Modelling the faint dSph galaxies of the Milky Way

Michael Fellhauer
Theory Group
Departamento de Astronomía
Universidad de Concepción

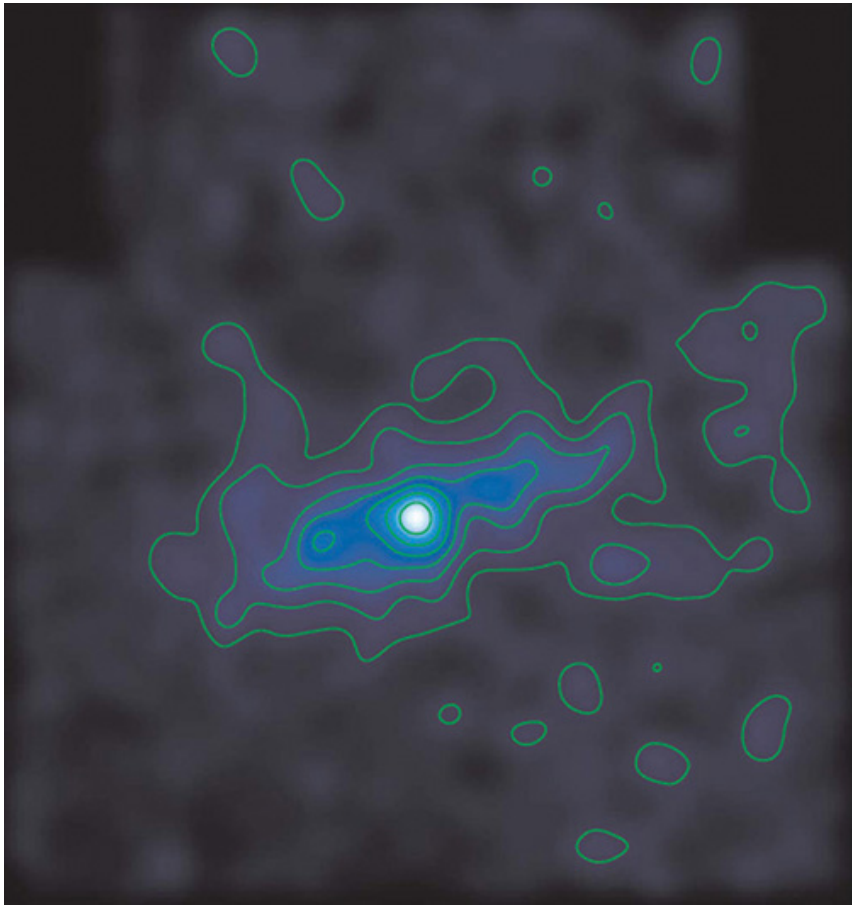
What solutions do we have?

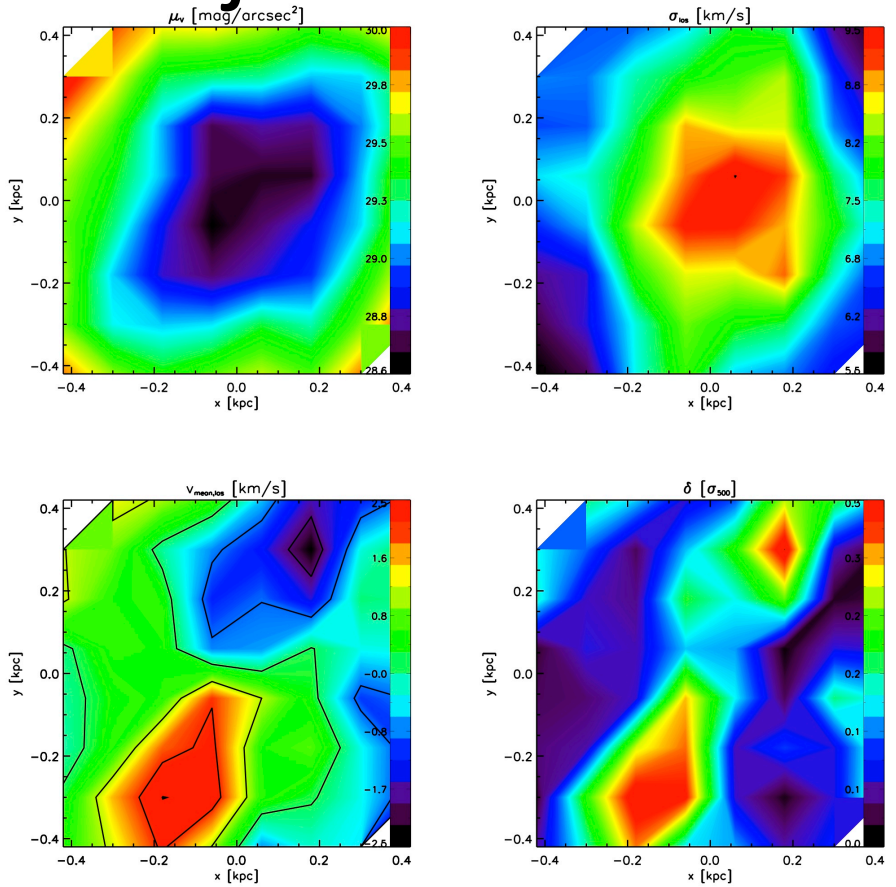
1. The dSph galaxies are heavily dark matter dominated → how can we explain the twisted shapes and substructure?
2. We have to invoke a new theory of gravitation – MOND → for some dSph not sufficient?
3. The dSph galaxies we see are TDG or star clusters on the brink of destruction. → we have to find a possible progenitor for every single one of them.

Scenario 1: Dark Matter rules

- If the high measured mass-to-light ratio is true, i.e. the dwarfs are highly dark matter dominated, then they are still well shielded from tidal effects to the luminous component.
- All the features of the dSph are not due to any orbit but are intrinsic and we do know nothing about their orbits.

Example: Hercules as a DM dominated object





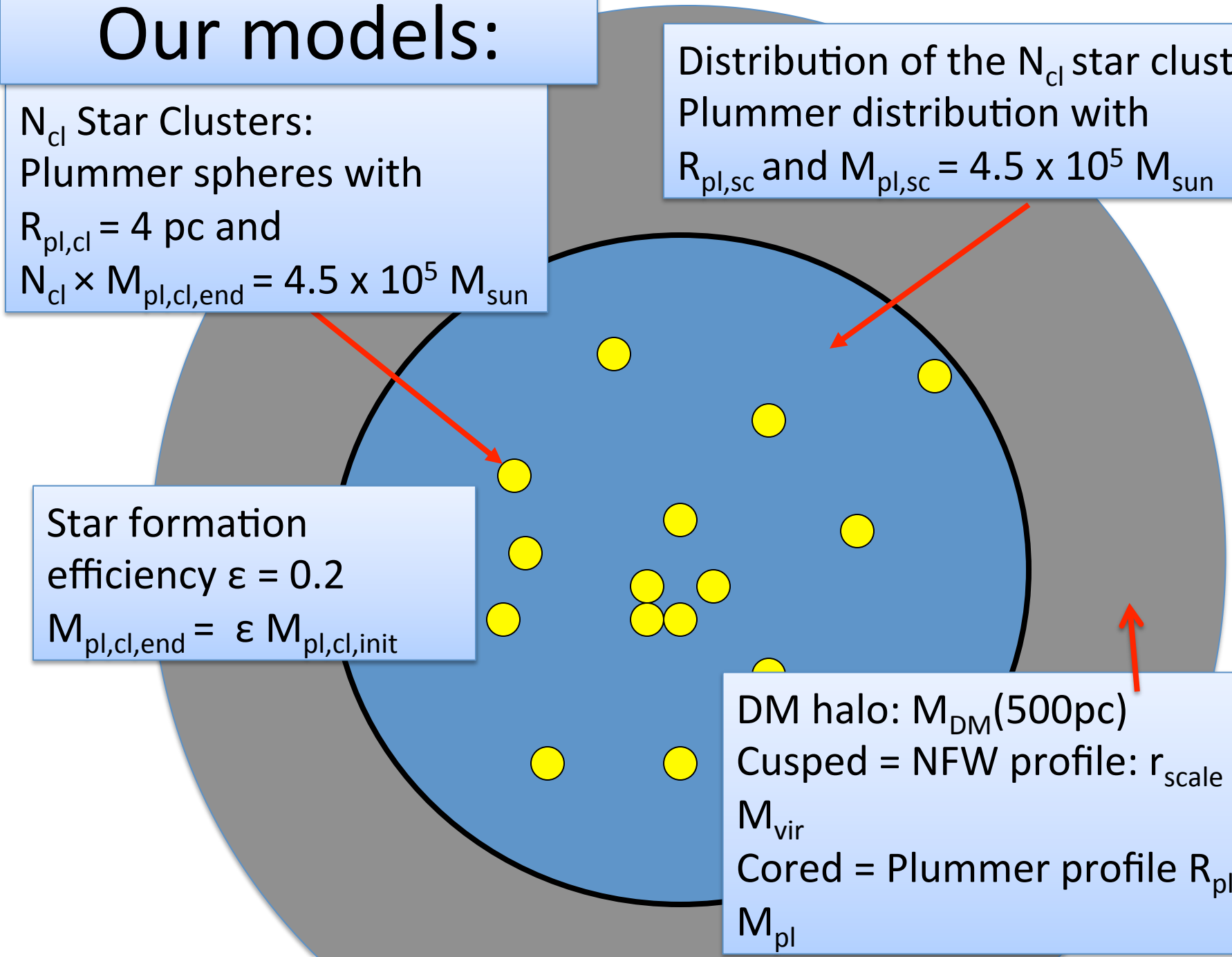
Hercules exhibits a velocity gradient

According to our models it could be DM dominated

Our models:

N_{cl} Star Clusters:
Plummer spheres with
$R_{pl,cl}$ = 4 pc and
$N_{cl} \times M_{pl,cl,end} = 4.5 \times 10^5\ M_{sun}$

Distribution of the N_{cl} star clusters:
Plummer distribution with
$R_{pl,sc}$ and $M_{pl,sc} = 4.5 \times 10^5\ M_{sun}$



Star formation
efficiency $\varepsilon = 0.2$
$M_{pl,cl,end} = \varepsilon\ M_{pl,cl,init}$

DM halo: M_{DM}(500pc)
Cusped = NFW profile: r_{scale} and M_{vir}
Cored = Plummer profile R_{pl} and M_{pl}

Scenario 2: MOND???

We have no models for this scenario yet, but G. Candlish develloped a MONDian N-body code called

RAyMOND (Ramses y Mond)

Scenario 3: Do we really need DM or strange gravity?

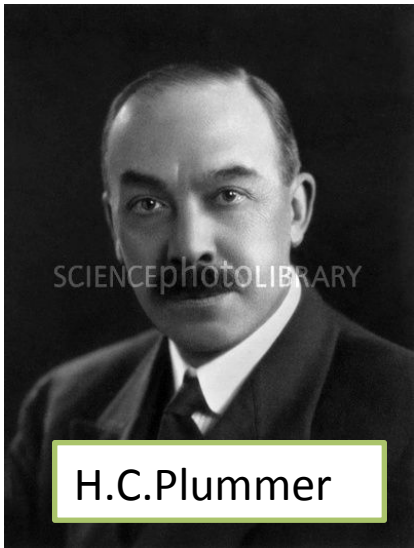
Or are the faint dwarfs just TDGs or star clusters in disruption?

Our Initial Models

One component model (i.e. no or no significant dark matter content)

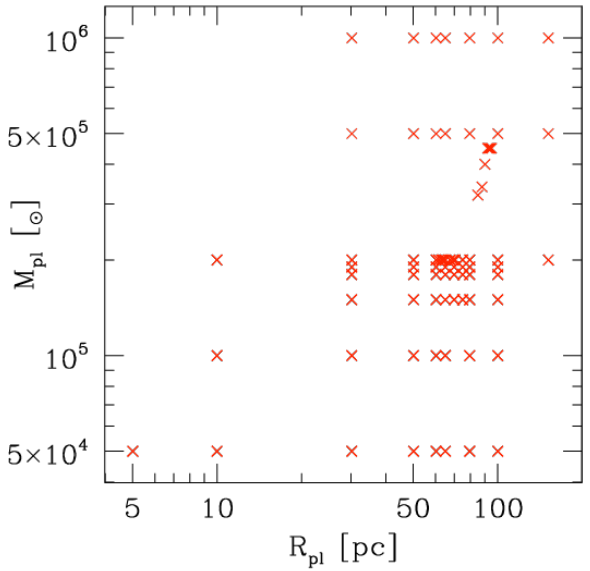
- Plummer spheres with two initial parameters:
  - Mass M_{pl}
  - Scale-length R_{pl}
- Generic Infall/Formation time of 10 Gyr.

Note: We also test for shorter orbital times (5Gyr) and different mass-profiles (Hernquist) -> will change initial parameters but not conclusions.



New Method

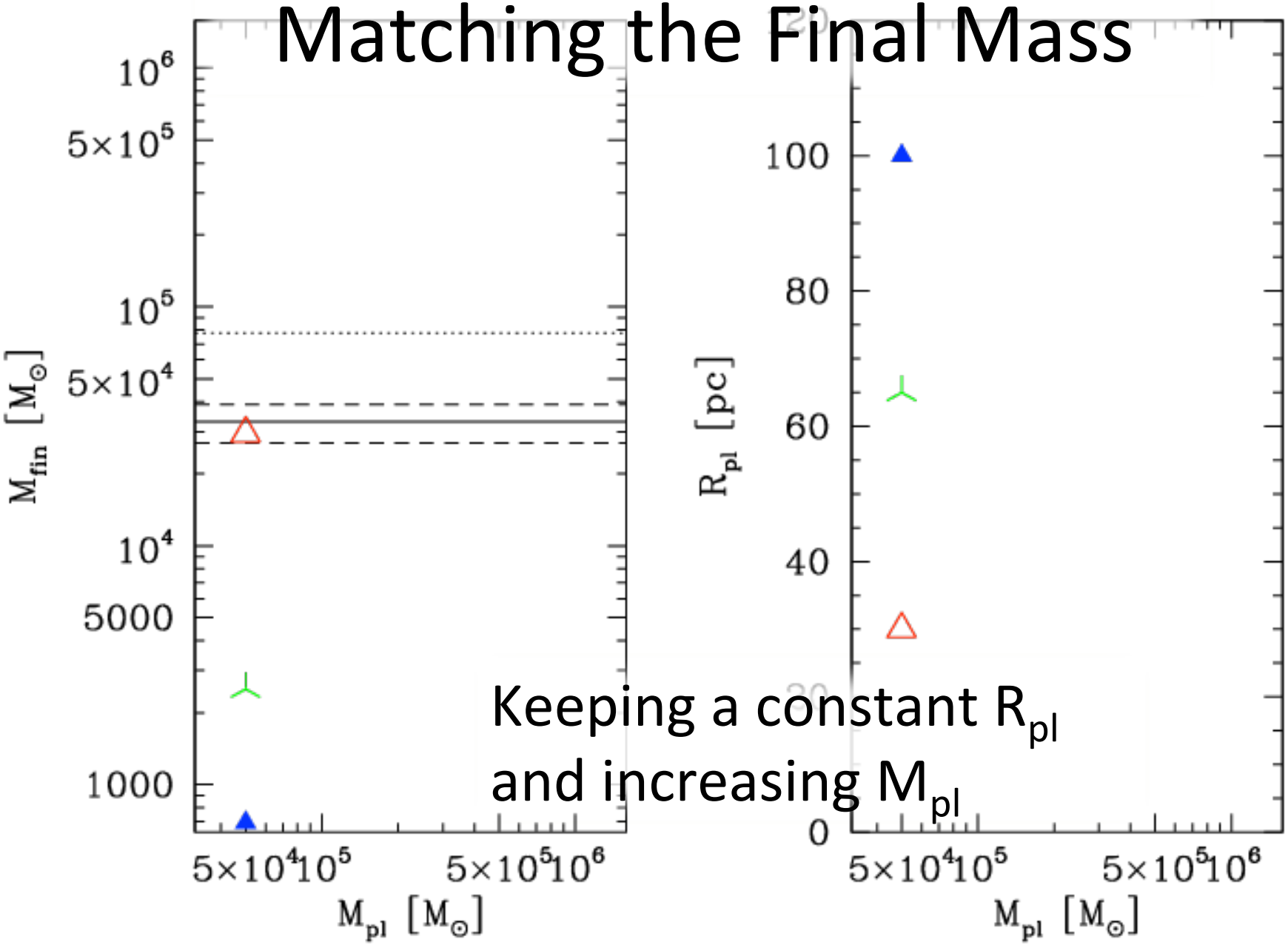
- Instead of searching for a best fitting model by try and error we investigate a wide parameter space of initial parameters and look for global relations to match the observed quantities separately to deduce the best fit model directly.
- Example: Hercules
  - R_{pl}: 5 to 120 pc
  - M_{pl}: 5x10^4 to 10^6 M_{sun}



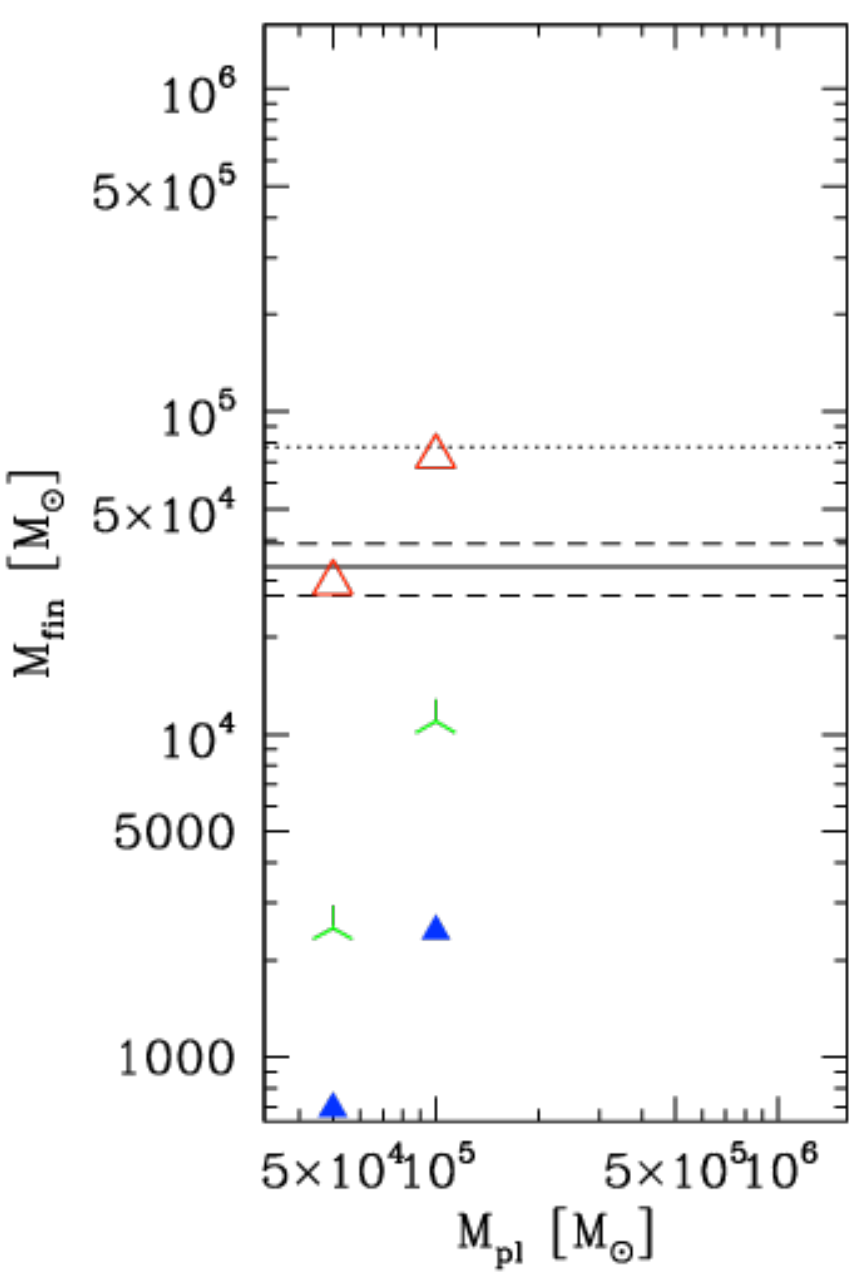
Hercules

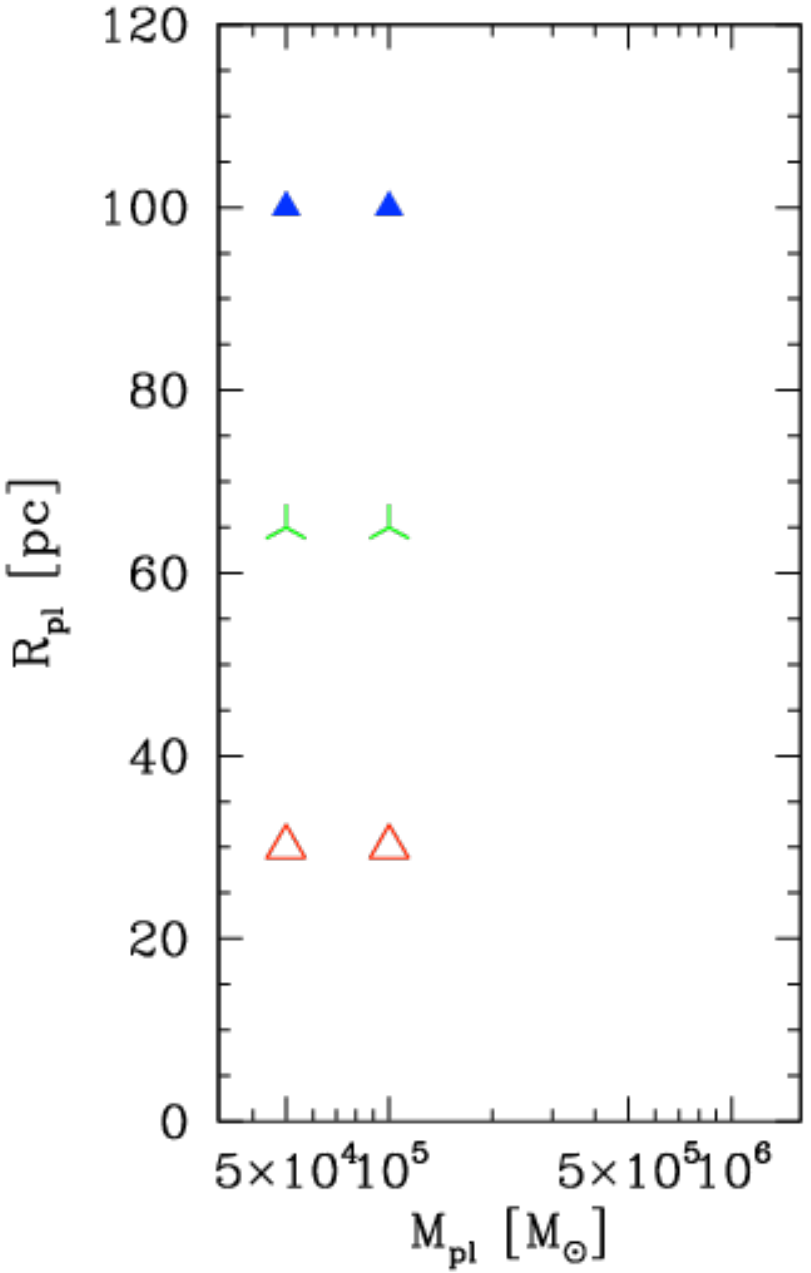
We assume the published orbit by Martin & Jin.

