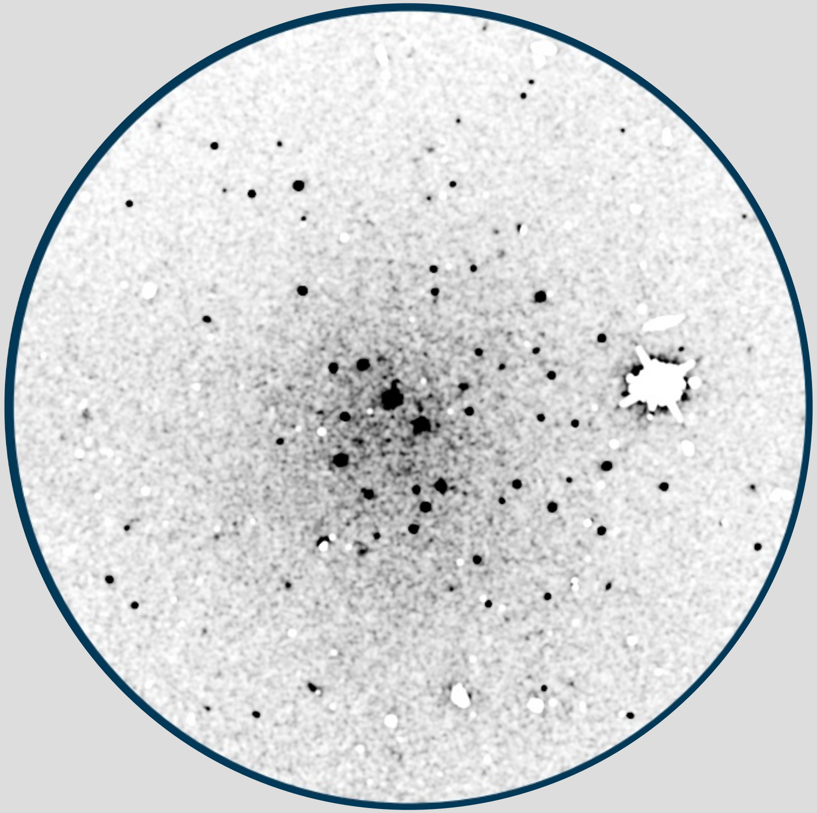
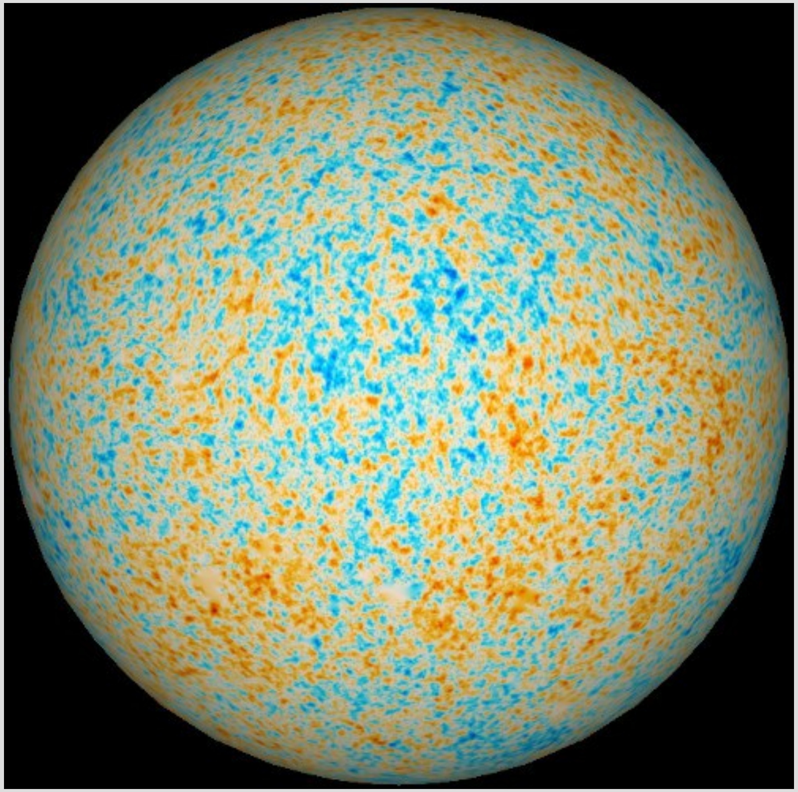
Dynamical view on dark matter from globular cluster orbits

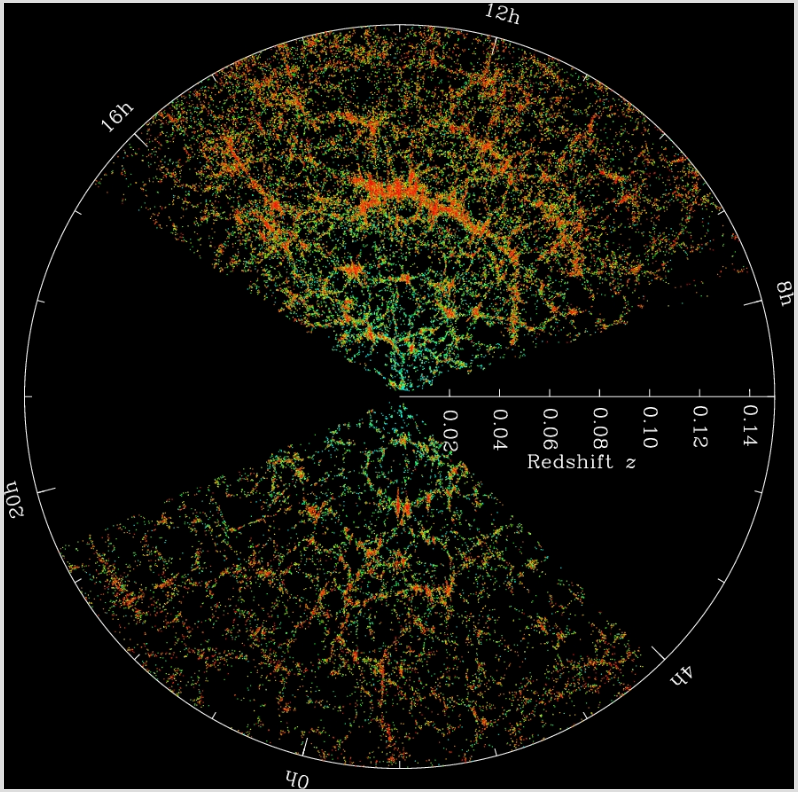


Kfir Blum / Rwanda DSU July 2023

Strong evidence for dark matter in large scale structure
(calculable given observed initial conditions).

On large scales, dynamics of dark matter is consistent with that of pressureless dust.

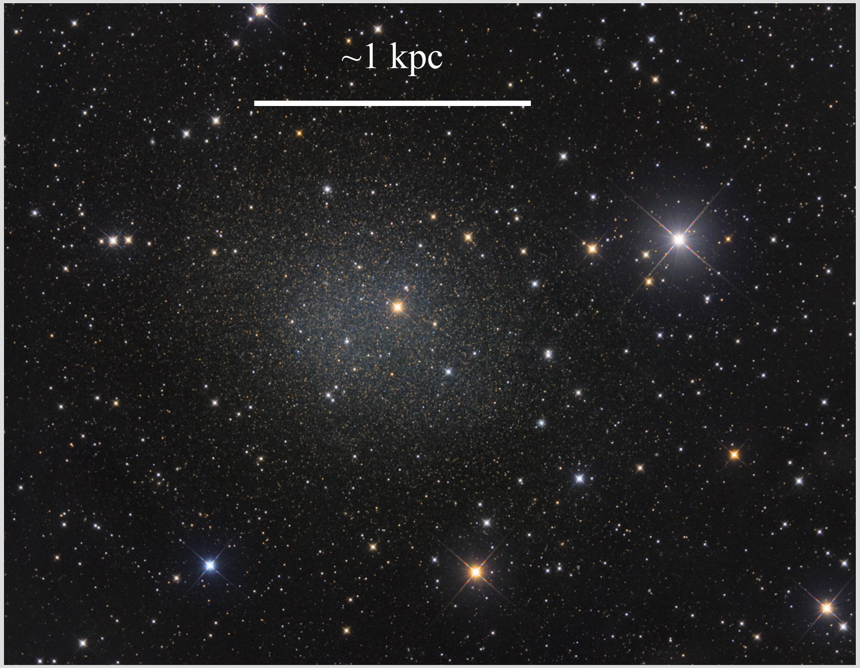




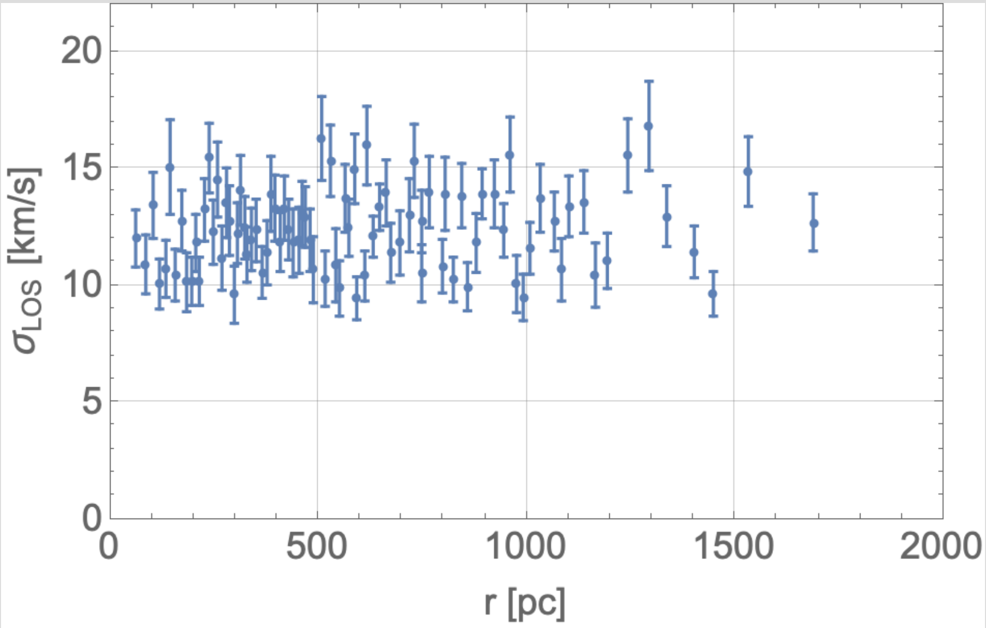
Strong evidence for dark matter in galaxies.
Hard to calculate.
A lot of data, difficult to interpret.

Note huge separation of scales
between LSS (> Mpc)
and galaxies (~ kpc).

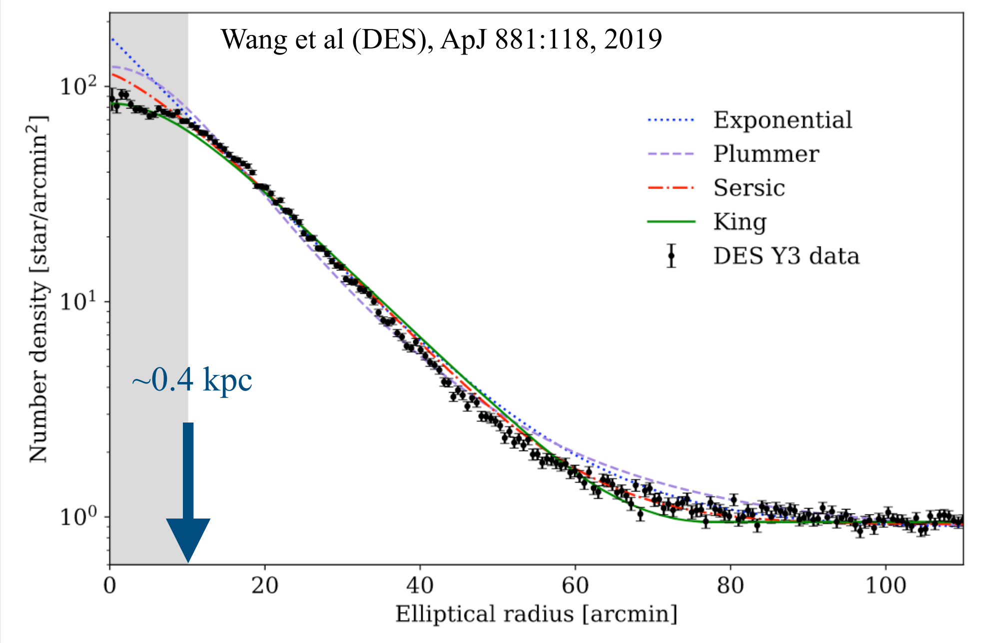
Many puzzles, plenty of room for surprises
in the physics of dark matter.



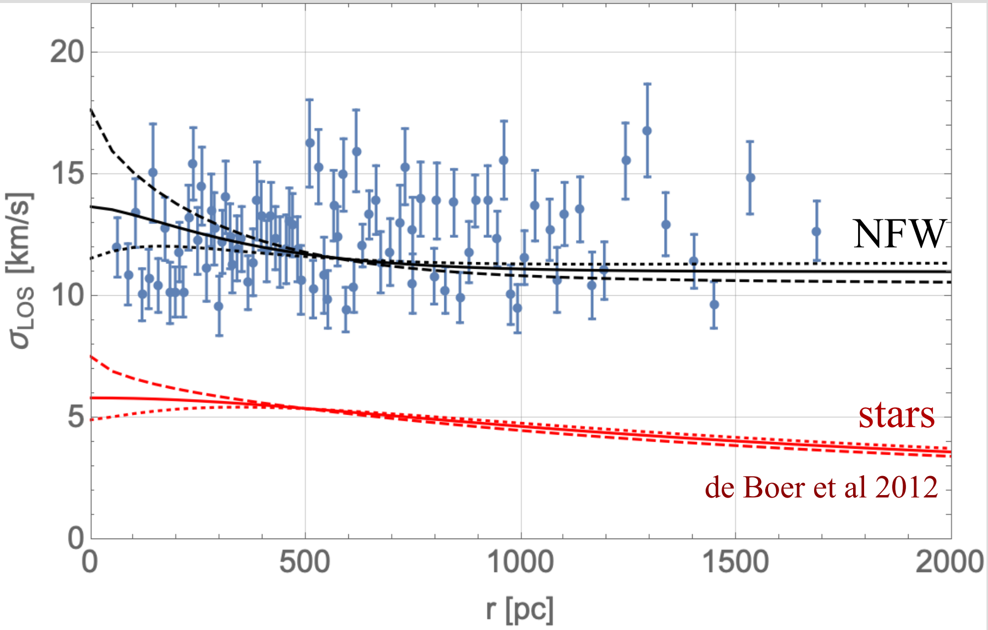
ESO/Digitized Sky Survey 2



Data from: Read, Walker, Steger, 1808.06634

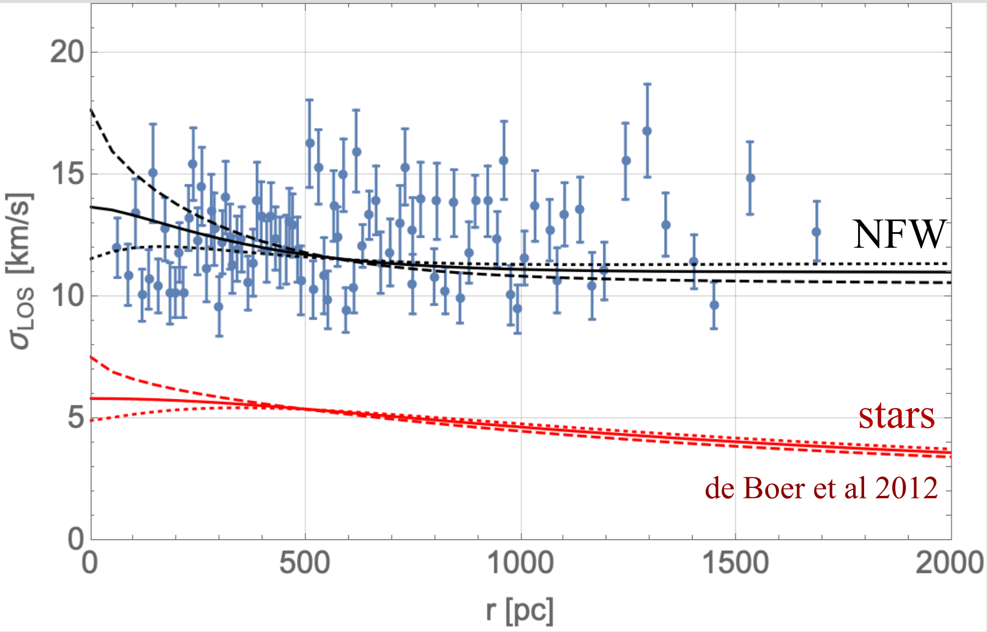

Wang et al (DES), ApJ 881:118, 2019

~0.4 kpc



de Boer et al 2012

$$\frac{d}{dr}\left(n\overline{v_r^2}\right)+\frac{2\beta}{r}n\overline{v_r^2}=-\frac{GM(r)}{r^2}n$$



$$\frac{d}{dr}\left(n\overline{v_r^2}\right)+\frac{2\beta}{r}n\overline{v_r^2}=-\frac{GM(r)}{r^2}n$$

Stellar velocities probe the mean-field induced by dark matter.

Can we observe dynamics *beyond* mean-field?

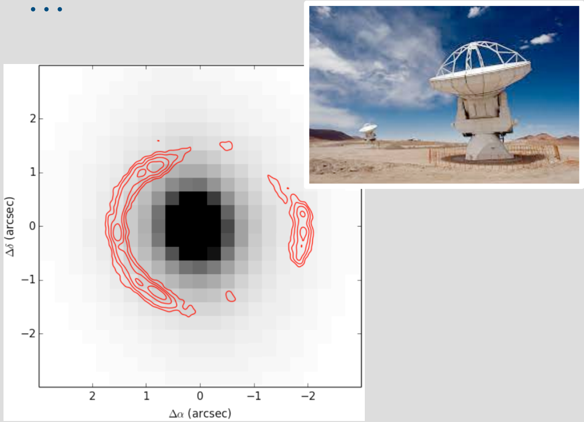
Can we observe dynamics
beyond mean-field?

