Tidal Dwarf Galaxies

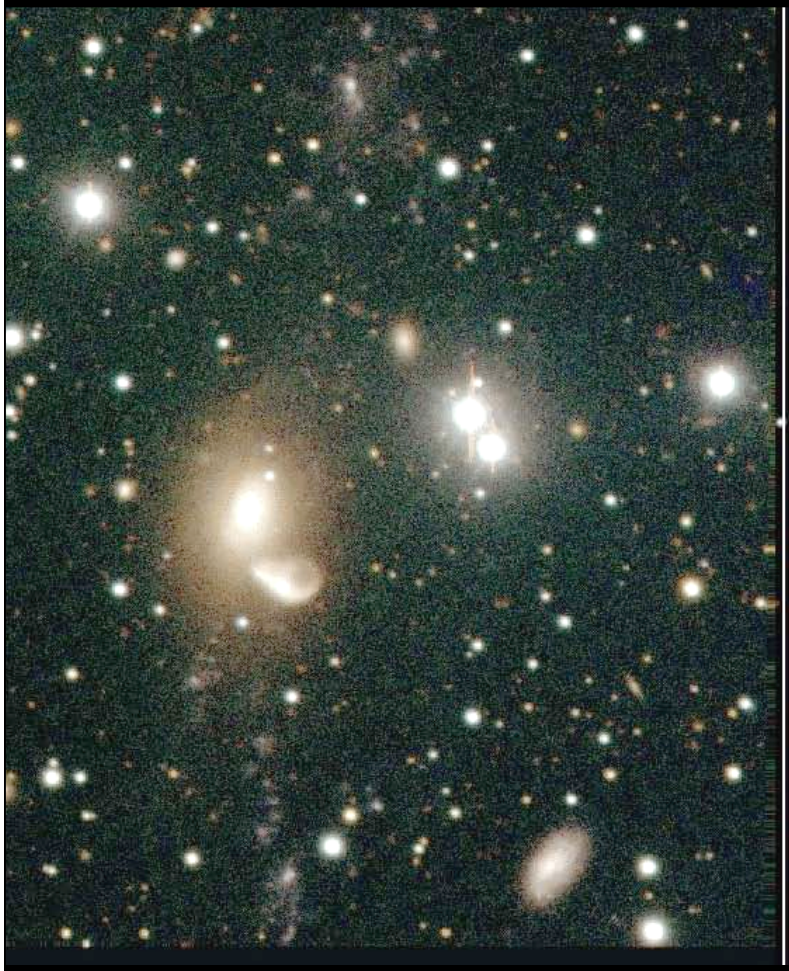
Probing Star, Galaxy Formation and Cosmology

Pierre-Alain Duc
AIM et CEA-Saclay

avec la collaboration de

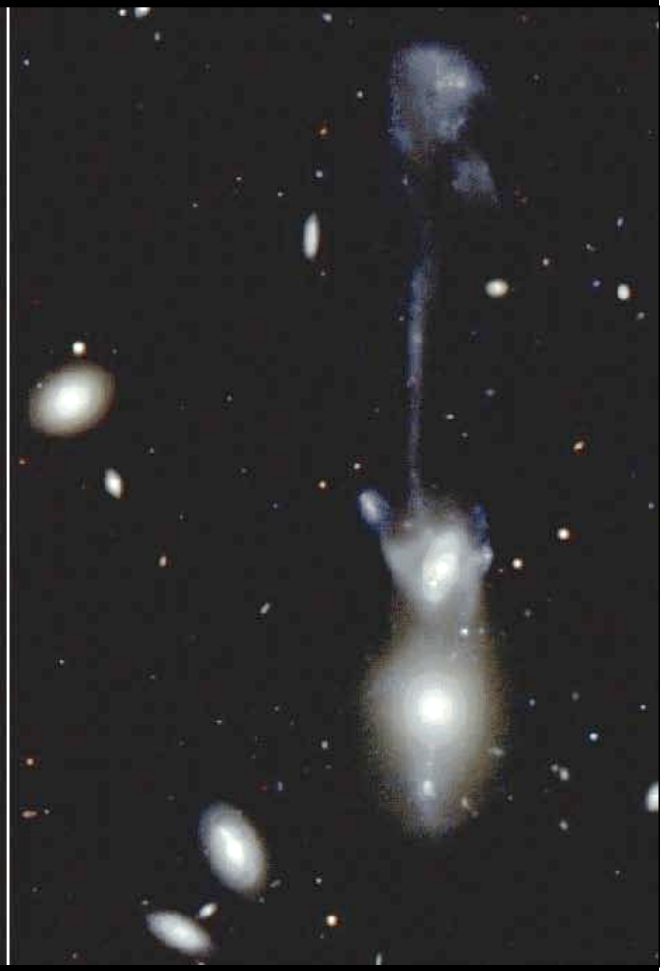
Frédéric Bournaud
Médéric Boquien
Jonathan Braine
Elias Brinks
Ute Lisenfeld
Vassilis Charmandaris
Peter Weilbacher
Philippe Amram

Extended Star Formation in the Tidal Tails of interacting galaxies



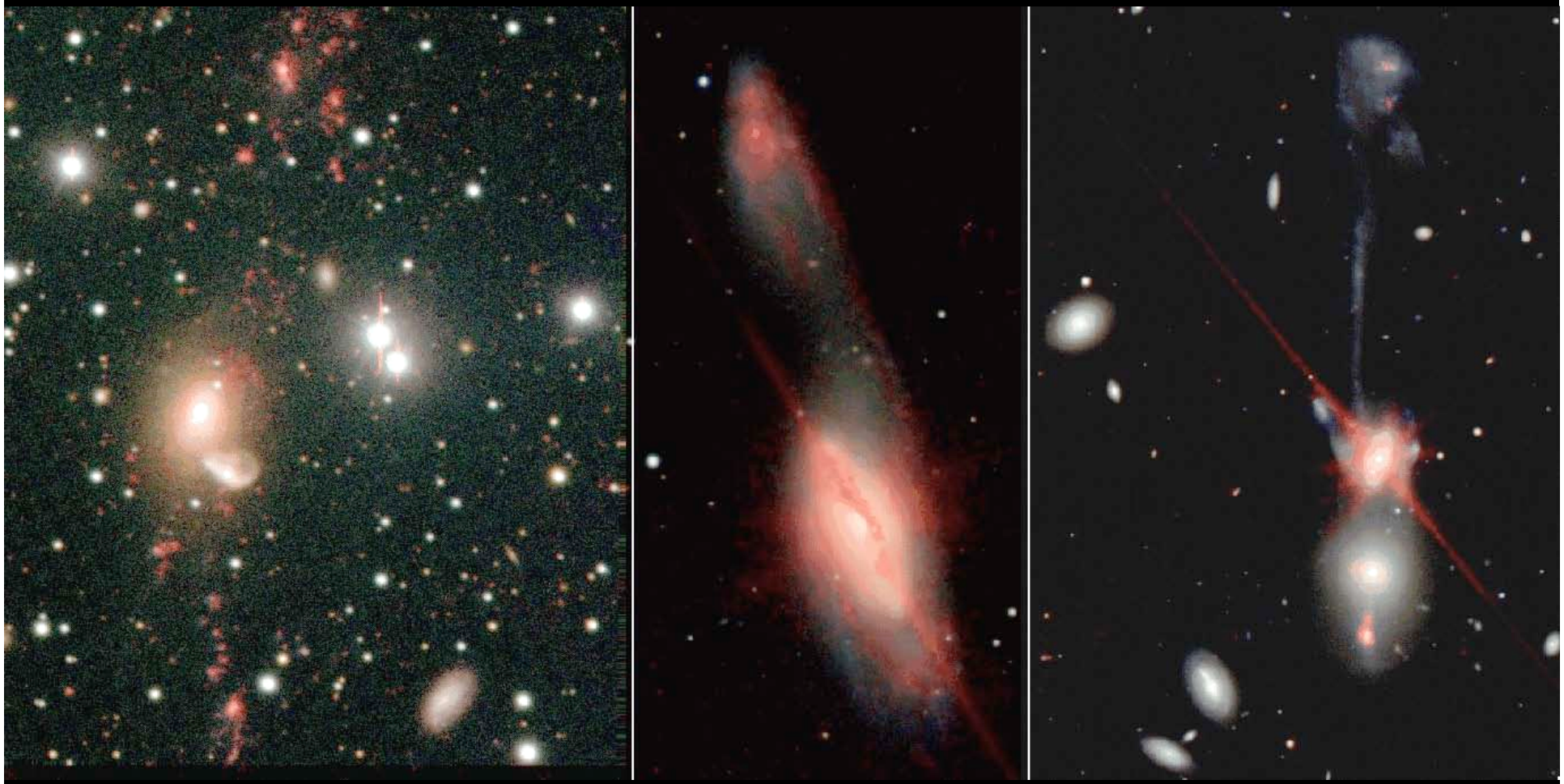
NGC 5291 (BVR - © ESO/NTT)

NGC 2992 (BVR - © ESO/NTT)



Arp 105 (BVR - © CFHT/MegaCam)

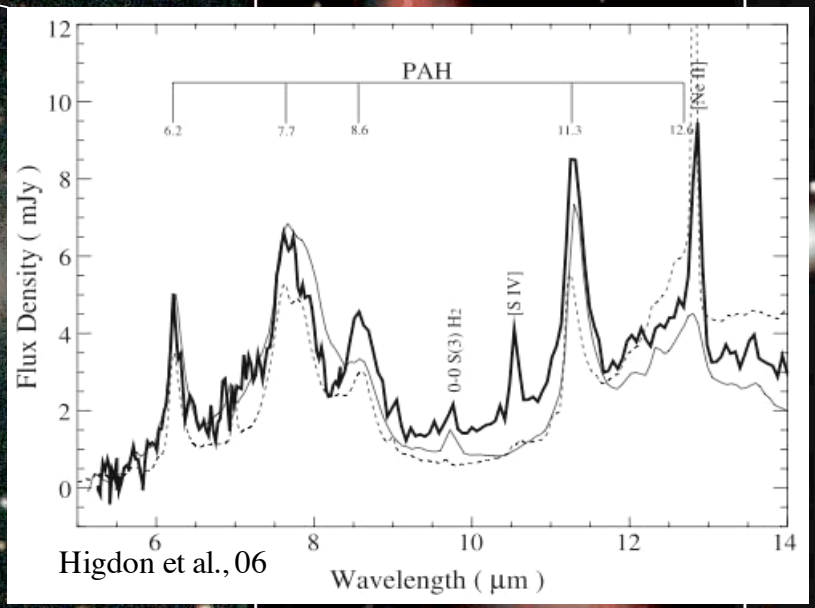
Extended Star Formation in the Tidal Tails of interacting galaxies



NGC 5291 (BVR + 8 μm © Spitzer/IRAC) *NGC 2992 (BVR + 8 μm © Spitzer/IRAC)* *Arp 105 (BVR +8 μm © Spitzer/IRAC)*

Extended Star Formation in the Tidal Tails of interacting galaxies

MIR emission, PAH dominated, as for typical SF regions in spirals



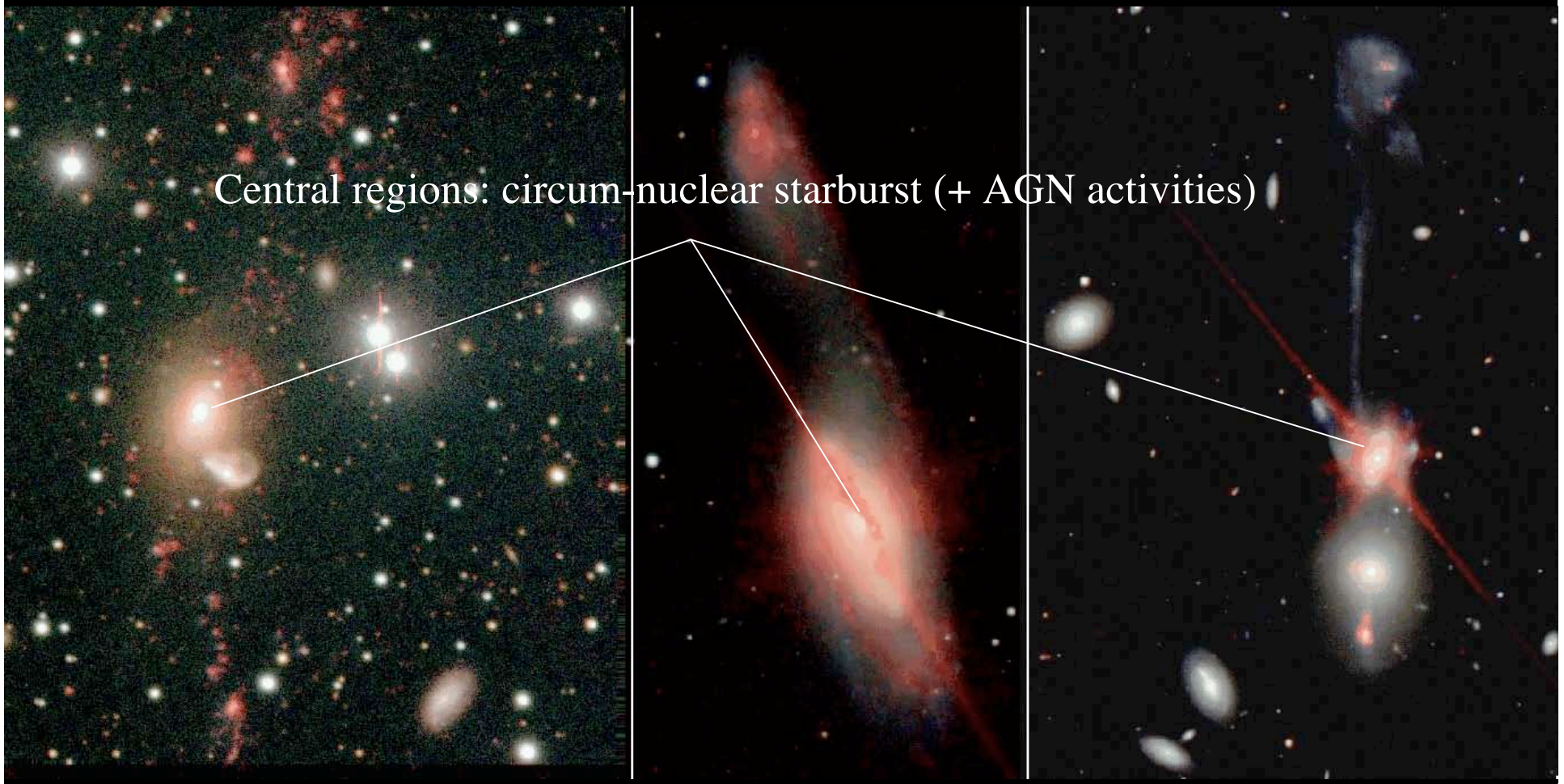
Higdon et al., 06

NGC 5291 (BVR + 8 µm © Spitzer/IRAC)

NGC 2992 (BVR + 8 µm © Spitzer/IRAC)

Arp 105 (BVR + 8 µm © Spitzer/IRAC)

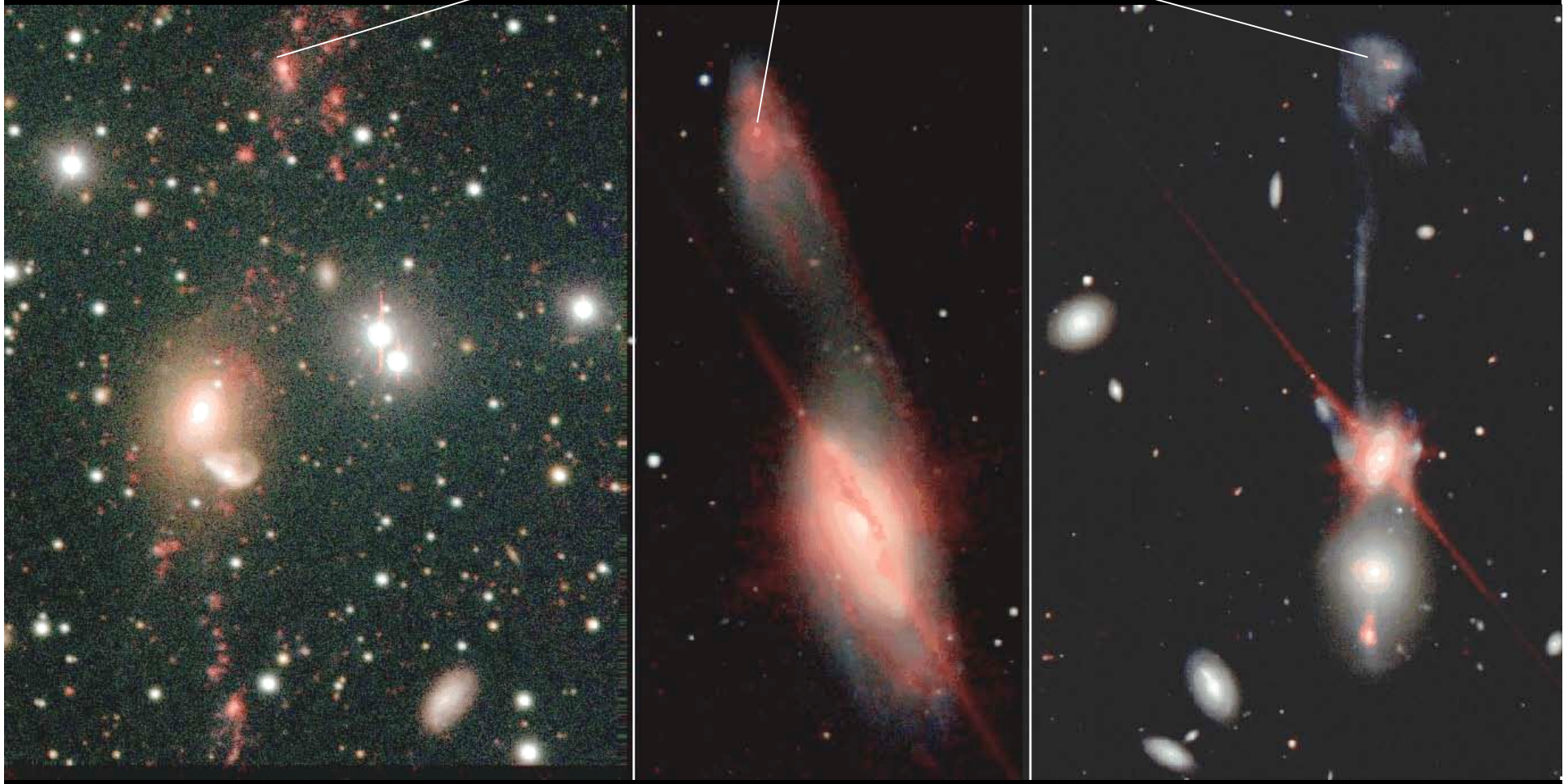
Extended Star Formation in the Tidal Tails of interacting galaxies



NGC 5291 (BVR + 8 μm © Spitzer/IRAC) *NGC 2992 (BVR + 8 μm © Spitzer/IRAC)* *Arp 105 (BVR +8 μm © Spitzer/IRAC)*

