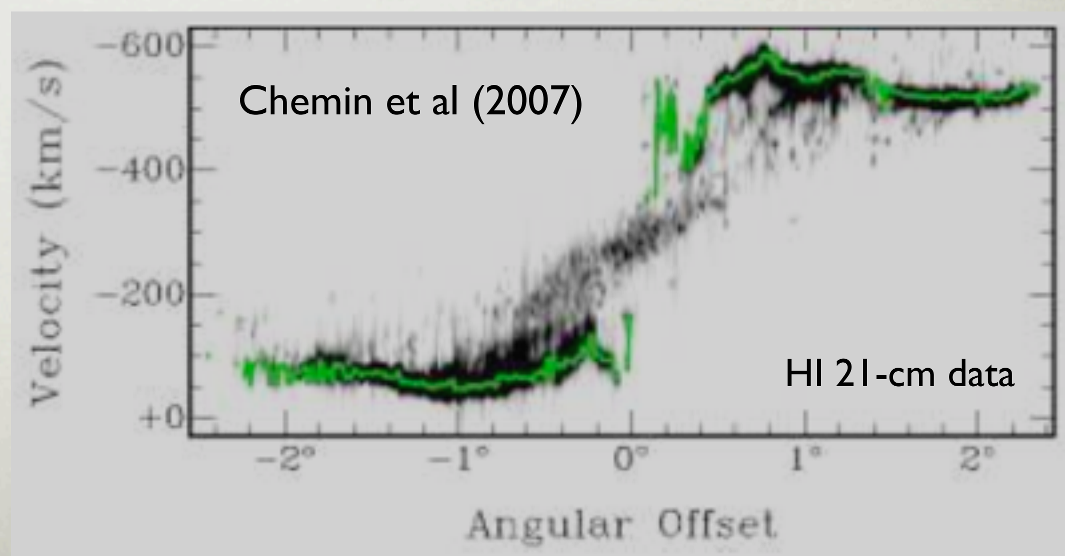
Rotation Curves of Galaxies

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



M31 (Andromenda)



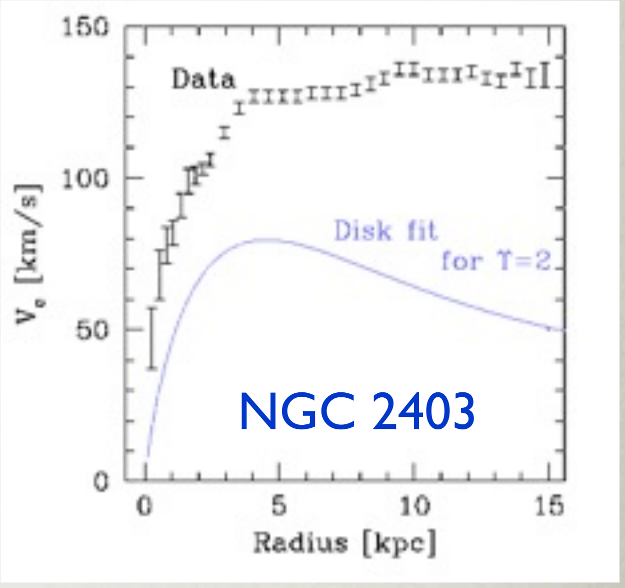


Rotation Curves of Galaxies

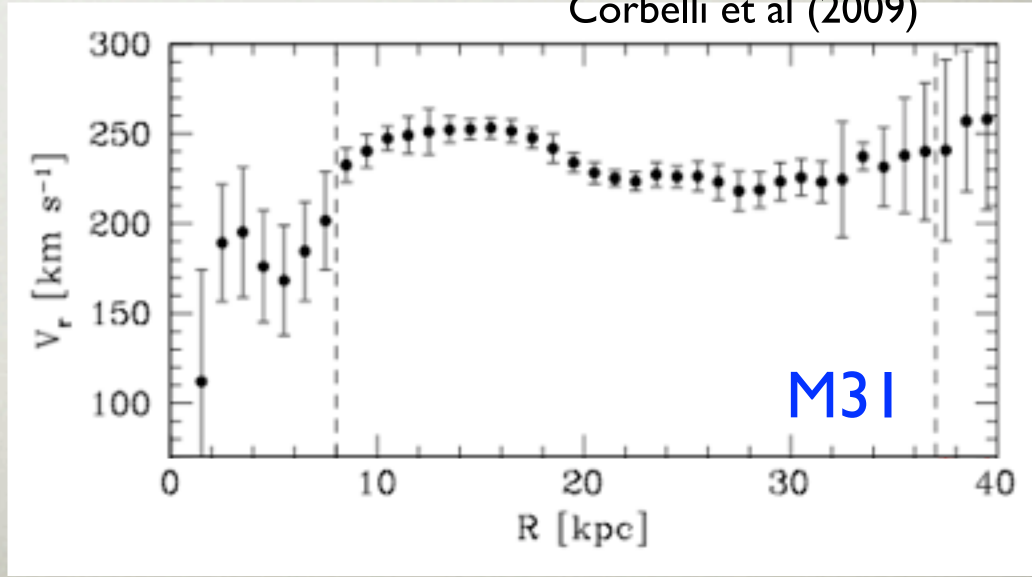
- From newtonian dynamics:

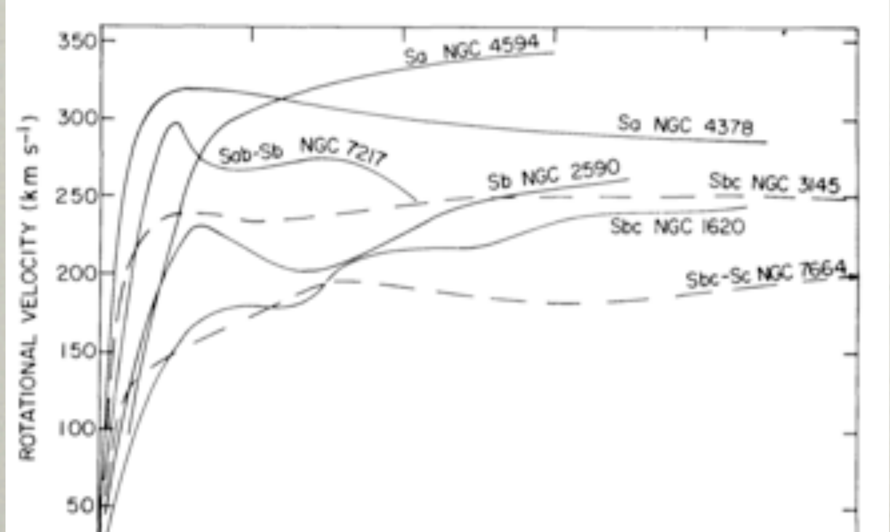
$$F = \frac{mv^2}{r} = G\frac{mM}{r^2}$$

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



Corbelli et al (2009)





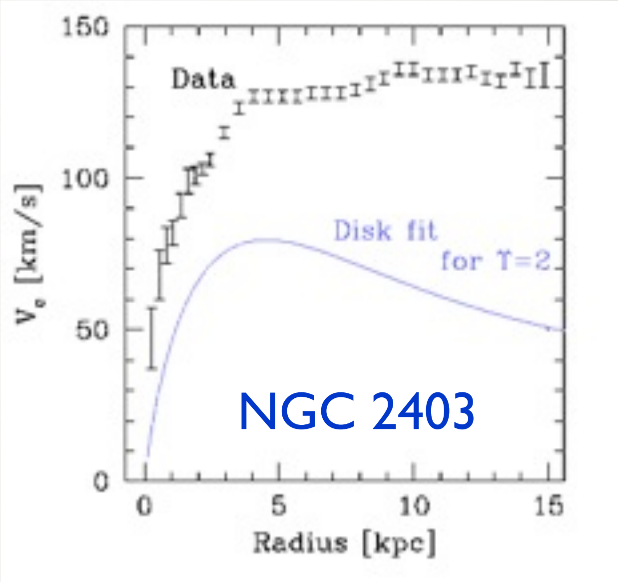
Rubin, Ford, Thonnard (1978)

Rotation Curves of Galaxies

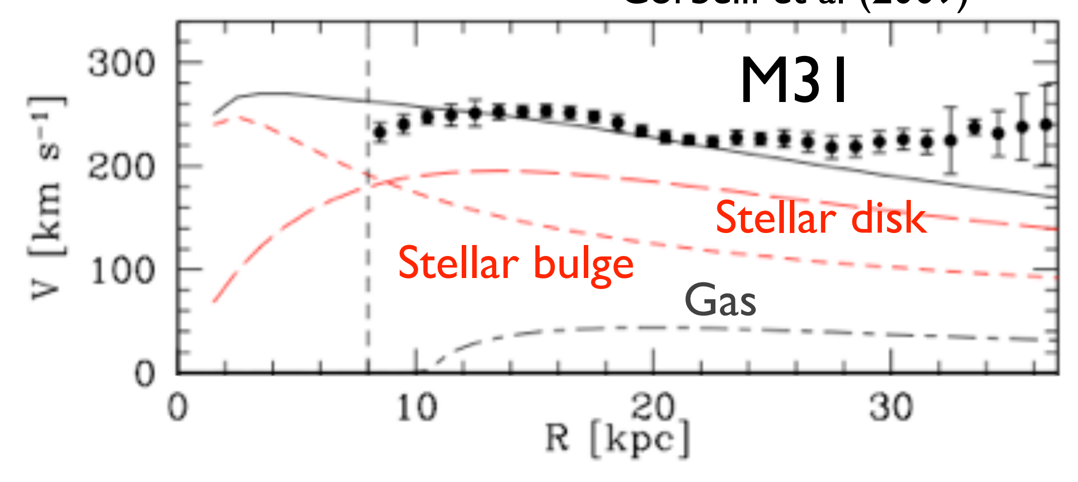
- From newtonian dynamics:

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

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



Corbelli et al (2009)



Rotation Curves of Galaxies

- From newtonian dynamics:

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

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

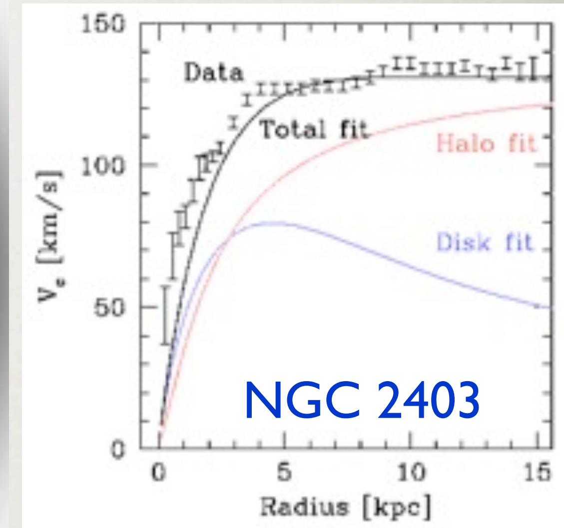
- For constant v:

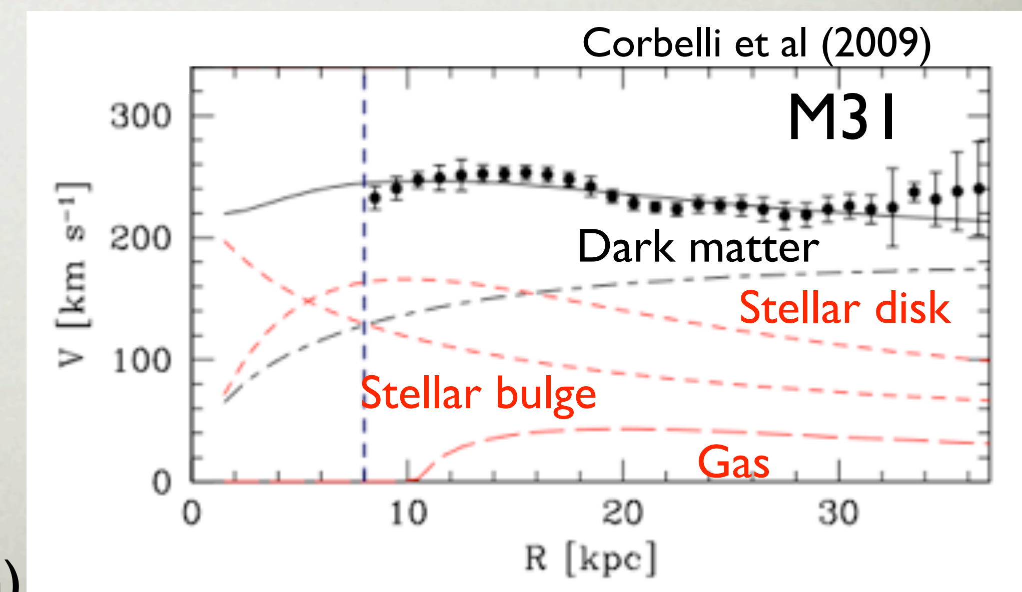
$$M(r) \propto r \qquad \rho(r) \propto r^{-2}$$

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:
ρ(8.5 kpc)~0.2-0.5 GeV/cm³ (direct detection)





Rotation Curves of Galaxies

- From newtonian dynamics:

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

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

- For constant v:

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

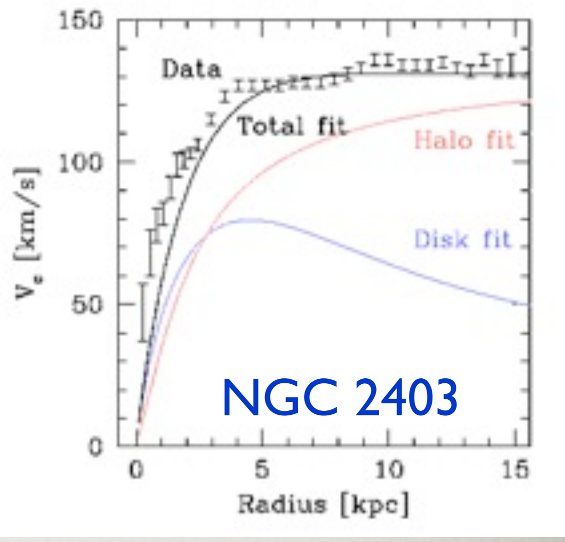
Mass density not as steeply falling as star density (exponential)!

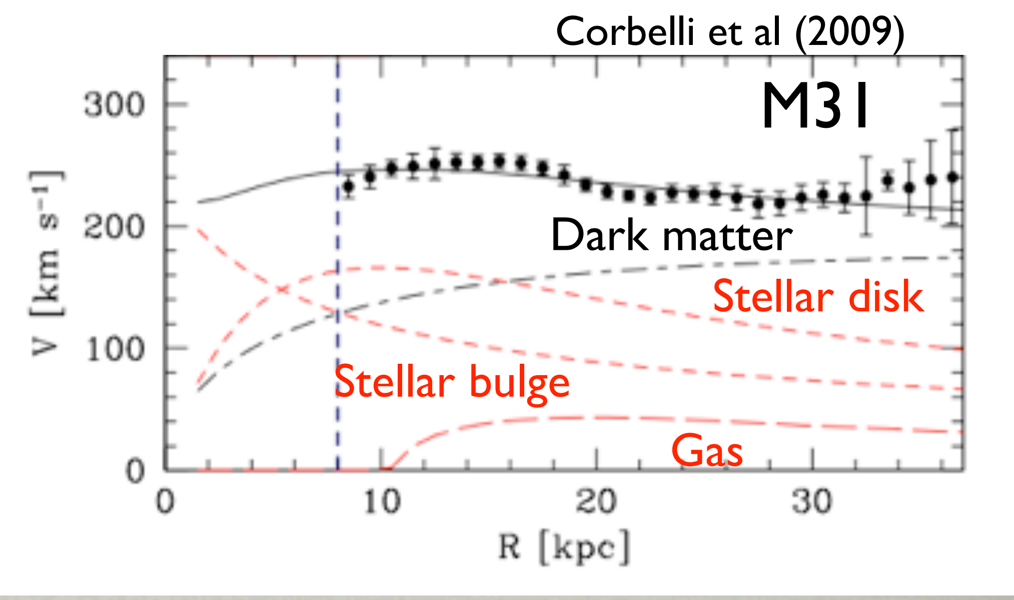
➡ By adding extended dark matter halo get good fit to the data.

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

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

➡ $M_\odot/L_\odot \sim 10$





Masses of M31 and MW

- 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):
  - 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

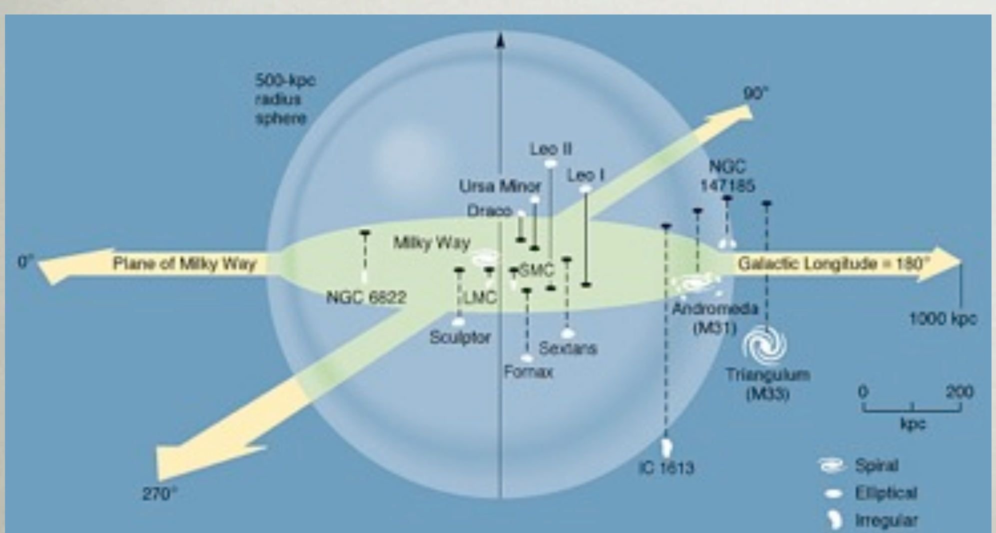


Table 1. Data table for the satellites of the Milky Way. Listed are Galactic coordinates (l, b) in degrees, Galactocentric distance r in kpc and corrected line-of-sight velocity in km s^{-1}.

