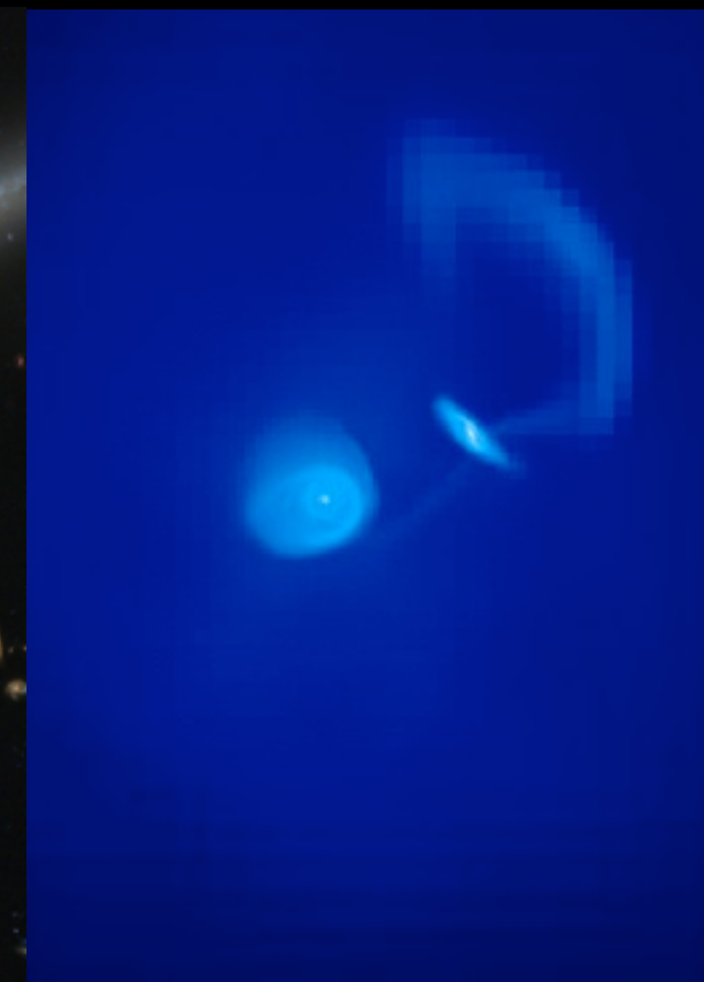
Satellite Accretion in Chemodynamical Simulations of Milky Way-like Galaxies



C. Gareth Few*

with Brad Gibson, Stéphanie Courty, Leo Michel-Dansac, Chris Brook, Greg Stinson
Romain Teyssier, Francesco Calura, Daisuke Kawata
Tomás Ruiz-Lara, Isa Perez,
Ivan Minchev, Patricia Sánchez-Blázquez, Estrella Florido.

UNIVERSITY OF EXETER

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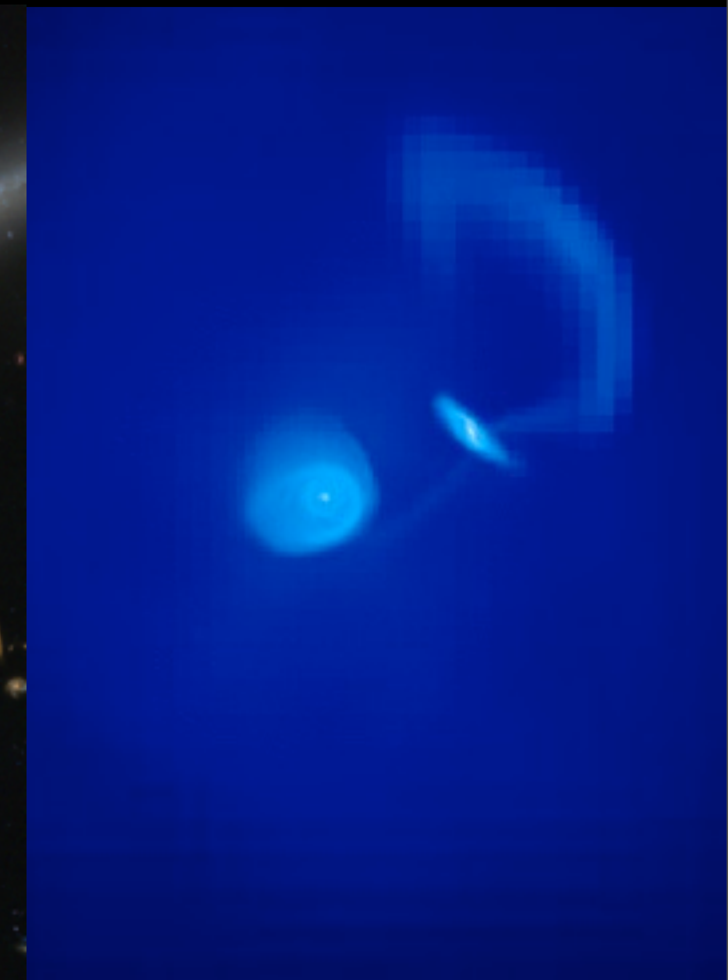

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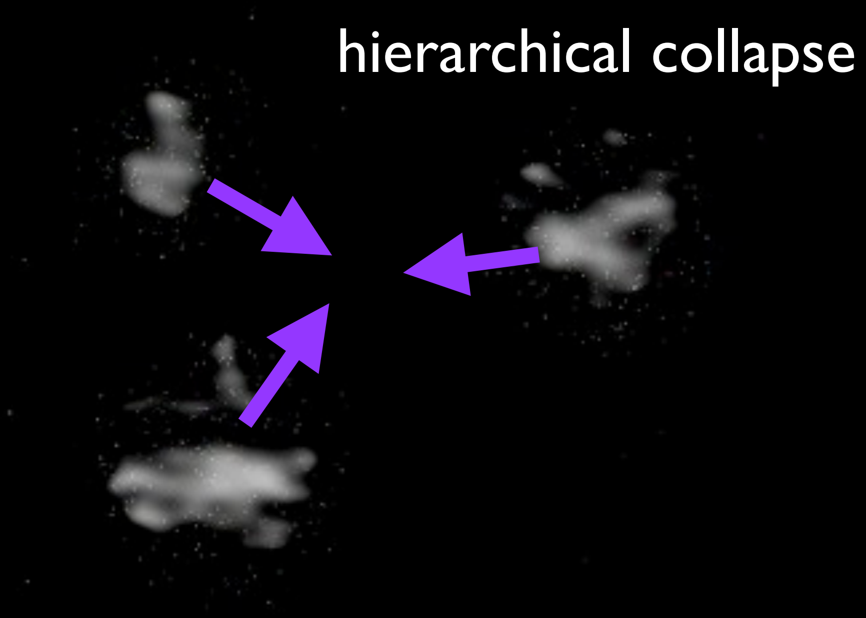
The plan...

- ✦ Introduction to galaxy assembly
- ✦ Building a galaxy in a (super)computer
- ✦ Disk profile breaks and the age distribution
- ✦ Satellite accretion
- ✦ Chemical evolution: relics of galaxy assembly

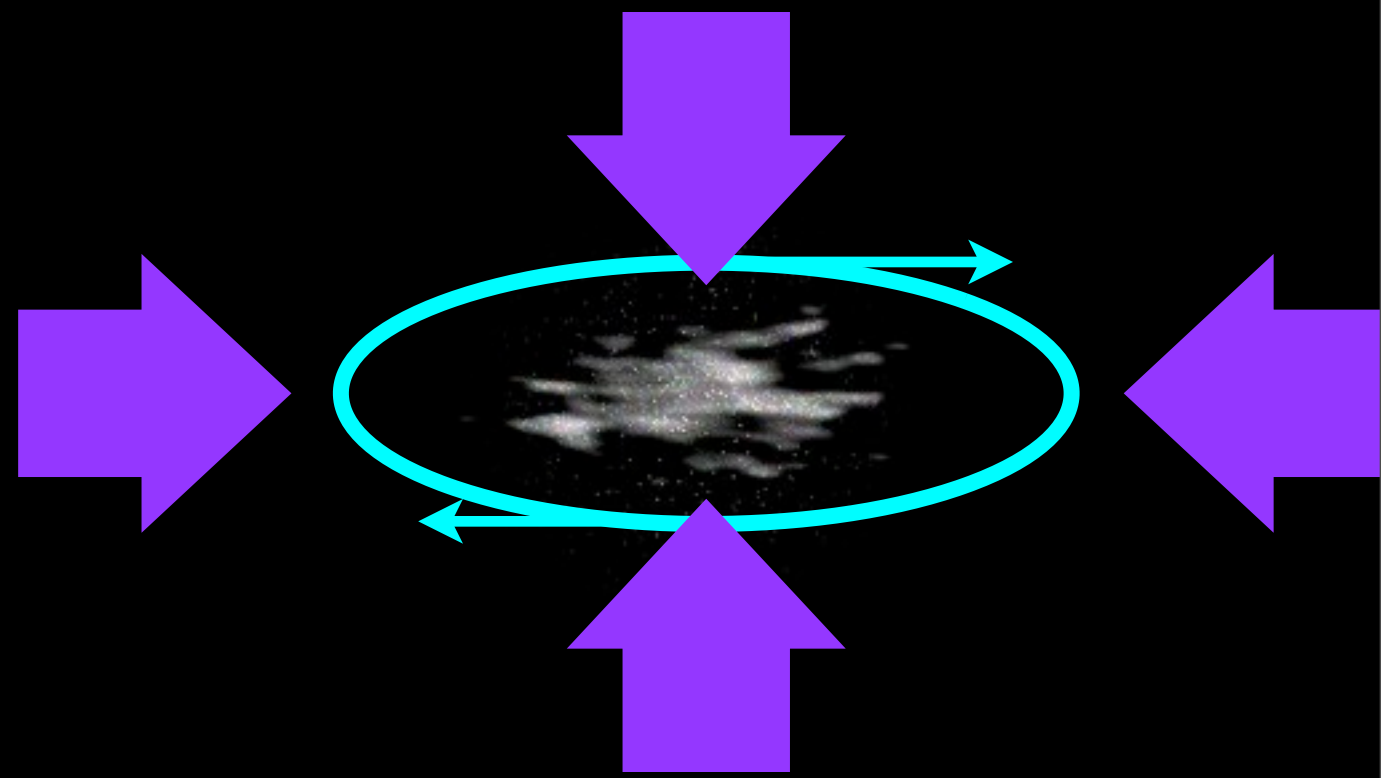
Basic galaxy formation - inside out



Basic galaxy formation - inside out

hierarchical collapse

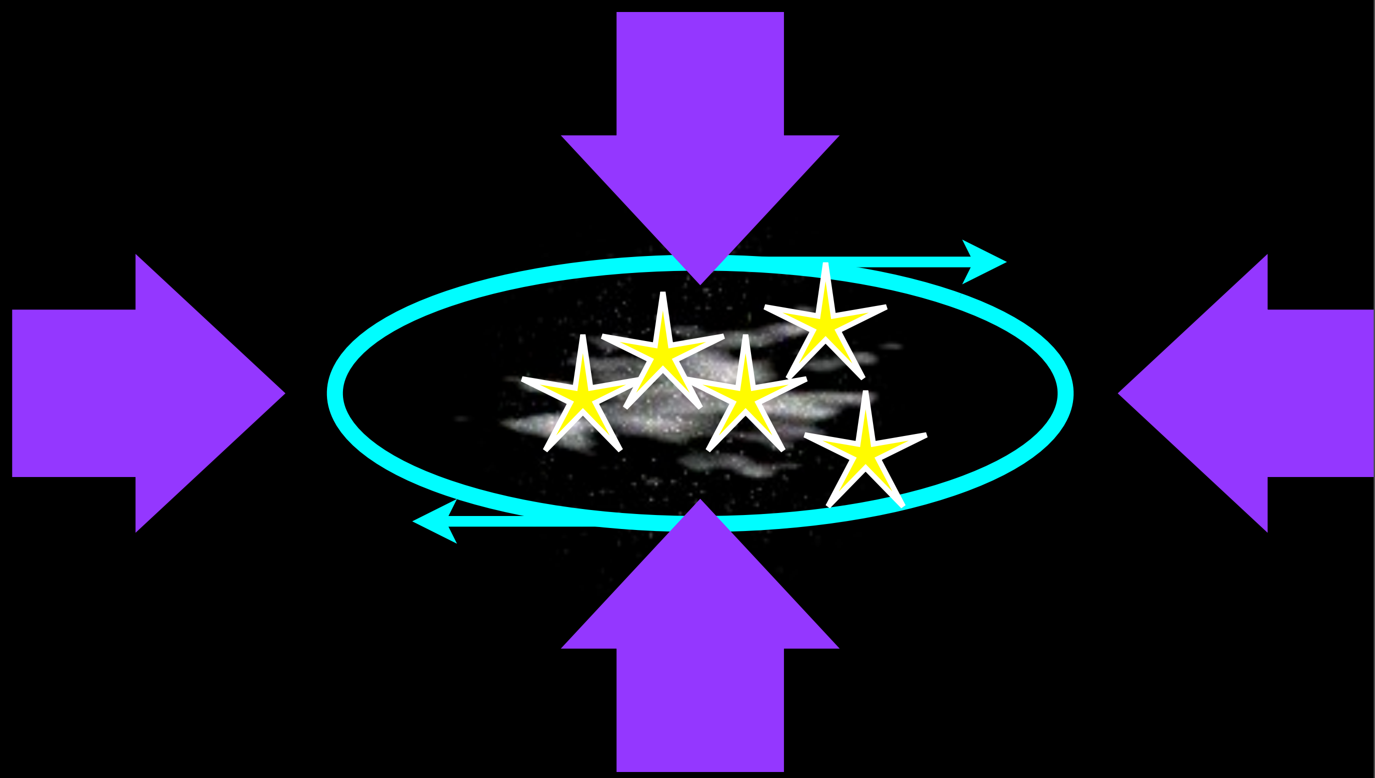
rotation speeds up,
continued gas accretion



Basic galaxy formation - inside out

hierarchical collapse

rotation speeds up,
continued gas accretion &
star formation



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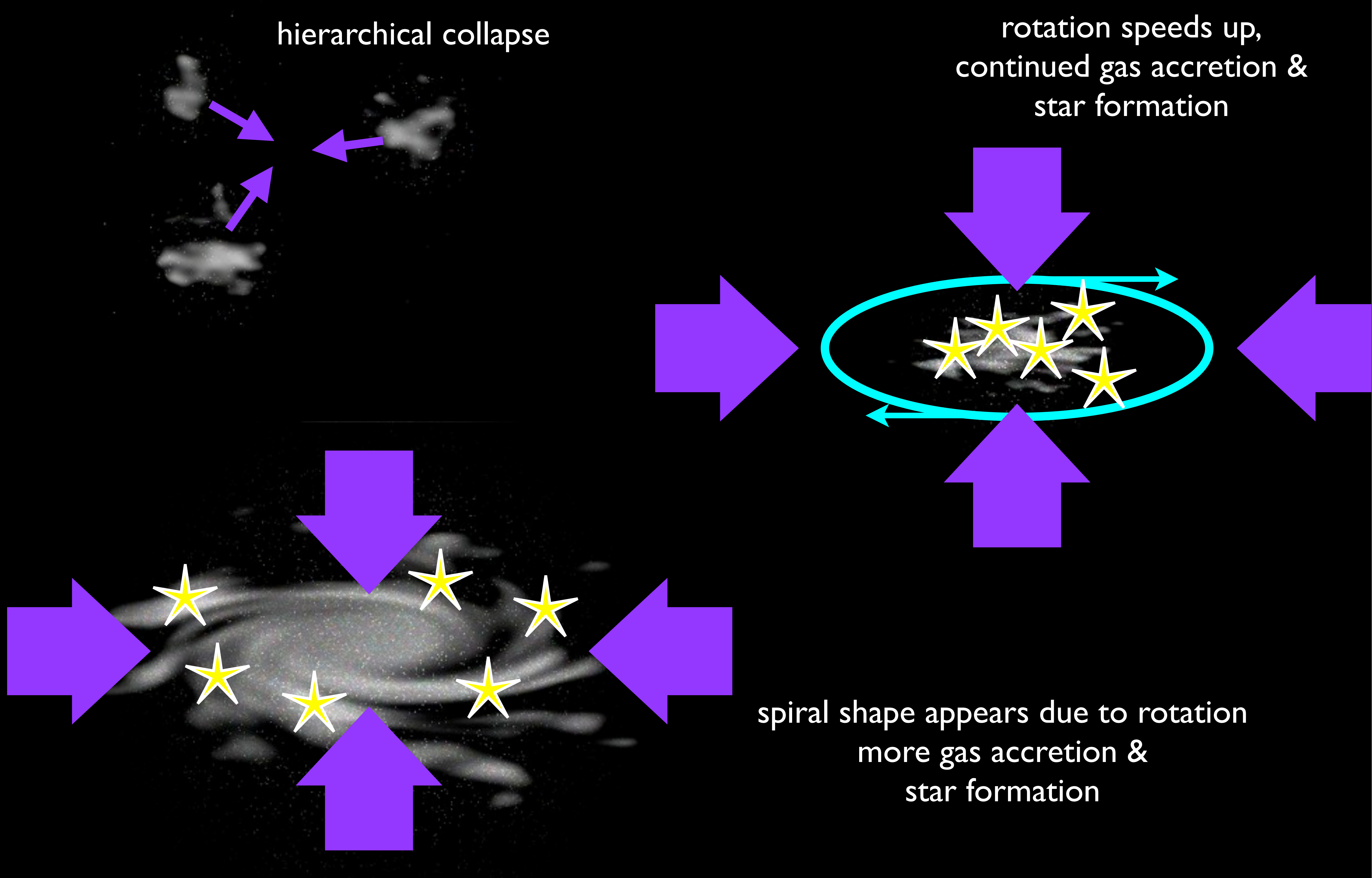

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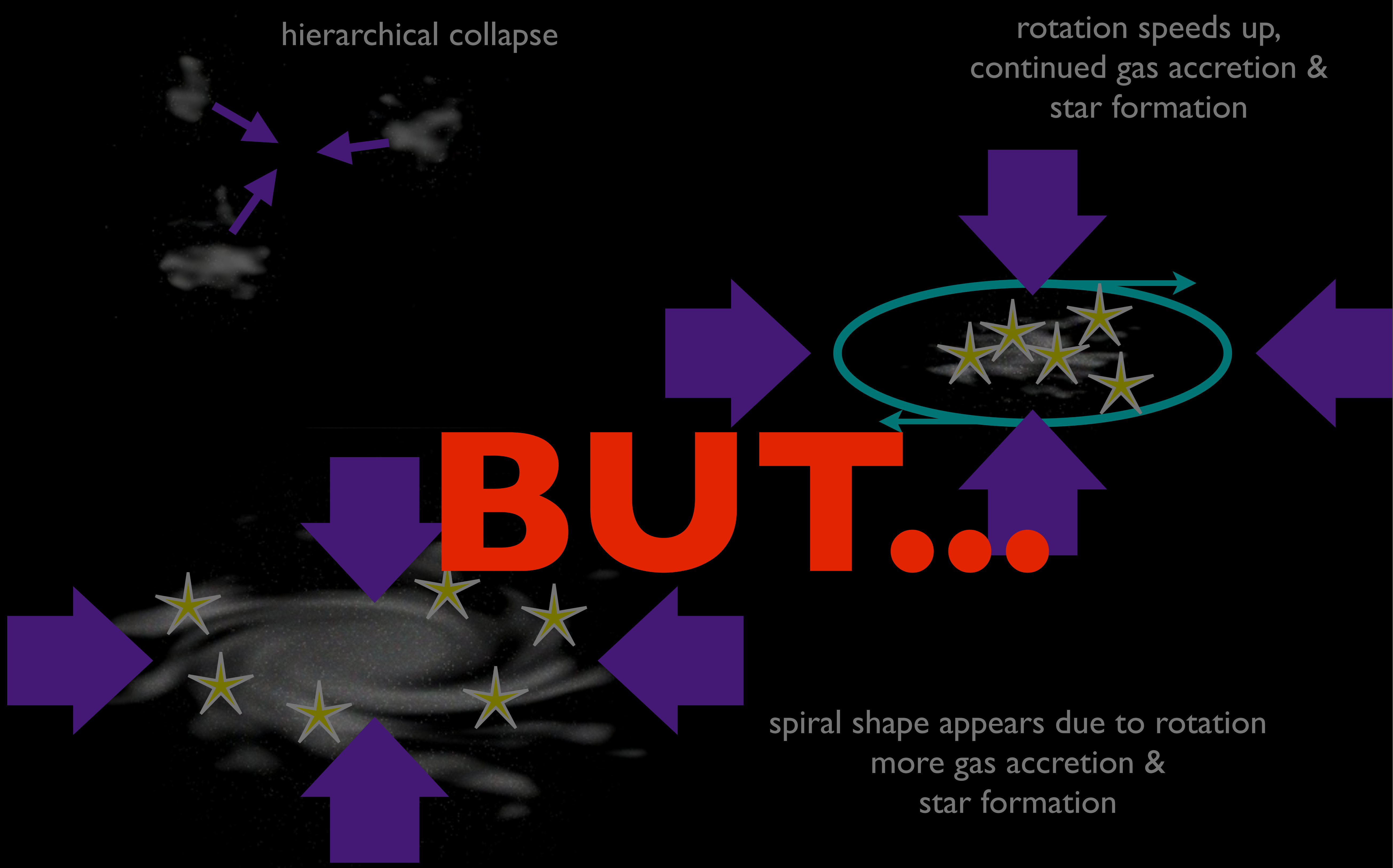
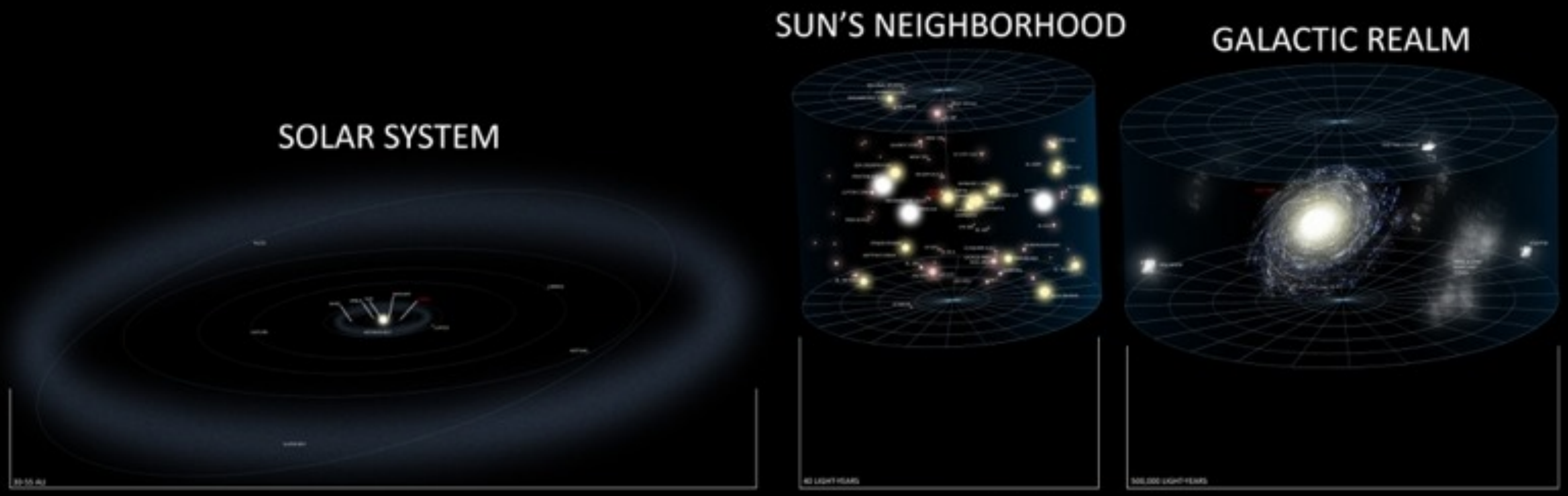