Extended Star Formation in the Tidal Tails of interacting galaxies

up to 100 kpc from the nucleii



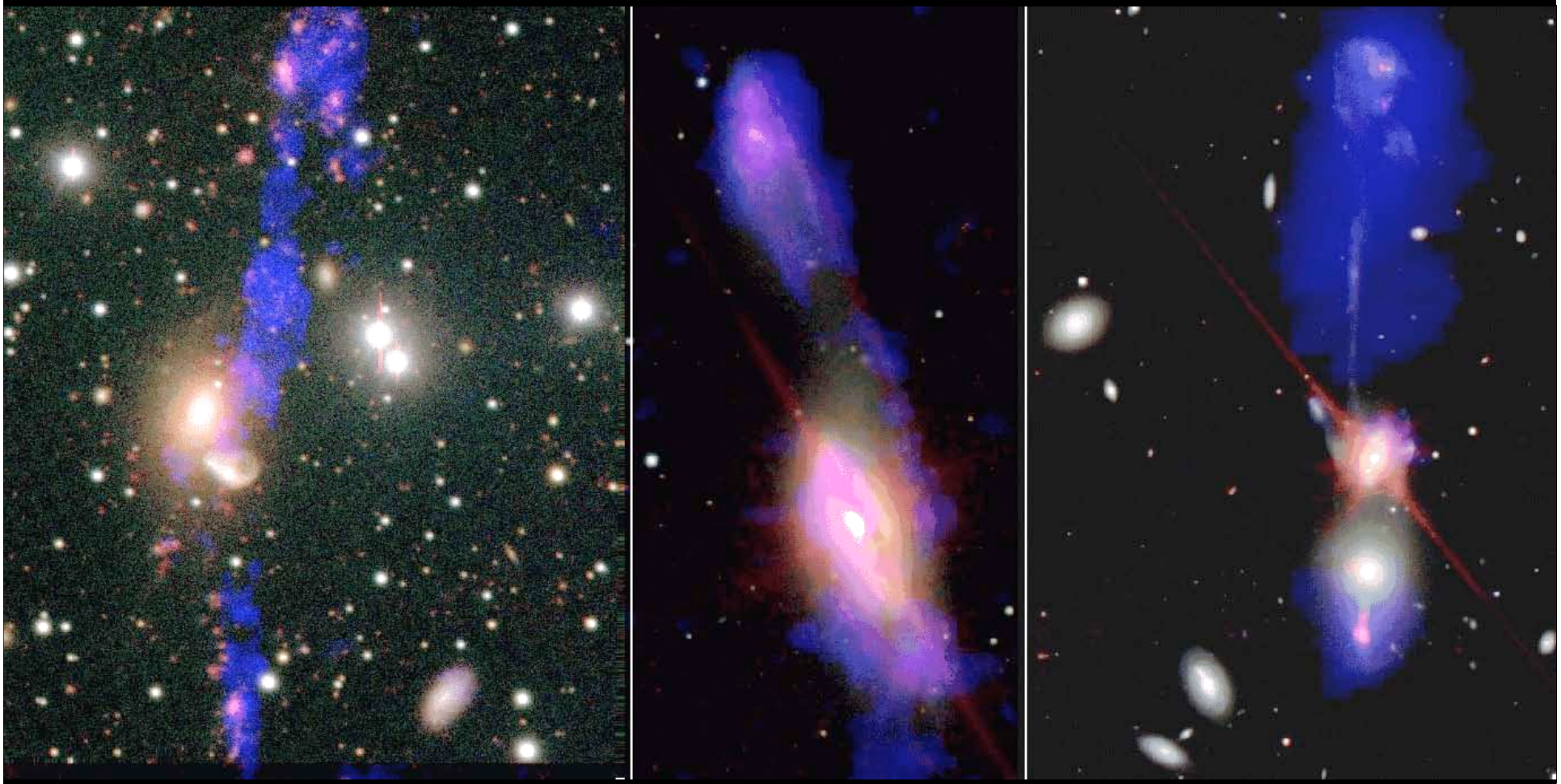
NGC 5291 (BVR + 8 μm © Spitzer/IRAC)

NGC 2992 (BVR + 8 μm © Spitzer/IRAC)

Arp 105 (BVR +8 μm © Spitzer/IRAC)

Extended Star Formation in the Tidal Tails of interacting galaxies

… fueled by large external, tidally expelled, gas reservoirs ($M_{HI} >= 10^9 M_{sun}$)



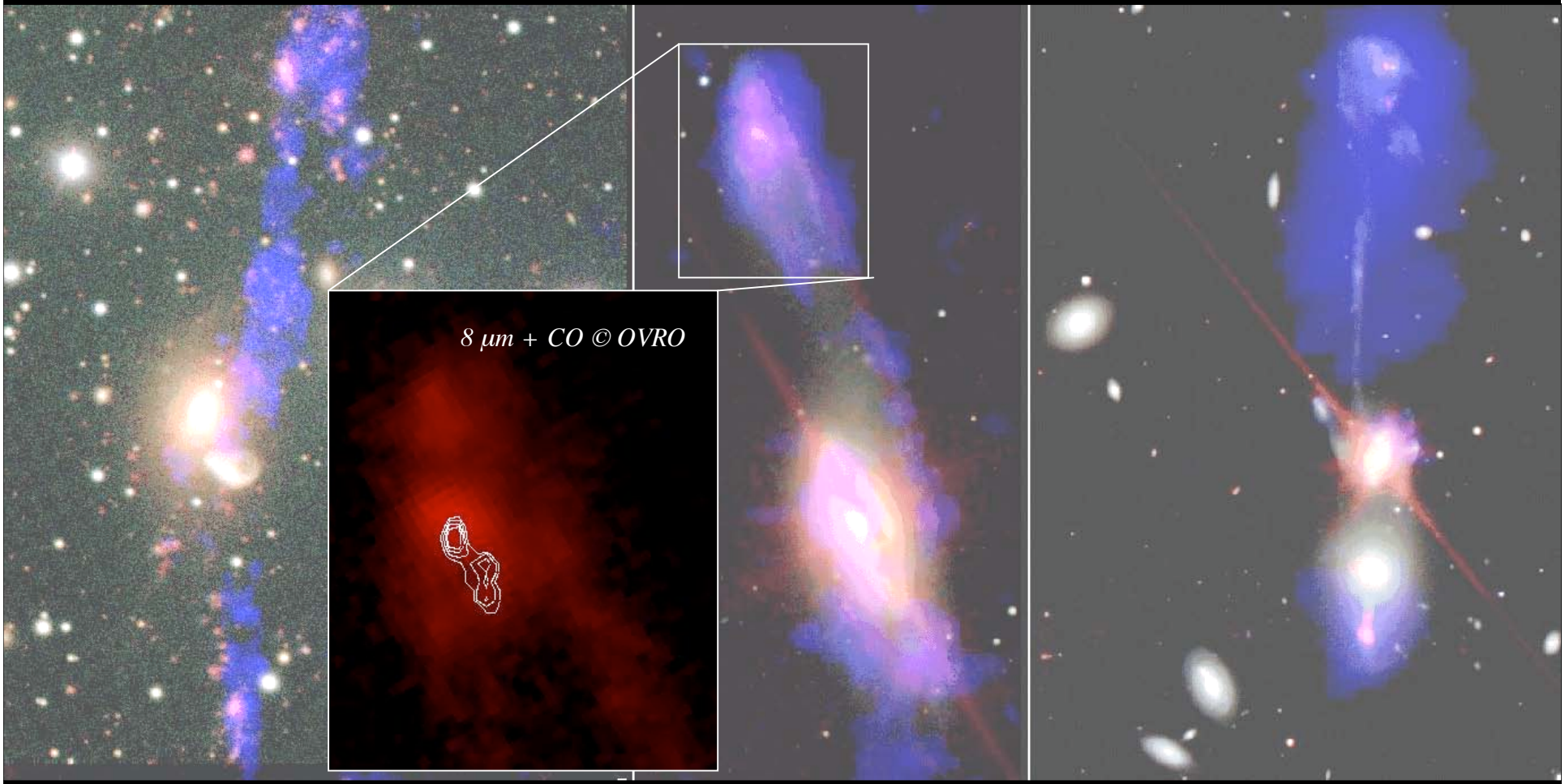
NGC 5291 (BVR - 8 + HI © VLA/B)

NGC 2992 (BVR - 8 + HI © VLA/B)

Arp 105 (BVR - 8 + HI- © VLA/C)

Extended Star Formation in the Tidal Tails of interacting galaxies

… associated molecular gas clouds detected in CO ($M_{H2} >= 10^8 M_{sun}$)



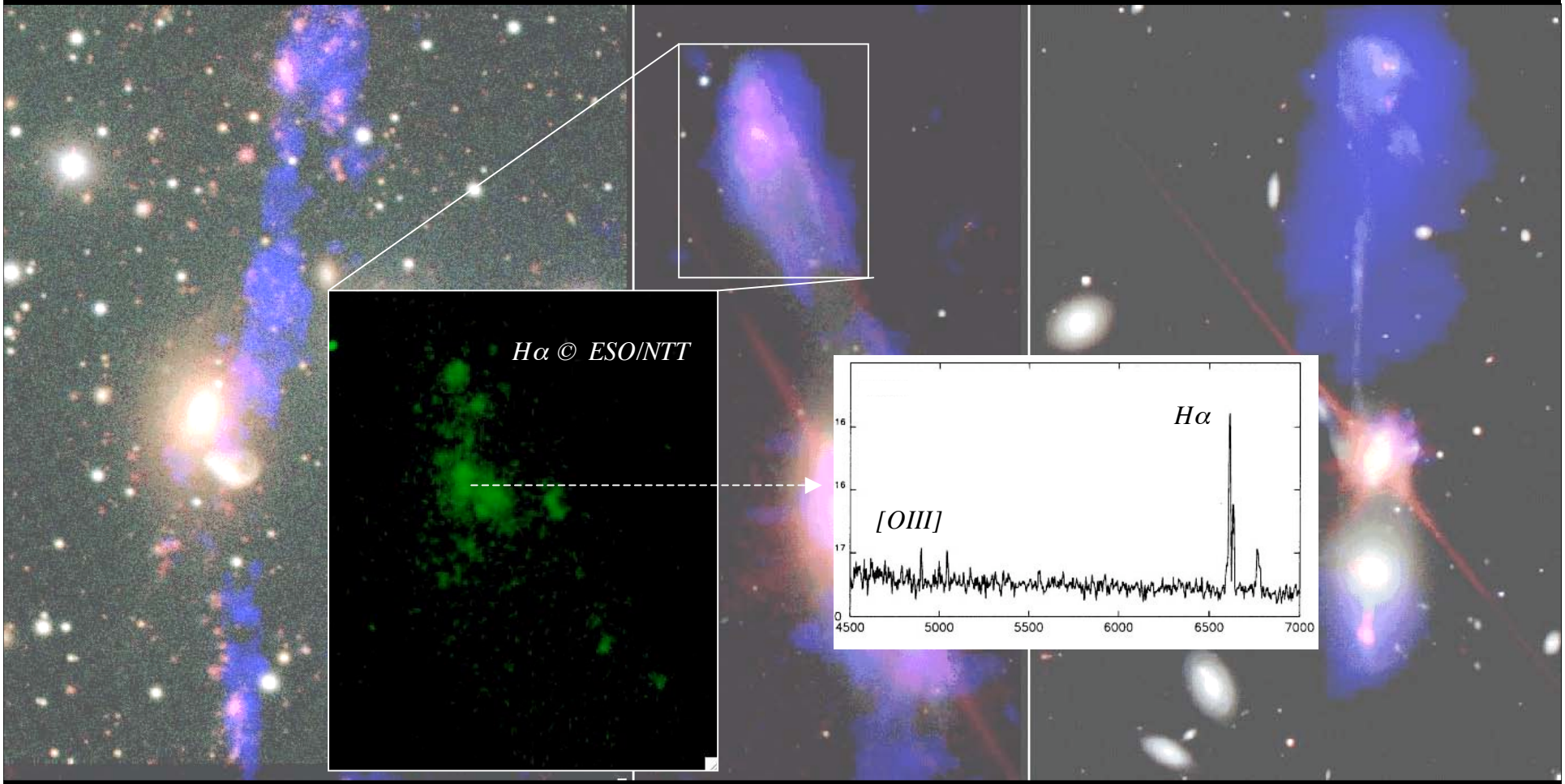
NGC 5291 (BVR - 8 + HI © VLA/B)

NGC 2992 (BVR - 8 + HI © VLA/B)

Arp 105 (BVR - 8 + HI- © VLA/C)

Extended Star Formation in the Tidal Tails of interacting galaxies

HII regions characterized by a relative high metallicity ($Z_{sun}/2$), despite their distance:
… unherited from their parent galaxies

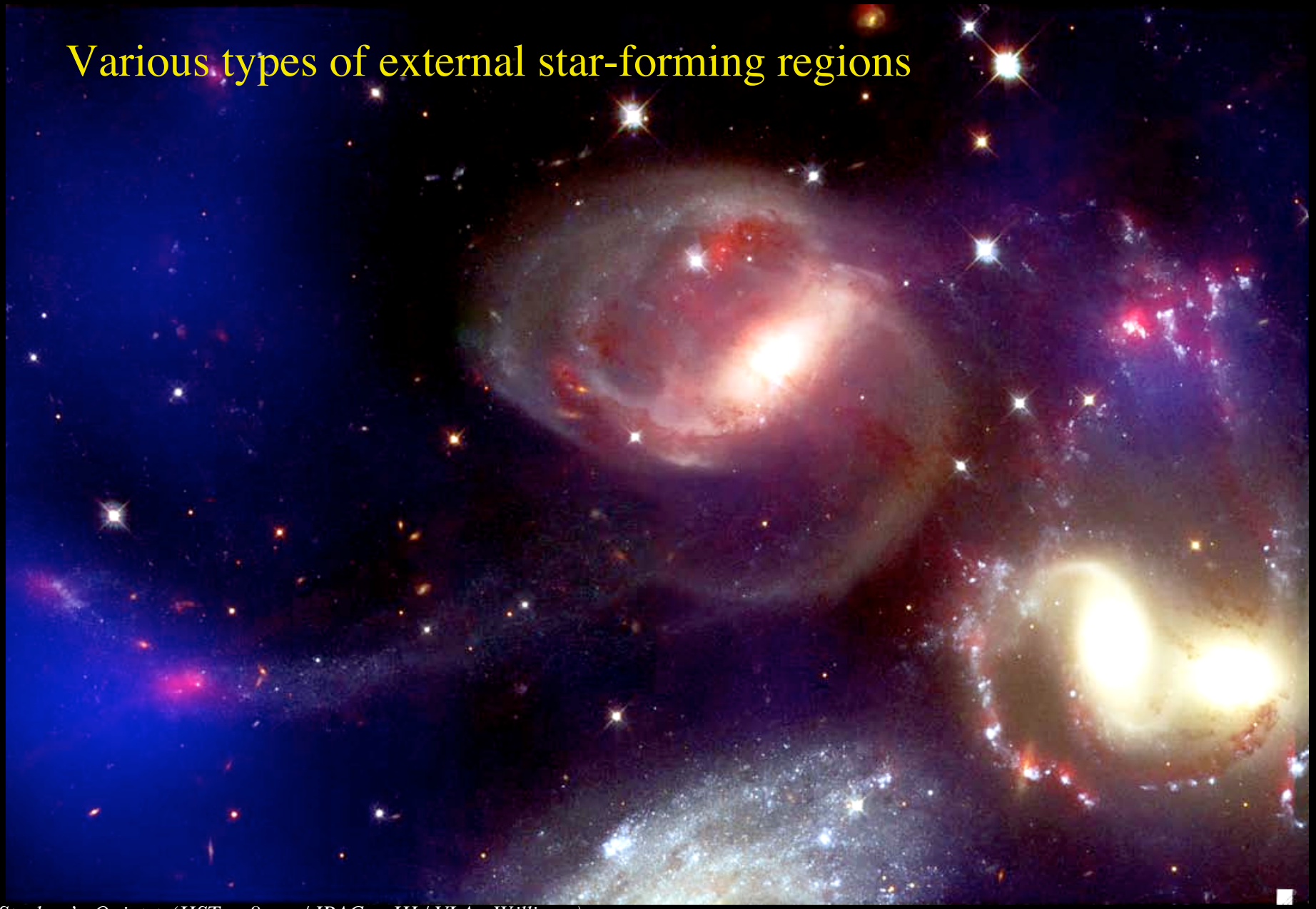


NGC 5291 (BVR - 8 + HI © VLA/B)

NGC 2992 (BVR - 8 + HI © VLA/B)

Arp 105 (BVR - 8 + HI- © VLA/C)

Various types of external star-forming regions



Stephan's Quintet (HST + 8 μm / IRAC+ HI / VLA - Williams)

Intergalactic HII regions

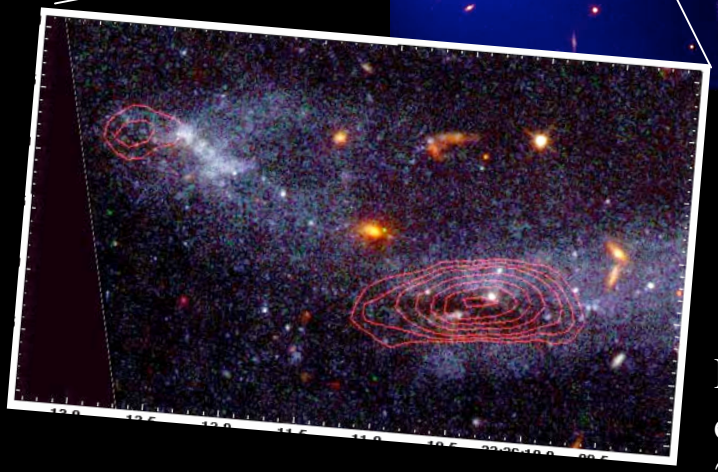
Mendes de Oliveira
et al., 2004

Stephan's Quintet (HST + 8 μm / IRAC+ HI / VLA)

Intergalactic shocks

Appleton
et al., 2006

Tidal Dwarf Galaxies



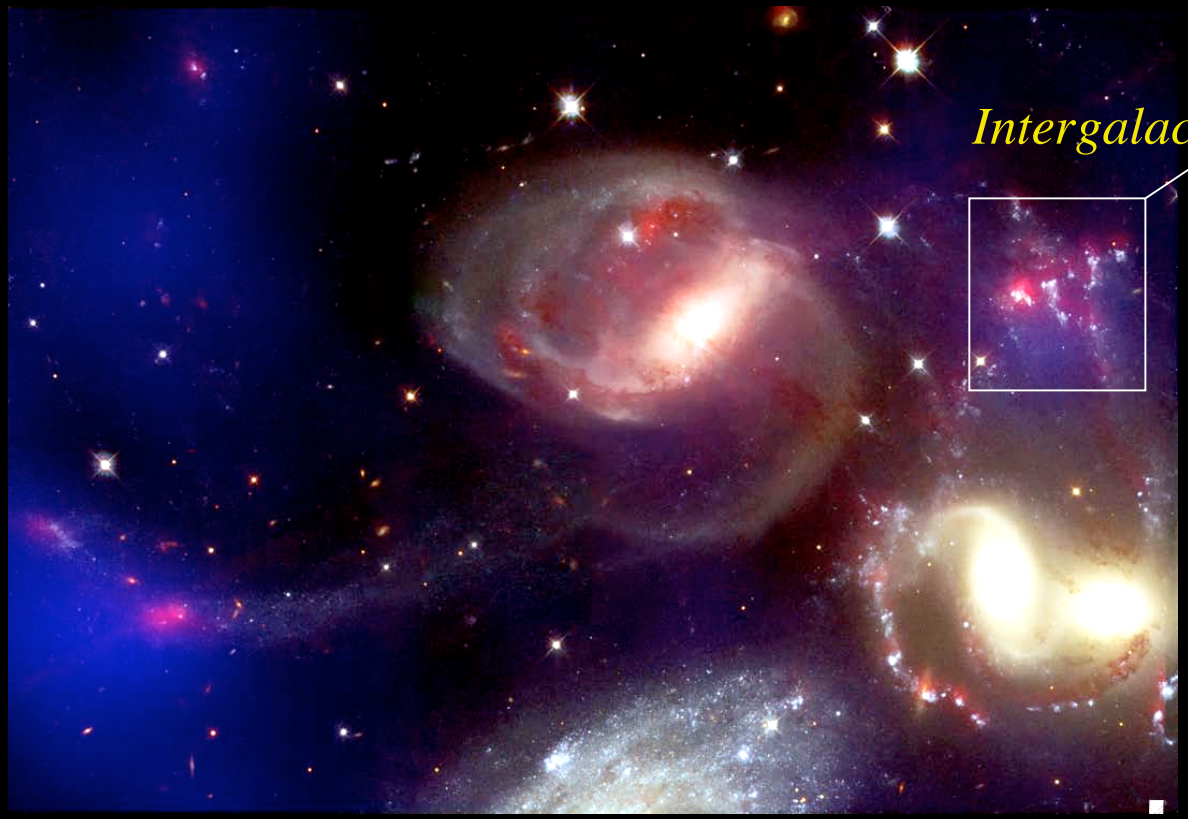
Lisenfeld
et al., 2002,
2004

(Super) Star Clusters

Gallagher
et al., 2001

Various types of external star-forming regions

Stephan's Quintet (HST + 8 μm / IRAC+ HI / VLA)



