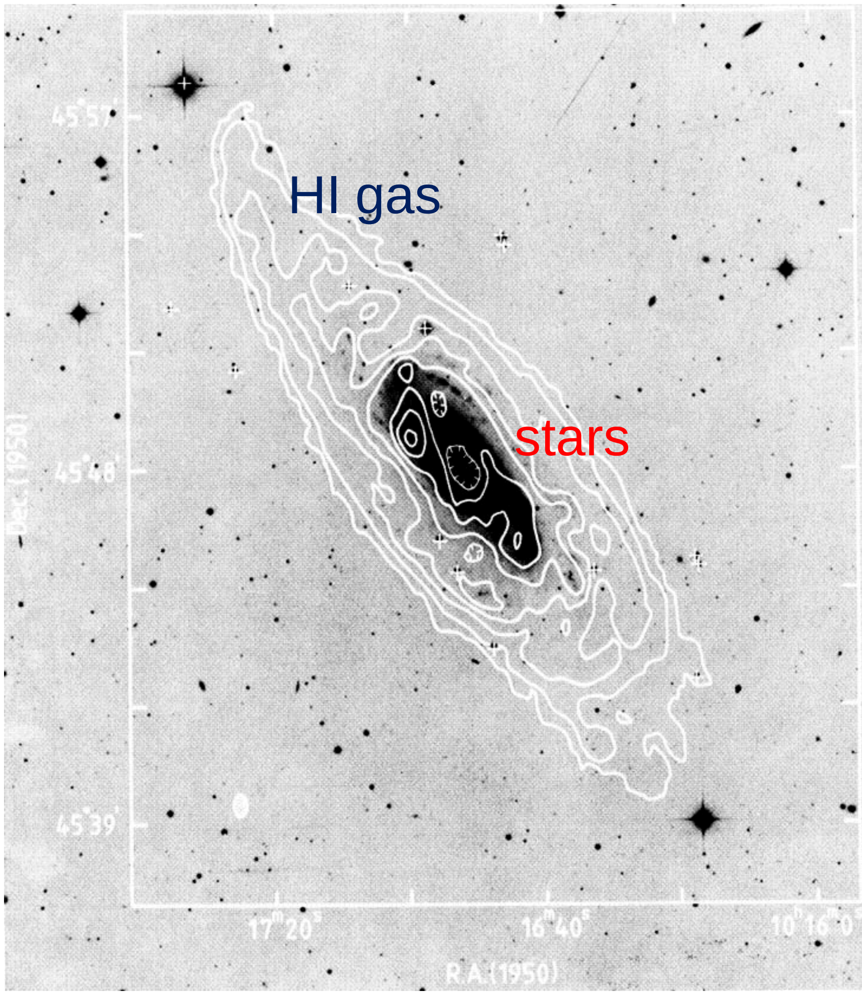
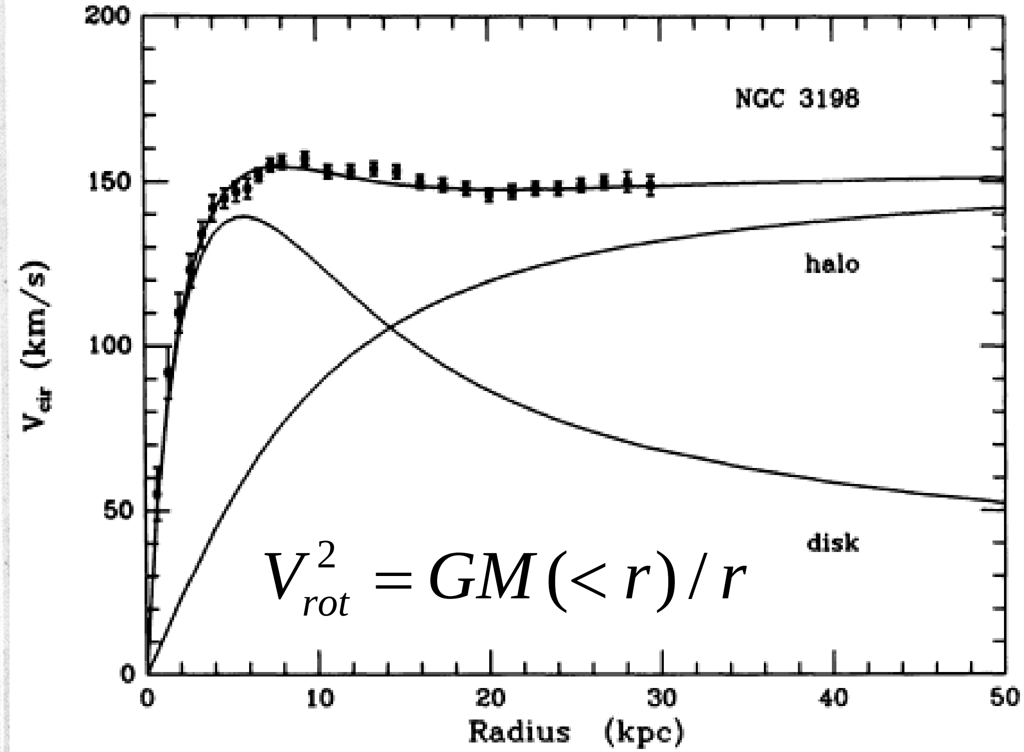
Dark matter structure in galactic and sub-galactic scales

Masashi Chiba
(Tohoku University, Sendai)

What is a galactic scale?





stars

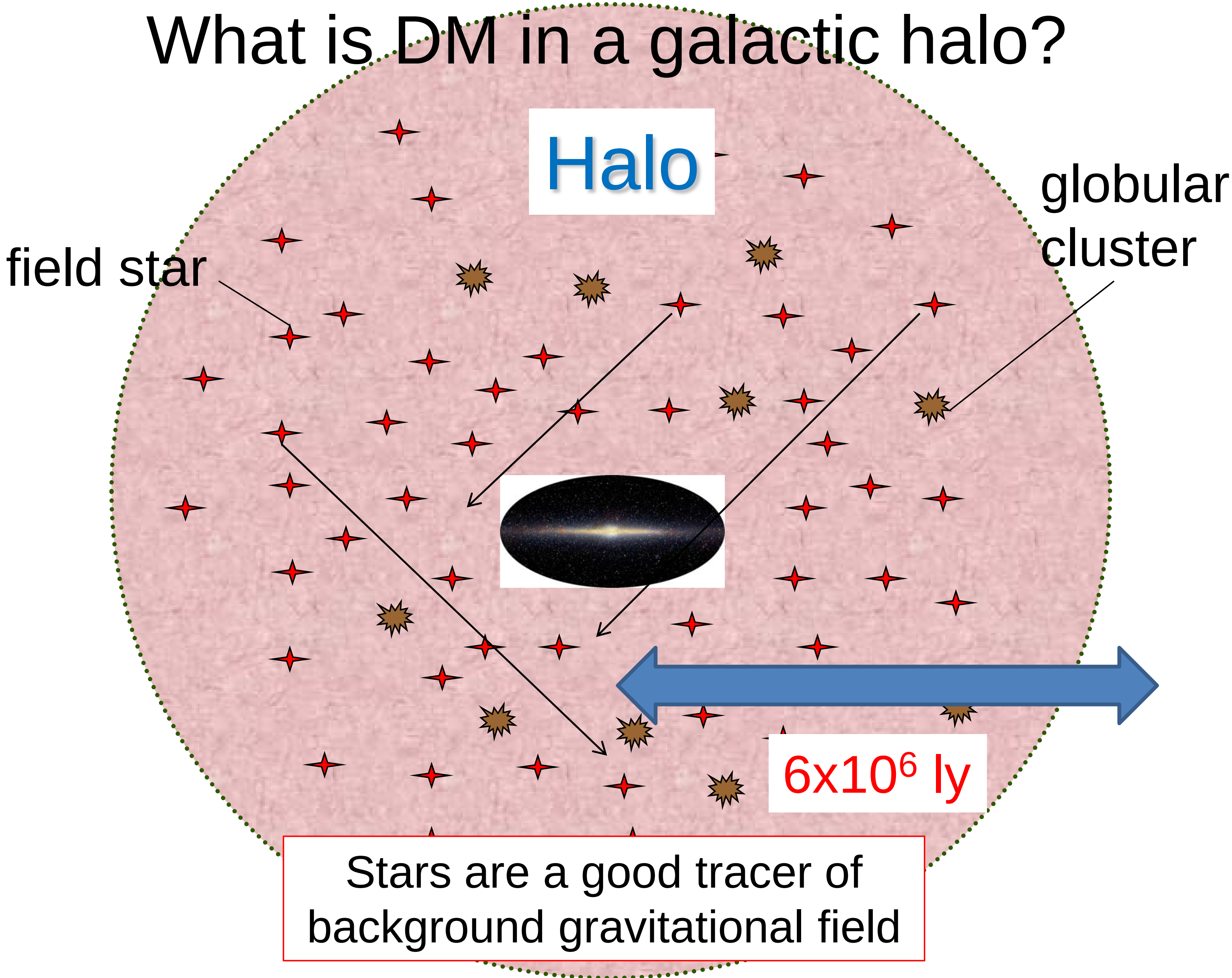
~ 3 x 10^4 light year

gas

~ 10^5 ly

Evidence for DM from rotation curve

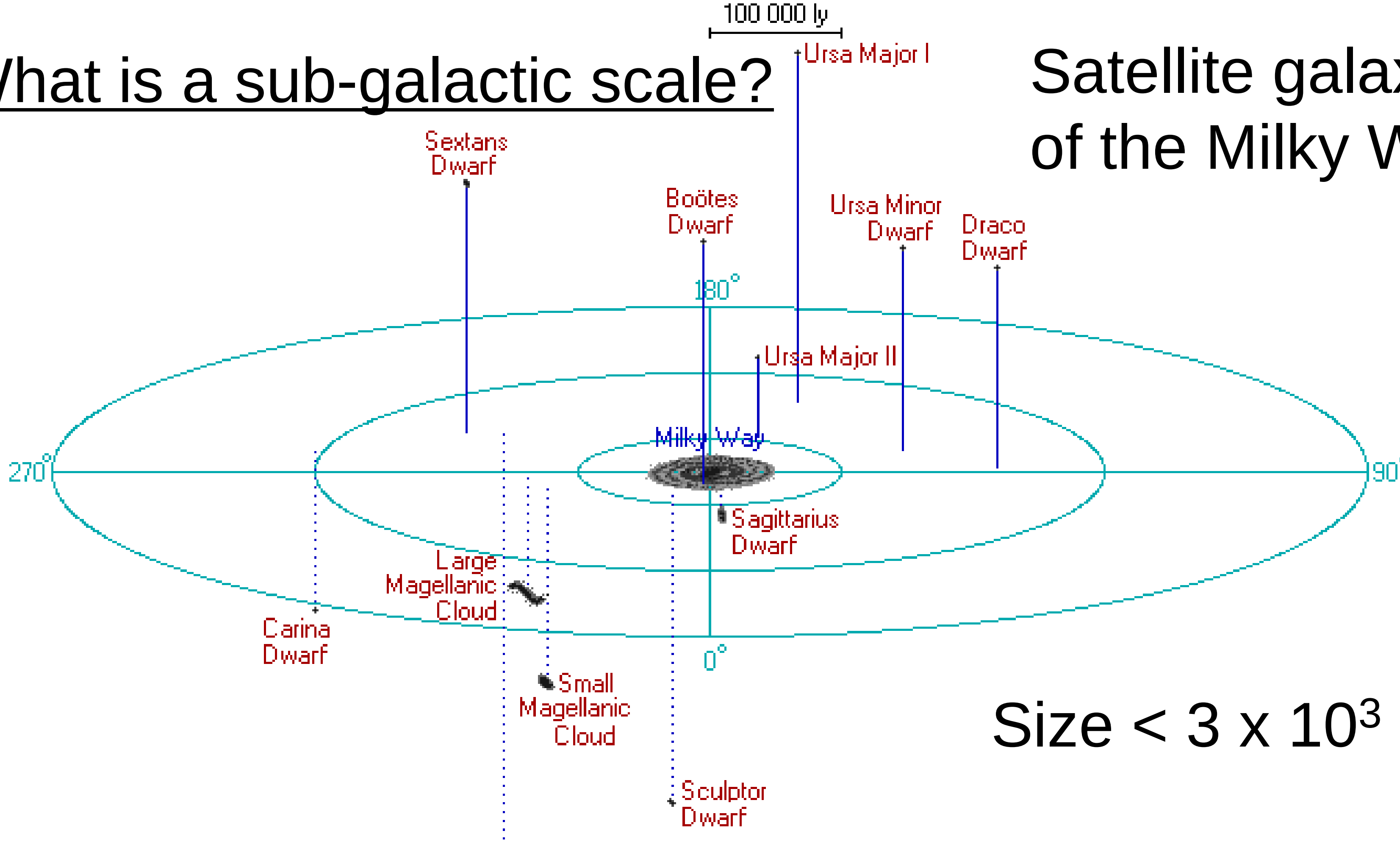
What is DM in a galactic halo?



Stars are a good tracer of background gravitational field

What is a sub-galactic scale?