Cosmological galaxy formation



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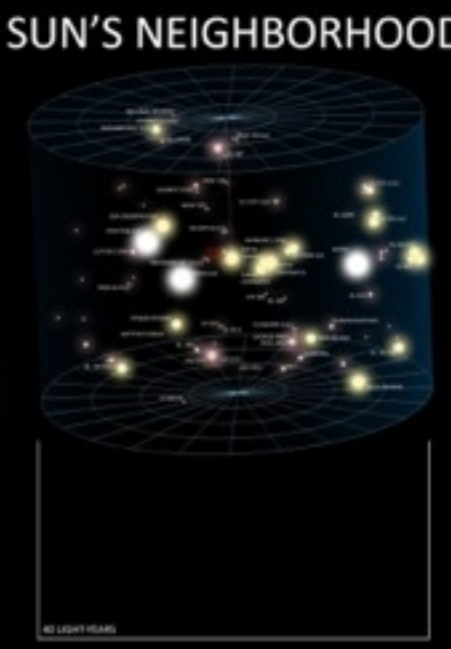

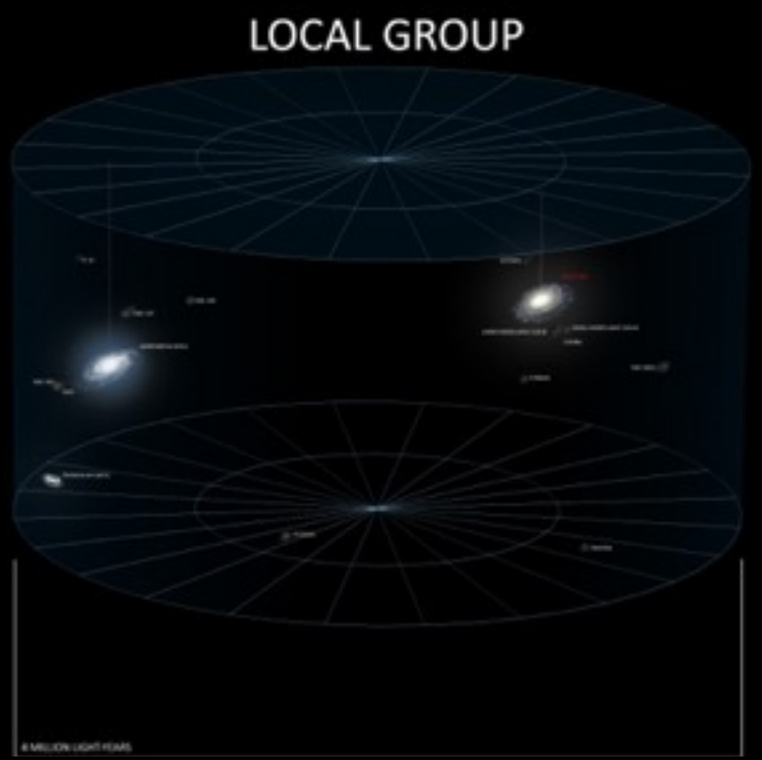

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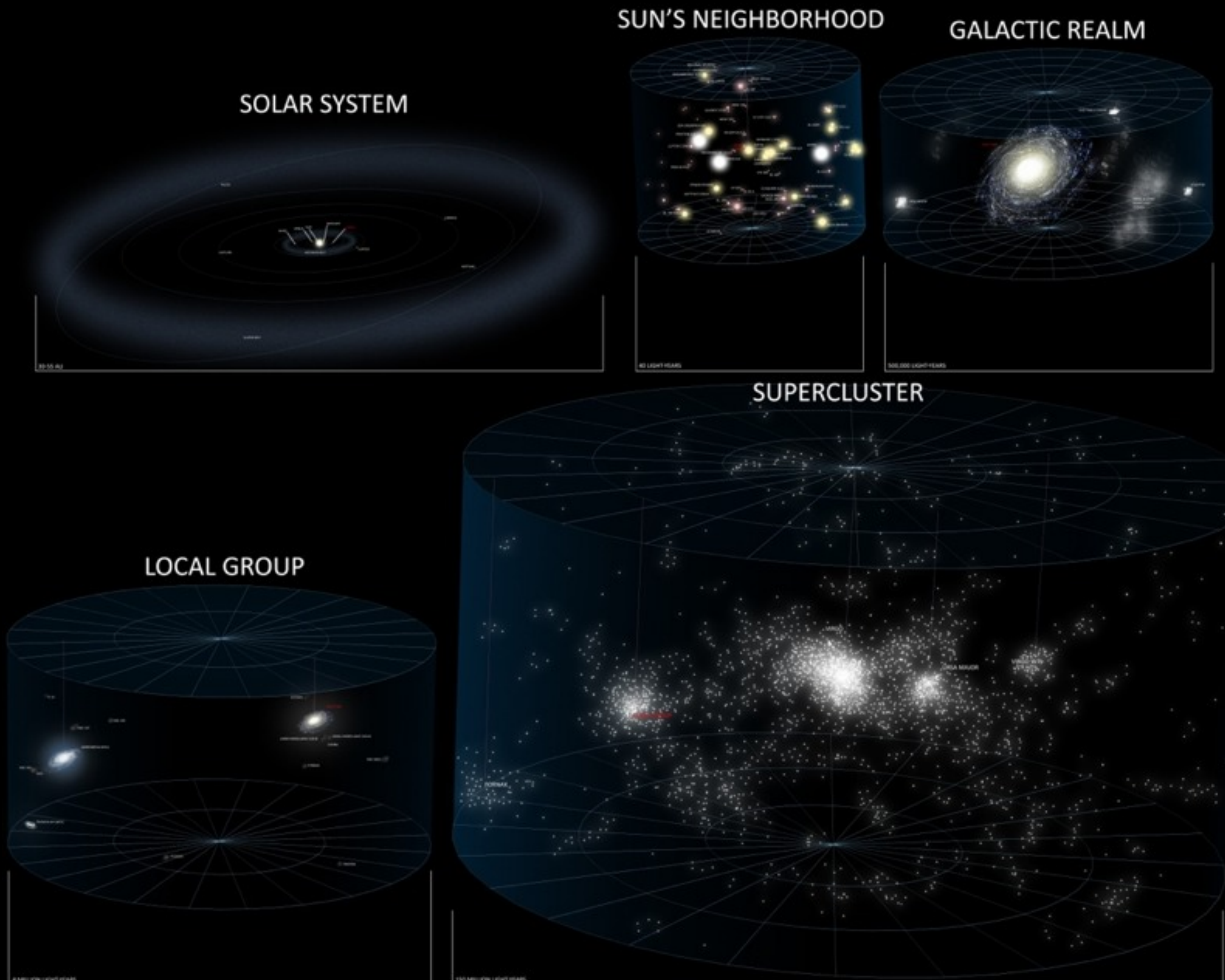
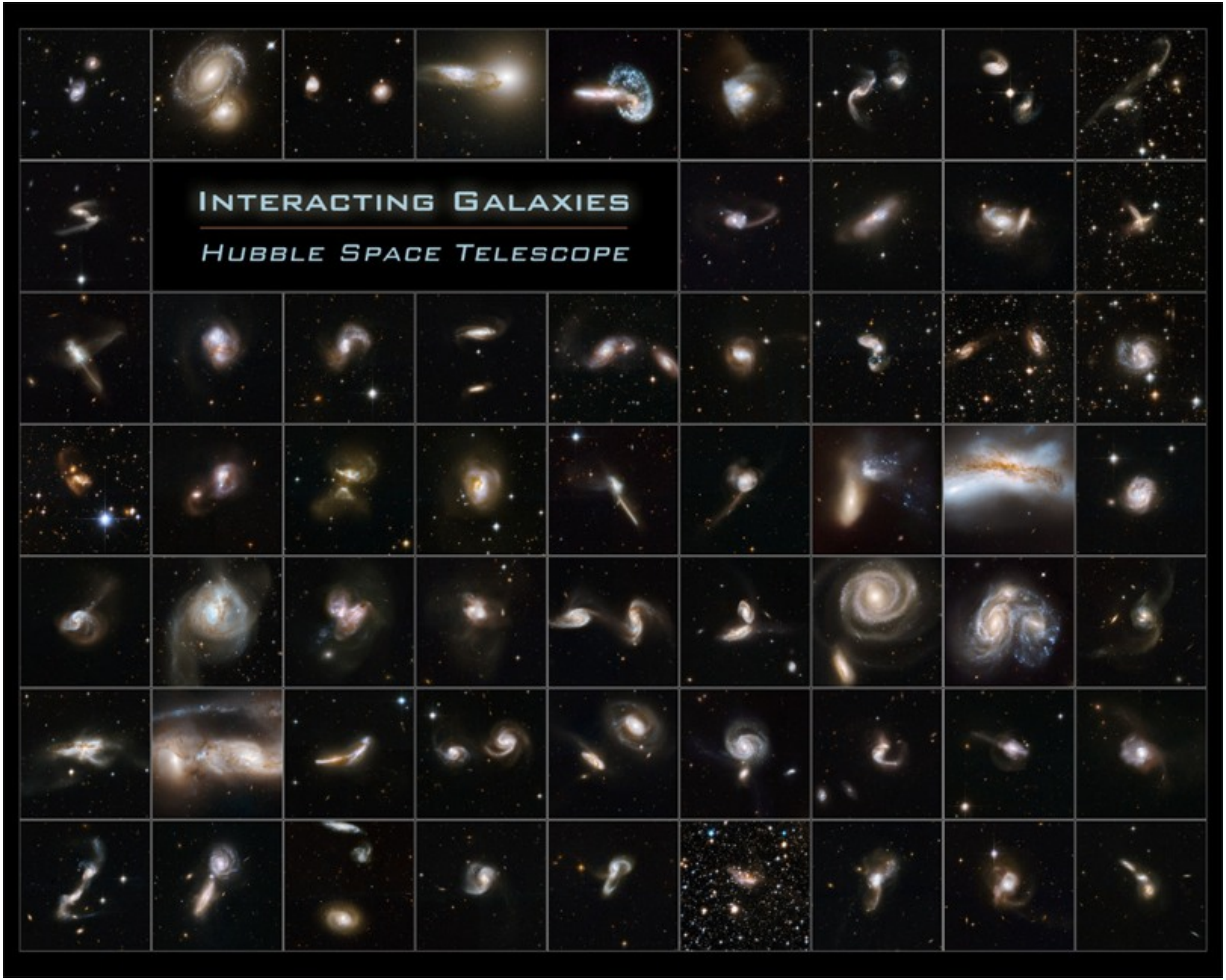
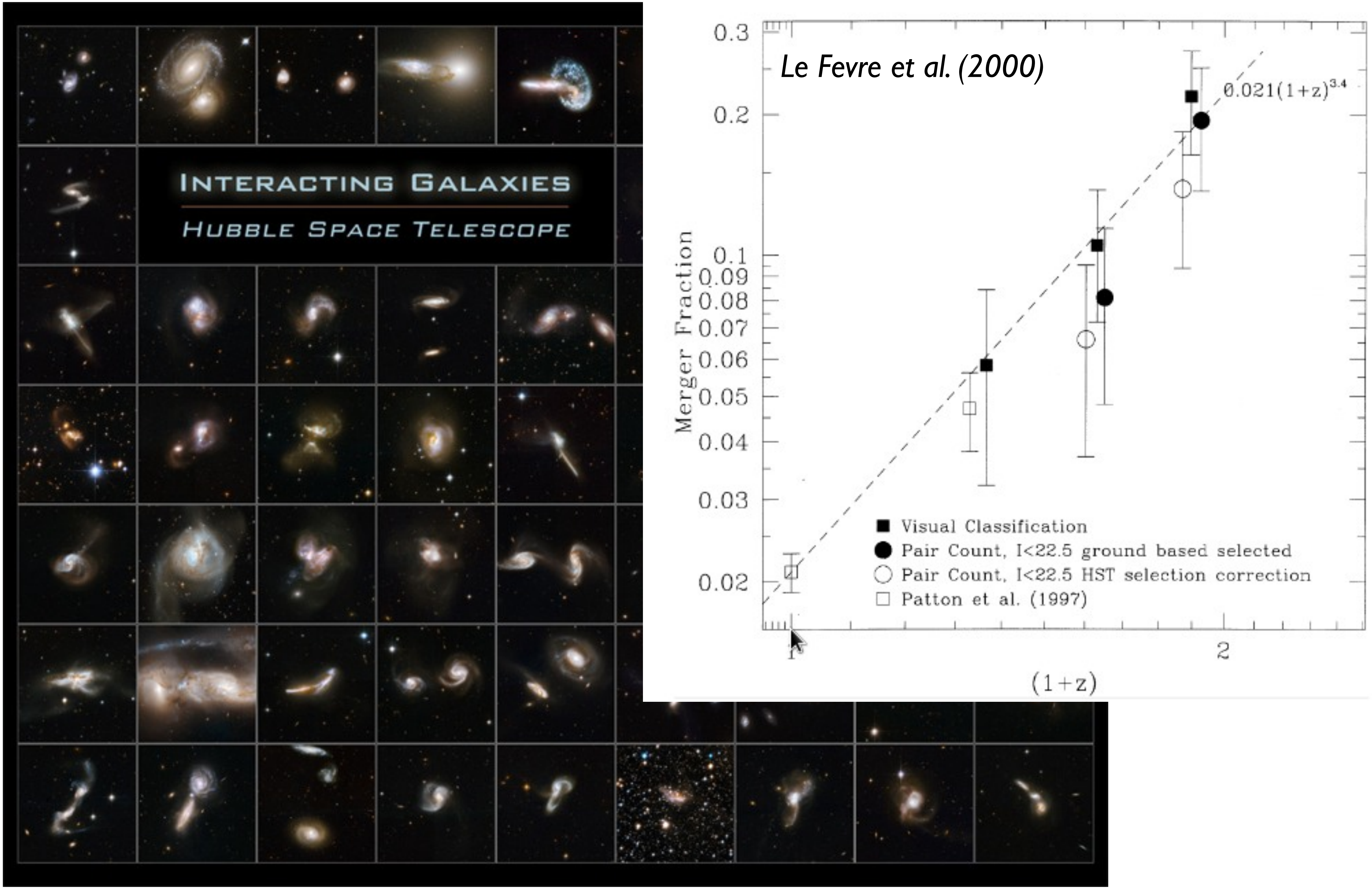


Mergers/accretion

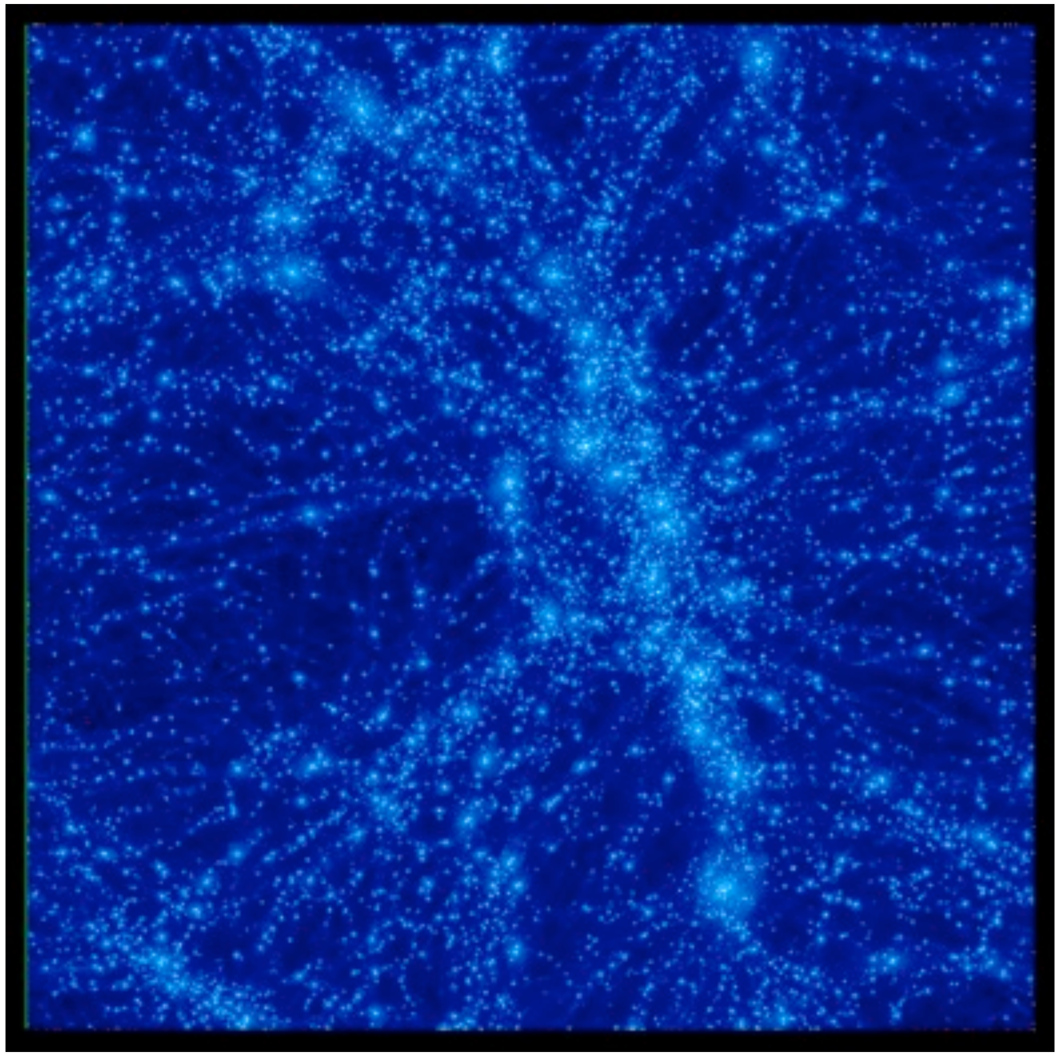


Minor mergers are several times more frequent and can contribute the build of a galaxy's mass (Lotz et al., 2011; Kaviraj, 2014)

Mergers/accretion



Cosmological context...



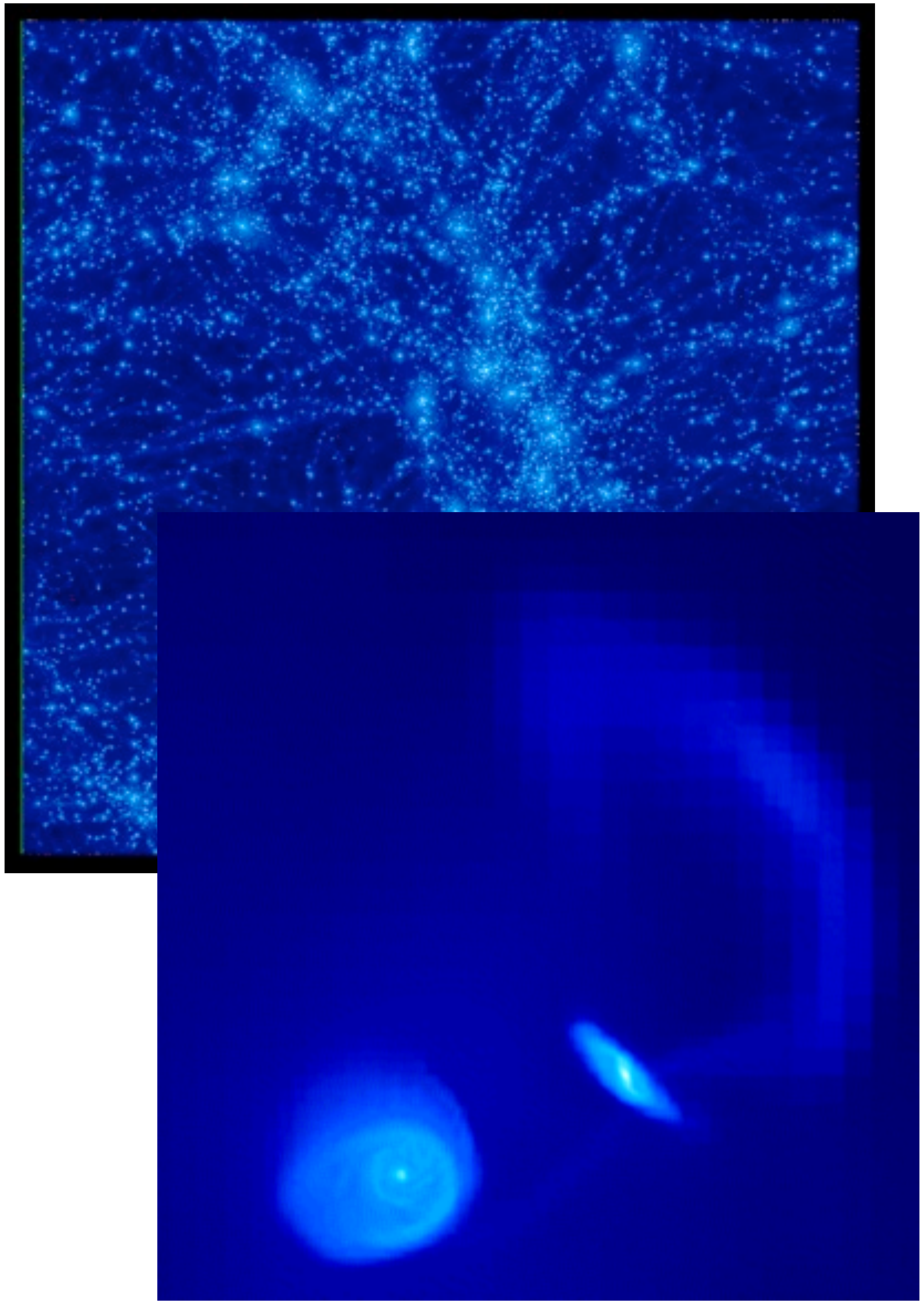
- Dark matter: gravitational potential

$$\frac{d\mathbf{r}_i}{dt} = \mathbf{v}_i$$

$$\frac{d\mathbf{v}_i}{dt} = -\nabla\Phi$$

$$\nabla^2\Phi = 4\pi G\rho$$

Cosmological context...



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$$\frac{\partial\rho_\mathrm{g}}{\partial t} + \nabla\cdot(\rho_\mathrm{g}\mathbf{u}) = 0$$

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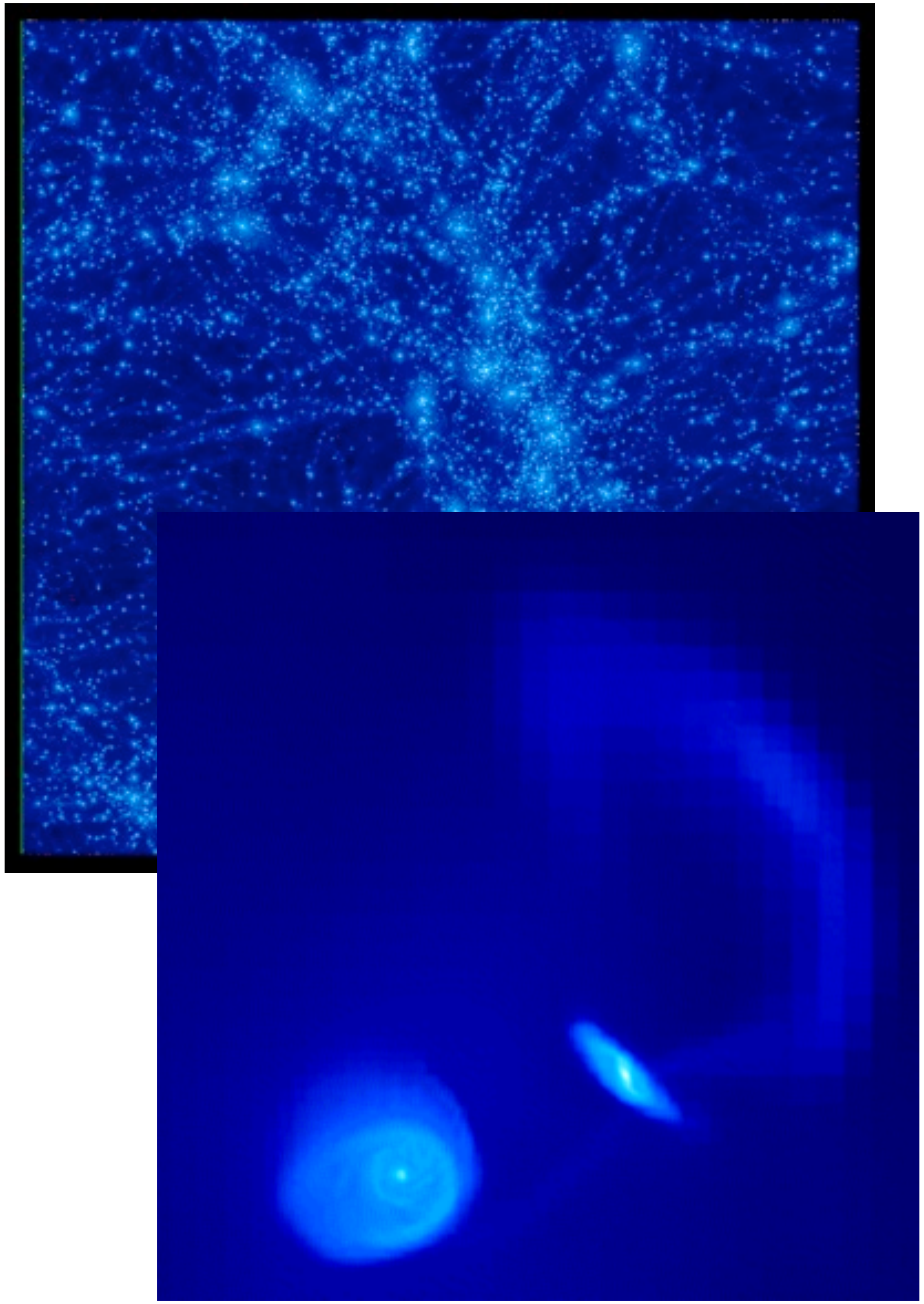
$$\frac{\partial\epsilon}{\partial t} + \mathbf{u}\cdot\nabla\epsilon + \frac{p}{\rho}\nabla\cdot\mathbf{u} = \frac{\Gamma-\Lambda}{\rho}$$

$$p = \rho\epsilon(\gamma-1)$$

Cosmological context...



