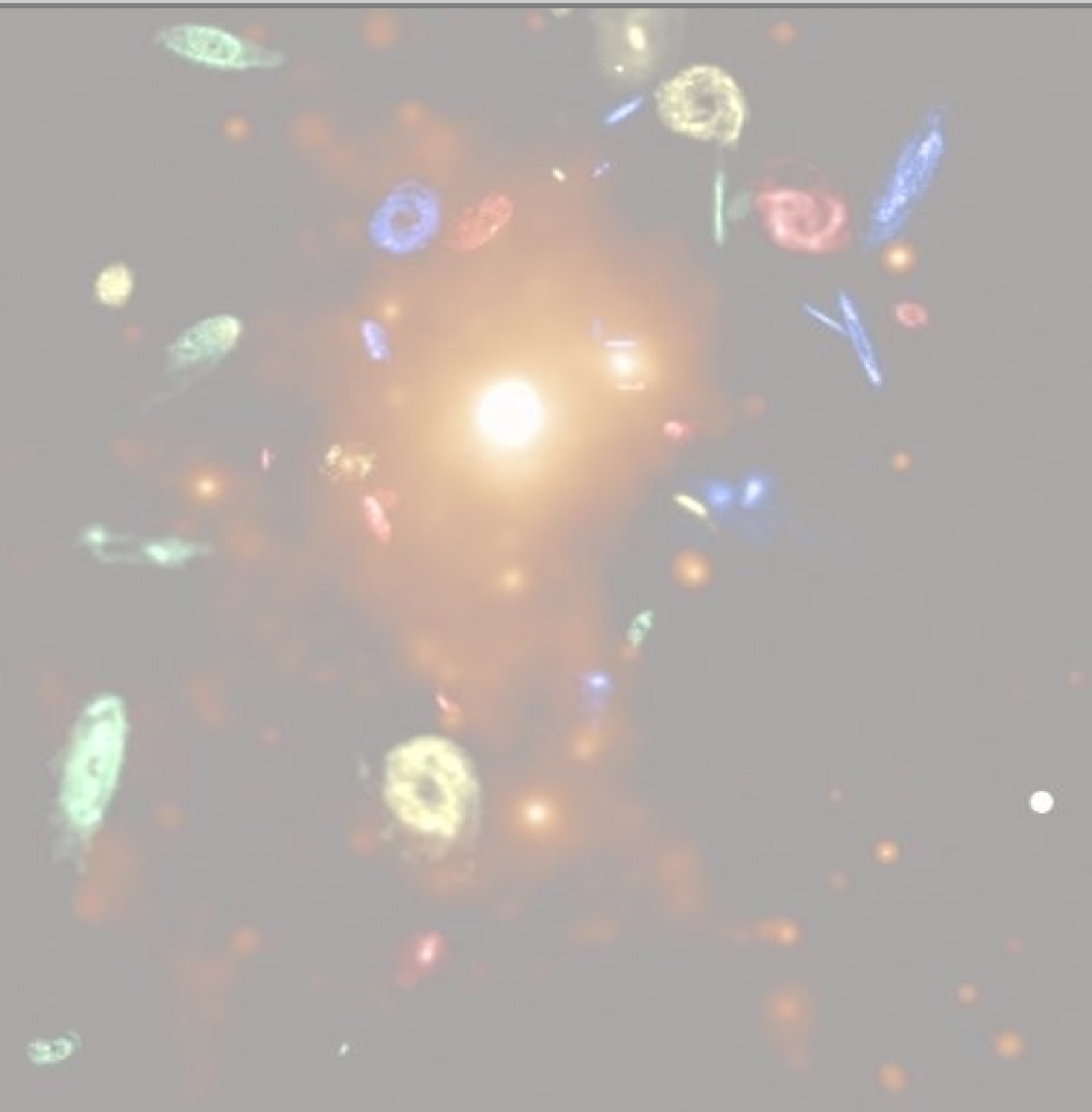
The Substantial Effects of Ram Pressure on Tidal Dwarf Galaxies Evolution



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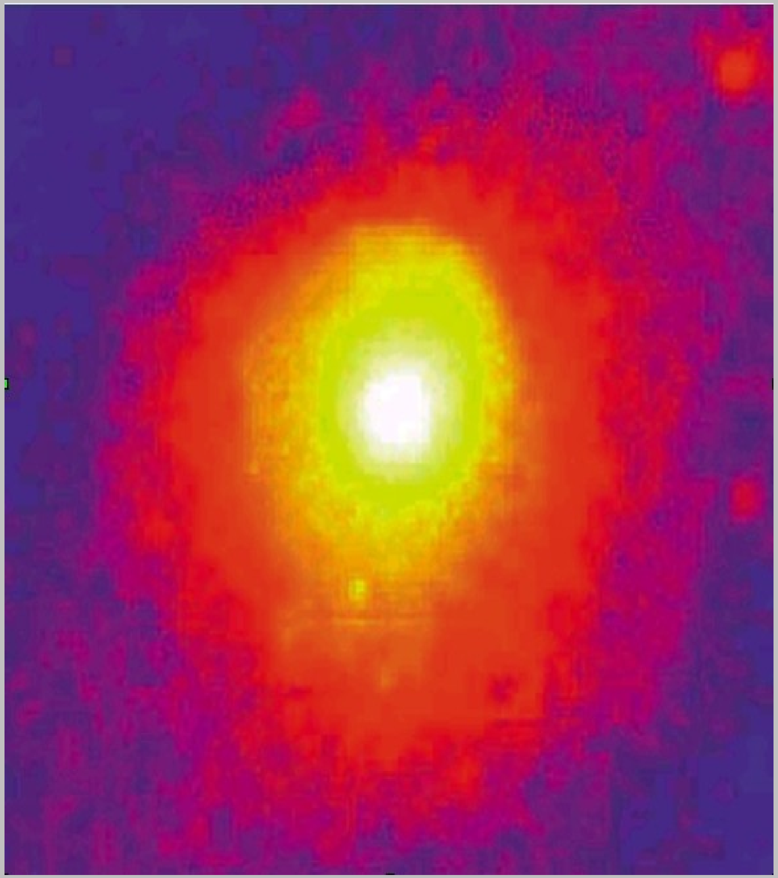
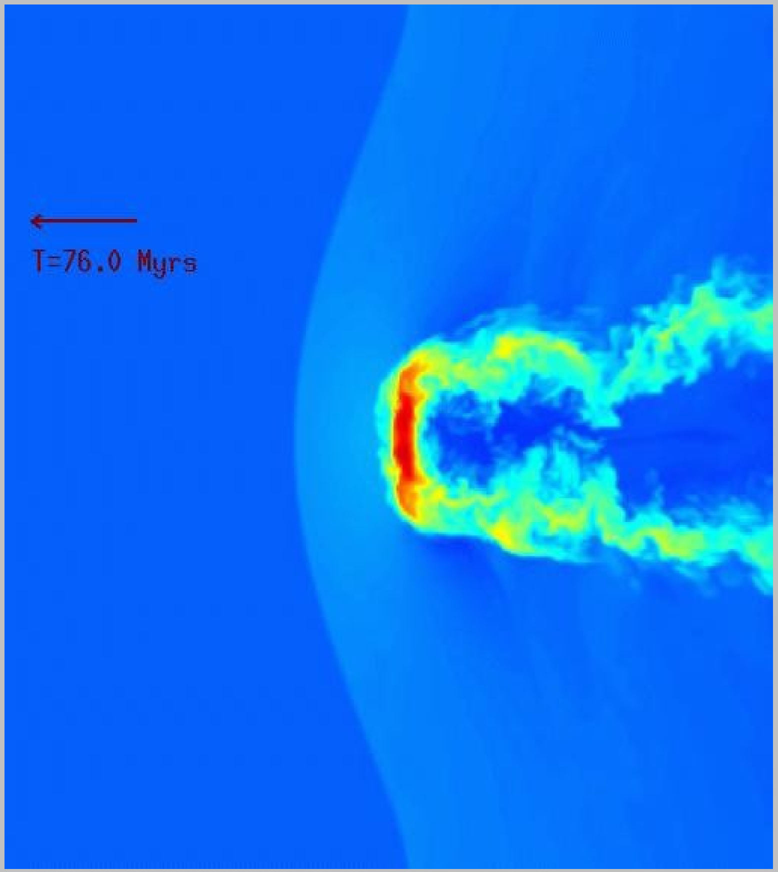
The Intra-Cluster Medium