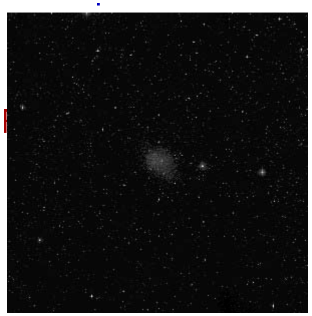
Satellite galaxies of the Milky Way

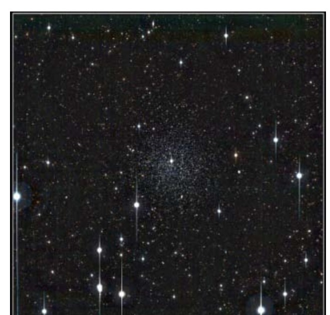


Size < 3 x 10^3 ly


Scl


Car

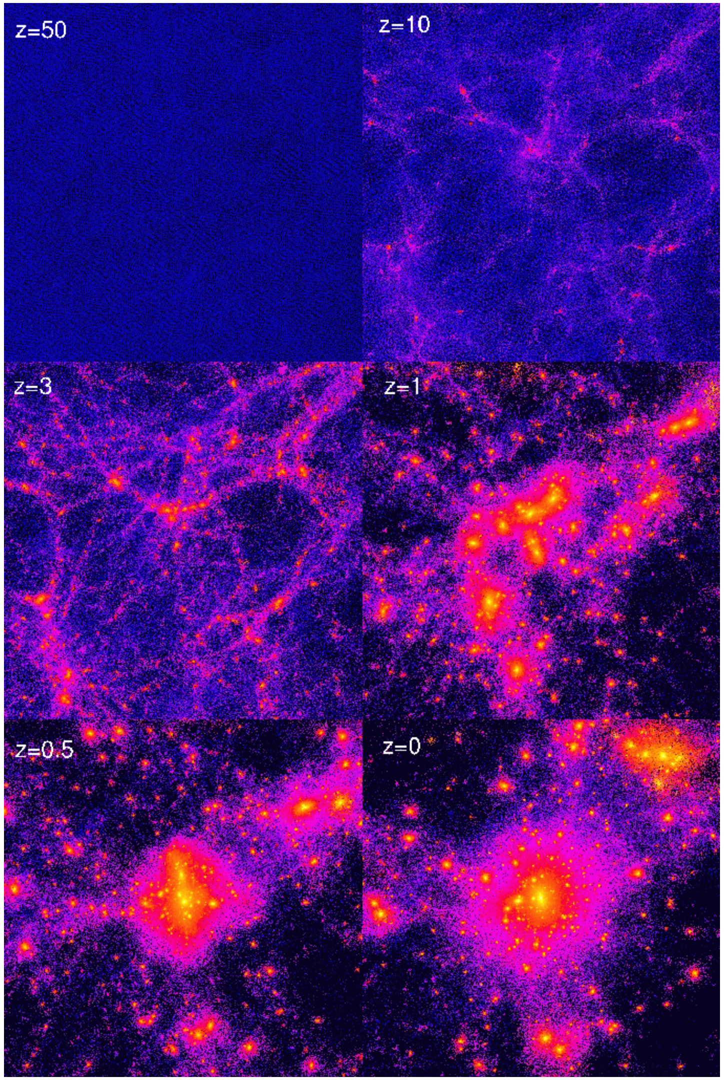

For


Leo II

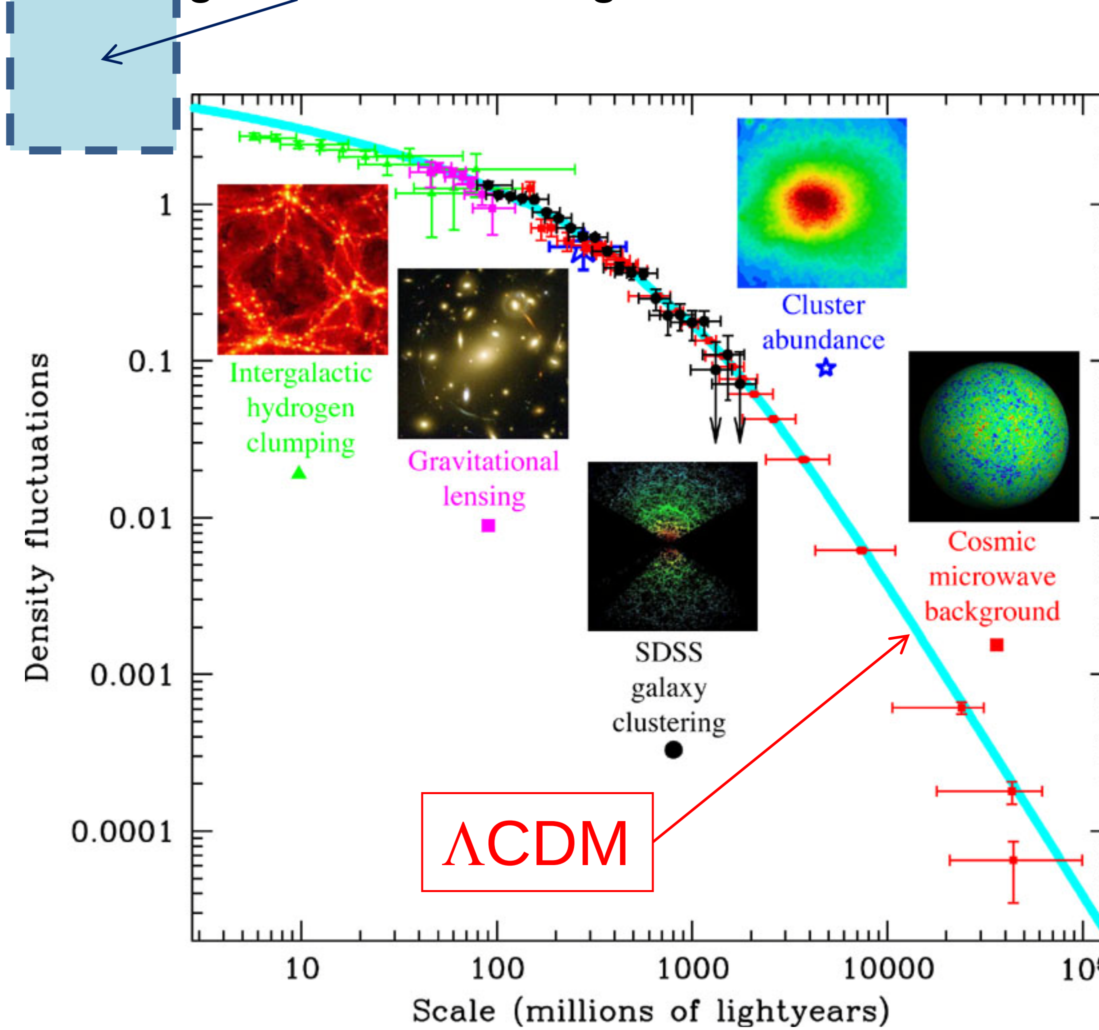
Leo I


Phe

Cold Dark Matter (CDM) is successful for explaining large-scale structures



galactic and sub-galactic scales?



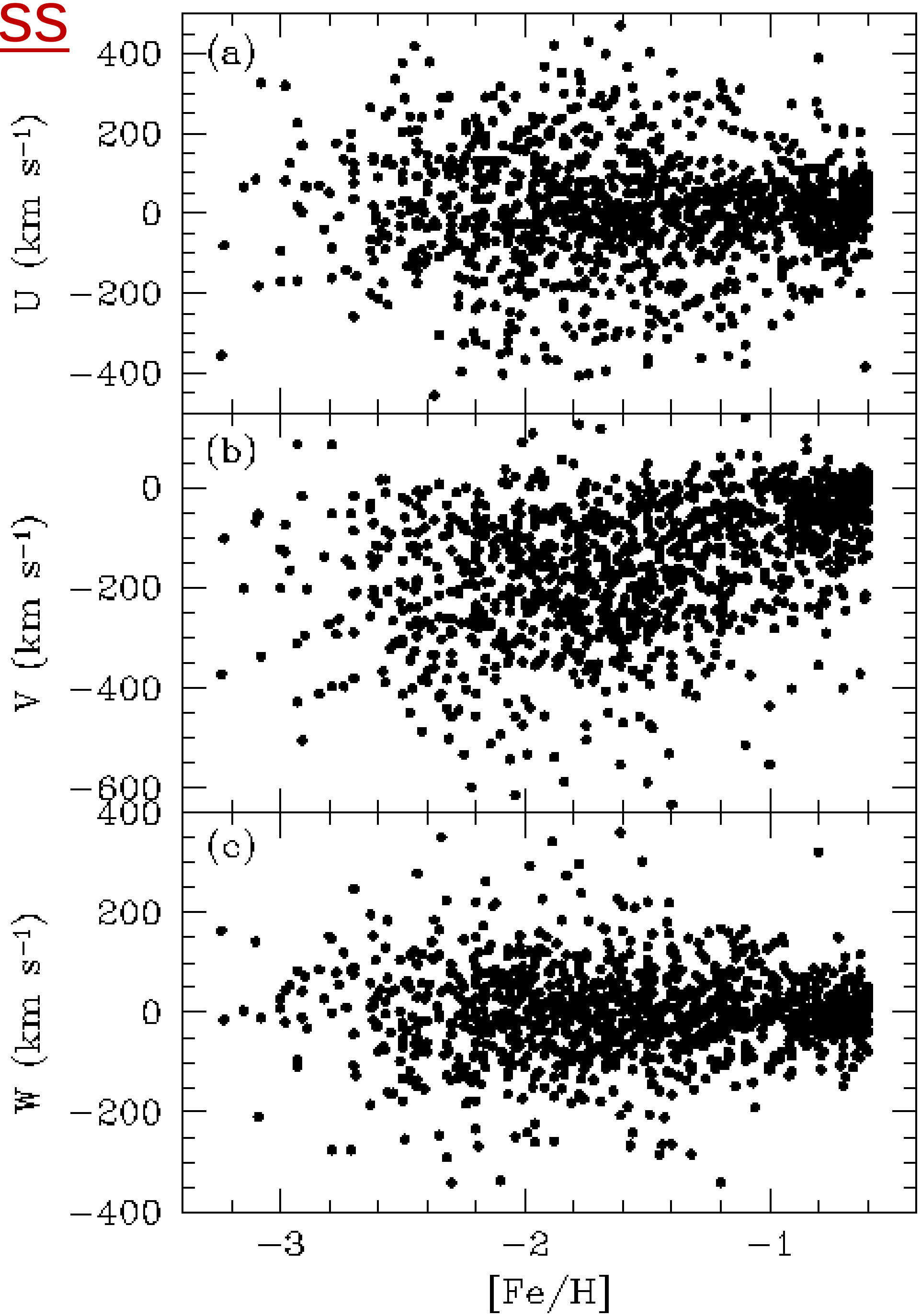
DM in a galactic scale

Total mass

V_R

V_ϕ
-220

V_z

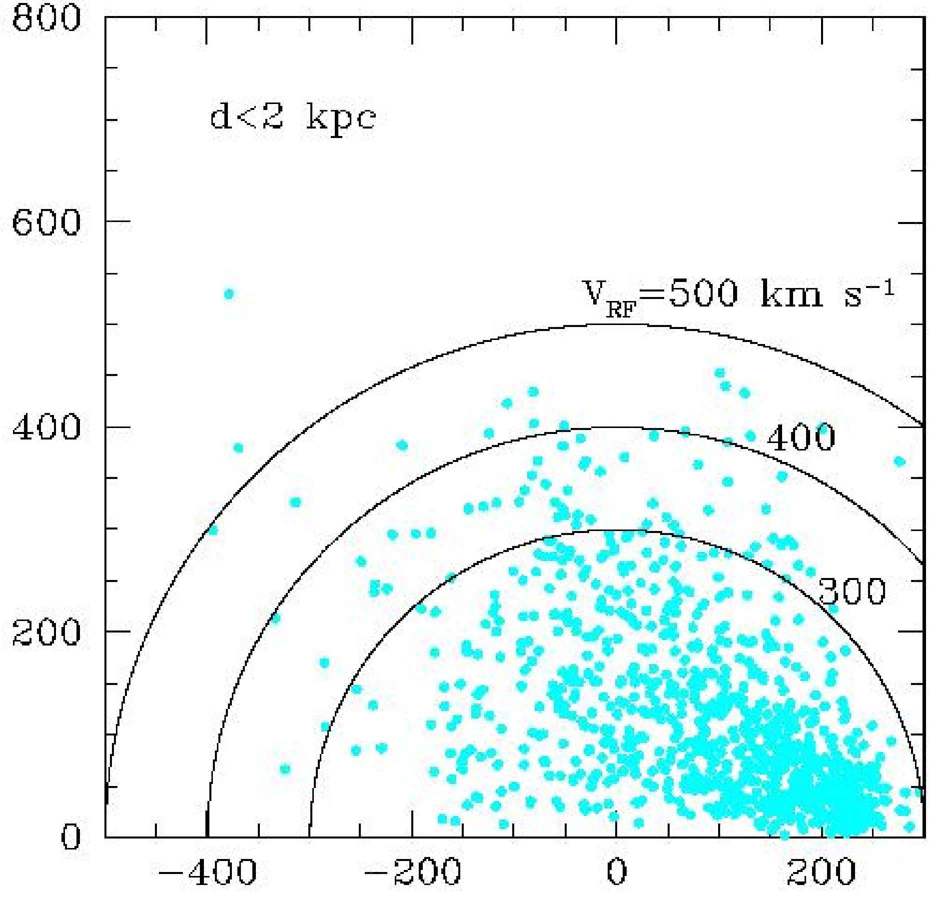


Velocities of stars near the Sun

Halo stars show velocity anisotropy
$(\sigma_R, \sigma_\phi, \sigma_z)$
$\approx$(150, 100, 100) km/s

Metallicity

Velocities of stars near the Sun



$(V_R^2+V_z^2)^{1/2}$ (km/s)

V_ϕ (km/s)

⇒ Escape velocity near the Sun: V_{esc}=500~550km/s

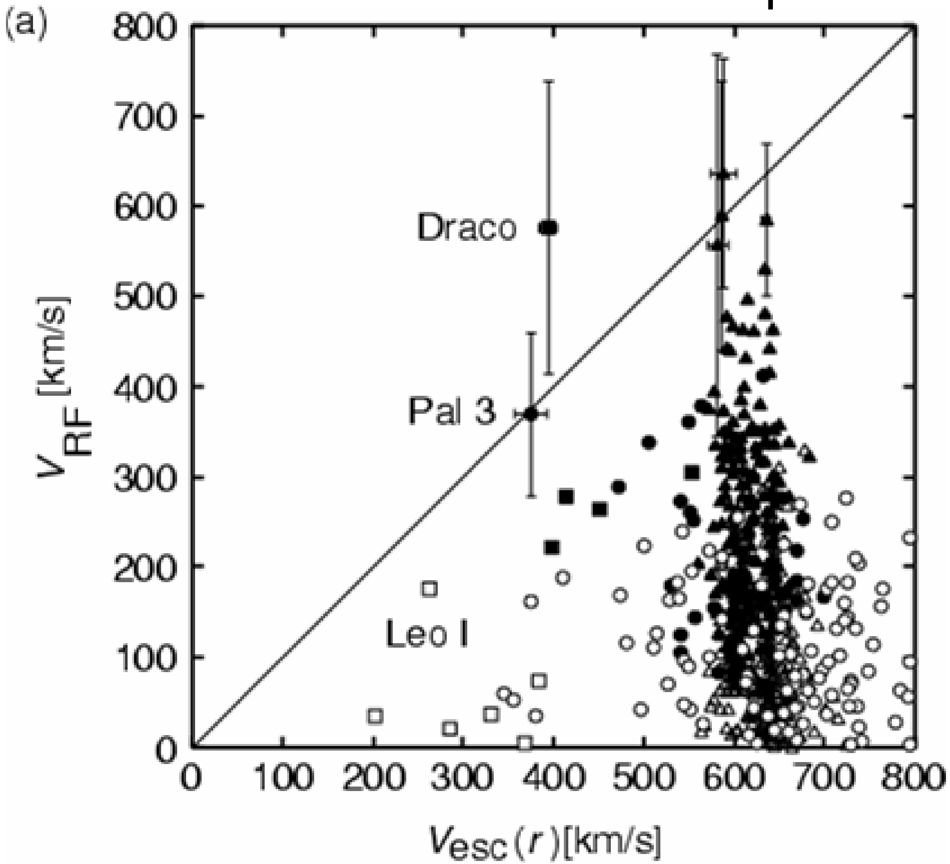
⇒ Limits on a gravitational potential Φ at $R=R_{sun}$

With more distant stars

Sakamoto+2003

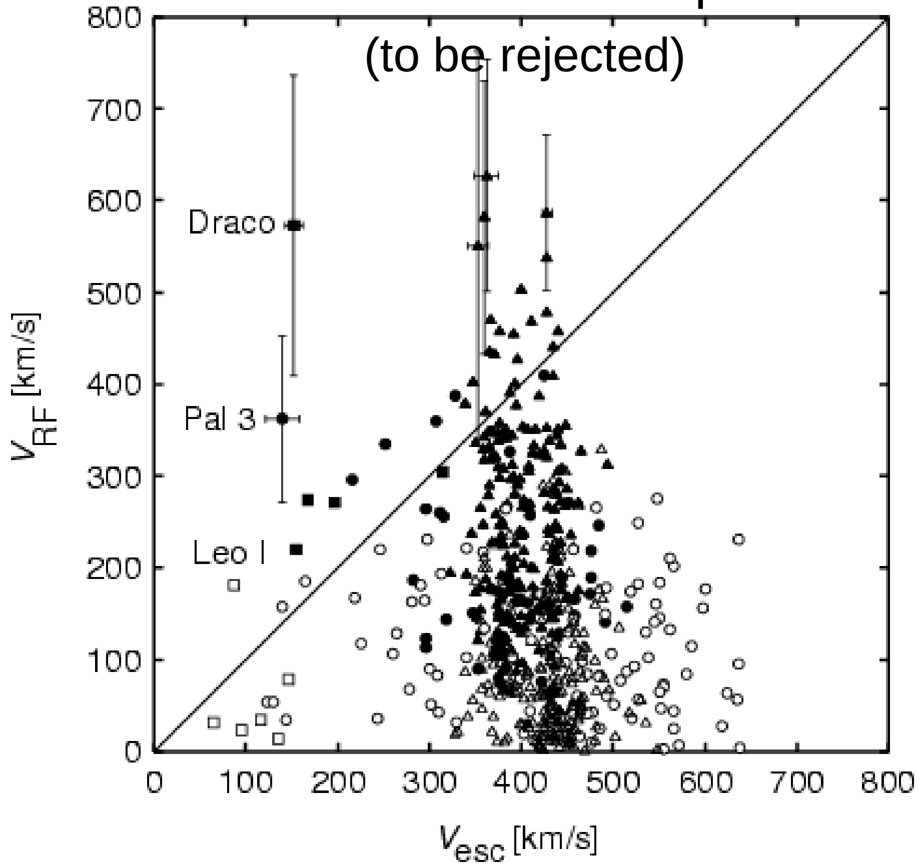
Rest-frame velocity: $V_{RF} \leq V_{esc} = (2\ \Phi)^{1/2}$

Model A: a = 195 kpc



Model B: a = 20 kpc

(to be rejected)