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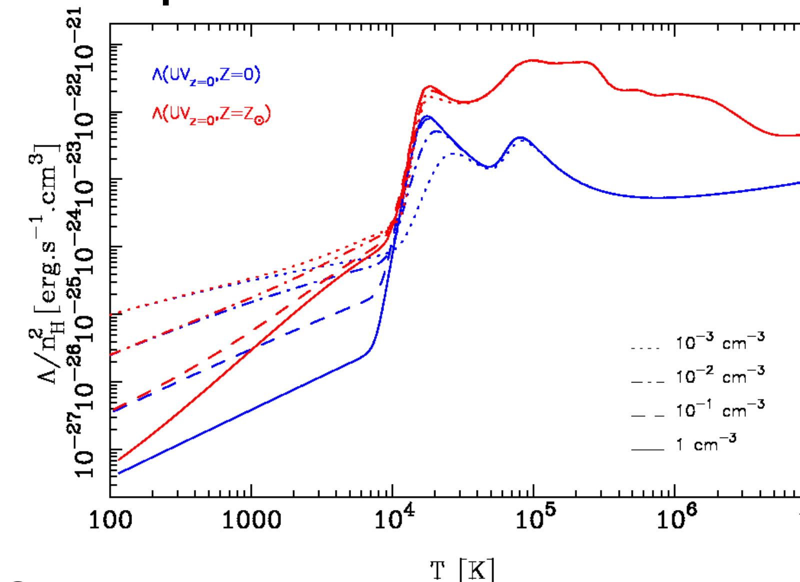

- Gas: gravity + hydrodynamics

Ferland et al. (1998)
Haardt & Madau (1996)
Rosen & Bregman (1995)

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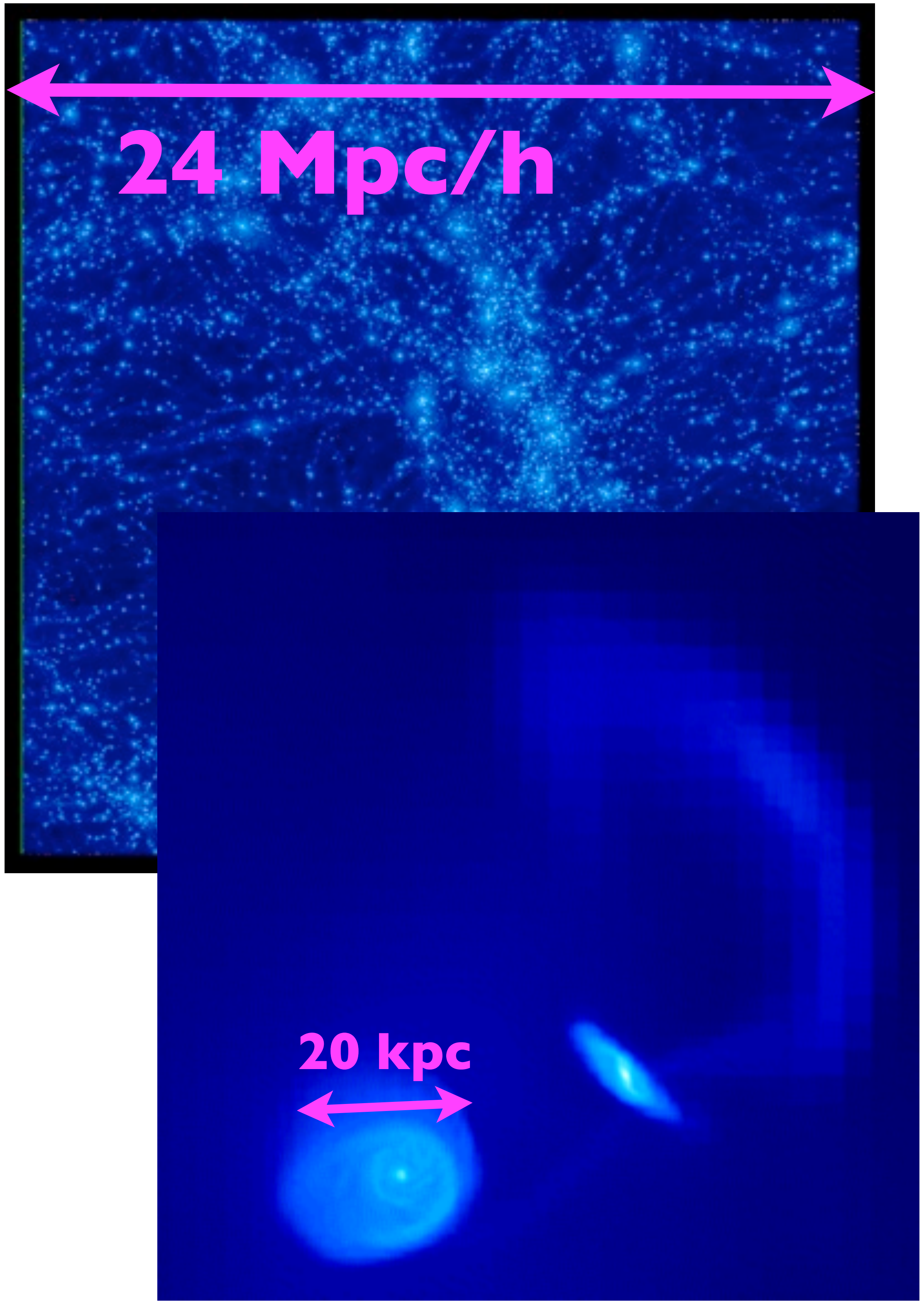
Cosmological context... ...with 'small' scale physics



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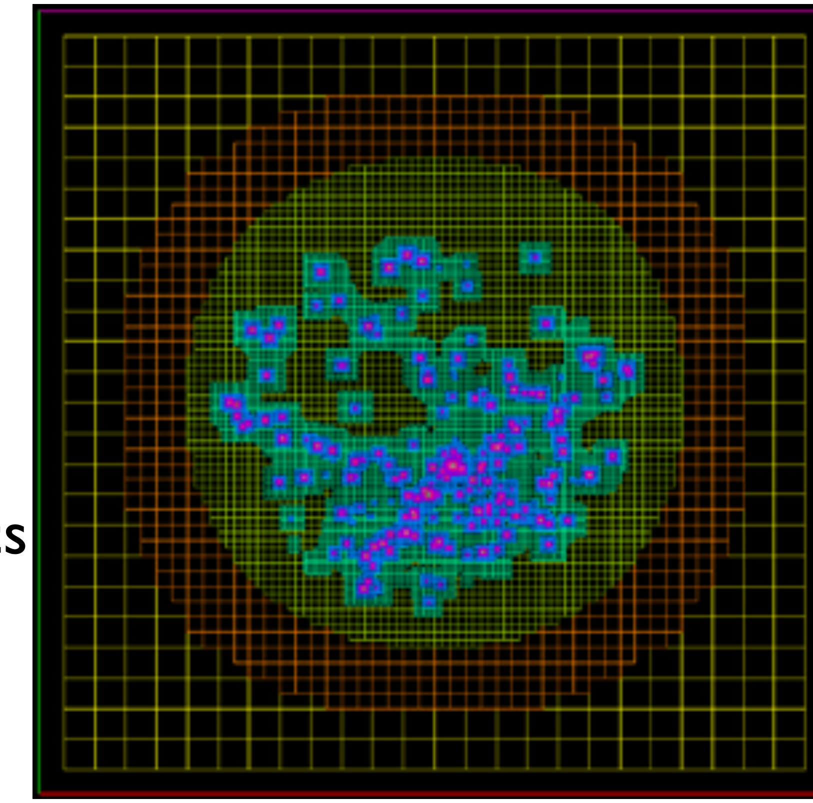

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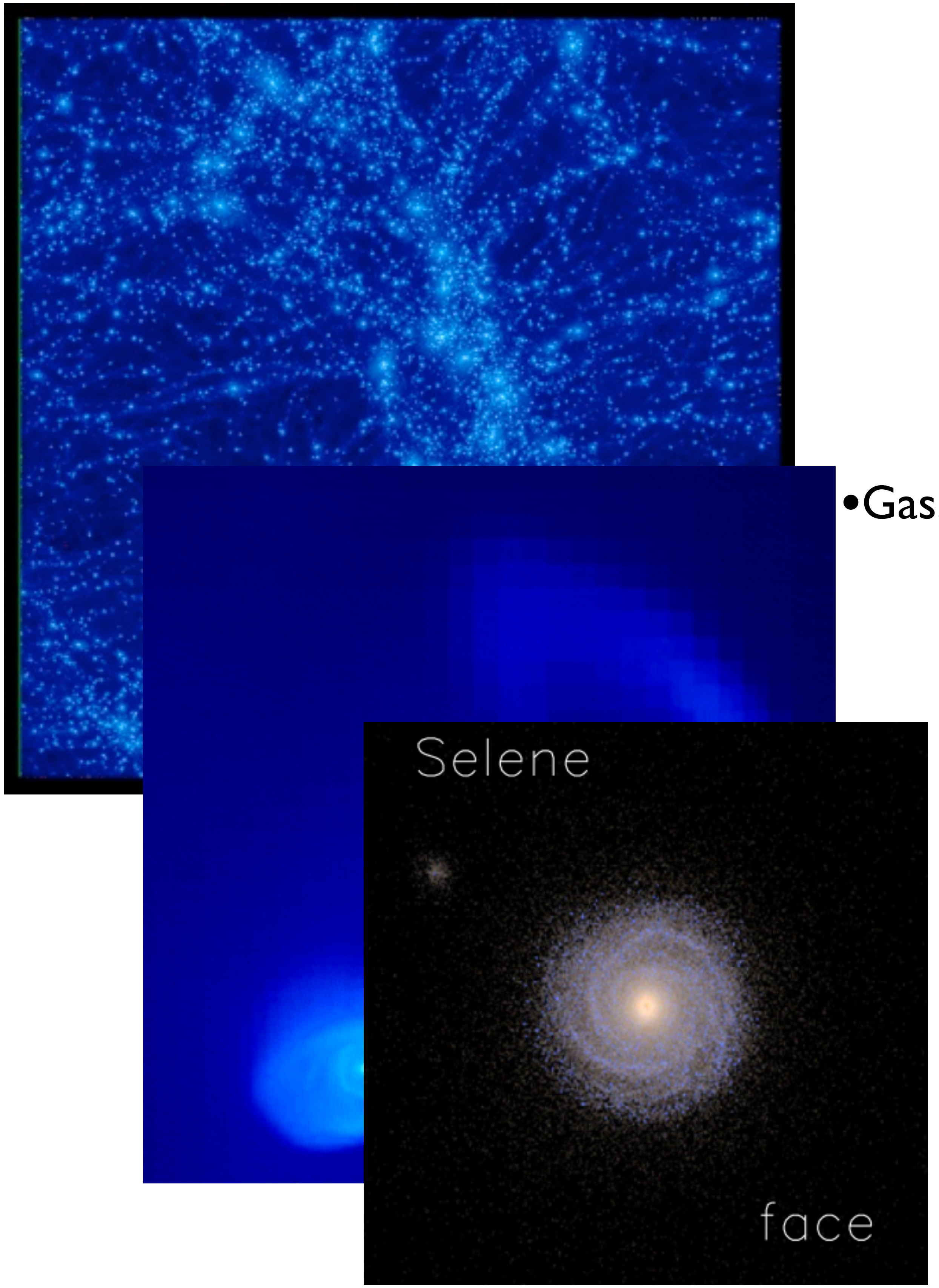
- Adaptive grid allows large and small scales together

Cosmological context... ...with ‘small’ scale physics



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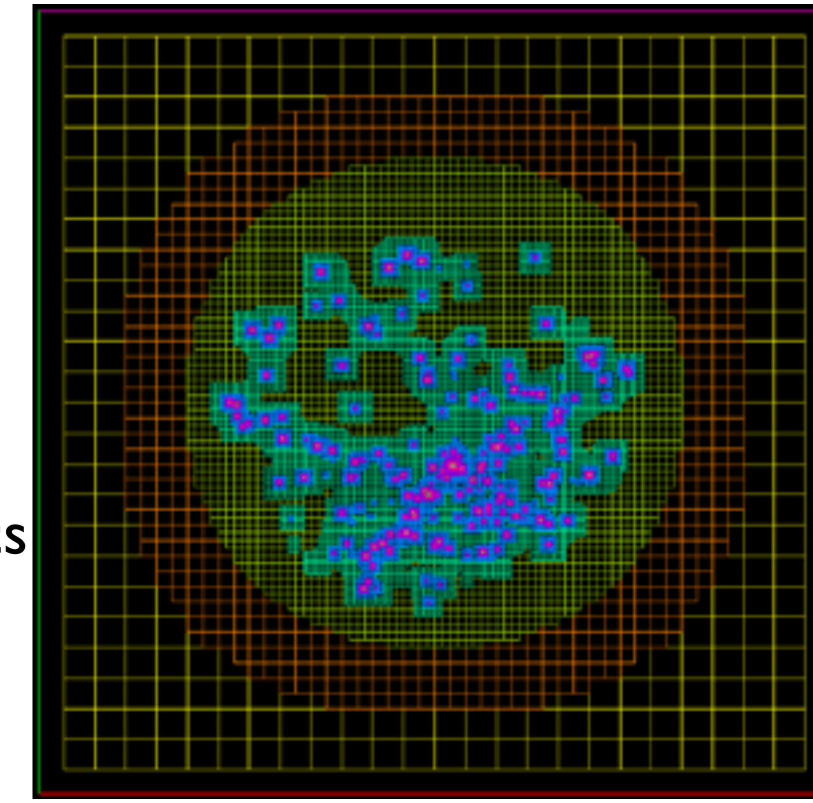

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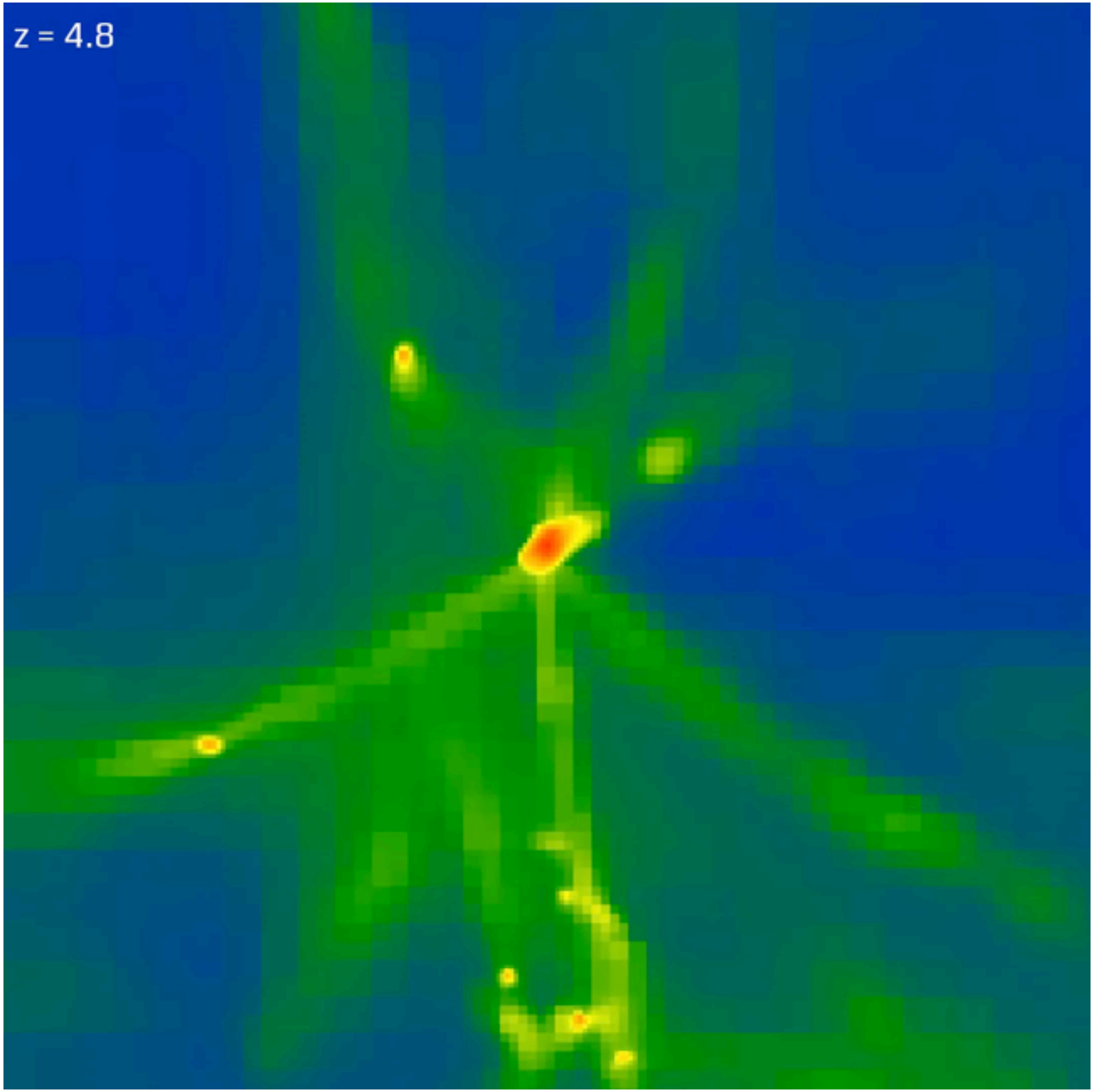
$\Gamma - \Lambda$ → atomic cooling, metal line cooling, UV background

$$p = \rho\epsilon(\gamma - 1)$$

- Adaptive grid allows large and small scales together
- Sub-grid physics includes star formation, supernovae, chemical enrichment

Cosmological assembly

Cosmological assembly

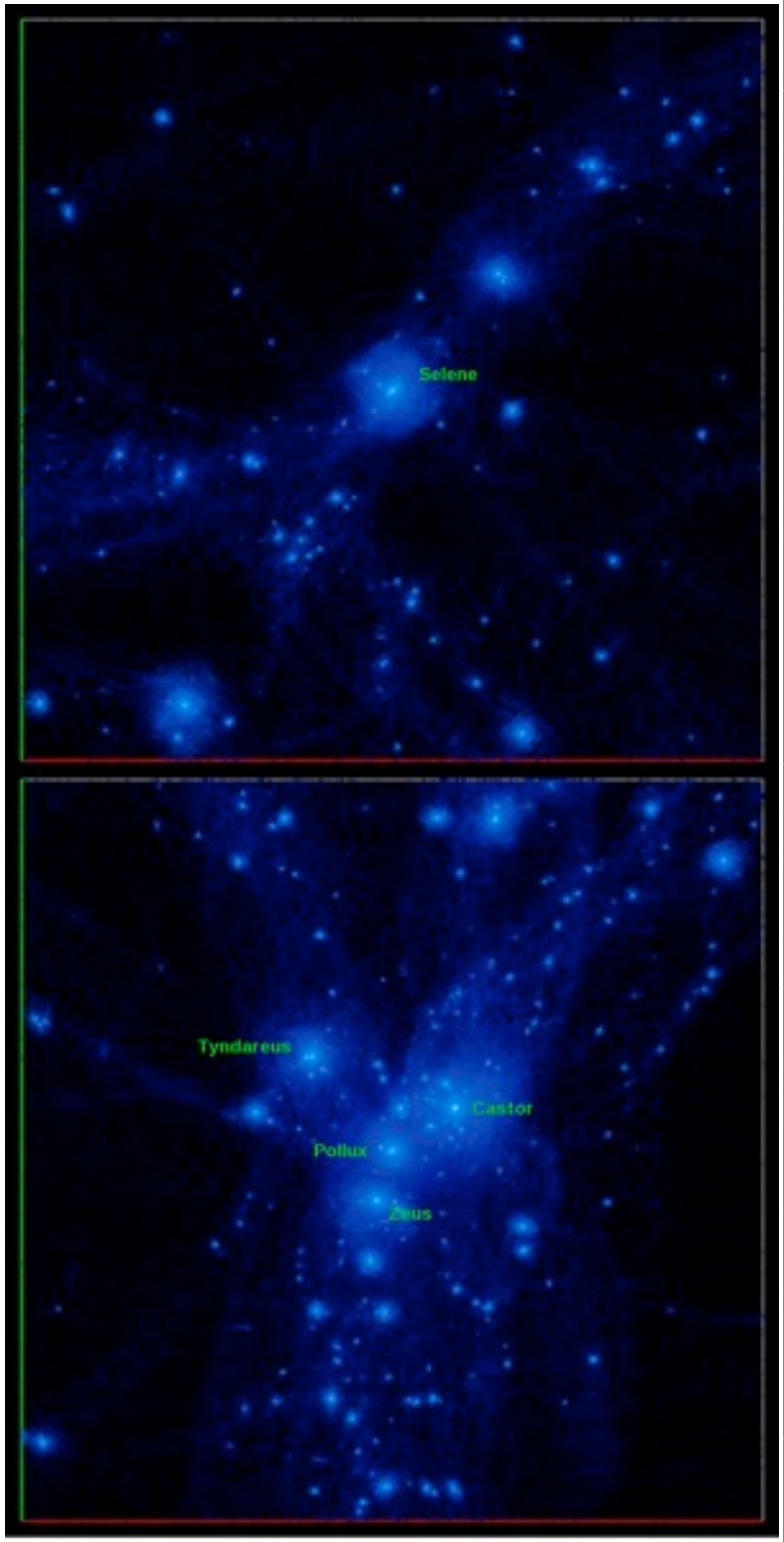


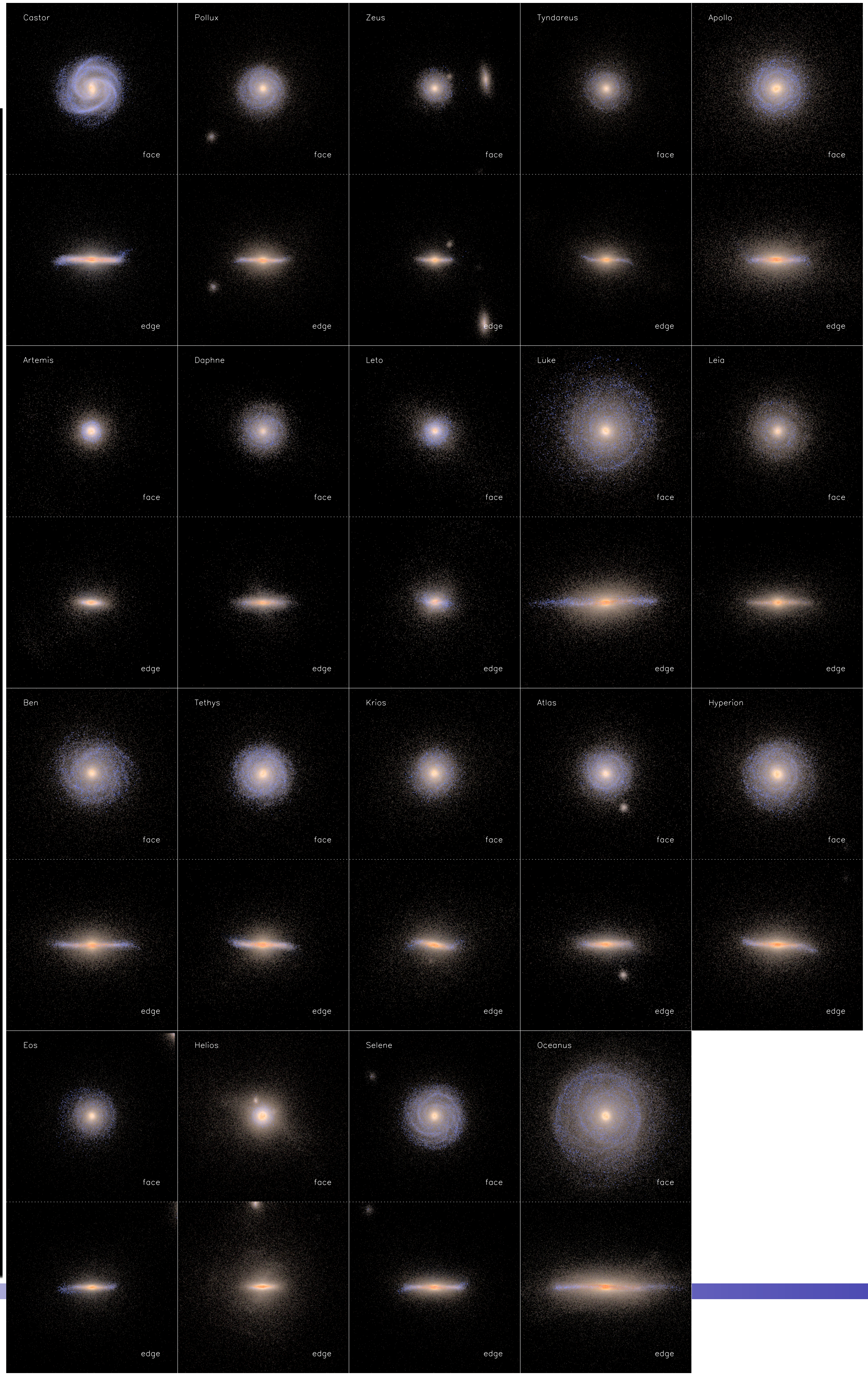
RaDES - Ramses Disk Environment Study

- A sample of 19 simulated galaxies in either a 'field' or 'loose group' environment

