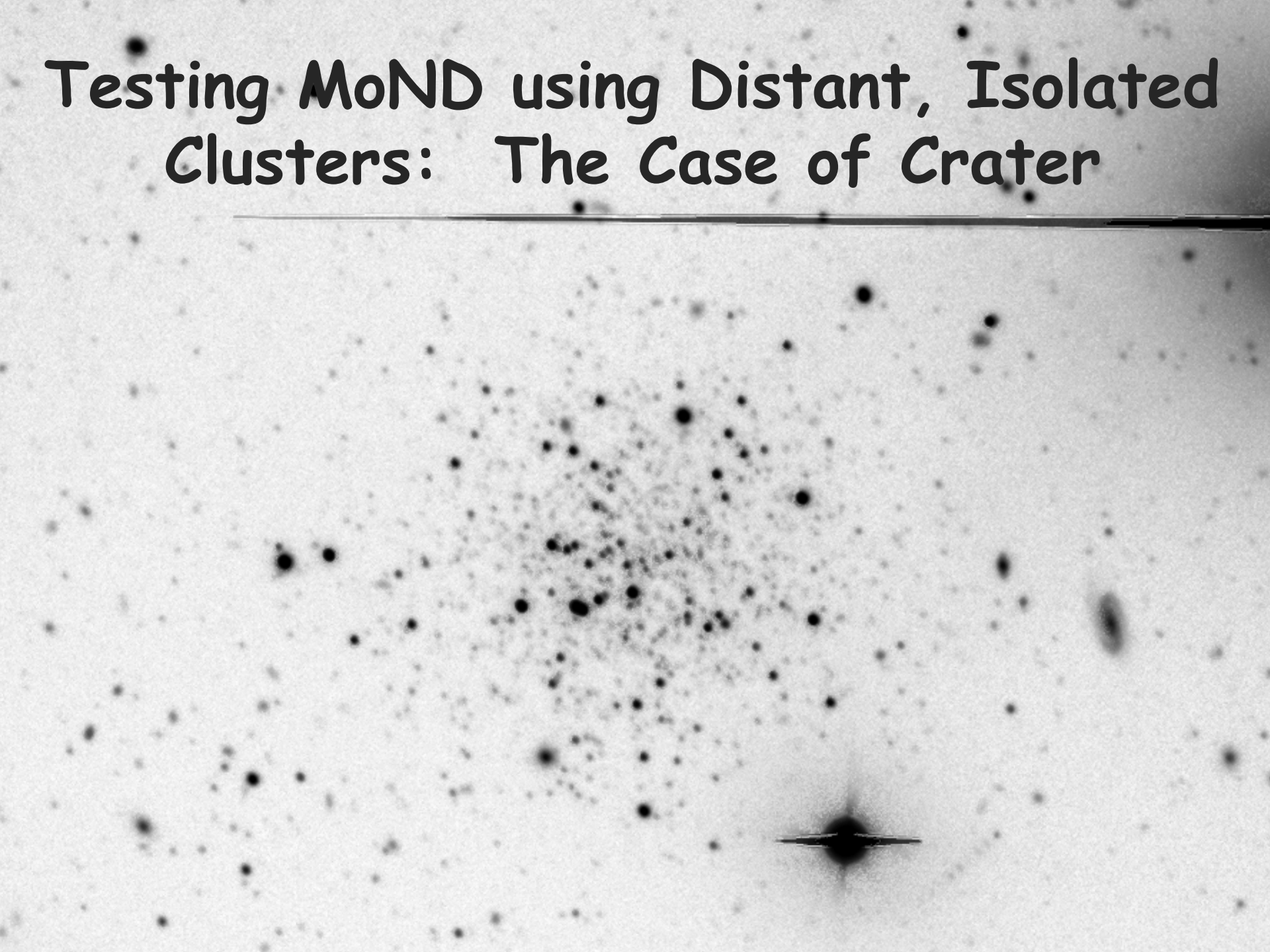
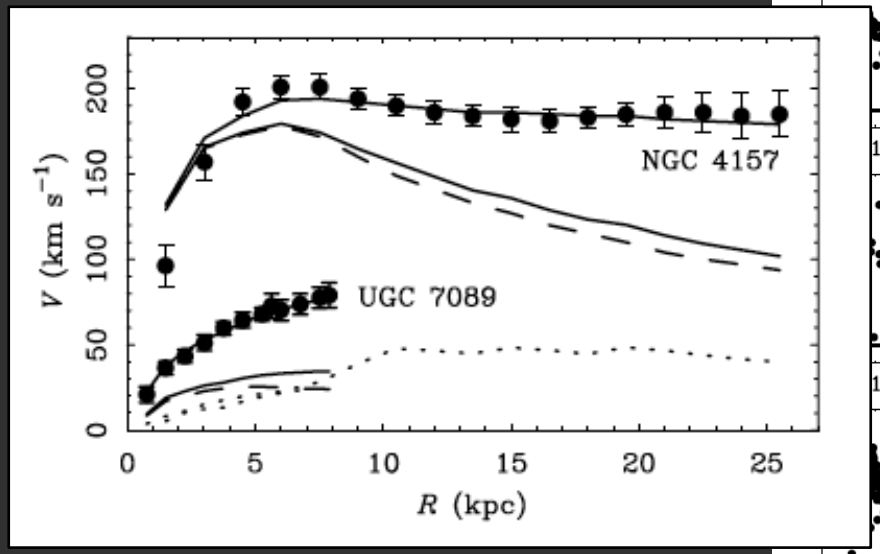
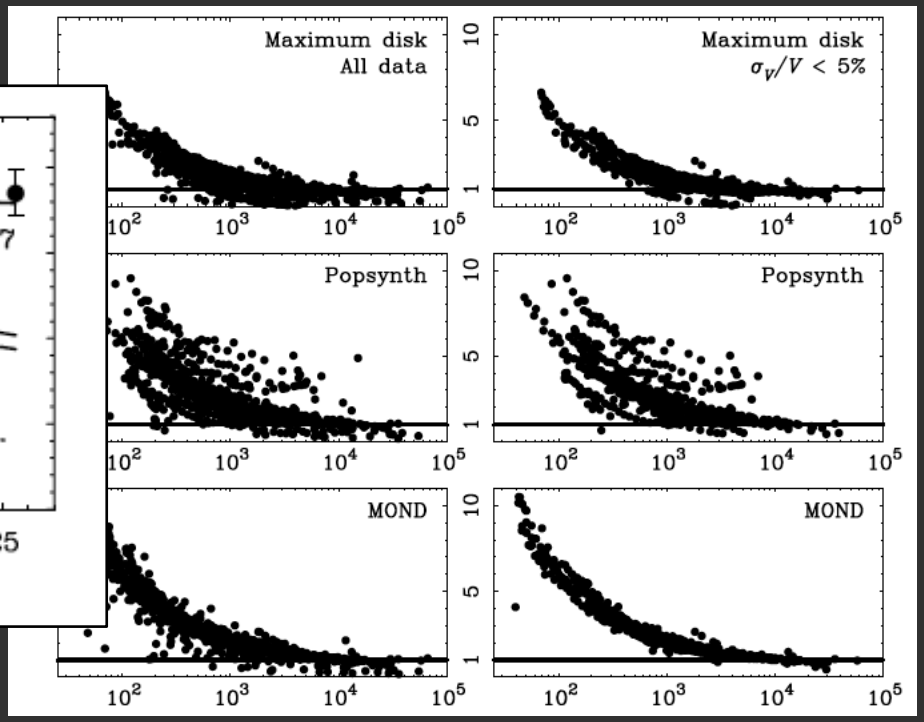
Testing MoND using Distant, Isolated Clusters: The Case of Crater

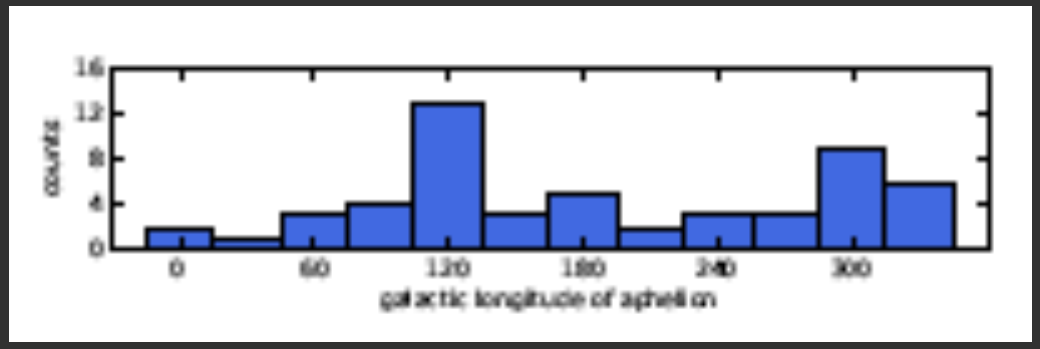


Testing MoND





Galaxy Dynamics



Cometary Orbits: Probing External Field Effects (Pauko and Klacka)

Can we devise tests that . . .

a) Invoke techniques similar to what we use for galaxy dynamical studies;
b) Identify systems where MoND should dominate the dynamics;
c) Avoid systems that are otherwise interpretable with DM?

Possibly: Remote Halo Star Clusters

What are we looking for?

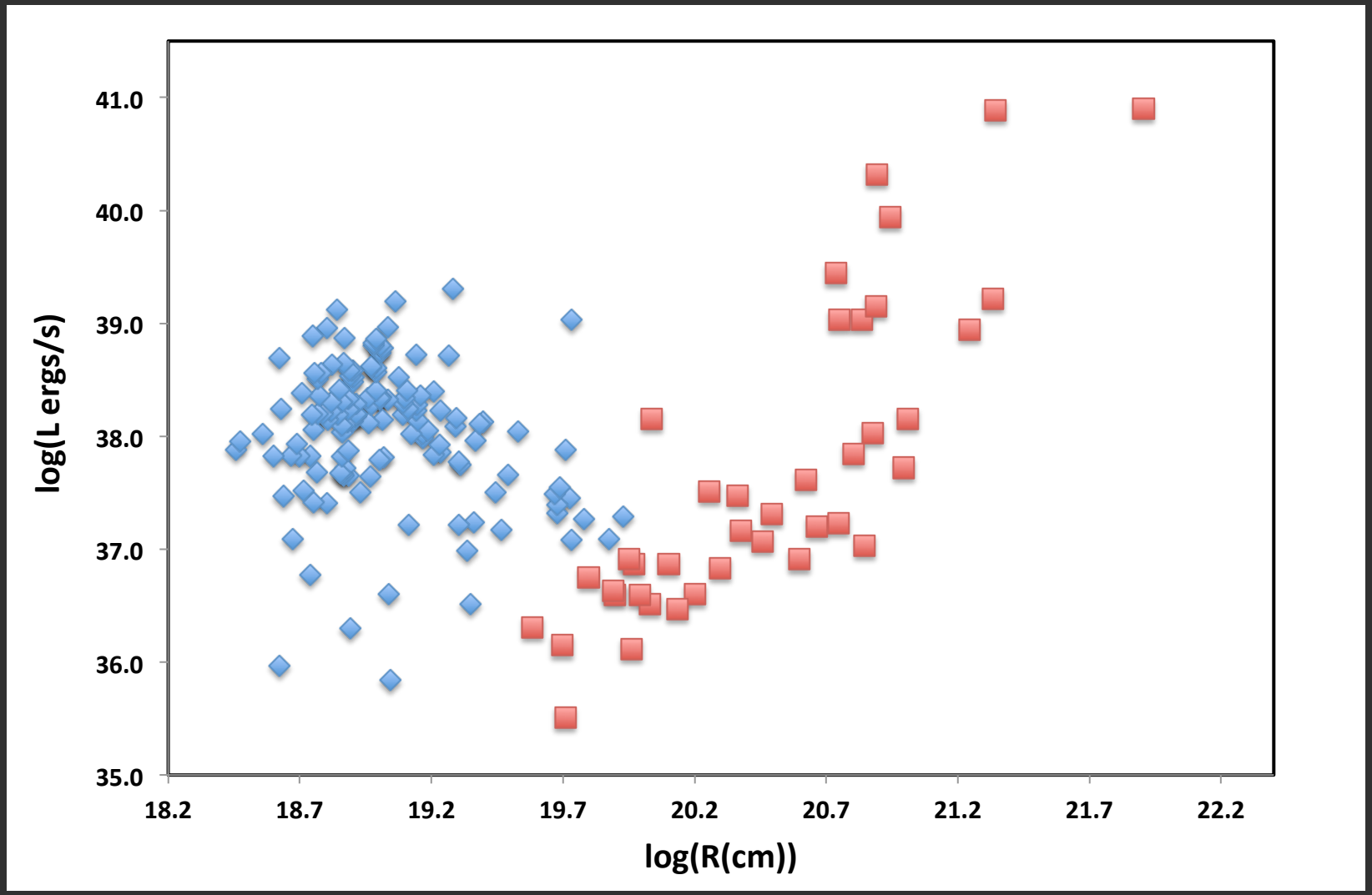
a_0 = MoND acceleration scale
$a_{1/2}$ = acceleration scale at $R_{1/2}$
a_{ext} = external acceleration from parent galaxy (EFE)