Intergalactic shocks

Appleton et al., 2006

Various types of external star-forming regions

Intergalactic HII regions

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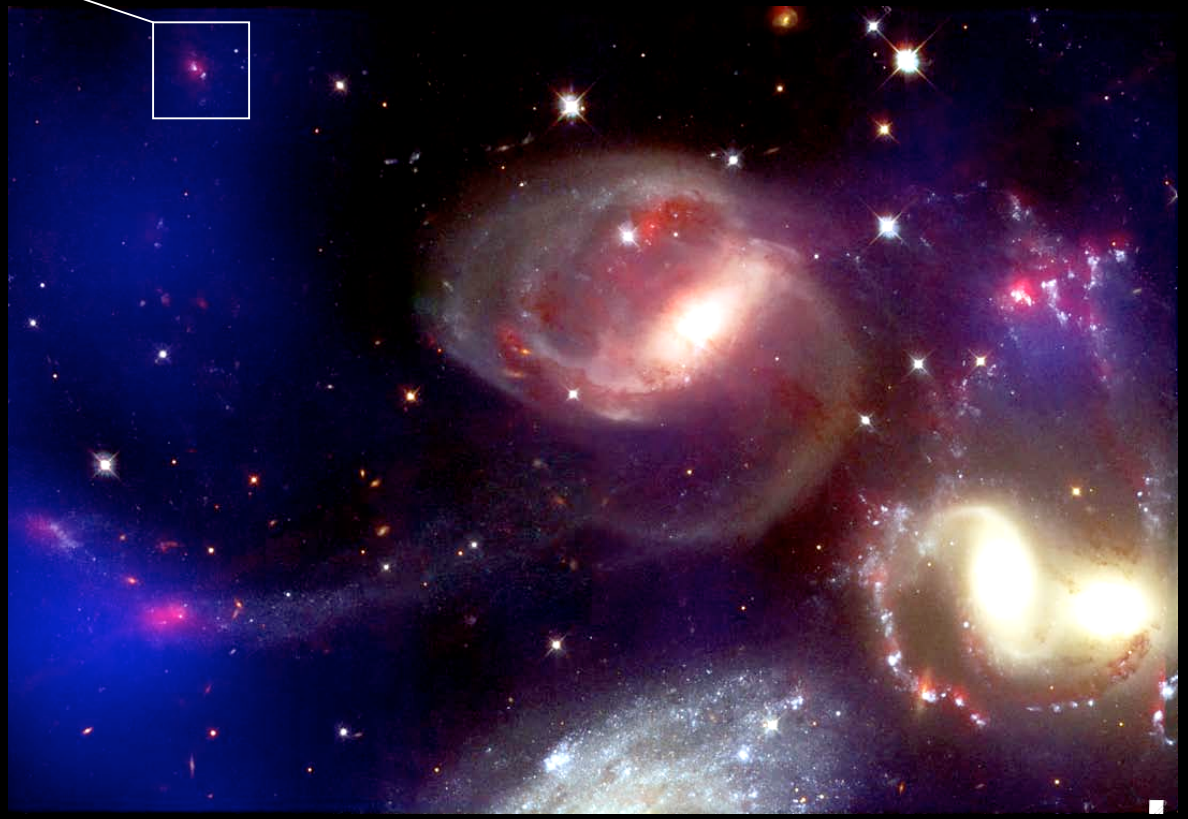
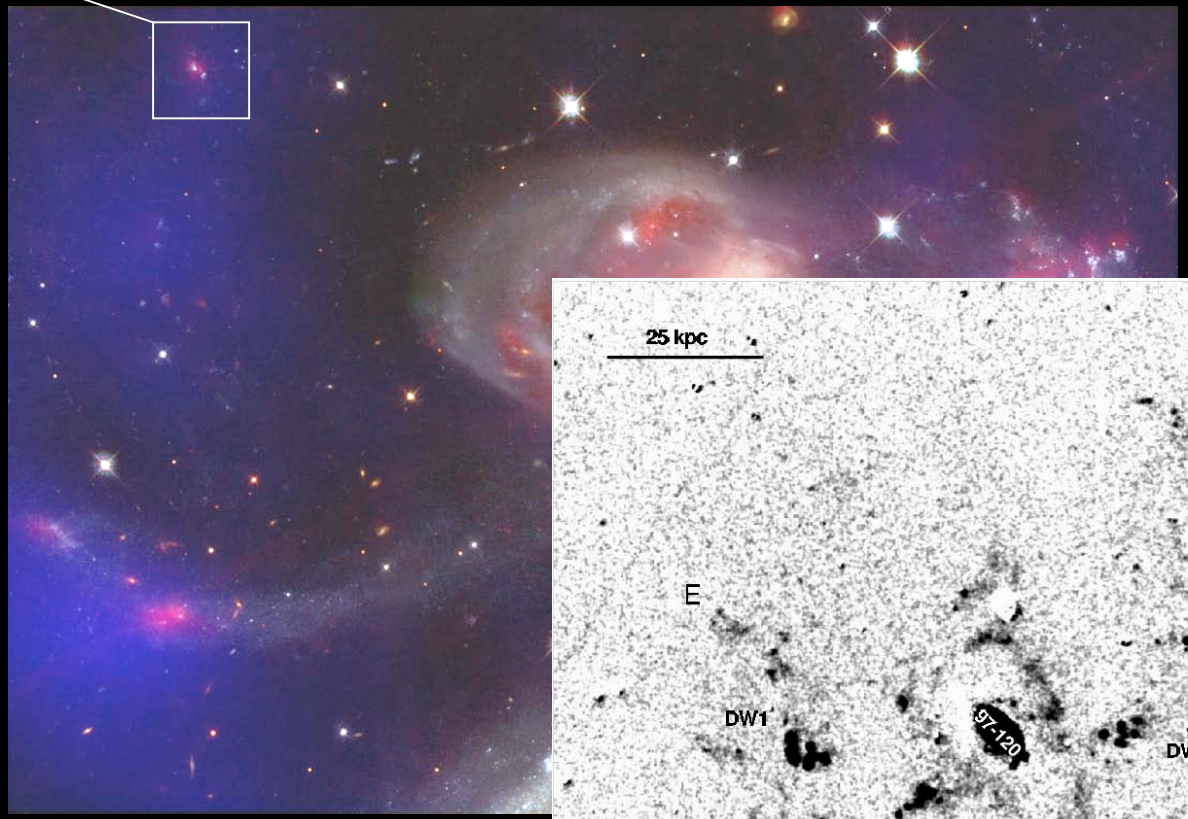


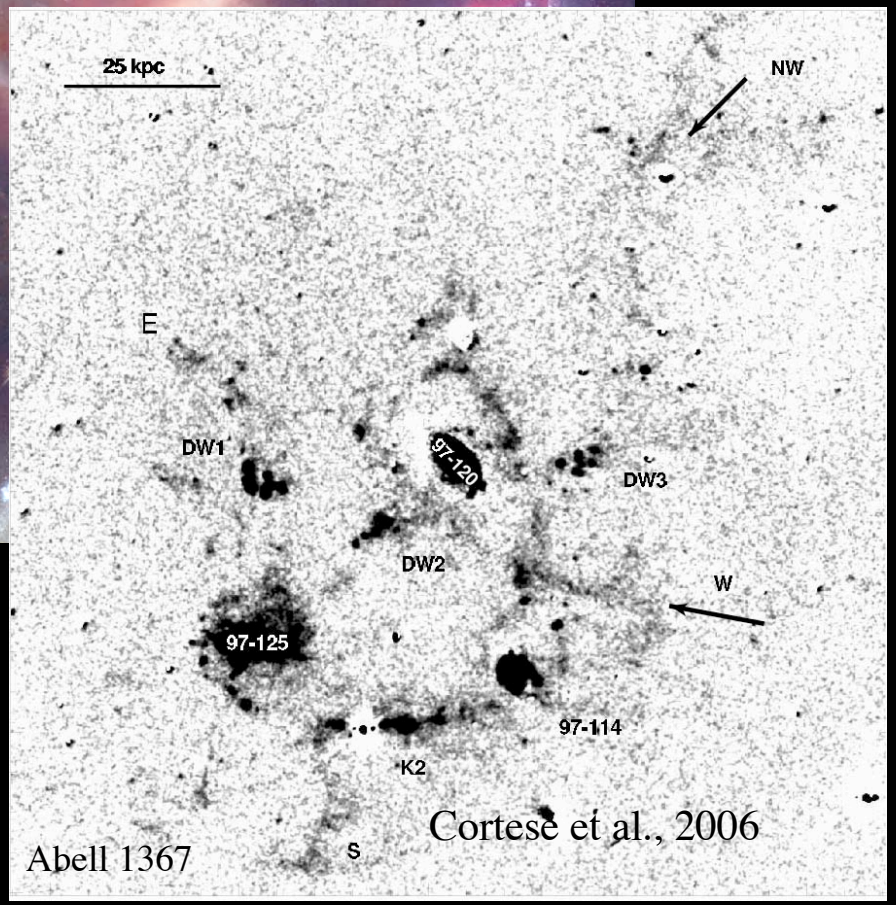
Various types of external star-forming regions

Intergalactic HII regions

Mendes de Oliveira et al., 2004

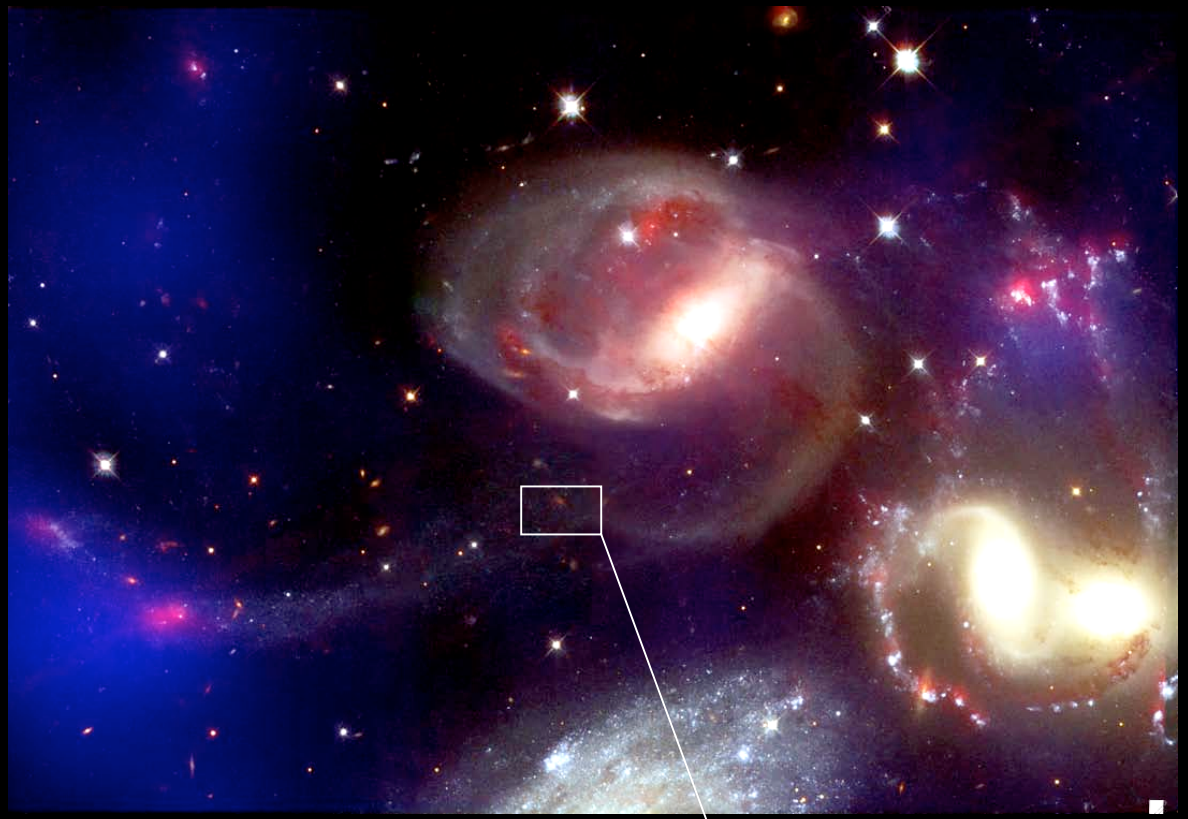
Stephan's Quintet (HST + 8 μm / IRAC+ HI / VLA)





- Small, unbound(?) HII regions, sometimes aligned along gigantic filaments
- Low individual SFR (< 0.01 M_{sun}/yr), but contribute directly to the enrichment of the IGM

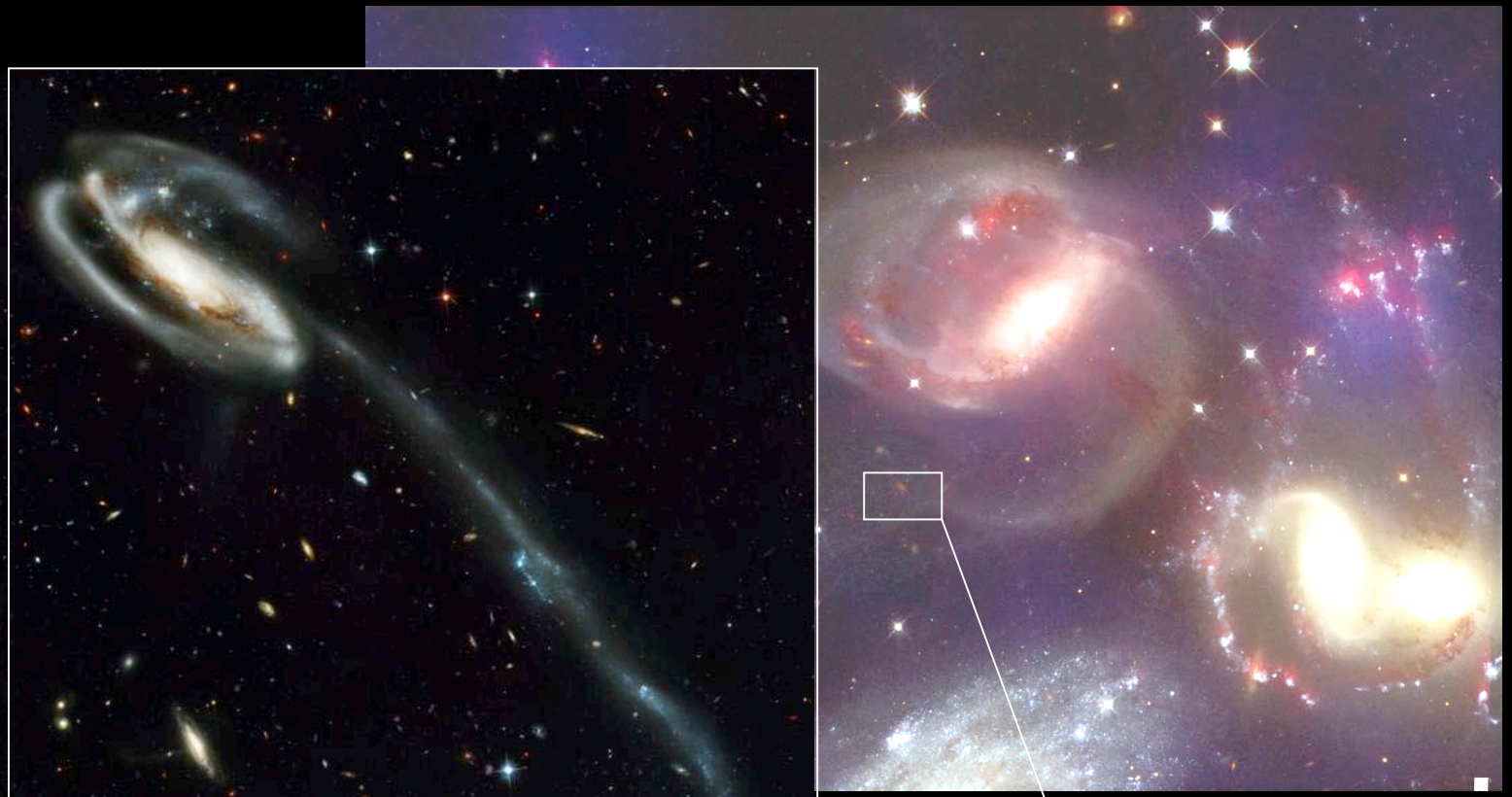
Stephan's Quintet (HST + 8 μm / IRAC+ HI / VLA)



(Super) Star Clusters

Gallagher et al., 2001

Stephan's Quintet (HST + 8 μm / IRAC+ HI / VLA)



Tadpole galaxy (HST/ACS)

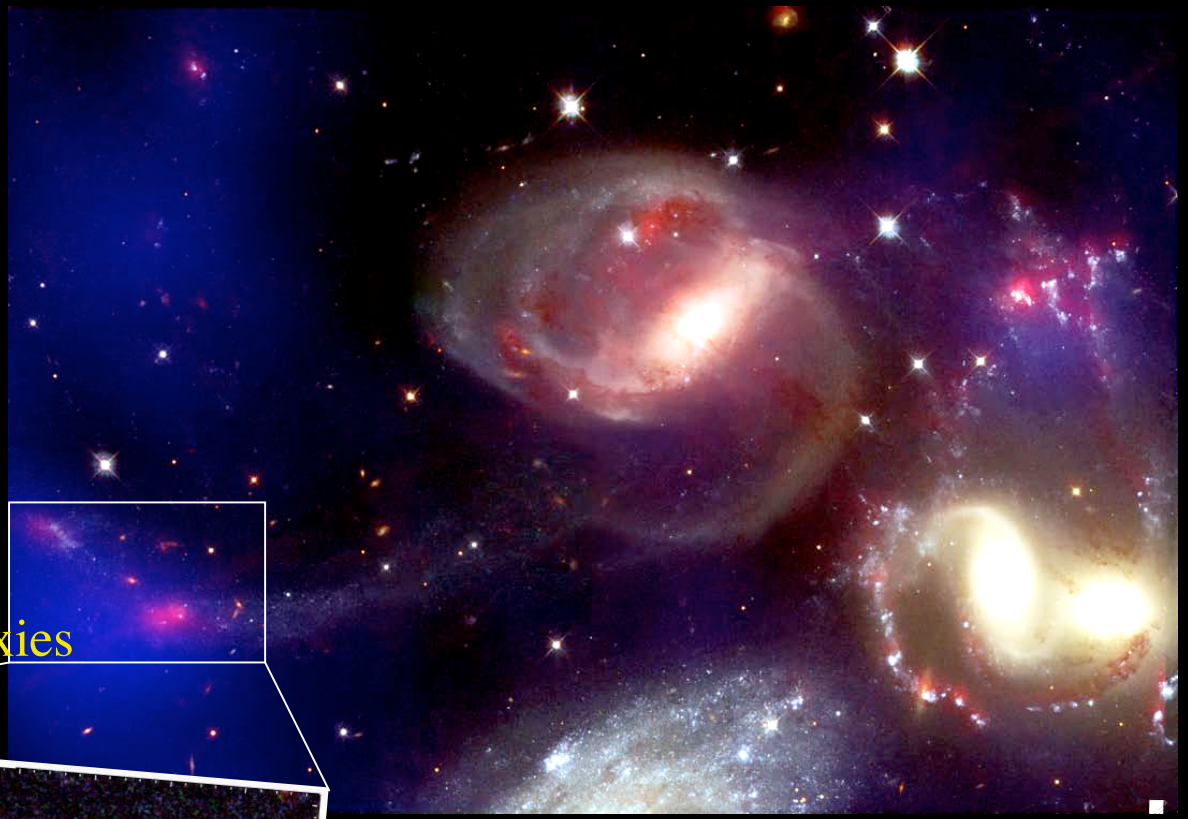
(Super) Star Clusters

Gallagher et al., 2001

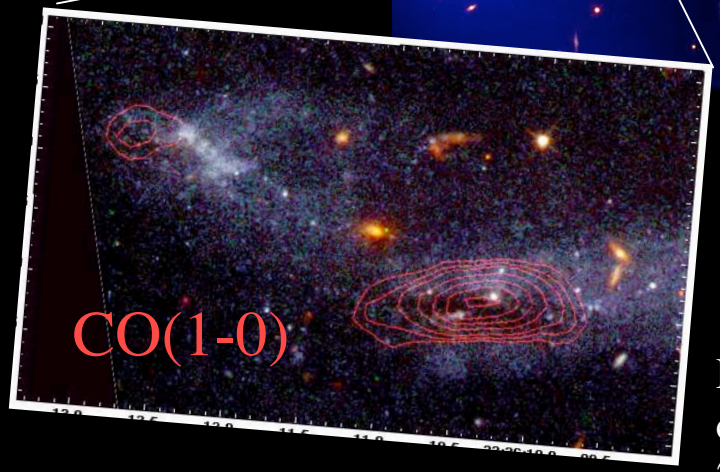
- 10^5 - 10^6 M_{sun}
- Progenitors of the merger induced globular clusters?

