From Galaxy Formation to Kinematics

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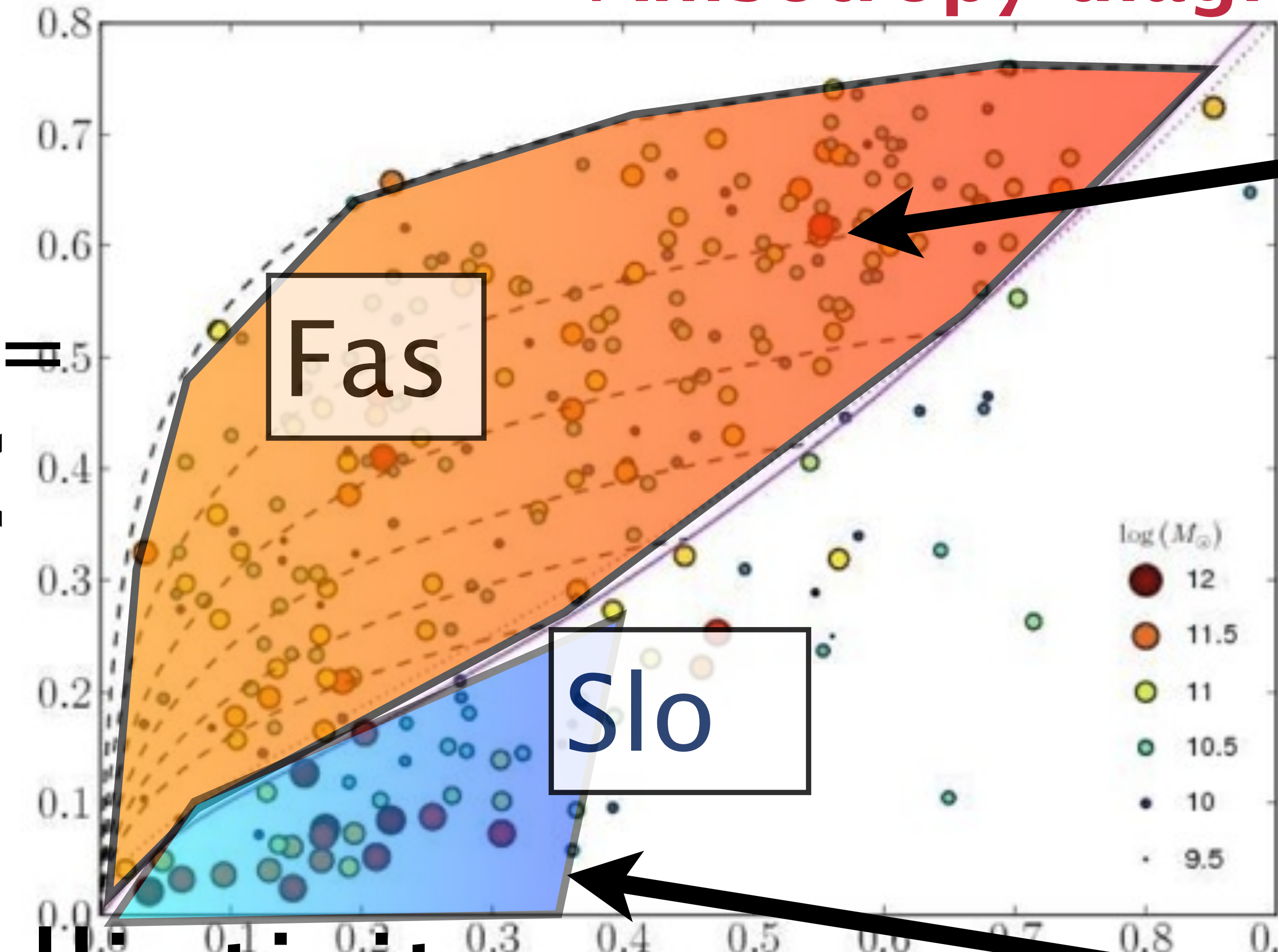
SAURON / ATLAS^{3D}

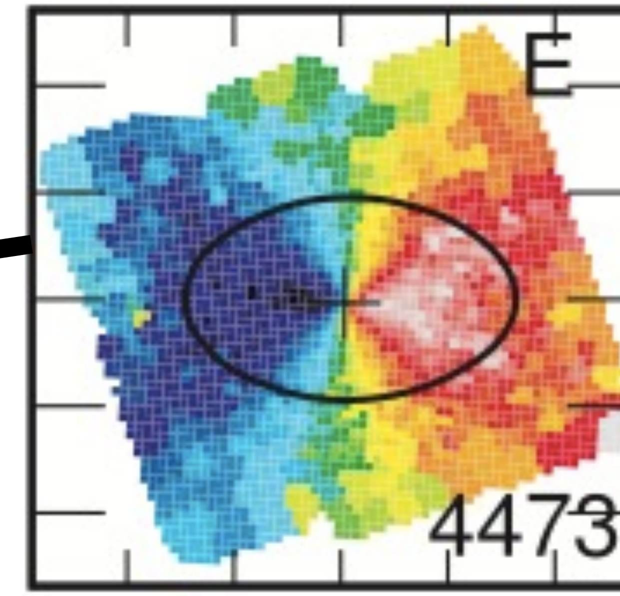
Anisotropy diagram

“rotation”= λ

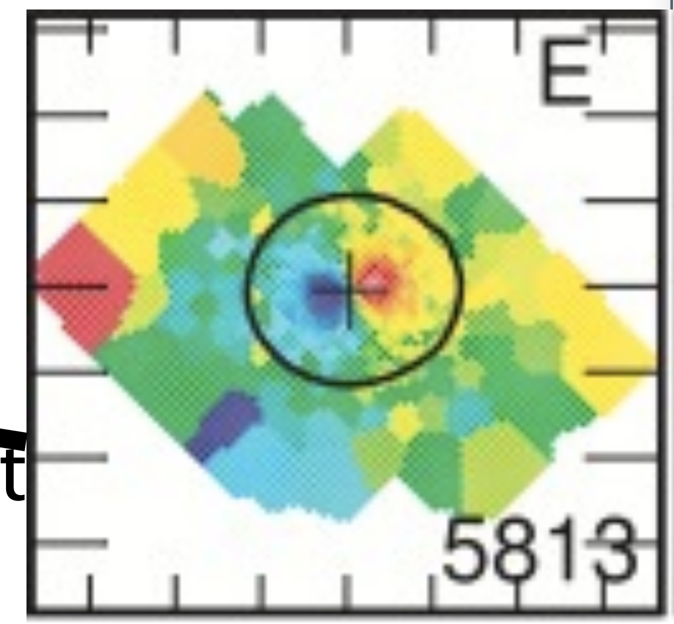


ellipticit =“projected shape”

Fast rotator



Slow rotator



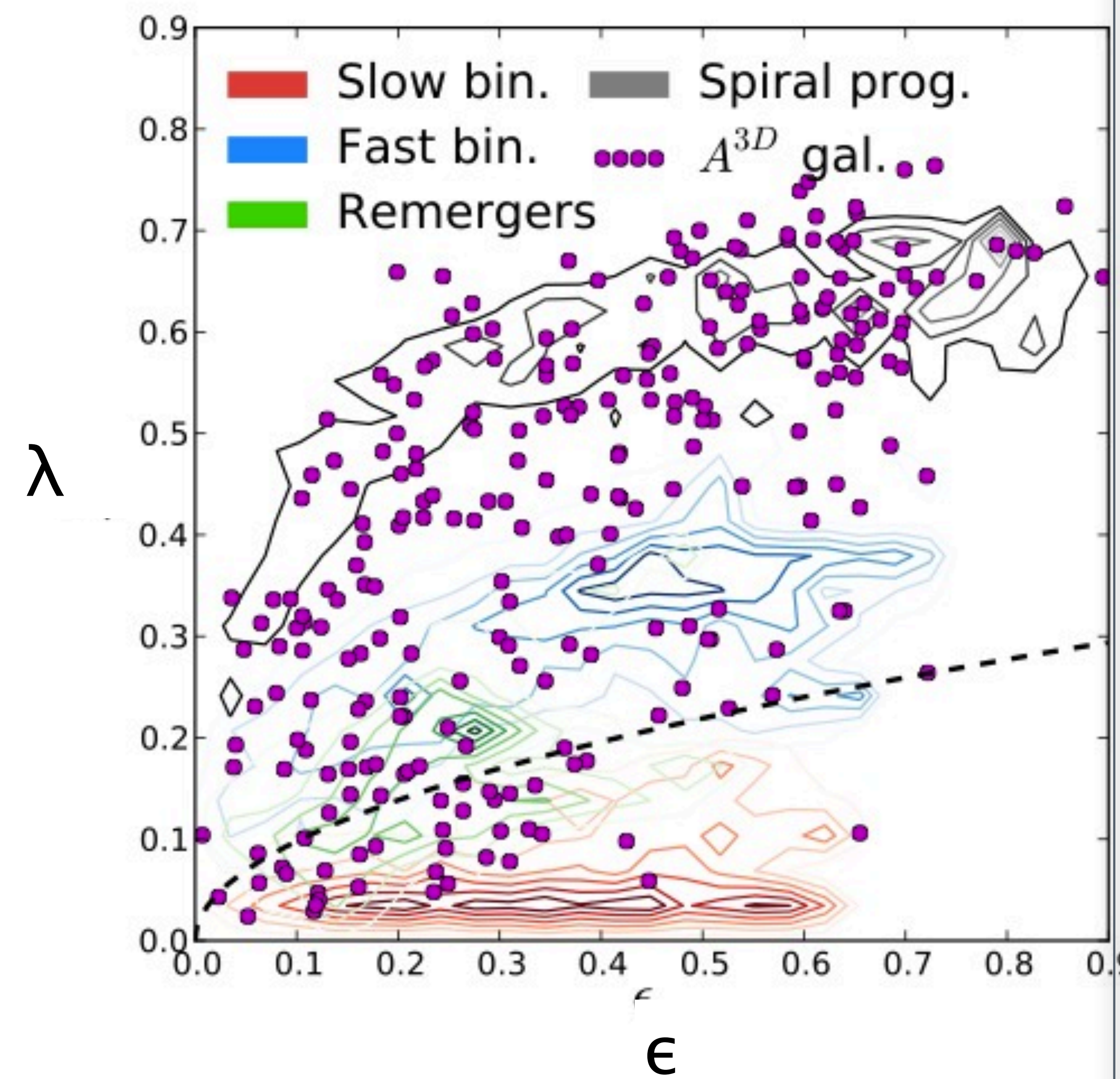
- Fast rotators are above the isotropic, oblate rotat
- Slow rotators are **not** scaled-down fast rotators
  - More massive
  - Round, have $\epsilon \sim 0.0-0.2$

How do slow rotators form?