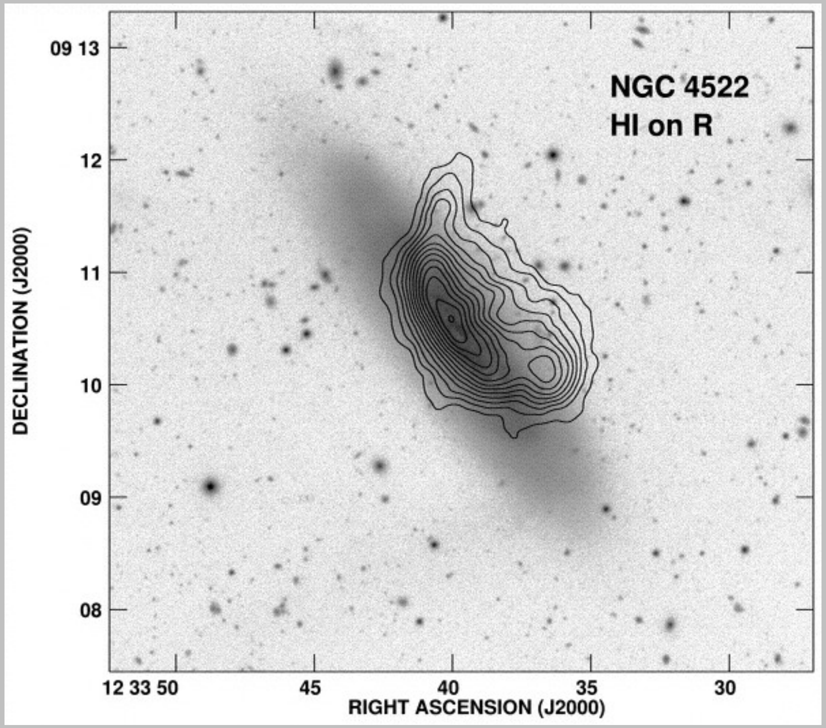
Virgo cluster in X-rays, ROSAT



Simulation of a galaxy disk undergoing RPS, Mayer 2005

The motion of a disk galaxy through the intra-cluster medium causes a drag force on it's atomic (HI) gas disk

Dynamical consequences for stars...?



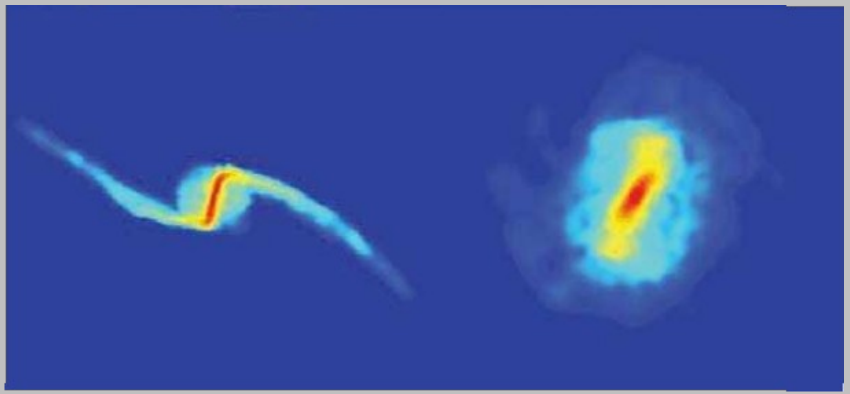
Kenney, 2004

...very little seen or expected!

- Gas stripped out but no clear signs of stars being disturbed
- Star have too small cross-section to feel ram pressure directly
- Gas removal has little impact on net galaxy potential (gas only ~10% of disk mass alone in normal big disk galaxies)

…. but not the case for *Tidal Dwarf Galaxies*

Ram Pressure –not just in clusters



Mayer,2005, star distribution after 1st (left) and 2nd (right) pericentre passage

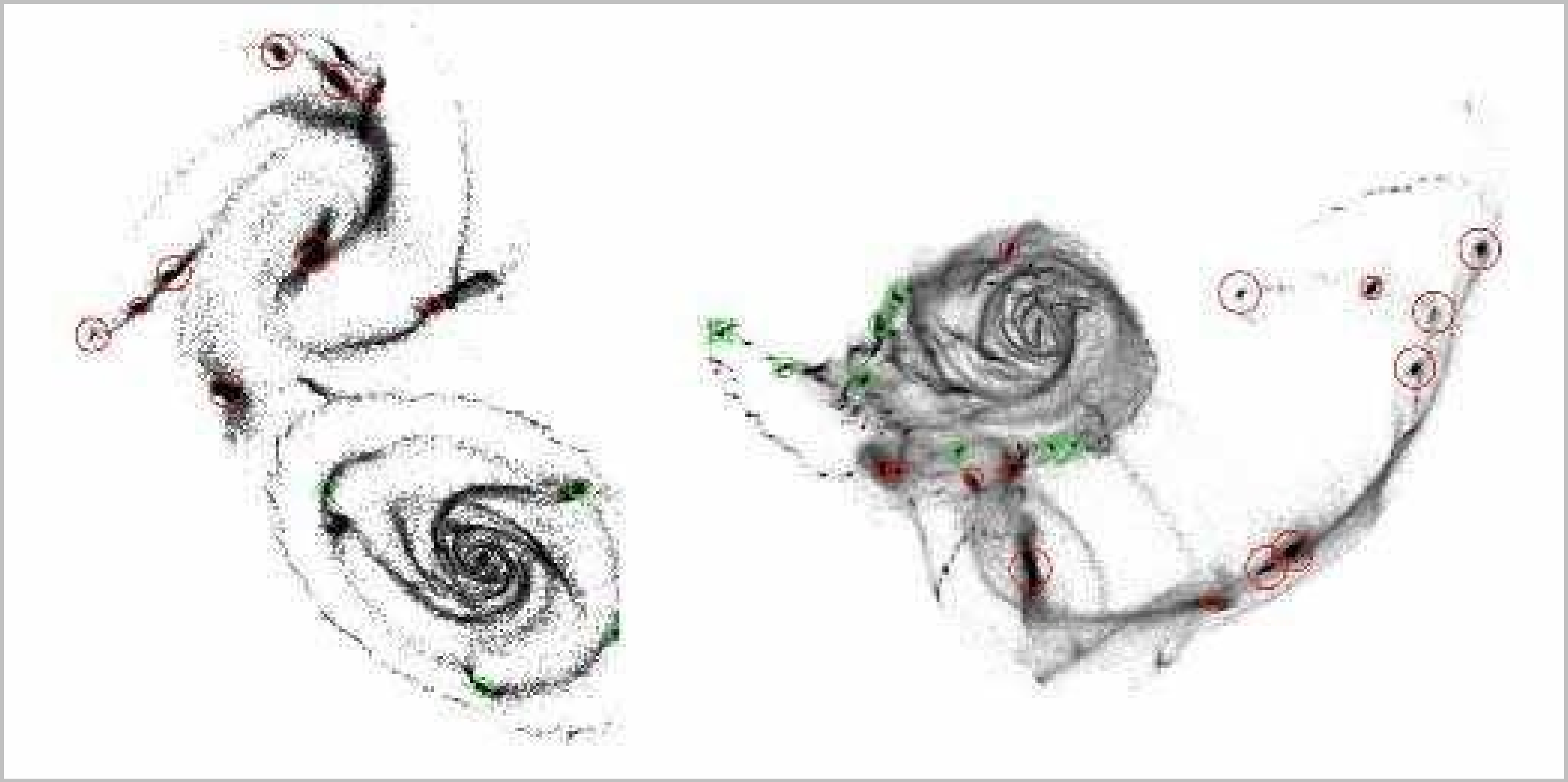
- **In groups of galaxies:**
  -X-ray emission detected (e.g Mushotsky,2004)
  - Effects of ram pressure on dwarf galaxies simulated (Marcolini, 2004)

- **In the Milky Way hot gaseous halo**
  -X-ray emission detected (Bregman & Lloyd-Davies 2007; Lehner et al. 2011; Gupta et al. 2012
  - Ram pressure + UV background + tidal stripping can convert disky star forming dwarfs into dSphs (Mayer,2005)
  - Assumed ram pressure halts star formation in dSphs Sextans & Carina, to put limits on hot gas halo density (Gatto,2013)

- **In other galaxies**
  - Difficult to detect hot gas directly, except in few cases (e.g Tumlinson,2011; Tripp,2011)
  - Presence of hot gas expected in Lamda-CDM framework (Feldmann 2013), and required to feed star formation ('starvation'; Larson 1980), form metallicity gradients (Pilkington 2012; Gibson 2013) & get correct disk morphologies (Hambleton 2011; Brook 2012)

"...Ram Pressure in many environments...
(at least for dwarf galaxies anyway)"

Tidal Dwarf Galaxies:



Duc P. A., 2012
Gas distribution in hi-resolution sims: (left) after first encounter, (right) after major merger

- Typically formed by interactions/merging of two spiral galaxies
- Large quantities of gas and stars liberated from disk galaxies
- Clumps of gas and stars form along tidal tails, creating new galaxies – Tidal dwarf galaxies.

