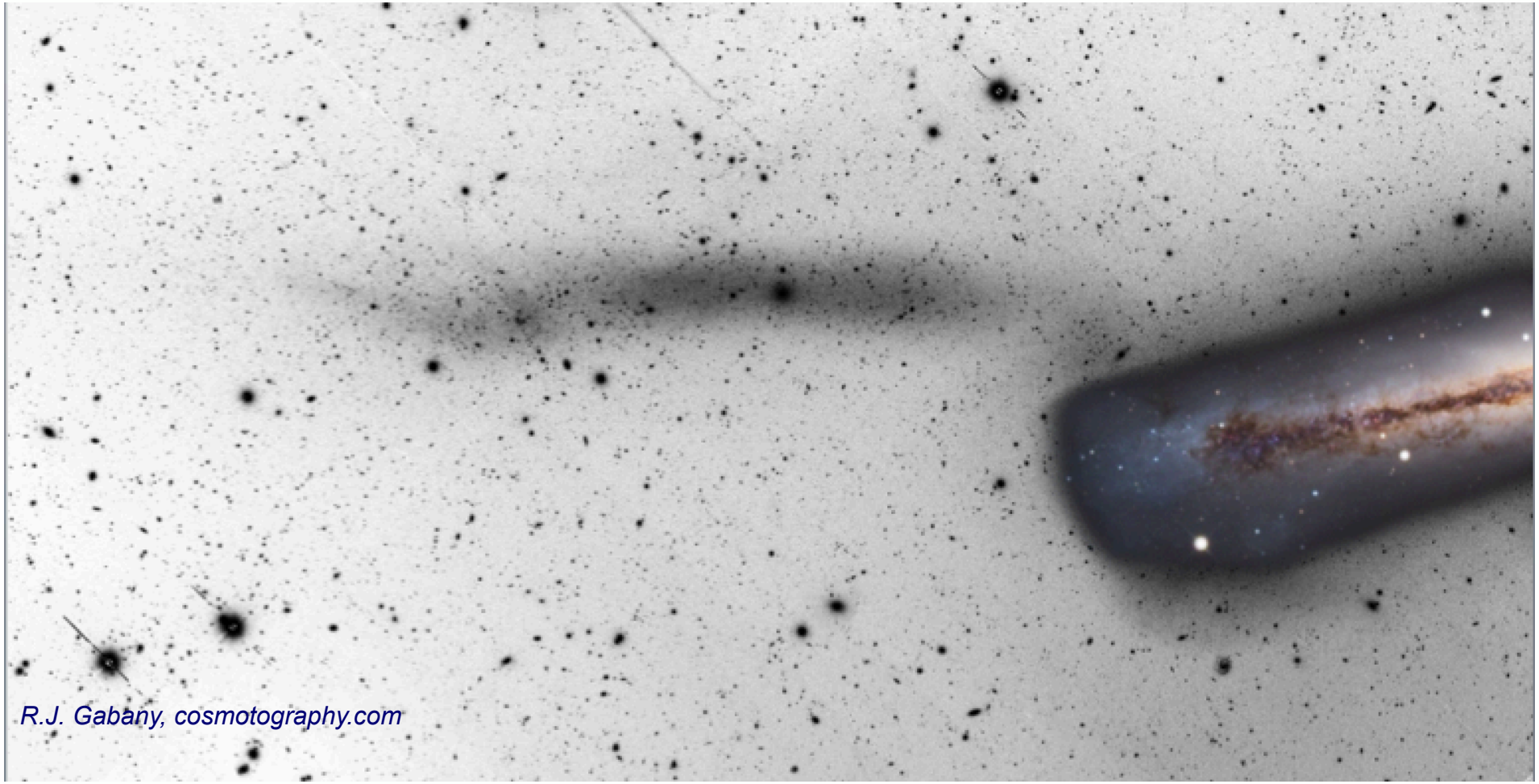
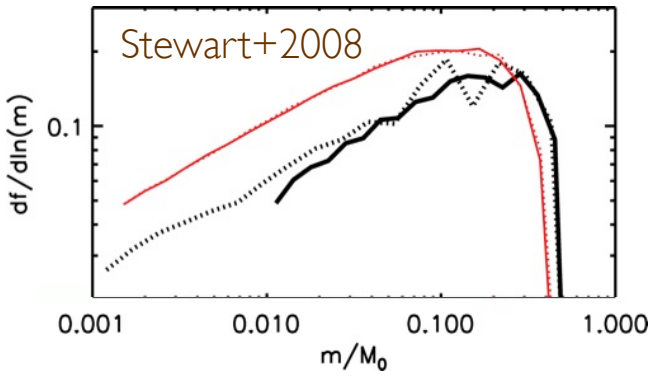
Tidal streams beyond the Local Group:
… from photometry to dynamics

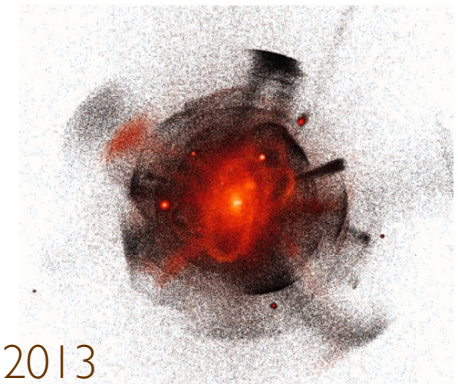


Aaron J. Romanowsky, San José State Univ., Univ. Calif. Observatories

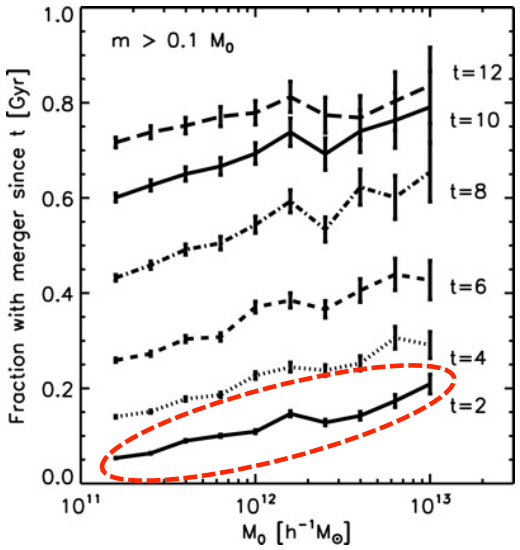
ΛCDM-based predictions for ~~substructure~~ & accretion

accreted mass fraction typically dominated by ~1:10 mass ratio



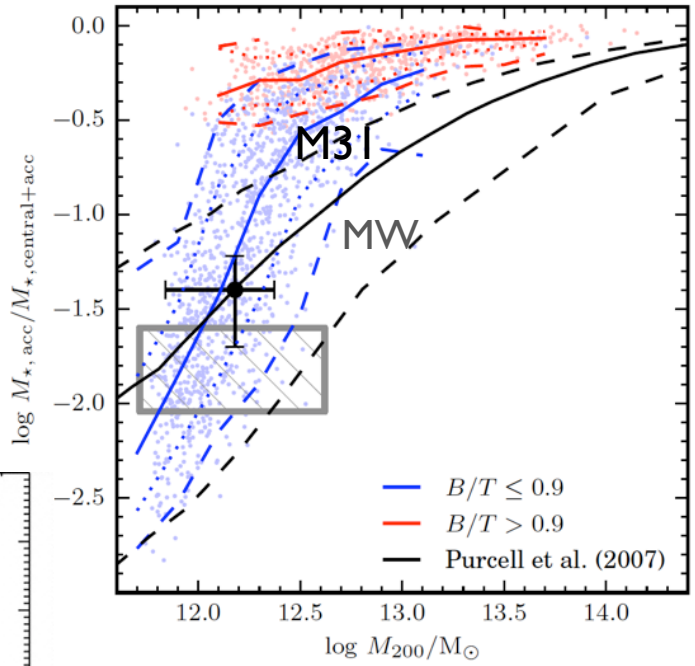


Cooper+2013



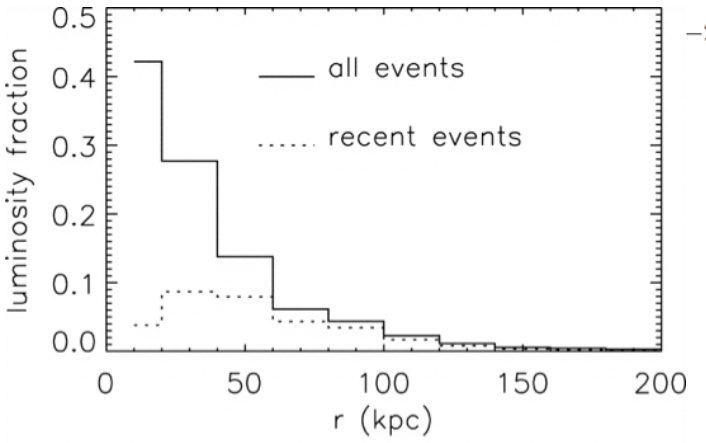
at $z = 0$, ~10% of galaxies had ≥ 1:10 merger in last 2 Gyr

accretion increases with host mass



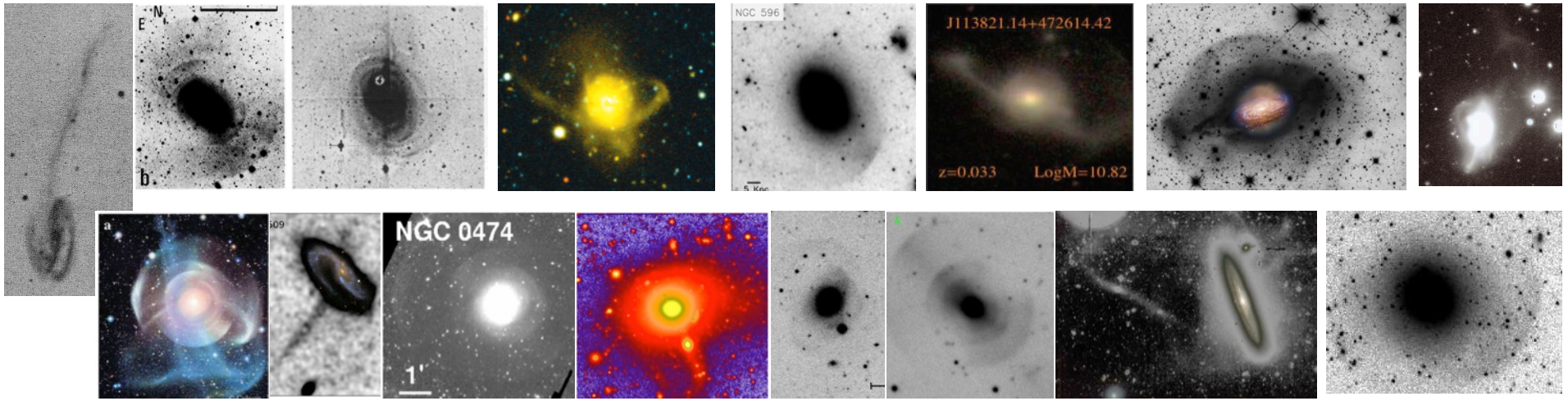
$z = 0$ accretion deposited in outer halo, r >~ 30 kpc

Bullock & Johnston 2005



elliptical galaxies more accretion-dominated than spirals

Photometric substructure surveys : *what have we learned?*



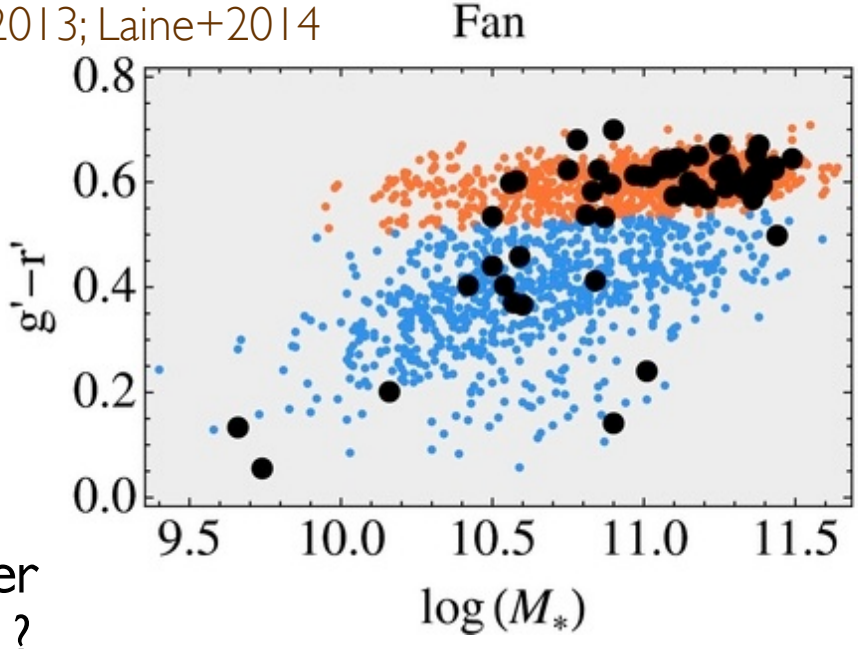
Arp 1966; Malin & Carter 1983; Schweizer & Seitzer 1988; van Dokkum 2005; Tal+2009; Nair & Abraham 2010; Martínez-Delgado+2010; Kaviraj 2010; Duc+2011; Miskolczi+2011; Kim+2012; Sheen+2012; Adams+2012; Atkinson+2013; Paudel+2013; Laine+2014

surveys found substructure fractions from 3% to 70%

→ depends on environment, substructure type, surface brightness limit, etc.

red galaxies twice as likely as blue to host tidal features (Atkinson+2013)

→ what about lower surface brightness, older streams, kinematics, chemical abundances ?