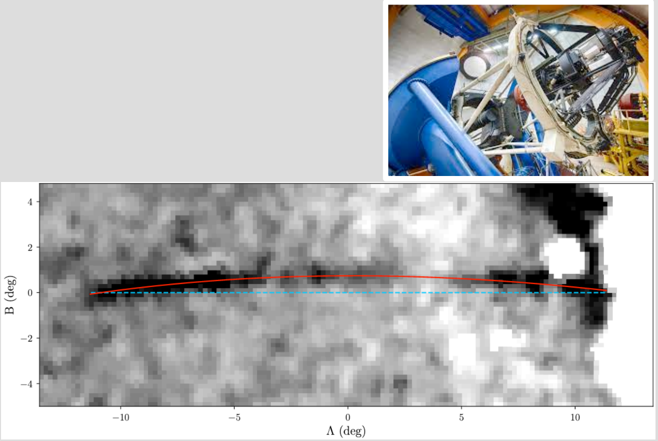
…A program I *will not* discuss here: substructure

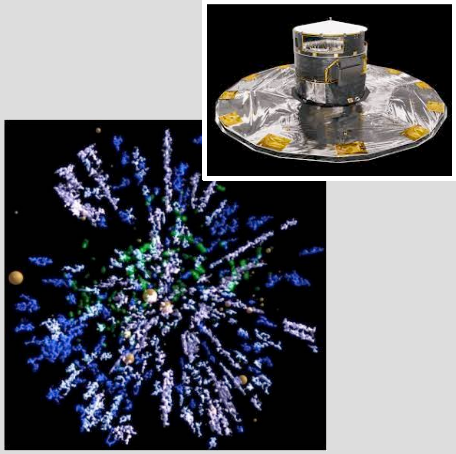
Dalal & Kochaneck astro-ph/0111456,
Vegetti & Vogelsberger 1406.1170,
Hezaveh et al 1601.01388,
Minor et al 2011.19627,
…

Bovy 1512.00452,
Banik et al 1911.02663,
…

Nacib, Lisanti, Belokurov 1807.02519,
Ravi et al 1812.07578,
…





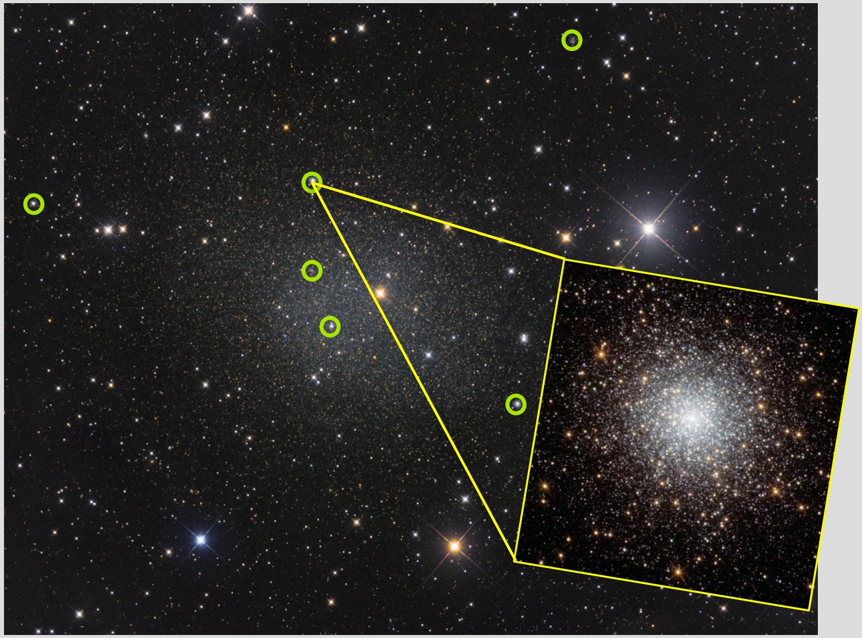


Can we observe dynamics beyond mean-field?

Can we observe dynamics beyond mean-field?

Globular Cluster: $5 \times 10^5\ M_\odot$

Massive “probe” traversing the halo.



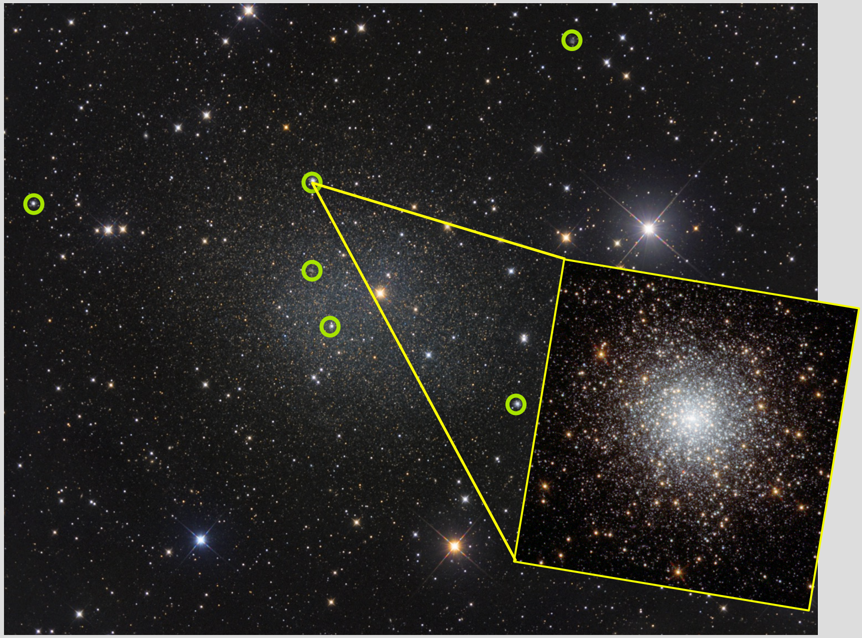
Globular Cluster: $5 \times 10^5\ M_\odot$

Massive “probe” traversing the halo.

Should slow down due to gravitational **dynamical friction**

Chandrasekhar 1943

$$\dot{\mathbf{V}} = -\frac{1}{\tau}\mathbf{V} \qquad \tau = \frac{V^3}{4\pi G^2 m_\star \rho C}$$



Coefficient C encodes state of the medium:

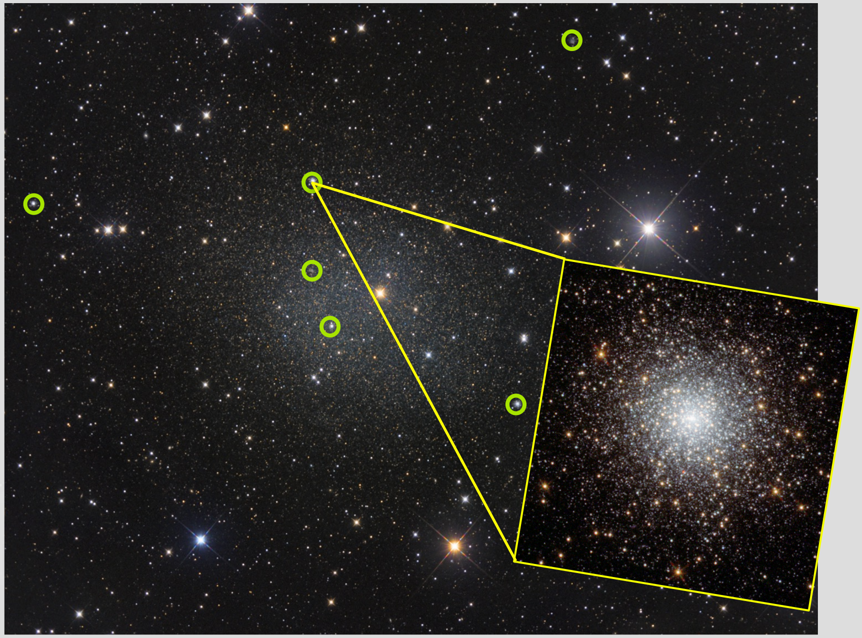
$$C_{\rm class} = 4\pi \ln\Lambda \int_0^V dv_m v_m^2 f_v(v_m)$$

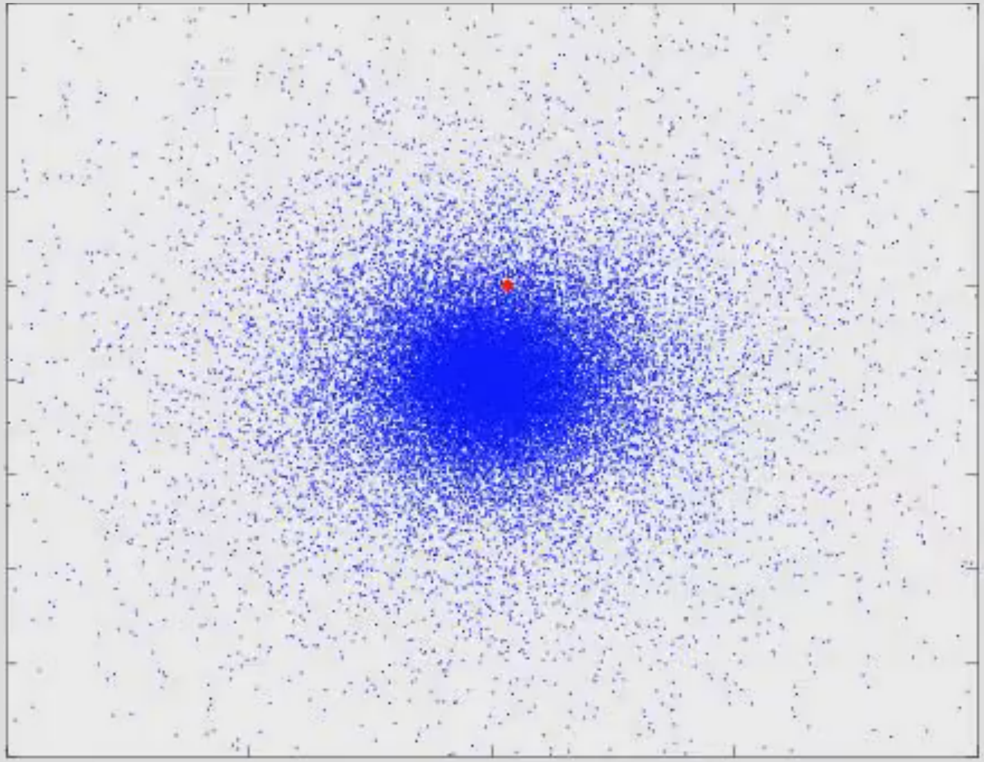
Globular Cluster: $5 \times 10^5\ M_\odot$

Massive “probe” traversing the halo.

Should slow down due to gravitational **dynamical friction**

Chandrasekhar 1943



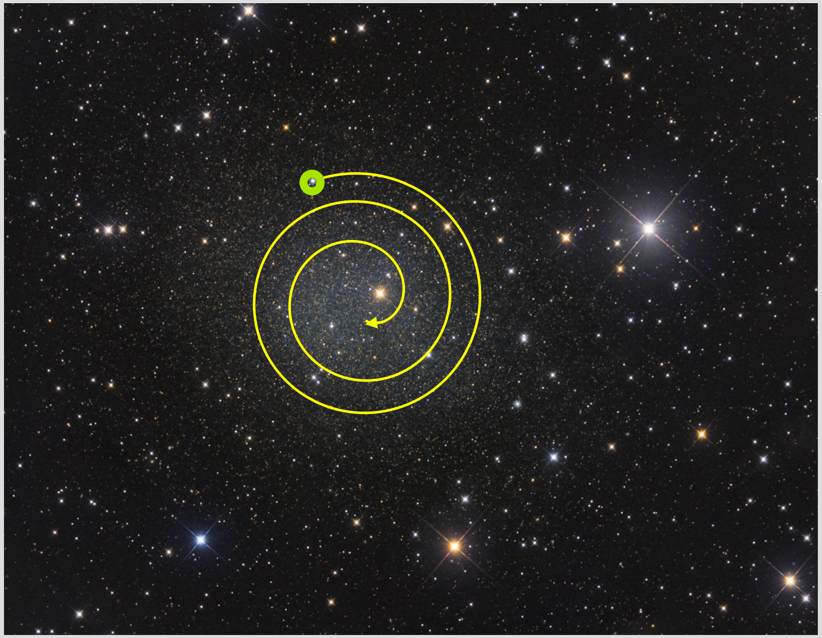


N-body simulation:
30K “star particles”
1 “GC”, about 100 times more massive than “stars”

Dynamical friction should:

— Cause more massive GCs to sink faster down the potential well (mass segregation),

— Cause GCs near the center to congregate, potentially form nuclear star cluster.



Can we detect this effect in dark matter-dominated systems?

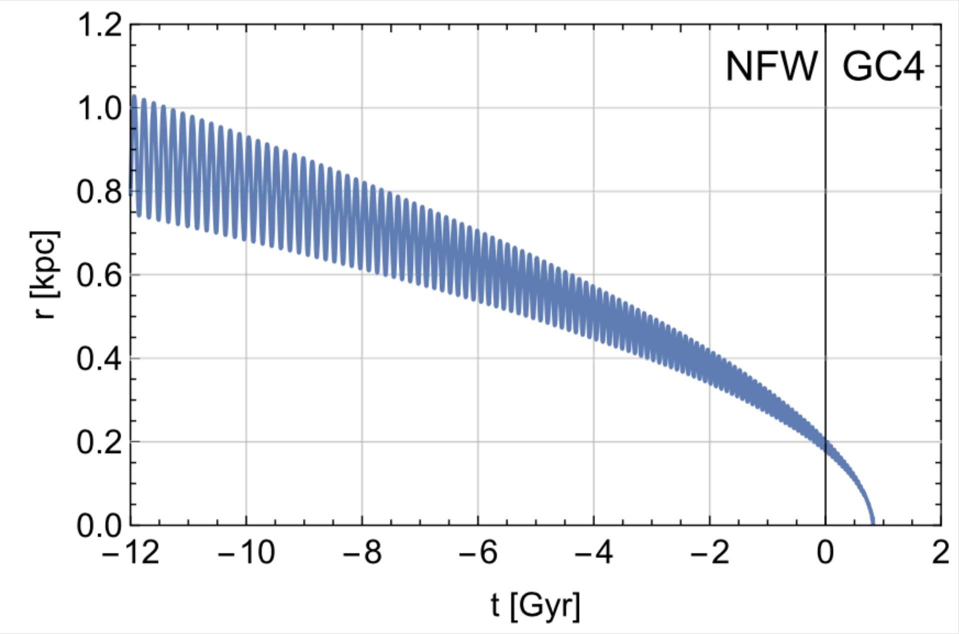
<u>Rest of talk: 3 examples</u>

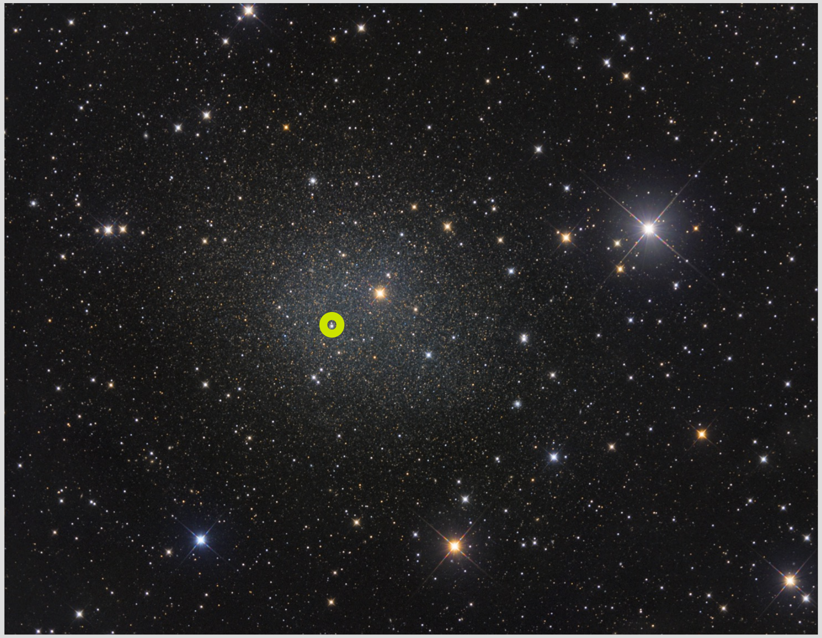
1. Fornax (a puzzle? an informative hint?)
2. Old analysis: stacked dwarf ellipticals (reiteration of Fornax?)
3. Ultra-diffuse galaxy with high statistics: *a textbook example?*

Example 1

Fornax GC timing problem

Tremaine 1976,
Oh, Lin, Richer 2000,
Petts, Gualandris, Read 2015,
Hui et al 2017, Lancaster et al 2019,
Meadows et al 2020, Bar et al 2021,
Shao et al 2021,…





Example 1

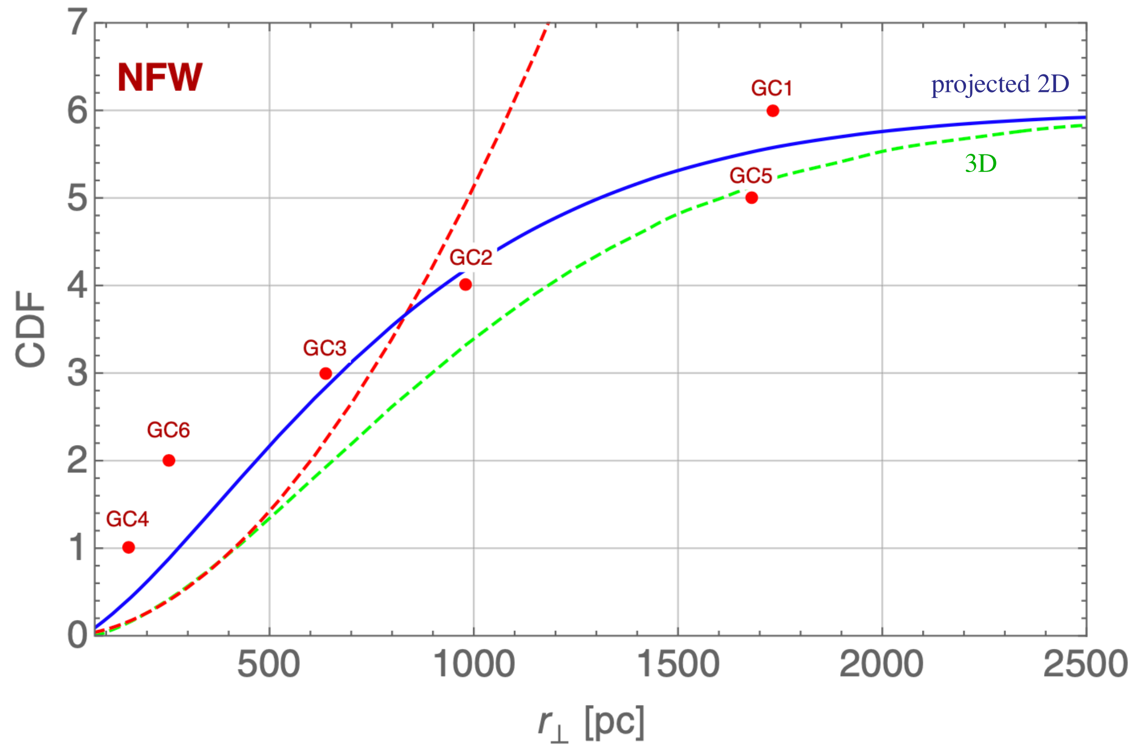
Lack of nuclear star cluster in Fornax?

Bar et al (Shao et al) find mild (~null) statistical timing problem, **ignoring the question of NSC.**

Tremaine 1976,
Oh, Lin, Richer 2000,
Petts, Gualandris, Read 2015,
Hui et al 2017, Lancaster et al 2019,
Meadows et al 2020, **Bar et al 2021,**
Shao et al 2021,…

Bar et al (Shao et al) find ~50% (~30%) of all GCs should have arrived at r~0.

In either case, we might have expected an NSC of ~10^6 solar mass.



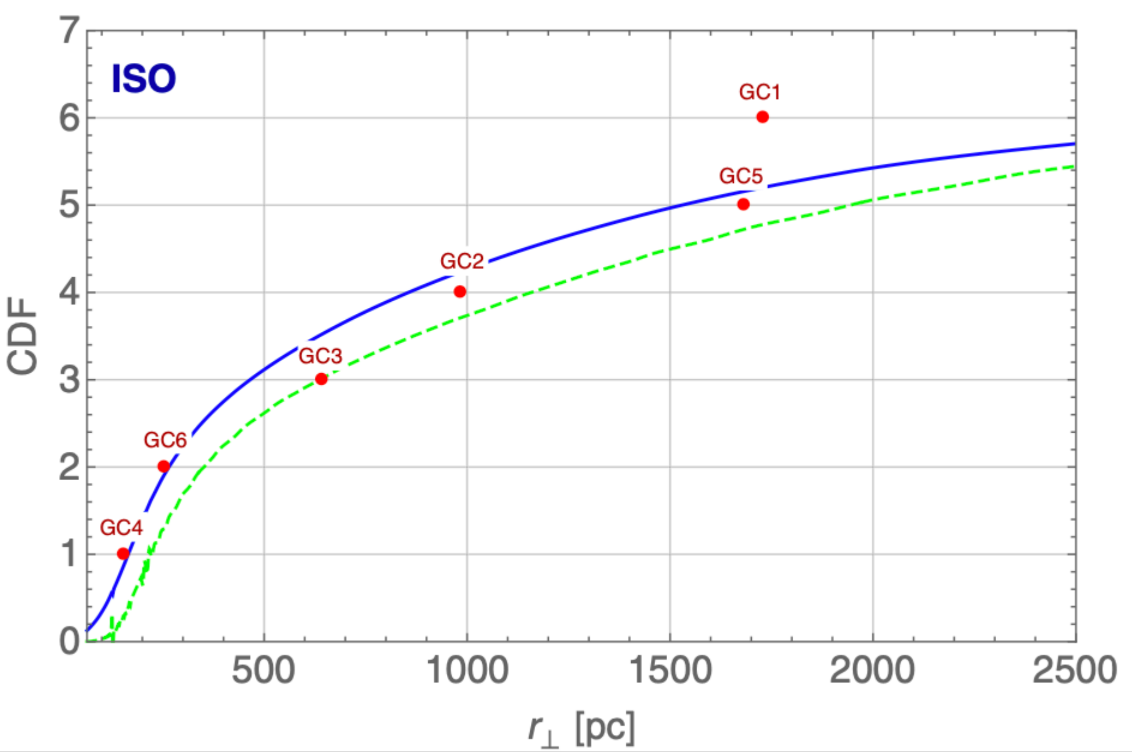
Example 1

A dark matter **core** in Fornax
— even only in the inner few 100 pc's —
could solve the GC timing / NSC puzzle.