Movie courtesy of Pierre-Alain Duc

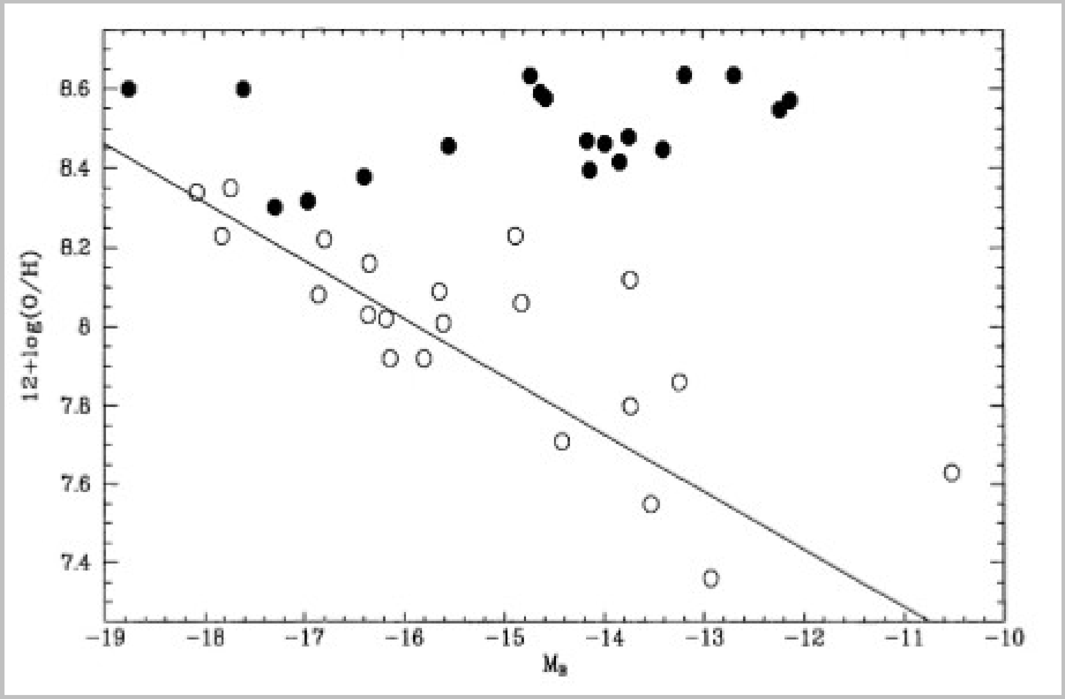
Tidal Dwarf Galaxy Properties

Like typical dwarf irregular galaxies:

- Similar luminosities/masses (~10^6-10^9 Msol)
- Similar scalelengths (Reff~kiloparsecs)
- Similar irregular morphologies
- Similar high gas fractions (f_{gas}~50-95%).

Unlike dwarf irregular galaxies:

- Enhanced metallicity for luminosity (formed from enriched gas)
- **NO DARK MATTER**
  → expected that Tidal Dwarf Galaxies very sensitive to their environment, i.e tides....***but also ram pressure***.



Metallicity vs luminosity: (open circles) isolated dwarfs, (filled circles) Tidal dwarfs. From Duc & Mirabel 1999

Modelling ram pressure on TDGs: Method

Numerical code:

- Name: '*gf*' (galaxy formation)
- Nbody/Treecode for gravitational accelerations (100 pc resolution)
- Smoothed Particle Hydrodynamics for HI disk gas

Toy ram pressure model:

- Based on model of Vollmer, 2001
- $accel_{rps} \propto \rho_{ICM} v^2$
- Cloud shielding criteria
- Tested against Gunn & Gott predictions (Smith et al. 2012)

Approach

Model TDG galaxies:

- Exponential disks of gas and stars;

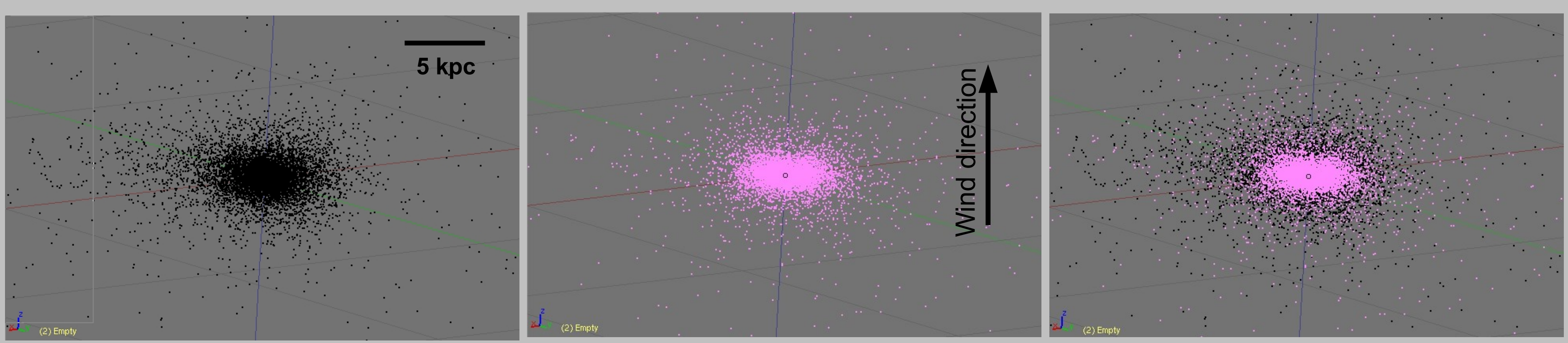
- Varied model properties:
  disk mass (1e7-1e8 Msol), effective radius (1-3 kpc), gas fraction (50%-90%)

'Wind tunnel' style tests:

- Fixed wind speed, and hot gas density => constant ram pressure for 2.5 Gyr
  face-on ram pressure only

- Hot gas density ~1e-4 Hatoms/cm3:
  equivalent of outer Virgo cluster (R~1000 kpc) or Milky Way hot halo

- Between tests we vary the wind speed (100-800 km/s),
  and vary the model TDG properties to conduct a parameter study