Name	l (deg)	b (deg)	r (kpc)	v_{los} (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 Bernices	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 km s^{-1}.

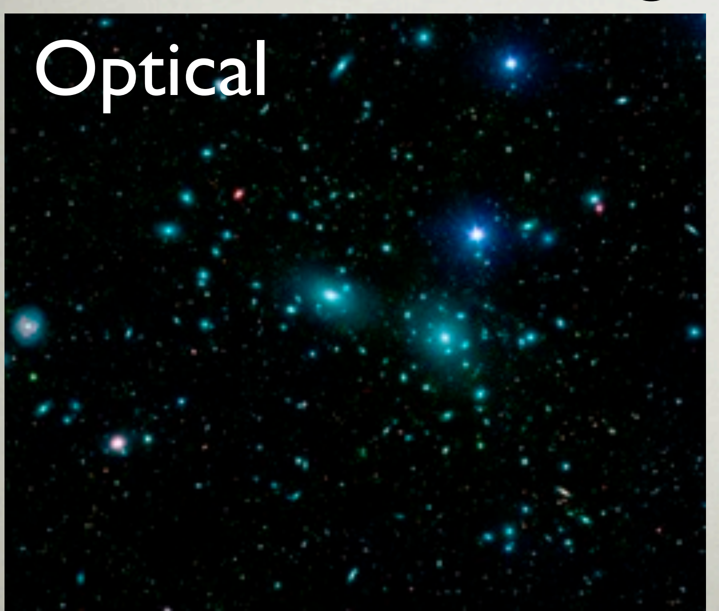
Name	l (deg)	b (deg)	r (kpc)	R (kpc)	v_{los} (km s^{-1})	Source
M33	133.6	-31.3	809	206	74	1,2
M32	121.1	-22.0	785	5	95	2,3
IC 10	119.0	-3.3	660	261	-29	2,3,4
NGC 205	120.7	-21.1	824	39	58	1,2
NGC 185	120.8	-14.5	616	189	106	1,2
IC 1613	129.8	-60.6	715	510	-56	2,3,5
NGC 147	119.8	-14.2	675	144	117	1,2
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

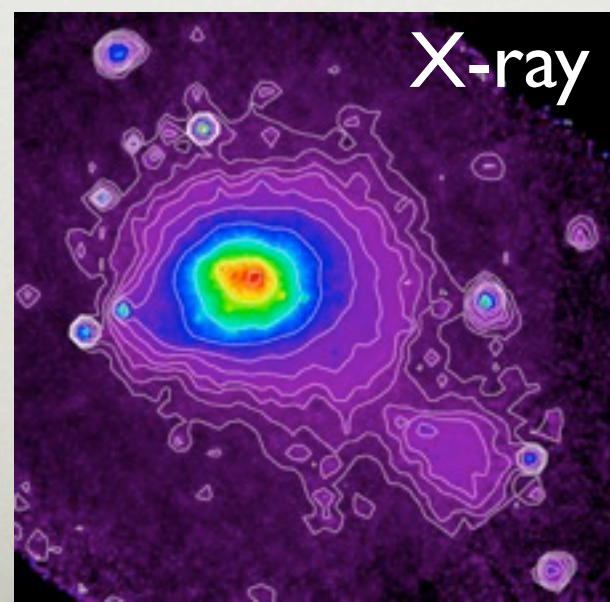
Galaxy clusters

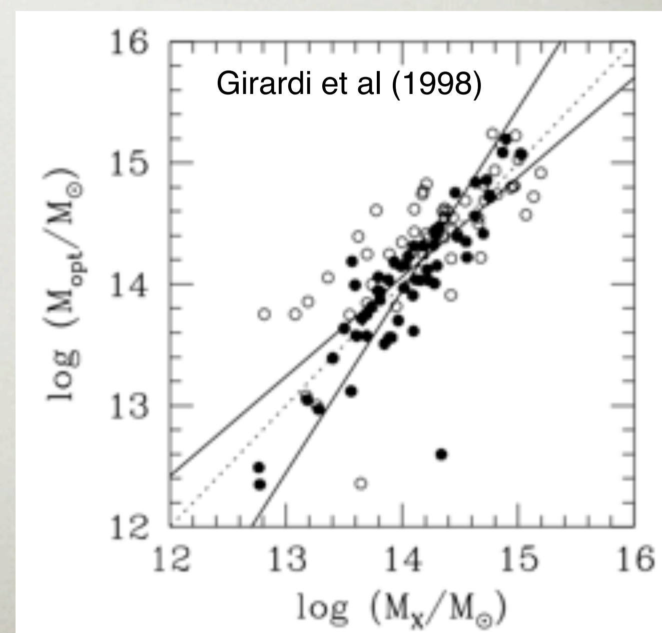
- X-ray emitted by very hot intracluster gas (10^7-10^8K) through bremsstrahlung.
- Gas mass and total mass in galaxy clusters measured by X-ray (assuming thermal equilibrium), lensing
- Mass determination consistent with clusters being dark matter dominated

Galaxy cluster:
~1-2% stars, ~5-15% gas, remaining is dark matter

Coma galaxy cluster

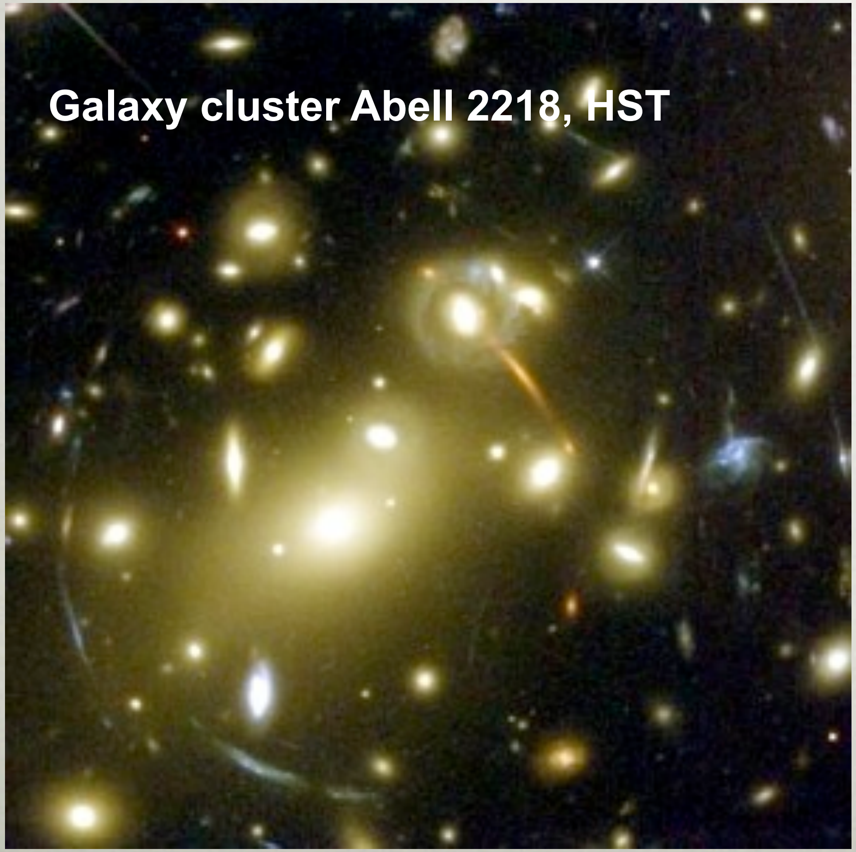


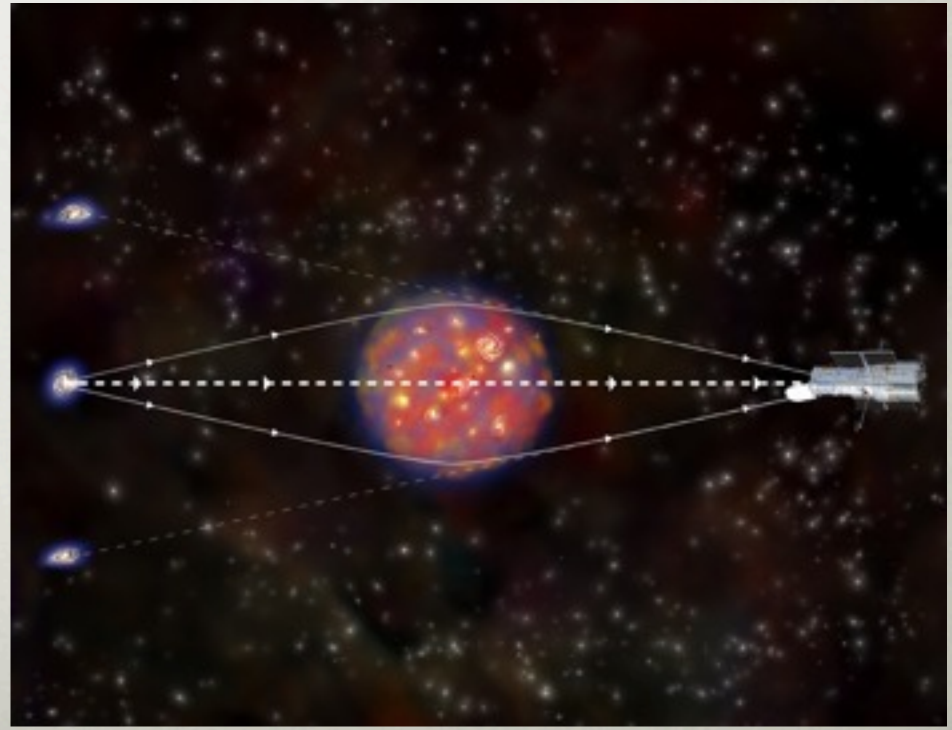




Gravitational Lensing

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

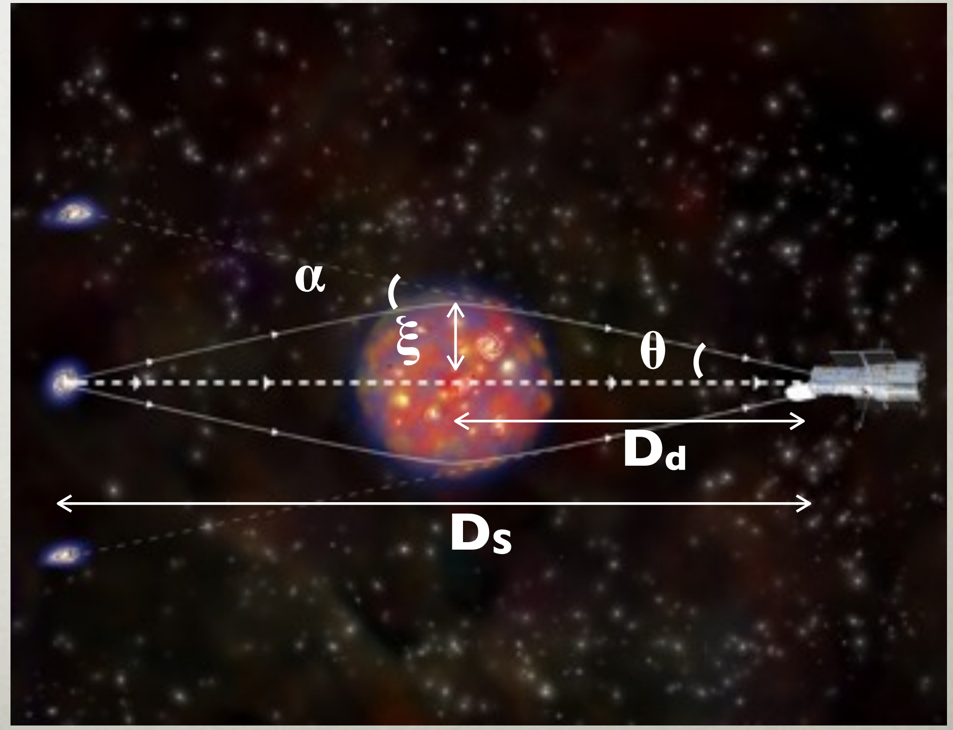




Gravitational Lensing

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

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

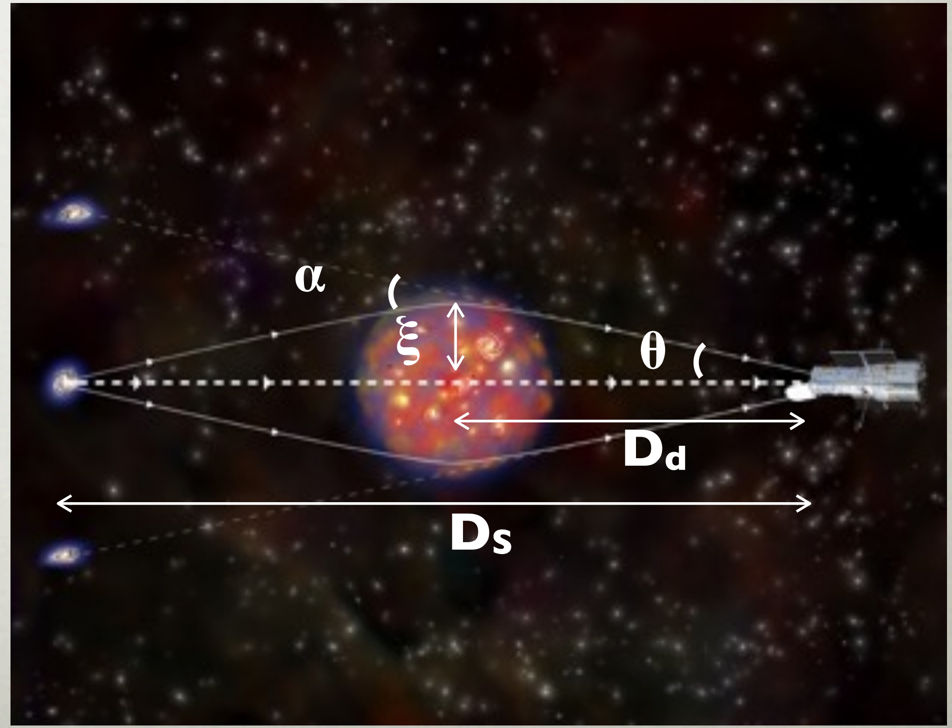


Gravitational Lensing

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

Deflection

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



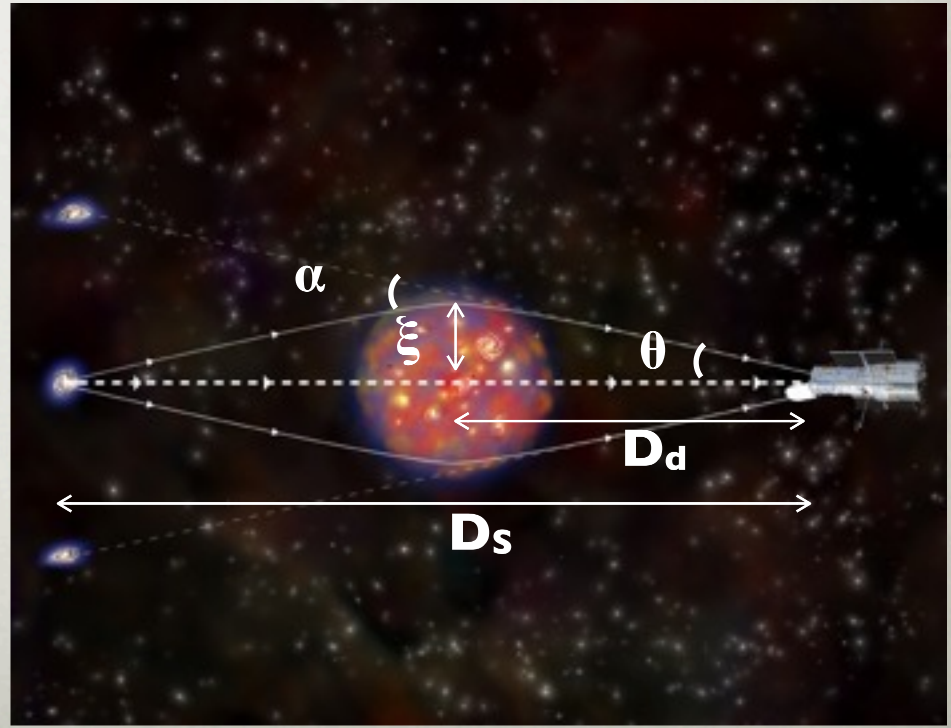
Gravitational Lensing

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

Lens mass

Deflection

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



Gravitational Lensing

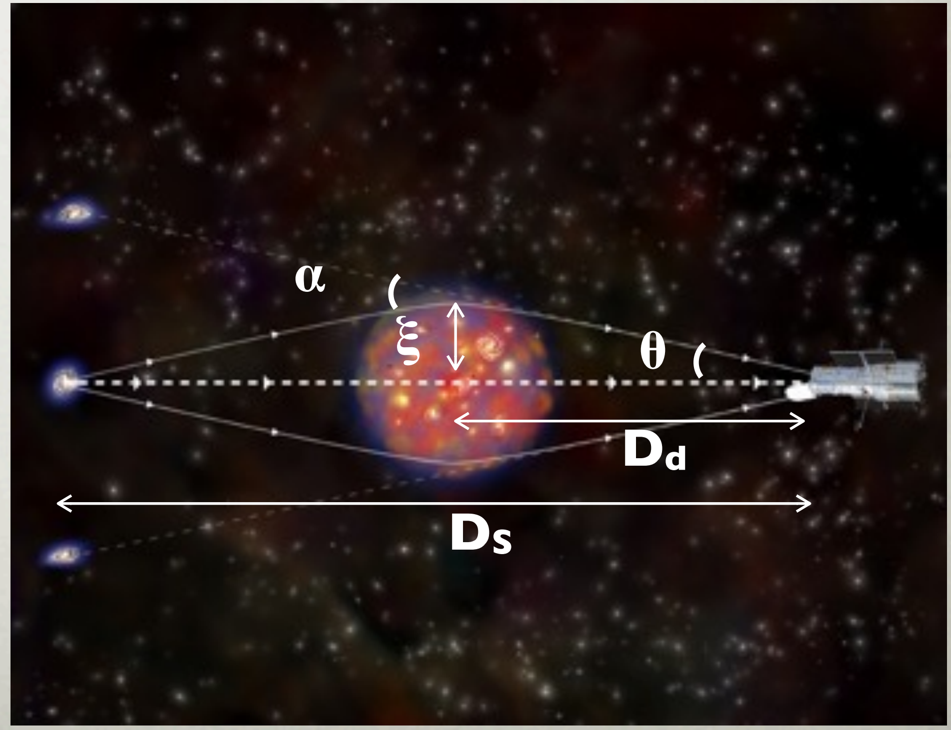
- Image distortion caused by intervening gravitational potential
- Sensitive to total mass