Tremaine 1976,
Oh, Lin, Richer 2000,
Petts, Gualandris, Read 2015,
Hui et al 2017, Lancaster et al 2019,
Meadows et al 2020, **Bar et al 2021,**
Shao et al 2021,…

“Core vs. cusp”:

Lack of NSC may add credence to core hypothesis.



What about other galaxies?

…we want GC-rich, dark matter-dominated galaxies.

Example 2

Lotz et al, 2001

51 dwarf elliptical galaxies (HST), up to 20 GCs/galaxy, stacking analysis.

Predicted NSCs more luminous than observed (…where are the missing GCs of the left panel?)

puzzle similar to that of Fornax?

But many assumptions: **(1)** GCs on circular orbits, **(2)** GCs started on same distribution as stars, **(3)** velocity dispersion from V magnitude, **(4)** scaled radii to 1/2 light radius, **(5)** semi-analytical DF…

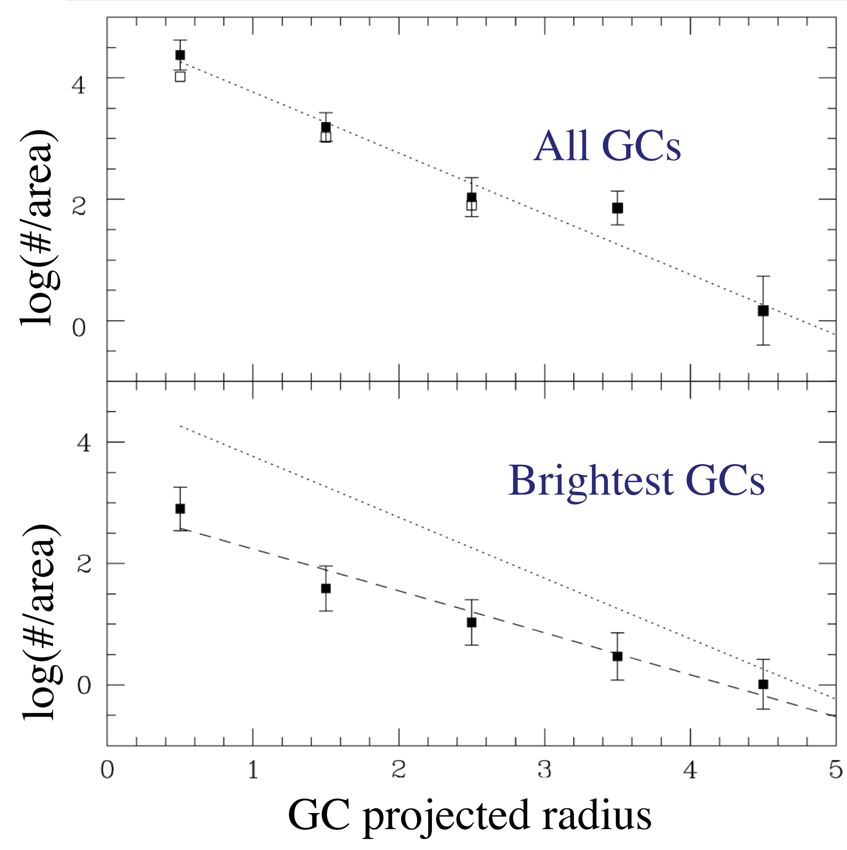


FIG. 5.—Summed radial distribution of the globular cluster candidates

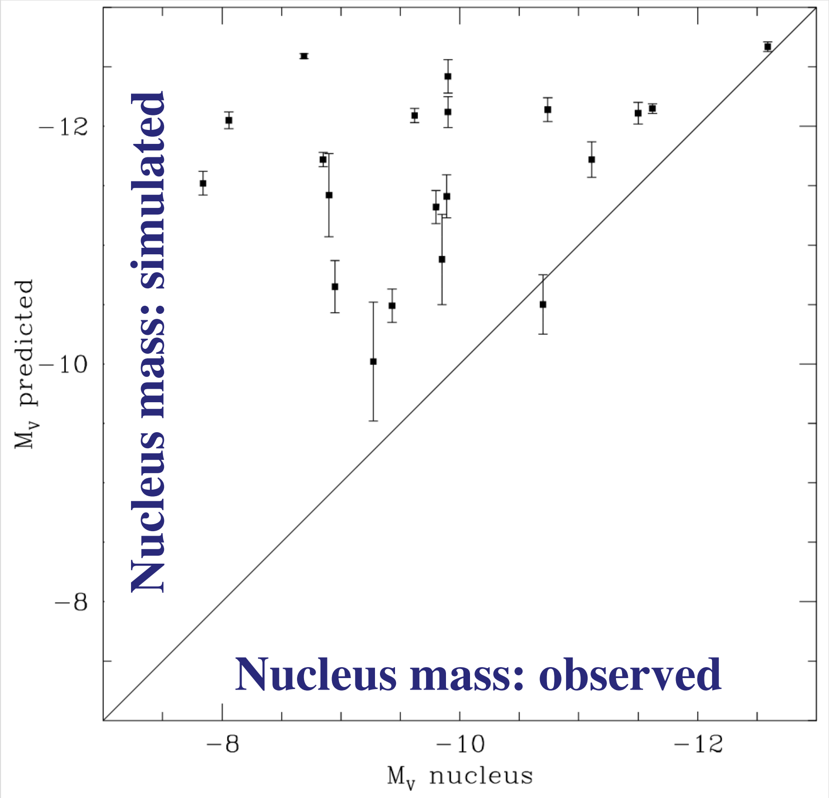
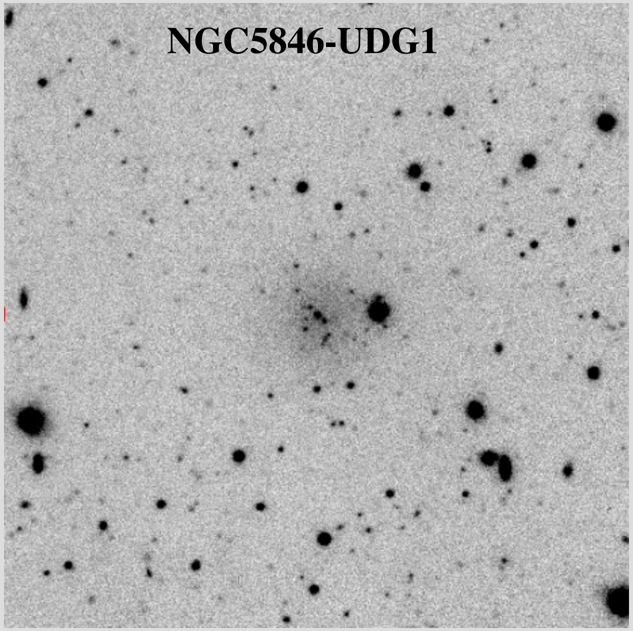


FIG. 8.—Predicted nuclear M_V from our Monte Carlo dynamical friction simulation vs. the observed nuclear M_V for each dE,N in our sample.

Example 3

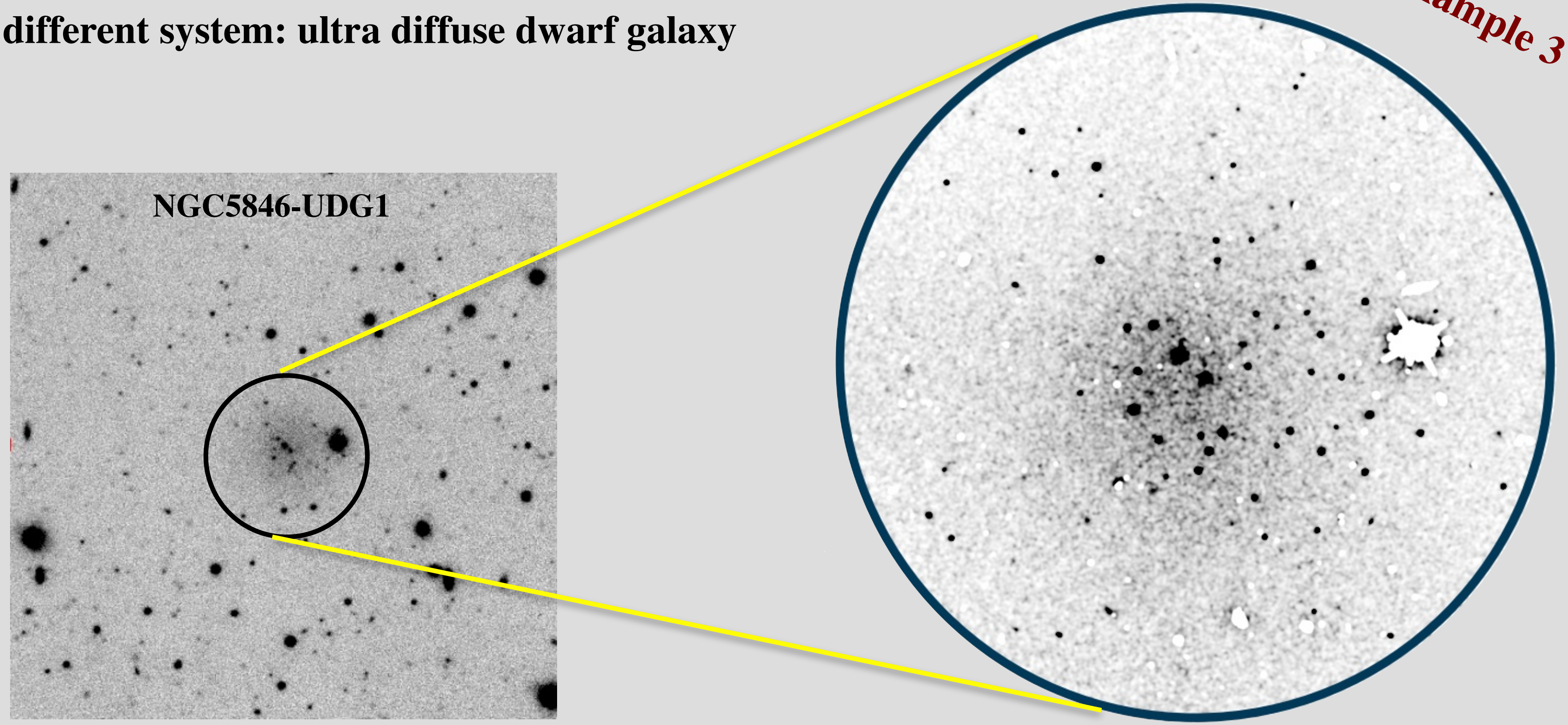
A different system: ultra diffuse dwarf galaxy



Forbes et al 2019, 2020,
Muller et al 2020, 2021,
Danieli et al 2022,
Danieli, Bar, KB 2022,…

Example 3

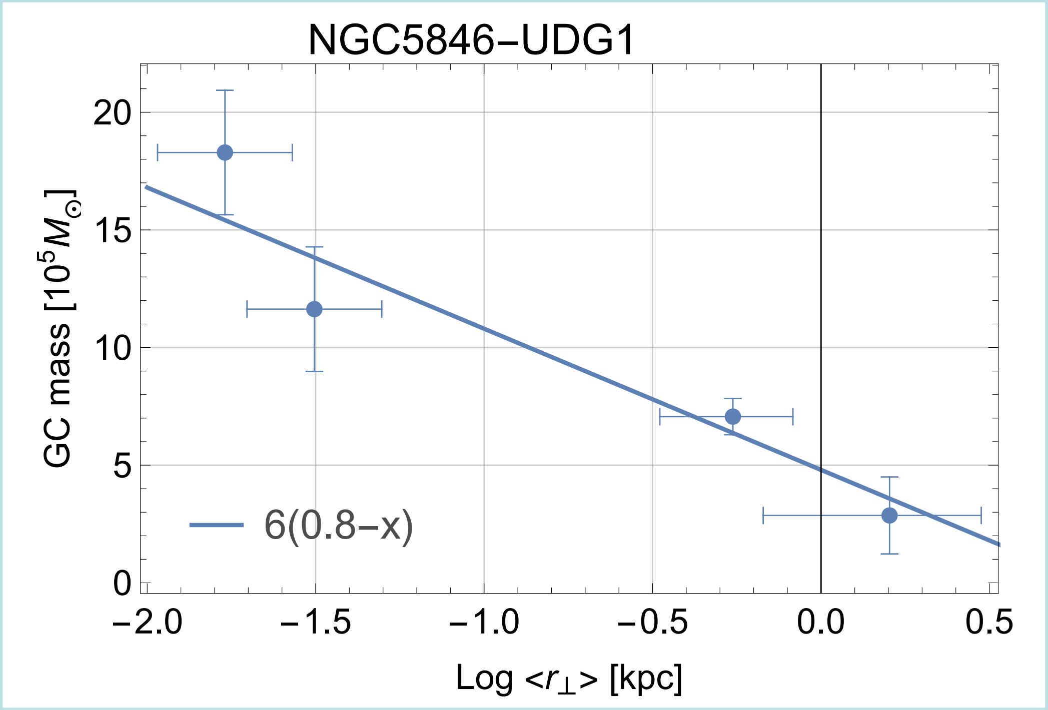
A different system: ultra diffuse dwarf galaxy

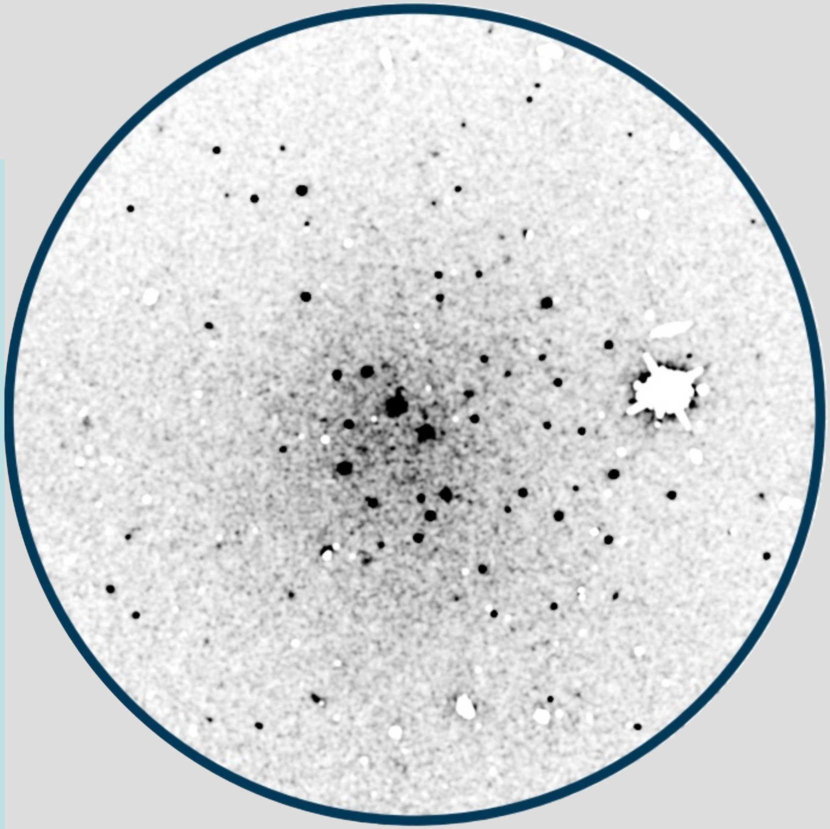


Forbes et al 2019, 2020,
Muller et al 2020, 2021,
Danieli et al 2022,
Danieli, Bar, KB 2022,…

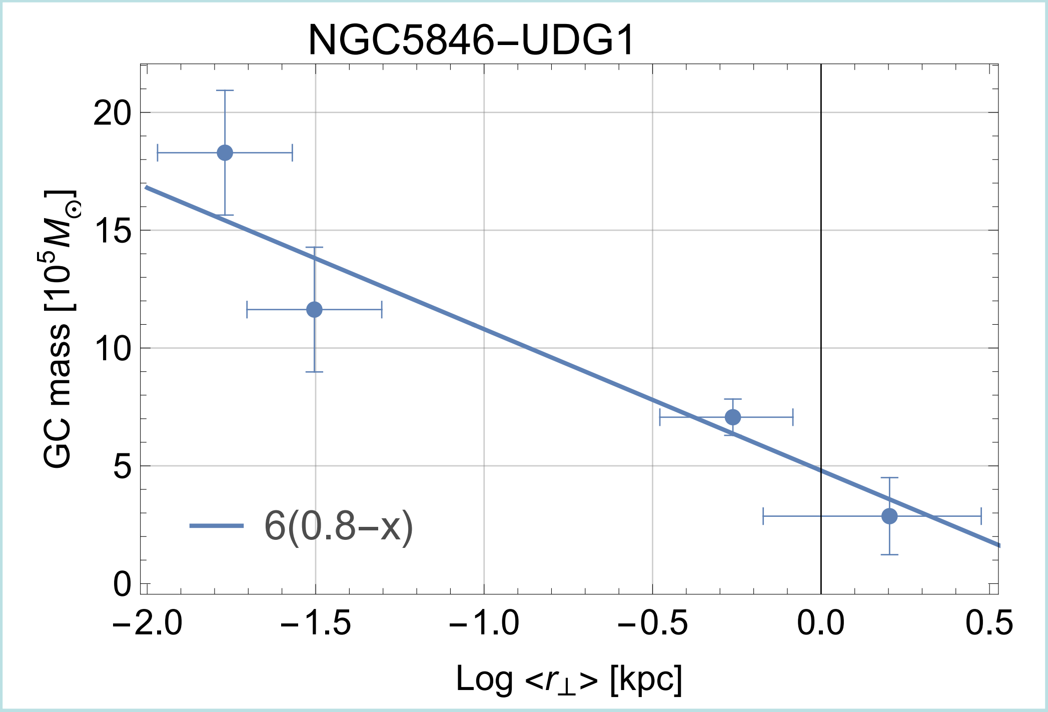
Evidence for dynamical friction in dark matter-dominated, GC-rich ultra diffuse galaxy

