Observational manifestations of DM on small astrophysical scales

Gerry Gilmore
IoA Cambridge

Dynamics with Matt Walker, Mark Wilkinson, Rosie Wyse, Jorge Penarrubia, Jan Kleyna, Andreas Koch, Wyn Evans,

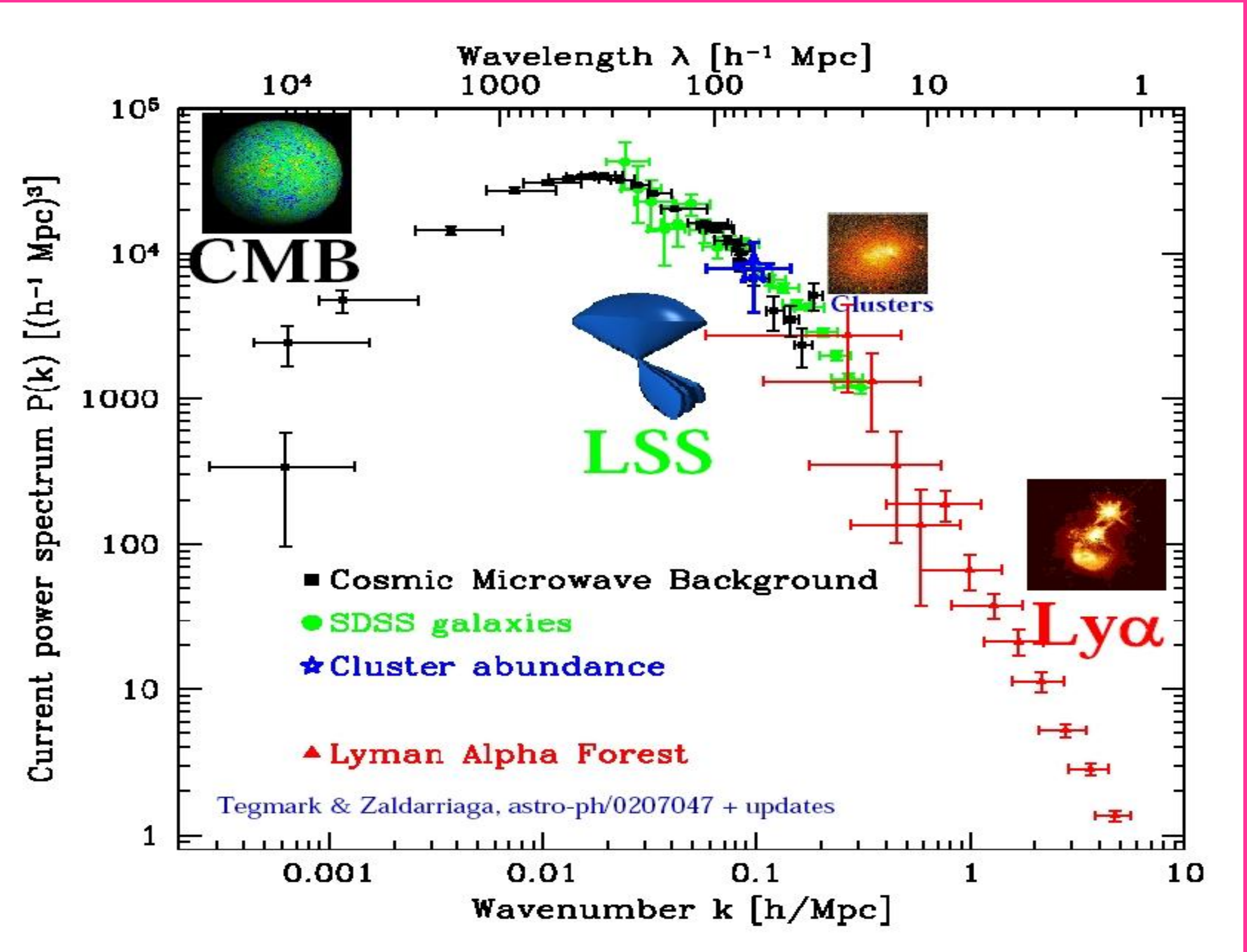
Chemistry also with John Norris

Discovery work with Vasily Belokurov, Dan Zucker, Sergey Koposov, et al

Small-scale DM: Are we making progress?

- Satellite counts – more puzzling
- Clustering – still puzzling
- dSph natural size: very little progress
- Abundances/feedback limits – substantial
- Core/cusp, dSph: kinematics – substantial
- Dynamics modelling - substantial

LCDM: impressive consistency over five orders in length scale



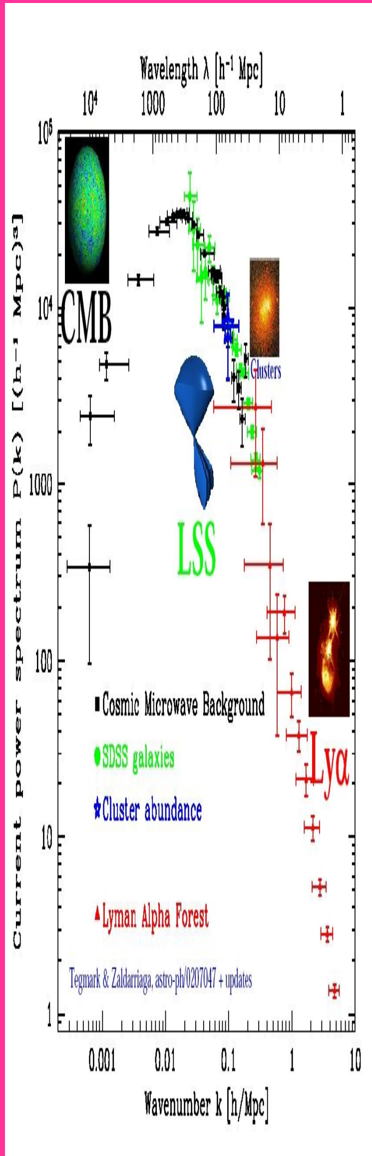
Impressive consistency over five orders in length scale

95 out of 100 orders leaves lots of discovery space

- And cuspy density profiles are still elusive. WHY??

There are 60+ orders of magnitude here, smoothed by inflation?

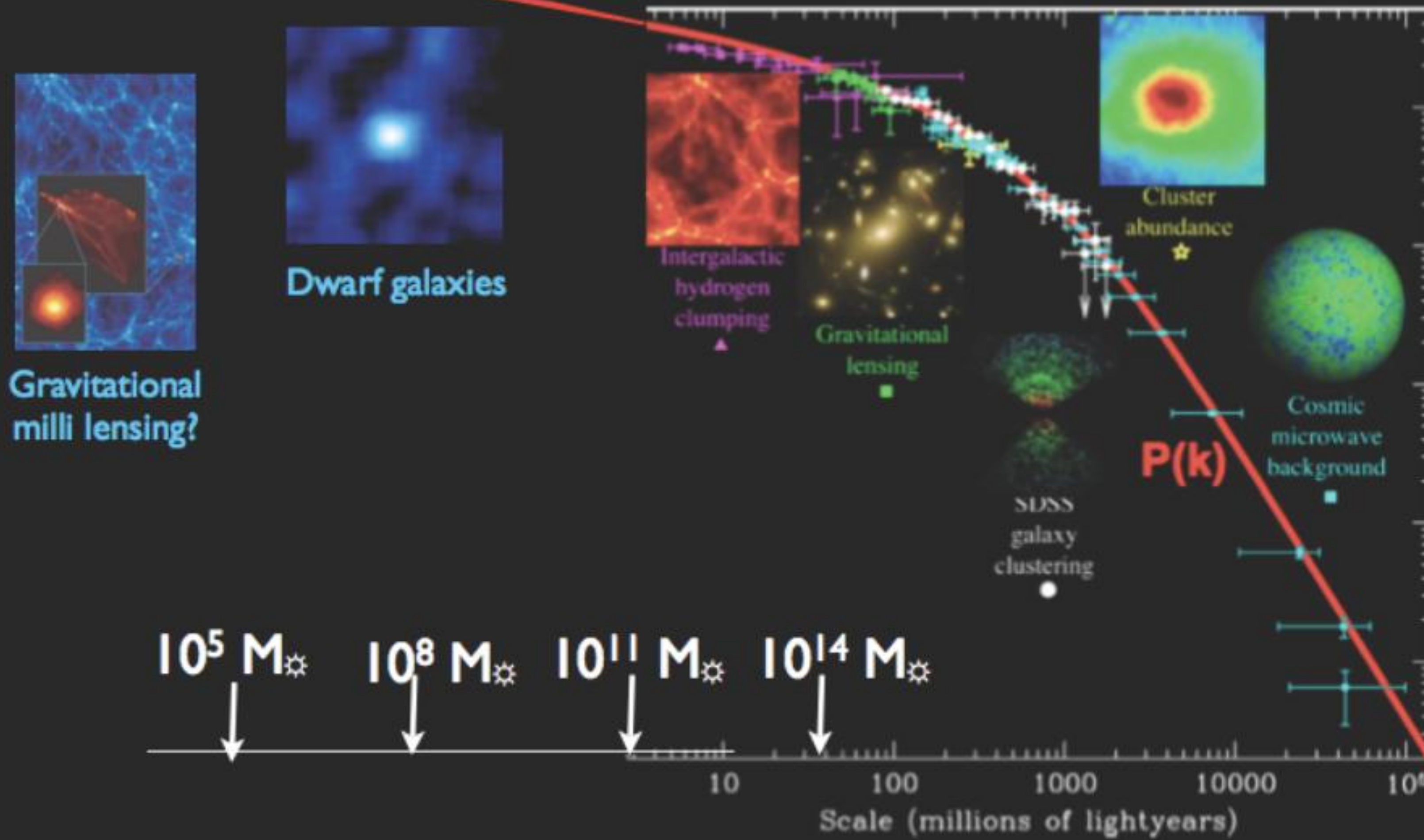
Searches for non-Gaussianity are standard cosmology



14 orders here to smallest bound systems – solar radius

37 orders to particle scales: electron radius

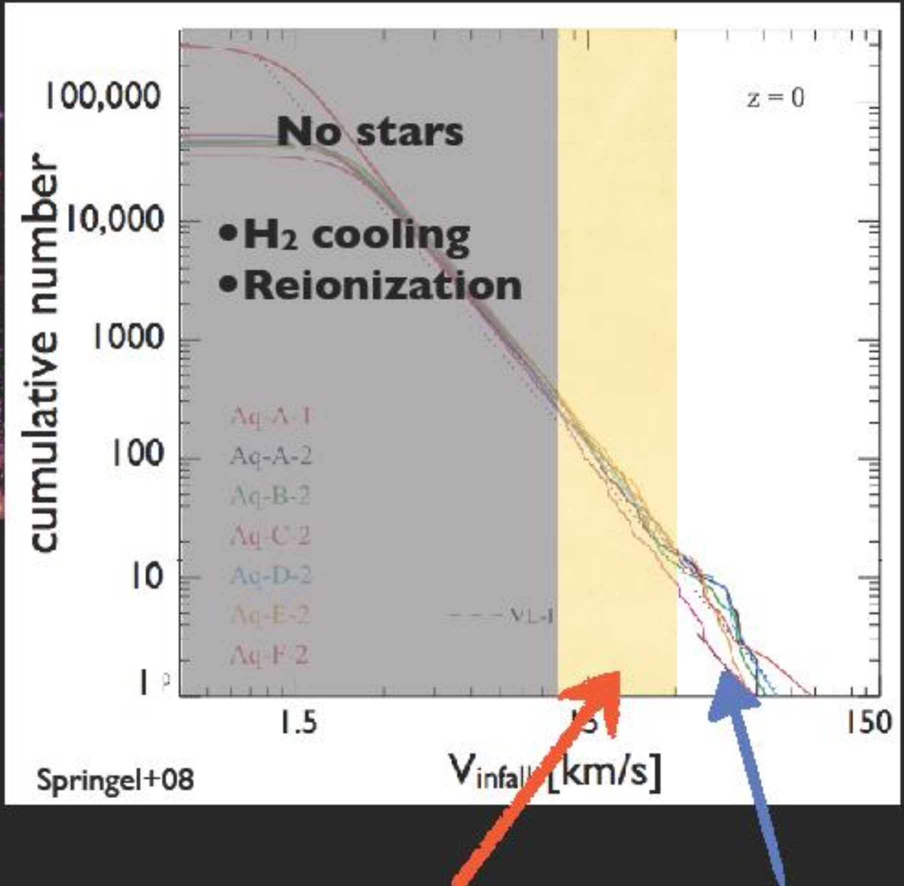
All this suggests looking at the smallest galaxies



Dwarf Spheroidals

- Low luminosity, low surface-brightness satellite galaxies, ‘classically’ $L \sim 10^6 L_\odot$, $\mu_V \sim 24$ mag/″• (~10 $L_\odot/pc^2$)
  - plus ultra-faint galaxies discovered in SDSS very much fainter
- Extremely gas-poor
- No net rotation, supported by stellar ‘pressure’, velocity dispersion
- Dark-matter dominated
  - velocity dispersion ~ 10km/s, $10 < M/L < 1000$
- Metal-poor, mean stellar metallicity $\lesssim 1/30$ solar value
- Extended star-formation histories typical, all from early epochs, perhaps before reionization??
- Most common galaxy in nearby Universe
- Crucial tests for models of structure formation and star formation