Ideally:

$a_{1/2} < a_0$ and $a_{ext} \ll a_0$

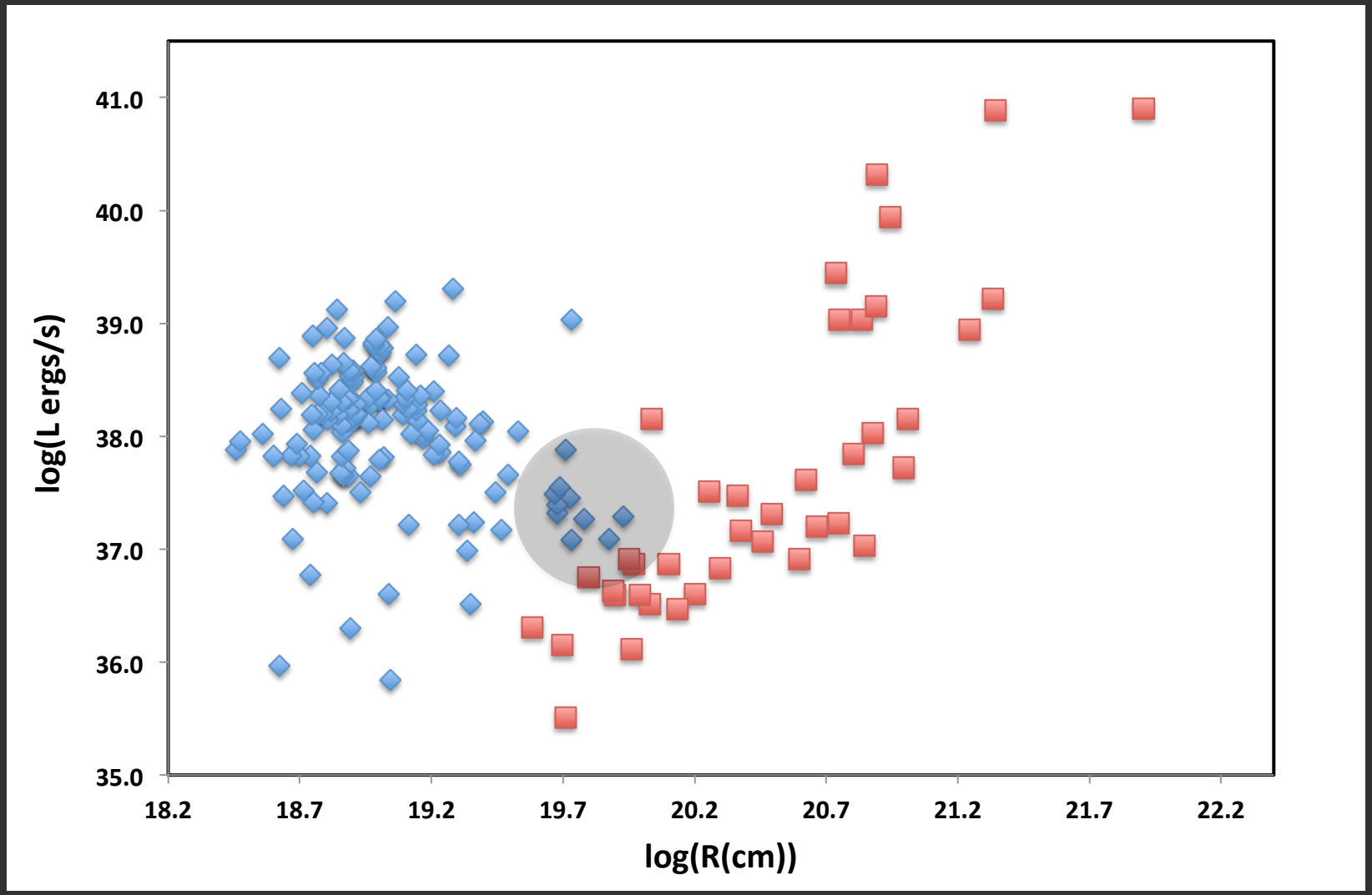
no DM

Do such thngs exist?



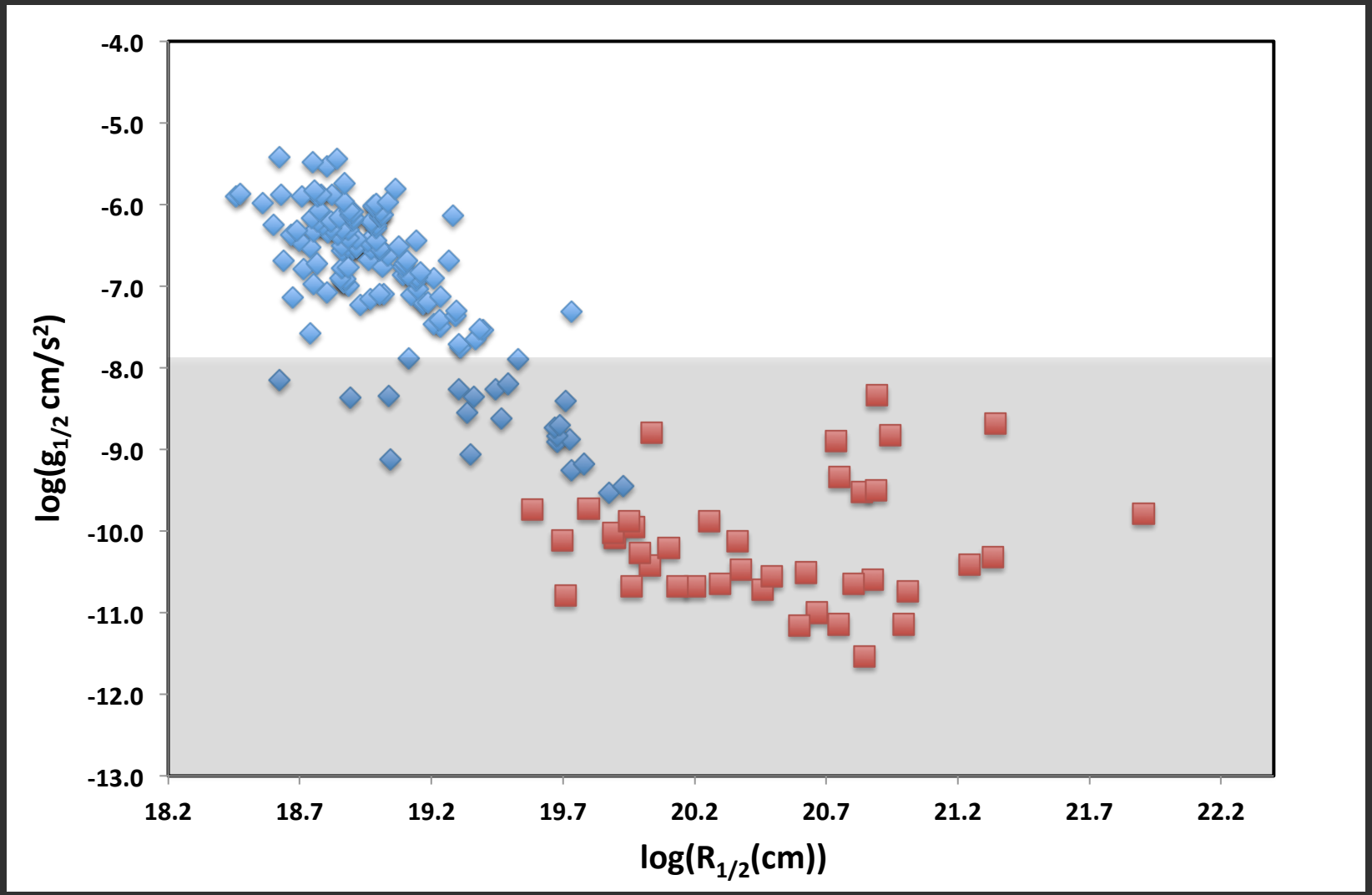
Candidates: Luminosity-Radius Plane

Do such thngs exist?