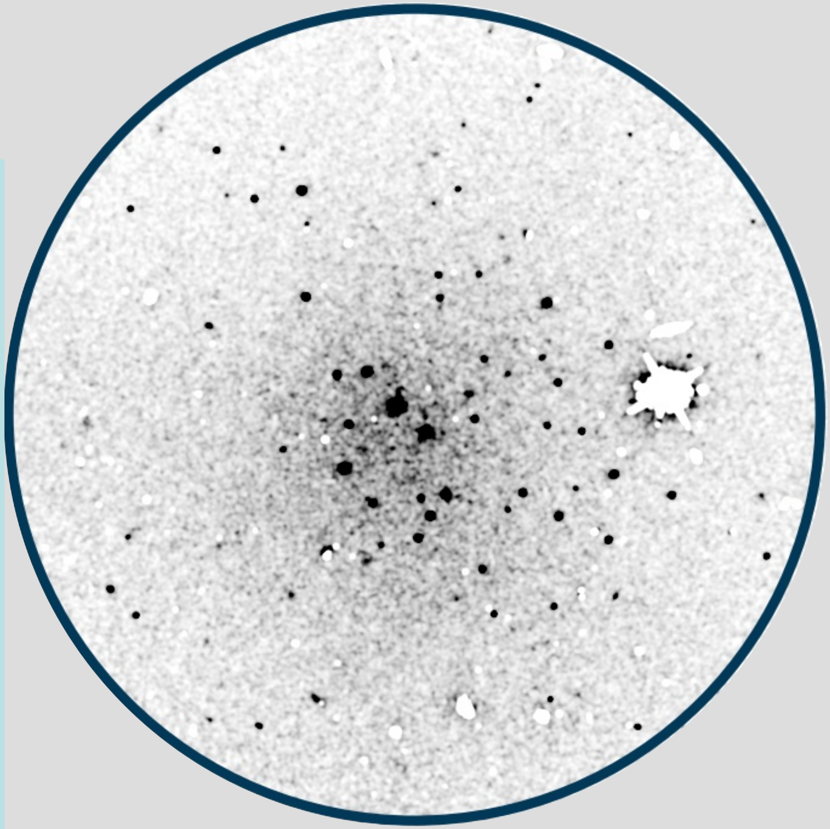
Danieli, Bar, KB 2202.10179





Danieli, Bar, KB 2202.10179



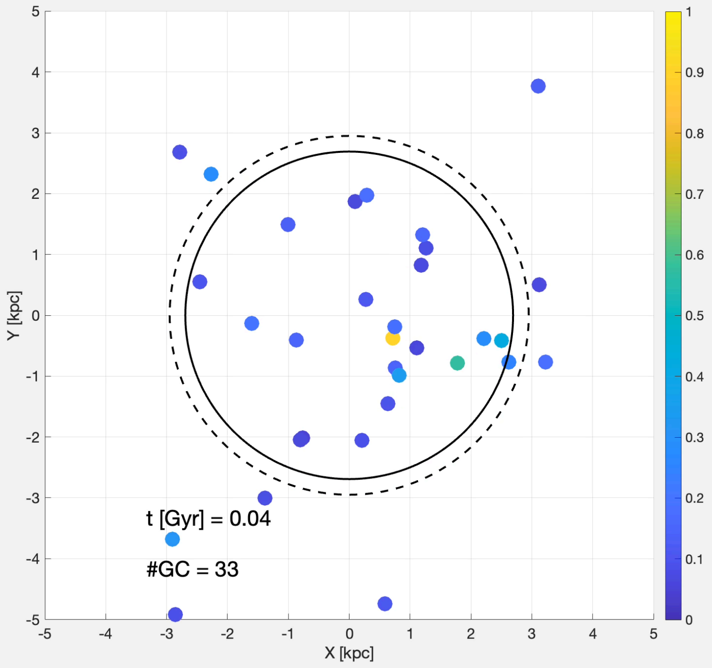


$$\frac{m_*}{m_*^{(0)}} \approx \frac{2\tau^{(0)}}{\Delta t}\left(\ln\langle r_{0,\perp}\rangle - \ln\langle r_\perp\rangle\right)$$

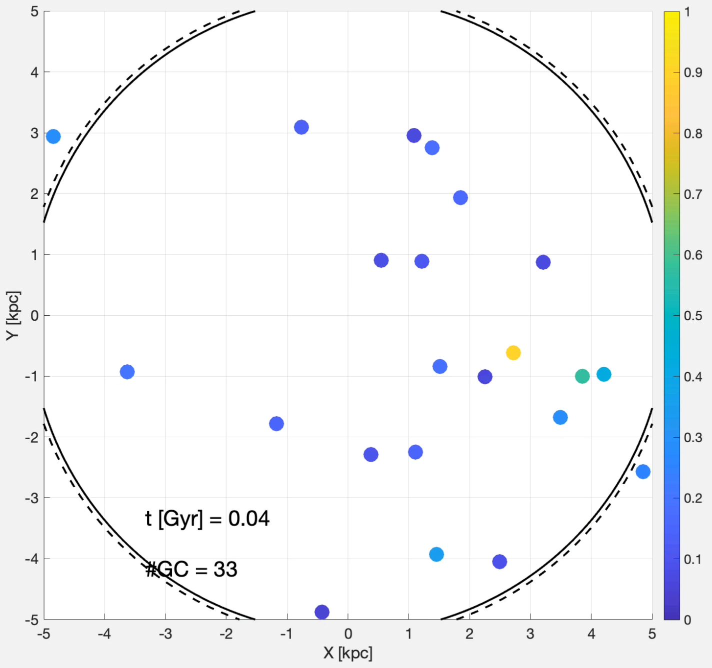
$$\tau^{(0)} \approx \frac{30}{C_{\rm DF}}\left(\frac{v}{20\ {\rm km/s}}\right)^3 \frac{10^7 \frac{M_\odot}{\rm kpc^3}}{\rho}\frac{10^5\ M_\odot}{m_*}\ {\rm Gyr}, \qquad \Delta t \approx 10\ {\rm Gyr}, \qquad \frac{2\tau^{(0)}}{\Delta t} \approx 6$$

Danieli, Bar, KB 2202.10179

massive dark matter halo:



no dark matter, only stars:

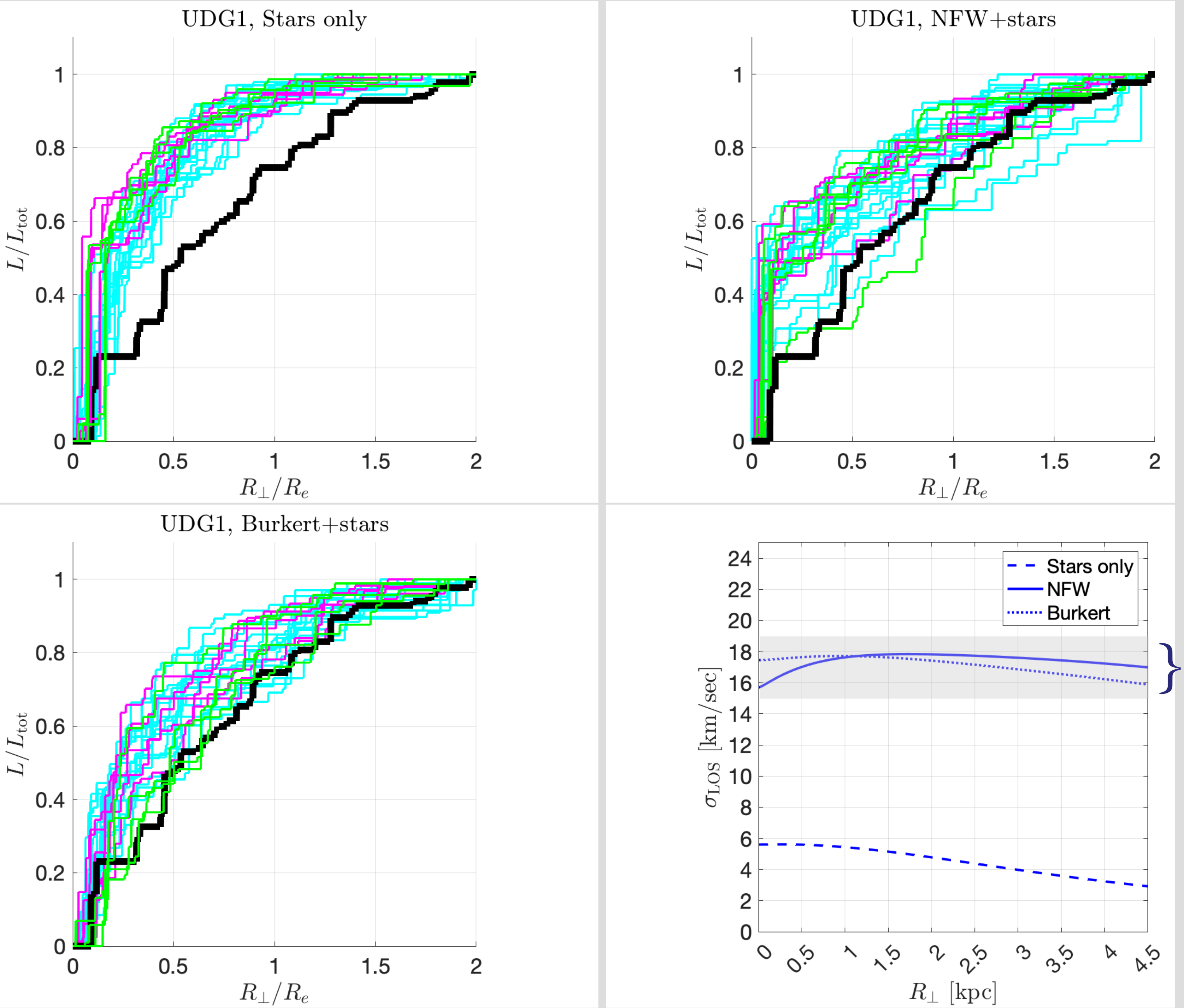


Lack of dark matter, or a low mass halo, comes with small velocity dispersion, and *overshoots* friction. To compensate, need tuned initial conditions.

Consistent with, and independent of stellar and GC kinematics (Forbes et al 2021).

What we hope to learn

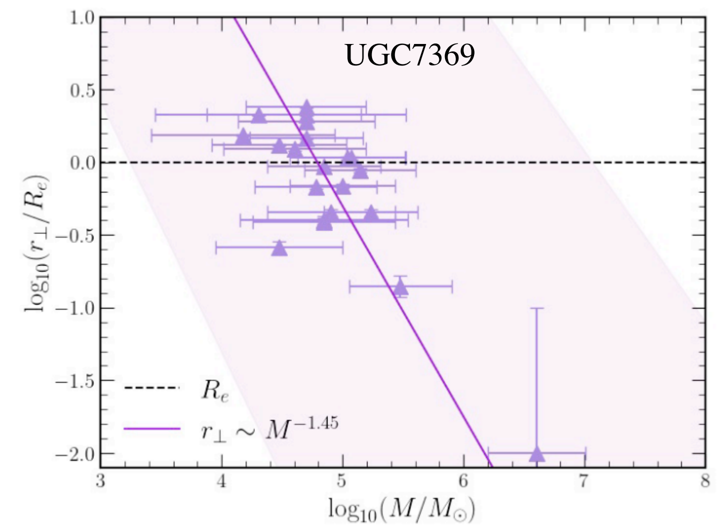
KB, in prep



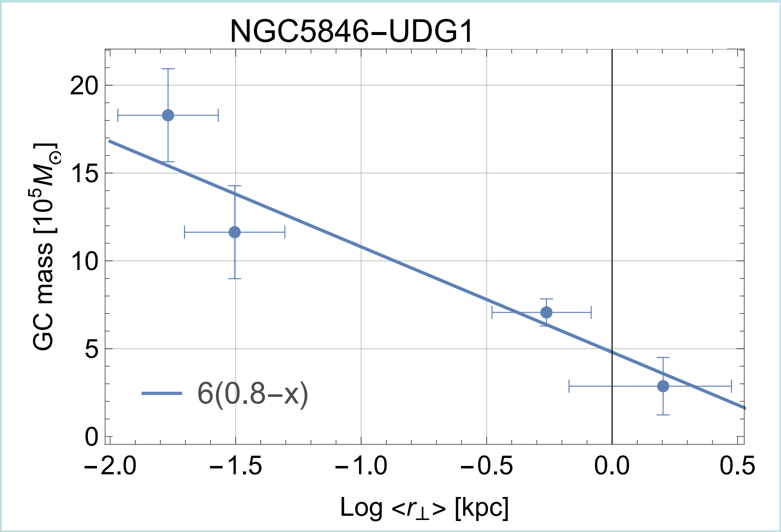
} Forbes et al 2021

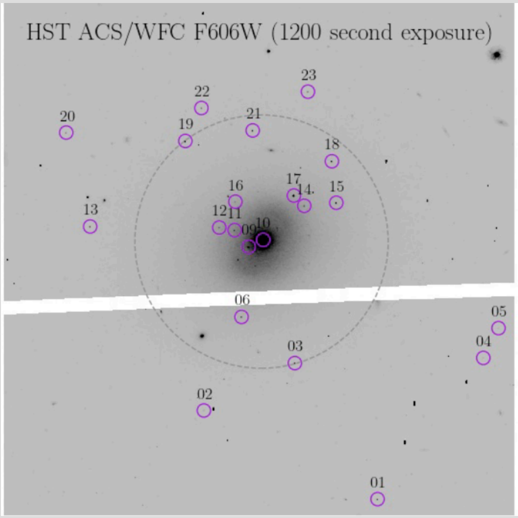
Many more UDGs/dwarfs to investigate.

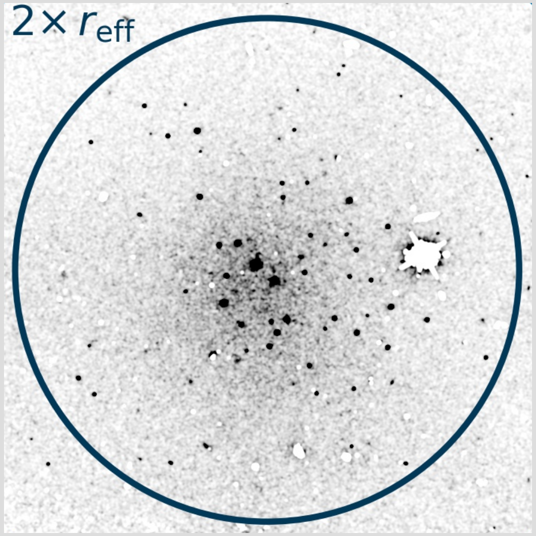
Modak, Danieli, Greene 2211.01384



Bar, Danieli, KB 2202.10179







Summary

Look for qualitatively new classes of observable phenomena to probe dark matter.

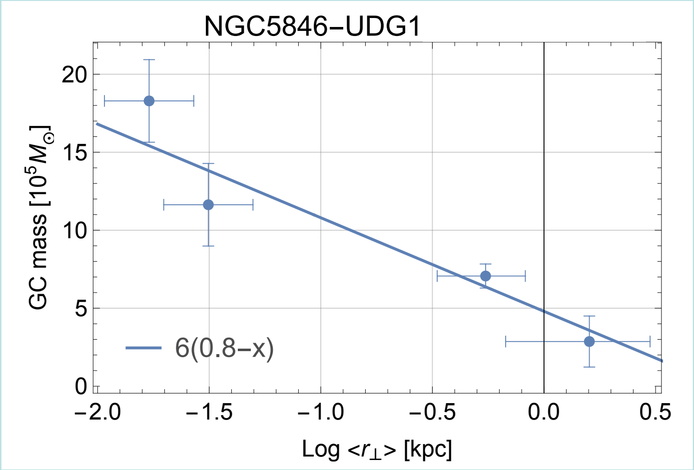
Dynamical friction in dark matter-dominated galaxies: beyond mean-field effect (Bar et al 2021).

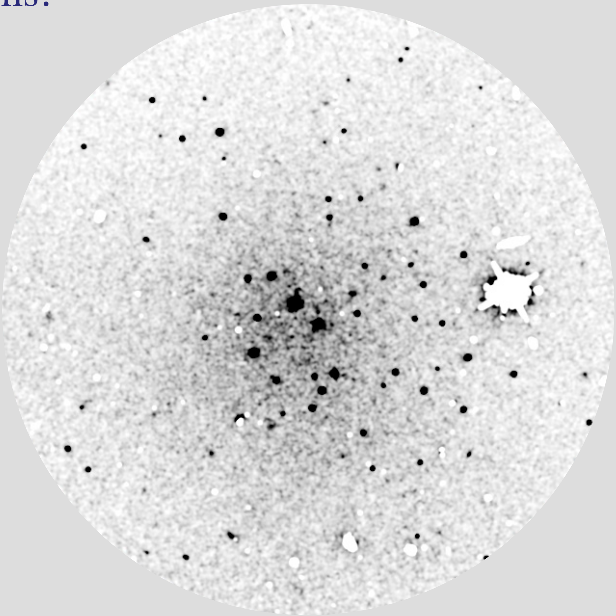
Fornax dwarf galaxy: puzzling lack of nuclear star cluster? …but small statistics…
Puzzle extends to other dwarf galaxies? (Lotz et al 2001; but simplified study, should improve!).
Ultra-diffuse GC-rich galaxies: UDG1 — smoking gun? (Danieli, Bar, KB 2022).

A lot of work to do: many more galaxies to analyze;
case of UDG1 must repeat itself; match velocity measurements.

Numerical challenge: develop fast N-body-calibrated semi-analytic sims.

Thank You!



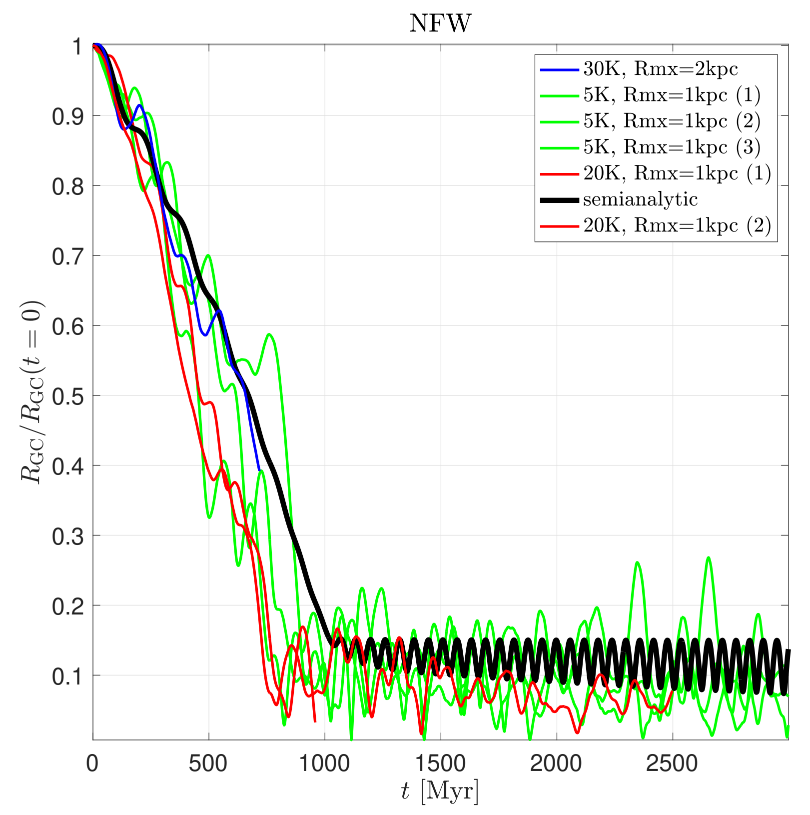


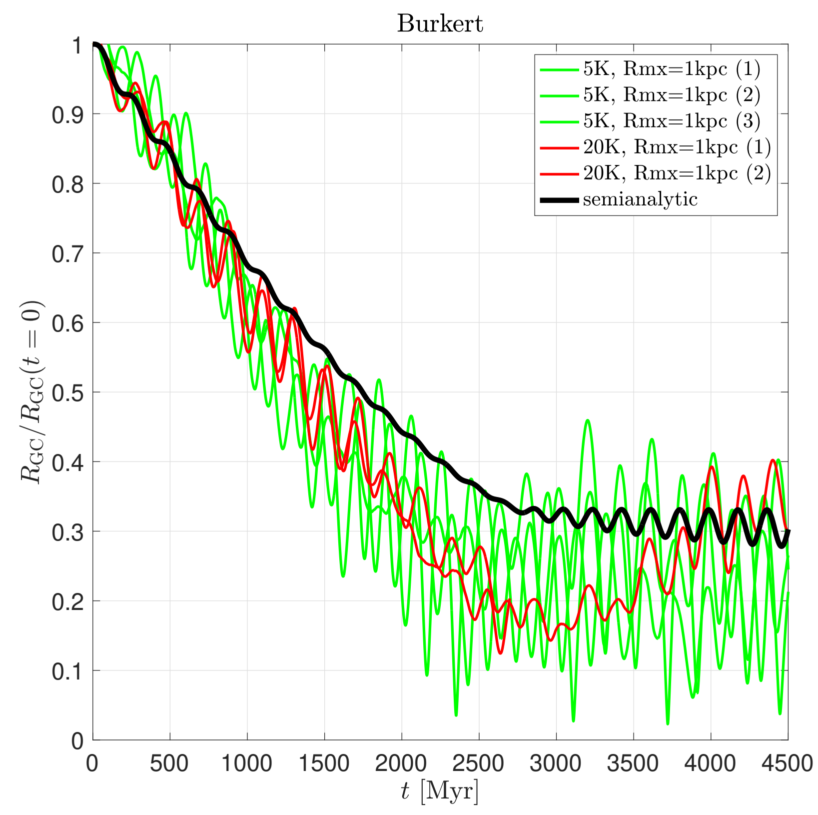
Xtra

Exploring the parameter space with fast semianalytic simulations (implementing core stalling, calibrating Coulomb Log)

