The chemo-dynamical evolution of

Tidal Dwarf Galaxies

Sylvia Ploeckinger

with:

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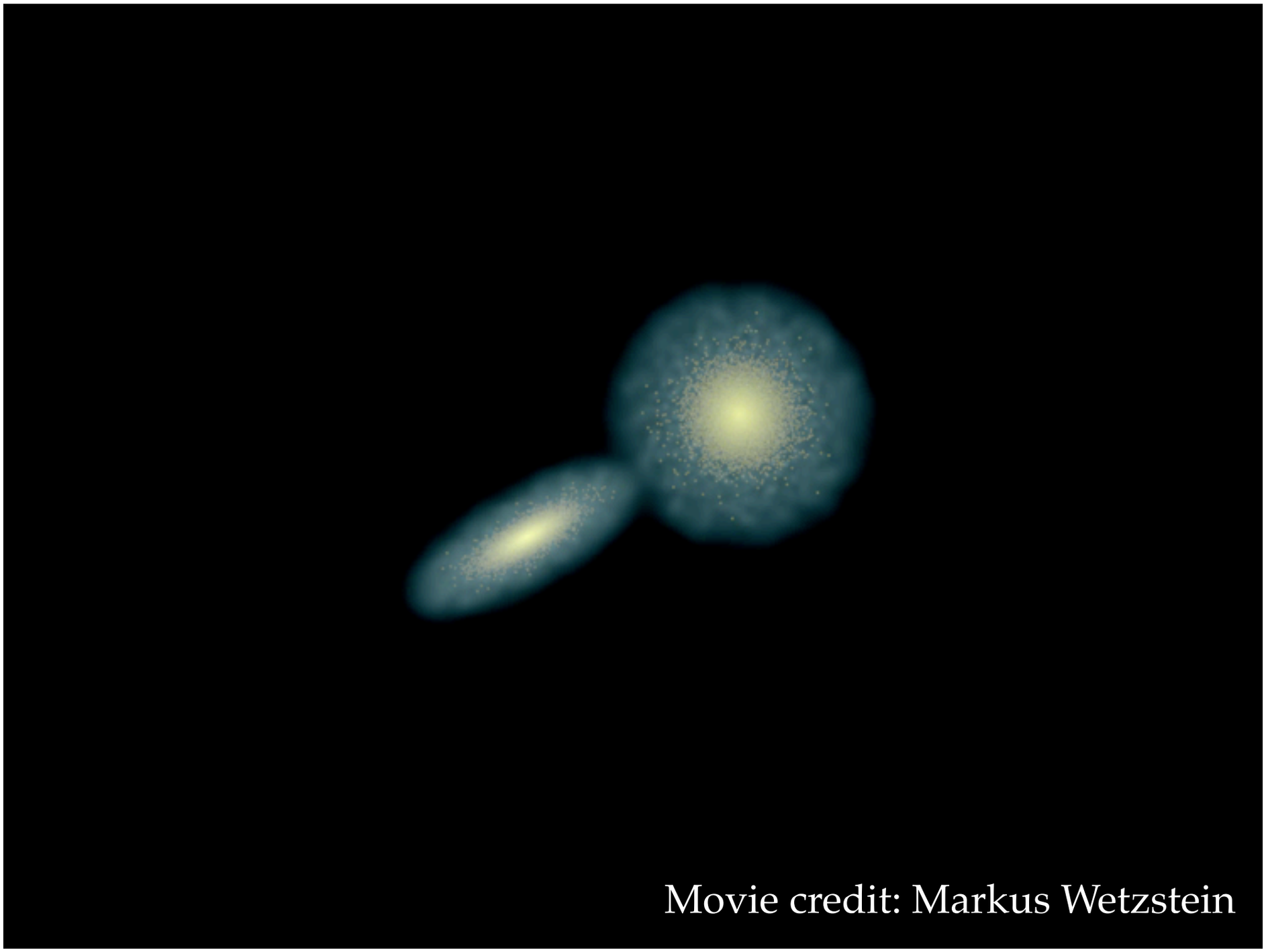
Pavel ***Kroupa*** *(Helmholtz Institute, Bonn), Marcel* ***Pawlowski*** *(CWR U., Ohio)*

Pierre-Alain ***Duc*** *(CEA Saclay)*

Paul ***Eigenthaler*** *(PUC, Santiago de Chile), Fernanda* ***Urrutia*** *(ESO Garching)*

2014

Formation of TDG



TDG definition

Observations

Simulations

TDG definition

Observations

Simulations

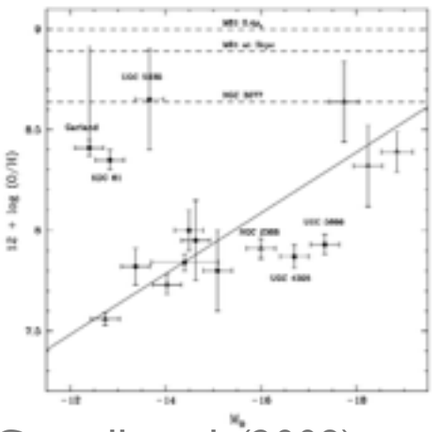
Tidal

Dwarf

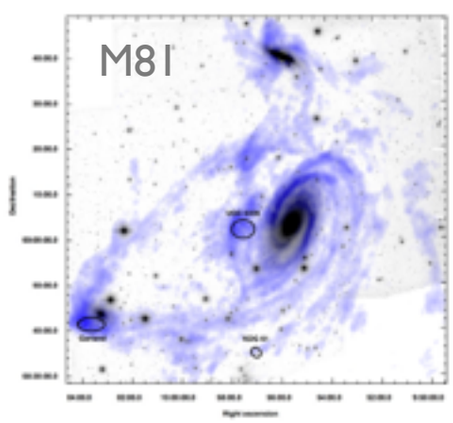
Galaxy

Tidal

Material that was tidally expelled from (interacting) galaxies



Croxall et al. (2009)



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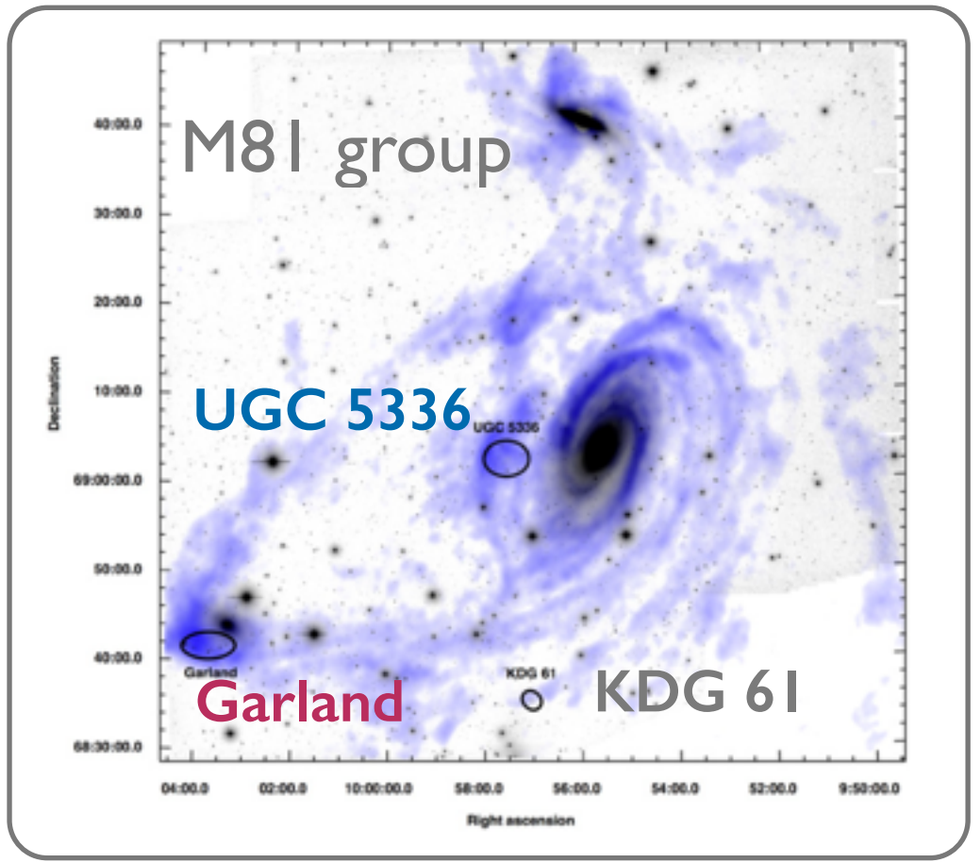
Dwarf

Galaxy



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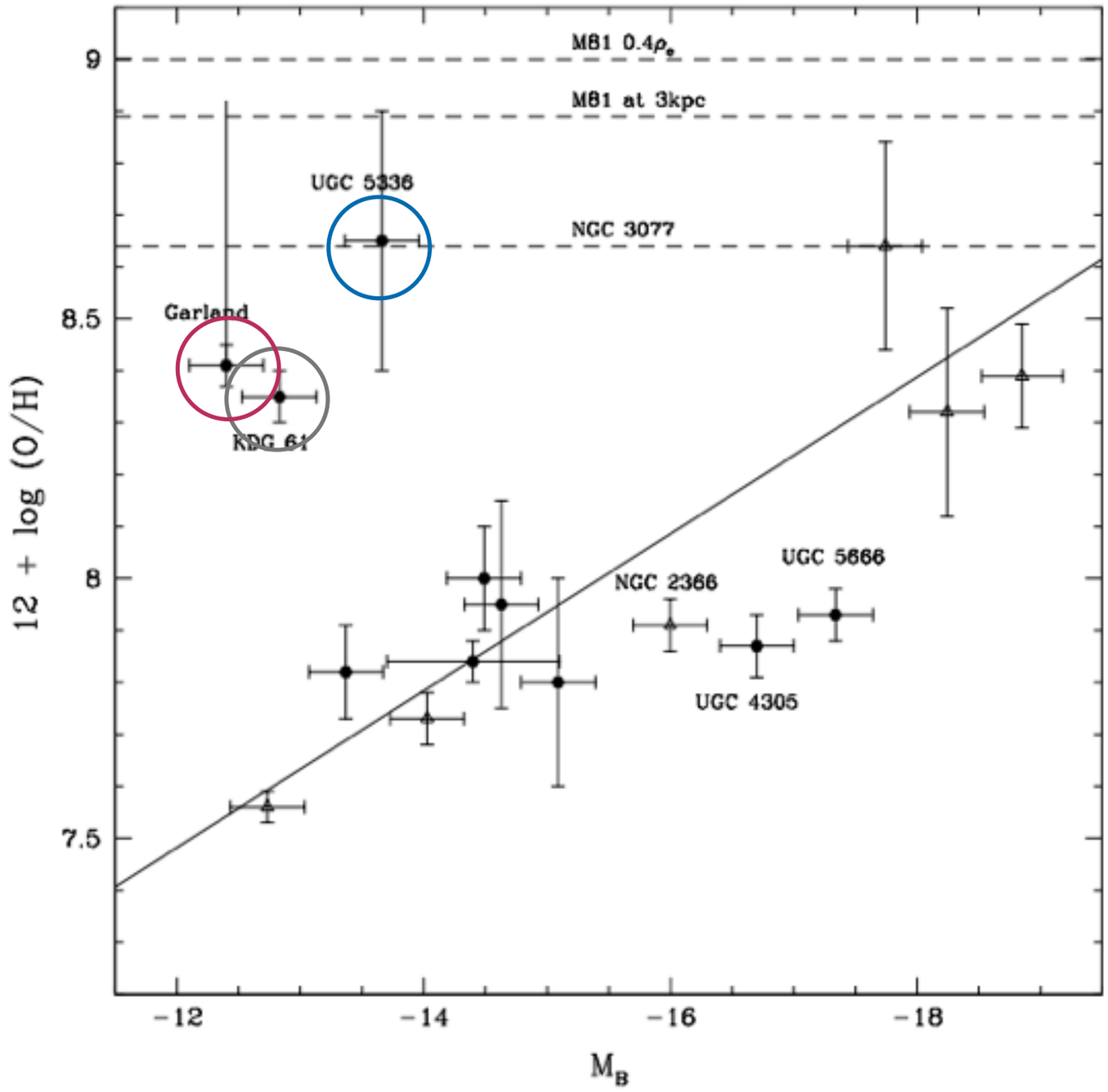

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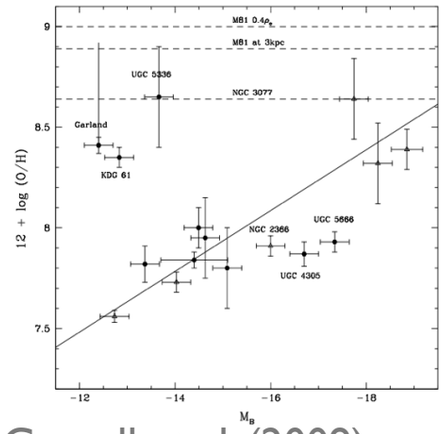

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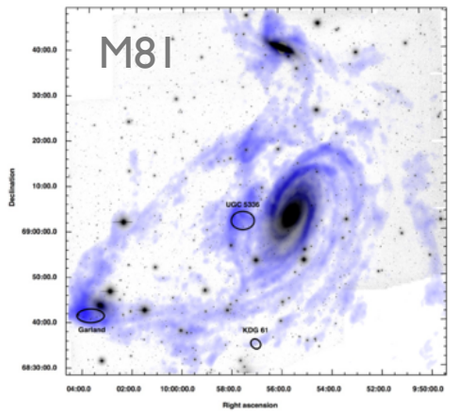

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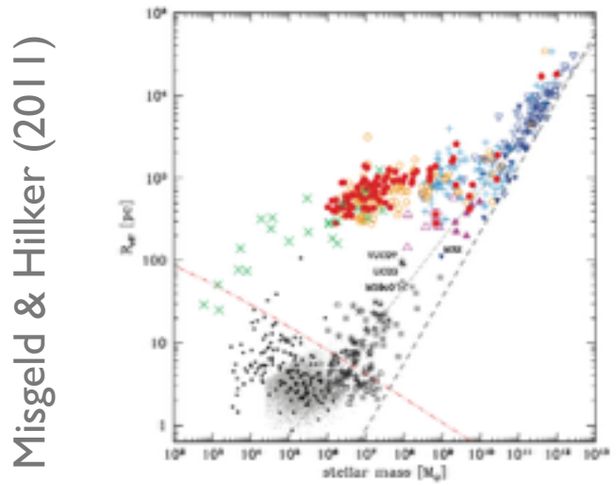
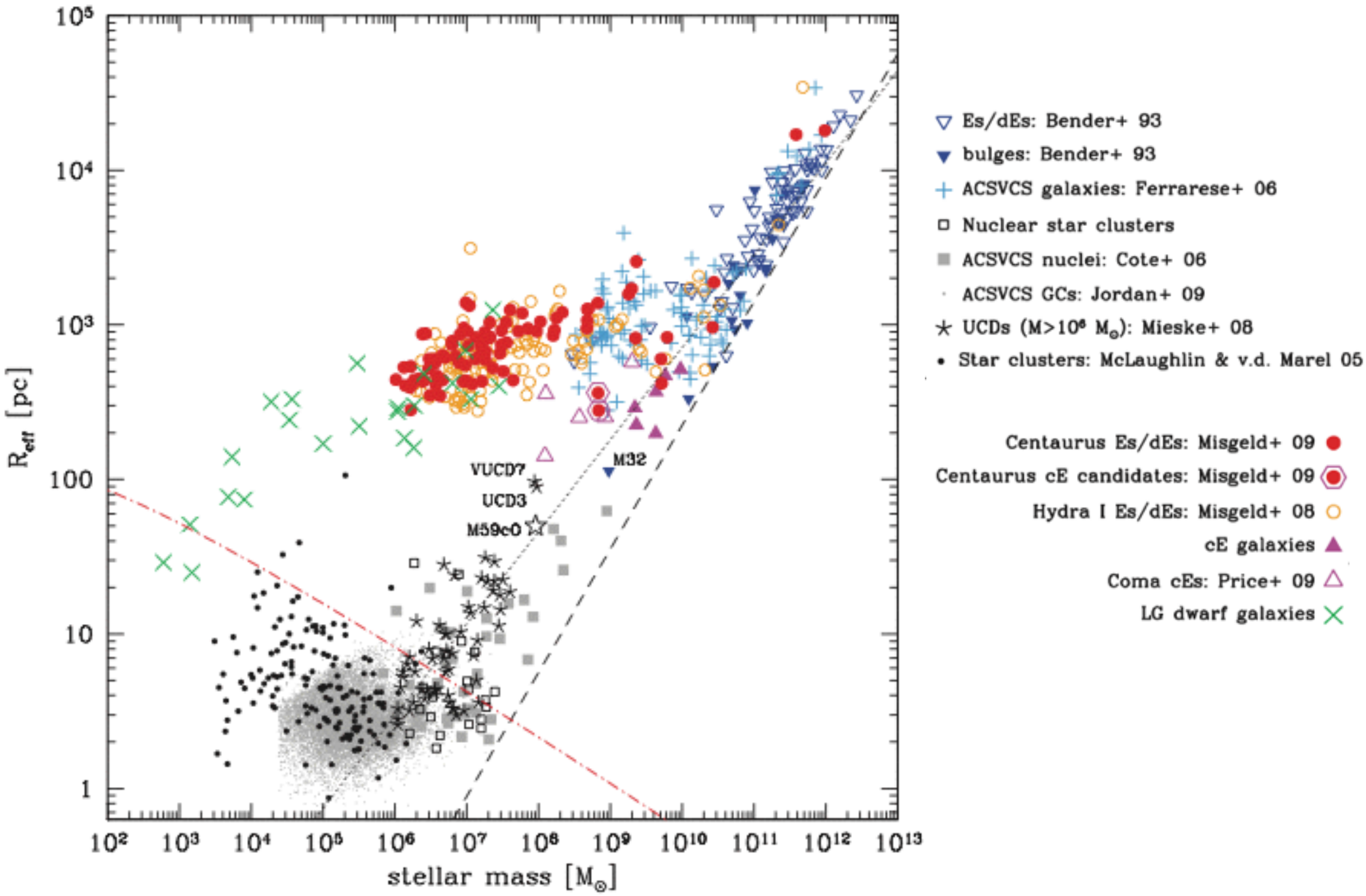


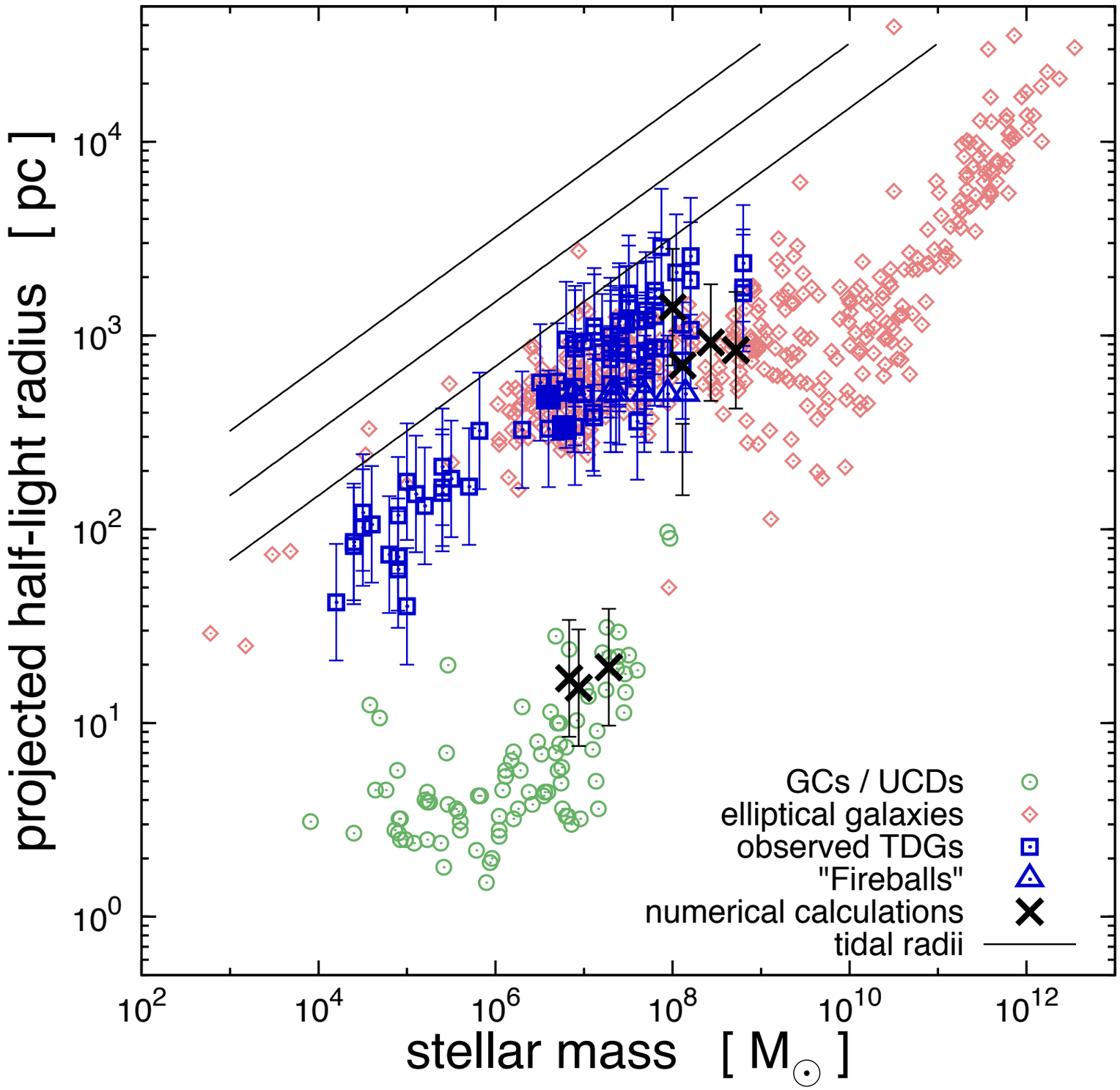
Dwarf

Size and mass comparable to dwarf galaxies

Galaxy



Misgeld & Hilker (2011)