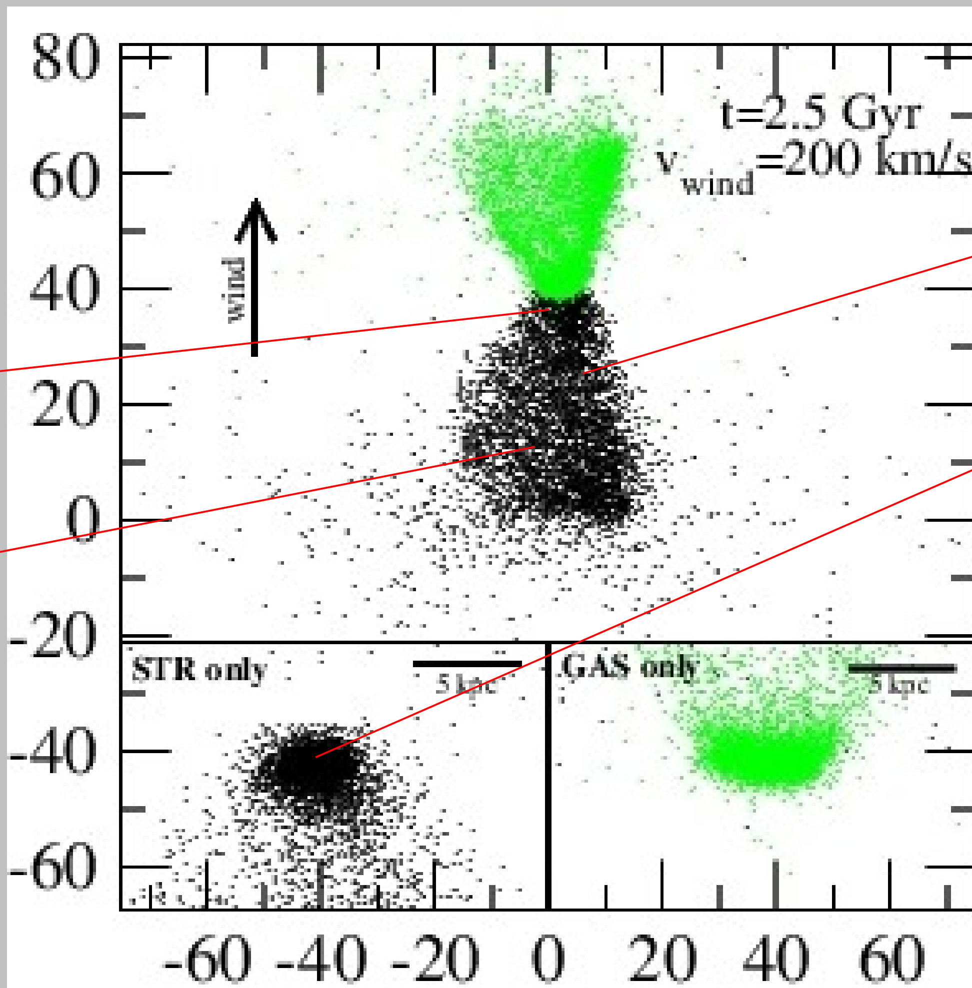


Edge-on TDG model: Stars (black), gas (pink); stars only (left), gas only (centre), combined (right)

Results: Key features

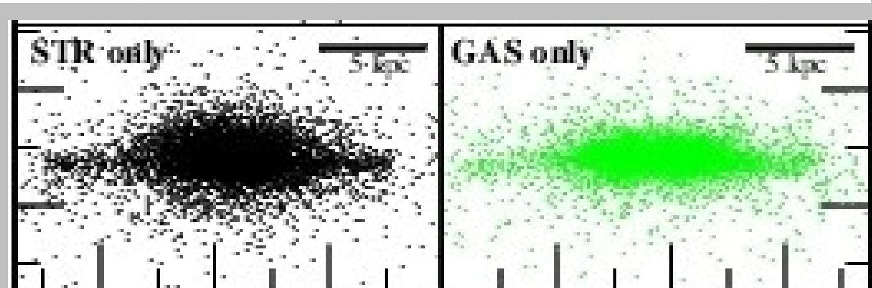
Bound stars (dragged in direction of wind)

Unbound stars (left behind in stream)



- Stars unbound by ram pressure
- Stellar disk truncated where gas stripped
- Stellar disk dragged, so unbound stars lie in stream

Initial:

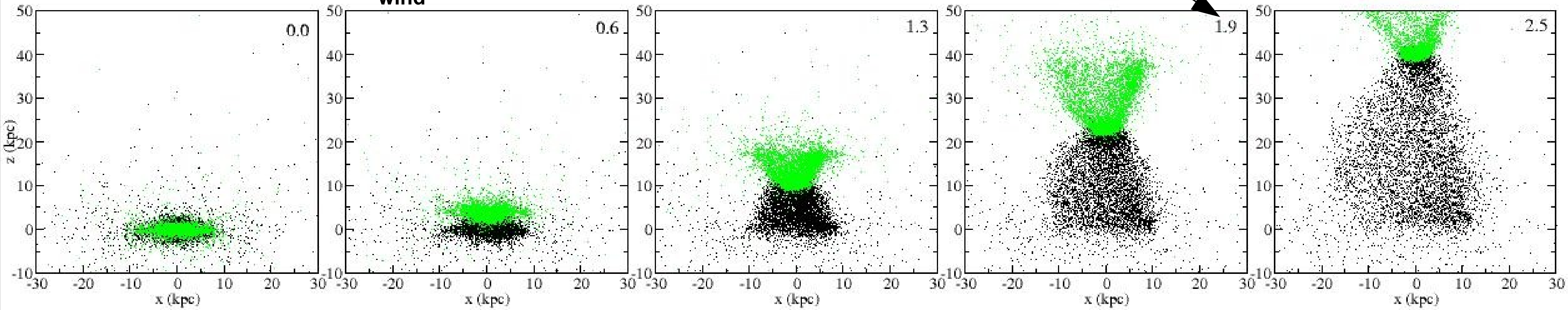


Results: Stellar losses

Weak ram pressure (v_{wind}=200 km/s):

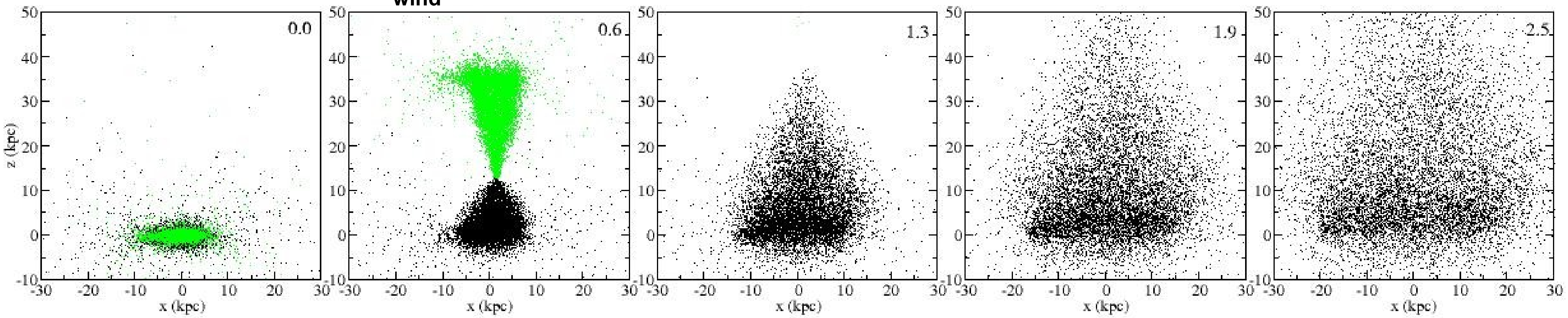
Time (Gyr)

50% stars unbound



Strong ram pressure (v_{wind}=600 km/s):