The missing satellite problem



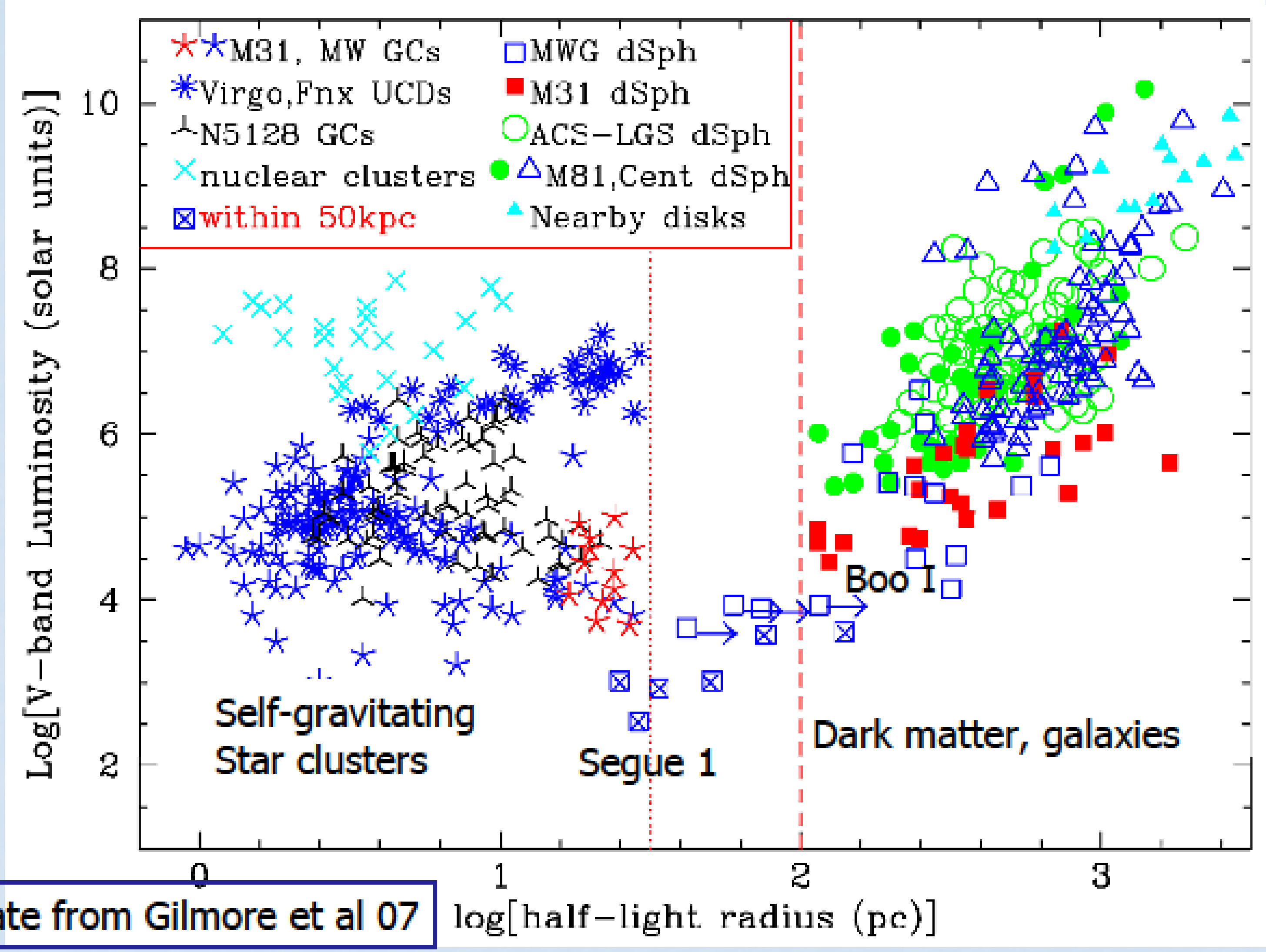
Mass function of visible satellites:

- Star formation/feedback in low-mass haloes (N-body + theory)
- Accuracy of mass estimates (dynamics)
- Survey completeness (observations/ technology)

faint dSphs: incomplete sample

Koposov+08; Tollerud+08

8 bright dSphs



Update from Gilmore et al 07

Add ~20 new satellites, galaxies and star clusters - but note low yield from Southern SEGUE/SDSS imaging : only Segue 2 and Pisces II as candidate galaxies, in 3/8 area (Belokurov et al 09,10)

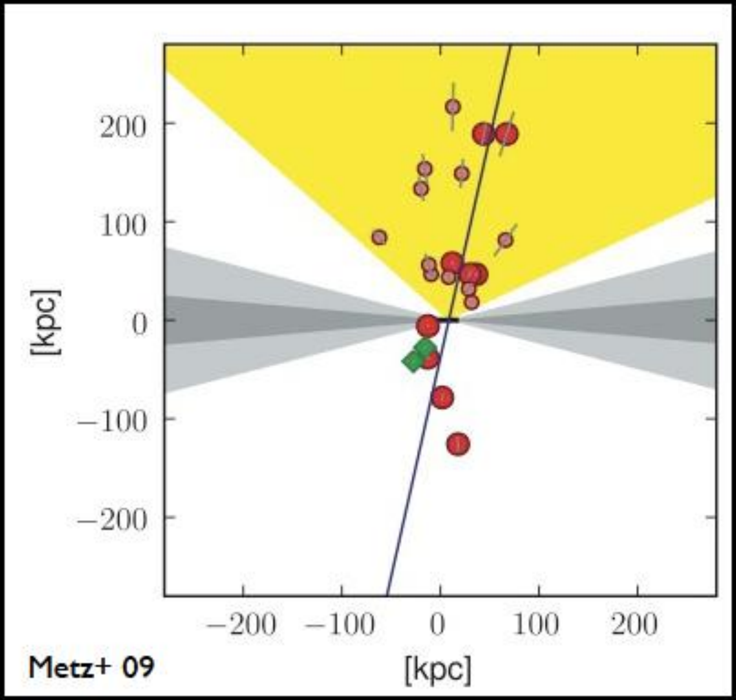
Minimum Dark Matter Length Scale?

- There is a well-established size bi-modality:
- isolated systems with size < 30pc are purely stellar

  $-16 < M_v < -1$, $M/L \lesssim 4$; e.g. globular clusters, nuclear star clusters..
- all systems with size greater than ~100pc have dark-matter halo : minimum scale of dark matter?
  - Expect dark matter scale length to be at least equal to stellar scale length (gas dissipates prior to star formation)
  - Extreme baryon loss in dSph– expand to new equilibrium
- no isolated equilibrium galaxies with half-light radius less than ~ 100pc
  - Exceptions are faint and closer than ~50kpc to Galactic center – regime of Sgr tidal tails/streams, may be associated – and on deep images often appear tidally disturbed systems

There is clearly still a lot to learn about small galaxies!!

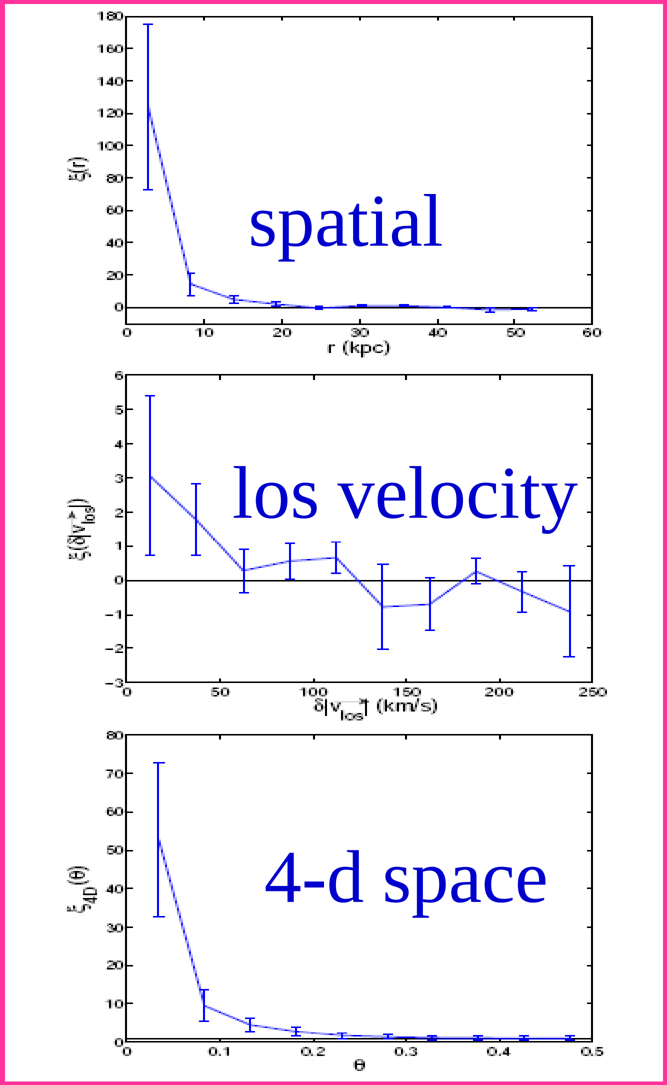
The missing satellite problem



The number of satellites in the Milky Way (24) and M31 (22) is far smaller (**factor ~20**) than predicted by CDM models:

- DM is not cold = low-mass substructures do not exist
- Star formation processes **inefficient** in low-mass ($M \lesssim 10^8 M_{sol}$) haloes = substructures are invisible

Spatial distribution of dSph is in a plane: not expected in – cf Deason etal 1101.0816; Bozek etal in prep



Talk to Brandon Bozek.

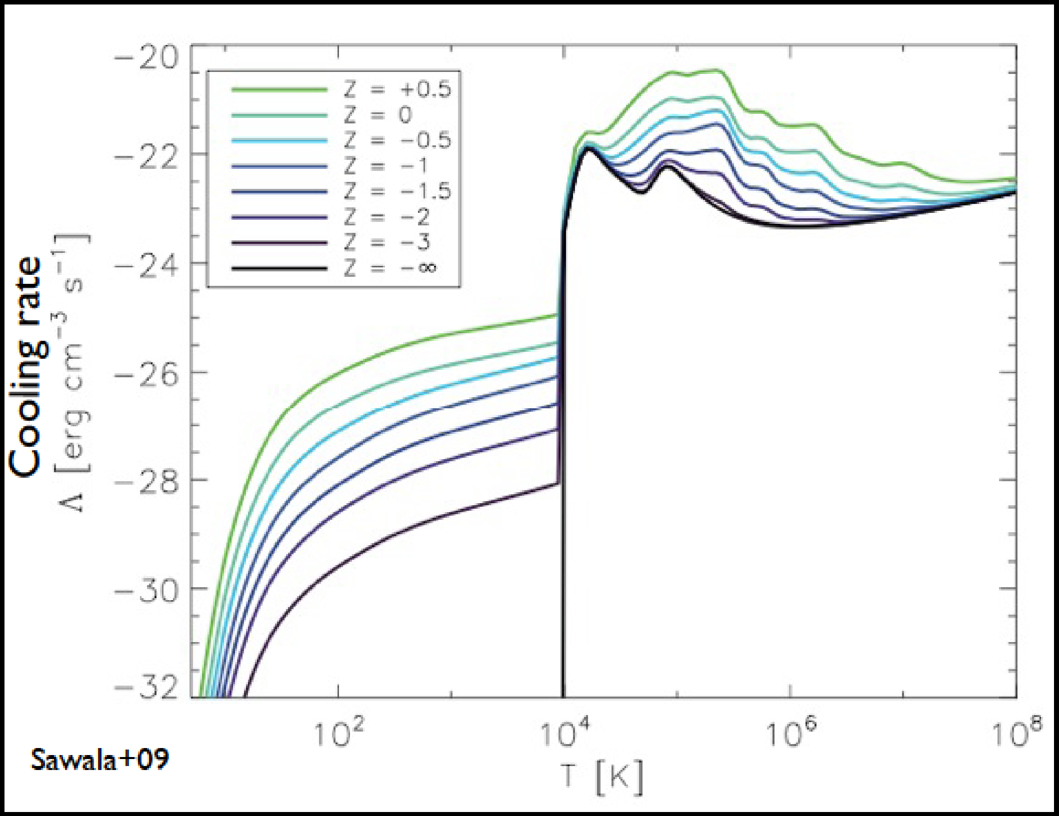
Spatial satellite distribution is not simply consistent with simulations – but small numbers

“spatial satellite problem”

Sgr dSph findable!!

There is a probable scale associated with baryonic physics

***"Dark"* CDM substructures**



In low-mass haloes gas cools through the formation H_2 molecules

↓

$M_{vir} \gtrsim 10^8 M_{sol}$ ($T_{vir} \gtrsim 10^4$ K)

Satellites with **$M_{vir} \lesssim 10^8 M_{sol}$** are expected to be devoid of baryons

"dark haloes"

White & Rees 1978; Haiman 2000; Bovill & Ricotti 2009, ...,

(Can we detect invisible/dark galaxies??)

Can we probe the existence of "dark" substructures?

- ✳ dSphs virial masses $M_{vir} \lesssim 10^9 M_{sol}$

  Strigari+07; Peñarrubia+08; Walker+09; Wolf+09

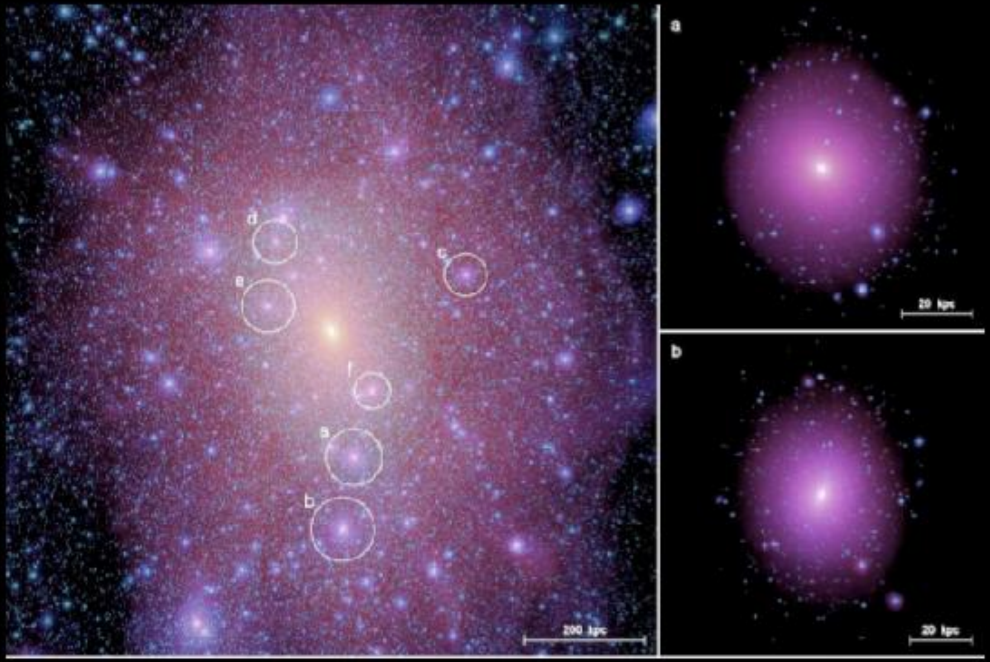
- ✳ CDM mass function:

  $dN/dm \propto m^{-1.9}$

  NFW97; Diemand+07; Springel+08

↓

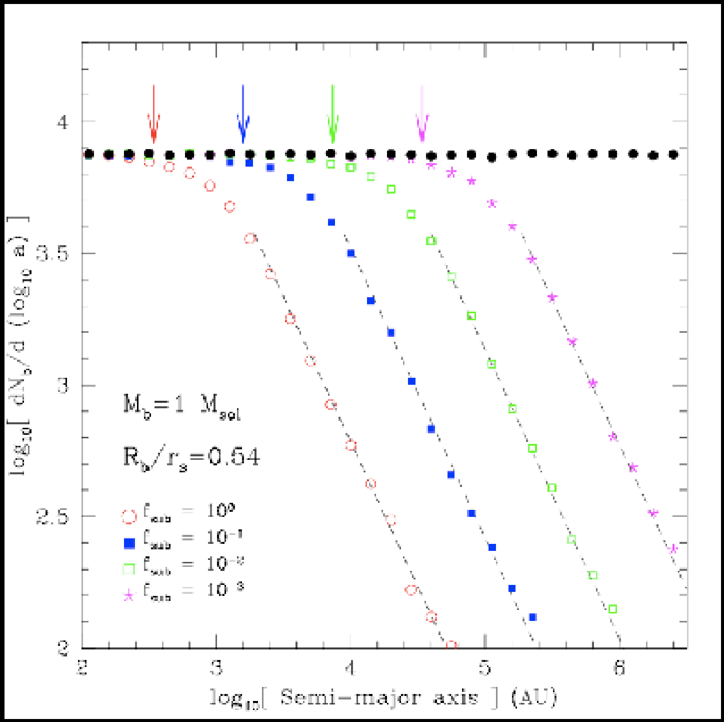
DM **substructures** in dSphs have $m \lesssim 0.01 M_{vir} \sim 10^7 M_{sol}$ expected to be "**dark**"



sub-sub haloes in CDM simulations (Springel+08)

Disruption of binary stars by "dark" substructures

Monte-Carlo/N-body simulations



Wide binaries have very low binding energies

$$E = - G M_b / 2a$$

small tidal perturbations can disrupt these systems

↓

Probes of **clumpiness** in the galaxy potential

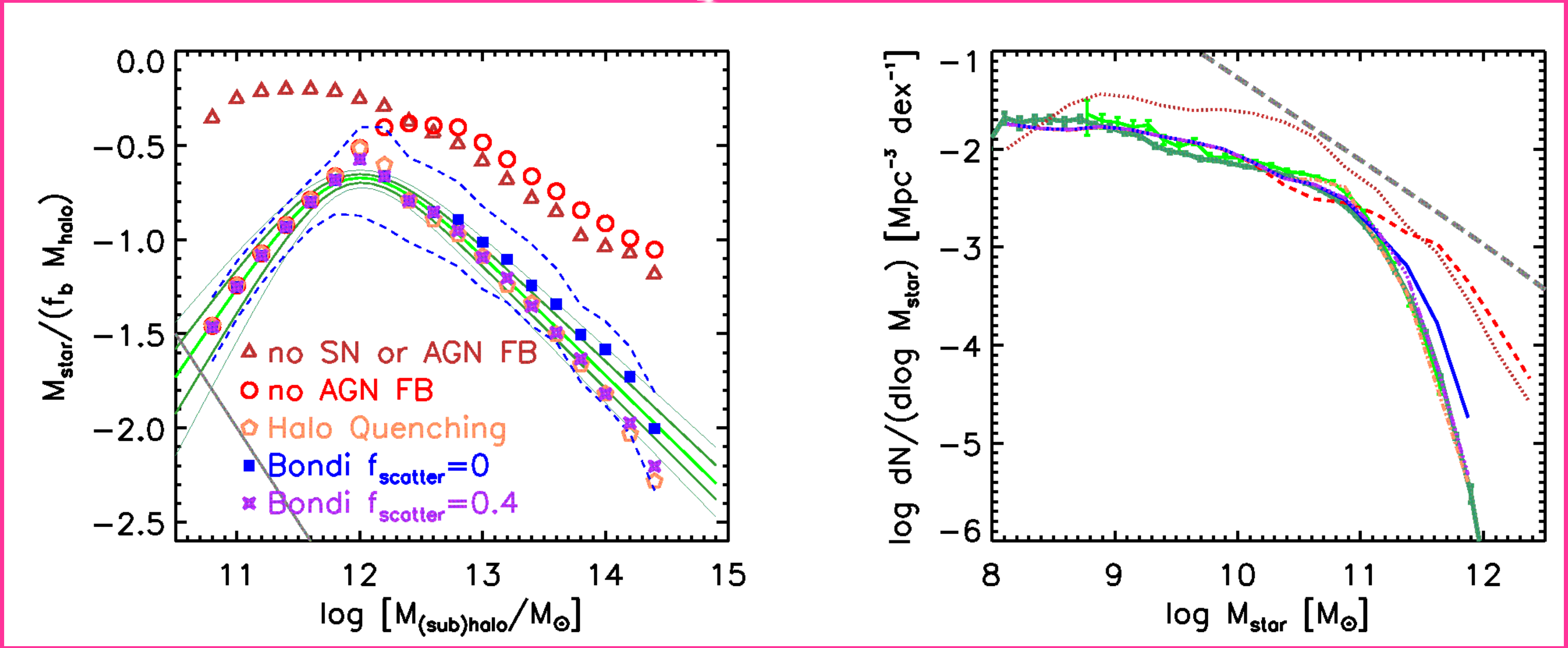
e.g MACHOS in the MW halo: Carr & Sakellariadou (1999); Chaname & Gould (2004)

✳**We expect a truncation in the binary separation function at** **$a_{max} \sim 10^4$ AU ≃ 0.05 pc**

✳**The *perturbed* separation function scales as $dN_b/da \propto a^{-2.1}$ for $a \gtrsim a_{max}$**

Back to the satellite number problem

Various ‘feedback’ recipes   Somerville et al 08



Right panel: Mass function of CDM halos is dashed grey line, observed galaxy luminosity function given by green symbols -- need ‘feedback’ at both faint and bright ends to populate halos with stars of correct total luminosity

High-mass AGN link motivated by Mbh-bulge relation

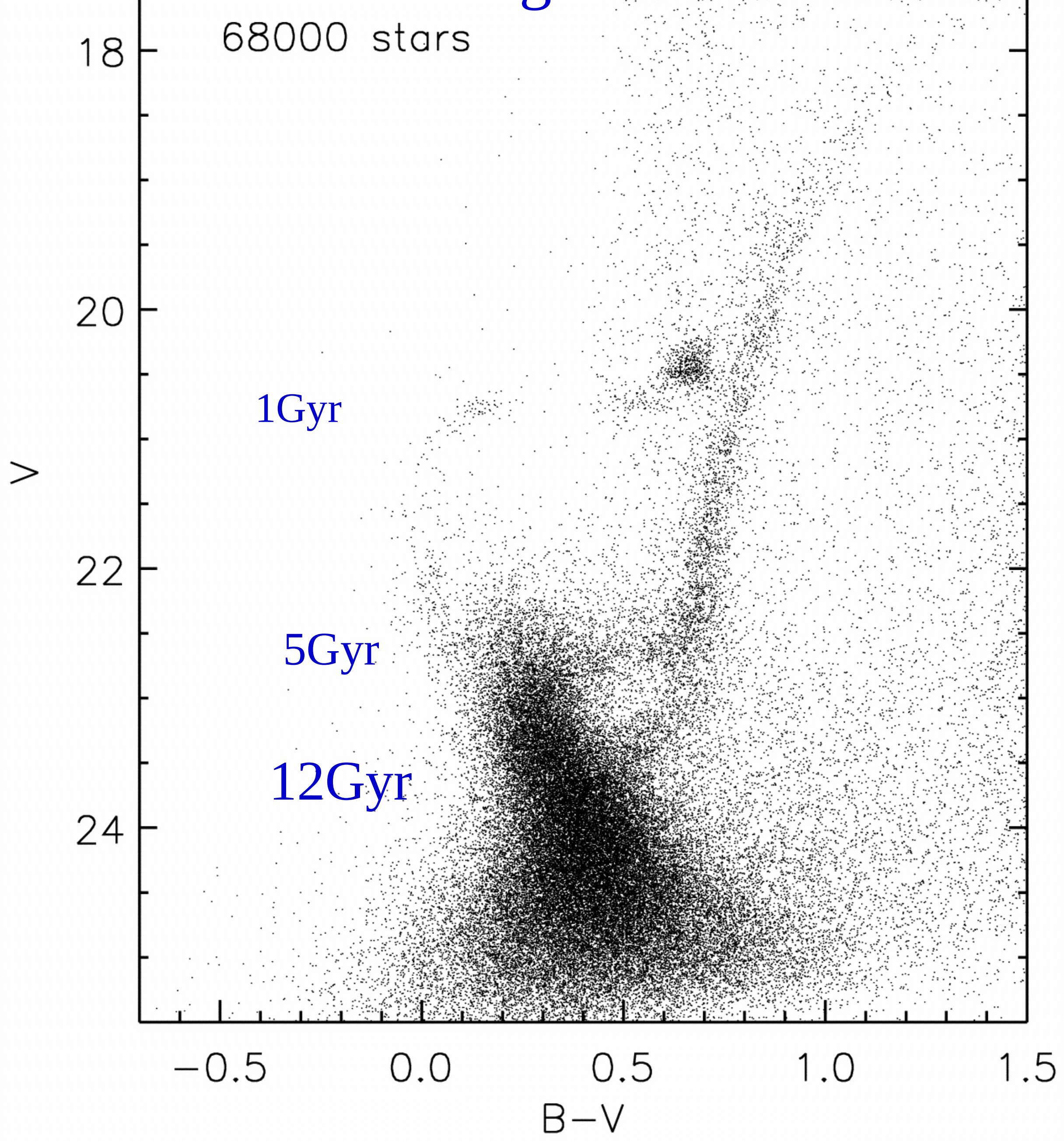
There is no hint of small-scale feedback physics: SNe???

Astrophysics ➔ dSph are stable ancient galaxies

Carina:
Photometry –

Luminous dSph have a very wide age range: they had extended very low star formation

➔ Minimal feedback



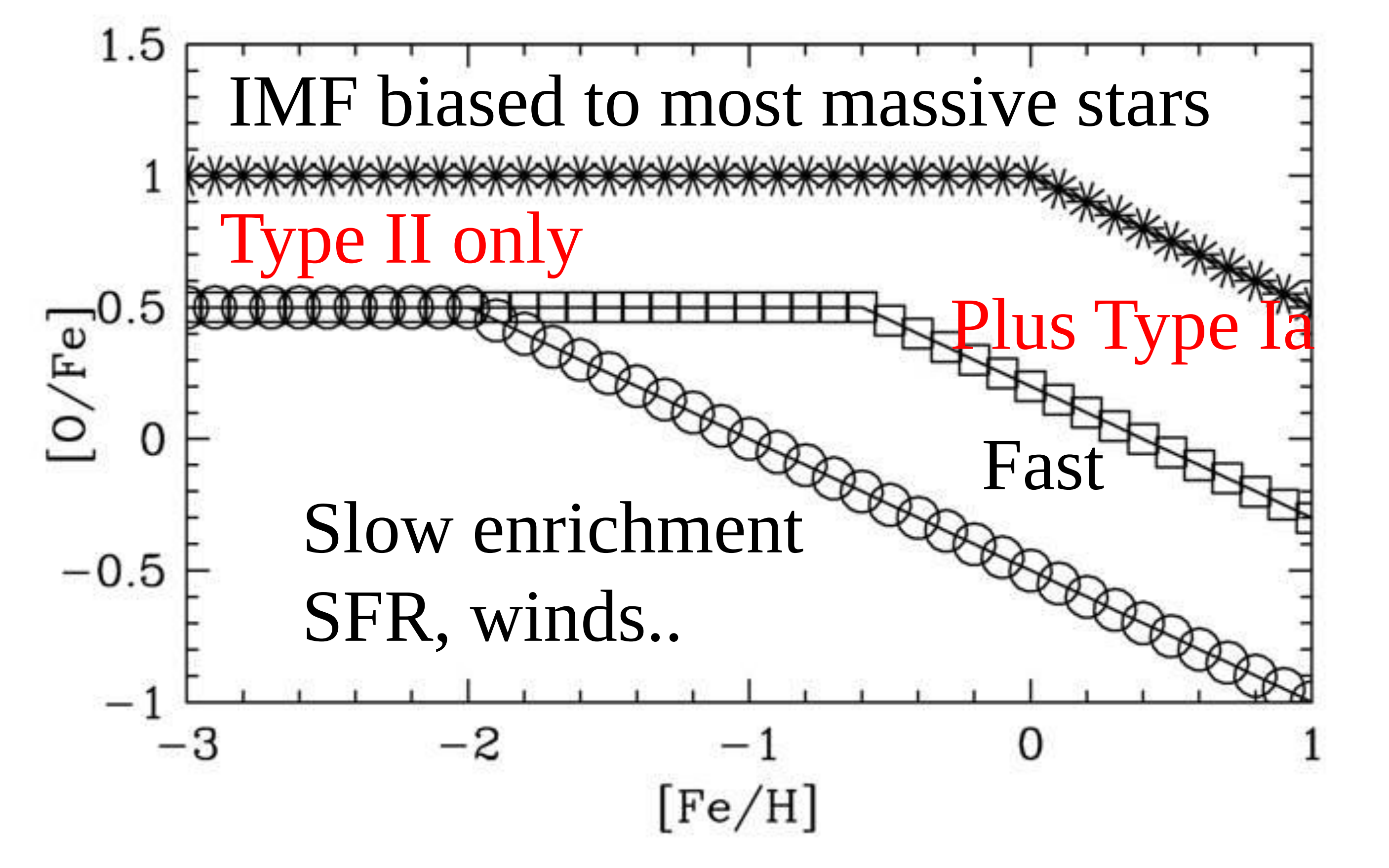
Chemical elements

- element production is very sensitive to SN progenitor initial stellar mass → primordial IMF
- → do we see a big scatter from single SNe?
- Metallicity DF defines length and time scale of SNe enrichment, and KE energy feedback/gas loss
- Did feedback destroy CDM cusps?????

- Do we see (near) zero abundances?
- If not, what pre-enriched the first halos? Did this same process affect Ly-alpha clouds?

Elemental Abundances: beyond metallicity

Alpha element and iron



Wyse & Gilmore 1993

Self-enriched star forming region.