- Loose groups are analogous to the Local Group - not true galaxy groups but looser associations of two-three main halos with masses comparable to MW and Andromeda

- Field galaxies have no significant nearby halos





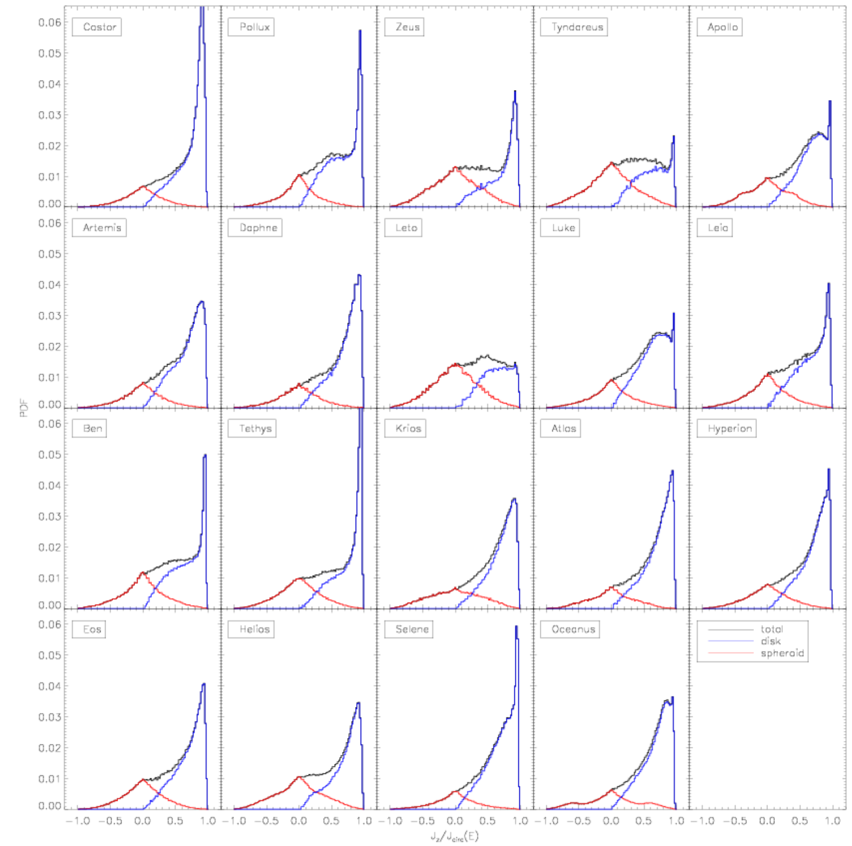
Few et al. 2012

RaDES - Ramses Disk Environment Study

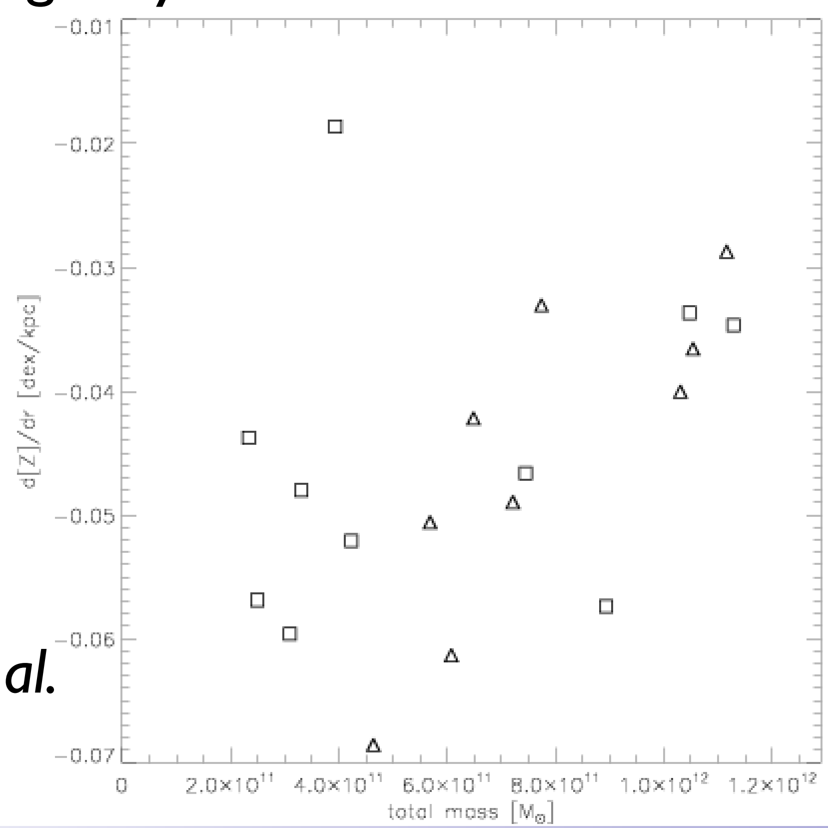
- Galaxies are disk dominated!
- "The best disks realised with a conventional energy feedback scheme" - no appeals to radiation pressure, delayed cooling or extreme initial mass functions

- Main findings: the difference in properties of loose group galaxies and field galaxies is so subtle that the individual assembly history dominates - no big surprise!

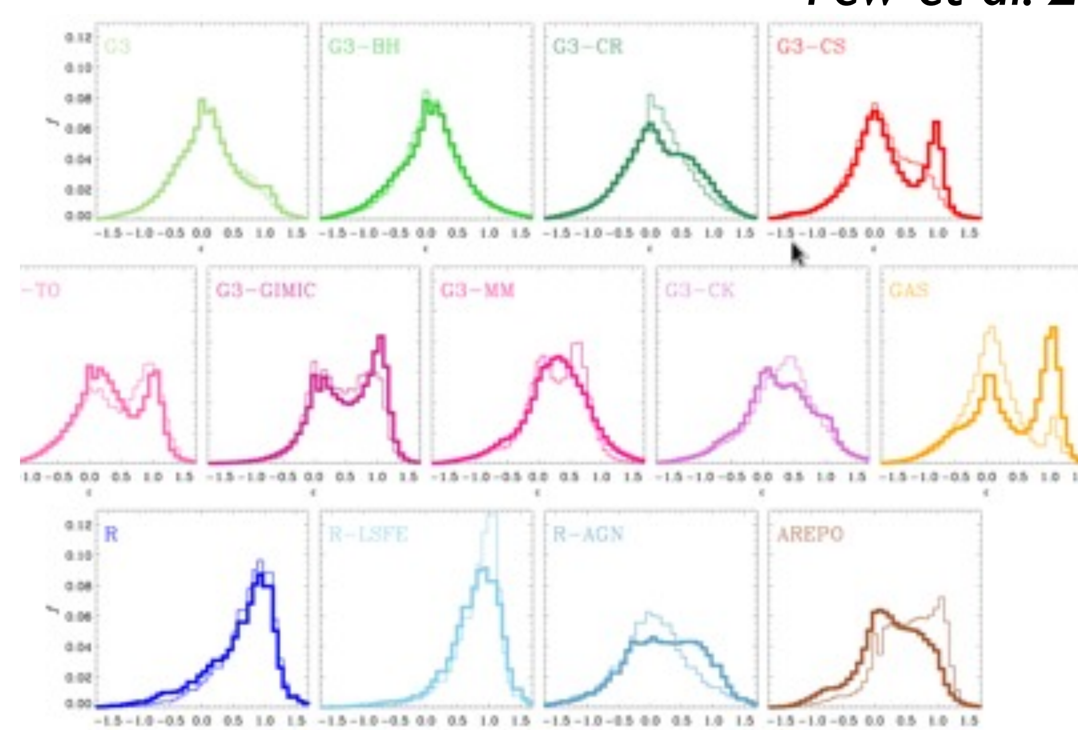
- Metallicity gradients fit observed trends *(Garnett et al., 1997; Van Zee et al., 1998; Prantzos & Boissier, 2000)*
- We also see inside-out galaxy formation...



Few et al. 2012b

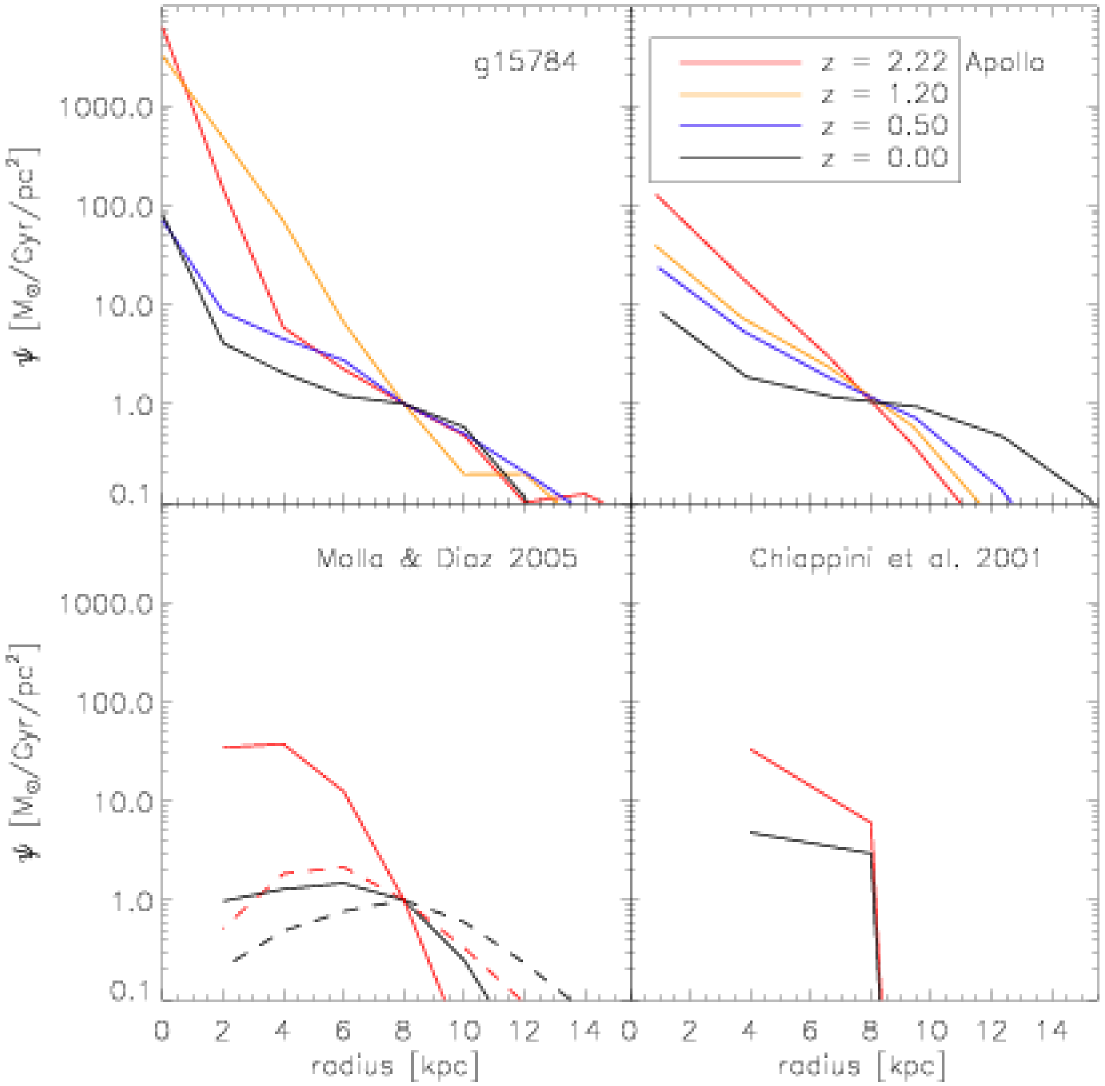


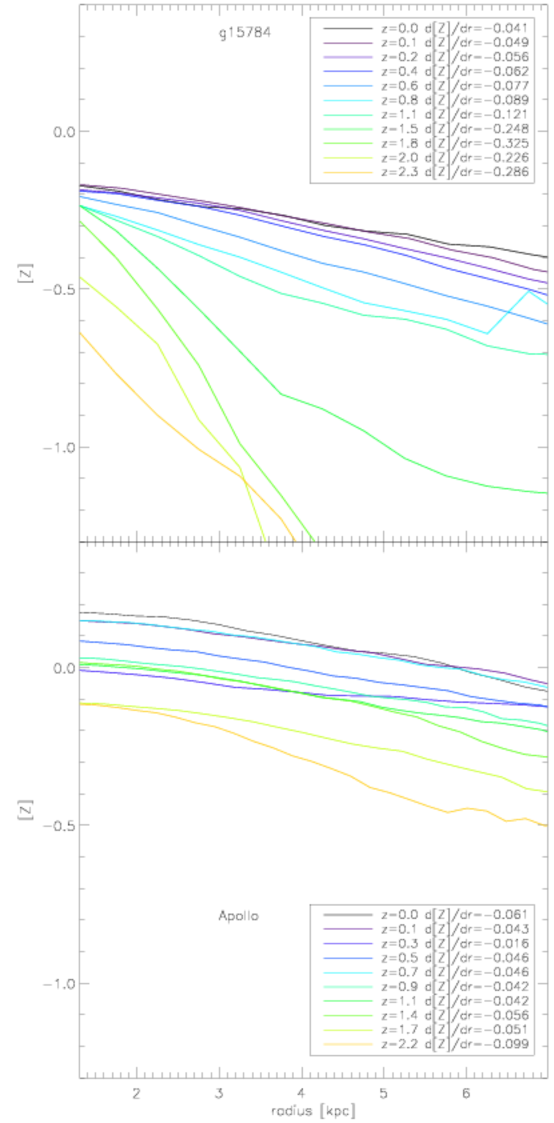
Pilkington, Few et al. 2012



Scannapieco et al. 2012

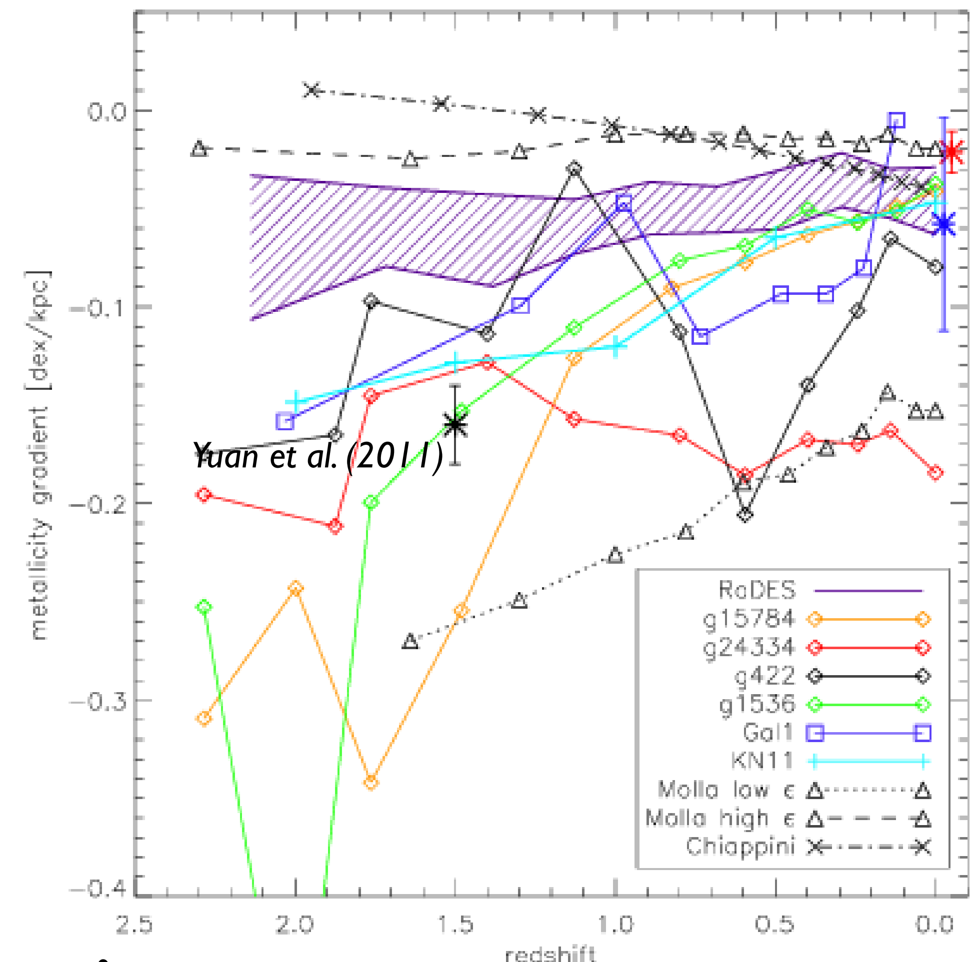
Inside-out formation in RaDES





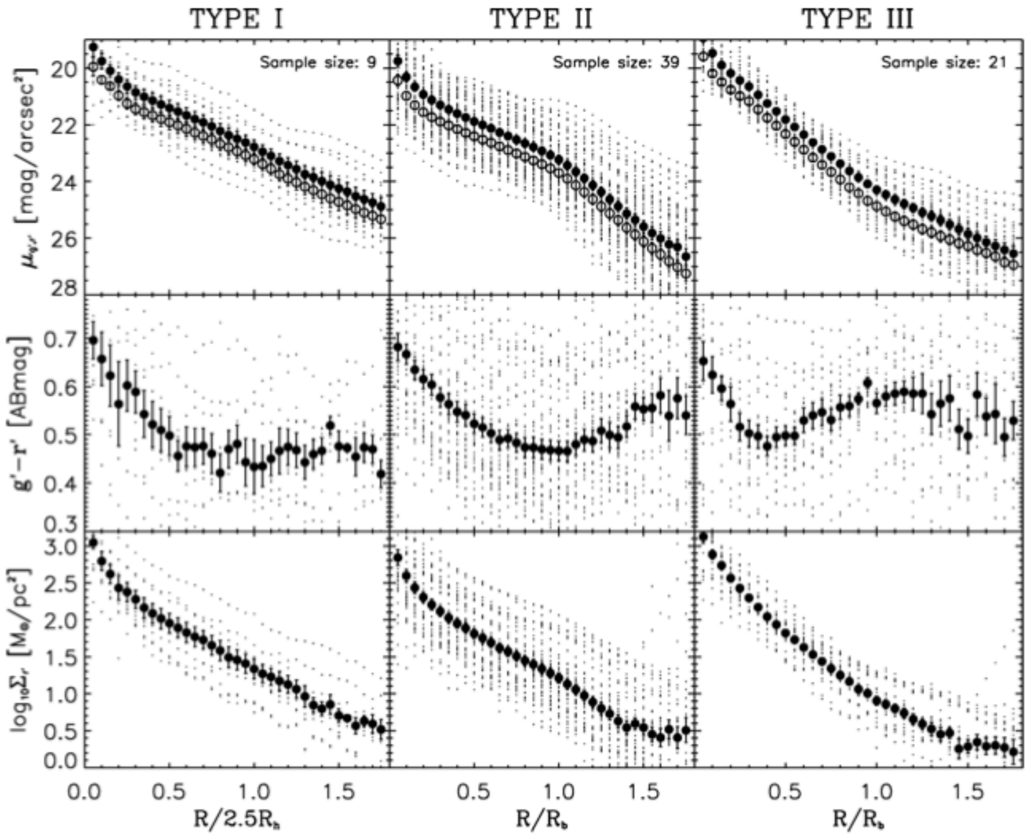
Pilkington, Few et al. (2012)
Metallicity Gradients in Disks:
Do galaxies form inside-out?

Yes, they do!