Lens mass

Deflection

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

Impact parameter



Gravitational Lensing

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

Lens mass

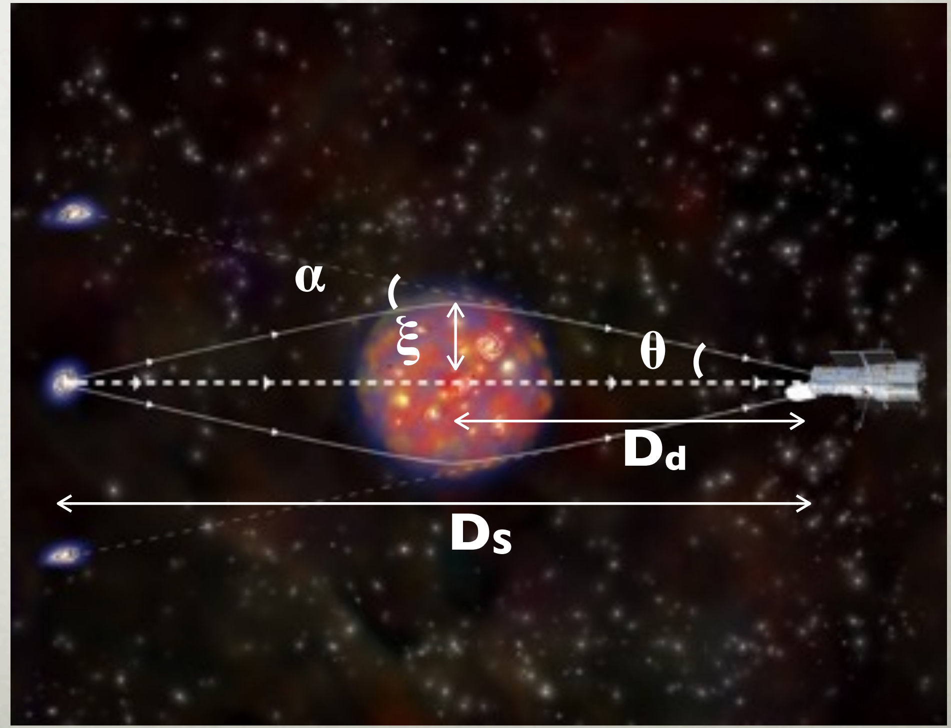
Deflection

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

Impact parameter

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

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



Gravitational Lensing

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

Lens mass

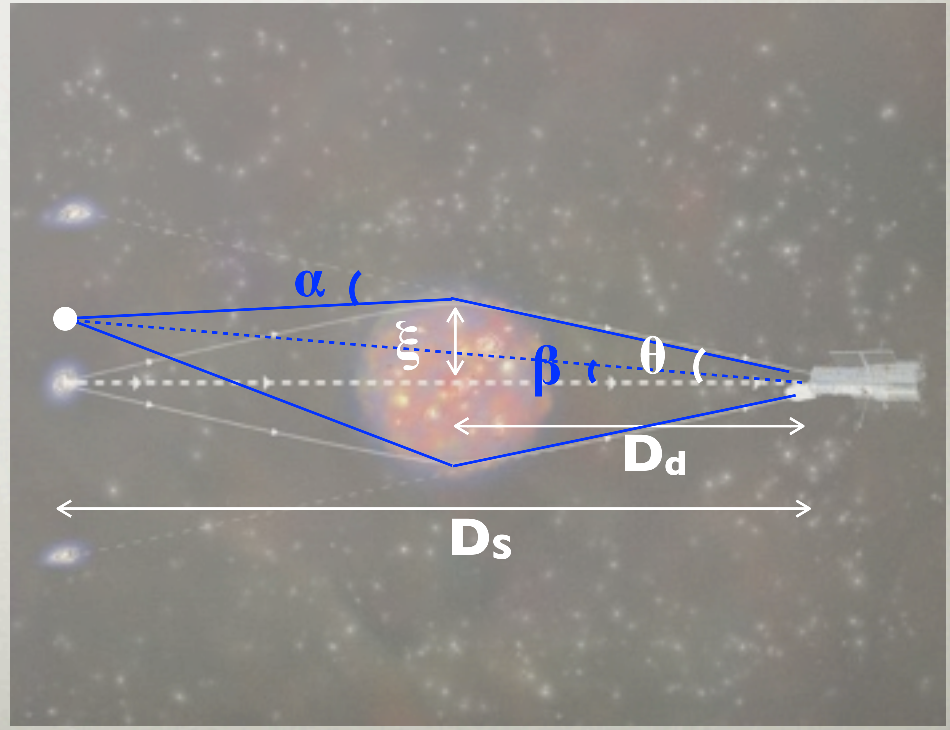
Deflection

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

Impact parameter

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

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



Gravitational Lensing

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

Lens mass

Deflection

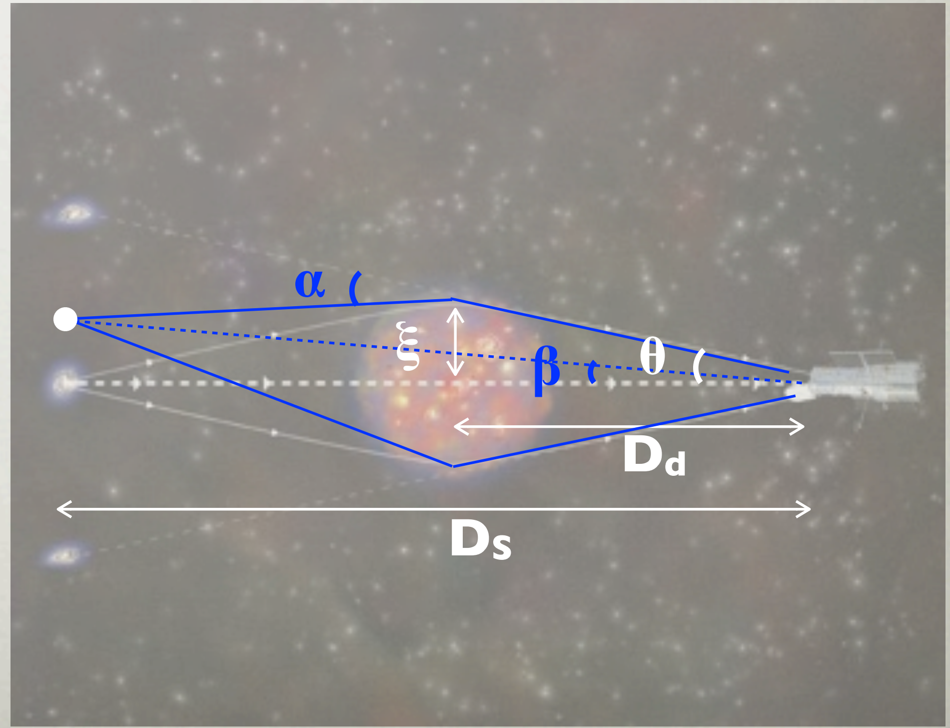
$$\hat{\alpha} = \frac{4GM}{c^2 \xi}$$

Impact parameter

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

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

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



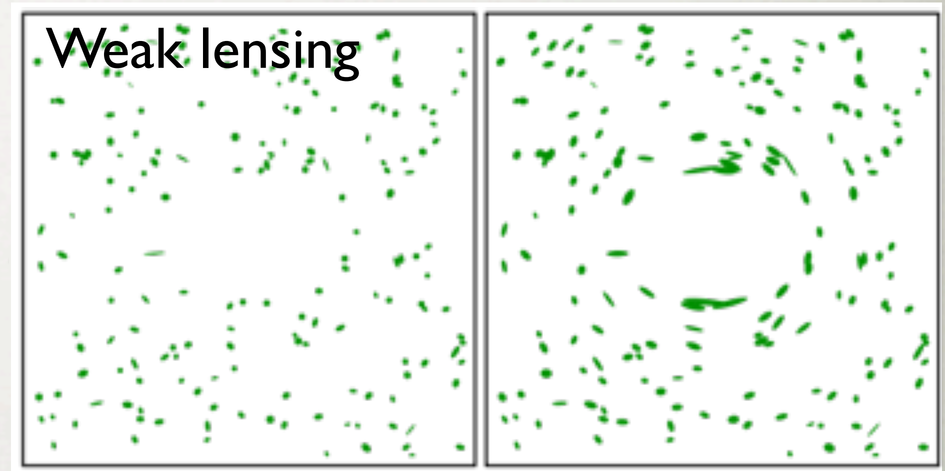
Gravitational Lensing

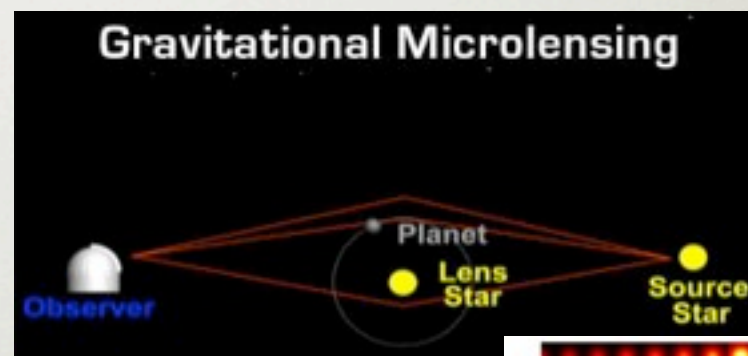
- Strong, weak, and microlensing

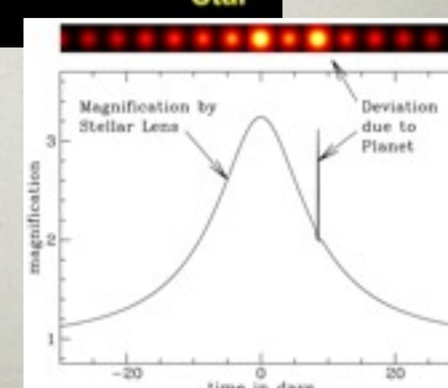
$$\theta_E = \left(\frac{4GM}{c^2} \frac{D_{ds}}{D_d D_s} \right)^{1/2}$$

M ~ 10^{15} M$_\odot$, D ~ Gpc ⇒ θ ~ 100 arcsec

M ~ M$_\odot$, D ~ kpc ⇒ θ ~ 10^{-3} arcsec







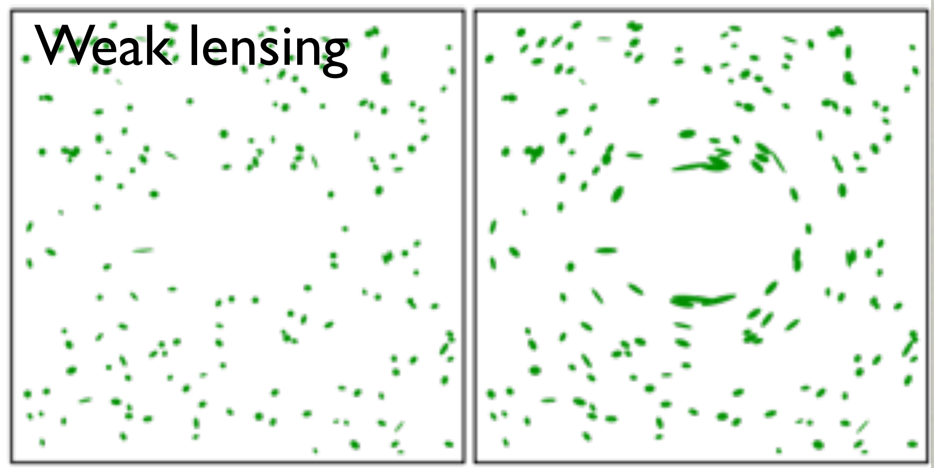
Gravitational Lensing

- Strong, weak, and microlensing

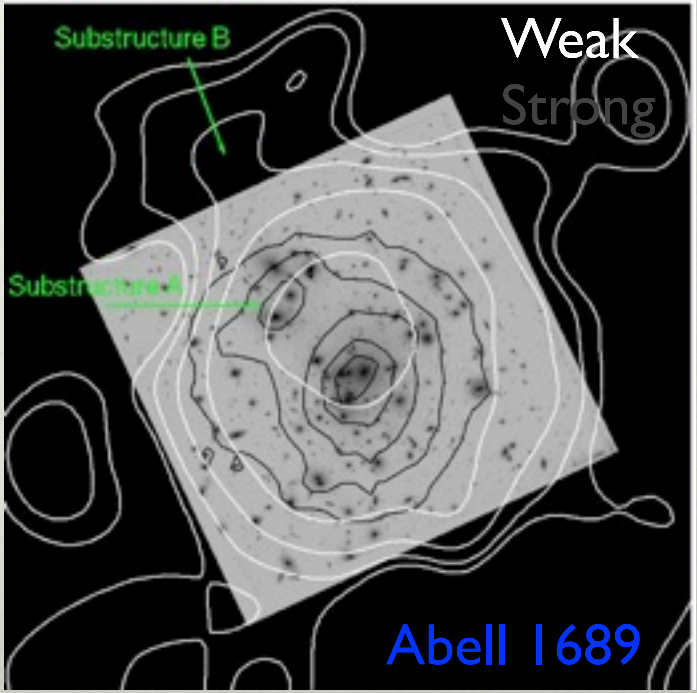
$$\theta_E = \left(\frac{4GM}{c^2} \frac{D_{ds}}{D_d D_s} \right)^{1/2}$$