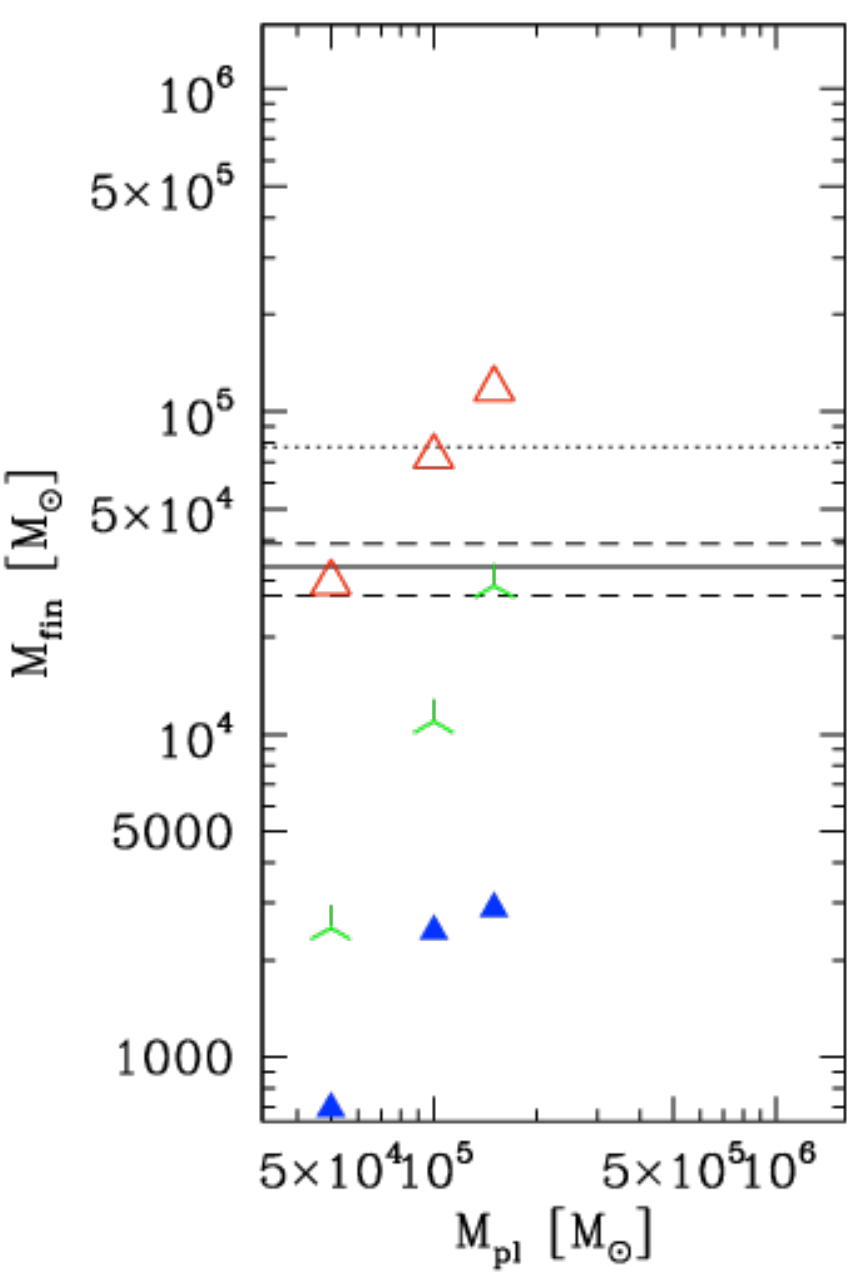
Matching the Final Mass

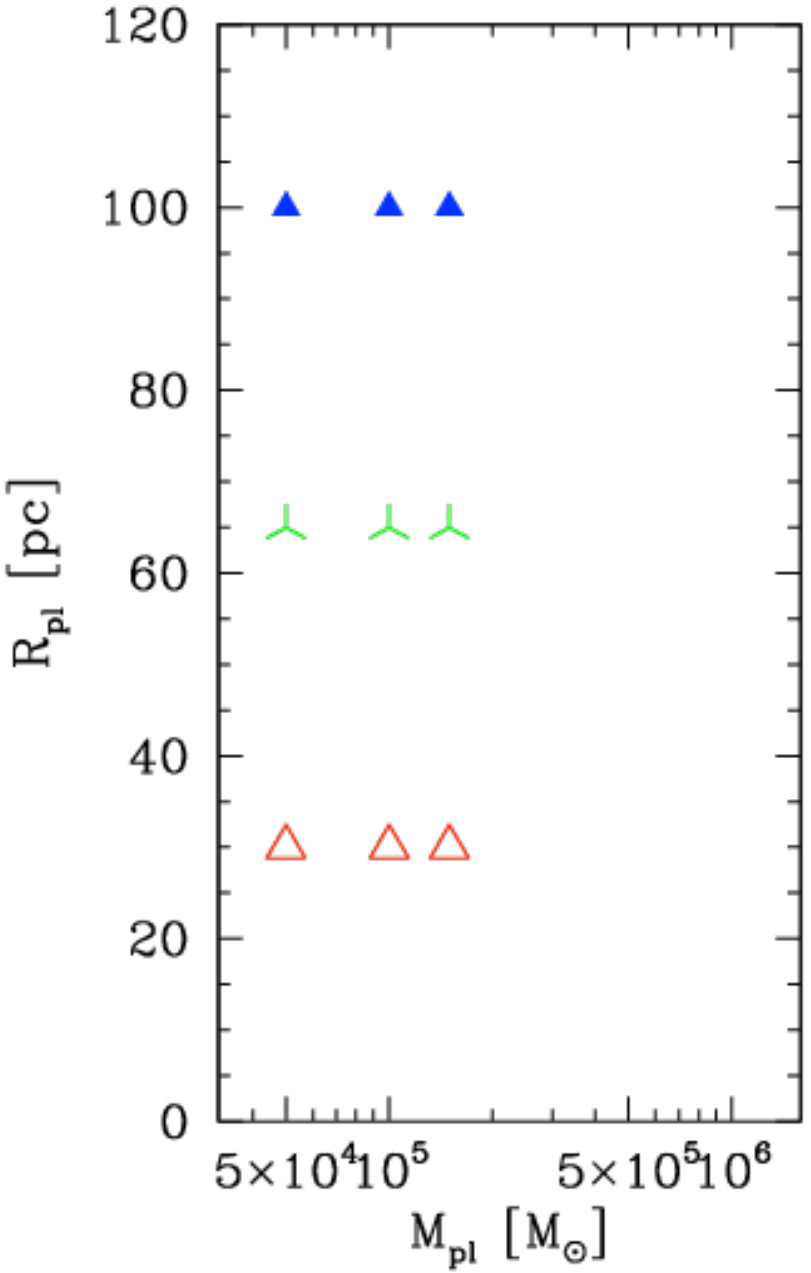


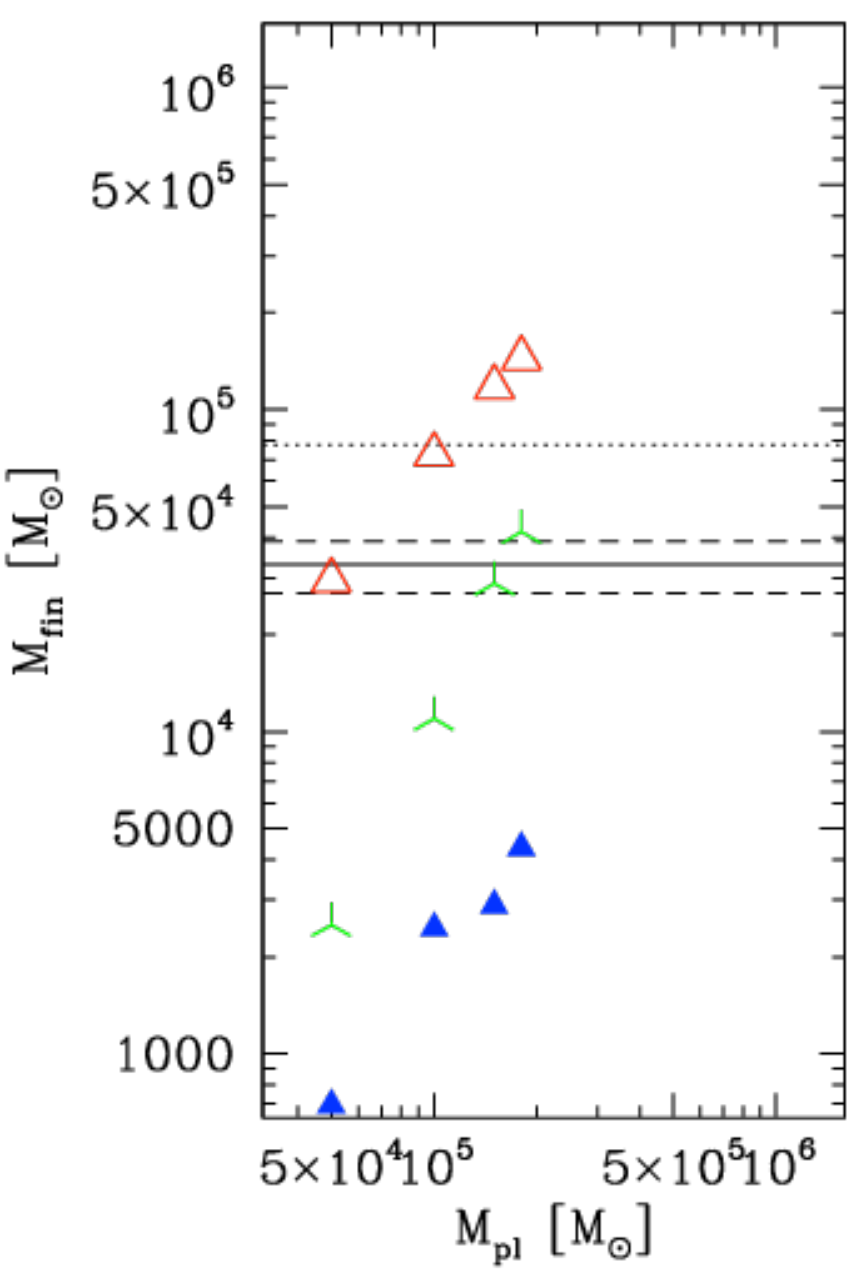
Keeping a constant R_{pl} and increasing M_{pl}

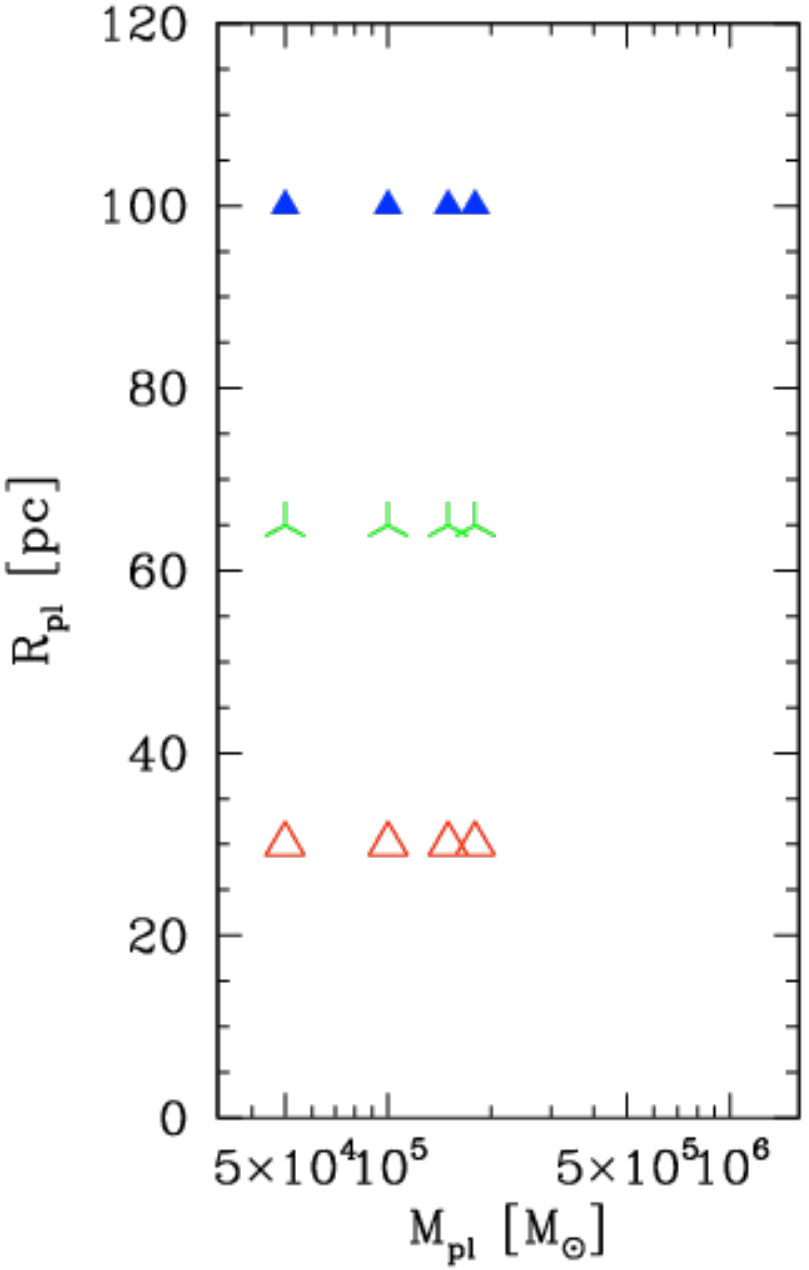

10^6
5×10^5
10^5
5×10^4
10^4
5000
1000
M_{fin} [$M_\odot$]
5×10^4
10^5
5×10^5
10^6
M_{pl} [$M_\odot$]

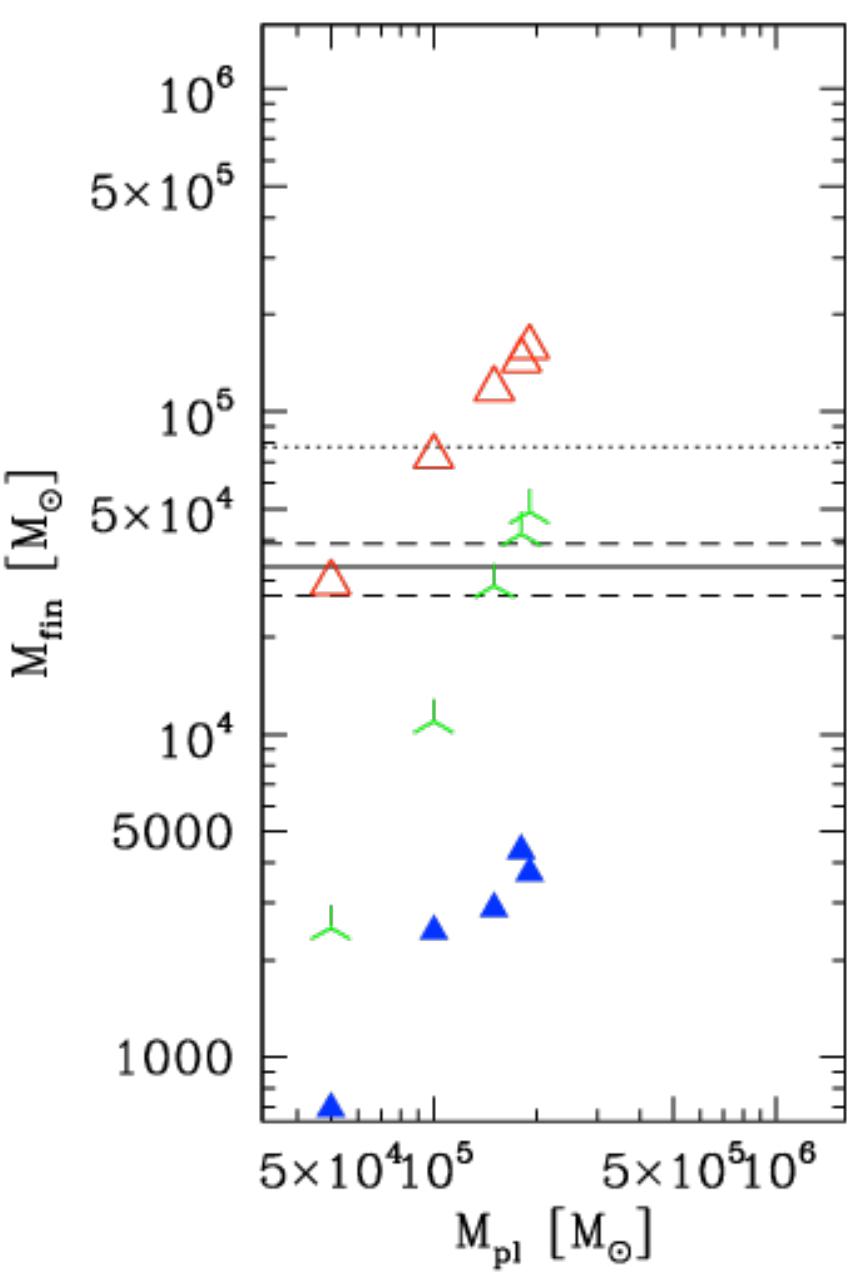

120
100
80
60
40
20
0
R_{pl} [pc]
5×10^4
10^5
5×10^5
10^6
M_{pl} [$M_\odot$]

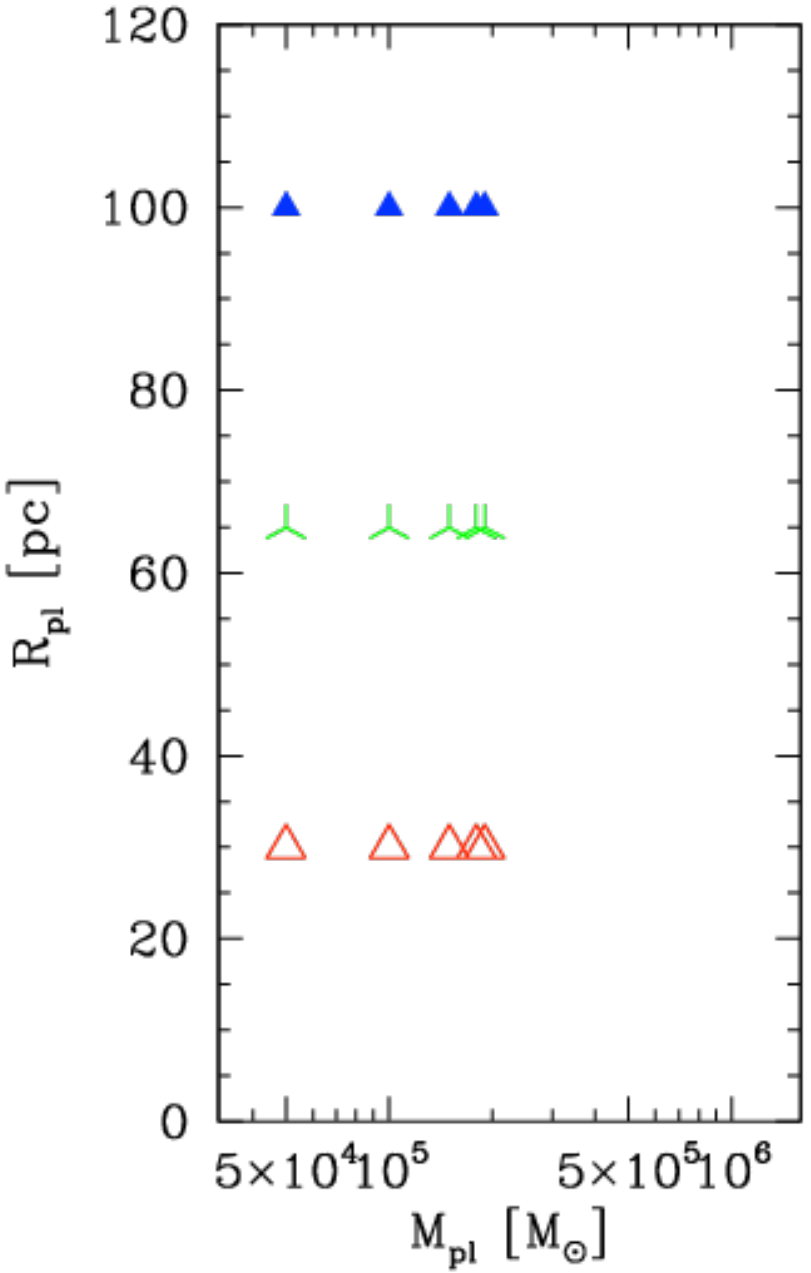

10^6
5×10^5
10^5
5×10^4
10^4
5000
1000
M_{fin} [$M_\odot$]
5×10^4
10^5
5×10^5
10^6
M_{pl} [$M_\odot$]

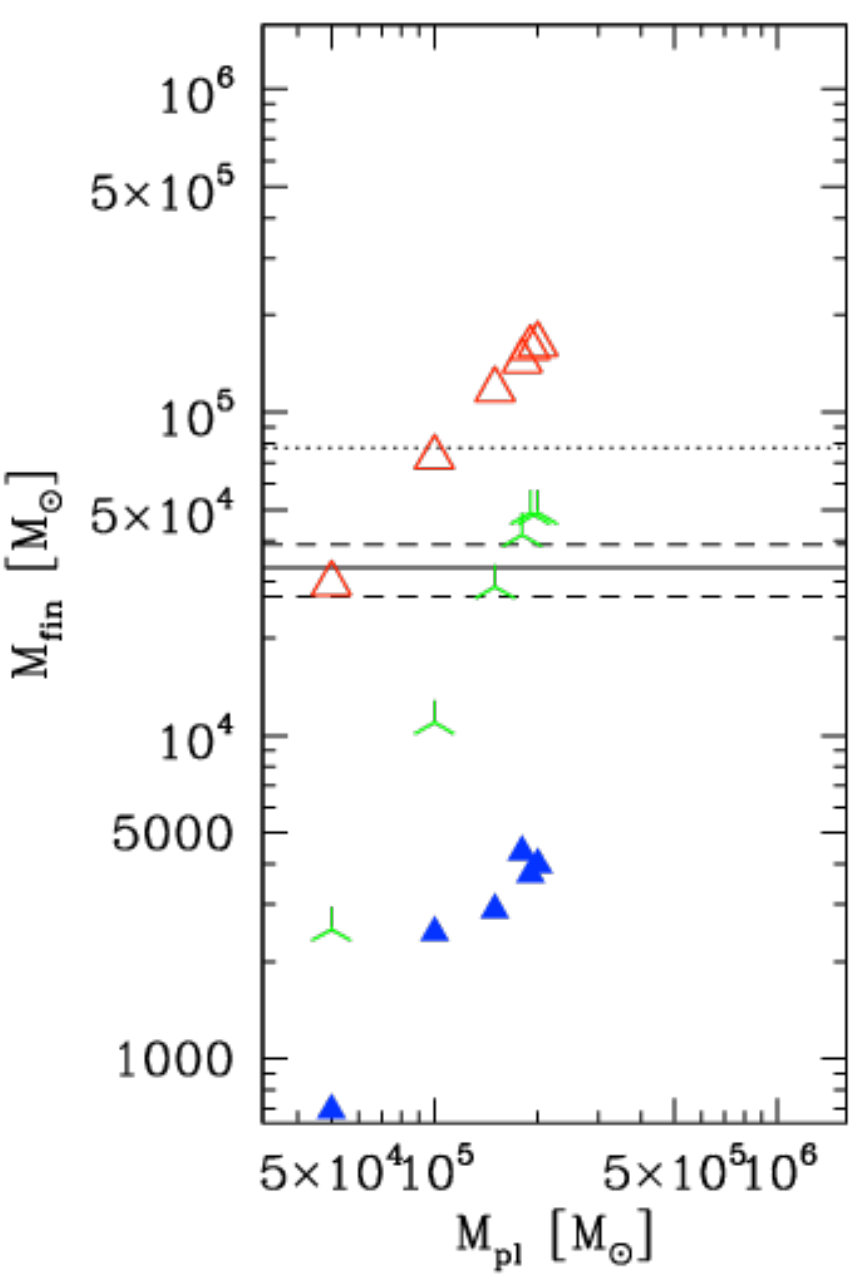

120
100
80
60
40
20
0
R_{pl} [pc]
5×10^4
10^5
5×10^5
10^6
M_{pl} [$M_\odot$]

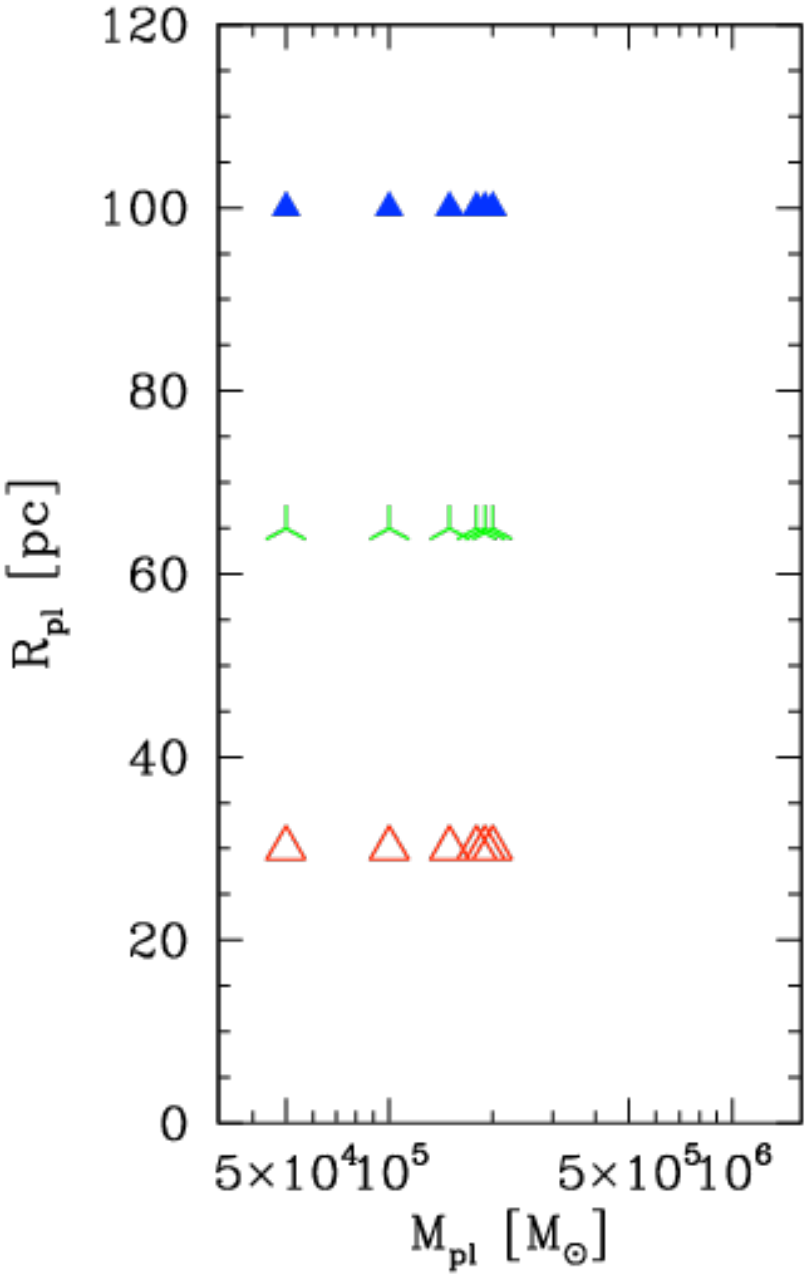

10^6
5×10^5
10^5
5×10^4
10^4
5000
1000
M_{fin} [$M_\odot$]
5×10^4
10^5
5×10^5
10^6
M_{pl} [$M_\odot$]