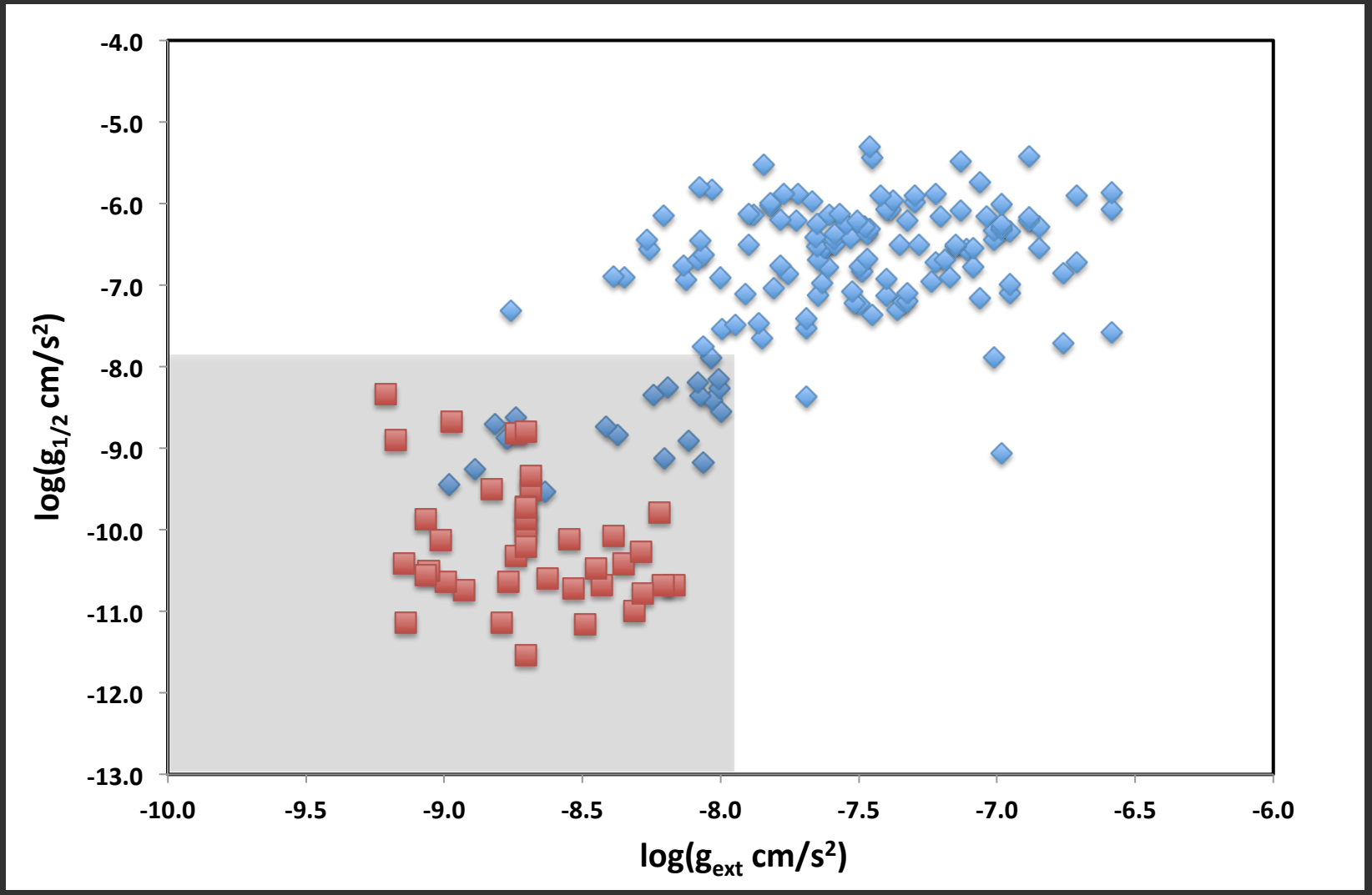


Candidates: Luminosity-Radius Plane

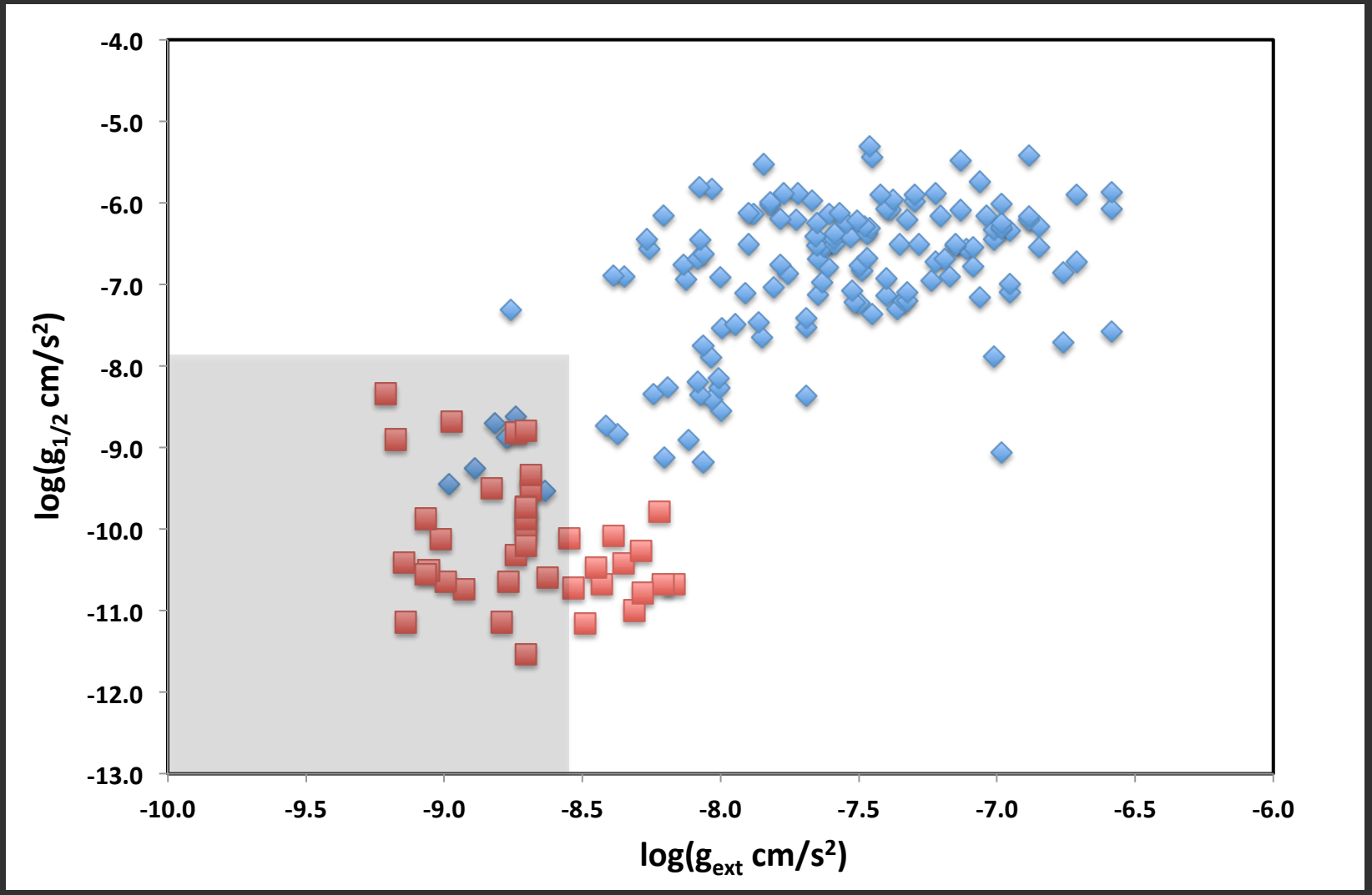
Candidates: $a_{1/2} < a_0$



Candidates: $a_{1/2} < a_0$ and $a_{ext} < a_0$



Candidates: $a_{1/2} < a_0$ and $a_{ext} << a_0$



This leads to a set of 'usual suspects':

Name	m_V	DistMod	log(L (ergs/s))	log(R 1/2 (cm))	g_1/2/a0	gext/a0
Pal 14	14.62	19.3	37.09	19.87	0.024	0.193
AM 1	15.72	20.4	37.08	19.73	0.046	0.108
Arp 2	11.96	17.2	37.31	19.68	0.102	0.638
Pal 3	14.17	19.8	37.45	19.73	0.111	0.141
Pal 15	12.76	18.2	37.39	19.68	0.121	0.353
Pal 4	14.17	20.0	37.55	19.69	0.166	0.127
Eridanus	14.64	19.5	37.18	19.46	0.196	0.152
NGC 2419	10.05	19.6	39.03	19.73	4.038	0.145

So, what's needed . . . ?

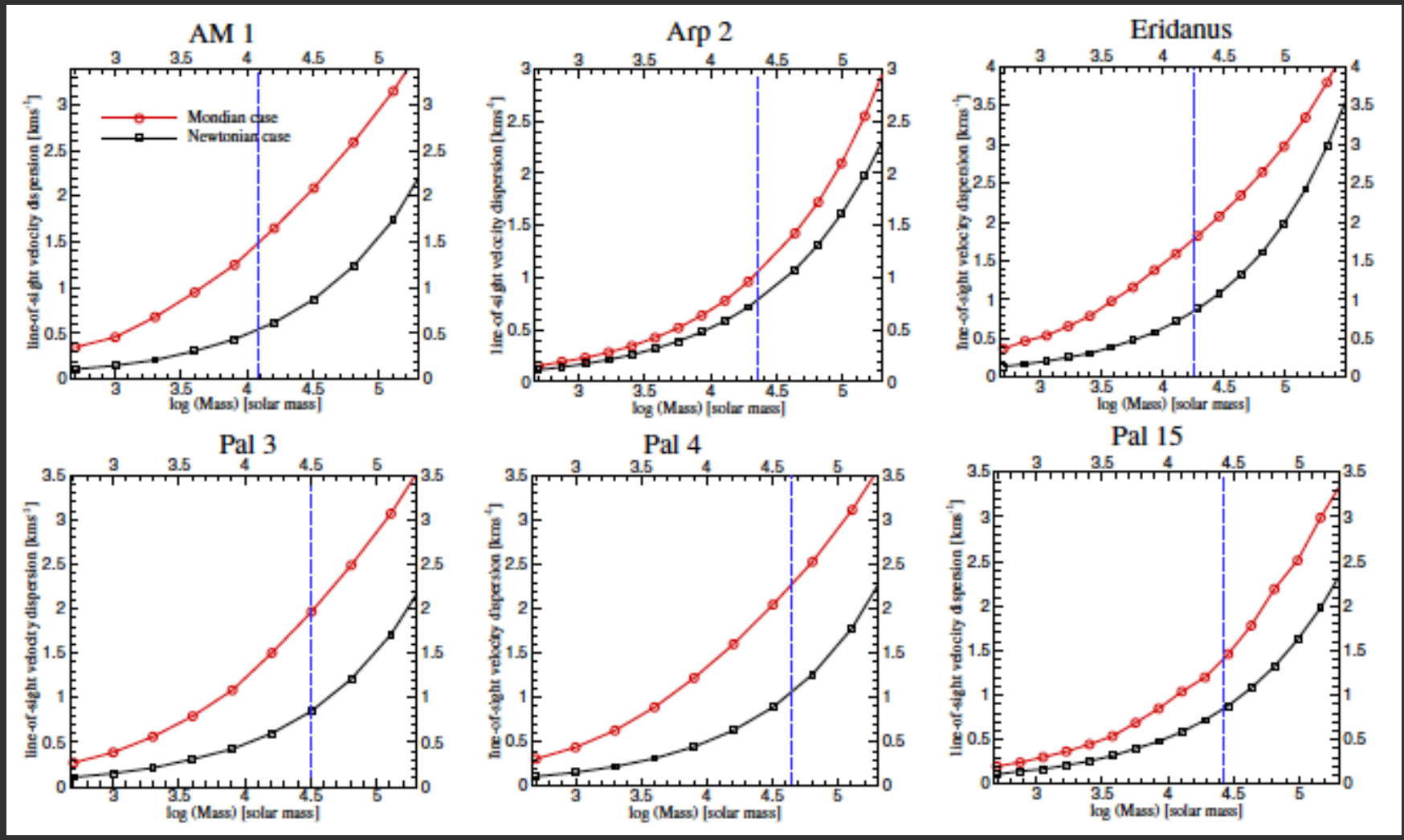
Following Haghi, Baumgardt and Kroupa (2011):

