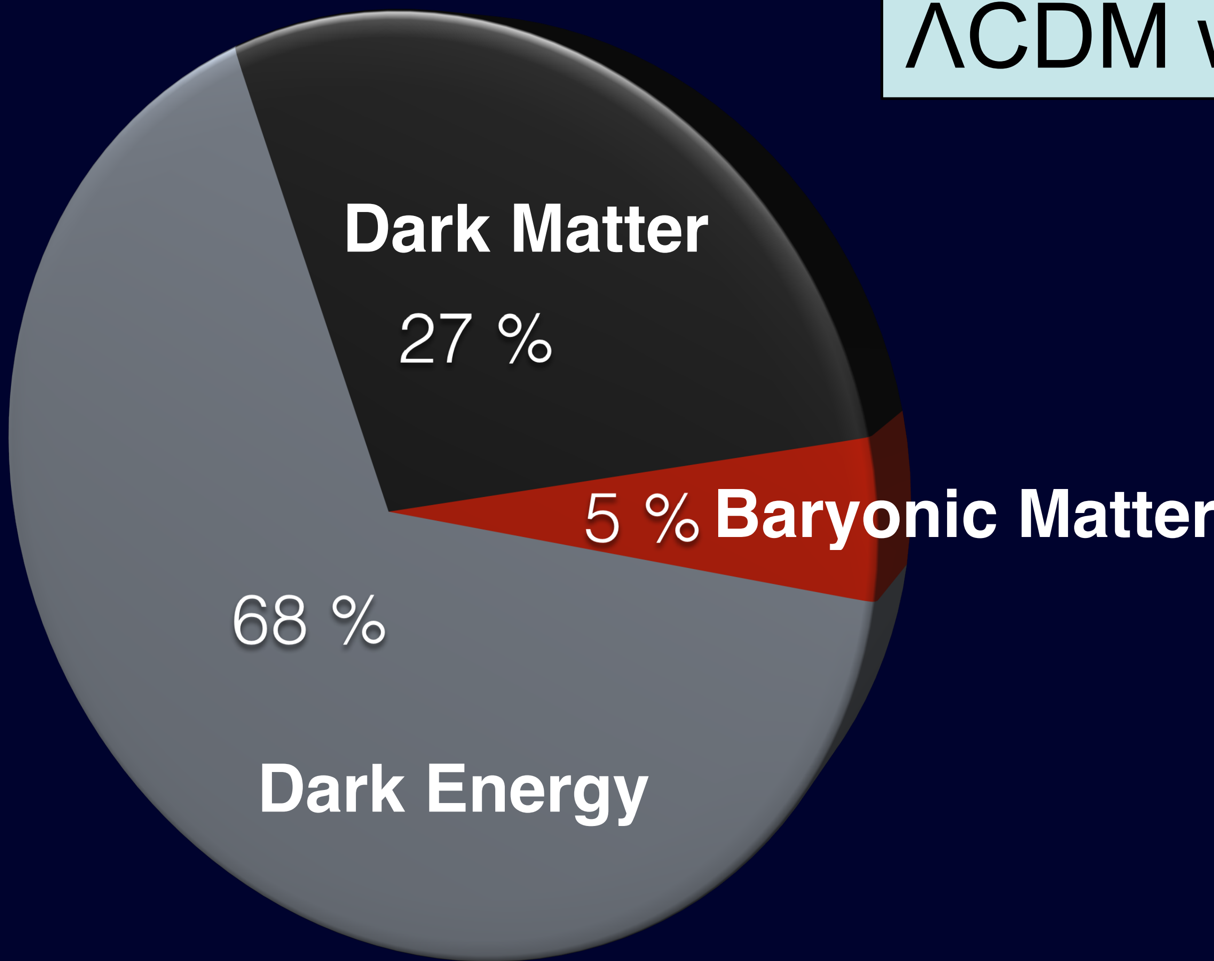
Dark matter on small scales: from giant galaxies to dwarf spheroidals

Mass in Universe: dominated by Dark Matter

ΛCDM with 85±1% Dark Matter



Nature of Dark Matter ***unknown***, except that it is

- dwarf galaxies ⇒ fairly **cold** (heavy)
- fairly **collisionless**

Motivations

1) Nature of Dark Matter:
- mass of particle(s)
- self-interaction cross section
- decay time

OR Modified Gravity?

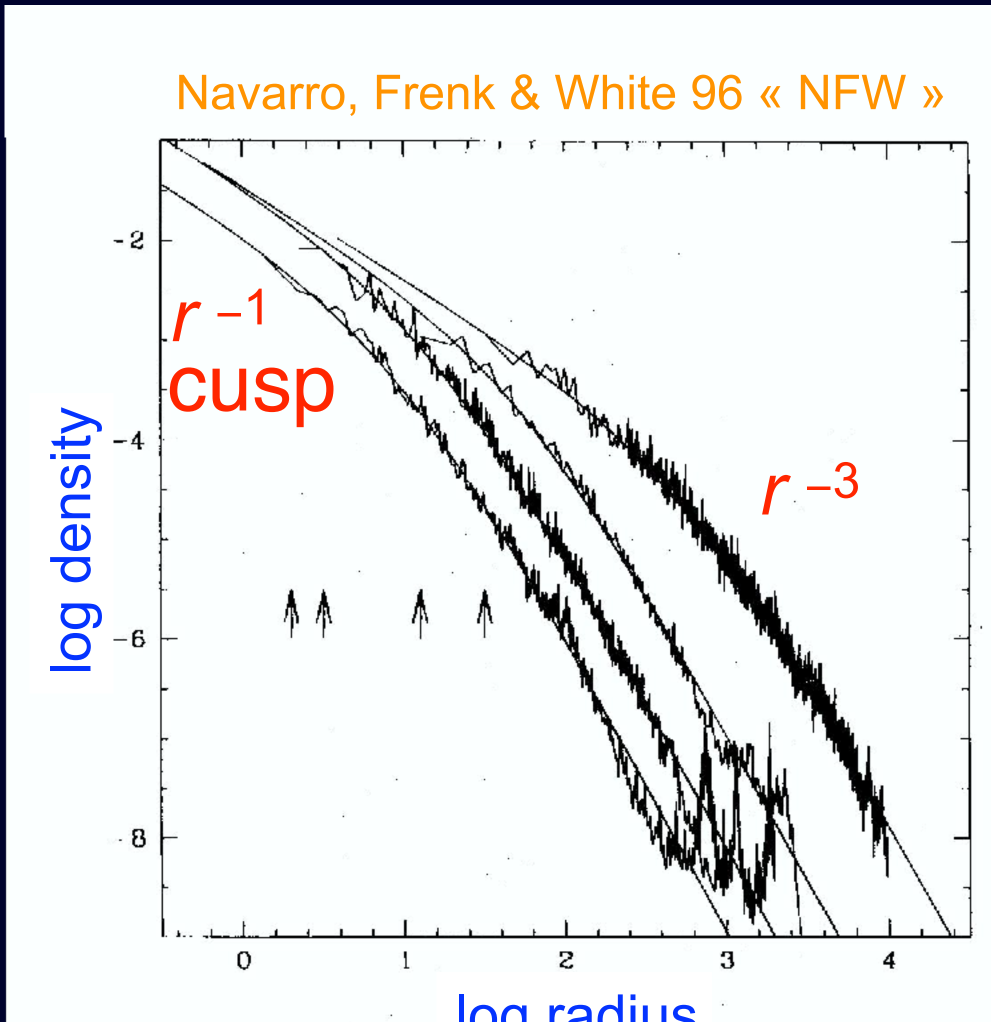
2) Reference for astrophysical studies

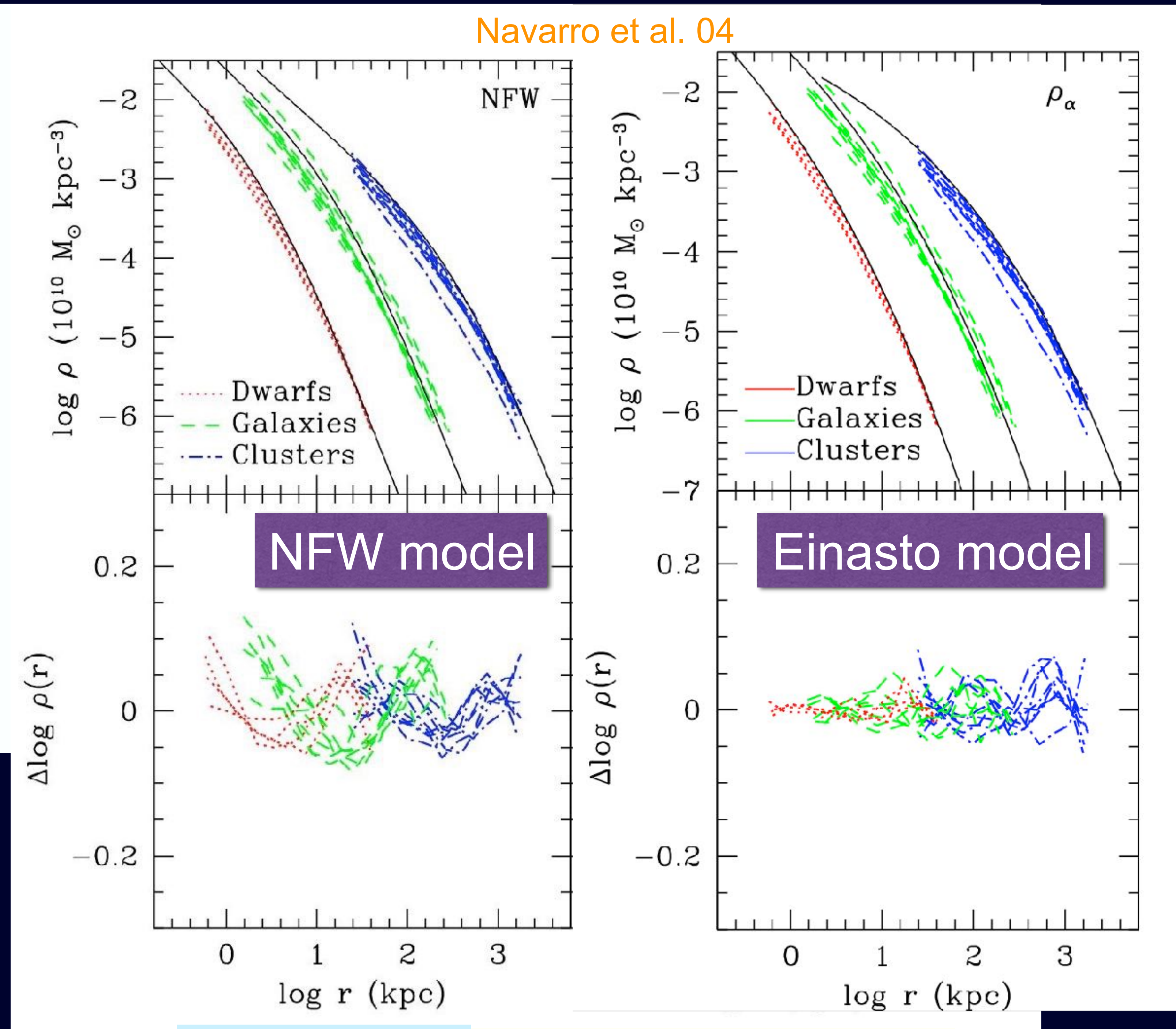
Dark matter characteristics to measure:
- normalization
- inner slope
- concentration