Dabringhausen et al. (2013)

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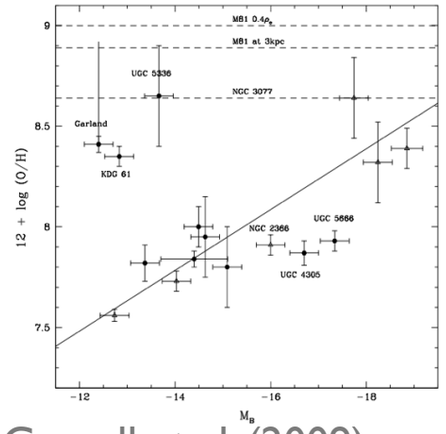

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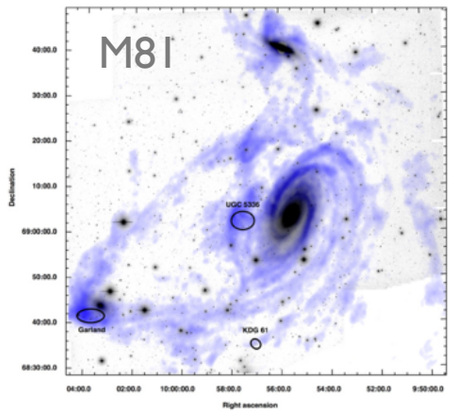

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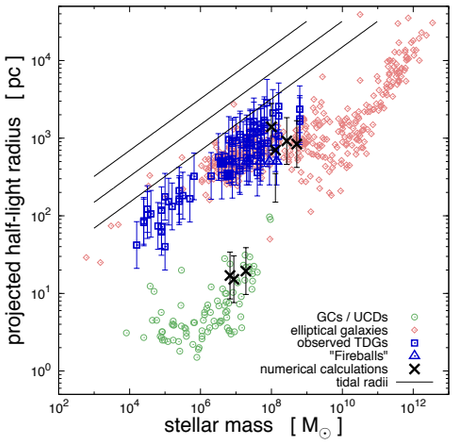

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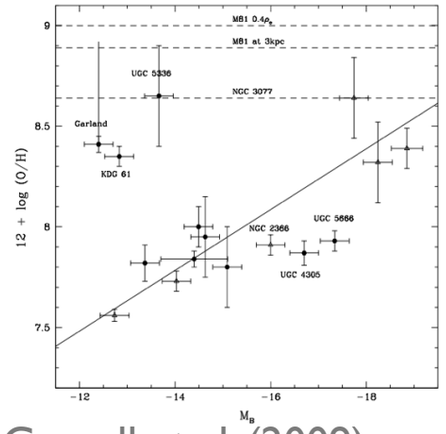

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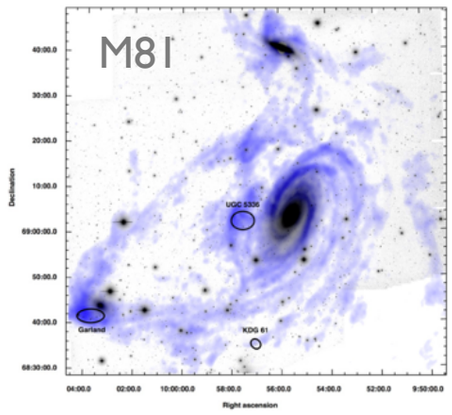

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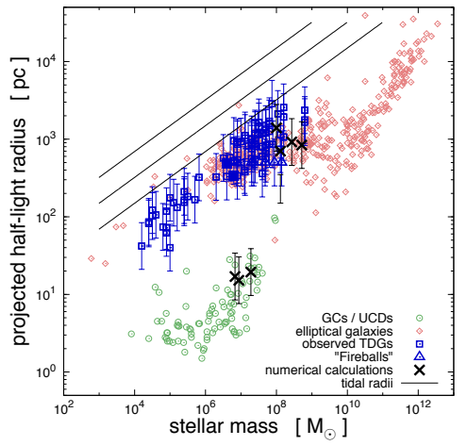

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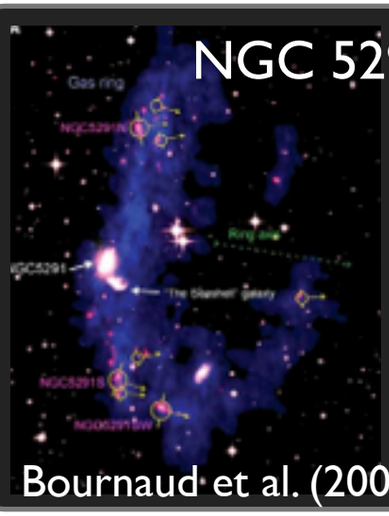
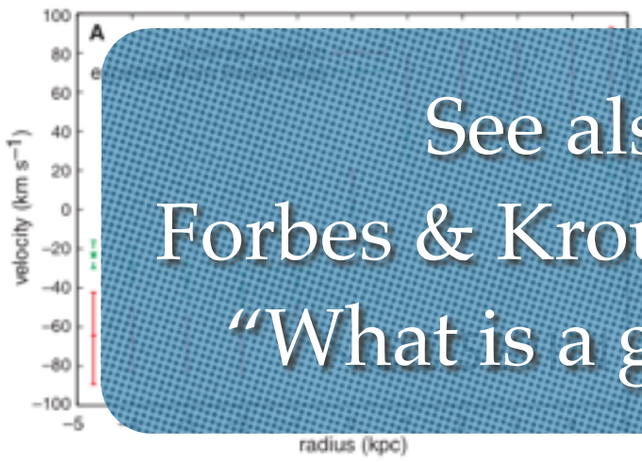


Bournaud et al. (2007)

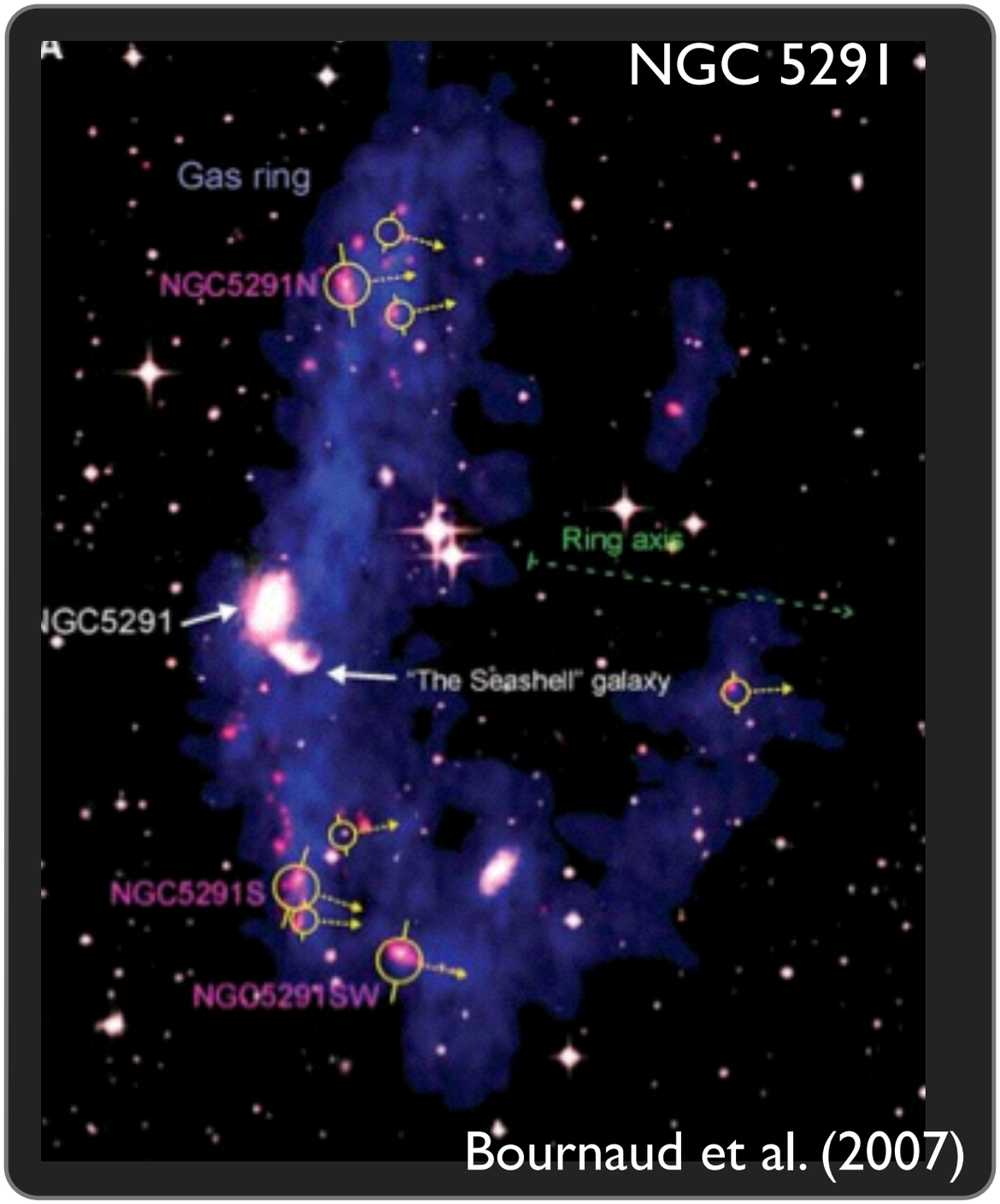


See also:
Forbes & Kroupa (2011)
"What is a galaxy?"

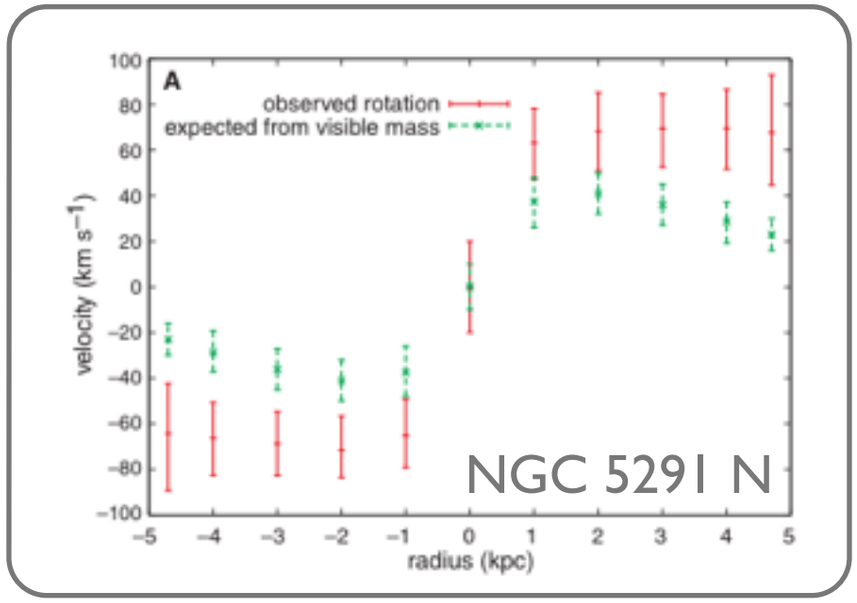
Kinematically ally

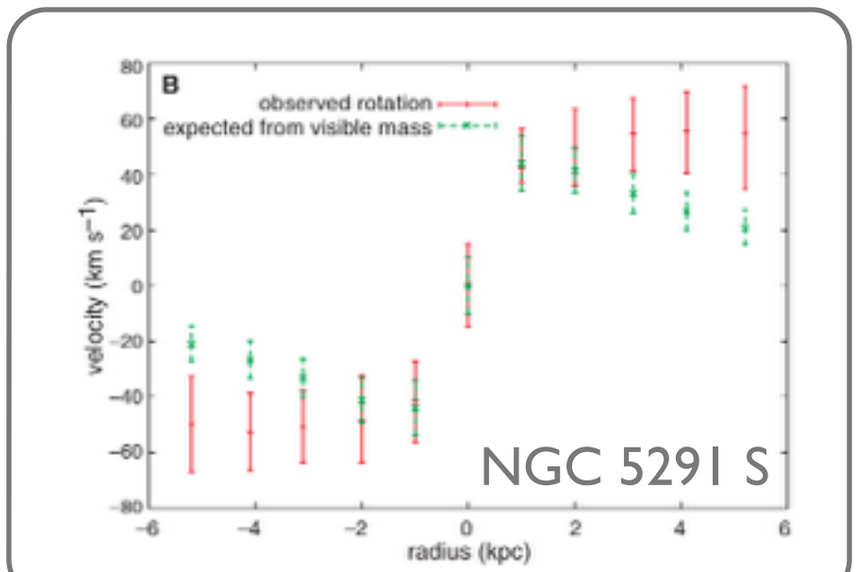
ally

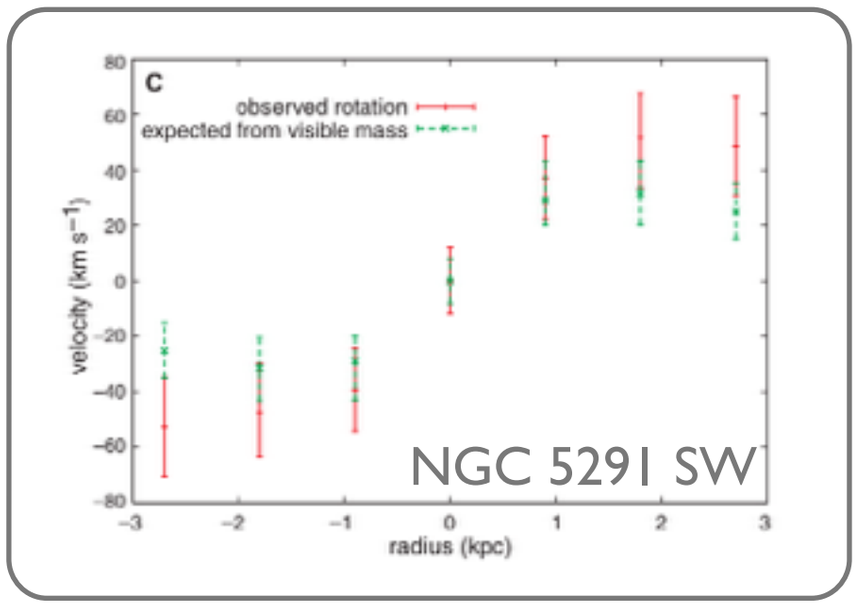
Galaxy



$$M_{\rm dyn}/M_{\rm vis} \approx 2-3$$







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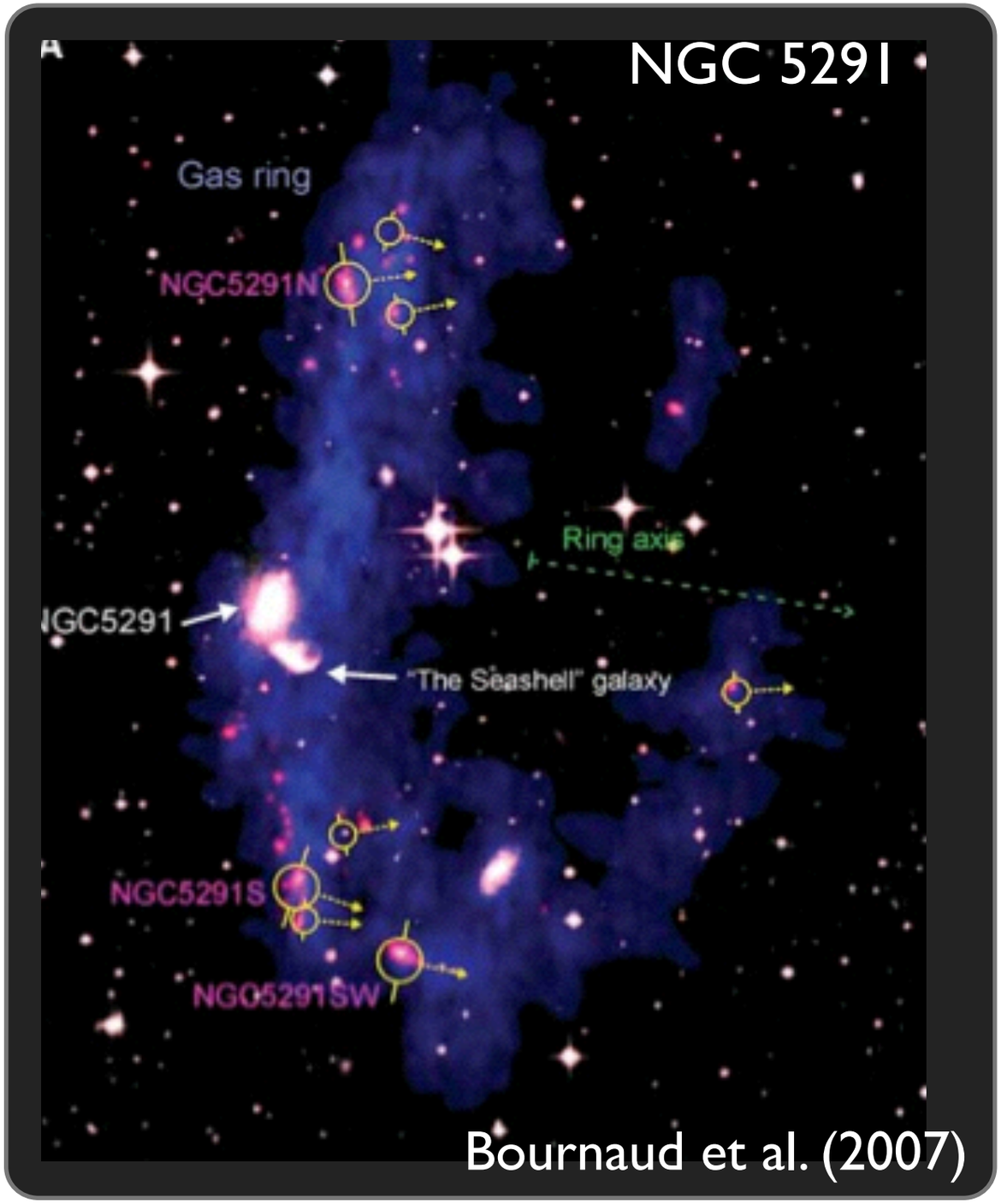
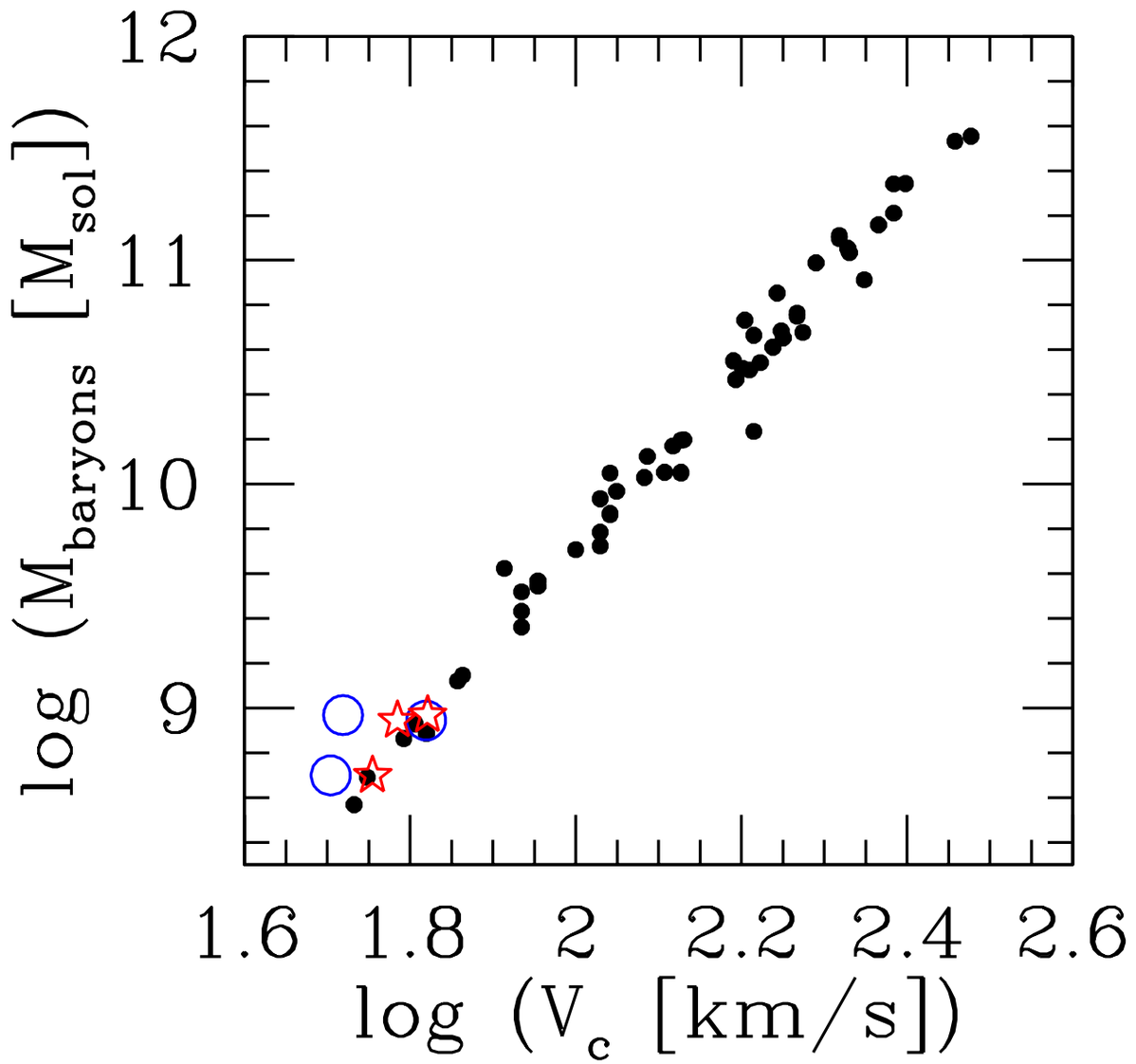