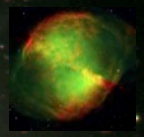


Substructure: dynamical tracers and timescales

L^* early-type galaxy with $v_c \sim 230$ km/s : $\tau_{dyn} \sim 1.0$ Gyr × (r / 100 kpc)

PN.S

$R \sim 40$ kpc,
$\tau_{dyn} \sim 0.6$ Gyr



$R \sim 20$ kpc,
$\tau_{dyn} \sim 0.3$ Gyr

SMEAGOL

$R \sim 10$ kpc,
$\tau_{dyn} \sim 0.15$ Gyr

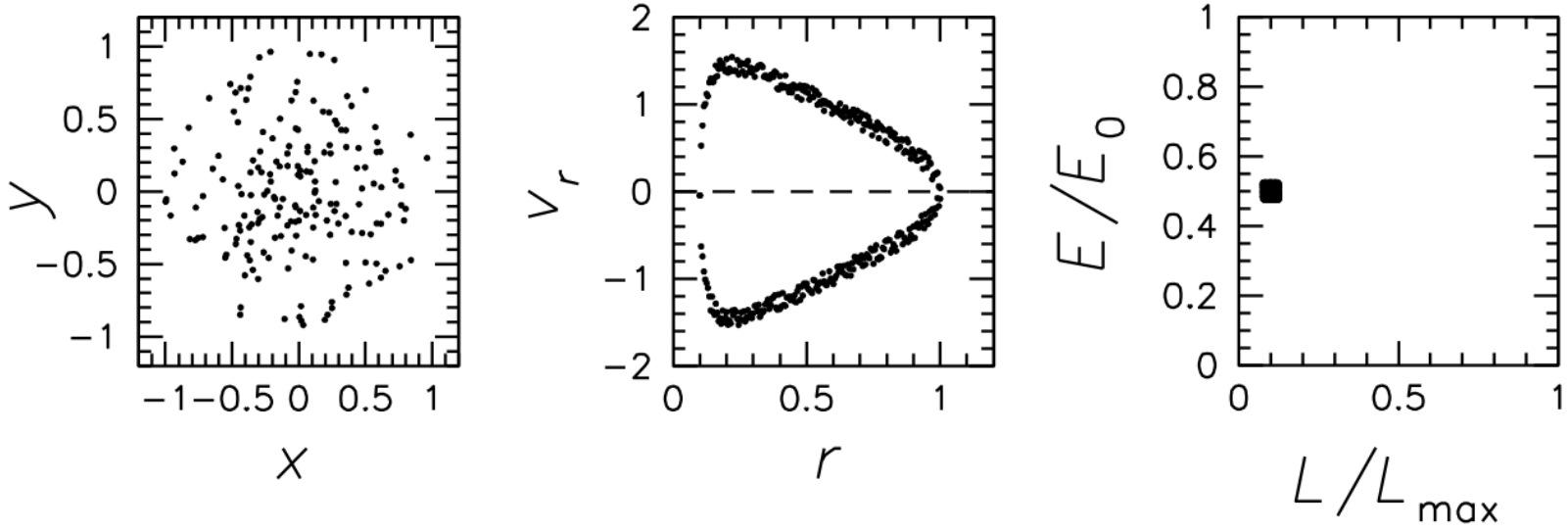
SLUGGS

SAURON

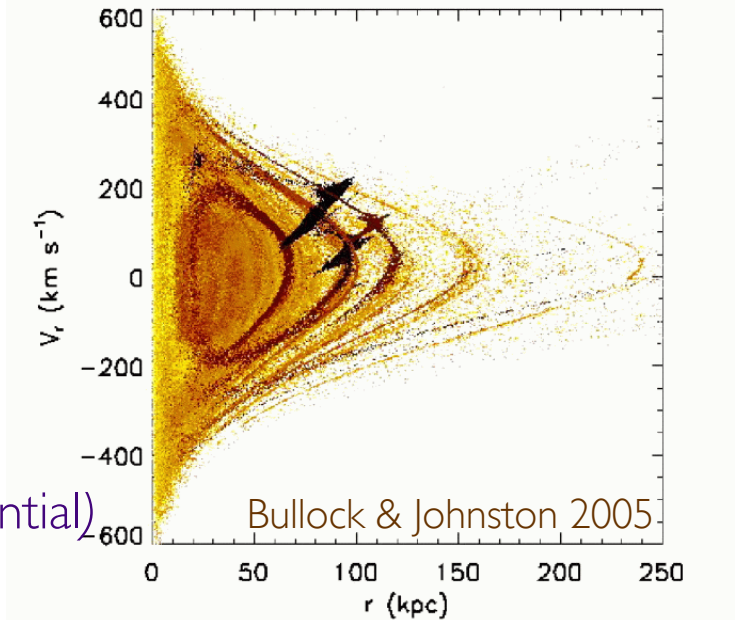
$R \sim 2$ kpc,
$\tau_{dyn} \sim 0.03$ Gyr

- need high-precision measurements: $\Delta v_i << \sigma_{host}$
- beyond Local Group (~1 Mpc), can't do it with stars:
  need brighter orbital tracers! (PNe, GCs)

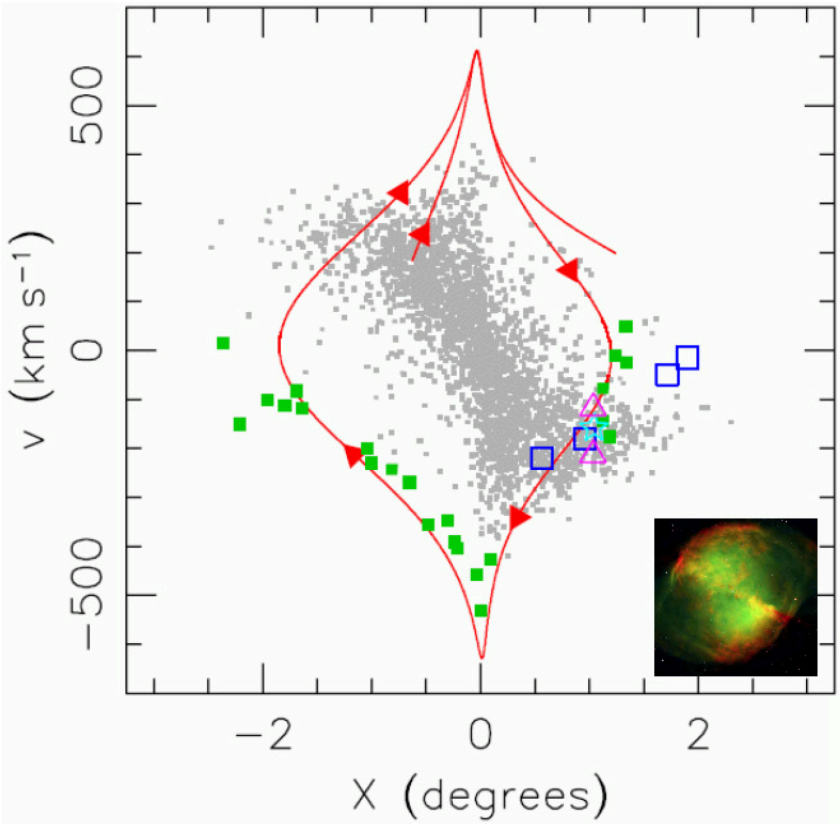
Mapping "invisible" substructures in phase−space

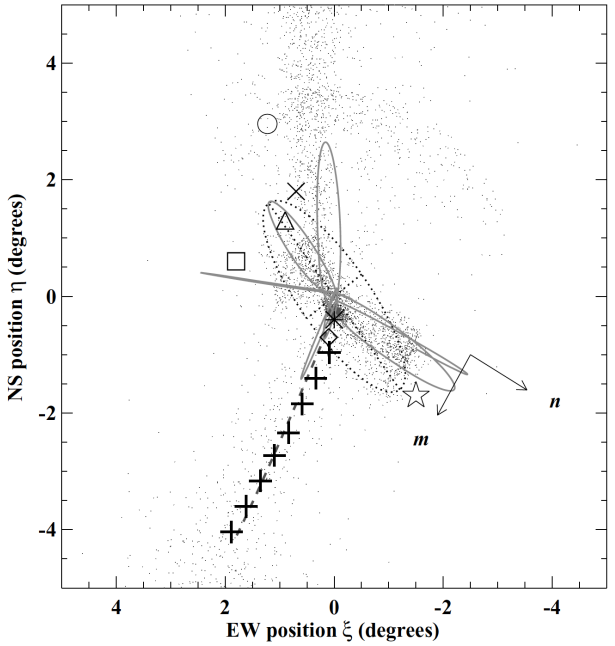


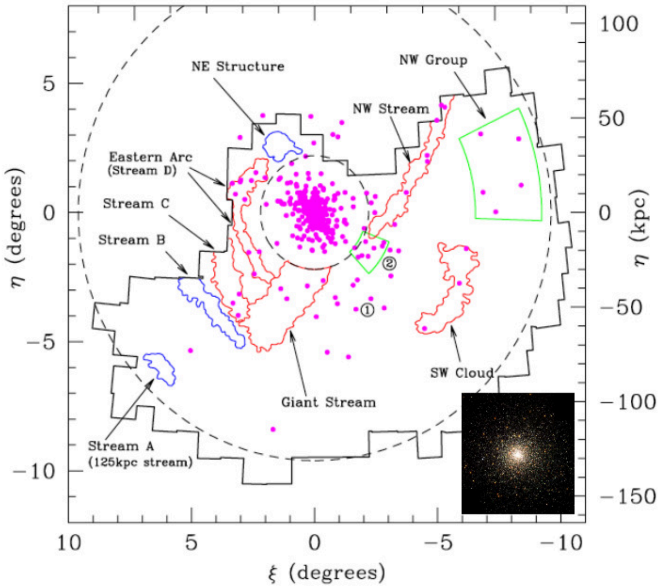
- substructures that are phase-mixed and undetectable in *configuration space* are preserved in position−velocity ***phase−space***
- more detectable using dynamical modeling to map to ***integrals of motion*** or actions
- cosmological simulation of satellite accretion in Milky Way-type halo: *long-lived cold streams in phase-space (but quasi-static potential!)*
- in "live" simulations, cold streams decay after ~1−2 t_{dyn} (phase-mixing + time-dependence of potential) (Rudick+2009)



M31: streams in GCs and PNe





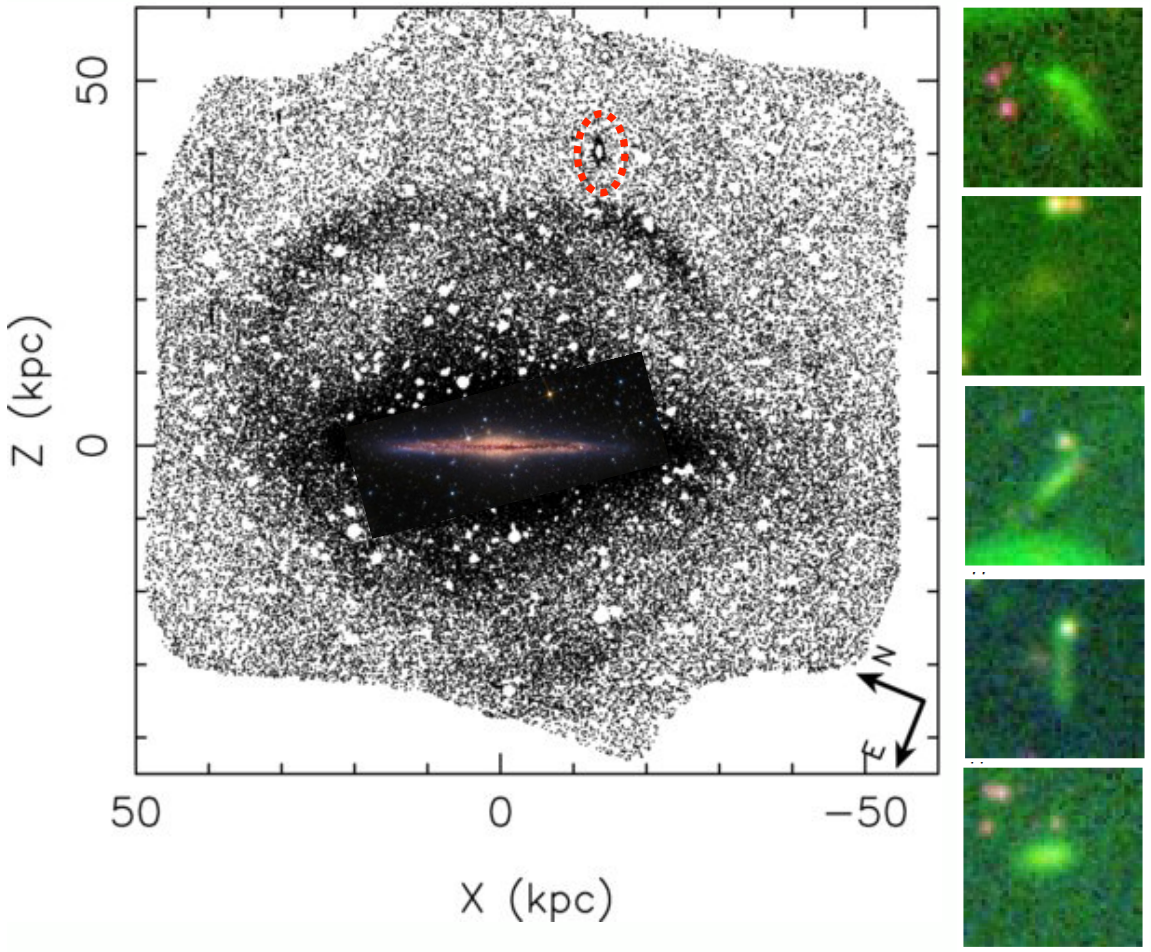


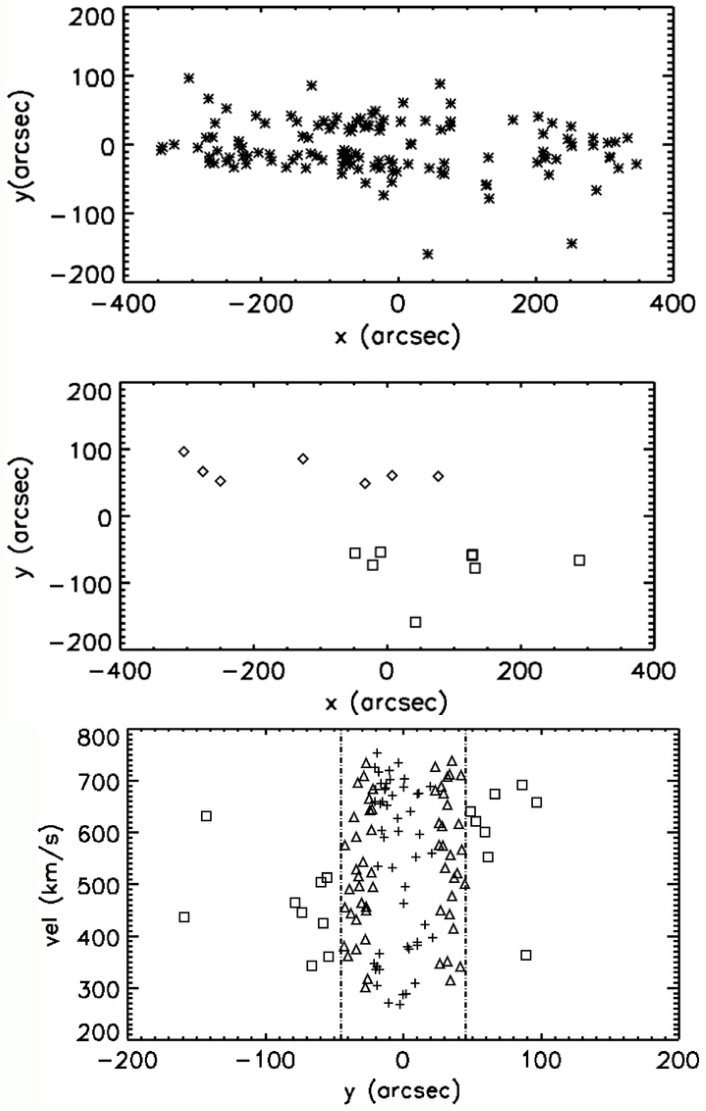
PNe trace phase−space trajectory of Giant Southern Stream across face of M31 disk (Merrett+2003,2006)

used to model stream orbit (Fardal+2006)

GCs associated with stellar streams (Mackey+2010; Veljanoski+2013)