$$\dot{\mathbf{V}} = -\nabla\Phi - \frac{1}{\tau}\mathbf{V}$$

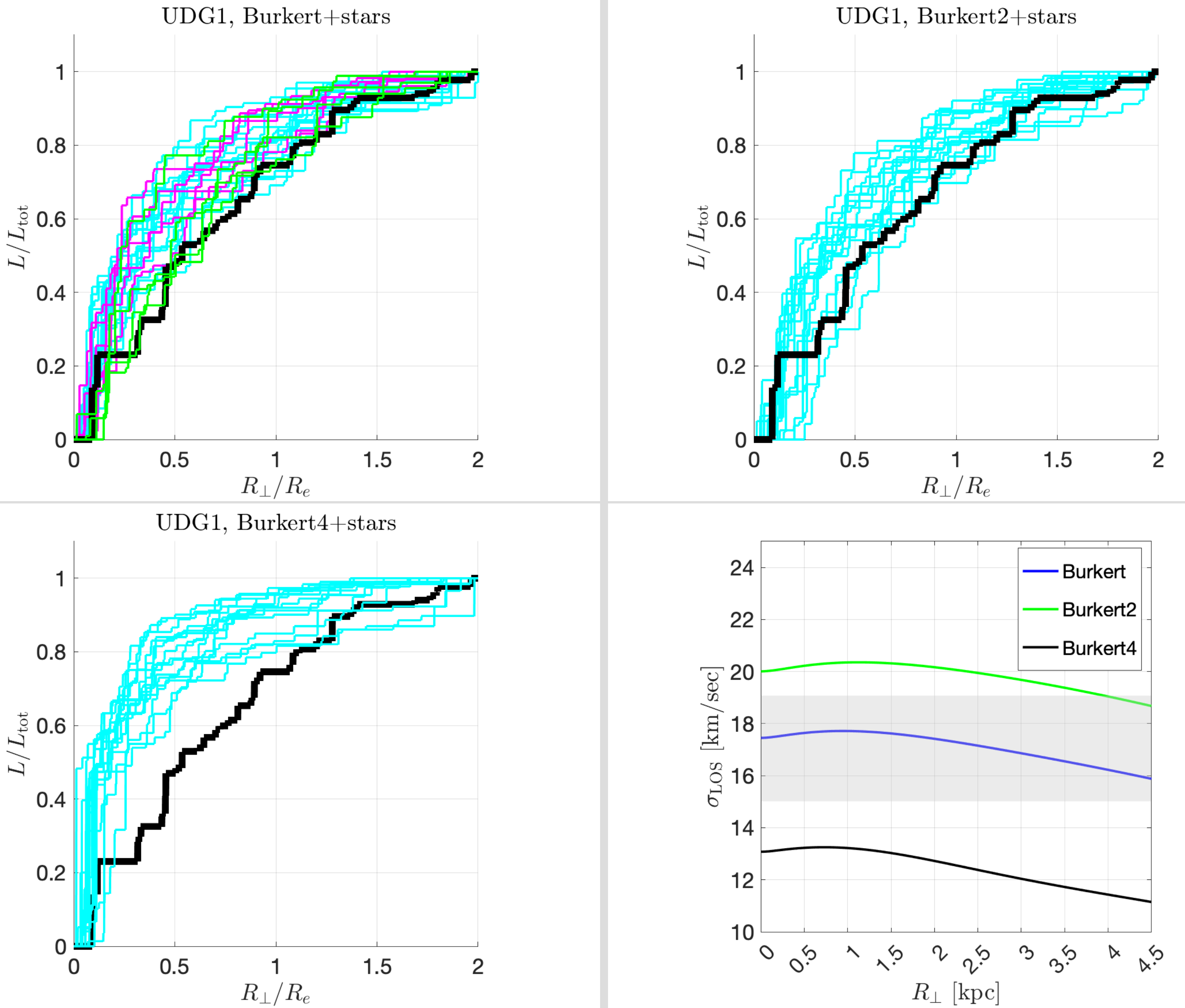
KB, in prep





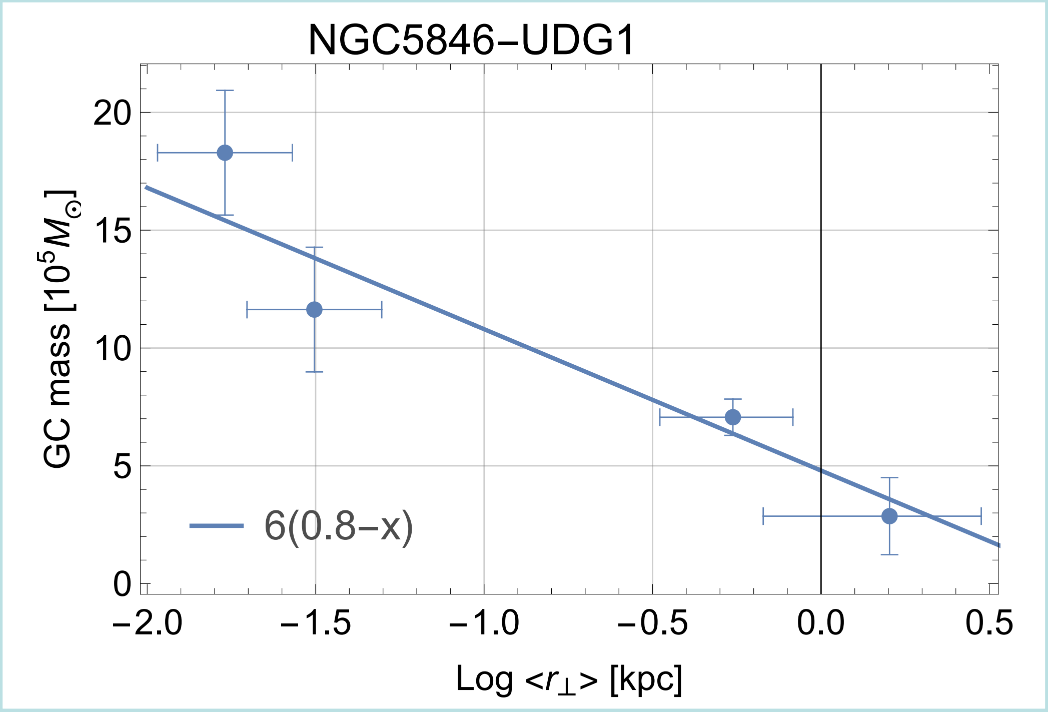
What we hope to learn

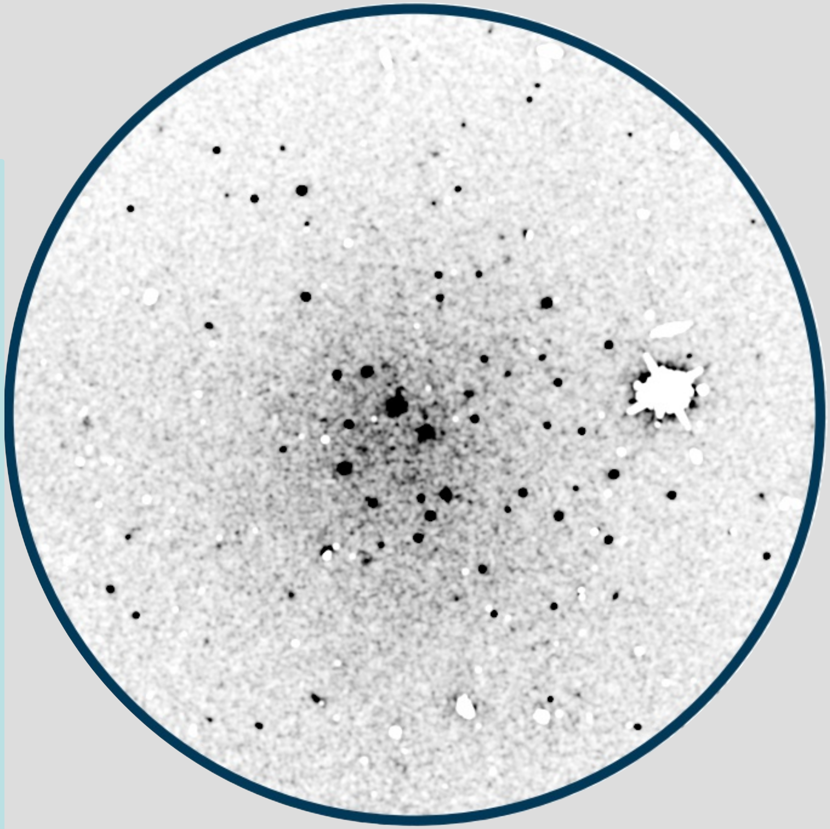
KB, in prep



Evidence for dynamical friction in dark matter-dominated, GC-rich ultra diffuse galaxy

Danieli, Bar, KB 2202.10179


NGC5846–UDG1



For approximately circular orbit:

$$\frac{\dot{r}}{r} \approx -\frac{2}{\left(1+\frac{d\ln M}{d\ln r}\right)\tau}$$

$$\alpha(r) = \frac{d\,\ln M(r)}{d\,\ln r}$$

$$\Delta t = \int_r^{r_0} \frac{dr'}{2r'}\left(1+\alpha(r')\right)\tau(r')$$

For approximately constant (core) density profile: $\alpha \approx 3$

$$\tau \approx \bar{\tau} \approx \text{Const}$$

$$\boxed{r_0(r, \Delta t) \approx e^{\frac{\Delta t}{2\bar{\tau}}}\, r}$$

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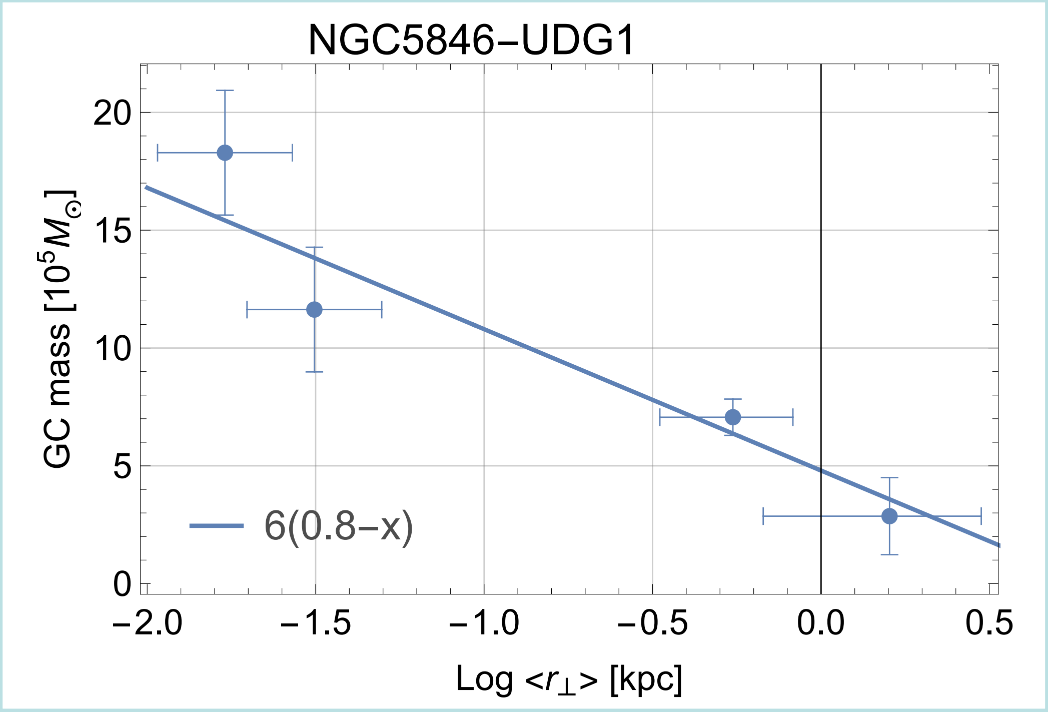
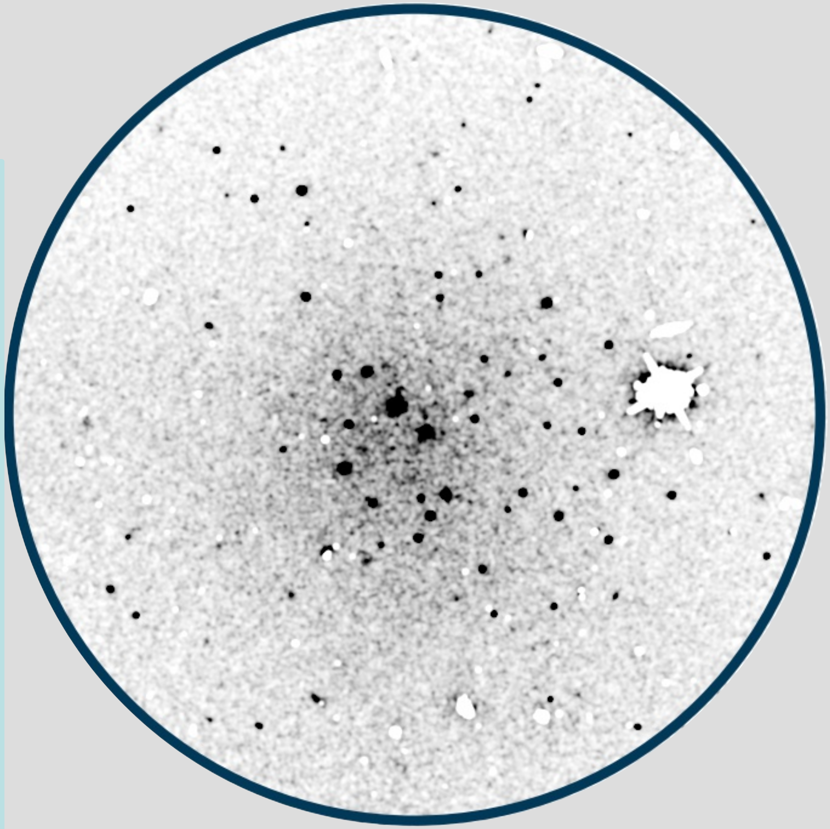
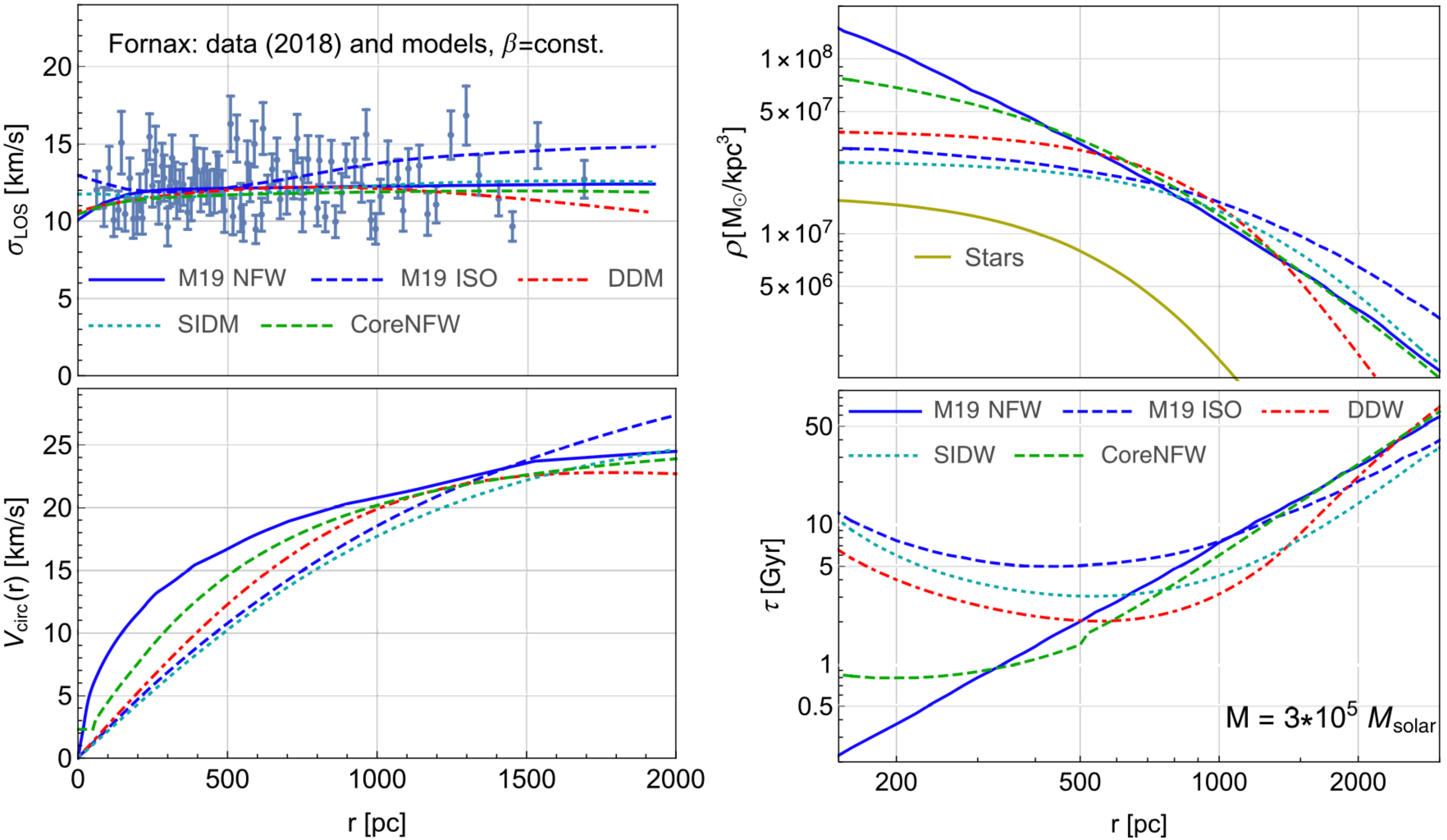
Danieli, Bar, KB 2202.10179