- MoNDian and Newtonian models of cluster dynamics
- Account for the External Field Effect (EFE):

$$\nabla . \left[\mu \left(\frac{|\boldsymbol{a}_c + \boldsymbol{a}_i|}{a_0} \right) (\boldsymbol{a}_c + \boldsymbol{a}_i) \right] = 4\pi G \rho_c .$$

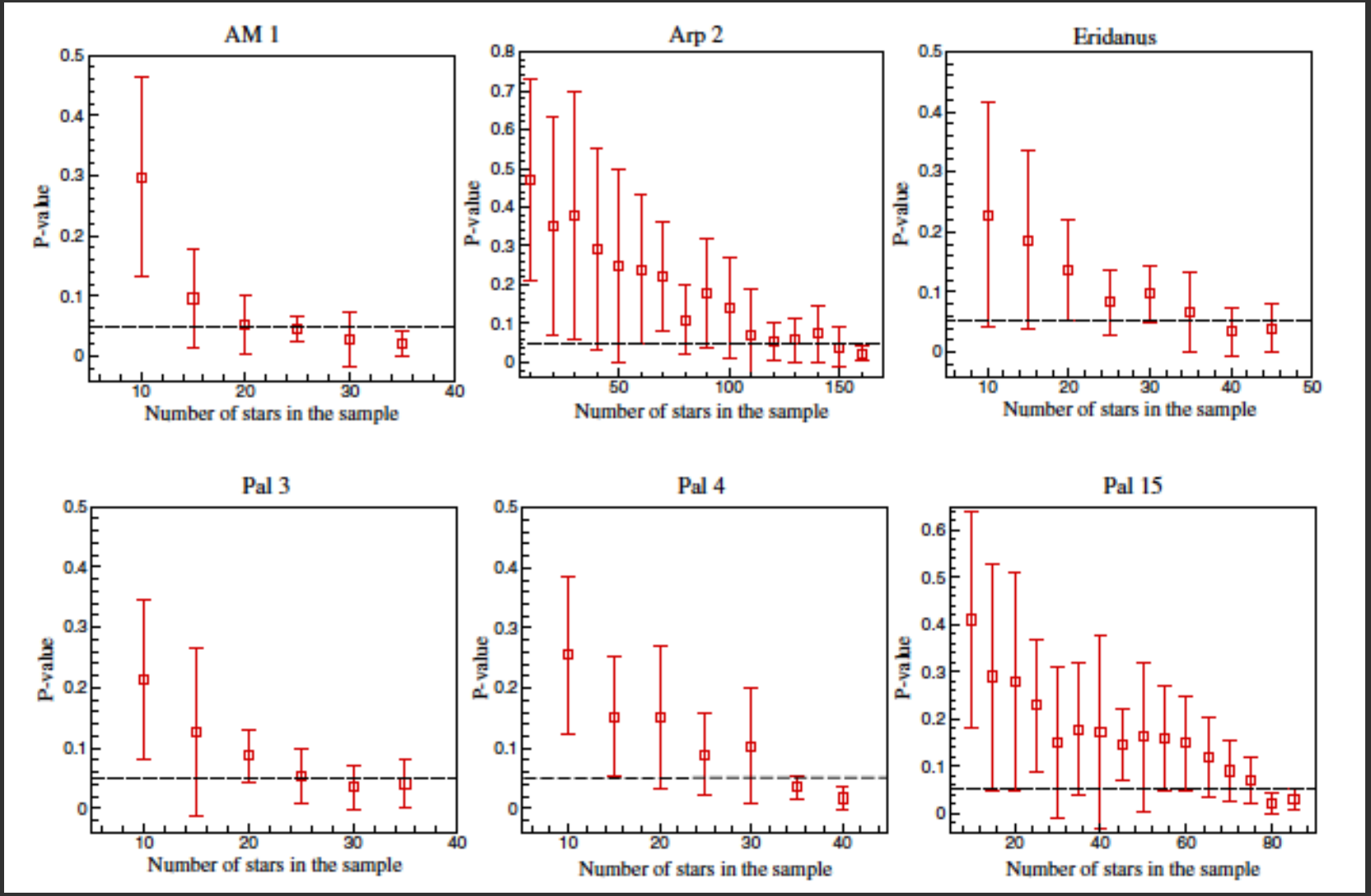
- Model stochastic sampling of kinematics

Predictions:



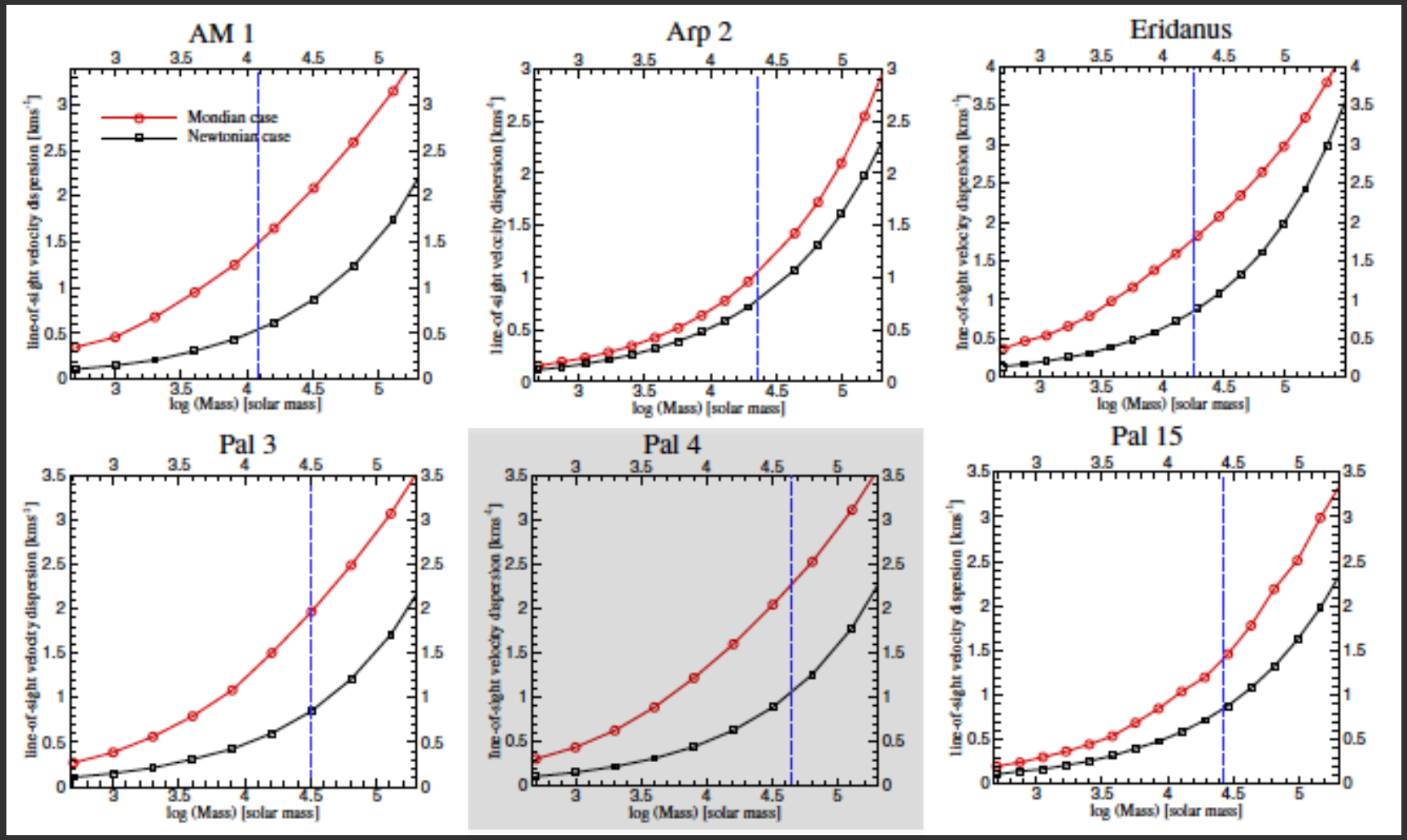
Haghi, Baumgardt and Kroupa 2011

So, what's needed . . . ? Sample size:



Haghi, Baumgardt and Kroupa 2011

A case study: Pal 4



Haghi, Baumgardt and Kroupa 2011

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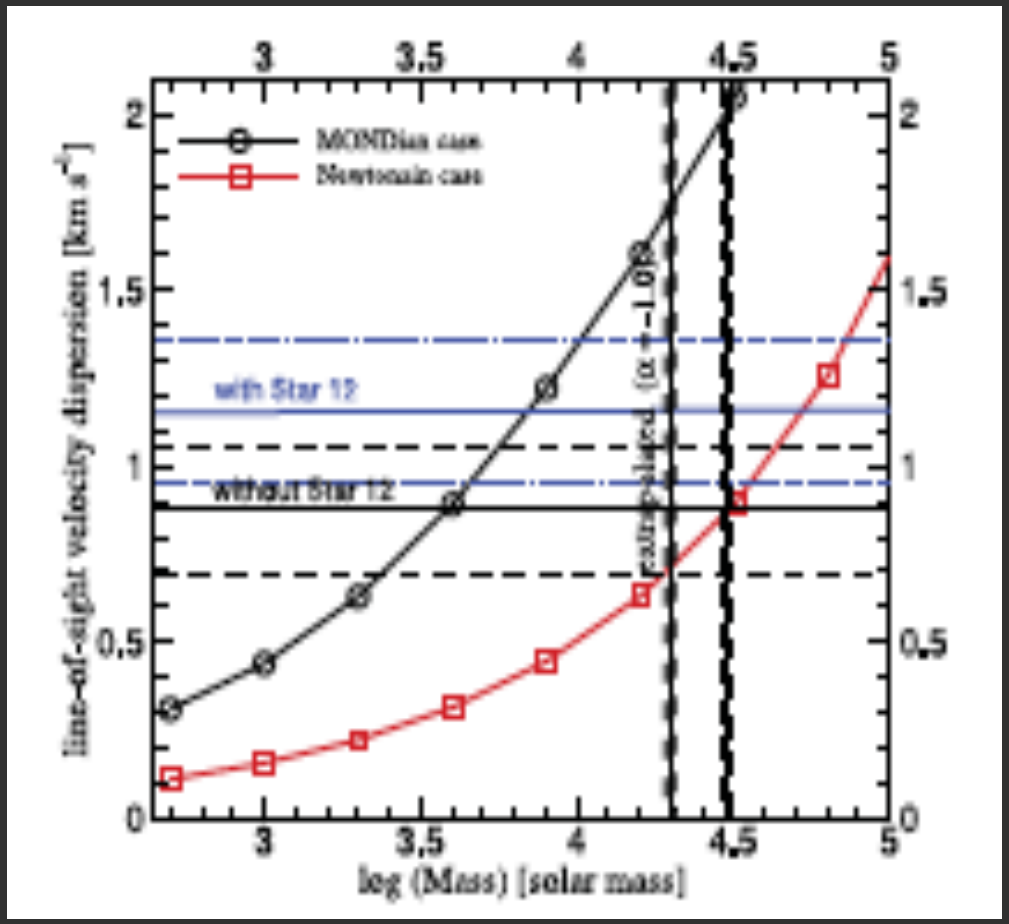