Substructure in MW twin NGC 891



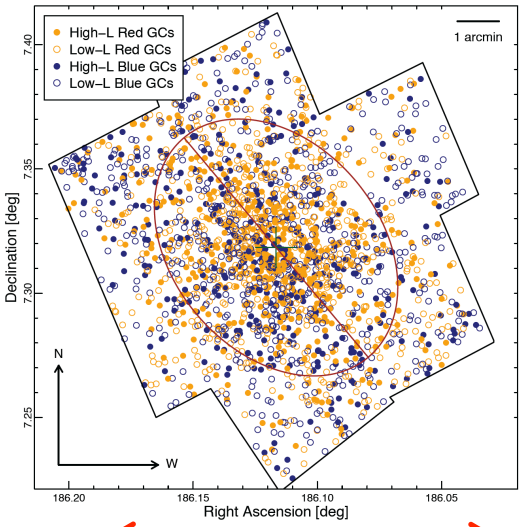


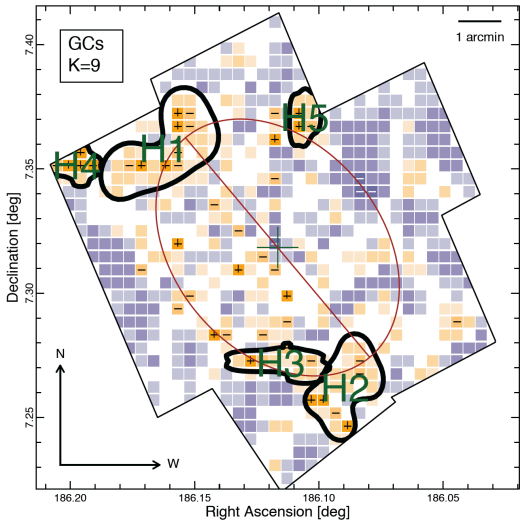
NGC 891 RGB star map: inner halo streams + stellar coccoon (Mouhcine+2010)

7 dSph candidates (Schulz 2014)

PN velocities: skewed, "thick ring", trace stellar stream? (Shih & Méndez 2010)

Substructures in globular cluster systems



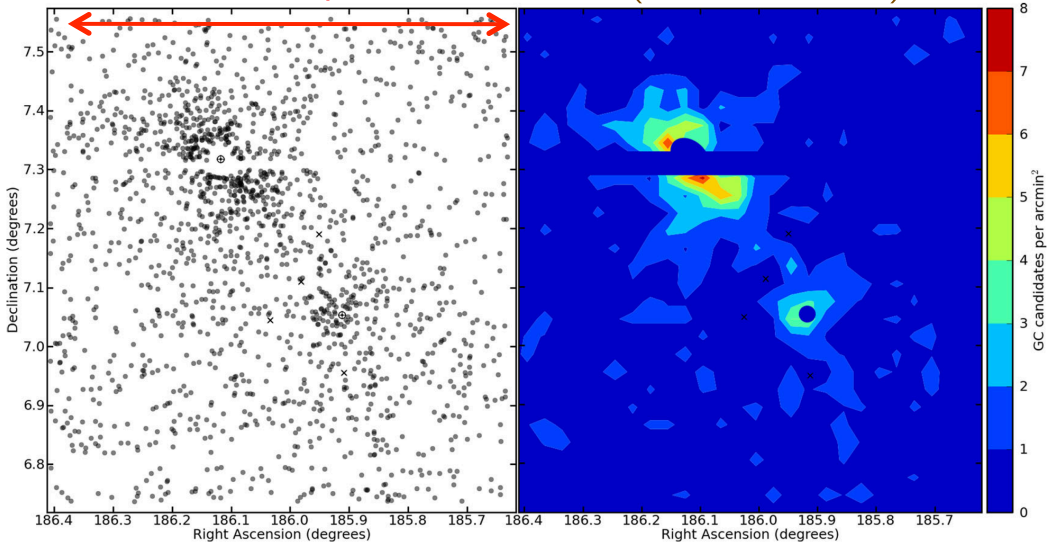


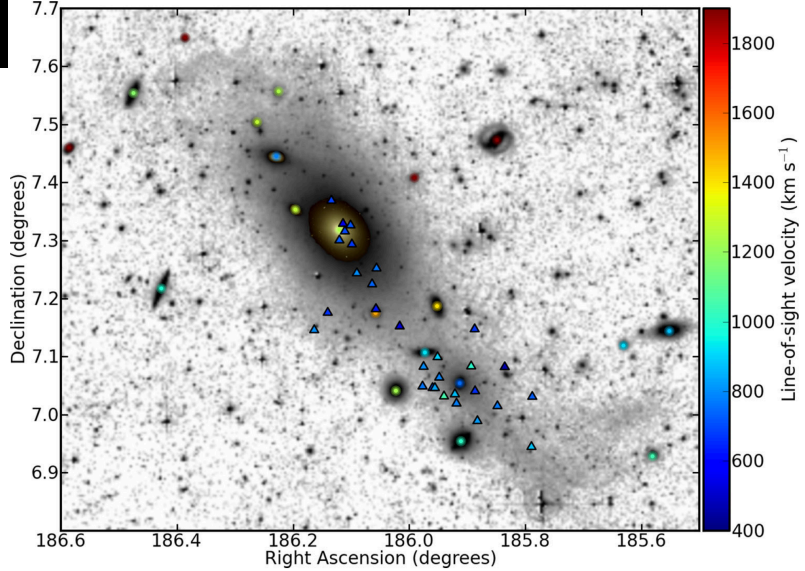
spatial-clumping of GCs around elliptical galaxy NGC 4365 using nearest-neighbor analysis + *HST*/ACS data (D'Abrusco+2015)

stream connected to compact S0 from large-scale GC photometry+kinematics

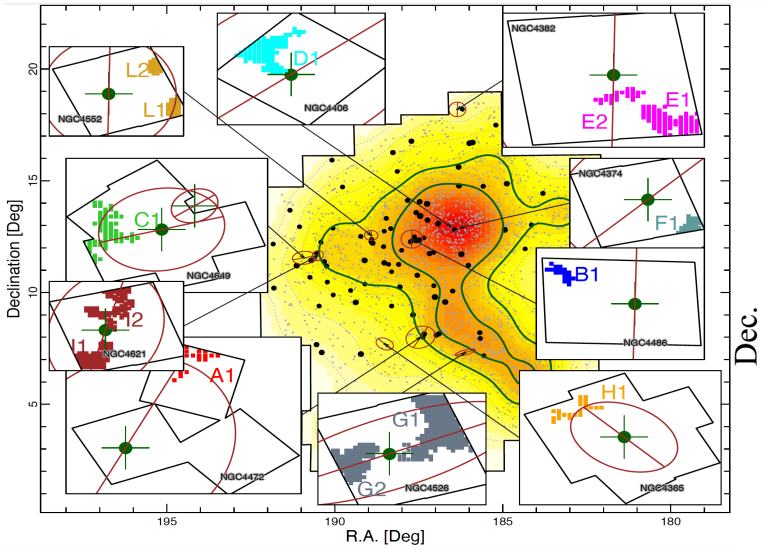
300 kpc

(Blom+2014)



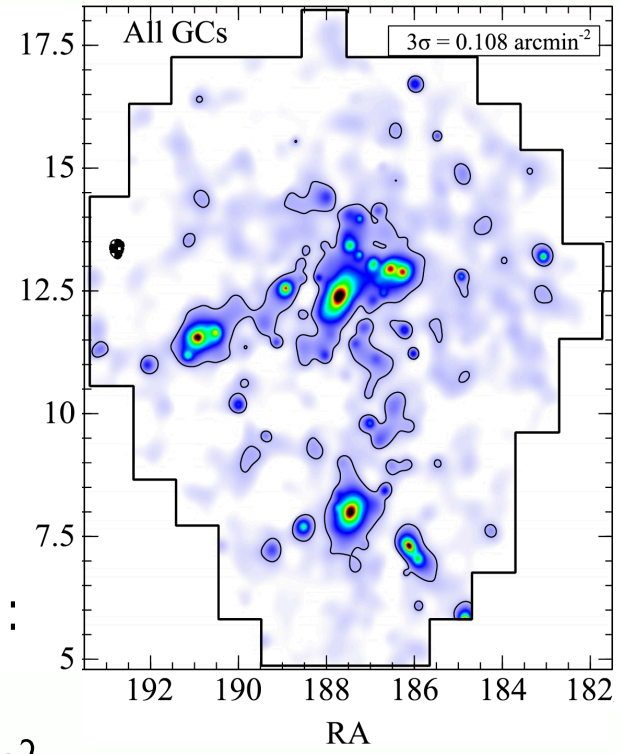


Virgo substructure with GCs

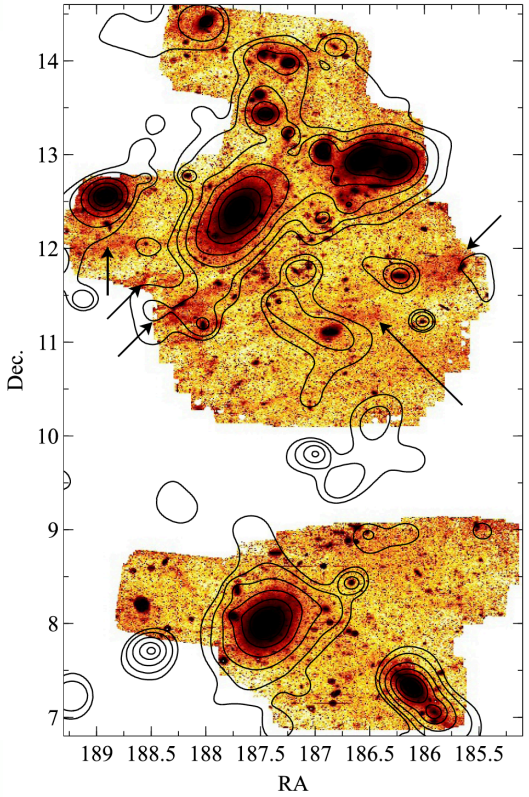


10 giant early-types with *HST* : substructures found preferentially along major axes? (D'Abrusco+2015)

spatial coverage very incomplete…

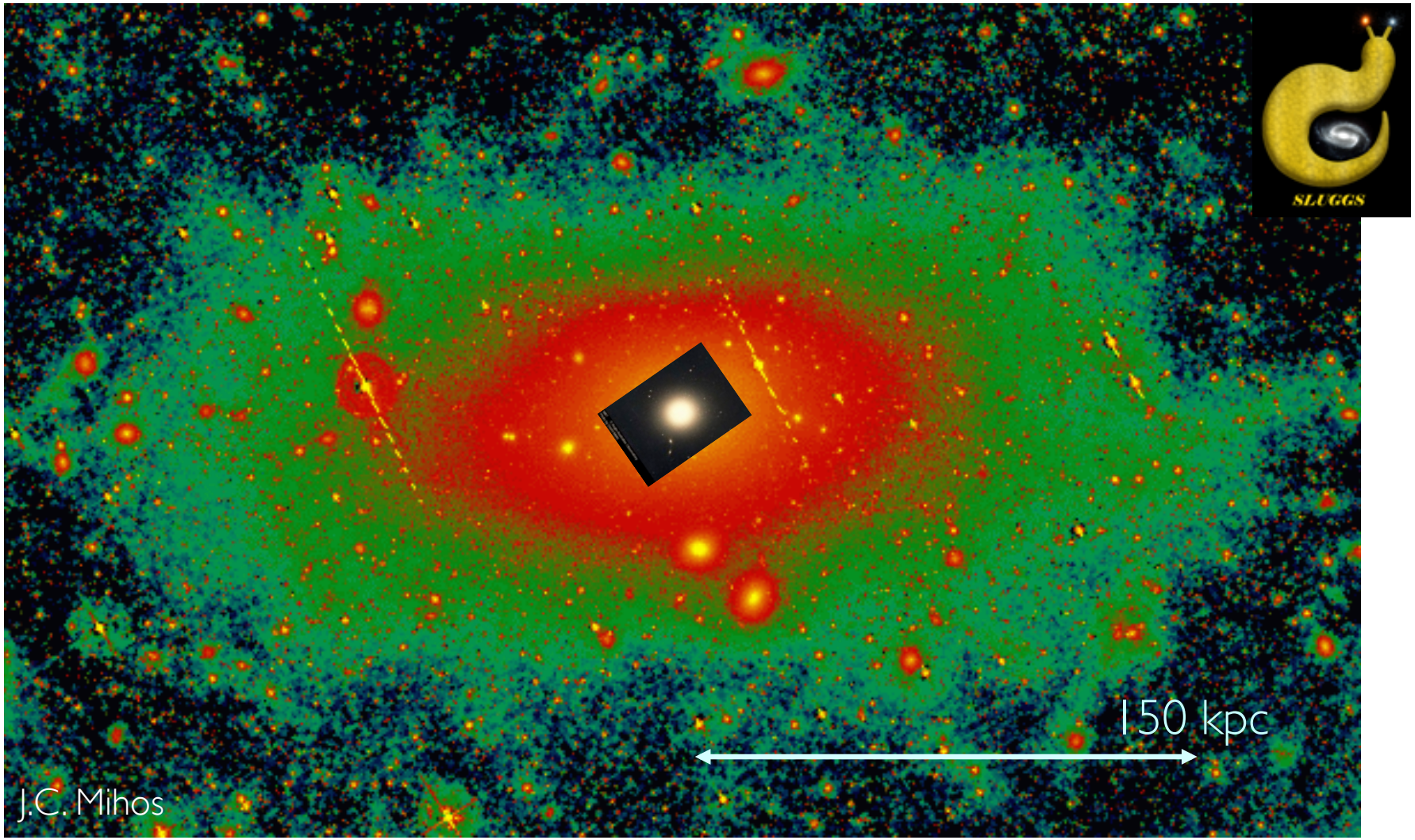


GC mapping of entire Virgo cluster: clumps and connections (Durrell+2014)



GCs match up to diffuse light distribution (Mihos+2005)

Ultra-wide-field kinematics of M87 globular clusters

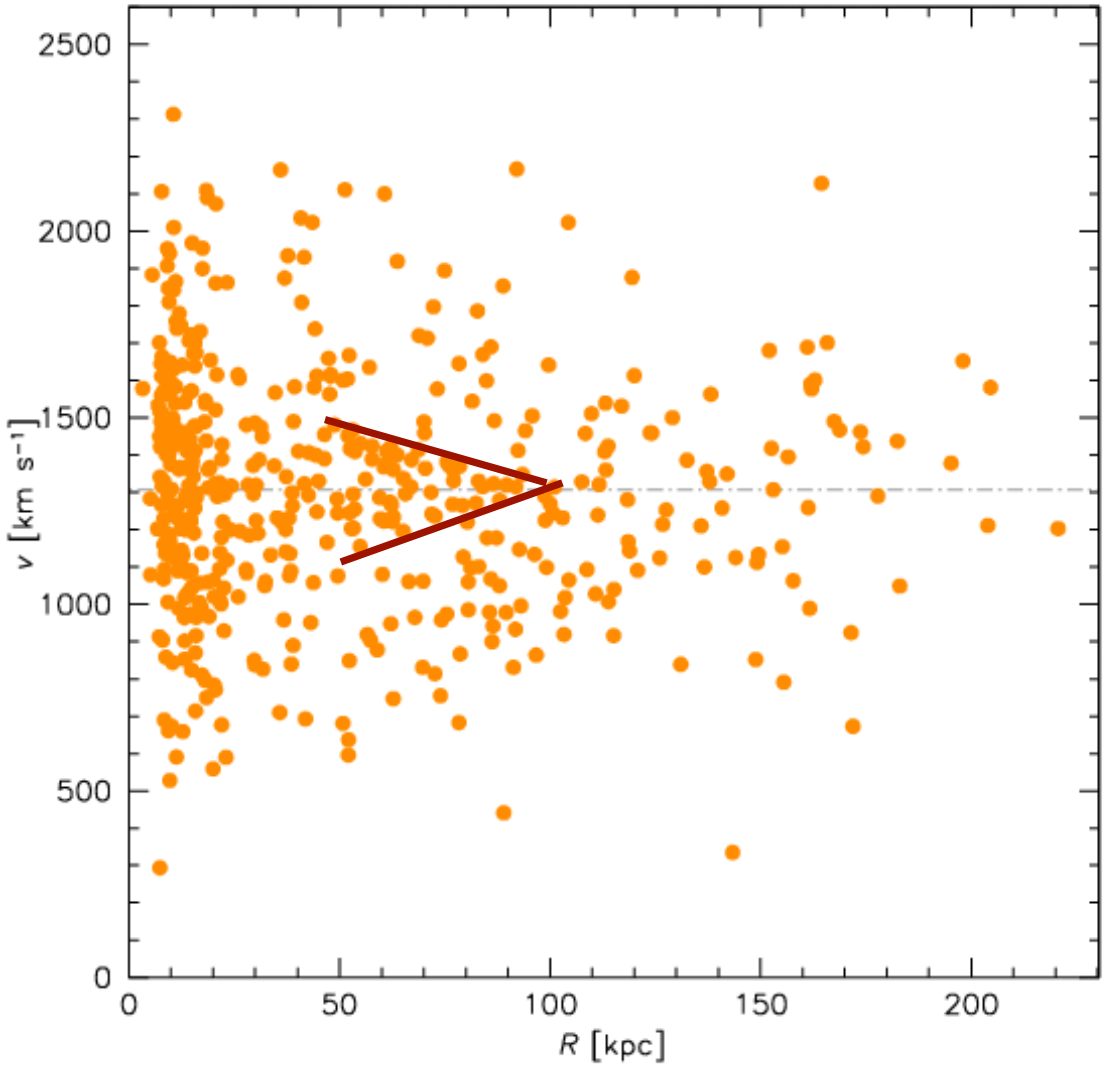


Keck/DEIMOS, LRIS, MMT/Hectospec (Strader+2011; Romanowsky+2012)