(Emsellem et al. 2011)

Simulated Binary Mergers

- Simulated binary mergers and remergers with varying mass ratios, initial conditions, and orbital parameters at high resolution
- Form galaxies with $\lambda<0.1$, but are far too elongated $\epsilon=0.0-0.4$



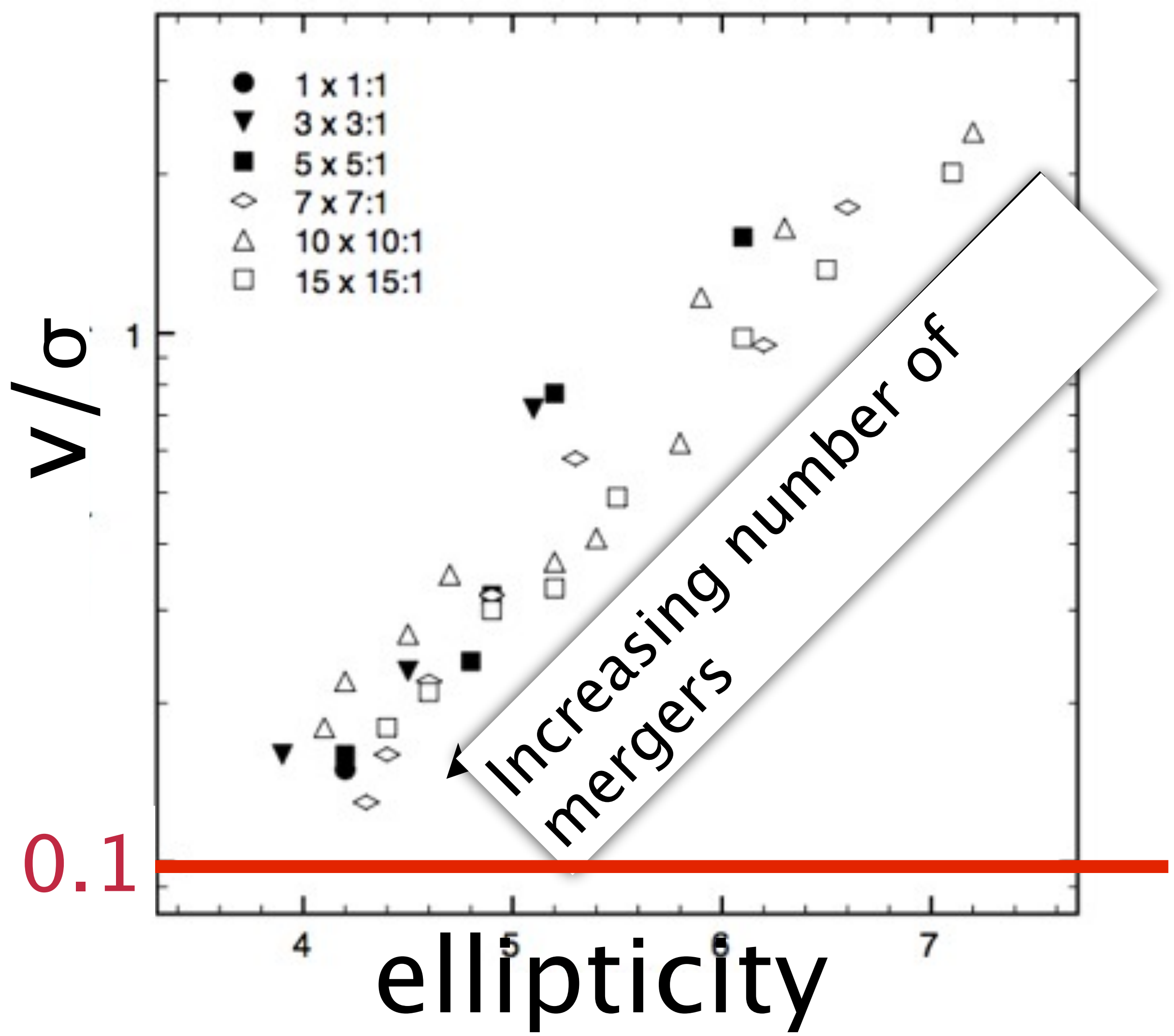
→ Do not form slow & round rotators in binary simulations

(Bois et al. 2011)

Simulated Multiple

- Bournaud et al. 2007 simulated 10 1:10 mergers, 5 1:5 mergers, etc.
- Multiple mergers decrease remnant v/σ, form rounder remnants
- Results are independent of mass ratio; only dependent on remnant mass

Repeated mergers



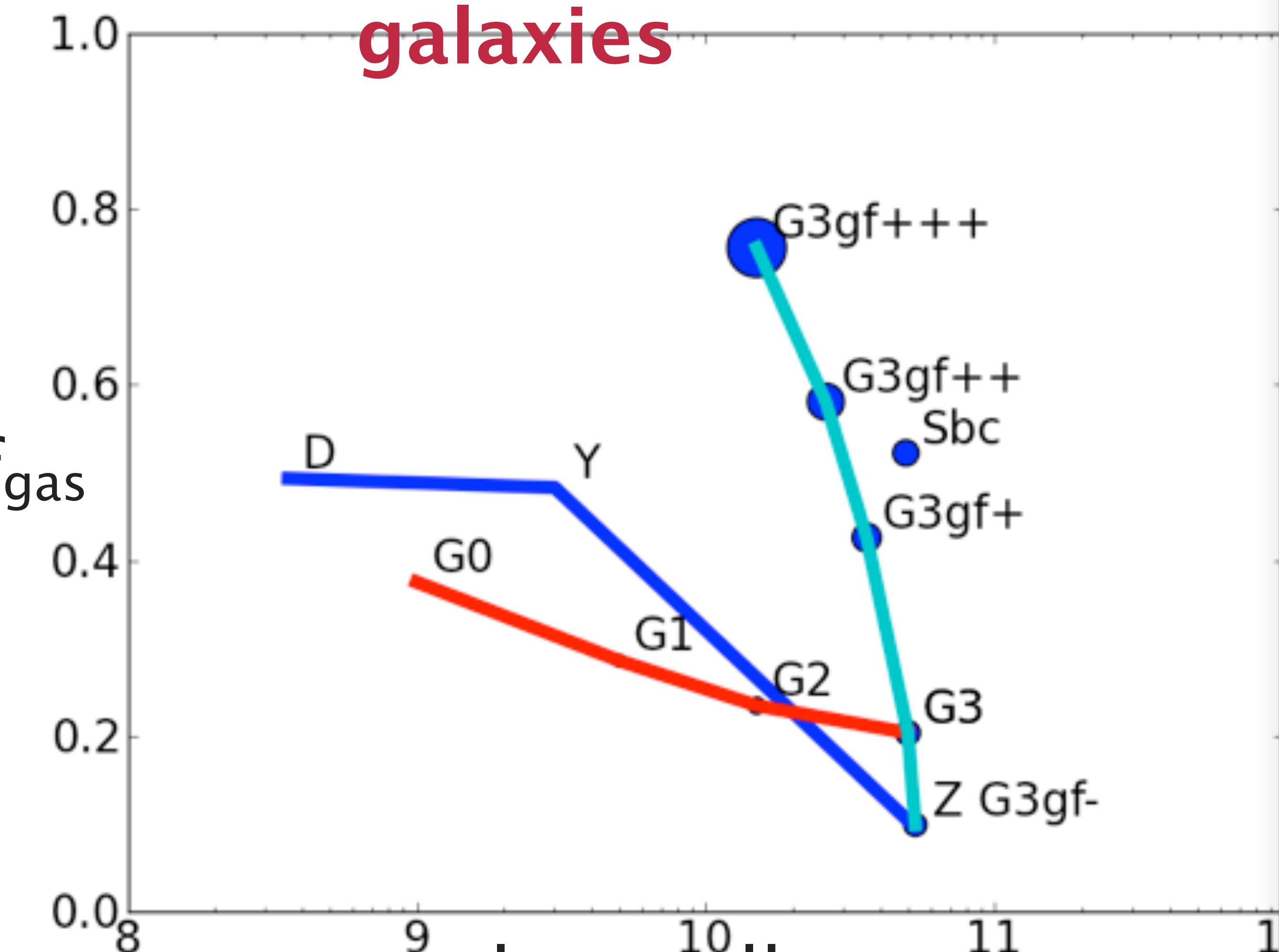
→ Did not reach slow or round rotators, but there is a trend towards slow/round with multiple mergers