Frank et al. 2012

- σ_0 = 0.87 ± 0.18 km/s
- Newtonian mass and mass inferred from stellar MF in good agreement
- MoND mass implies very low M/L and poor agreement with stellar MF

Falsification of MoND?
Maybe not yet:

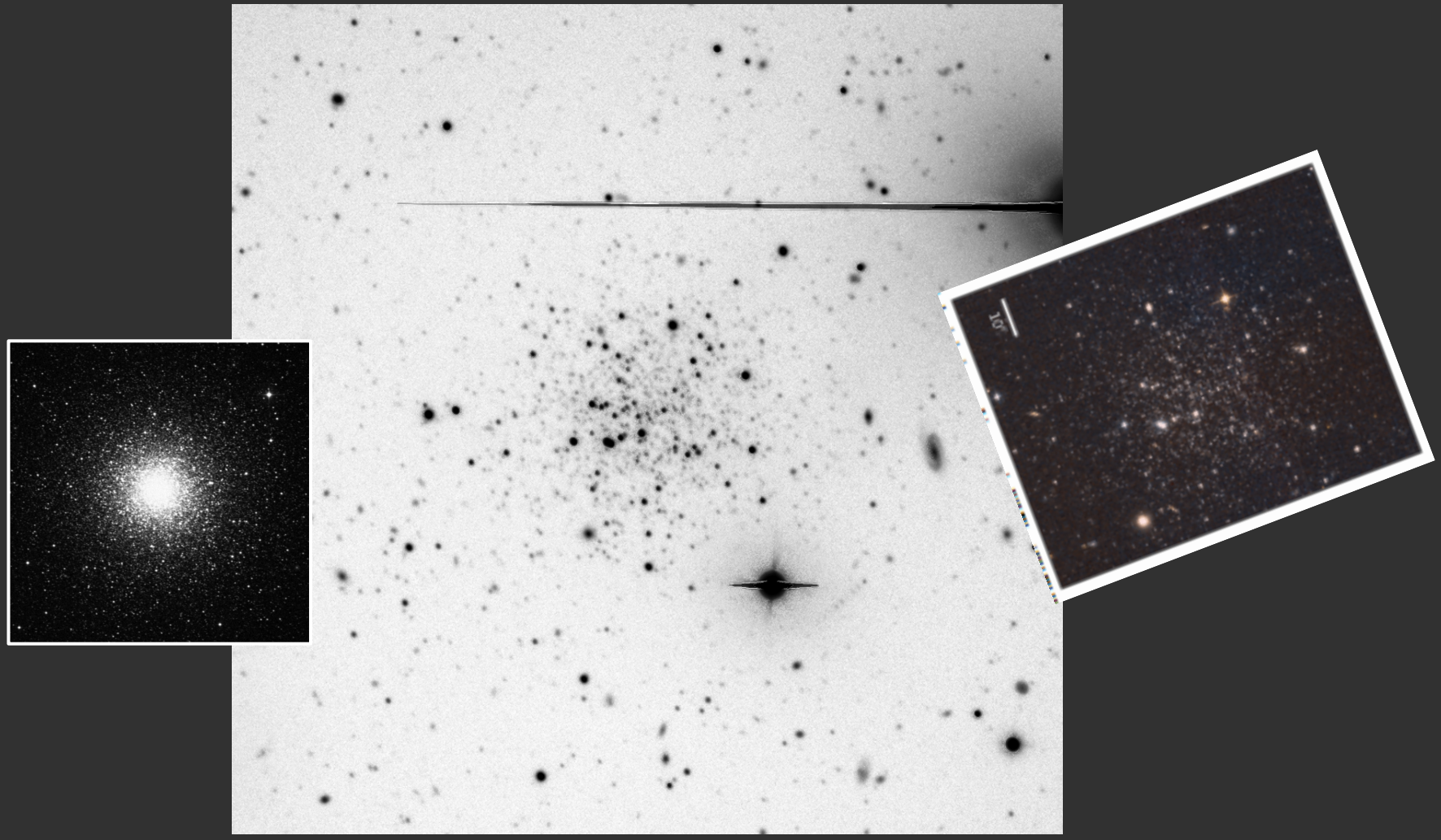
P_{MoND}~20%

Enter: Crater

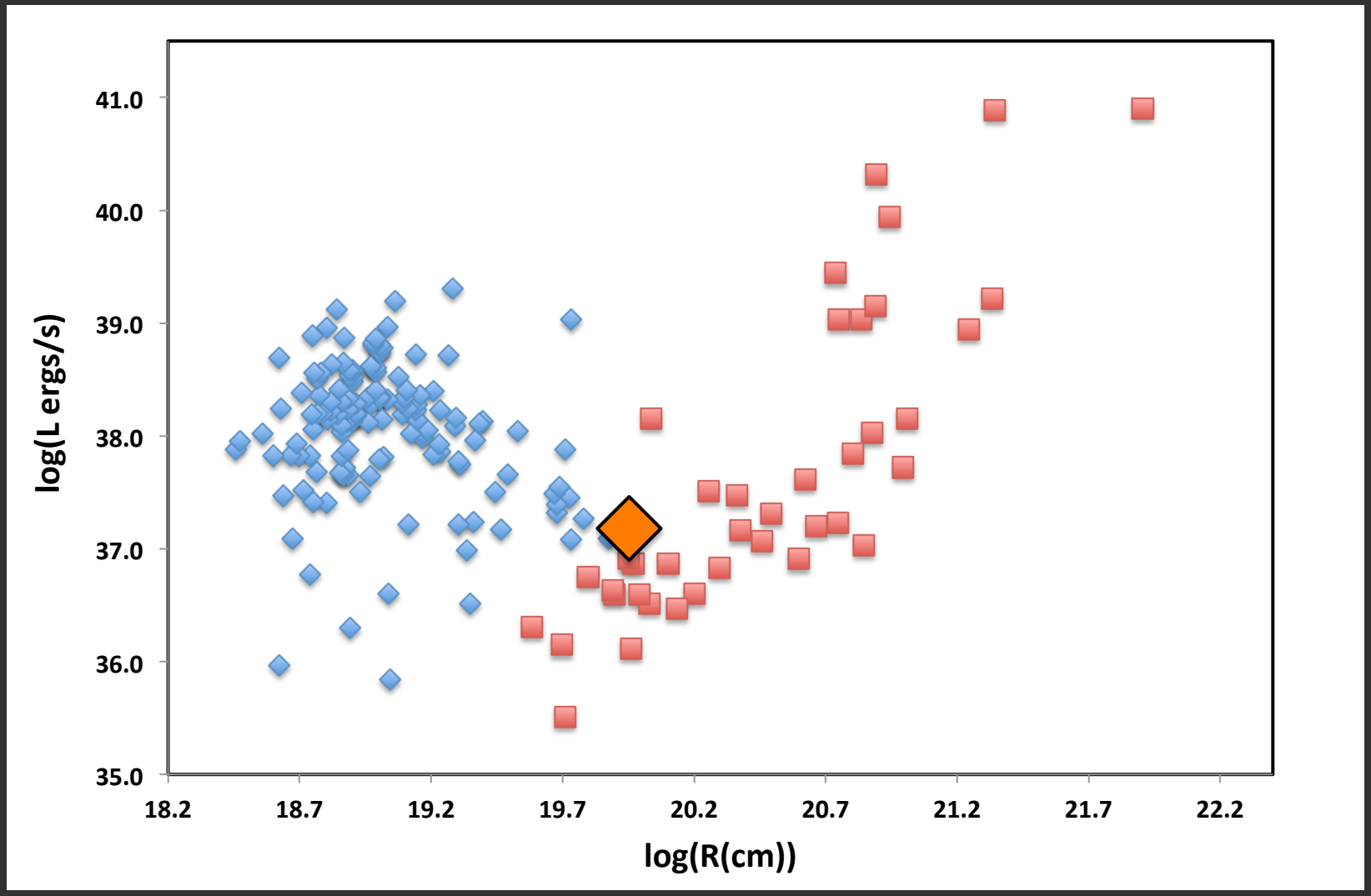
Discovery:

- Atlas/VLT (Belokurov et al. 2014)
- Dist ~ 150 kpc
- Nature initially uncertain: Ultra-faint dwarf or GC?

Crater: What is it?

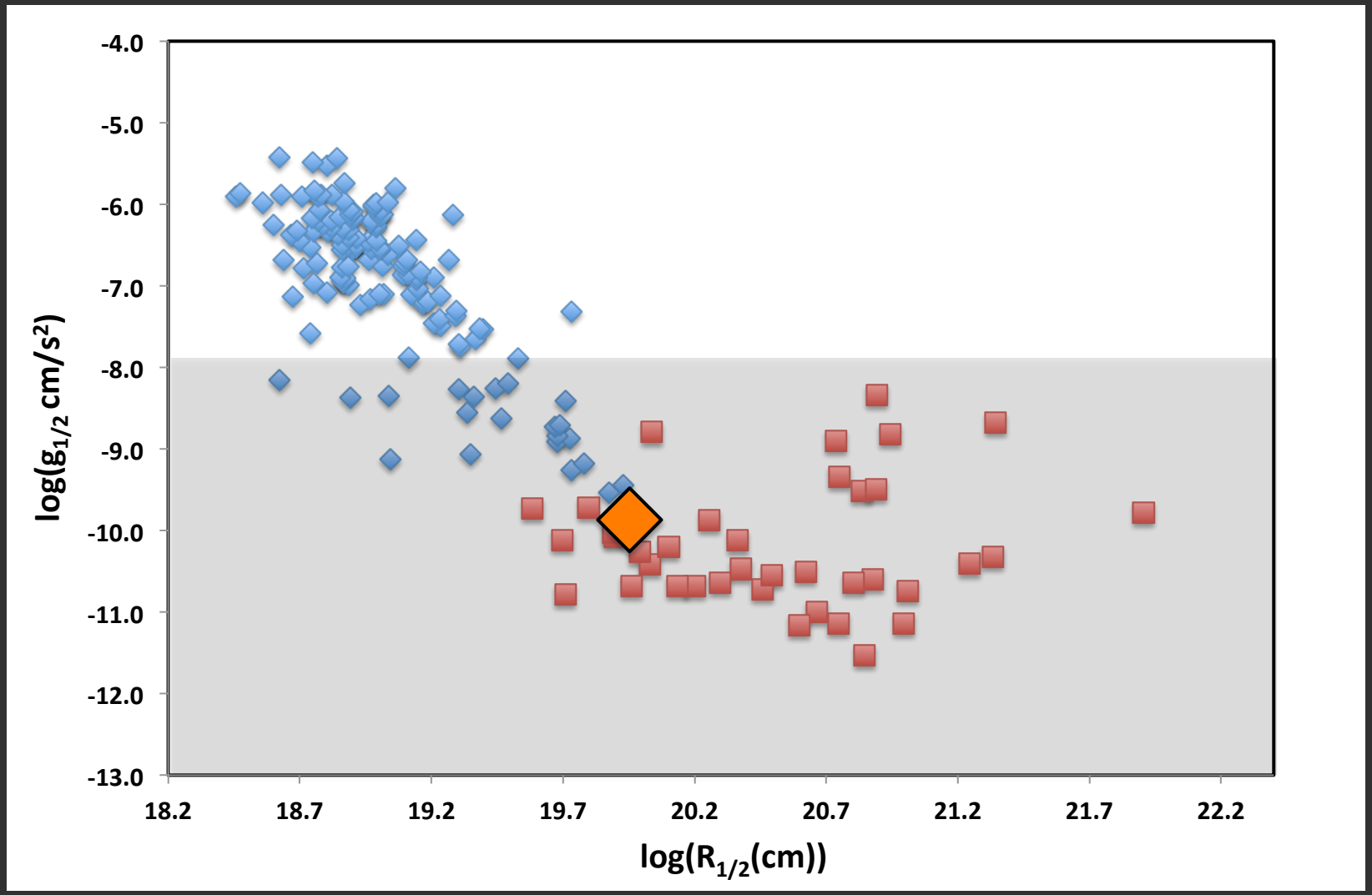


Crater is ambigious in all structure scalings:



Candidates: Luminosity-Radius Plane

But it is deeply in the MoND regime:



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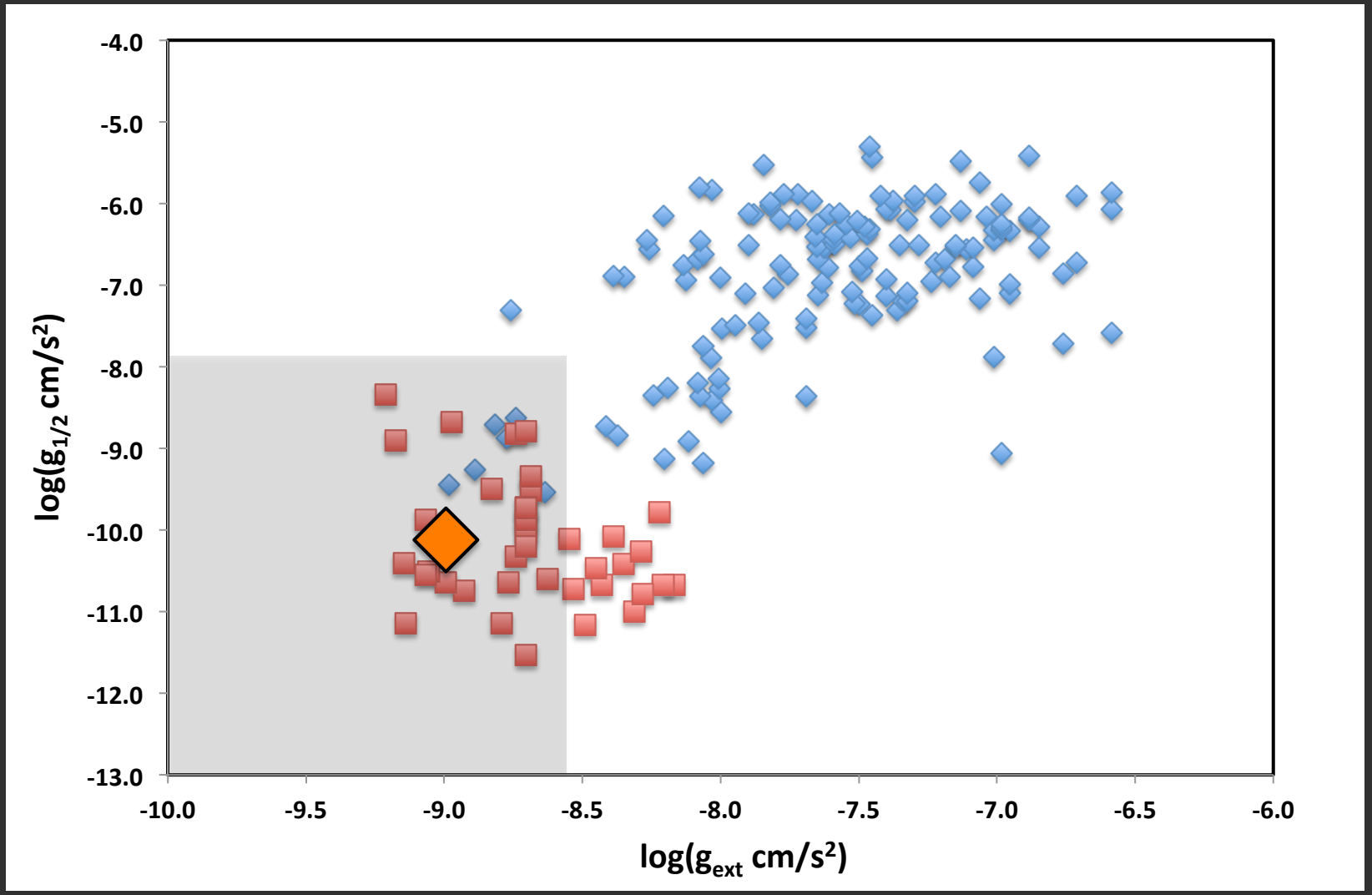
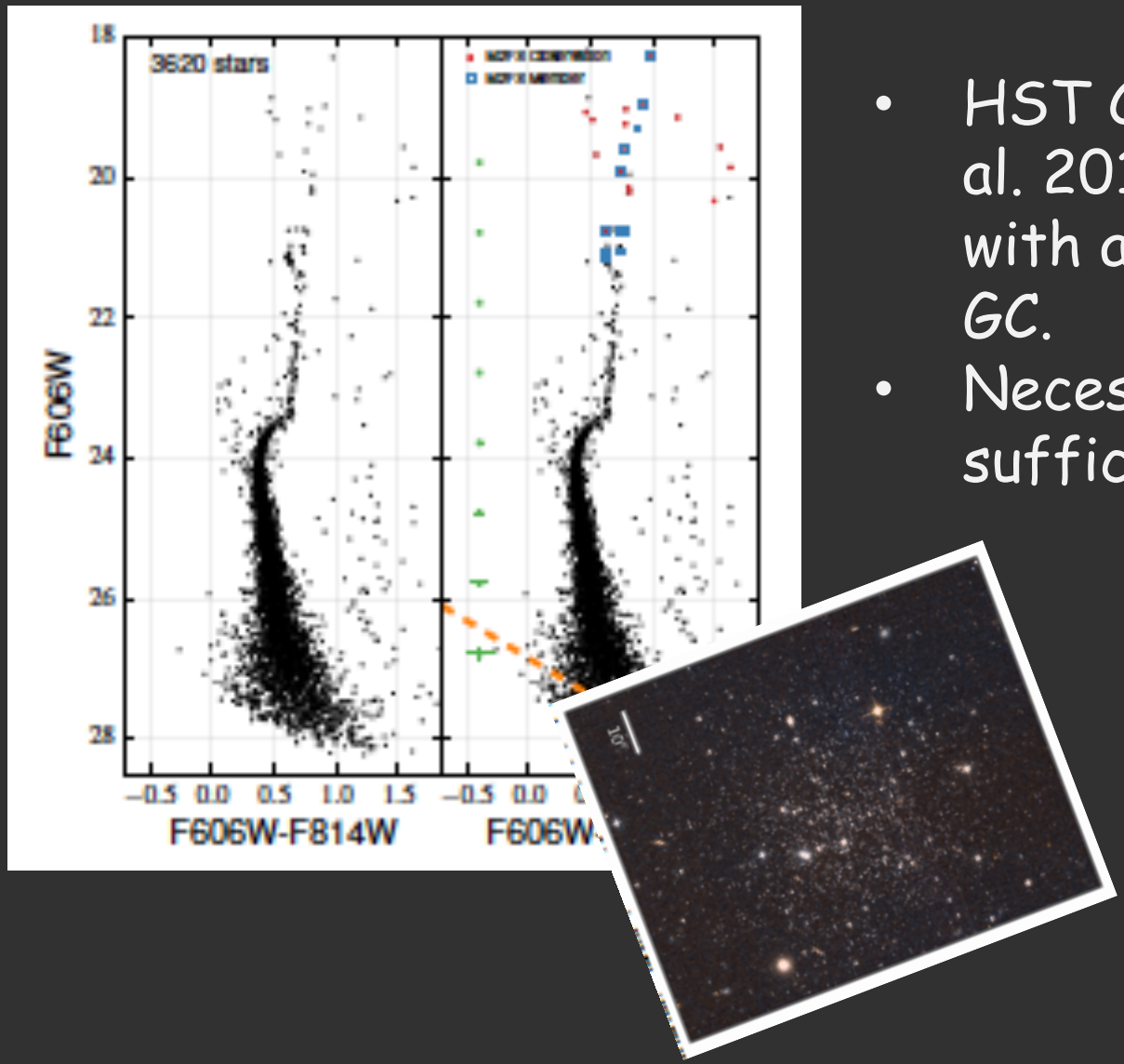
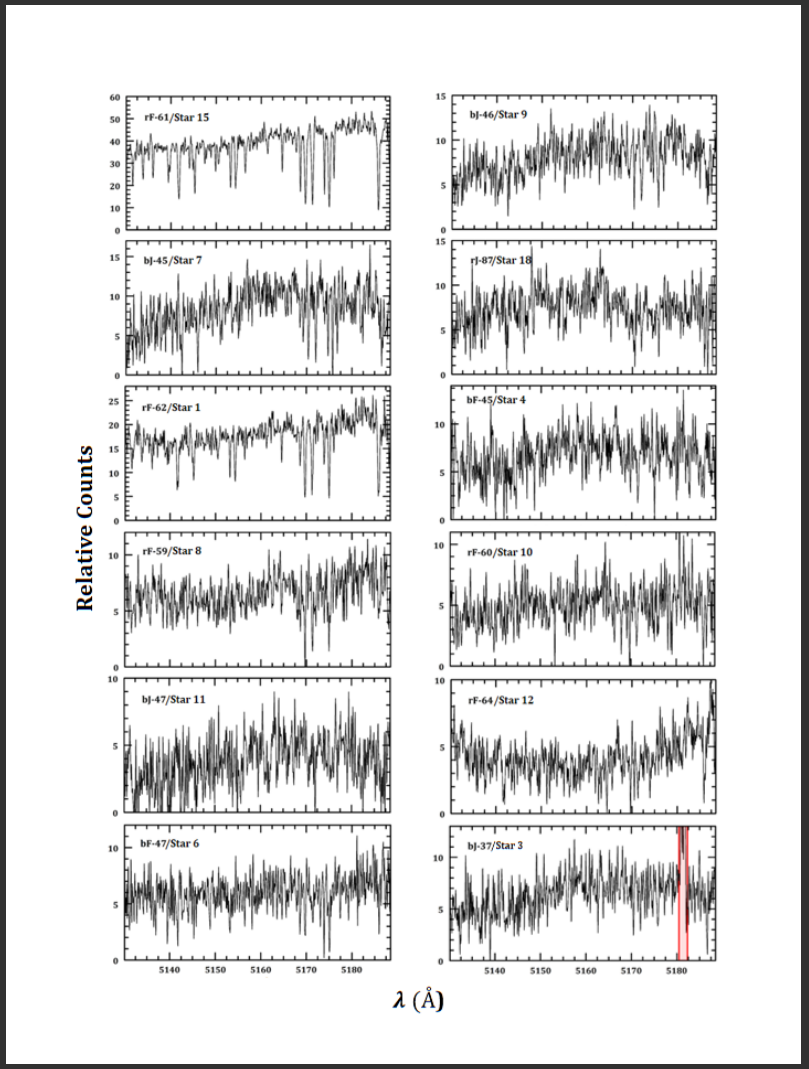


Crater: Is it a UFD? Umm . . .