- The steepness in the star formation rate drives the changing metallicity gradient over time
- Inside-out formation is thus well established in the simulations

Surface brightness profiles

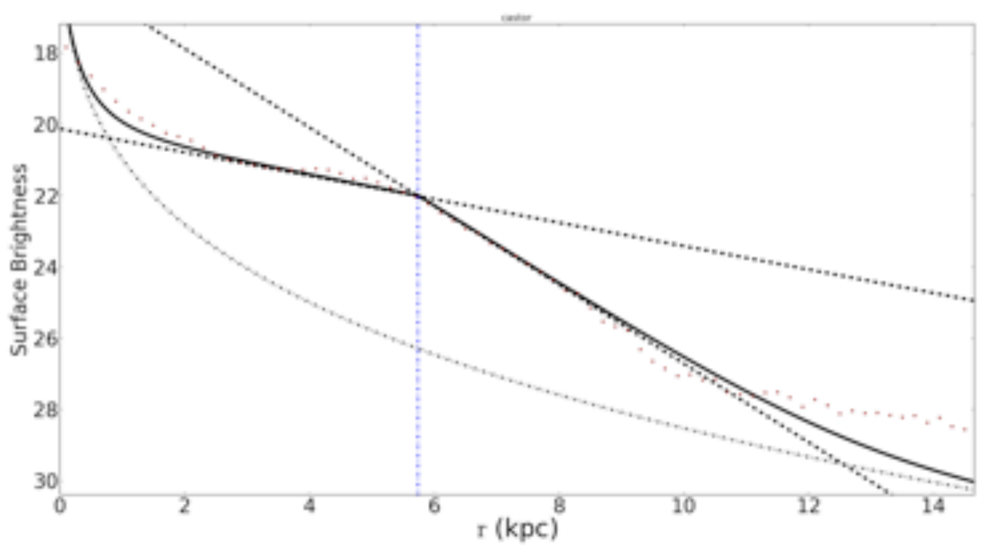


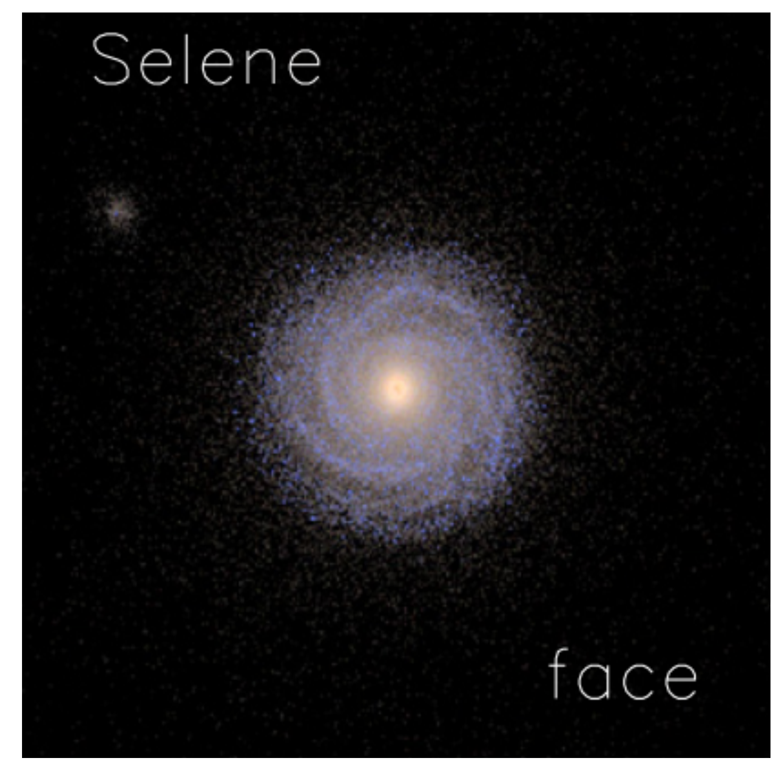
Bakos et al. (2008)

Do you see breaks in surface brightness profiles in simulations?

Tomas Ruiz-Lara

Yes, they do,
those things are annoying!

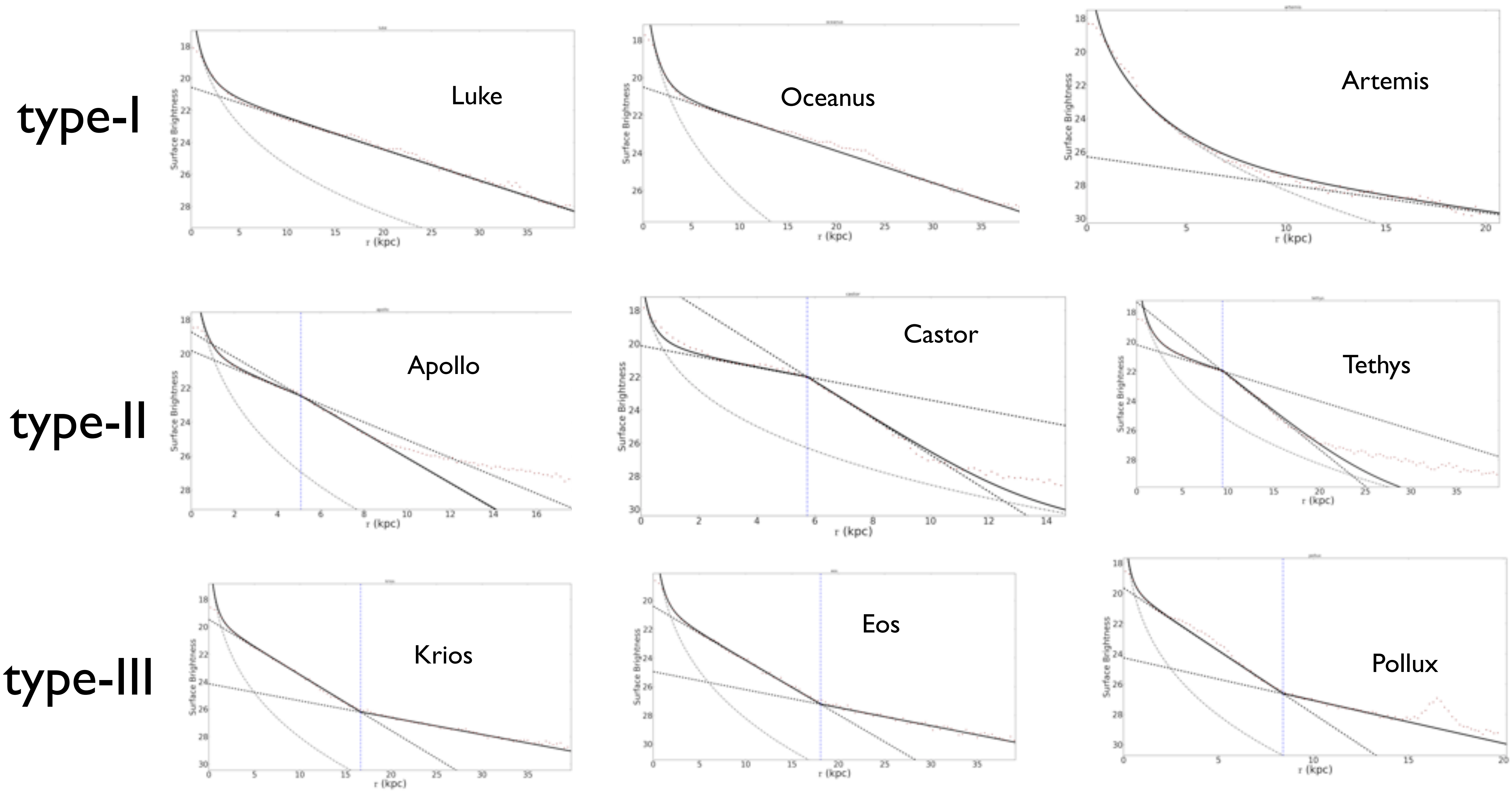




- *SUNRISE* (Jonsson, 2006) combines *Starburst99 (*Leitherer et al. 1999*)* and ray tracing
- We produce model ‘observations’ of the RaDES galaxies

Disk breaks

The majority of cosmological simulation get exclusively type-II disks, but RaDES has the full range



Age distribution

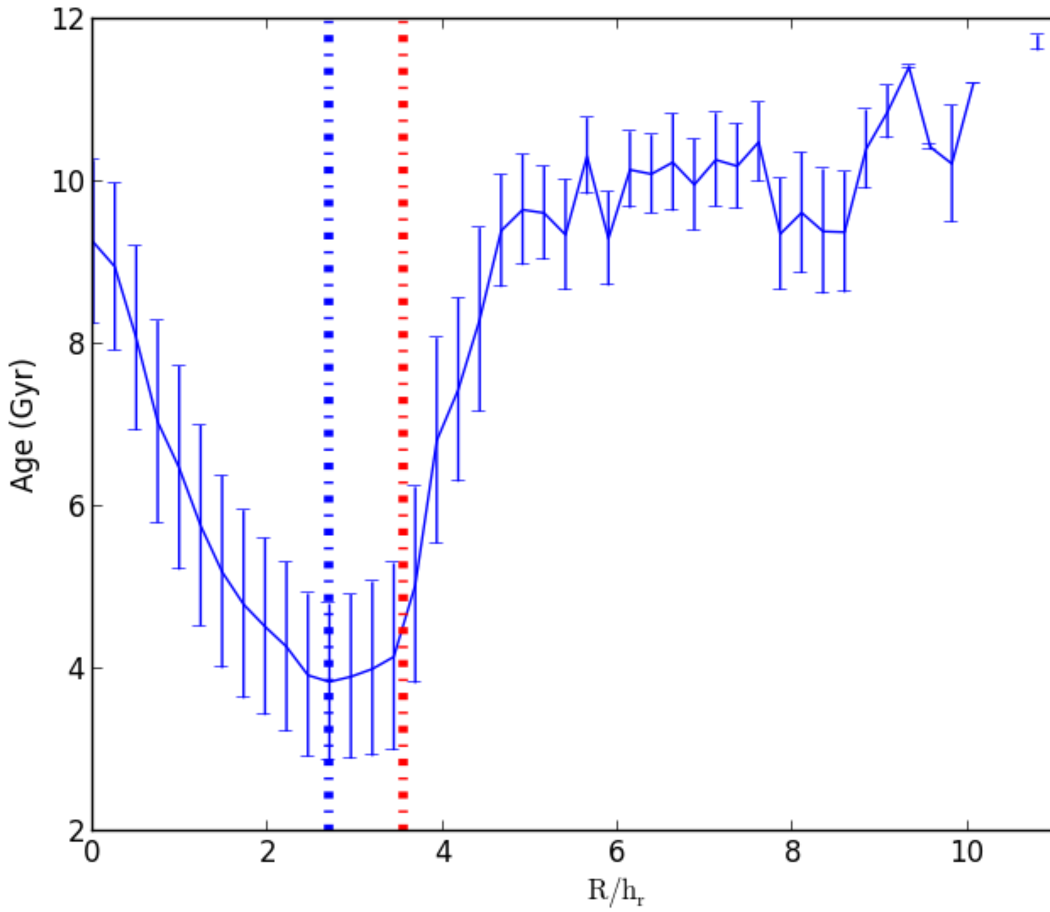
- "U-shaped" age distributions are observed features
- *Ferguson & Johnson, 2001* (M31); *Davidge, 2003* (NGC 2403, M33); *Galleti et al., 2004* (M33) all find disk edges that are old and have high metallicities

- *Roskar et al. (2008)* find U-shaped age distributions in "isolated halo" simulations. Attributed to spiral arm induced radial migration, i.e. An inner disk forms from regular star formation with an outer disk being made of migrated stars.

- *Sanchez-Blazquez et al. (2009)* find U-shaped age distributions in cosmological simulations finding the same "migrated outer disk" but note some of the outer disk stars form "in-situ"

- It has been suggested that in a CDM universe where inside-out formation prevails, these U-shapes are not expected (*Ferguson & Johnson, 2001*)

Tomas Ruiz-Lara



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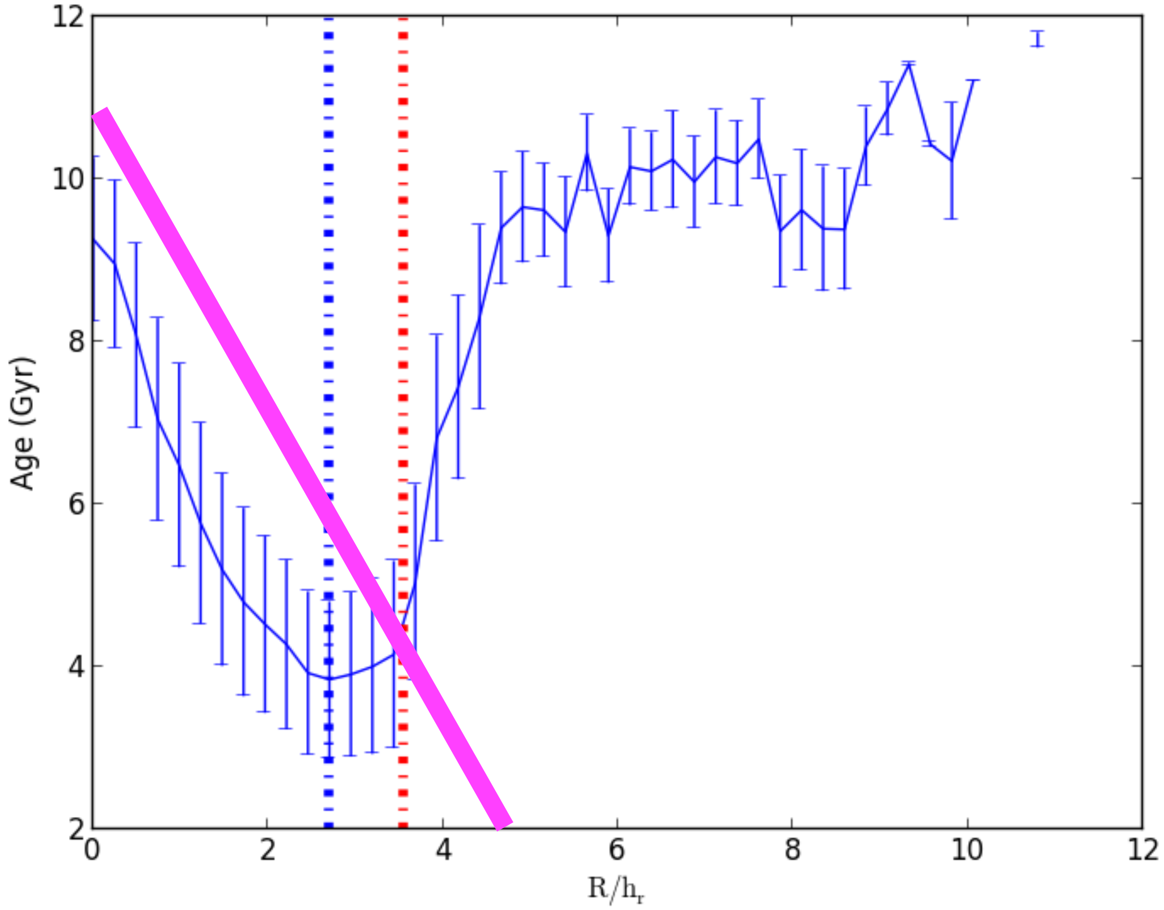

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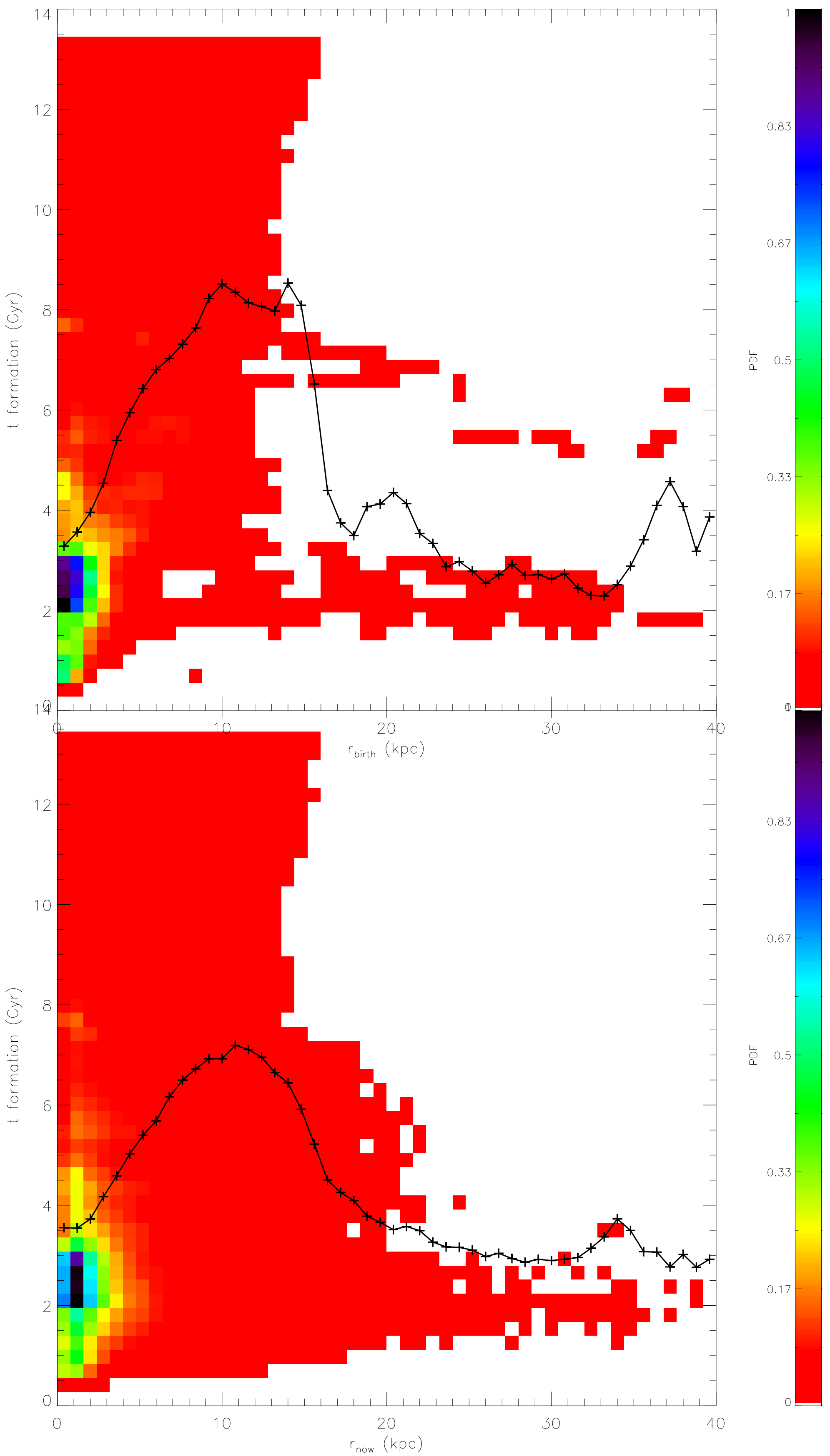