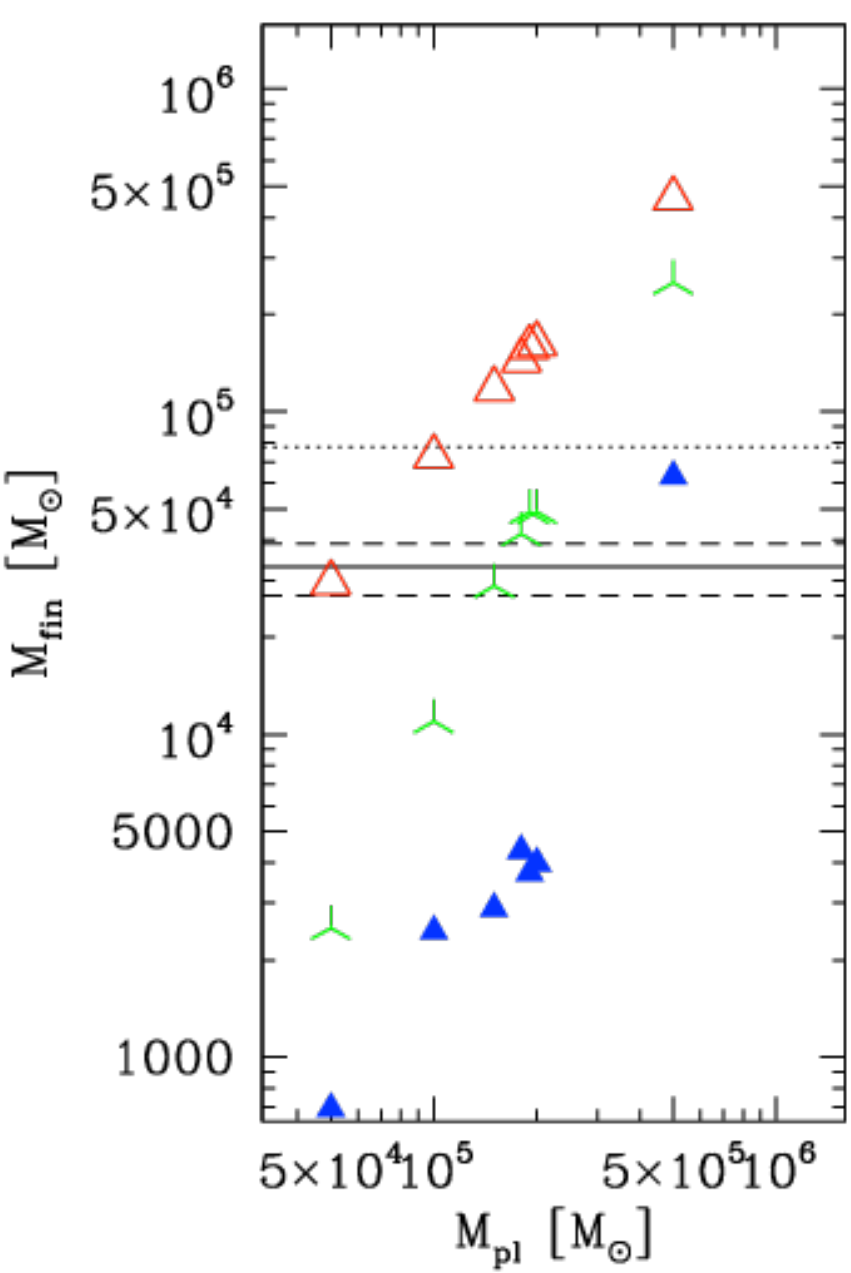

120
100
80
60
40
20
0
R_{pl} [pc]
5×10^4
10^5
5×10^5
10^6
M_{pl} [$M_\odot$]

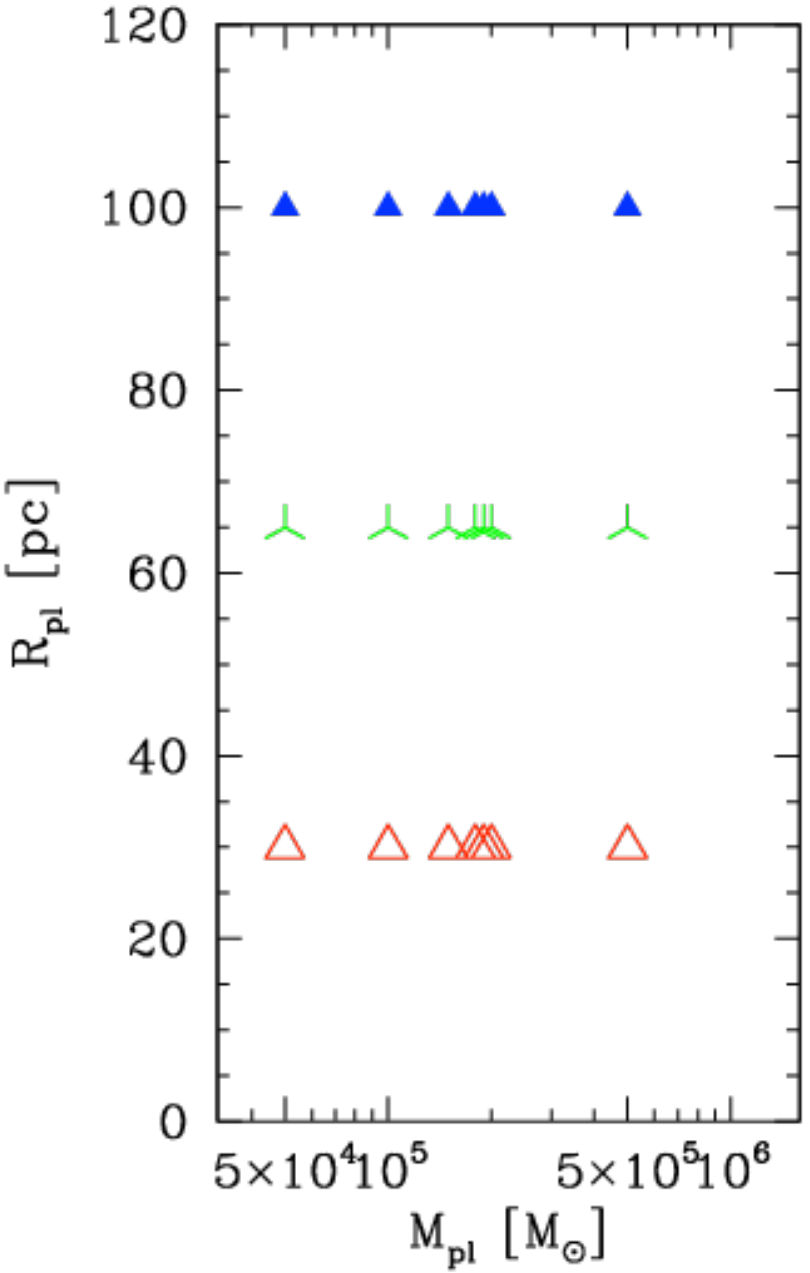

10^6
5×10^5
10^5
5×10^4
10^4
5000
1000
M_{fin} [$M_\odot$]
5×10^4
10^5
5×10^5
10^6
M_{pl} [$M_\odot$]

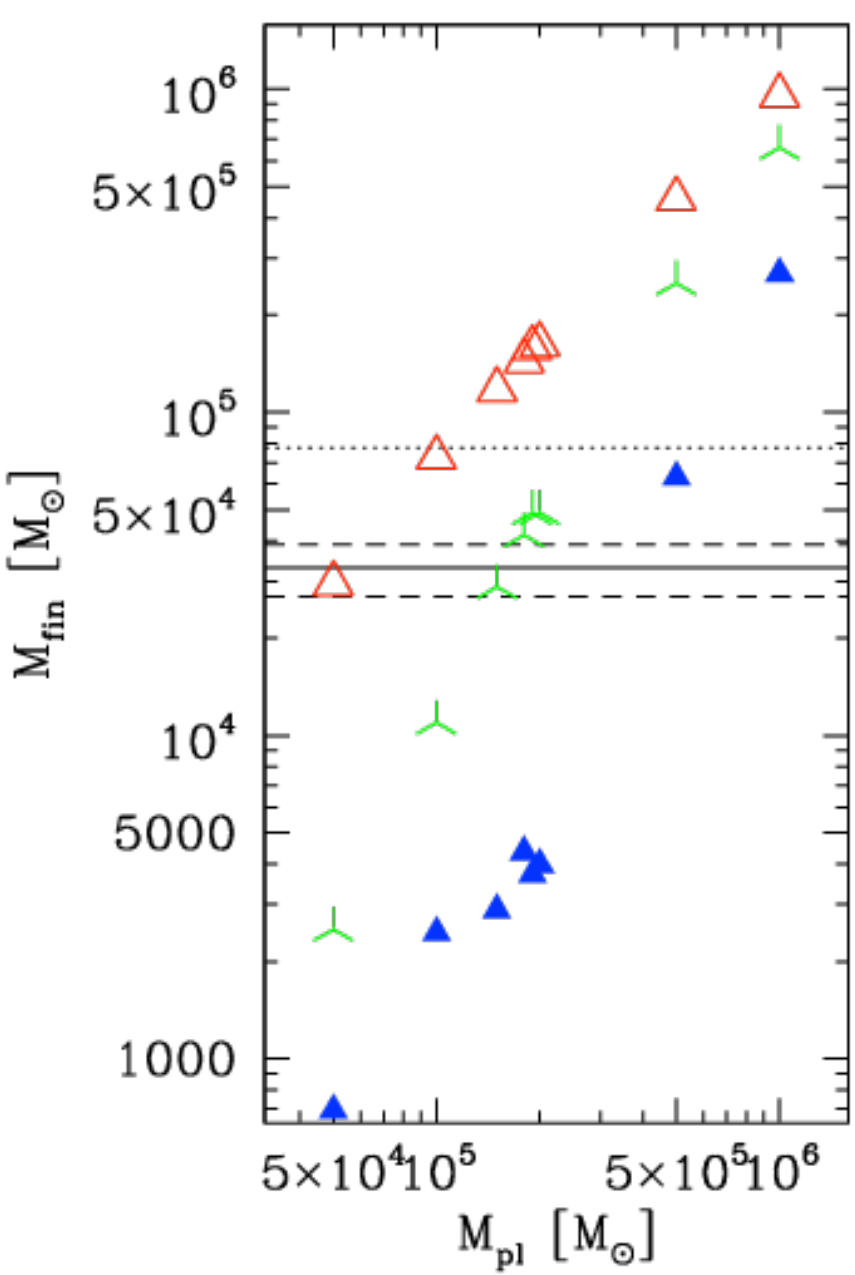

120
100
80
60
40
20
0
R_{pl} [pc]
5×10^4
10^5
5×10^5
10^6
M_{pl} [$M_\odot$]

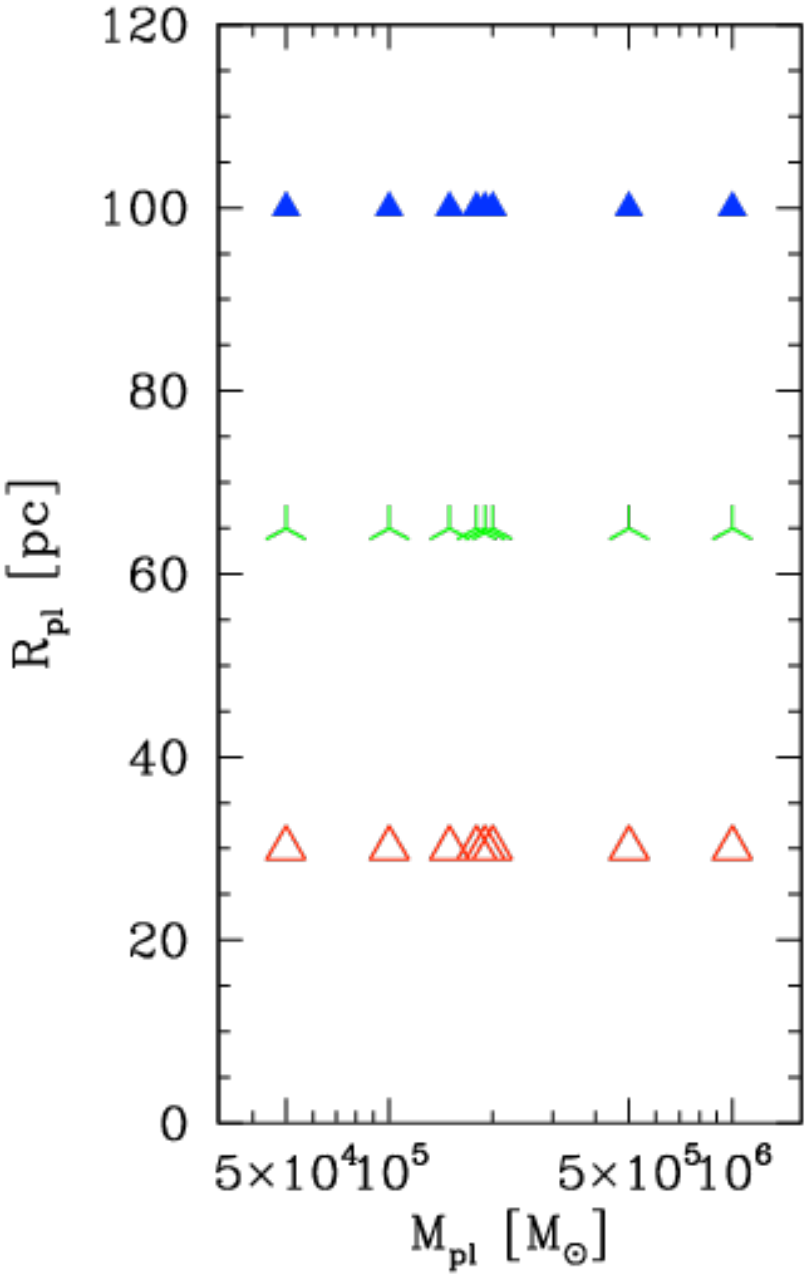

10^6
5×10^5
10^5
5×10^4
10^4
5000
1000
M_{fin} [$M_\odot$]
5×10^4
10^5
5×10^5
10^6
M_{pl} [$M_\odot$]

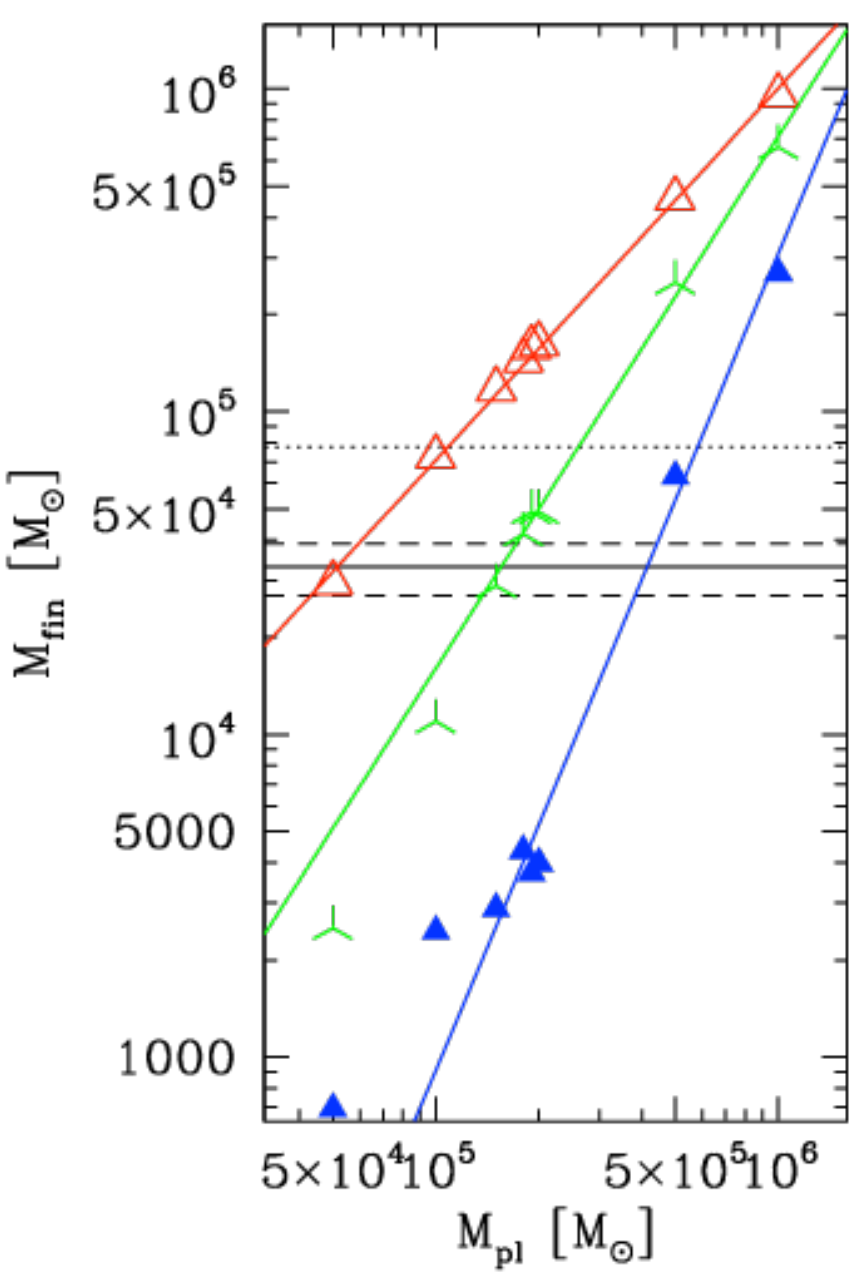

120
100
80
60
40
20
0
R_{pl} [pc]
5×10^4
10^5
5×10^5
10^6
M_{pl} [$M_\odot$]

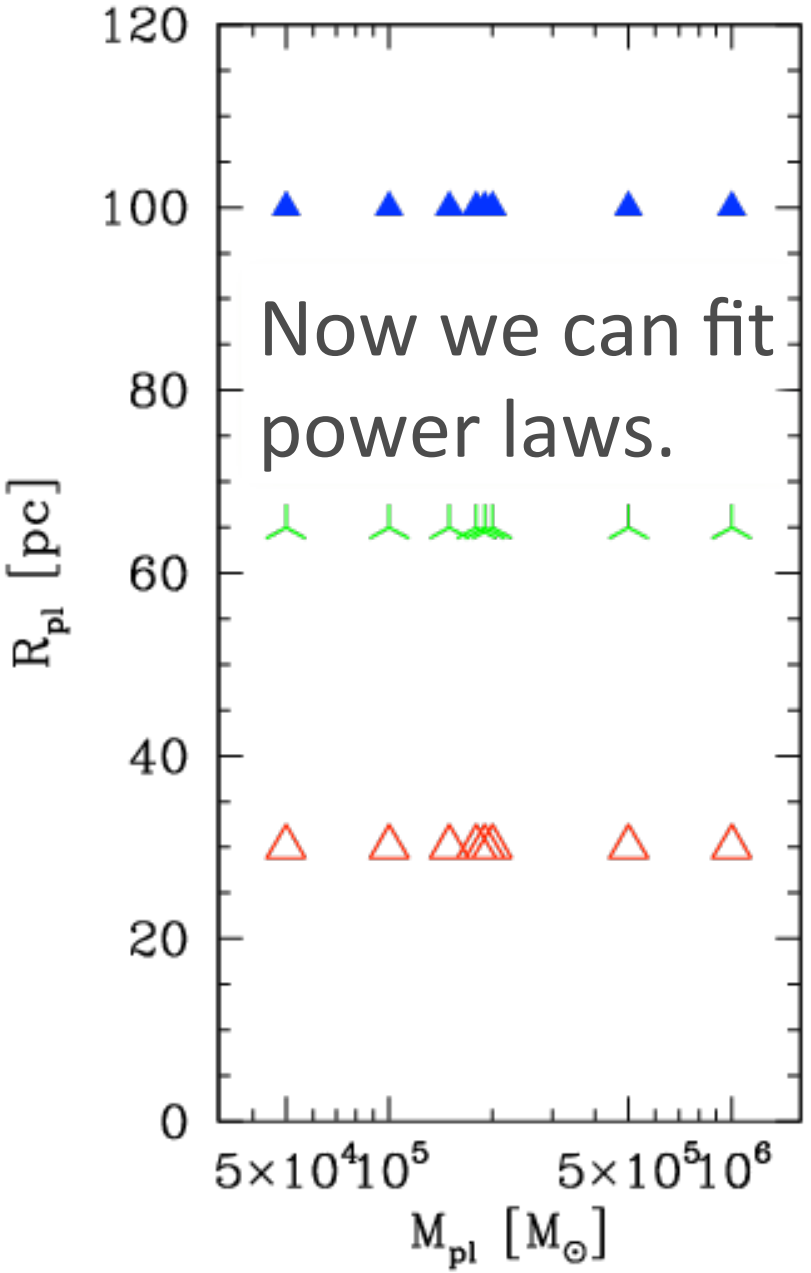

10^6
5×10^5
10^5
5×10^4
10^4
5000
1000
M_{fin} [$M_\odot$]
5×10^4
10^5
5×10^5
10^6
M_{pl} [$M_\odot$]


120
100
80
60
40
20
0
R_{pl} [pc]
5×10^4
10^5
5×10^5
10^6
M_{pl} [$M_\odot$]

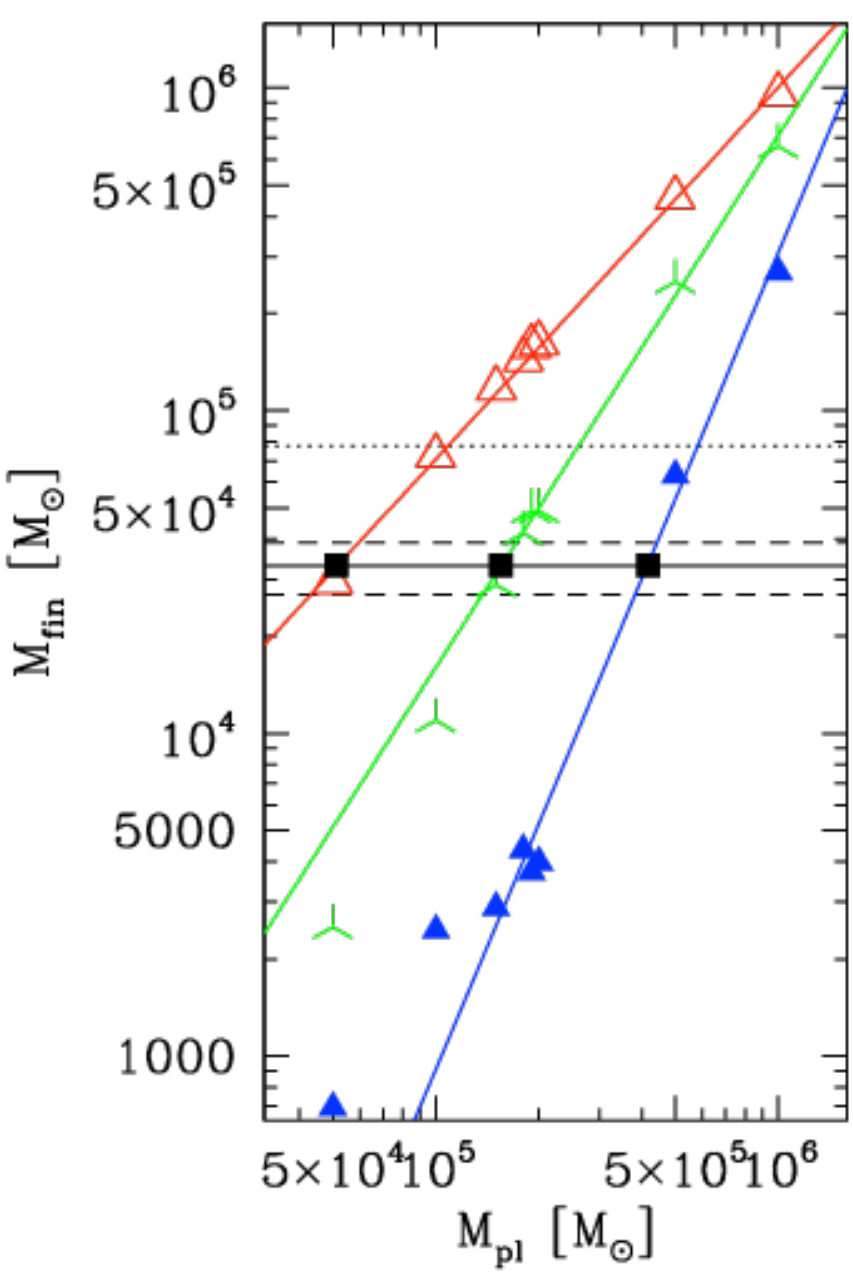

10^6
5×10^5
10^5
5×10^4
10^4
5000
1000
M_{fin} [$M_\odot$]
5×10^4
10^5
5×10^5
10^6
M_{pl} [$M_\odot$]