100% stars unbound

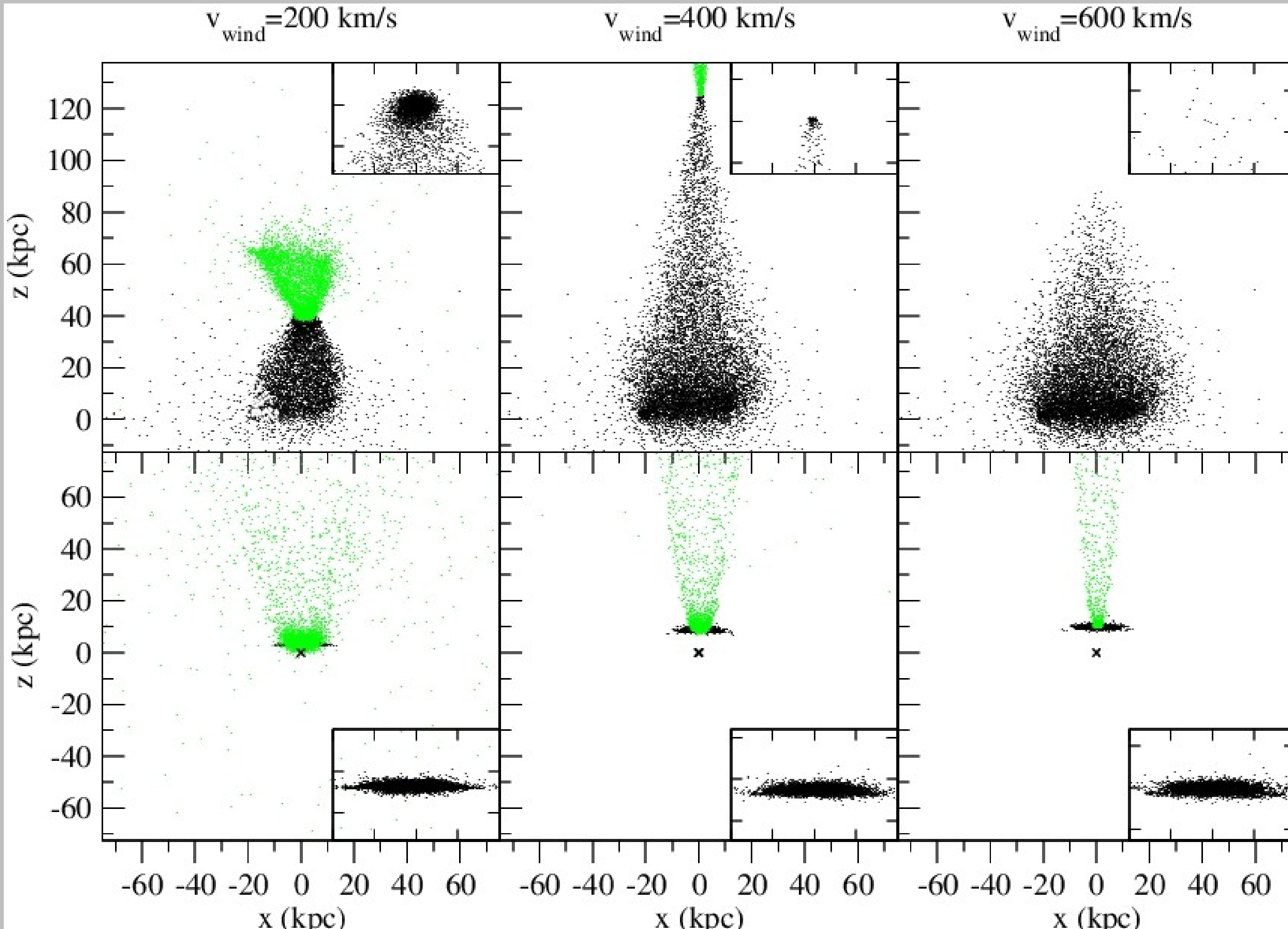


- Often assumed that ram pressure only affects gas in galaxies, and leaves stars dynamically unaffected:
  NOT TRUE FOR Tidal Dwarf Galaxies (TDGs)!

- Large quantities of ***stars*** unbound when the gas is stripped
  → *For weak ram pressures, ~half the stars are unbound*
  → *For strong ram pressures, **ALL** stars are unbound i.e. the dwarf is entirely destroyed!*

- **Rule of thumb: Equal fraction of stars and gas lost, in our models**

Stars unbound (with/without halo):



(Upper row) Tidal Dwarf Galaxy model – no halo

(Lower row) Dwarf Irregular model – with halo

Stars lost in Tidal dwarf models because:

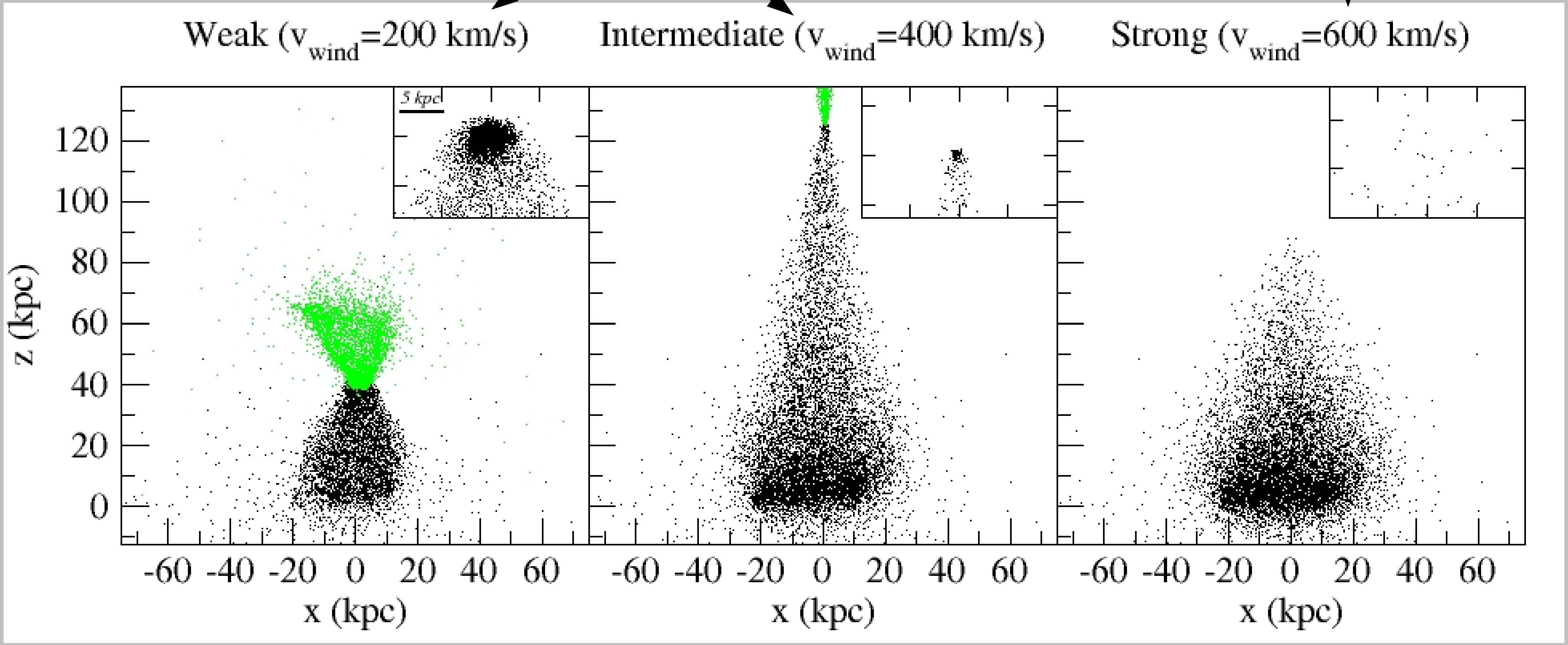
- Loss of gas represents significant reduction in potential of galaxy
- There is no dark matter to hold galaxy together

Effect on surface density profiles:

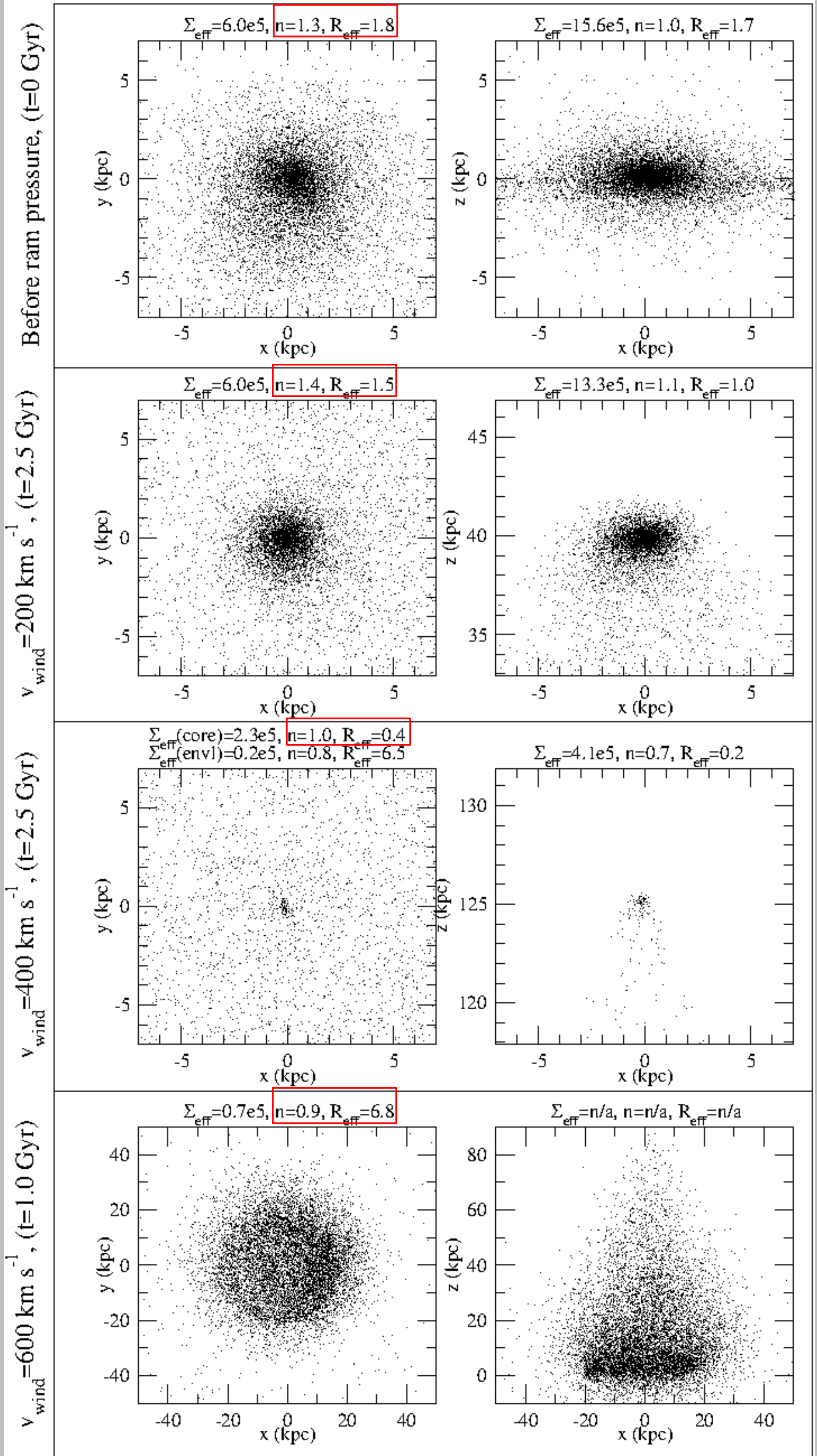
Stars preferentially lost where gas is stripped (from outside inward):