Total mass = 2×10^{12} M_{sun} over ~ 200 kpc

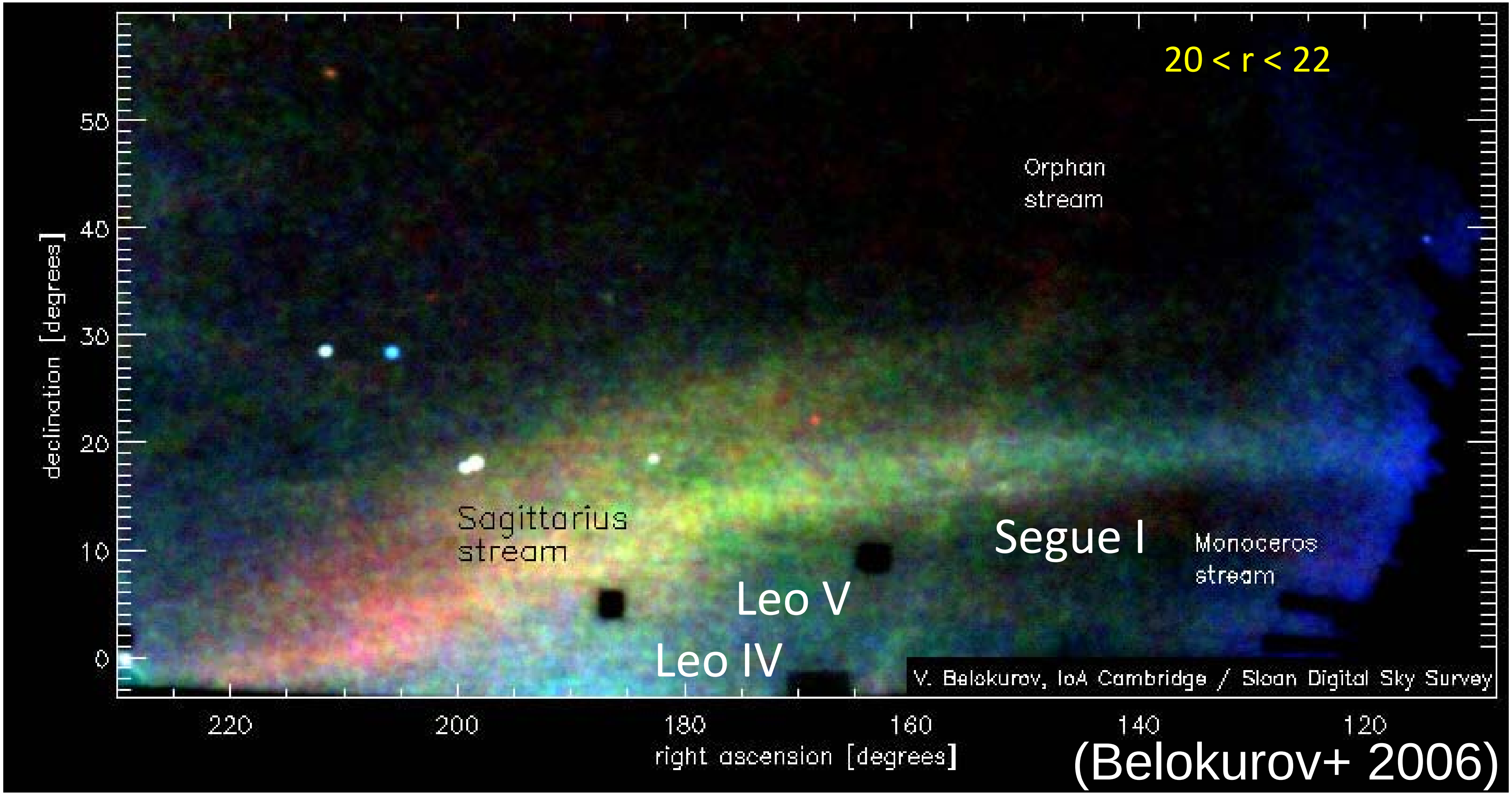
Visible mass = 10^{11} M_{sun} over ~ 15 kpc

⇒ We see only 10 % of the total mass

Shape

Stellar stream as tidally disrupted dwarf galaxy

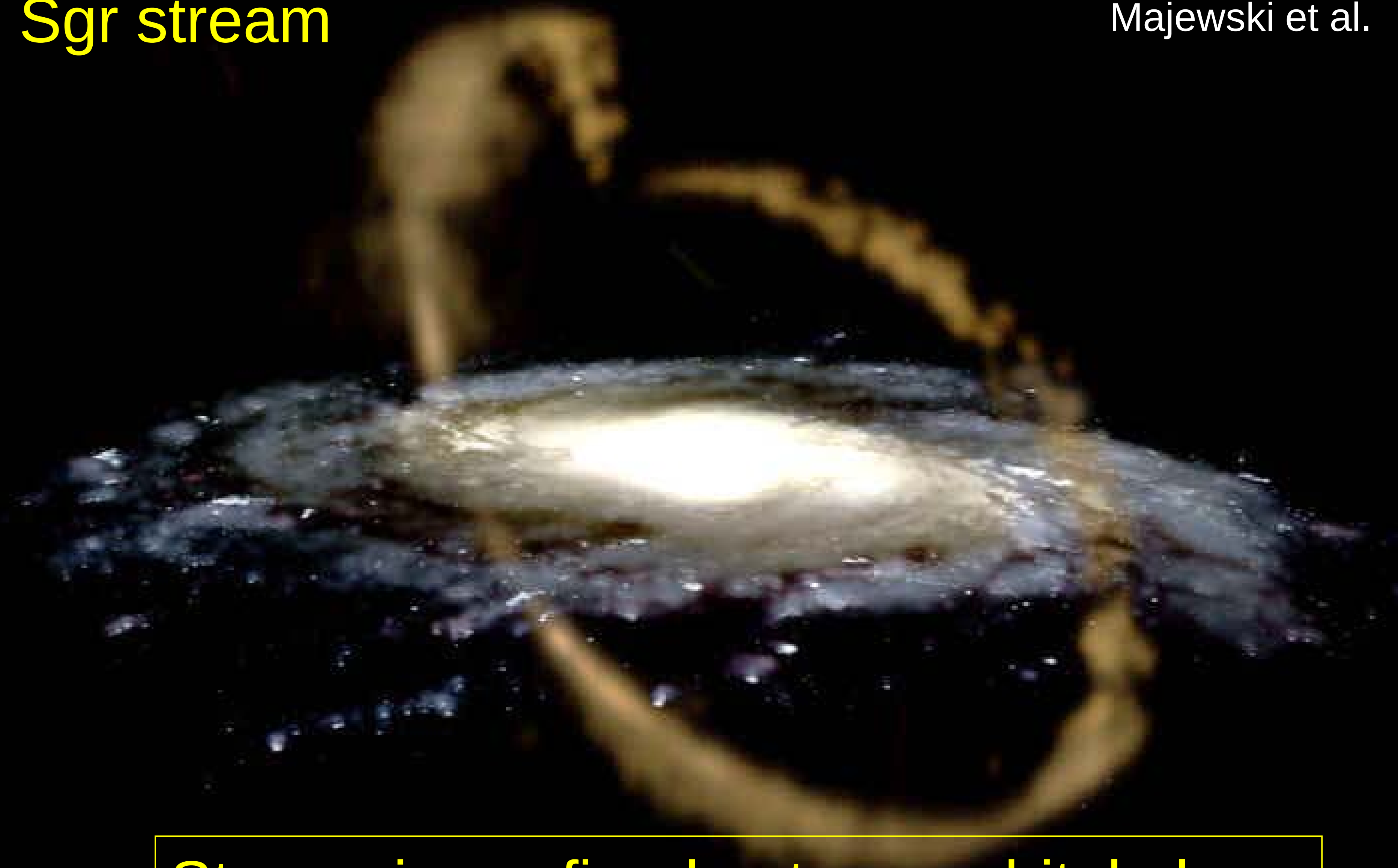
'Field of Streams' seen in star distribution



(Belokurov+ 2006)

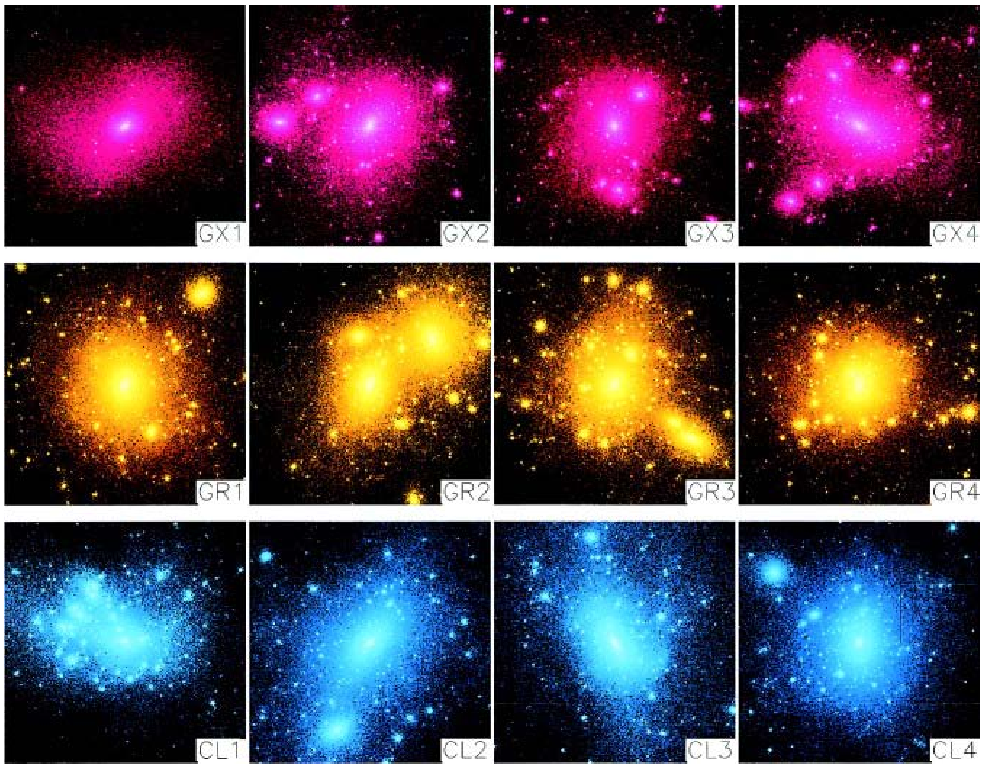
Sgr stream

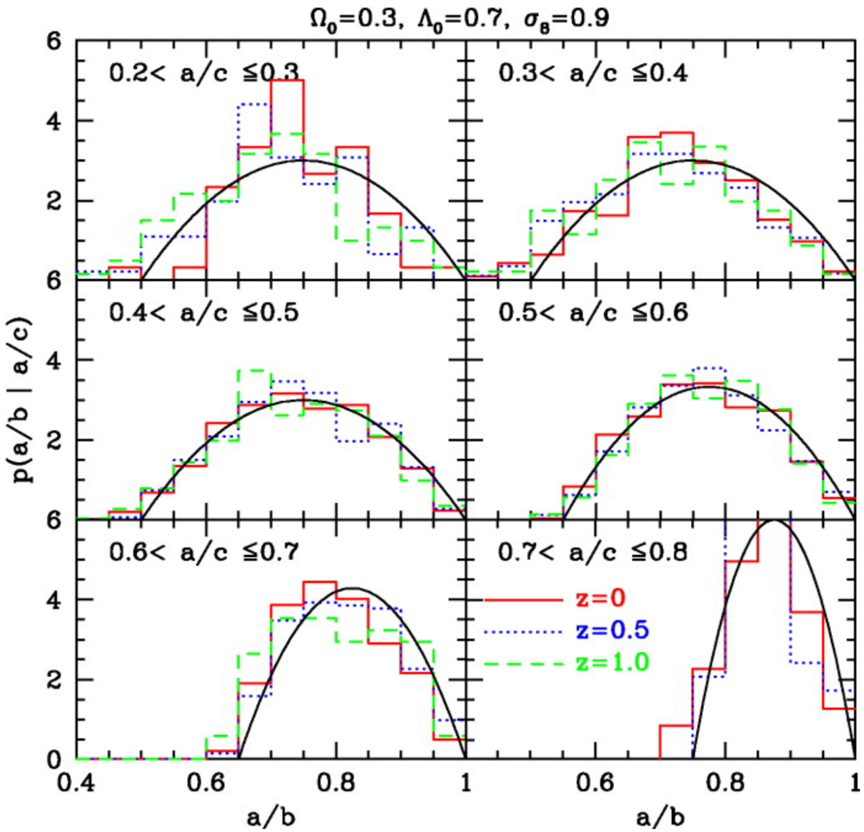
Majewski et al.



Stream is confined onto an orbital plane
⇒ round dark halo at $15 < r < 60$ kpc

However, CDM halos are generally triaxial / prolate.
(Jing & Suto 2000, 2002)

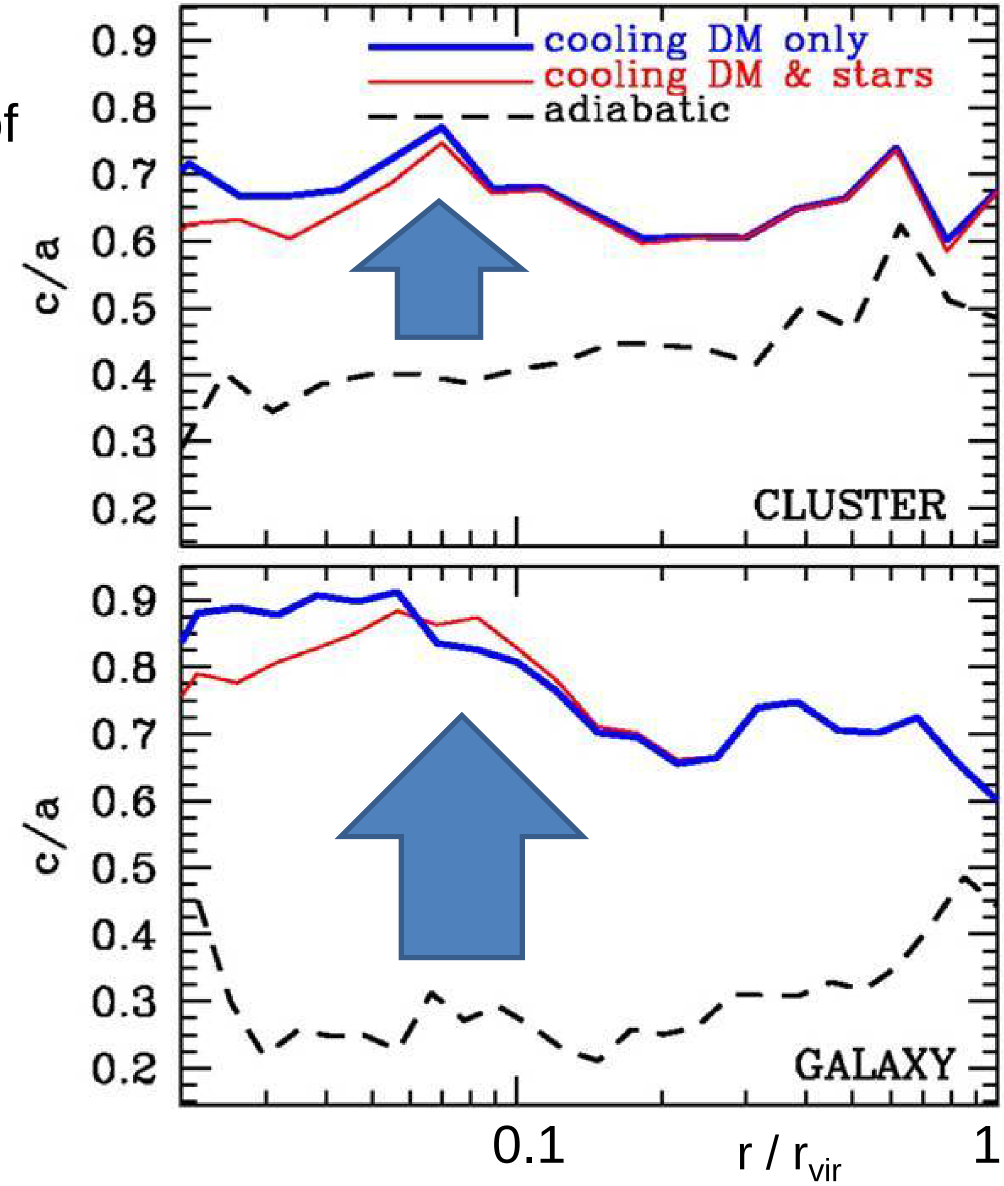


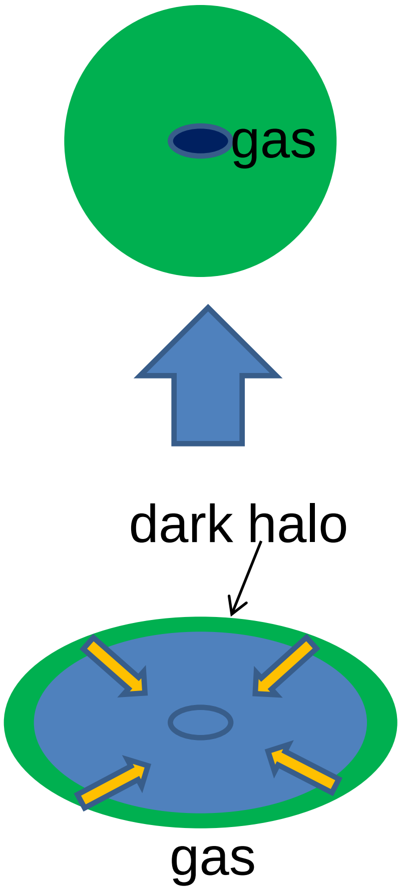


Hayashi+07: $(c/a)_\Phi$ = 0.72, $(b/a)_\Phi$ = 0.78 in central parts

Gas cooling makes CDM halos rounder.
(Kazantzidis et al. 2004, ApJ, 611, L73)