(Bournaud et al. 2007)

Simulations: Progenitors

- All late-type galaxy models
- Designed to model SDSS galaxies
- D, Y, Z series are bulgeless
- G3, G2, G1, G0 in order of descending mass
- G3 also a gas fraction series
- G3BL is a G3 without a bulge (not shown)
- Sbc series have small bulges

Model spiral galaxies

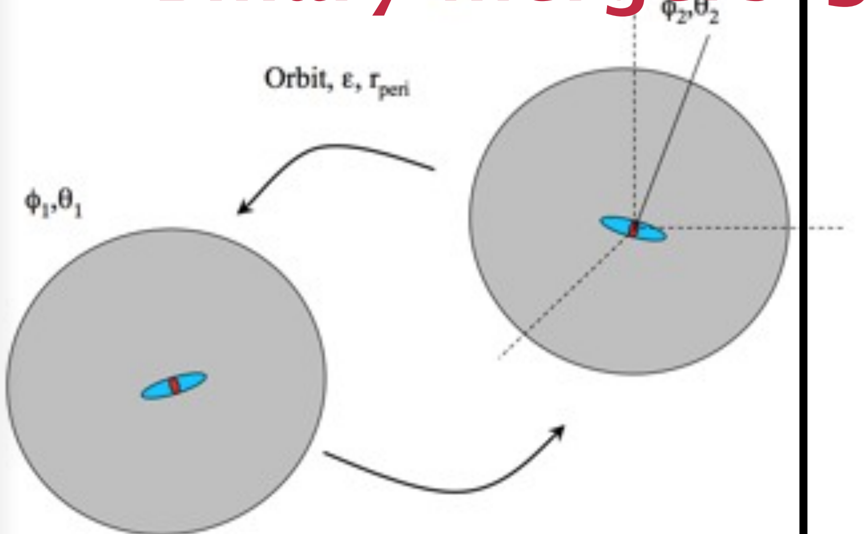


log stellar mass
(B/D ∝ size of blue circle)

→ Progenitors cover a range of gas fractions (‘gf’) and mass ranges, and may be bulgeless (‘BL’)

Schematic: Assembly

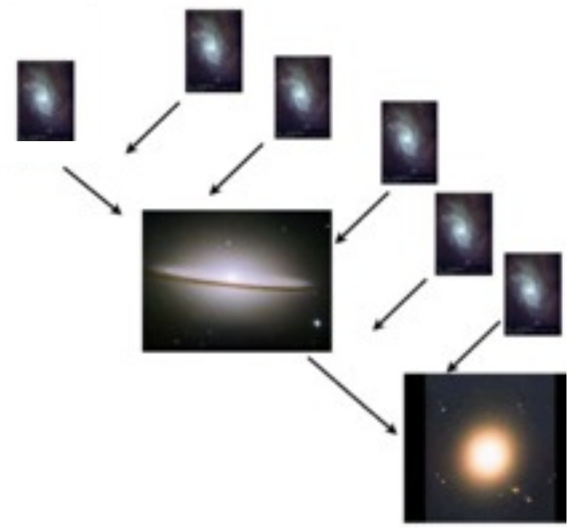
Binary mergers



- Two progenitors
- Minor, major mergers
- R_{peri}, ϵ,

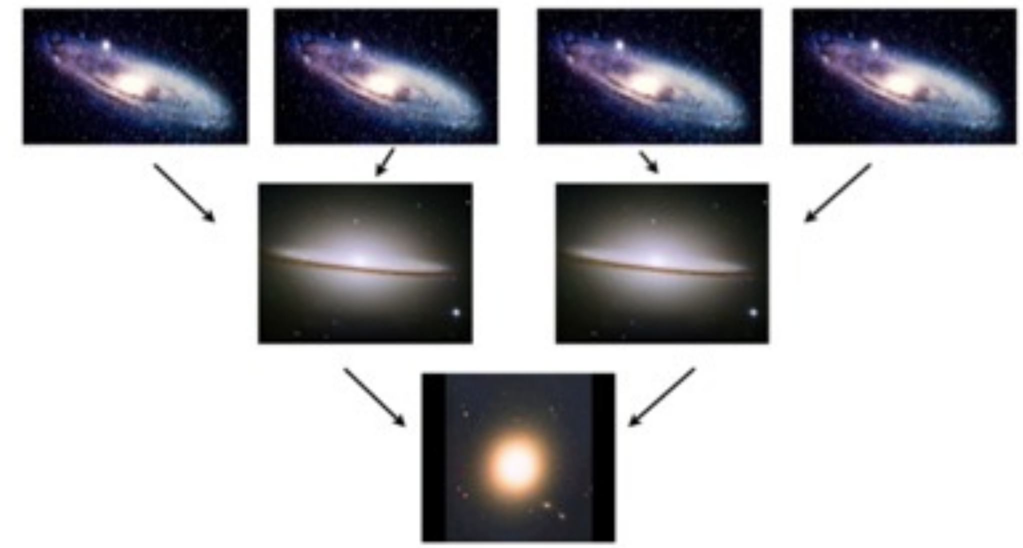
Cosmologically-motivated orbits. Not statistical.