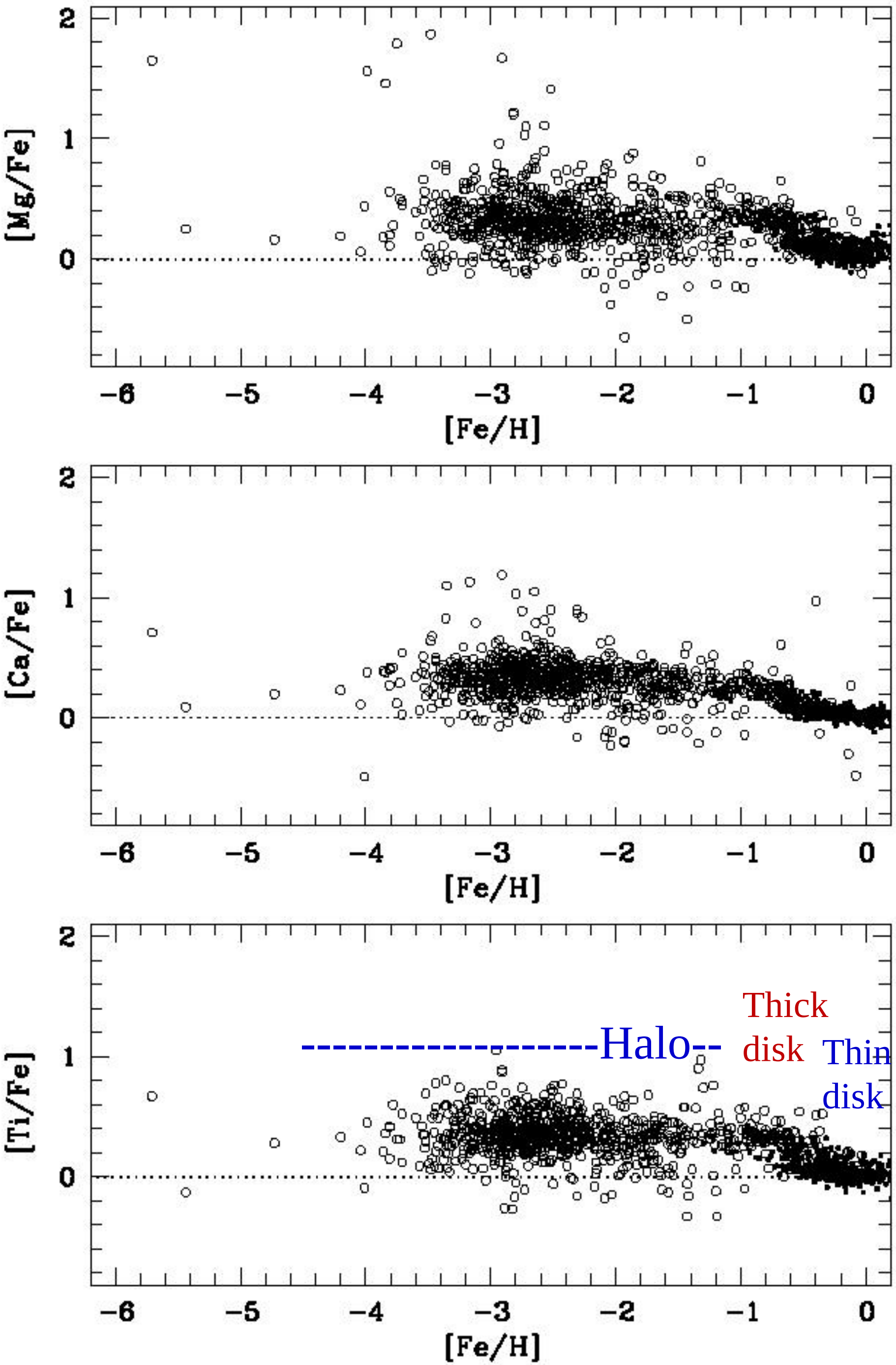
This model assumes good mixing so IMF-average yields

Galactic halo field shows very low scatter, just a systematic of constant IMF, fast star formation, well-mixed ISM, only very old stars.

Is this consistent with many small accretions? How??

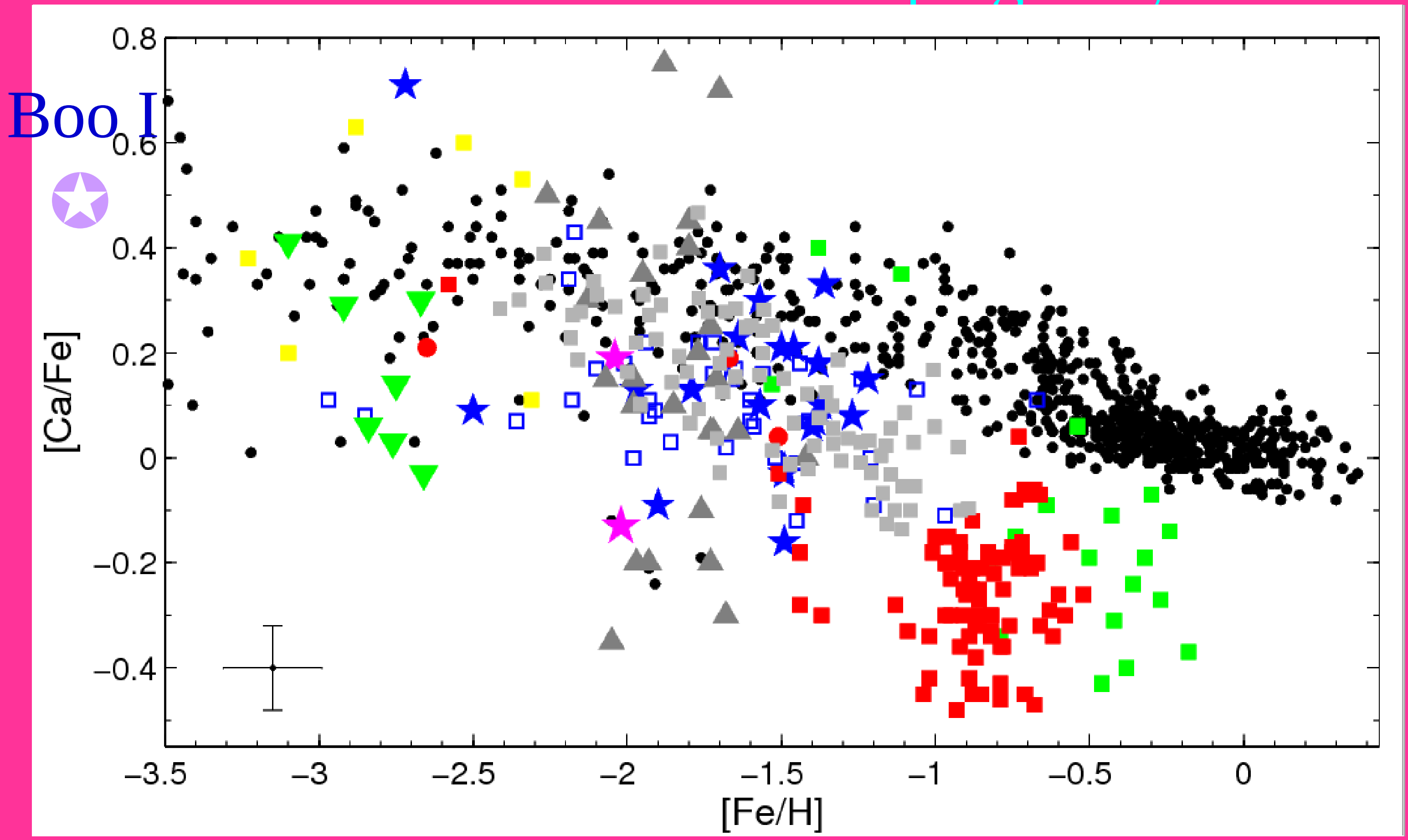
mean halo star at [Fe/H]=-1.5

Compilation by Frebel (2010)



dSphs vs. MWG abundances

halo/thick disk is not a dSph graveyard

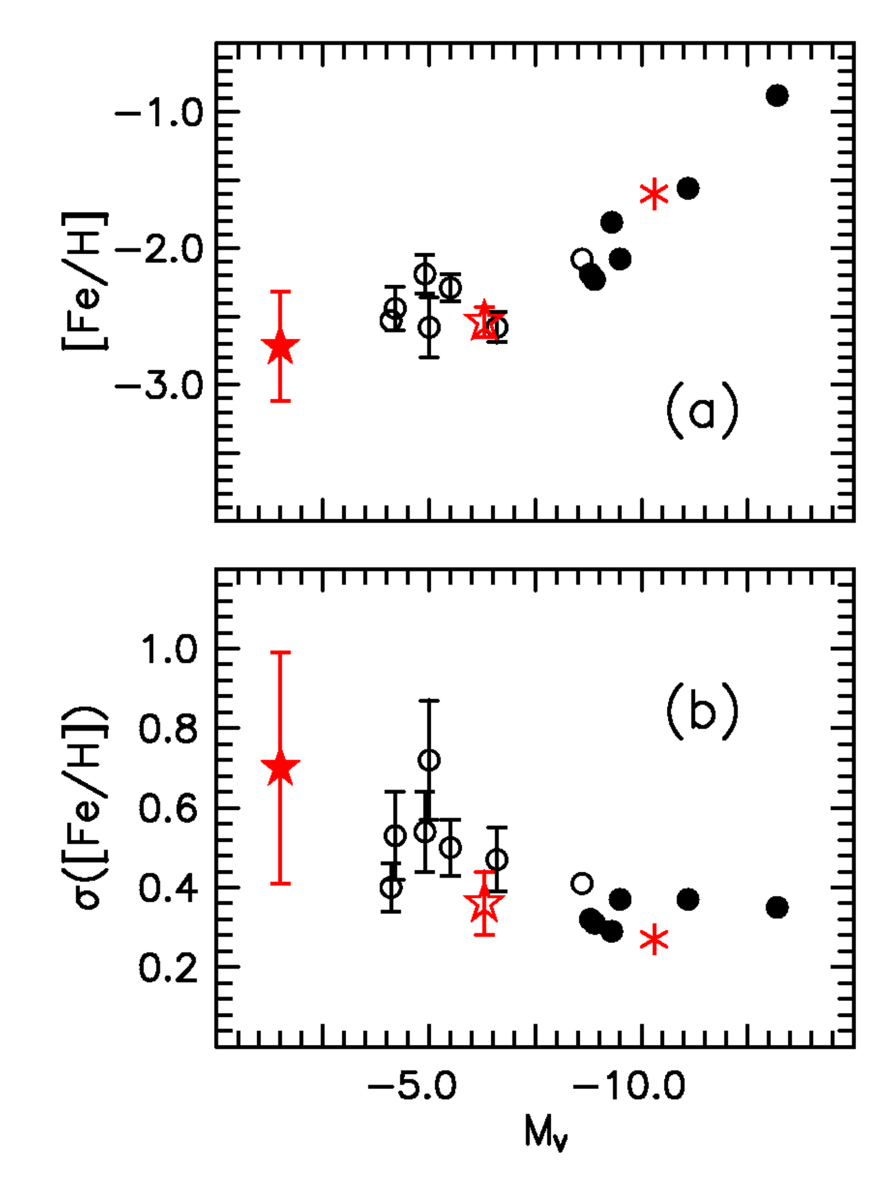


Shetrone et al. (2001, 2003): 5 dSphs
Sadakane et al. (2004): Ursa Minor
Monaco et al. (2005): Sagittarius
Koch et al. (2006, 2007): Carina
Letarte (2006): Fornax

Koch et al. (2008): Hercules
Shetrone et al. (2008): Leo II
Frebel et al. (2009): Coma Ber, Ursa Major
Aoki et al. (2009): Sextans
Hill et al. (in prep): Sculptor

Chemical abundances: dispersion (self enrichment) is evidence for early massive halos in extreme low luminosity systems

Norris, GG et al 2010a



Mean iron abundance of member stars against total luminosity of host system: clear trend, hard to maintain if significant tidal stripping of host ➔ are any of the dSph tidally stripped?
➔ Interesting? since cusps survive, but cores don’t in simulations.

Segue 1 (filled red star) based on only 4 stars – caution!

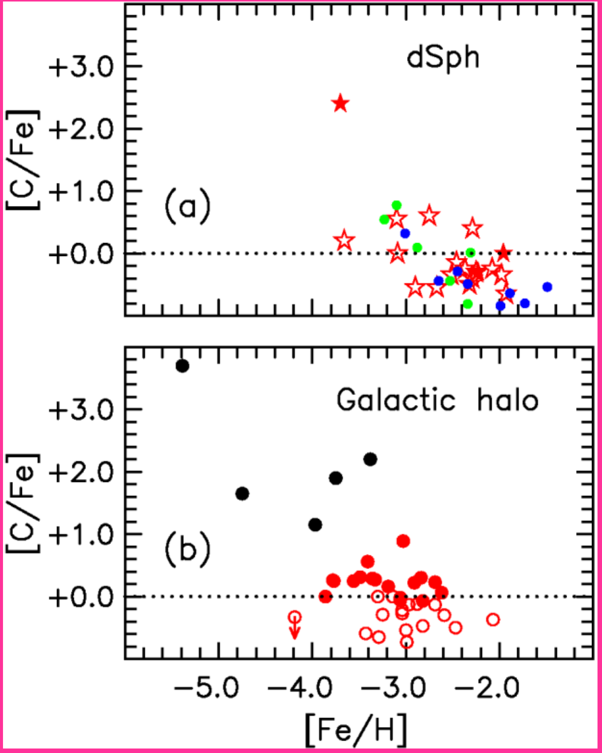
Dispersion in metallicity increases as luminosity decreases – consistent with inhomogeneous stochastic enrichment in low-mass halos, gentle feedback: Highly variable SFR models predict high element **ratio** scatter

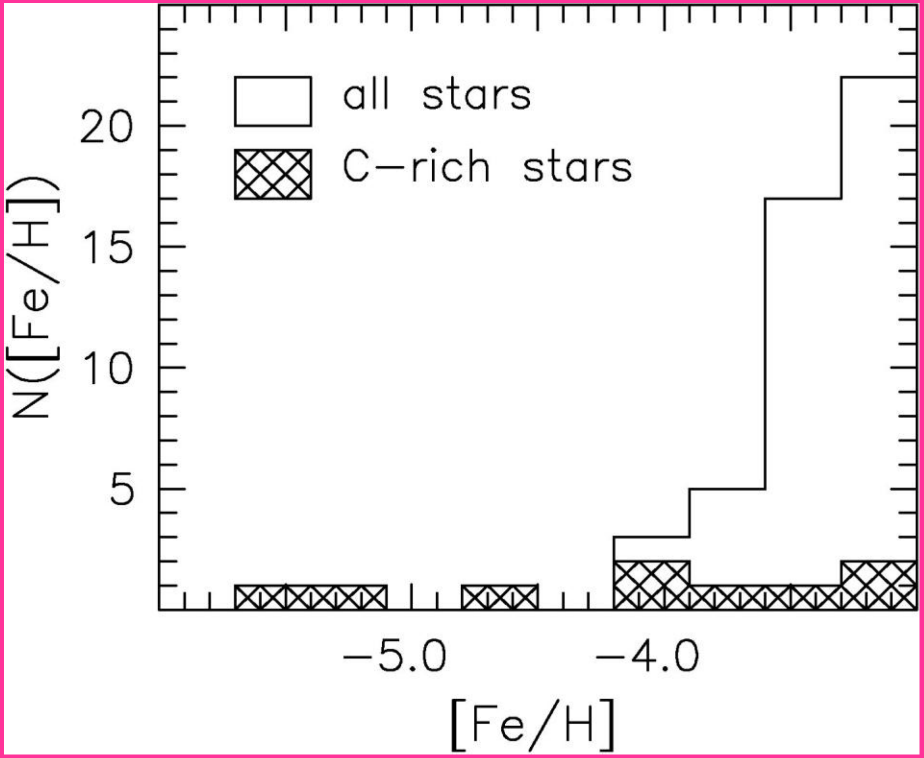
A CARBON-RICH, EXTREMELY METAL-POOR (CEMP-no) STAR IN THE SEGUE 1 SYSTEM[1]

JOHN E. NORRIS[1], GERARD GILMORE[2], ROSEMARY F.G. WYSE[3], DAVID YONG[1], AND ANNA FREBEL[4]

Very high carbon from zero-metallicity first SNe?