M ~ 10^{15} M$_\odot$, D ~ Gpc ⇒ θ ~ 100 arcsec

M ~ M$_\odot$, D ~ kpc ⇒ θ ~ 10^{-3} arcsec



S. Riemer-Sørensen et al, 2009

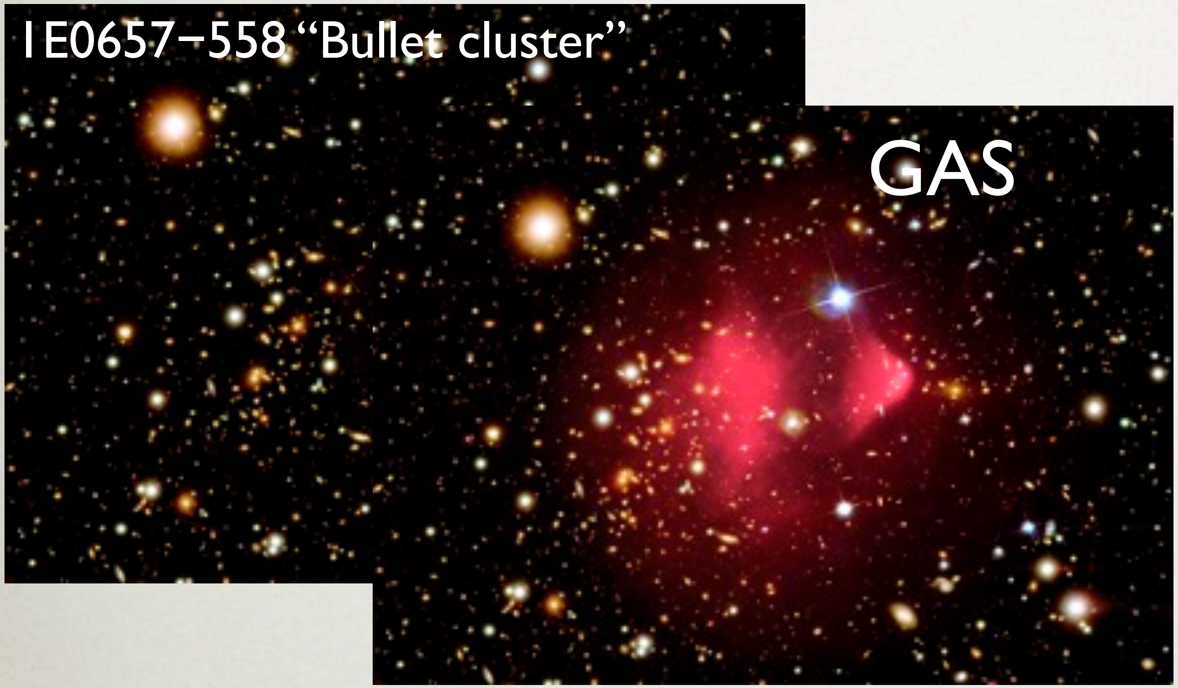


Cosmic Supercolliders

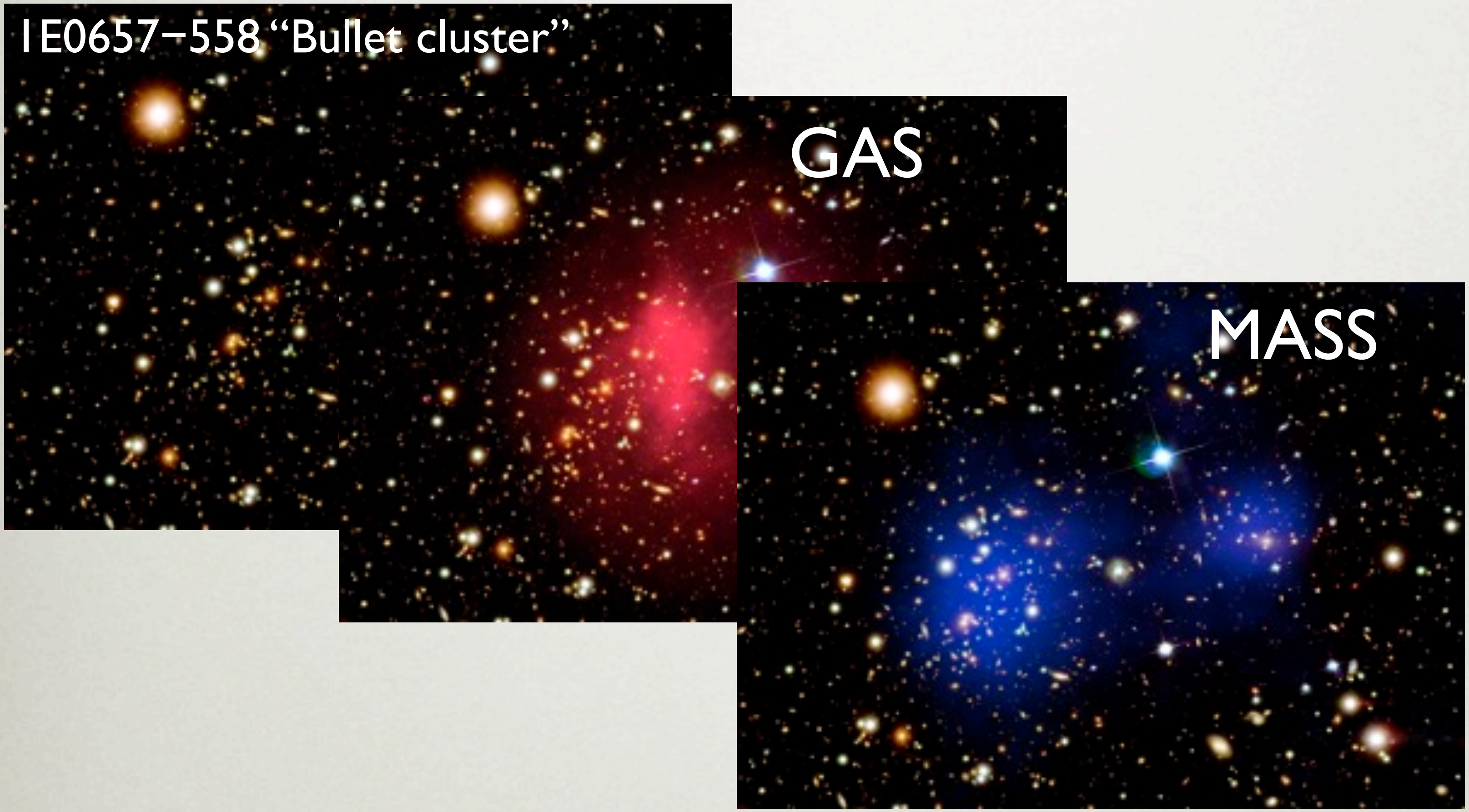
- Systems where the presence of dark matter can be inferred and it is not positionally coincident with ordinary matter strongly endorse the dark matter hypothesis
- Galaxy cluster mergers