Sequential mergers



- Either G2 or G1
- Either 4 or 8 overlapping major+ minor mergers

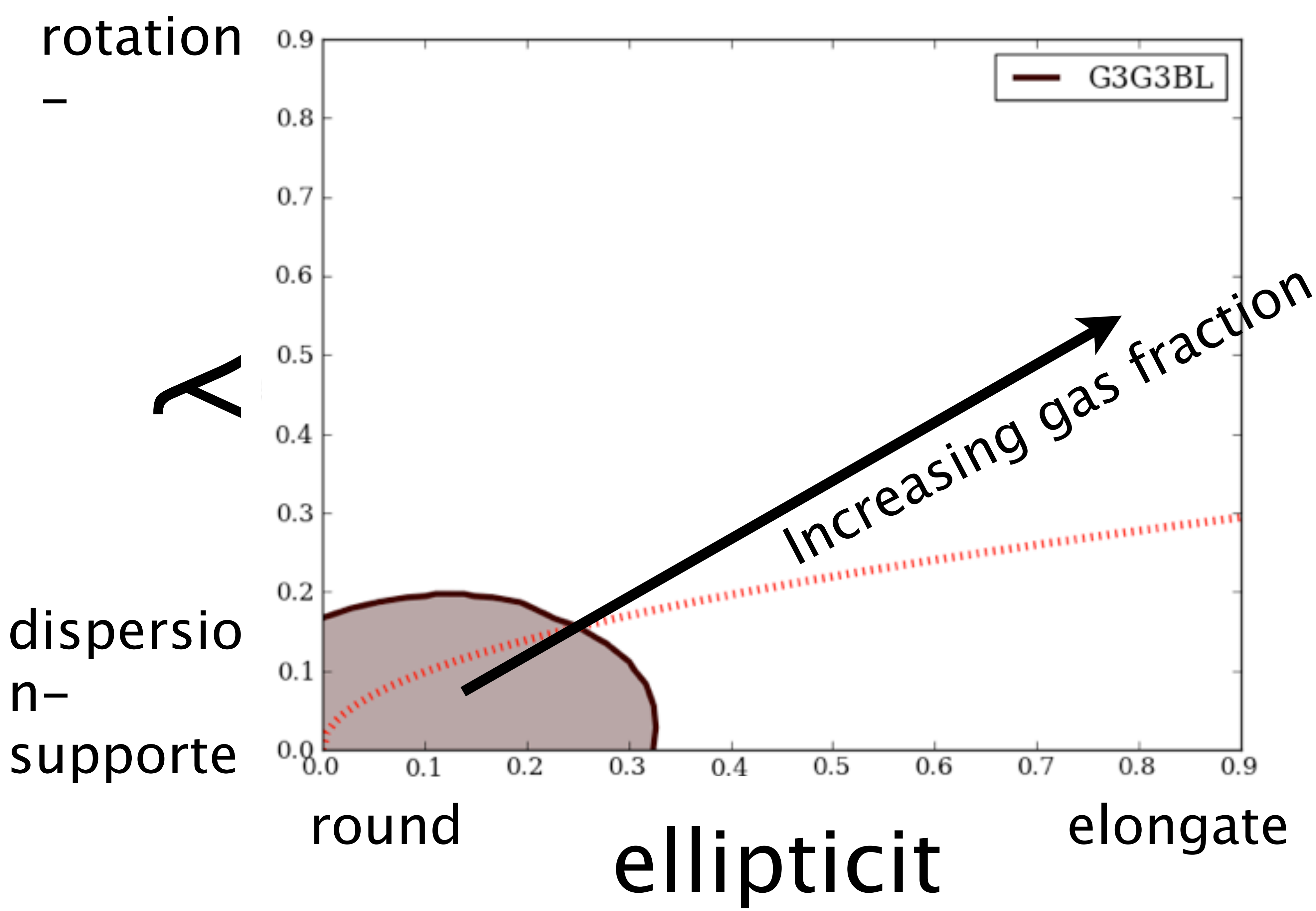
Remergers



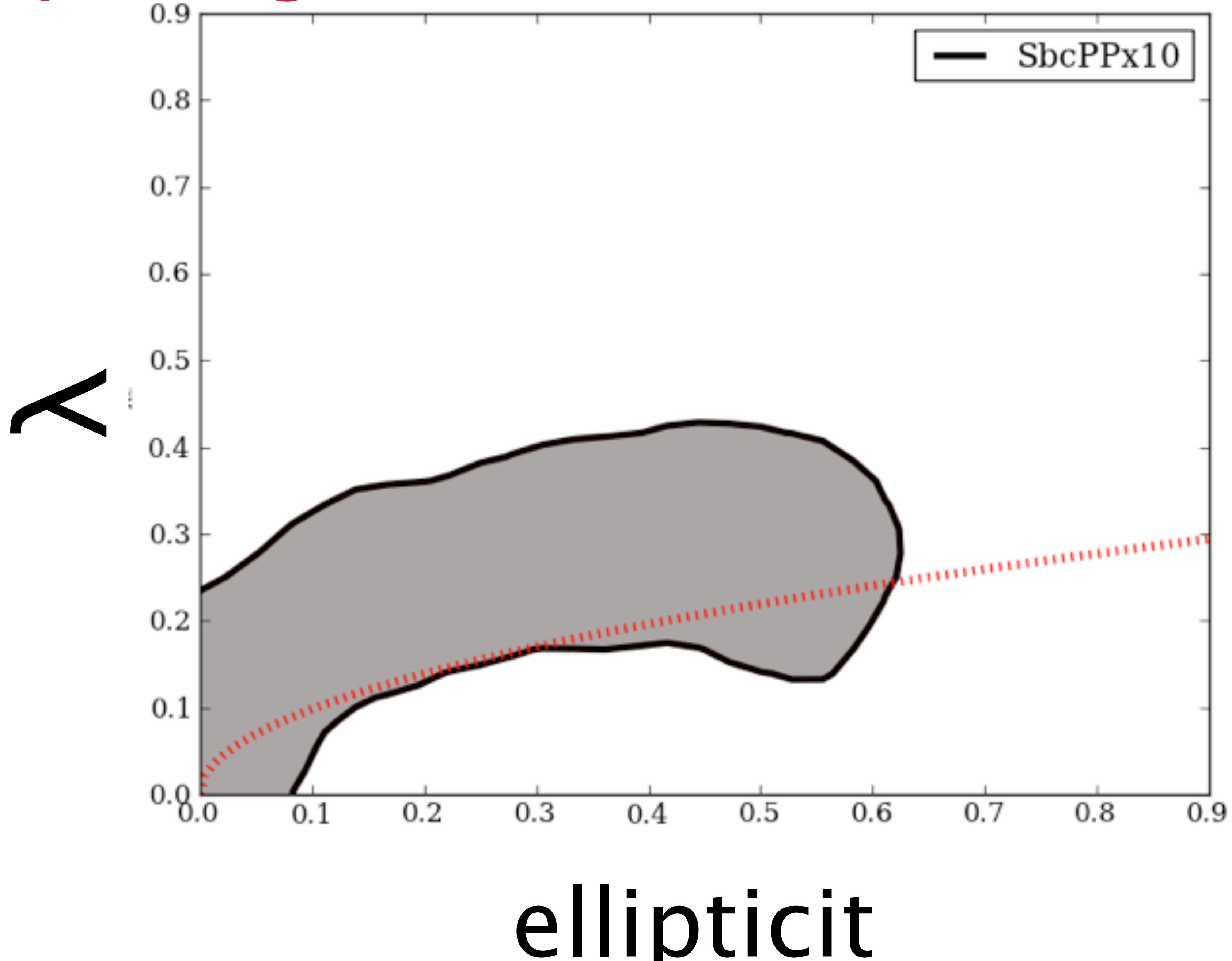
- Either G2 or G1
- Also, 4 and 8 progenitors
- Every merger a is always a remerger

Randomly chosen initial orientations, impact parameters. Idealized simulations.