Axial ratio of a dark halo

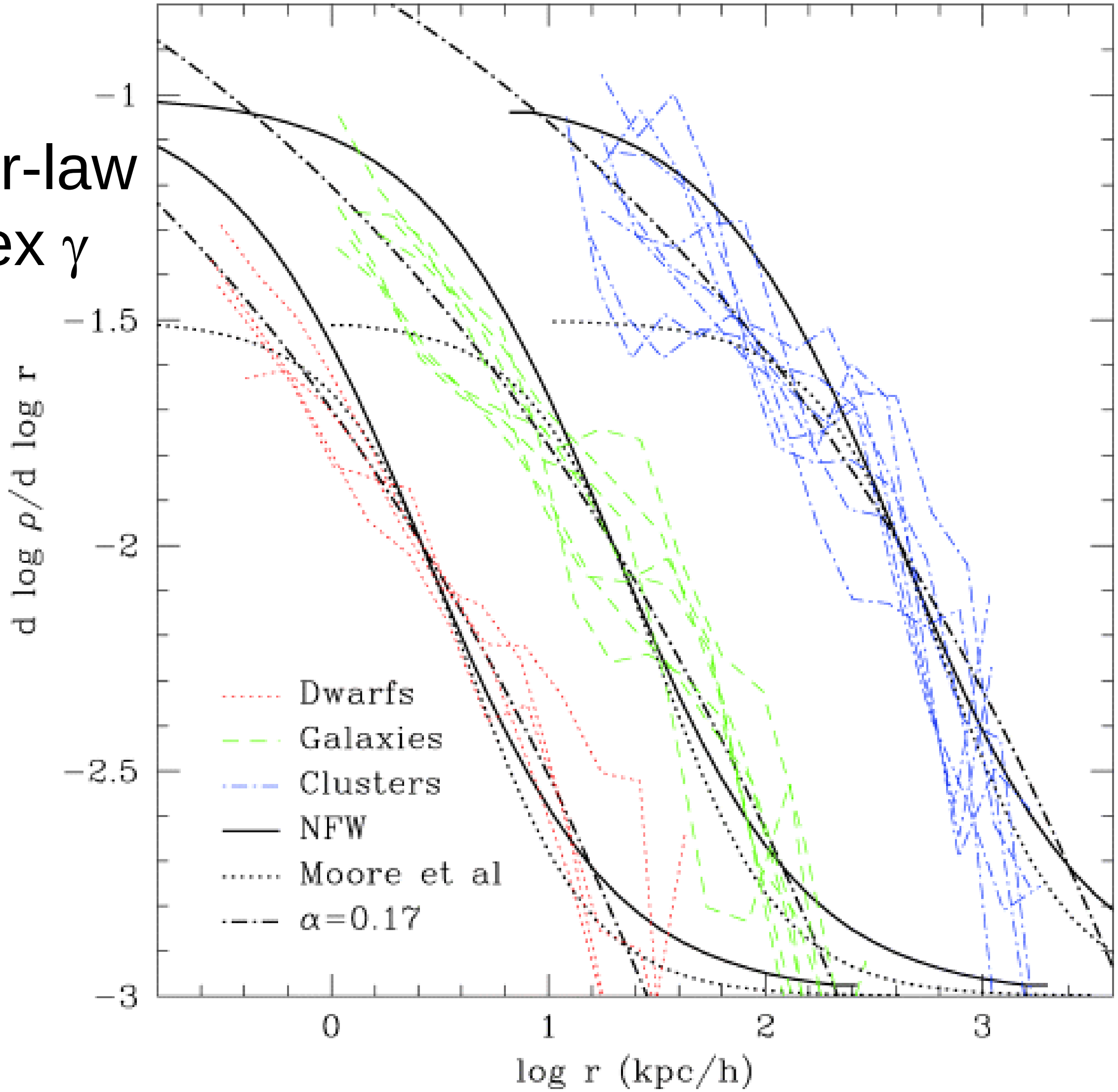




Density profile

CDM halos have cuspy central density profile

Power-law Index γ



$\rho \propto r^{-\gamma}$

at inner parts

$\gamma = 1$: NFW

$\gamma = 1.5$: Moore et al.

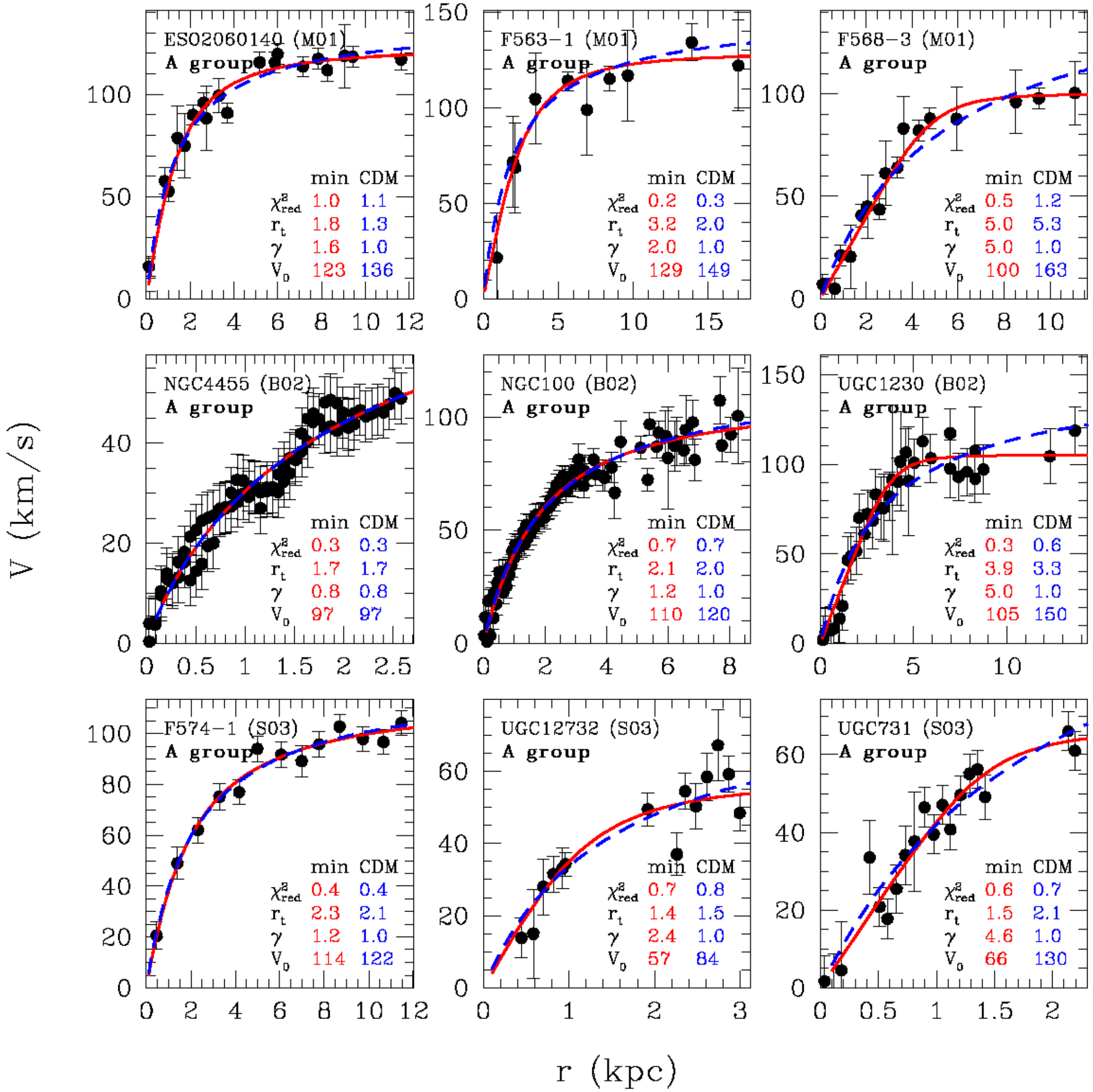
No universal γ

$1 < \gamma < 1.5$

Einasto profile:

$$\ln \rho(r)/\rho_{-2} = (-2/\alpha)\left[(r/r_{-2})^{\alpha} - 1\right]$$

Fitting to rotation curves of LSB galaxies (Hayashi et al. 2004, MNRAS, 355, 794)



$$V(r) = V0 / (1 + x^{-\gamma})^{1/\gamma}$$
$$x \equiv r / r0$$

Obs: $0 < \gamma < 5$
Fitting with $\gamma \sim 1$

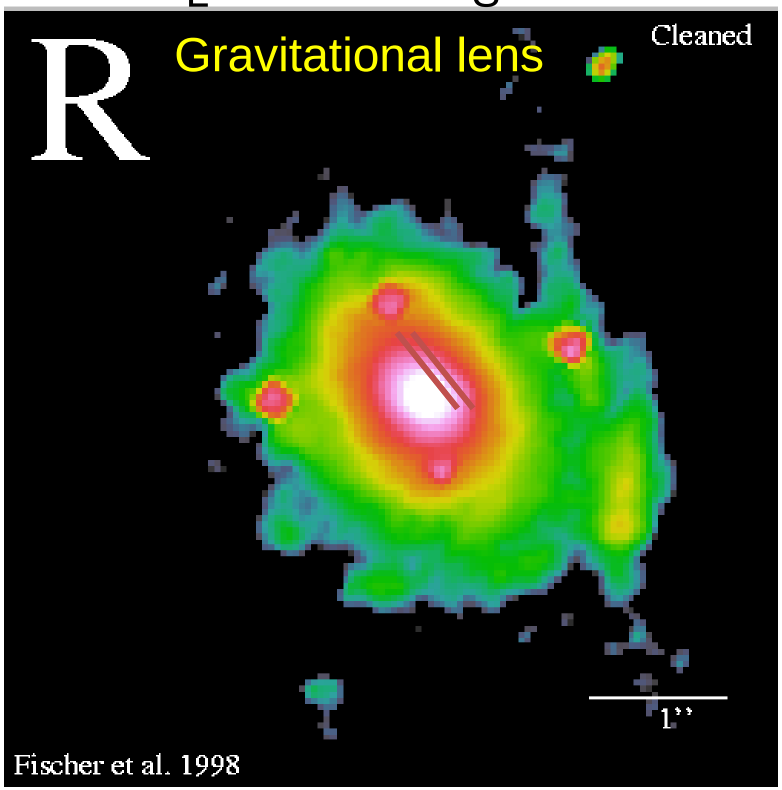
~70% sample galaxies are consistent with CDM

More on DM density profile:
Stellar dynamics + lens analysis

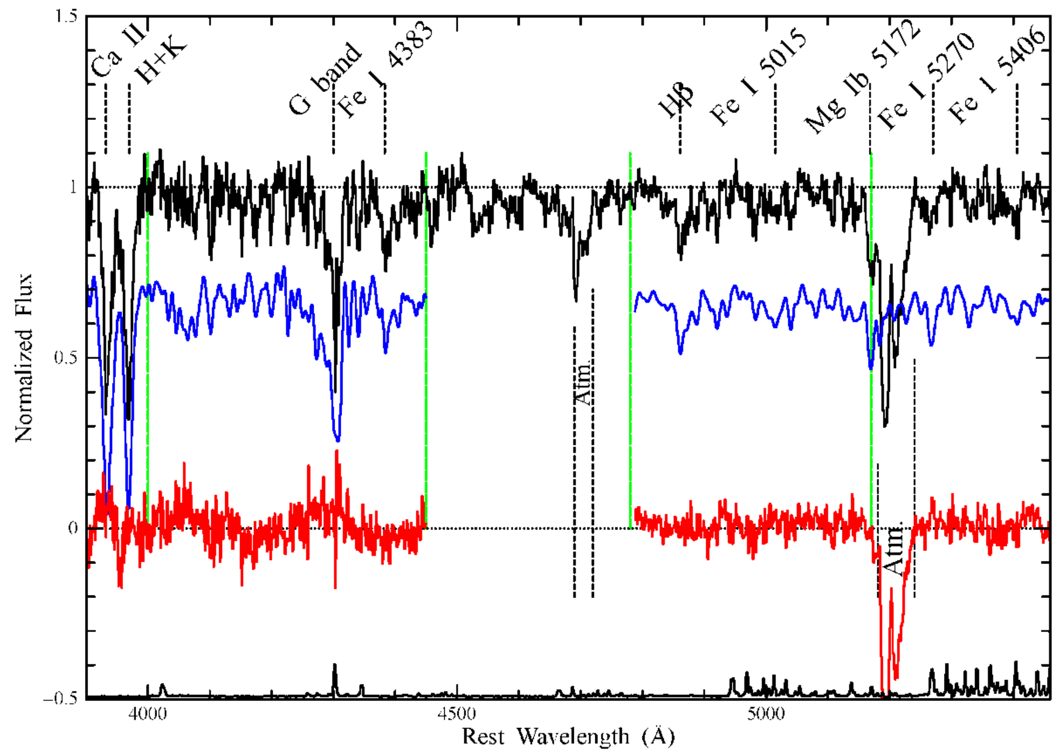
Hamana+ 2005

HST14113+5211

$z_L = 0.47$, $z_S = 2.8$



Subaru FOCAS spectrum



Velocity dispersion = 174 ± 20 km/s

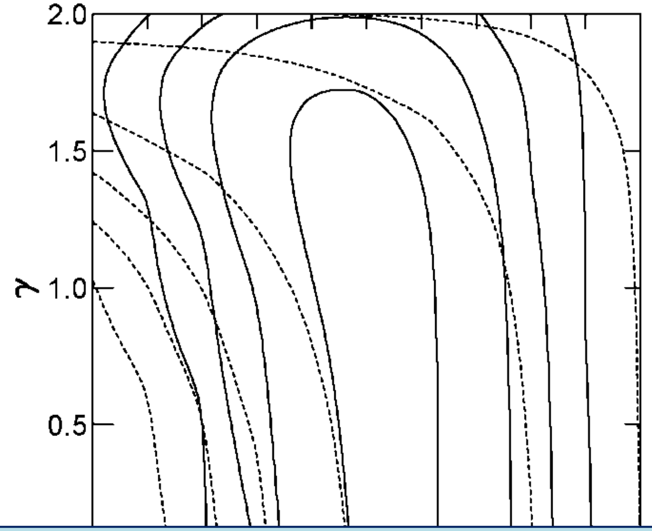
Stars ($r^{1/4}$ profile) + DM with $\rho_{DM}(r) \propto r^{-\gamma}$

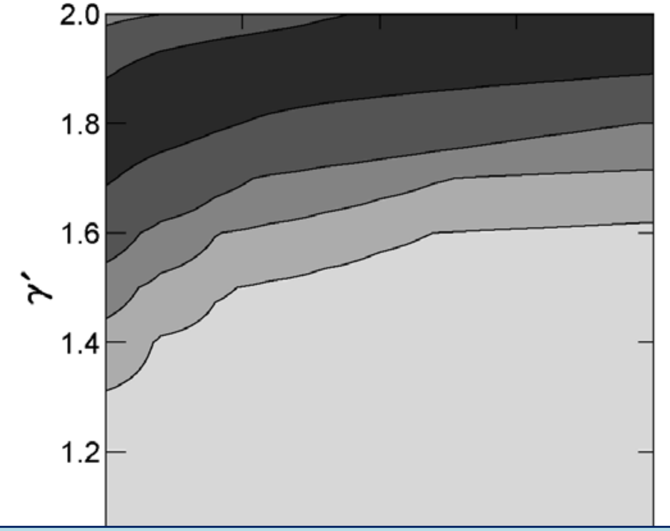
Total density profile $\rho_{tot}(r) \propto r^{-\gamma'}$

HST14113+5211

Model B
β=const.