Cosmic Supercolliders

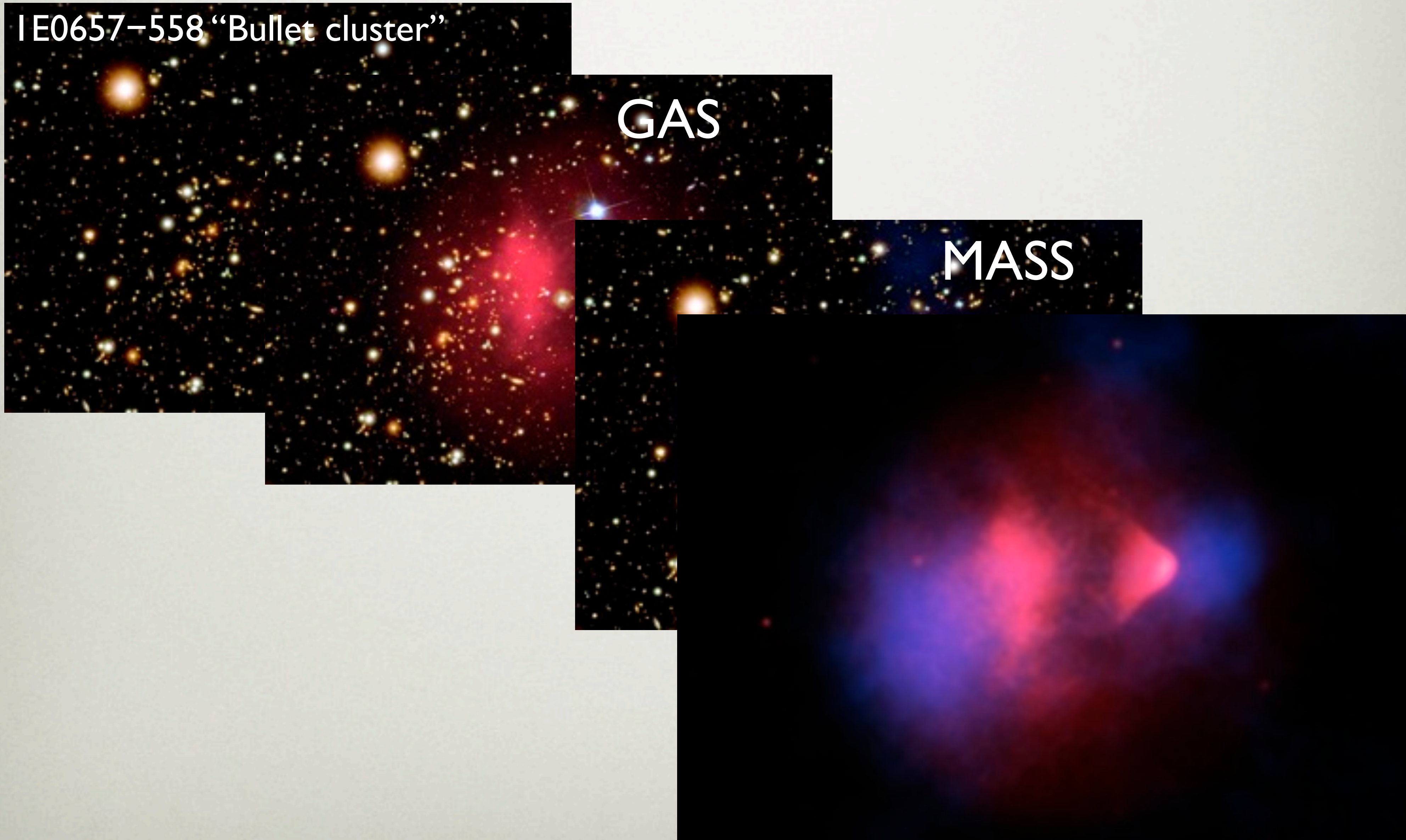
Cosmic Supercolliders



Cosmic Supercolliders



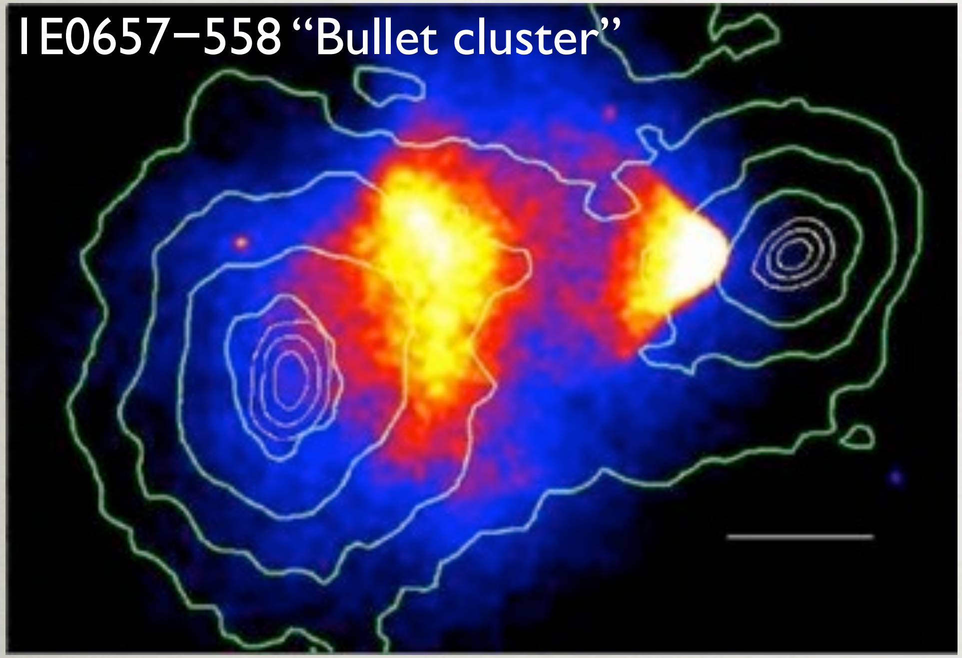
Cosmic Supercolliders



Cosmic Supercolliders

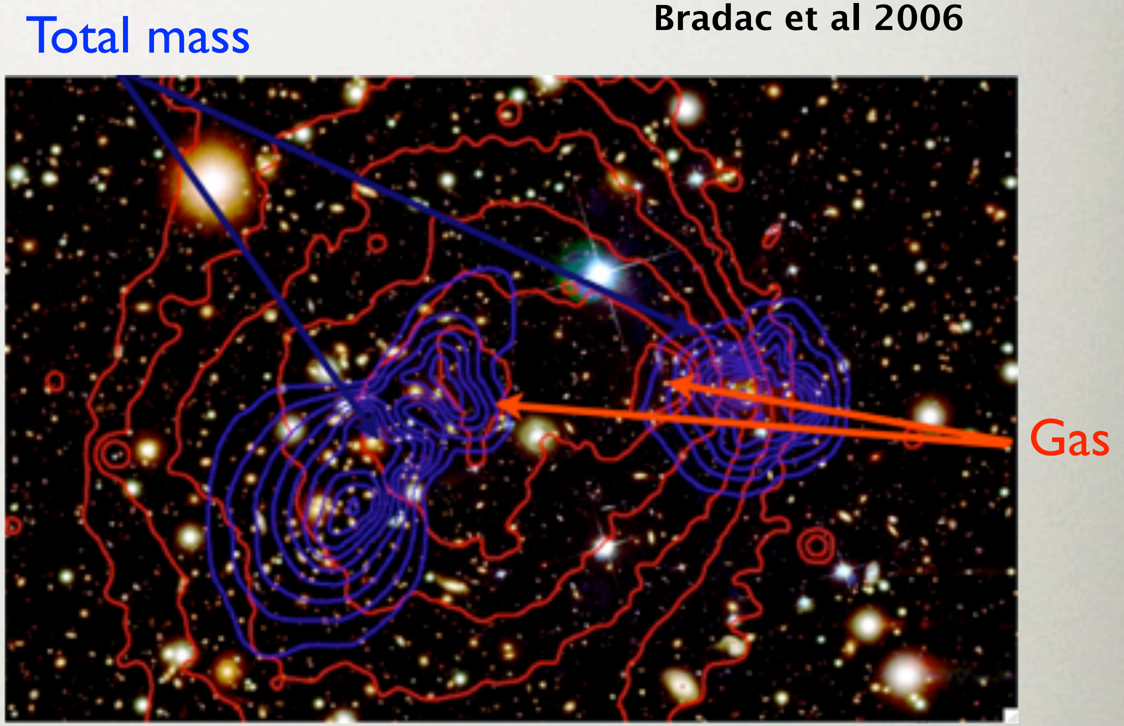
Weak lensing

Clowe et al 2006



Weak and strong lensing

Bradac et al 2006

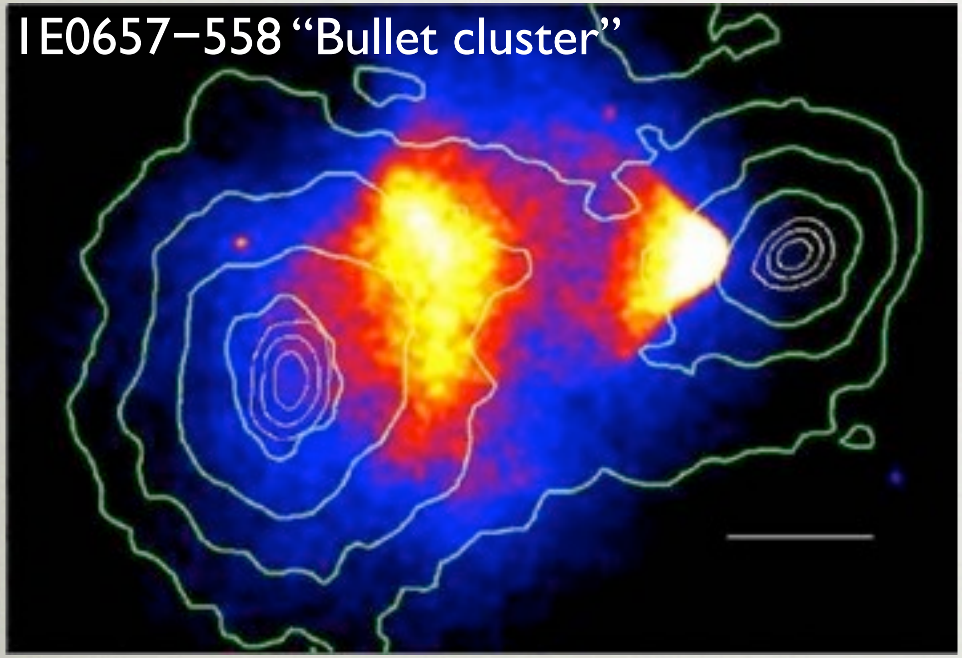


Most of the matter in the system is collisionless* and dark

Cosmic Supercolliders

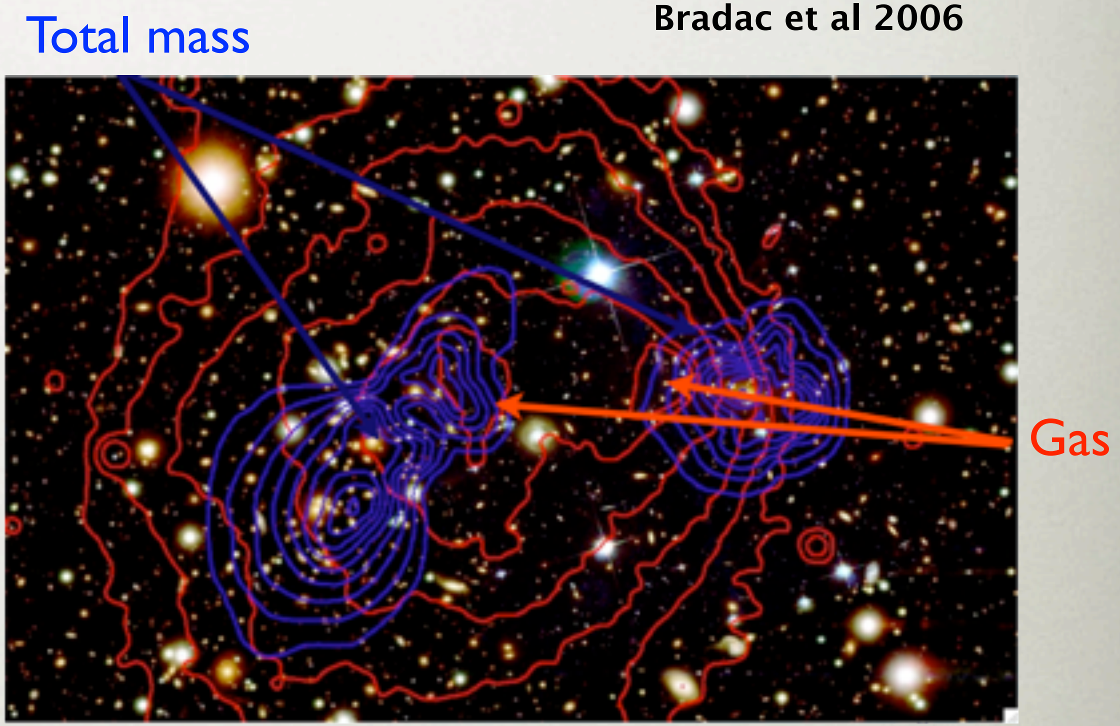
Weak lensing

Clowe et al 2006



Weak and strong lensing

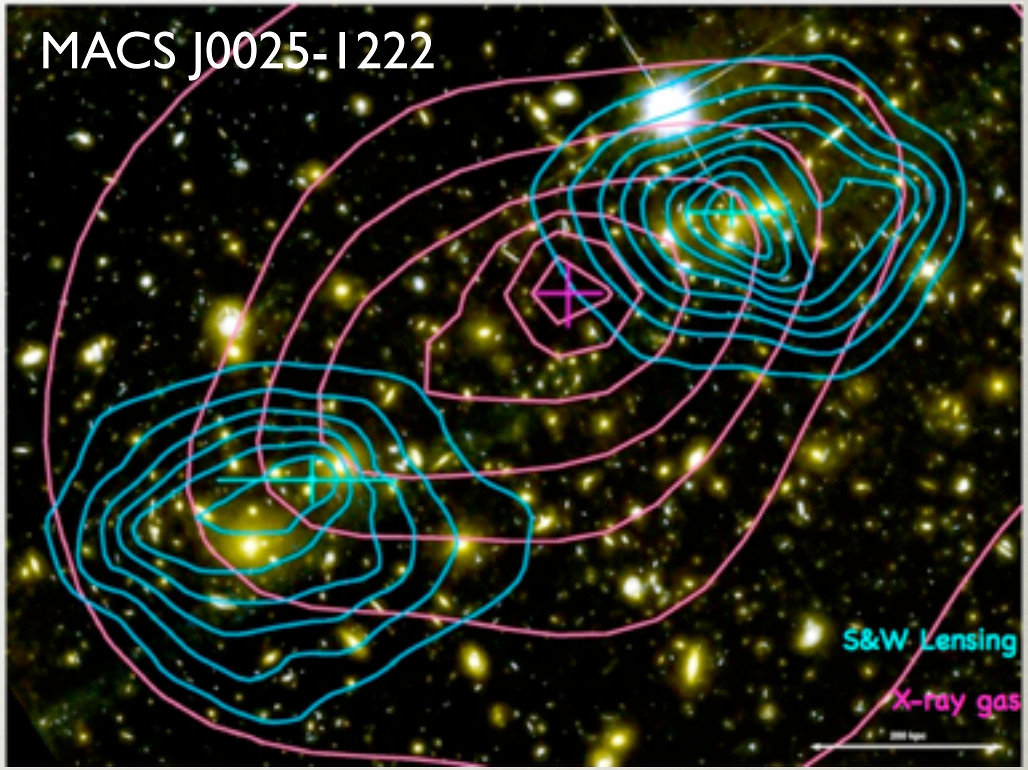
Bradac et al 2006



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

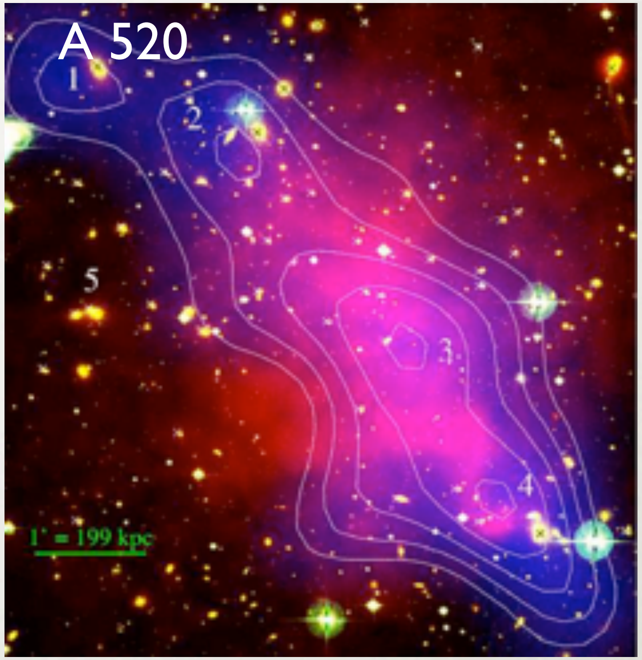
More Cosmic Supercolliders

Bradac et al 2008b



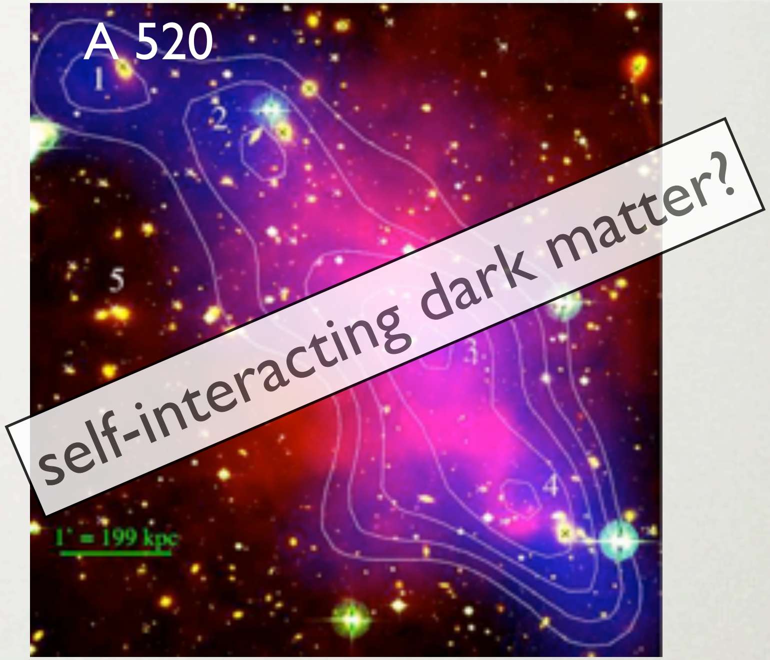
More Cosmic Supercolliders

Mahdavi et al 2007



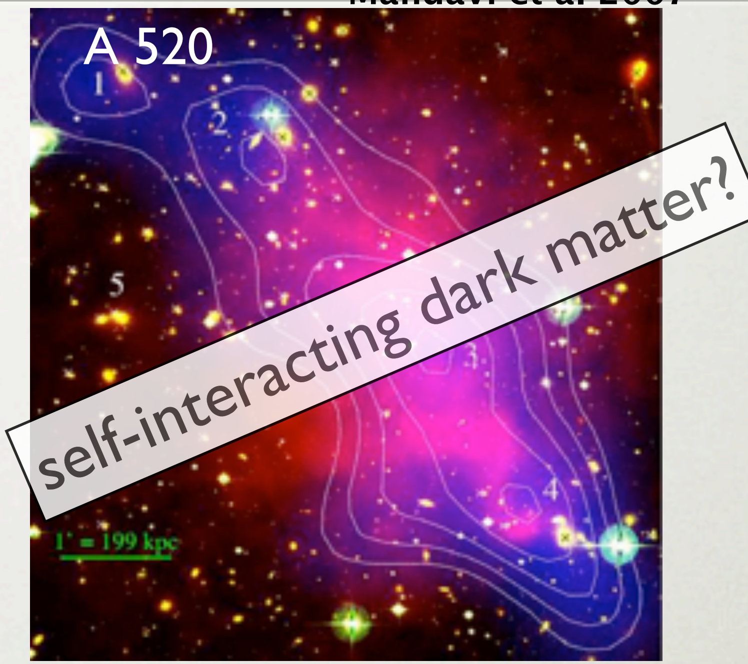
More Cosmic Supercolliders

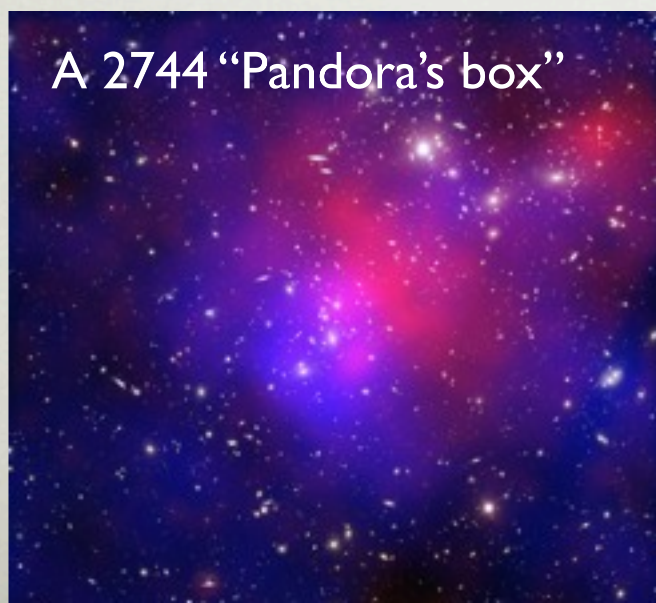
Mahdavi et al 2007



More Cosmic Supercolliders

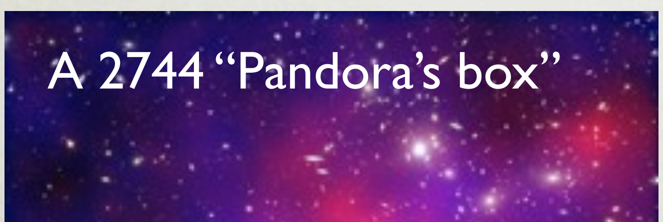
Mahdavi et al 2007





More Cosmic Supercolliders

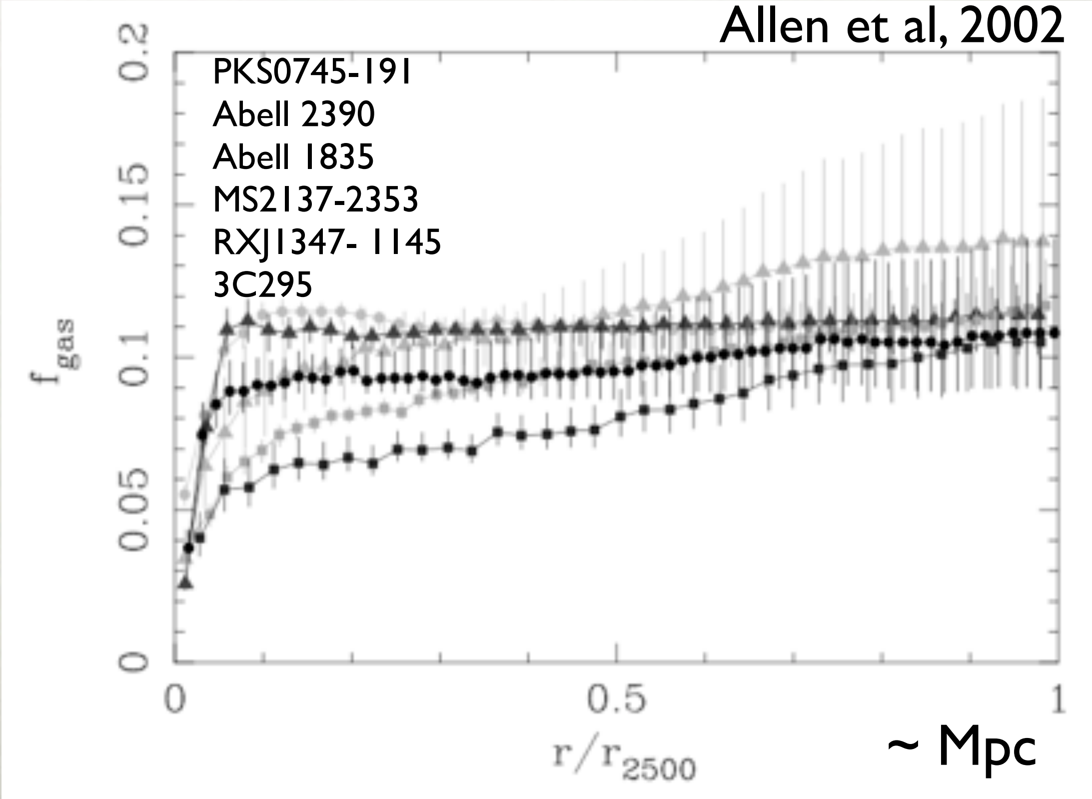
Mahdavi et al 2007



More of these systems have been found and more data is coming. 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
  ⇒ constrain the Universe total matter density!



Constrain matter density:

$\mathbf{\Omega_M}$ ($\Omega_B\ \rho_M/\rho_B \sim \Omega_B/f_{gas}$)**~0.3**

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

ρ_c: Critical energy density of the Universe (flat)

Big Bang Nucleosynthesis

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

$$p + n \rightarrow D + \gamma$$

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

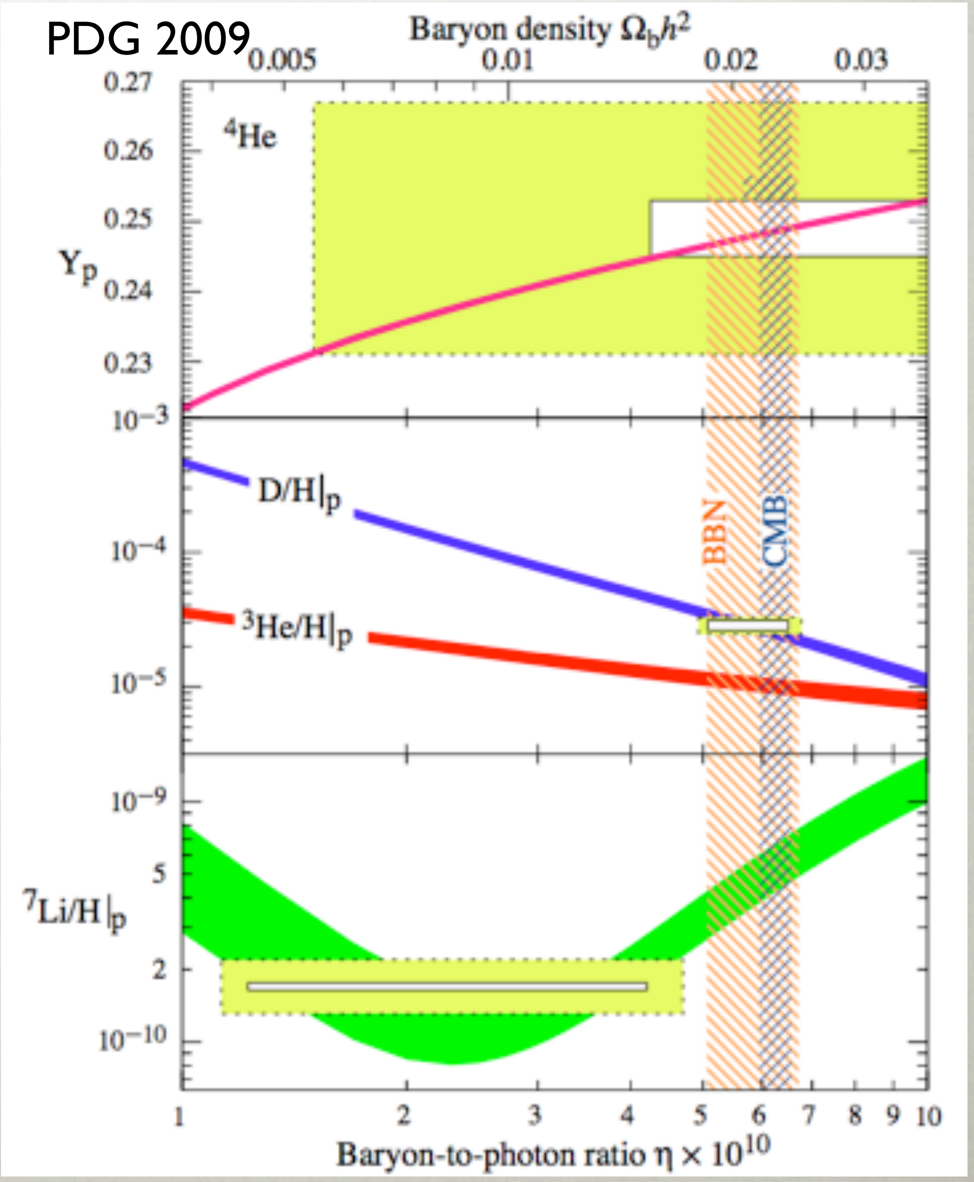
Constrains baryon density: Ω_B~ few %

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

ρ_c: Critical energy density of the Universe (flat)

➡ Most matter in the Universe is non-baryonic

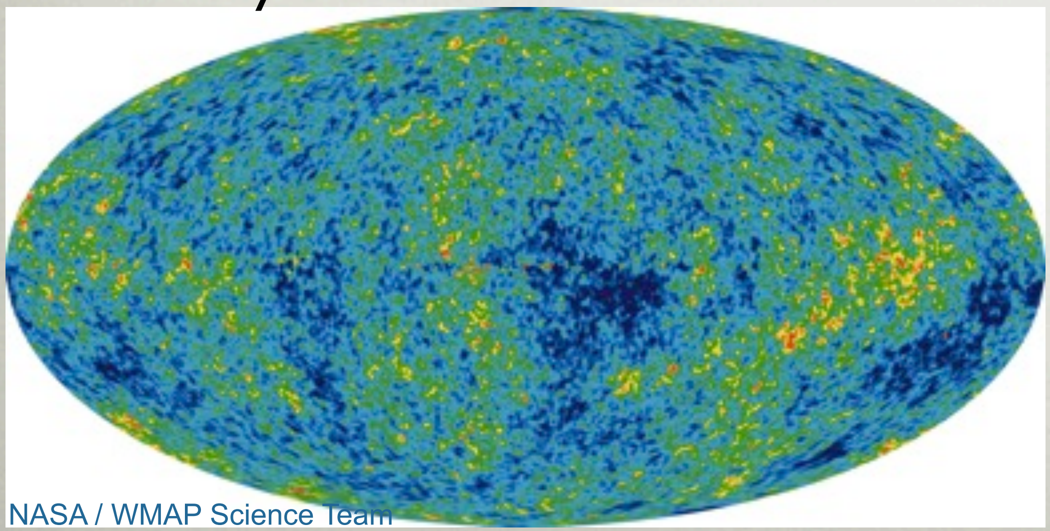
- Remarkable agreement with CMB estimate of baryon density (more later)