See talks by R. de Grijs (S235), B. Whitmore, G. Tenorio-Tagle (S237)

Stephan's Quintet (HST + 8 μm / IRAC+ HI / VLA)

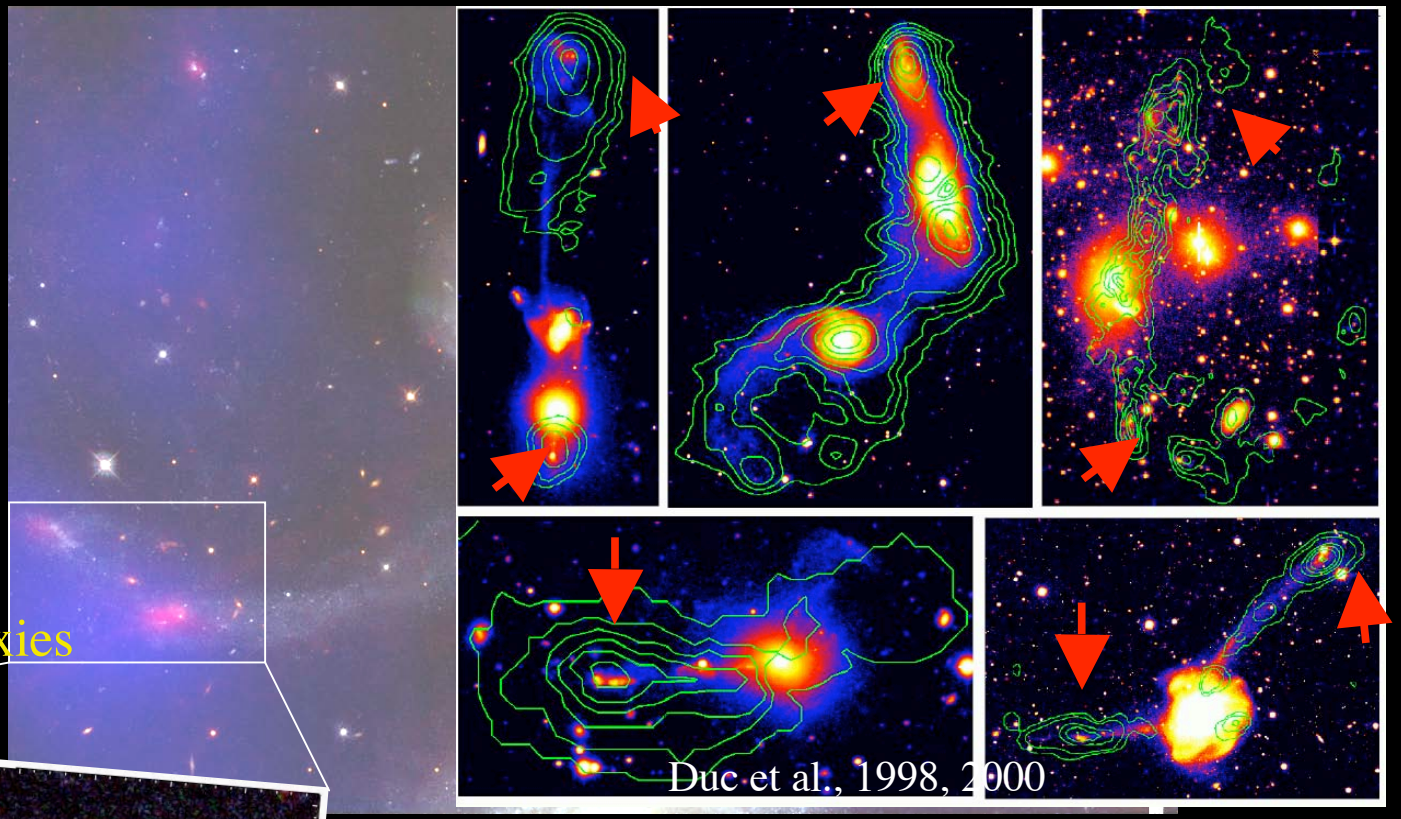


Tidal Dwarf Galaxies



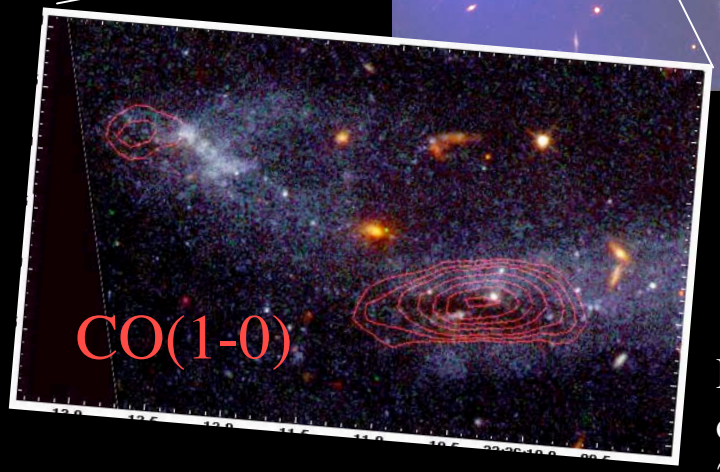
Lisenfeld et al., 2002, 2004

Stephan's Quintet (HST + 8 μm / IRAC+ HI / VLA)



Duc et al., 1998, 2000

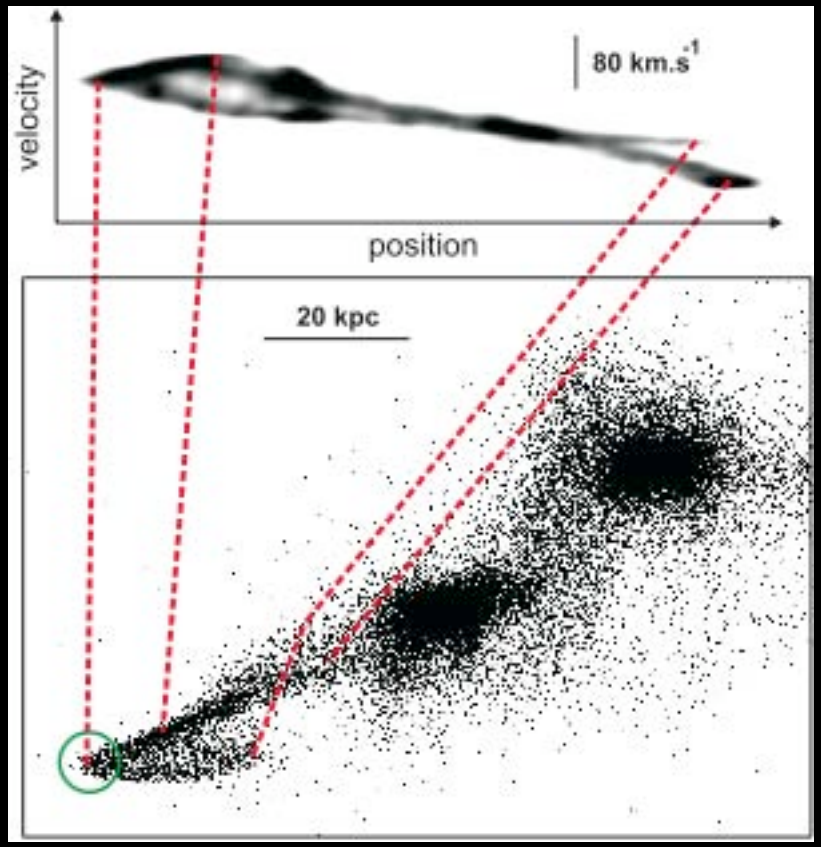
Tidal Dwarf Galaxies



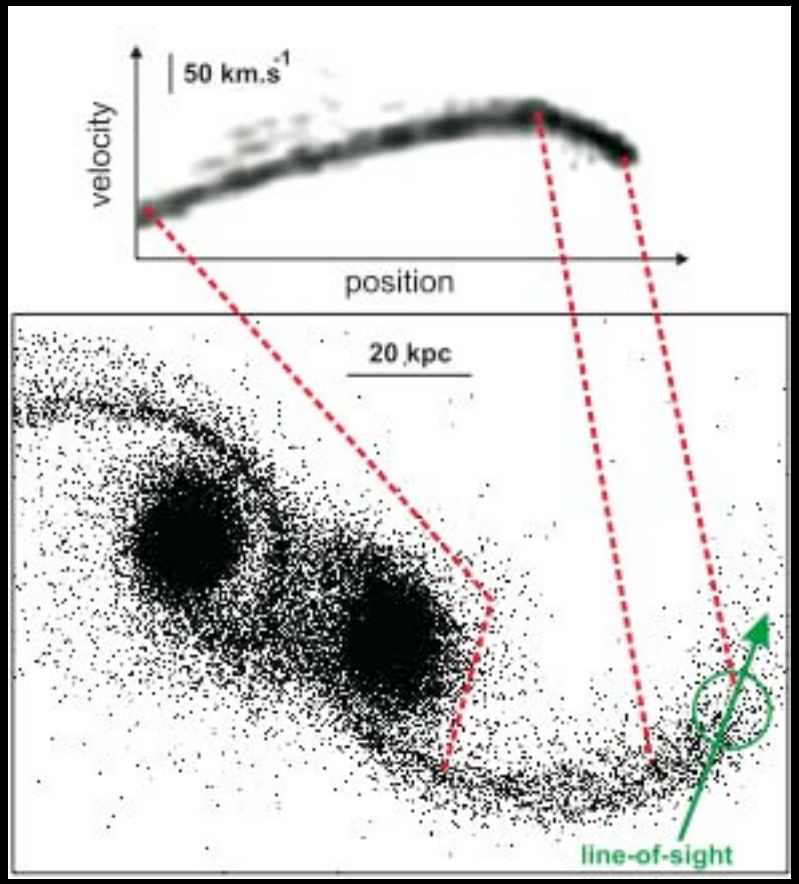
Lisenfeld et al., 2002, 2004

- Massive (> 10^9 M_{sun}), gas-rich, gravitationally bound objects, usually located near the end of tidal tails
- SFR > 0.05 M_{sun}/yr
- Properties similar to dwarf galaxies

Projection effects in tidal tails

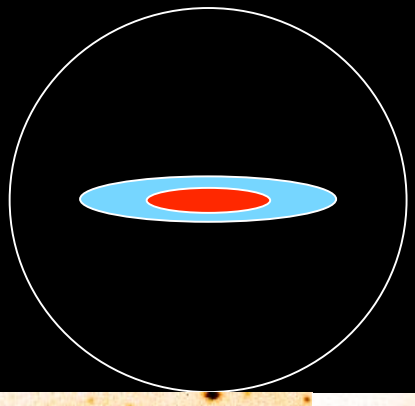


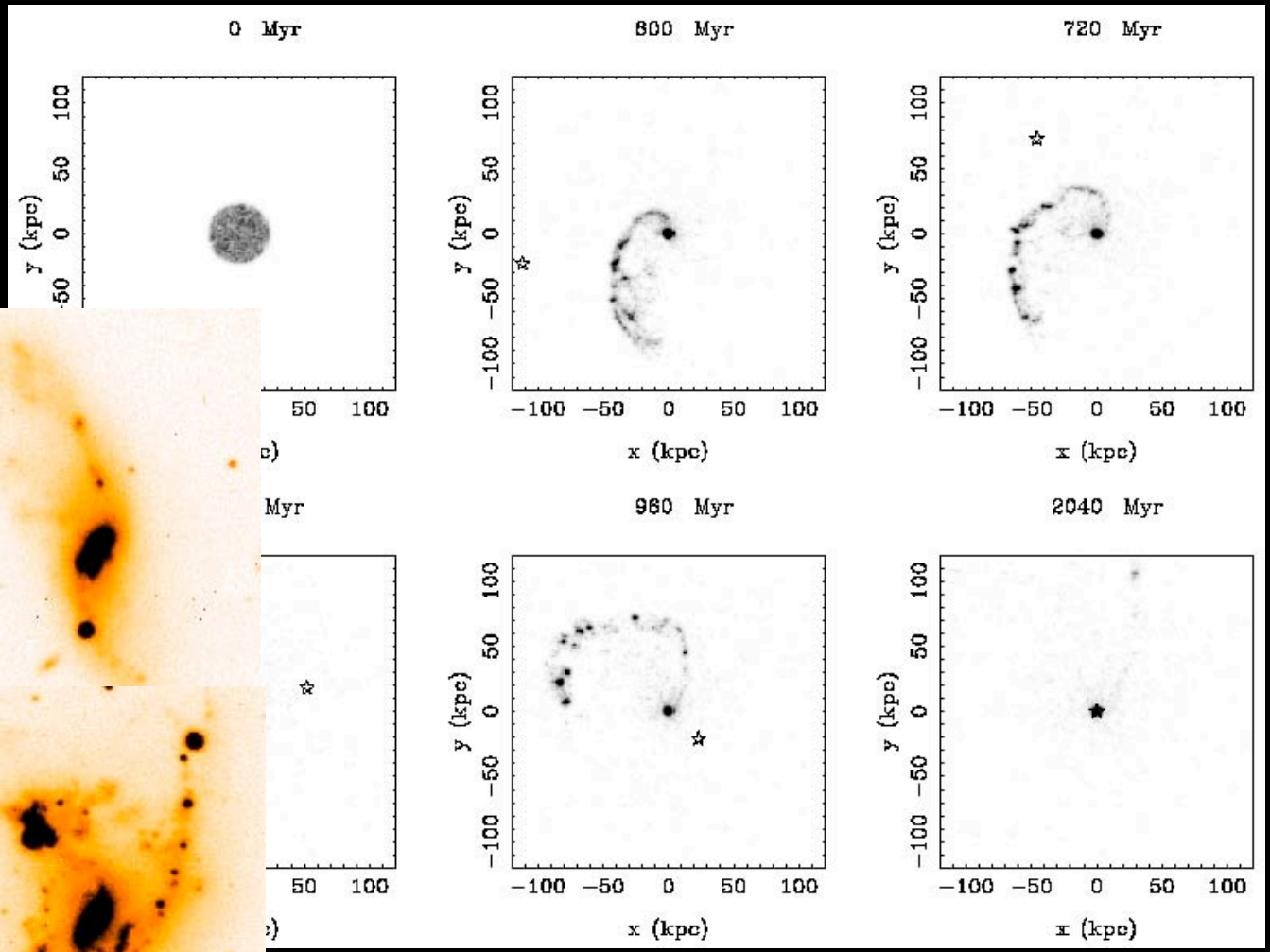
Bournaud et al., 2004

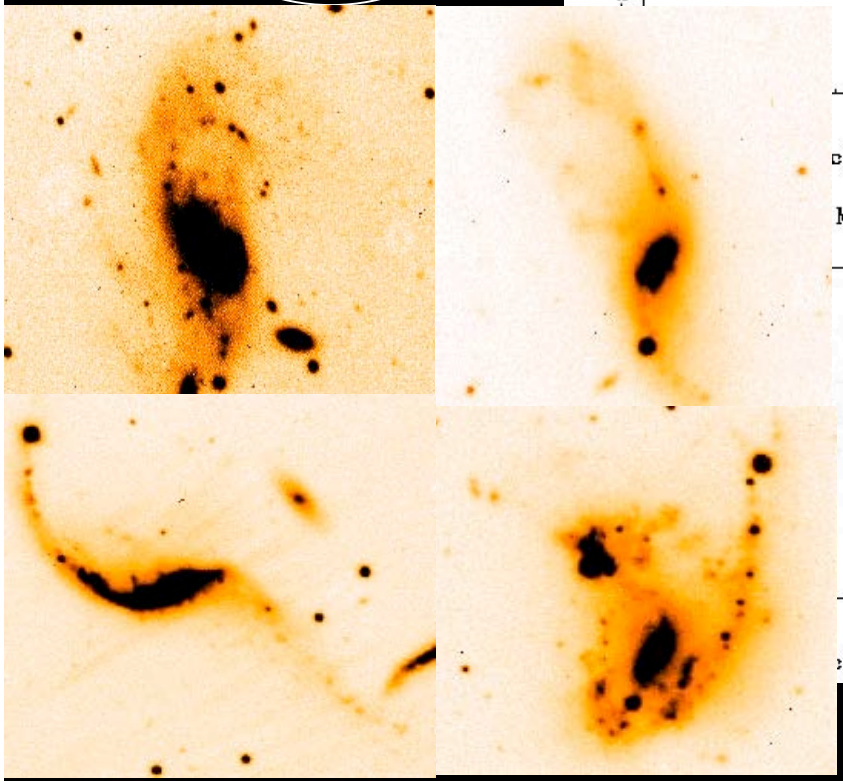


A kinematical signature: a change in the velocity gradient before the end of the tail