468 velocities to $i \sim 22.5$, $R \sim 200$ kpc ; typical $\Delta v \sim 18$ km s^{-1}

344 *HST* size measurements

M87: halo substructure discovered with GCs

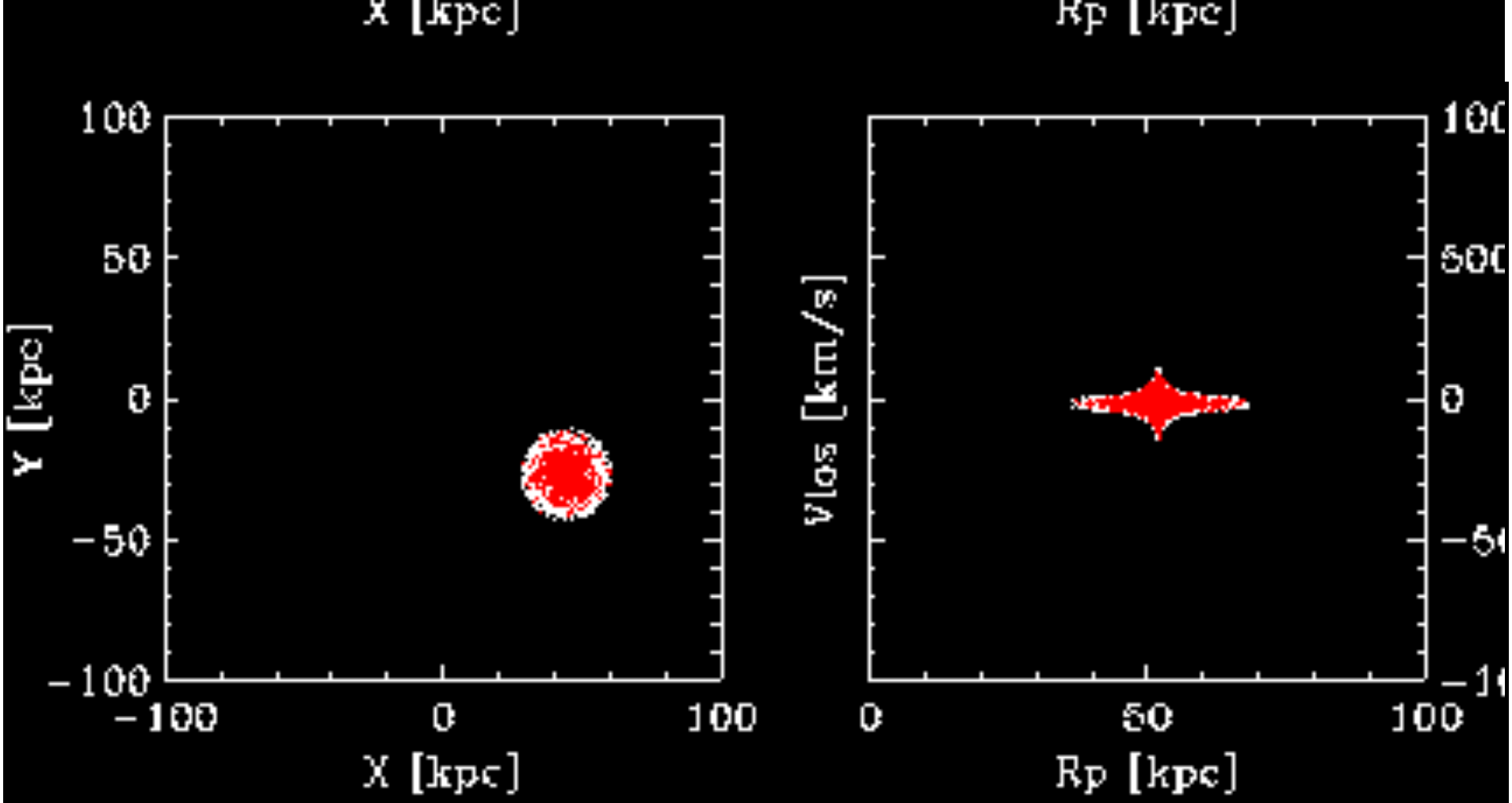


Romanowsky+2012

high velocity precision reveals cold kinematic structure in halo

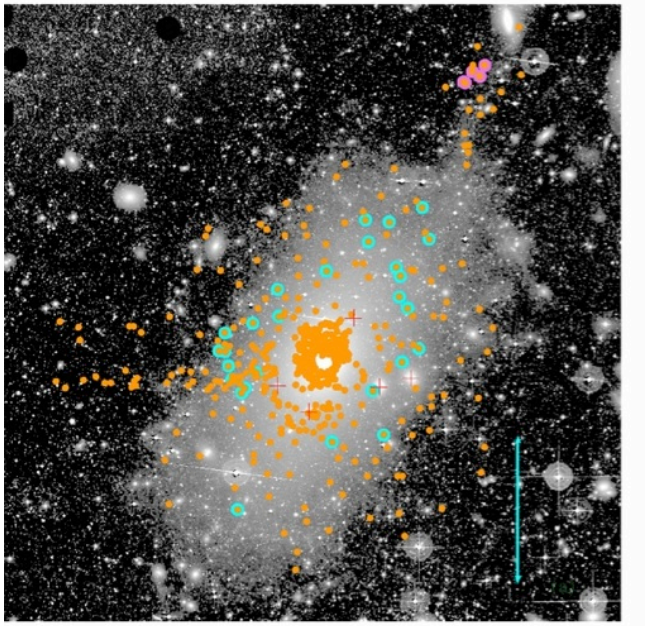
chevron morphology is classic signature of accretion shell

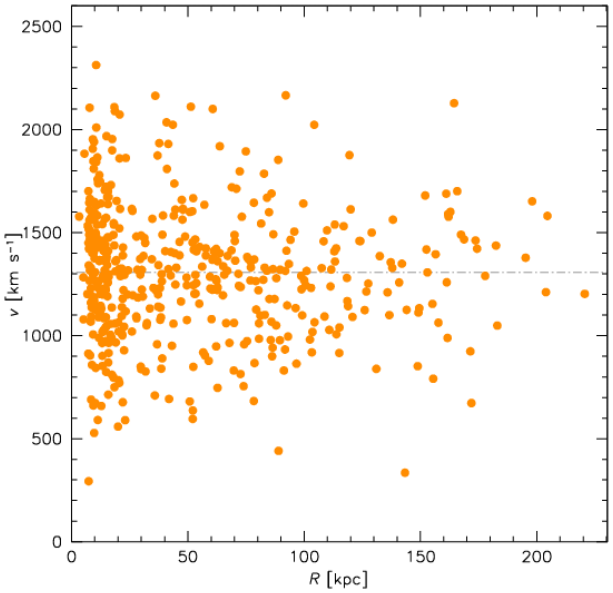
(e.g., Hernquist & Quinn 1988; Fardal+2007)

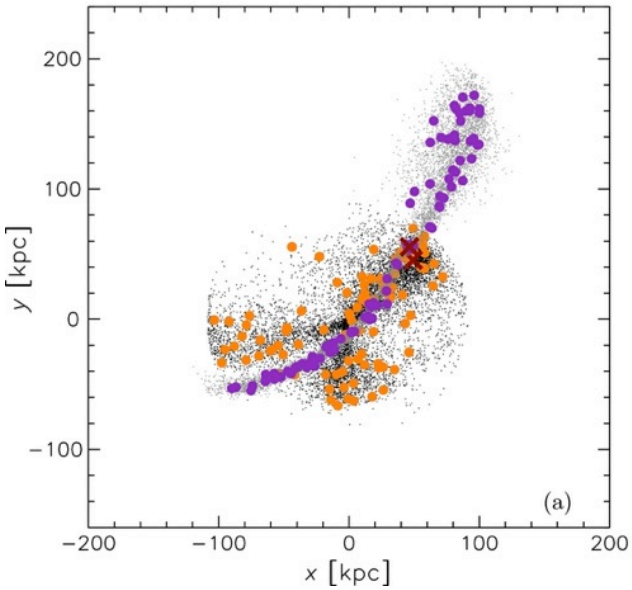


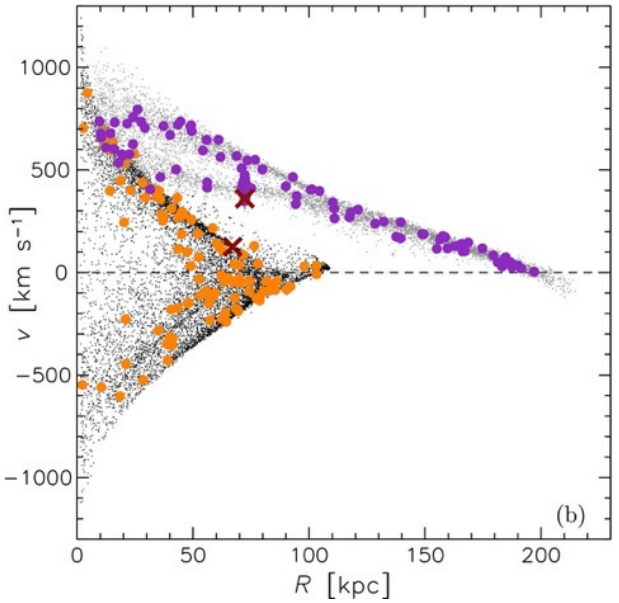
N-body model
dwarf galaxy, low angular momentum orbit

M87: shell dynamics





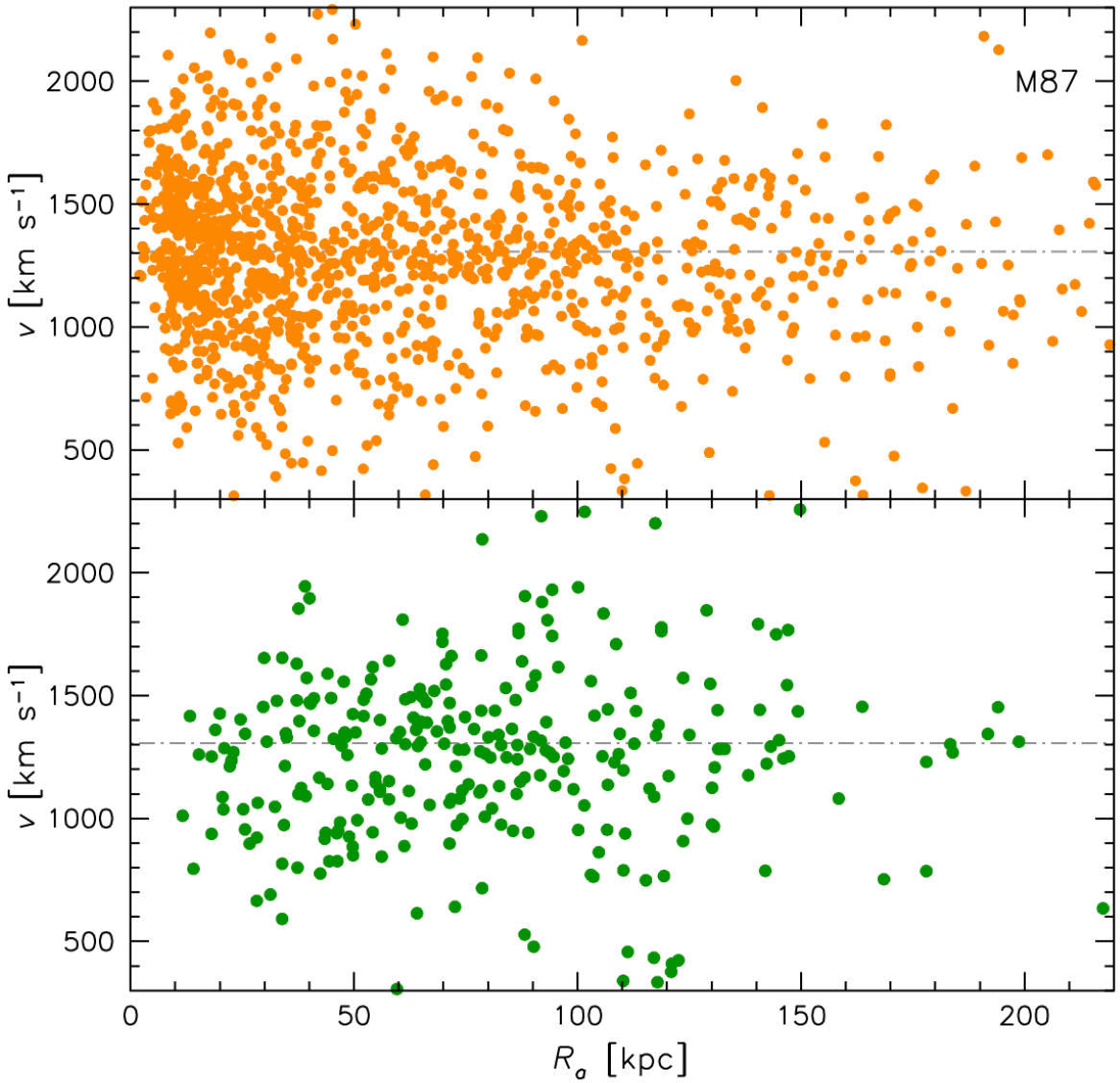




simple *N*-body accretion models reproduced broad shell features

but $\sigma \sim 20$ km s^{-1} suggested dE accretion not L^* (fr GC numbers)