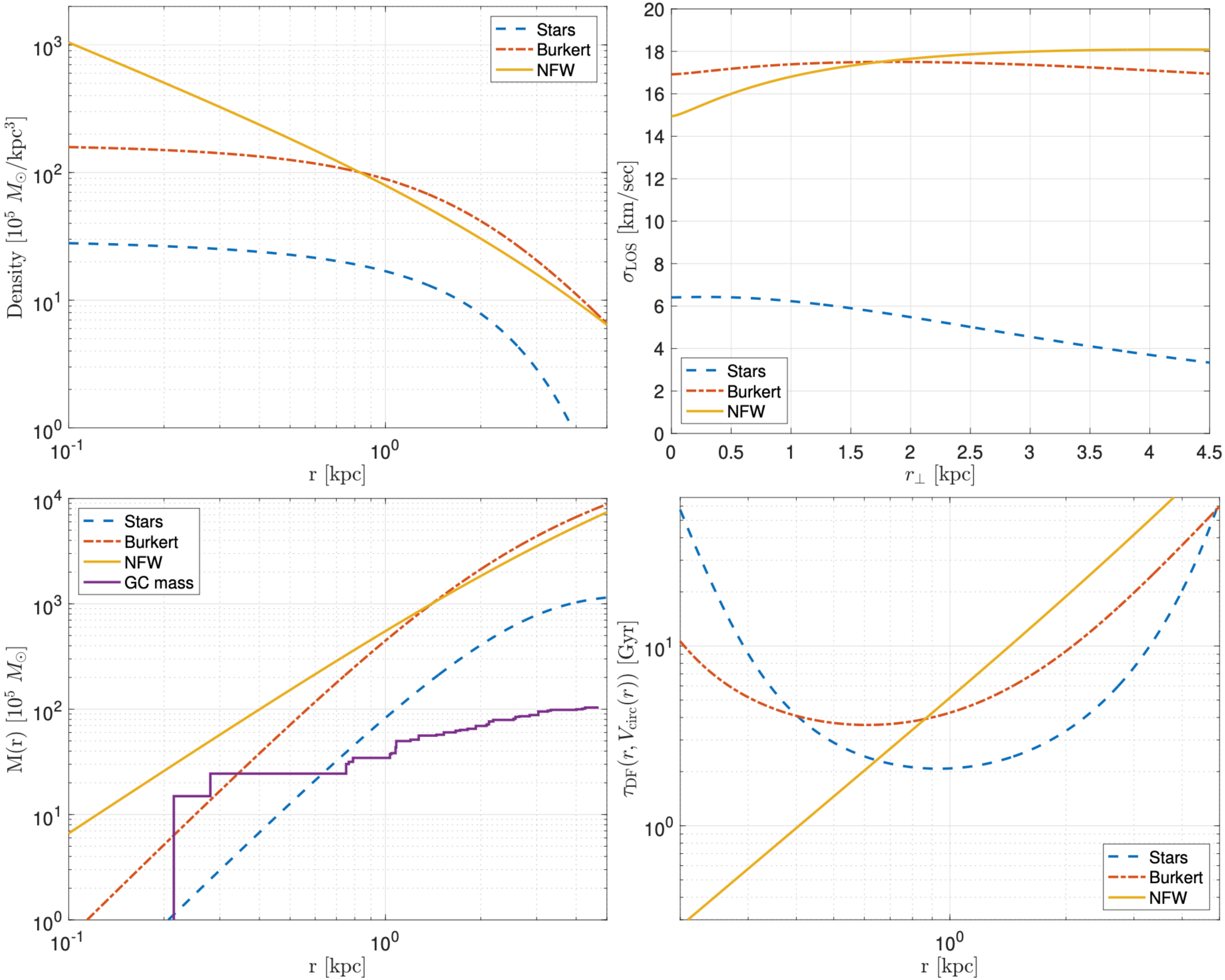




For a core density profile: $$N_{\Delta t}(r) = N_0\left(r_0(r,\Delta t)\right) \approx N_0\left(e^{\frac{\Delta t}{2\bar{\tau}}}\, r\right)$$

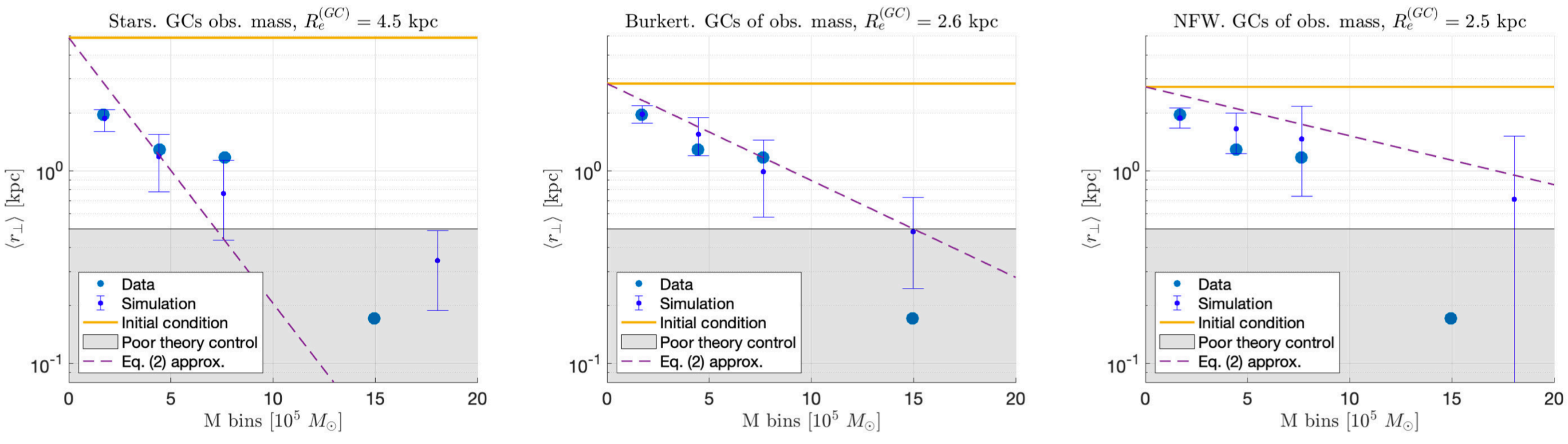
$$\Rightarrow \quad \langle r_\perp \rangle_{\Delta t} \approx e^{-\frac{\Delta t}{2\bar{\tau}}} \langle r_\perp \rangle_0$$


Fornax: data (2018) and models, β=const.
σ_{LOS} [km/s]
0
5
10
15
20
M19 NFW
M19 ISO
DDM
SIDM
CoreNFW
$V_{circ}(r)$ [km/s]
0
5
10
15
20
25
0
500
1000
1500
2000
r [pc]
$\rho[M_\odot/kpc^3]$
1×10^8
5×10^7
1×10^7
5×10^6
Stars
M19 NFW
M19 ISO
DDW
SIDW
CoreNFW
τ [Gyr]
0.5
1
5
10
50
$M = 3{*}10^5\ M_{solar}$
200
500
1000
2000
r [pc]


Stars
Burkert
NFW
Density $[10^5\ M_\odot/\mathrm{kpc}^3]$
10^0
10^1
10^2
10^3
10^{-1}
10^0
r [kpc]
σ_{LOS} [km/sec]
0
2
4
6
8
10
12
14
16
18
20
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
$r_\perp$ [kpc]
GC mass
M(r) $[10^5\ M_\odot]$
10^4
$\tau_{\mathrm{DF}}(r, V_{\mathrm{circ}}(r))$ [Gyr]

Evidence for dynamical friction in dark matter-dominated, GC-rich ultra diffuse galaxy

Danieli, Bar, KB 2202.10179



Dynamical friction in a massive dark matter halo naturally produces observed mass segregation.

Lack of dark matter, or a low mass halo, comes with small velocity dispersion, and **overshoots** friction.
…Alternatively, compensate by fine-tuned initial condition for GCs?

Consistent with, and independent of stellar and GC kinematics (Forbes et al 2021).

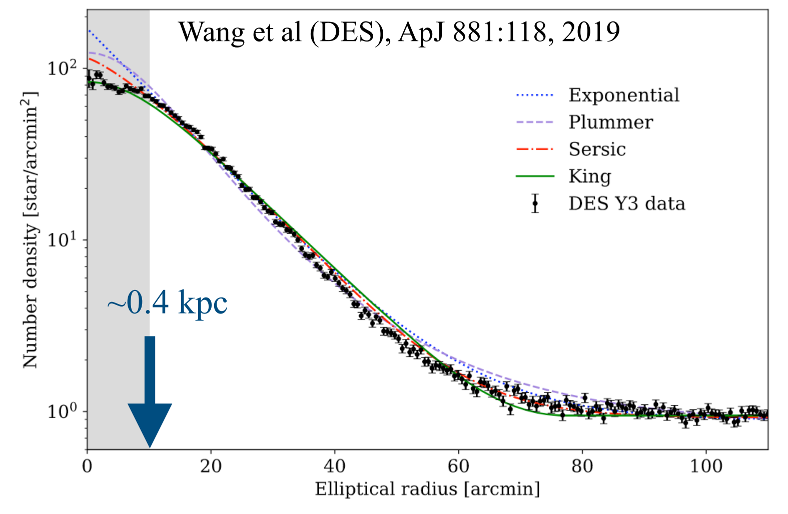
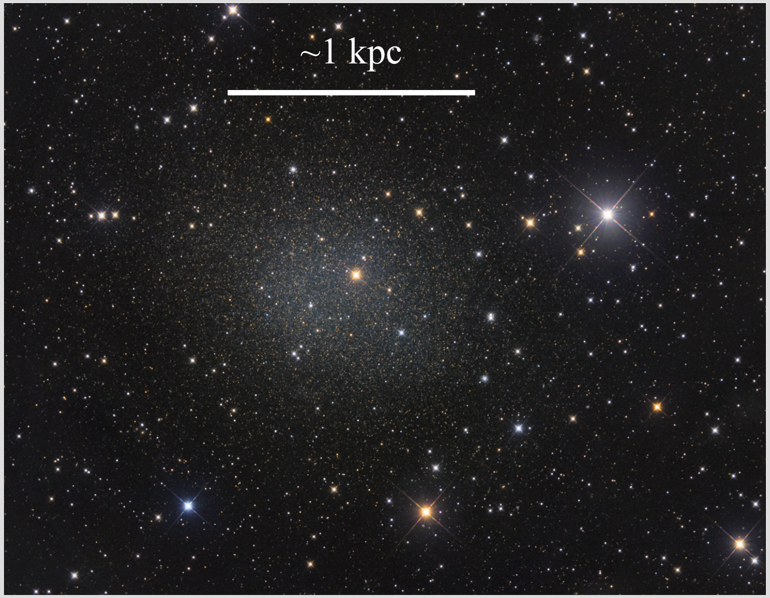
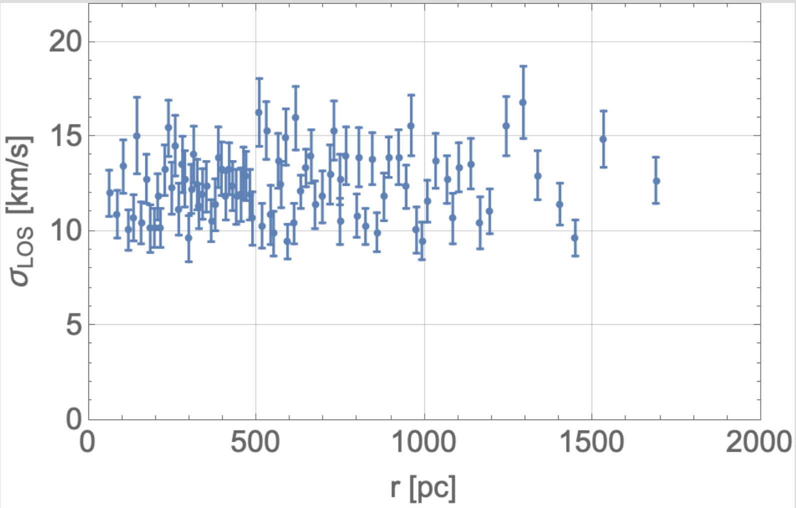


Figure 1. Surface density profile for Fornax dSph galaxy with overlaid best-



Data from: Read, Walker, Steger, 1808.06634

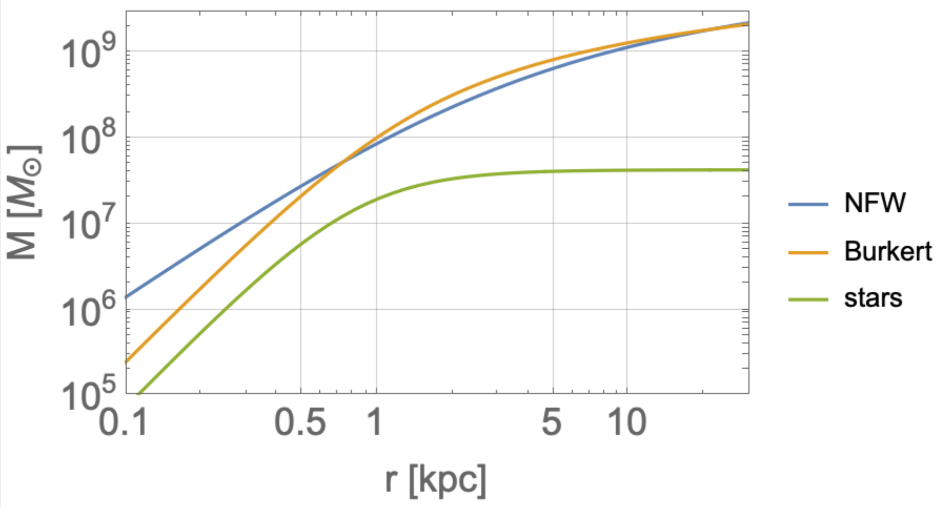


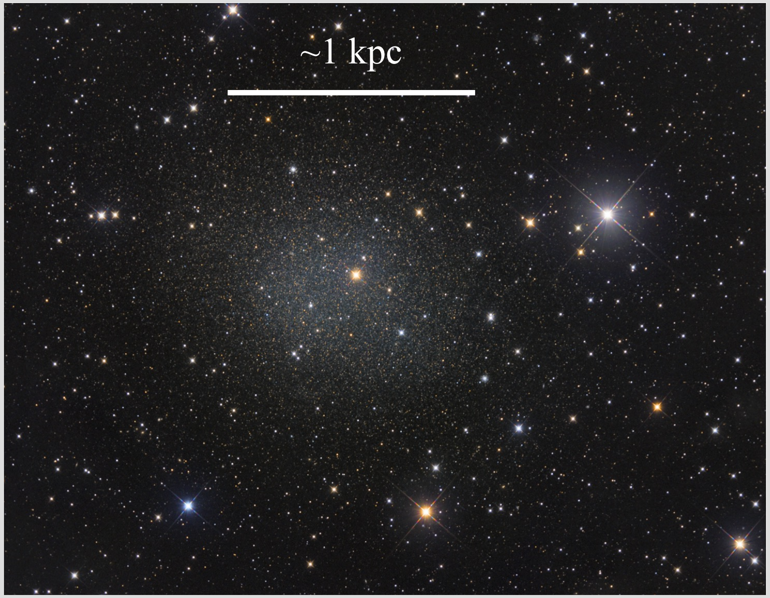
Steady-state, spherical:

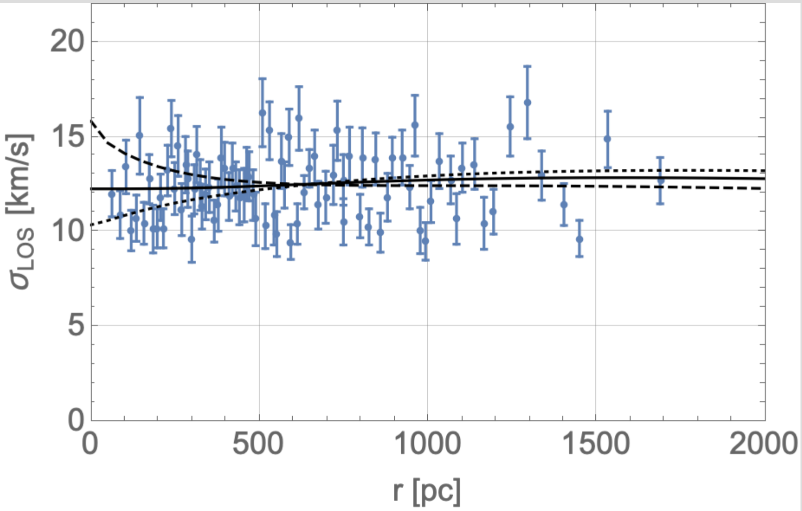
$$\frac{d}{dr}\left(n\overline{v_r^2}\right) + \frac{2\beta}{r} n\overline{v_r^2} = -\frac{GM(r)}{r^2} n$$

Observed:

$$\boxed{\sigma^2_{\rm LOS}(r) = \frac{2}{I}\int_r^\infty dy \left(1 - \frac{\beta r^2}{y^2}\right)\frac{y\, n\overline{v_r^2}(y)}{\sqrt{y^2 - r^2}}}$$







Burkert (core)

$$\frac{d}{dr}\left(n\overline{v_r^2}\right) + \frac{2\beta}{r} n\overline{v_r^2} = -\frac{GM(r)}{r^2} n$$

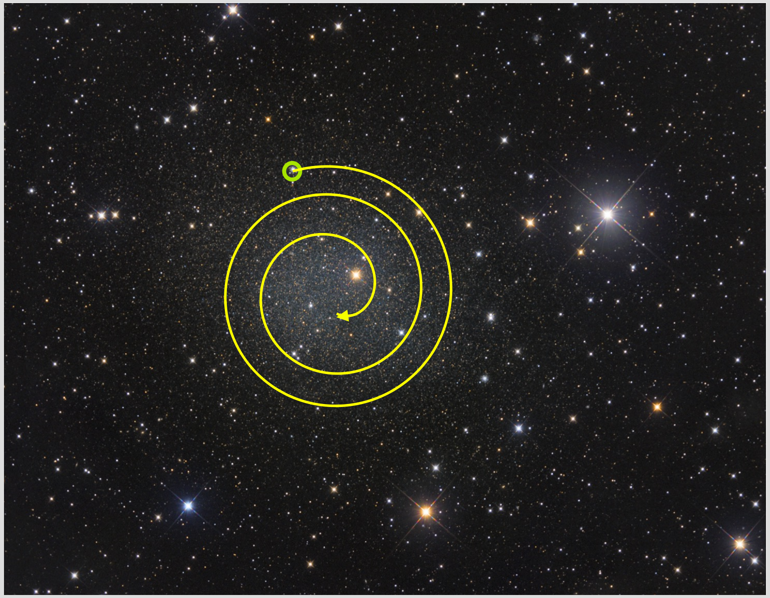
Globular Cluster (GC3): $5 \times 10^5\ \mathrm{M}_\odot$

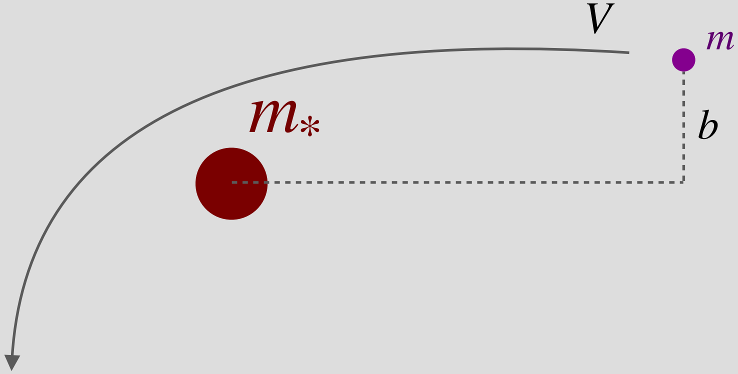
Massive “probe” traversing the halo.