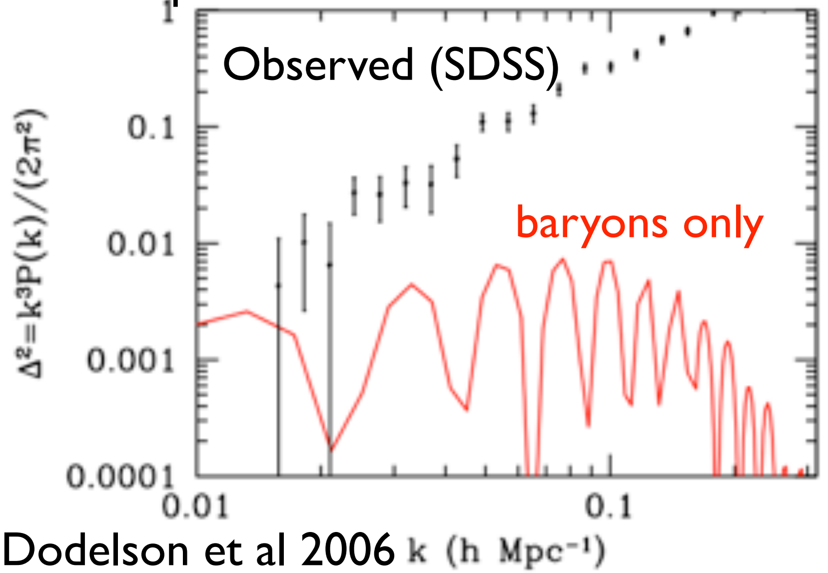
Cosmic Microwave Background

- Relic of a time in the early Universe when matter and radiation decoupled (protons and electron form neutral hydrogen and become transparent to photons, ~100,000s years after Big Bang, ~ 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 ➡ Require additional matter to start forming structure earlier (decoupled from baryons and radiation, neutral)
$\Delta T \sim 200\ \mu K$

WMAP 7 year data



Power spectrum of matter fluctuations



Dodelson et al 2006

Cosmic Microwave Background

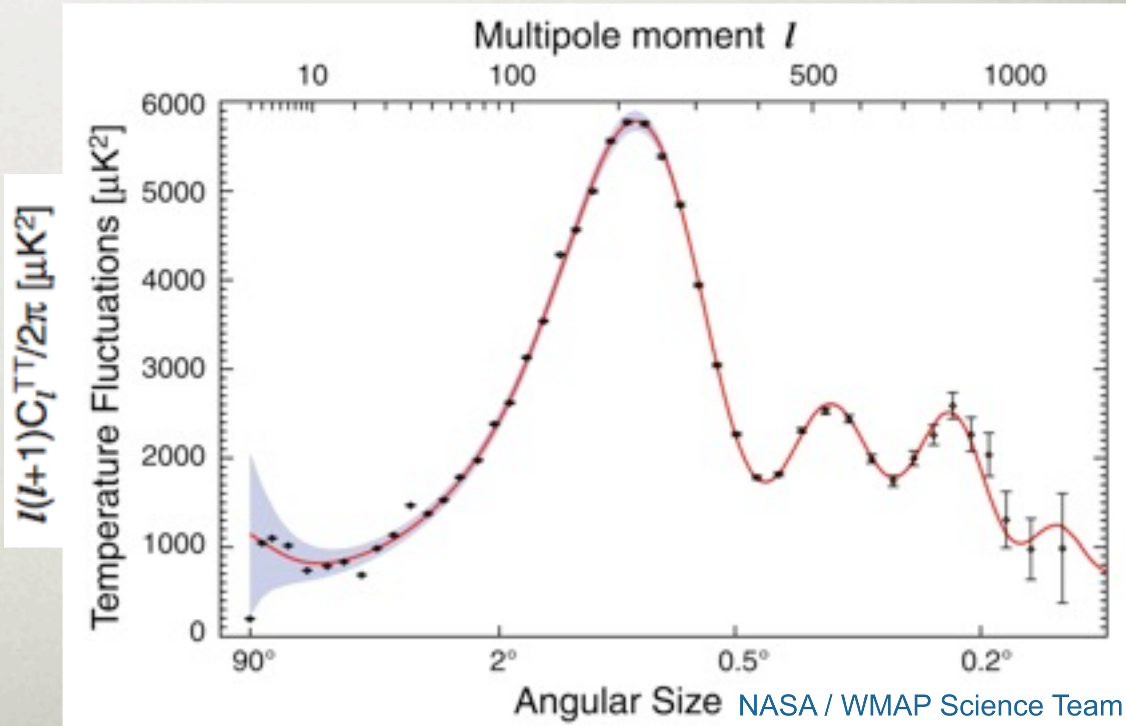
- The CMB angular power spectrum depends on several parameters, including Ω_B, Ω_M, Ω_Λ (Ω_Λ is the vacuum density)

- Decompose temperature field into spherical harmonics

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

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

WMAP 7 year data

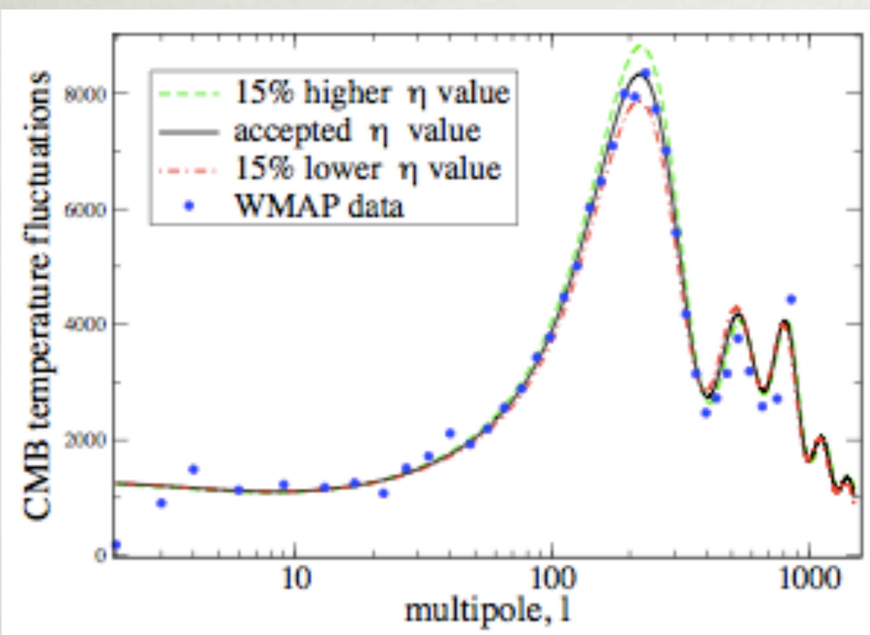


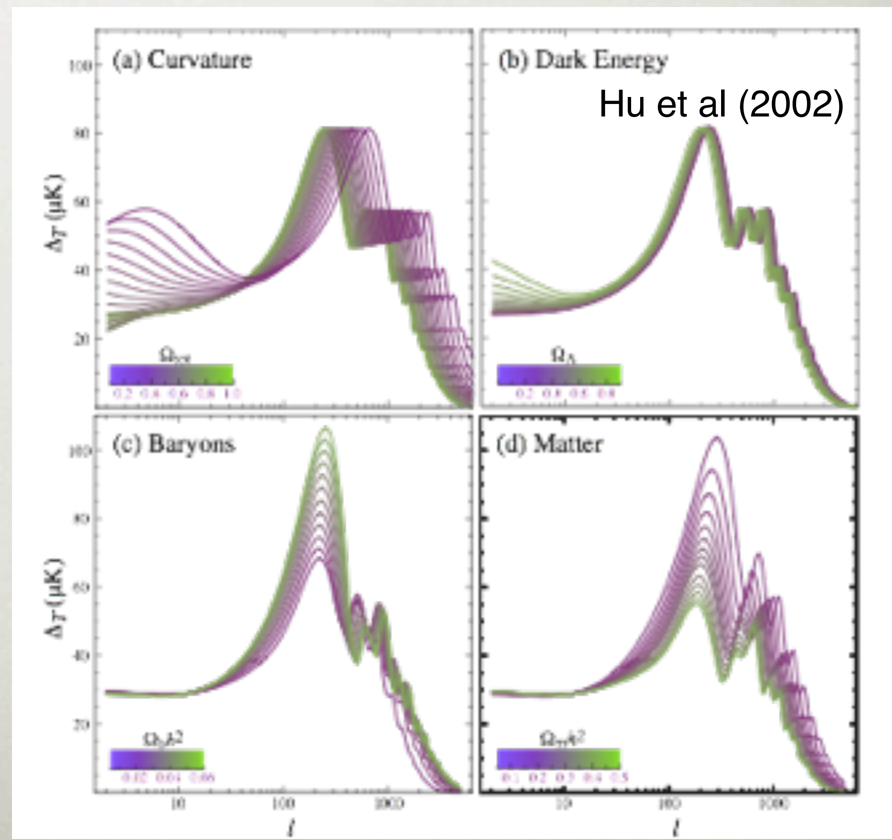
Cosmic Microwave Background

- The CMB angular power spectrum depends on several parameters, including Ω_B, Ω_M, Ω_Λ (Ω_Λ is the vacuum density)
- Matching location and heights of the peaks constrains these parameters and geometry of the Universe (flat, Ω_{total}=1)

Jarosik et al. 2011

Ω_B 0.0449 ± 0.0028
DM density 0.222 ± 0.026
Ω_Λ 0.734 ± 0.029

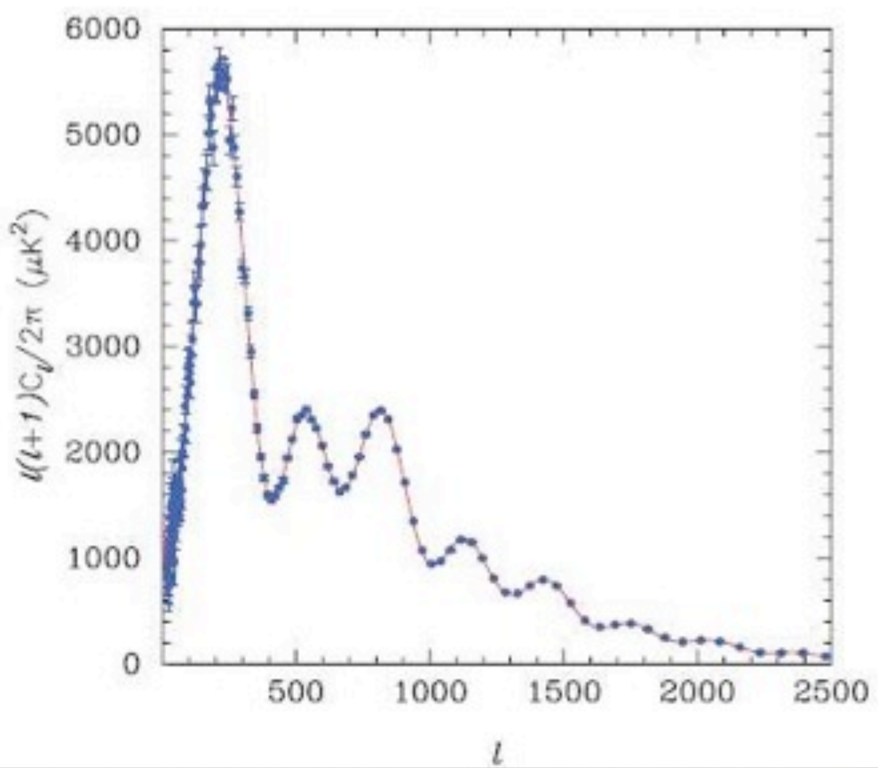




Cosmic Microwave Background

- The CMB angular power spectrum depends on several parameters, including Ω_{B}, Ω_{M}, Ω_{Λ} (Ω_{Λ} is the vacuum density)
- Matching location and heights of the peaks constrains these parameters and geometry of the Universe (flat, Ω_{total}=1)

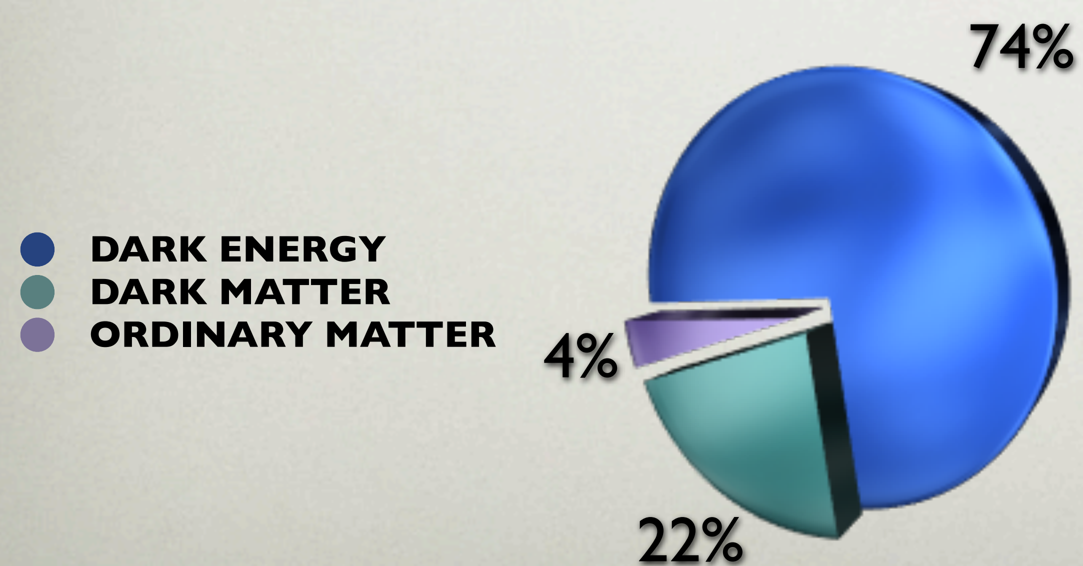
Predictions for Planck

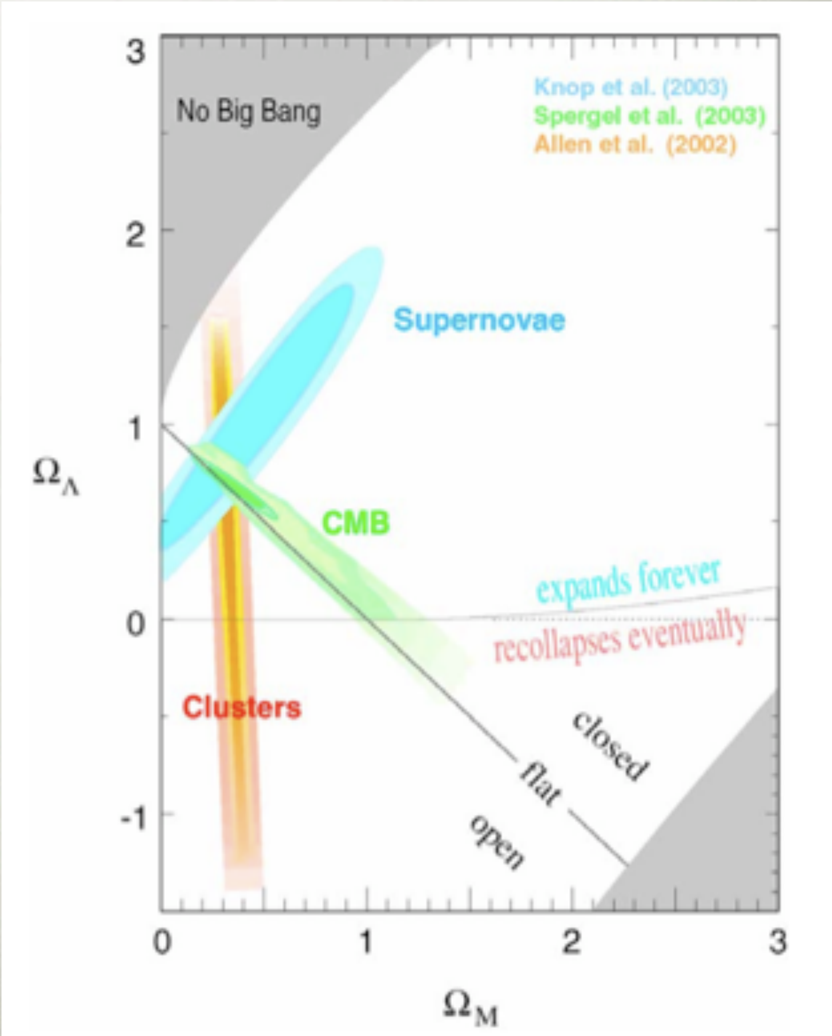


Concordance

- Extraordinary agreement in precision cosmology
- Present Universe mostly made out of dark energy, dark matter, and small contribution from baryonic matter