Kroupa (2012)

$$M_{\rm dyn}/M_{\rm vis} \approx 2-3$$

Properties: Summary

Dwarf galaxies

Tidal dwarf galaxies

Cover the same mass range
Gravitationally bound

Bottom-up
Dark matter dominated
(Isolated) self-enrichment

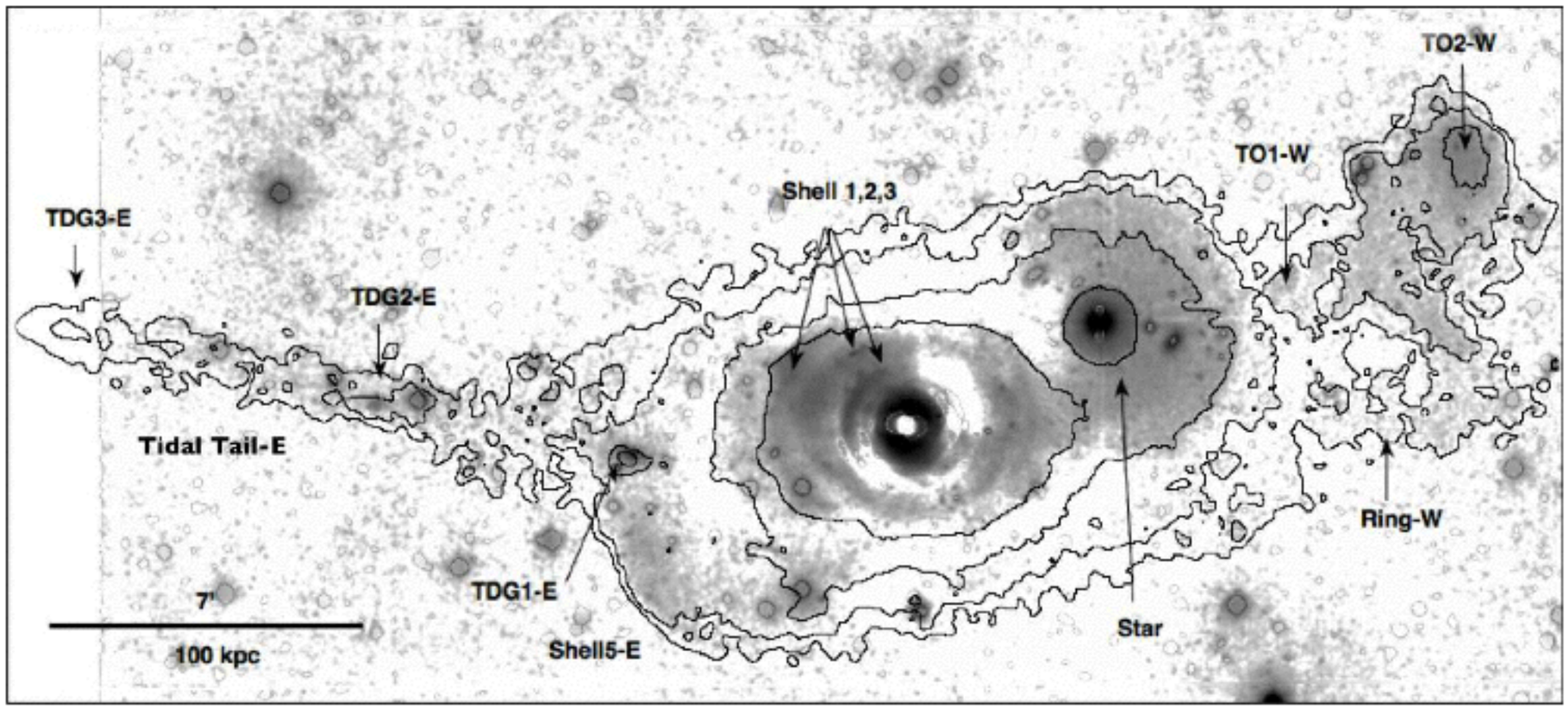
Top-down
No dark matter content
Pre-enriched material

Some statistics…

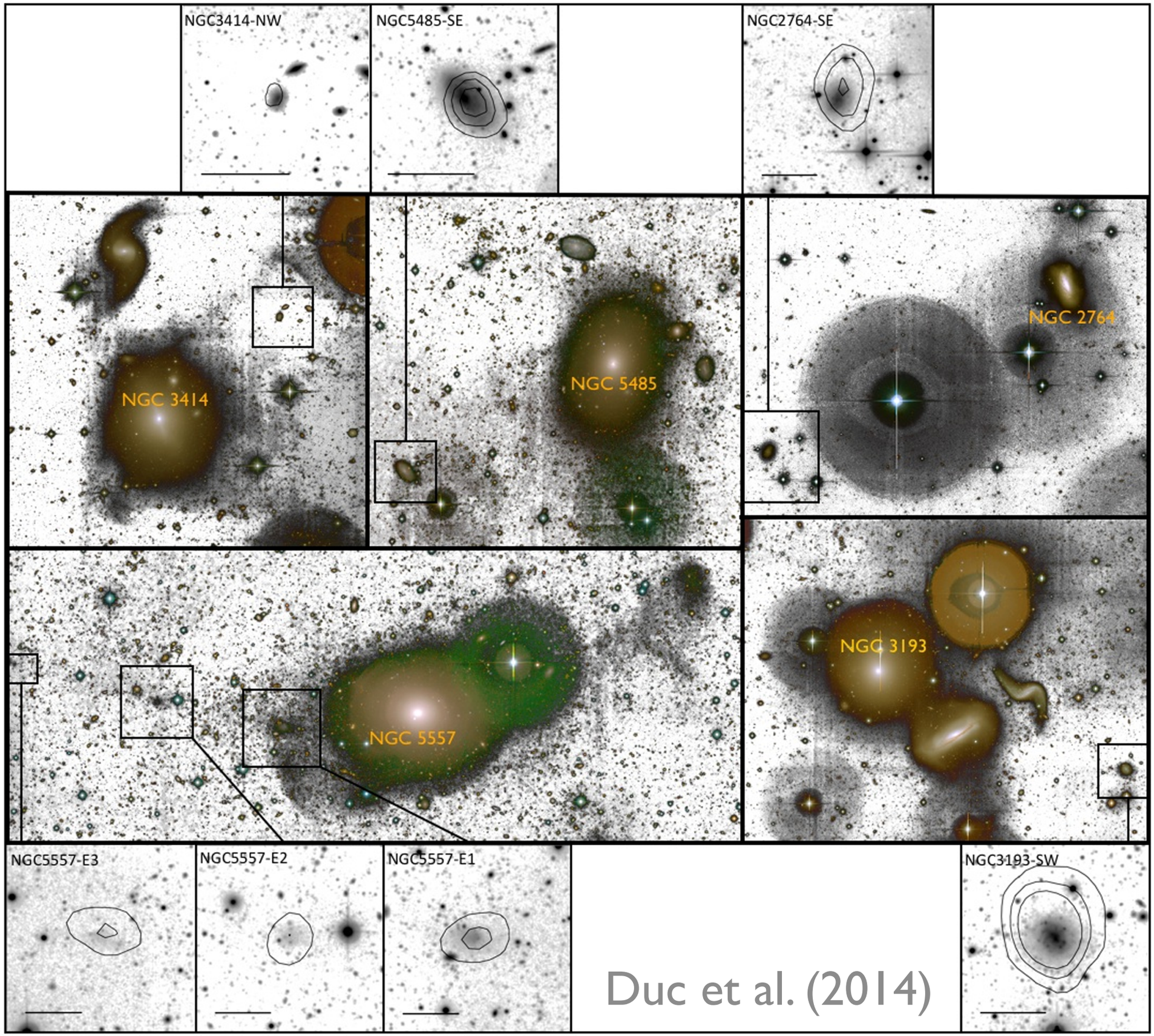
#TDGs/ merger	TDG lifetime	#TDGs/#DGs	Author
1 - 2	10 Gyrs	1	Okazaki & Taniguchi (2000)
0.1 - 0.2	10 Gyrs	0.1	Bournaud & Duc (2006)
0.8	1 Gyr	0.1	Bournaud & Duc (2006)

Aged TDGs

Age = 2 ... 5 Gyr



Duc et al. (2011) NGC 5557

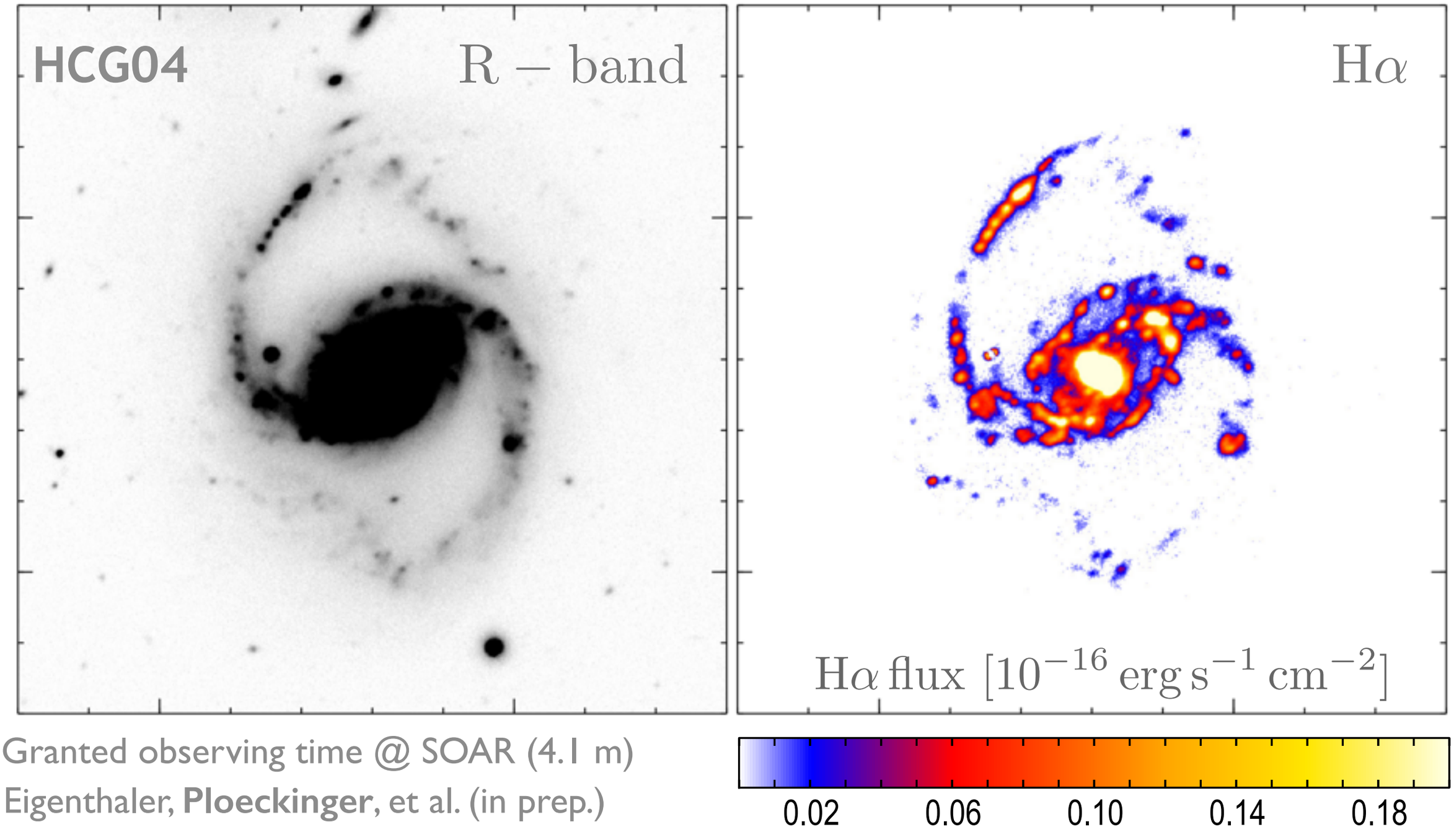

NGC3414-NW
NGC5485-SE
NGC2764-SE
NGC 3414
NGC 5485
NGC 2764
NGC 5557
NGC 3193
NGC5557-E3
NGC5557-E2
NGC5557-E1
NGC3193-SW
Duc et al. (2014)

TDG definition

Observations

Simulations

Tidal Features in Compact Groups



Granted observing time @ SOAR (4.1 m)

Eigenthaler, **Ploeckinger**, et al. (in prep.)

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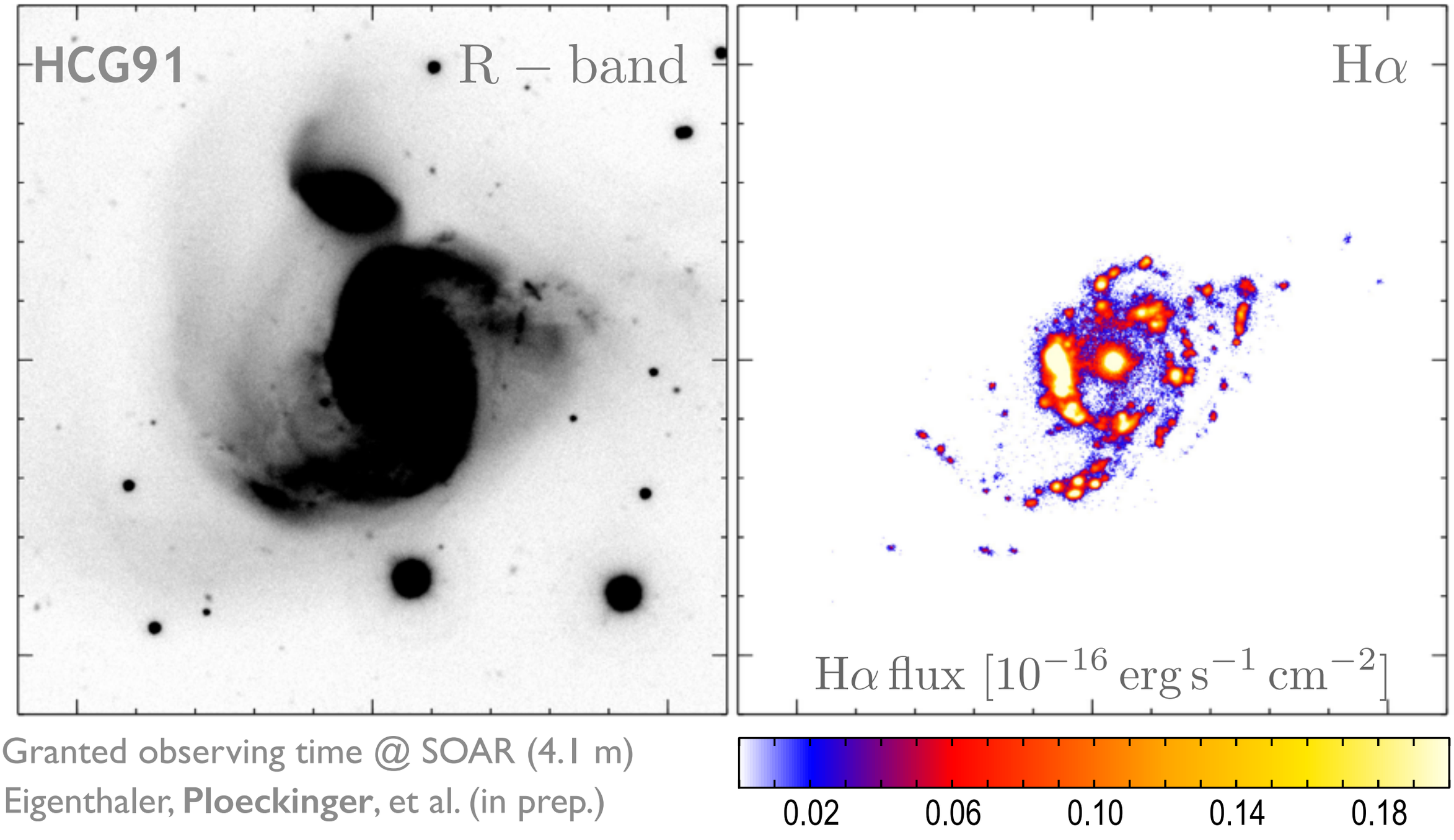

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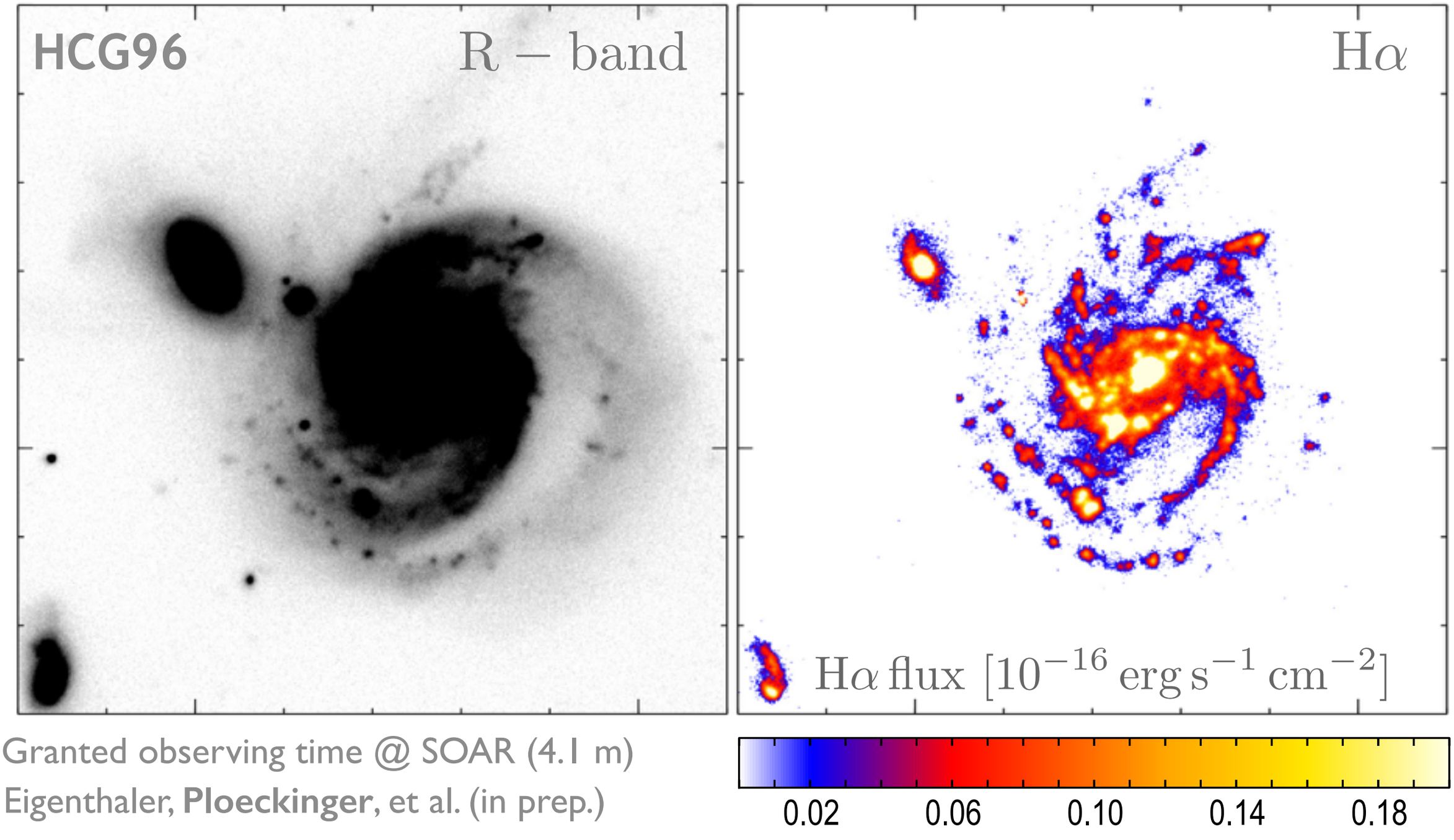