for z=0 galaxies of ≠ masses & types
+ scatter

Expectations from cosmological dynamical simulations & abundance matching

Density profiles in cosmological N body simulations





NFW model

$$\rho(r) \propto \frac{1}{(r/r_{-2})\ (1+r/r_{-2})^2}$$

projected NFW ≈ m=3 Sérsic

Łokas & Mamon 01

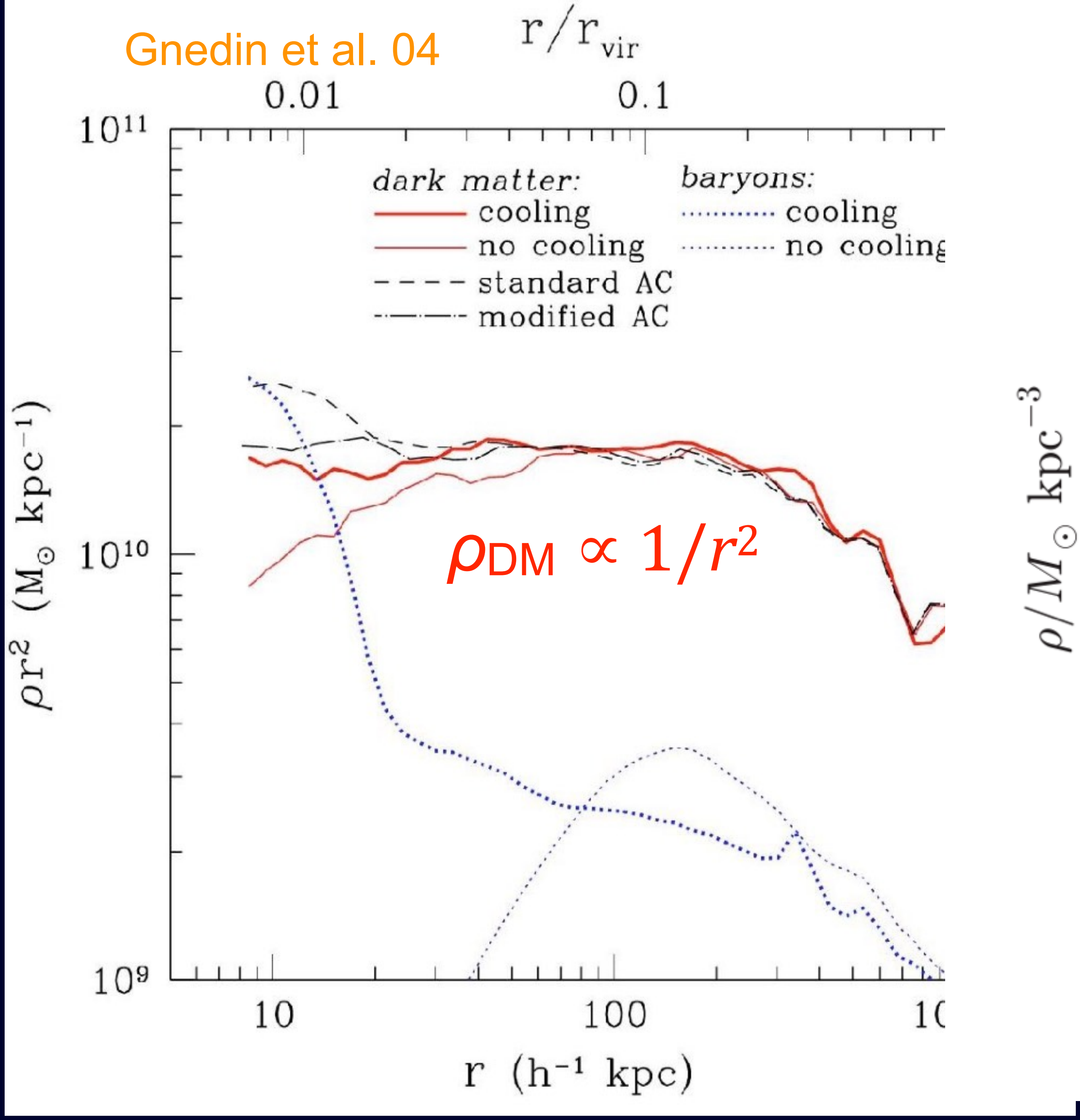
3D Sérsic

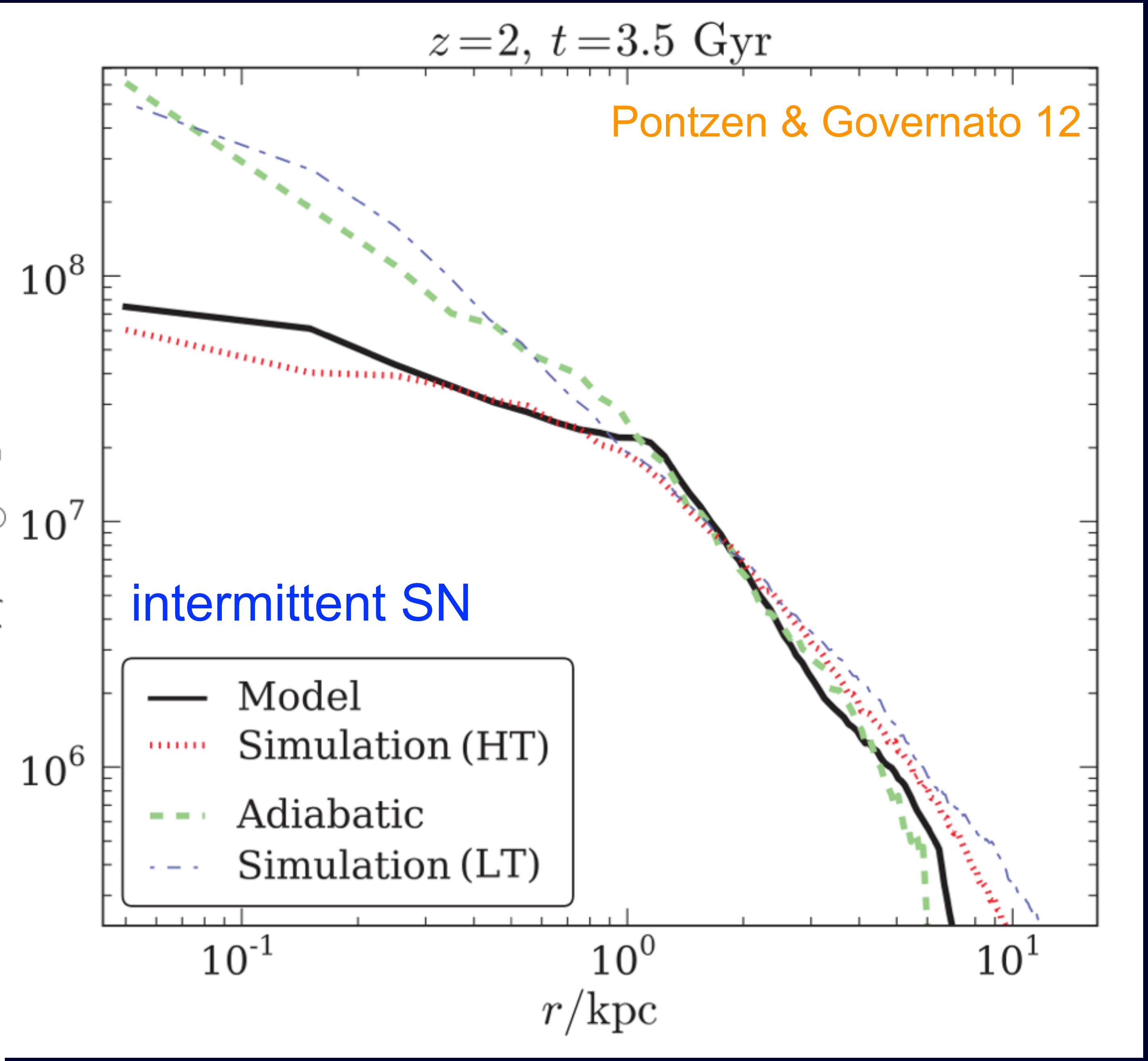
Einasto 63

$$\rho(r) \propto \exp\left[-2\mu\left(\frac{r}{r_{-2}}\right)^{1/\mu}\right]$$

inner slope ≈ –1.2 @ 0.01 r_{vir}

DM density profiles from cosmological N-body simulations with gas



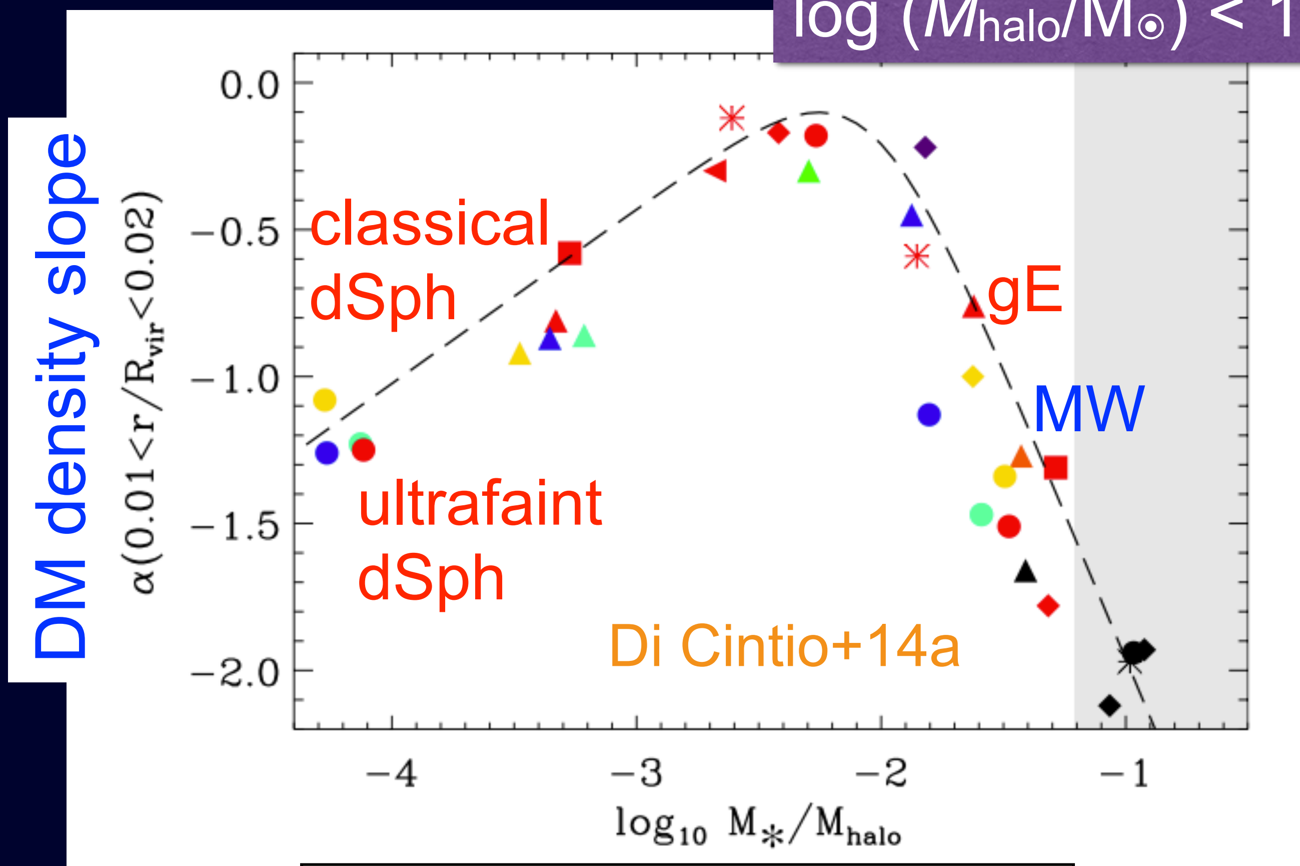


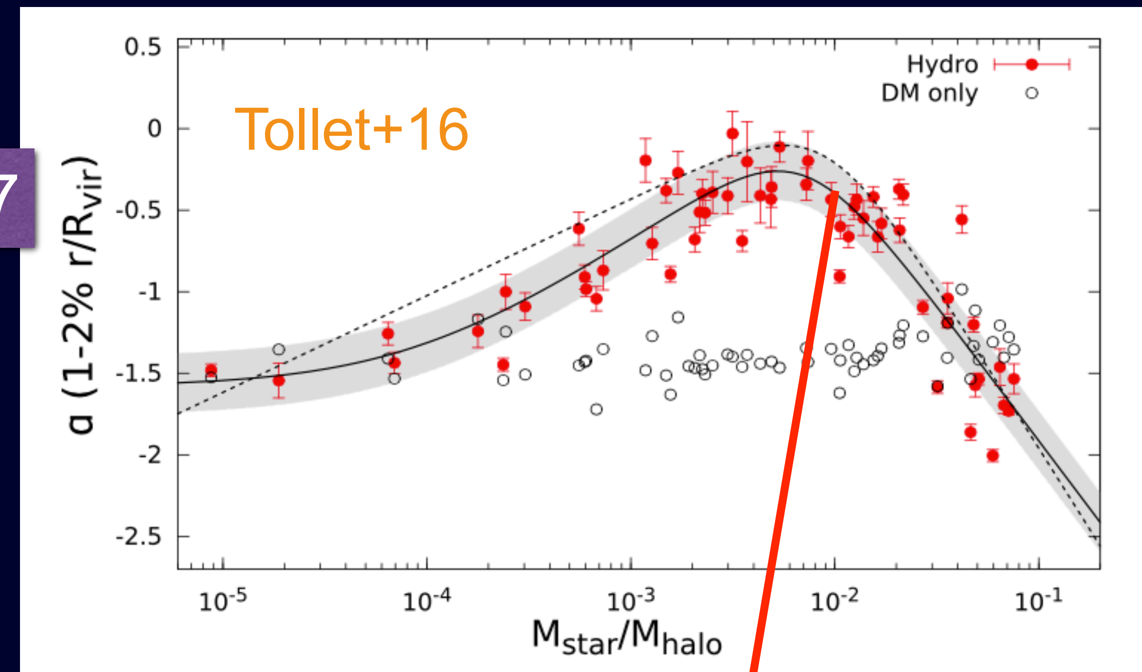
dominant baryons that radiate & cool → even cuspier DM

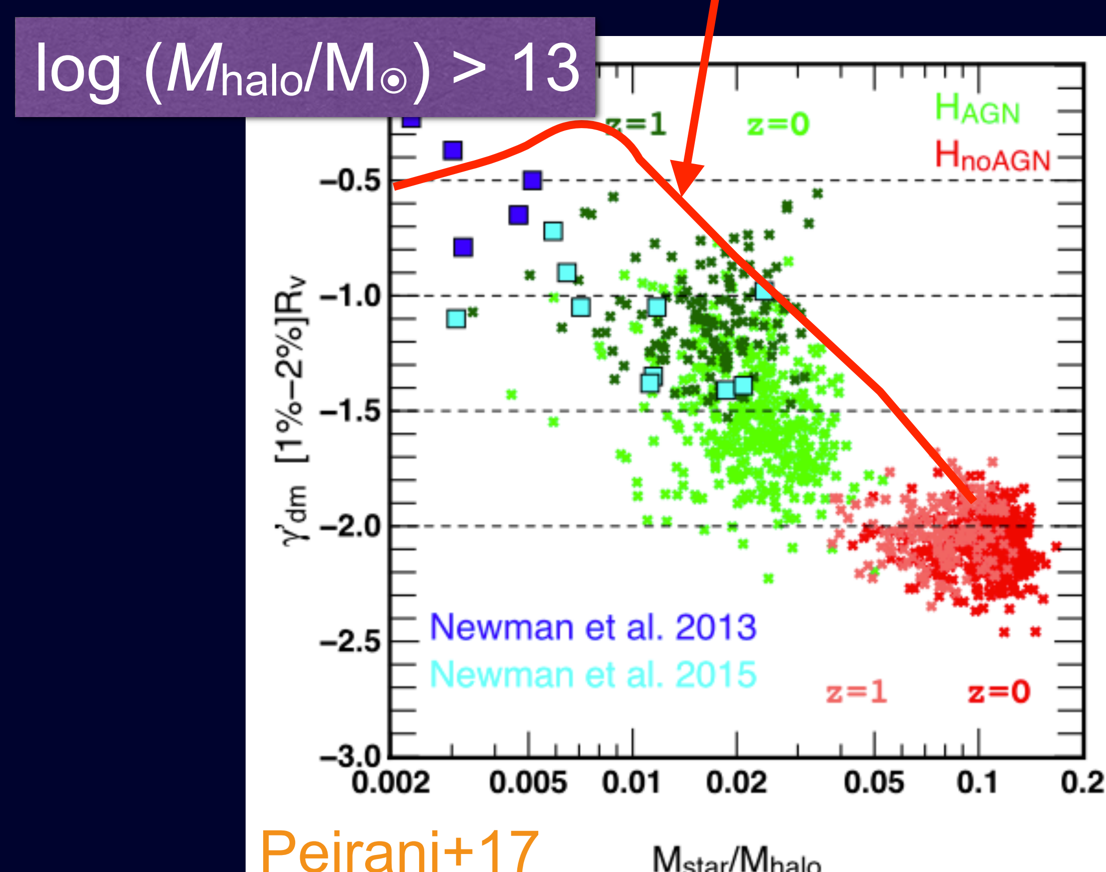
intermittent SN feedback → cored DM

Cusps vs. Cores

Hydro cosmological simulations
w SN feedback
at different resolutions





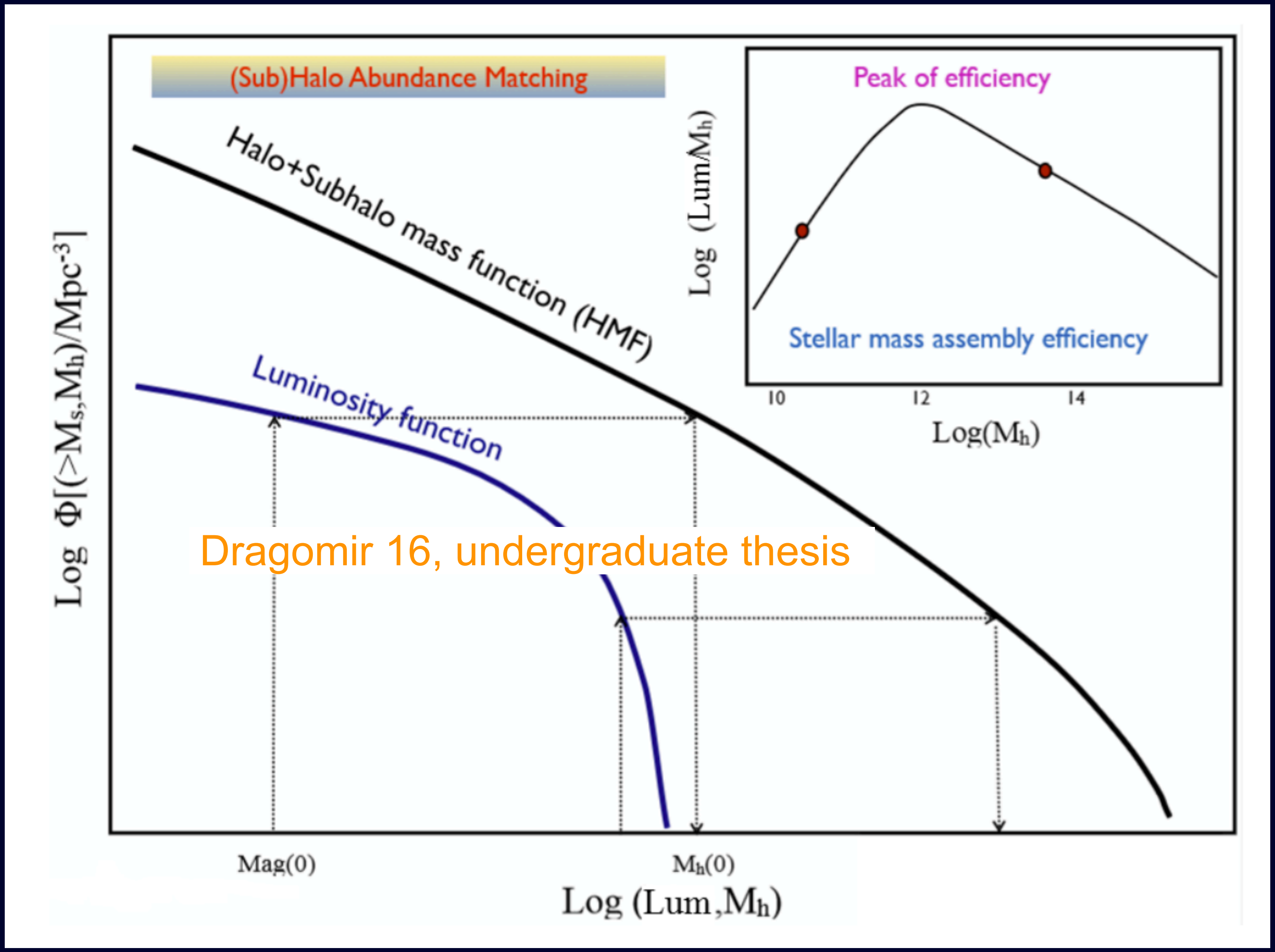


MW-mass very cuspy
giant ellipticals cuspy
classical dSph cored
ultra-faint dSph cuspy

inner slope ≠ $f(m_{stars}/M_{halo})$

DM normalization from Abundance Matching

equate the cumulative halo and observable mass functions



massive galaxies should have *more* DM
very low mass galaxies should be *fully dominated by* DM