➡ ΛCDM (Lambda Cold Dark Matter), standard model of cosmology

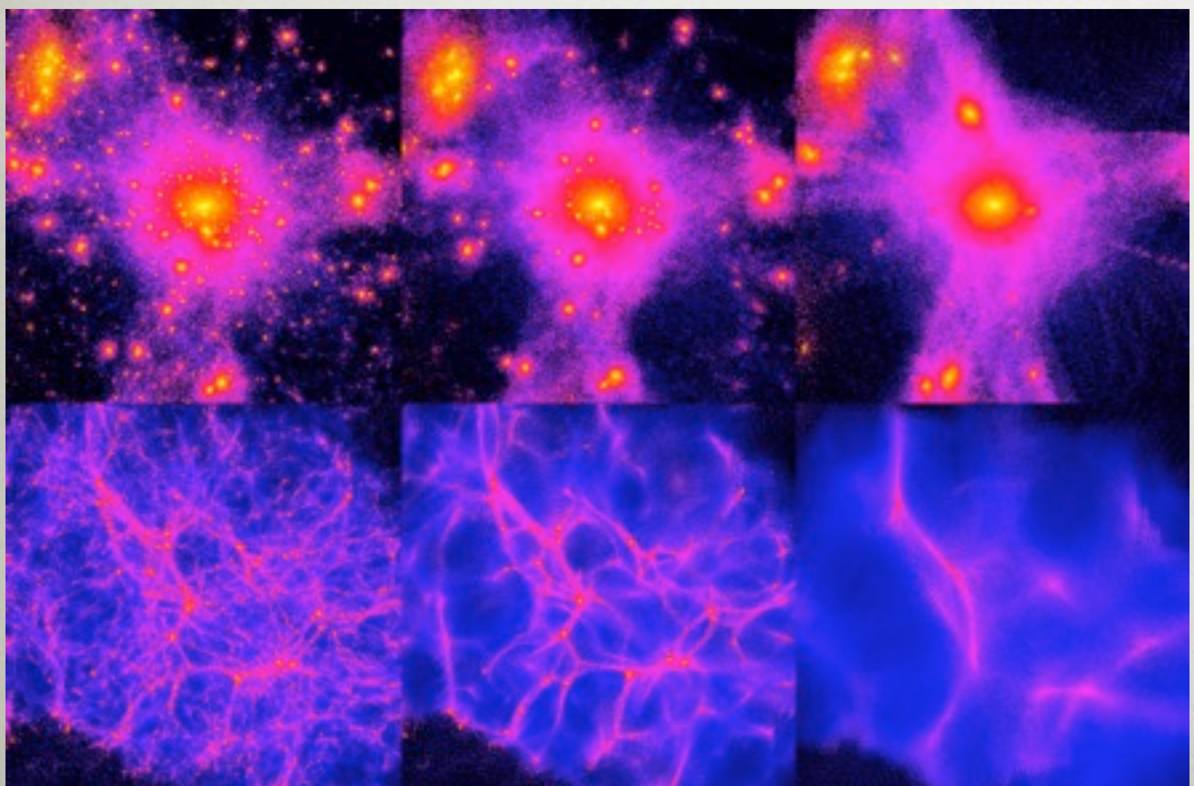




CDM

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

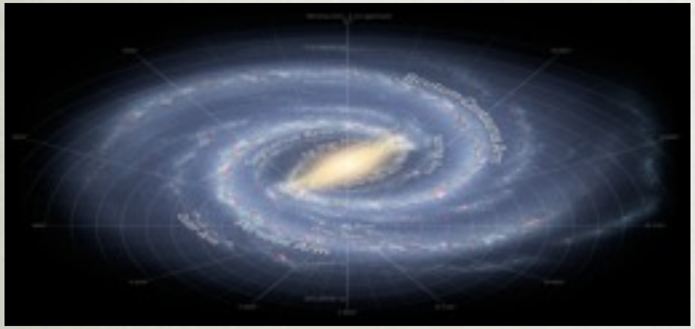
COLD WARM HOT

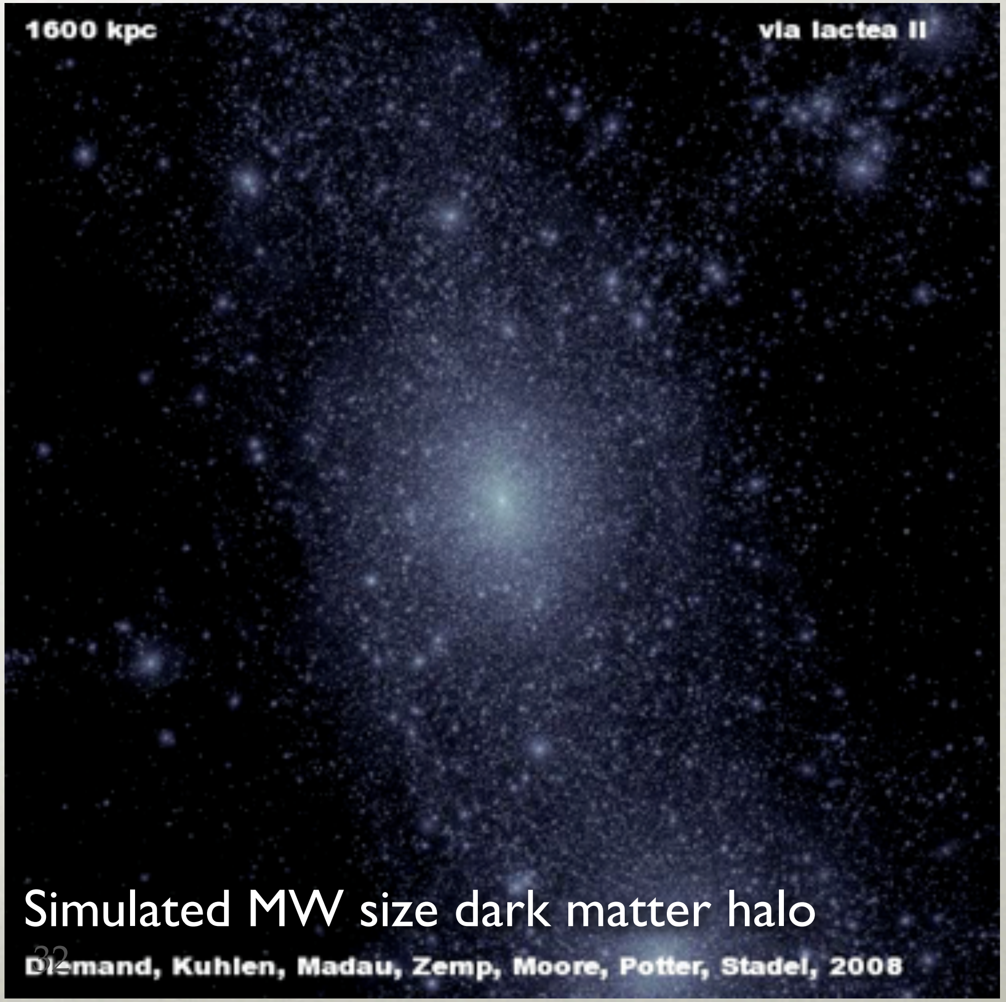


Dark Matter Distribution

- 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



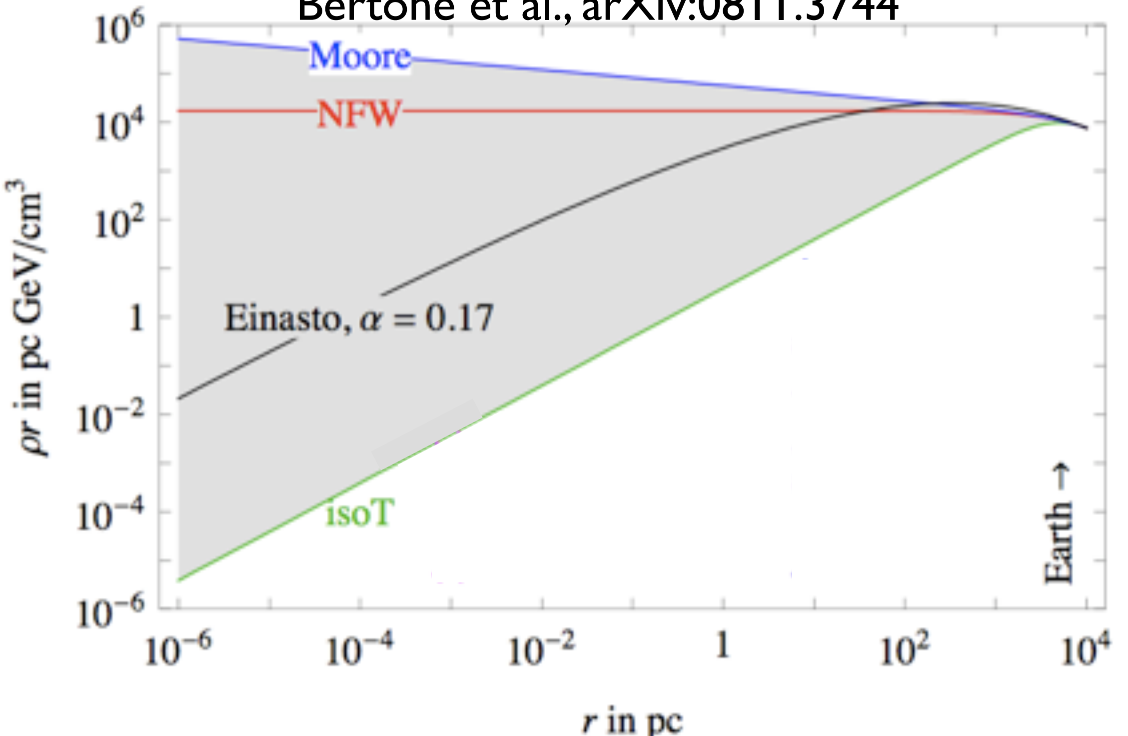


Simulated MW size dark matter halo

Dark Matter Distribution

- Cuspy dark matter profile
- Lots of substructure

Bertone et al., arXiv:0811.3744



NFW profile

Navarro, Frenk, and White 1997

$$\rho(r) = \rho_0 \frac{r_0}{r} \frac{1 + (r_0/a_0)^2}{1 + (r/a_0)^2}$$

$$\rho_0 = 0.3 \text{ GeV/cm}^3$$

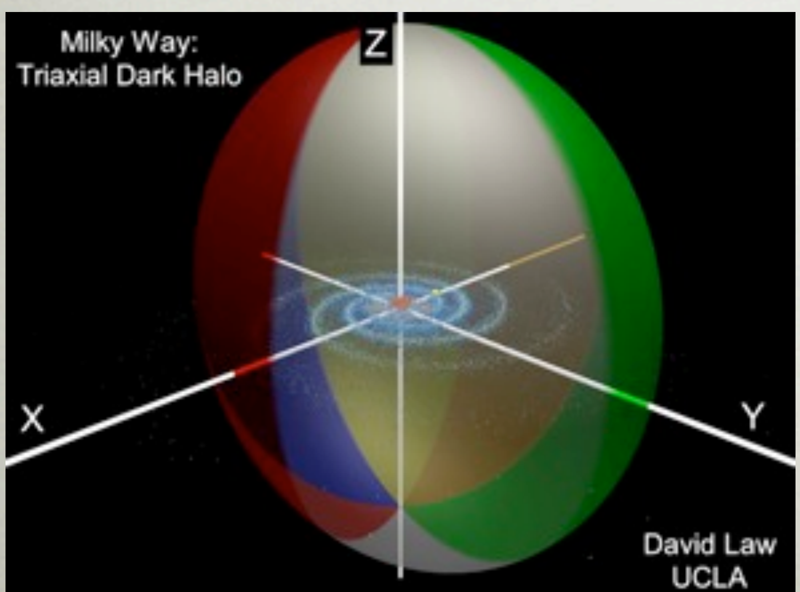
$$a_0 = 20 \text{ kpc}, \ r_0 = 8.5 \text{ kpc}$$

✓ Via Lactea II (Diemand et al 2008) predicts a cuspier profile, $\rho(r) \propto r^{-1.2}$

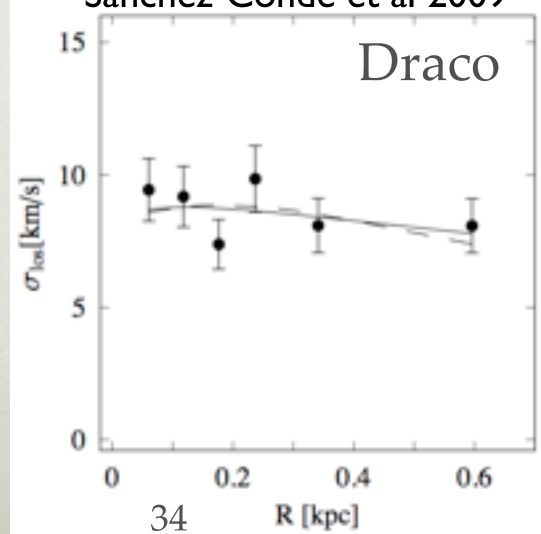
✓ Aquarius (Springel et al 2008) predicts a shallower than r^{-1} innermost profile

Dark Matter Distribution

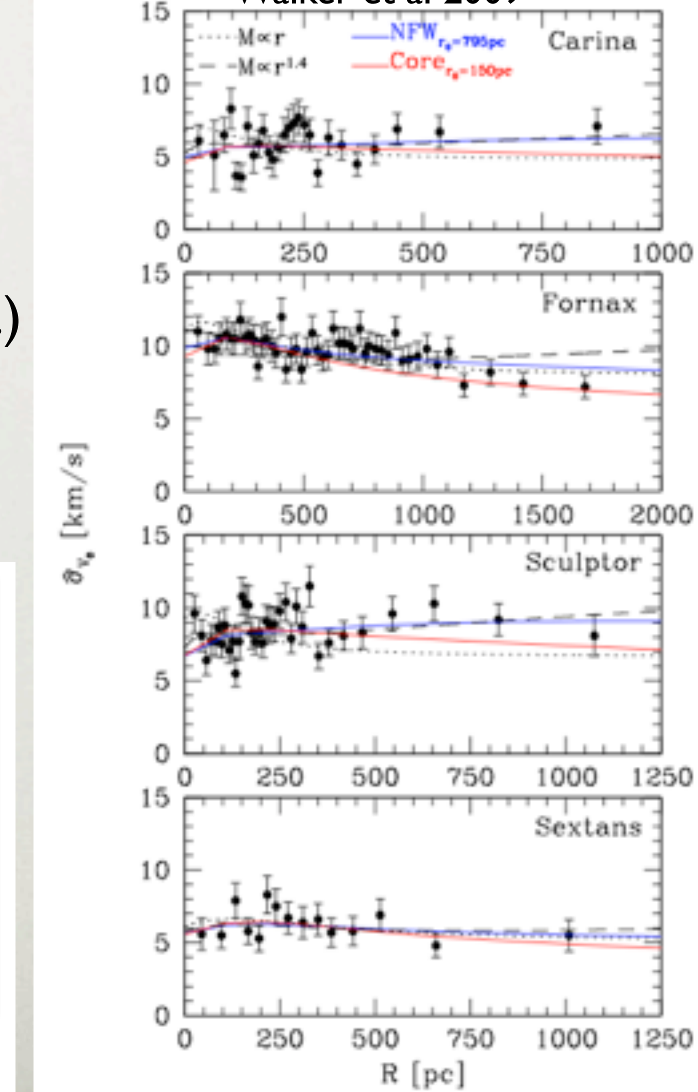
- Strong predictions from ΛCDM on how DM is distributed
- ... but much is still unknown, e.g.:
  - cuspiness of the profile
  - halo shape (spherical, prolate, oblate, triaxial, dark disk, ...)
  - substructure



Sanchez-Conde et al 2009

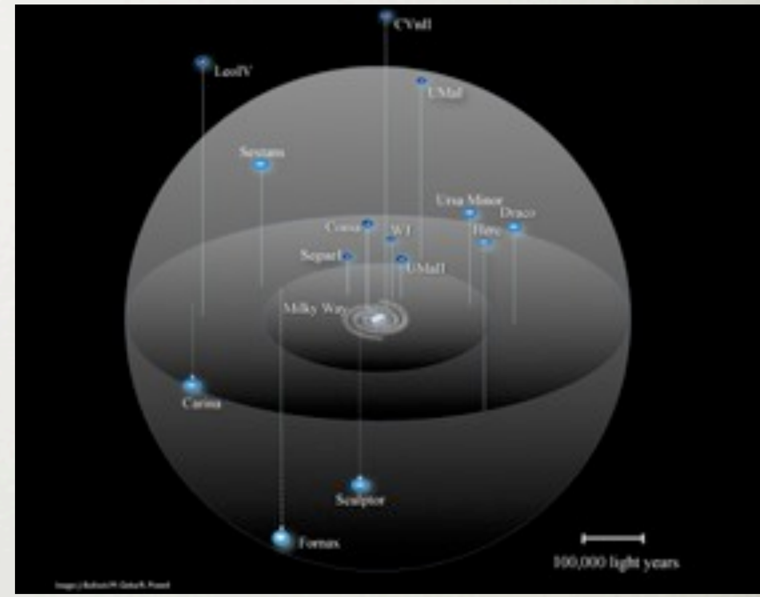


Walker et al 2009



DM Substructures

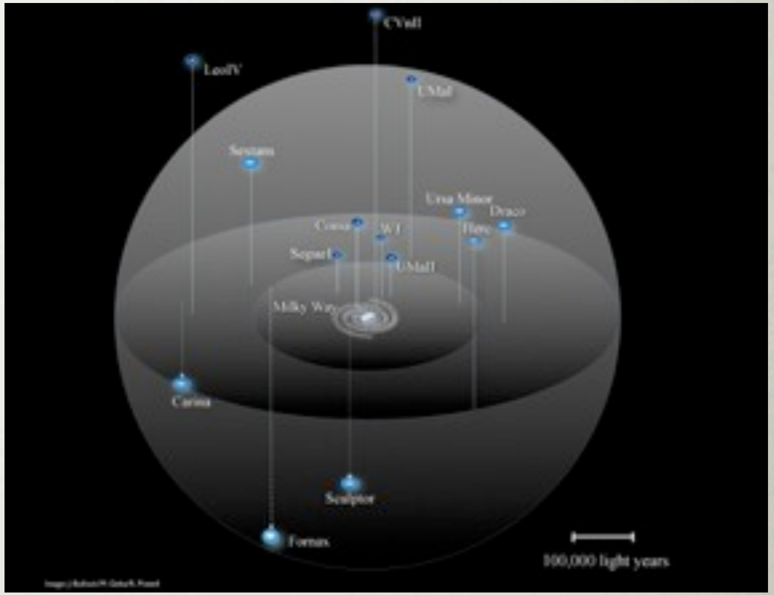
- Optically observed dwarf spheroidal galaxies (dSph): largest clumps predicted by N-body simulation.
  - Very large M/L ratio: 10 to ~> 1000 (M/L ~10 for Milky Way)
  - More promising targets could be discovered by current and upcoming experiments! (SDSS, DES, PanSTARRS, ...)