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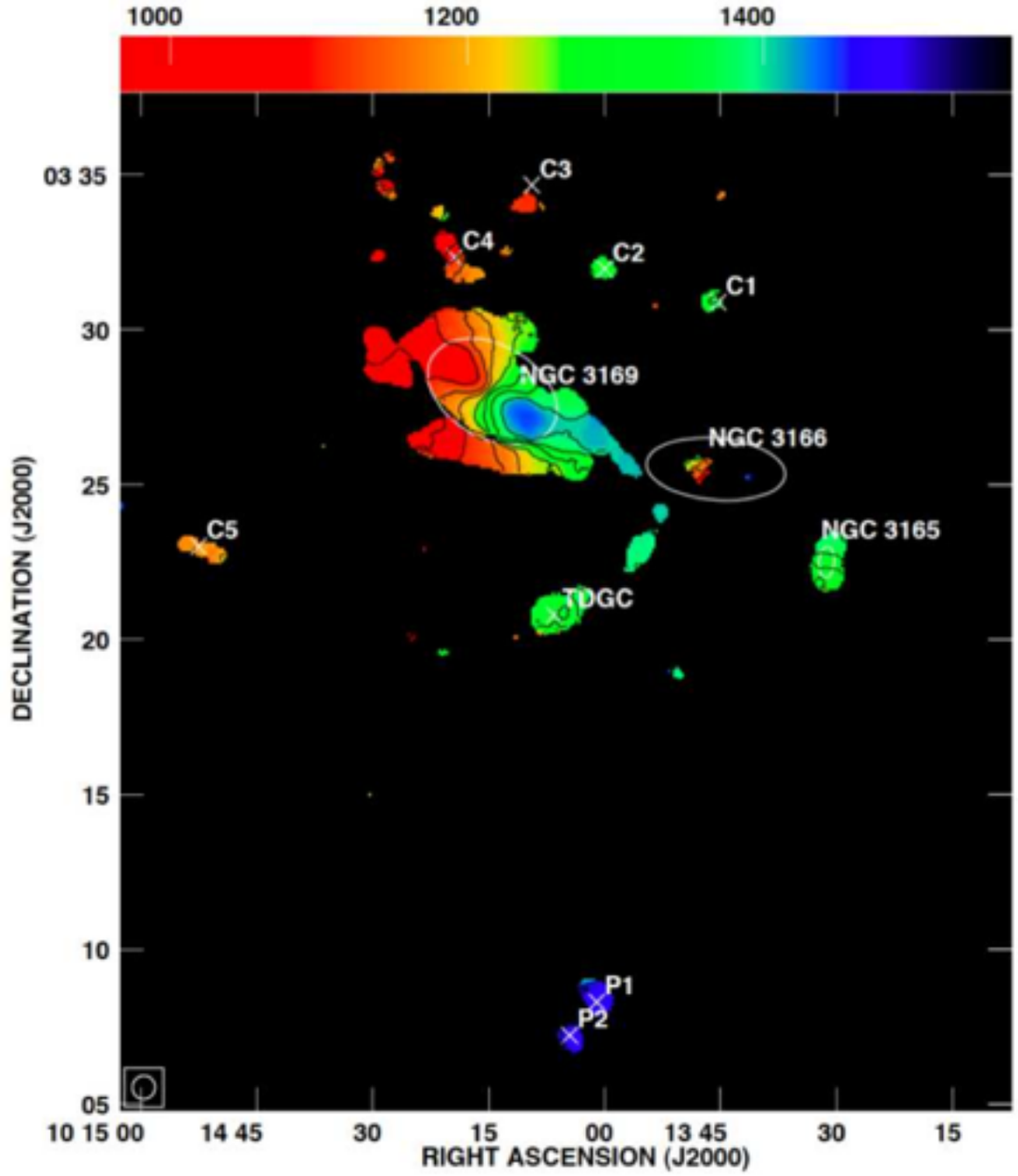


HI velocity map of the NGC 3165/ 3166 group
Lee-Waddell et al. (2013)

$M_{dyn} = 4 \times 10^8 M_{sol}$

$M_{baryon} = 3.2 \times 10^8 M_{sol}$

$M_{stellar} = 1 \times 10^7 M_{sol}$

Observing time granted for Gemini South (IFU) to investigate the internal kinematics of the TDGC.

PI: Urrutia, Co-I: Eigenthaler, Mendes de Oliveira, **Ploeckinger**

TDG definition

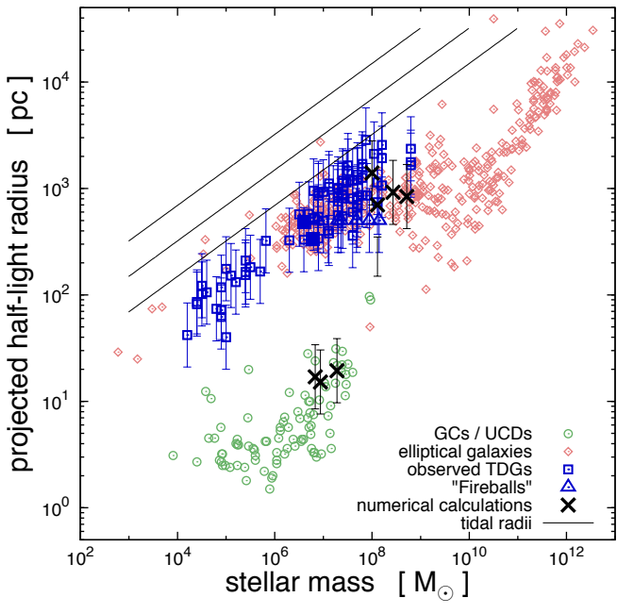
Observations

Simulations

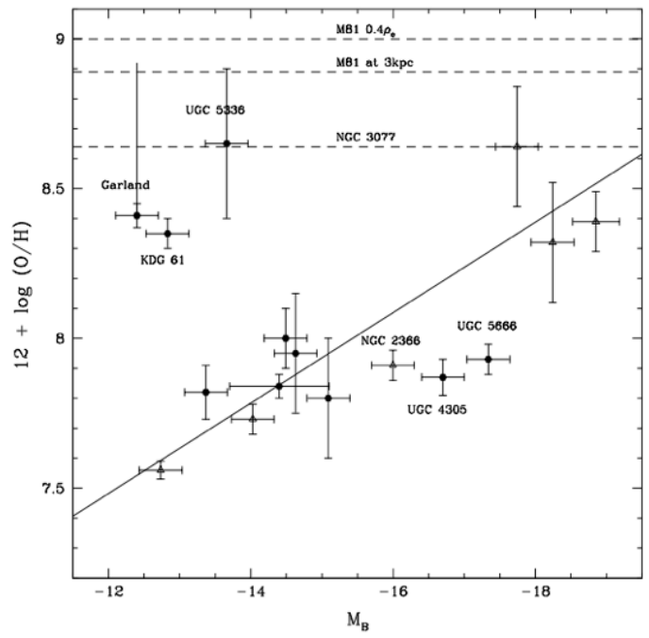
Aims

- Study the early evolution of TDGs
- Under which circumstances can they survive?
- How do fossil TDG look like?

Dabringhausen et al. (2013)

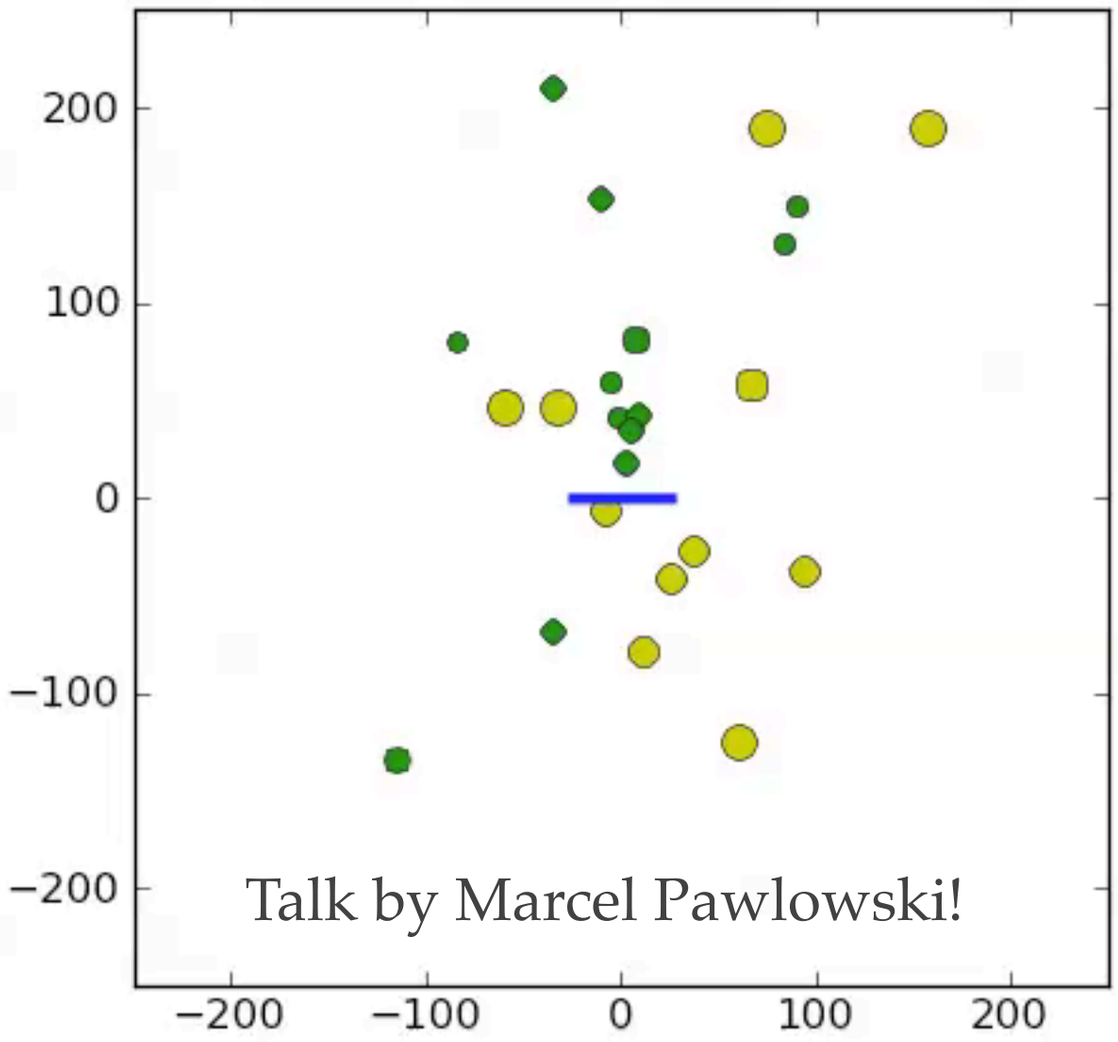


Croxall et al. (2009)



The Local Group

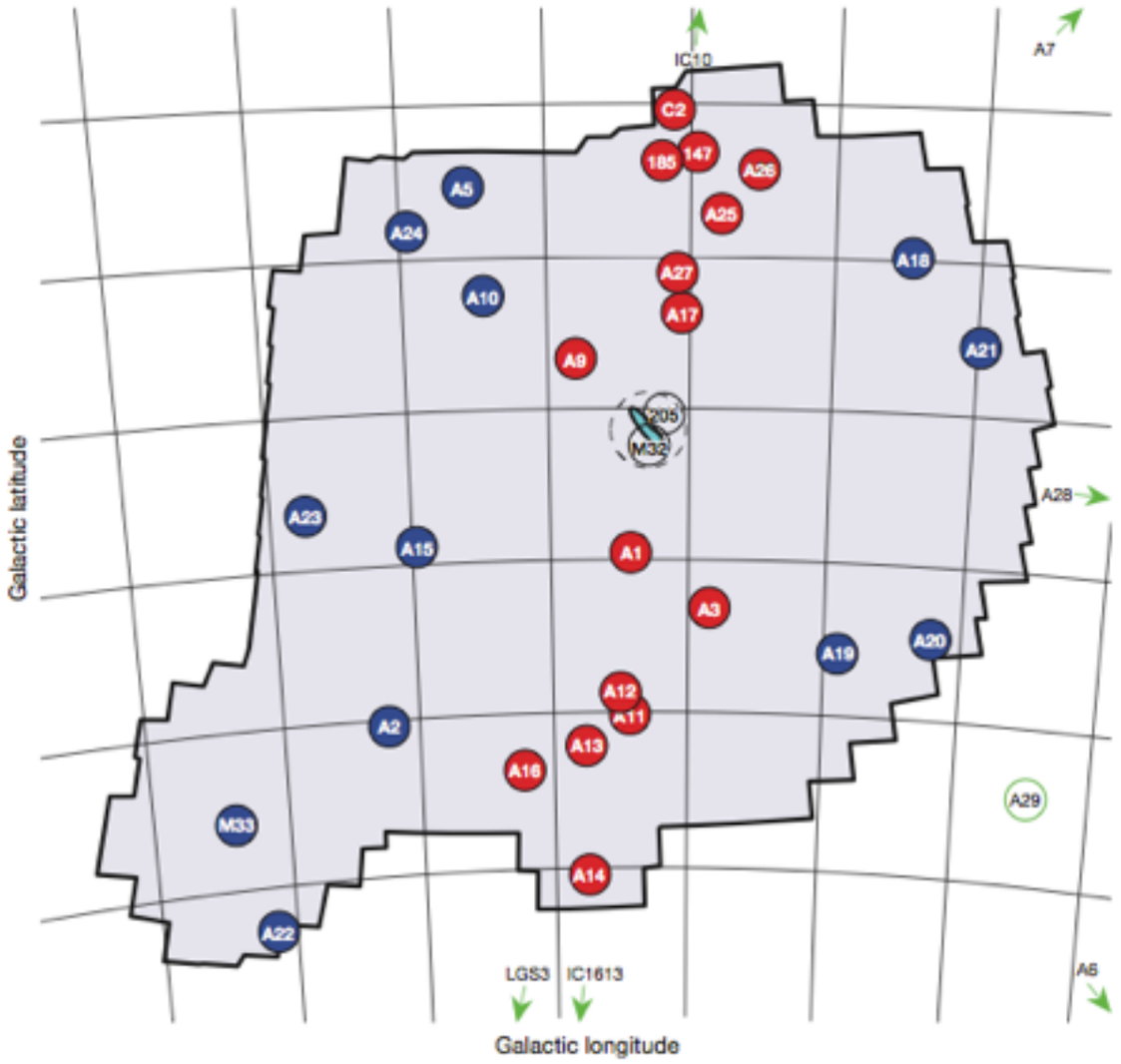
Milky Way satellites:



Classical satellite galaxies ● ● Faint satellite galaxies

Pawlowski, Pflamm-Altenburg & Kroupa (2012)

Andromeda satellites:



Ibata et al. (2013)

Simulation setup

Additional modules for FLASH, developed for the TDG simulations:

- Implicit solver for radiative cooling
- Tidal field
- Self-regulated star formation
- Stellar feedback
- Alternative stellar population descriptions (IMF)

Ploeckinger et al. (2014, MNRAS)

Flash Center
for computational science

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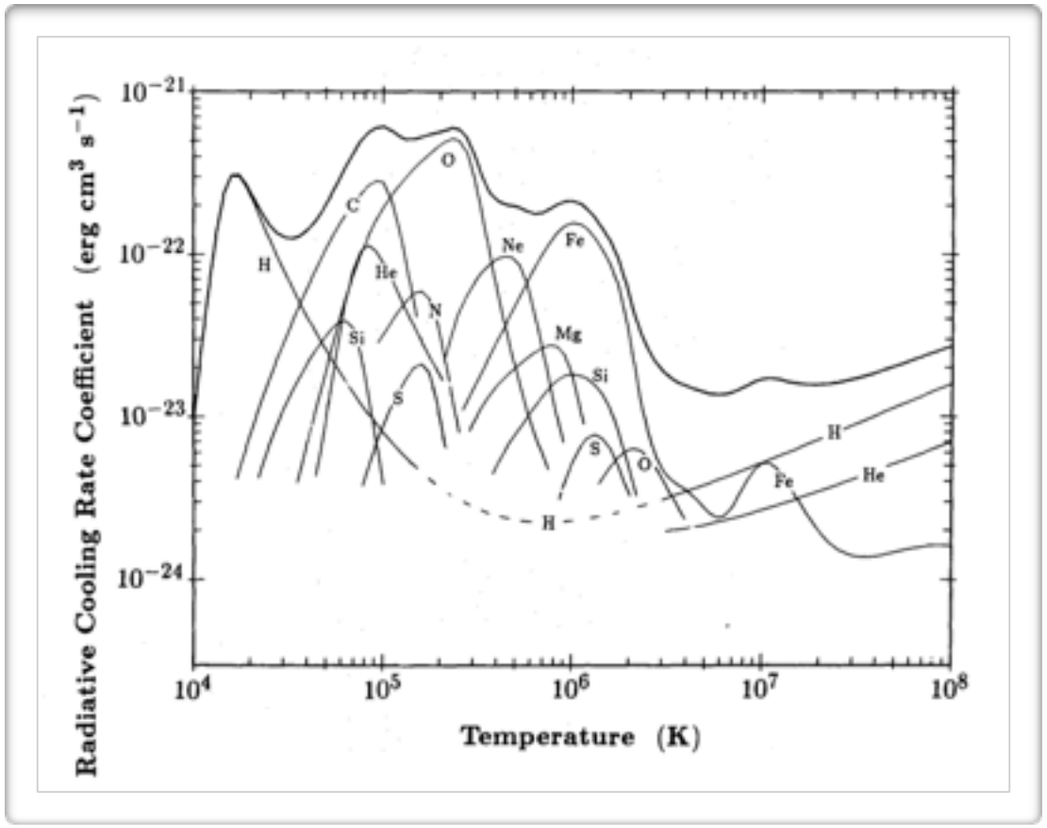

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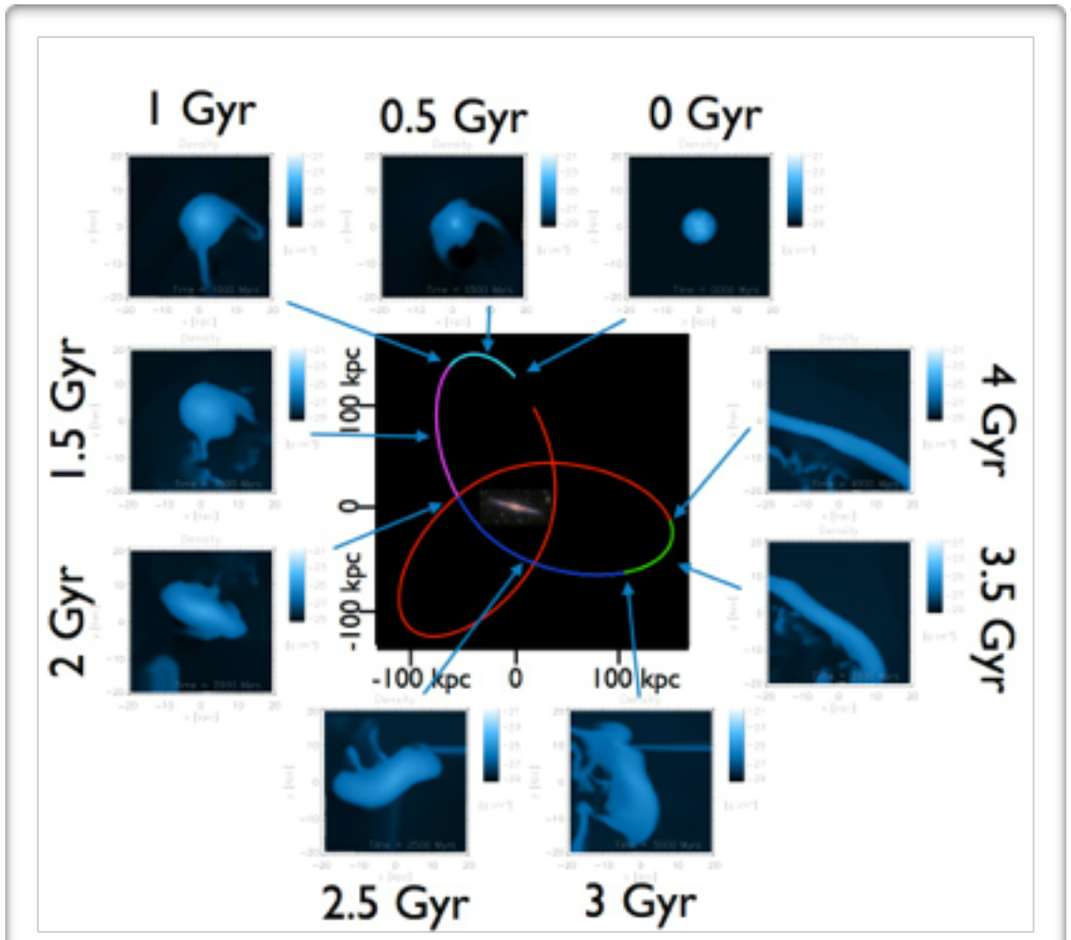