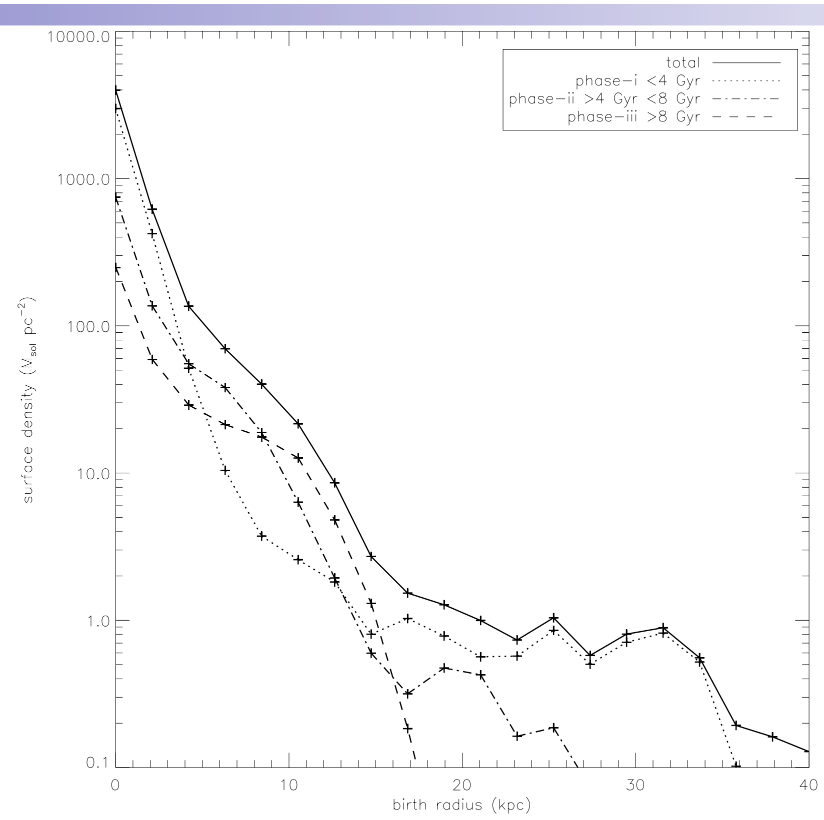

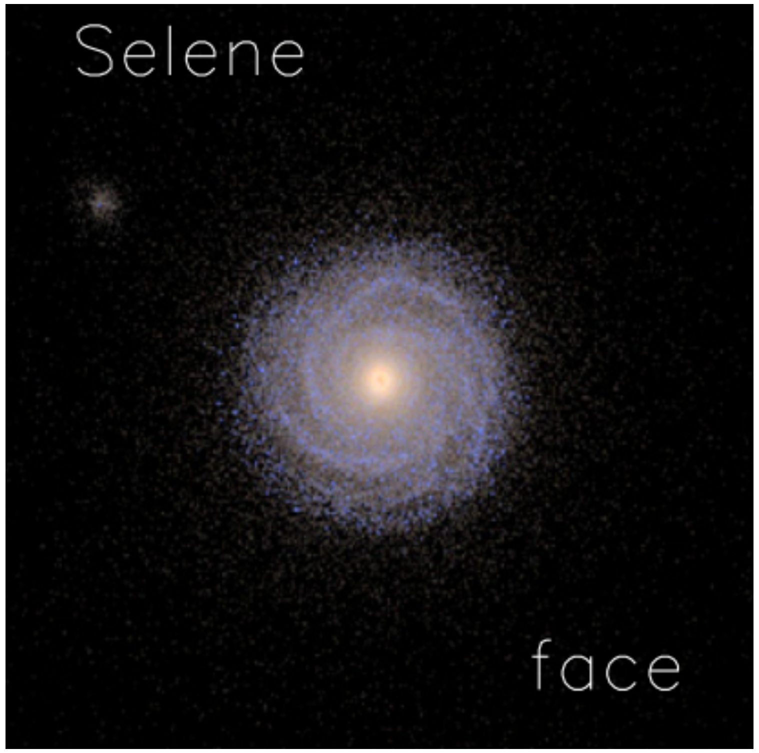

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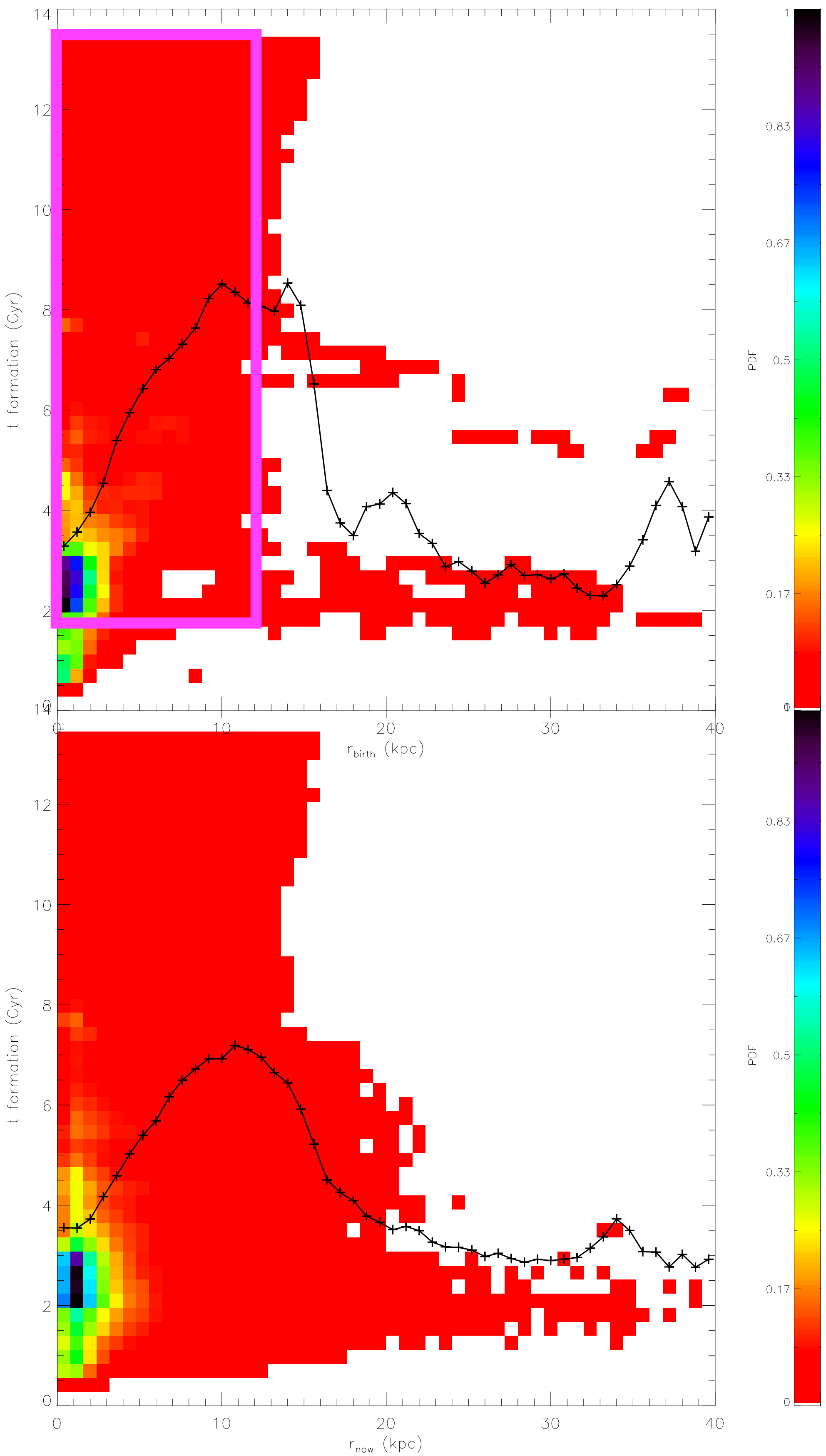
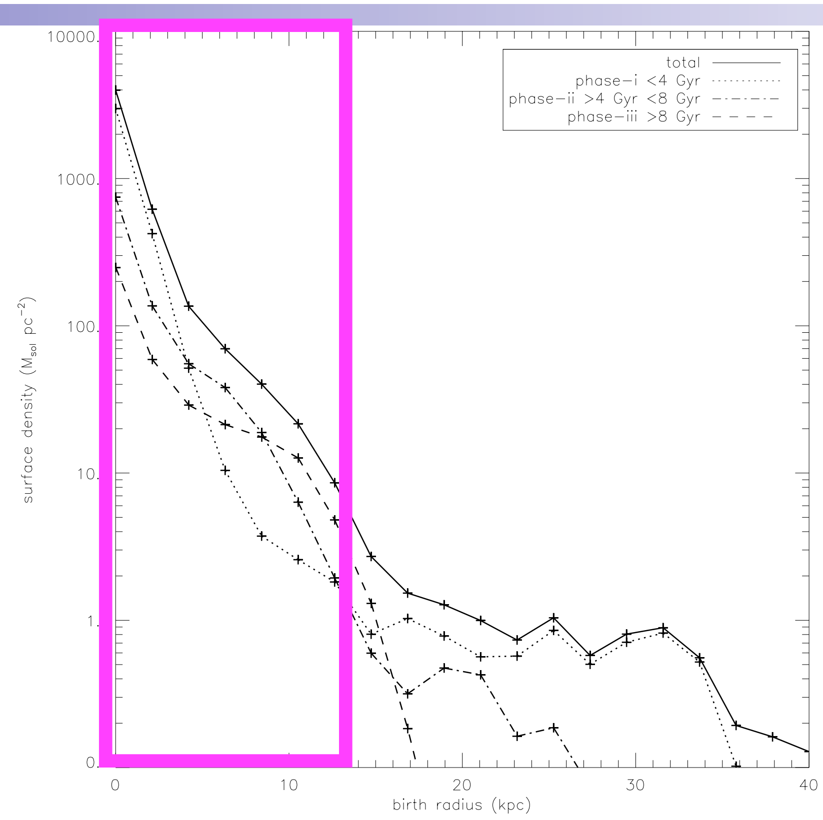
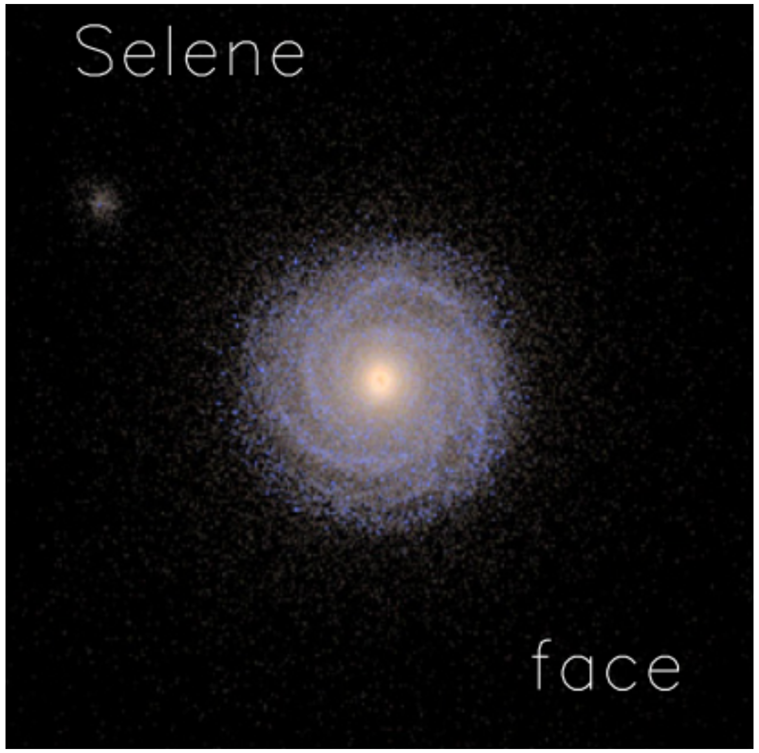
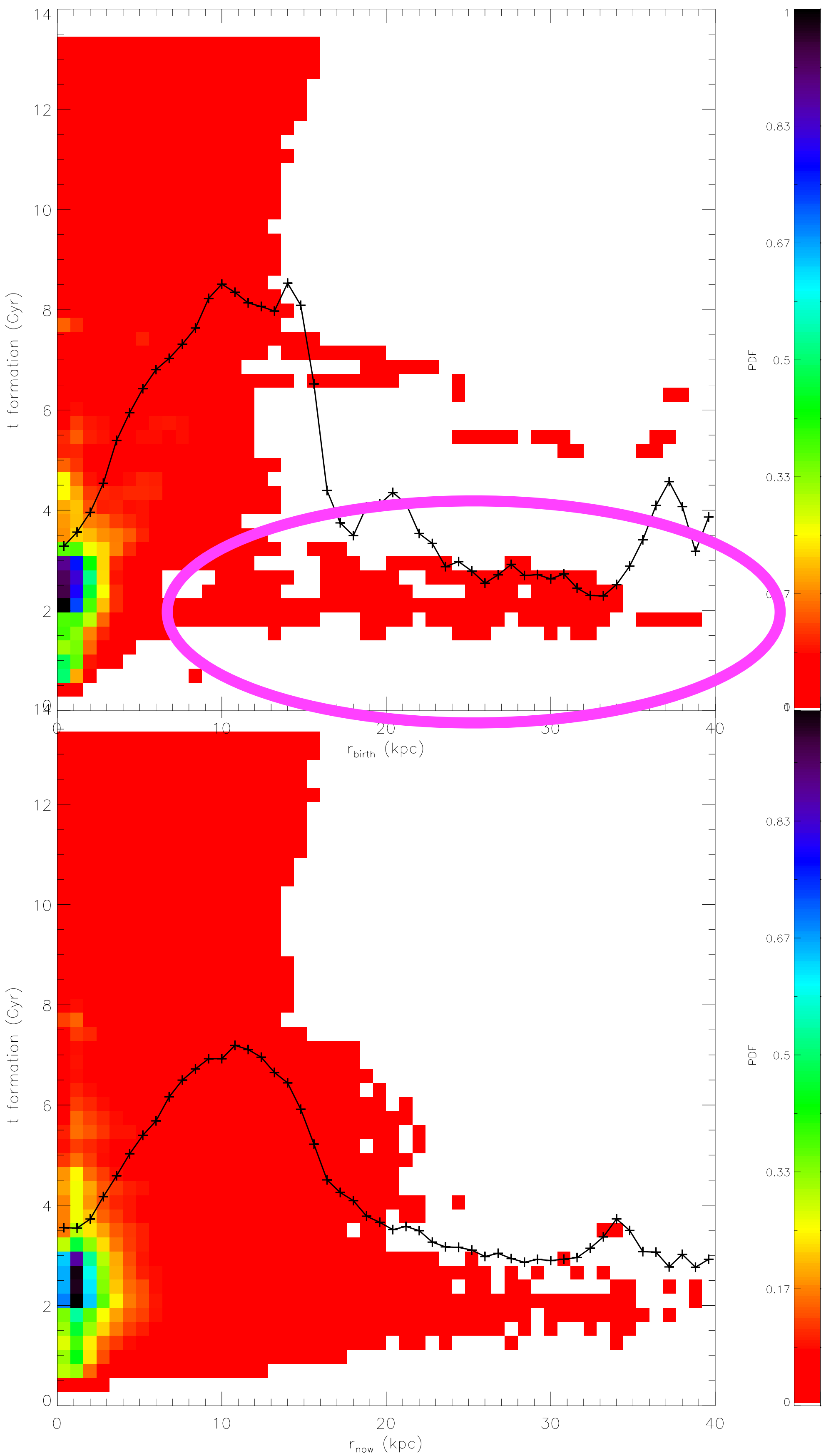


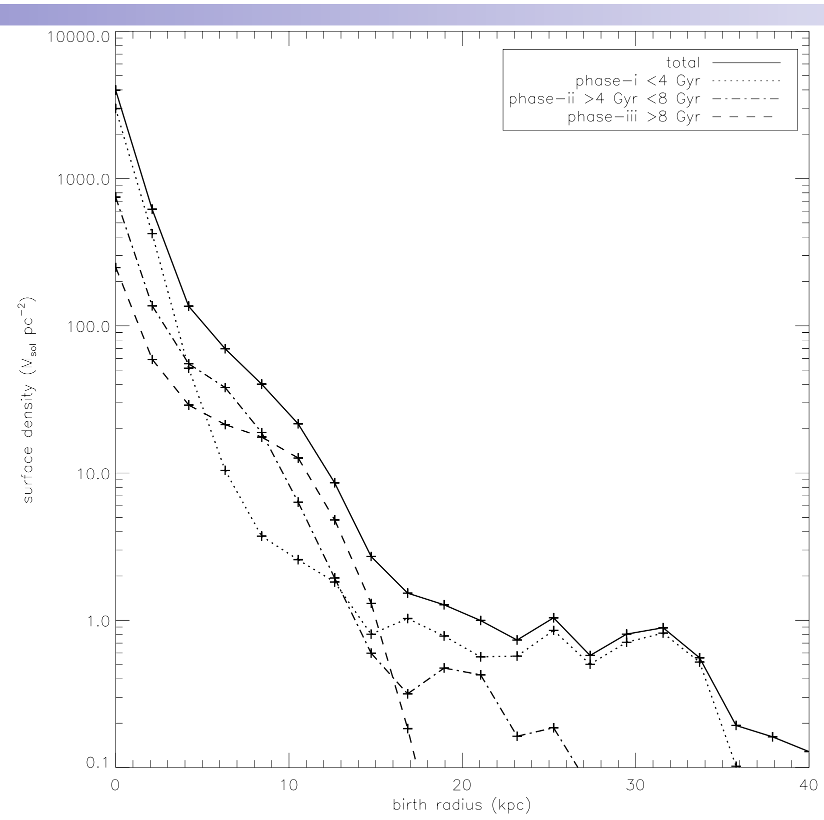


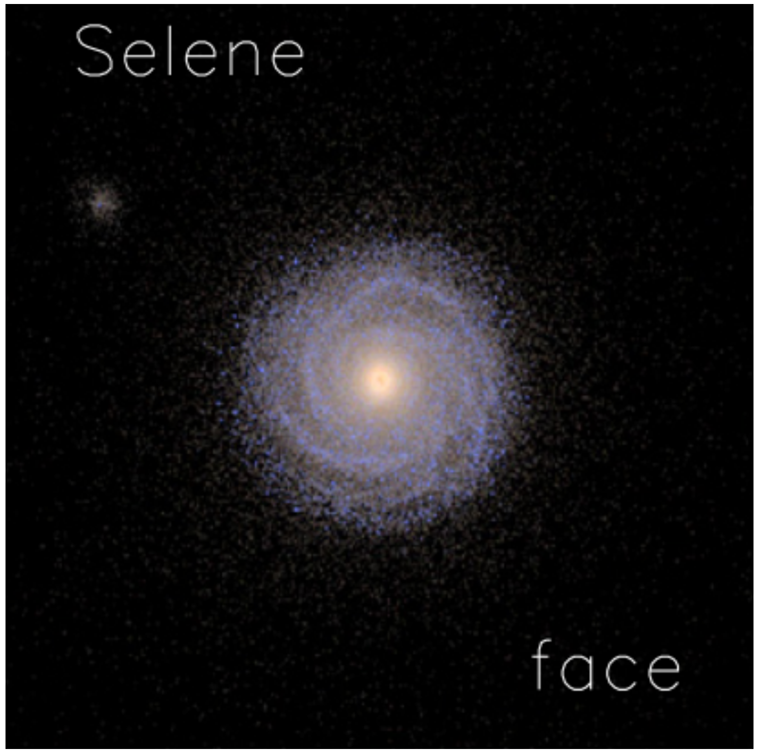


- Inside-out is still happening - yipee!

Age distribution







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- The old outer region is formed in-situ

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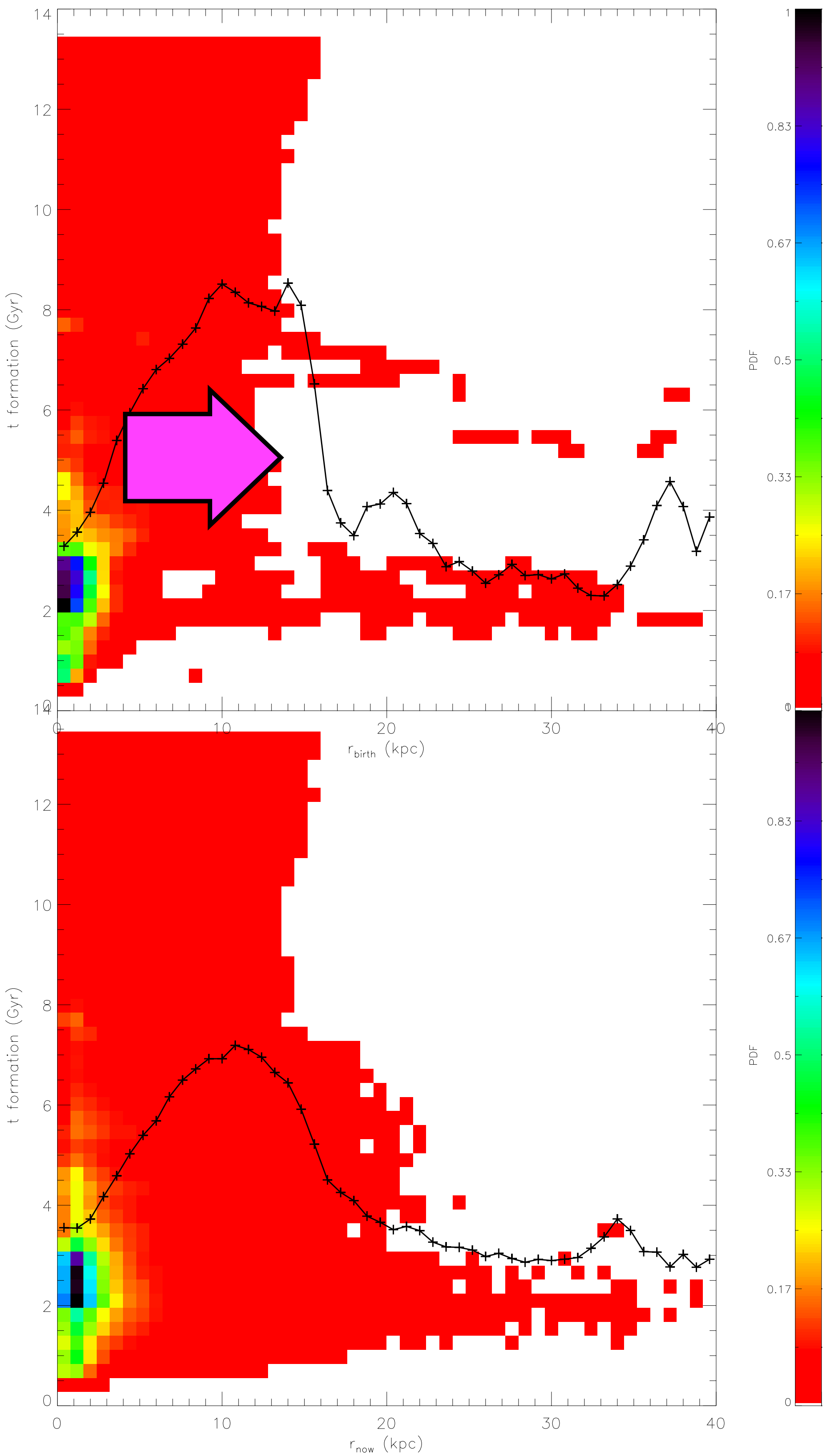