Should slow down due to gravitational **dynamical friction**

Chandrasekhar 1943

$$\dot{\mathbf{V}} = -\frac{1}{\tau}\mathbf{V} \qquad \tau = \frac{V^3}{4\pi G^2 m_\star \rho C}$$





$$\frac{Gm_*}{b} \sim V^2 \qquad \sigma \sim \pi b^2 \sim \frac{G^2 m_*^2}{V^4}$$

$$\Gamma \sim n\sigma V \sim \frac{\rho}{m}\frac{G^2 m_*^2}{V^4}V$$

$$\Delta P = -\Delta p \sim -mV$$

$$\dot{P} = m_*\dot{V} \sim \Delta P \Gamma \sim -mV\frac{\rho}{m}\frac{G^2 m_*^2}{V^3} \longrightarrow \dot{V} \sim -\frac{G^2 m_* \rho}{V^3}V$$

Globular Cluster (GC3): $5 \times 10^5\ M_\odot$

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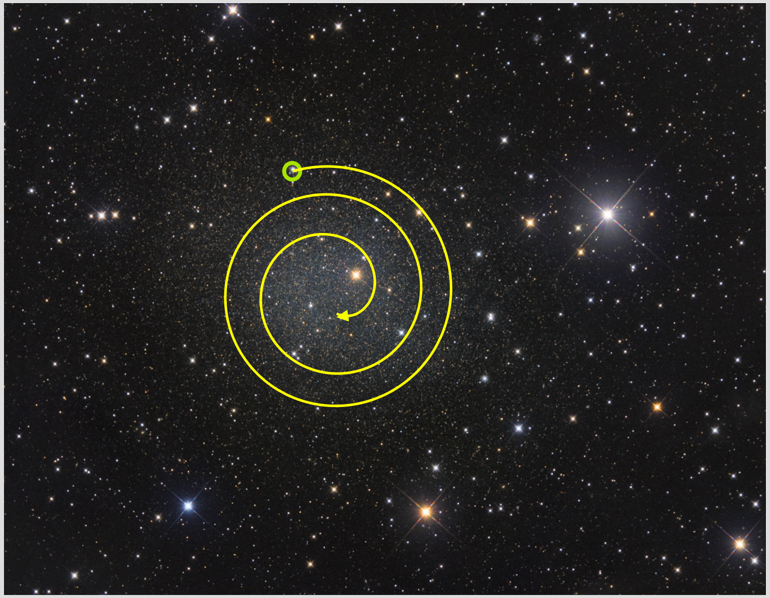


More generally: $C = -\frac{V^2 D_{||}}{4\pi G^2 m_\star^2 \rho}$

Bar, Blas, KB, Kim 2102.11522

$$\frac{df_1}{dt} = \int \frac{d^3p'}{(2\pi)^3}\left[S(\mathbf{p}',\mathbf{p})f_1(p')(1 \pm f_1(p)) - S(\mathbf{p},\mathbf{p}')f_1(p)(1 \pm f_1(p'))\right]$$

$$= -\frac{\partial}{\partial p^i}\left[f_1(1 \pm f_1)D_i\right] + \frac{1}{2}\frac{\partial}{\partial p^i}\left[\frac{\partial}{\partial p^j}(D_{ij}f_1) \pm f_1^2 \frac{\partial}{\partial p^j}D_{ij}\right]$$

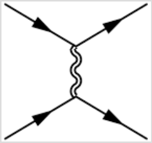
$$D_i(\mathbf{p}) = \int \frac{d^3q}{(2\pi)^3} q^i S(\mathbf{p},\mathbf{p}+\mathbf{q}), \qquad D_{ij}(\mathbf{p}) = \int \frac{d^3q}{(2\pi)^3} q^i q^j S(\mathbf{p},\mathbf{p}+\mathbf{q})$$

$$S(\mathbf{p},\mathbf{p}') \equiv \frac{(2\pi)^4}{2E_p 2E_{p'}} \int d\Pi_k d\Pi_{k'} \delta^{(4)}(p+k-p'-k')\,|\bar{\mathcal{M}}|^2 f_2(k)(1 \pm f_2(k'))$$

In a dark matter-dominated system, observing the imprint of DF is a probe of the ~local~ phase space distribution of DM.

Micorphysics of DM can have an imprint.

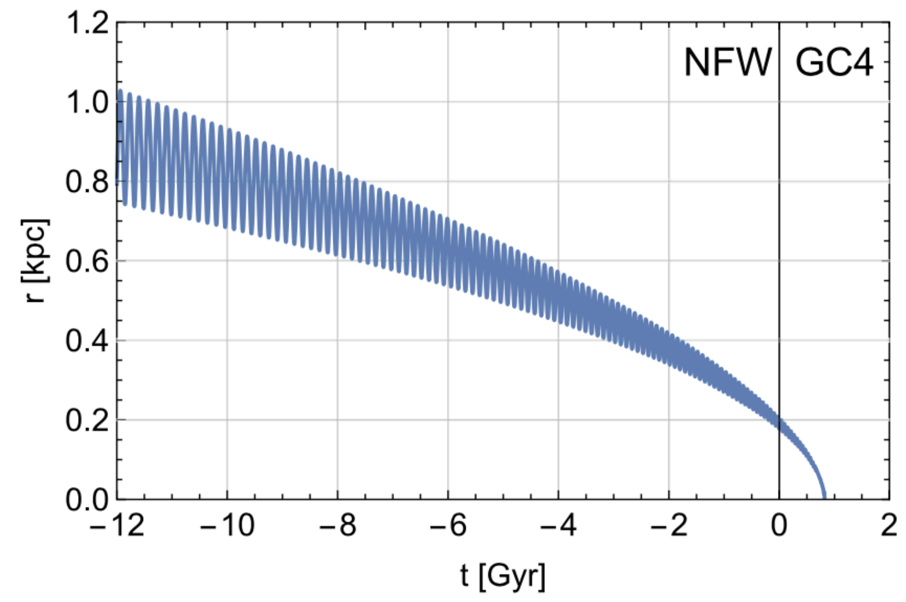
$$|\bar{\mathcal{M}}|^2 = \frac{1}{2s+1}\frac{(16\pi G)^2 m^4 M^4}{[(q^0)^2 - \mathbf{q}^2]^2}$$

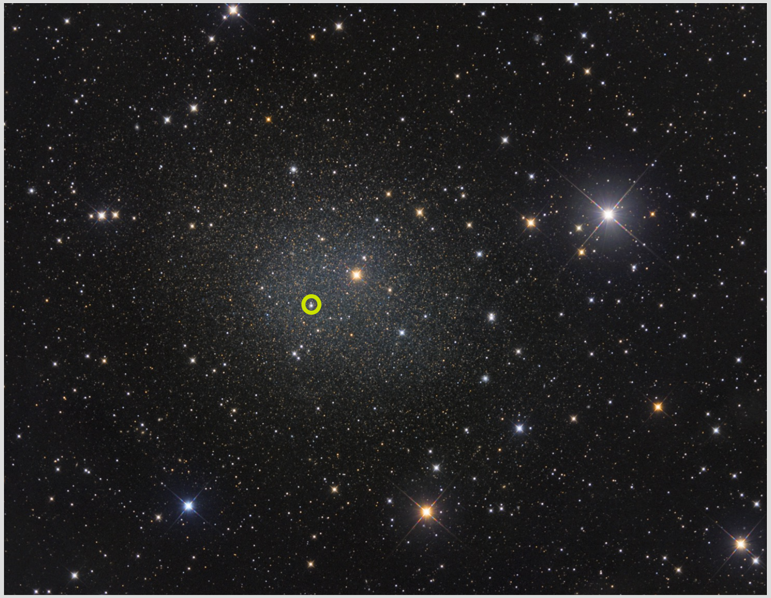


"Fornax GC timing problem"

…expect: $N_{\Delta t}(r) \propto \frac{\tau(r)}{\Delta t}$

Tremaine 1976,
Oh, Lin, Richer 2000,
Petts, Gualandris, Read 2015,
Hui et al 2017, Lancaster et al 2019,
Meadows et al 2020, **Bar et al 2021,**
Shao et al 2021,…





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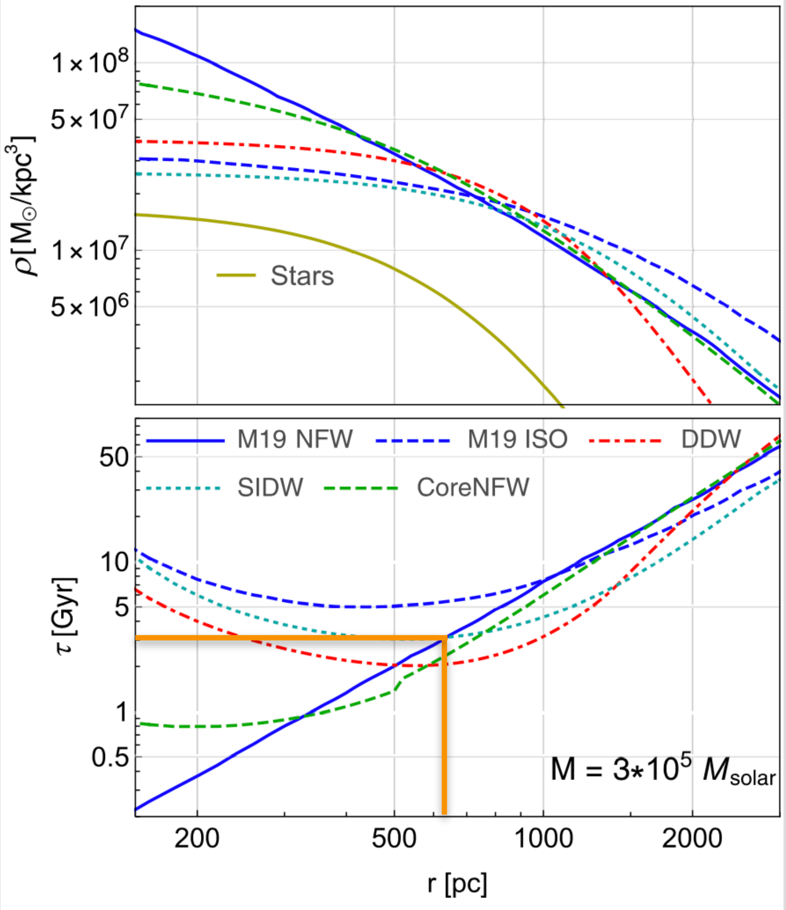

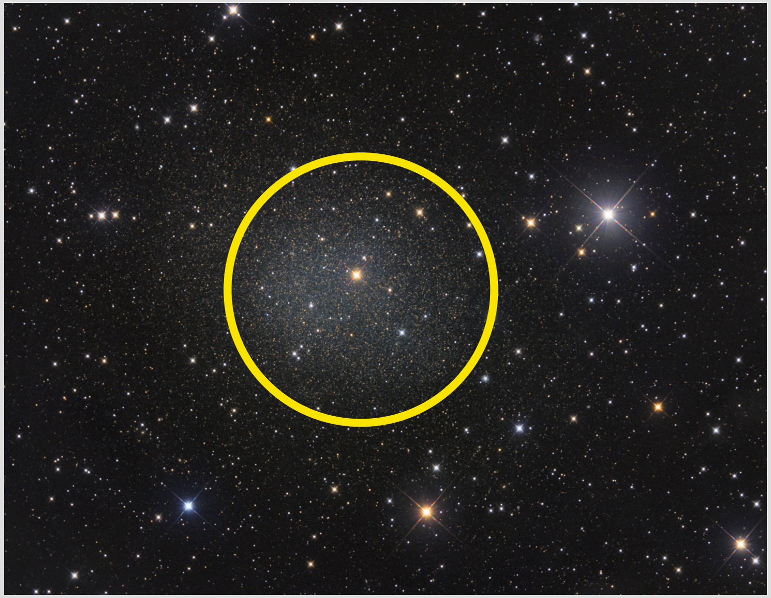

For approximately circular orbit:

$$\frac{\dot{r}}{r} \approx -\frac{2}{(1+\frac{d\ln M}{d\ln r})\tau}$$

$$\alpha(r) = \frac{d\,\ln M(r)}{d\,\ln r}$$

$$\Delta t = \int_r^{r_0} \frac{dr'}{2r'}(1+\alpha(r'))\tau(r')$$

For approximately power law density profile:
(e.g. NFW $\beta \approx 2,\ \alpha \approx 2$)

$$\tau = \bar{\tau}(r/\bar{r})^\beta$$

There is a **critical radius**:

$$\boxed{r_{\rm cr} = \bar{r}\left(\frac{2\beta}{1+\alpha}\frac{\Delta t}{\bar{\tau}}\right)^{1/\beta}}$$

Tremaine 1976,
Oh, Lin, Richer 2000,
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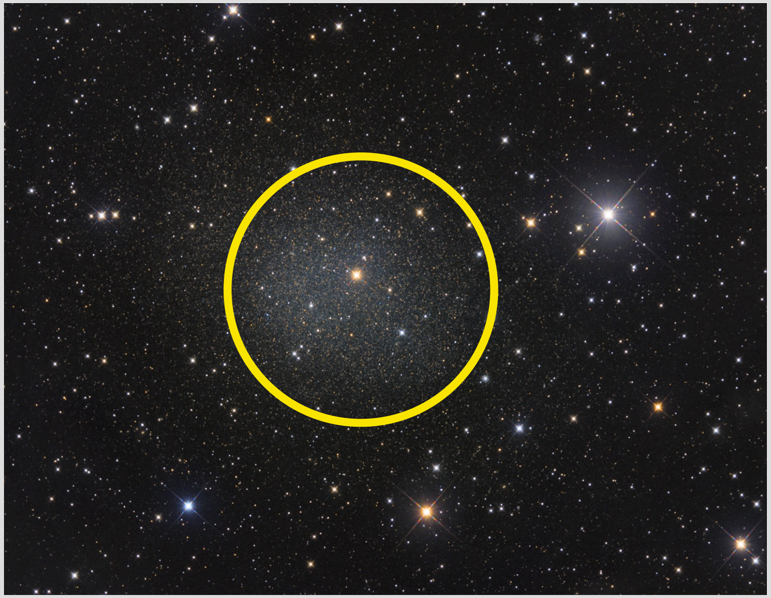

➡ GCs that start at $r<r_{\rm cr}$ at t=0, arrive at r=0 by t=Δt

Should we expect to see GCs inside the kill circle?

…Not many: GCs that are now inside critical radius (*but not in nuclear cluster*) come from a small sliver of space:

Tremaine 1976,
Oh, Lin, Richer 2000,
Petts, Gualandris, Read 2015,
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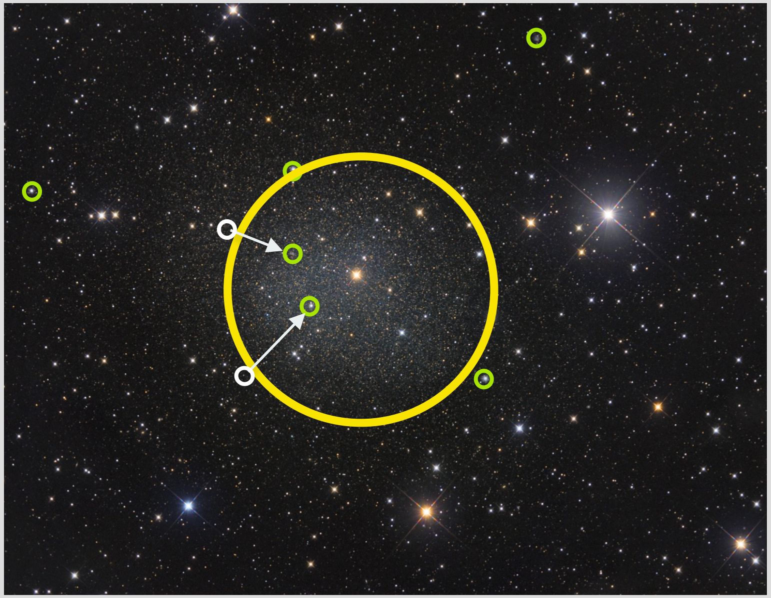
$$r_0(r;\Delta t) = r_{\rm cr}\left(1+\left(\frac{r}{r_{\rm cr}}\right)^{\beta}\right)^{1/\beta}$$

$$= r_{\rm cr}\left(1+\frac{1+\alpha}{2\beta^2}\frac{\tau(r)}{\Delta t}+\cdots\right)$$



Cumulative count of GCs (CDF):

$$N_{\Delta t}(r) \approx N_0(r_{\rm cr}) + \frac{1+\alpha}{2\beta^2}N_0'(r_{\rm cr})r_{\rm cr}\frac{\tau(r)}{\Delta t}+\ldots$$

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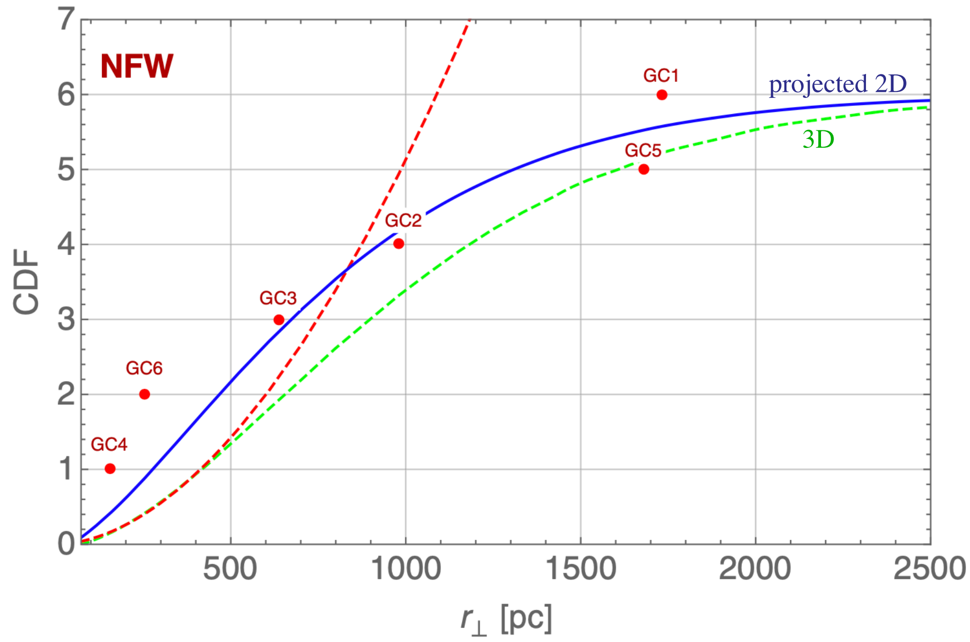

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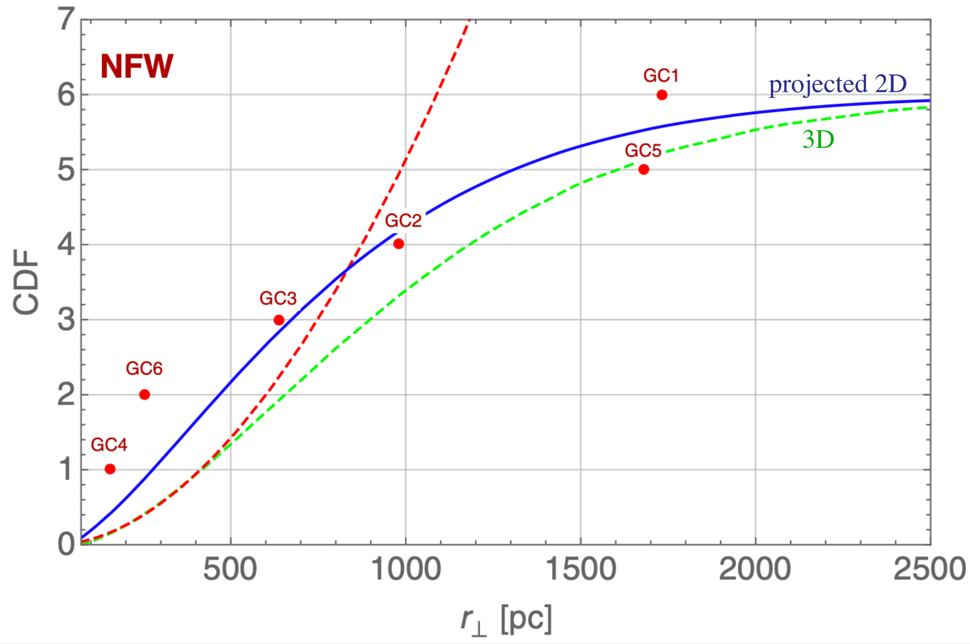

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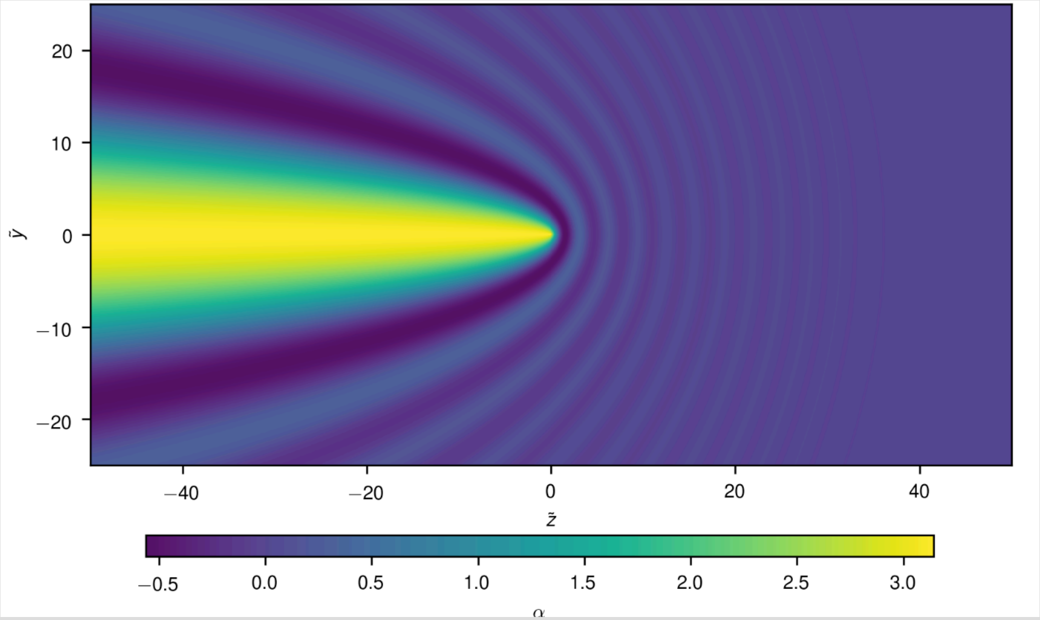
Nuclear cluster?!
Fornax does not seem to have one…

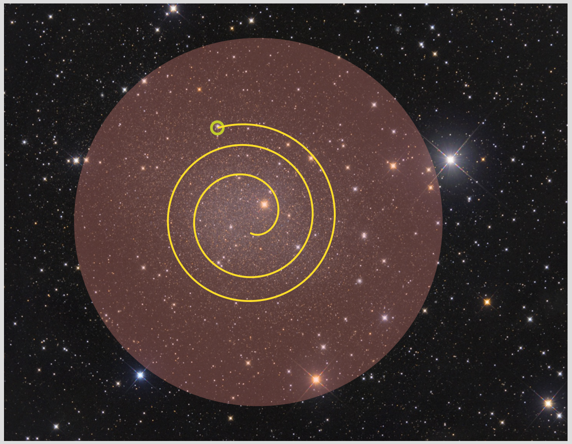
Examples how it could become very interesting — ultralight dark matter

If the system is entirely inside the coherent region (the *soliton*), dynamical friction is suppressed

Hui et al, 1610.08297;
Bar-Or, Fouvry, Tremaine, 1809.07673; 2010.10212
Lancaster et al, 1909.06381



Proposed for Fornax GC timing puzzle
Hui et al 2016.