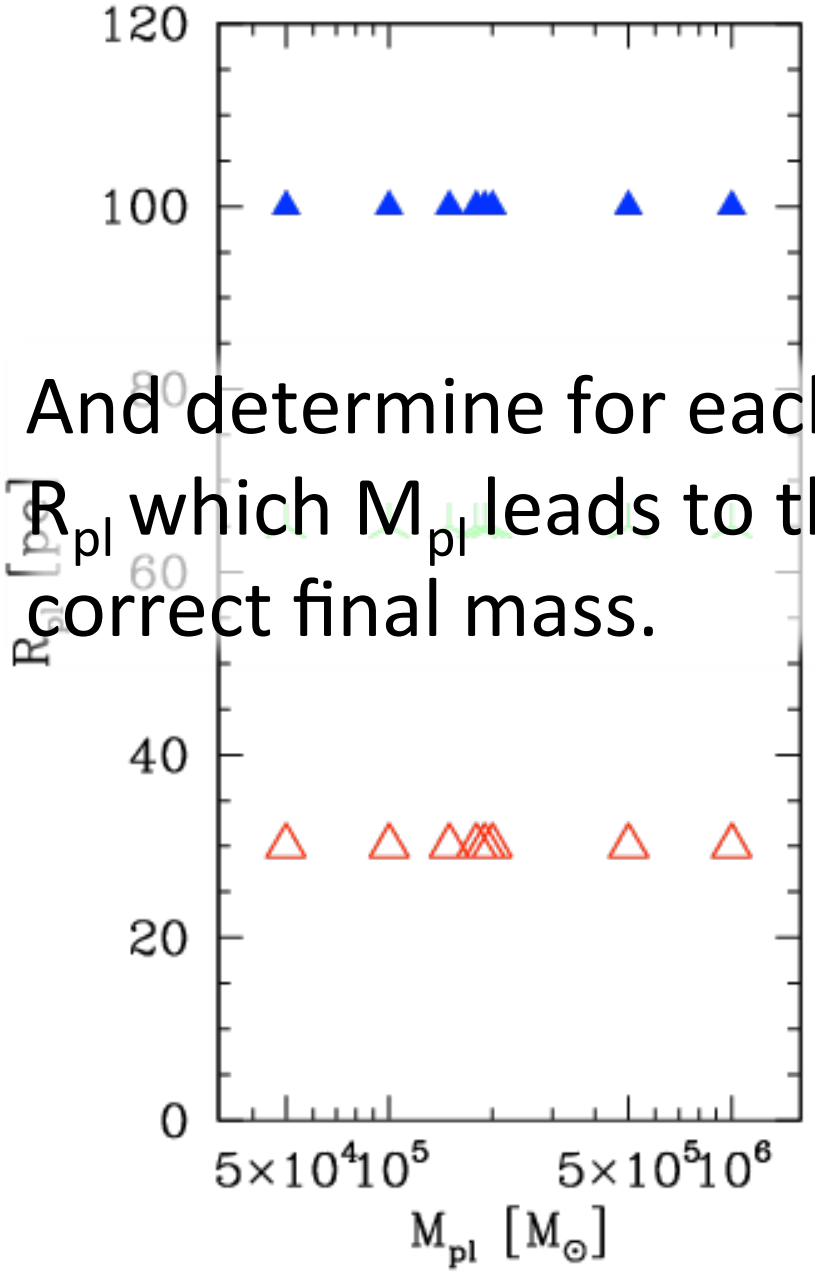

120
100
80
60
40
20
0
R_{pl} [pc]
5×10^4
10^5
5×10^5
10^6
M_{pl} [$M_\odot$]





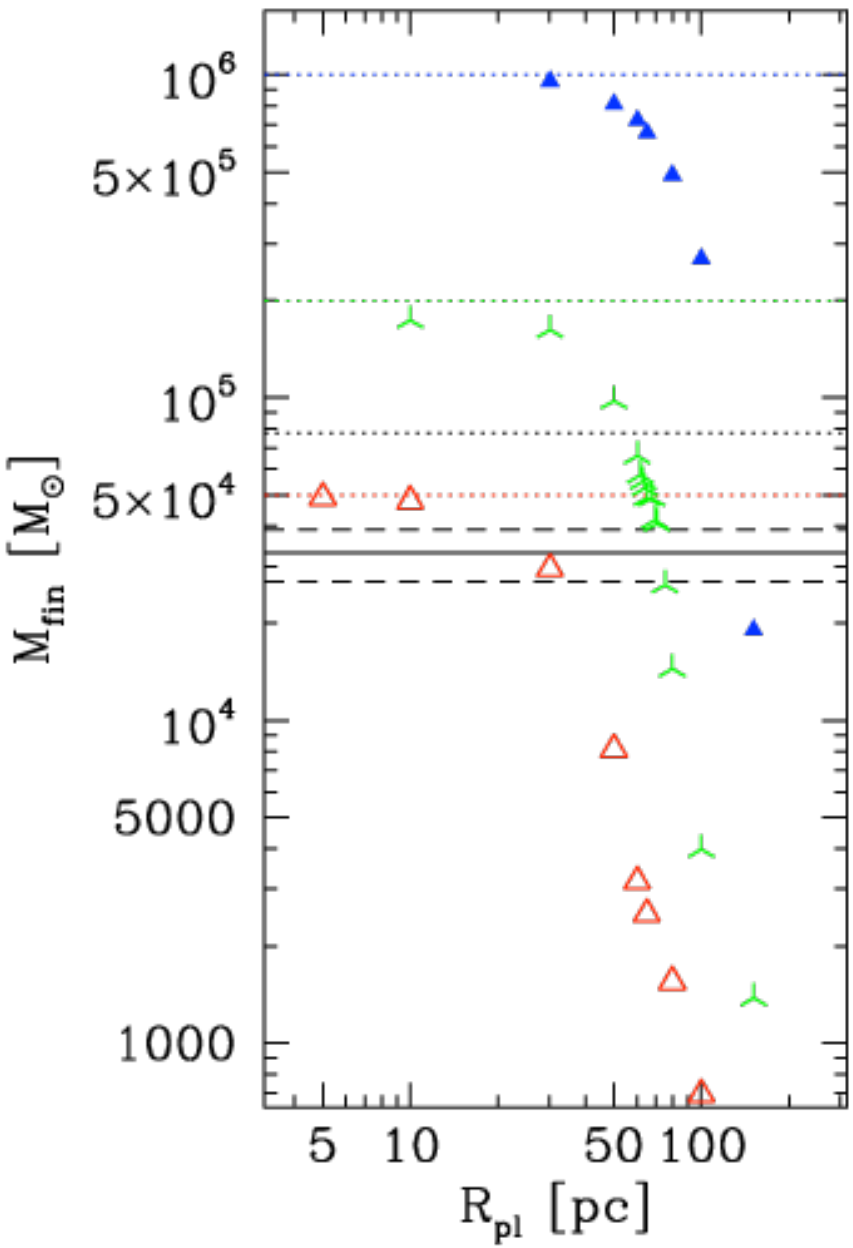
Now we can fit power laws.

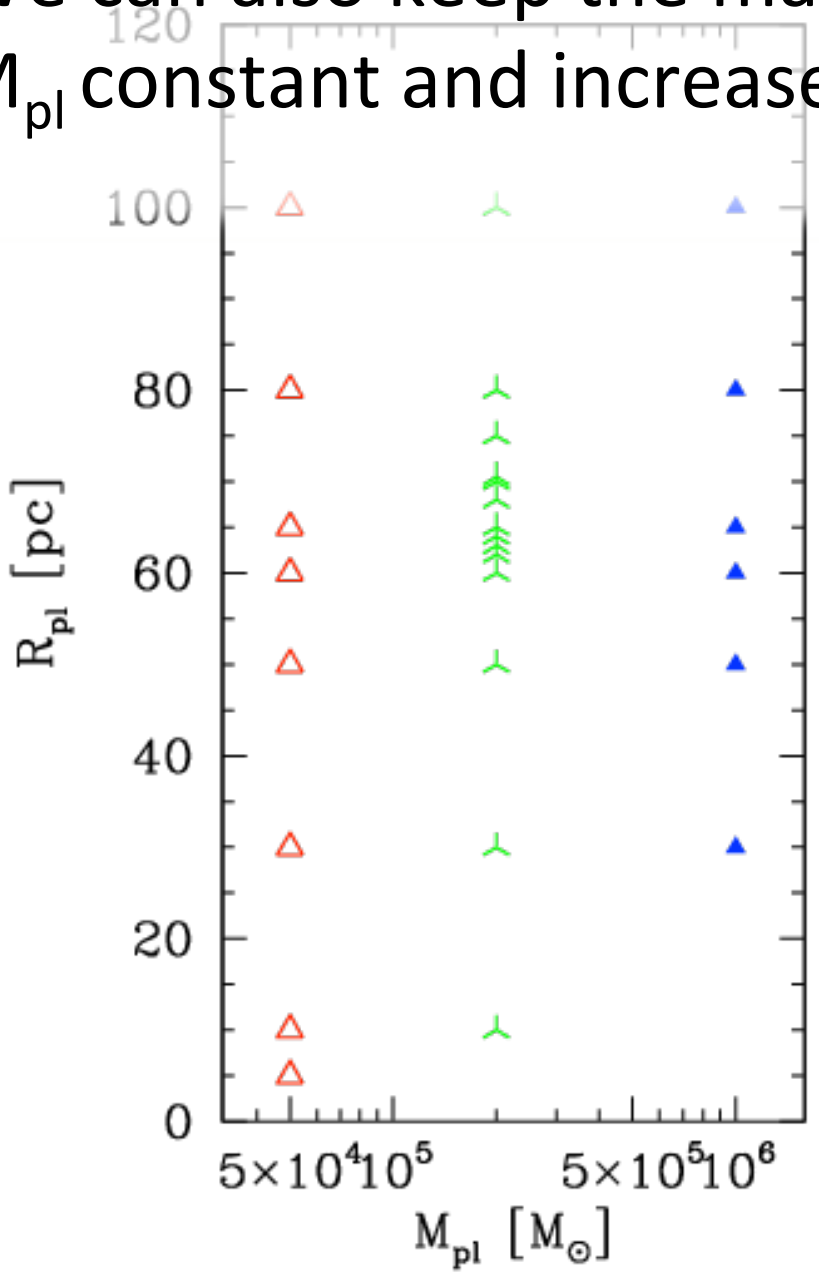


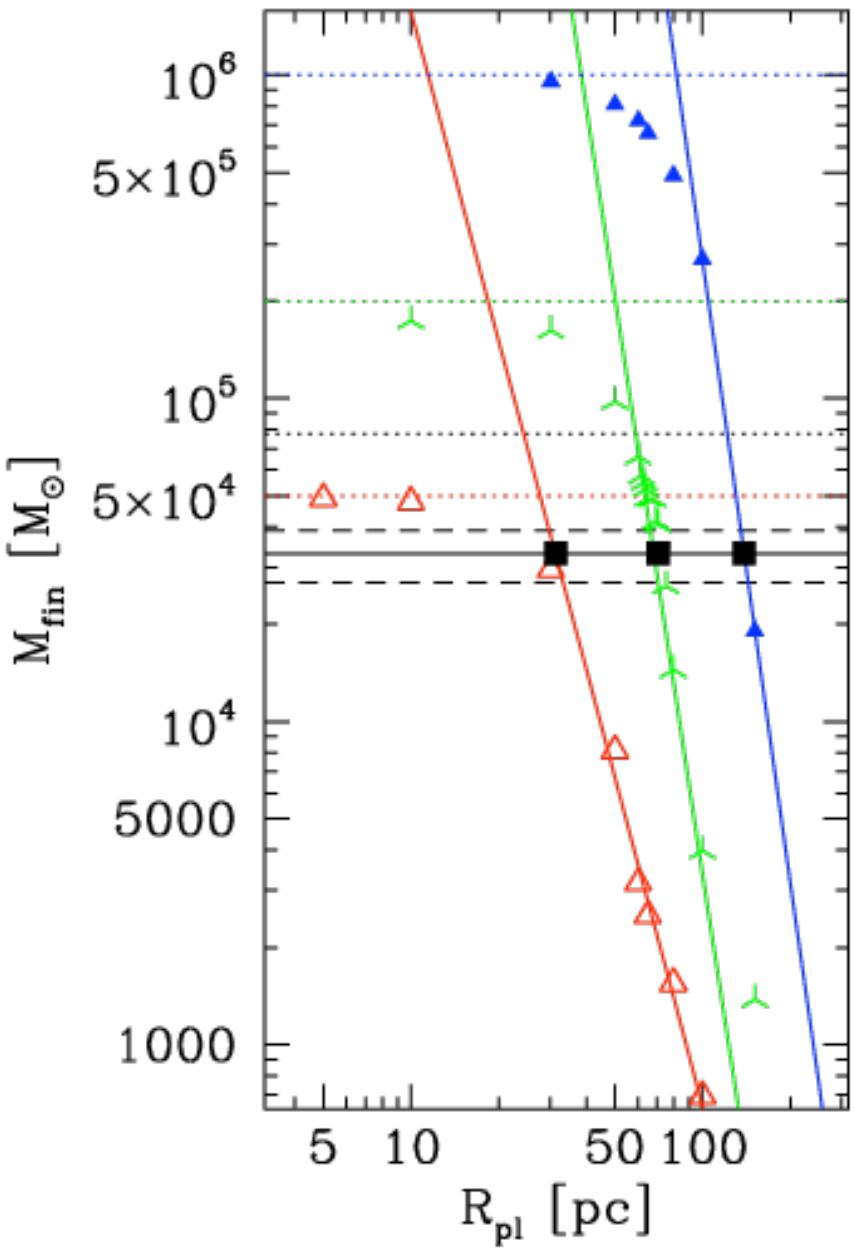


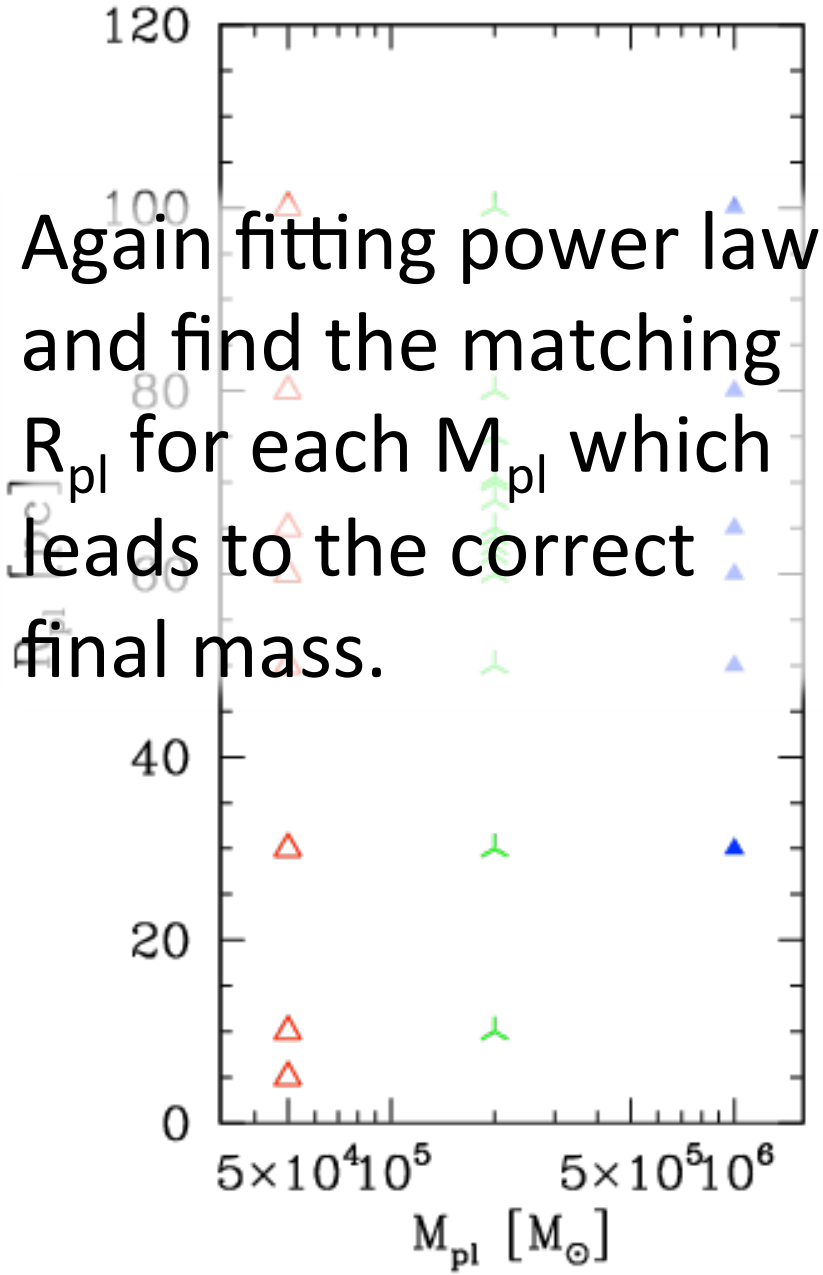
And determine for each R_{pl} which M_{pl} leads to the correct final mass.

We can also keep the mass M_{pl} constant and increase R_{pl}



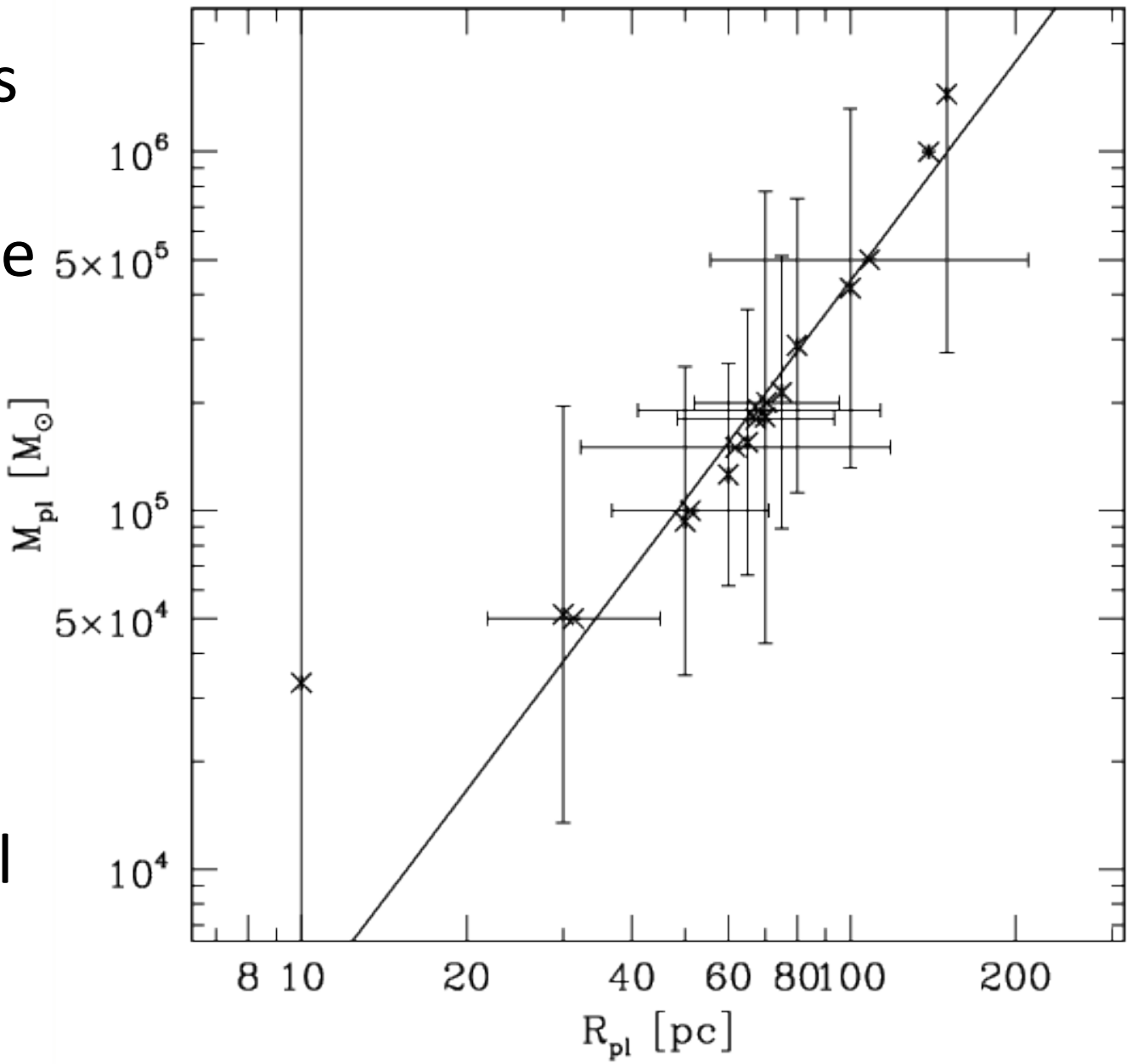




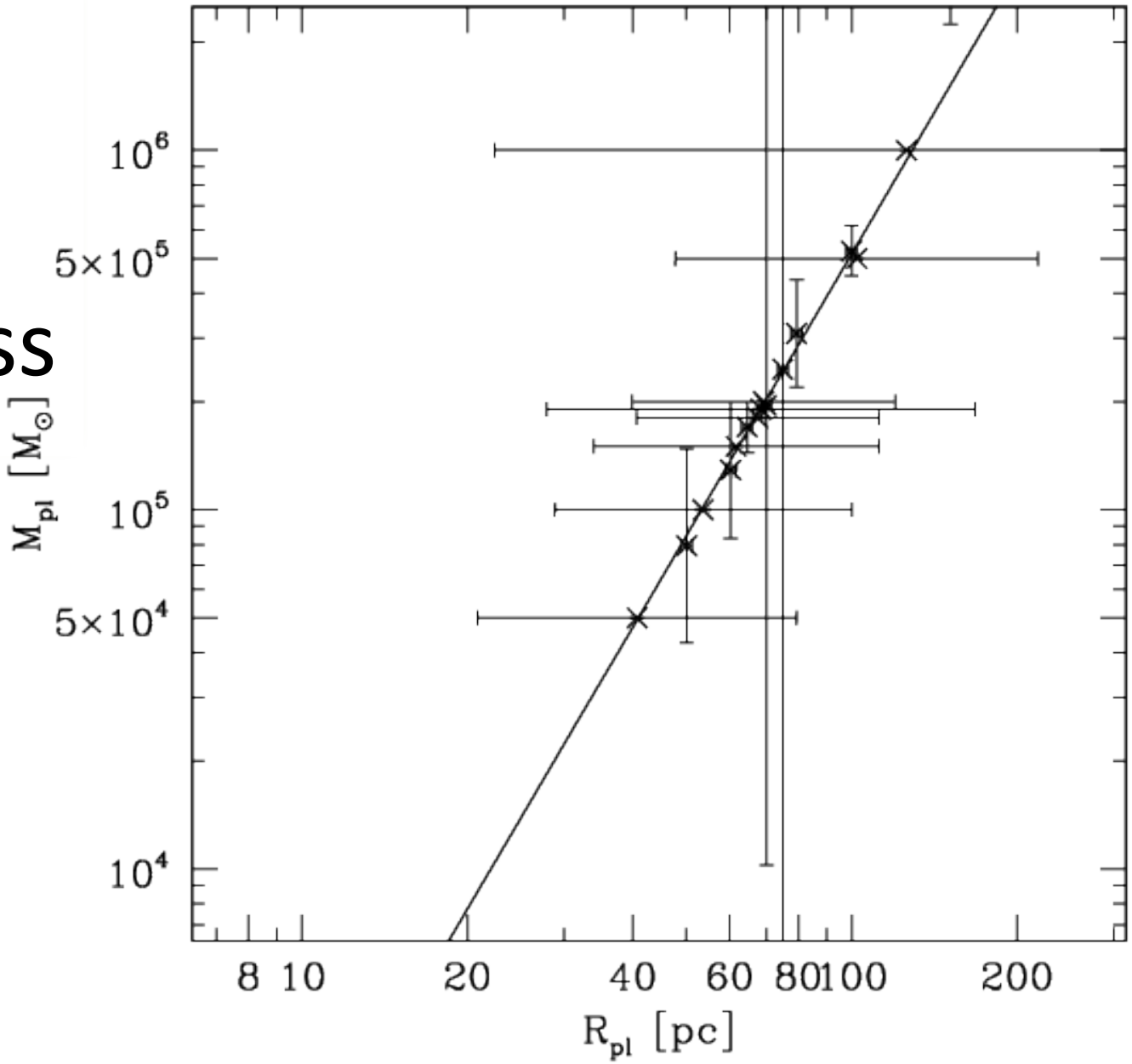


Again fitting power laws and find the matching R_{pl} for each M_{pl} which leads to the correct final mass.