Astrophysics ➔ faintest galaxies are the first bound systems





Galactic field stars

Carbon spreads in dSph – Norris, GG etal 2010

Simulations show low luminosity galaxies retain primordial DM profile
but still fail to make plausible galaxies x10 problem

Forming Realistic Late-Type Spirals in a LCDM Universe: The Eris Simulation
Guedes, Javiera; Callegari, Simone; Madau, Piero; Mayer, Lucio
eprint arXiv:1103.6030

The Baryons in the Milky Way Satellites

O. H. Parry[1*], V. R. Eke[1], C. S. Frenk[1] and T. Okamoto[1,2]
[1] Institute for Computational Cosmology, Department of Physics, University of Durham, Science Laboratories, South Road, Durham DH1 3LE
[2] Center for Computational Sciences, University of Tsukuba, 1-1-1 Tennodai, Tsukuba 305-8577 Ibaraki, Japan

We investigate the formation and evolution of satellite galaxies using smoothed particle hydrodynamics (SPH) simulations of a Milky Way (MW)-like system, focussing on the best resolved examples, analogous to the classical MW satellites. Comparing with a pure dark matter simulation, we find that the condensation of baryons has had a relatively minor effect on the structure of the satellites' dark matter halos. The

data; the most massive examples are most discrepant. A statistical test yields a ~ 6 percent probability that the simulated and observationally derived distributions of masses are consistent. If the satellite population of the MW is typical, our results could imply that feedback processes not properly captured by our simulations have reduced the central densities of subhalos, or that they initially formed with lower concentrations, as would be the case, for example, if the dark matter were made of warm, rather than cold particles.

What is the (Dark) Matter with Dwarf Galaxies?

Till Sawala[1*], Qi Guo[3], Cecilia Scannapieco[2], Adrian Jenkins[3] and Simon White[1]
[1] Max-Planck Institute for Astrophysics, Karl-Schwarzschild-Strasse 1, 85748 Garching, Germany
[2] Astrophysikalisches Institut Potsdam, An der Sternwarte 16, 14482 Potsdam, Germany
[3] Institute for Computational Cosmology, Department of Physics, University of Durham, South Road, Durham DH1 3LE, UK

galaxy formation in similar mass haloes. Our final objects have structures and stellar populations consistent with observed dwarf galaxies. However, in a ΛCDM universe, $10^{10}\mathrm{M}_\odot$ haloes must typically contain galaxies with much lower stellar mass than our simulated objects if they are to match observed galaxy abundances. The dwarf galaxies formed in our own and all other current hydrodynamical simulations are more than an order of magnitude more luminous than expected for haloes of this mass. We discuss the significance and possible implications of this result.

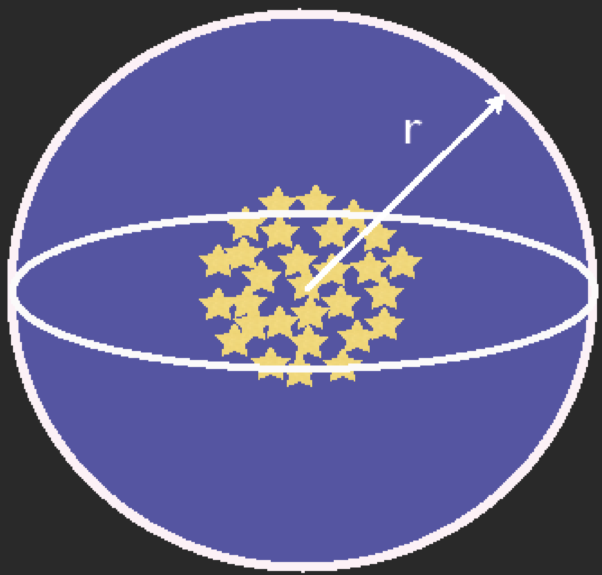
If the observed stellar mass function is complete, and the hydrodynamical simulations correctly capture the relevant physics of galaxy formation, the Millennium-II Simulation (and similar ΛCDM simulations) overpredict the number of $10^{10}\mathrm{M}_\odot$ dark matter haloes. This would seem to require the underlying physical assumptions of the ΛCDM model to be revised. Warm Dark Matter may offer a possibility, but only for particle masses of ~ 1 keV, below the limit apparently implied by recent Lyman-α observations.

Of the three proposed scenarios, it appears that missing astrophysical effects in the simulations are the most likely cause of the discrepancy, and the most promising target in search of its resolution. While the three scenarios differ in nature, none is without significant implications for galaxy formation, which will have to be addressed in the future.

Where are we with chemistry

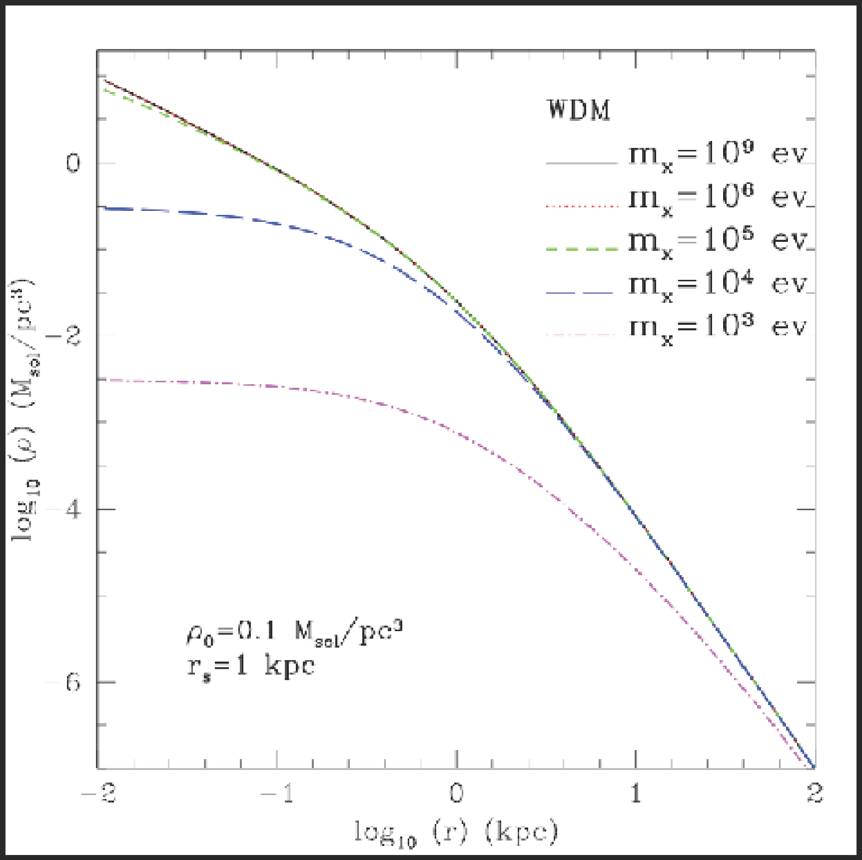
- There is a [Fe/H] vs Mv correlation at bright magnitudes, perhaps not below Mv=-8
- There is a high abundance dispersion in dSph → they really do/did have massive halos (>10^7?)
- At least the very lowest luminosity dSph have near zero-abundance stars. Probably all do.
- Stars in dSph are younger, have different chemistry, than halo & thick disk stars → what formed the halo?
- Star formation rates low – minimal feedback, primordial DM profile is unchanged
- Still major problems making plausible systems in CDM

DM distribution in galaxies
"Core vs Cusp"



$$r_c > 32\left(\frac{10\mathrm{km/s}}{\sigma}\right)^{1/2}\left(\frac{\mathrm{keV}}{m_\chi}\right)^2 \mathrm{pc}$$

Bode+01



Theory prediction:

CDM haloes follow a universal density profile that **diverges** at r=0 (**cusp**)

Collision-less N-body sims. of structure formation

Dubinsky & Carlberg 91, NFW97, Moore+98, Diemand+ 05)

DM distribution in galaxies
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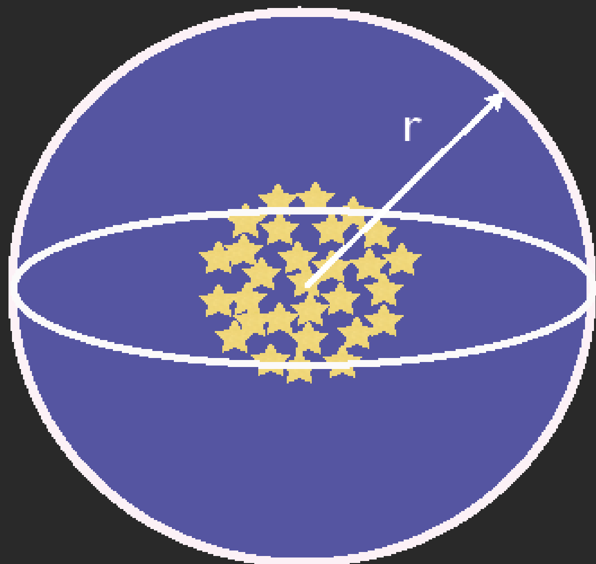
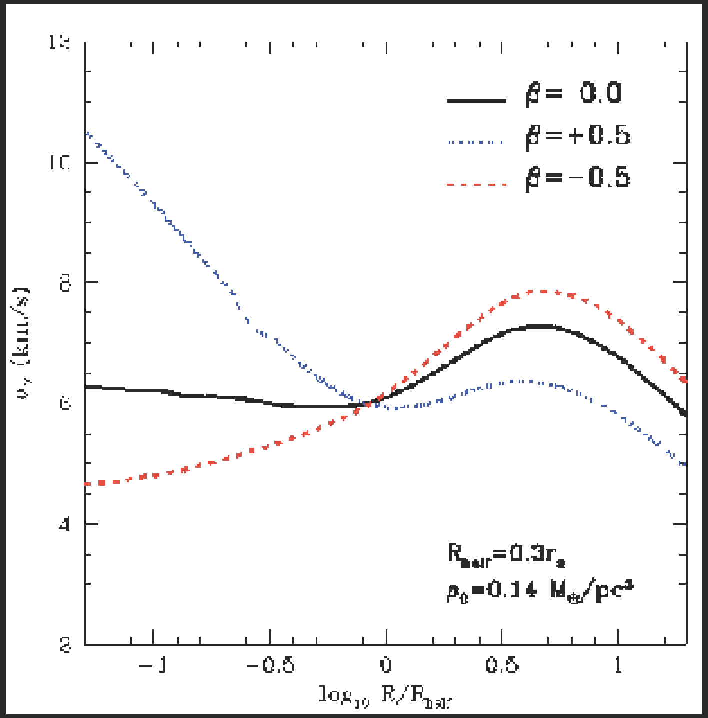


$$\frac{1}{\nu}\frac{d}{dr}(\nu\bar{v_r^2}) + 2\frac{\beta\bar{v_r^2}}{r} = -\frac{GM(r)}{r^2}$$

$$\beta \equiv 1 - \frac{\bar{v_t^2}}{2\bar{v_r^2}}$$ anisotropy (unknown)



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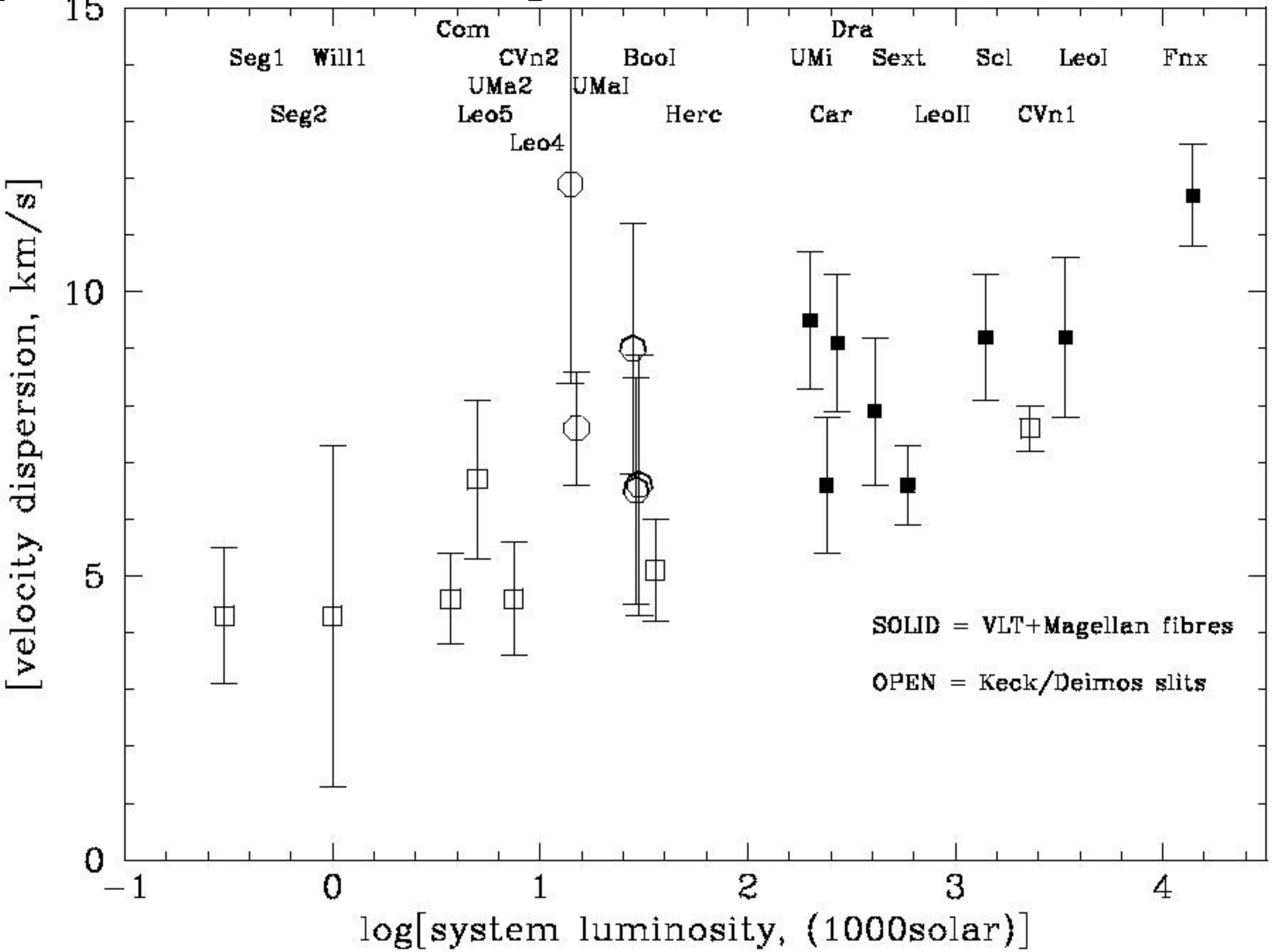
Substantial improvements in measured velocity precision
Koposov, Gilmore etal ApJ 736 146, 1105.4102