(left: β=0)

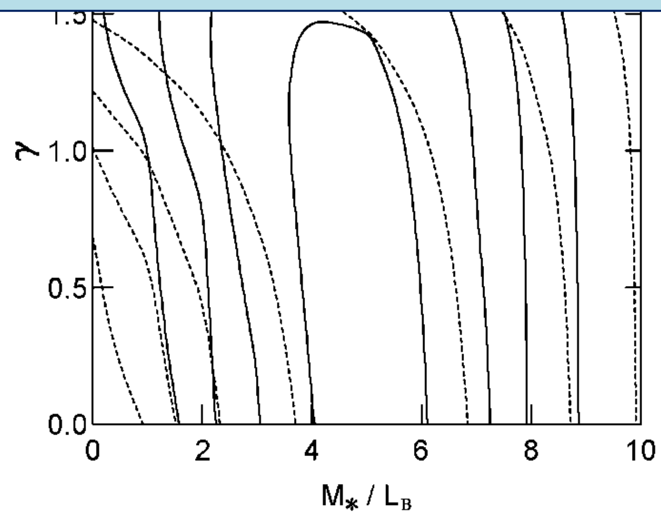


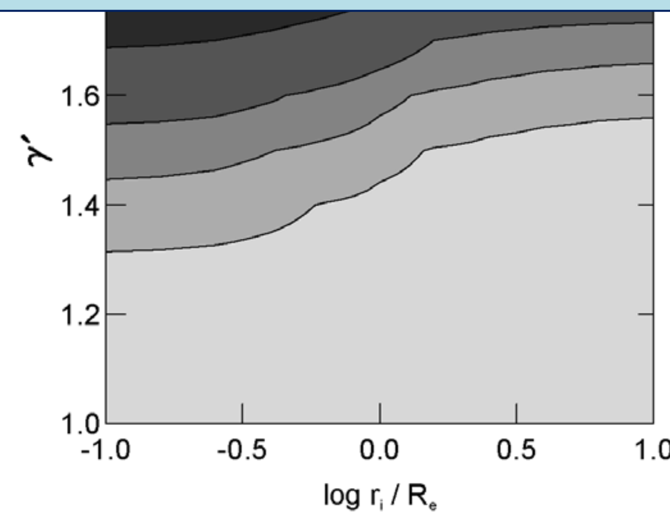


Stars ($r^{1/4}$ profile) + DM with $\rho_{DM}(r) \propto r^{-\gamma}$, γ<1.5
Total density profile $\rho_{tot}(r) \propto r^{-\gamma'}$, γ' =1.6~1.9
Consistent with CDM prediction

Model A
$\beta = r^2/(r^2+r_i^2)$

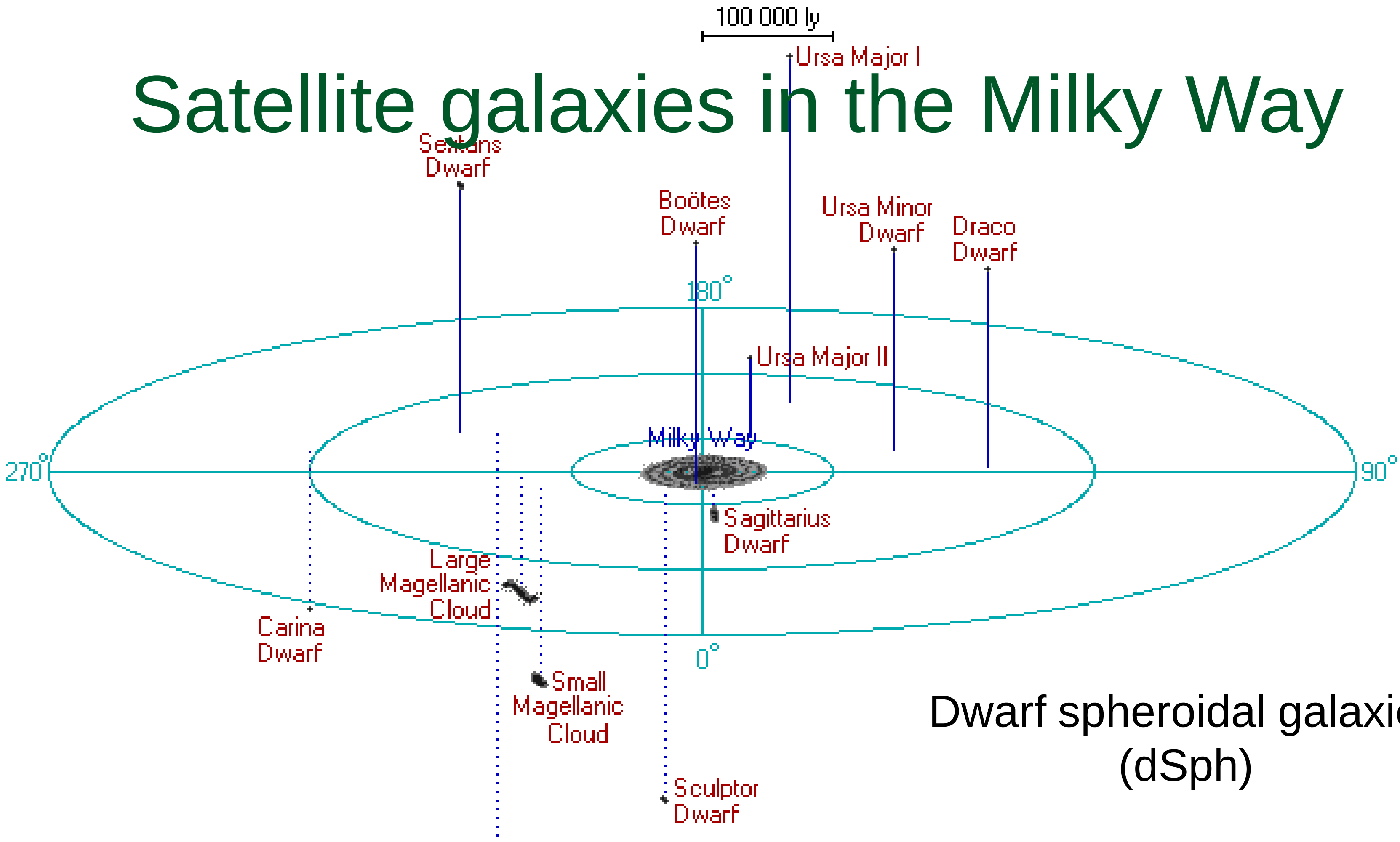
(left: $r_i=R_e$)





DM in a sub-galactic scale

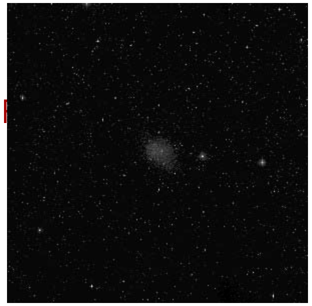
Satellite galaxies in the Milky Way



Dwarf spheroidal galaxies (dSph)

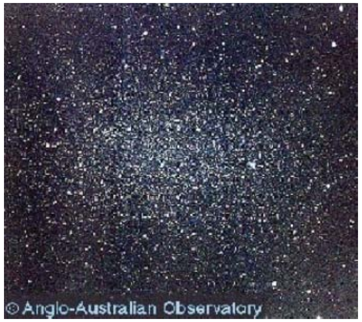
Scl

Car



For

Leo II



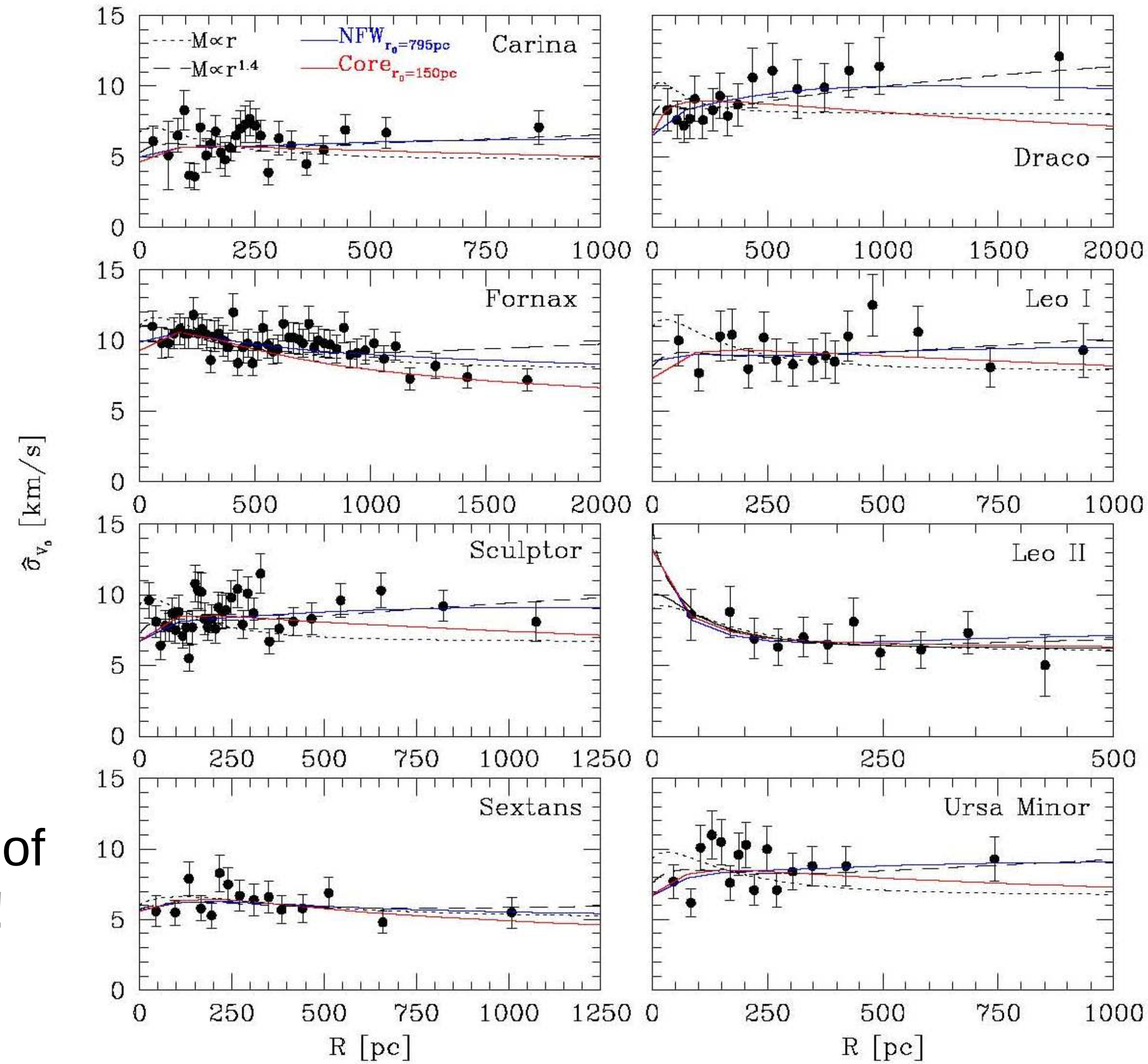
Leo I

Phe

Deriving DM profiles from line-of-sight velocity dispersion profile of stars (Walker+2009)

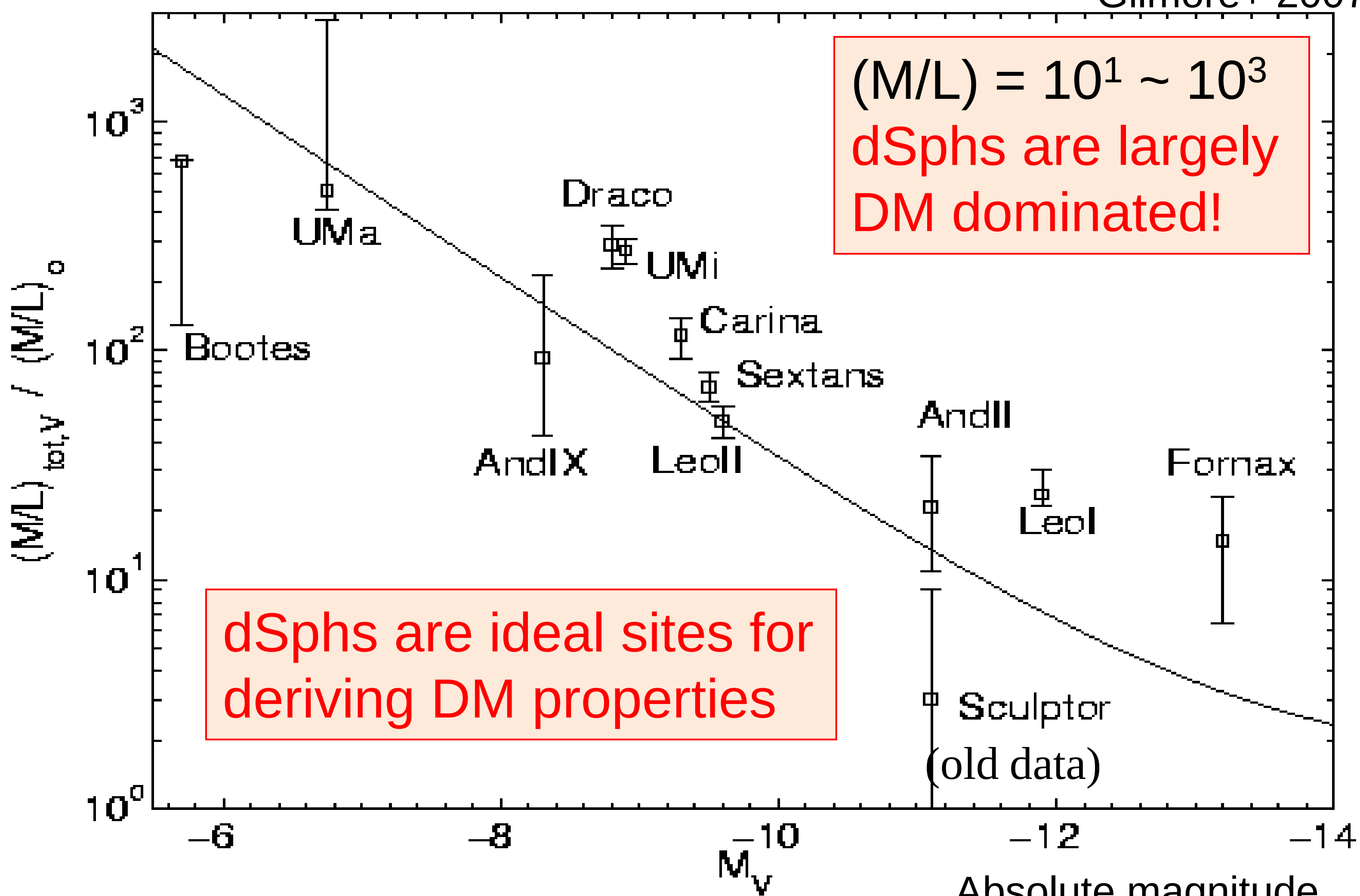
(spherically-averaged) velocity dispersion profile

Much larger than expected from self-gravity of stellar system !