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Self-regulated star formation

SF criteria:

- Convergent flow
- SBF threshold

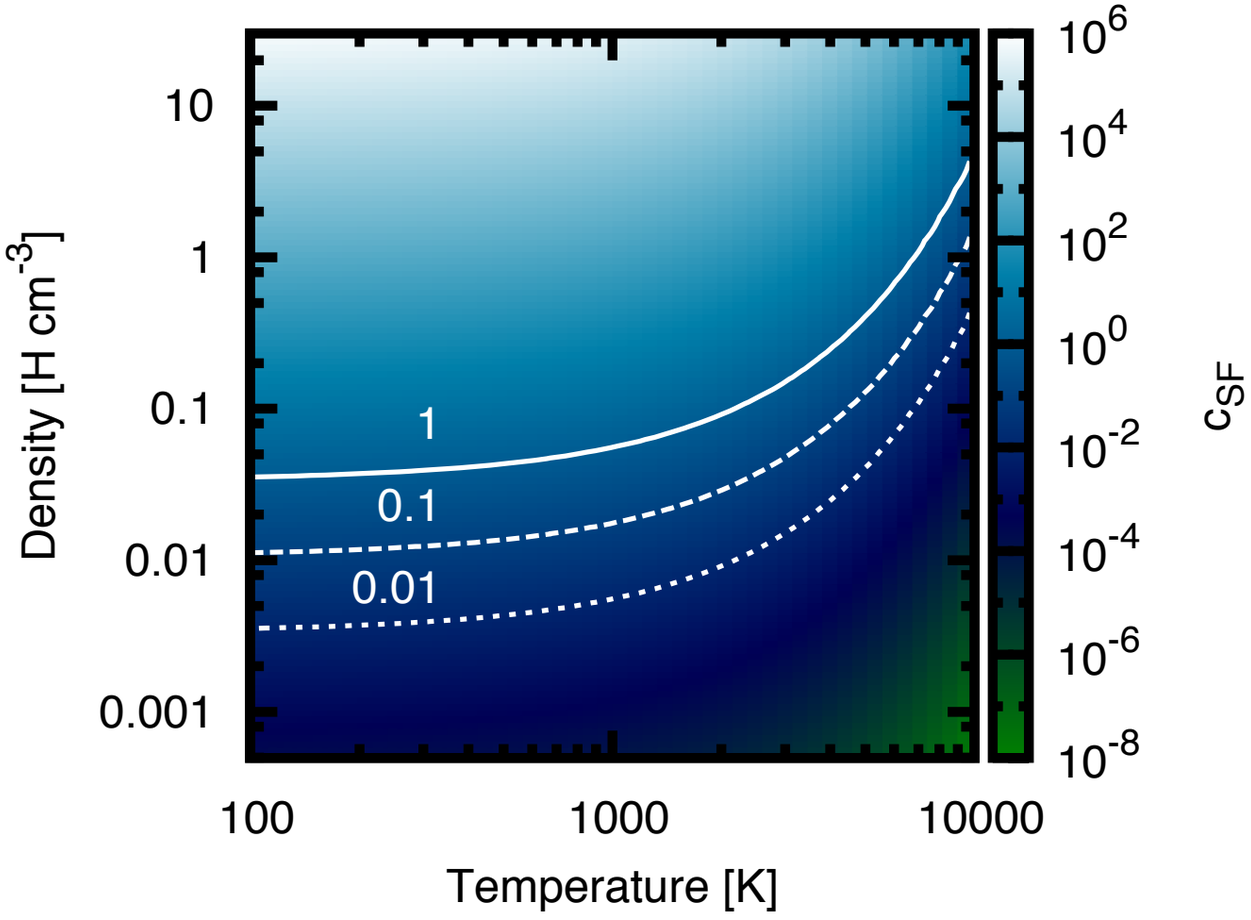
Stellar birth function:

$$\Psi(\rho, T) = C_n \rho^2 e^{-T/T_s}$$

Köppen, Theis & Hensler (1995)

ρ . . . gas density

T . . . gas temperature



$$[c_{SF}] = M_{\rm min,ecl}\ V^{-1}\ \tau_{sf}^{-1}$$

$$M_{\rm min,ecl} = 100\,{\rm M}_\odot$$

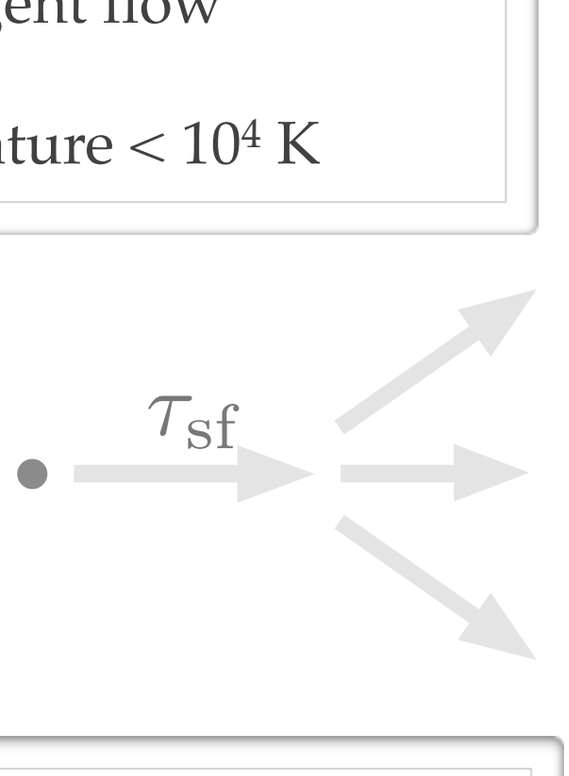
$$V = \frac{4\pi}{3}(150\,{\rm pc})^3$$

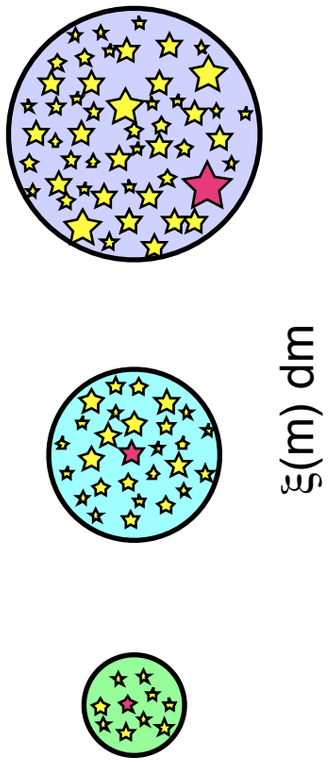
$$\tau_{sf} = 10\,{\rm Myr}$$

Self-regulated star formation

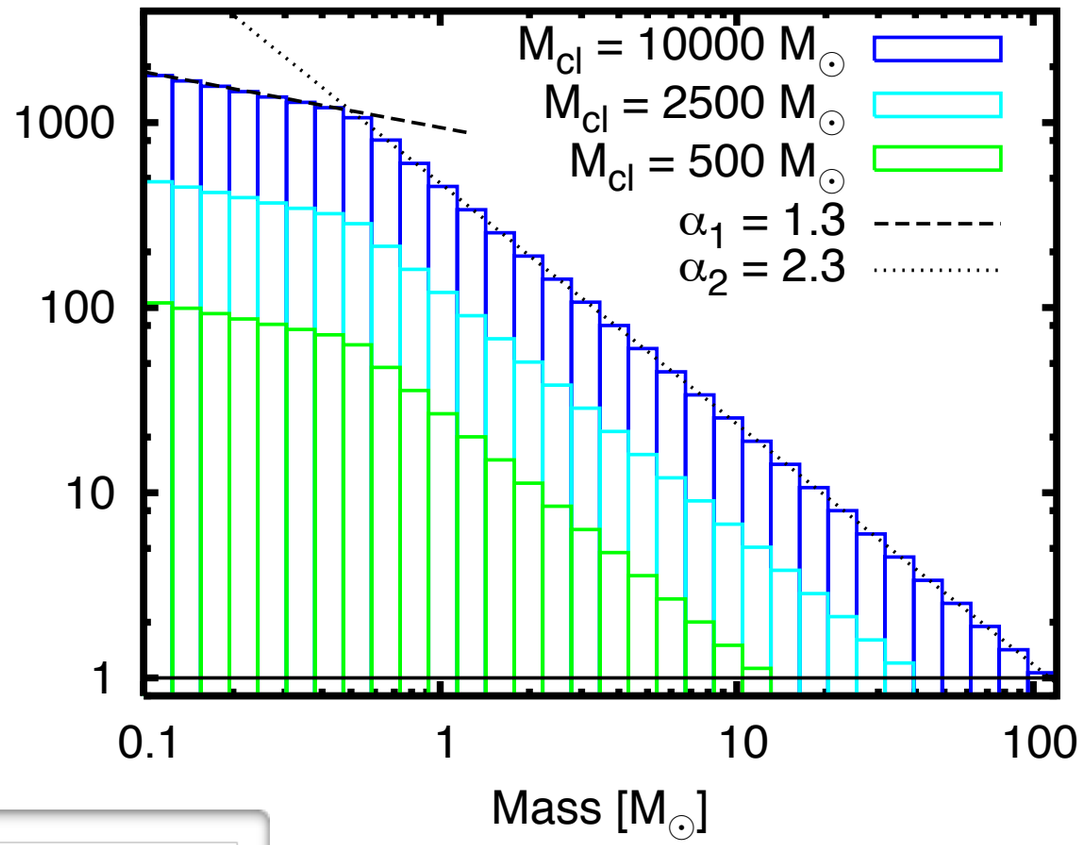
SF criteria:

- Convergent flow
- Temperature < 10^4 K





Truncated Kroupa (2001) IMF



Ploeckinger et al. (2014, MNRAS)

Stellar birth function:

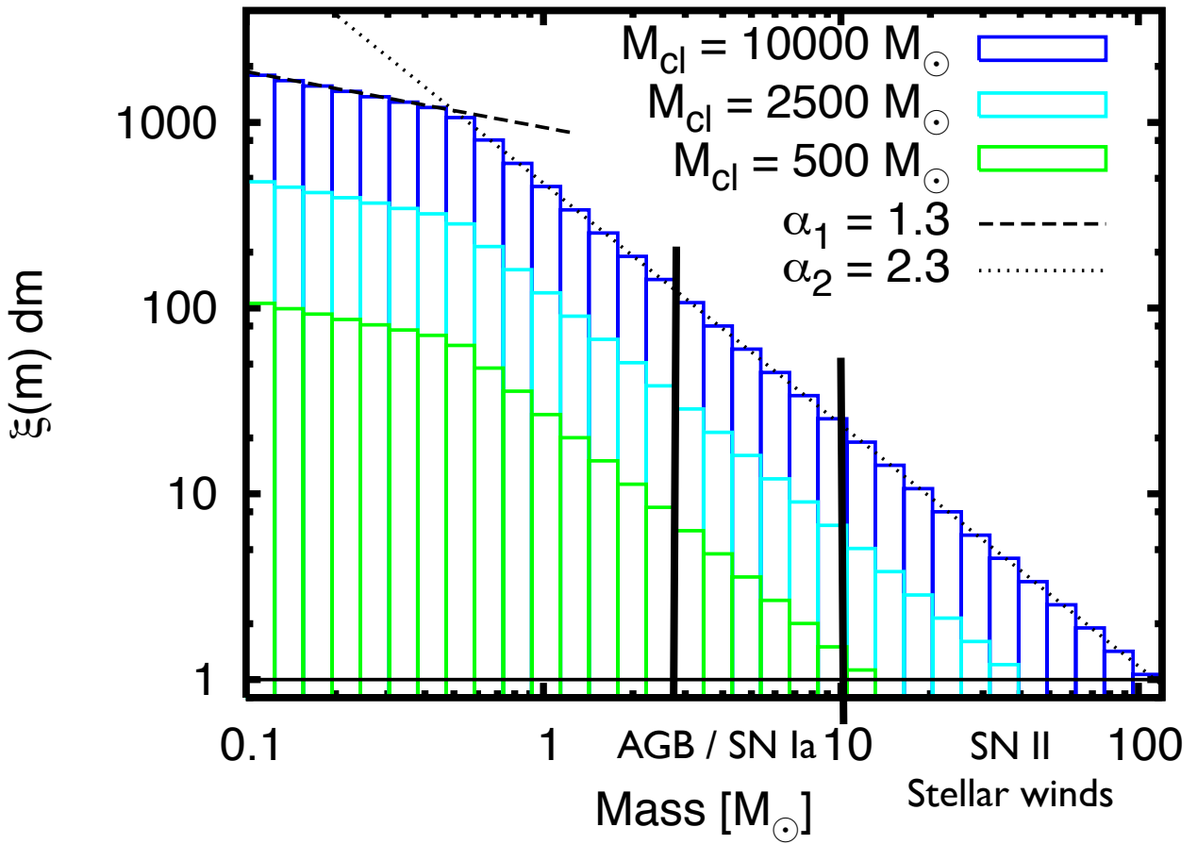
$$\Psi(\rho, T) = C_n \rho^2 e^{-T/T_s}$$

Köppen, Theis & Hensler (1995)

$$m_{\rm max} - M_{\rm ecl}$$

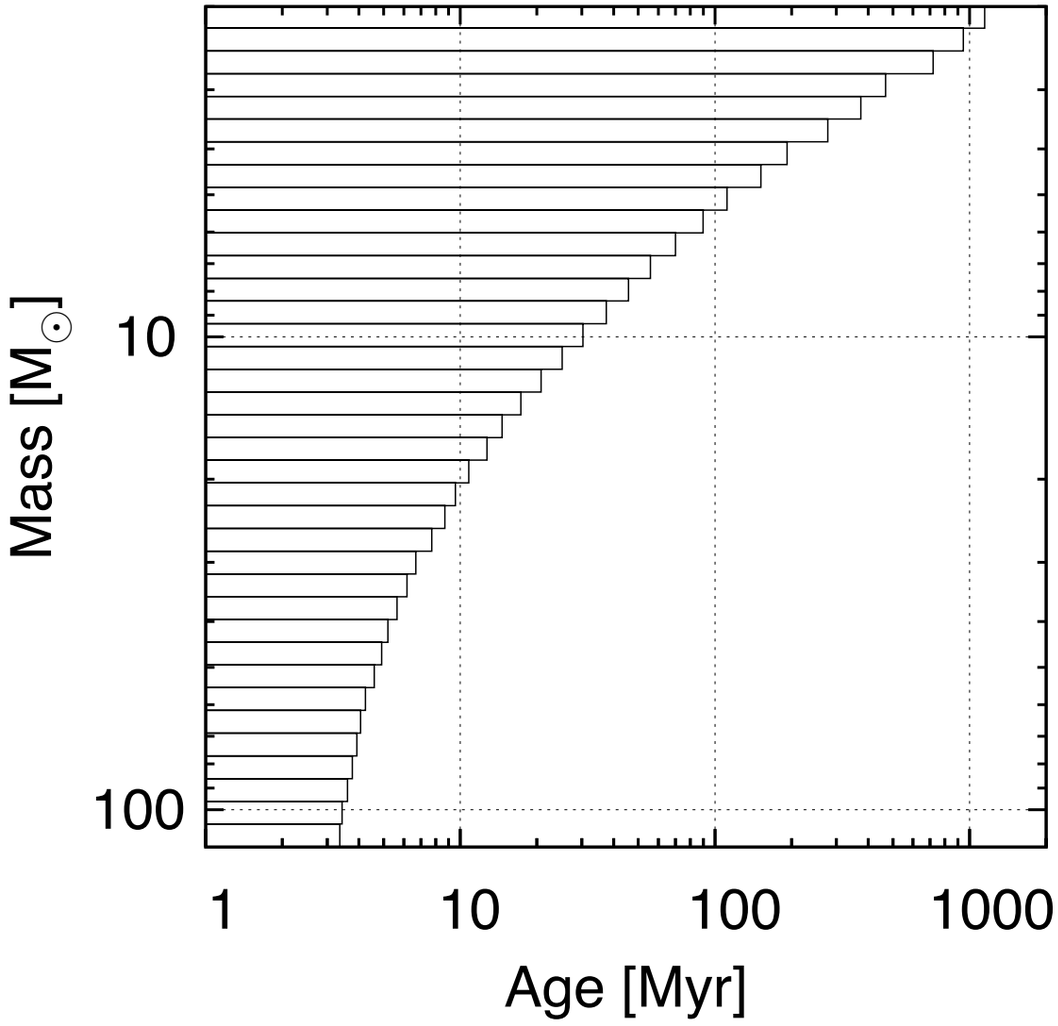
Talk by Carsten Weidner!

Stellar feedback



Ploeckinger et al. (2014, MNRAS)

Stellar lifetimes from Portinari et al. (1998)



Ploeckinger et al. (2014, PhD thesis)

Stellar feedback

During their lifetime:
Wind from massive stars +
Lyman continuum radiation

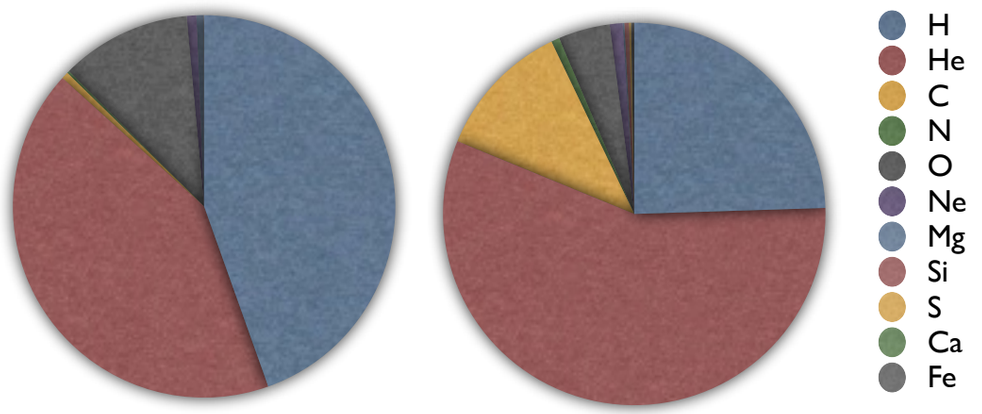
At the end their lifetime:
Supernova Ia (Energy + stellar yield)
Supernova II (Energy + stellar yield)
AGB (Stellar yield)

$$\left.\frac{\partial e_{th}}{\partial t}\right|_{OB} = \frac{1}{2}\dot{m}v_\infty^2 + \eta_{Ly}L_{Ly}(m)$$

$$\begin{aligned} L_{Ly}(m) &= 10^{40}\left(\frac{m}{M_\odot}\right)^6 \text{ photons s}^{-1}\,\text{star}^{-1} \\ \dot{m} &= -10^{-15}\left(\frac{Z}{Z_\odot}\right)^{0.5}\left(\frac{L}{L_\odot}\right)^{1.6} \text{M}_\odot\,\text{yr}^{-1} \\ v_\infty &= 3\cdot 10^3\left(\frac{m}{M_\odot}\right)^{0.15}\left(\frac{Z}{Z_\odot}\right)^{0.08} \text{km s}^{-1} \end{aligned}$$

Theis, Burkert, Hensler (1992)