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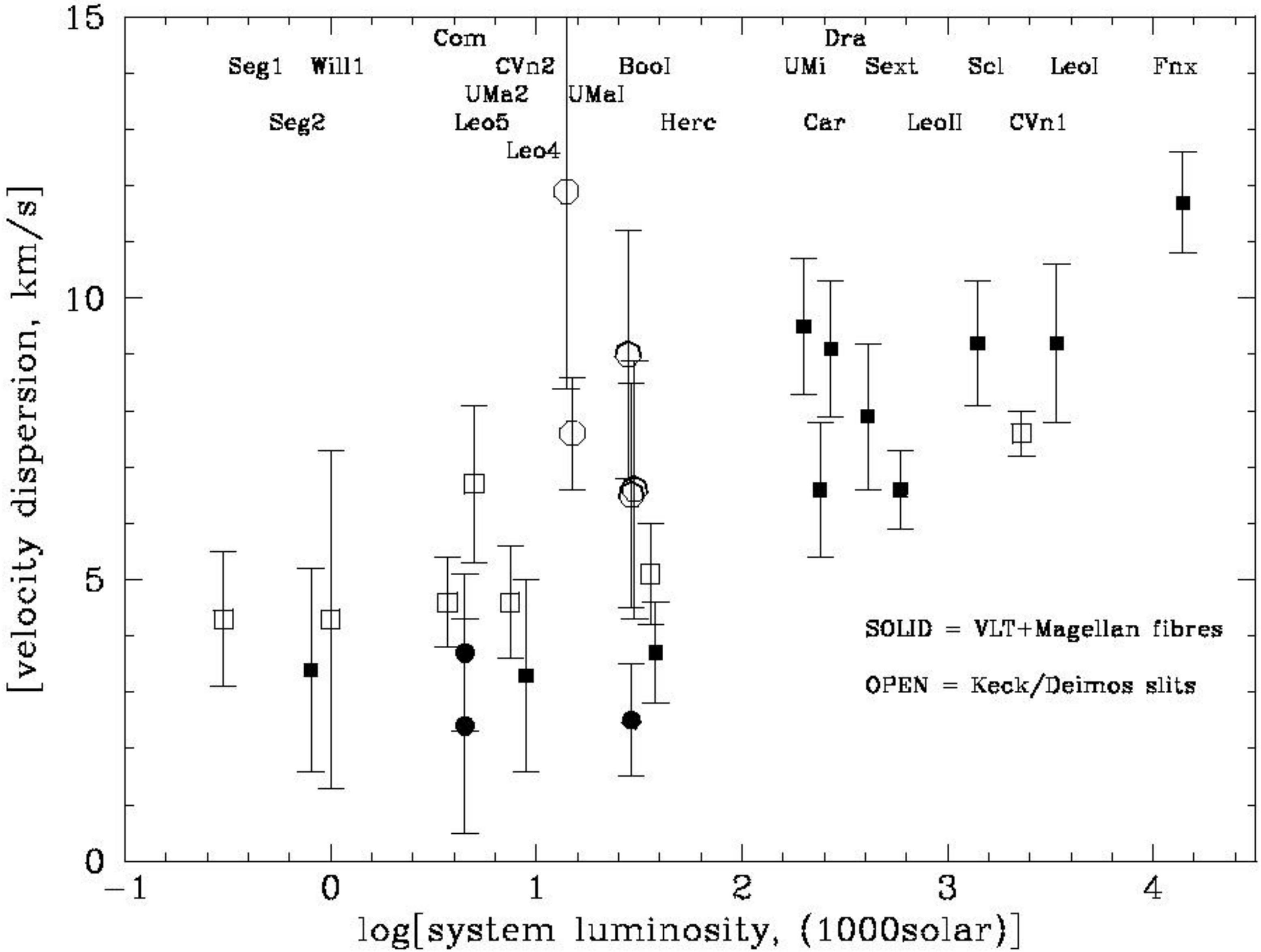
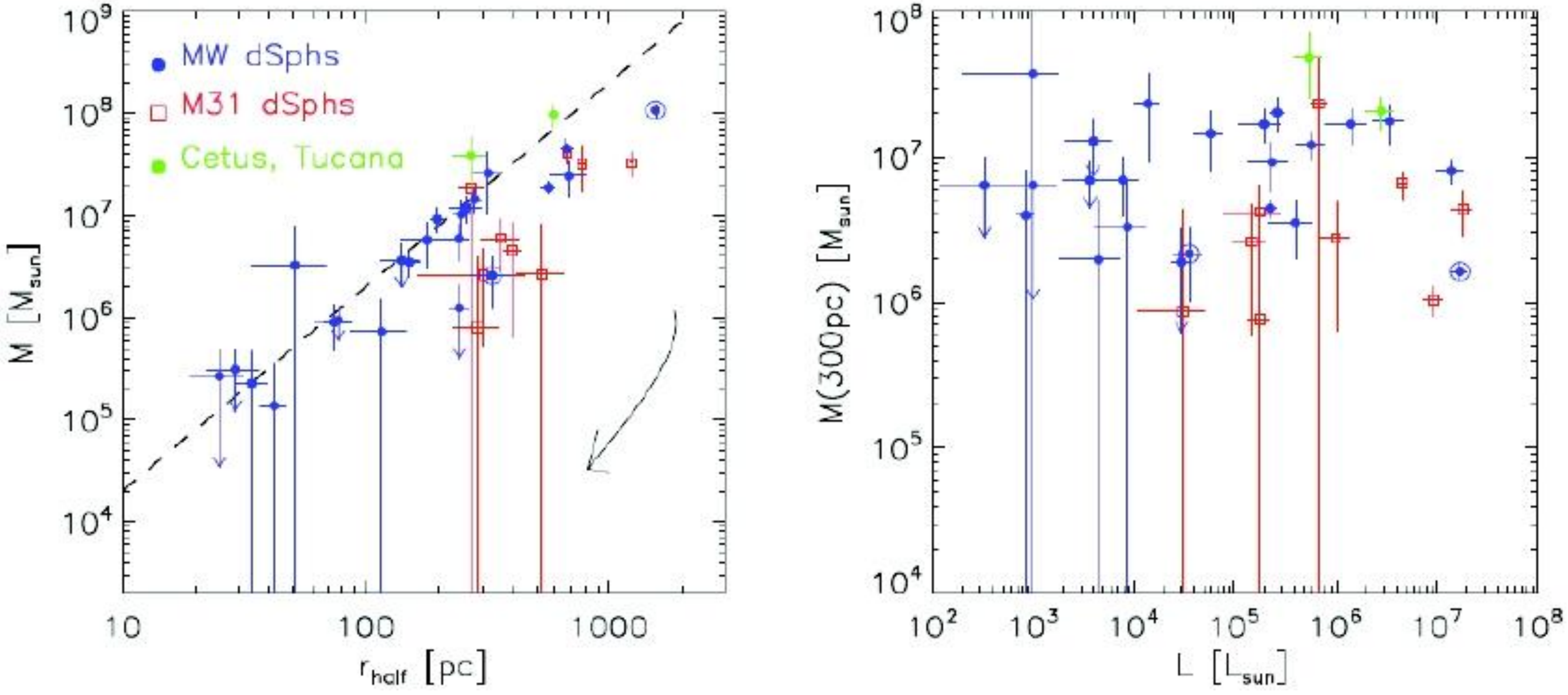
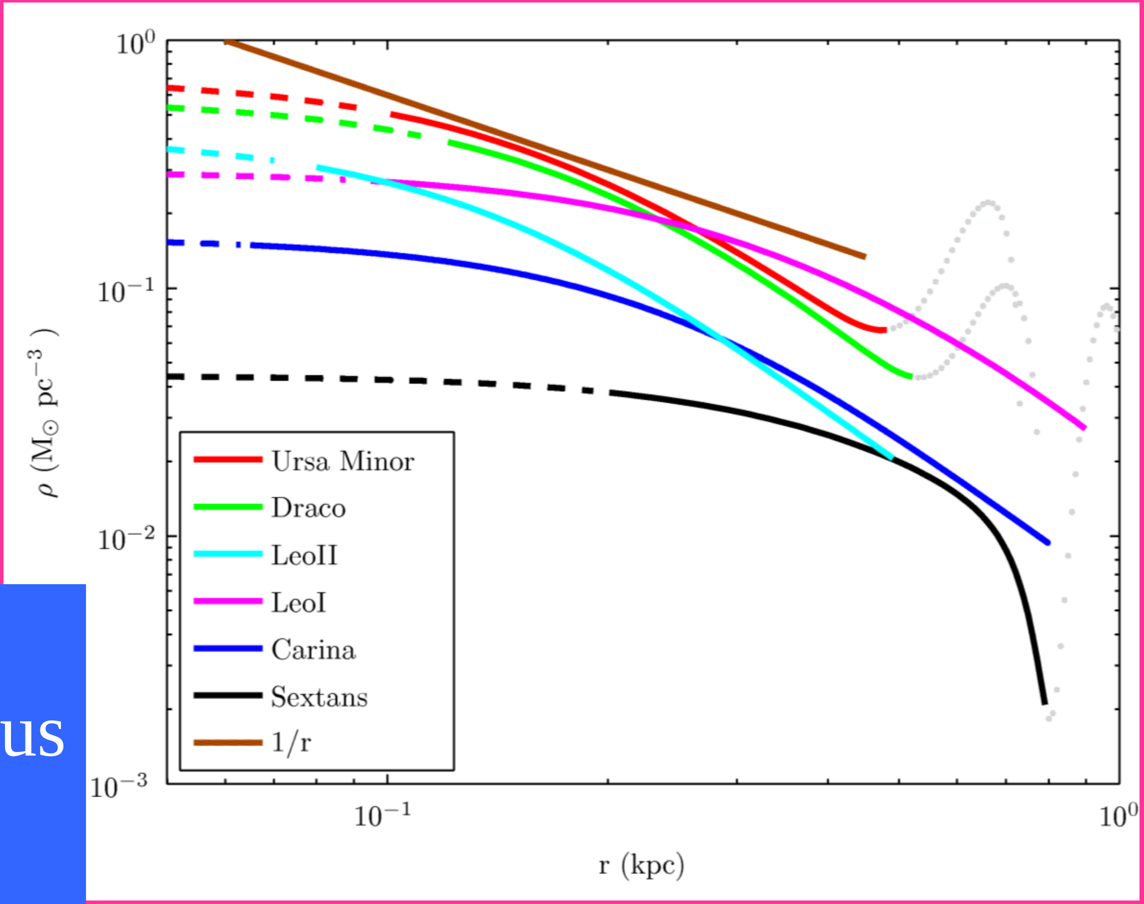


Current dSph kinematics: is there a standard mass?



Derived mass density profiles:

Jeans' equation with ***assumed isotropic*** velocity dispersion: all consistent with cores.



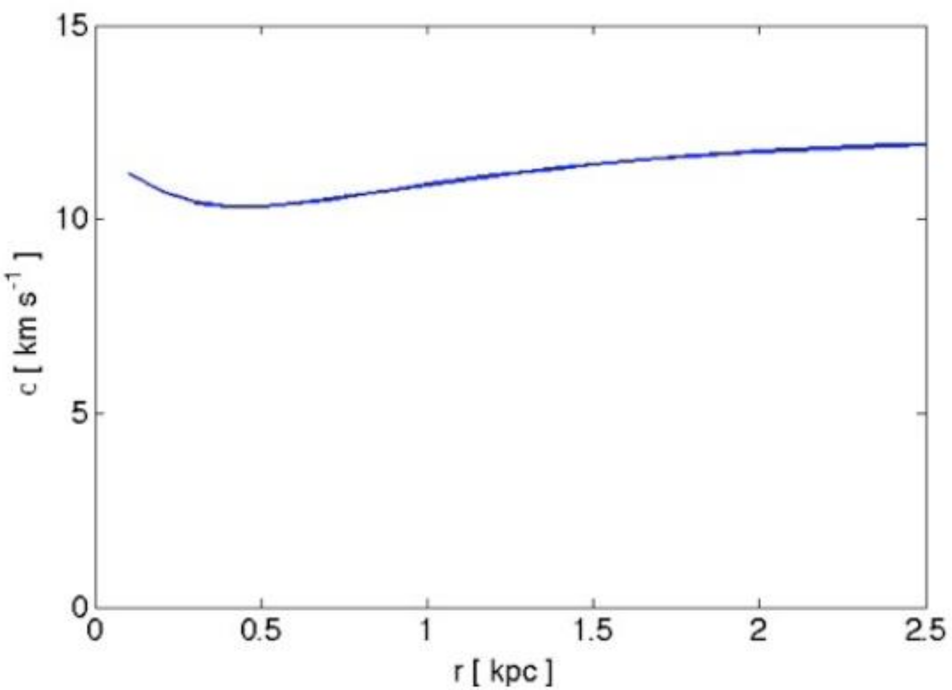
CDM predicts slope of -1.3 at 1% of virial radius and asymptotes to -1 (Diemand et al. 04)

NB these Jeans' models are to provide the most objective sample comparison – DF fitted models agree with these