Methods for inferring the Dark Matter distribution

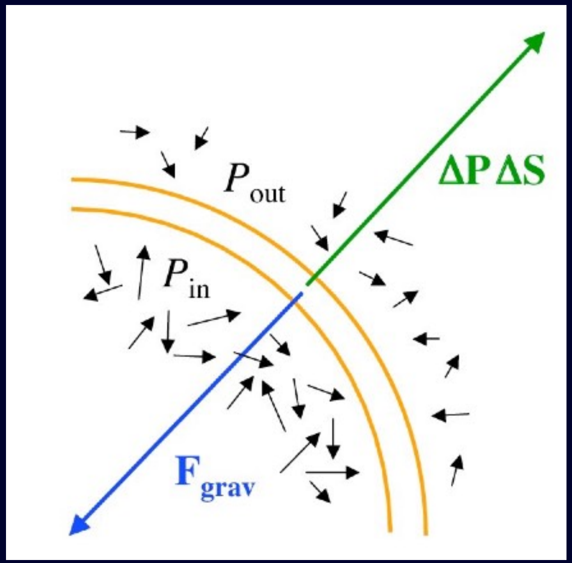
Spheroidal systems: using different physics

Newtonian dynamics: mass/orbit modeling

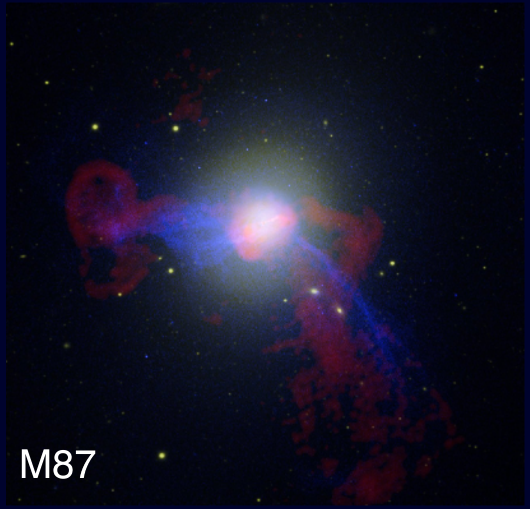
Jeans Equation

$$\nabla \cdot \boldsymbol{P} = -\nu \, \nabla \Phi$$

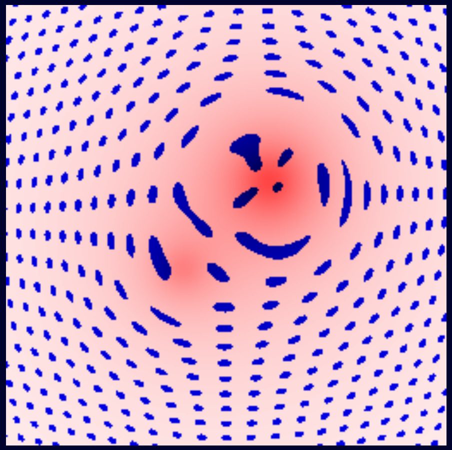
$$\frac{d\left(\nu\sigma_r^2\right)}{dr} + 2\frac{\beta(r)}{r}\,\nu\sigma_r^2 = -\nu\frac{GM(r)}{r^2}$$



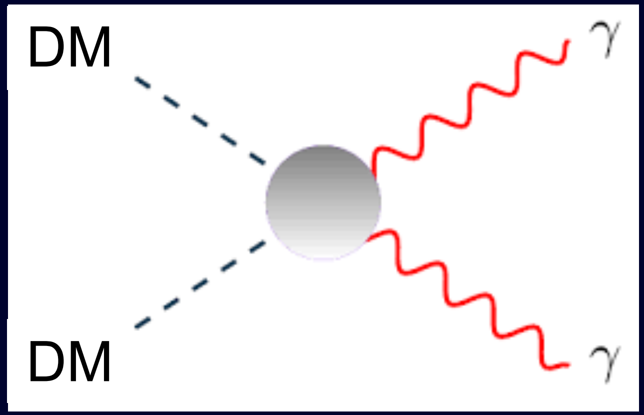
Hydrodynamics: hydrostatic equilibrium of X-ray gas



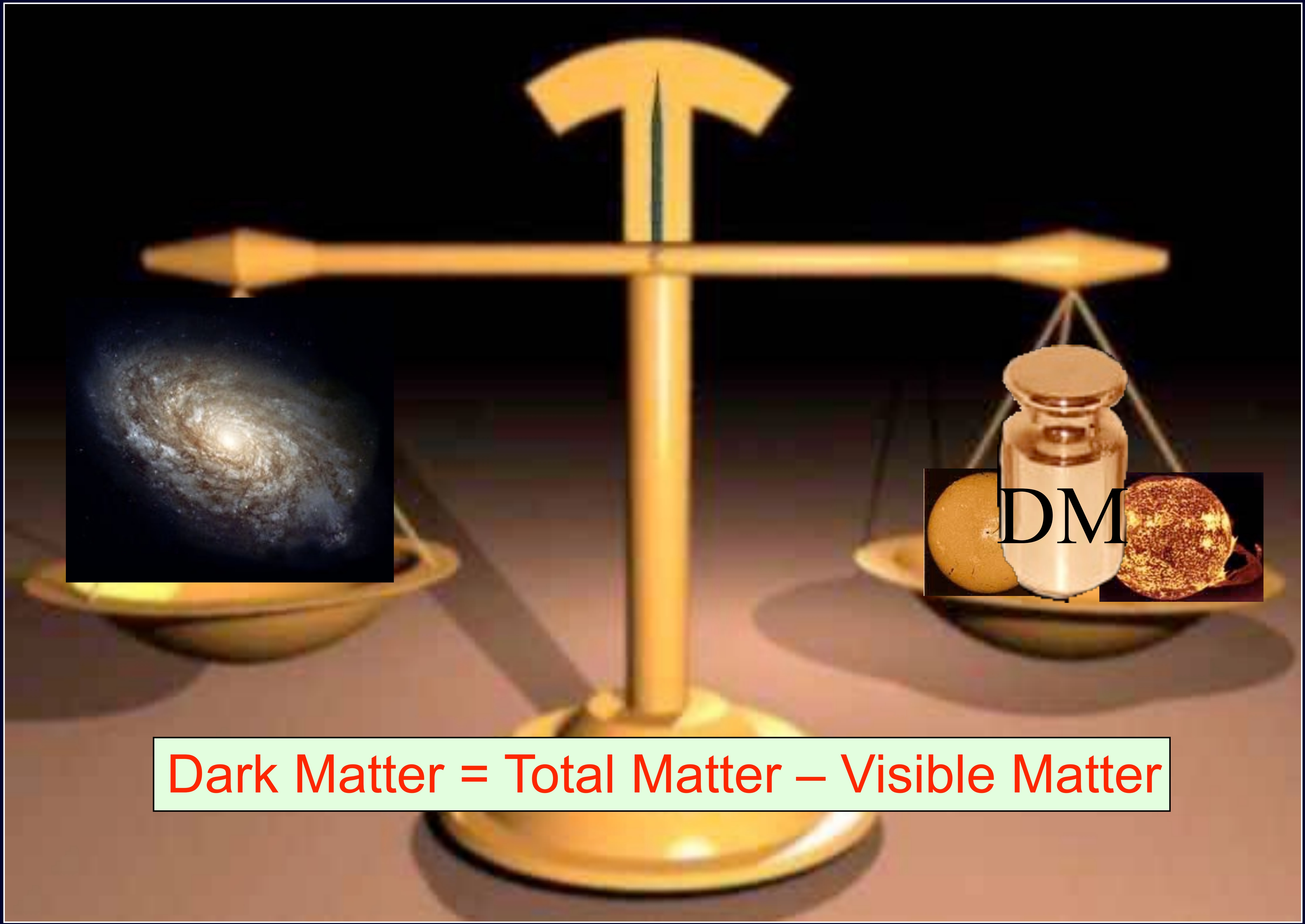
General relativity: gravitational lensing



Particle physics: γ-ray annihilation or decay

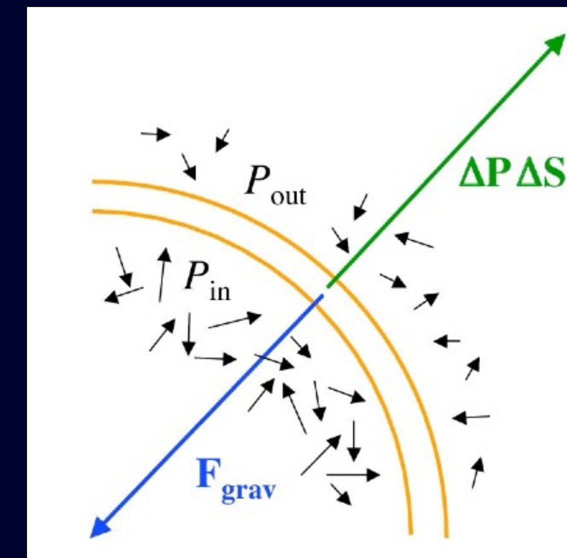


Subtract off visible matter!



Dark Matter = Total Matter – Visible Matter

Spheroidal systems: ***using different physics***



Newtonian dynamics: mass/orbit modeling

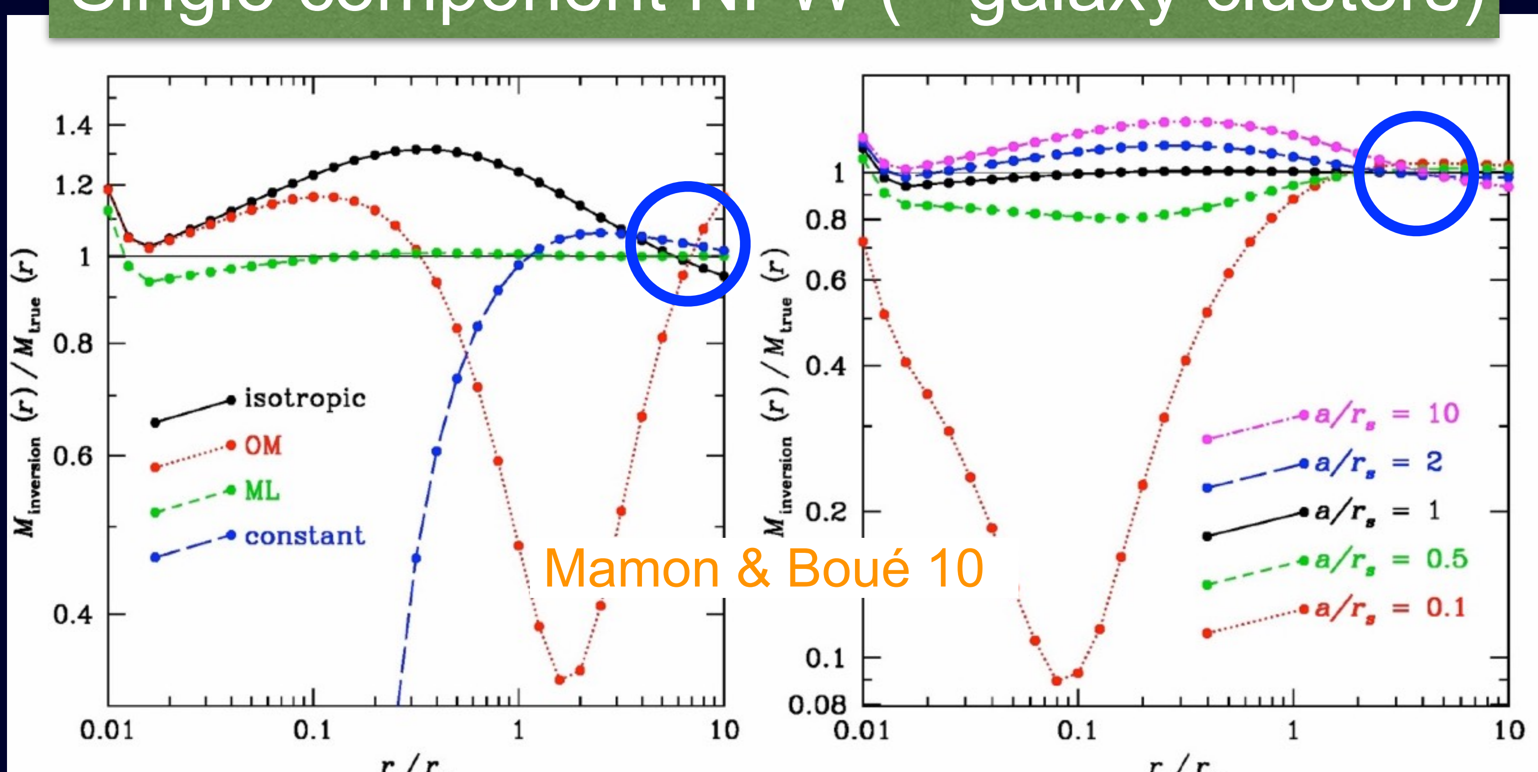
Jeans Equation

$$\nabla \cdot P = -\nu \, \nabla \Phi$$

$$\frac{d\left(\nu\sigma_r^2\right)}{dr} + 2\frac{\beta(r)}{r}\,\nu\sigma_r^2 = -\nu\frac{GM(r)}{r^2}$$