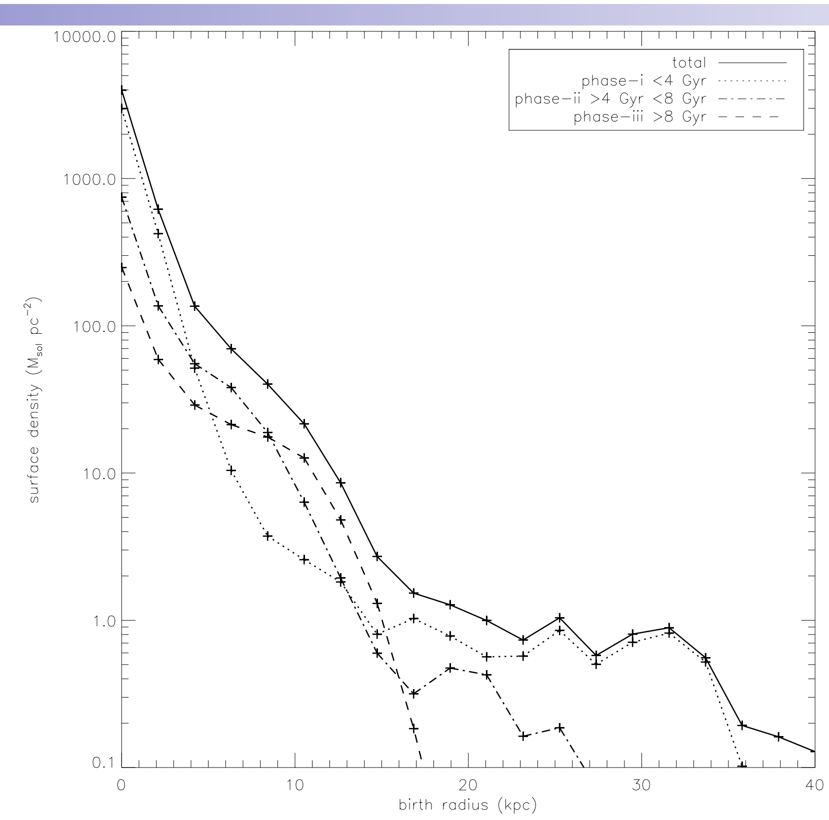

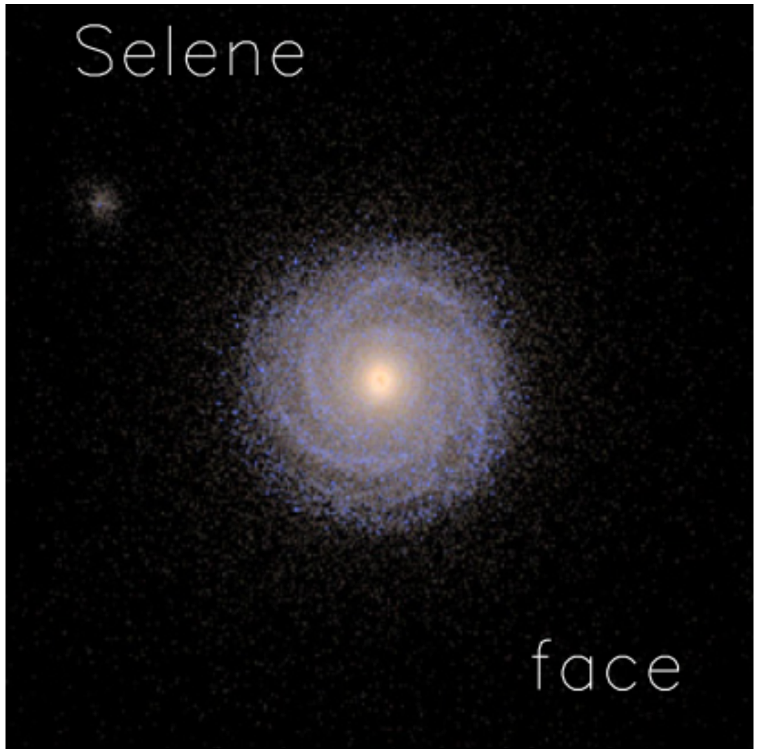

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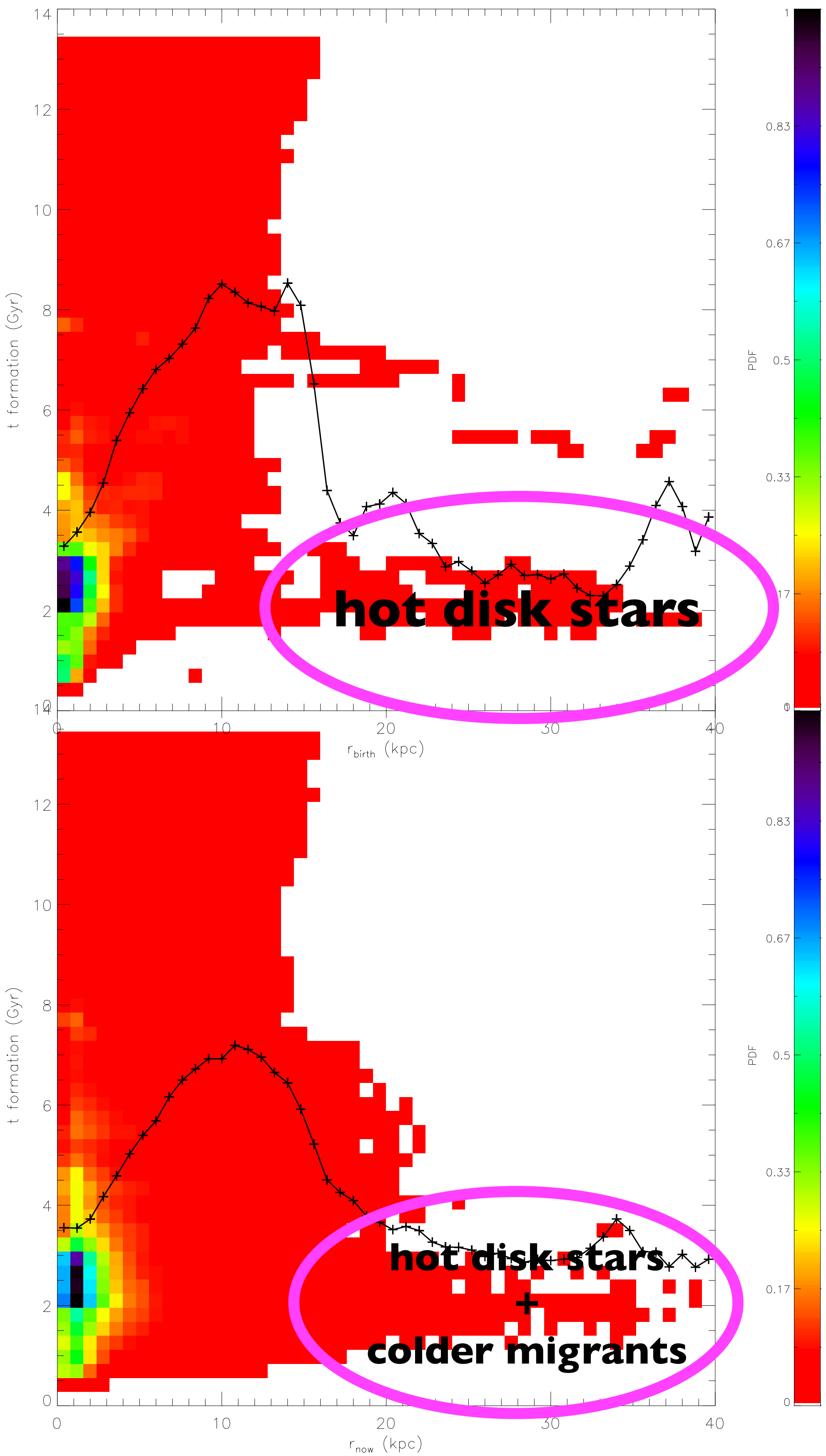
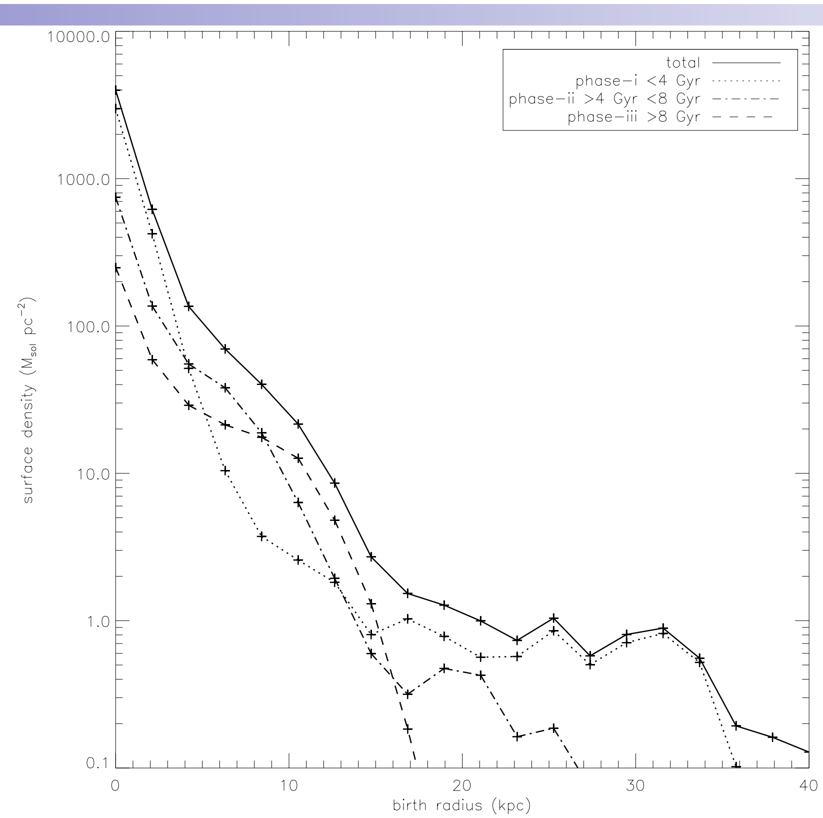
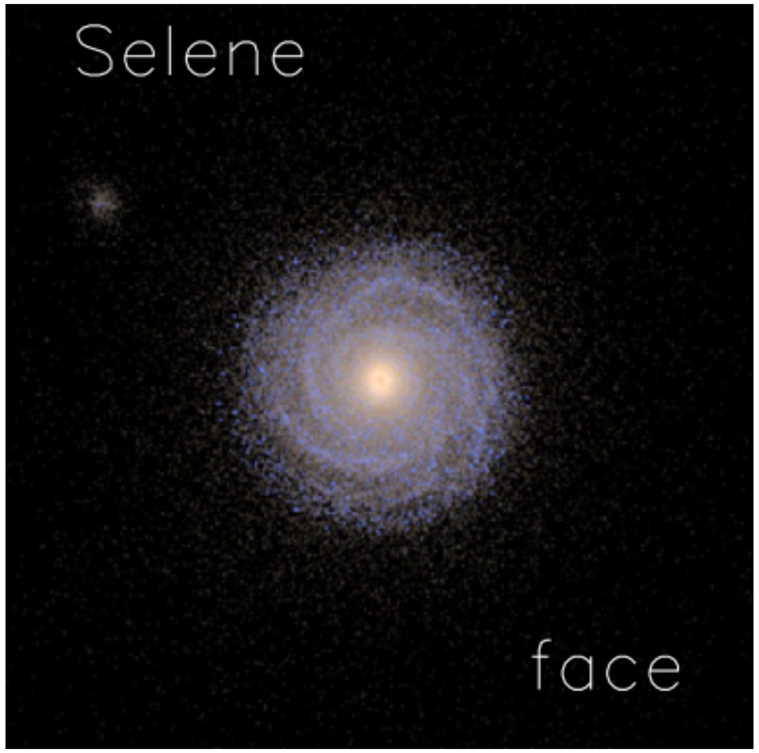
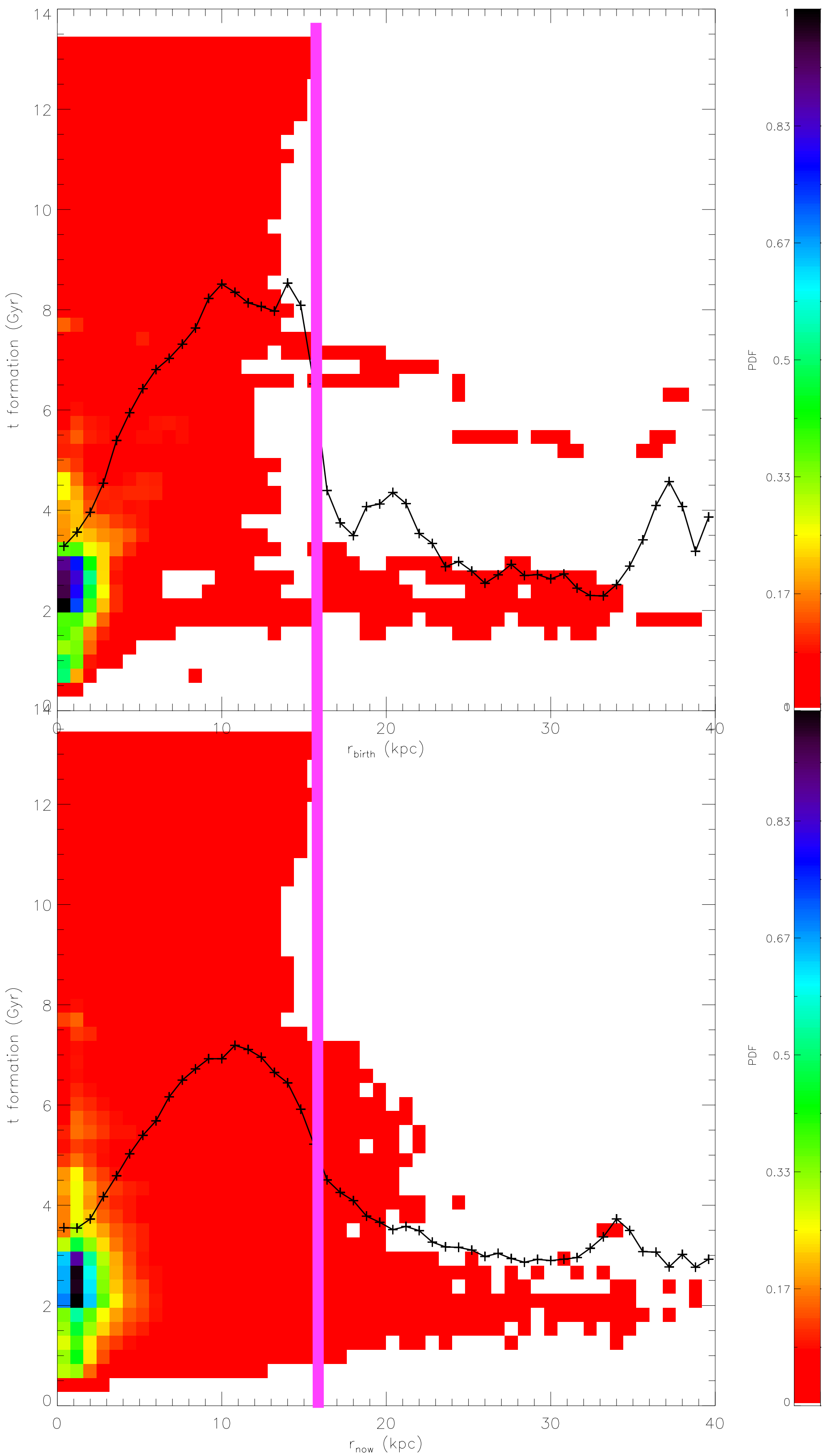


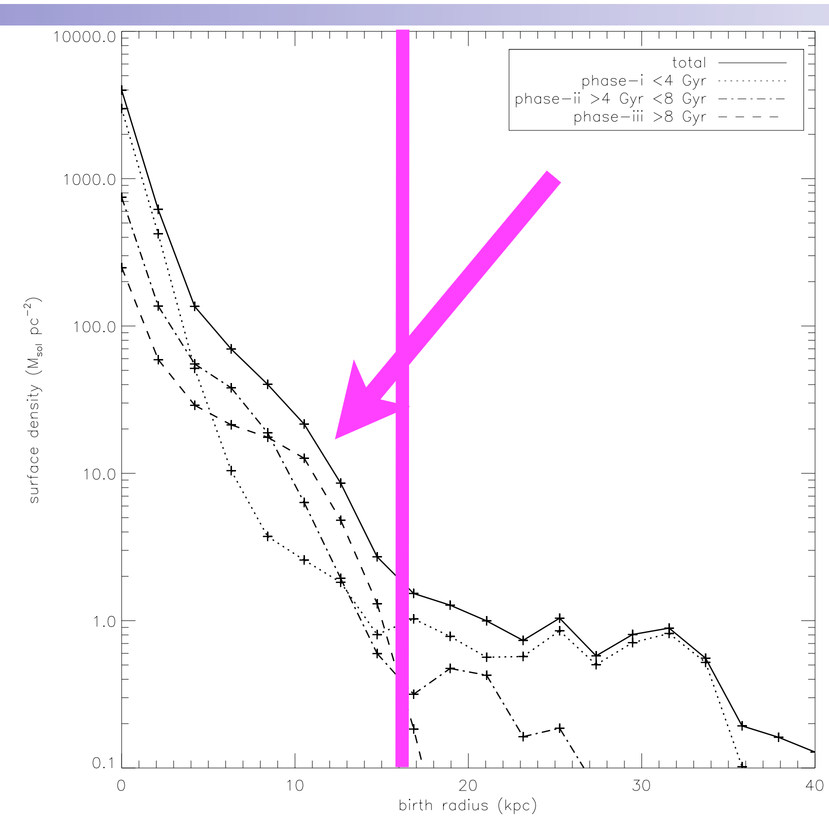


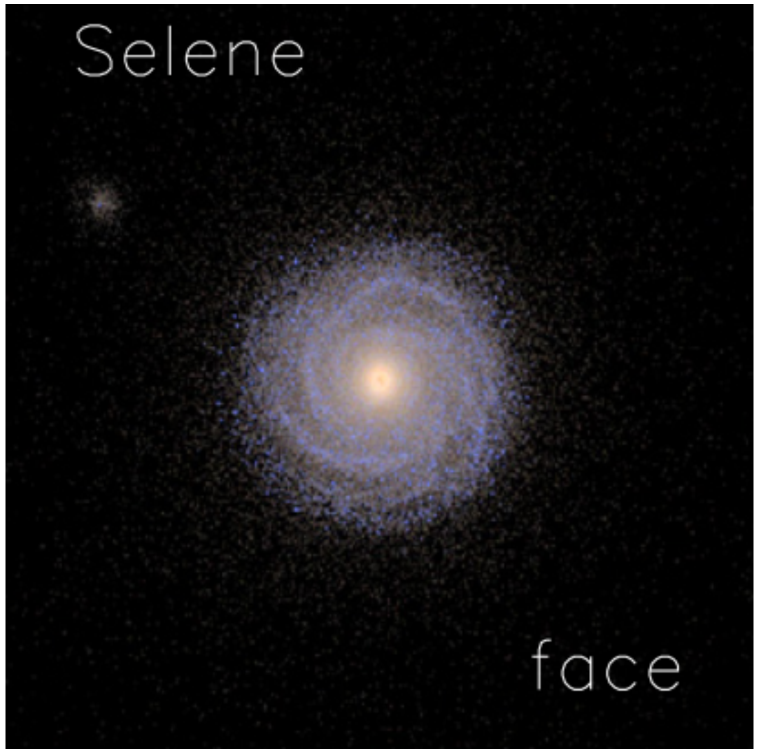


- Inside-out is still happening - yipee!
- The old outer region is formed in-situ
- Migration tends to move stars outwards
- If you look at the most 'disky' stars the outer region is dominated by migrants (the in-situ ones have greater velocity dispersion)

Age distribution

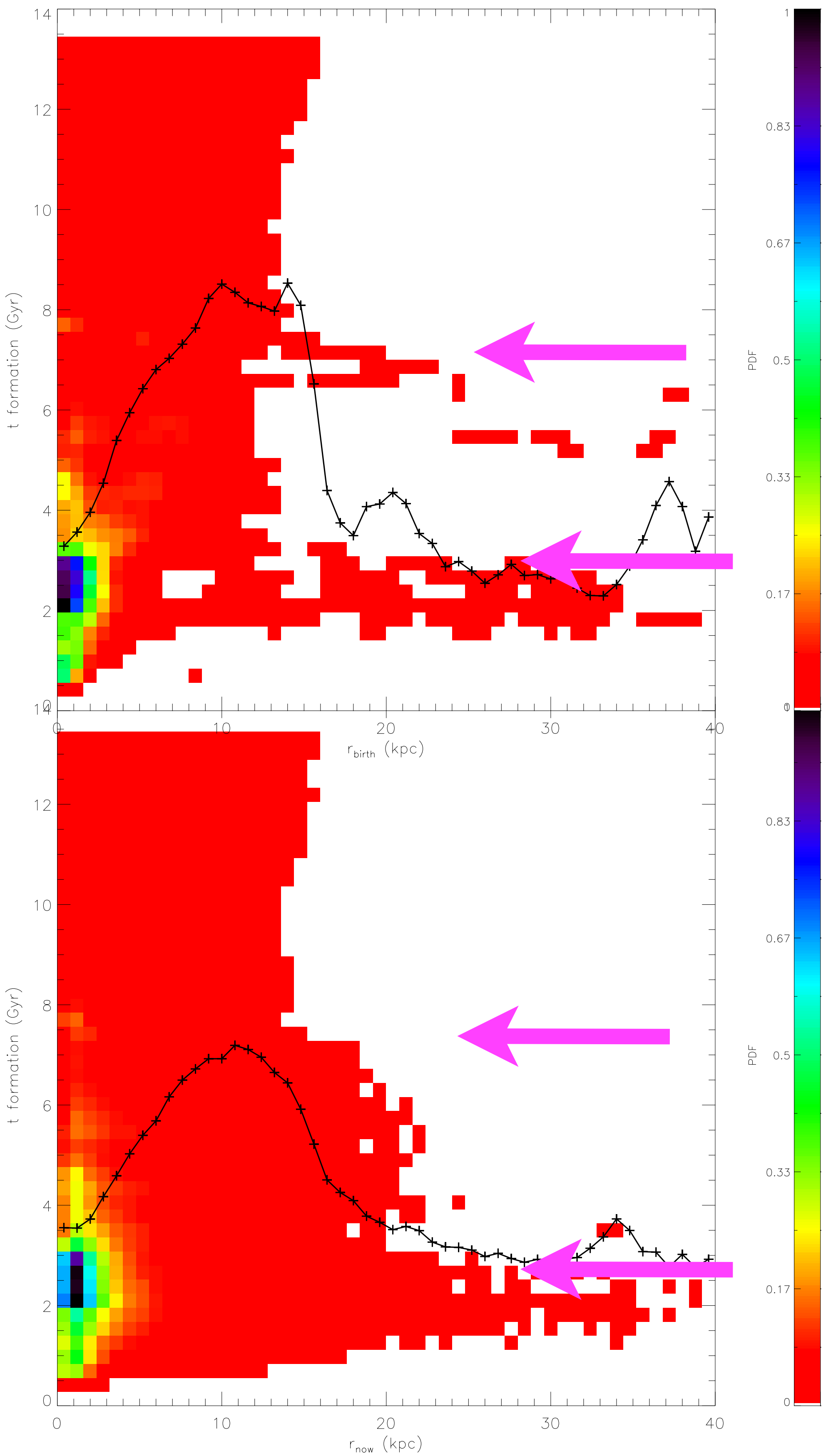


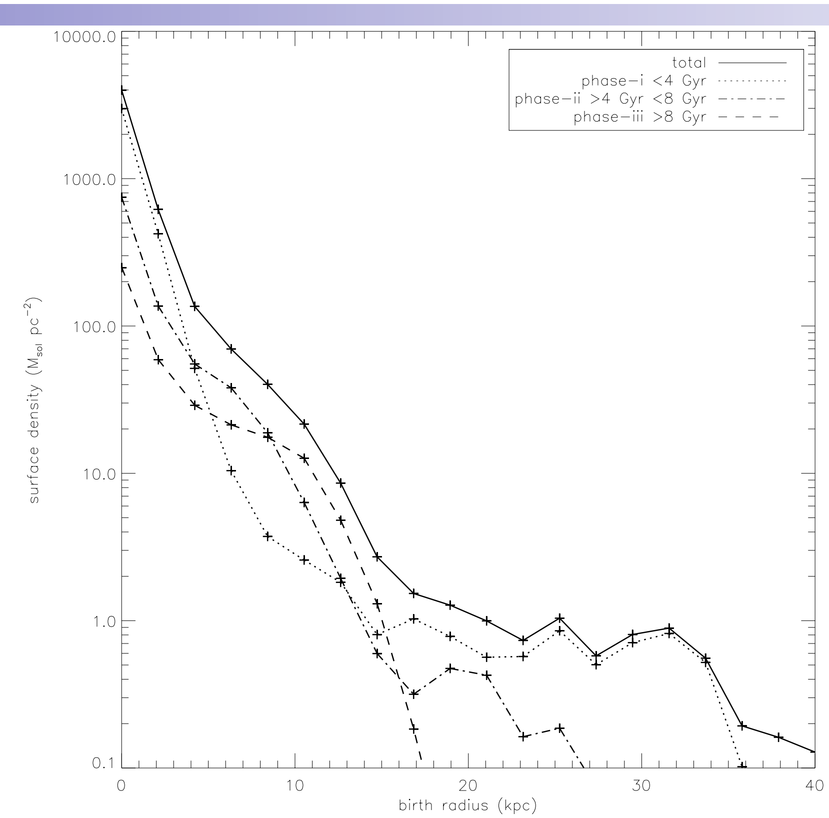


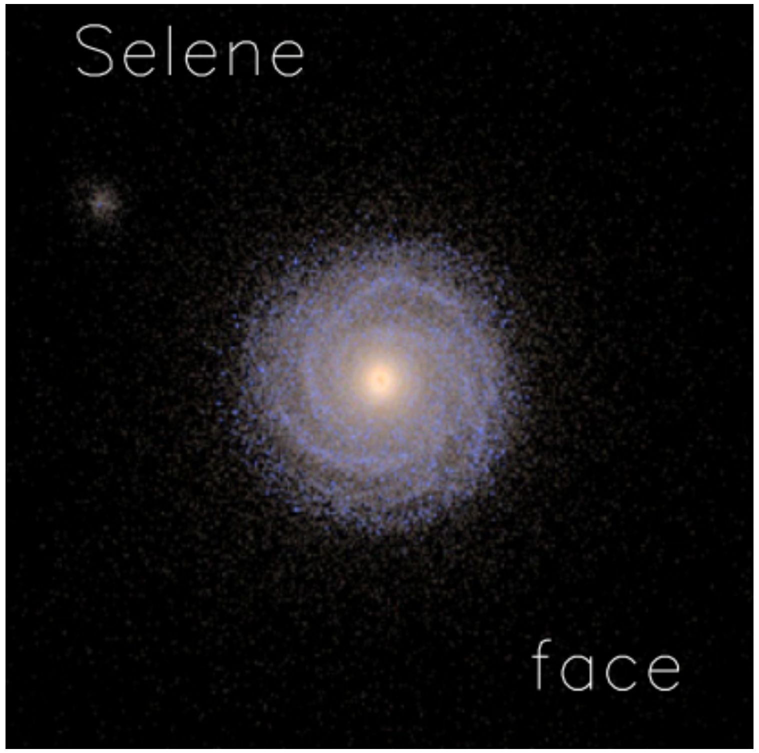


- Inside-out is still happening - yipee!
- The old outer region is formed in-situ
- Migration tends to move stars outwards
- If you look at the most ‘disky’ stars the outer region is dominated by migrants (the in-situ ones have greater velocity dispersion)
- The break is the edge of recent star formation