Mass enclosed within stellar extent (~ 4 x $10^7 M_\odot$) in dSph galaxies

Gilmore+ 2007



Absolute magnitude

New mass limits on dSphs: Axisymmetric model (Hayashi & Chiba 2012)

* Stellar component

Vol. density: $\nu(R,z) = \frac{3L}{4\pi b_*^3}\left[1+\frac{m_*^2}{b_*^2}\right]^{-5/2}$ $\quad m_*^2 = R^2 + \frac{z^2}{q^2}$

q : axis ratio

Surface density $I(x,y) = \frac{L}{\pi b_*^2}\left[1+\frac{m_*'^2}{b_*^2}\right]^{-2}$ $\quad m_*'^2 = x^2 + \frac{y^2}{q'^2}$

$q'^2 = \cos^2 i + q^2 \sin^2 i$

(i : inclination)

* DM component

$$\rho(R,z) = \rho_0 \left(\frac{m}{b_{halo}}\right)^{\alpha}\left[1+\left(\frac{m}{b_{halo}}\right)^2\right]^{\delta} \quad m^2 = R^2 + \frac{z^2}{Q^2}$$

α = -1, δ = -1 ; NFW model
α = 0, δ = -1.5 ; with a core

Q: DM's axis ratio

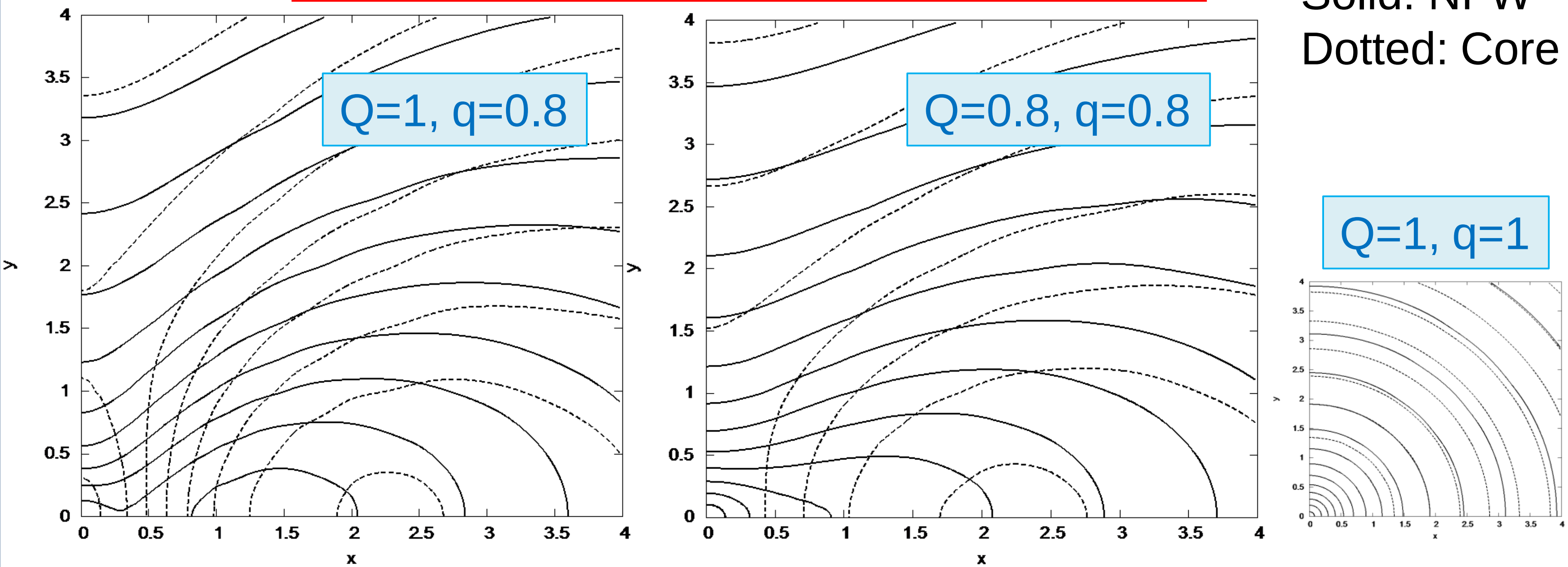
Gravity can be calculated by 1D integral:

$$\boldsymbol{g} = -\nabla\Phi = -\pi G Q a_0 \int_0^{\infty} d\tau \frac{\rho(m^2)\nabla m^2}{(\tau + a_0^2)\sqrt{\tau + Q^2 a_0^2}}$$

New mass limits on dSphs: Axisymmetric model
(Hayashi & Chiba 2012)

q: axis ratio of stellar system
Q: axis ratio of DM halo

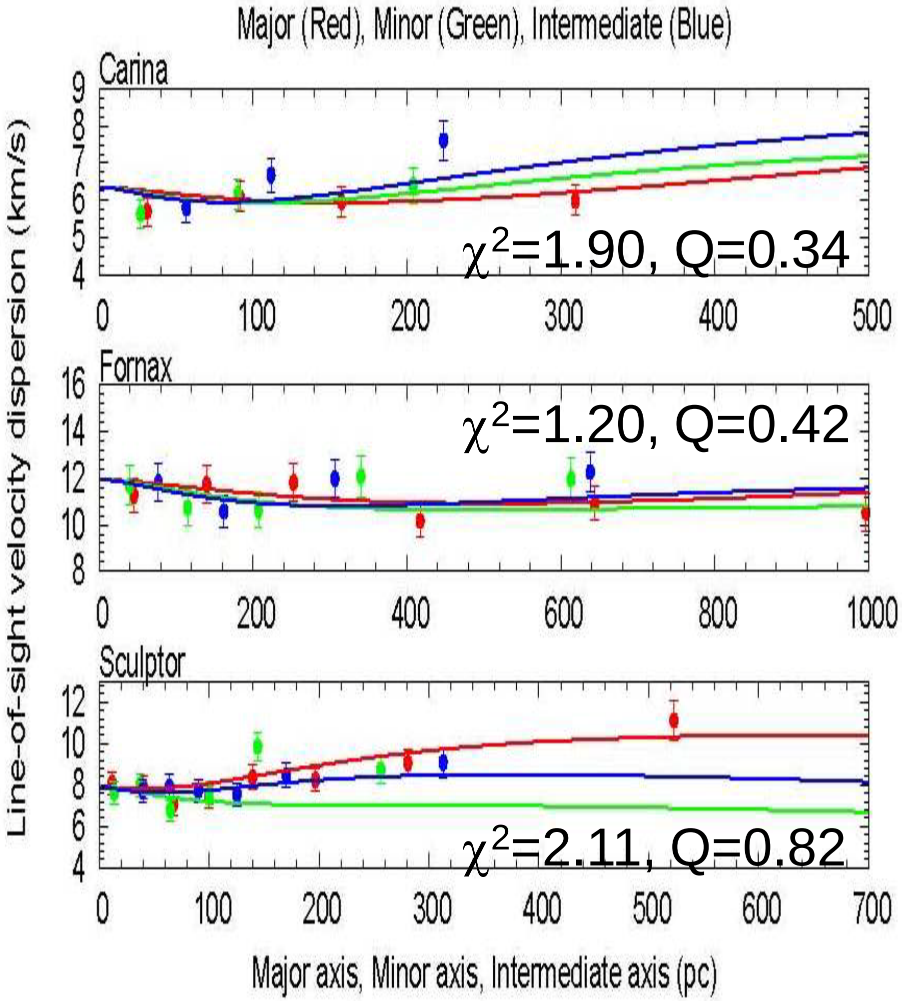
Contours of l-o-s velocity dispersion



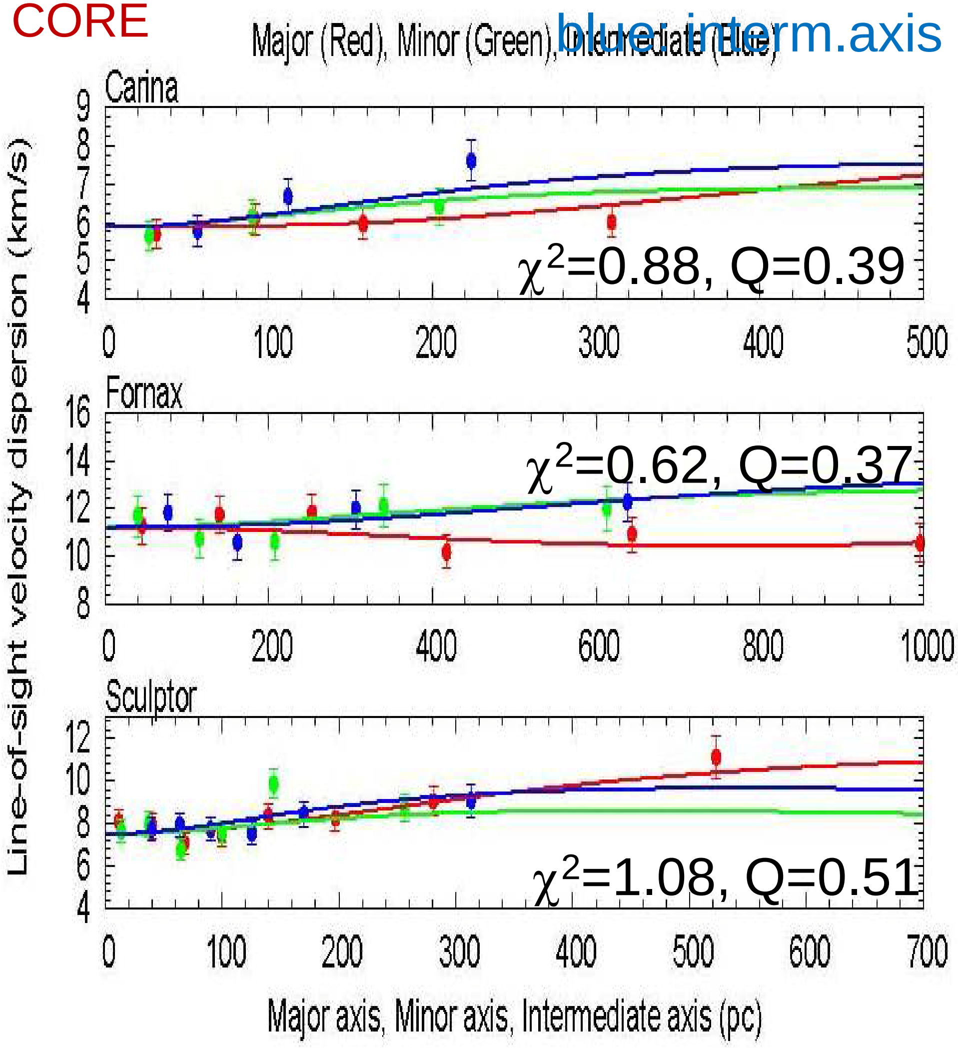
New mass limits on dSphs (I)
Carina, Fornax, Sculptor

red：major axis
green: minor axis
blue: interm.axis

NFW



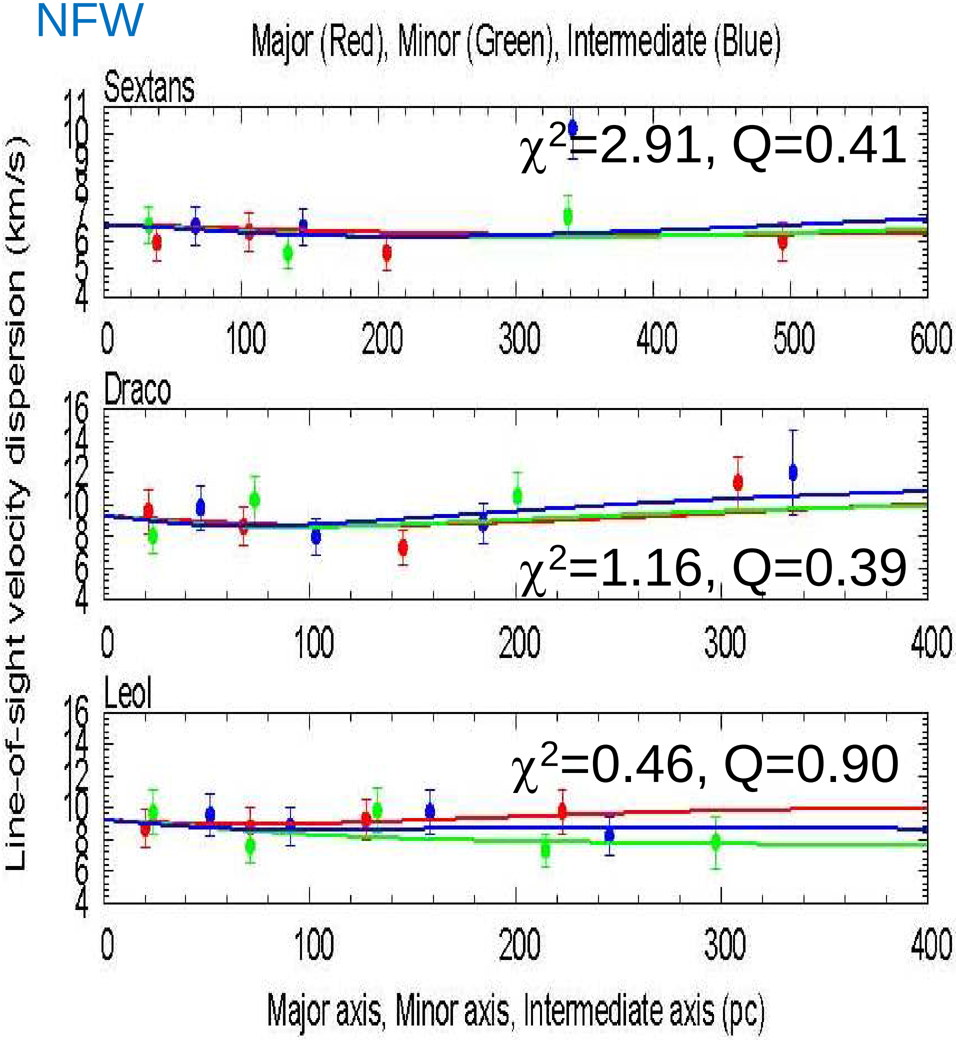
CORE



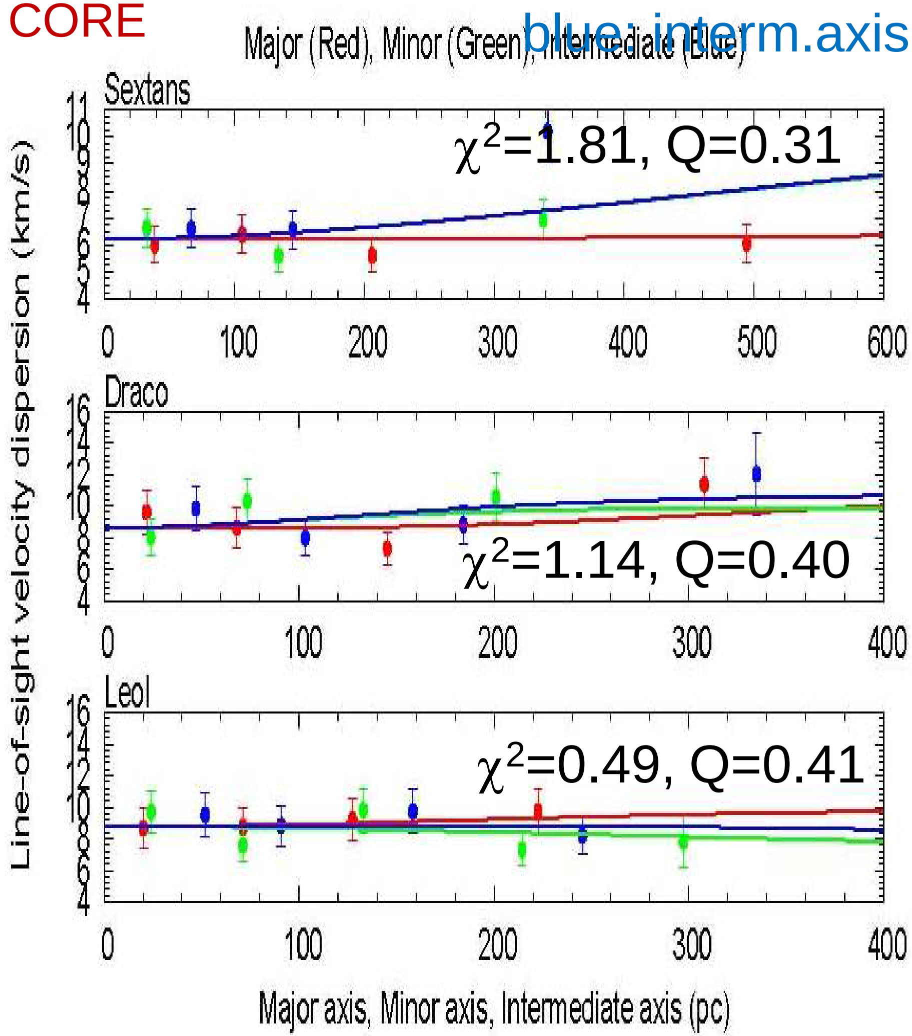
New mass limits on dSphs (II)
Sextans, Draco, Leo I

red : major axis
green: minor axis
blue: interm.axis

NFW



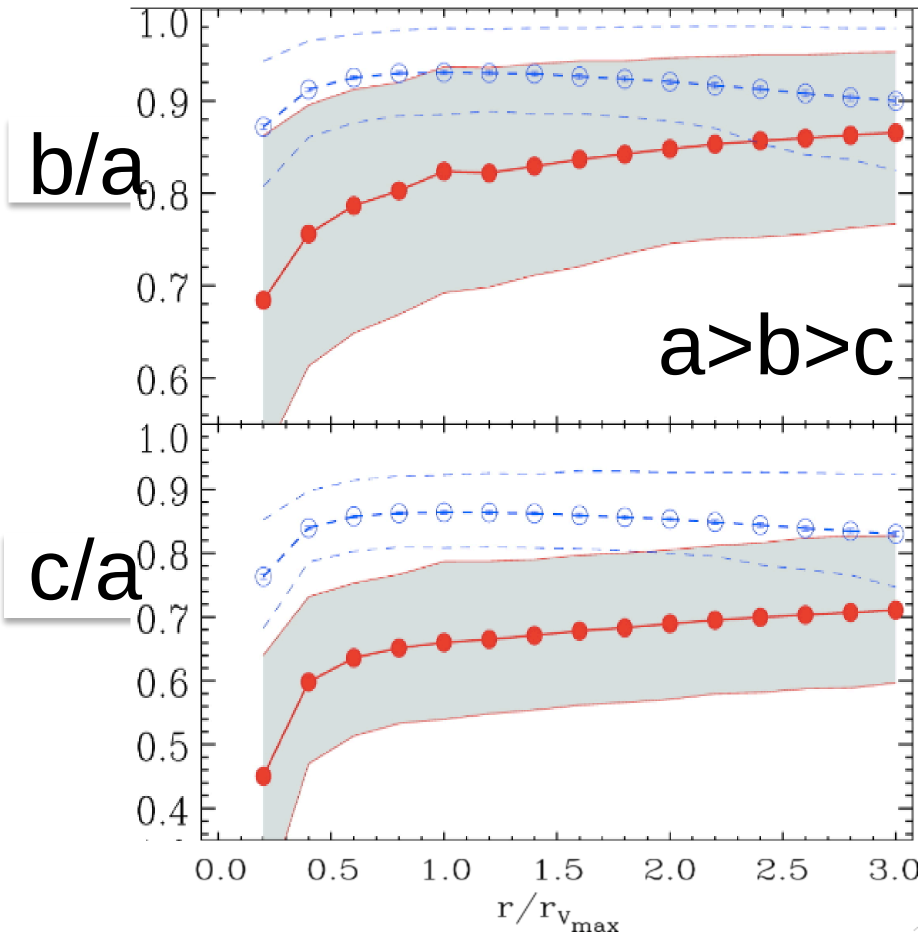
CORE



Comparison with N-body models

Via Lactea simulation (Kuhlen+ 2007)