With increasing gas fraction: faster rotators, higher ellipticity

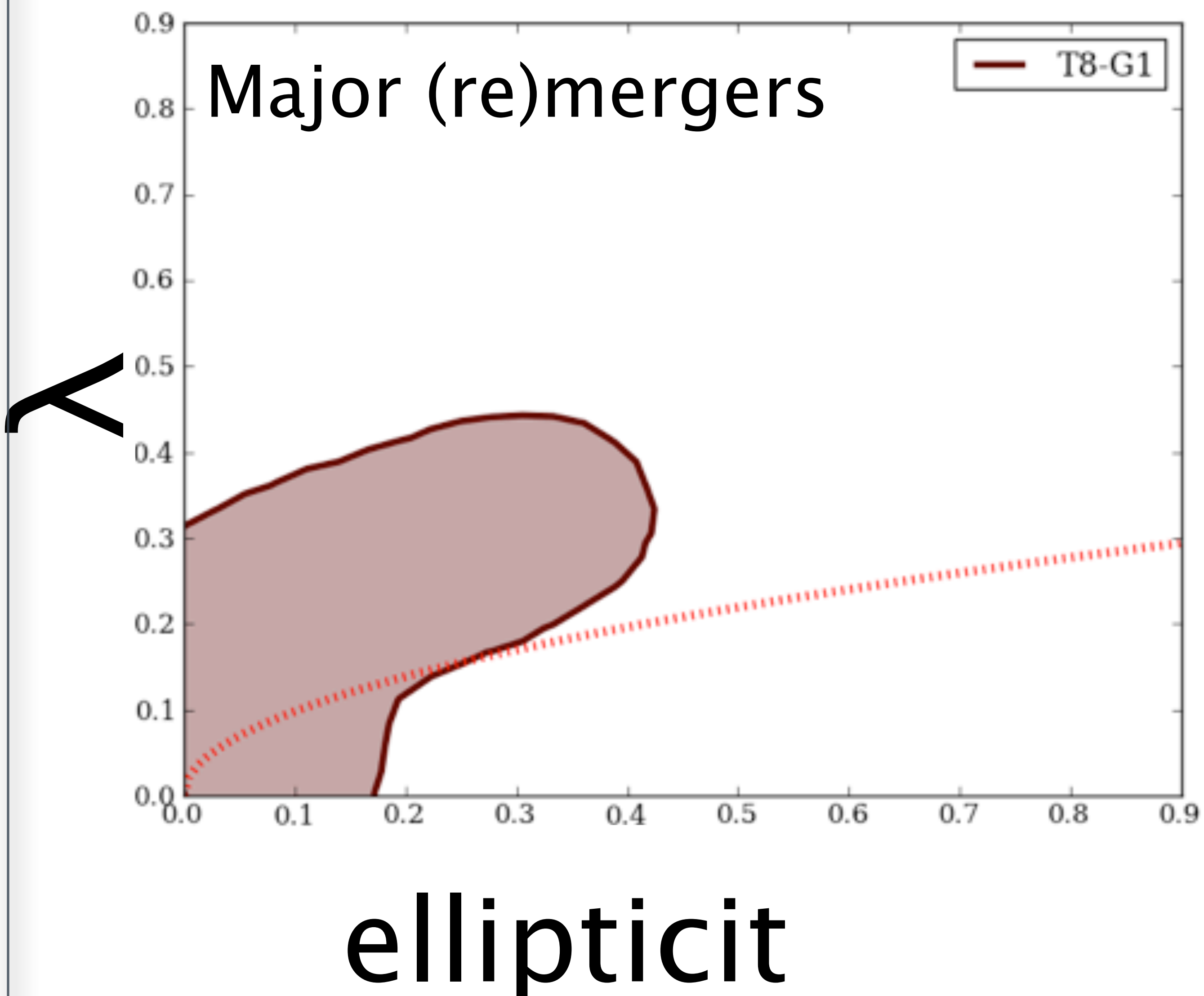


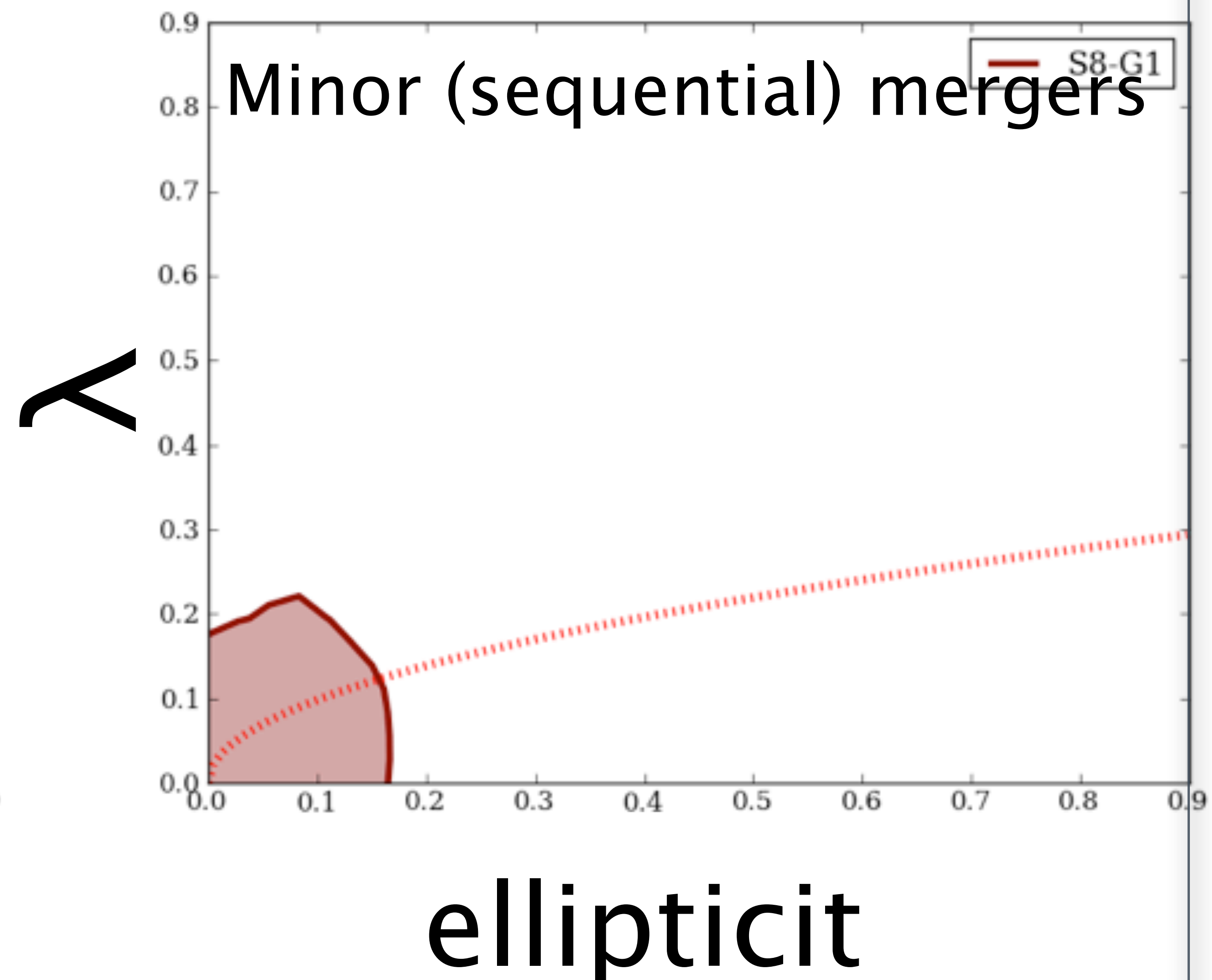
Binary Mergers: Orbital Variations



- Varying orbital initial conditions:
  - Spin (pro/retrograde), varying pericenter, orbital ellipticities
- Only specially constructed initial zero angular momentum case is a slow rotator – but quite elongated

Multiple mergers: Major vs. minor

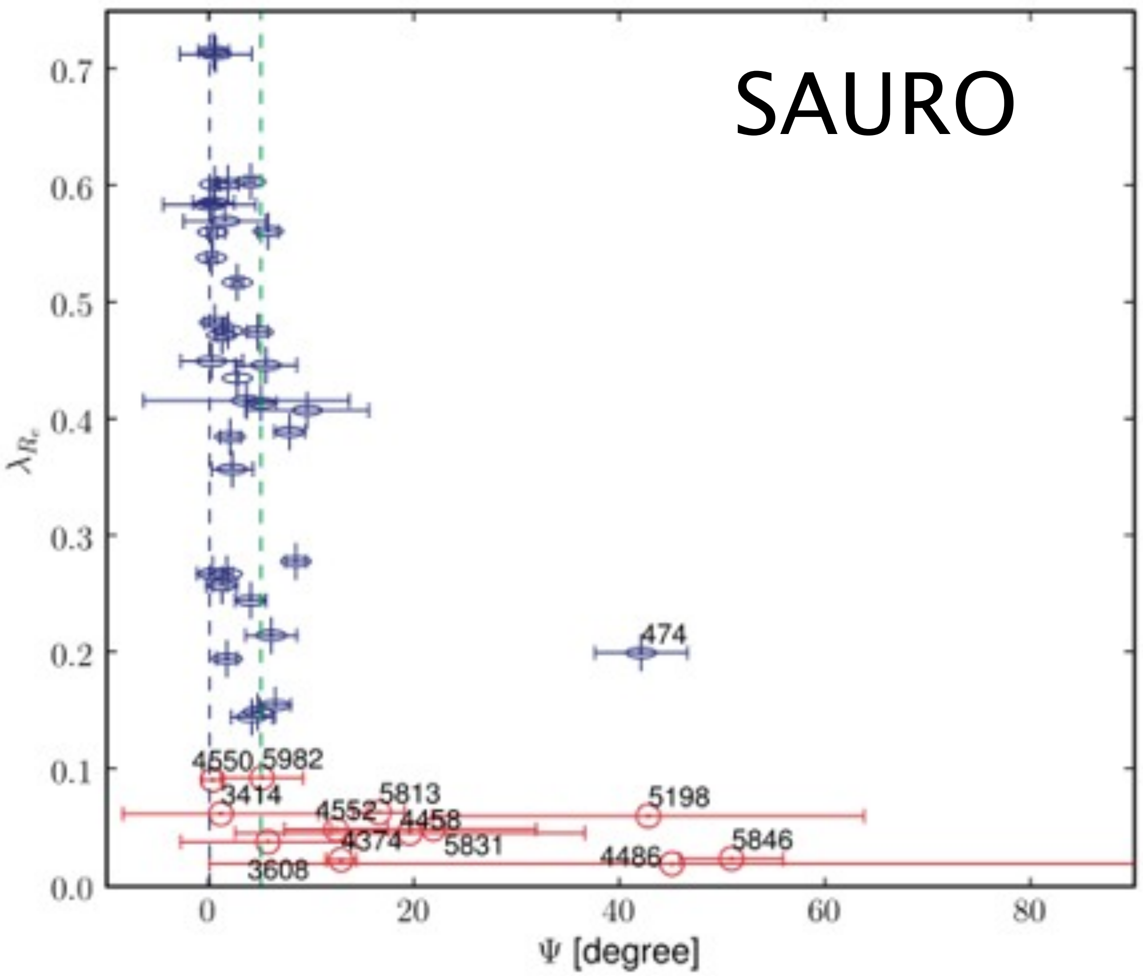




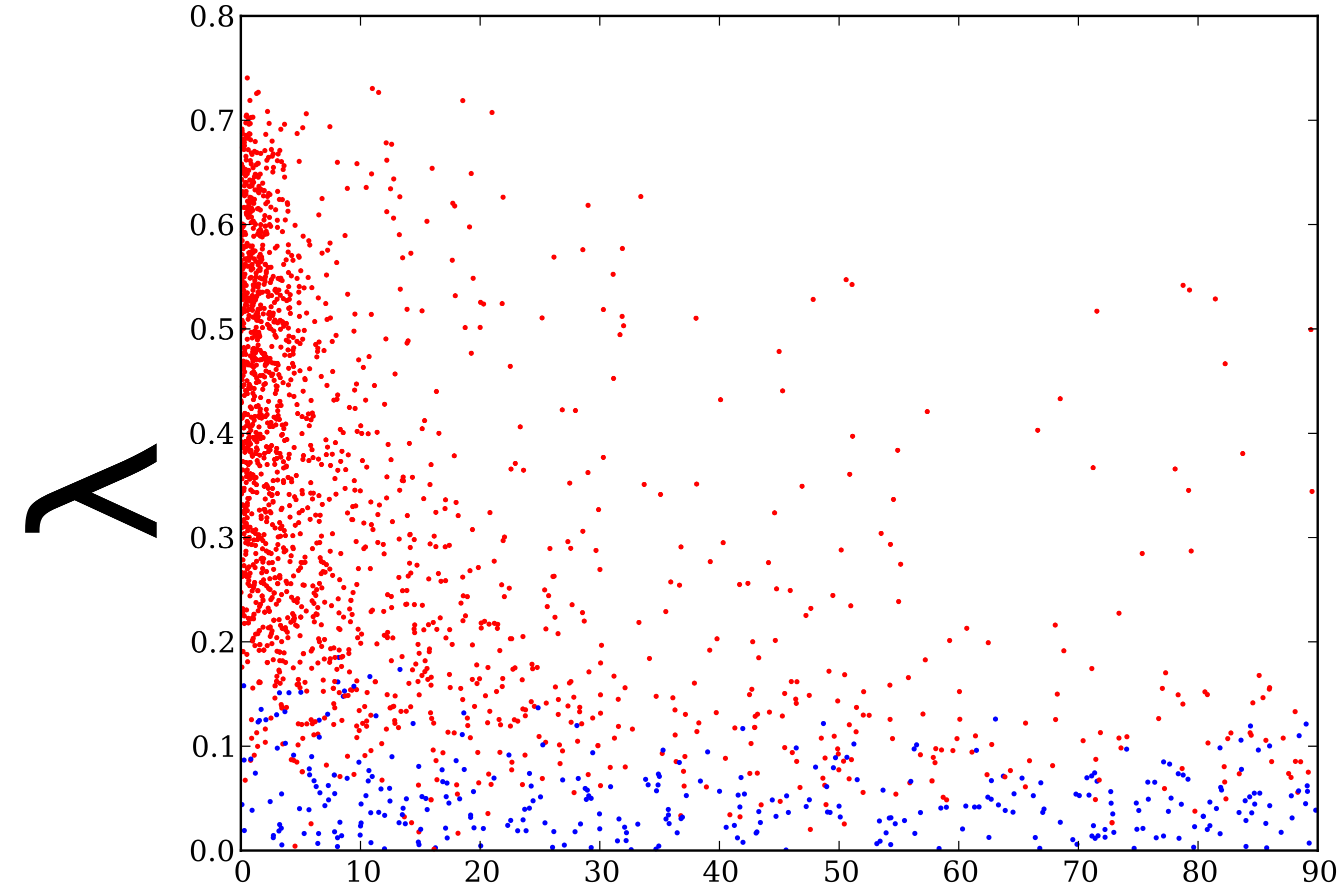
- Both sets of simulations have same number of identical progenitors
- **Multiple minor merger remnants are slower and rounder**

Misalignments

- Fast rotators ~5°
- Slow rotators 0°–90°



(Emsellem et al. 2007)