New M87 kinematics results



GC data set expanded to ~1100 velocities

(Strader++ in prep)

shell less defined: relieves tension

~300 PN velocities

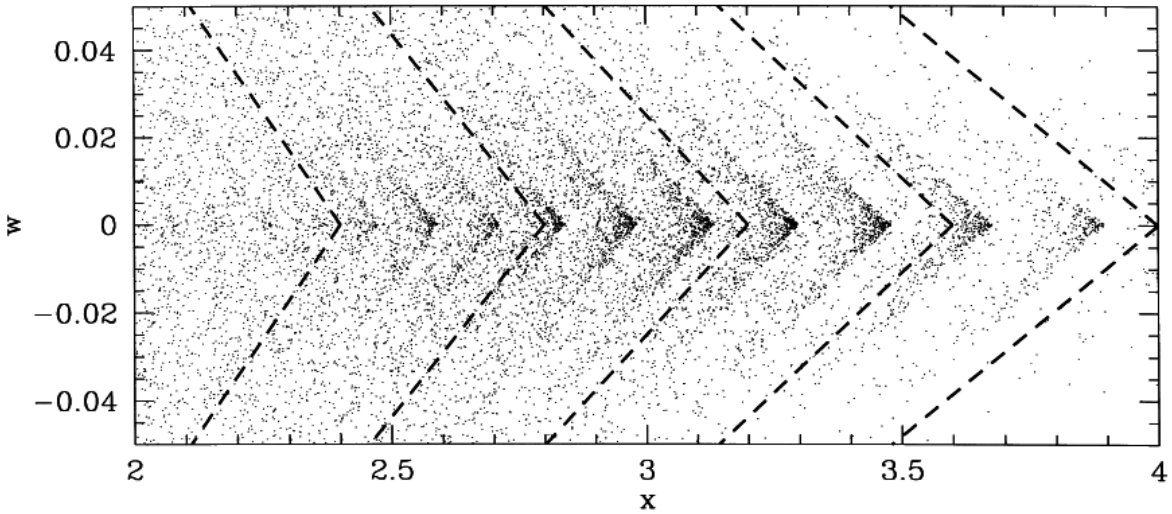
(Longobardi+2015a,b)

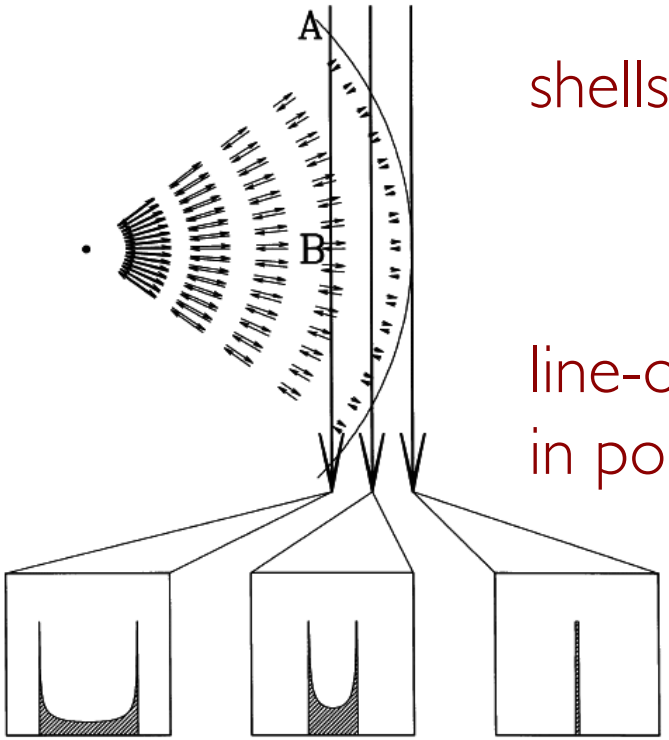
very similar shell detected!

hypervelocity GC+PNe at ~ −2300 km/s may be product of same merger

(Caldwell+2014)

Cold shells as probes of gravitational potentials





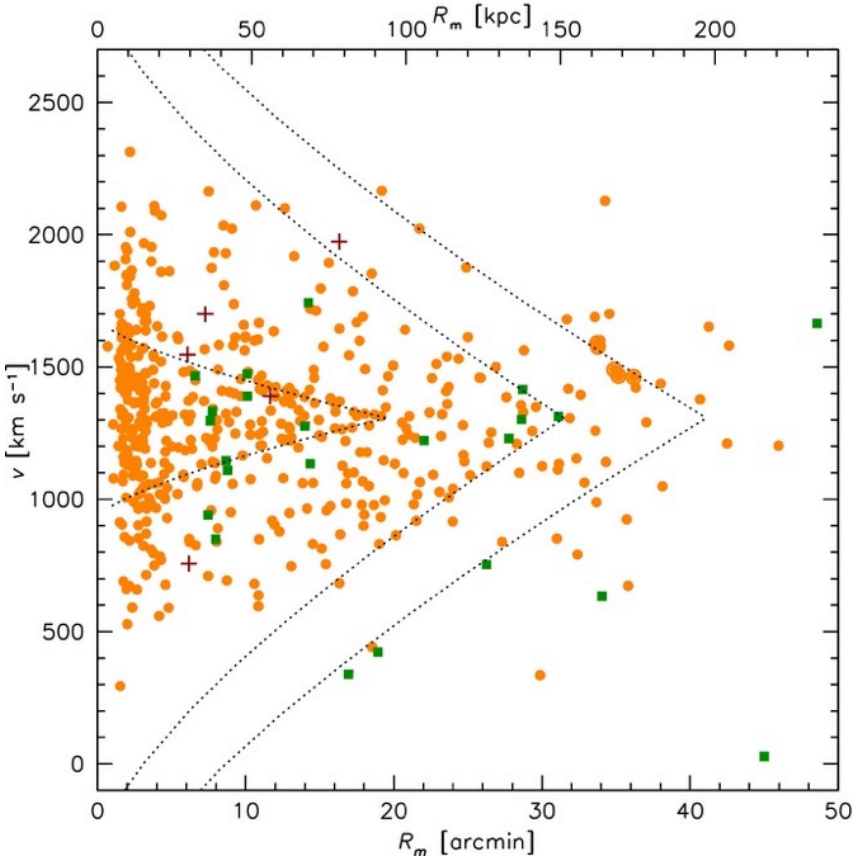
shells represent orbits of constant energy

$$v_{\rm LOS}^2 = 2\left(1-\frac{R^2}{r^2}\right)\left[\Phi(r_{\rm apo})-\Phi(r)\right]$$

line-of-sight projection to chevron structure in position−velocity phase-space

(Merrifield & Kuijken 1998)

M87 shells: probing the potential

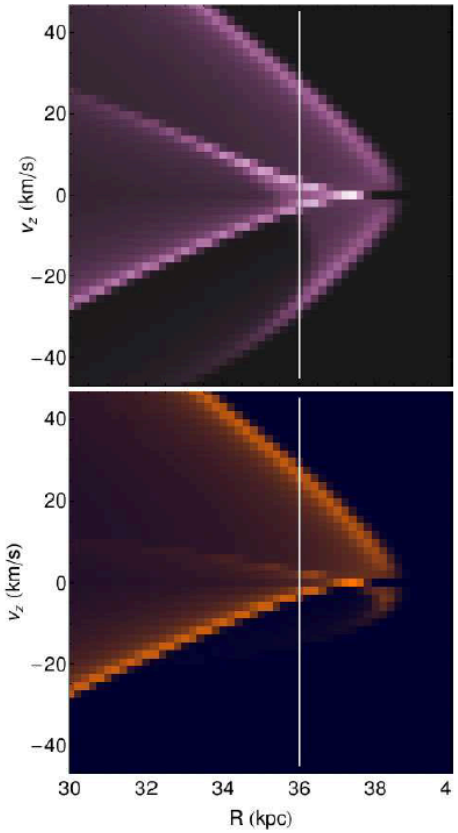


caustic fitting implies implausible

$v_c \sim$ 270, 1400 km/s at

$r \sim$ 90, 200 kpc

→ *limitations of spherical, radial-orbit approximation*

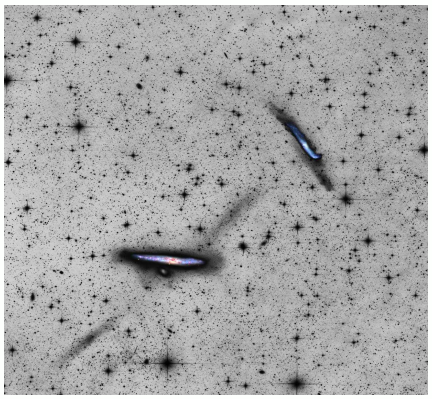


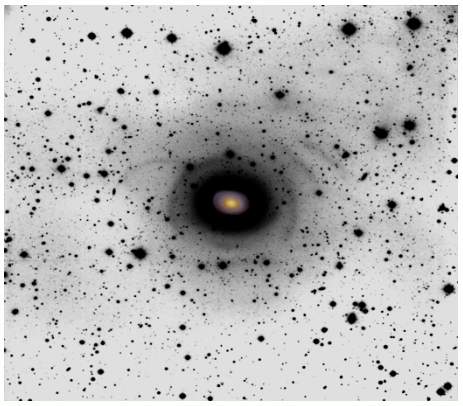
Sanderson & Helmi (2013) :

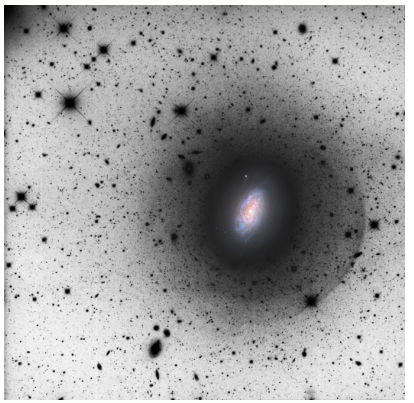
new methods to model flattening, expansion speed

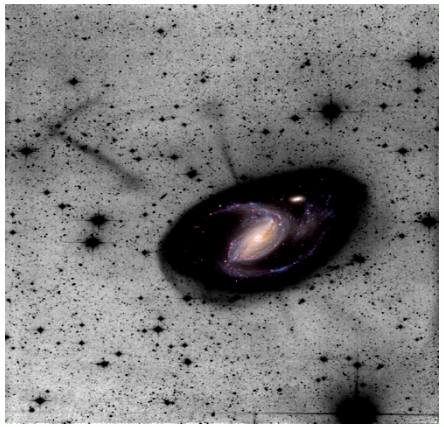
The Stellar Tidal Stream Survey

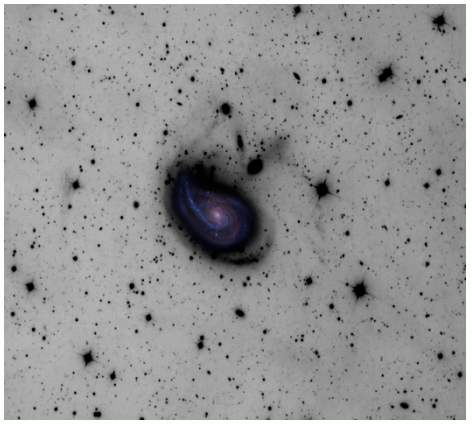
(PI: D. Martínez-Delgado; poster: G. Morales)

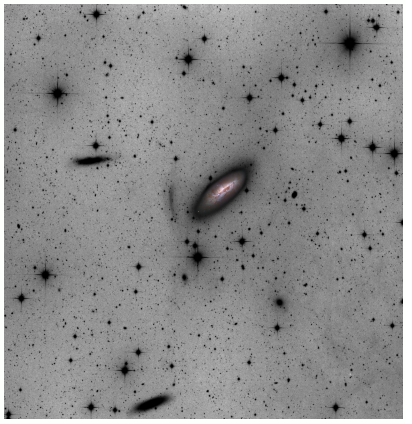






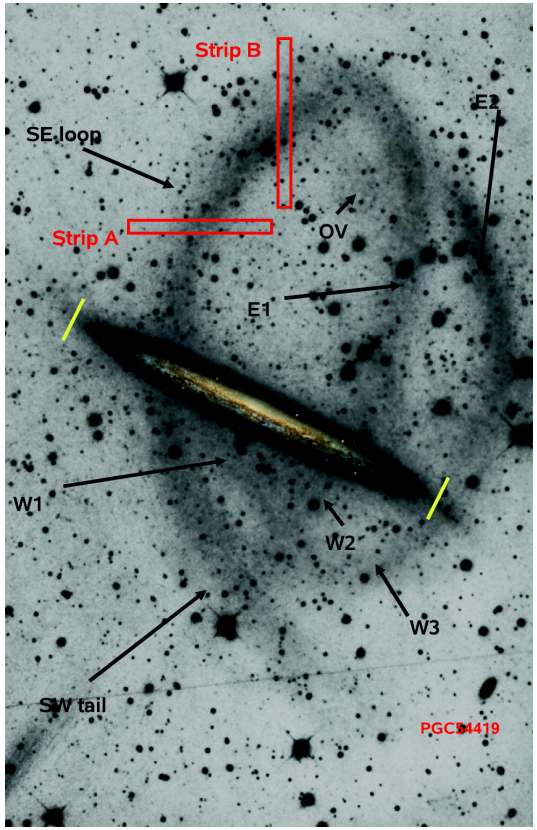




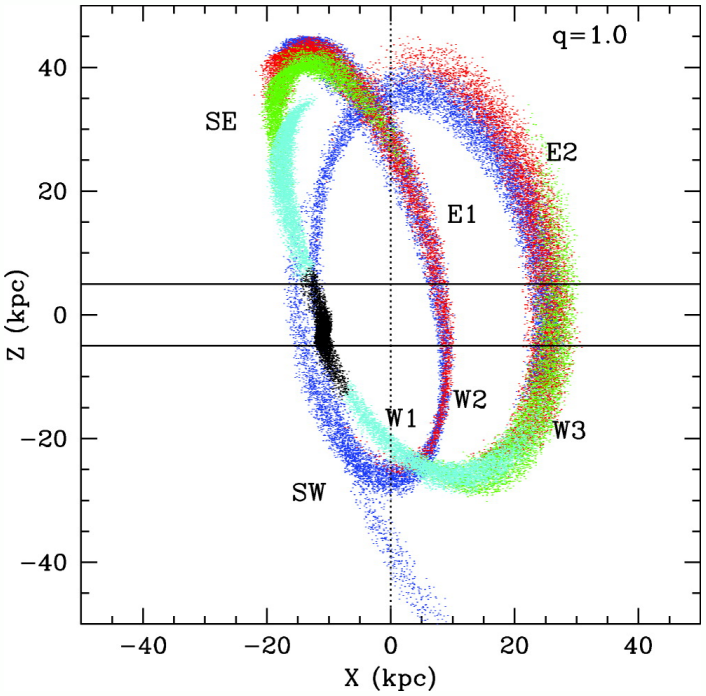


- network of 5 robotic, amateur telescopes in Europe, Chile, USA
- Milky Way-like galaxies within ~70 Mpc
- ~50 streams discovered so far