$M_\star = 100\,\text{M}_\odot$



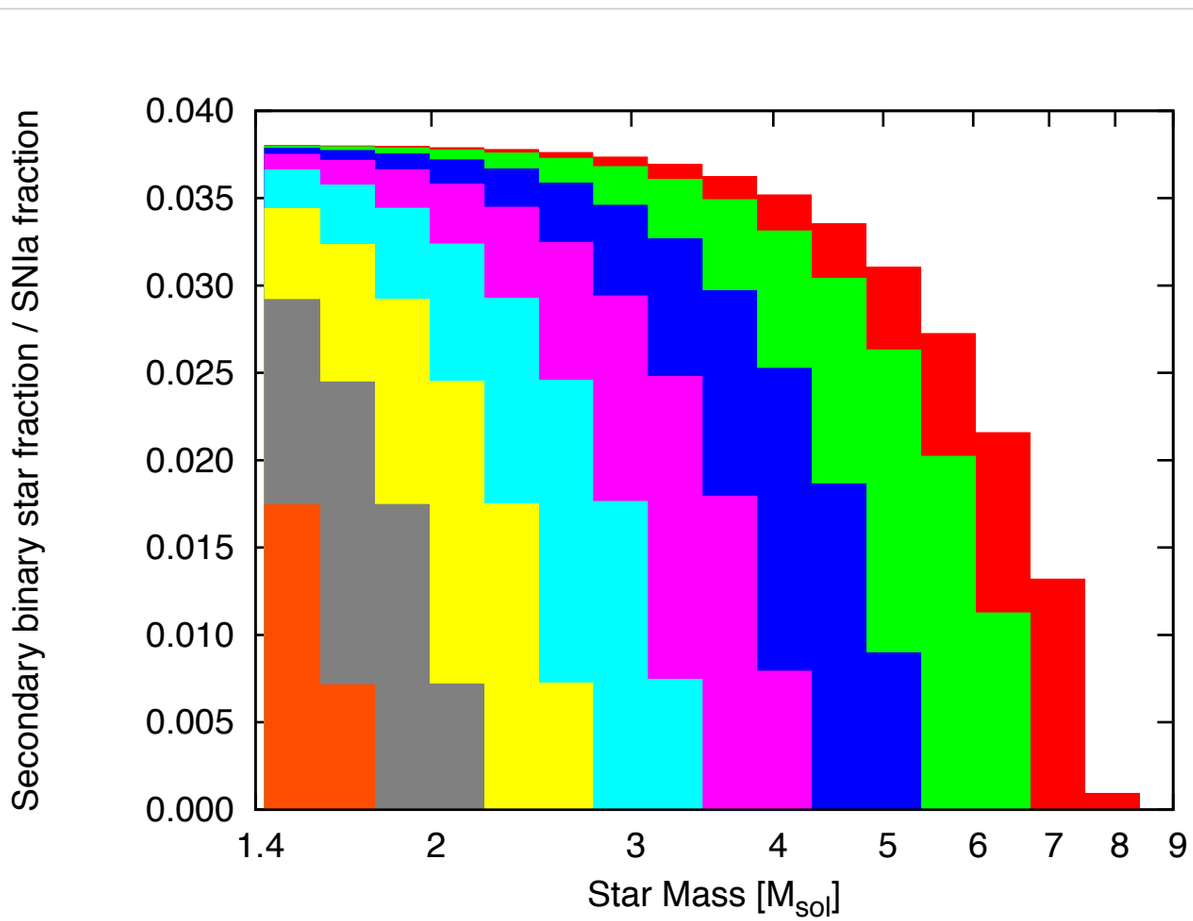
$Z_\star = 0.3\,\text{Z}_\odot$ $Z_\star = 1.5\,\text{Z}_\odot$

Yields: Portinari et al. (1998) + Marigo et al. (1996)

Supernovae Ia

Recchi, Calura & Kroupa (2009):

$$R_{\mathrm{SNIa}}(t) = A \int_{m_{\mathrm{B,\,inf}}}^{m_{\mathrm{B,\,sup}}} \int_{\mu_{\min}}^{\mu_{\max}} f(\mu)\, \psi(t - \tau_{m_2})\, \xi_{\mathrm{IGIMF}}\left[m_{\mathrm{B},\,\psi(t-\tau_{m_2})}\right] \mathrm{d}\mu\, \mathrm{d}m_{\mathrm{B}}$$



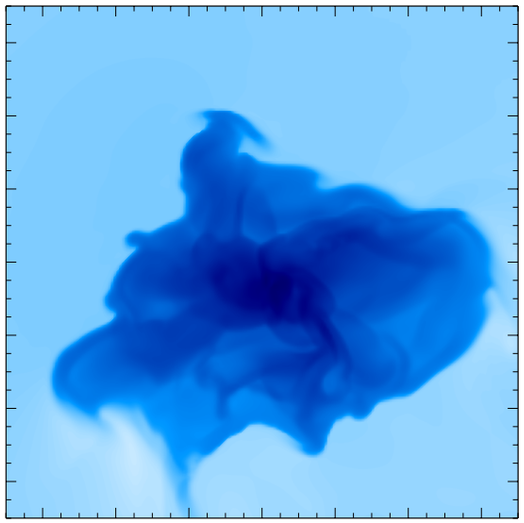
A	normalisation constant (A = 0.09)
$m_{\mathrm{B,\,inf}}$	minimum total binary mass ($m_{\mathrm{B,\,inf}} = \max(2 \cdot m_2(t), 3\,\mathrm{M}_\odot)$
$m_{\mathrm{B,\,sup}}$	maximum total binary mass ($m_{\mathrm{B,\,sup}} = 8\,\mathrm{M}_\odot + m_2(t)$)
μ	ratio between the mass of the secondary star m_2 to the total binary mass m_B ($\mu = \frac{m_2}{m_B} = \frac{m_2}{m_1+m_2}$)
$\mu_{\max}$	maximum ratio μ for equal masses for the primary star m_1 and the secondary star m_2 ($\mu_{\max} = 0.5$)
$\mu_{\min}$	minimum ratio μ for the largest possible difference between the mass of the primary and the mass of the secondary star ($\mu_{\min} = \max\left[\frac{m_2(t)}{m_B}, \frac{m_B - 8\,\mathrm{M}_\odot}{m_B}\right]$)
$f(\mu)$	distribution function of mass ratios in binary systems ($f(\mu) \propto \mu^\gamma$, $\gamma = 2$)
ξ_{IGIMF}	initial mass function; in case of the IGIMF description ξ_{IGIMF} is dependent on the star formation rate ψ at the time when the star was born
τ_{m_2}	lifetime of the secondary star with mass m_2

Advantages of this setup

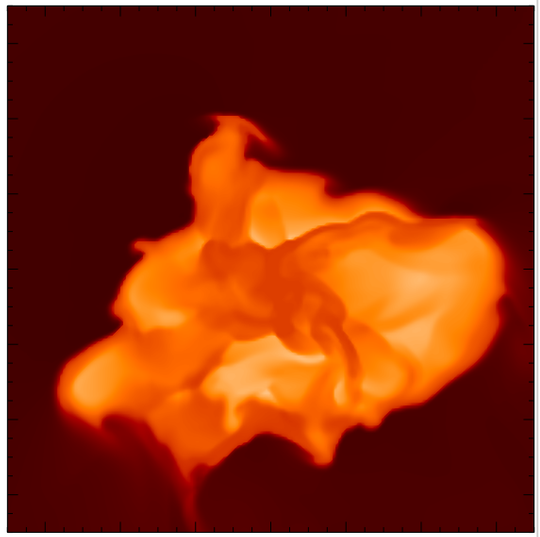
- No discrete density / temperature thresholds necessary for star formation
- Star formation is self-regulated (stellar winds, SNe)
- SNe are discrete events at the correct rate with accurate stellar yields
- Variable, self-consistent star cluster masses allow additional analysis on the ECMF
- The IGIMF and its impact on the dynamical evolution and metal enrichment of galaxies can be tested

Results

Early evolution



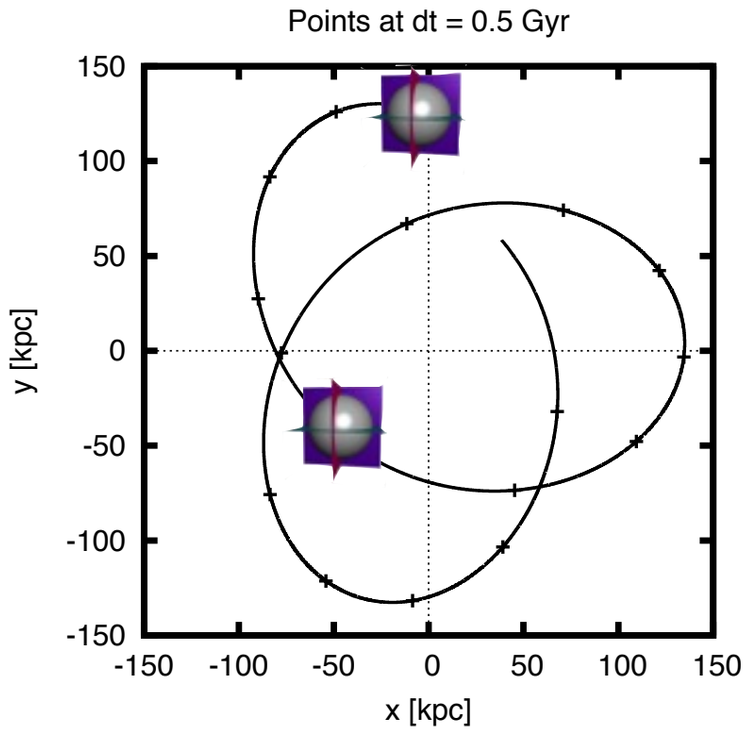
Gas density



Gas temperature

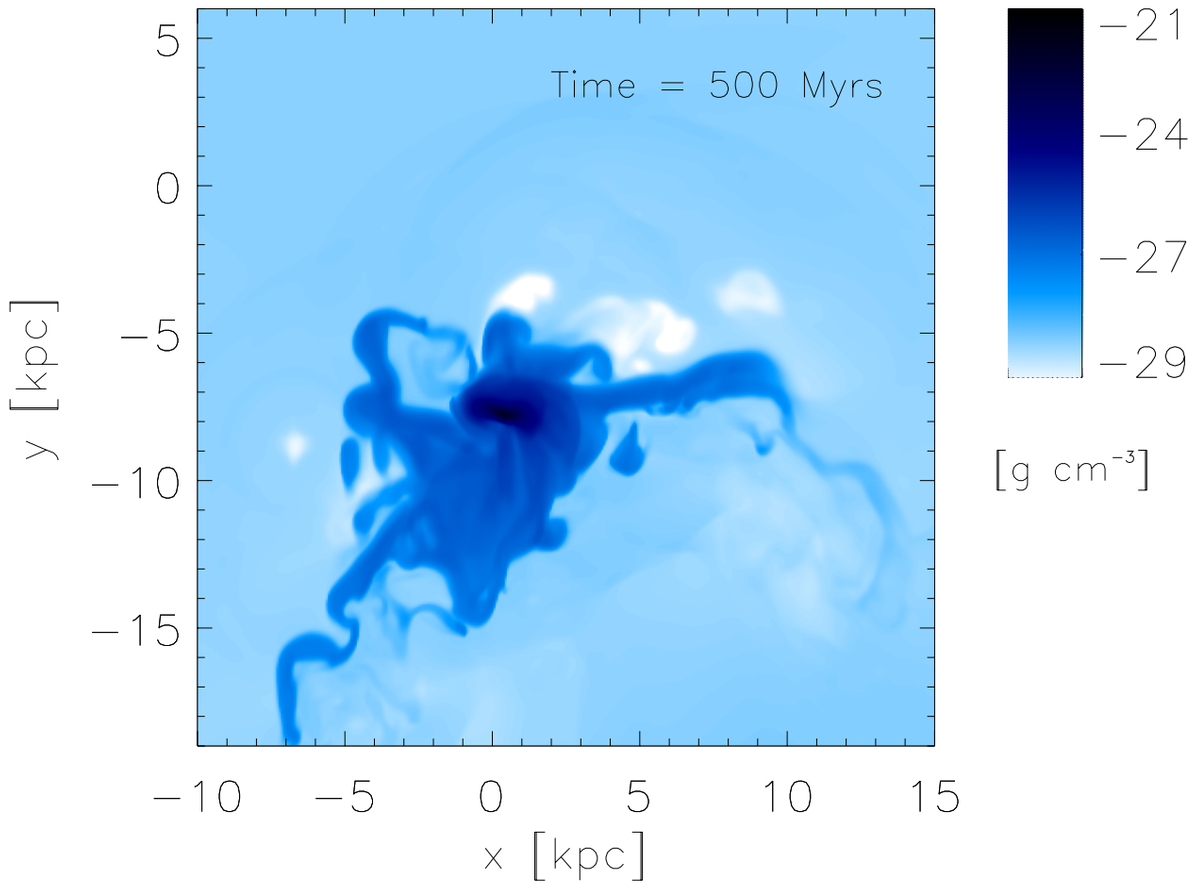
Ploeckinger et al. (2014, MNRAS),
Recchi (2014, AdAst)

Long term evolution

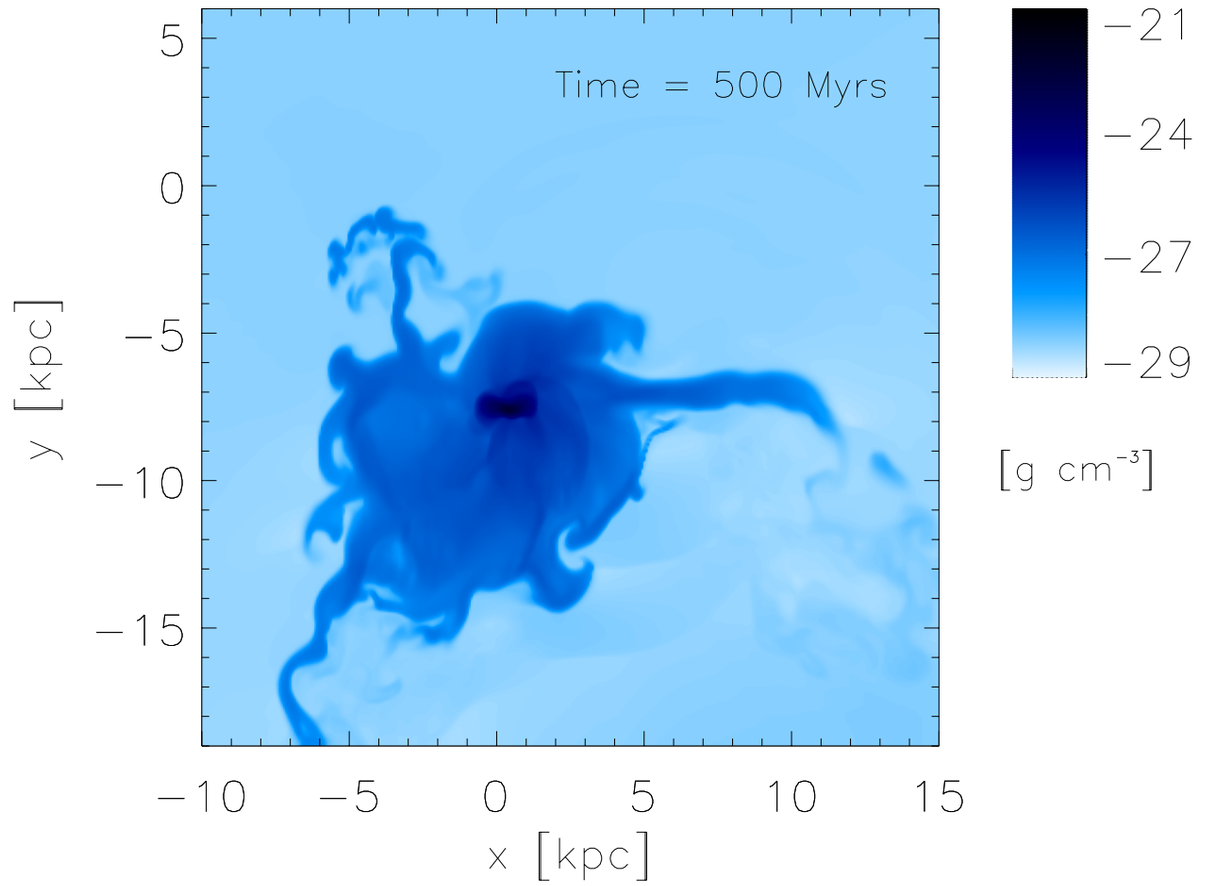


Ploeckinger et al. (2014, in prep.)

Truncated IMF



Filled IMF

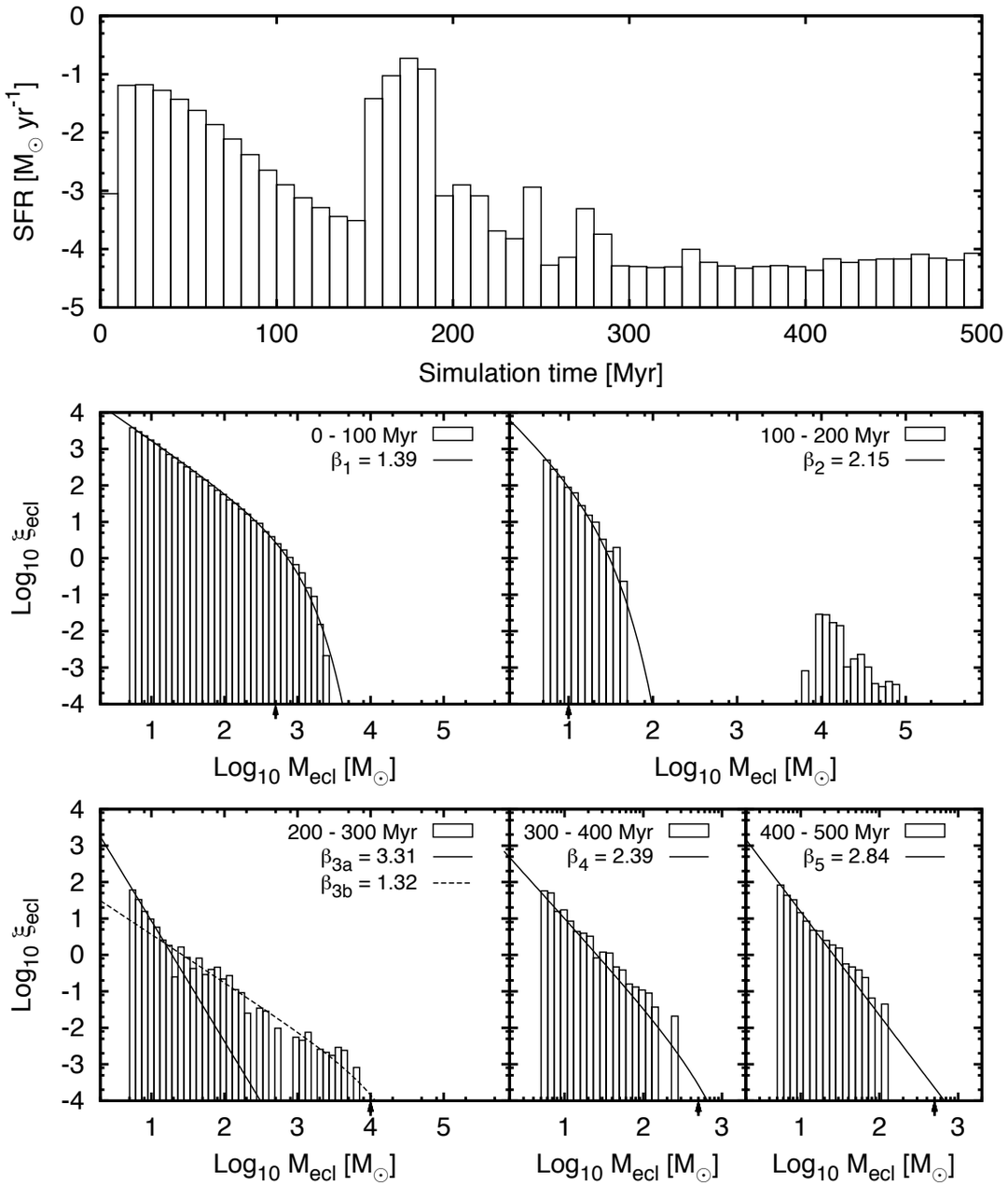


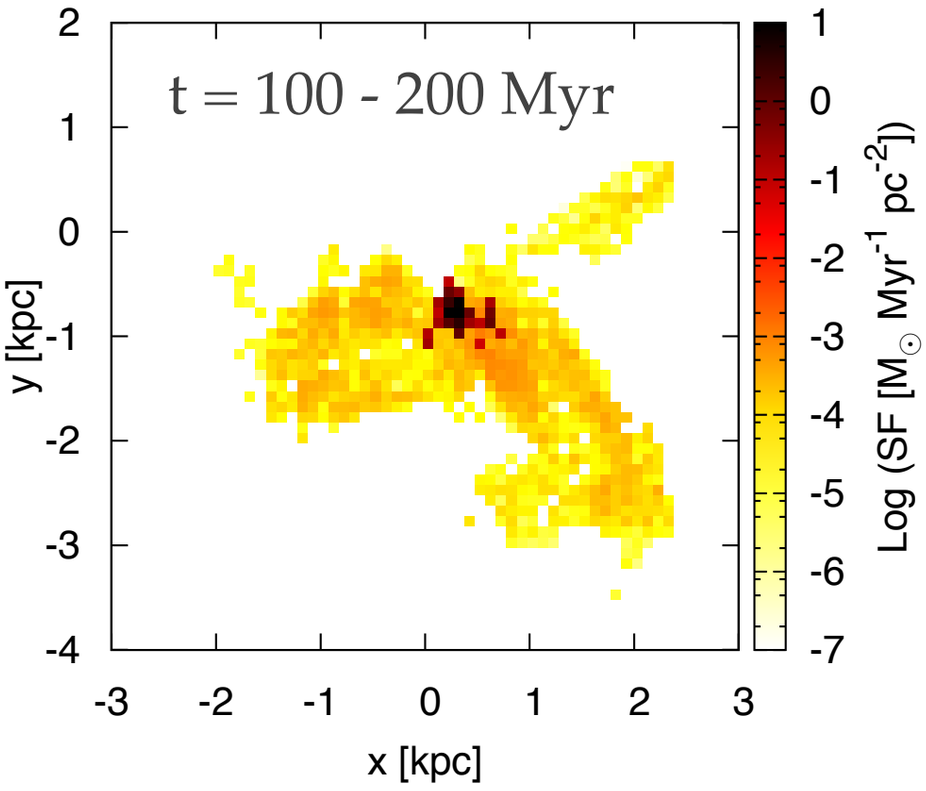
Bound gas mass:	$1.31 \times 10^8\ M_{sol}$
Stellar mass:	$5.73 \times 10^6\ M_{sol}$
Total TDG mass:	$1.37 \times 10^8\ M_{sol}$