➡ DM density inferred from the stellar data!

DM Substructures

➡ DM substructures: excellent targets for indirect DM searches!



- Optically observed dwarf spheroidal galaxies (dSph): largest clumps predicted by N-body simulation.
  - Very large M/L ratio: 10 to ~> 1000 (M/L ~10 for Milky Way)
  - More promising targets could be discovered by current and upcoming experiments! (SDSS, DES, PanSTARRS, ...)

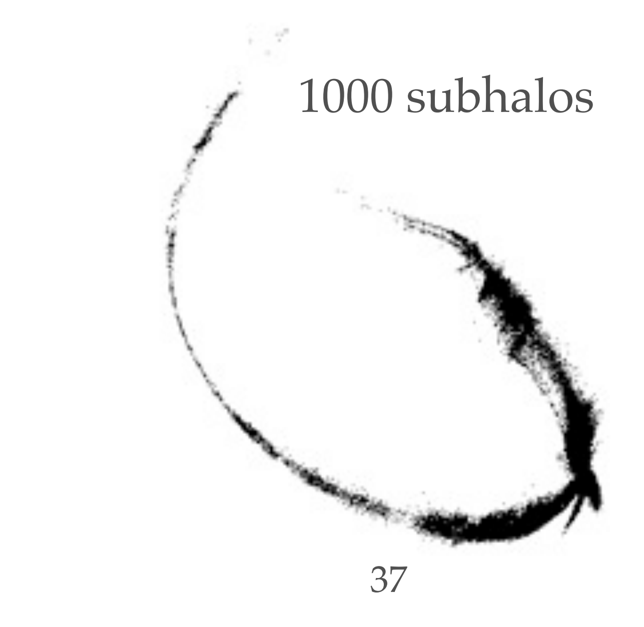
- Never before observed DM substructures:
  - Would significantly shine only in radiation produced by DM annihilation/decay
  - But we don't know where they are!

Testing DM Substructures

Work by Ray Carlberg et al (arXiv:1102.3501)

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

Simulated star stream



Testing DM Substructures

Work by Ray Carlberg et al (arXiv:1102.3501)

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

Star stream north-west of M31 (Andromeda)

Measurements seem to be consistent with lumpy!

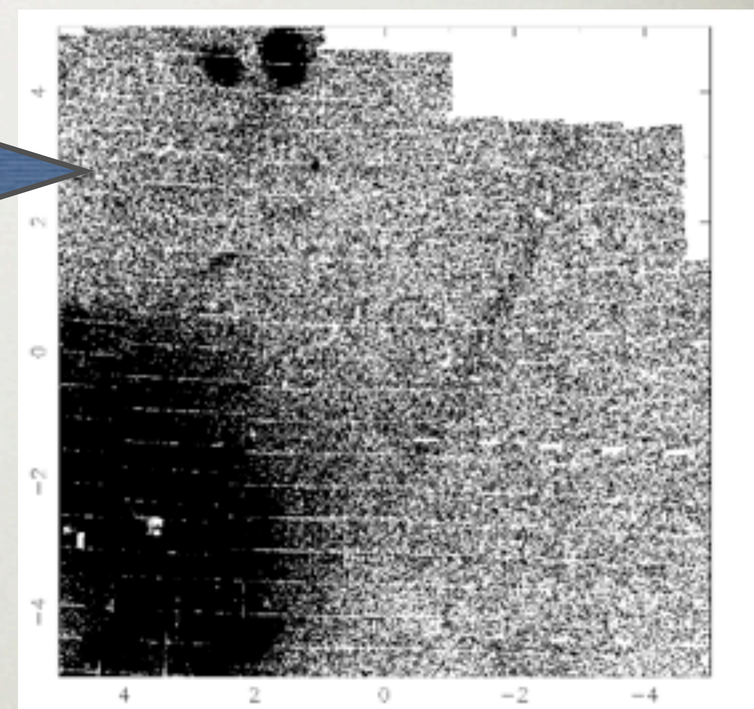
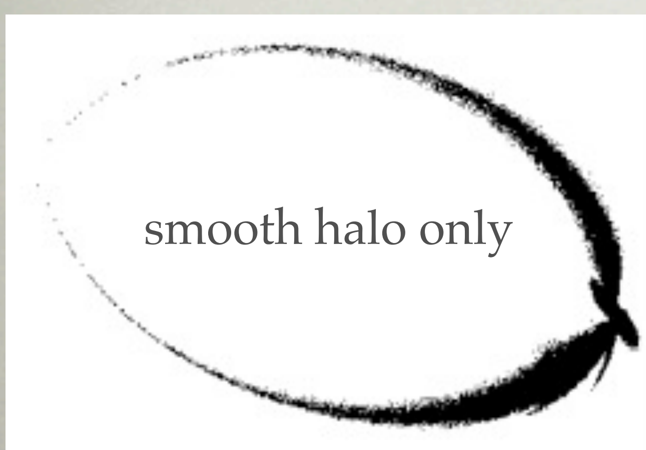
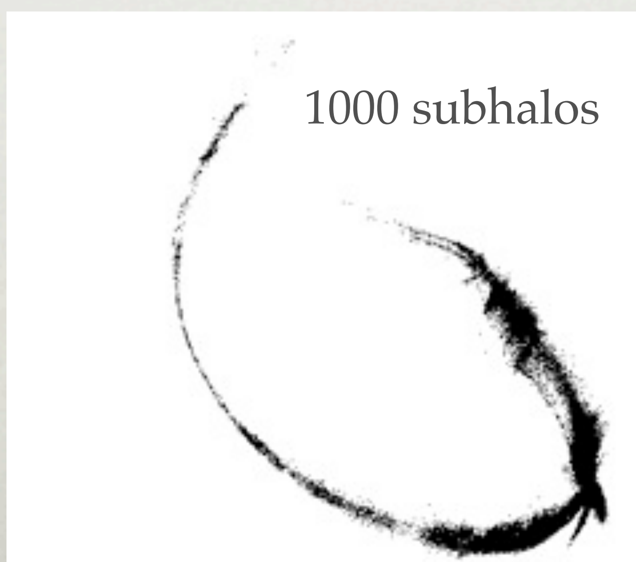


Fig. 1.— The spatial distribution of the [Fe/H]= [-0.6, -2.4] red giant stars in the NW region of M31. A full field version is presented in Richardson et al. (2011) The image is 10° across in the tangent projection co-ordinates, which are centered in the exact middle of this map.

Simulated star stream

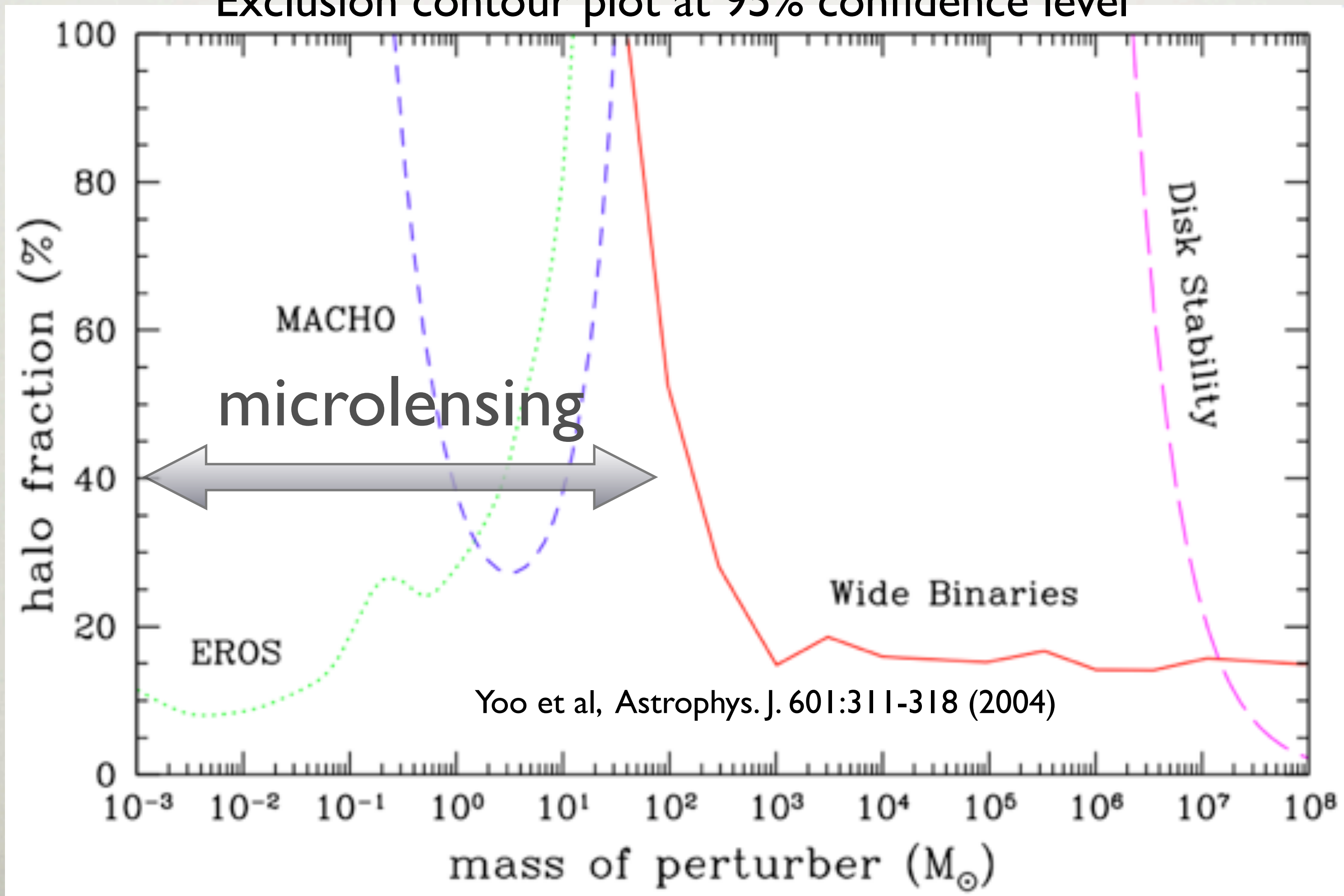




MACHOs

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

Exclusion contour plot at 95% confidence level



MOND

- Modified Newtonian Dynamics. 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 ($1.2 \times 10^{-10}\,\mathrm{ms}^{-2}$, determined by observations):

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

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

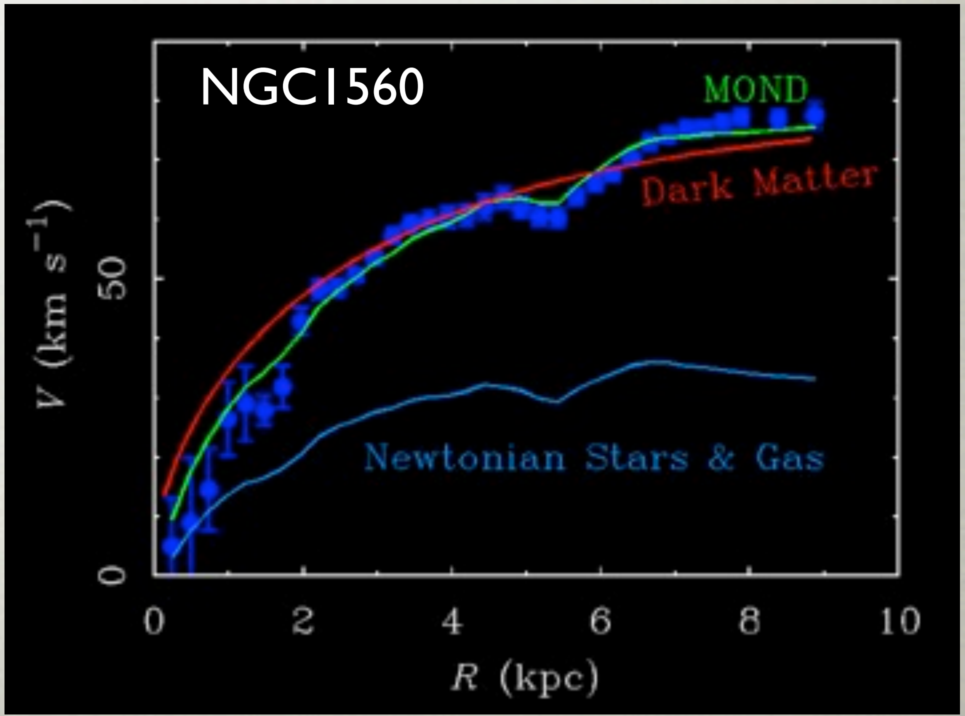
total mass

flat rotation velocity

$$a_0 G M_b = V_f^4$$

- MOND fails at larger scales, galaxy clusters

Begeman et al 1991
Sellwood et al 2005



For a review:
Sanders and McGaugh, Ann.Rev.Astron.Astrophys.40:263-317,2002.

MOND

- Modified Newtonian Dynamics. 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 ($1.2 \times 10^{-10}\,\mathrm{ms}^{-2}$, determined by observations):

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

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

total mass

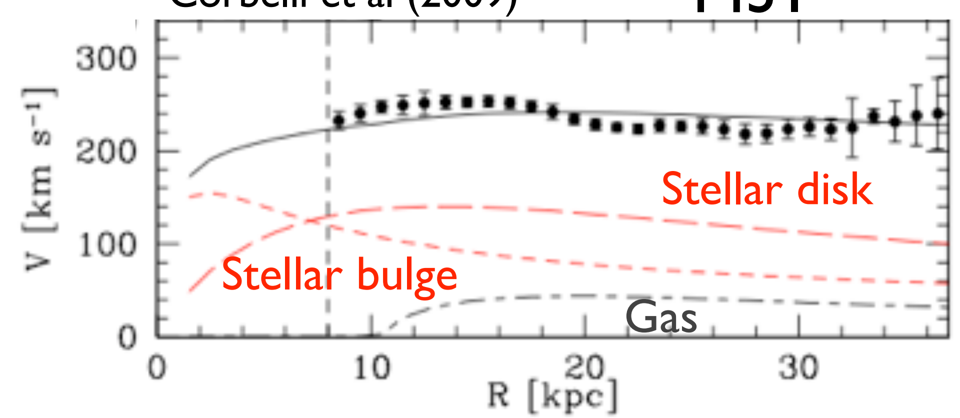
flat rotation velocity

$$\underbrace{}_{}a_0 G M_b = V_f^4$$

- MOND fails at larger scales, galaxy clusters

Corbelli et al (2009)

M31



For a review:
Sanders and McGaugh, Ann.Rev.Astron.Astrophys.40:263-317,2002.

MOND

- Modified Newtonian Dynamics. 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 ($1.2 \times 10^{-10}\,\mathrm{ms}^{-2}$, determined by observations):

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

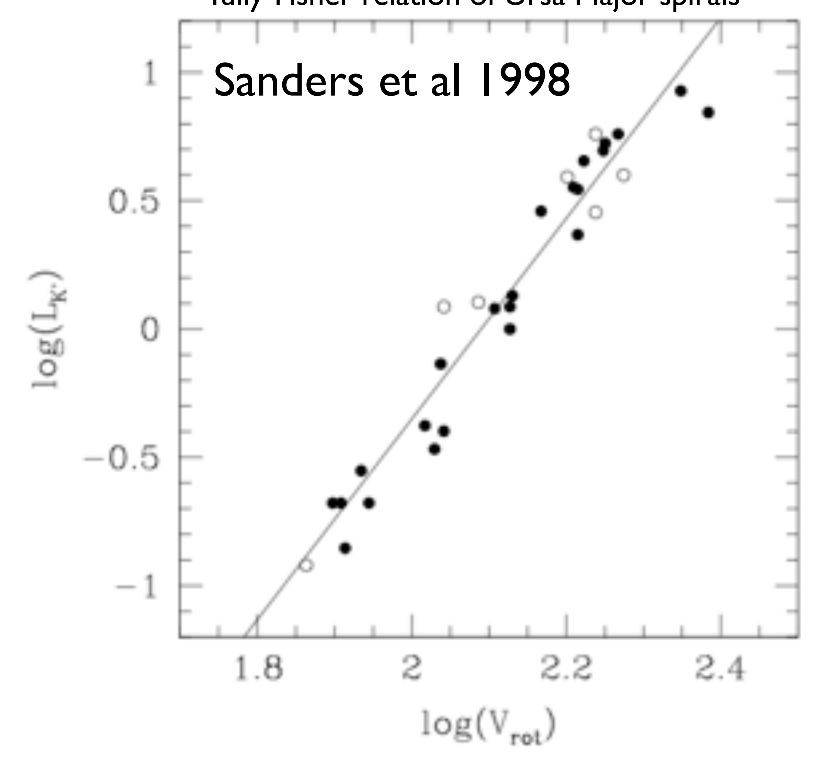
  $a \ll a_0$ modified dynamics $\quad \frac{a^2}{a_0} = \frac{MG}{r^2}$

total mass

flat rotation velocity

$$a_0 G M_b = V_f^4$$

Tully-Fisher relation of Ursa Major spirals



- MOND fails at larger scales, galaxy clusters

For a review:
Sanders and McGaugh, Ann.Rev.Astron.Astrophys.40:263-317,2002.

Summary

- 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...