Jeans equations allow unphysical models

Jeans equations give simple relation between kinematics, the light distribution and the underlying mass distribution

$$M(r) = -\frac{r^2}{G}\left(\frac{1}{\nu}\frac{\mathrm{d}\,\nu\sigma_r^2}{\mathrm{d}\,r} + 2\,\frac{\beta\sigma_r^2}{r}\right) \qquad \beta(r) = 1 - \frac{\langle v_\mathrm{t}^2\rangle}{2\langle v_\mathrm{r}^2\rangle}$$



Plummer profile for stars

+

NFW profile for dark matter

+

isotropic velocity distribution

=

unphysical distribution function

Going beyond velocity moments:
Construct line of sight velocity distributions
MCMC comparison to data

- Fit surface brightness profile
- Use method by P. Saha to invert integral equation for all DFs consistent with observed ρ

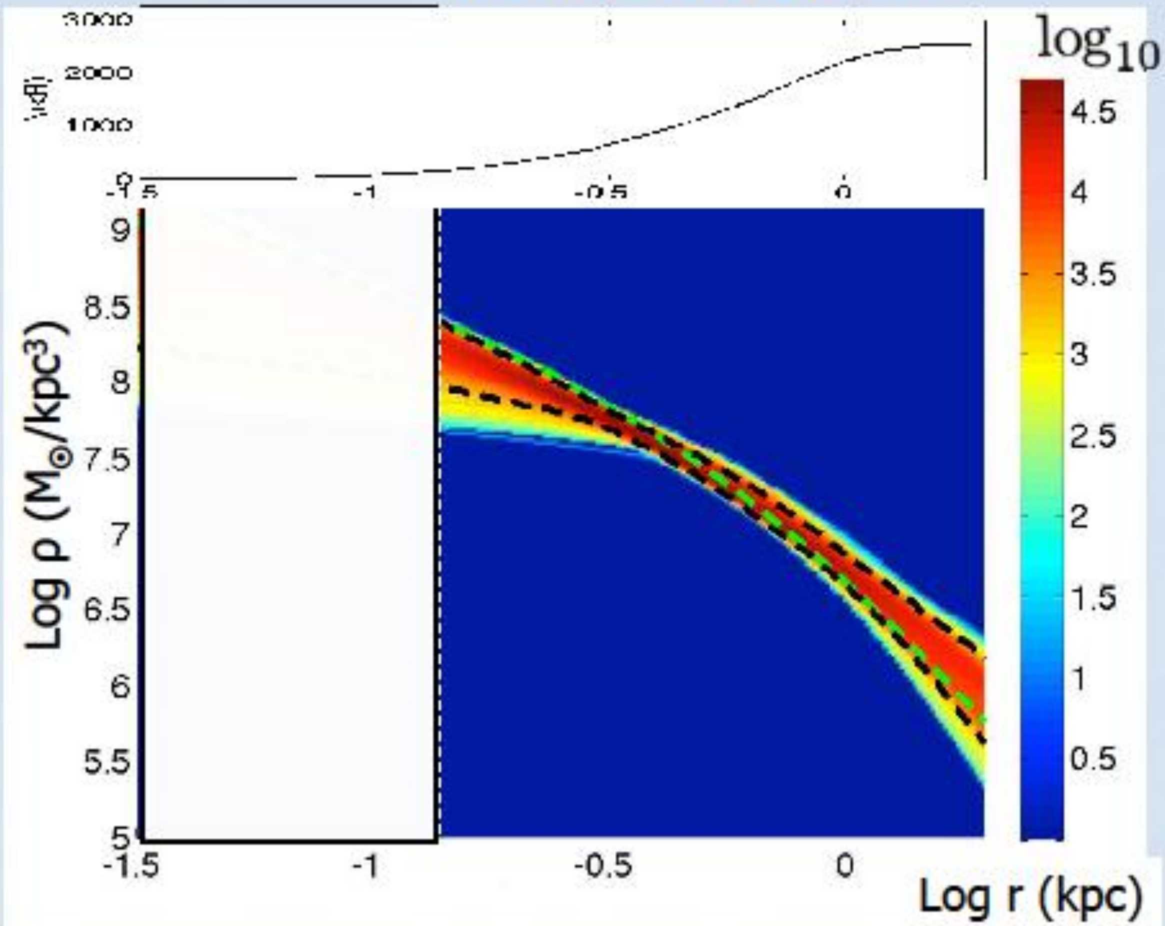
$$\rho(\Phi) = \frac{4\pi}{r^2}\int_0^{\Phi} w(E)\,\mathrm{d}E \int_0^{L_{\max}} \frac{g(E,L)L\,\mathrm{d}L}{\sqrt{2(\Phi-E)-L^2/r^2}}$$

where

$$L_{\max} = \sqrt{2(\Phi-E)}r$$

- Project to obtain LOS velocity distribution on a grid of R and $v_{\rm los}$
- convolve with individual velocity errors, and compare to data (MCMC)

Fornax: real data - PRELIMINARY density profile



- 3 MCMC chains combined: total of ~5000 models
- At radii where most of data lie, clear constraints on profile
  - Inner regions uncertain, few stars observed

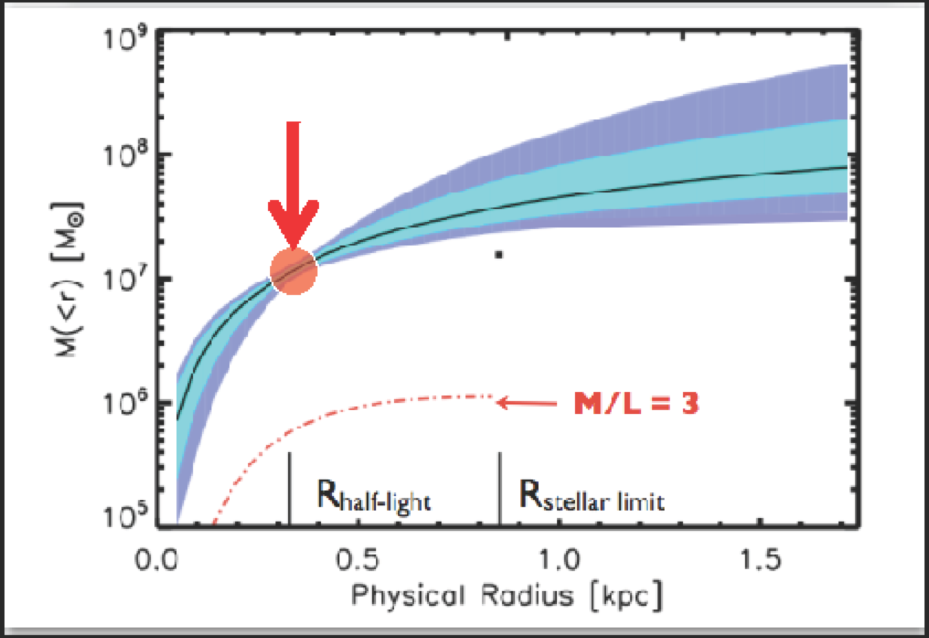
➔ Mass profiles are now/soon being derived from kinematics

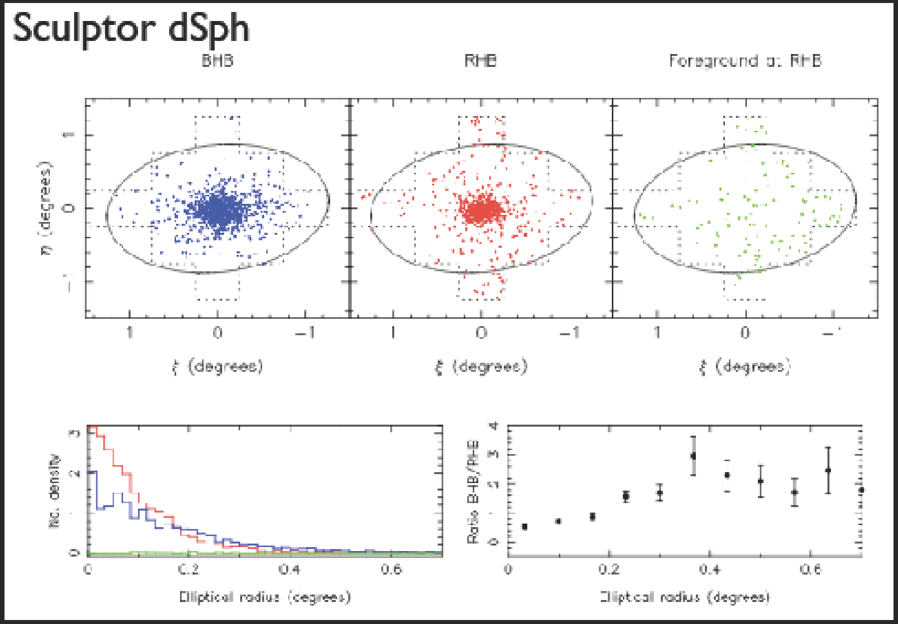
DM distribution in galaxies
"Core vs Cusp"

M -- β degeneracy breaks at R≃R_{half}

Peñarrubia+08; Walker+09; Wolf+10; Amorisco & Evans 10

Some dSphs show
spatially + kinematically
distinct stellar components





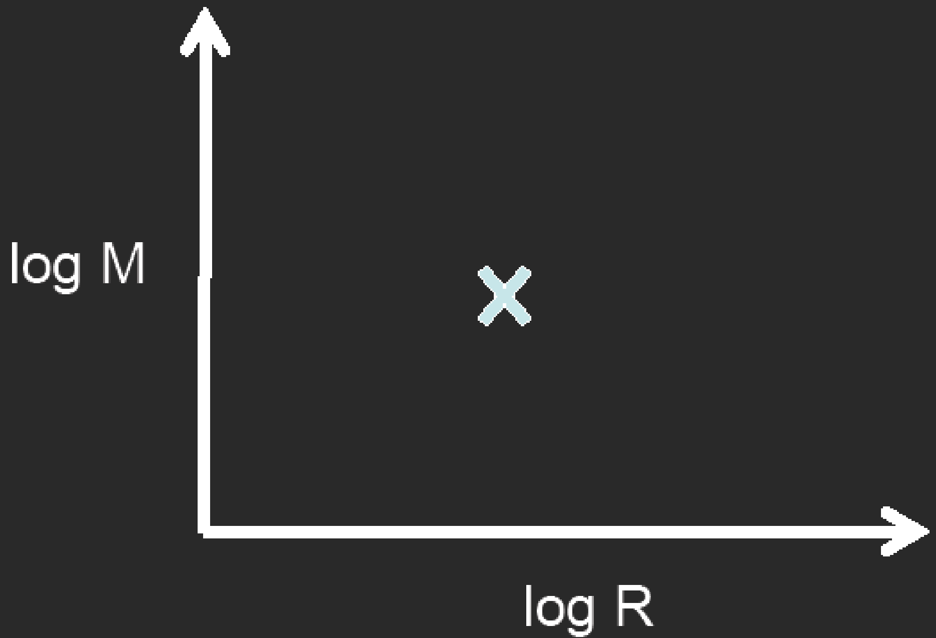
$$M(R_{\rm half}) \approx \mu R_{\rm half} \langle \sigma_V \rangle^2$$

$\mu \approx 480 M_\odot \mathrm{pc}^{-1} \mathrm{km}^{-2} \mathrm{s}^{-2}$ (Walker+09)

Tolstoy + 04 (see also Battaglia+08)

THE IDEA

Walker & Peñarrubia (2011)



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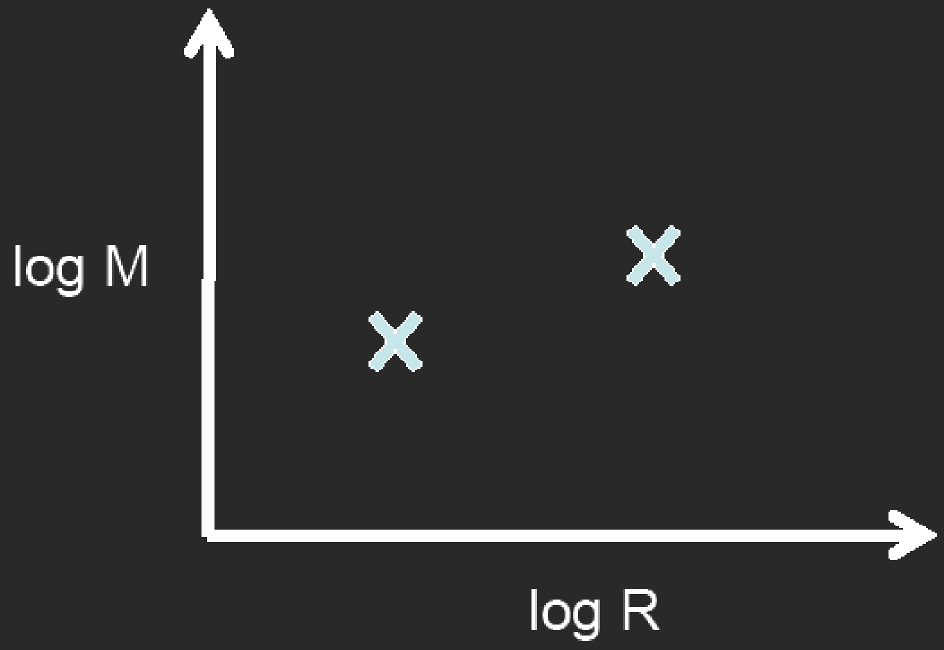