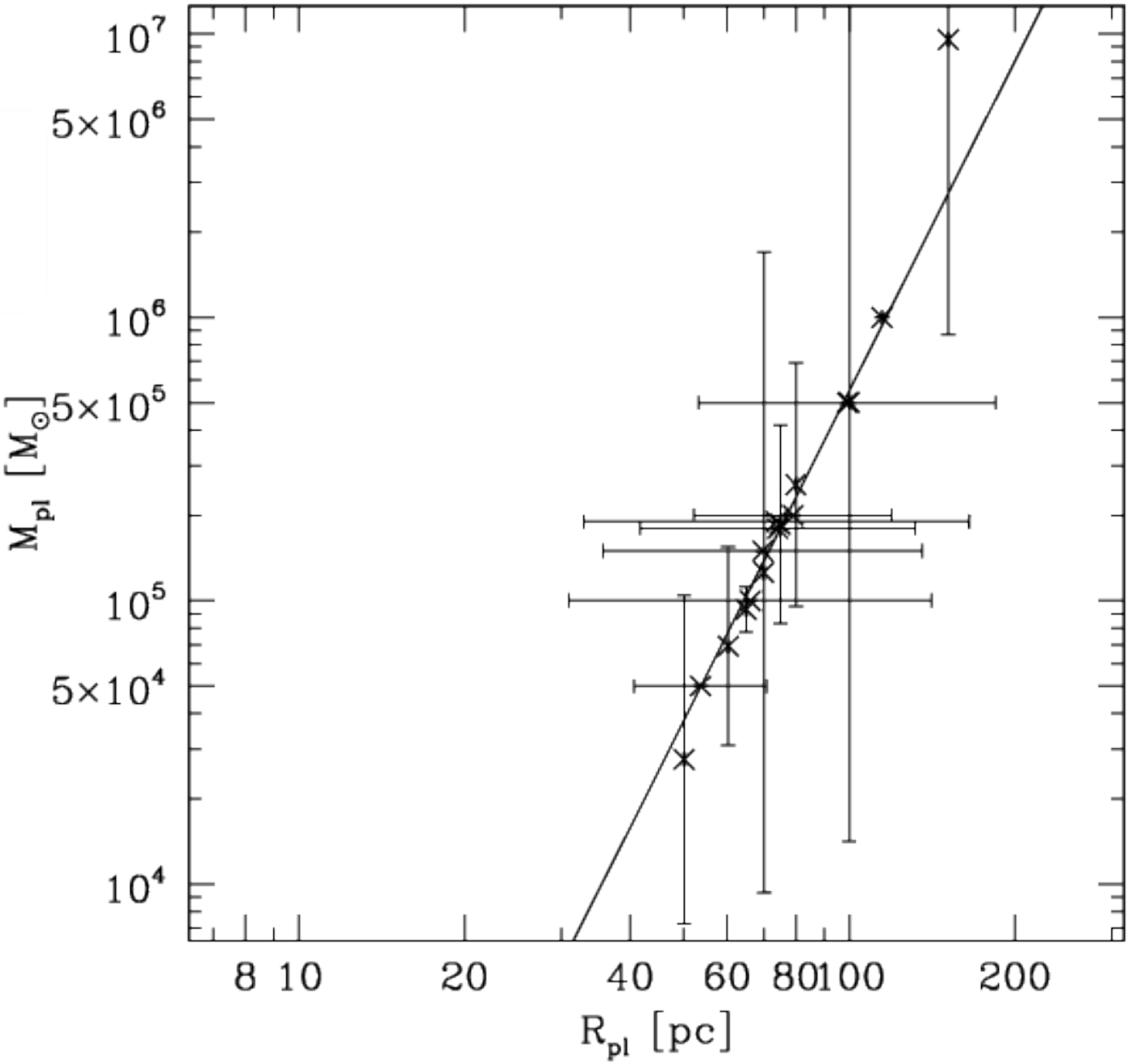
Plotting all matching points in the initial parameter plane we can fit a power law describing all pairs of initial conditions which lead to the correct final mass.



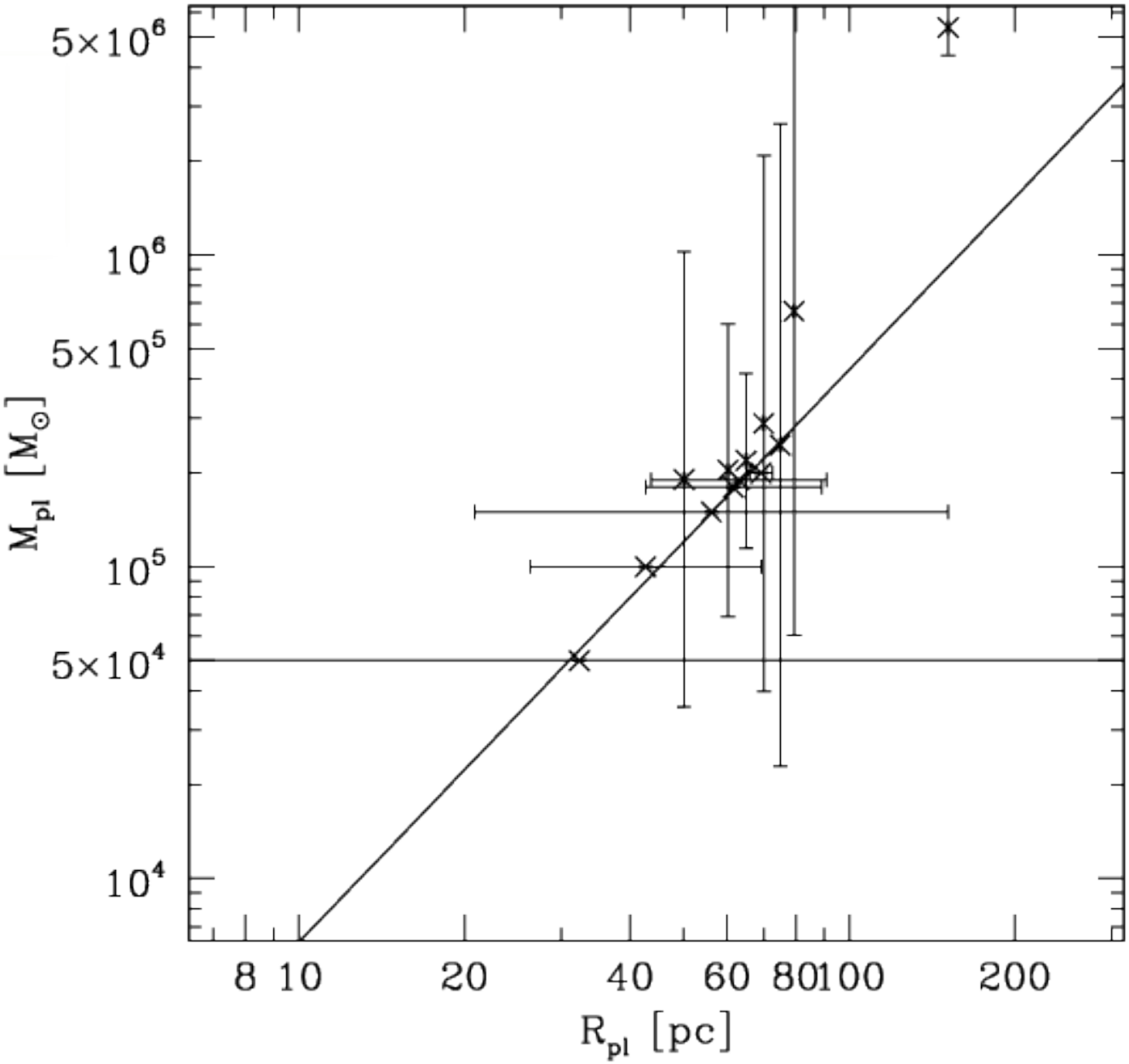
Central Surface Brightness



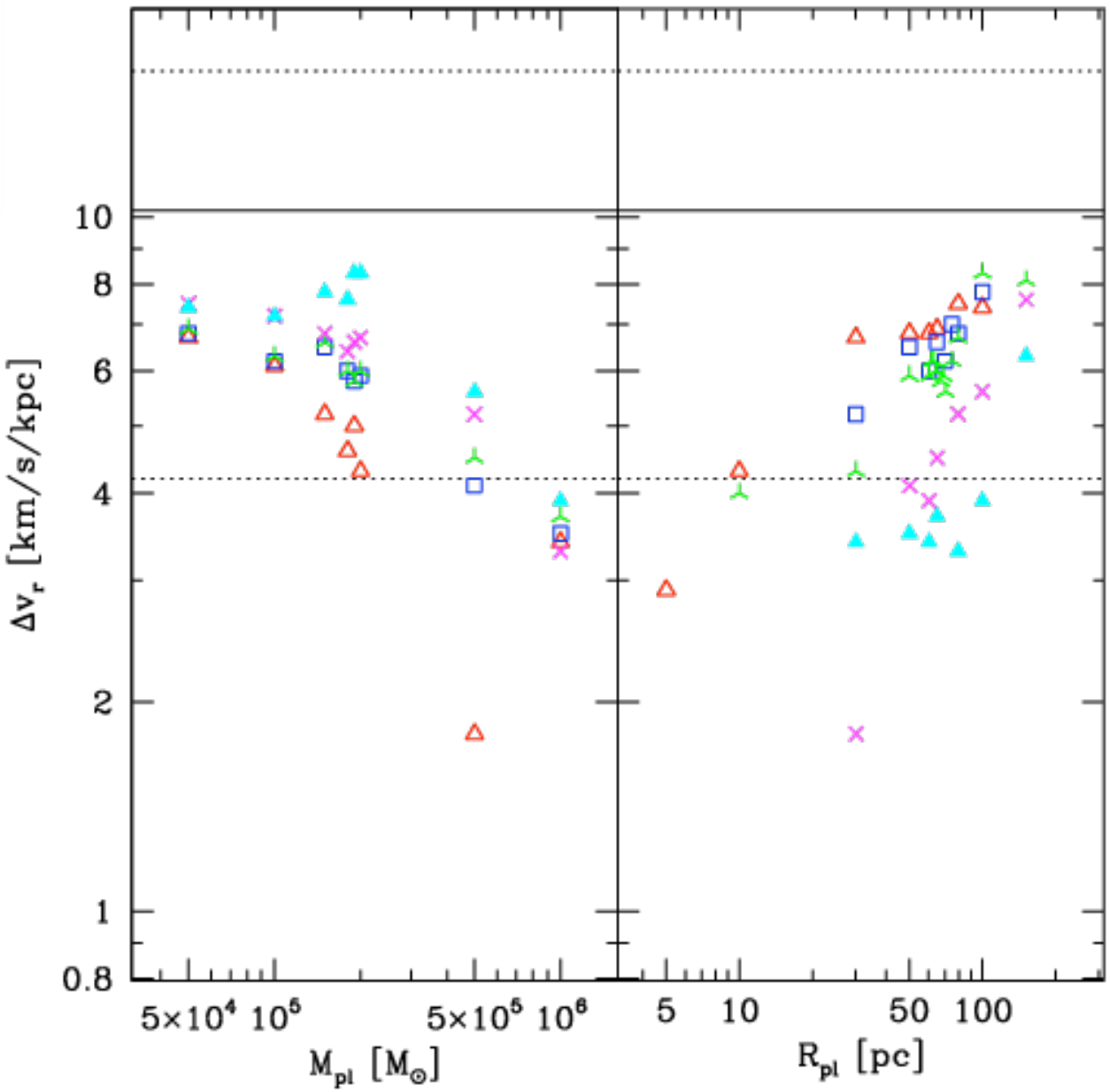
Velocity Dispersion



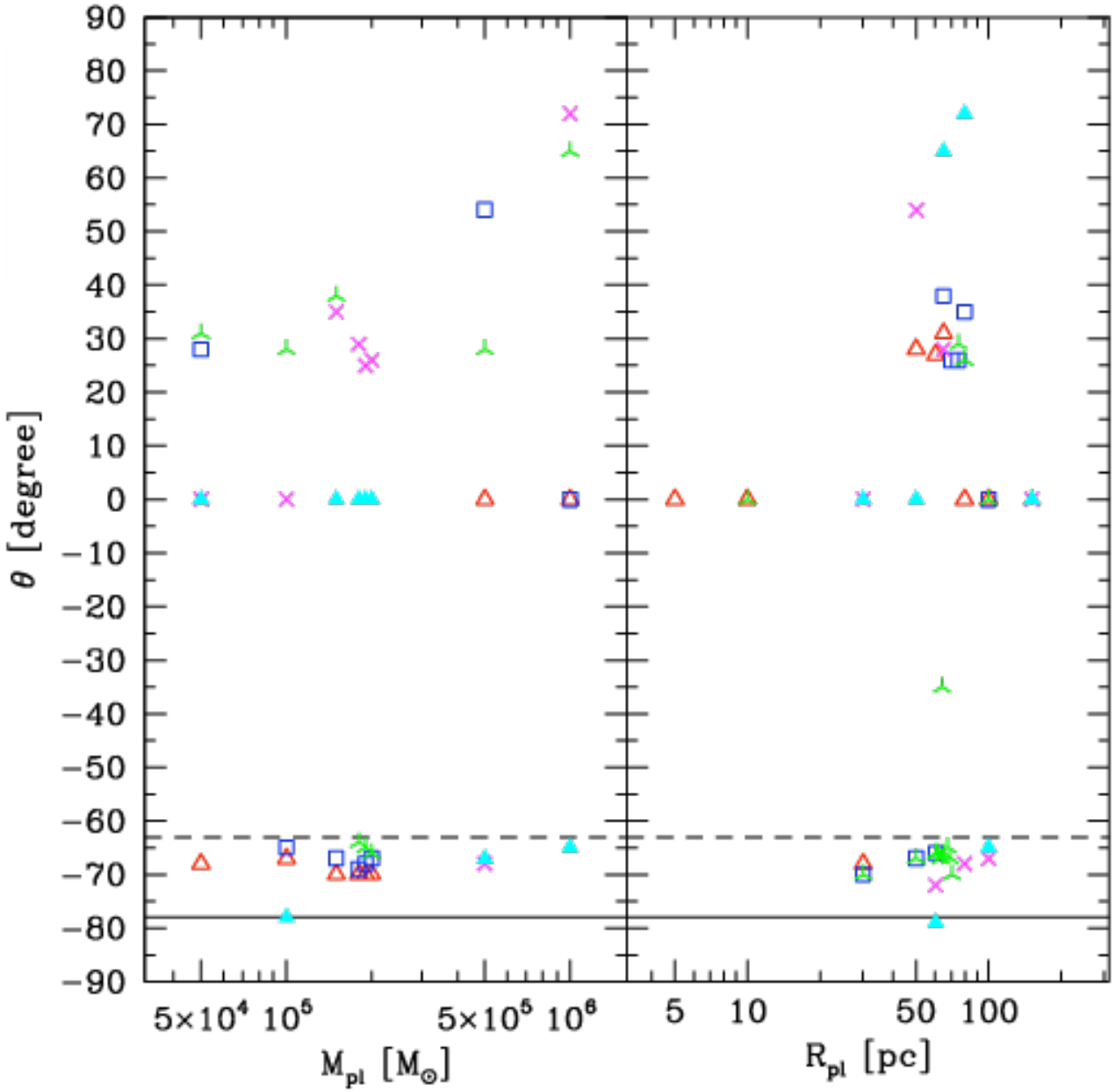
Effective Radius



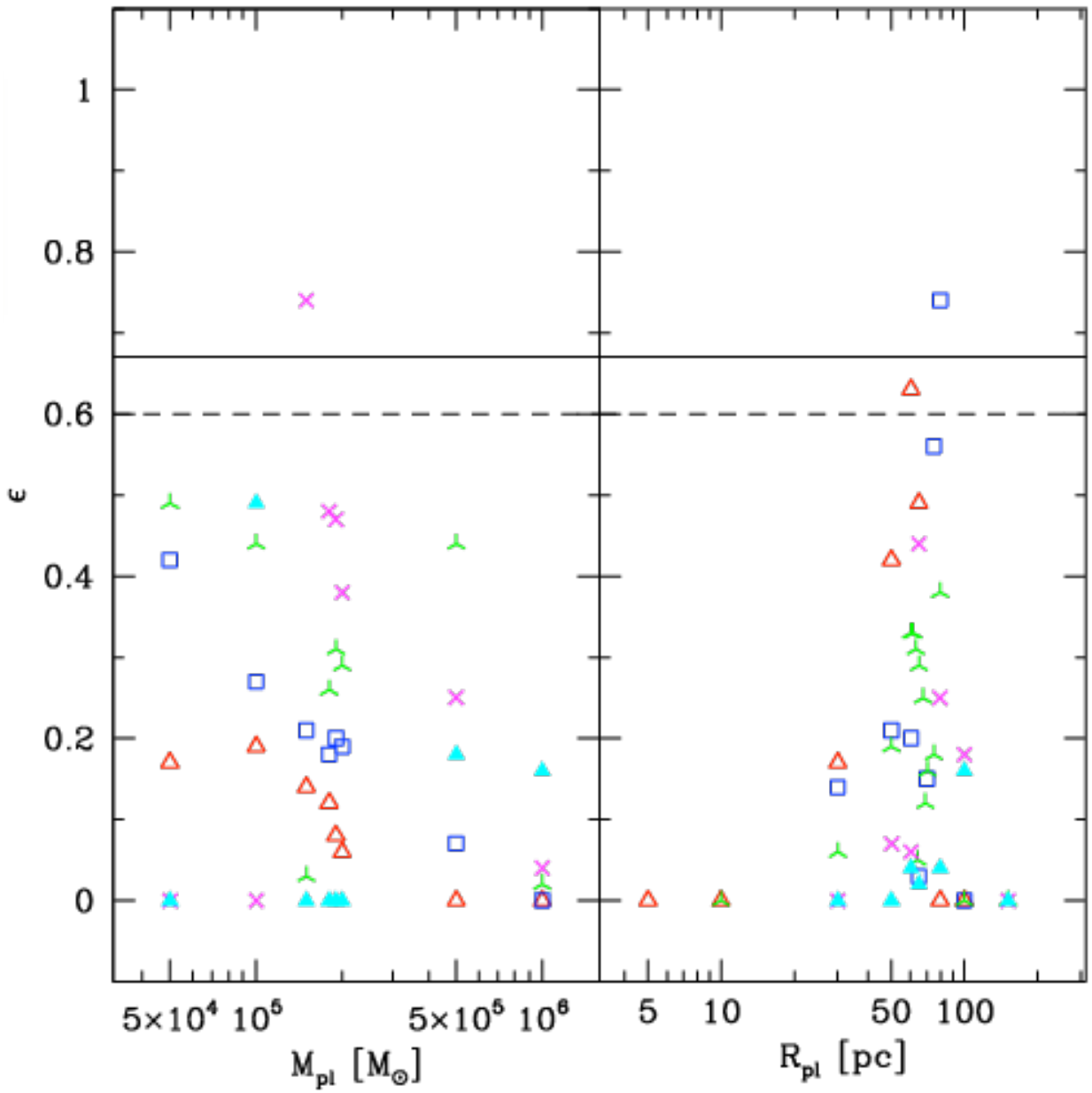
Velocity Gradient



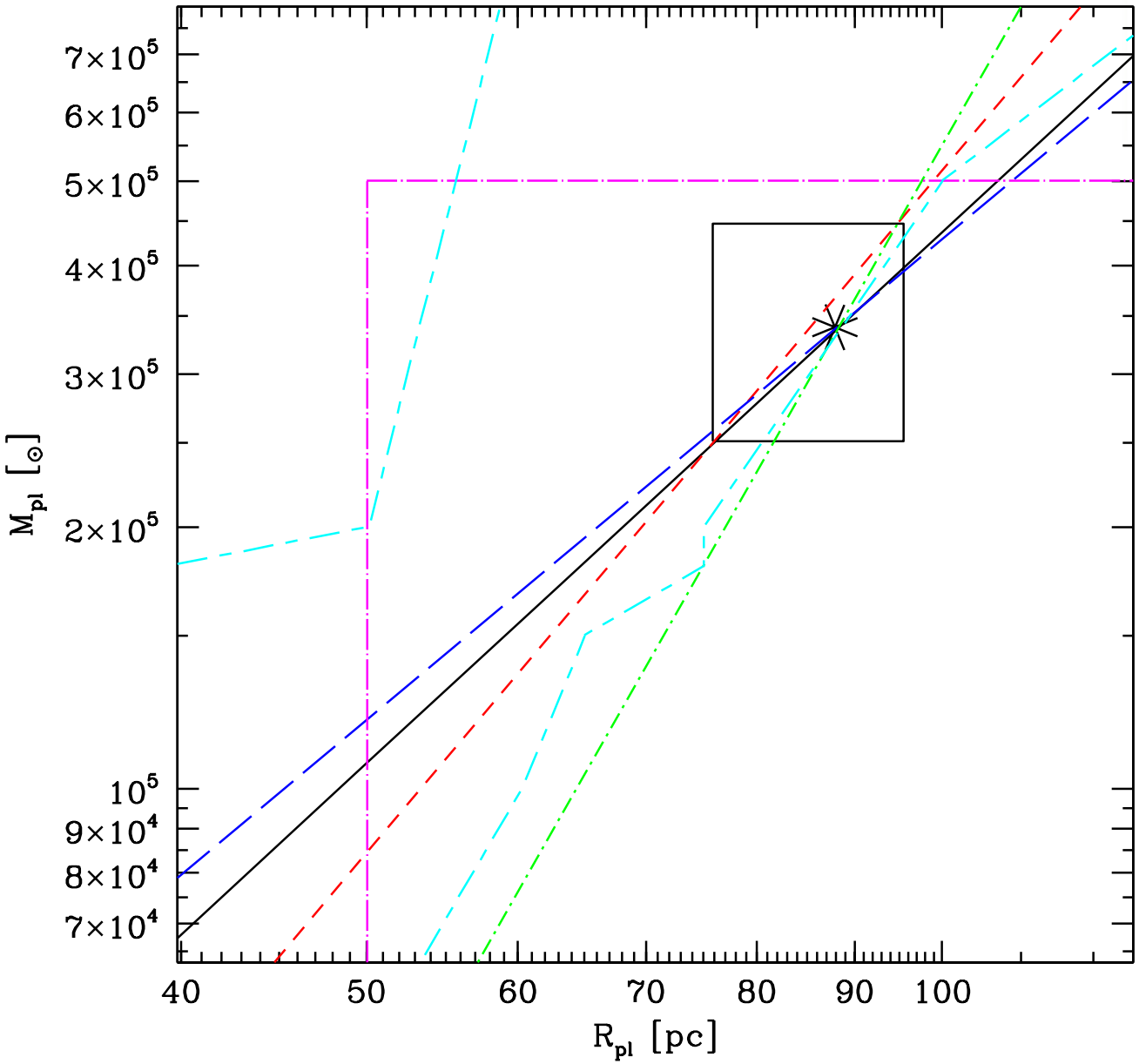
Position Angle



Elongation



Best fit model



Excluding the elongation which we cannot match:

R_{pl} = 76 – 96 pc

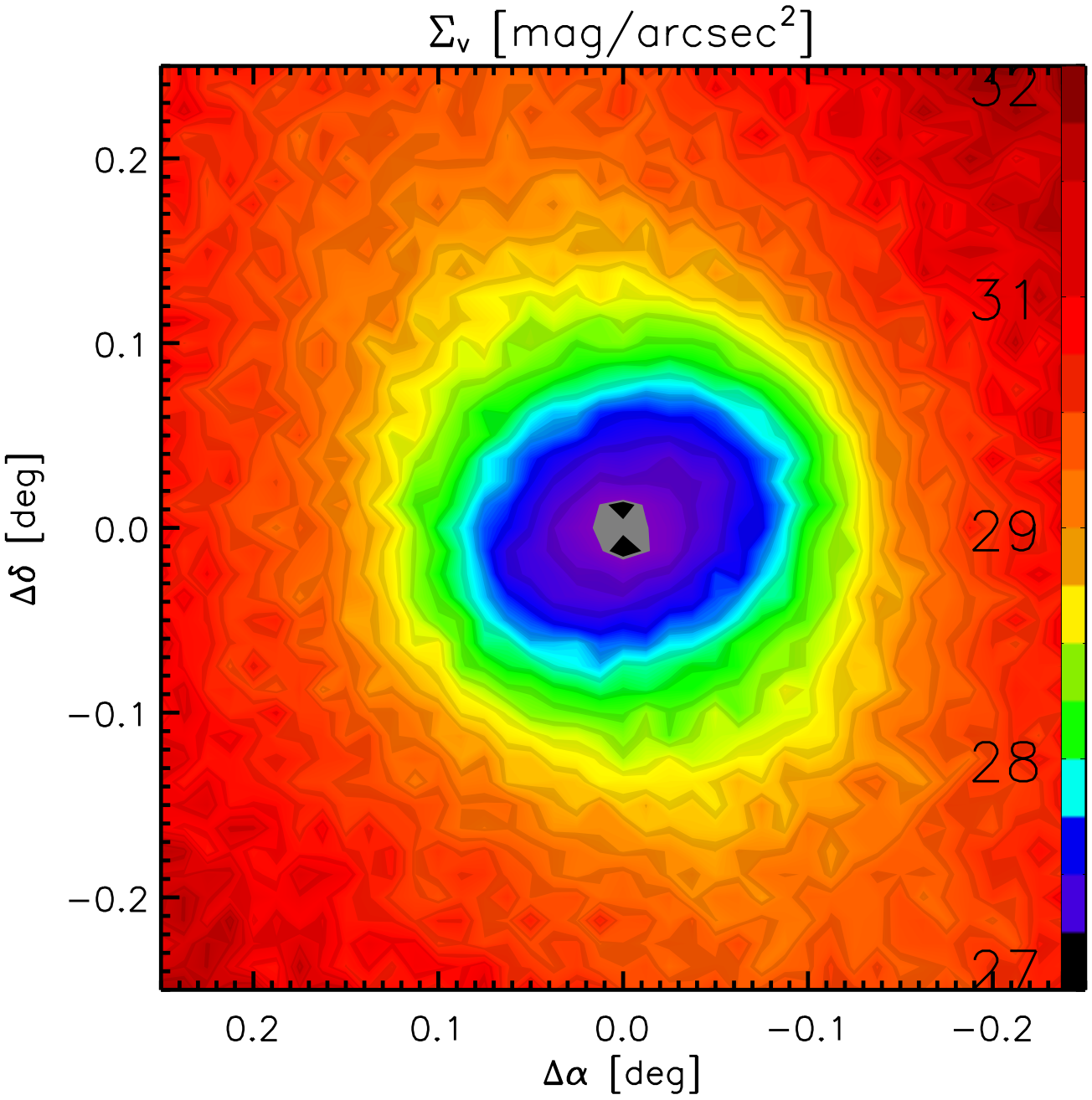
M_{pl} = 2.5 – 4.4 x 10^5 M_{sun}

Best match at:

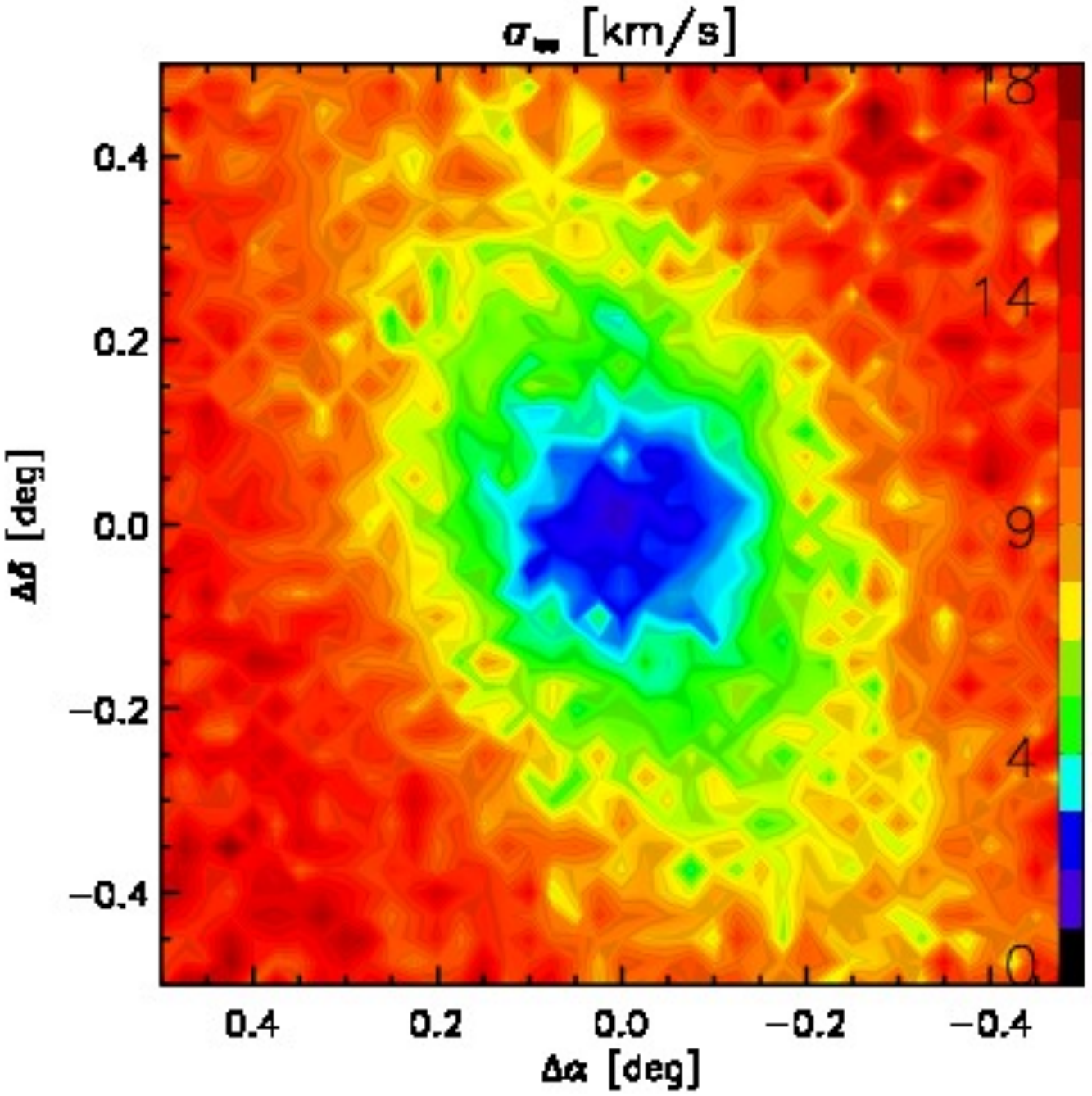
R_{pl} = 88 pc

M_{pl} = 3.4x10^5 M_{sun}

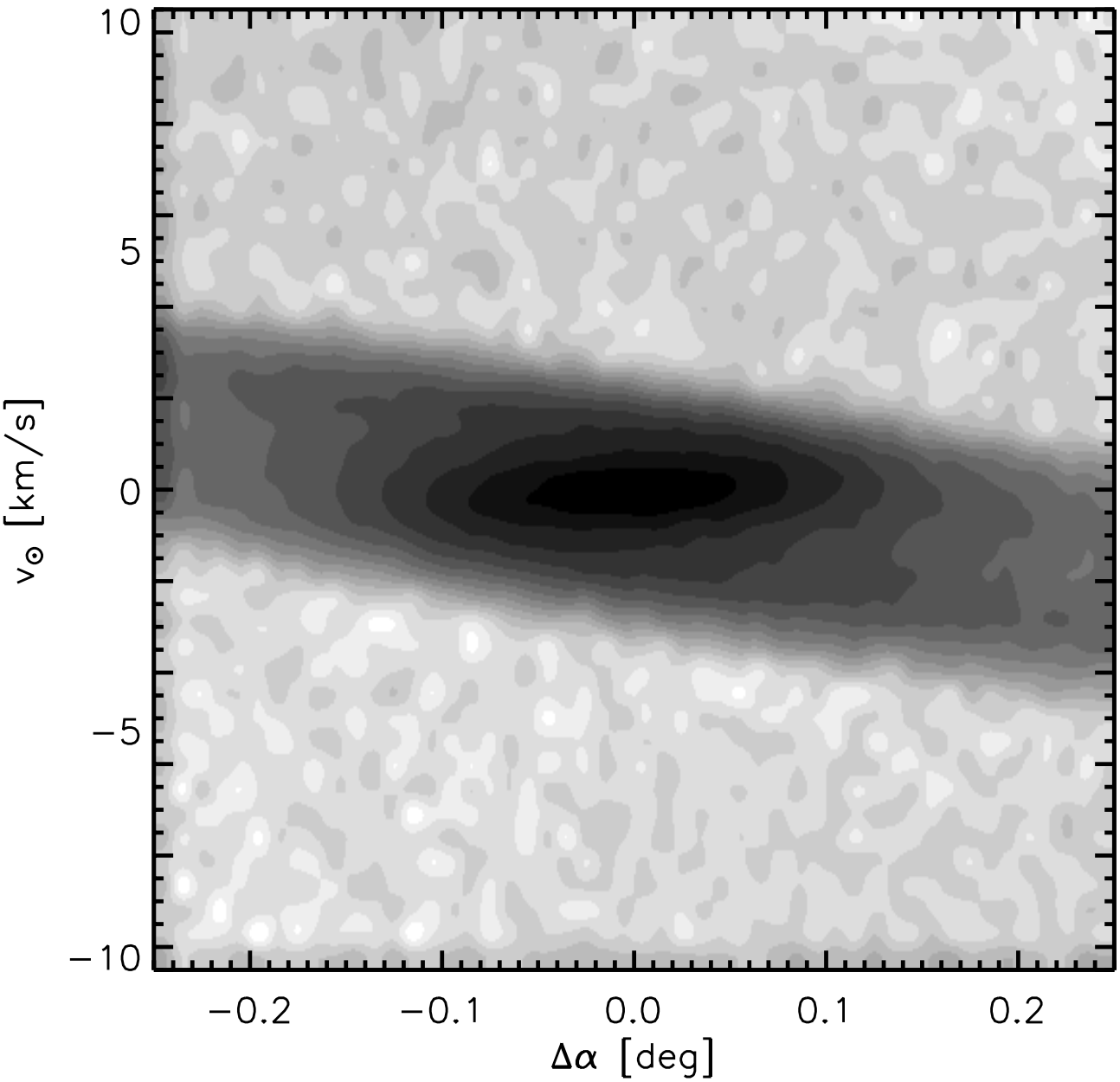
Surface Brightness Contours



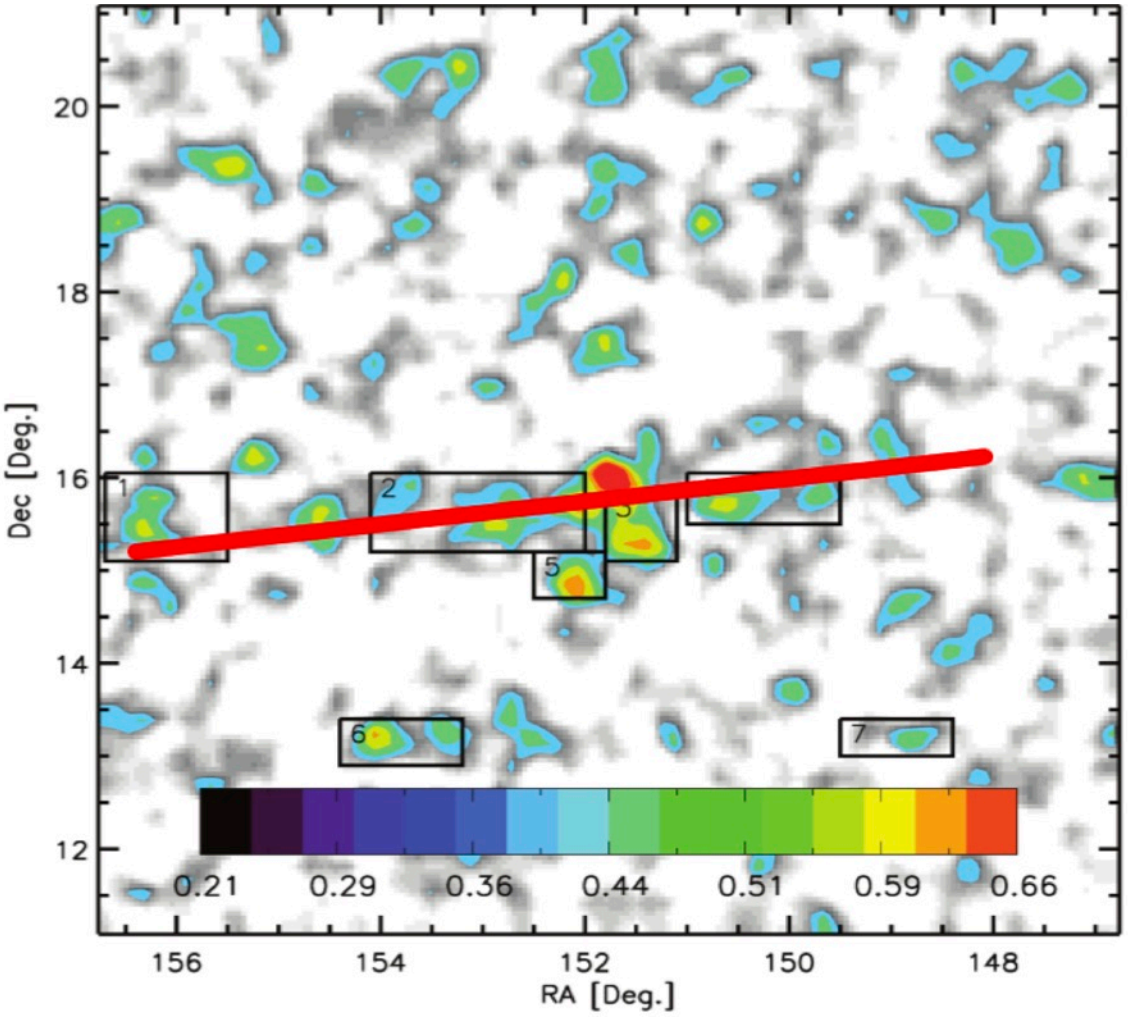
Velocity Dispersion Contours



Velocity Gradient

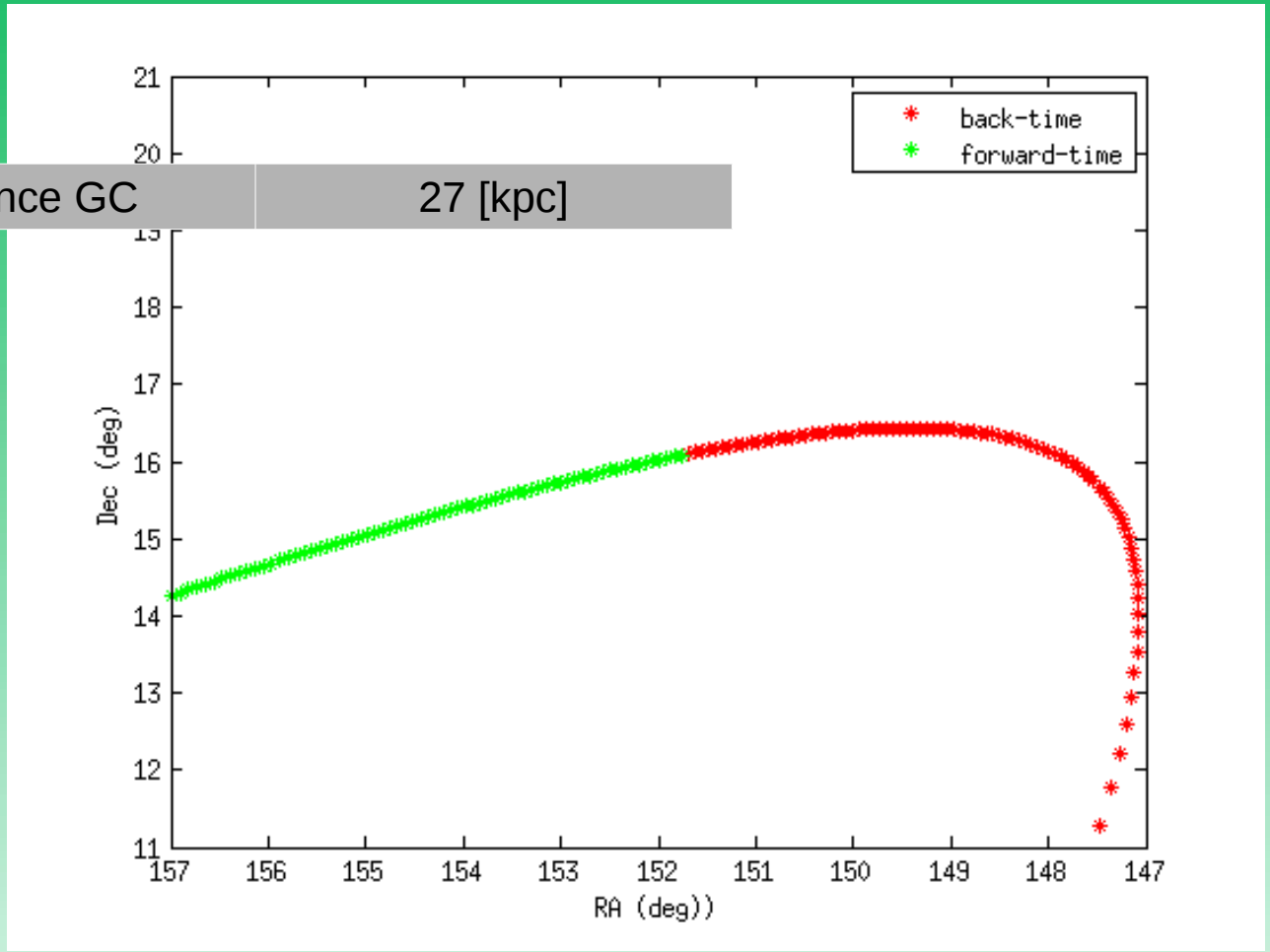


Segue 1


20
18
16
14
12
Dec [Deg.]
156
154
152
150
148
RA [Deg.]
1
2
3
5
6
7
0.21
0.29
0.36
0.44
0.51
0.59
0.66

ORBITS

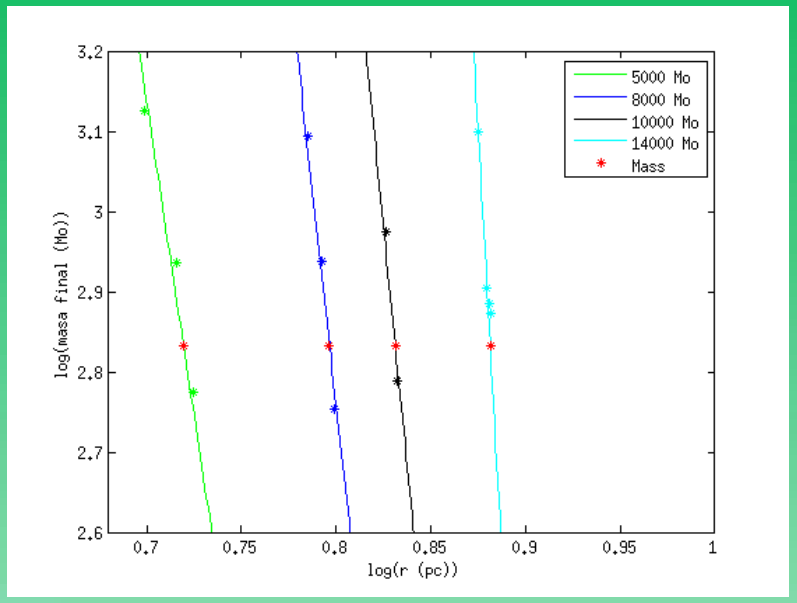
Distance GC	27 [kpc]



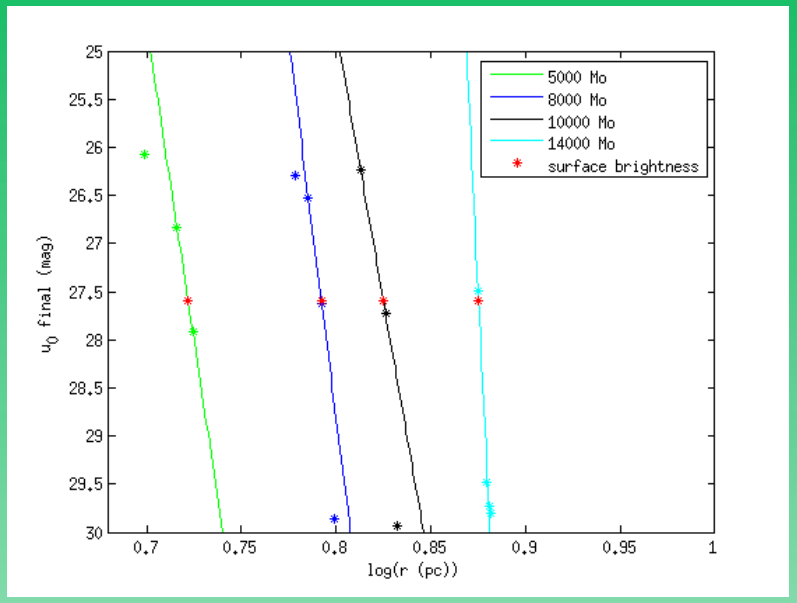
Proper motion	Value
μ_α	-0.19 [mas/yr]
μ_δ	-1.9 [mas/yr]

Apocenter	31.62 [kpc]
Pericenter	2.86 [kpc]

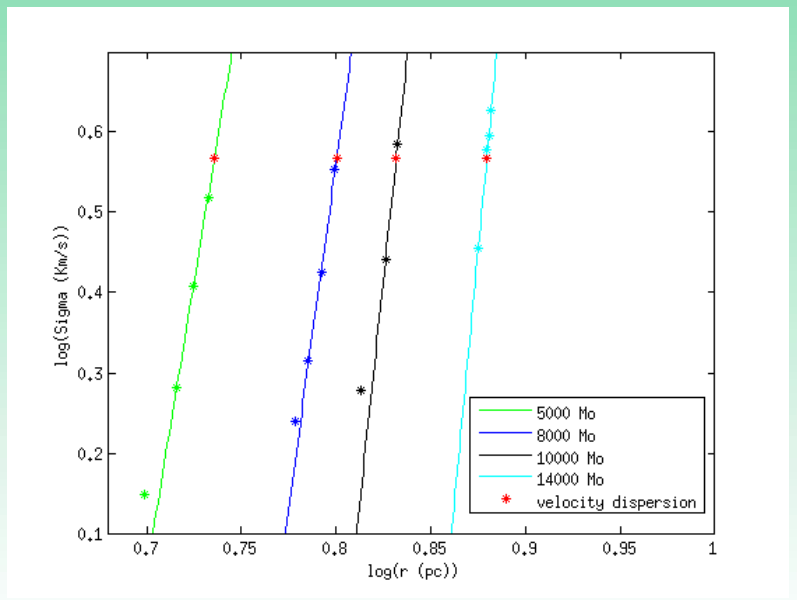
MASS



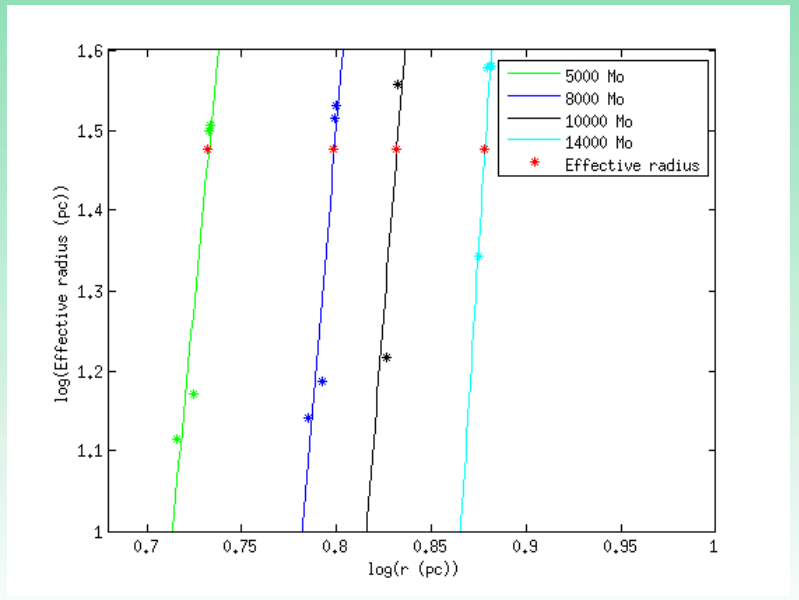
SURFACE BRIGHTNESS



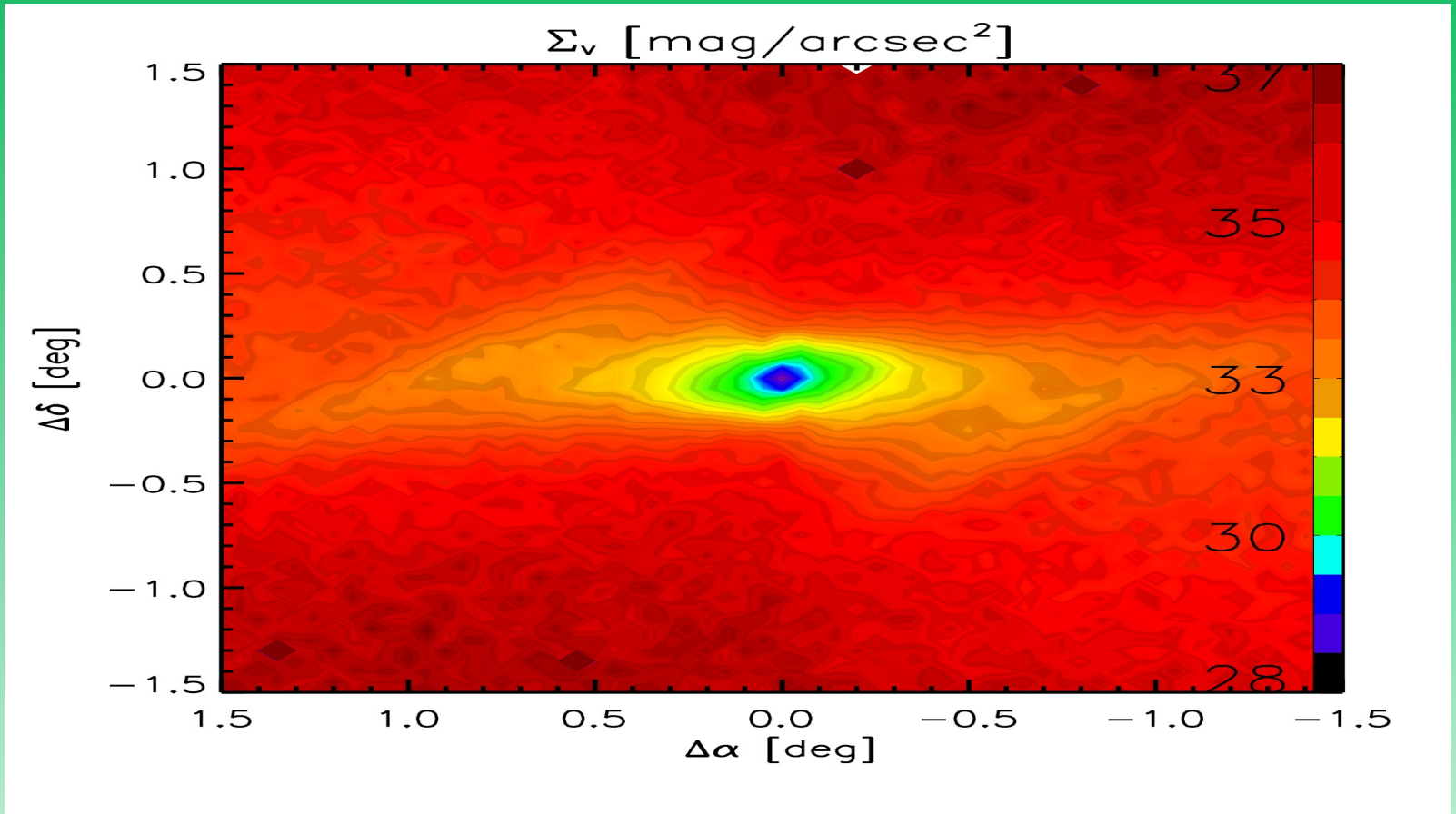
DISPERSION



EFFECTIVE RADIUS



FINAL MODEL



Initial parameter	Value
Plummer Mass	7673 [M_o]
Plummer Radius	6.15 [pc]