Formation of sub-structures along tidal tails

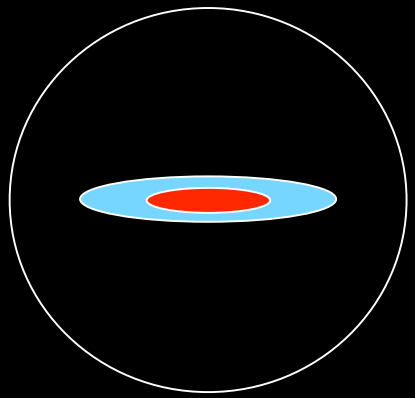


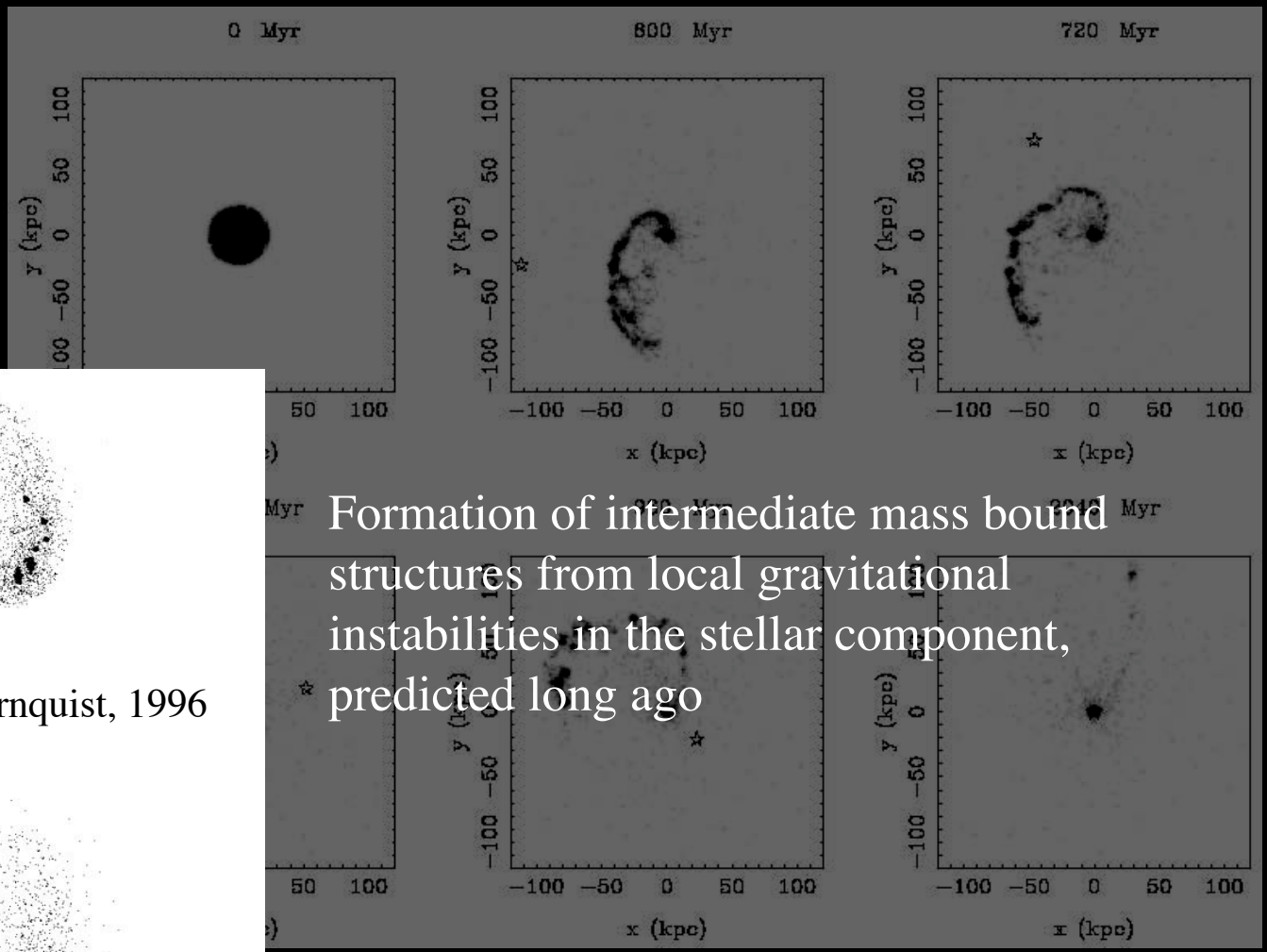


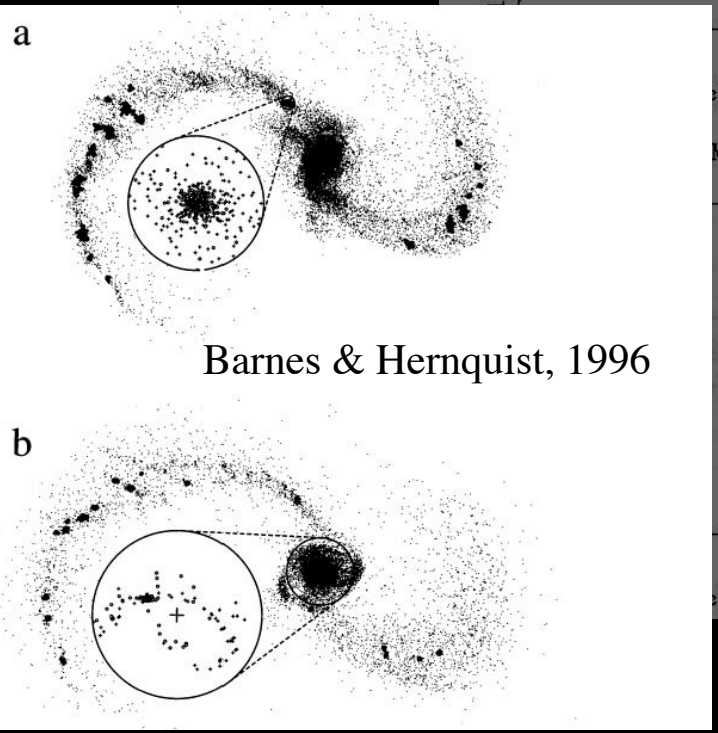


Bournaud, Duc & Masset, 2003

Formation of sub-structures along tidal tails



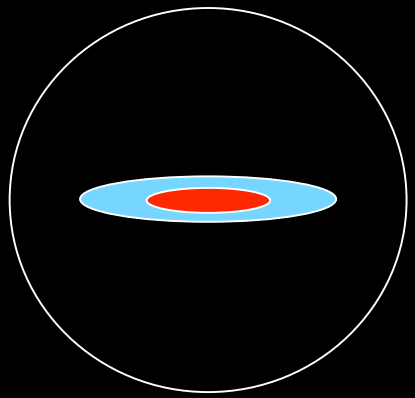


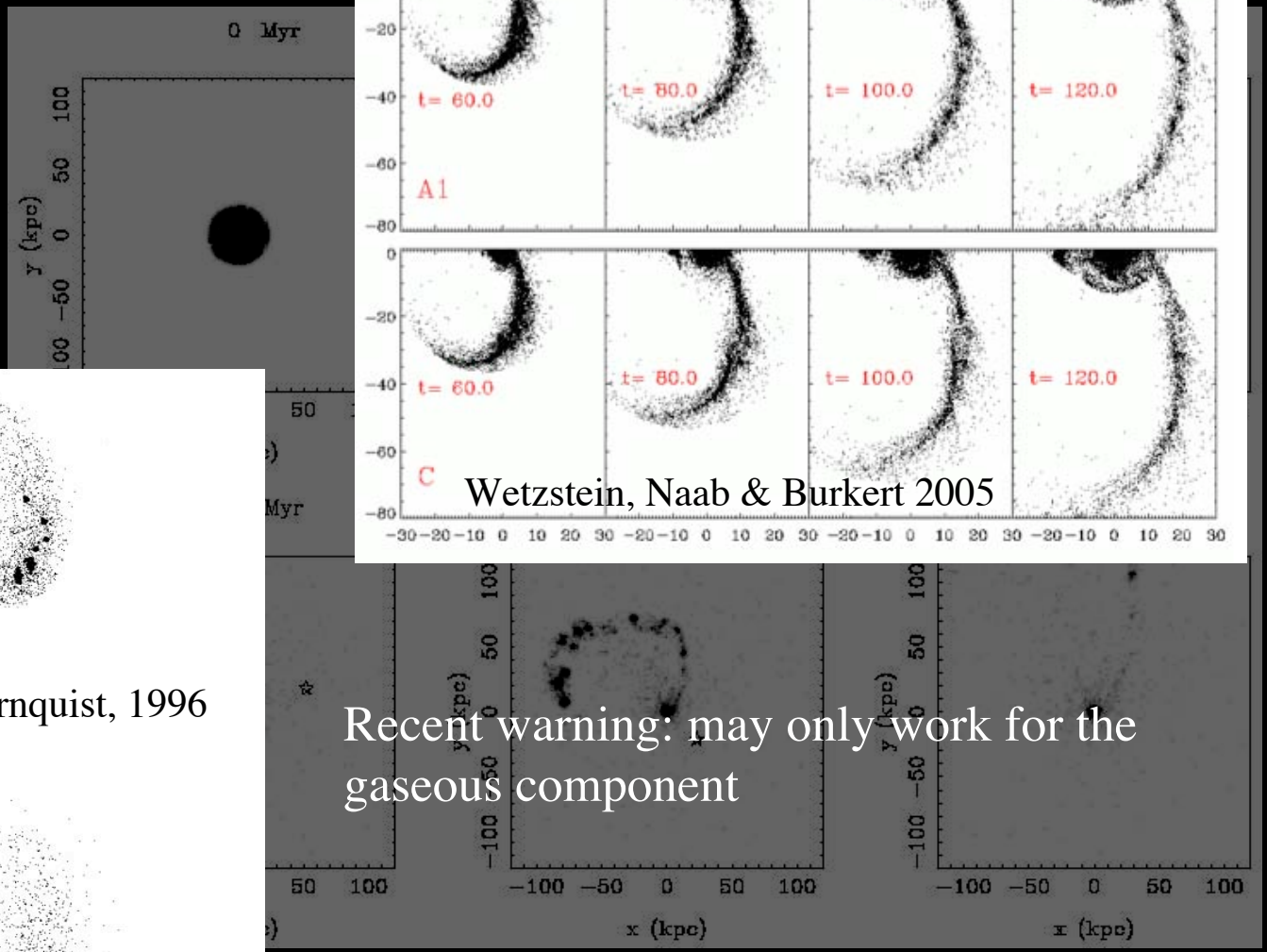


Barnes & Hernquist, 1996

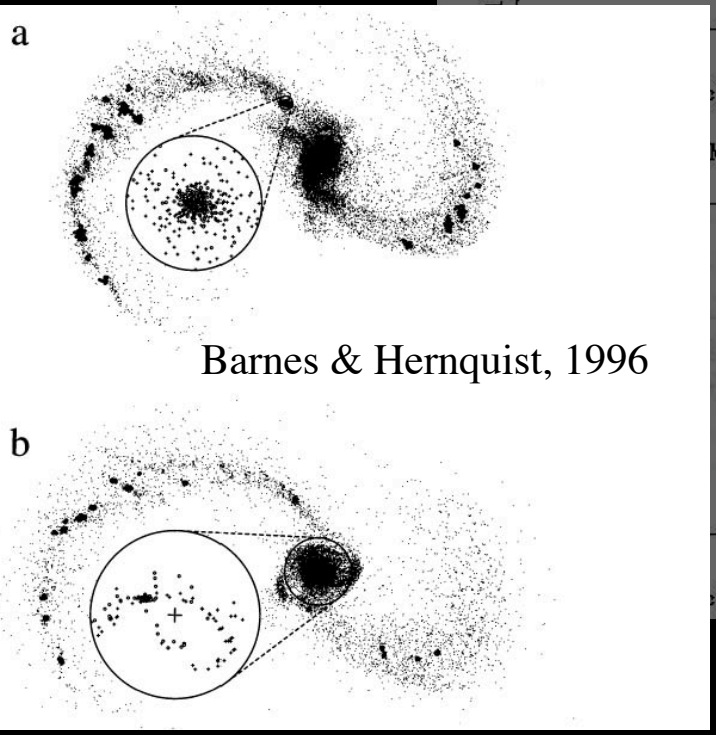
Formation of intermediate mass bound structures from local gravitational instabilities in the stellar component, predicted long ago

Formation of sub-structures along tidal tails





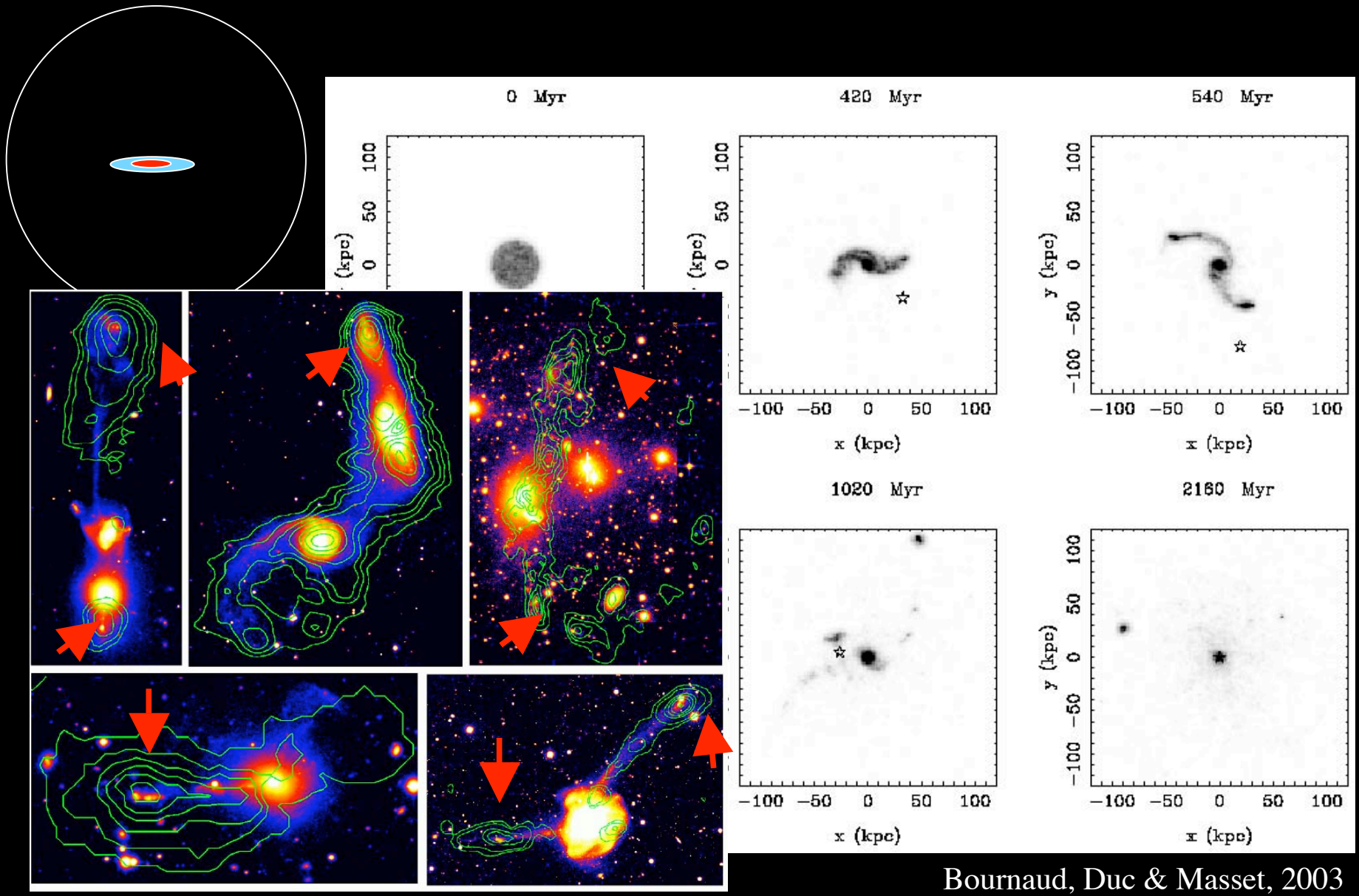
Wetzstein, Naab & Burkert 2005



Barnes & Hernquist, 1996

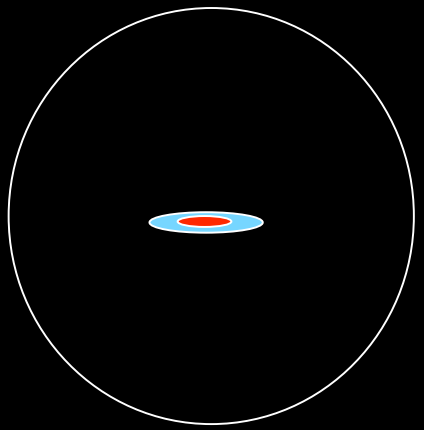
Recent warning: may only work for the gaseous component

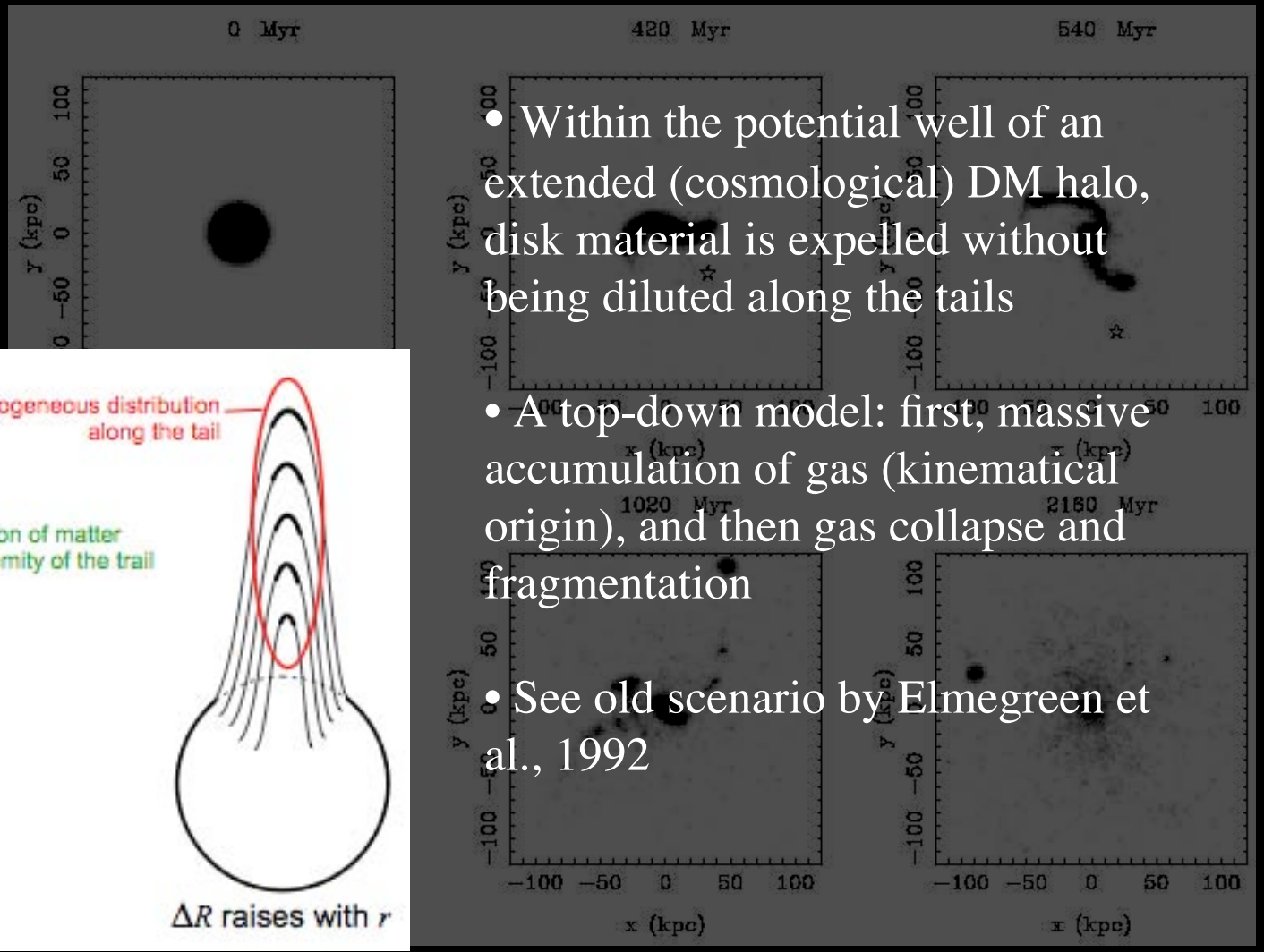
Formation of sub-structures near the tip of tidal tails



Bournaud, Duc & Masset, 2003

Formation of sub-structures near the tip of tidal tails

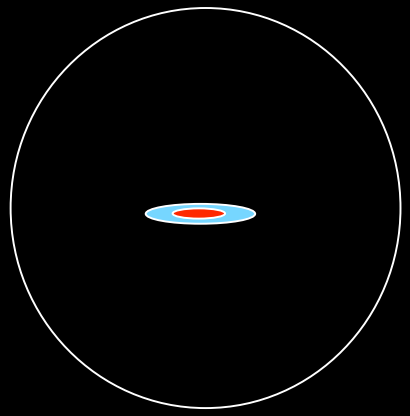




- Within the potential well of an extended (cosmological) DM halo, disk material is expelled without being diluted along the tails
- A top-down model: first, massive accumulation of gas (kinematical origin), and then gas collapse and fragmentation
- See old scenario by Elmegreen et al., 1992