Partial gas stripping:
truncated gas disk = truncated star disk

All gas stripped:
Stars all unbound into
rotating & expanding cloud



We fit models with a Generalised Sersic profile to quantify effects on surface density profiles (see following slide)



Pre-ram pressure model

n=1.3, Reff=1.8 kpc

Outer disk gas stripped:

n=1.4, Reff=1.5 kpc

Almost all disk gas stripped:

n=1.0, Reff=0.4 kpc

Disk remains near exponential,
effective radius reduced as disk truncated

All gas stripped:

n=0.9, Reff=6.8 kpc

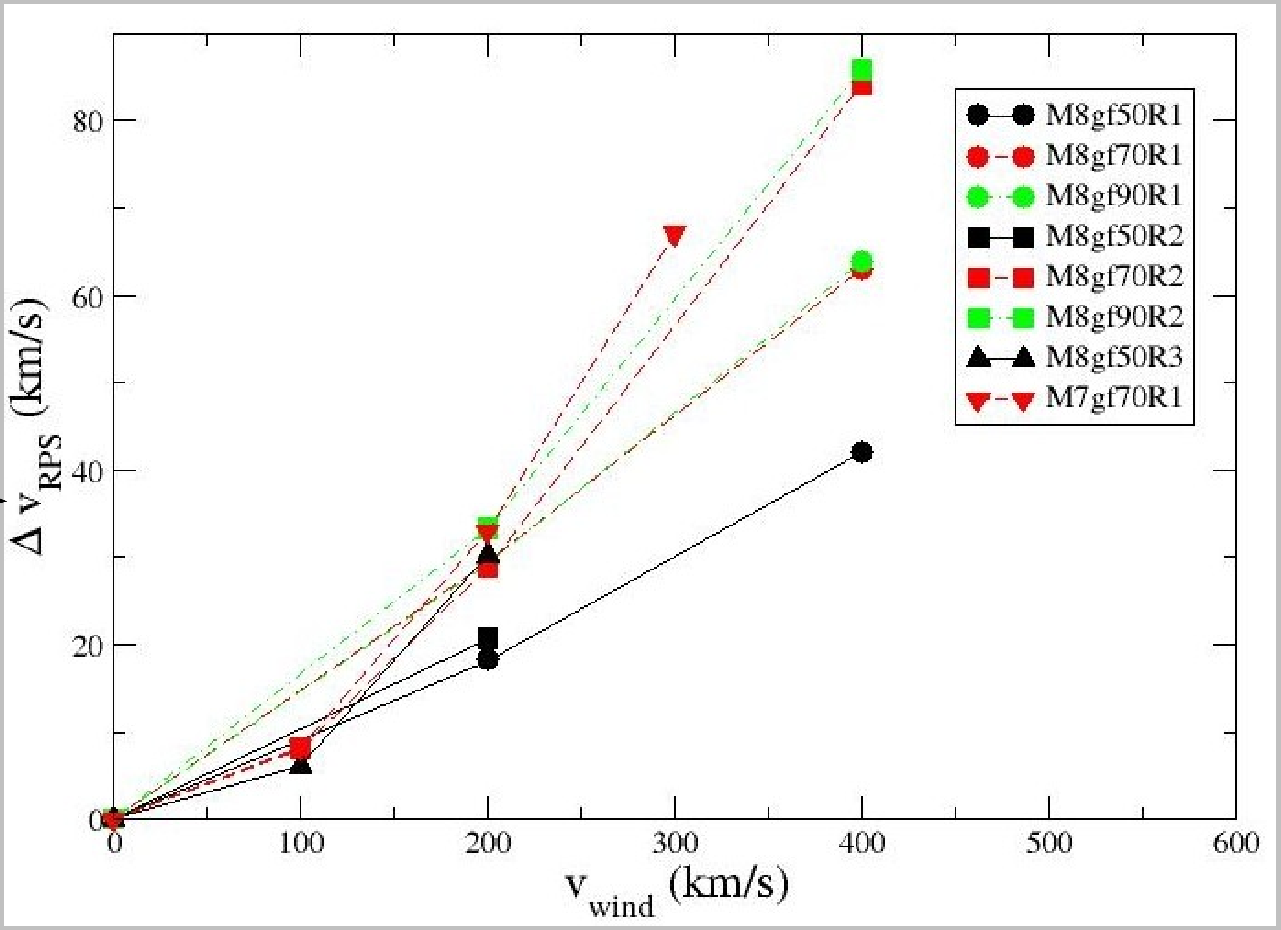
Remains near exponential,
effective radius grows as cloud of unbound stars expands & rotates

Ram pressure drag

Only the gas feels the ram pressure...
….so how can the stellar disk be dragged?

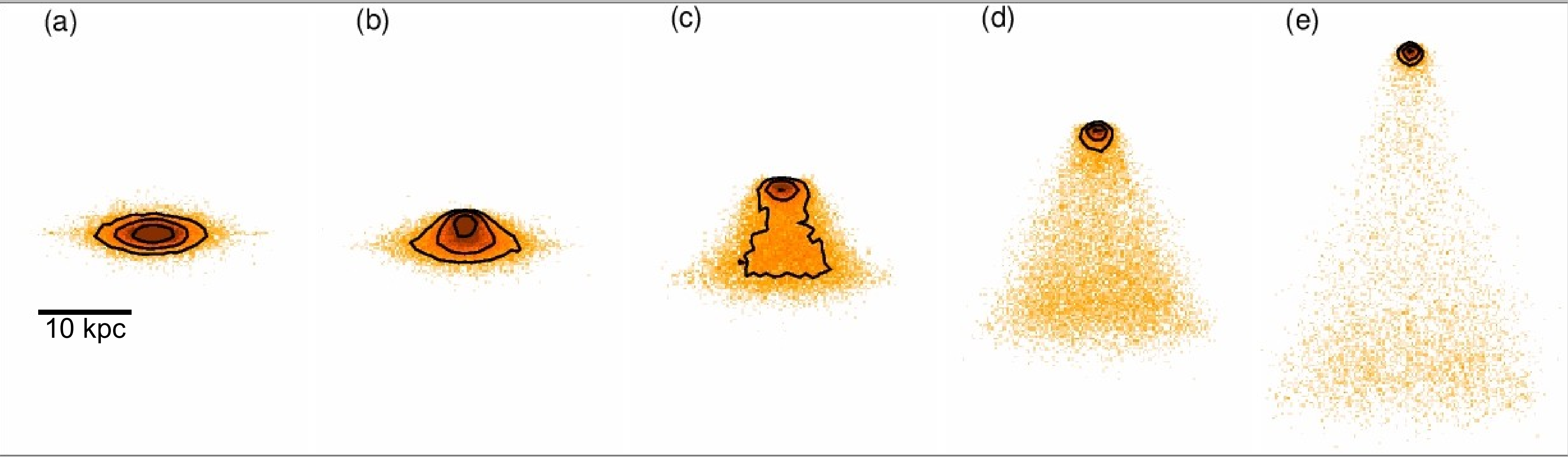
→ The stellar disk is towed along by the gravity of the gas disk