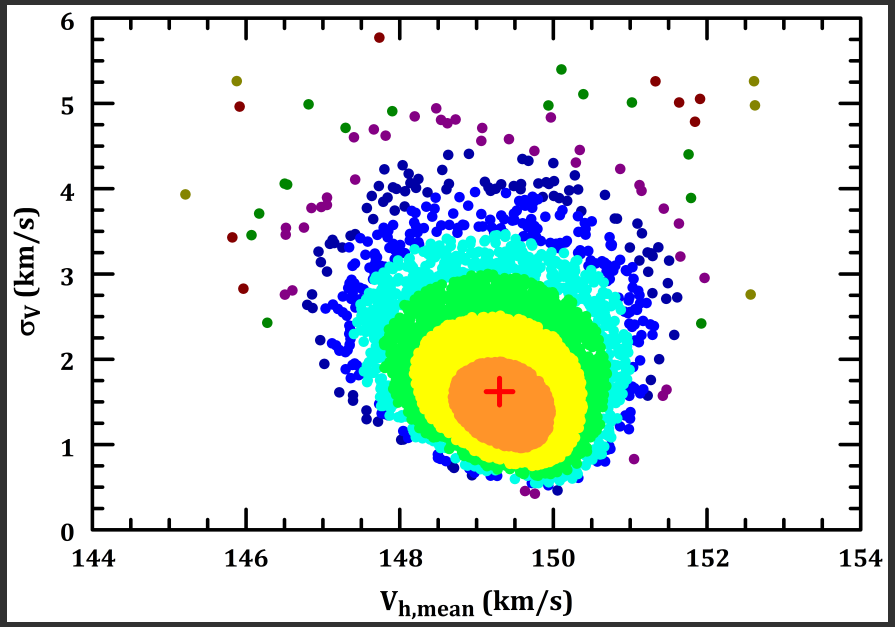


- HST CMD (Weisz et al. 2016) consistent with a classical, old GC.
- Necessary but not sufficient result.

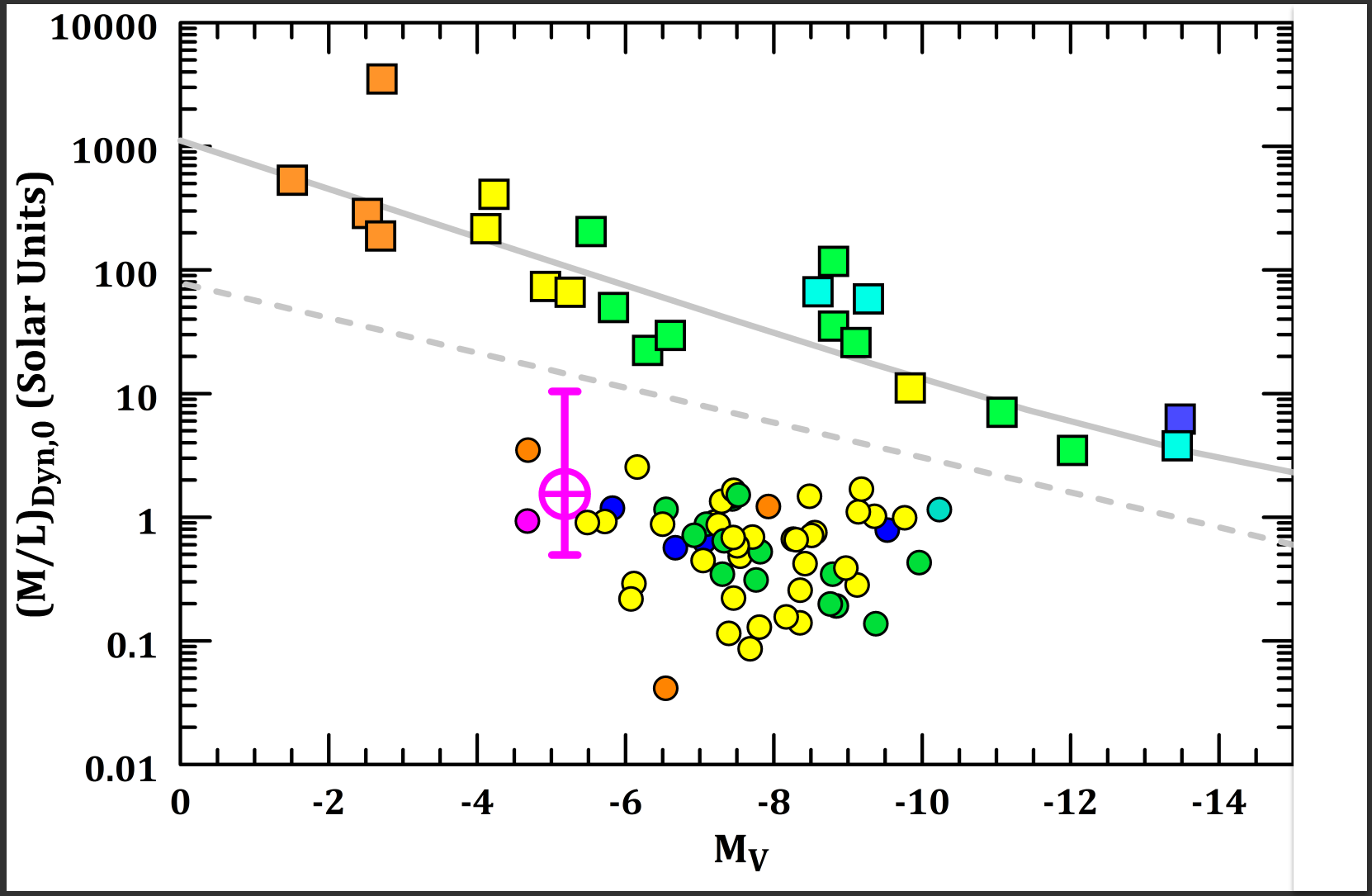
Crater: Is it a UFD? No?



Kinematics make the case.

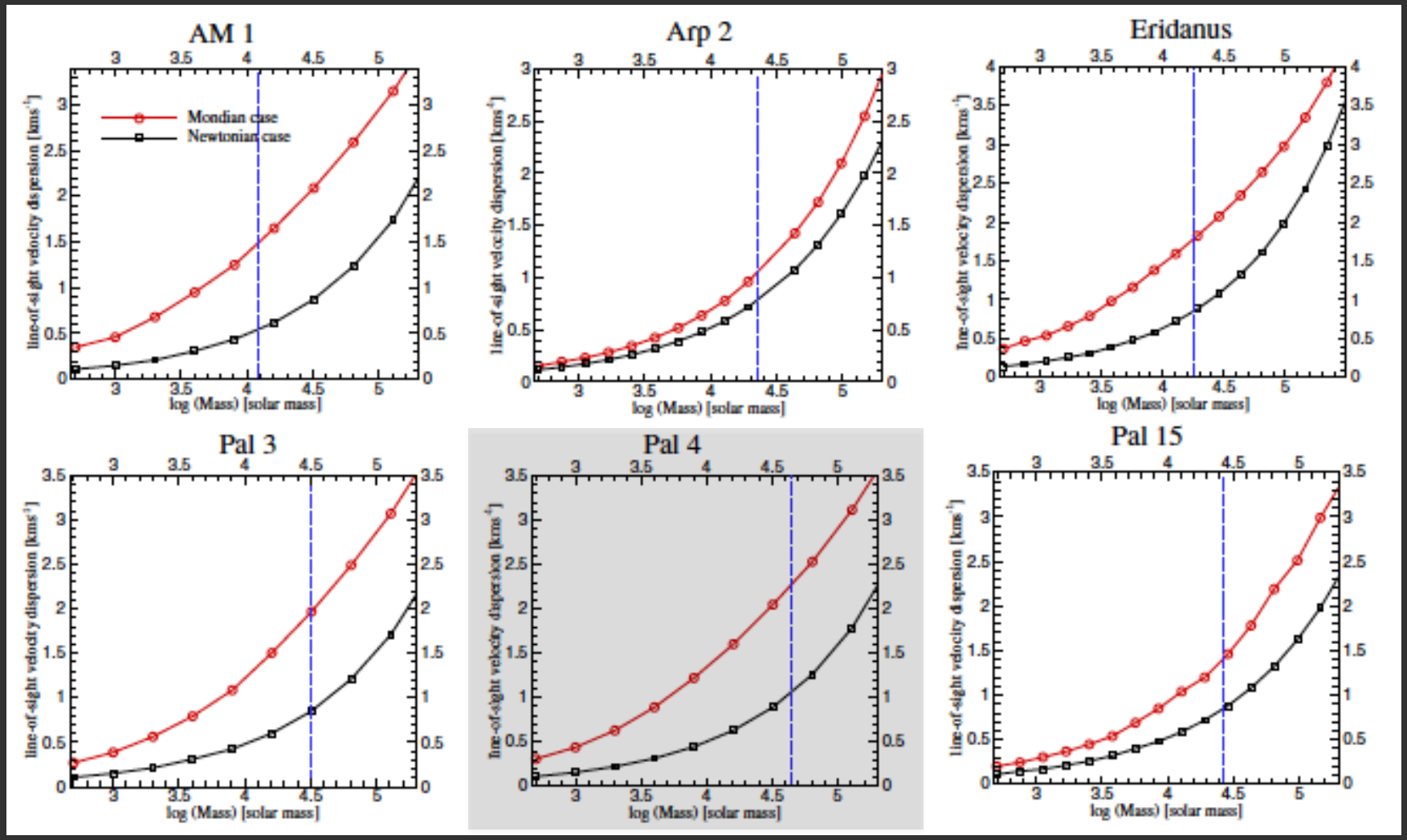


Crater: Is it a UFD? NO!



Looks like a keeper!

Crater: What about MoND?