Examples how it could (have) become very interesting — ultralight dark matter

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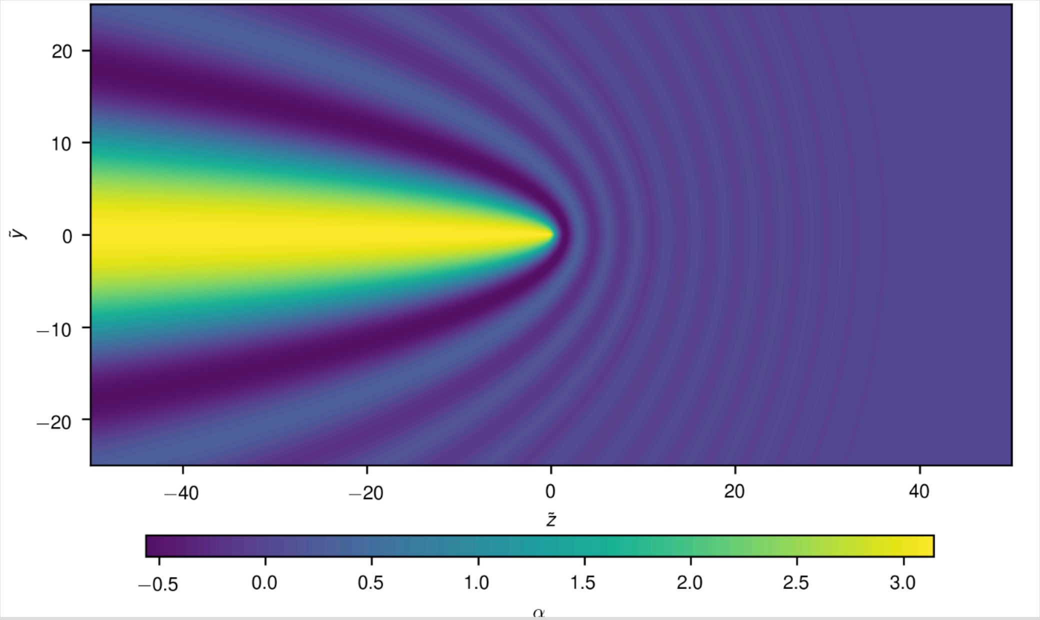
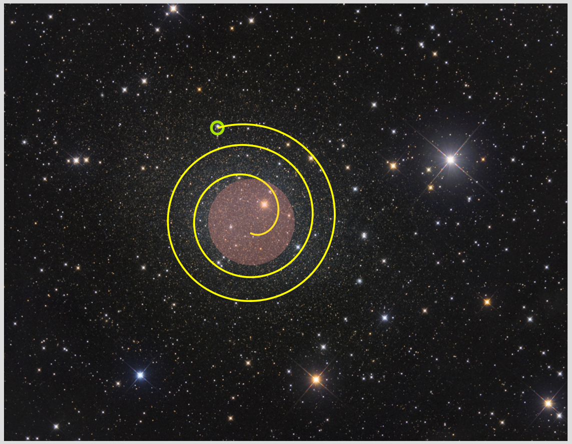


Proposed for Fornax GC timing puzzle
Hui et al 2016.
But only works for $m < 10^{-21}$ eV (Lancaster et al 2019),
in tension w/ LSBGs, Ly-α which suggest $m > 10^{-21}$ eV



Examples how it could become very interesting — ultralight dark matter

Effective **quasi-particles**

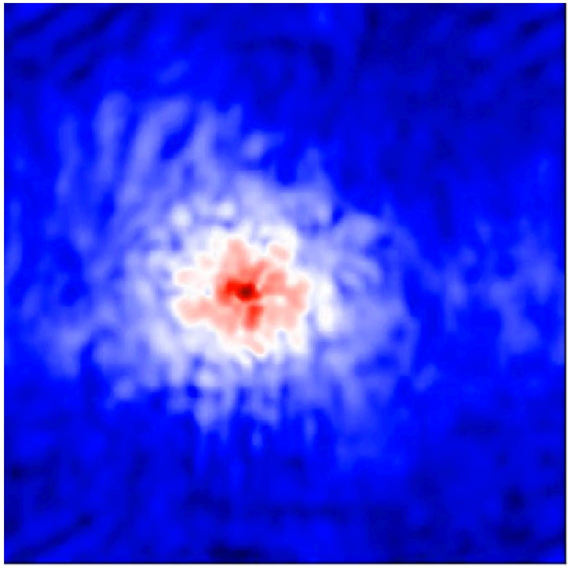
(Bar-Or, Fouvry, Tremaine 1809.07673)

$$m_{\mathrm{eff}} = \frac{\pi^{3/2}\hbar^3\rho_{\mathrm{b}}}{m_{\mathrm{b}}^3\sigma^3} = \rho_{\mathrm{b}}\left(f\lambda_\sigma\right)^3$$

$$\lambda_\sigma = h/(m_{\mathrm{b}}\sigma)$$

$$f = 1/(2\sqrt{\pi}) = 0.282.$$

Dynamical *heating*



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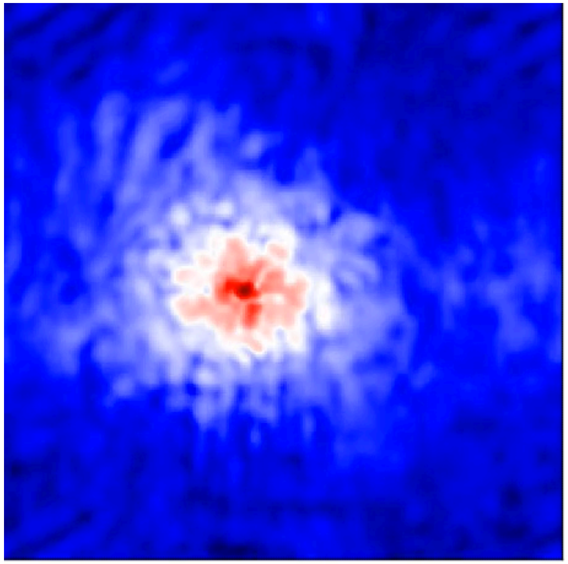
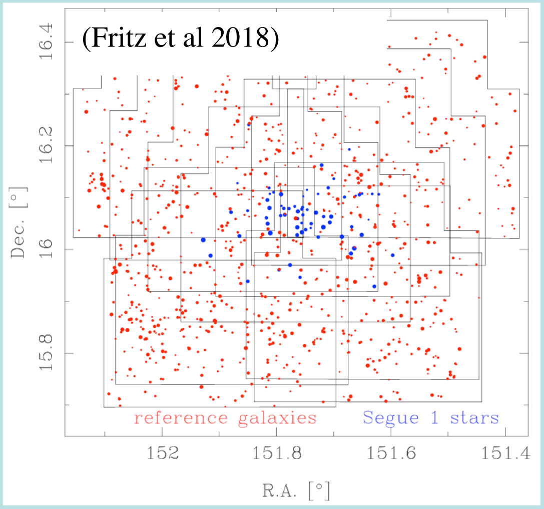




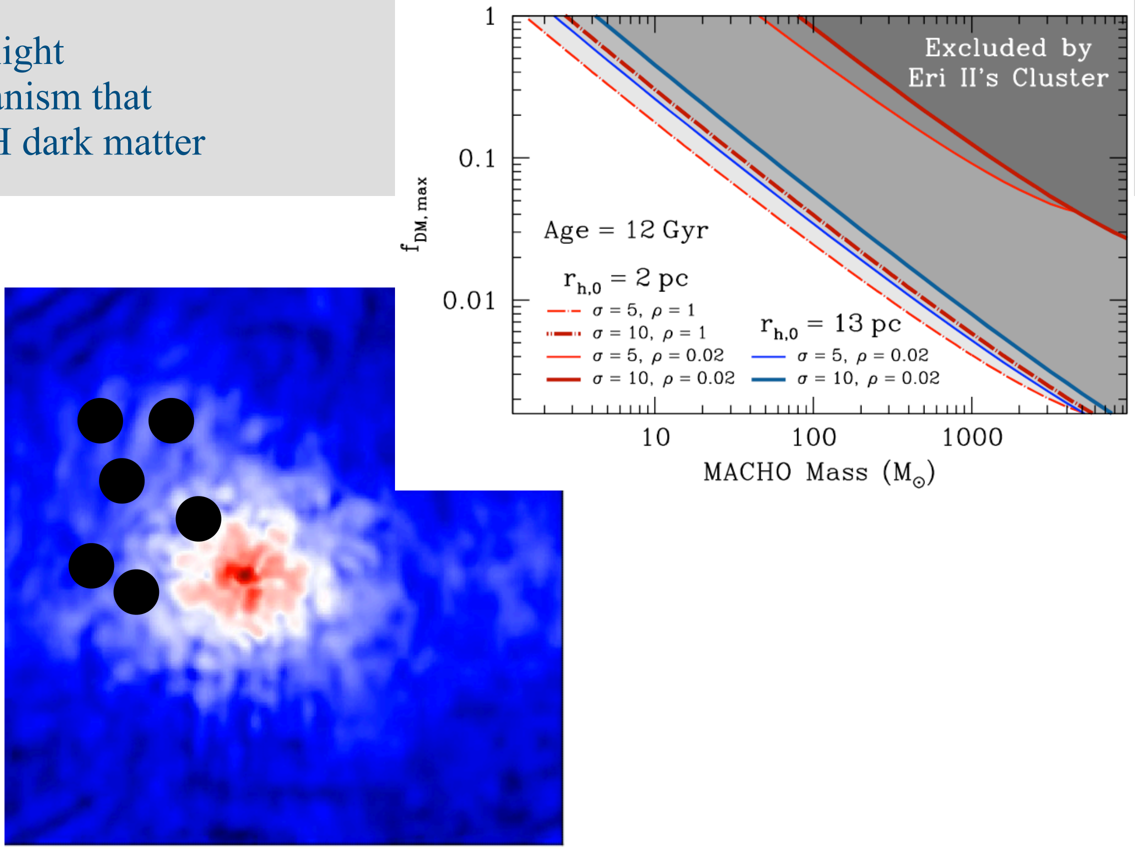
Dalal, Kravstov 2203.05750:
would have dispersed star cluster in Segue-I?

$$m_{\mathrm{eff}} \approx 430\ \mathrm{M}_\odot \left(\frac{10\ \mathrm{km/s}}{\sigma}\right)^3 \left(\frac{\rho}{10^7\ \mathrm{M}_\odot/\mathrm{kpc}^3}\right) \left(\frac{10^{-20}\ \mathrm{eV}}{m}\right)^3$$

Examples how it could become very interesting — ultralight dark matter

Amusing fact:
Dynamical heating constraints on ultralight dark matter come from the same mechanism that constrains ultra heavy MACHO or PBH dark matter

Brandt 1605.03665



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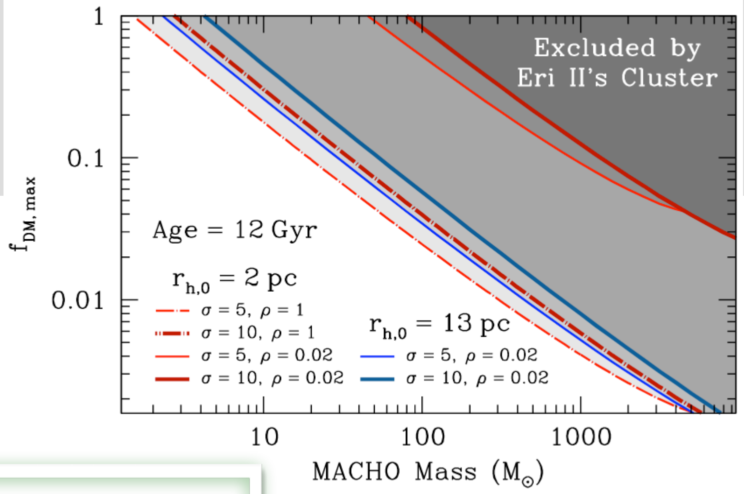
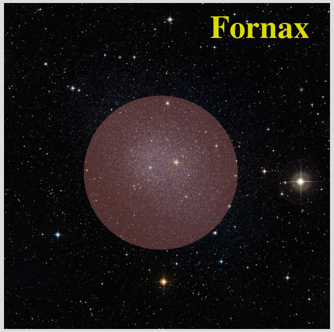


Hypothesis:
If you go far enough in the extreme right,
you end up in the extreme left.

Examples how it could become very interesting — light *fermion* dark matter

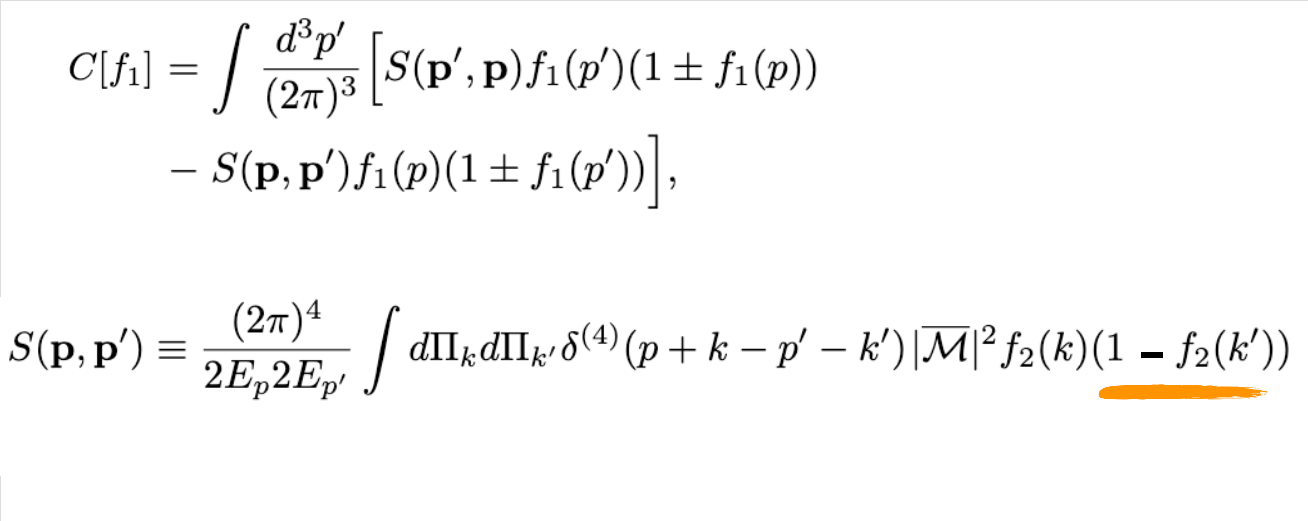
It was suggested that Milky Way dwarf satellite galaxies may point to degenerate fermion dark matter with $m \sim 200$ eV

Domcke, Urbano, 1409.3167
Randall, Scholtz, Unwin, 1611.04590



Examples how it could become very interesting — light *fermion* dark matter

The collision operator:



$$C[f_1] = \int \frac{d^3p'}{(2\pi)^3} \Big[S(\mathbf{p}', \mathbf{p}) f_1(p')(1 \pm f_1(p)) - S(\mathbf{p}, \mathbf{p}') f_1(p)(1 \pm f_1(p')) \Big],$$

Transfer function S:

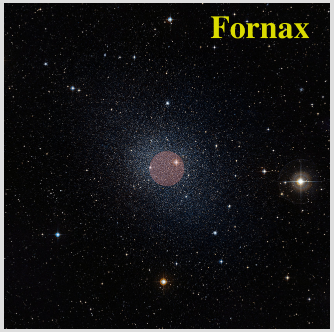
$$S(\mathbf{p}, \mathbf{p}') \equiv \frac{(2\pi)^4}{2E_p 2E_{p'}} \int d\Pi_k d\Pi_{k'} \delta^{(4)}(p + k - p' - k') |\overline{\mathcal{M}}|^2 f_2(k)(1 \underline{- f_2(k'))}$$

Reddy, Prakash, Lattimer, astro-ph/9710115
Bertoni, Nelson, Reddy, 1309.1721
Bar et al, 2102.11522

$$C_{\mathrm{DF}} \to \frac{V^3}{v_F^3}\,, \qquad \text{instead of the classical gas result:} \quad C_{\mathrm{DF}} \to \frac{\sqrt{2}V^3}{3\sqrt{\pi}\sigma^3}$$

Examples how it could (have) become very interesting — light *fermion* dark matter

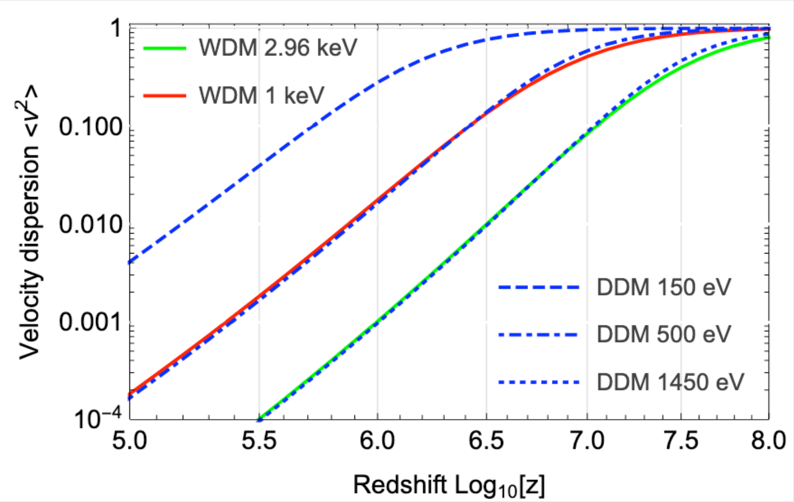
Bar et al, 2102.11522



DDM must be hot at high redshift due to unavoidable degeneracy pressure.

The minimal possible velocity dispersion can be compared with “standard” hot dark matter.

Ly-α limit $m > 2.96$ eV (Baur et al, 1512.01981) rules out dwarf galaxy cores as proposed in Domcke, Urbano, 1409.3167; Randall, Scholtz, Unwin, 1611.04590



Many more UDGs/dwarfs to investigate.

Saifollahi et al, 2201.11750: Coma cluster UDGs