Change in velocity of galaxy due to ram pressure drag



Disks accelerated with change in velocity ~10-90 km/s (over 2.5 Gyr)

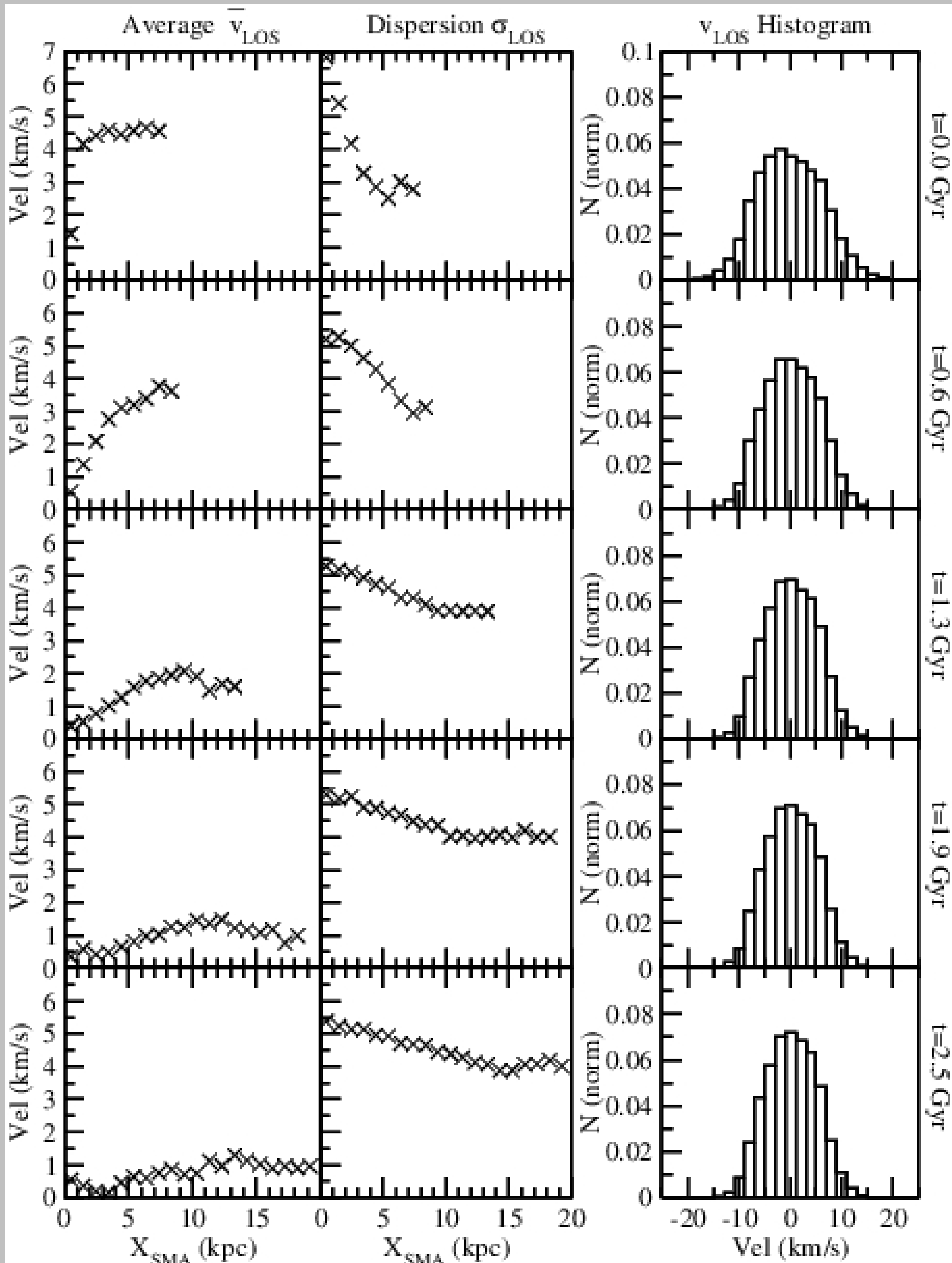
Drag causes unbound stars to lie on streams



Surface brightness at (a) t=0 Gyr, (b) t=0.6 Gyr, (c) t=1.2 Gyr, (d) t=1.9 Gyr, (e) t=2.5 Gyr. Contours at 29, 30, 31 $mag_v/arcsec^2$ (assuming fixed stellar mass-to-light ratio=1)

….but streams are very low surface brightness!

Stellar dynamics of unbound model:



Dynamics of unbound model, measured down a line of sight. (left) average velocity, (centre) dispersion, (right) histograms

- Model is completely unbound, and out of dynamical equilibrium
- Yet no obvious signs of expansion in model dynamics (if seen at any one instant)
- If assume dynamical equilibrium, dynamical masses could be heavily over estimated.

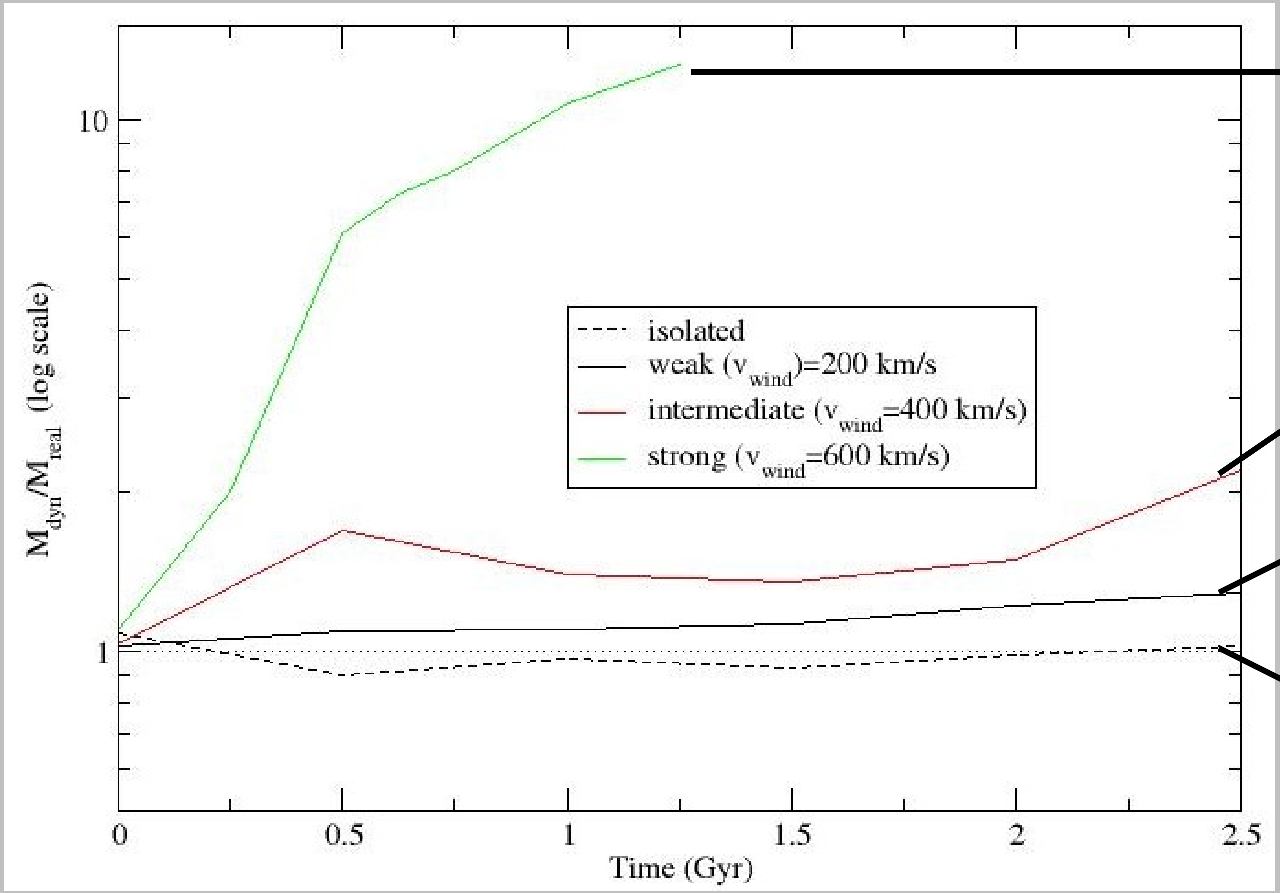
Dynamical mass-to-light ratios – effects of unbound stars:

<u>Technique for measuring dynamical mass (e.g. Evans 2003, Beasley 2006, Beasley 2009):</u>

1) Assume mass tracers in dynamical equilibrium

2) $M_{dyn}=M_{rot}+M_{disp}$ (total dynamical mass from sum of mass supported by rotation & dispersion)
$M_{rot}= G^{-1} <v_{rot}^2> R_{1/2}$ (Evans 2003), $M_{disp}= 3 G^{-1} <\sigma^2> R_{1/2}$ (Wolf 2010)

3) We measure M_{real} (the actual mass, measured directly from the simulation).
→ If $M_{dyn}/M_{real}=1$, dynamical mass has measured real mass perfectly.