Pal 4 is the closest analog

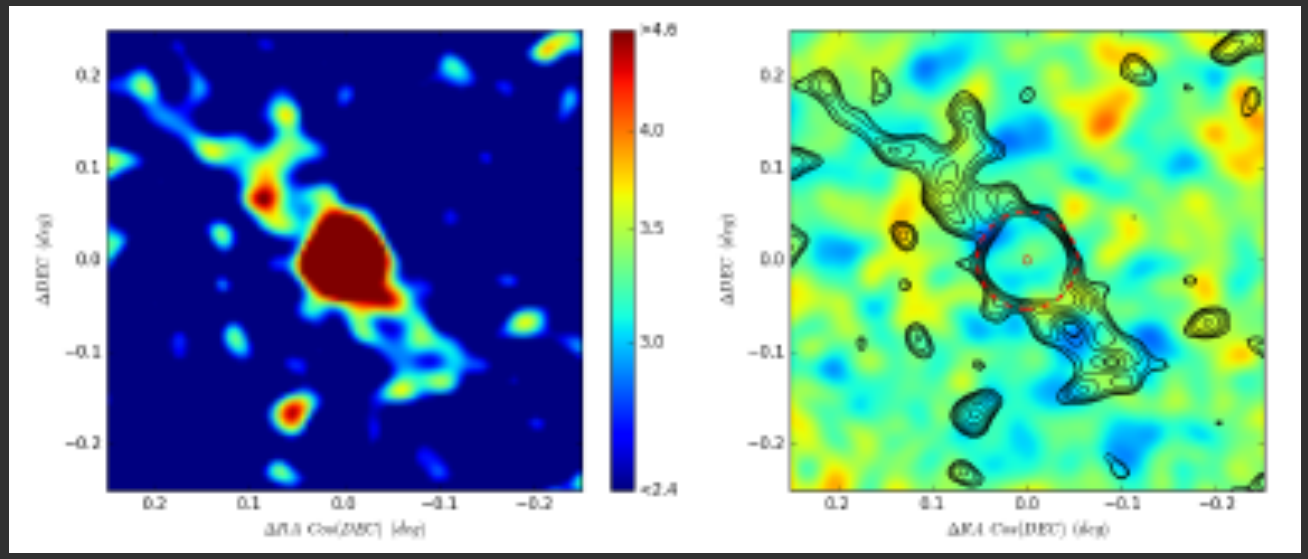
Comparing Crater and Pal 4:

	Crater	Pal 4
D_{GC} (kpc)	150	102
R 1/2 (pc)	27.5	15.6
Lum (Msol)	9.8×10^3	4.9×10^3
$a_{1/2}$ (a_0)	0.030	0.166
a_{ext} (a_0)	0.087	0.127
σ_N (km/s)	0.6	1.1
σ_M (km/s)	2.2	2.3
σ_0 (km/s)	1.6	0.9
P_N	6%	70%
P_M	26%	20%

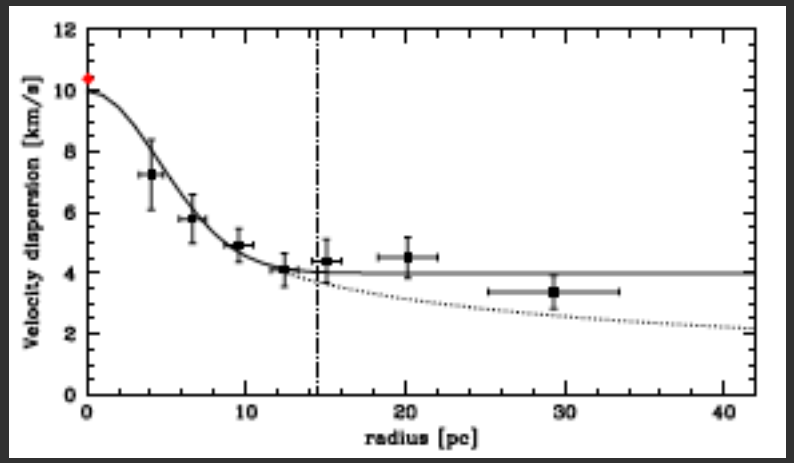
Is there a verdict here?

- Pal 4, Pal 14, NGC 2419, Crater all have central dispersions smaller than MoND predictions even when latter include EFE corrections (though Scarpa et al. 2011).
- No single case is convincing; is the ensemble?
- NGC 2419 generated much discussion between Ibata et al. and Sanders; dynamical models, anisotropy, assumed mass distributions, streaming, orbit details all matter.

Is there a verdict here?



Eridanus; Myeong et al. 2017



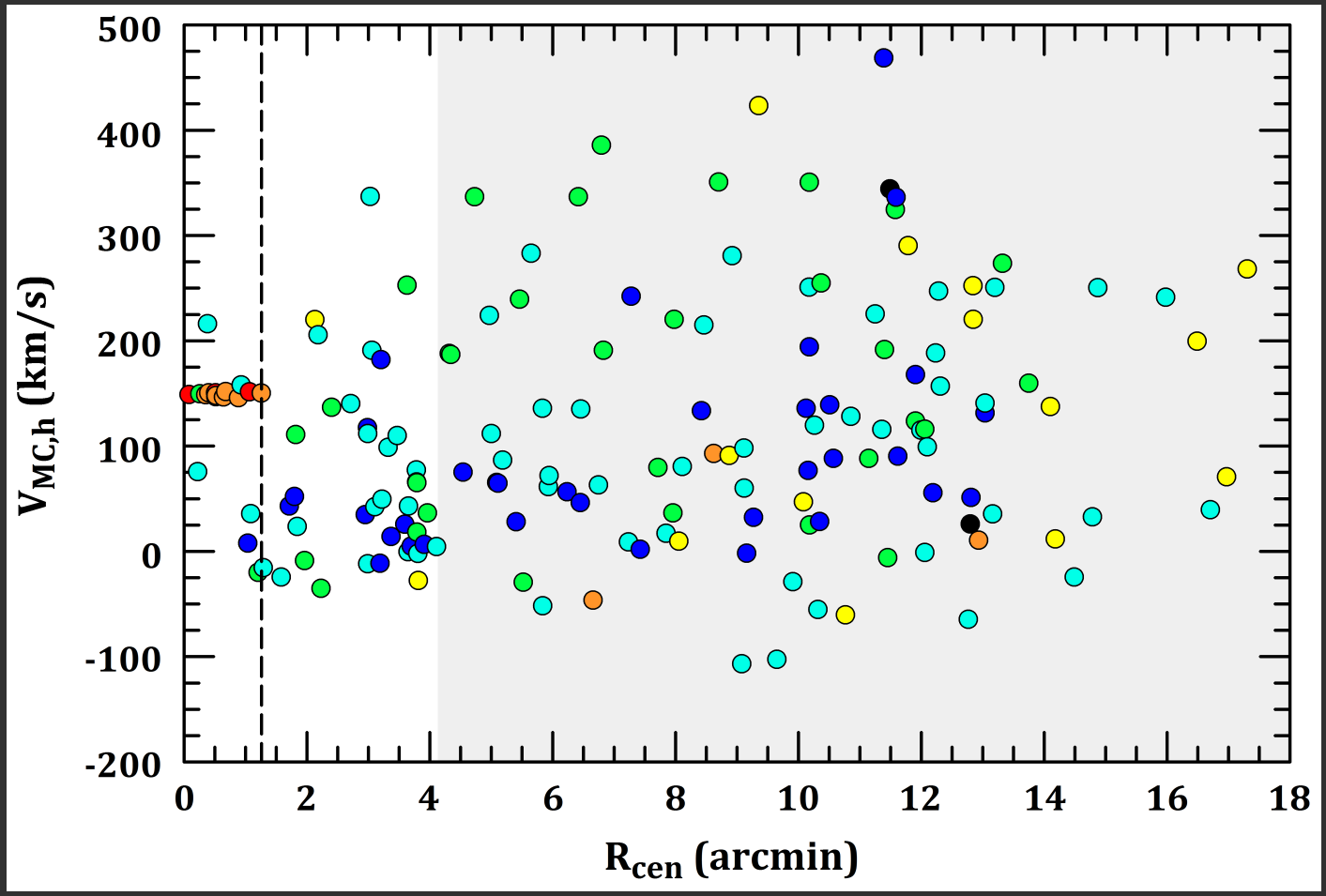
Scarpa et al. 2011

Or is it hopeless?

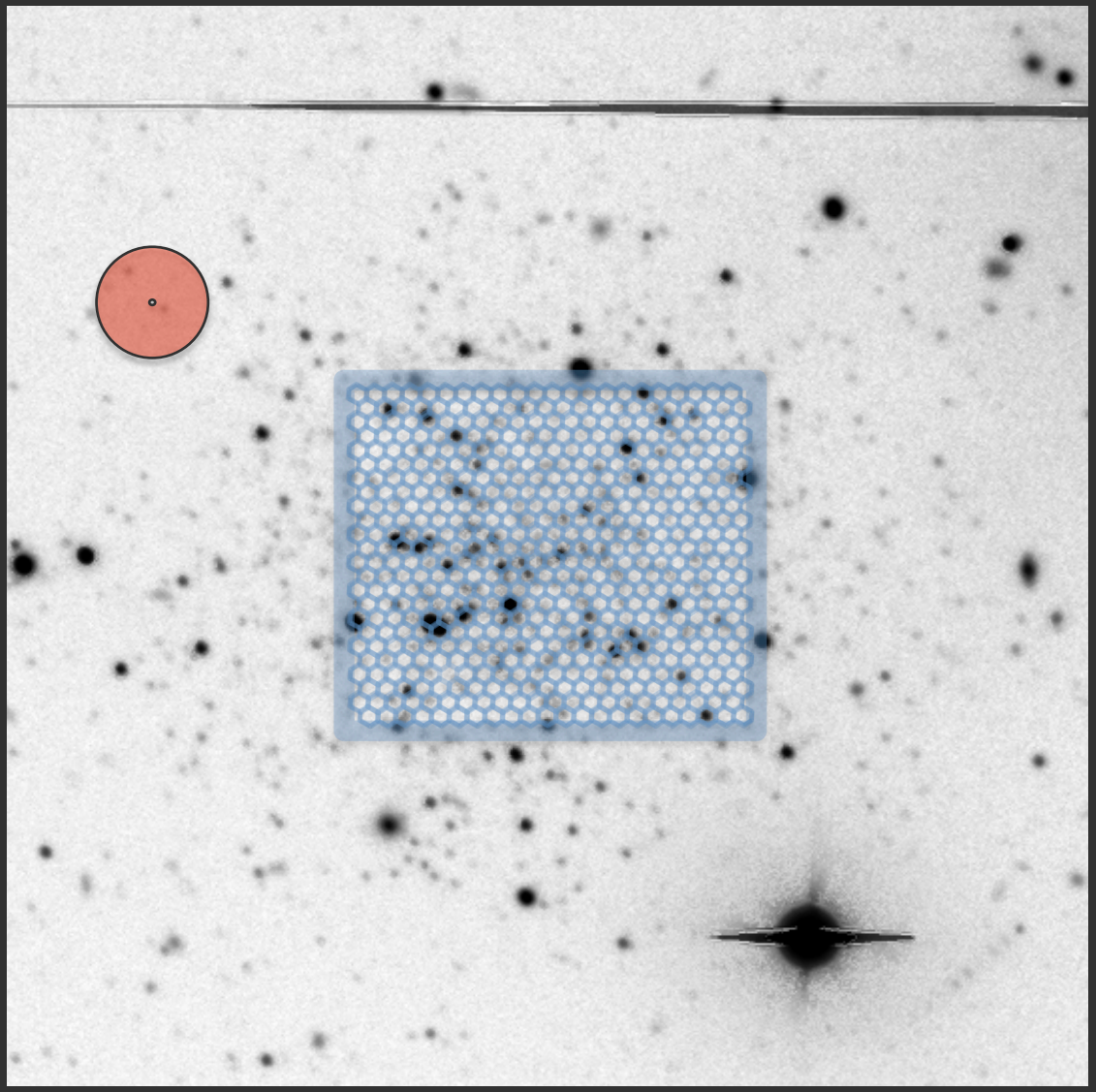
The point is that conceivable but undetectable intrinsic systematic effects vitiate the value of likelihood analyses (I have not even mentioned the 'unknown unknowns' – effects that we have not thought of). If so, it would not be the first time that sophisticated statistical analyses have been applied to astronomical observations dominated by systematic effects.

Sanders 2012

Or do we just need more/better data?



Mean Vel of Crater = Solar Reflex: Purely tangential. Proper motion of 0.30 mas/yr if circular; Orbit is knowable.



IFU-M: R~20000-40000, 1.0 arcsec resolution.