→ mass / (velocity) anisotropy degeneracy

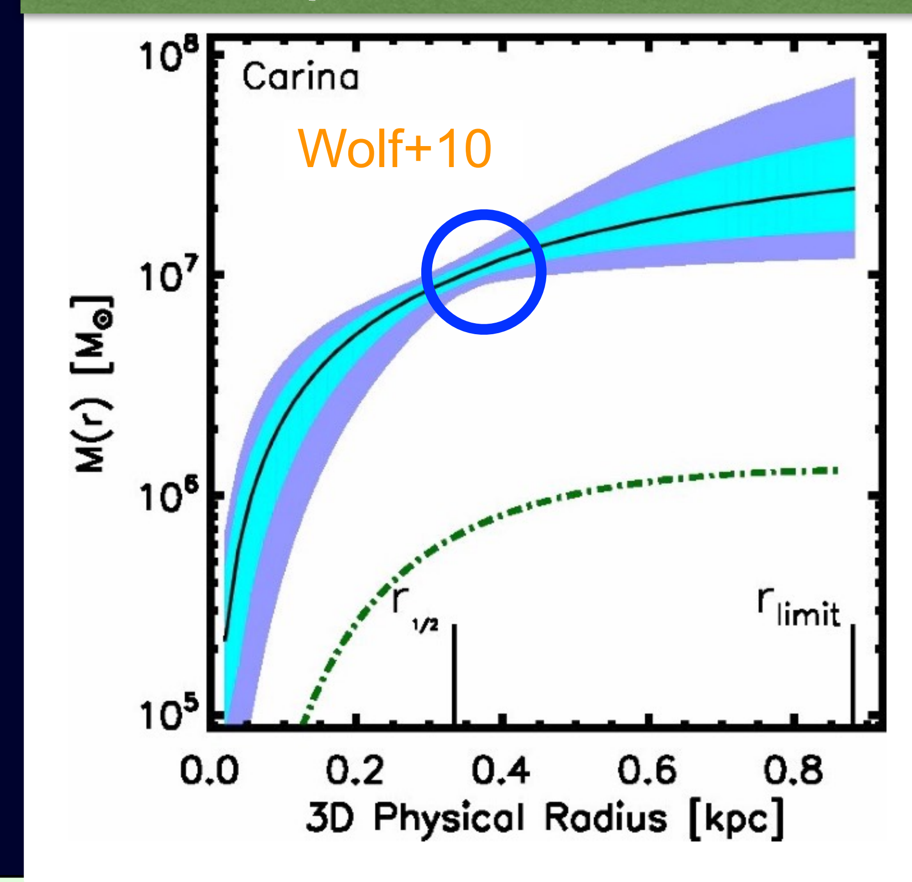
Single component NFW (~ galaxy clusters)