Parameter	Final value
Mass	672 [M_o]
Surface brightness	28.49 [mag]
Velocity dispersion	3.43 [km/s]
Effective radius	27.4 [pc]

FINAL MODEL

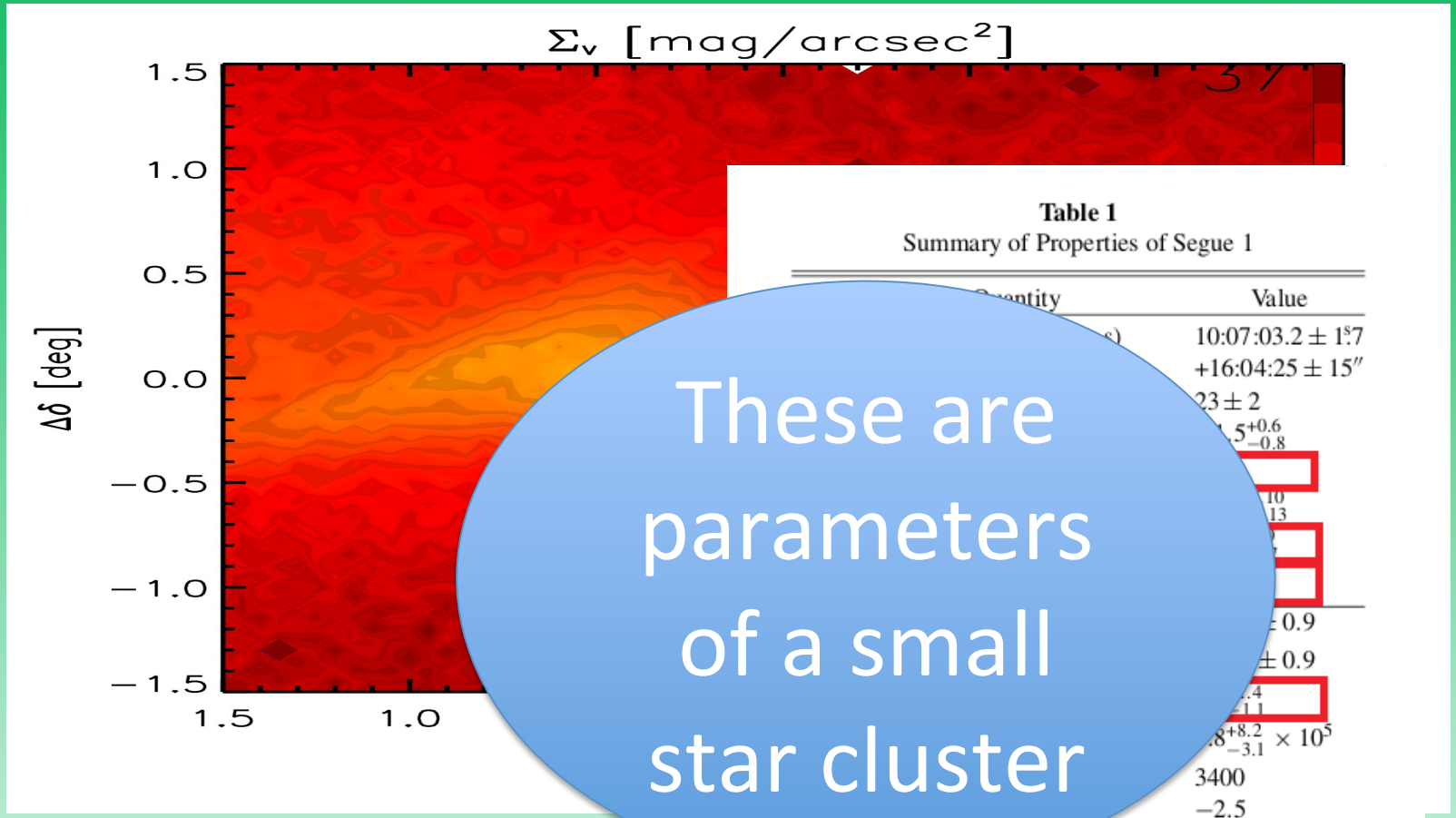


Table 1
Summary of Properties of Segue 1

Quantity	Value
	10:07:03.2 ± 1.7
	+16:04:25 ± 15″
	23 ± 2
	$5^{+0.6}_{-0.8}$
	10
	13
	0.9
	± 0.9
	.4
	.1
	$^{+8.2}_{-3.1} \times 10^5$
	3400
	−2.5

These are parameters of a small star cluster

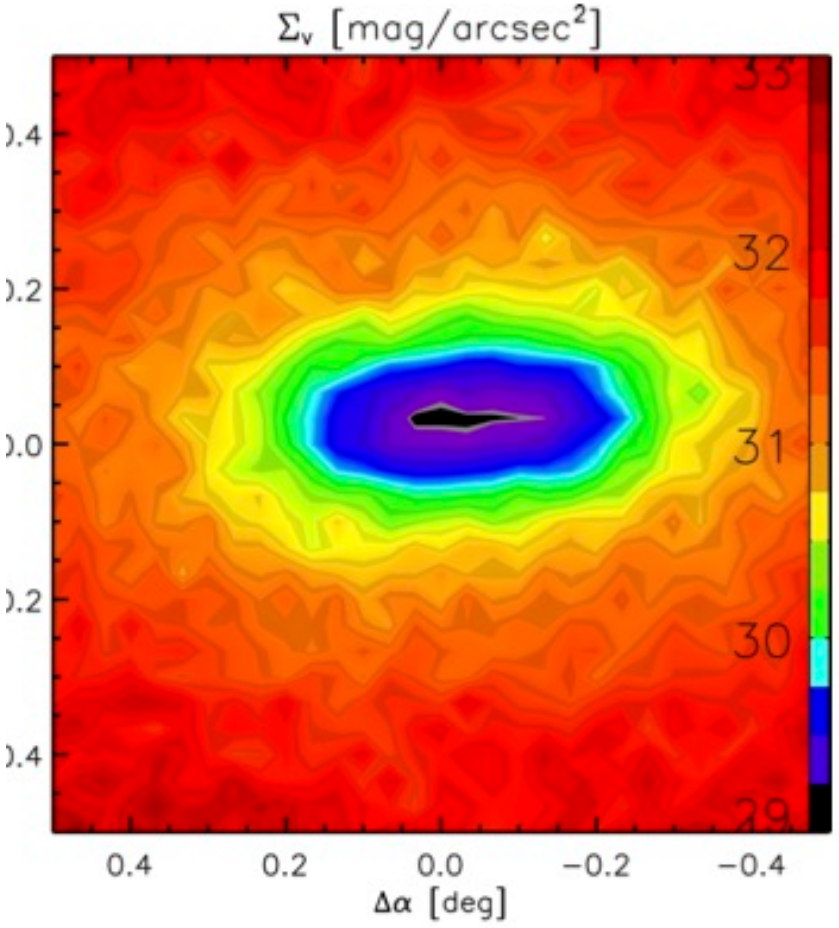
lummer Mass	7673 [M_o]
mmer Radius	6.15 [pc]

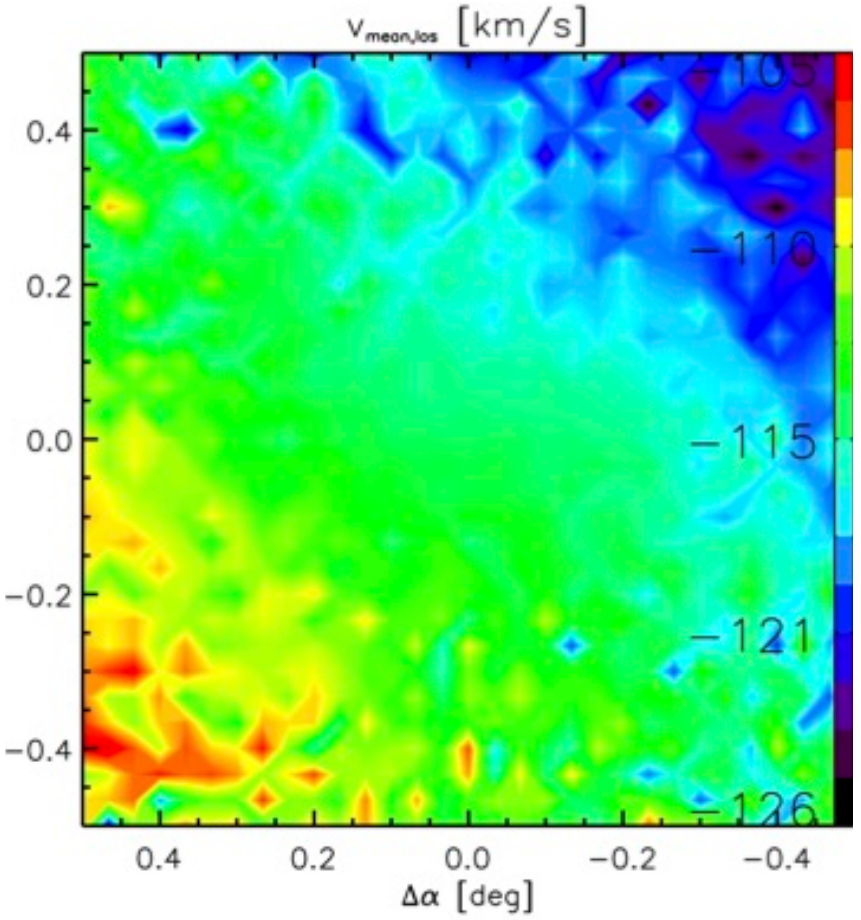
arameter	Final value
Mass	672 [M_o]
urface brightness	28.49 [mag]
Velocity dispersion	3.43 [km/s]
Effective radius	27.4 [pc]

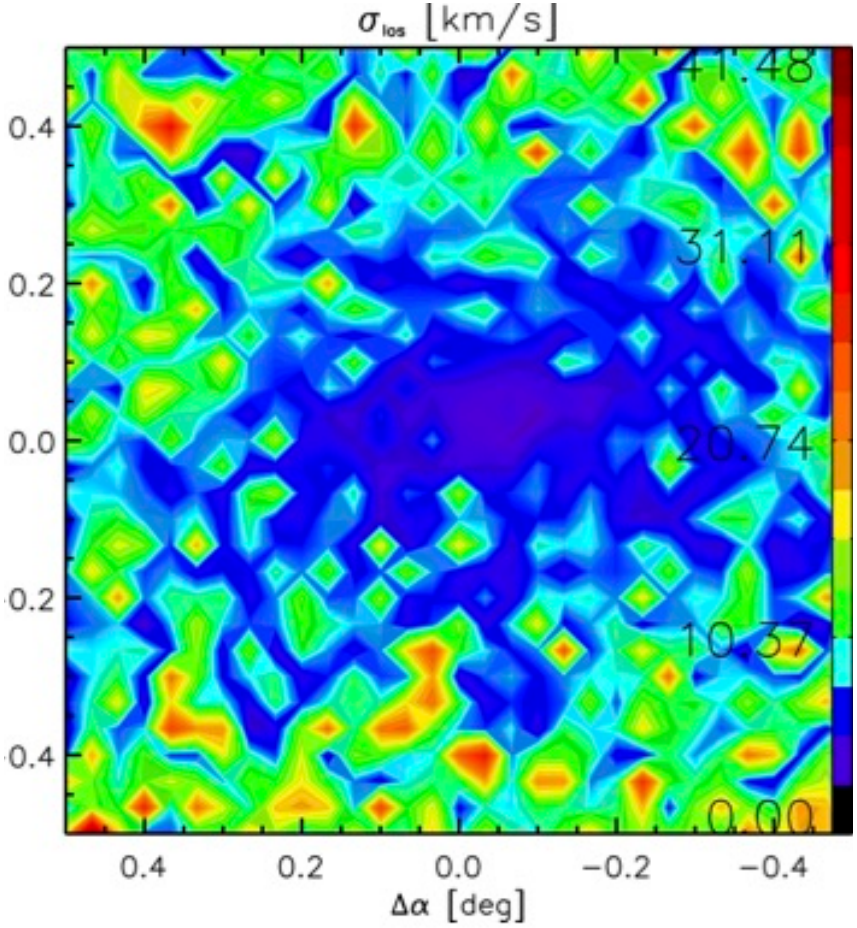
Older Models:

Done the old fashioned trial and error way

Ursa Mayor II (Smith et al. 2012) no connection with the Orphan Stream

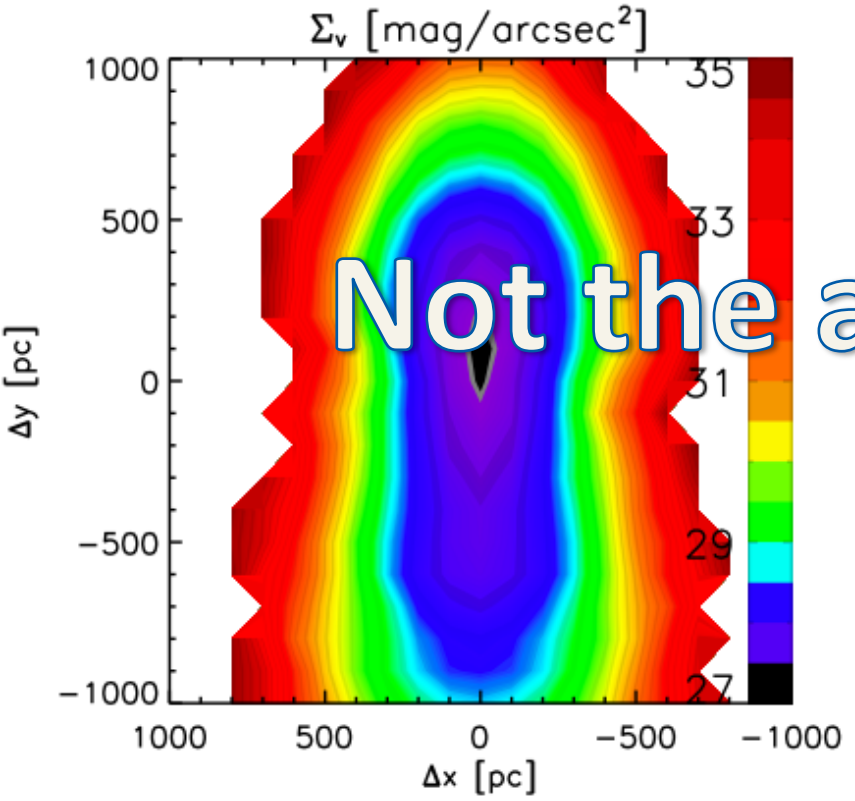


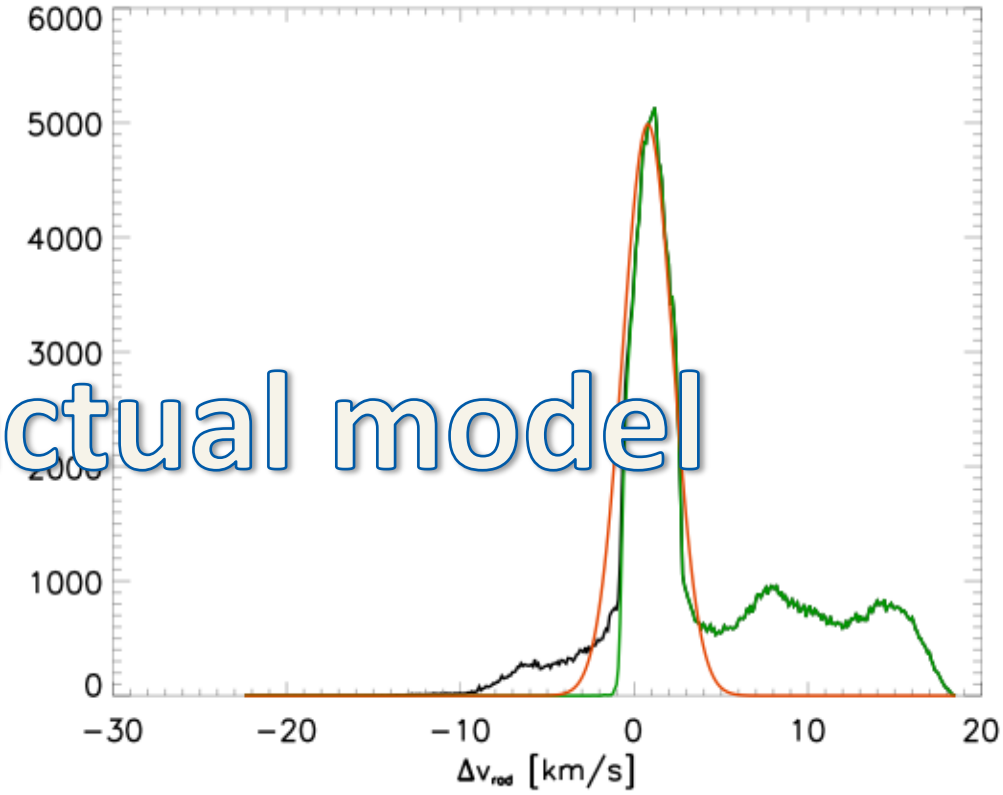




- Initial mass: 7.57 x 10^5 M_{sun}
- Initial scale radius: 11.7 pc
- μ_α = -0.3 mas/yr
- μ_δ = -1.4 mas/yr
- R_{peri} = 2.4 kpc
- R_{apo} = 36.5 kpc
- e = 0.87
- T = 0.43 Gyr

Bootes I





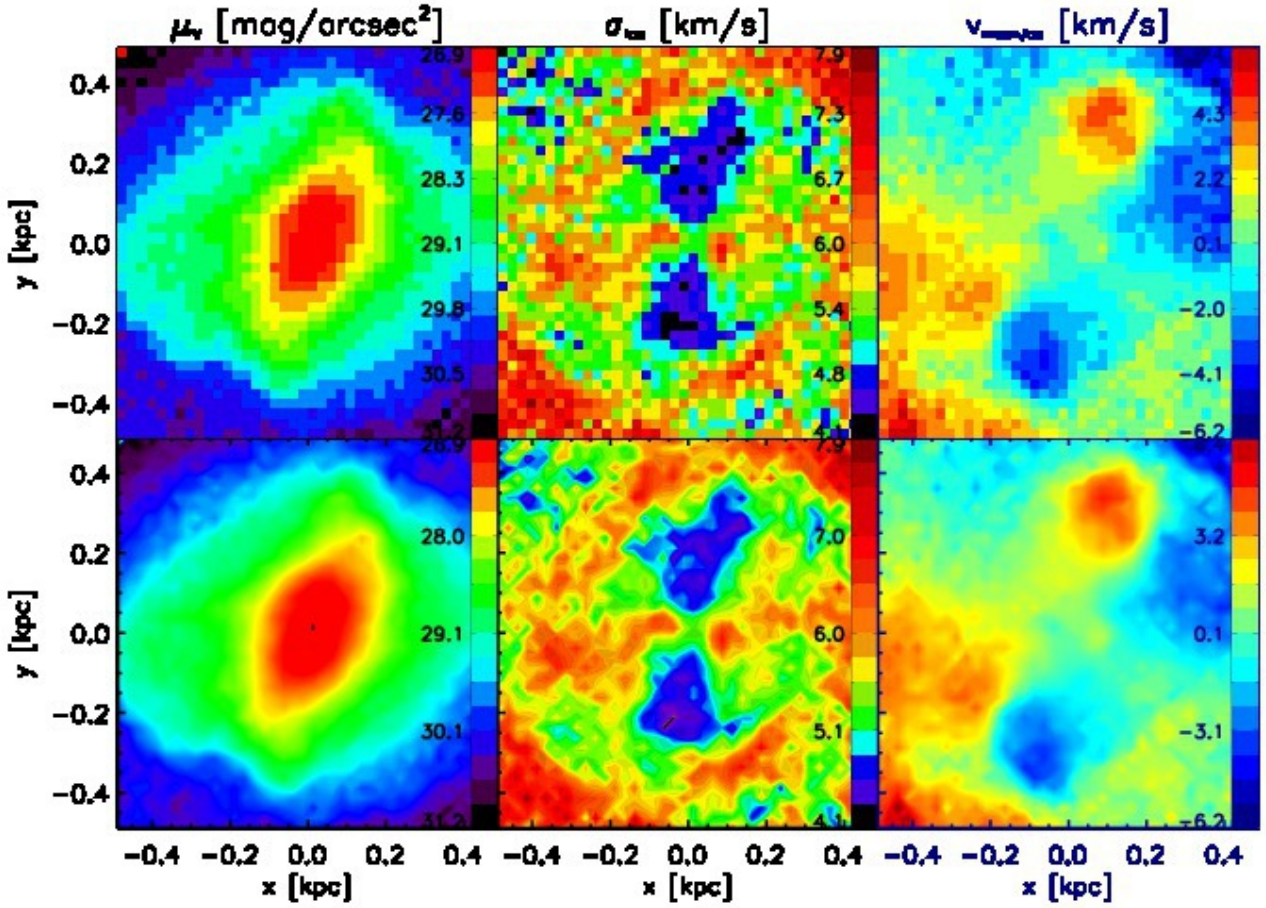
Not the actual model

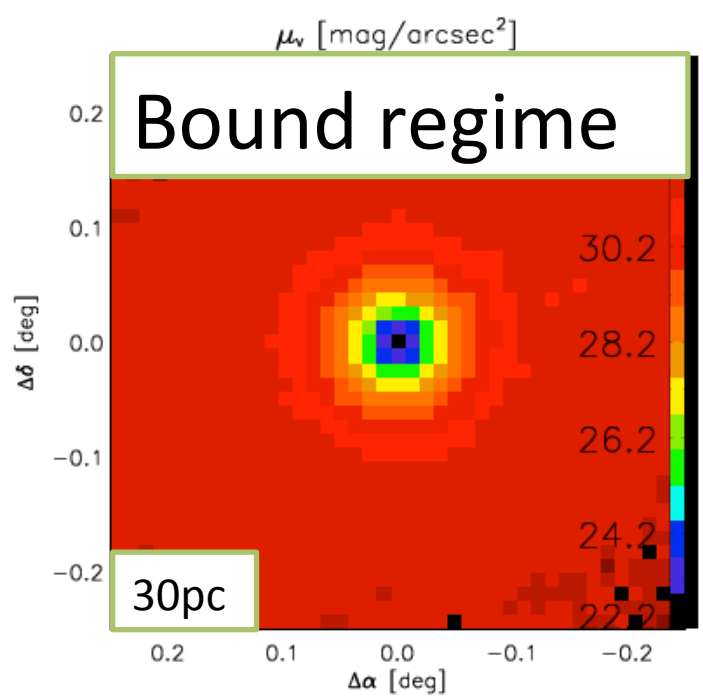
- σ_{bound} = 0.8 km/s (red)
- $\sigma_{all\ distances}$ = 5.7 km/s (black)
- $\sigma_{d<500pc}$ = 5.0 km/s (green)

Yes, we published that Bootes I cannot be modelled as a DM free object.
BUT: That was before the corrected (and much smaller) velocity dispersion was observed and communicated to the public.
One of our old models, shows the correct velocity dispersion and matches all other parameters of Bootes I.