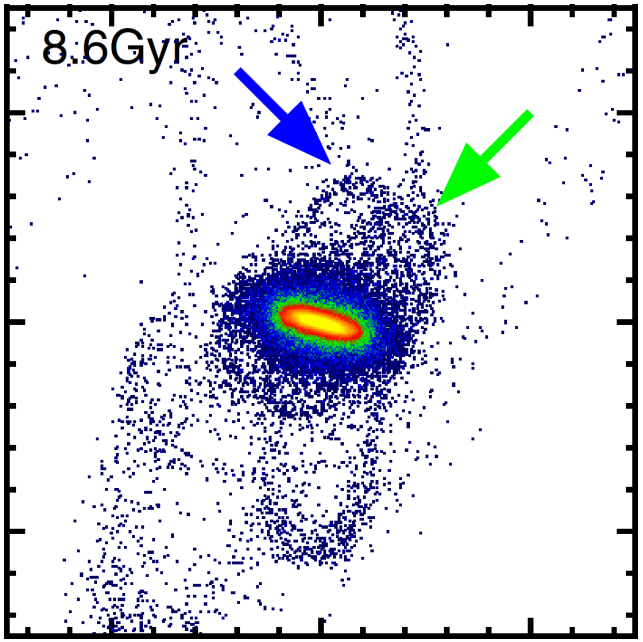
Stellar stream around NGC 5907



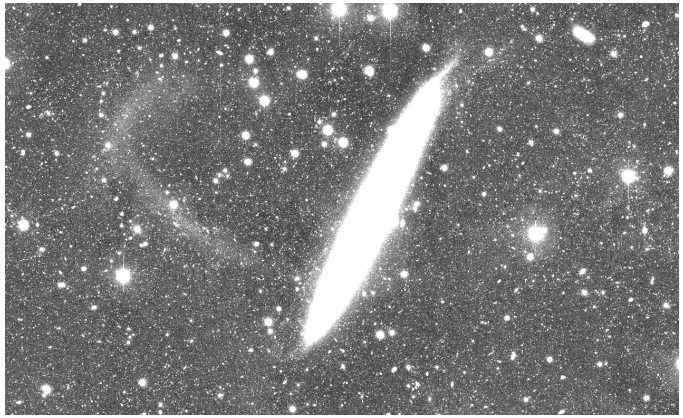
(Martínez-Delgado+2008)



minor merger



or major merger?
(Wang+2012)



analysis of kinematics and stellar populations (Suprime-Cam+*Spitzer*) underway…
(Alabi++; Laine++)

Chemo-dynamics of substructure in galaxy halos

→ **first** survey for stellar substructure **kinematics** and **metallicities** beyond the Local Group

- 0.15-0.5 m finder scopes (NMS, BBO, FSQ, RdS, Mrk)
- 8-m imager for GCs and PNe (Subaru/Suprime-Cam)
- 10-m spectroscopy (Keck/DEIMOS)

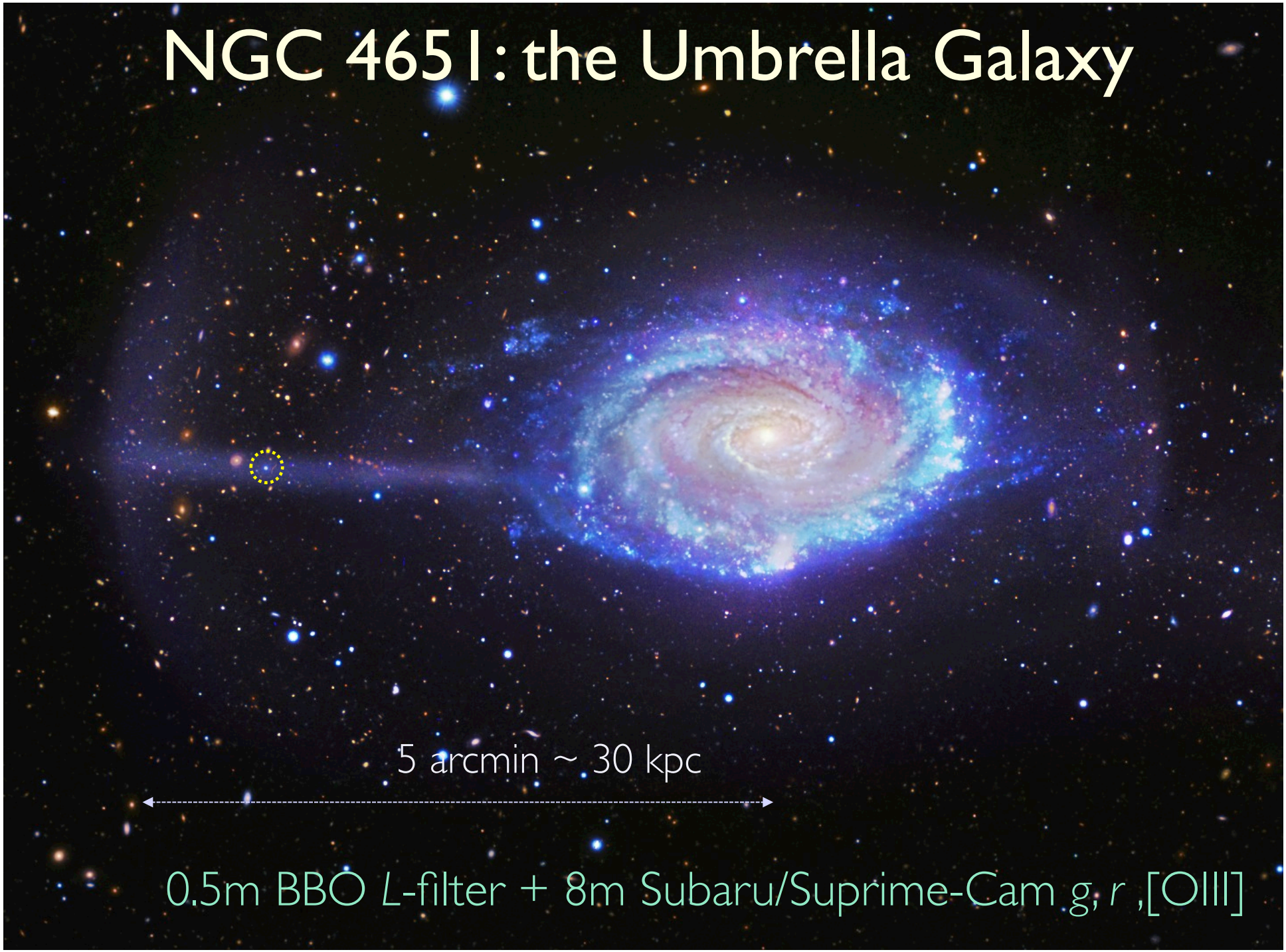
J. Brodie, A. Romanowsky, Z. Jennings, D. Martínez-Delgado, R.J. GaBany, et al.

NGC 4651: the Umbrella Galaxy

Fig. 5. Drawing of some of the structural features of NGC 4651 and of its faint companion as they can be recognized on good photographs taken with the 200-inch telescope. Coordinates, R.A. $12^h\ 41^m\ 21^s$, Decl. $+16°\ 41'\ 40''$ (1950).

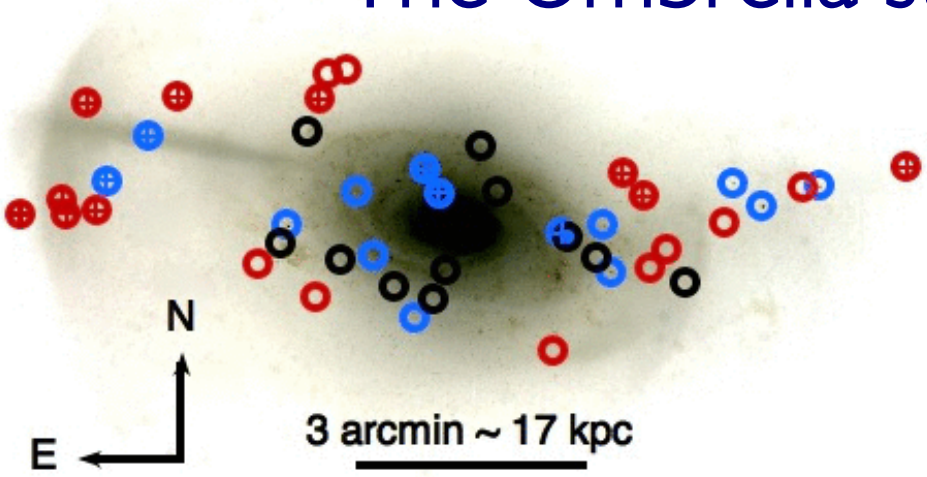
Zwicky (1956)

NGC 4651: the Umbrella Galaxy



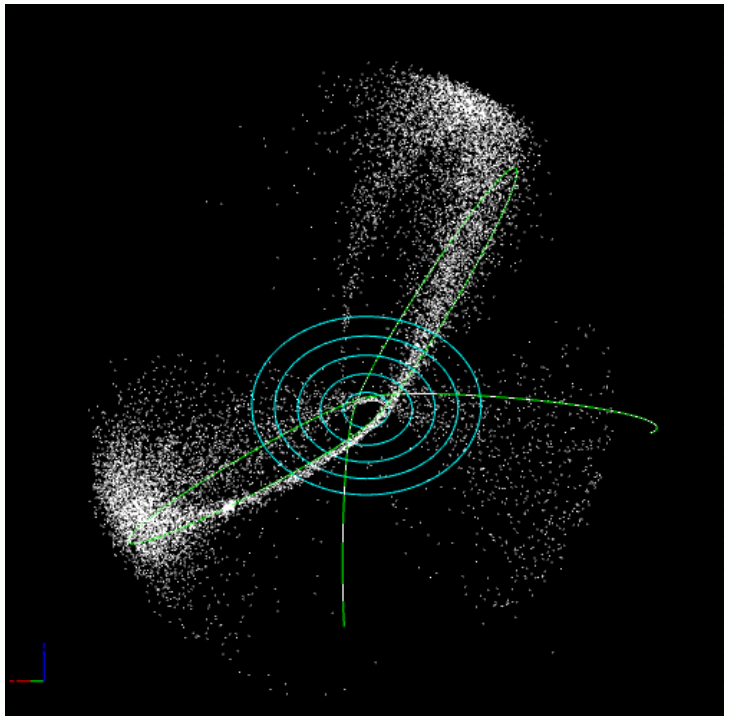
0.5m BBO *L*-filter + 8m Subaru/Suprime-Cam *g*, *r* ,[OIII]

The Umbrella stream modeling

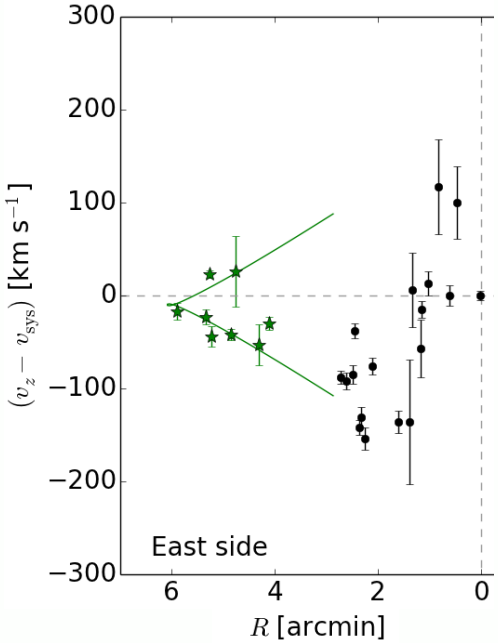


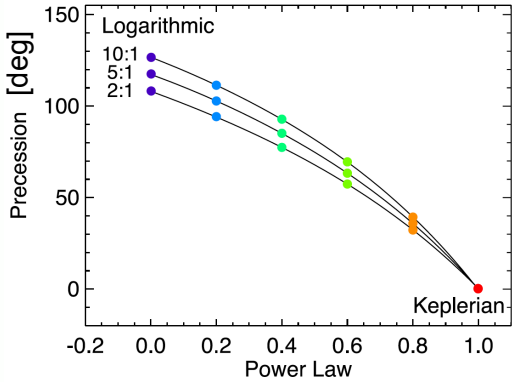
the Umbrella Galaxy (NGC 4651): MW/Sgr stream analogue with PN, GC kinematics from Keck/DEIMOS (Foster, Lux, Romanowsky+2014)

simplified 3D orbit-fitting model



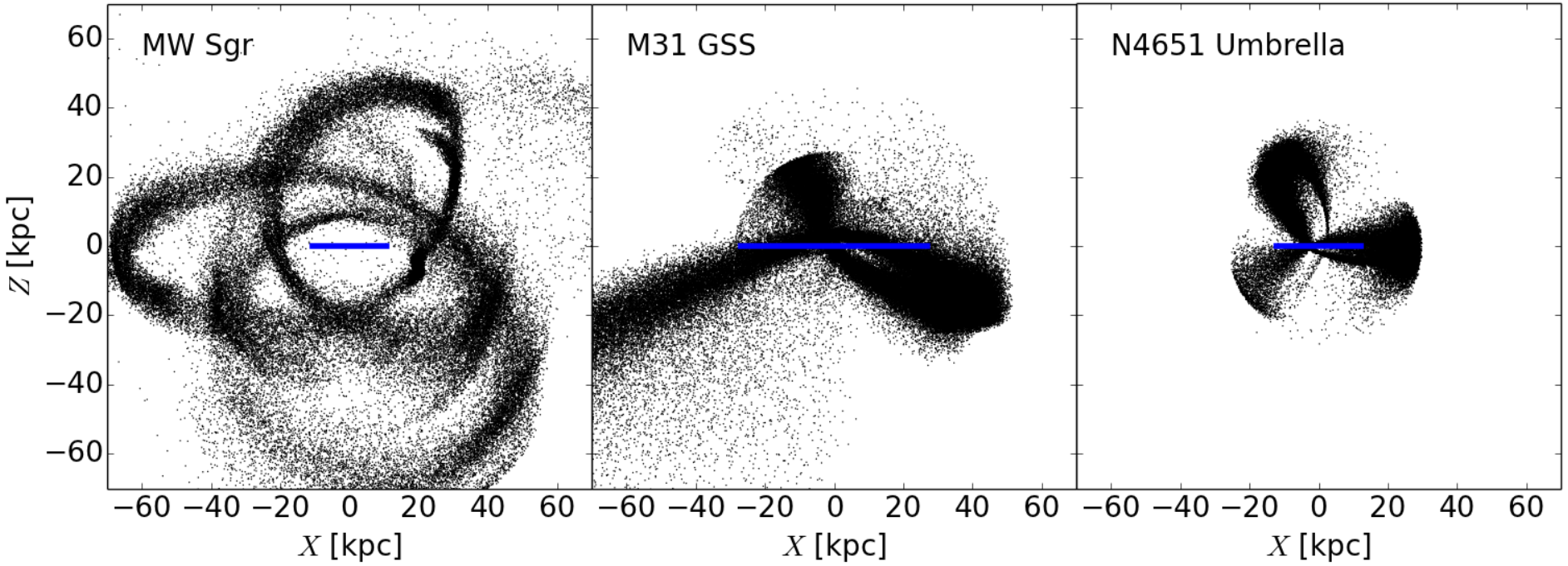
prospects for **halo mass** from caustics and **density slope** from precession





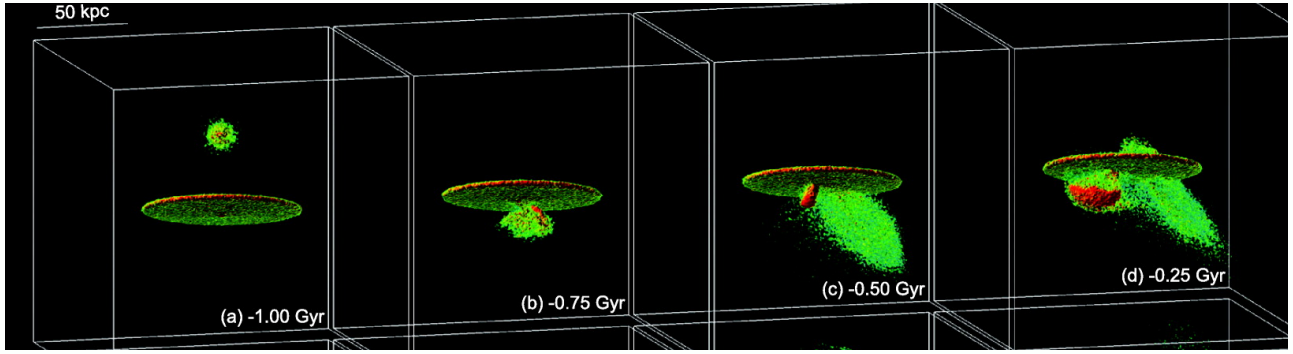
(Belokurov+2014)