wrong anisotropy model

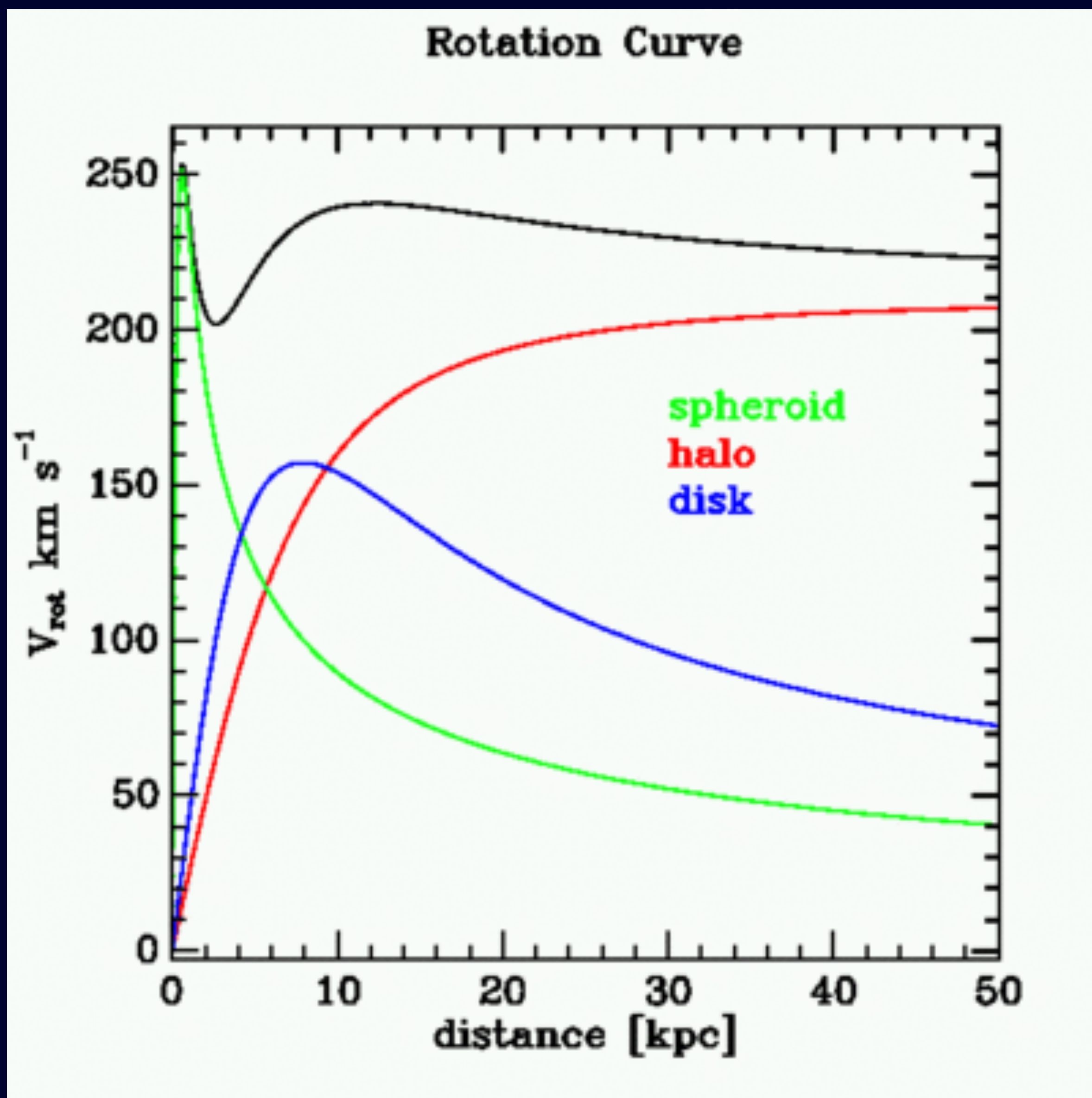
wrong anisotropy radius

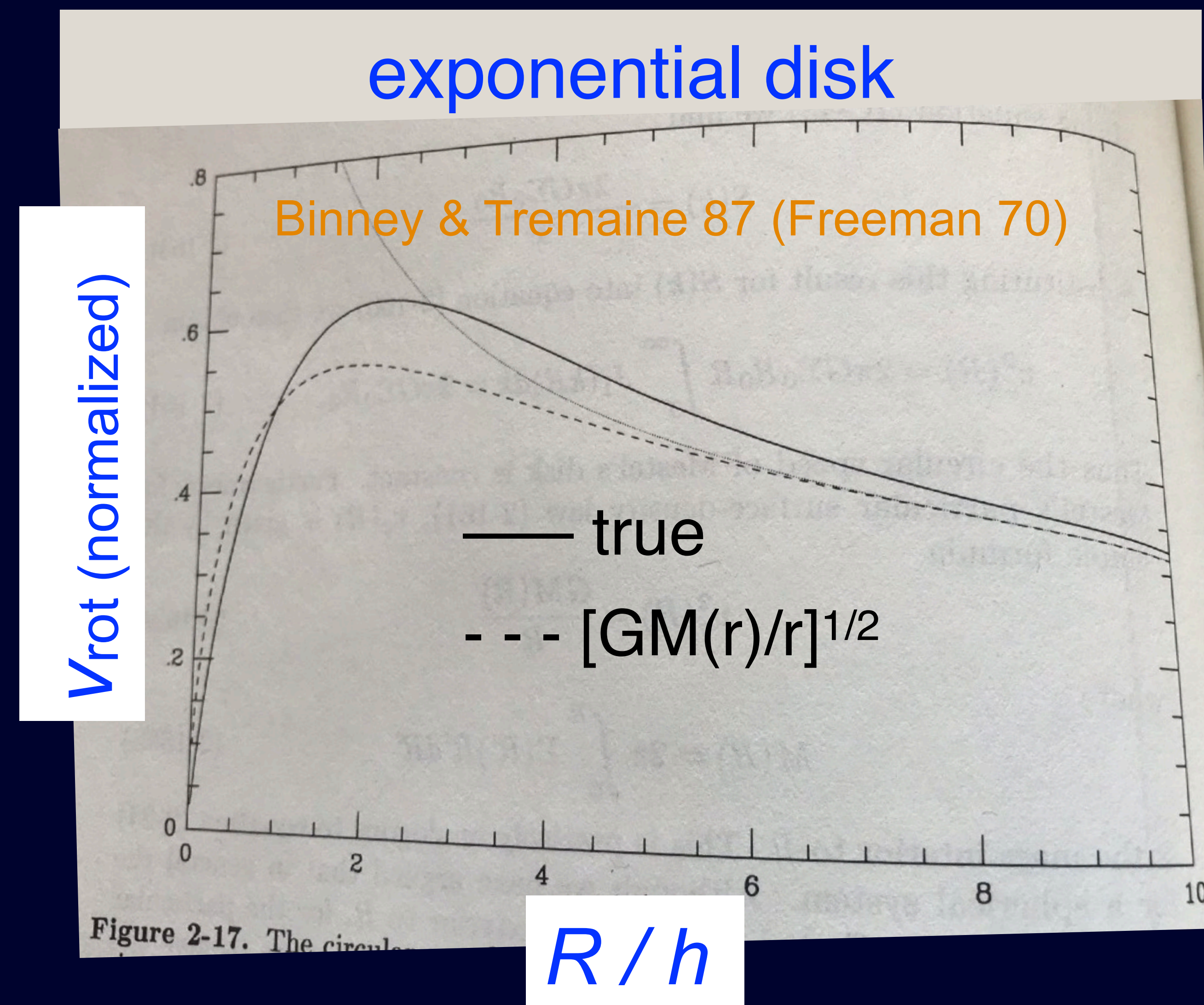
Dwarf Spheroidal Galaxies



"sweet" radius where mass independent of anisotropy

Disk galaxies: using Newtonian dynamics

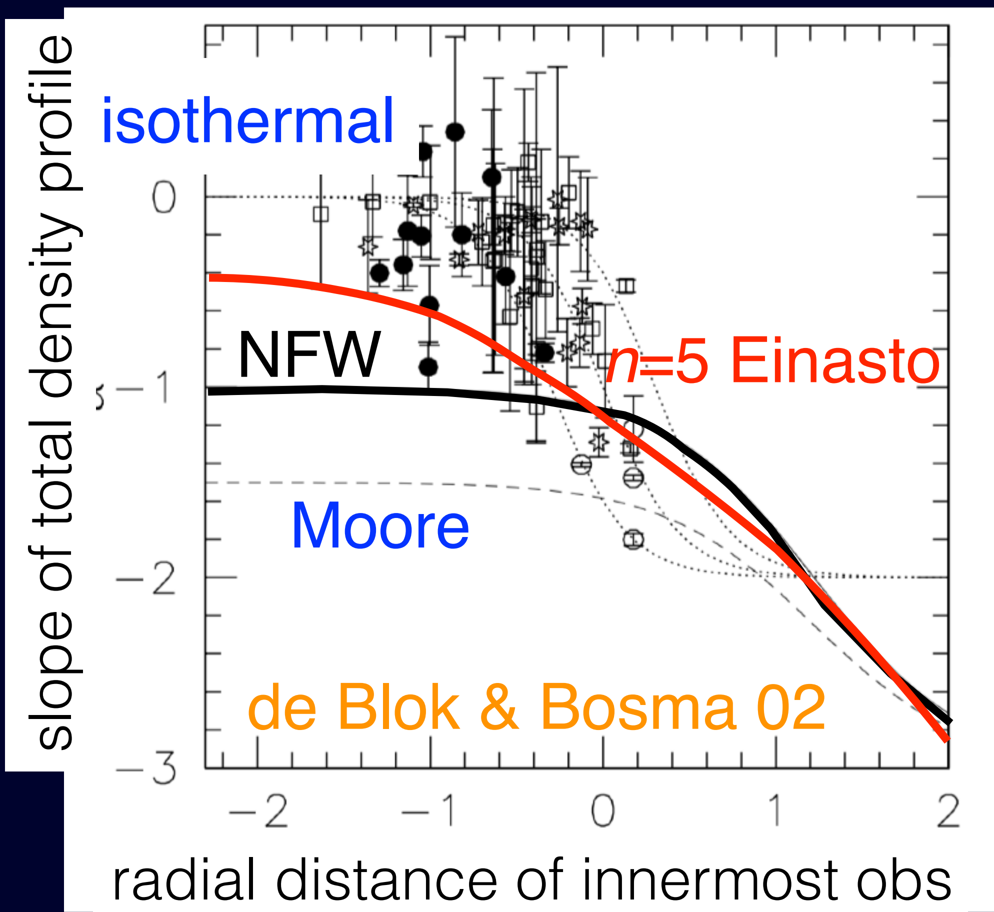




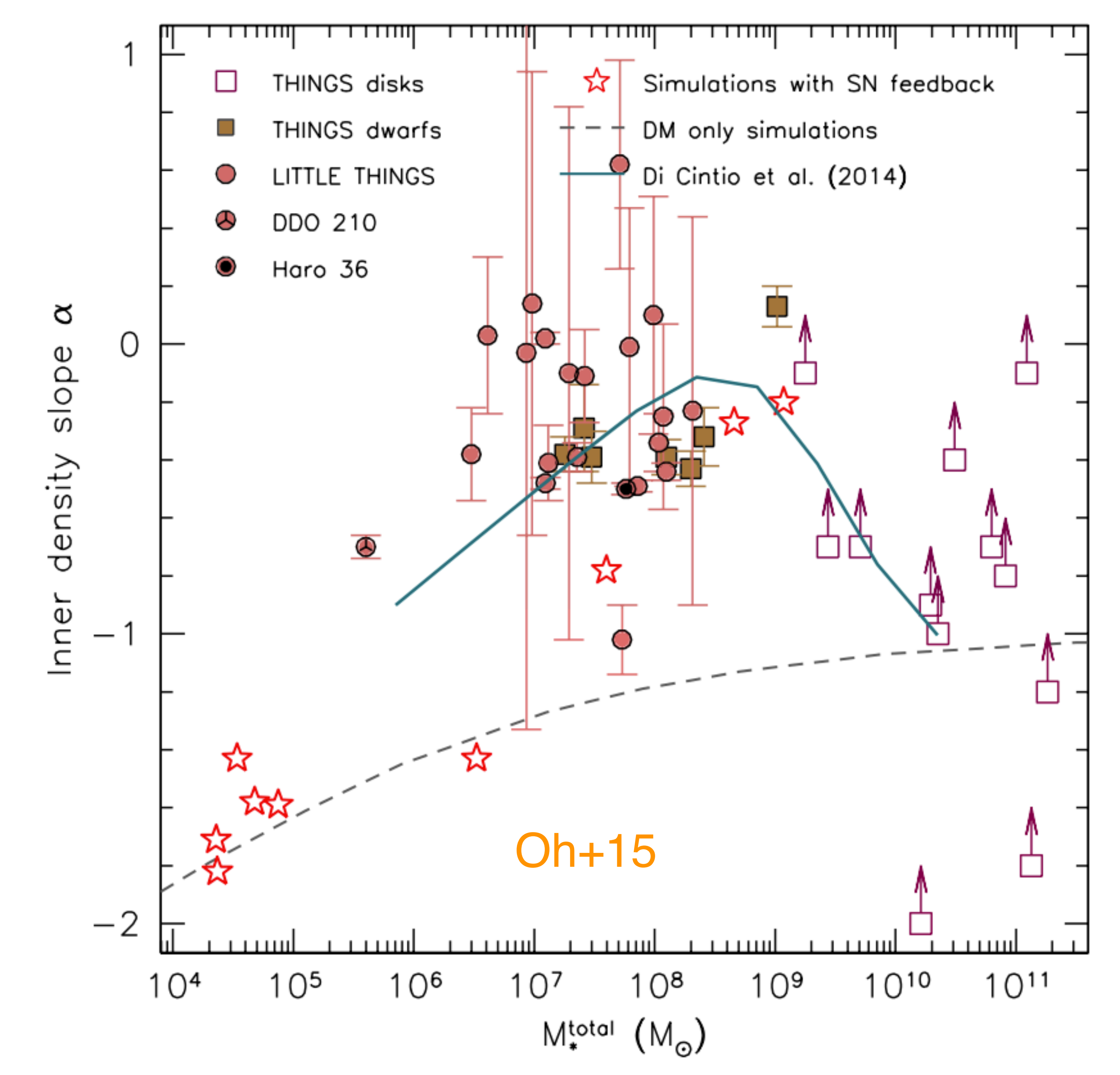
Dark Matter
in
spiral galaxies

Inner slopes of DM in disk galaxies

THINGS galaxies

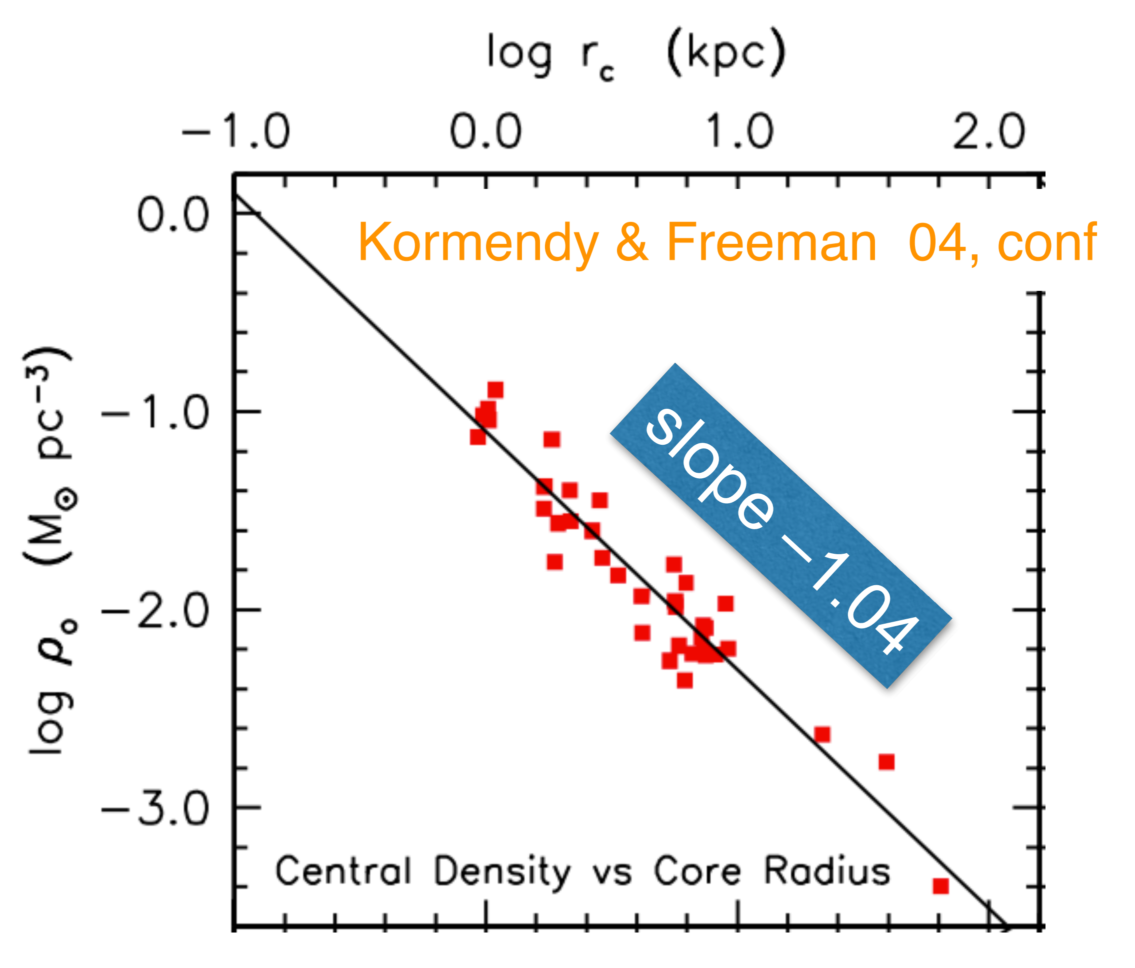


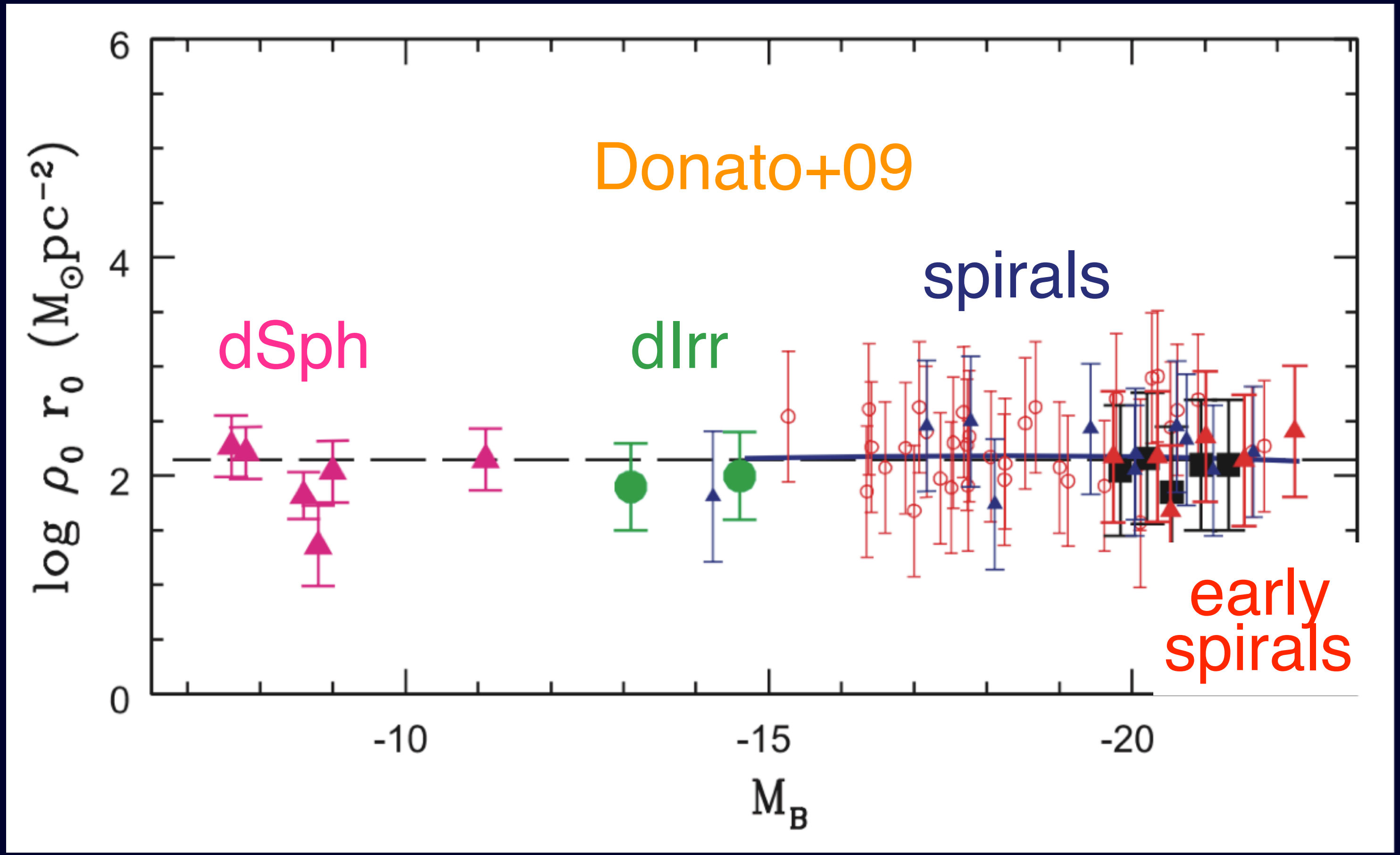
Einasto fits ⇒
n correlated with mass
Chemin+11; Ghari+19



gas-rich dwarfs have DM cores (in agreement with SPH sims)

Constant surface density DM cores of disk galaxies





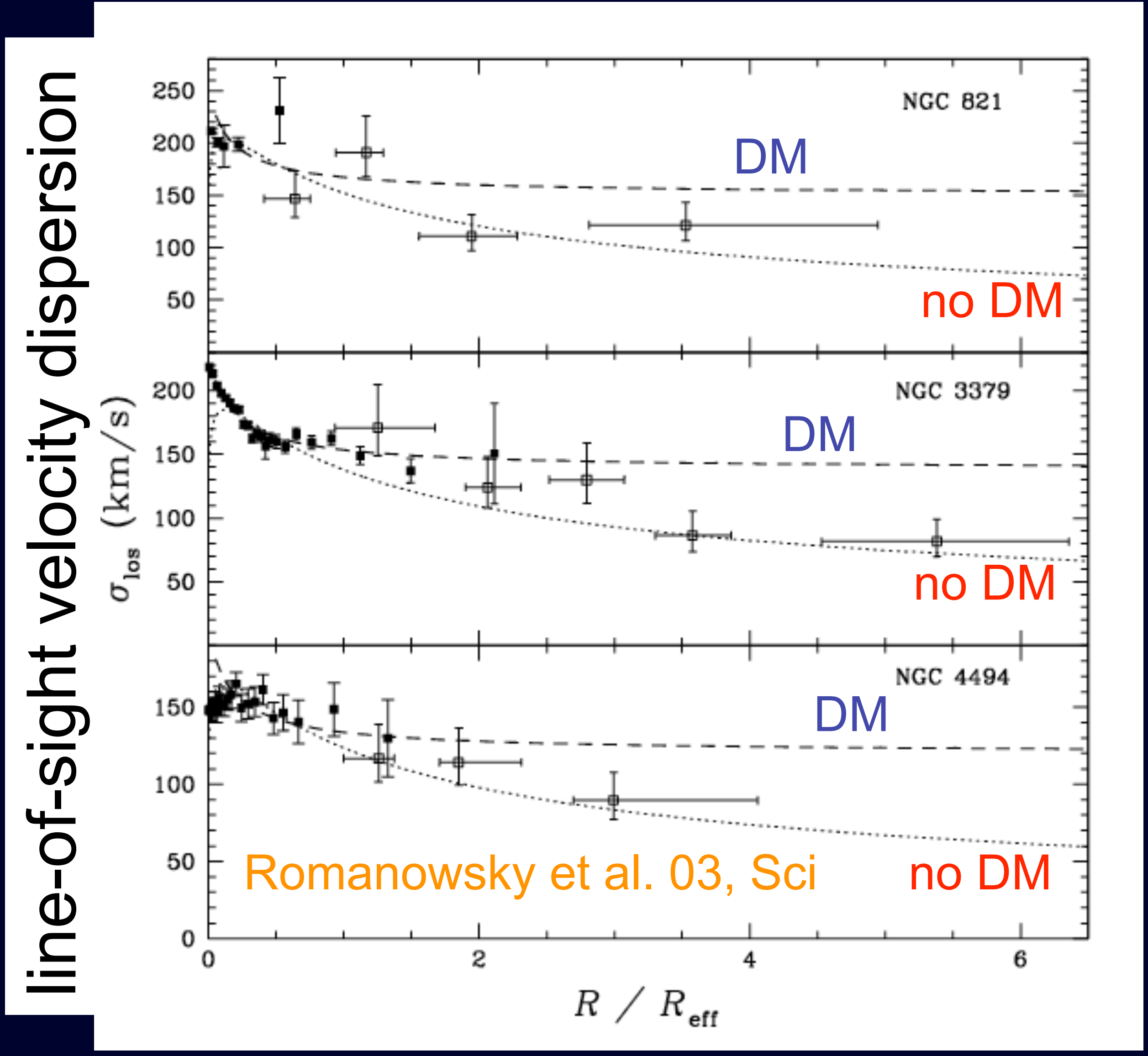
Dark Matter
in
elliptical galaxies

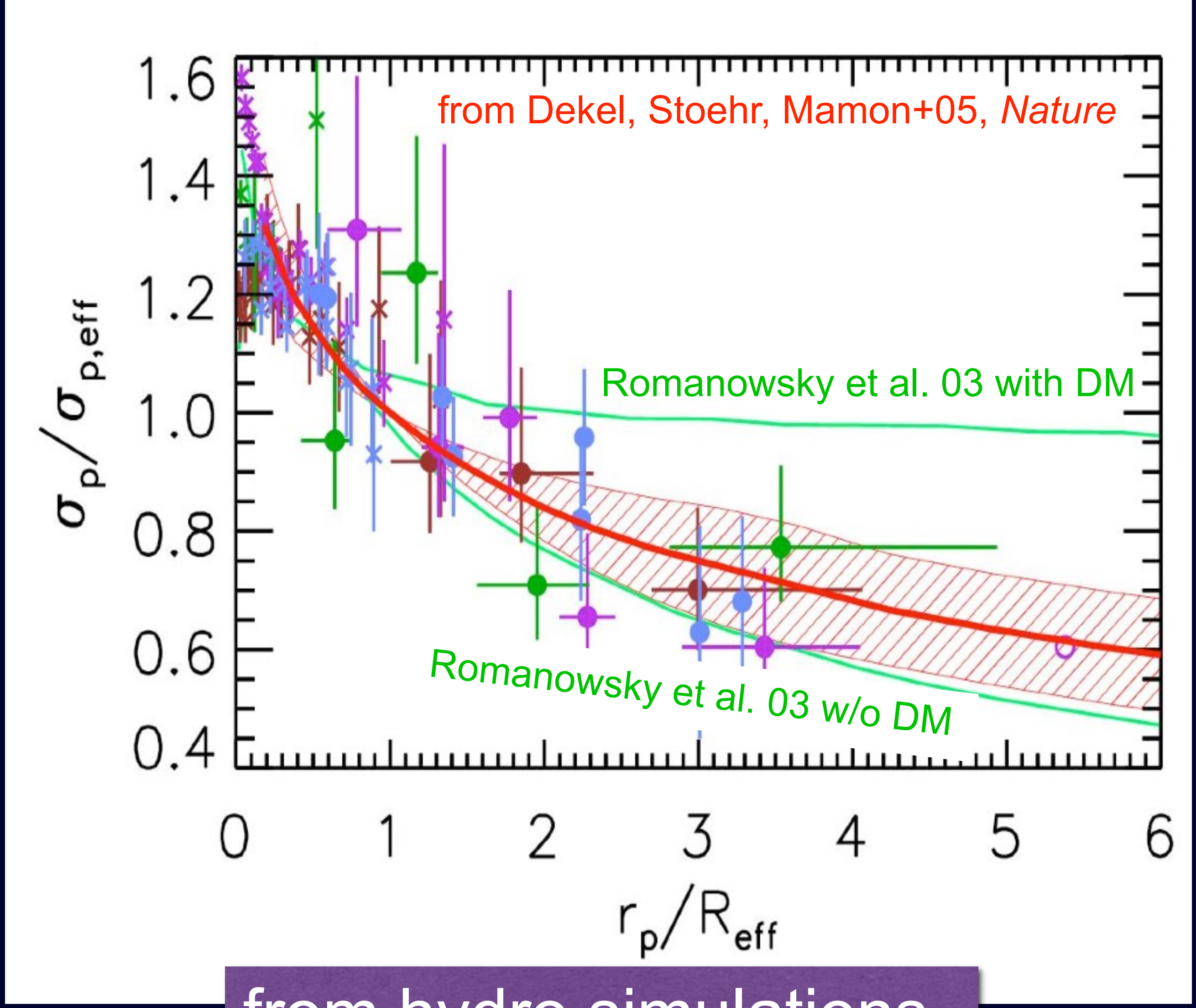
Missing Dark Matter in ellipticals?