Red line : axis ratio of a subhalo



This work:
(axisymmetric model)

$Q=0.4\sim0.5$

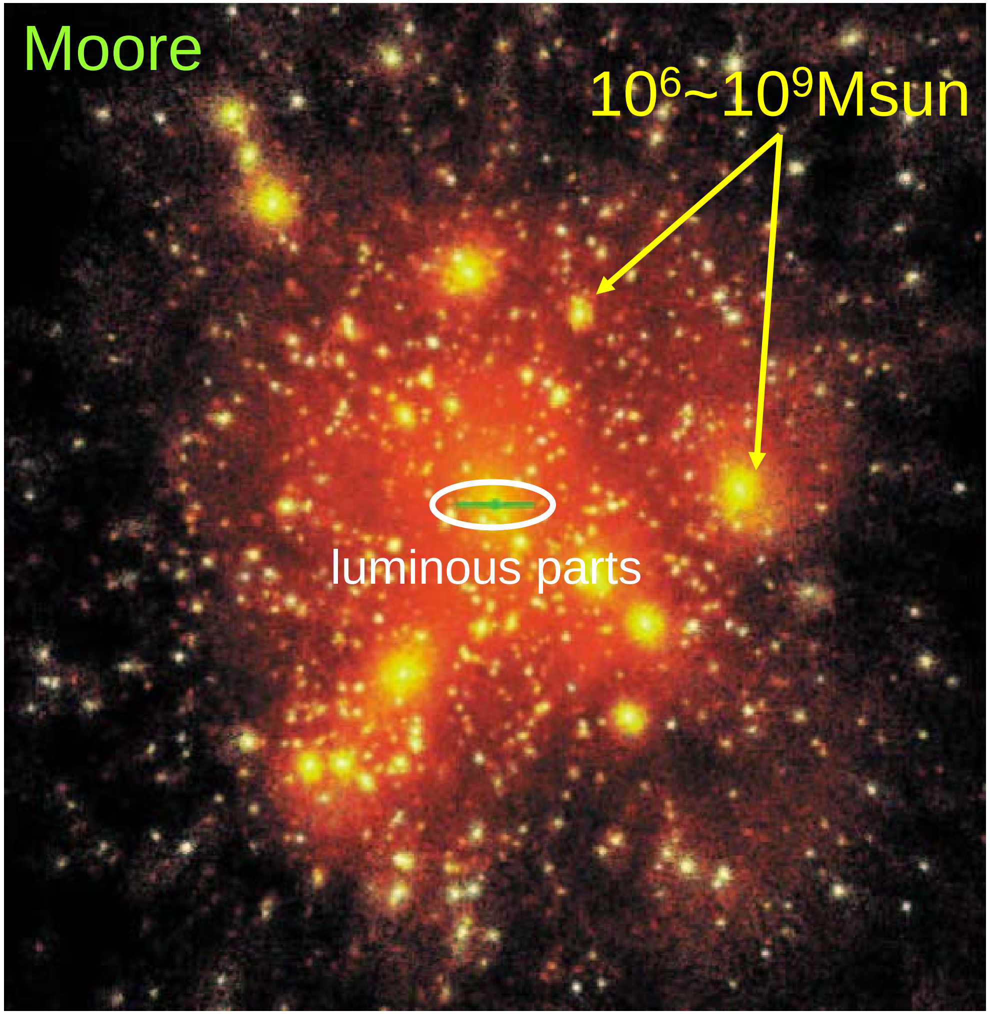
$\leq (b/a,\ c/a)_{CDM}$

More flattened
than CDM subhalos

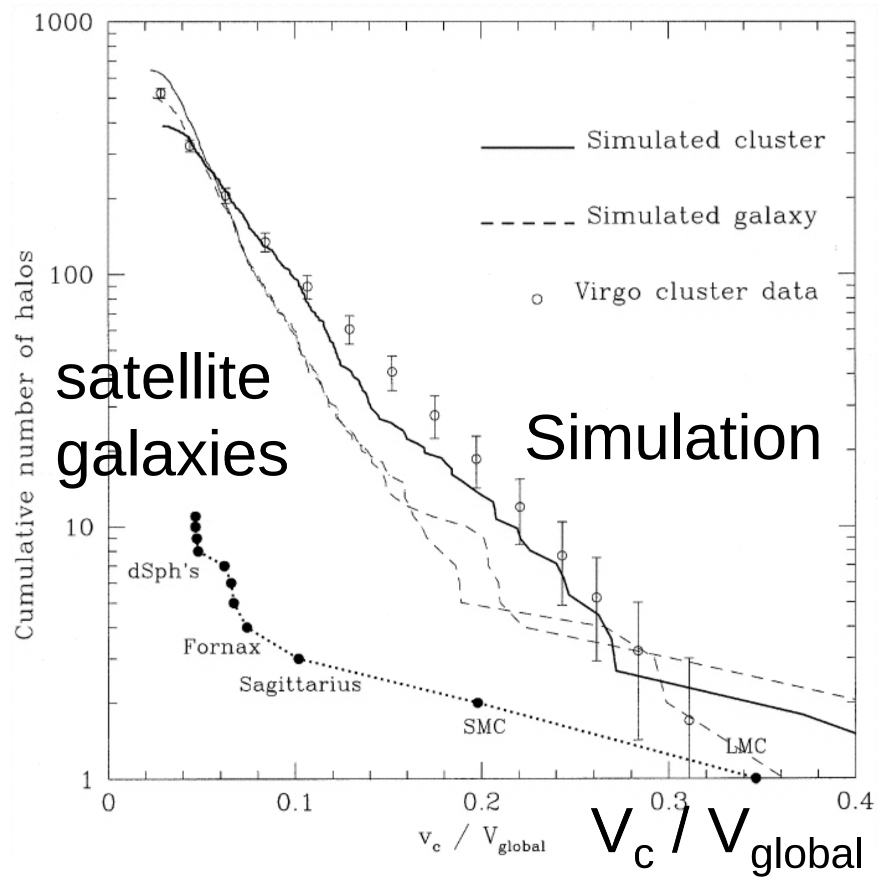
Is CDM correct in a sub-galactic scale?

Missing satellites problem

Simulated CDM distribution



Cumulative number of halos

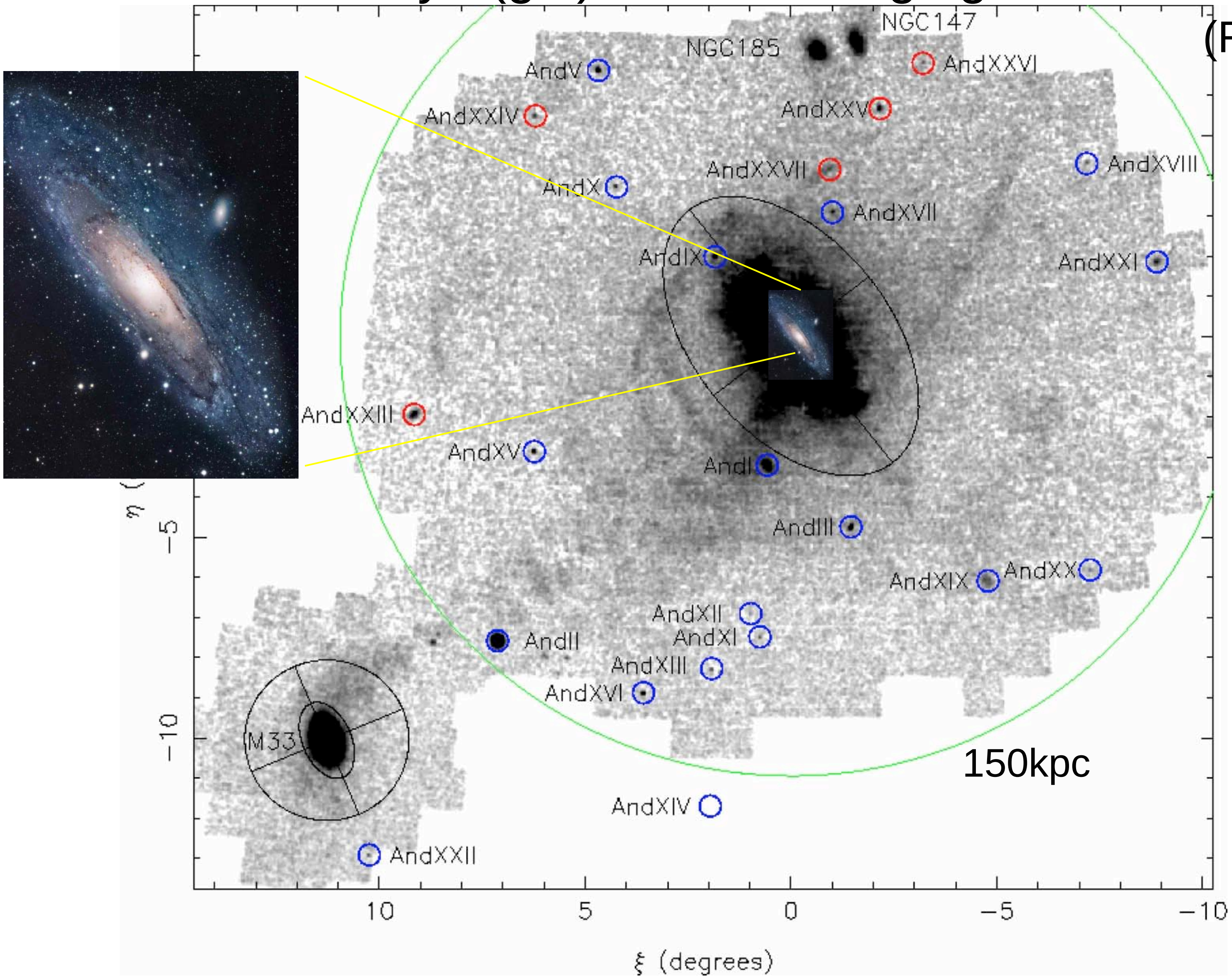


Is CDM correct in a sub-galactic scale?

Stellar halo in Andromeda

PAndAS survey: (g, i) 2-color imaging with CFHT

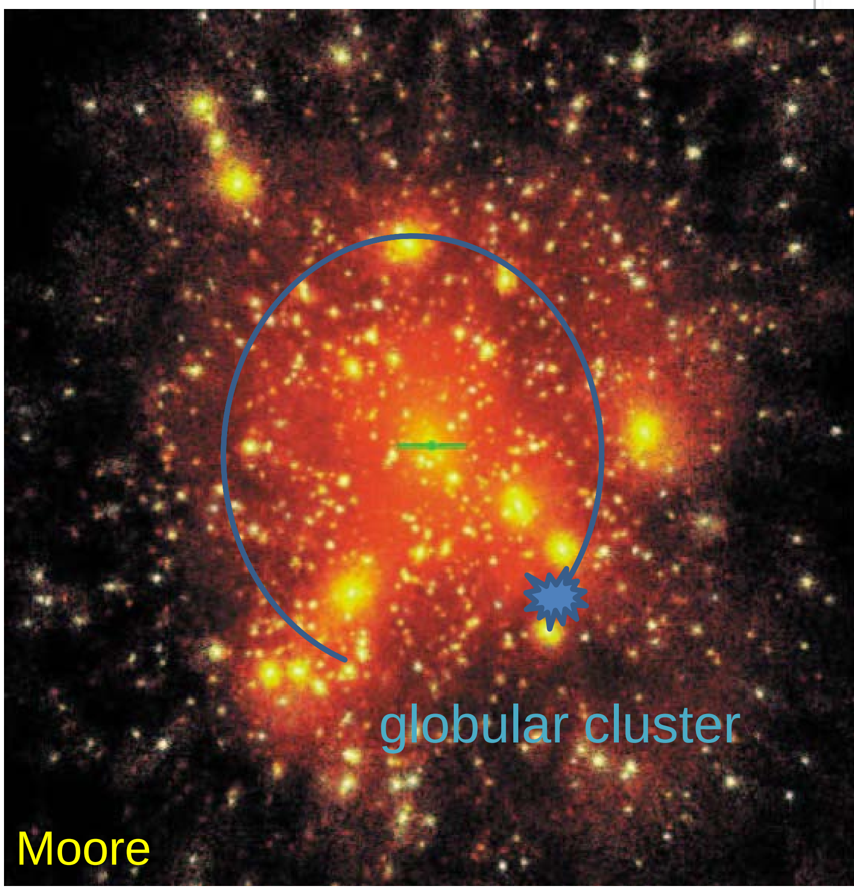
(Richardson+11)



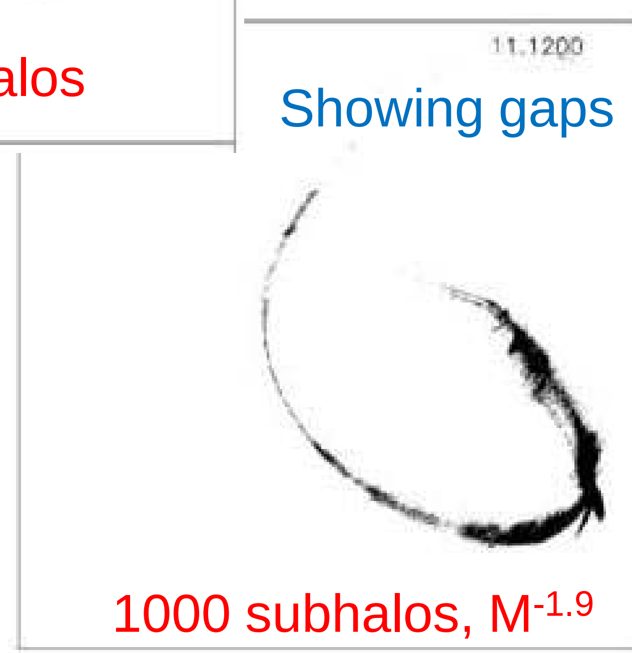
RGB
with i<23.5

Are there many CDM subhalos in a galaxy-sized halo? (Carlberg 2011)

CDM halo in a galaxy

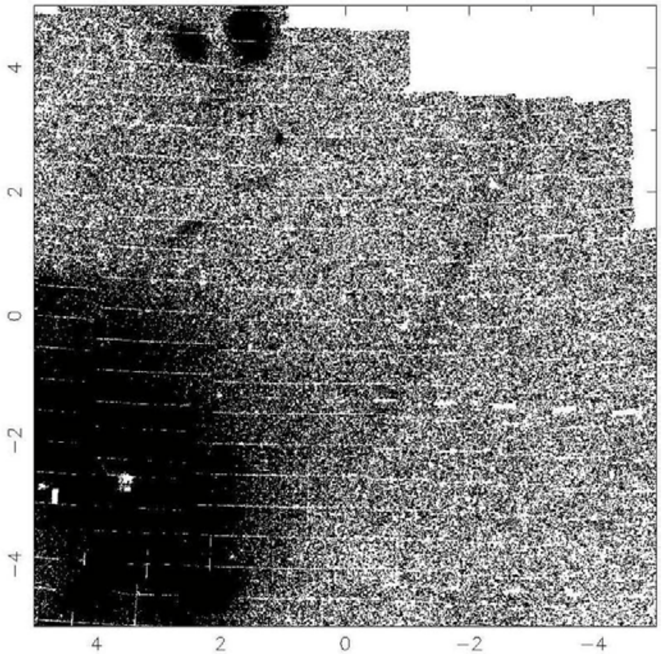


dynamical effects on stellar stream ($M_{star}=10^6 M_{sun}$

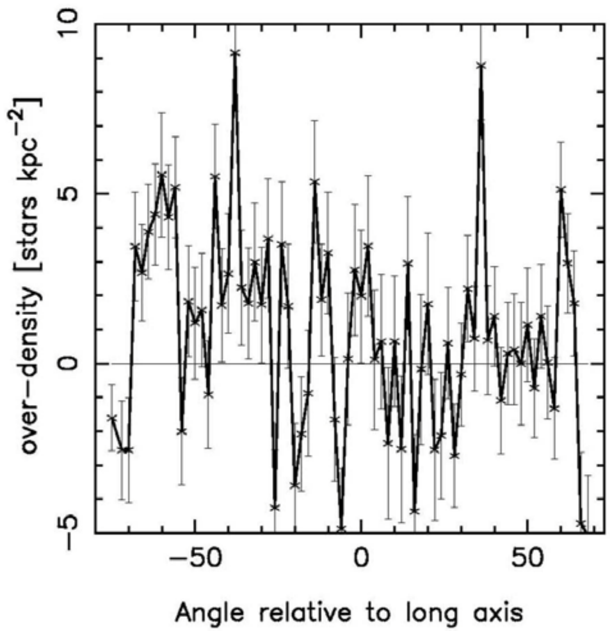


Are there many CDM subhalos in a galaxy-sized halo? (Carlberg 2011)