Bound gas mass:	$1.233 \times 10^8\ M_{sol}$
Stellar mass:	$8.35 \times 10^5\ M_{sol}$
Total TDG mass:	$1.242 \times 10^8\ M_{sol}$

Ploeckinger et al. (2014, MNRAS)

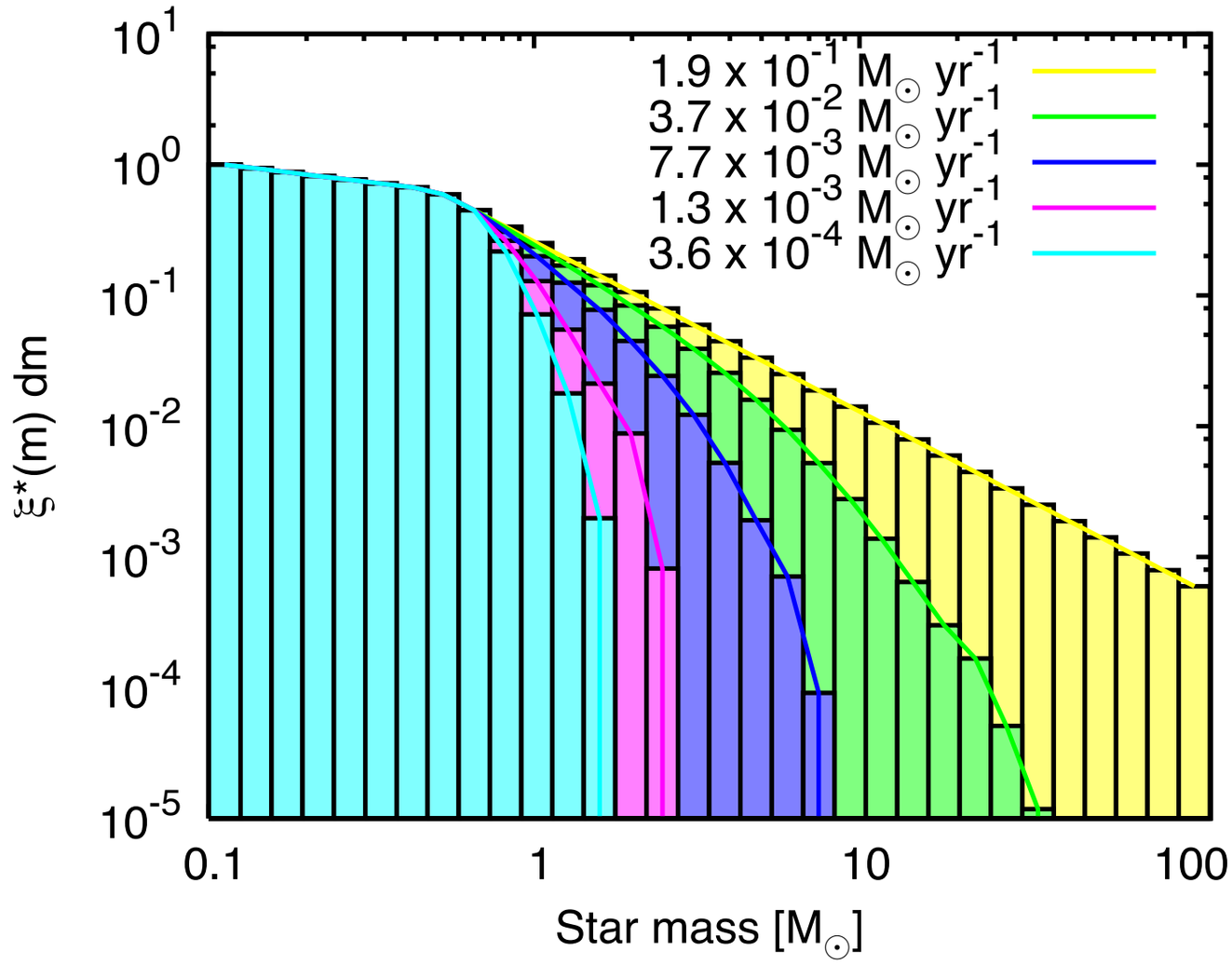
Star cluster mass function





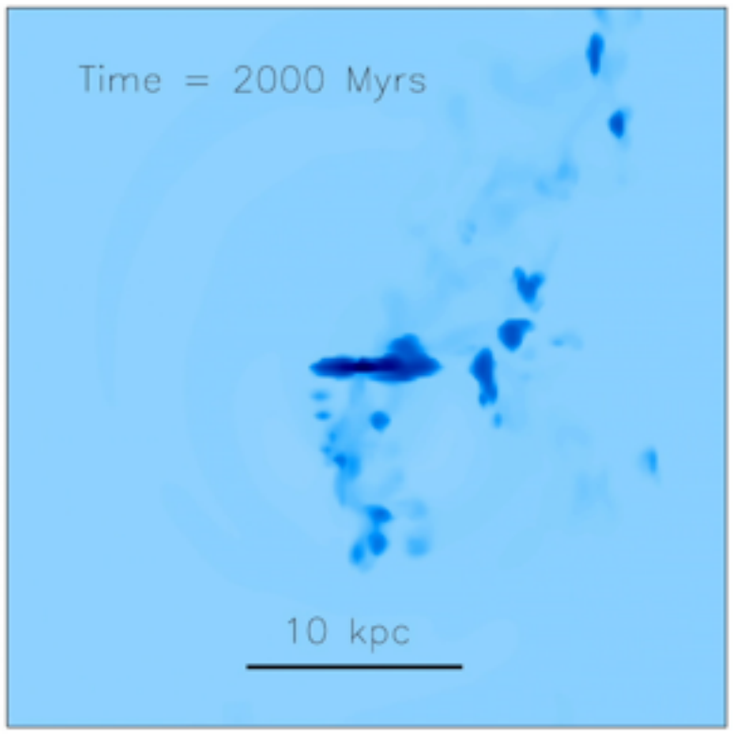
Ploeckinger et al. (in prep.)

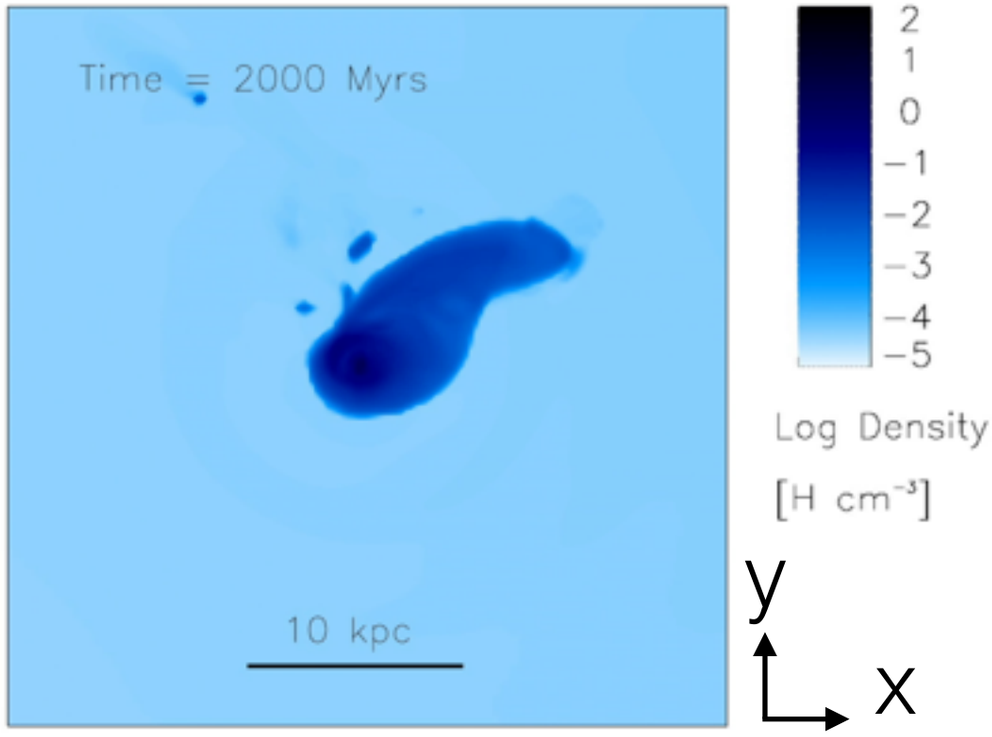
Integrated galactic IMF

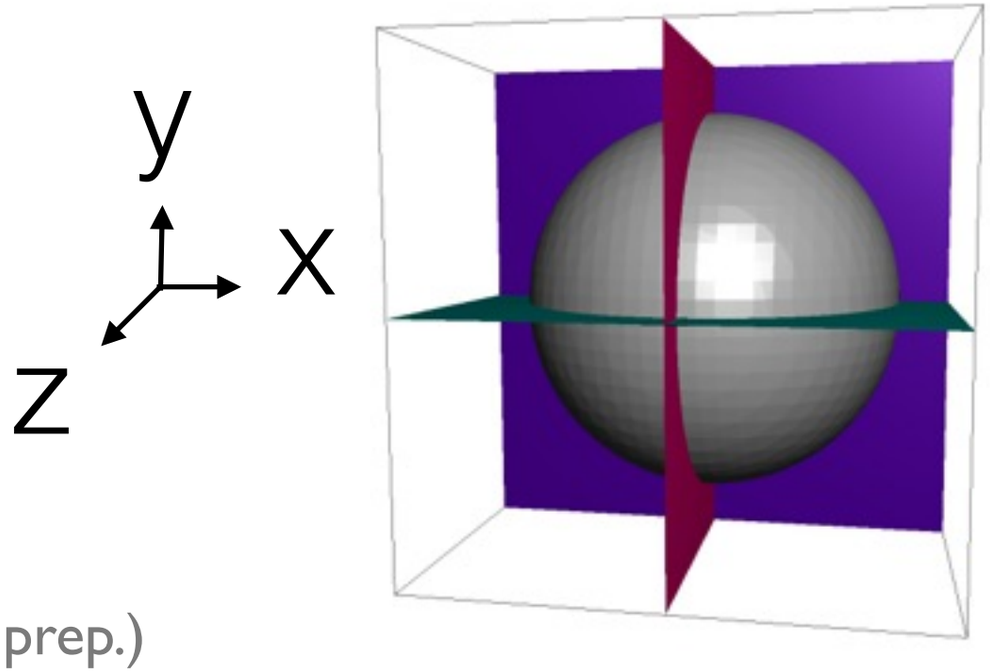


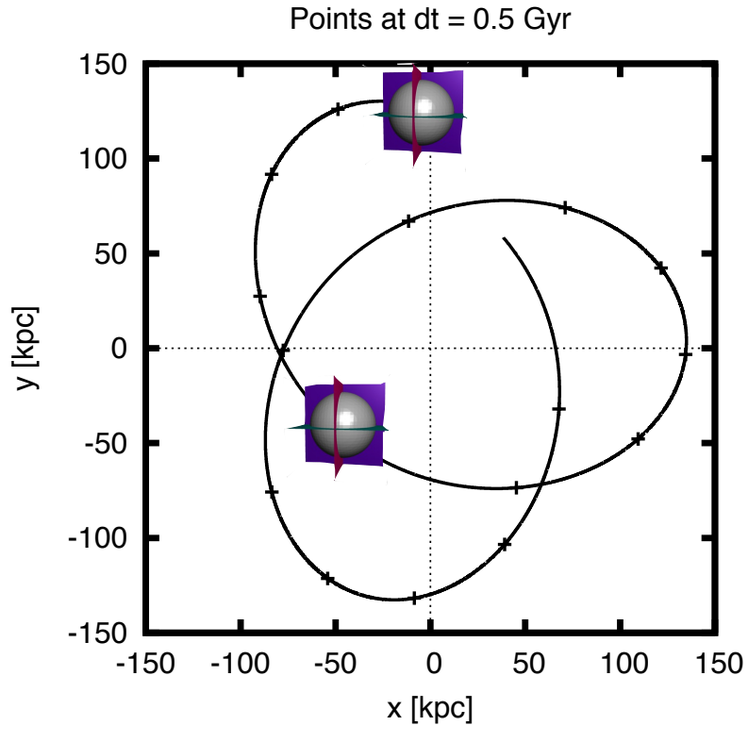
Ploeckinger et al. (2014, MNRAS)

Disk formation in TDGs



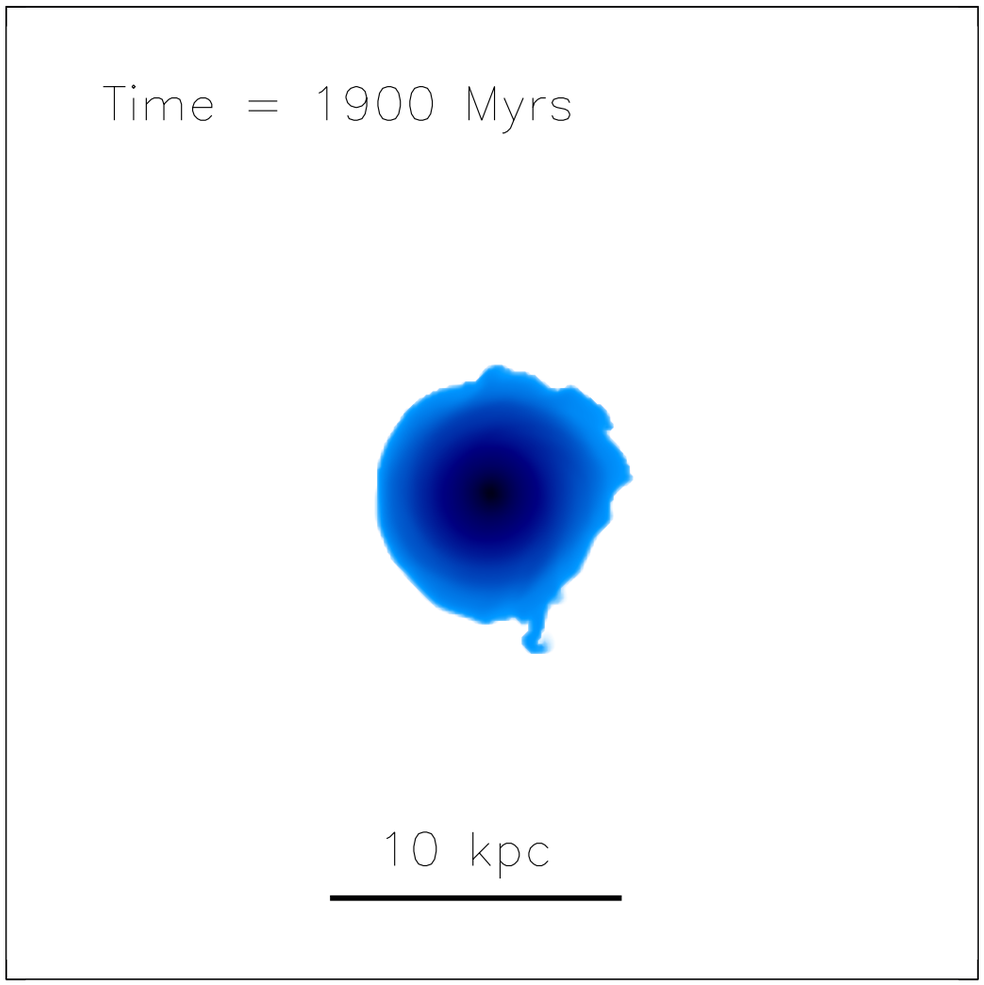


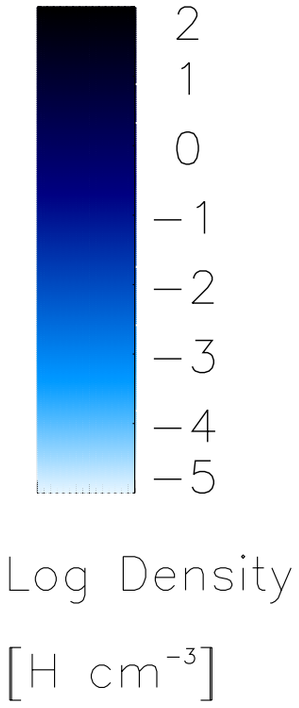




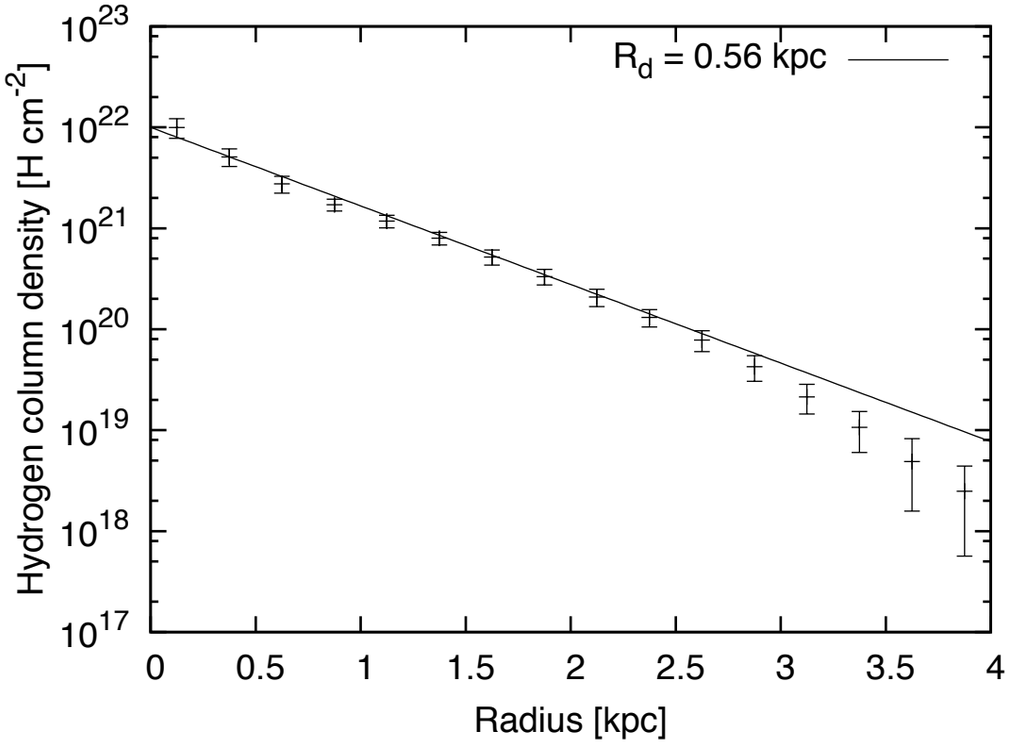
Ploeckinger et al. (in prep.)