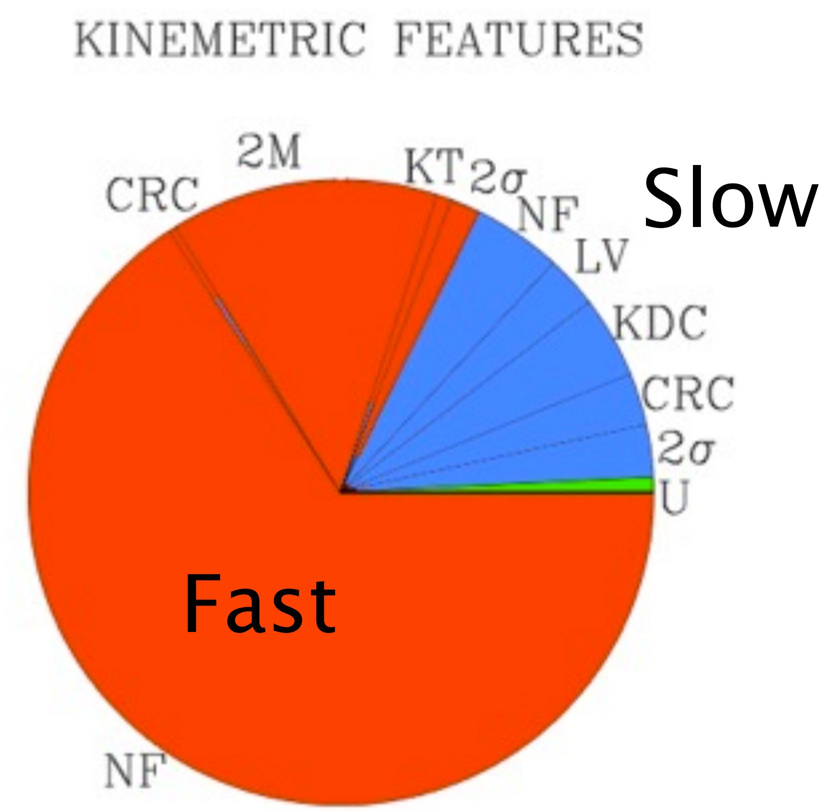


photometric–
kinemetric

- SAURON and simulations in good agreement

Kinematic Classification

- ATLAS^{3D} finds kinematically decoupled cores and other non regular rotators with high frequency in their slow rotator sample
- How do these features arise?
- 82% Fast Rotators
- 17% Slow Rotators, many with either KDC or CRC features

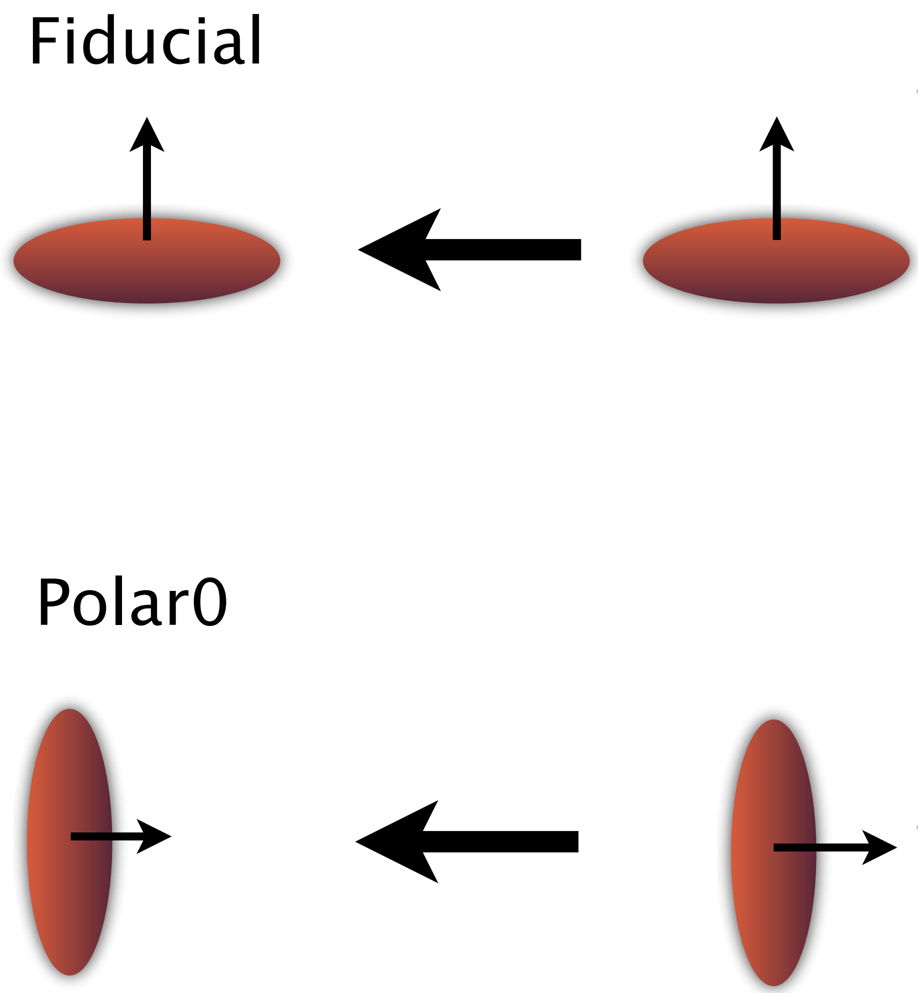


ATLAS^{3D} Kinematic Classification

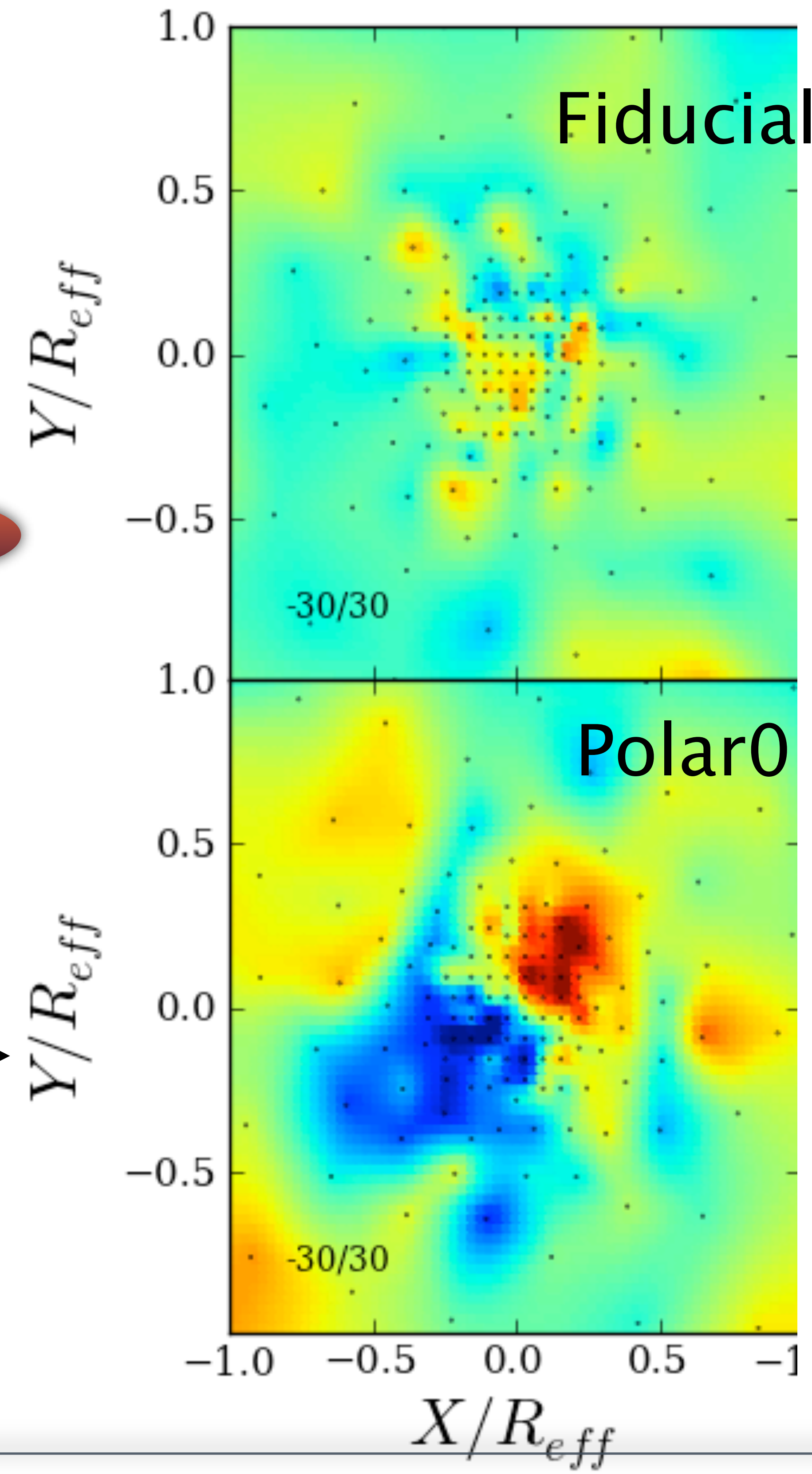
(Krajnović et al. 2011)

Polar orbits yield fast rotators but also KDCs

- Polar orbits impart significant momentum out of the plane of the progenitor galaxy