The Umbrella in context



- ~ polar orbits; GSS and Umbrella very radial
- stream luminosities ~10^8 $L_\odot$, [Fe/H] ~ −1 to −0.5
- stellar mass ratios ~ 1:50, implied **total** mass ratios ~ 1:7
- consistent with observed bright stream statistics,
  predictions for ~1:10 merger events

Impact of accretion on host galaxies



Mori & Rich (2008)

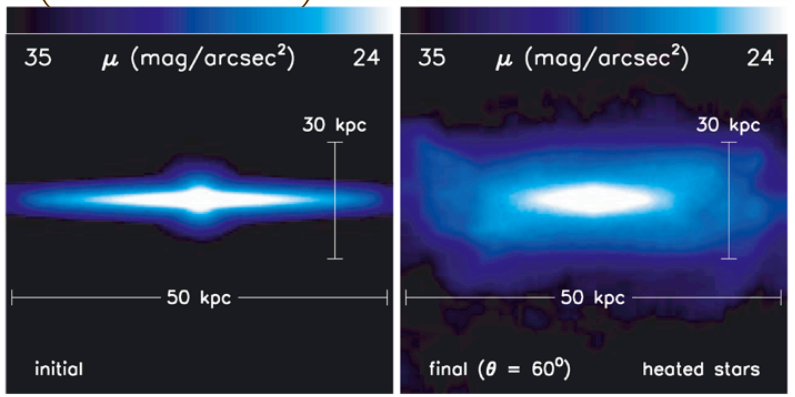
disk heating constraint on satellite mass **at impact** :

$$M_s <\sim \sqrt{\frac{M_d v_s^2 \Delta z_d}{4G}}$$

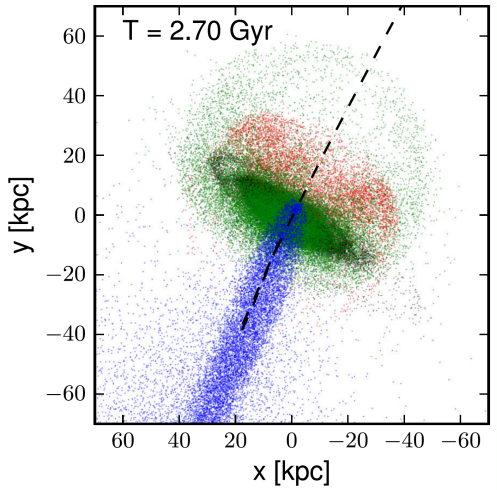
$$<\sim 5 \times 10^9 M_{Sun}$$

however, abundance matching predicts $M_s \sim 10^{11}\ M_\odot$ **(at infall)** !

(Purcell+2010)

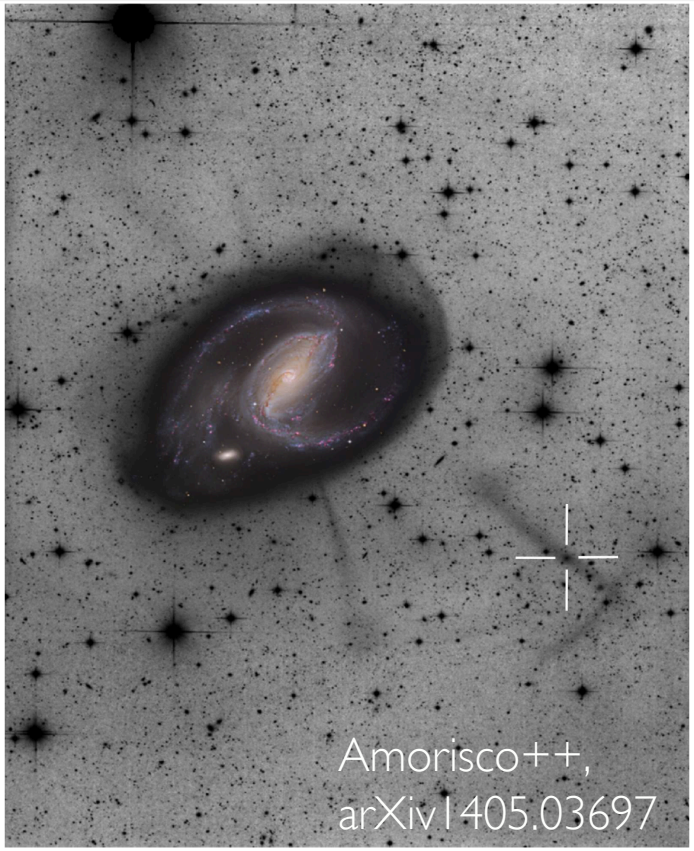


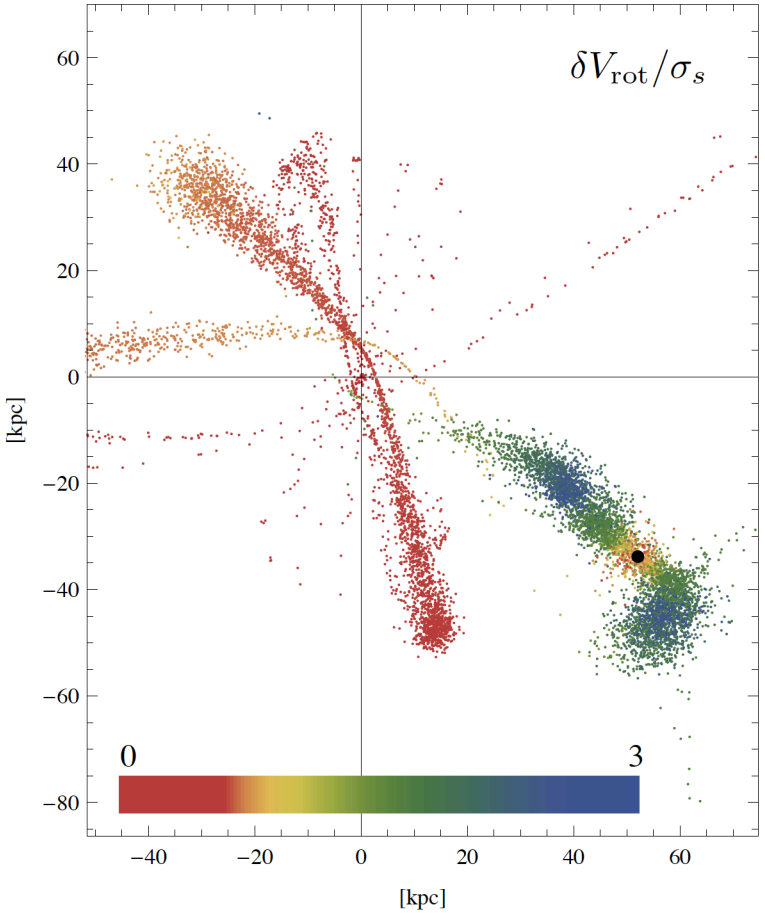
Sadoun+2014: had to reduce initial GSS mass by factor of 5 to not disrupt M31 disk!



new constraint on total dark matter content of satellites? (insensitive to central densities)

The dog leg stream around NGC 1097

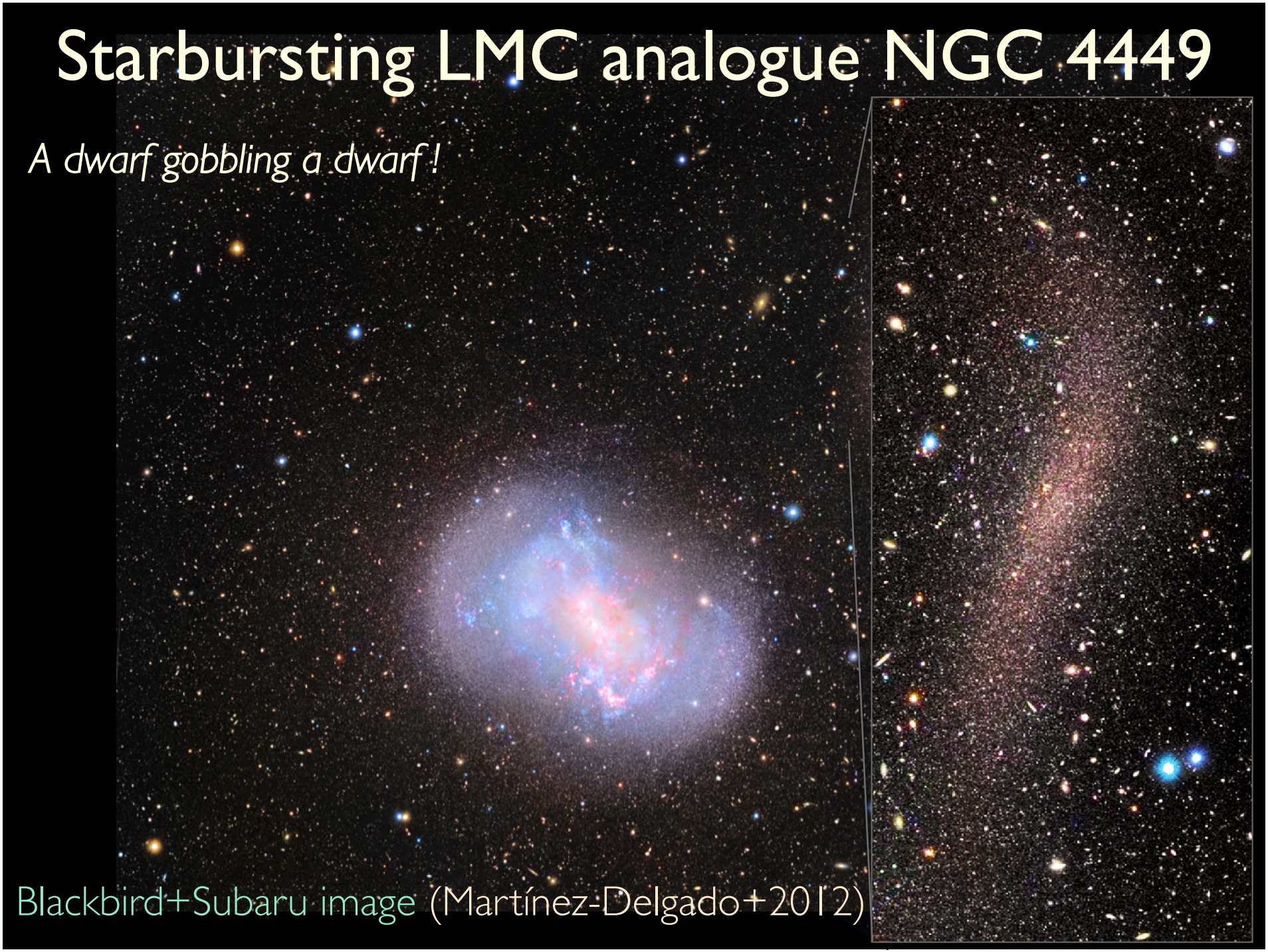




- fit of stream density map with mock stream, parameterized shedding
- sharp turn is signature of rotation in progenitor dwarf
- seems to require spherical potential !
- constrains density slope from ~4 to 150 kpc ! $(\gamma_{\rm out} = -3.9 \pm 0.5)$

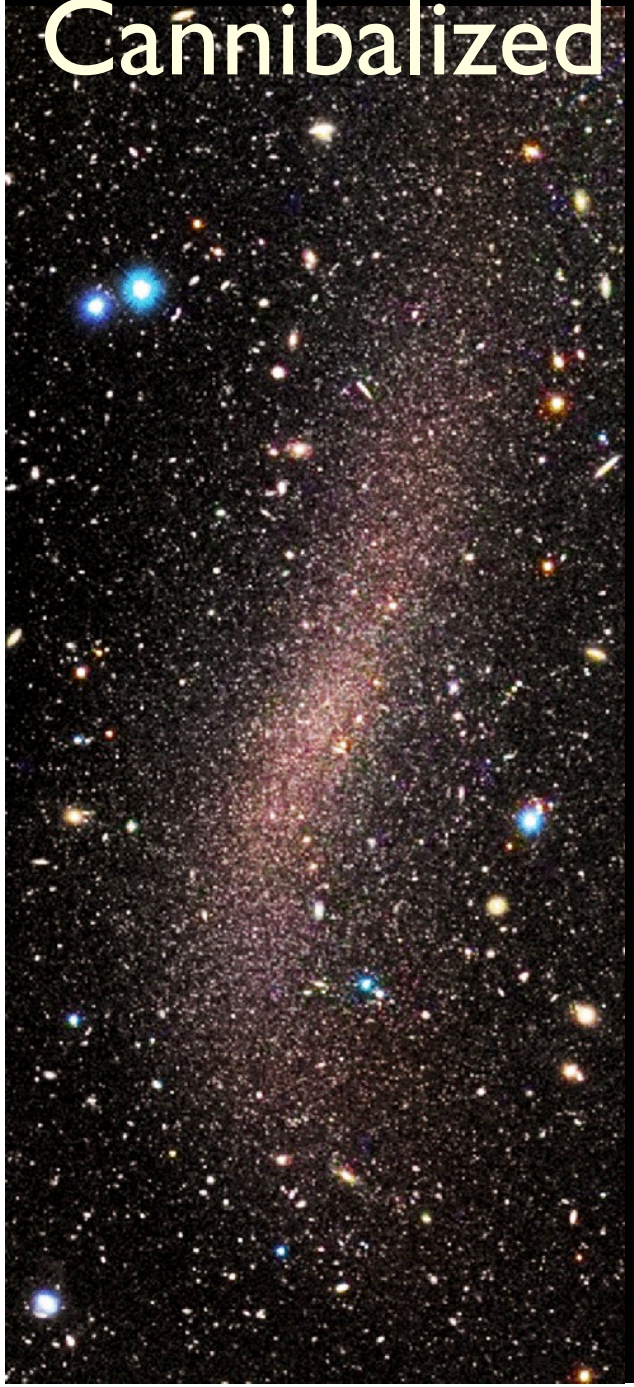
Starbursting LMC analogue NGC 4449

A dwarf gobbling a dwarf !



Blackbird+Subaru image (Martínez-Delgado+2012)

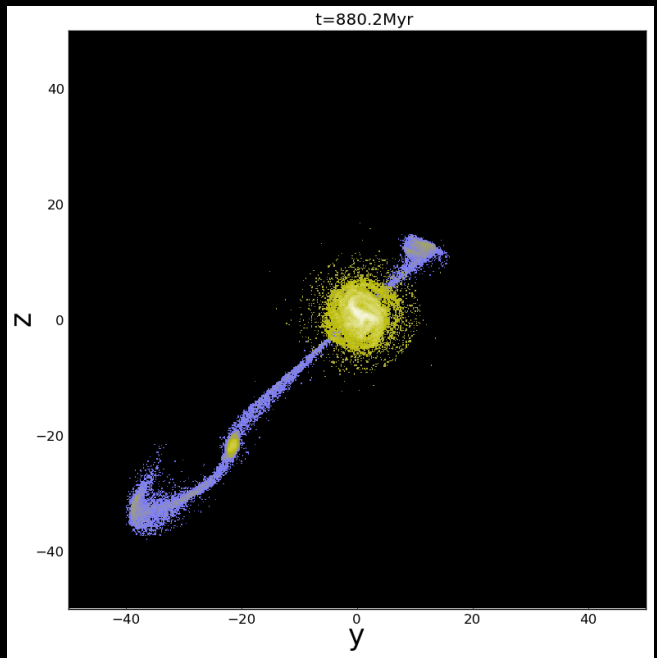
Cannibalized dwarf in halo of NGC 4449



Subaru resolves into stars!