Science 2003

A Dearth of Dark Matter in Ordinary Elliptical Galaxies

Aaron J. Romanowsky,[1,2*] Nigel G. Douglas,[2] Magda Arnaboldi,[3,4] Konrad Kuijken,[5,2] Michael R. Merrifield,[1] Nicola R. Napolitano,[2] Massimo Capaccioli,[3,6] Kenneth C. Freeman[7]



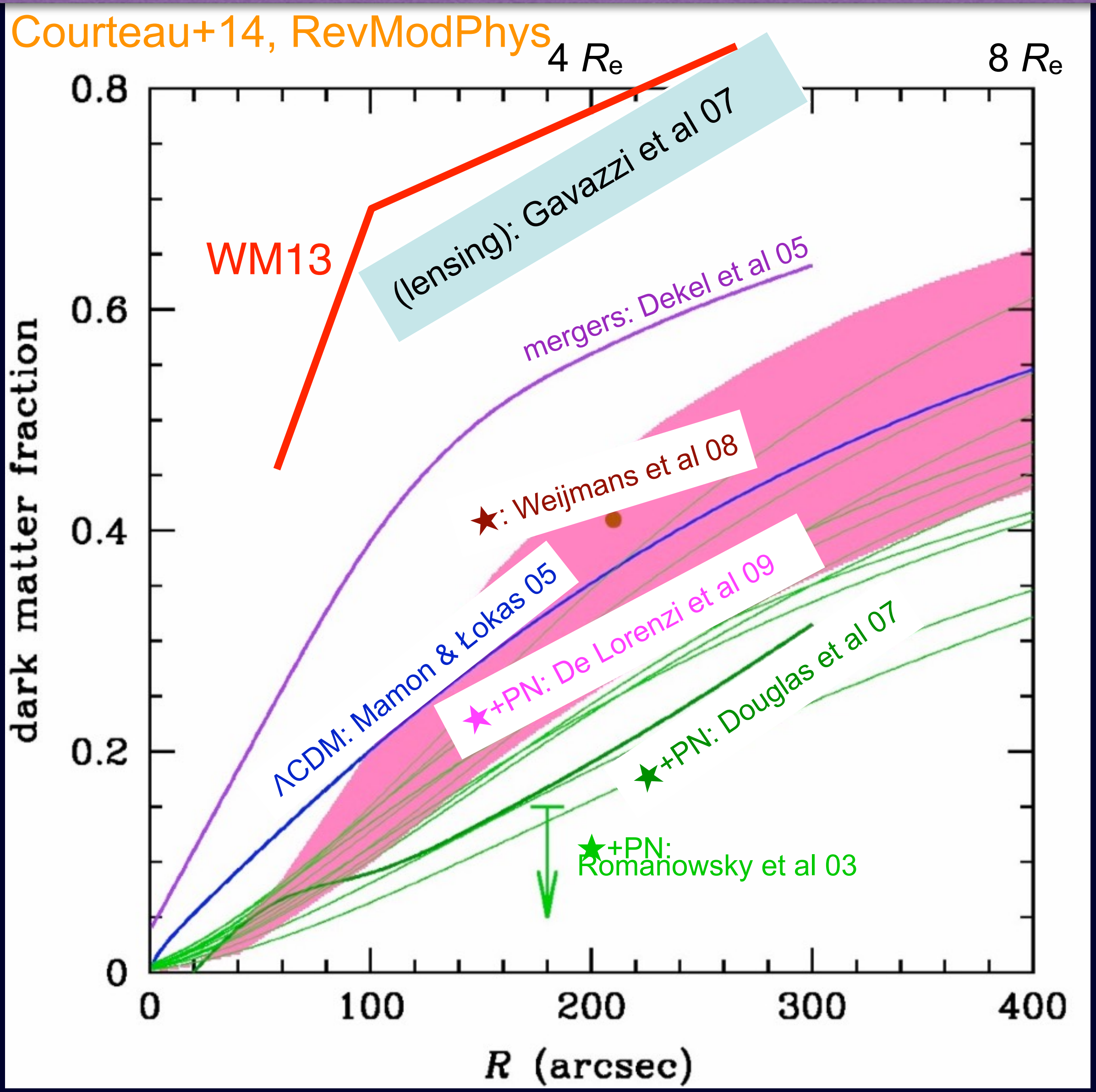


from hydro simulations of galaxy mergers

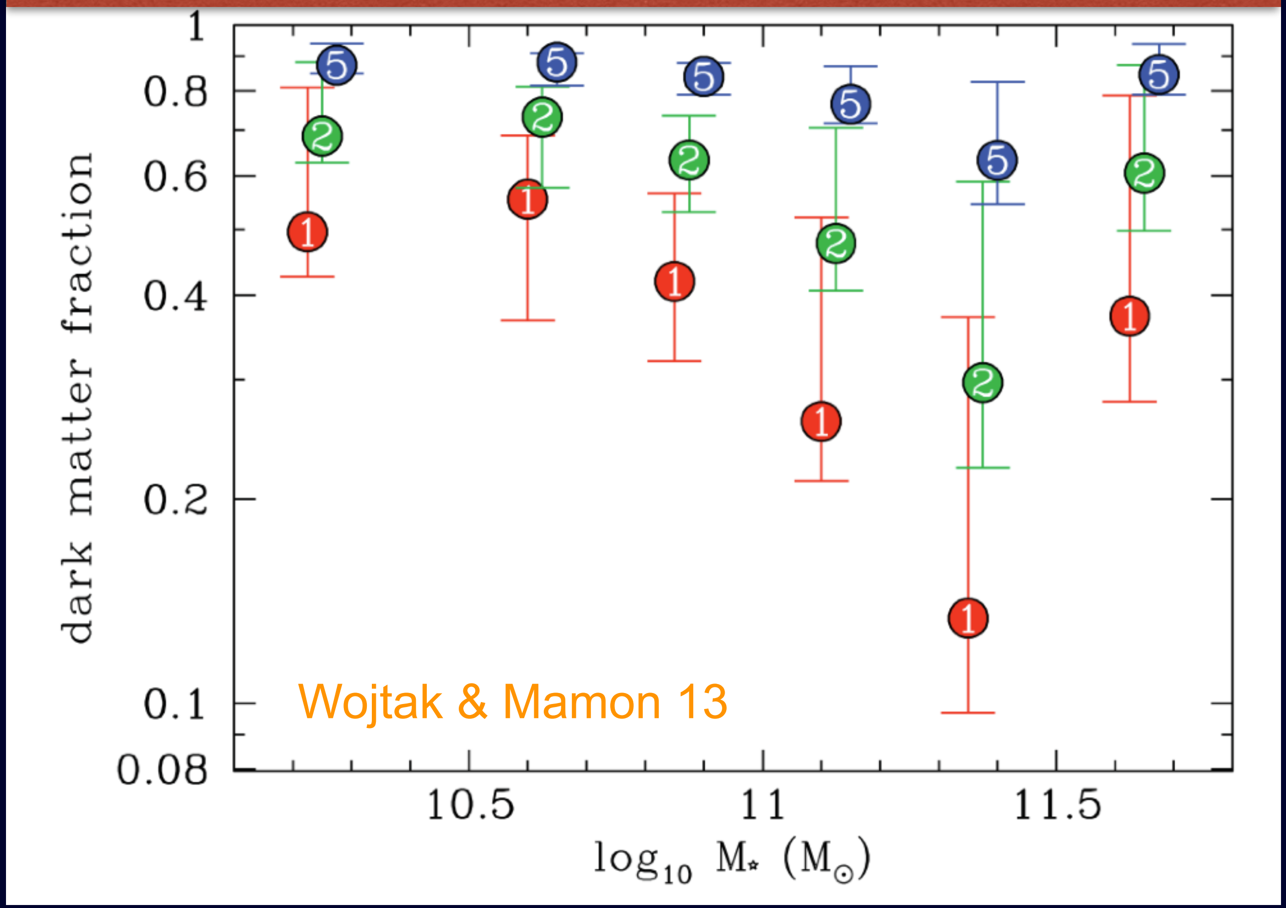
~ radial outer orbits!

Fractions of Dark Matter vs. radius

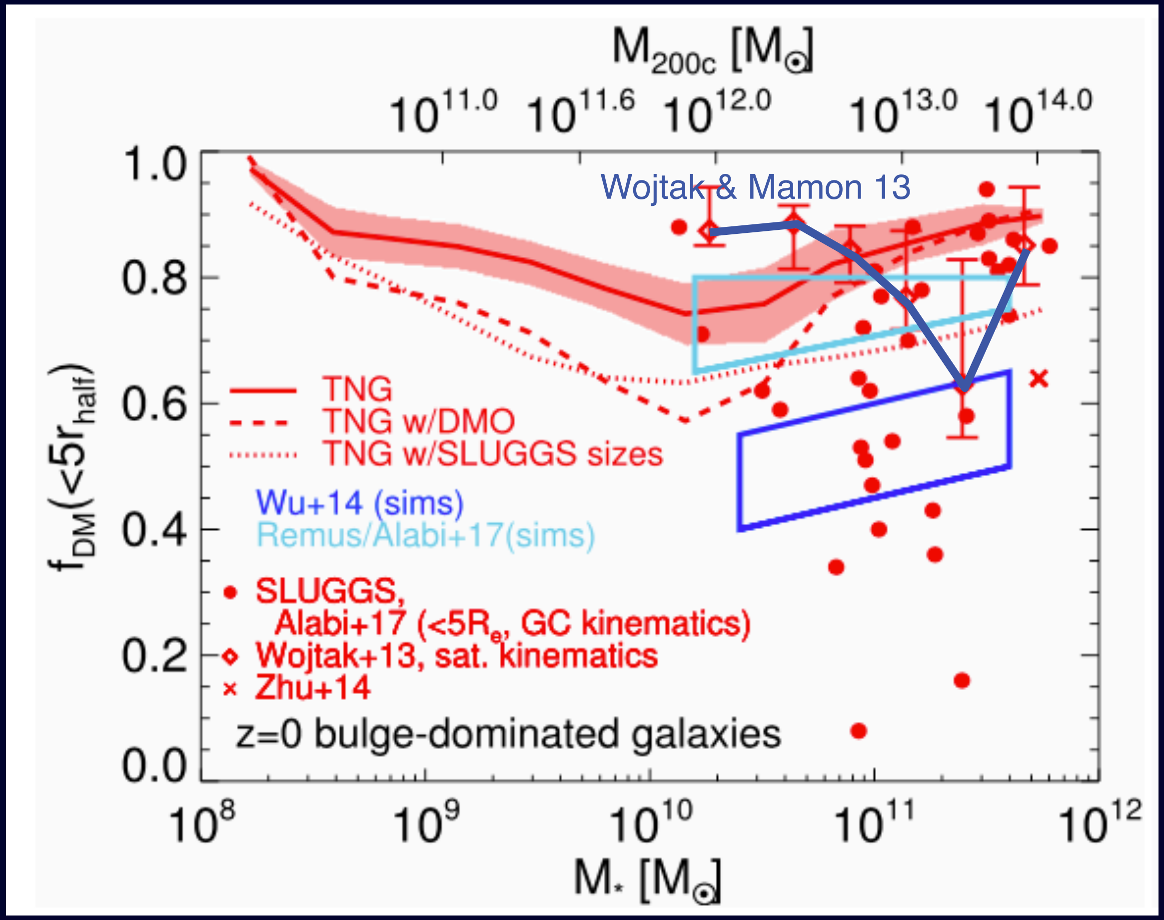
DM fraction vs radius for NGC 3379 (log M_{stars}=10.75)

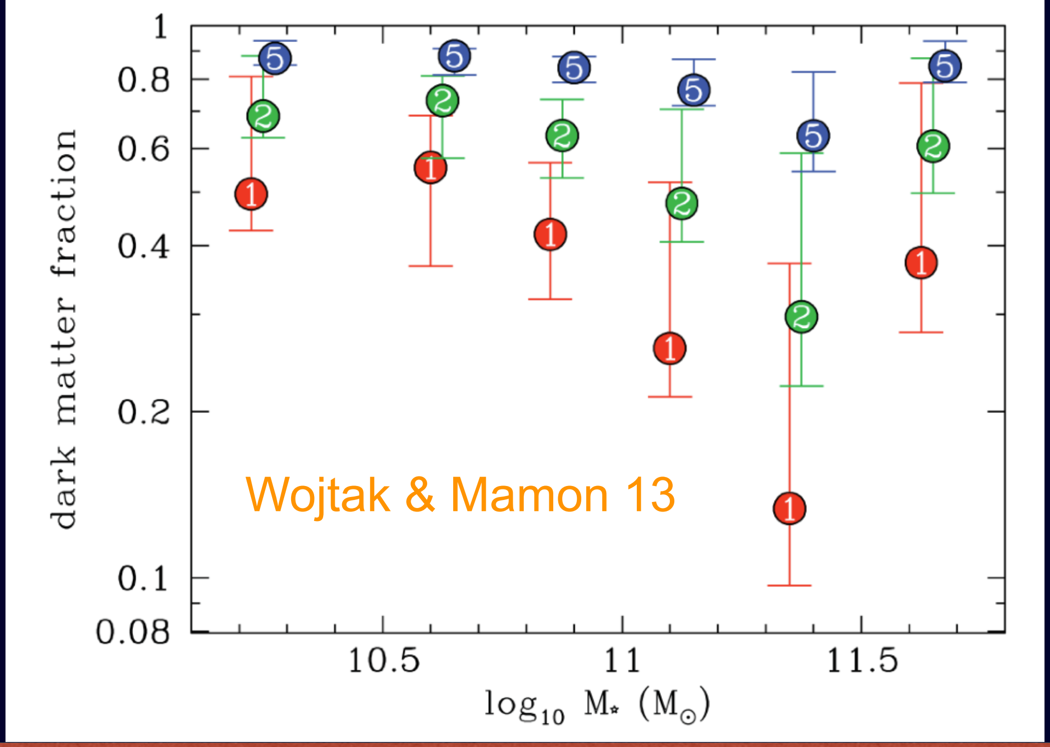


dark matter fraction vs mass at 1, 2 & 5 R_{eff} from satellite kinematics of SDSS galaxies