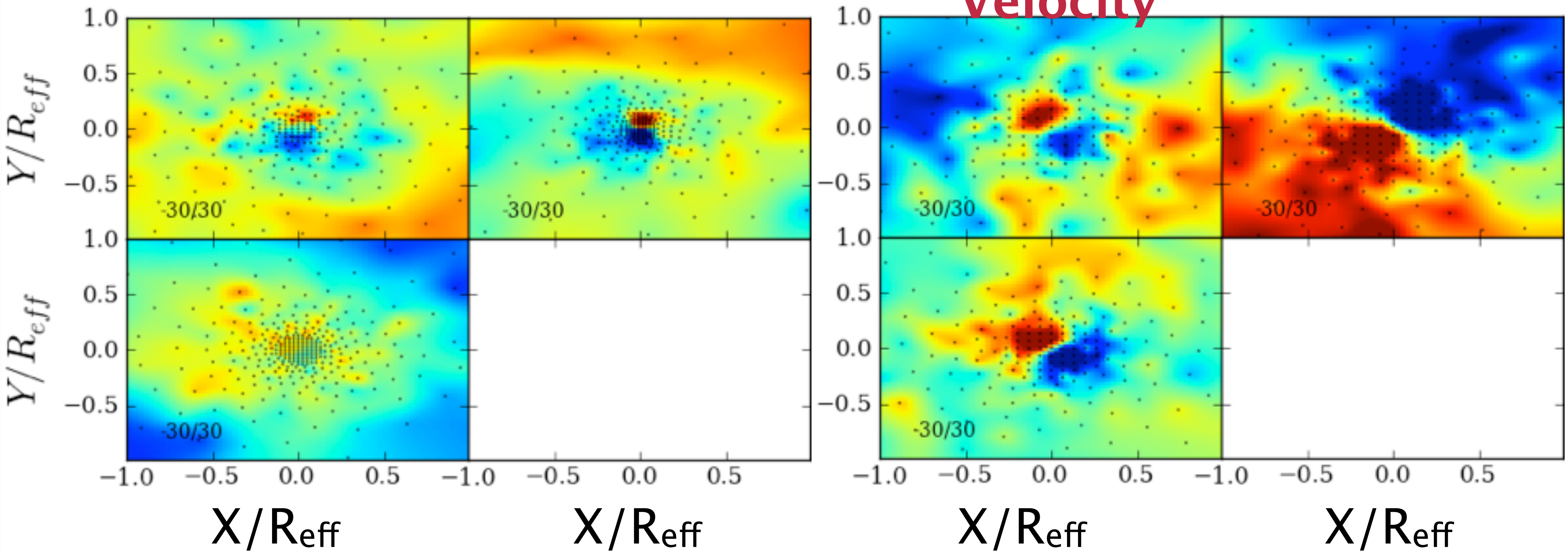


Face on velocity



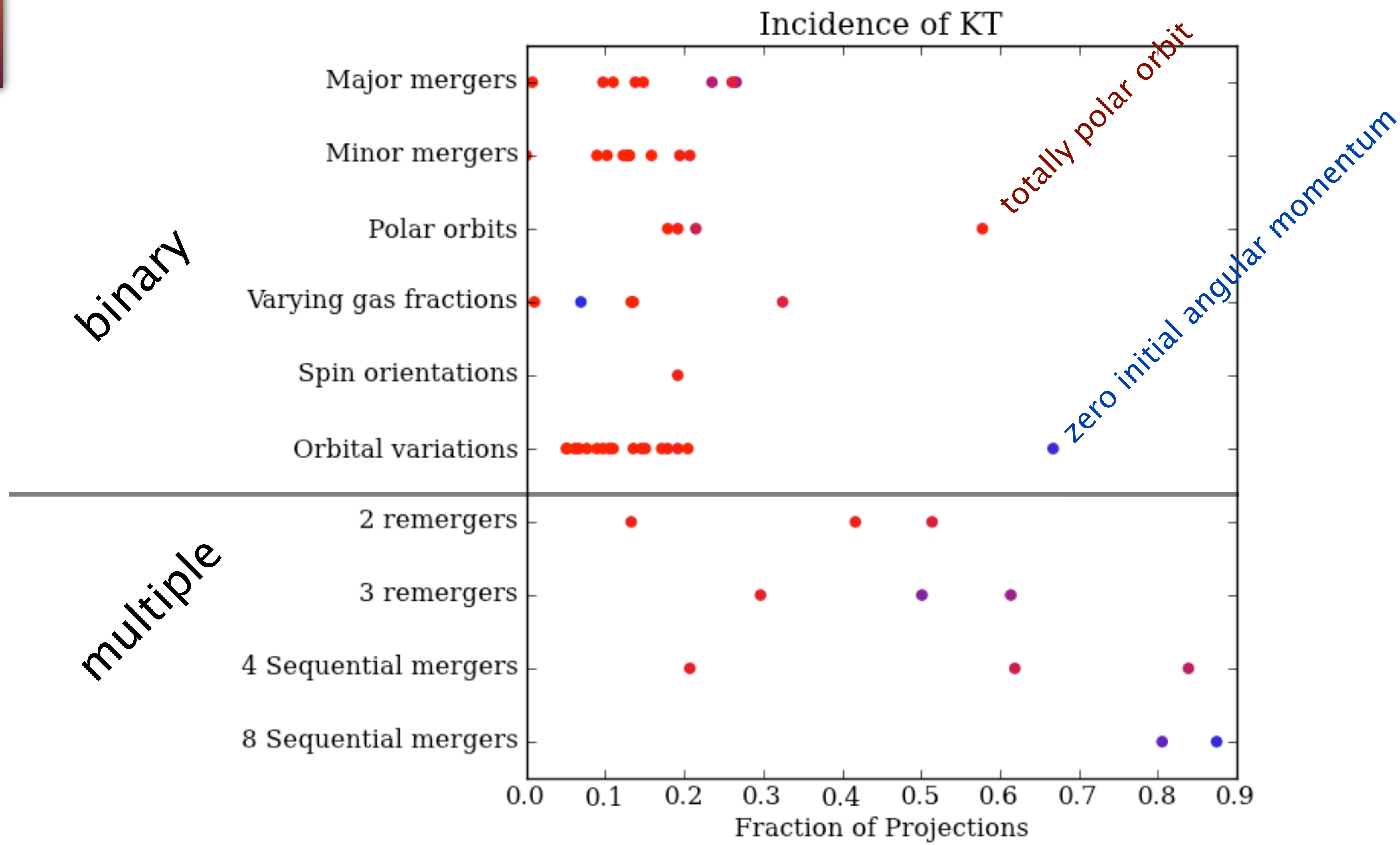
Sequential Merger KDCs

8xG1 Face-on Velocity **4xG2 Face-on Velocity**



- Small-scale KDCs present in many velocity maps for sequential series
- Major mergers result in a more disrupted remnant kinematic structure

Overall kinematic twist incidences



- **Multiple** mergers have KT rates of **20%–90%**
- **Binary** mergers have KT **<30%**, with exceptions

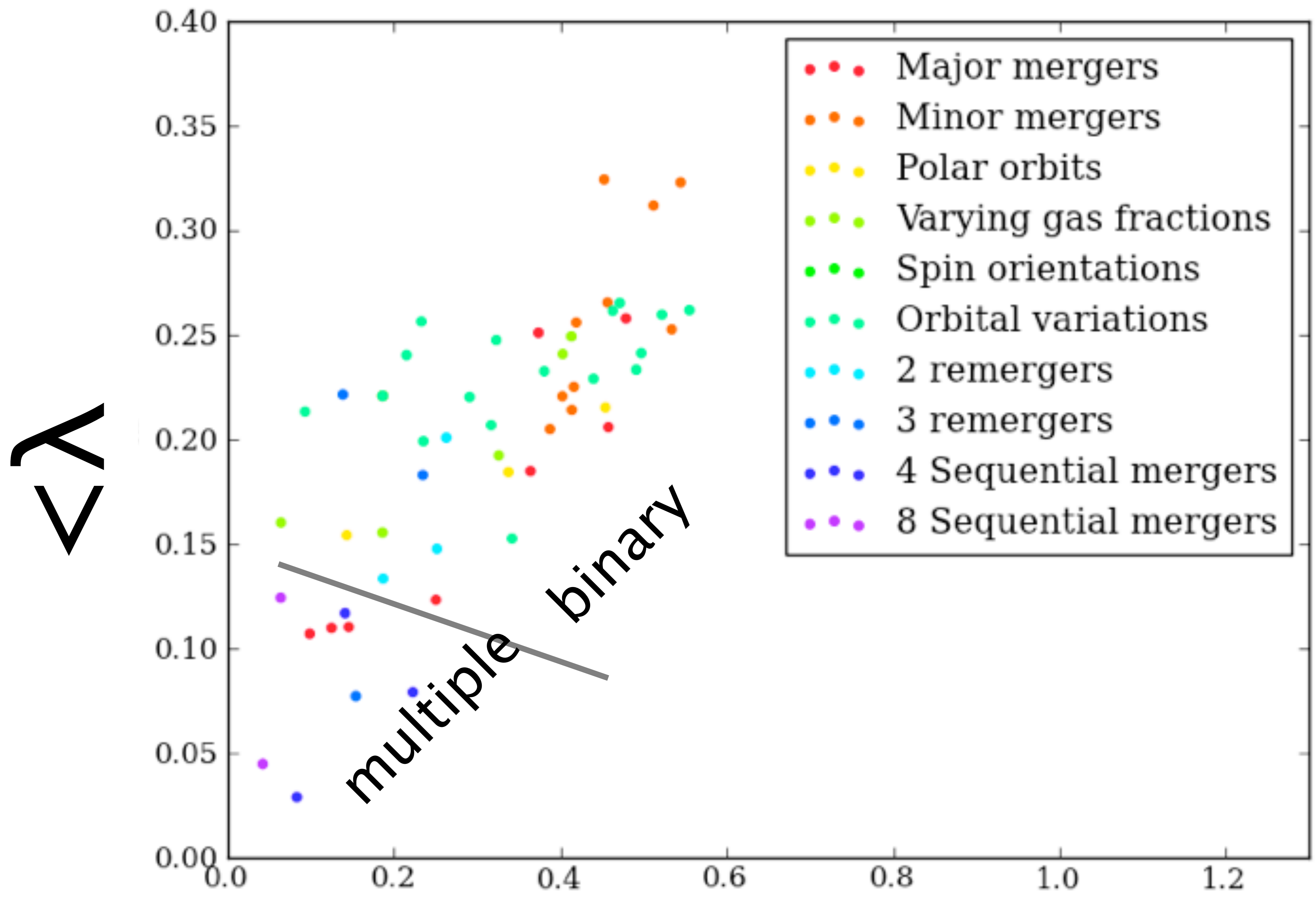
Conclusions

- Binary mergers generically form fast rotators
- Slow rotators are in general not formed in dissipational binary major mergers. The exceptions depend on unique initial conditions:
  - Bulgeless galaxies that are essentially dry mergers
  - Zero initial angular momentum