Strong:
Factor ~10 over estimate of M_{dyn}

Intermediate:
Up to ~factor 2 overestimate of M_{dyn}

Weak:
Up to ~30% overestimate of M_{dyn}

Isolated:
M_{dyn} accurate to ~10%

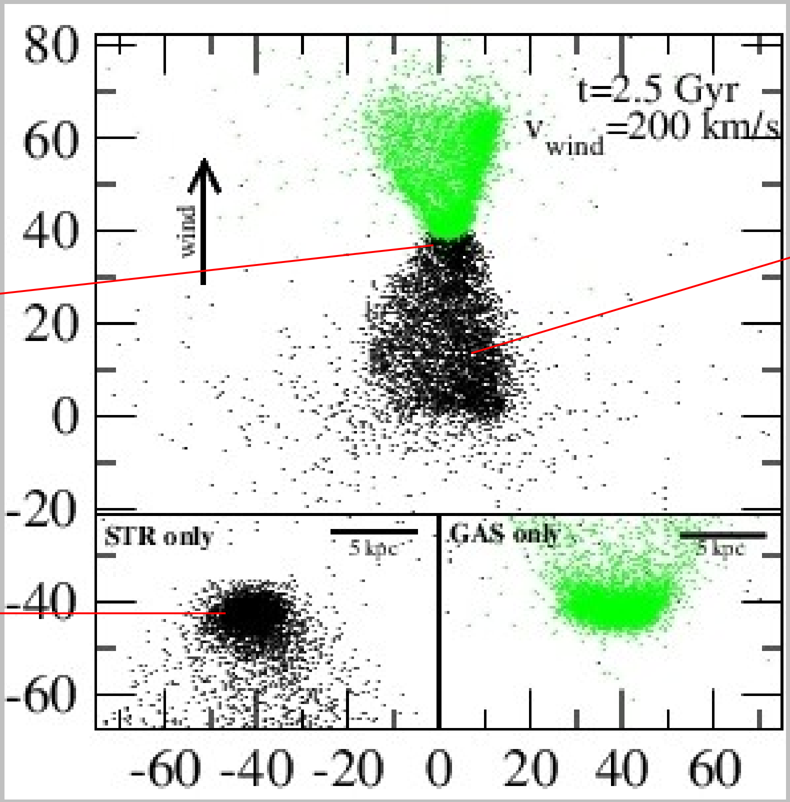
Dragging helps to remove unbound stars from line of sight

Summary:

- Ram pressure strips gas **and stars** from TDGs.
- Stellar disks truncated or destroyed
- Stripped stars on very low surface brightness streams or envelopes
- Unbound stars can enhance dynamical masses by factor ~10

Stellar disk dragged

Stellar disk truncated



Stream of unbound stars

The bigger picture:

• Environment highly destructive to Tidal Dwarf Galaxies – reduce fraction of dwarf galaxies assumed to have tidal origin

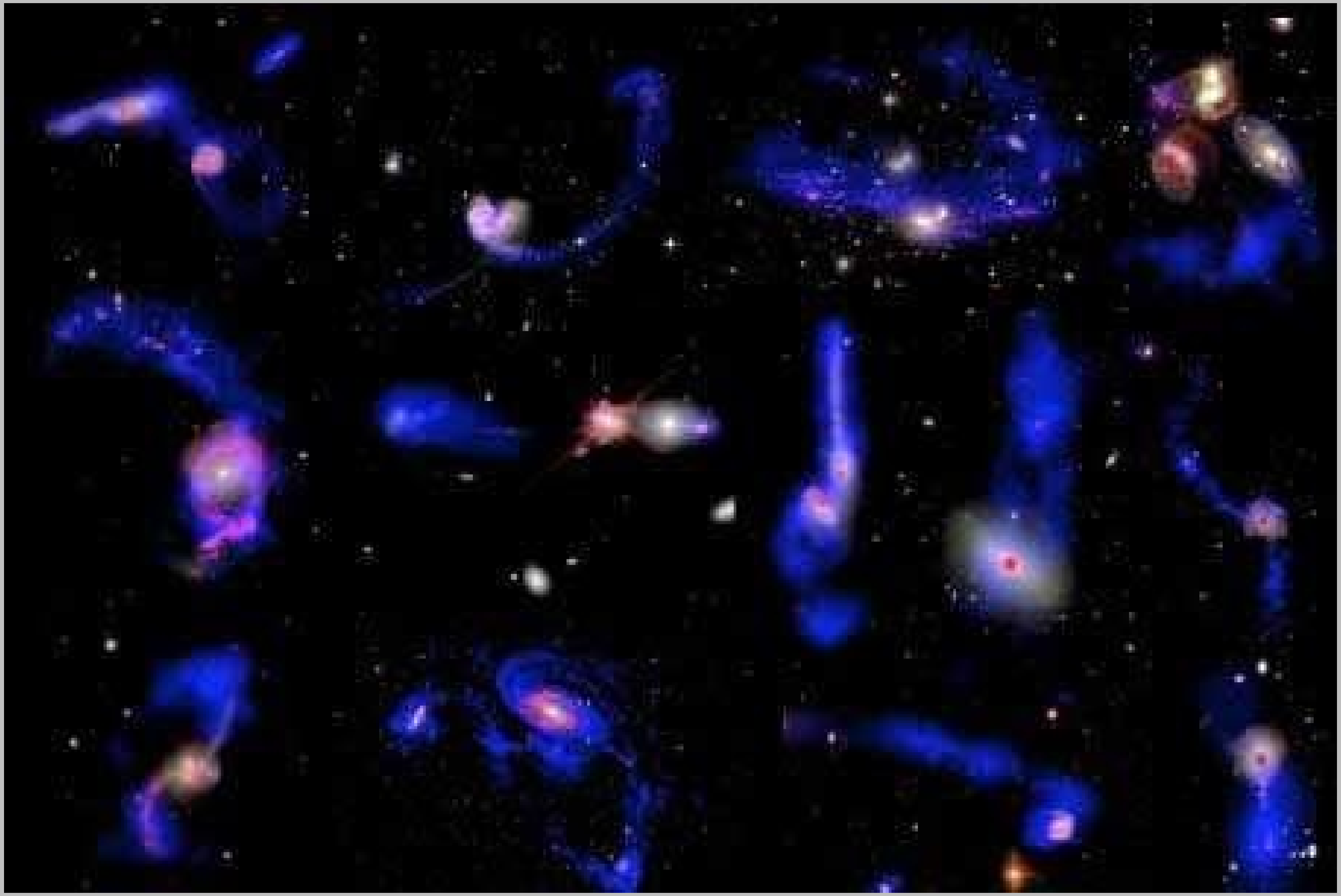
• Surviving Tidal Dwarfs follow evolutionary scenarios:
→ to avoid ram pressure (small disks, no plunging orbits, etc)
→ some may actually have been destroyed!

• Tidal streams of gas & stars ***even more*** sensitive to ram pressure
→ this may indirectly affect Tidal Dwarf evolution as they form from streams
→ sensitive probes of hot gas content in external galaxies?
→ Do most other galaxies not have much hot gas???

For the future:

High-resolution interacting galaxies simulations, but with hot gas content added

Aligned tidal streams of gas and stars



Duc P. A., 2012
Atomic gas (HI) in blue
Young stars (NUV) in pink
Older stars (optical) in yellow