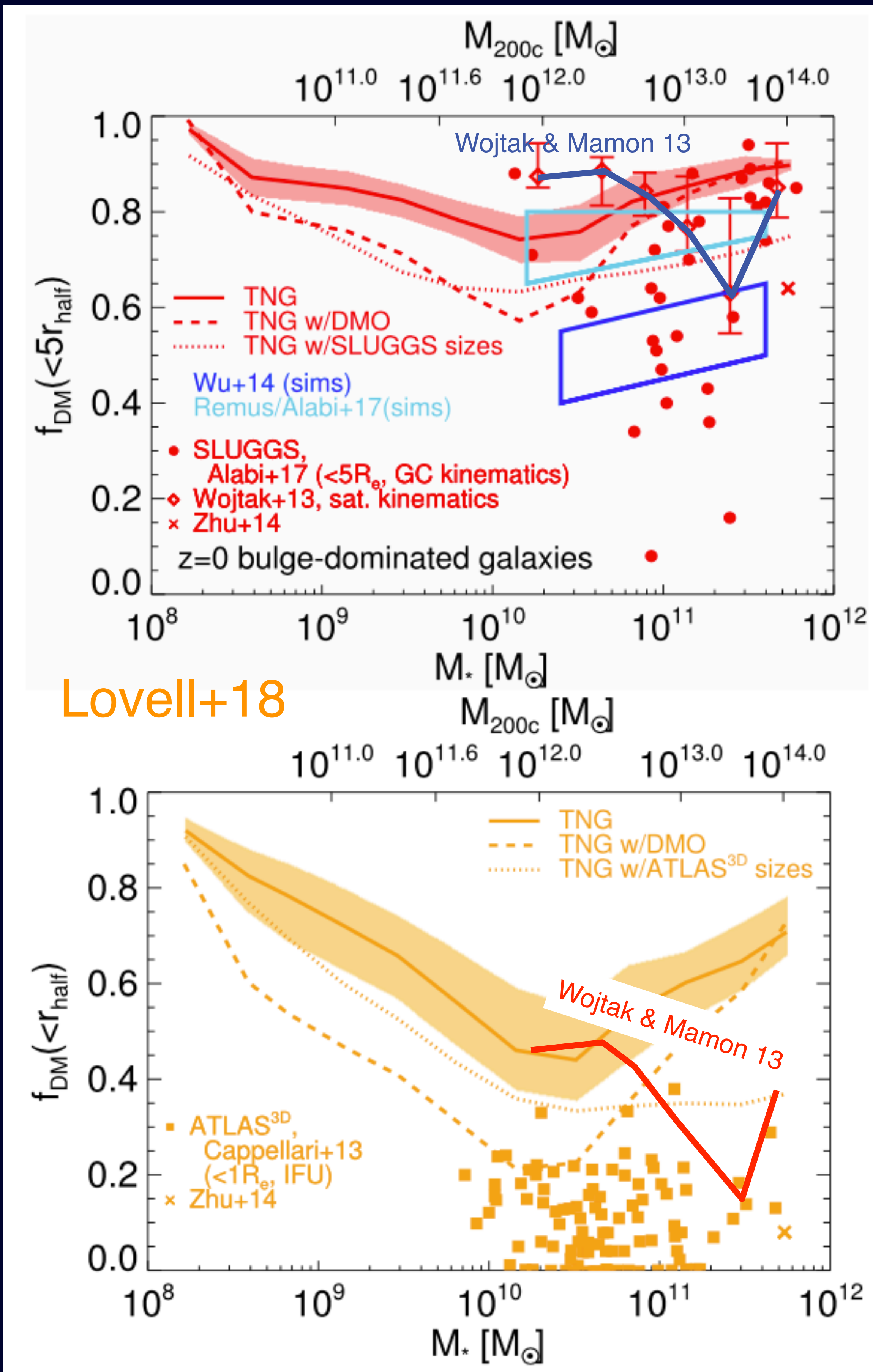
Dark Matter fractions

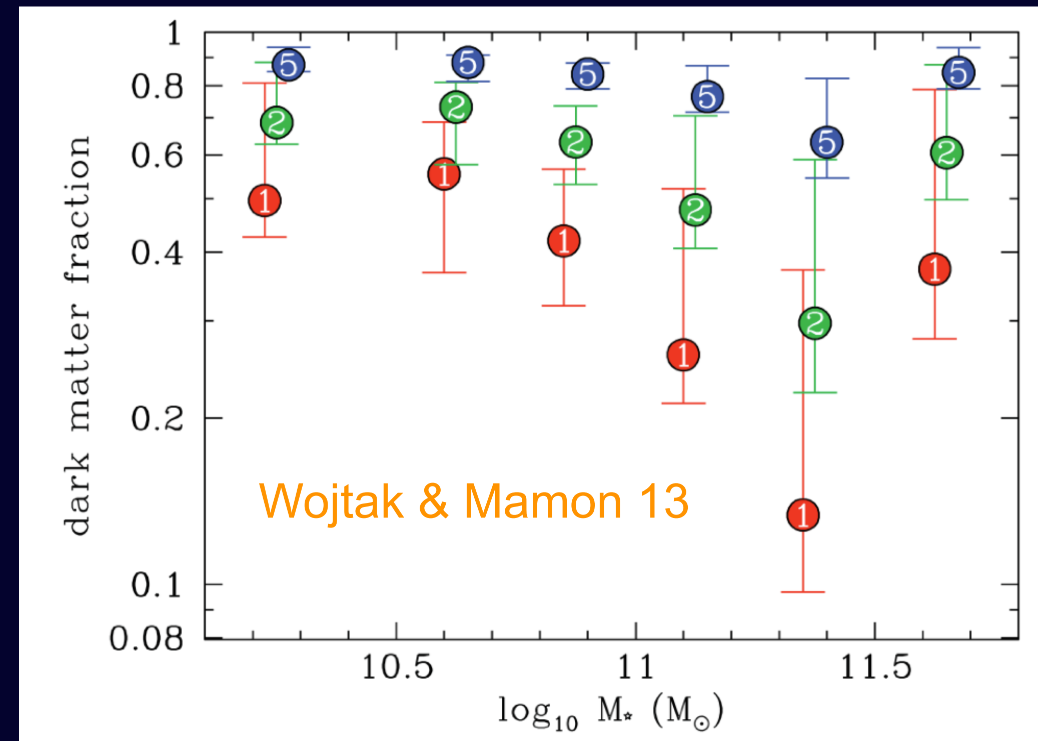




dark matter fraction vs mass at 1, 2 & 5 R_{eff}

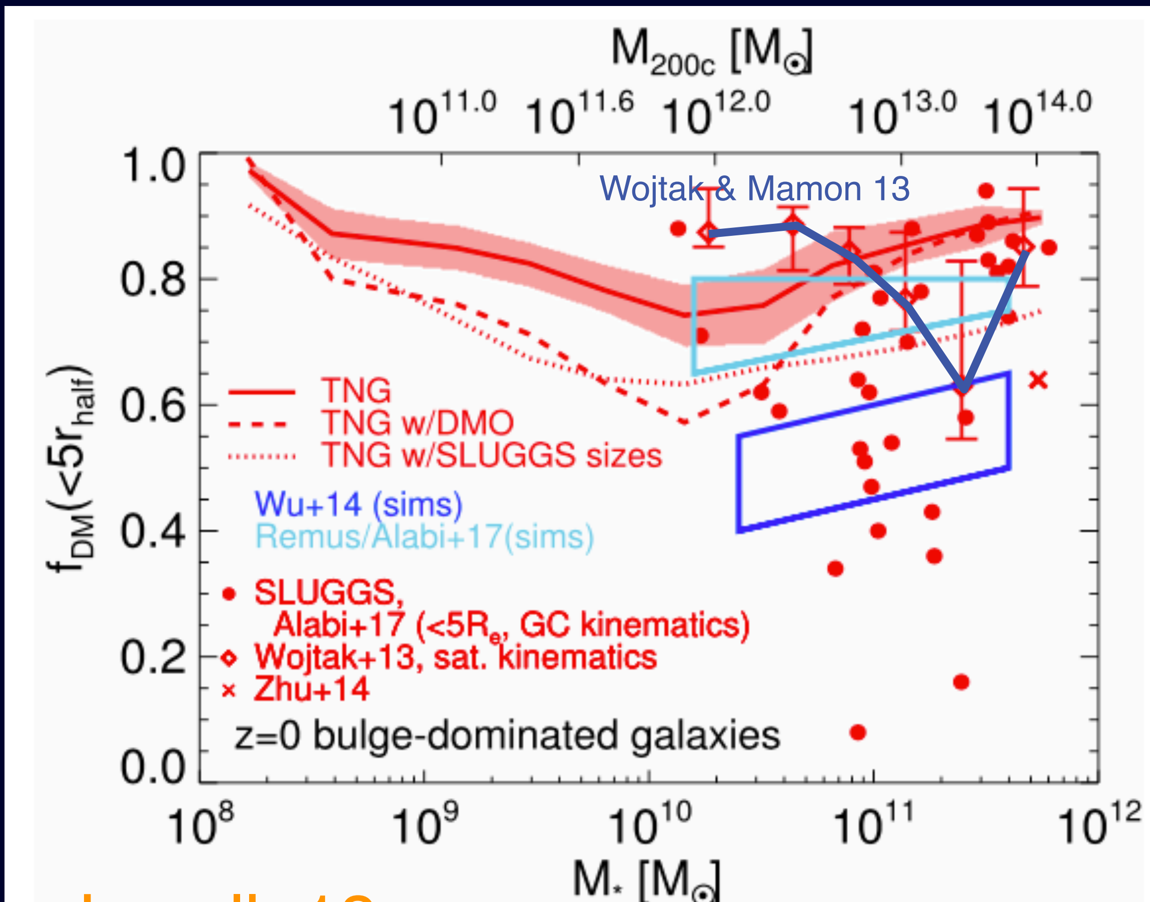
Dark Matter fractions



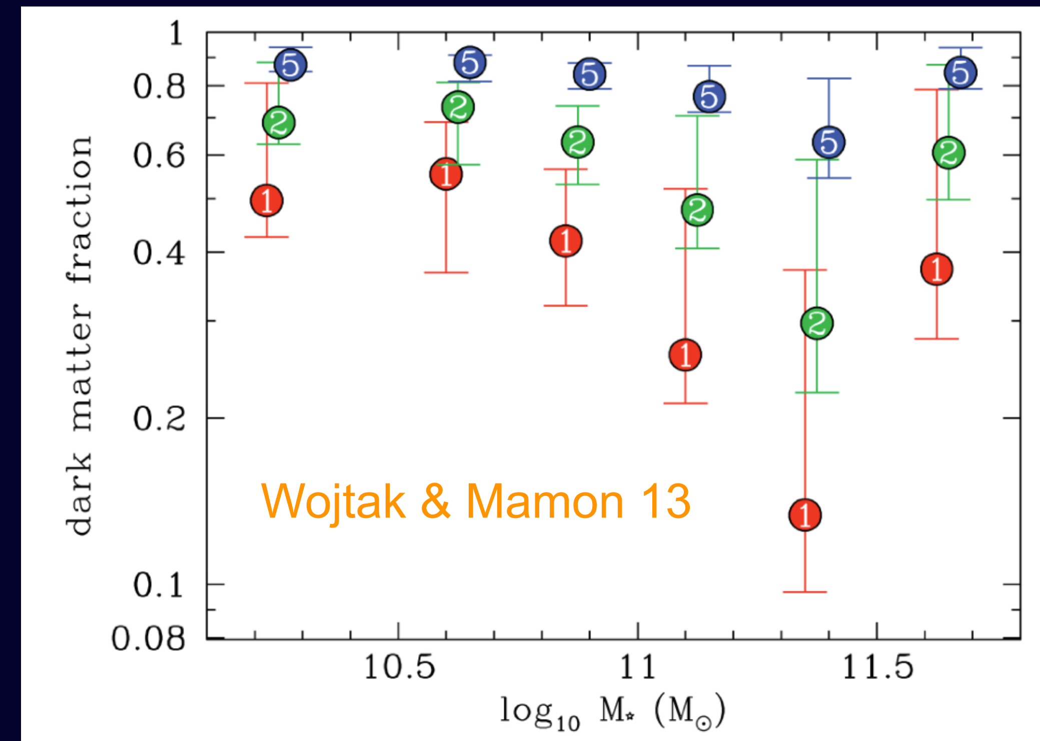


dark matter fraction vs mass at 1, 2 & 5 R_{eff}

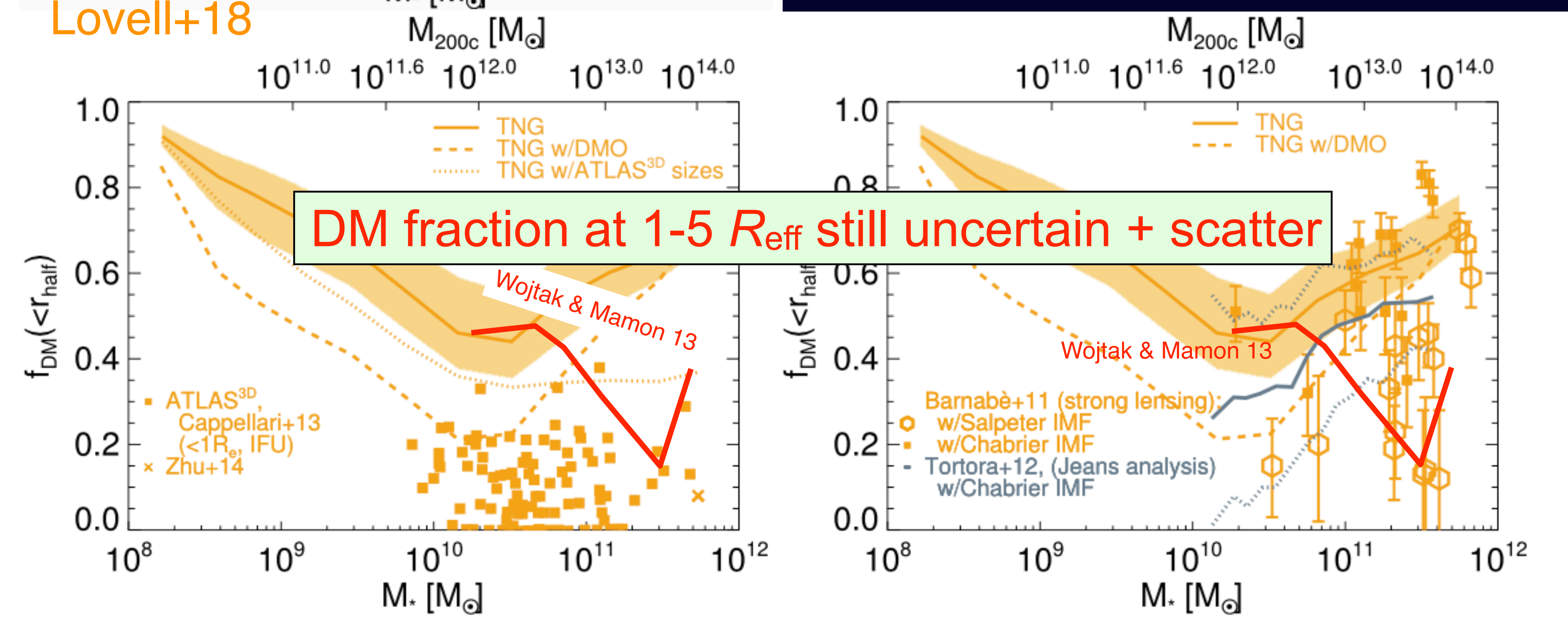
Dark Matter fractions



Lovell+18



dark matter fraction vs mass at 1, 2 & 5 $R_{\rm eff}$



DM fraction at 1-5 $R_{\rm eff}$ still uncertain + scatter

Missing Dark Matter in Ultra-diffuse galaxies?

LETTER van Dokkum+18, *Nature*

doi:10.1038/nature25767

A galaxy lacking dark matter

Pieter van Dokkum[1], Shany Danieli[1], Yotam Cohen[1], Allison Merritt[1,2], Aaron J. Romanowsky[3,4], Roberto Abraham[5], Jean Brodie[4], Charlie Conroy[6], Deborah Lokhorst[5], Lamiya Mowla[1], Ewan O'Sullivan[6] & Jielai Zhang[5]

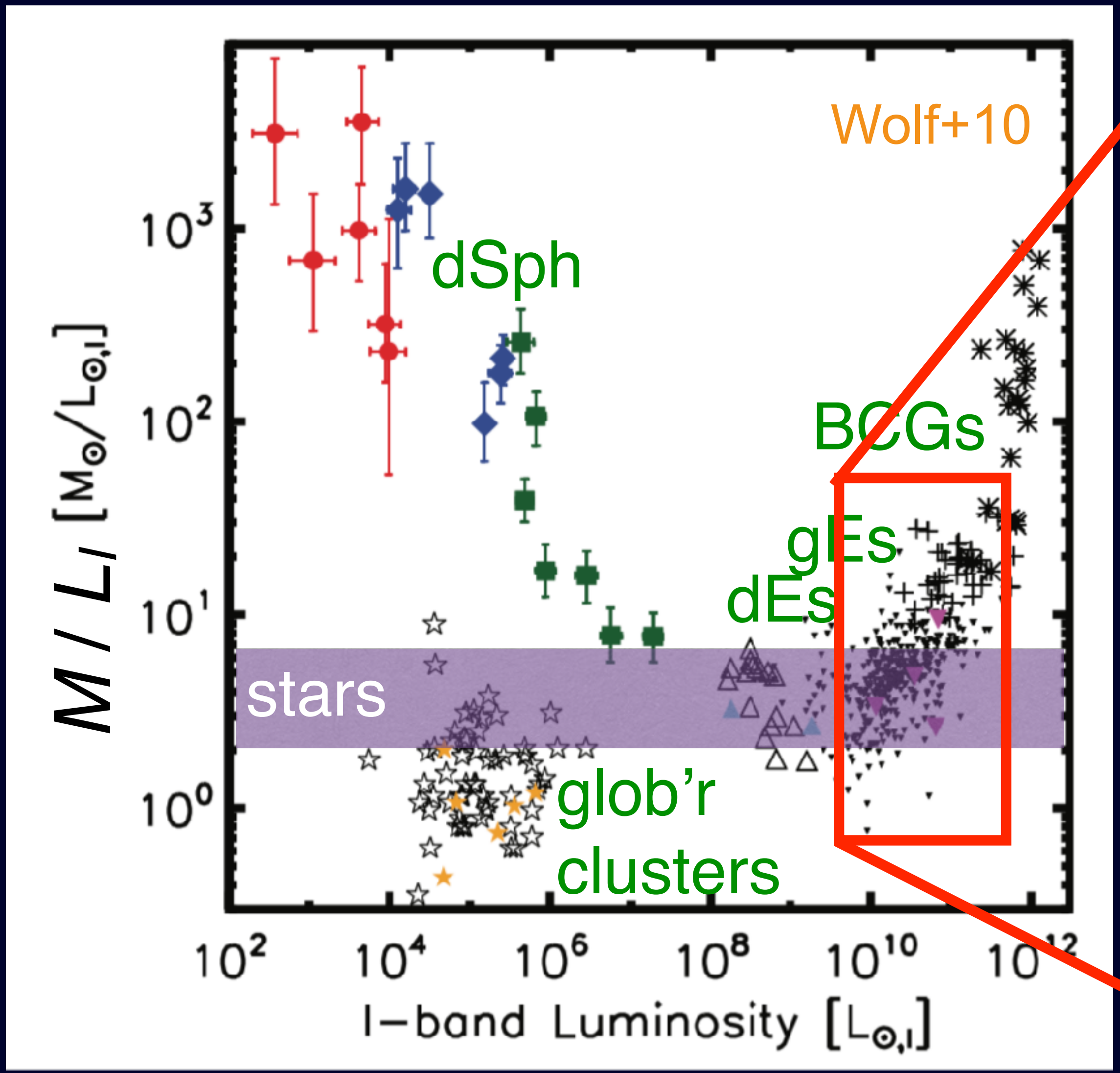
10 globular cluster redshifts
→ $\sigma_{\rm LOS}$ ~8 km/s (incl. one outlier) ⇒ $\sigma_{\rm intrinsic}$ ~3 km/s