THE IDEA

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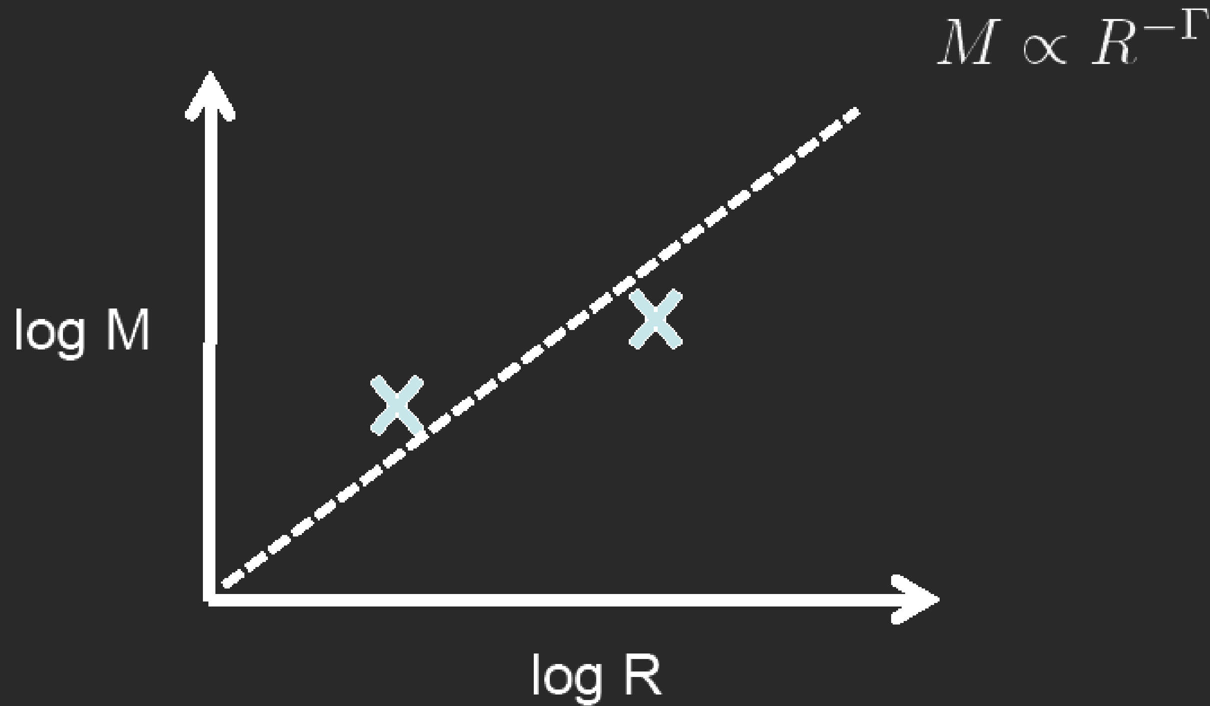


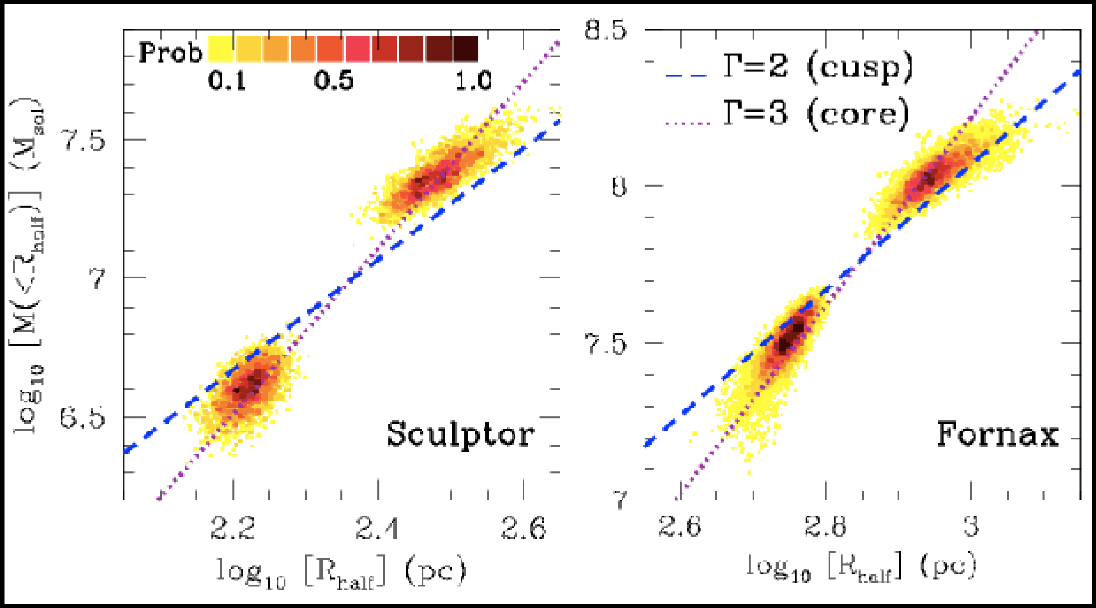
$$dM = 4\pi \rho_{\mathrm{DM}} r^2 dr$$

$$\rho_{\mathrm{DM}} \propto r^{-1} \longrightarrow \Gamma \approx 2$$

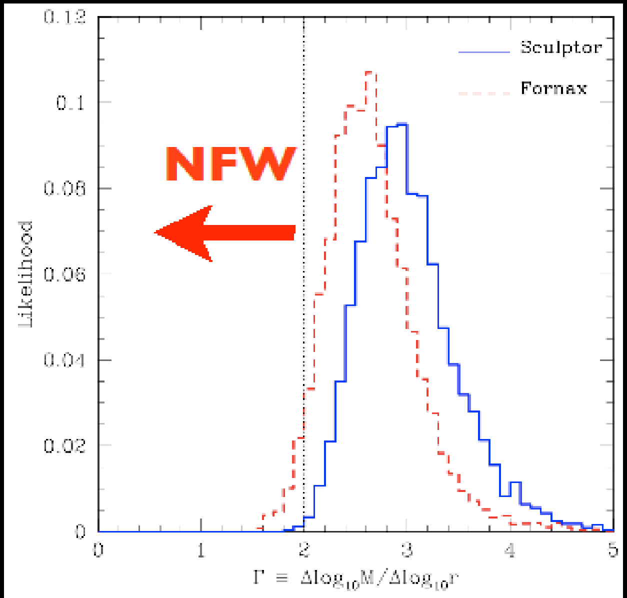
$$\rho_{\mathrm{DM}} \propto \mathrm{const.} \longrightarrow \Gamma \approx 3$$

Results

Walker & Peñarrubia (2011)



N_{sample}=1497 N_{sample}=2603



DM cusps ruled out in Fornax and Sculptor at a 96% and 99% confidence level

Further dSph candidates for holding multiple stellar populations

- **MW**: UMi, Dra, CVe I, Leo I and II
- **M31**: And I, II and VI

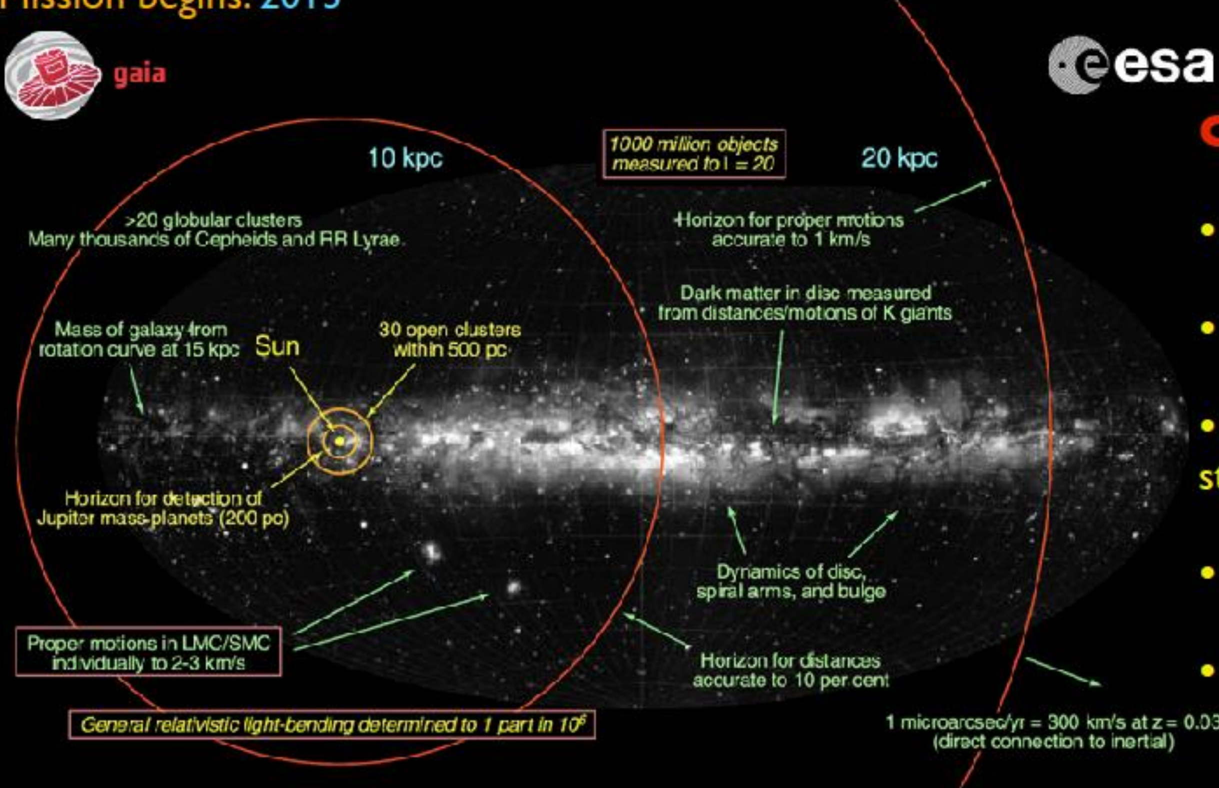
In a near future...

Major photometric and spectroscopic surveys of the MW coming up, e.g. :

• Pan-STARRS 0.5--1.0 mag deeper than SDSS; 30,000 deg^2 (3.6 times larger area than SDSS).
Mission begins : March 2010

• GAIA + 300 nights (!) VLT spectroscopic survey 10^9 stars with full phase-space information.
Mission begins: 2013

gaia



esa

Cosmology with Gaia:

• Accretion History of MW

• Orbits of satellites $r<r_{vir}$

• Internal dynamics of tidal streams and nearby dSphs

• DM density at solar neighb.

• Accreted GC pop. -- dSph

Pattern matching in positions/proper motions

Constraint on very low frequency gravitational waves:

- constraint on stochastic GW flux with $\nu < 3\times10^{-9}$ Hz
  (similar study done for VLBI: Gwinn et al., ApJ, 1997)

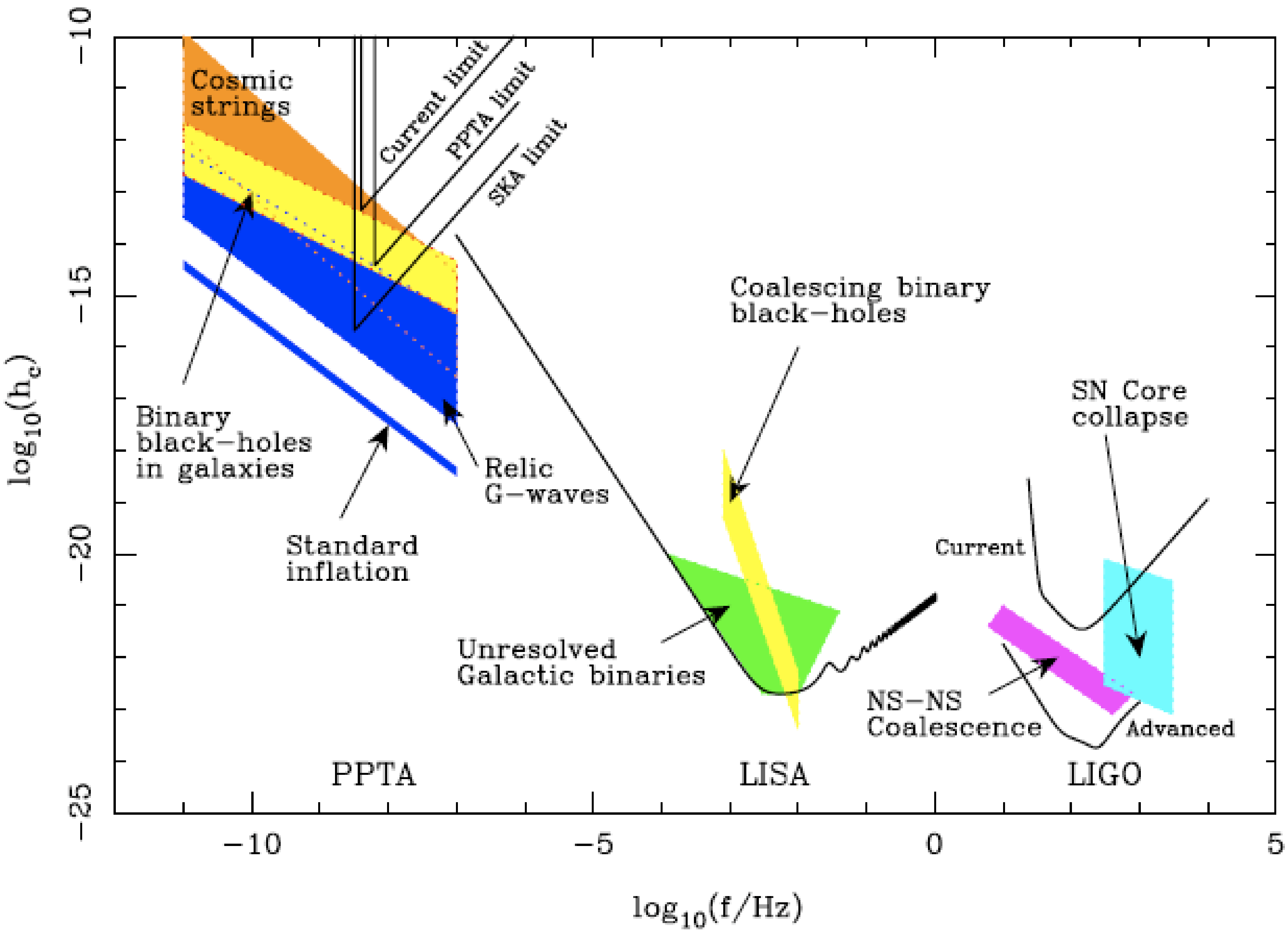
- attempts to fit a pattern of apparent motions induced by an individual GW with $\nu < 1.3\times10^{-7}$ Hz
  (matched filtering can be used, synergy with LISA & ground based)

The harmonic coefficients for n>1 give the GW-flux constraints

From Gaia for $\nu < 3\times10^{-9}$ Hz (95% confidence; preliminary analysis):

$$h^2\,\Omega_{GW} < 0.001 \div 0.005$$

Gravitational Wave Spectrum



Small-scale DM: Are we making progress?

- Satellite counts – still puzzling – many new deep surveys starting, exciting future
- Clustering, sizes – still puzzling – see above
- New tests, eg binary stars - promising
- Abundances/feedback limits – exciting!
- Core/cusp, dSph: kinematics – substantial!
- Dynamics modelling - substantial
- and still nothing yet from particle physics

Pattern matching in positions/proper motions

Example: a GW of strain h and frequency ω propagating in the direction δ=90° :

$$\vec{\mu} = \frac{1}{2}\omega h \sin \omega T \cos\delta \left(\cos 2\alpha\, \vec{\boldsymbol{e}}_{\delta} + \sin 2\alpha\, \vec{\boldsymbol{e}}_{\alpha}\right)$$