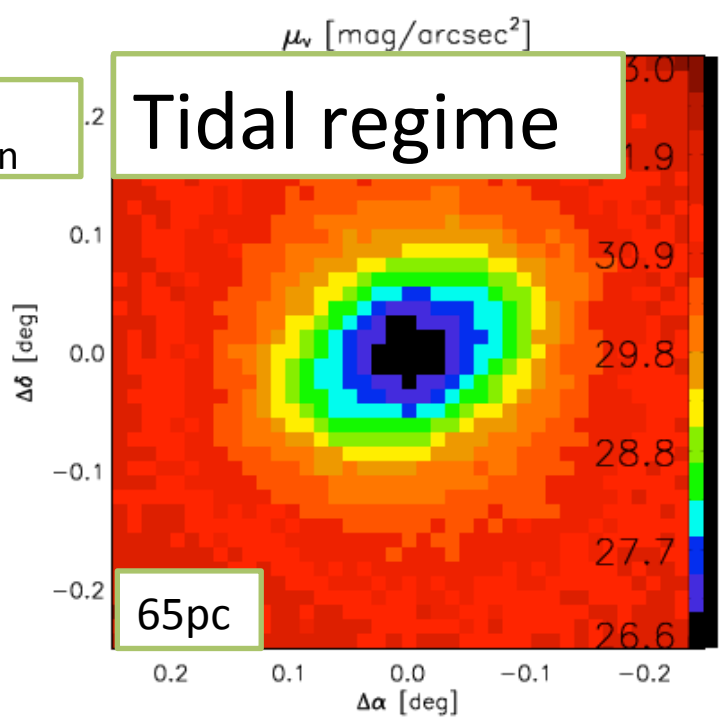
Conclusions

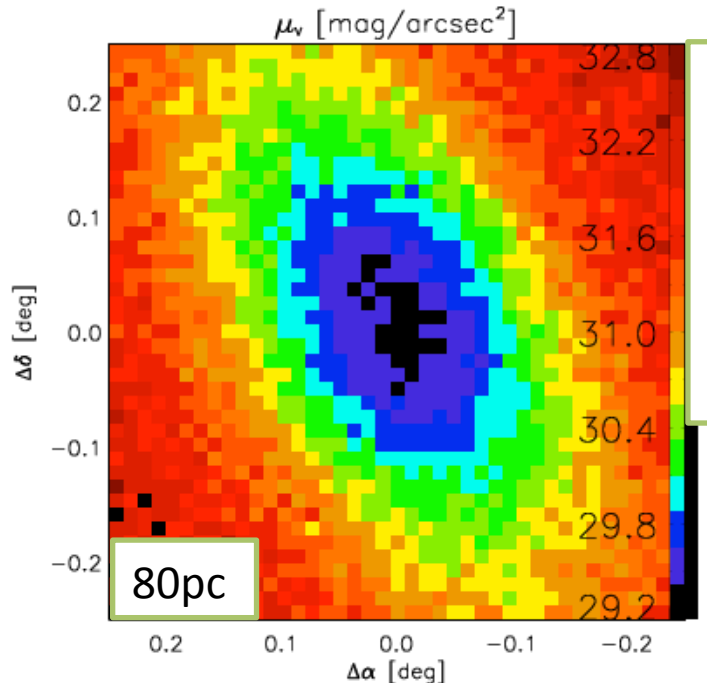
- So far for each faint dSph galaxy we investigated, we found a DM free progenitor model.
- The solutions have in common that we see the objects close to their apogalacticon (very likely), on eccentric orbits (not unusual) and after a long history of tidally induced mass-loss (also very likely).


μv [mag/arcsec²]
σlos [km/s]
vrot/σ [km/s]
y [kpc]
x [kpc]
0.4
0.2
0.0
−0.2
−0.4
27.6
28.3
29.1
29.8
30.5
7.3
6.7
6.0
5.4
4.8
4.3
2.2
0.1
−2.0
−4.1
−6.2
28.0
29.1
30.1
7.0
6.0
5.1
3.2
0.1
−3.1

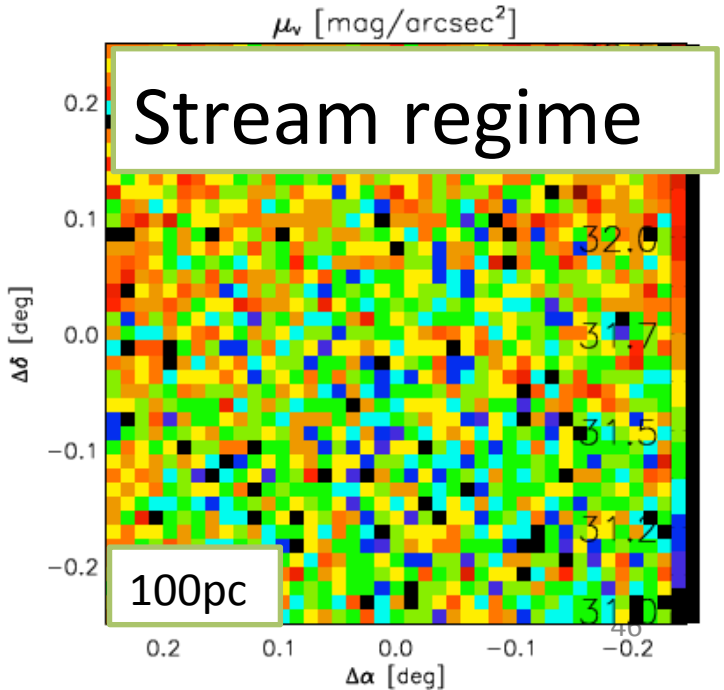


Mpl = 2×10^5 M_{sun}

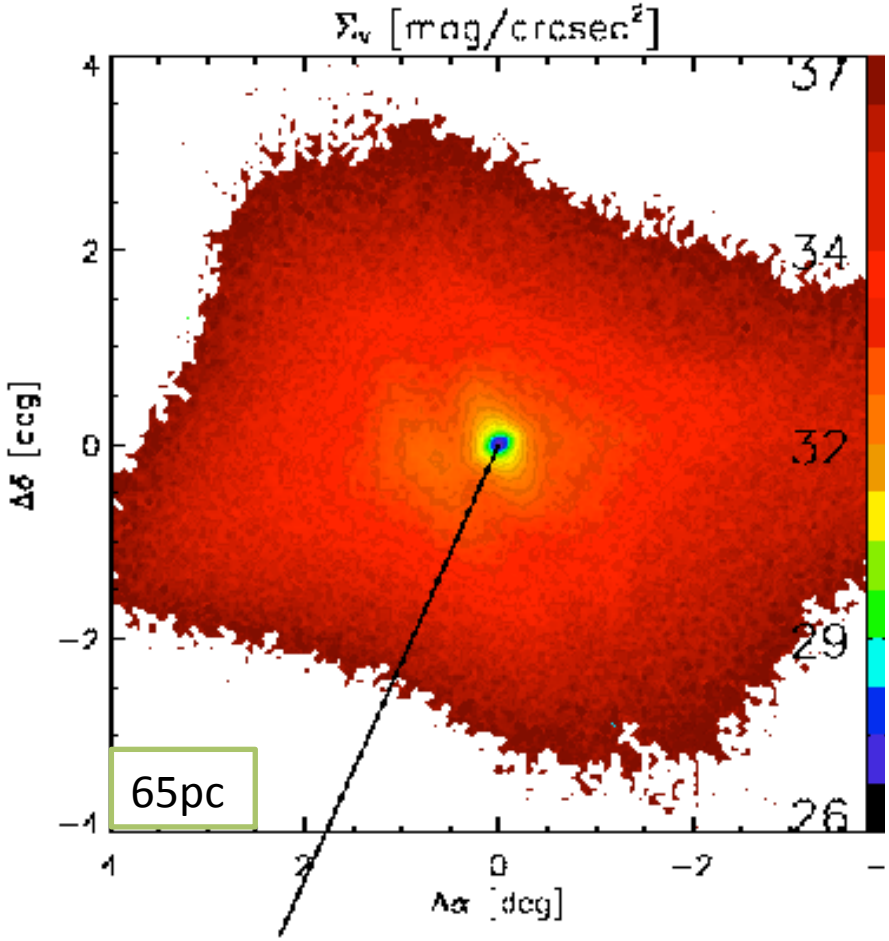


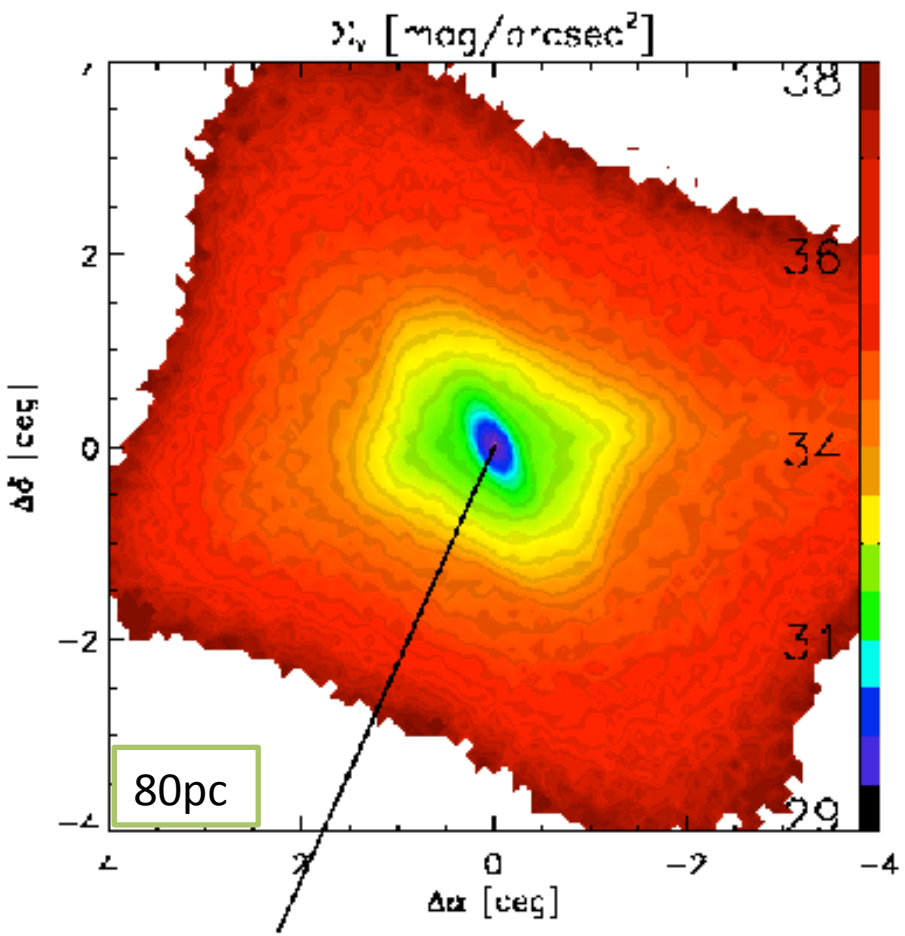


Strange regime with flipped orientation

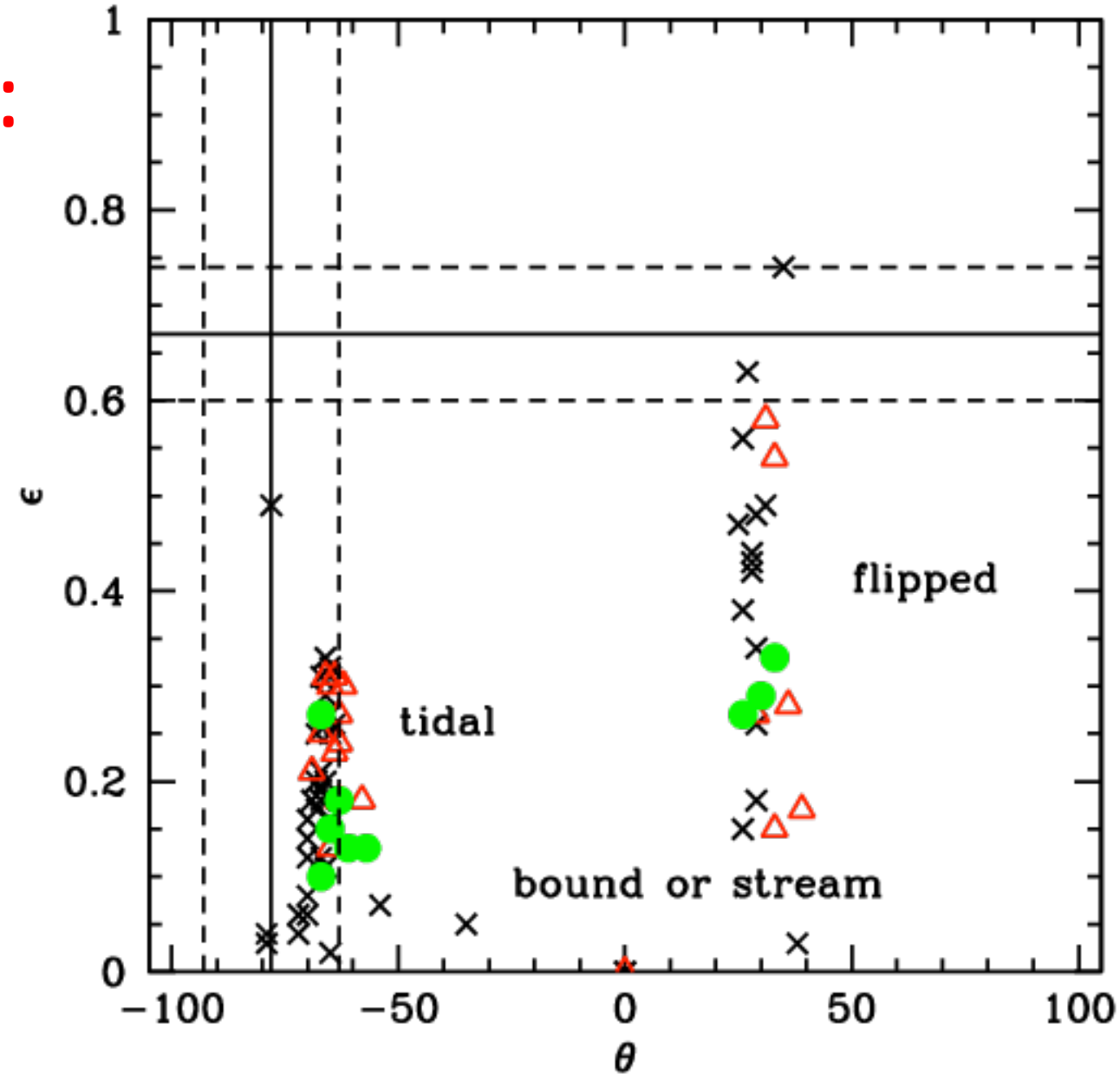


X-Wing effect





BUT:

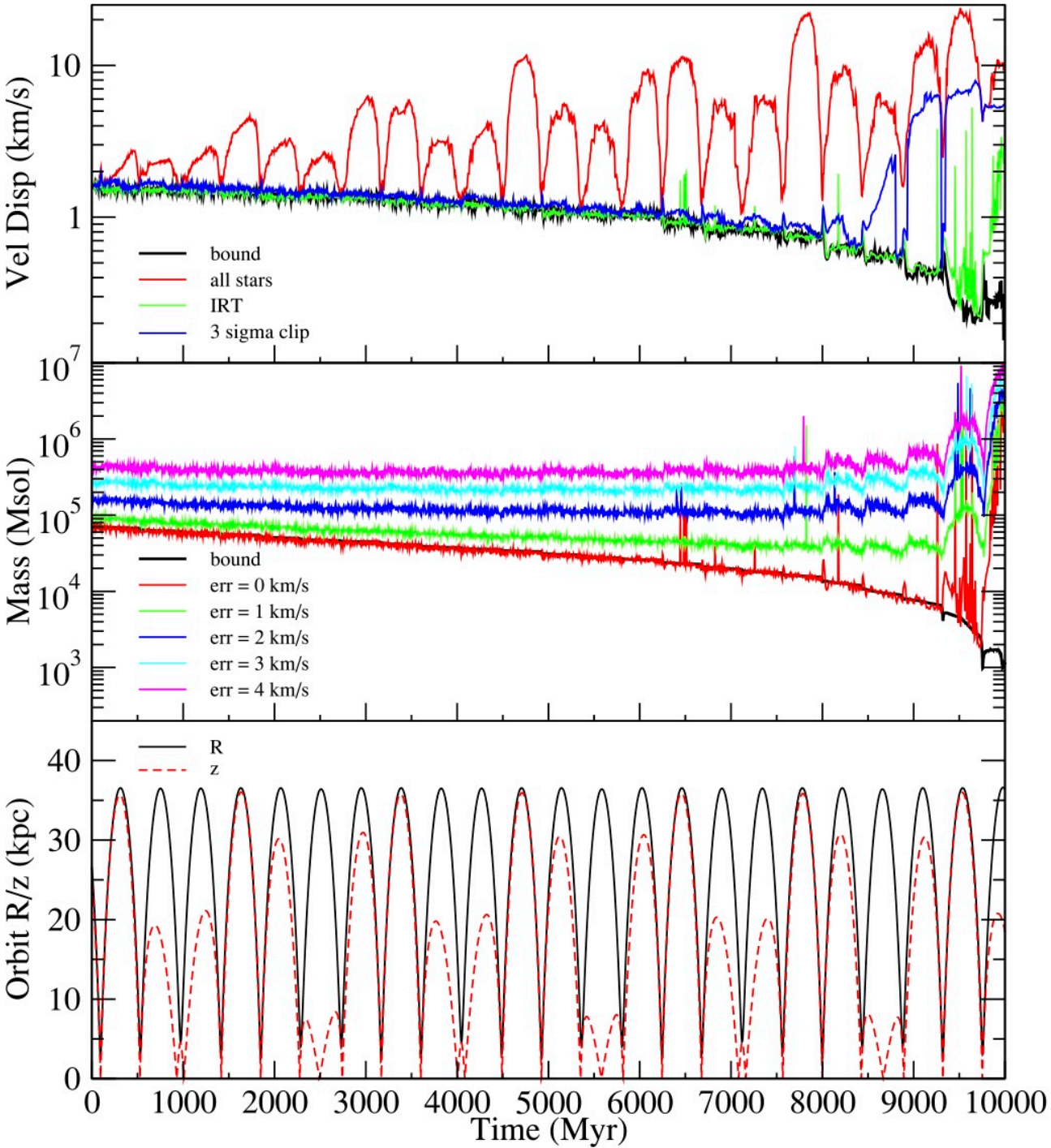


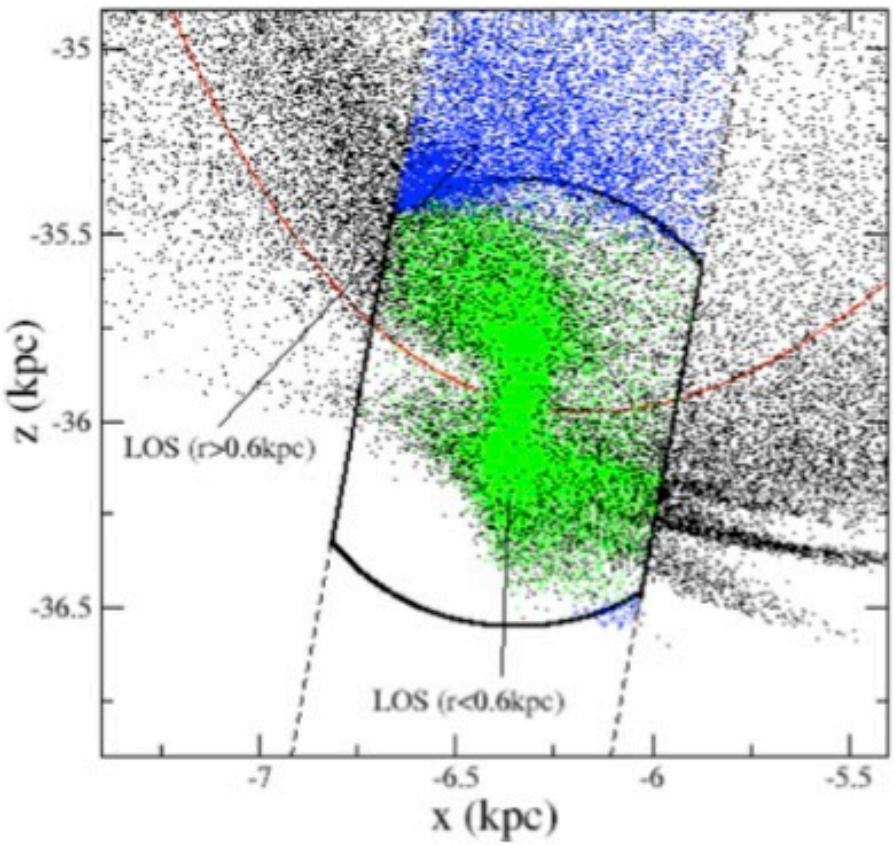
Conclusion for Hercules:

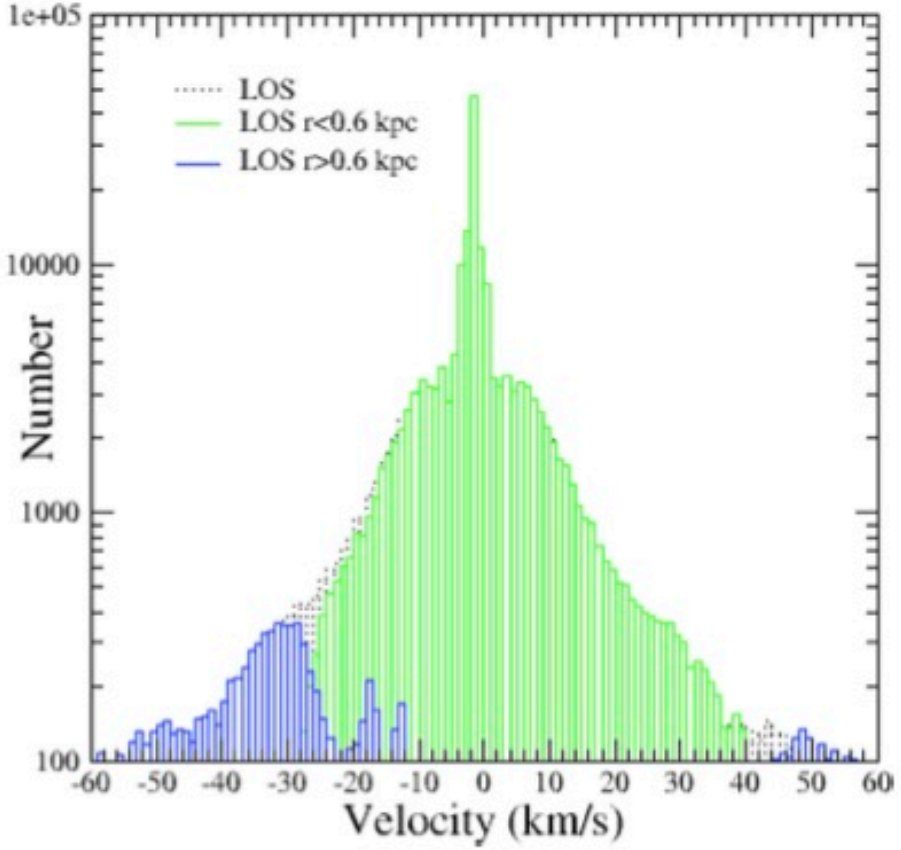
- We only reach sufficient elongation when the position angle is already flipped.
- Simulations with correct position angle do not match the elongation.

➔ ➔ ➔ ➔ ➔ ➔ ➔ ➔ ➔ ➔ ➔ ➔ ➔ ➔ ➔

- Either the measured elongation of Hercules is wrong.
- OR: the published orbit is wrong.


Vel Disp (km/s)
10
1
bound
all stars
IRT
3 sigma clip
Mass (Msol)
10^7
10^6
10^5
10^4
10^3
bound
err = 0 km/s
err = 1 km/s
err = 2 km/s
err = 3 km/s
err = 4 km/s
Orbit R/z (kpc)
40
30
20
10
0
R
z
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000
Time (Myr)


-35
-35.5
-36
-36.5
z (kpc)
LOS (r>0.6kpc)
LOS (r<0.6kpc)
-7
-6.5
-6
-5.5
x (kpc)


1e+05
10000
1000
100
Number
LOS
LOS r<0.6 kpc
LOS r>0.6 kpc
-60
-50
-40
-30
-20
-10
0
10
20
30
40
50
60
Velocity (km/s)