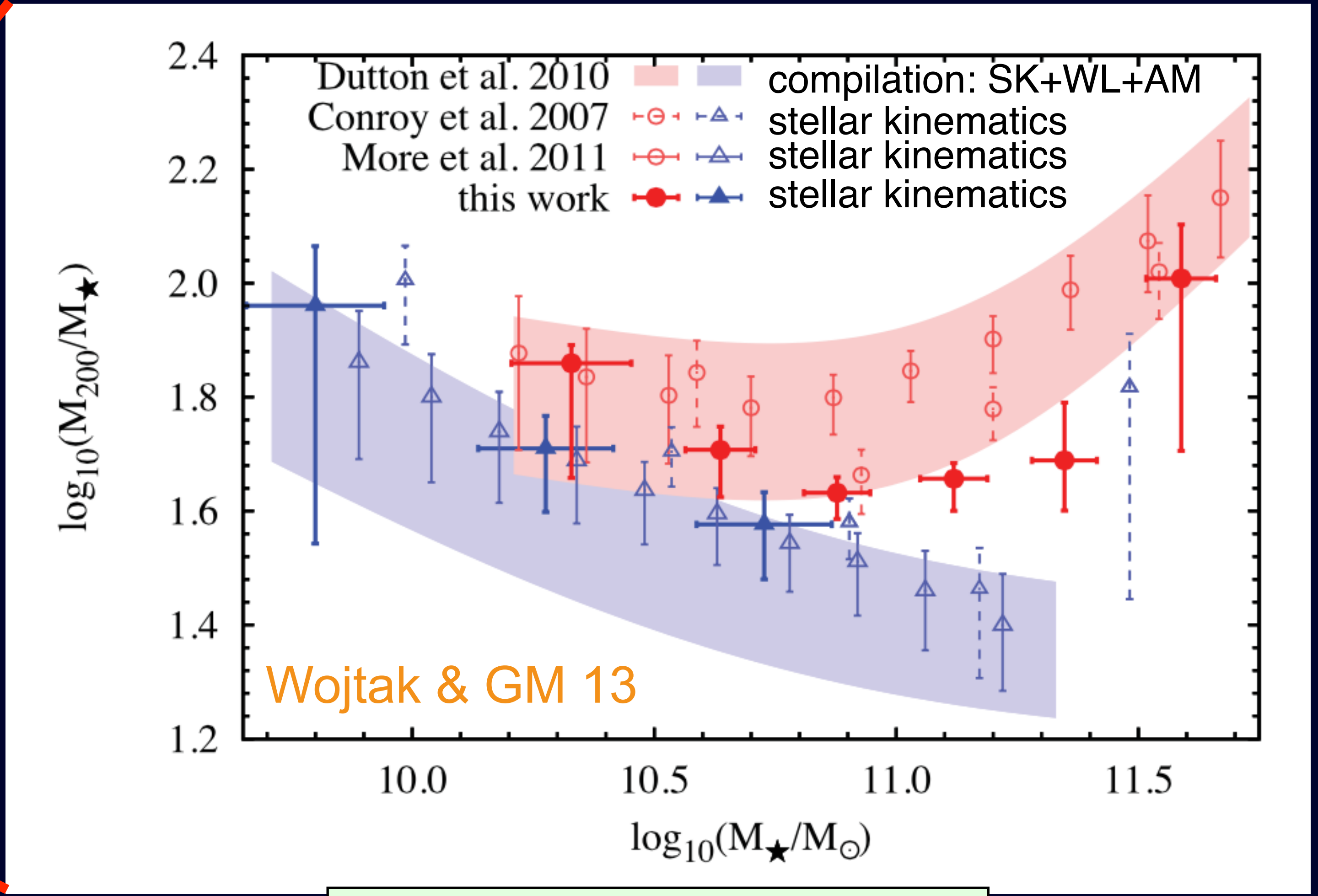
⇒ dark matter fraction($R_{\rm max}$) < **0.4** (90% confidence)

- Re-analysis of velocity dispersion Martin+18; Laporte+19
- Stellar mass — halo mass prior Wasserman+18
- Surface density of GC distribution: Sersic instead of power-law Hayashi & Inoue 18
- Modeling with tides Nusser 19
- 30% closer distance Trujillo+19
- Velocity dispersions: stellar > GC Emsellem+19

DM fraction($R_{\rm max}$) < **0.9** (90% cl)

Low-mass dwarfs are darker

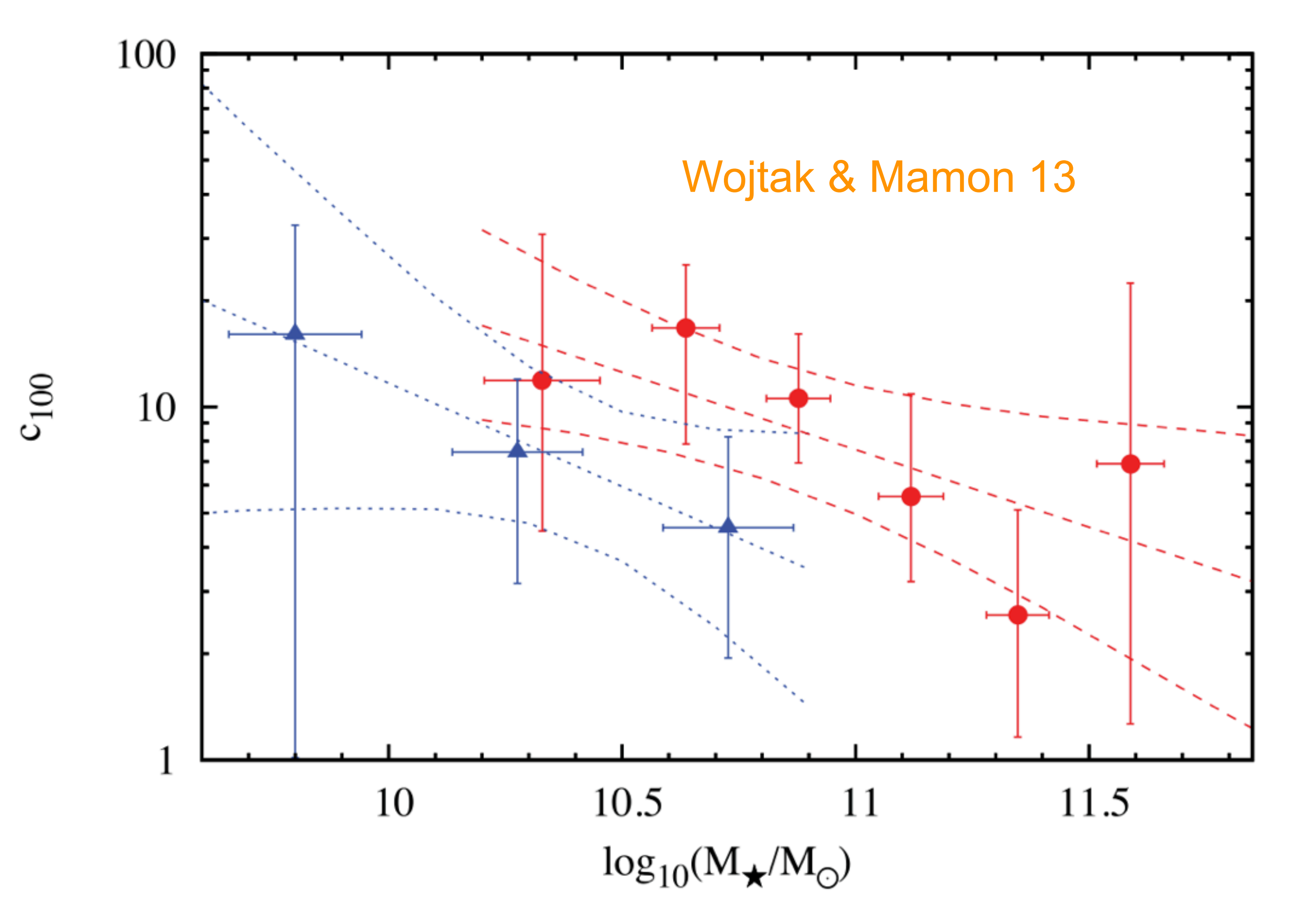




color-dependence

Dark matter concentration

DM concentration vs. mass



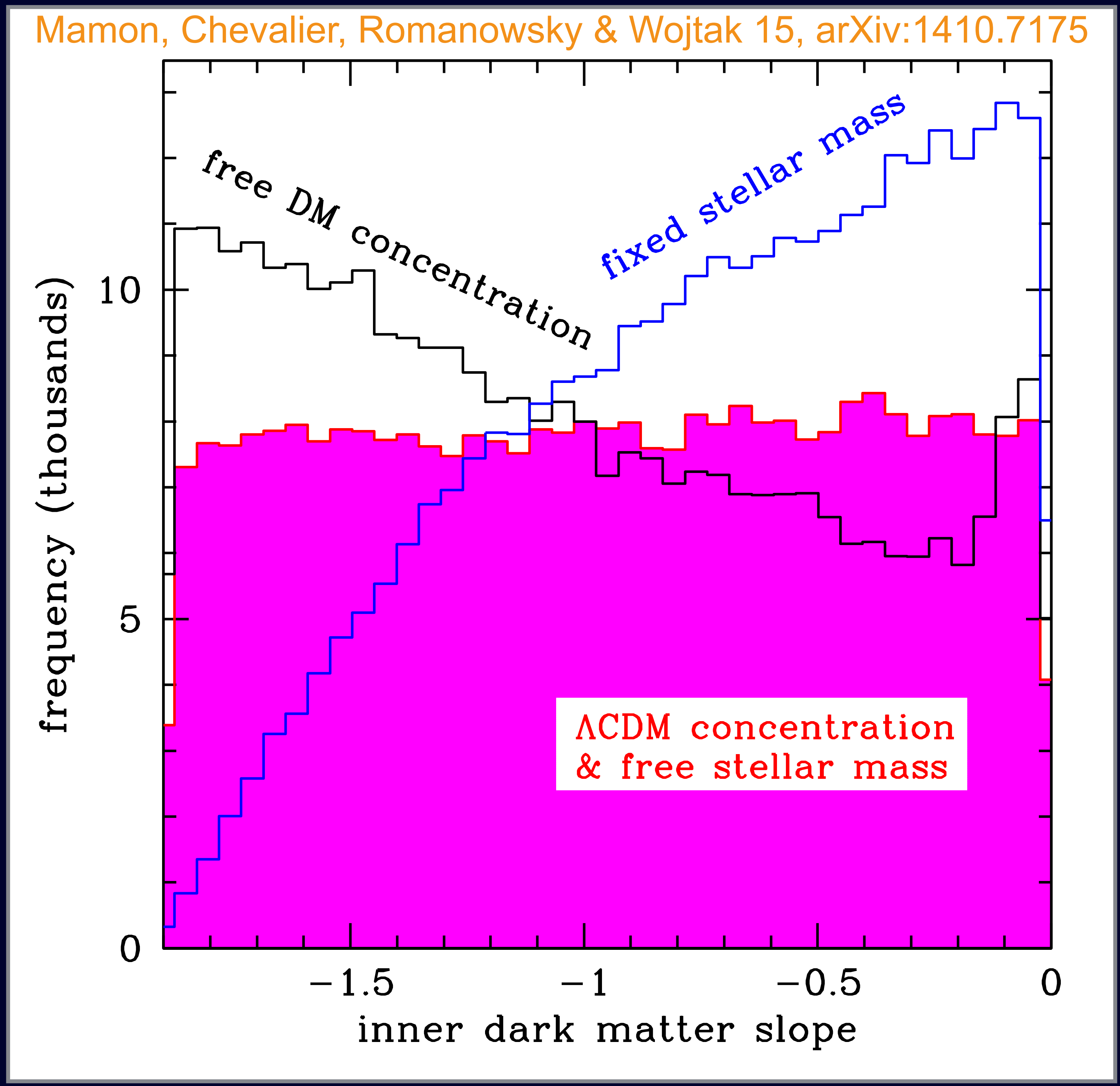
red galaxies have *greater DM concentration* than blue galaxies of same stellar (or total) mass

Signature of *galaxy assembly bias*:
old (young) stellar populations in galaxies whose DM halos assembled earlier (later)

Fornax: core (WP11, AAE13, Diak+17) OR cusp (BH13)
Sculptor: core (WP11, Breddels+13) OR cusp (RF14, BH13, SFW17) OR in between (Zhu+16)

Authors	Galaxies	Method	Results	Comments
Walker & Penãrrubia 11	Fornax & Sculptor	Wolf pinch with 2 populations	both core	non-cst σ_{LOS}?
Jardel+13	Draco	orbit (non-parametric)	cuspy: γ = –1±0.2	
Amorisco, Angello & Evans 13	Fornax	Wolf pinch with 3 populations	core: $r_0 = 1^{+0.8}_{-0.4}$ kpc OR huge c	1 pop has non-cst σ_{LOS}
Richardson & Fairbairn 14	Sculptor	dispersion-kurtosis	cuspy if Plummer tracer	
Breddels+13	Sculptor	orbit model'g fit to σ_{LOS} & κ_{LOS}	core, but cusp not ruled out	
Breddels & Helmi 13	Fornax, Sculptor, Carina & Sextans	orbit model'g fit to σ_{LOS} & κ_{LOS}	joint: cuspy	
Mamon+15, conf	Fornax	MAMPOSSt	cuspy, core or undetermined	depends on priors!
Pace 16	Ursa Minor	2 populations	core, but cusp not ruled out	
Zhu+16	Sculptor	Watkins	γ = –0.5±0.3	Gaussian v_{LOS}, non-spherical
Strigari, Frenk & White 17	Sculptor	separable $f(E,J)$ on binned data	consistent with NFW	only tried NFW Gaussian σ_{LOS} error
Diakogiannis+17	Fornax	non-param. β inversion	mass follows light!	tangential outer anisotropy: merger

DM inner slope depends on priors!



Conclusions

DM required in galaxies in standard gravitational physics

Kinematic studies ≈ confirm U-shaped $M_{\mathrm{tot}}/m_{\mathrm{stars}}$ vs m_{stars}
DM dominates in massive galaxies @ ~ 2 R_{eff} (scatter!)

DM concentration → halo "ages" correlated with stellar ages (TBC)

Inner slopes of spirals ≈ don't yet confirm ∧-shaped vs $m_{\mathrm{stars}}/M_{\mathrm{tot}}$

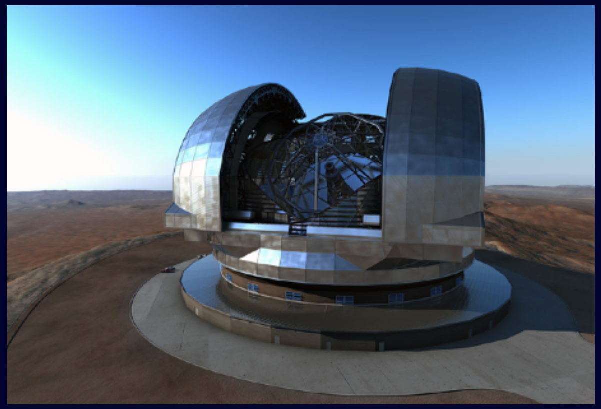
Inner slopes of dSphs:
- Fornax & Sculptor → inconclusive
- need more data on (DM-dominated) ultra-faint dwarfs

Hydro simulations are not yet trustworthy
(resolution with high statistics;
sub-grid recipes for SN & AGN feedback; effects of cosmic rays …)

Perspectives

massive galaxies

E-ELT / HIRES R=10^5 → z to 0.5 km/s
→ LOS component of acceleration field?
= finer probe of potential
… baseline $\Delta t = r^2\,\Delta v / [G\,M(r)] < 10$ yr for $r < 2$ pc! 🙁



dSph galaxies

CTA Cerenkov array
→ 1st spatially resolved γ-ray annihilation or decay
… complex background from particle showers 😐

dSph galaxies

Need much, much better proper motions than Gaia DR2 😀
→ HST+JWST repeated observations on dSphs
→ proposed Theia mission of ultra-fine astrometry (65x Gaia)