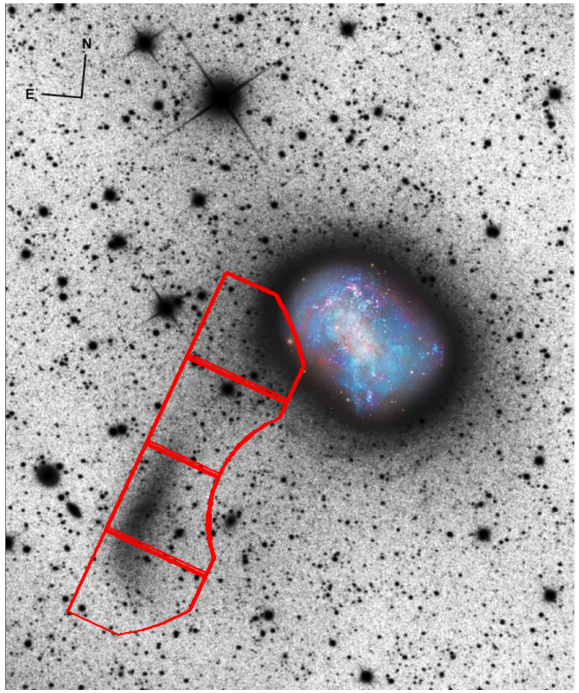
dSph, $M_* \sim 10^7\,\mathrm{M}_\odot$ (host $\sim 3\times10^9\,\mathrm{M}_\odot$)

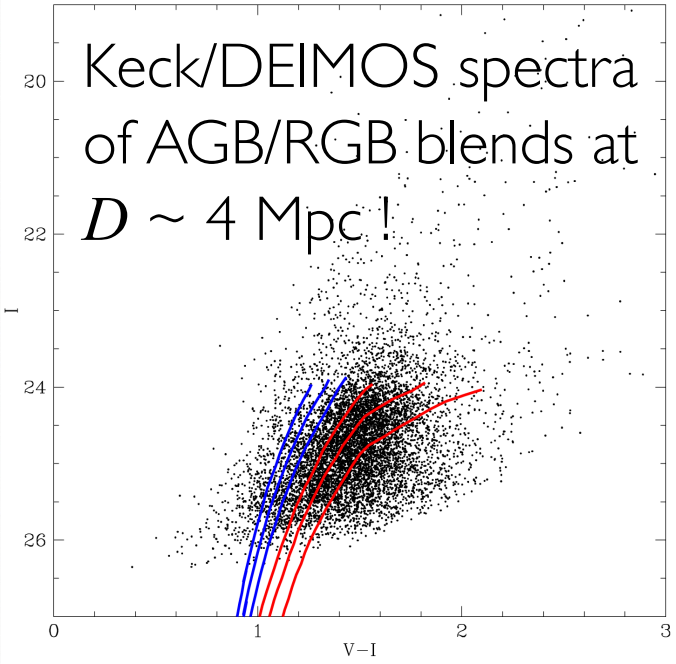
- accretion important for stellar halo build-up and starbursts in dwarfs
- ΛCDM halo matching predicts mass ratio up to ~1:5 (!?)
- dynamical analyses underway

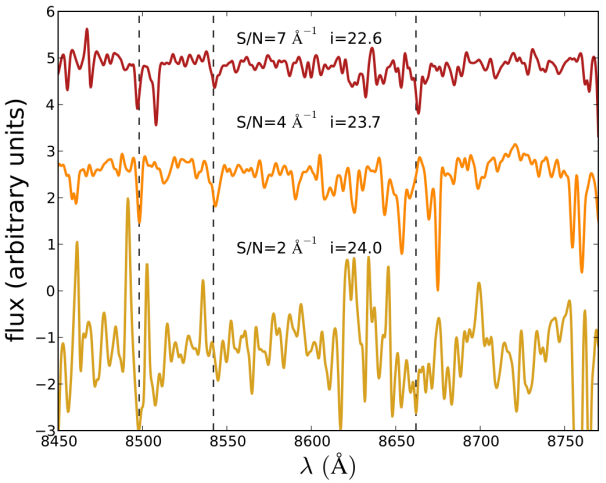


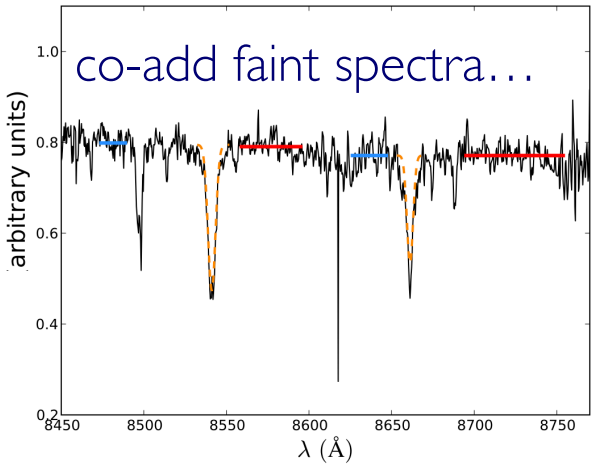
(E. D'Onghia)

Spectroscopy of resolved stars in N4449 stream

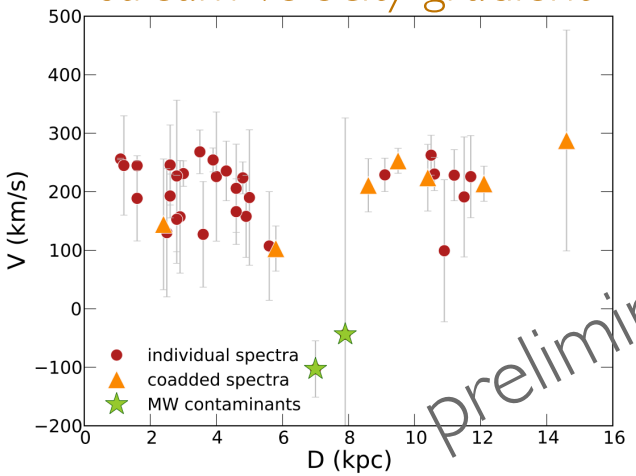


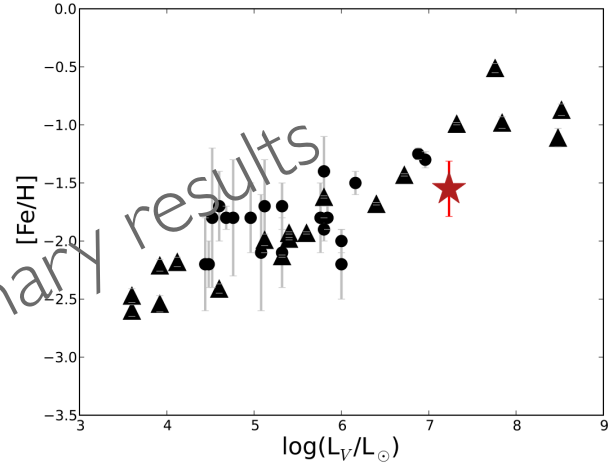






stream velocity gradient

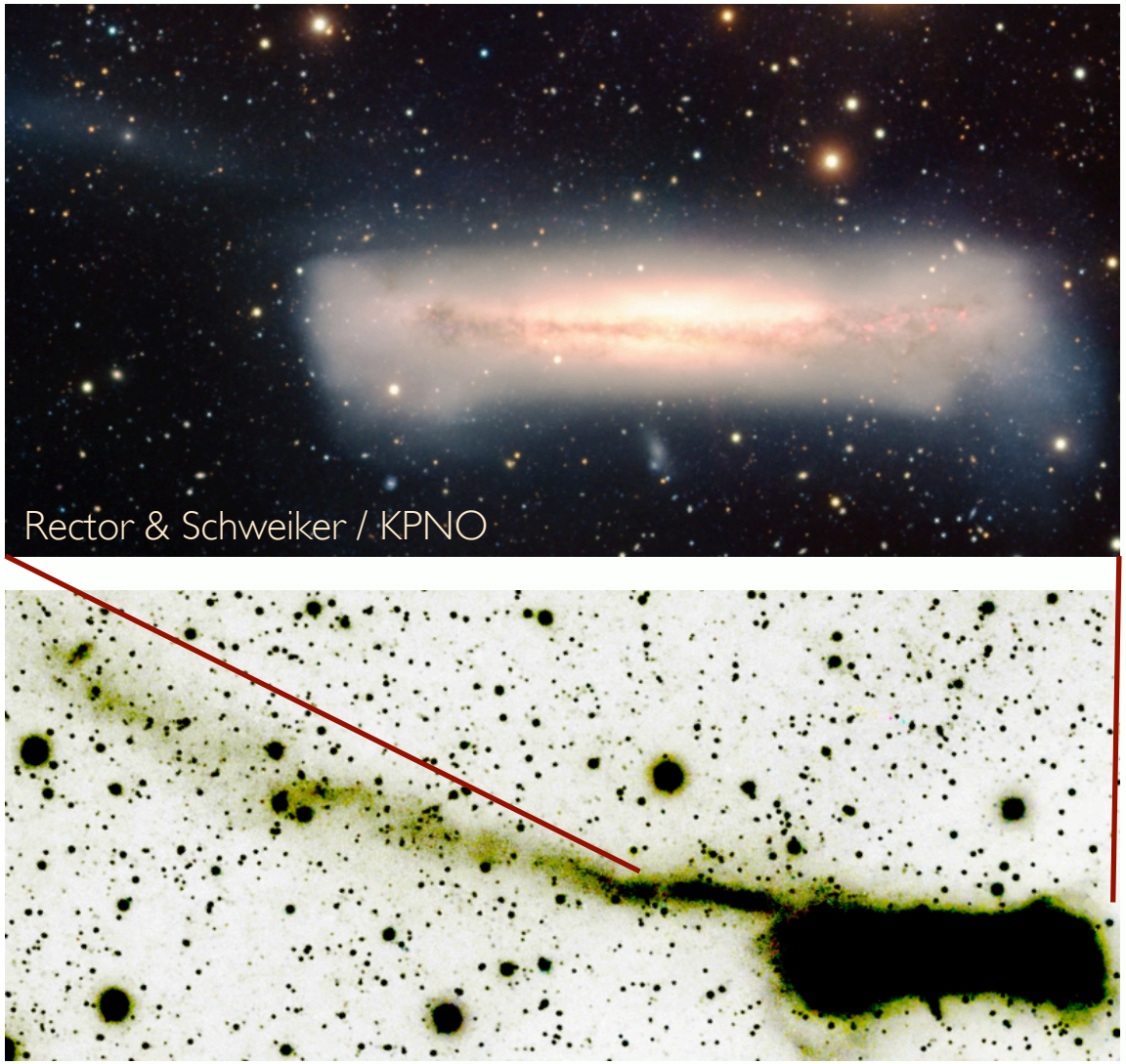




preliminary results

stream metallicity vs.
dwarf sequence

The Hamburger Galaxy (NGC 3628)

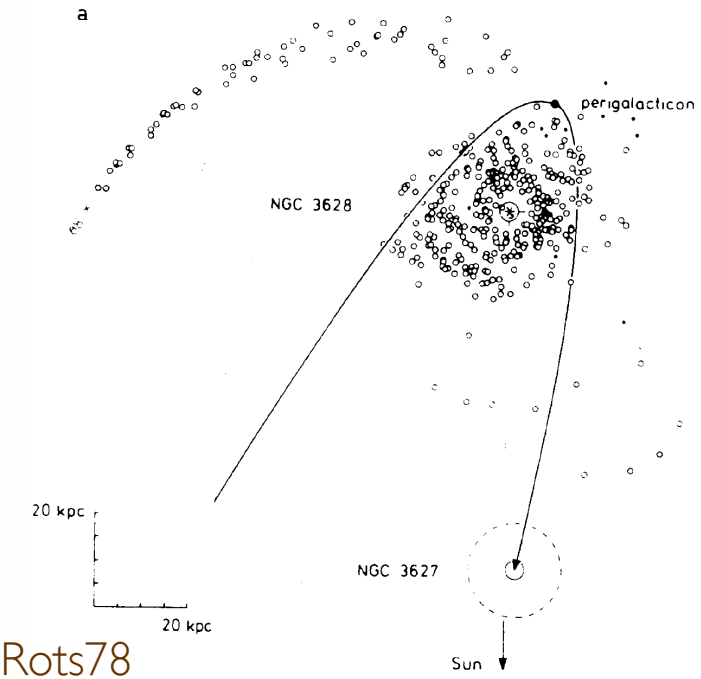


S. Mandel

brightest tidal feature in nearby Universe:

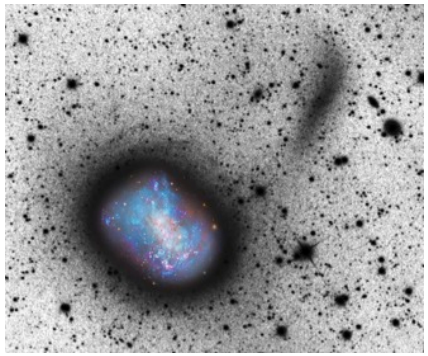
pre-major merger fly-by or minor merger?

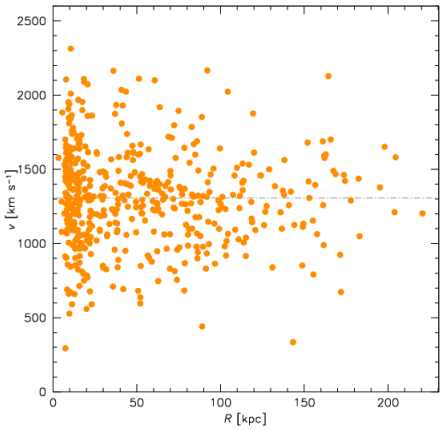
(spilled sauce or falling french-fry?)

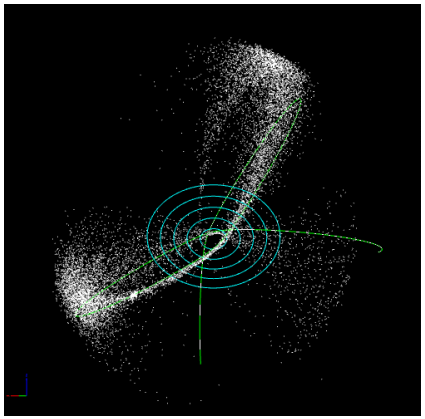


Rots78

Streams summary







- streams and substructures expected in all galaxies from giants to dwarfs: but need predictions and statistics as function of mass and environment
- new techniques for mapping substructure chemo-dynamics beyond Local Group : spectra of discrete tracers including stars
- massive shell around M87 persists in phase-space
- new particle-release modeling methods show great promise
- use full hydro simulations to constrain dark matter content of dwarfs through disk splash?