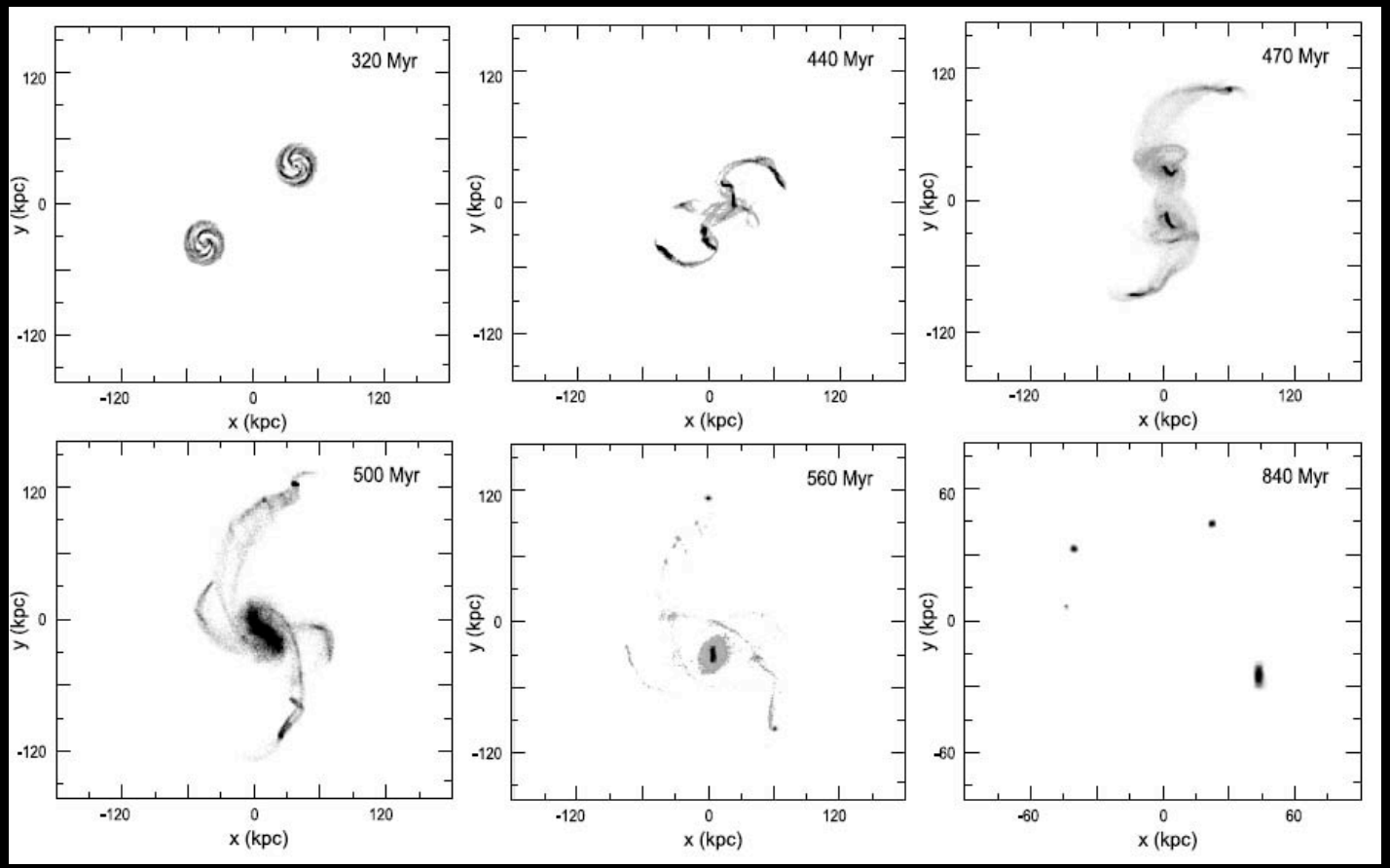
Duc, Bournaud & Masset , 2004

Formation of sub-structures near the tip of tidal tails



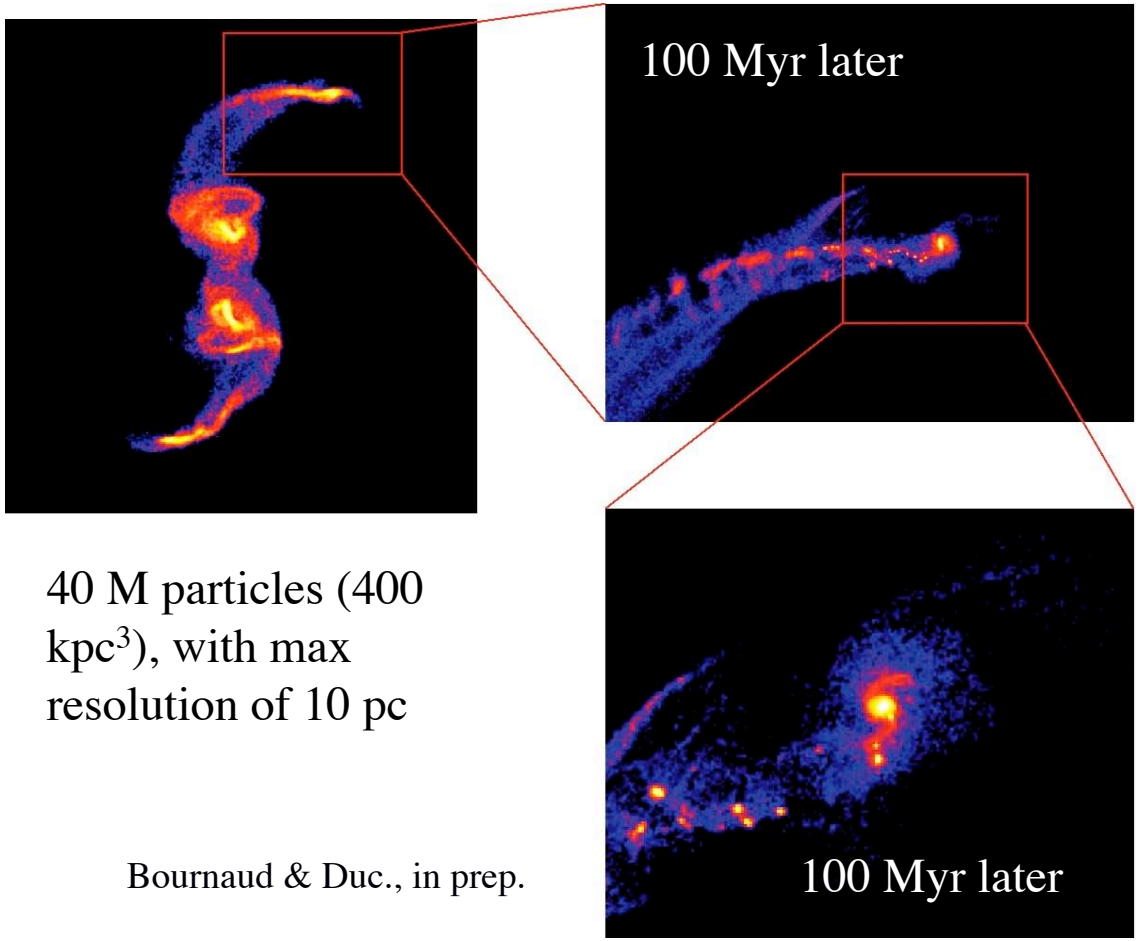
- *Stars: 10^6 particules*
- *Gaz: 10^6 particules*
- *Dark matter: 2 x 10^6*

• Same results increasing the resolution



Duc et al., 2004

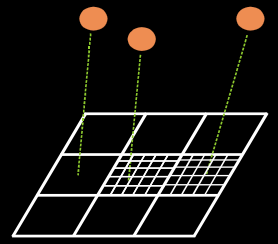
Evolution of sub-structures near the tip of tidal tails



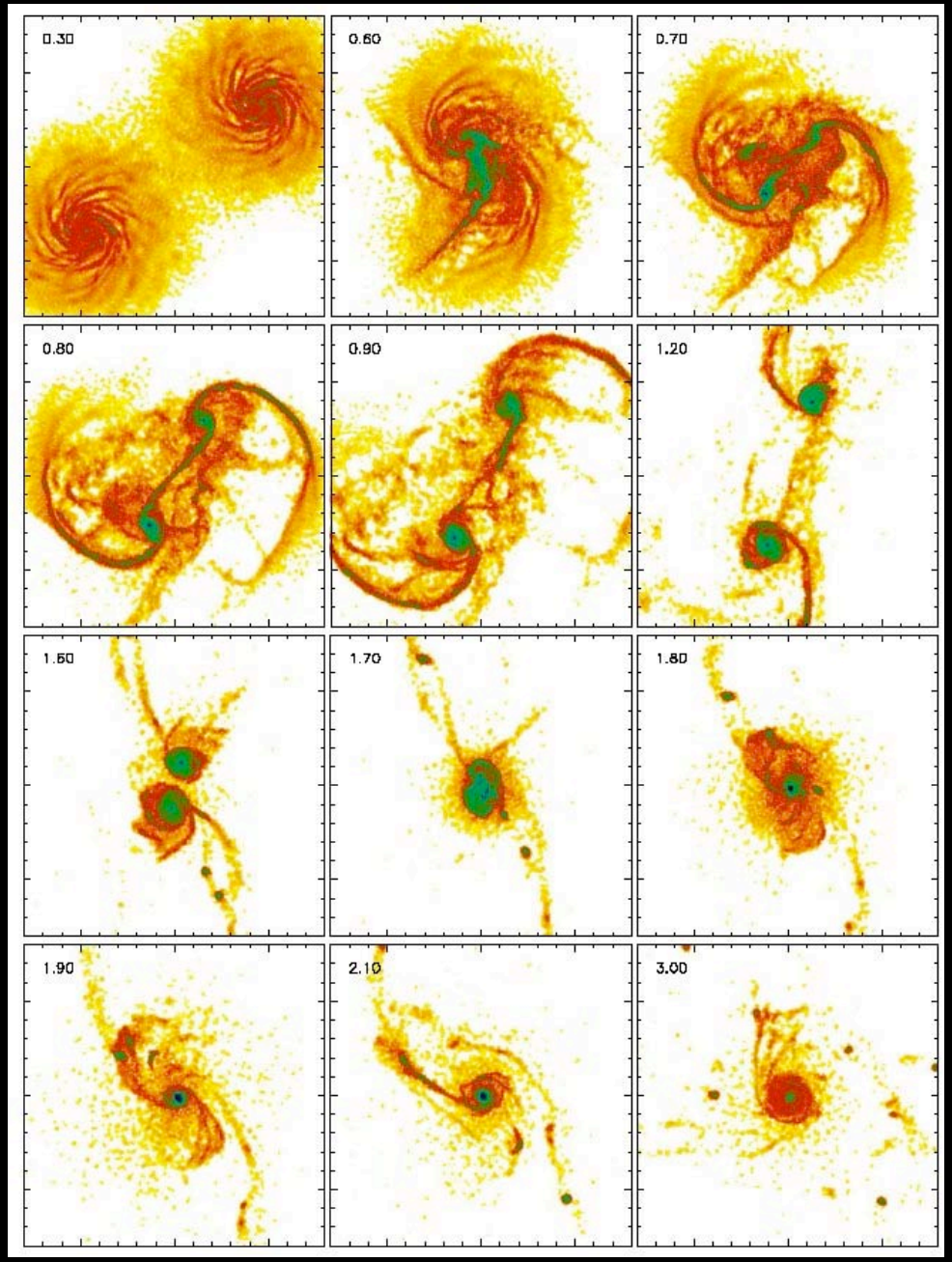
40 M particles (400 kpc^3), with max resolution of 10 pc

Bournaud & Duc., in prep.

• Higher resolution simulations required to probe secondary effects (feedback, friction) or the fate of the less massive tidal objects



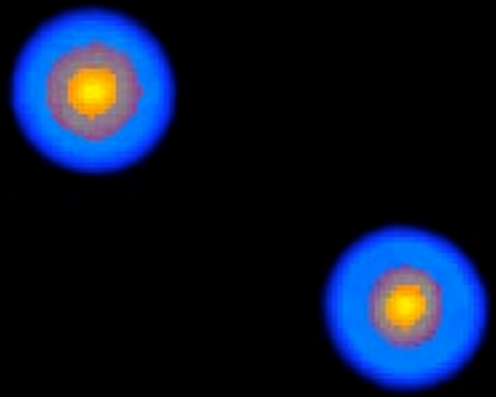
Simulations
N body, particle mesh/FFT, sticky
+ Zooming on the forming TDG candidate



- Same result with SPH instead of sticky particles!

T.J. Cox

From
star-forming
Tidal
Dwarf
Galaxies



to
Satellite
Galaxies

Bournaud & Duc,
2006

From
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Tidal
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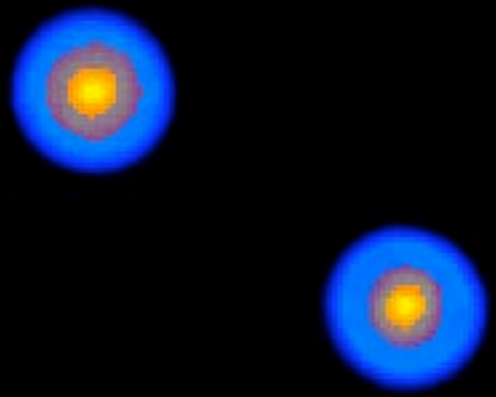
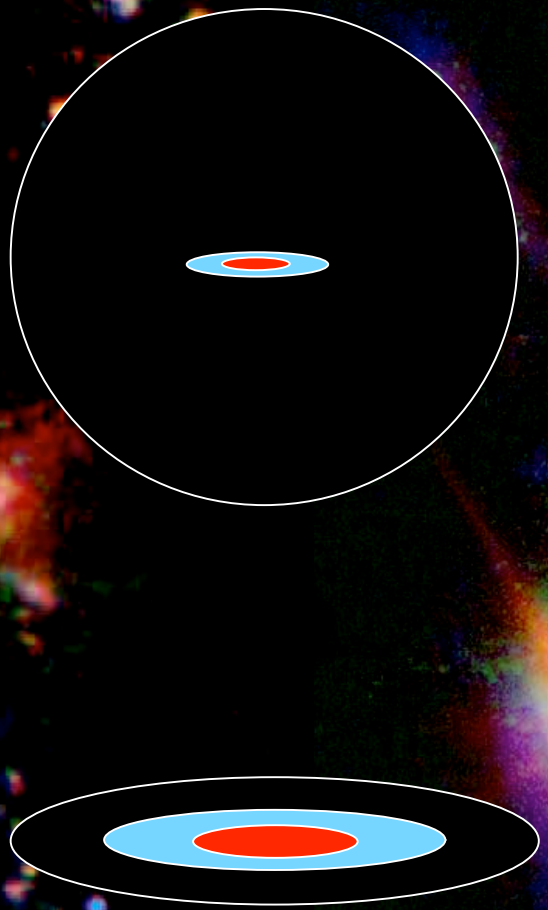


to
Satellite
Galaxies

Bournaud & Duc,
2006

Probing Dark Matter with TDGs



• Cosmological DM

Simulations -> an extended (at least 10 times the optical radius) DM halo required to produce massive TDGs

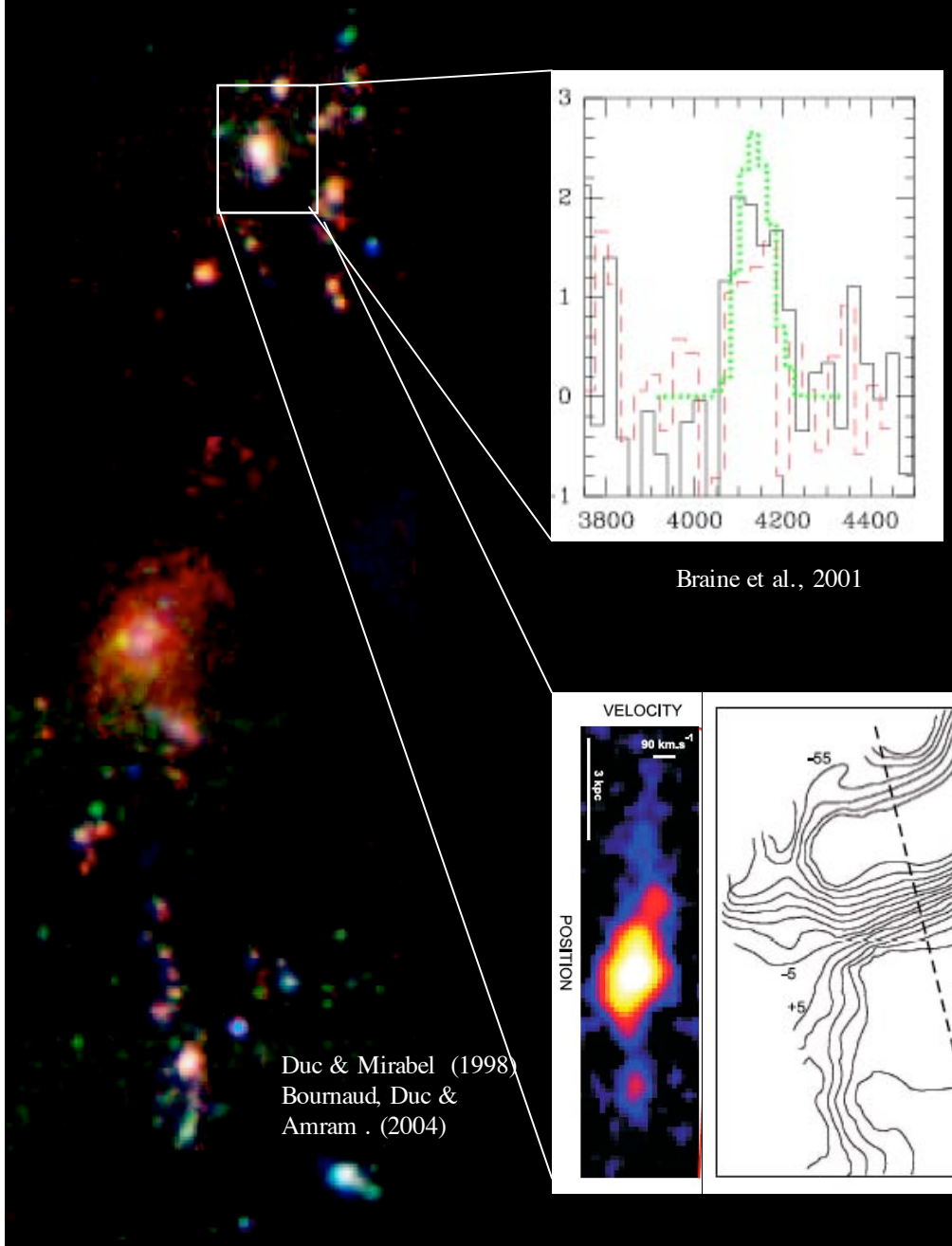
(in fact, the potential well associated with it)

On the other hand, TDGs accreted only a small amount of DM from the halo (less than 15%): DM free objects?

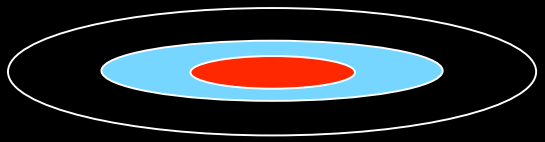
• A baryonic DM component?

If existing in the disk, it should also be present in tidal tails, and hence in TDGs, contributing to their dynamical mass

Probing baryonic Dark Matter with TDGs



Braine et al., 2001

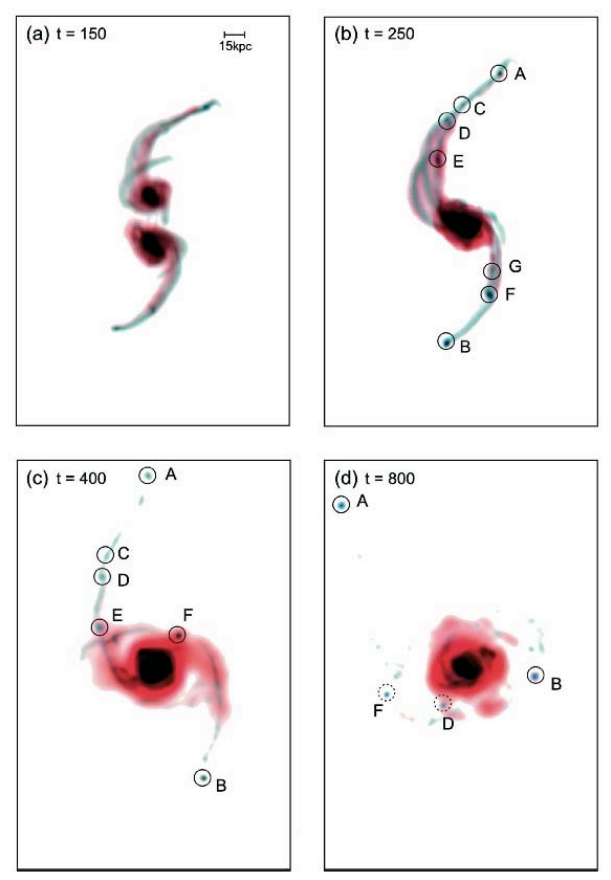


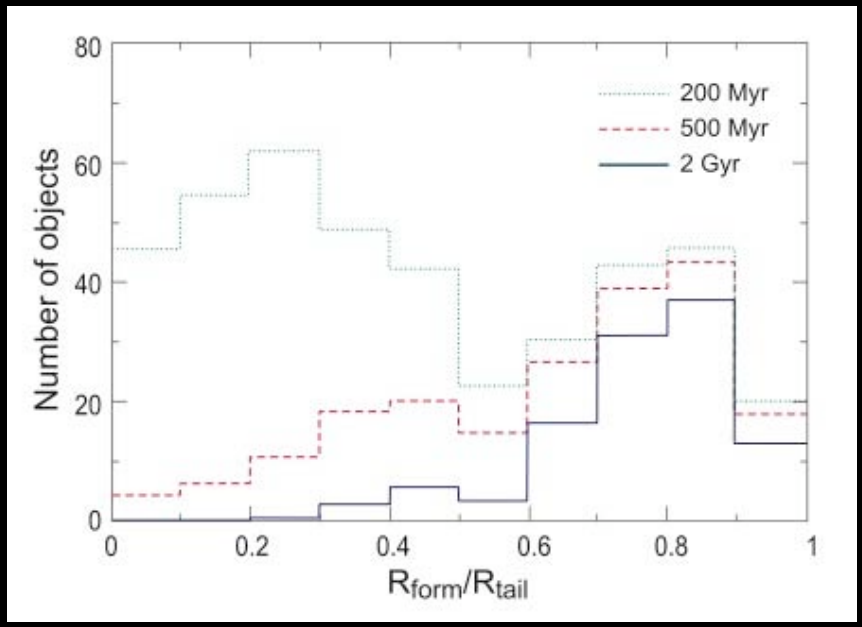
- From the CO line width (hyp: local production of the mol gas)