  } still quite elongated
- Sequential multiple mergers can form round slow rotators

- Kinematic twists much more prevalent in polar orbits and slow rotators

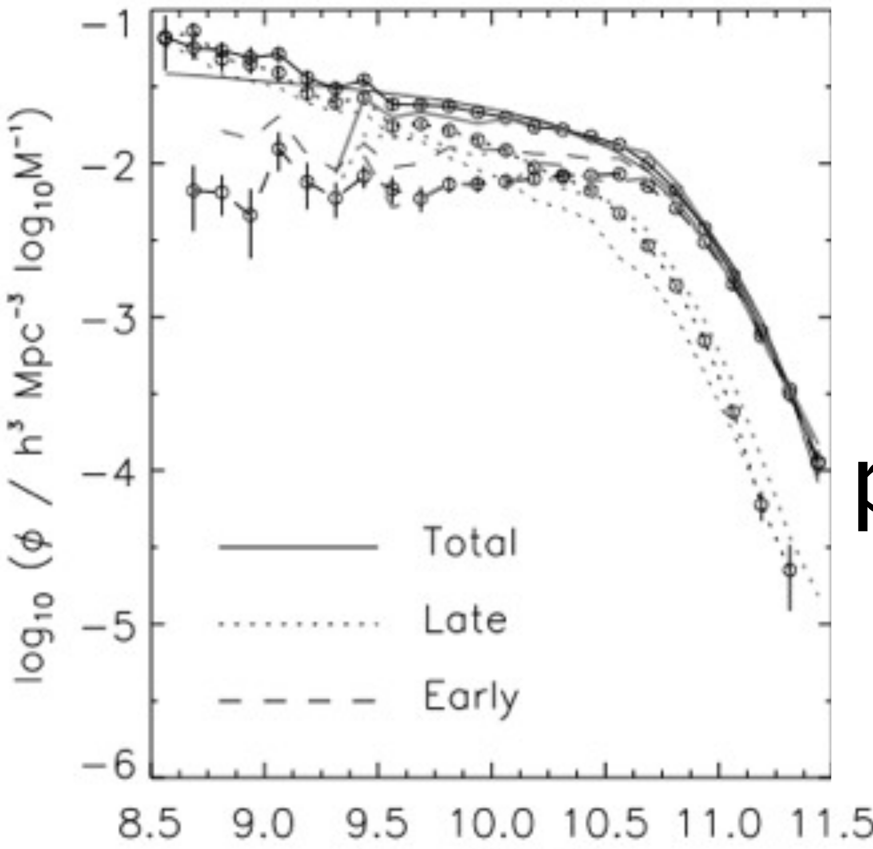
Overall Trends (averaged over all projections)



Multiple Mergers

SDSS mass function

Number density



log stellar mass

Semi-analytic model predictions

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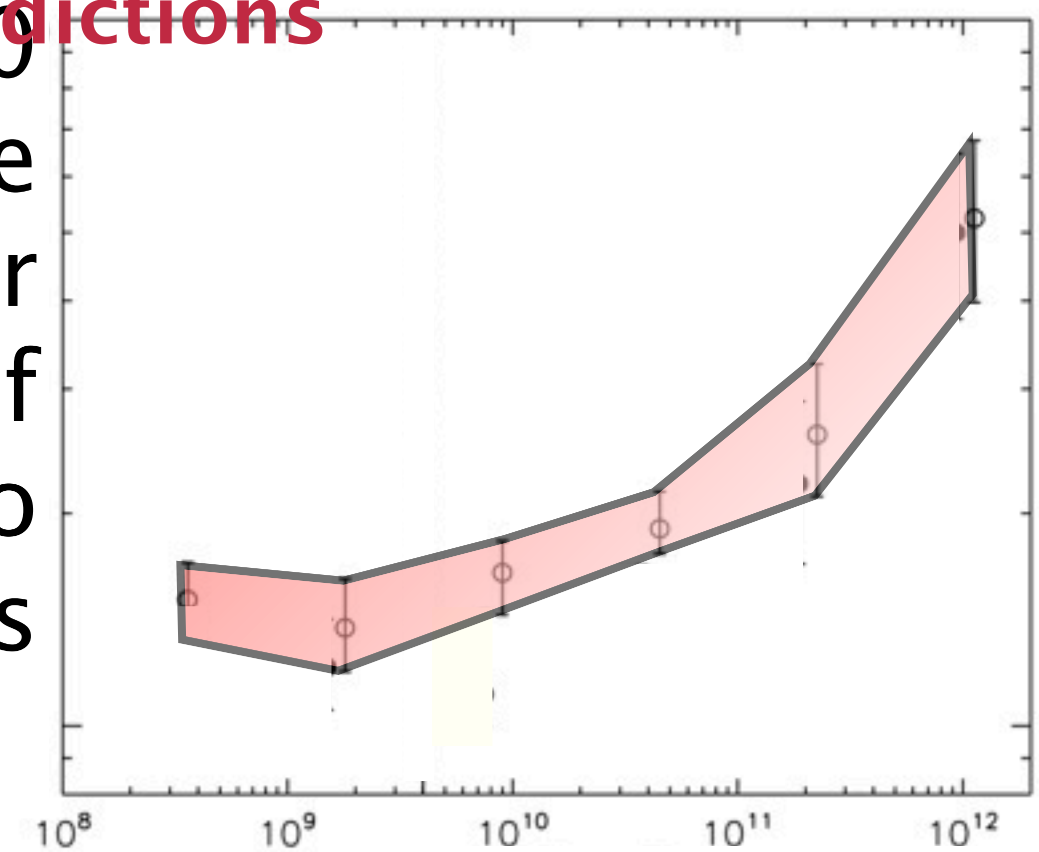
Effective number of progenitors



stellar mass

- Spiral progenitors are at least 1:10 stellar mass ratio
- Effective number of progenitors is mass-weighted
- Semi-analytic models predict that the most massive systems form by multiple mergers
- Multiple, minor mergers are a relevant scenario

(Left: Bell et al. 2003, Right: de Lucia et al. 2006)

Title

(Cites)

Simulation parameters

Extra

Table 1. Properties of progenitor galaxy models. M_{tot} is total mass, baryons plus dark matter; c is concentration (R_{vir}/r_s); M_{stars} is the initial stellar mass; B/D is the bulge-to-disc ratio; f_g is the initial gas mass divided by M_{tot}; $R_{1/2}$ is the initial three-dimensional stellar half-mass radius.

Type	M_{tot} (10^{10} M$_\odot$)	c	M_{stars} (10^{10} M$_\odot$)	B/D	f_g	$R_{1/2}$ (kpc)
Milky Way series						
D	1.4	20	0.036	0	0.025	1.16
Y	14.0	15	0.3	0	0.02	2.85
Z	143.0	12	5.1	0	0.004	4.04
Sbc series						
Sbc	81.4	11	4.92	0.26	0.066	7.15
G series						
G0	5.0	14	0.1	0.02	0.012	1.84
G1	20.0	12	0.5	0.06	0.010	2.33
G2	51.0	9	1.5	0.11	0.009	2.90
G3	116.0	6	5.0	0.22	0.011	3.90
G3 gas fraction series						
G3gf1	116.0	6	3.6	0.32	0.023	3.49
G3gf2	116.0	6	2.6	0.52	0.031	2.89
G3gf3	116.0	6	1.5	1.34	0.040	1.77
G3gf4	116.0	6	5.3	0.20	0.005	3.96

(Covington 2008, Cox 2004, Cox et al. 2006)

Simulation parameters

Extra

Table 1. Progenitor galaxy properties, grouped by series.

Type	M_{tot} $10^{10} M_{\odot}$	c	M_{baryon} $10^{10} M_{\odot}$	f_{gas}	B/D	$R_{1/2}$ (kpc)
Milk Way Series						
D	1.4	20	0.53	0.49	0	1.16
Y	14	15	0.76	0.48	0	2.85
Z	143	12	0.67	0.10	0	4.04
Sbc Series						
Sbc	81.4	11	10.00	0.52	0.26	7.15
G Series						
G0	5	14	0.44	0.38	0.02	1.84
G1	20	12	0.70	0.29	0.06	2.33
G2	51	9	2.00	0.23	0.11	2.9
G3	116	6	6.20	0.20	0.22	3.9
G3 gas fraction series						
G3gf1	116	6	3.09	0.43	0.32	3.49
G3gf2	116	6	4.18	0.58	0.52	2.89
G3gf3	116	6	5.40	0.76	1.34	1.77
G3gf4	116	6	0.68	0.10	0.2	3.96

(Covington 2008, Cox 2004, Cox et al. 2006)