Disk formation in TDGs



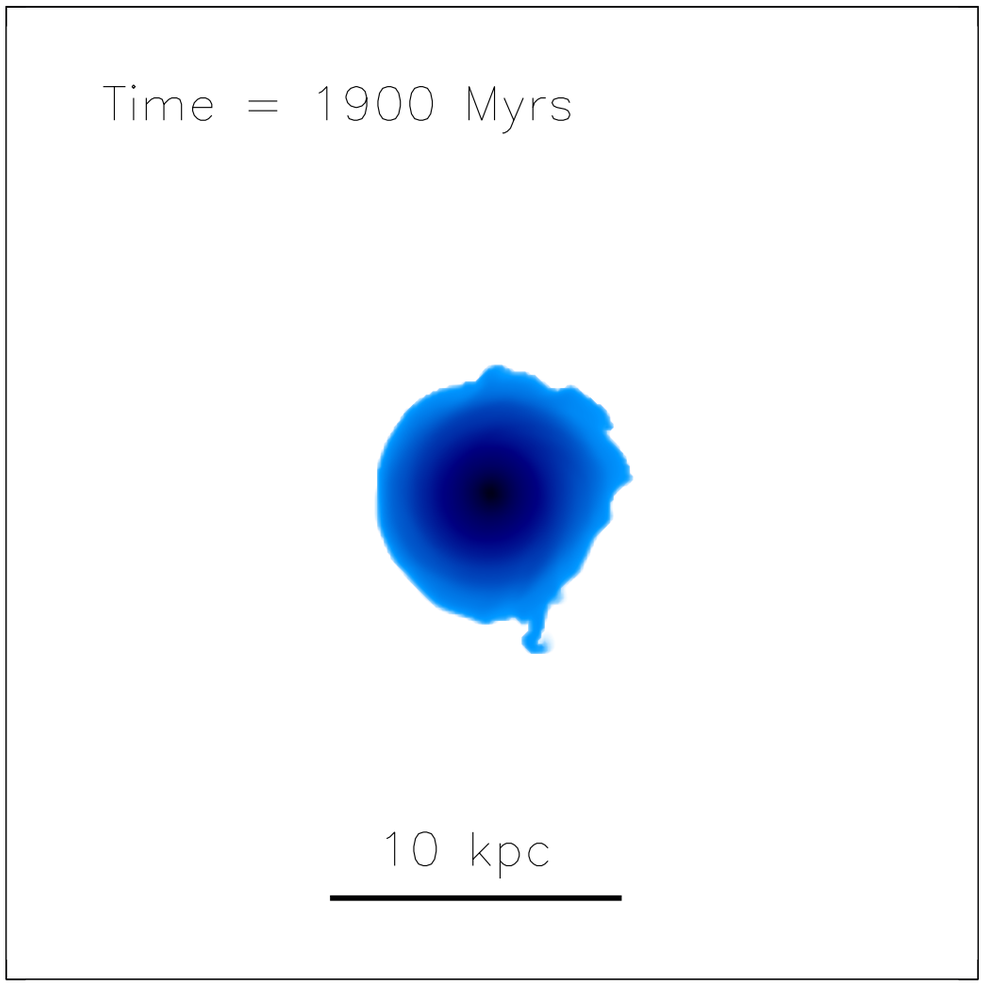


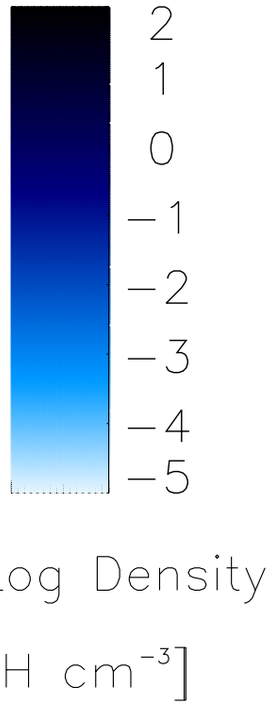
Column density

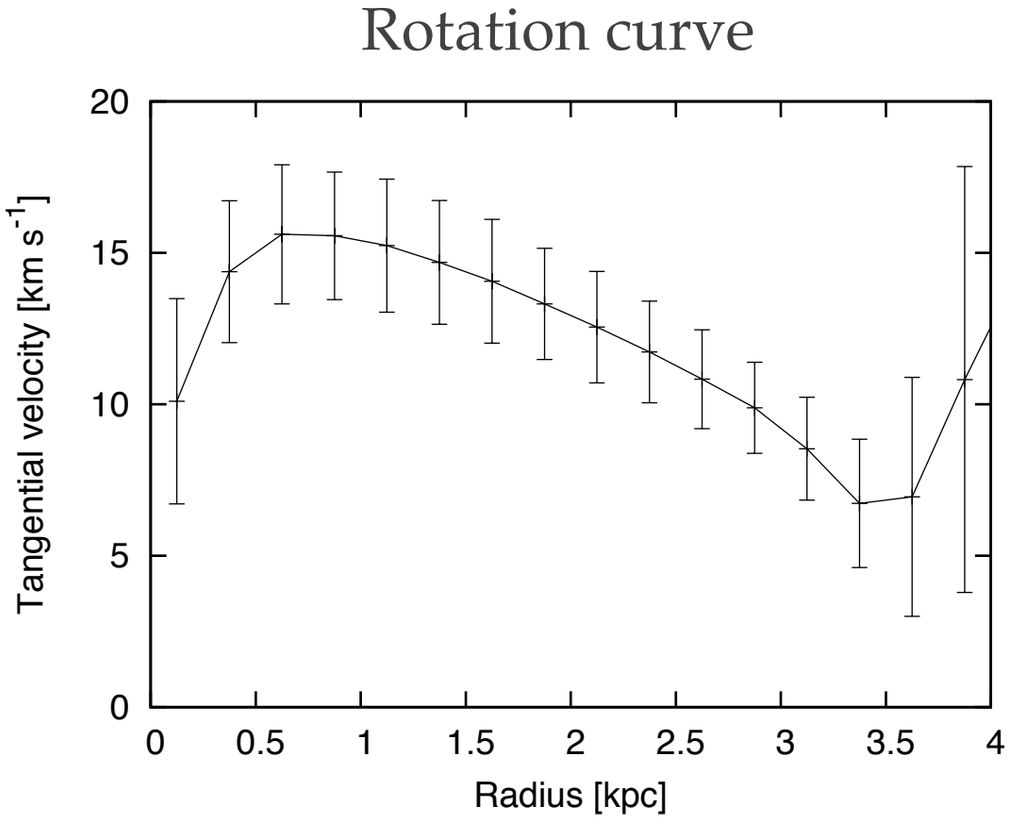


Ploeckinger et al. (in prep.)

Disk formation in TDGs

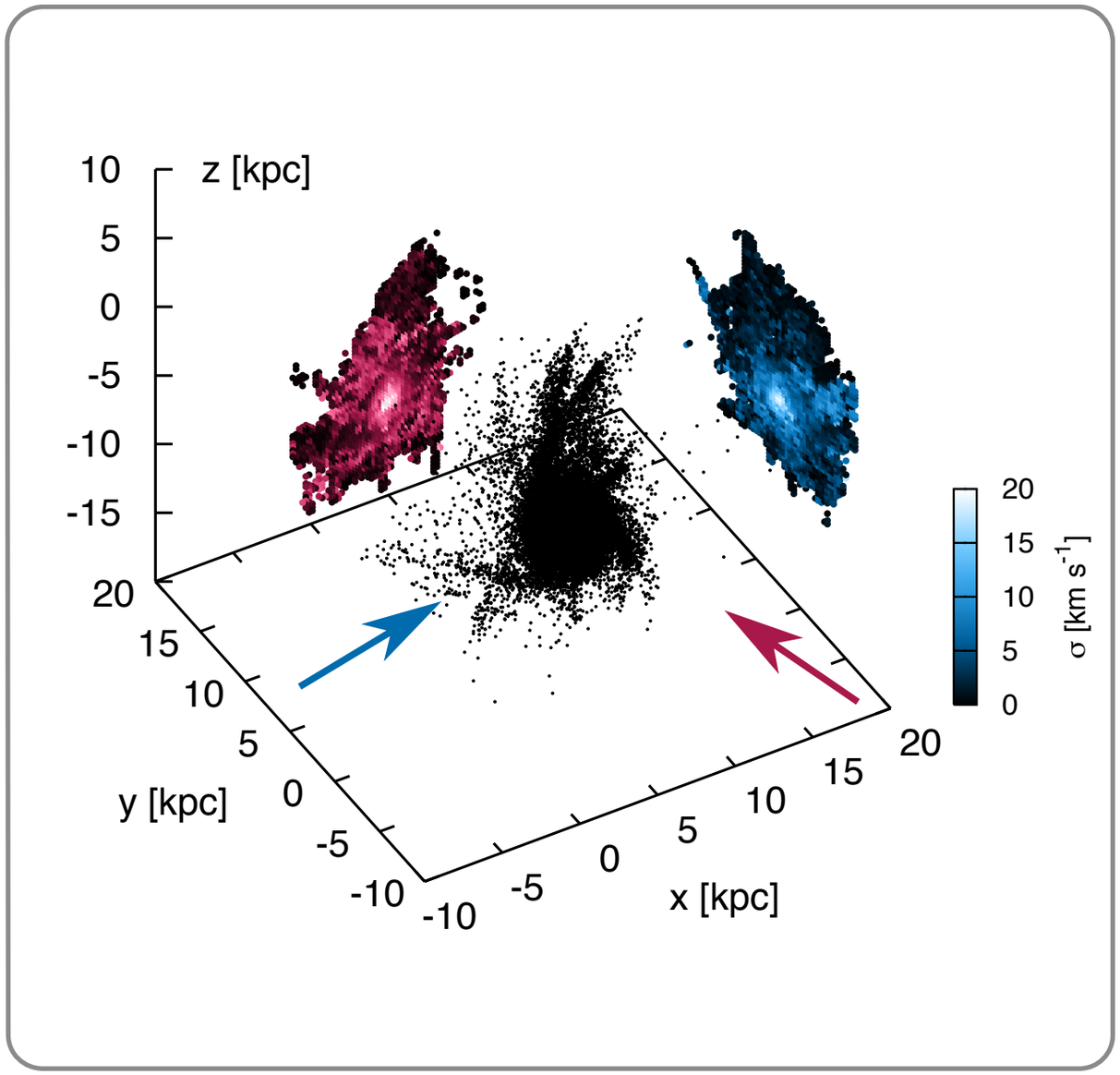






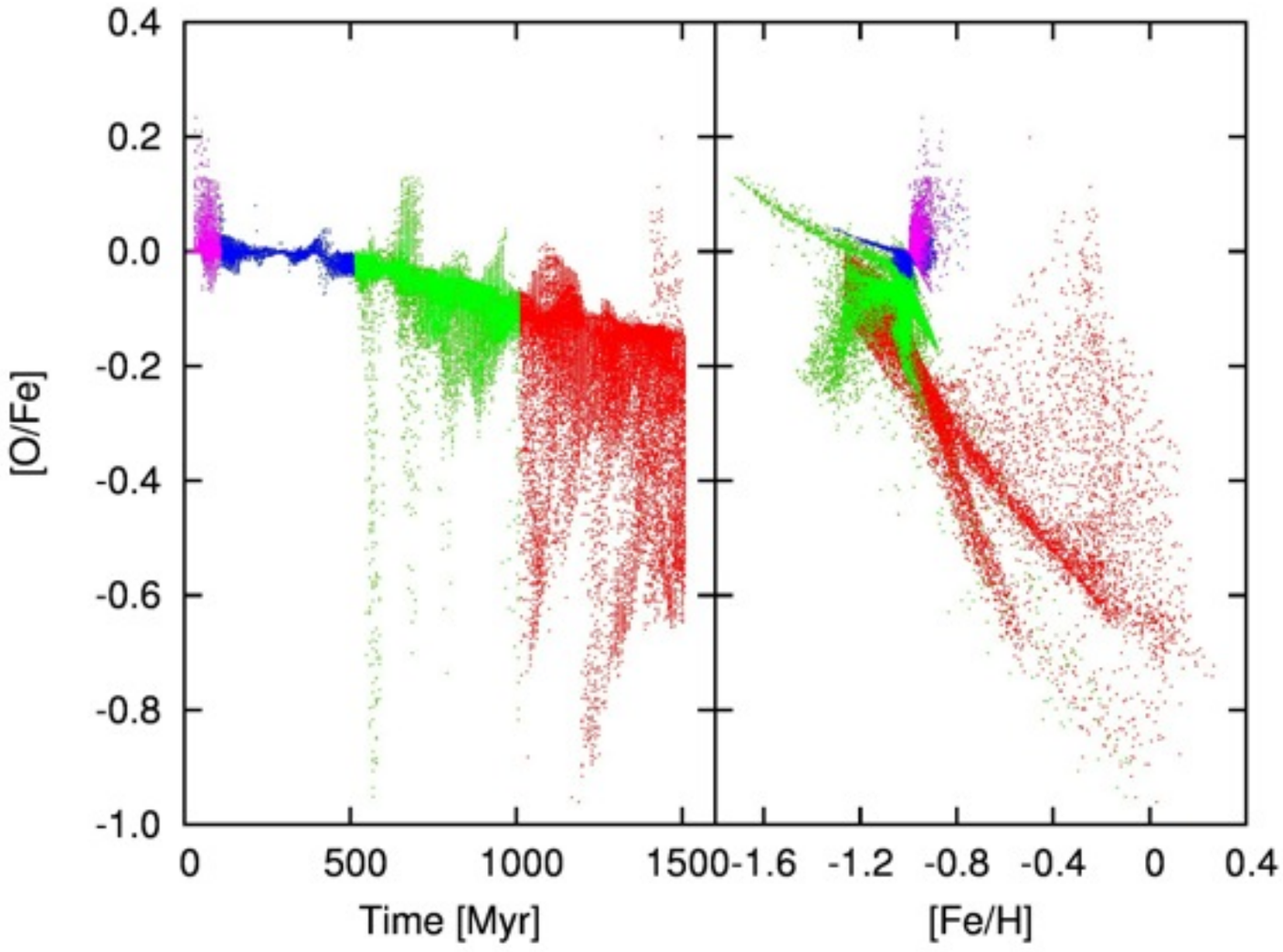
Ploeckinger et al. (in prep.)

Stellar kinematics



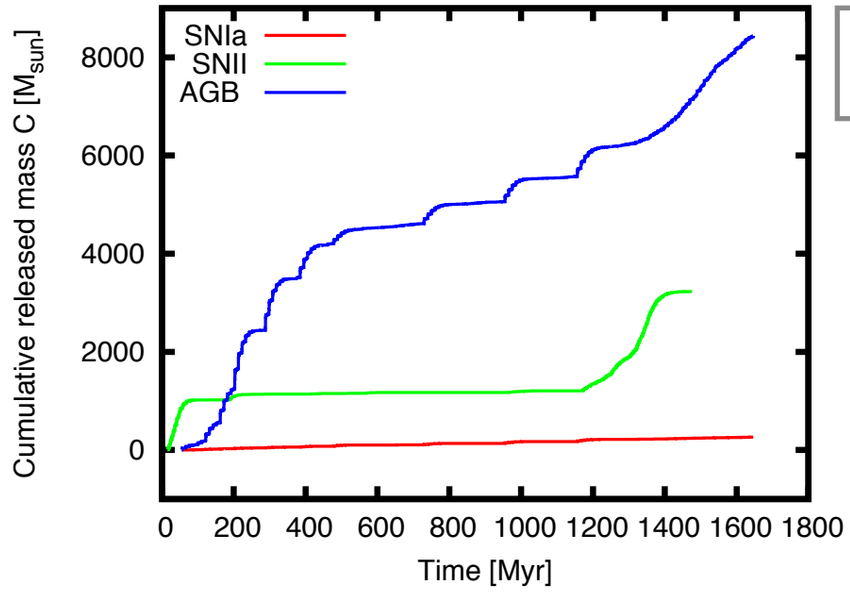
Ploeckinger et al. (in prep.)

Abundances



Ploeckinger et al. (in prep.)

C



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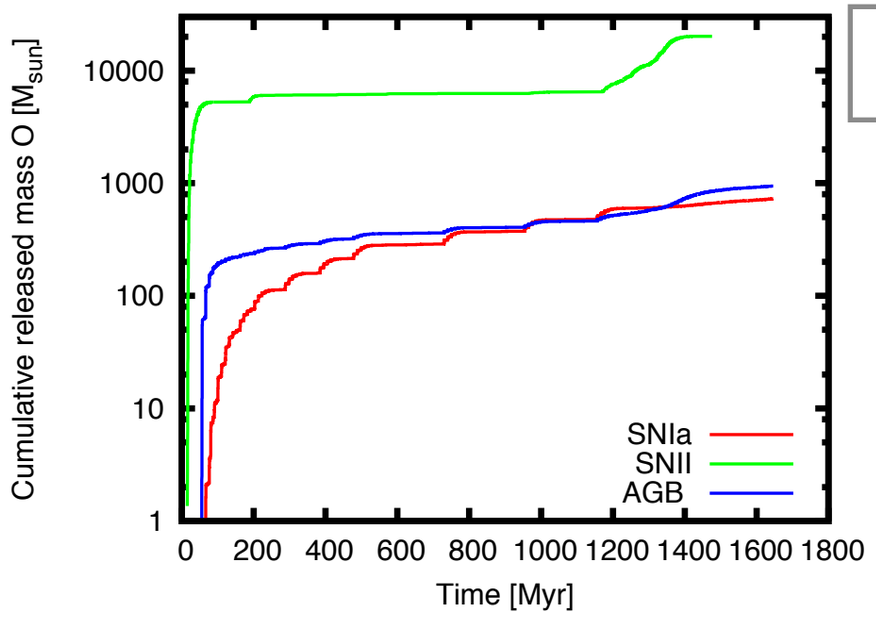

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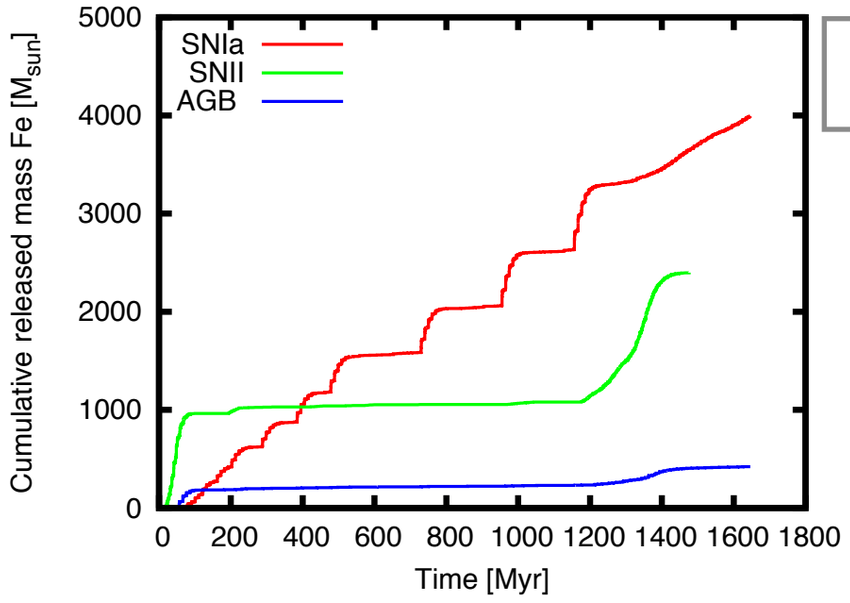
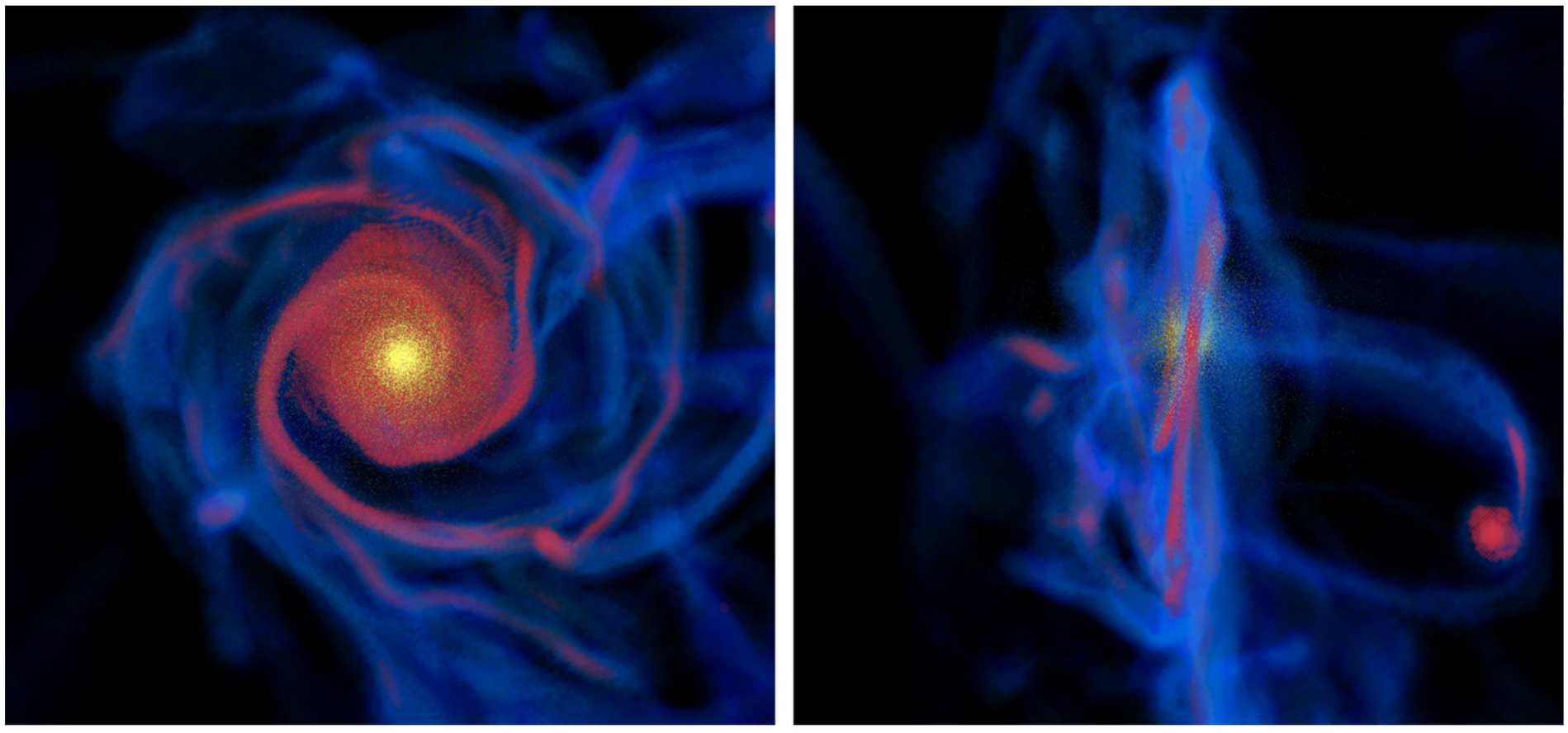


Next steps



Zemp et al. (2012)

Thank you for your attention!

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