Duc & Mirabel (1998)
Bournaud, Duc & Amram . (2004)

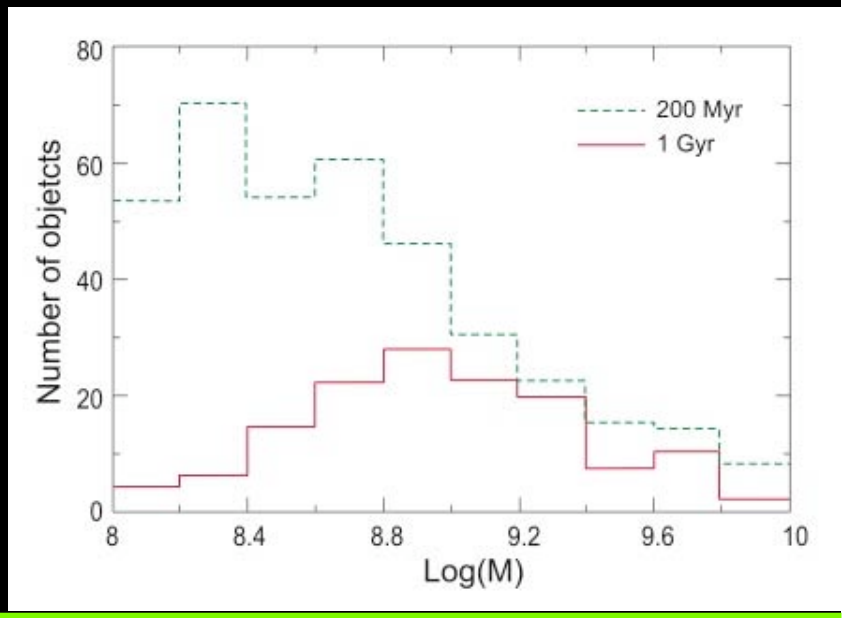
- From the HI/Hα rotation curve (hyp: identification of the kinematically detached, grav. bound object)

Survival of of tidal objects





Bournaud & Duc, 2006



- Among the tidal objects (with $M > 10^8 M_{sun}$), only the most massive ones, originally formed near the end of the tails, survive more than 1 Gyr. Others fall back or are destroyed
- About 1/4th of them in our 100 simulations (i.e. 2-3 per favorable merger)

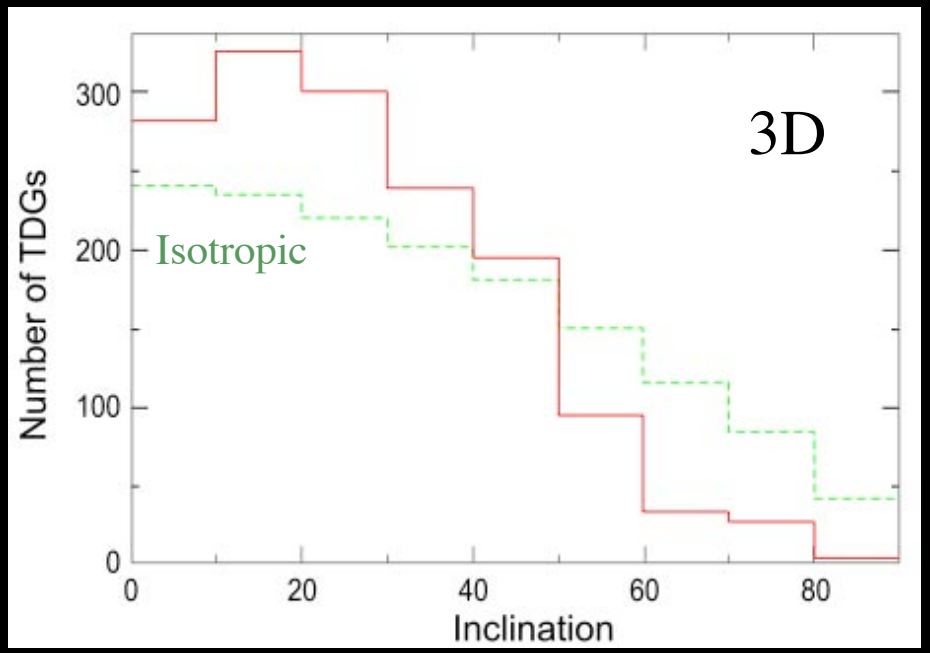
Required conditions to form long-lived TDGs in mergers

- ✓Relative velocities: 50 - 250 km/s
- ✓Impact parameters: 30 - 200 kpc
- ✓Orbit inclination: 0 - 40 degrees
- ✓Orbit orientation: prograde
- ✓Mass ratio: 4:1 to 1:8 (TDG progenitor: tidally disturbing)

How many of them?

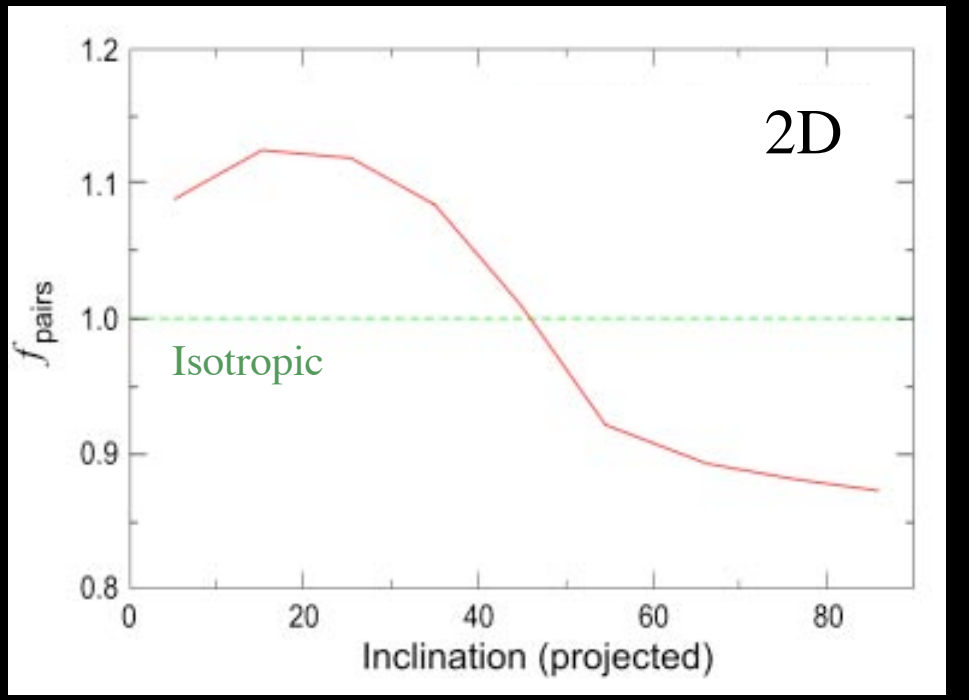
⇒ production of 0.8 long-lived TDG per favorable merging pair
20% survive 10 Gyr => 0.1 - 0.2 very long lived TDG / merger
⇒ Counting number of collisions as a function of redshift
⇒At most 10% of all dwarfs are of tidal origin, at least a few %
⇒Depends on the environment and on the geasous mass of the progenitors

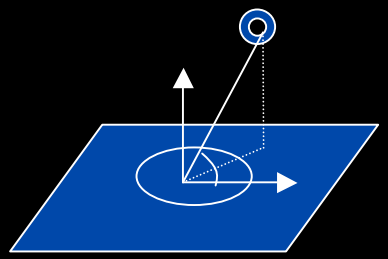
Distribution of long-lived tidal objects



• Clear anisotropy: long lived TDGs preferentially distributed close to the equatorial plane of their parent disk

Bournaud & Duc, 2006

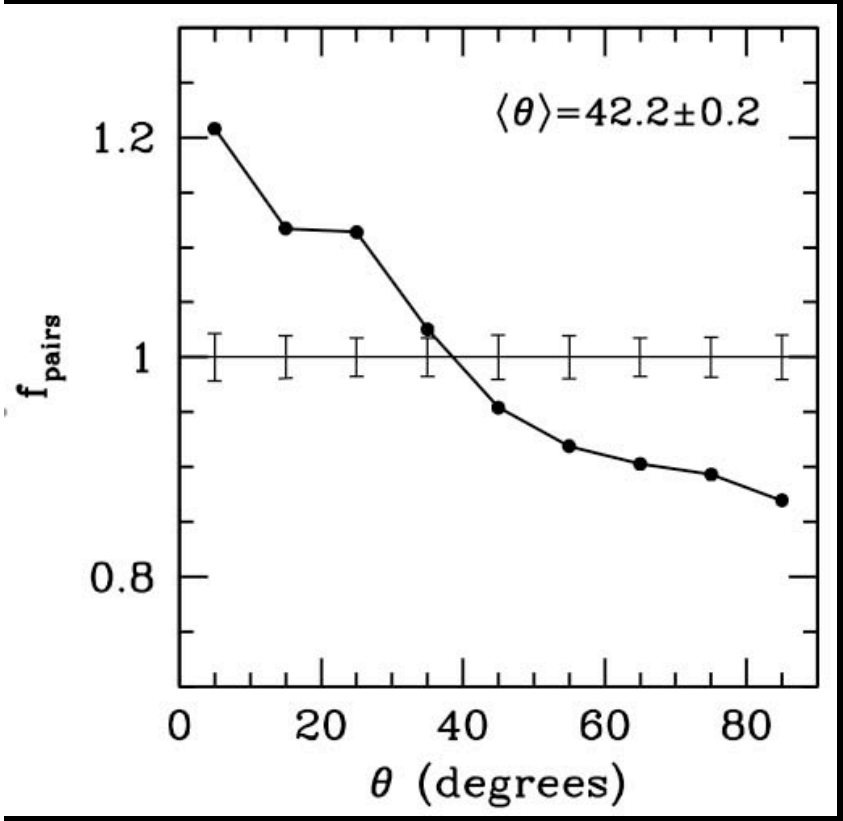




• Projected: along the major axis of their parent

Distribution of long-lived tidal objects

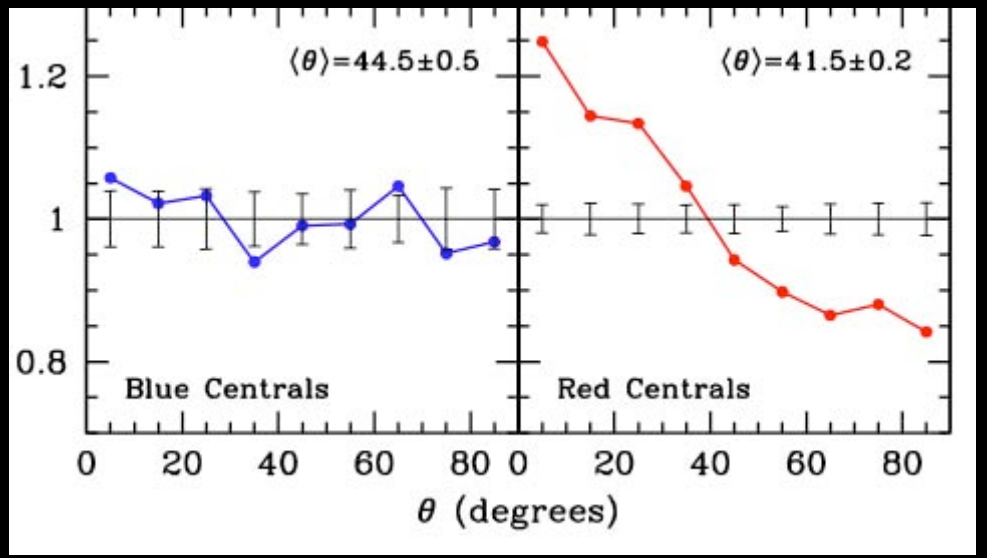
Statistics on SDSS (2dF)



Yang et al. (2005)

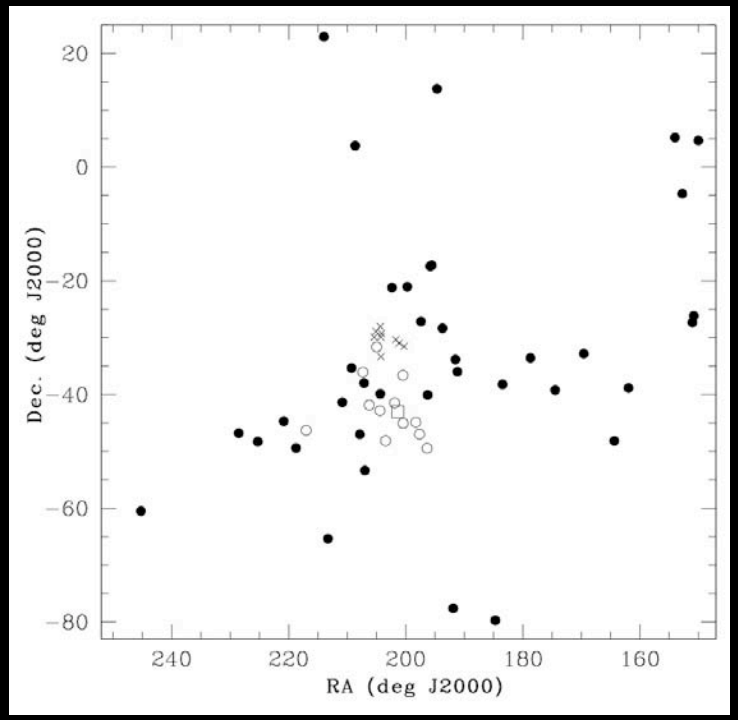
- Significant anisotropy confirmed: alignement of the satellites along the major axis of the host galaxy (contrary to the Holmberg effect)
- Even stronger for red hosts

Due to the tri-axial haloes, accretion along filaments … or a contamination by tidal objects?

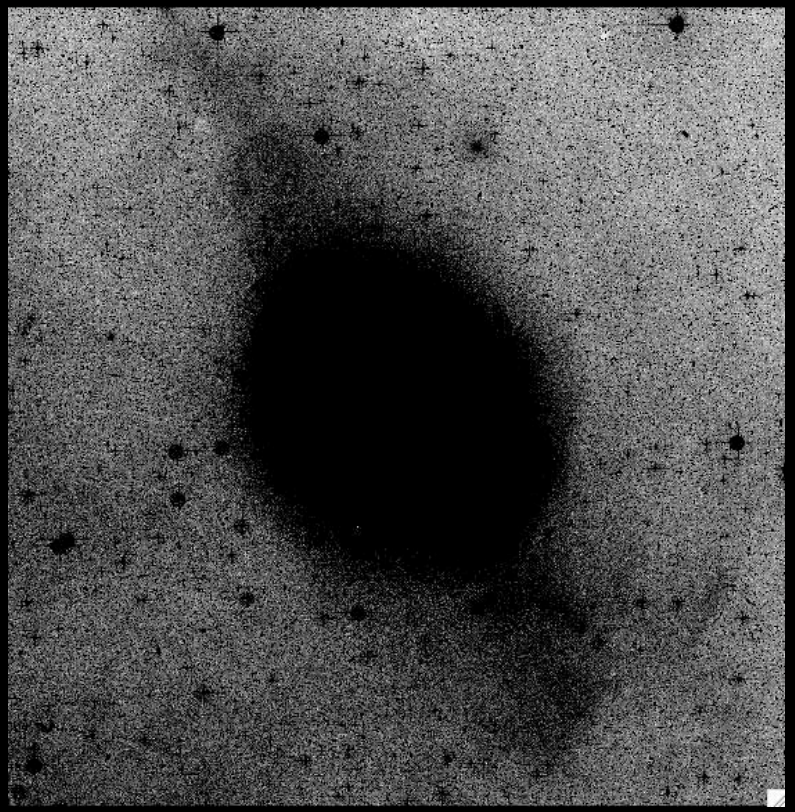


Observations, identification and census of old TDGs

✓ From their spatial distribution, around massive hosts



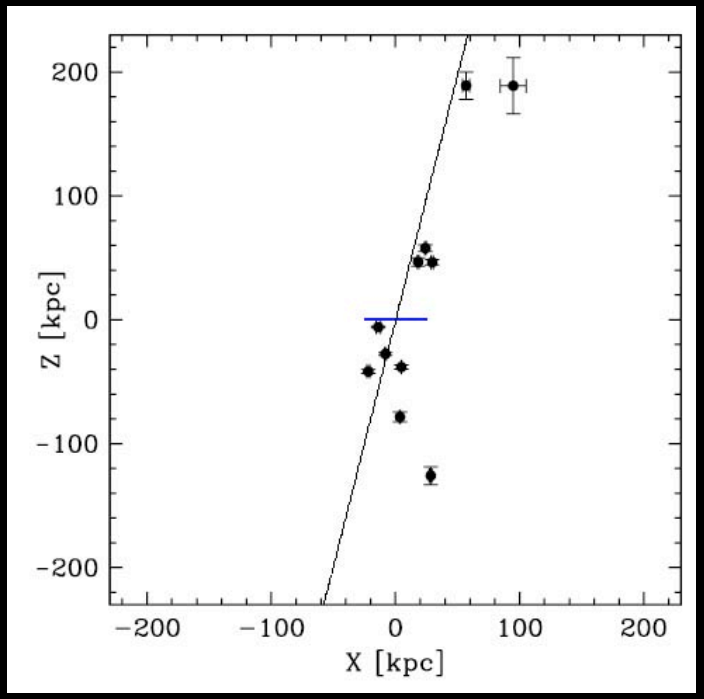
Woodley, 2006



Satellite galaxies around NGC 5128

Observations, identification and census of old TDGs

✓ From their spatial distribution, around massive hosts

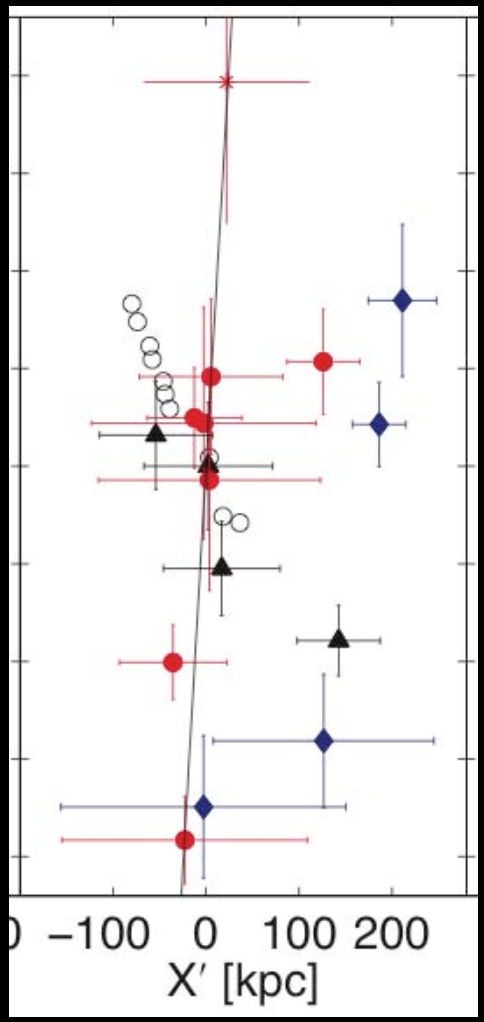


MW

Kroupa et al., 2005

Satellite galaxies in the Local Group

M31



Koch & Grebel, 2005

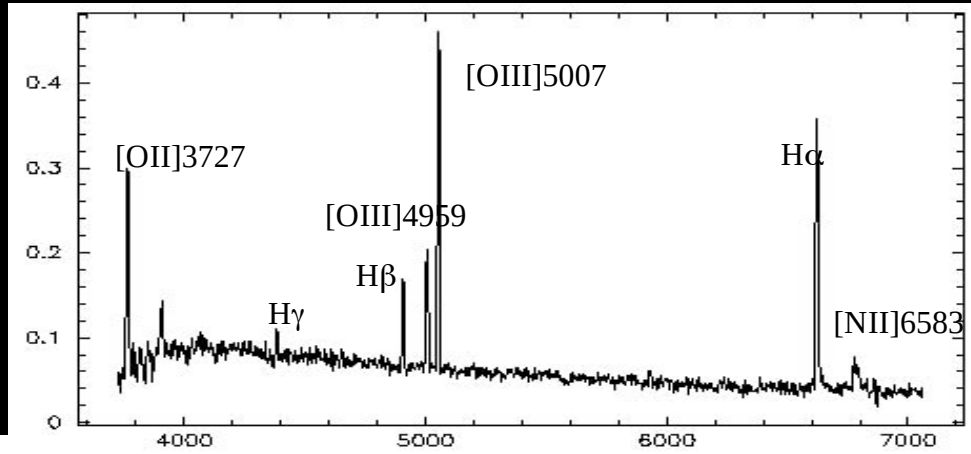
✓ Co-planar (perpendicular to the plane of the Milky Way)