NW stream in M31
(Richardson+ 2011)

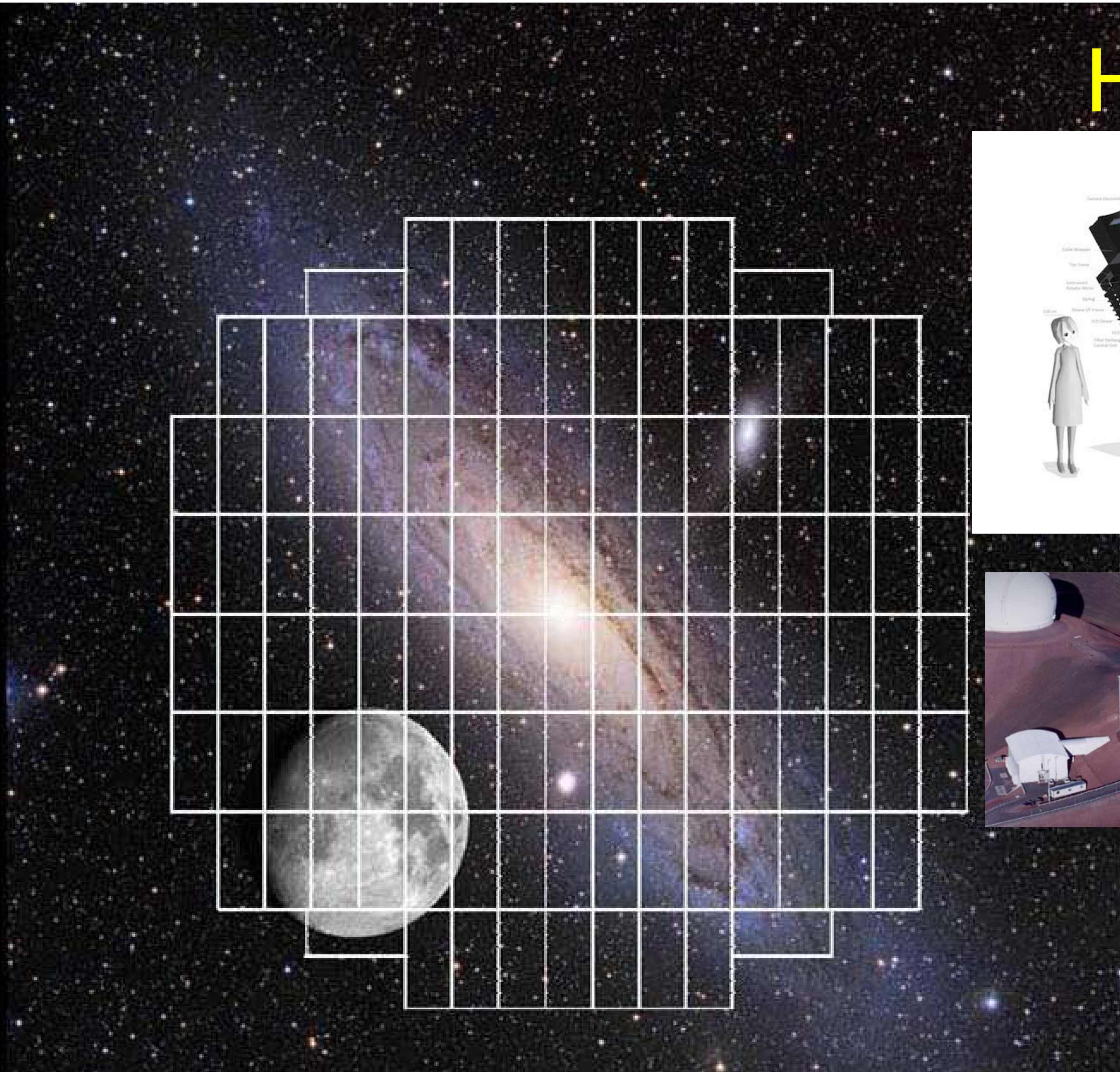


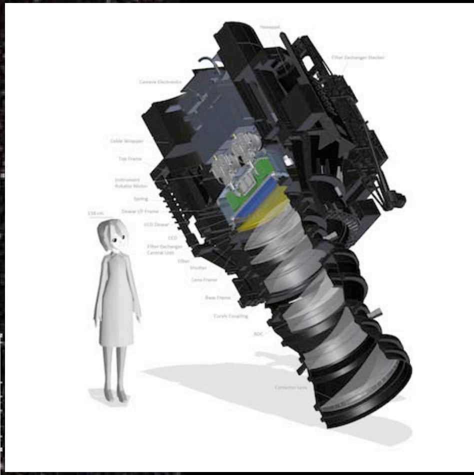
Non-uniform density distribution
(~12 gaps⇒consistent with CDM?)



Careful subtraction of foreground stars and more studies on a stream are needed!

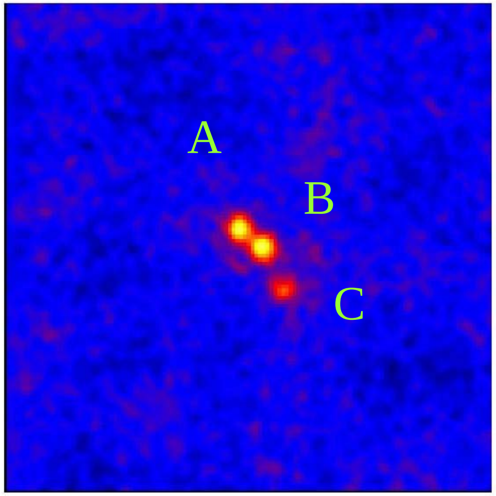
HSC





Wide-field FoV is essential for mapping stars

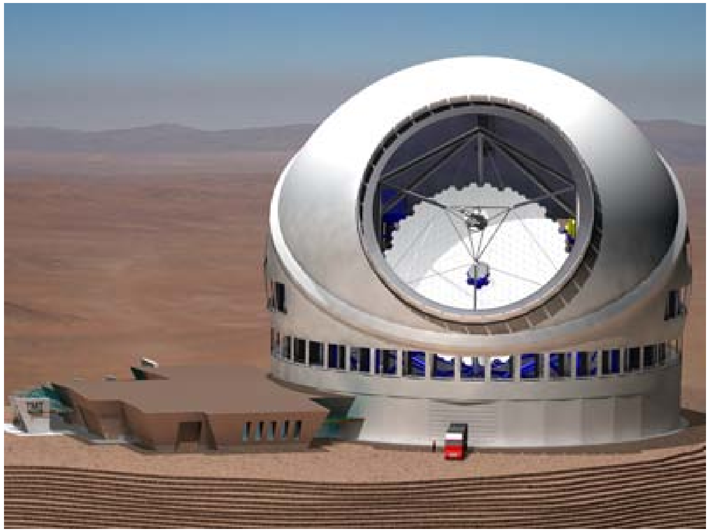
Gravitational lensing as a probe of CDM subhalos



Flux –ratio distribution, especially in mid-infrared waveband, provides substructure of lens mass distribution (Chiba+2005; Minezaki+2008)
Signatures for CDM subhalos!

TMT

(Thirty Meter Telescope)



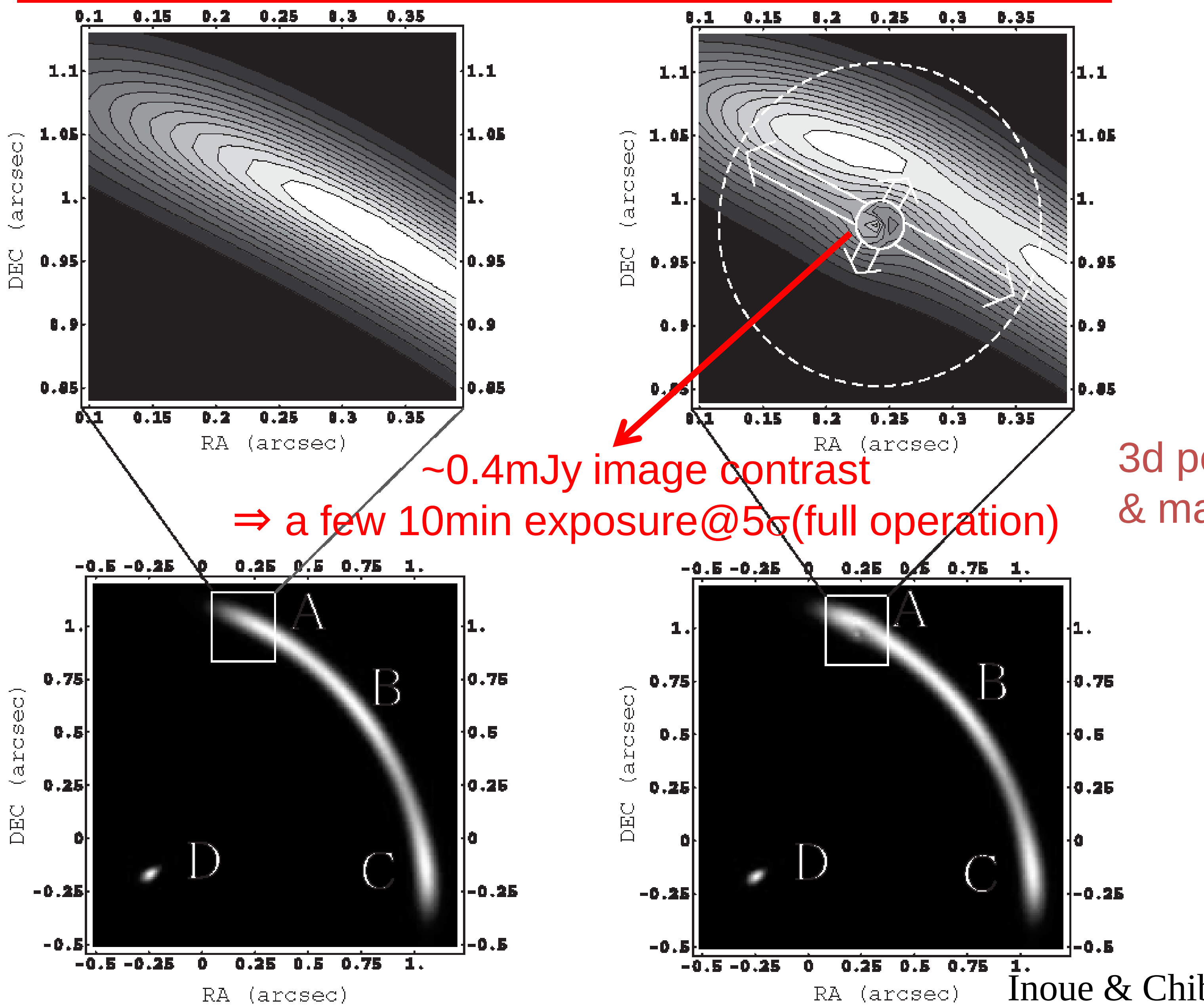
MIR observations of lensed QSOs
with MICHI (みち)
"Mid-IR Camera, High-disperser,
and Integral field unit"

ALMA

High-reso. sub-millimeter
observations of lensed
QSOs

Lens mapping of CDM substructures

2×10^8 Msun subhalo at resolution 0.01 arcsec

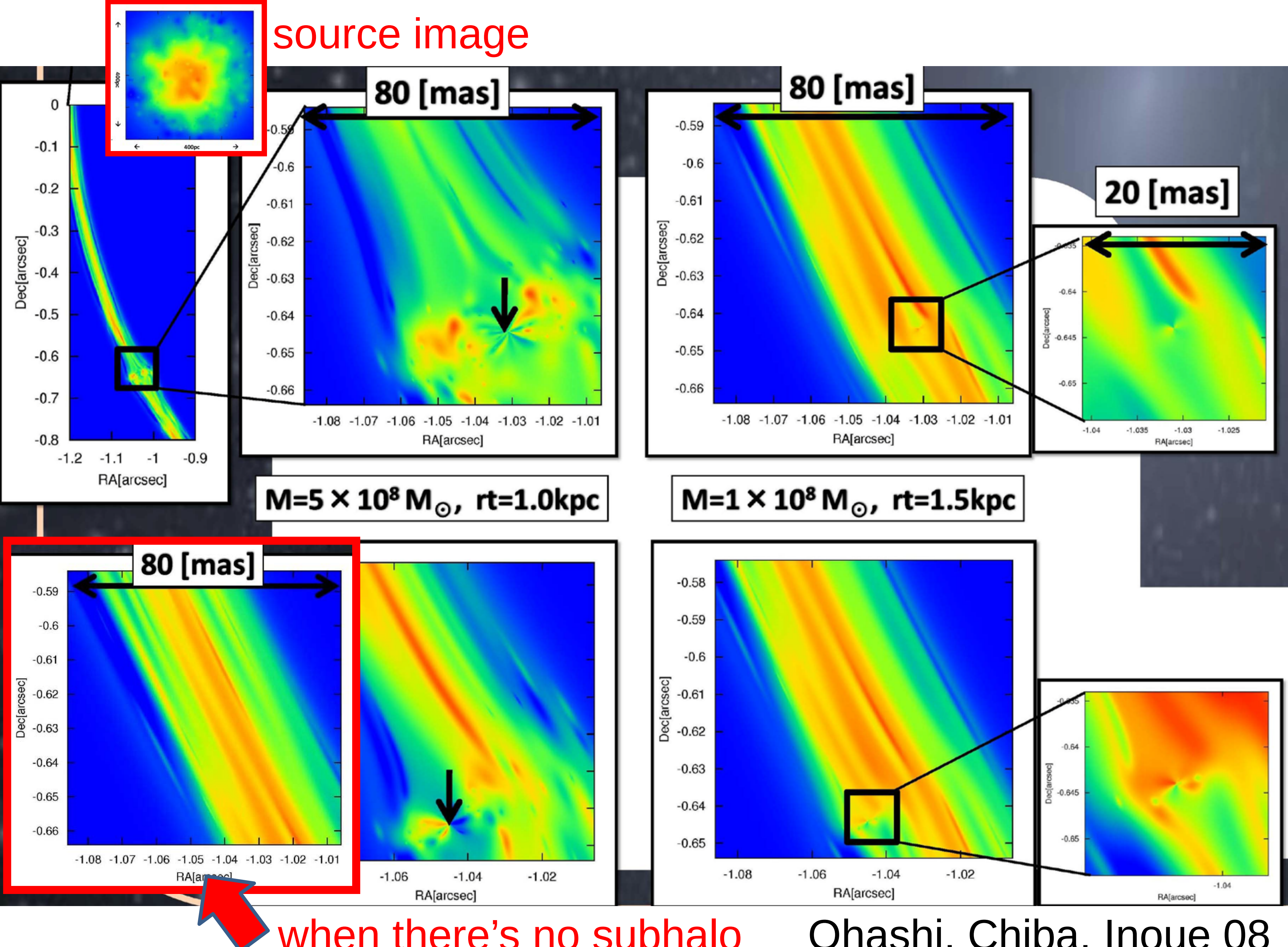


~0.4mJy image contrast

⇒ a few 10min exposure@5σ(full operation)

3d position
& mass

Inoue & Chiba 2005



Ohashi, Chiba, Inoue 08

Conclusion

- DM properties in a galactic scale can be understood in a framework of CDM models.
- DM properties in a sub-galactic scale are NOT well understood.
- Future observing program with Subaru/HSC, ALMA, and TMT/MICHI will provide DM substructures in detail.

End