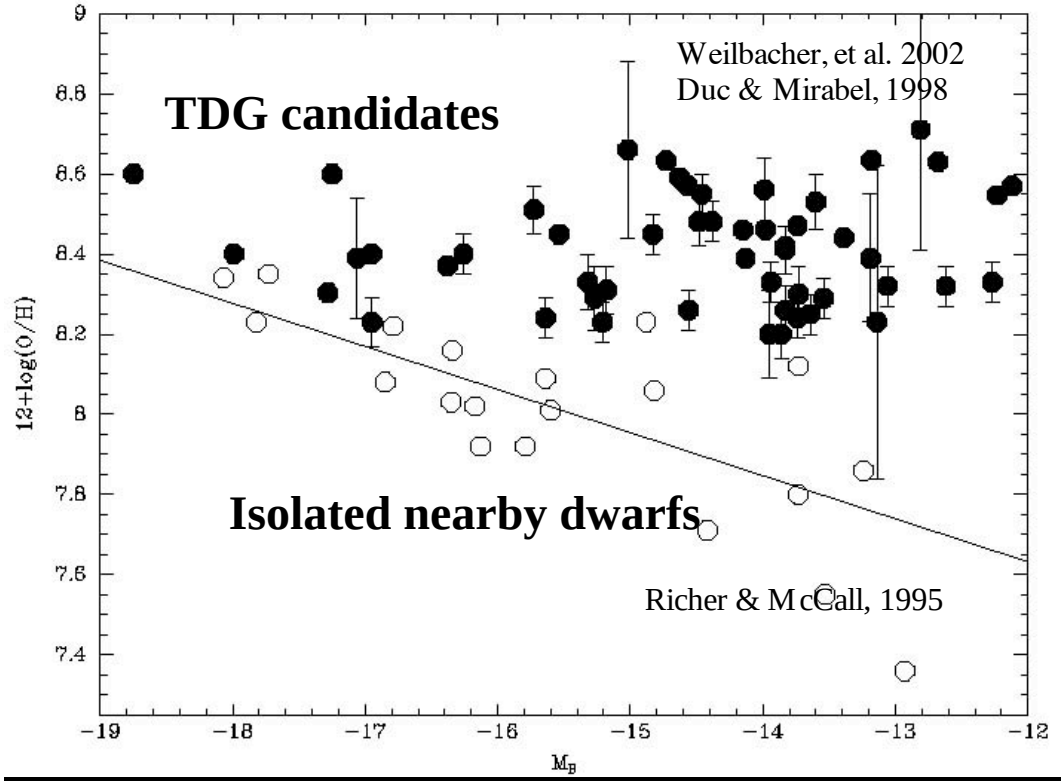
✓ On one or several great circles

Observations, identification and census of old TDGs

✓ From their genes

• Deviation from the metallicity-luminosity/mass relation





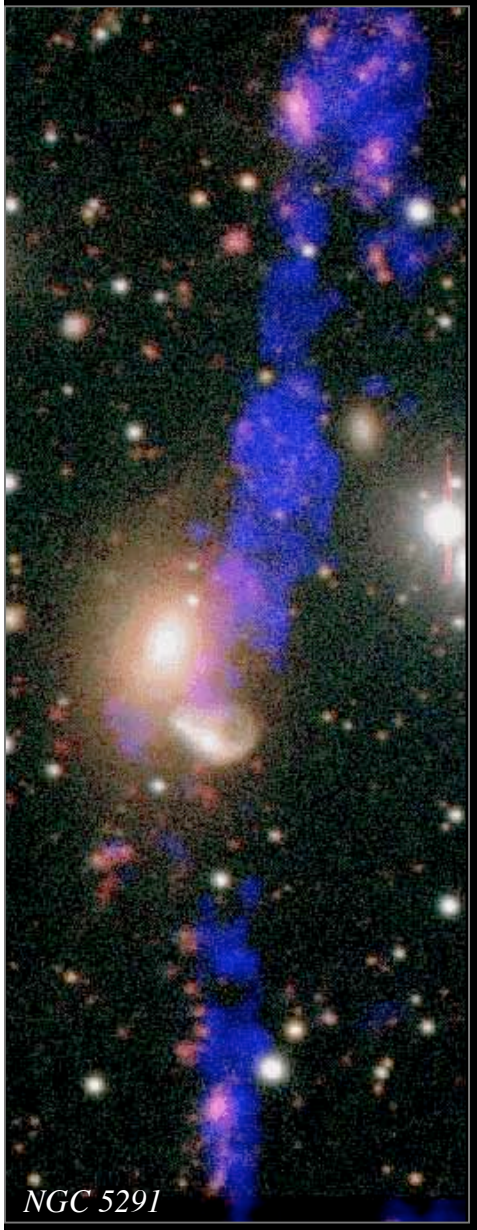
• A paternity test, which, however, is not 100% sure:

- could be remnant of a former larger galaxy (UCDs)
- could trace an unusual chemical evolution (e.g. in clusters)
- does not work for old objects
- does not tell whether its tidal (other mechanisms to expell matter from galaxies)

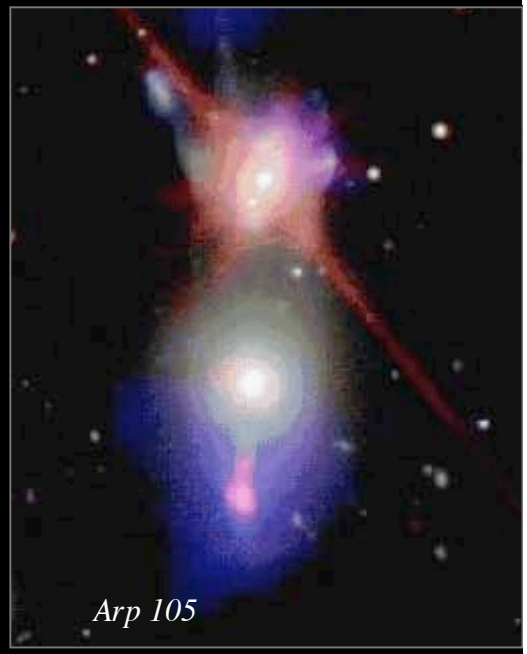
Observations, identification and census of old TDGs

- ✓ From their dark matter content

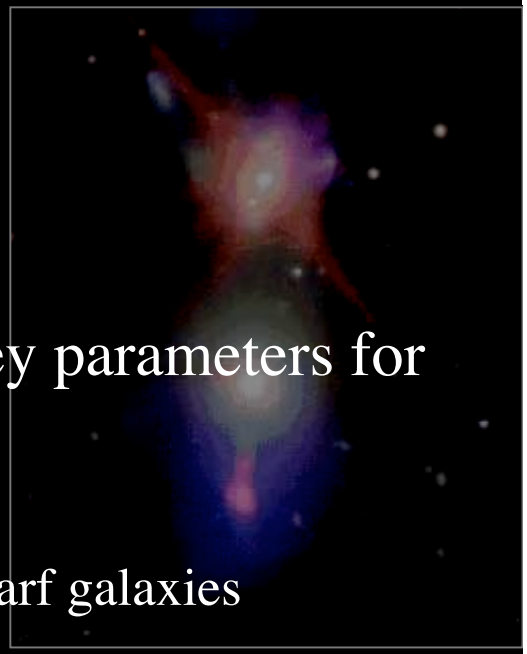
Physical properties of the « intergalactic » star forming regions and TDGs



BVR + 8 μm (red) + HI (blue)



Physical properties of the « intergalactic » star forming regions and TDGs



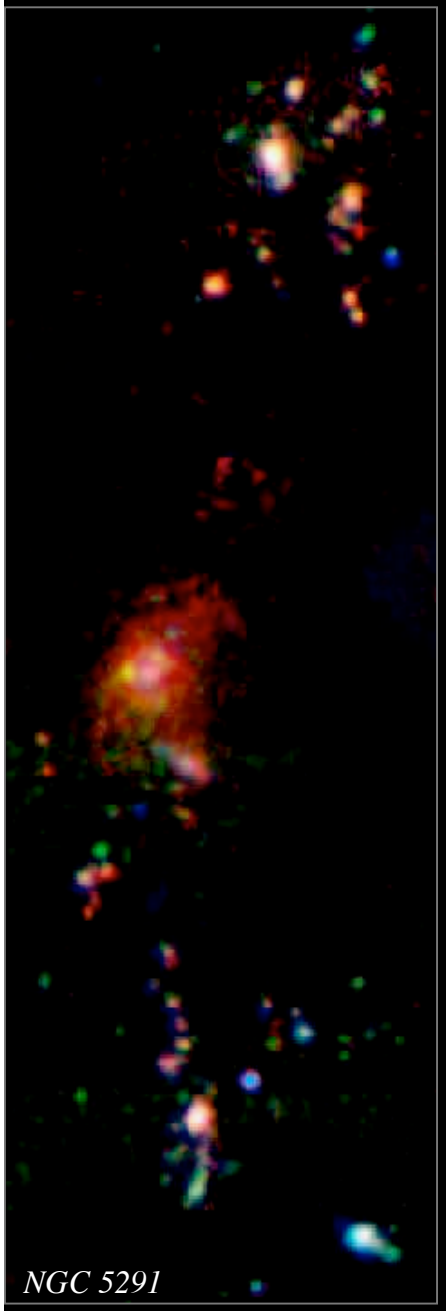
• Useful laboratories to probe the role of several key parameters for Star Formation

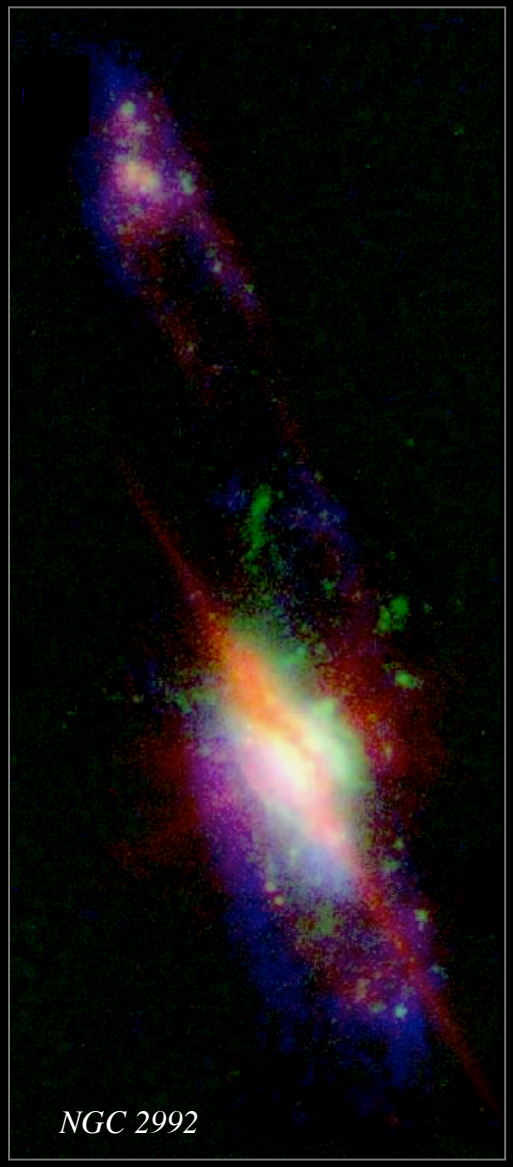
✓ Properties intermediate between those of star-forming dwarf galaxies (BCDGs) and individual HII regions of spiral disks
The mass and SFR of dwarfs, the chemistry of the HII regions

✓« Simple », detached, dark-matter free, objects, easy to study:

- IMF and metallicity
- Large scale vs small scales triggering mechanisms

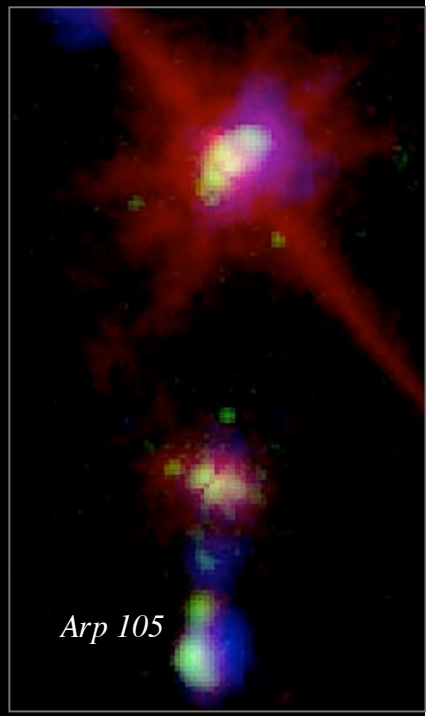
Physical properties of the « intergalactic » star forming regions

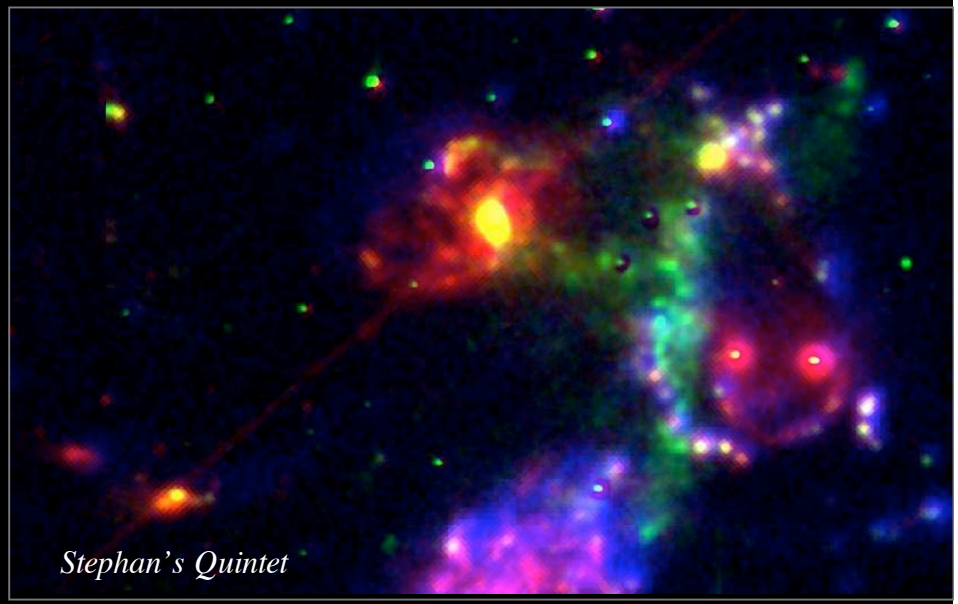

NGC 5291


NGC 2992

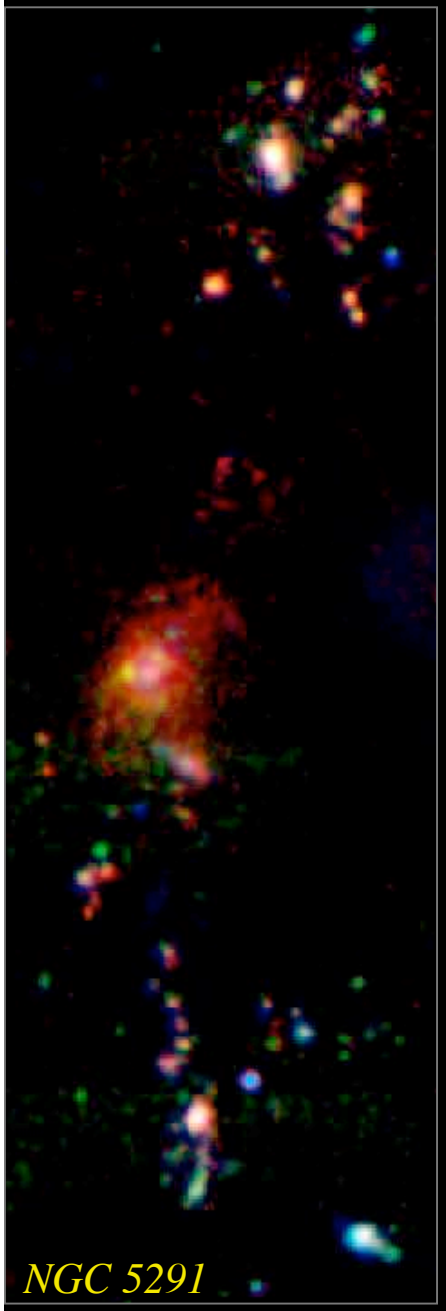
- Combination of three tracers of Star Formation:

-UV from GALEX (blue)
- Hα from CFHT/ESO (green)
- MIR (8 μm) from Spitzer/IRAC (red)


Arp 105


Stephan's Quintet

A case study: NGC 5291



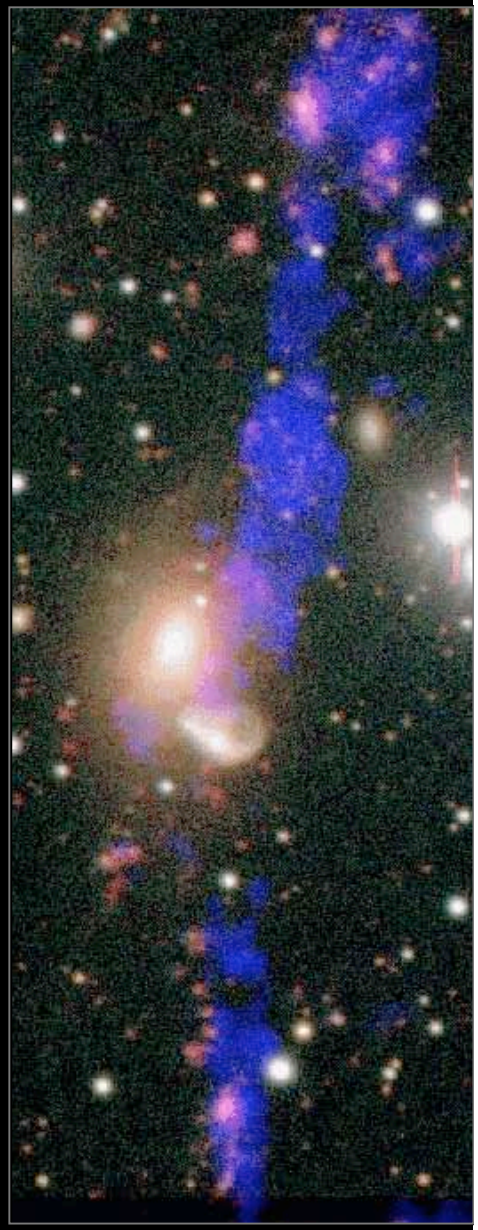
- Along the HI structure, 30 intergalactic star-forming regions identified with individual SFRs of up to 0.5 M_{sun}/yr (integrated: 3 M_{sun}/yr)

- No evidence for the presence of an old (> 1 Gyr) stellar population

- Strong UV excess in comparison with star-forming regions in spirals and dwarfs, with however from one region to the other, a large scatter in their physical properties

- Consistent with instantaneous Starbursts (age < 10 Myr)

⇒Truely young objects observed at their birth



Conclusions

• Various types of Star Forming Objects around interacting systems, with different origins and fates

✓ Growing instabilities in tidal debris vs gas accumulations with a kinematical origin

✓ Progenitors of short lived objects, Star Clusters or even Satellite Dwarf Galaxies

• The study of the most massive ones provides interesting cosmological constraints (need for an extended dark matter halo, nature of dark matter, number and distribution of satellites galaxies)

• Their star forming regions, lying in unusual environment, are interesting and simple laboratories to understand the process of star formation