Age distribution







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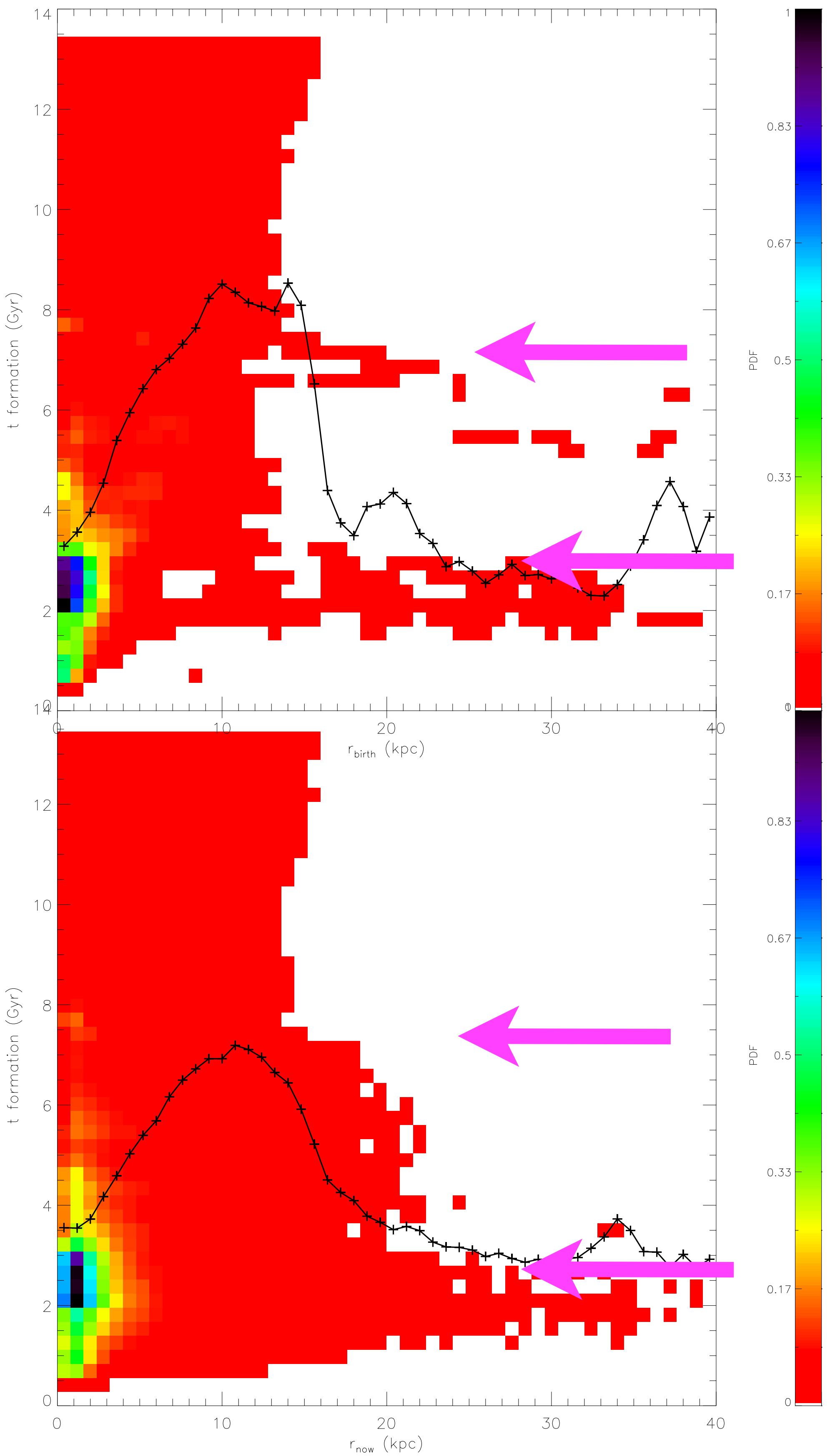
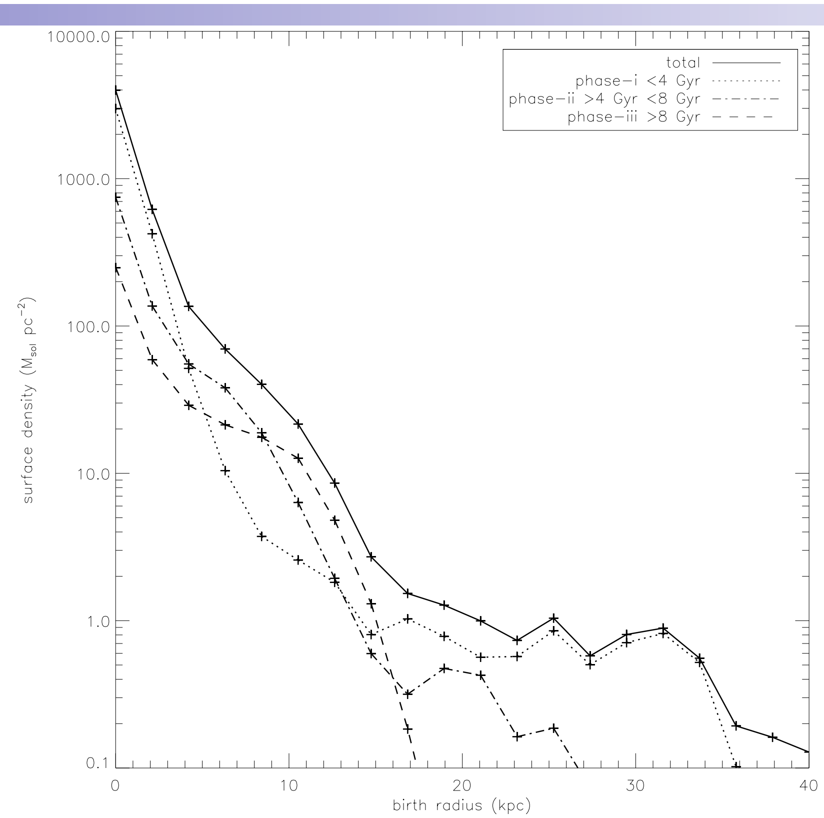
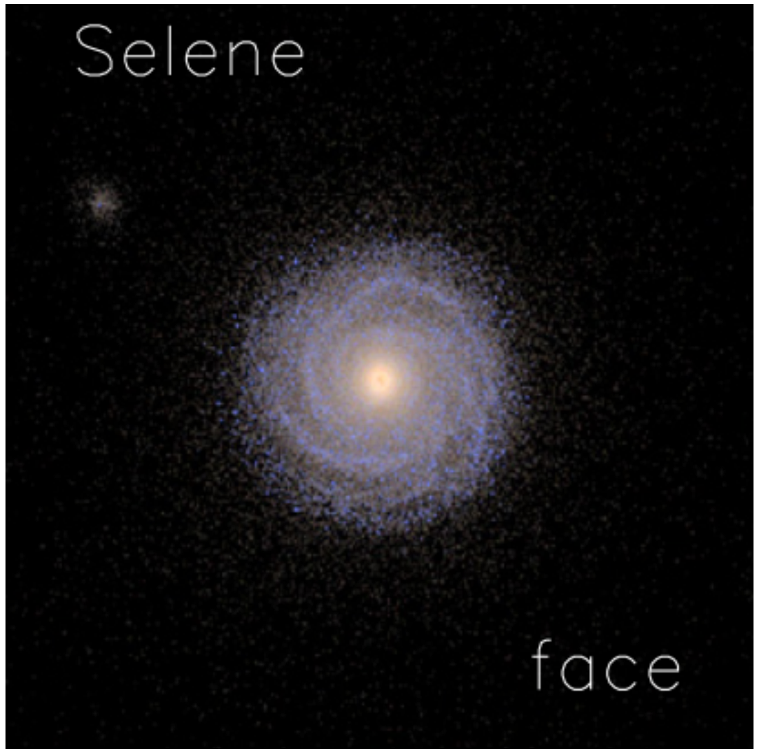
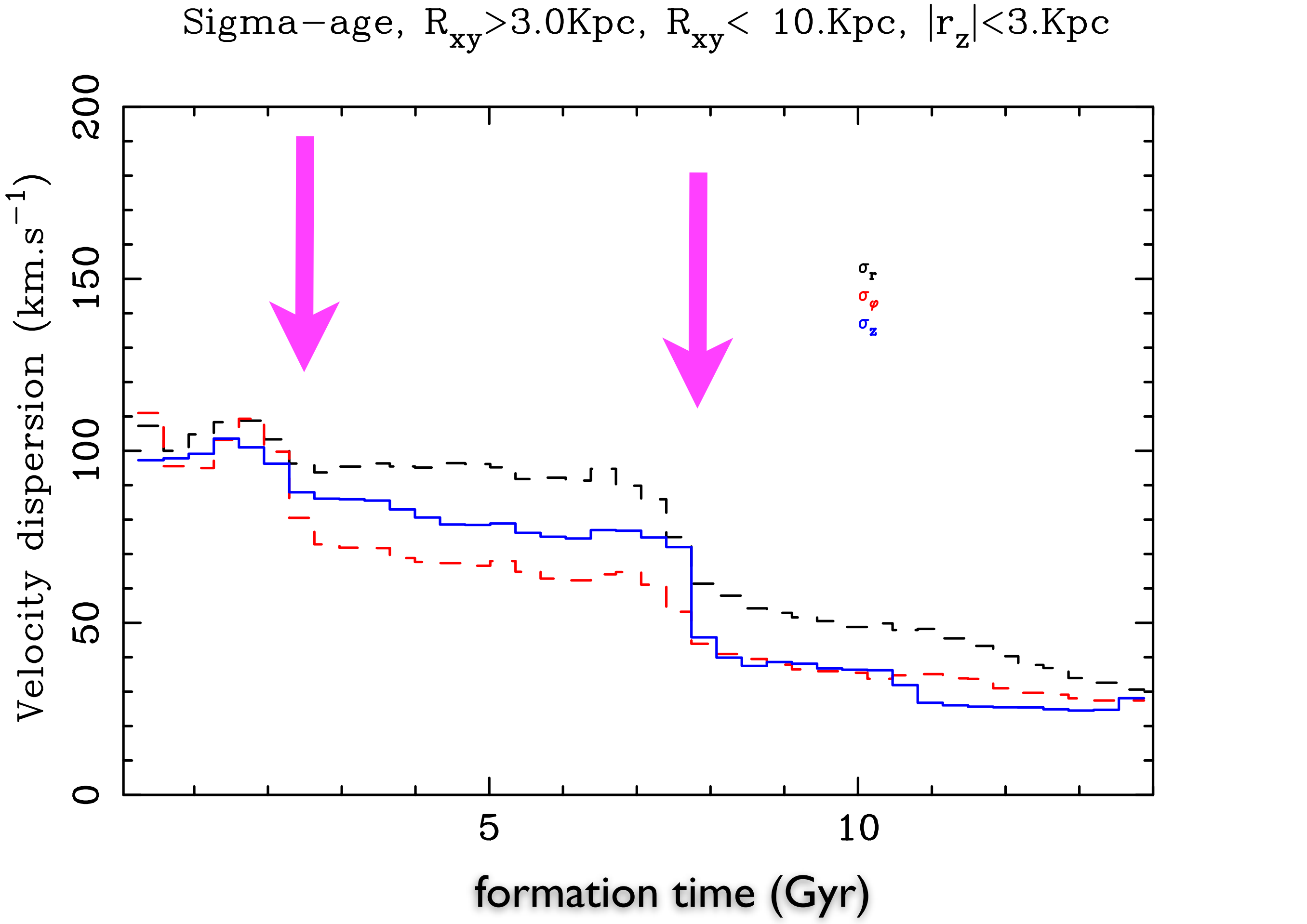
- What about those steps at particular times?

Age distribution

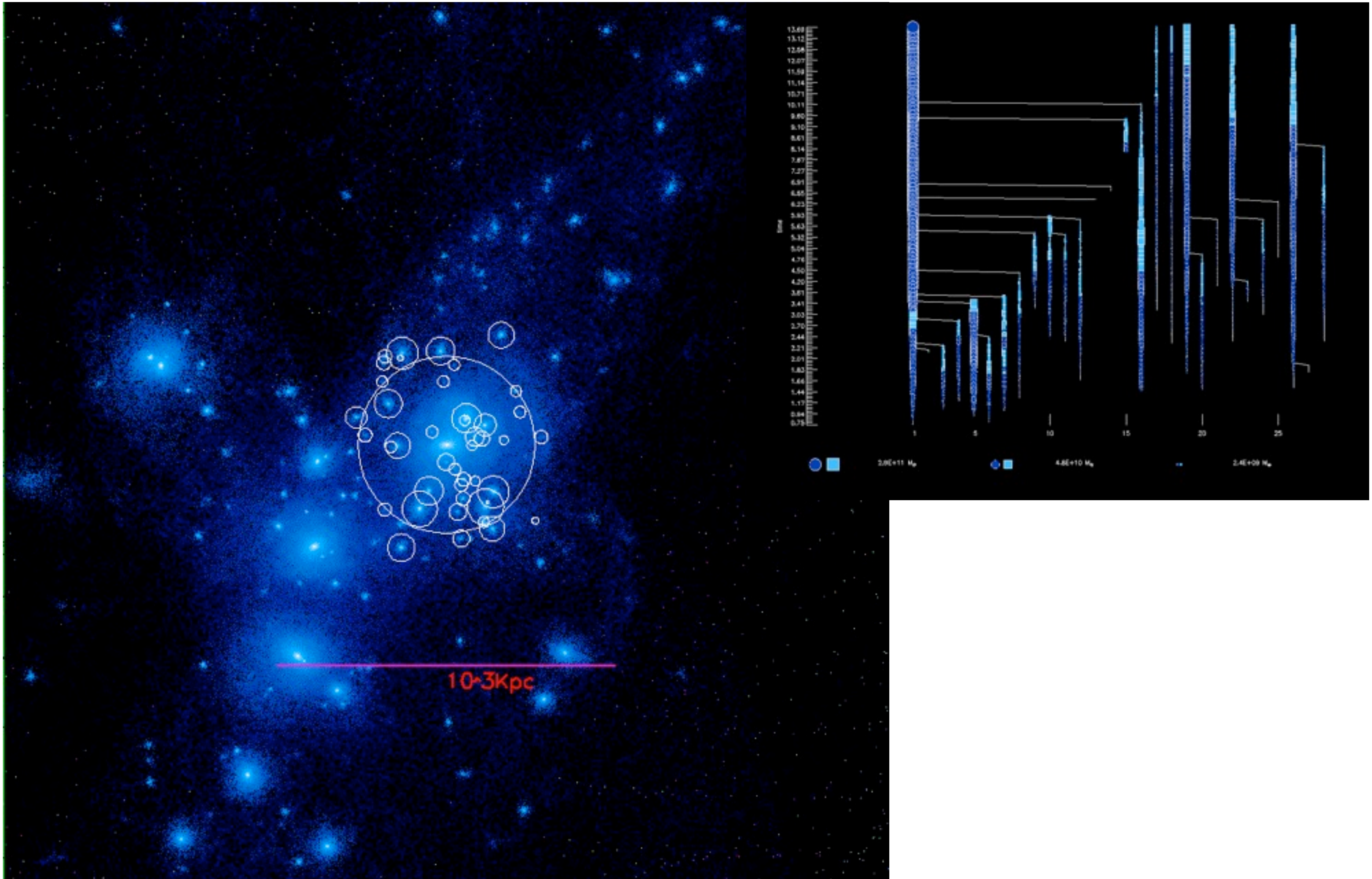




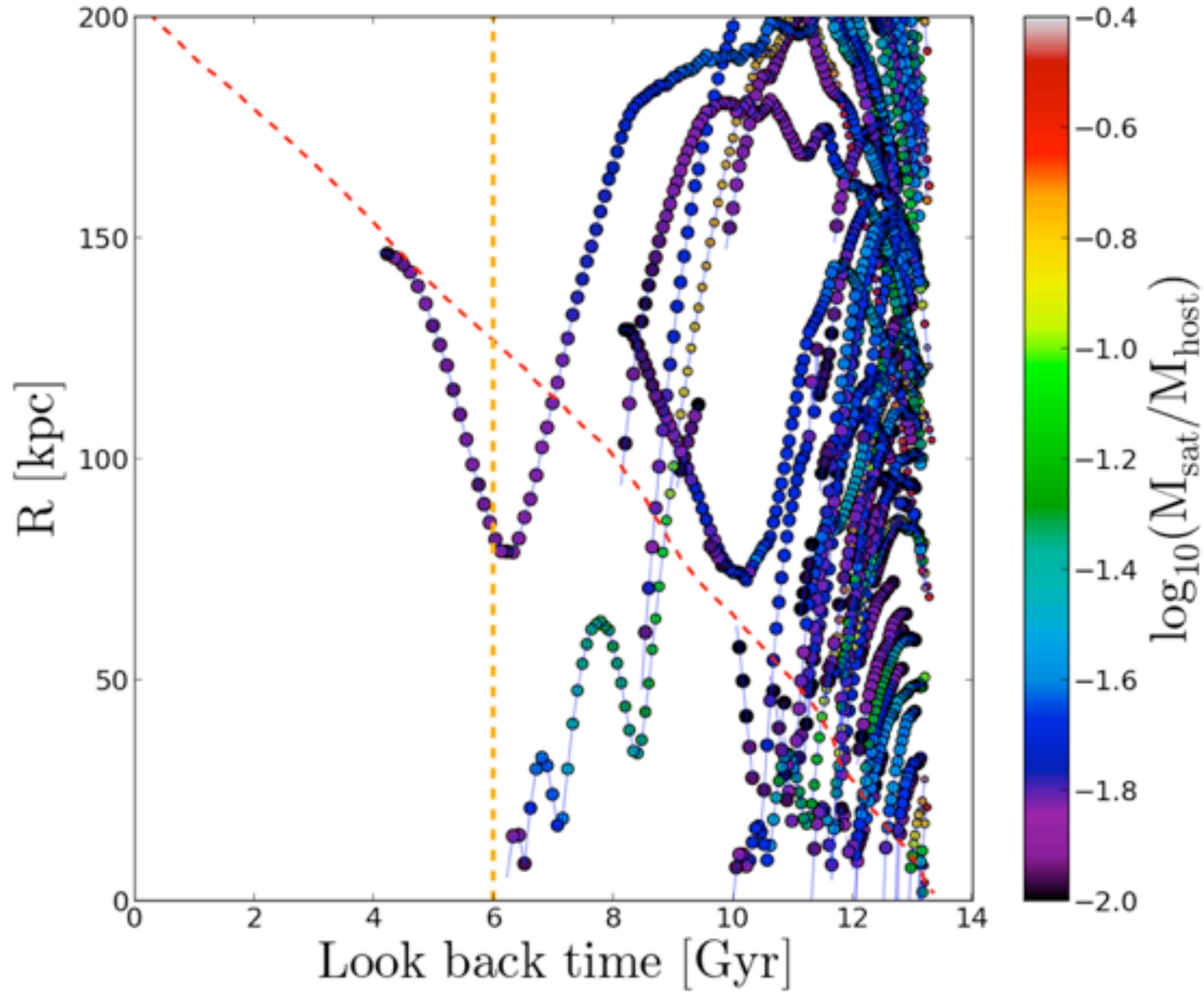




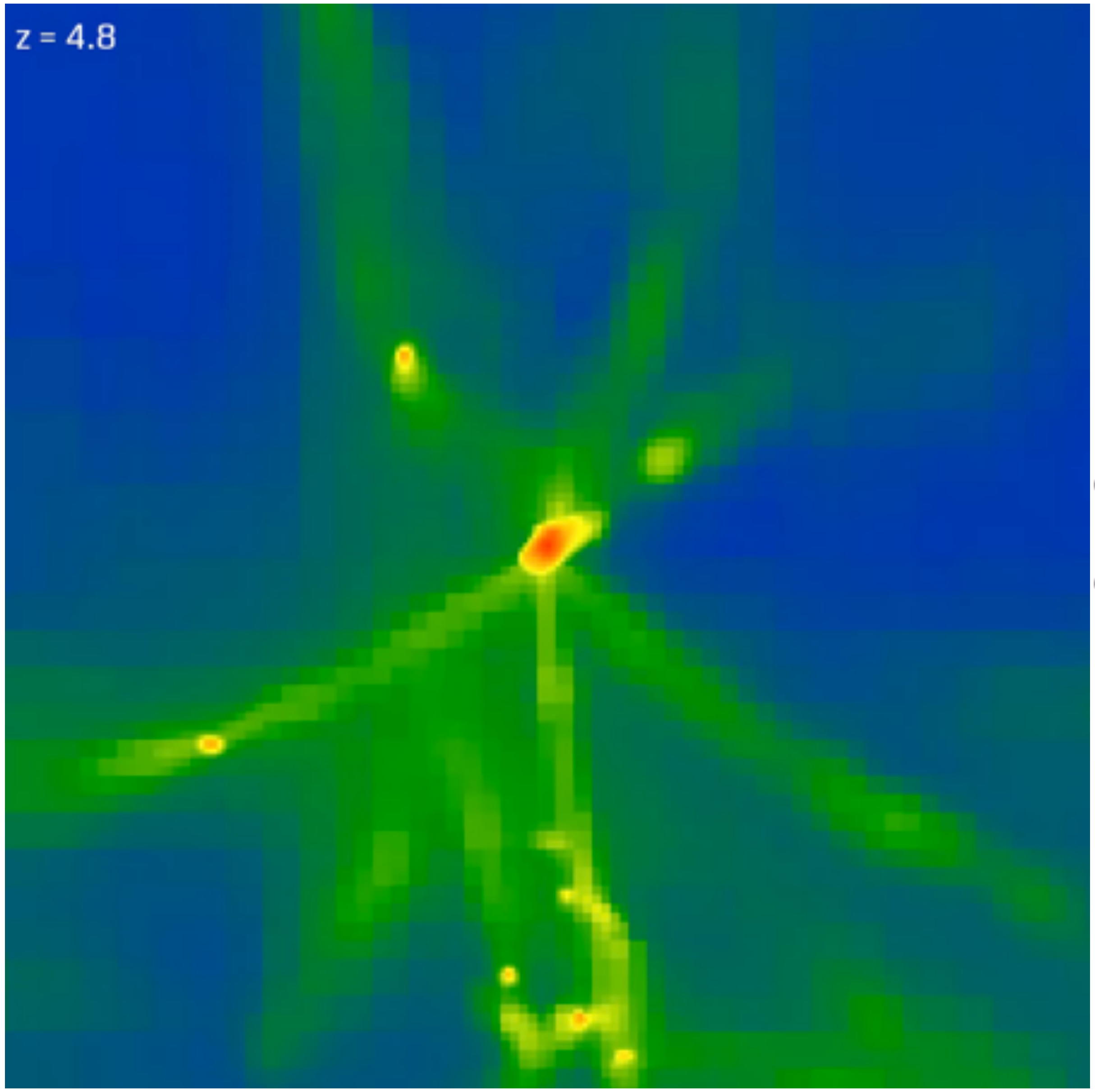
Merger tree

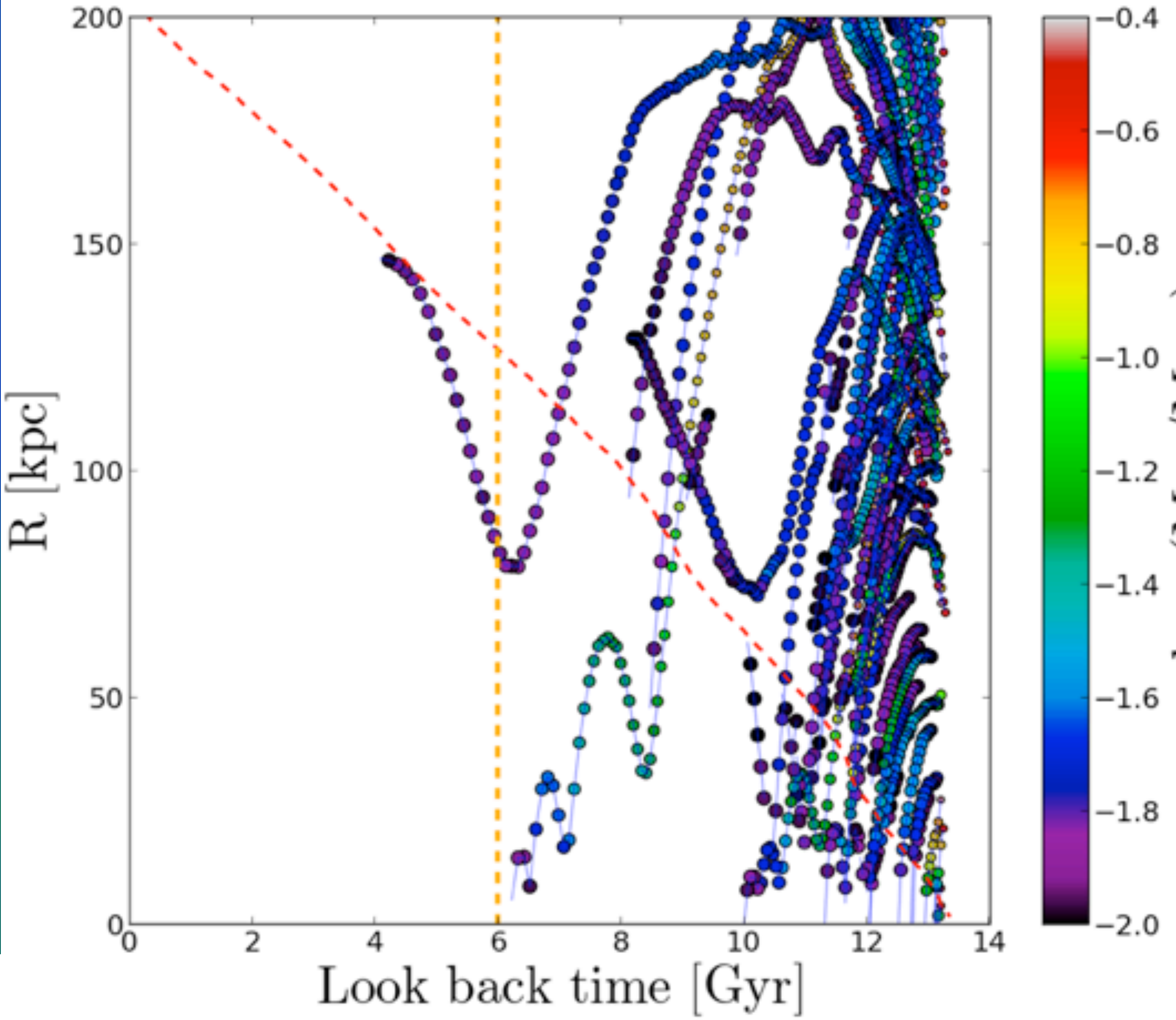


A better kind of merger analysis

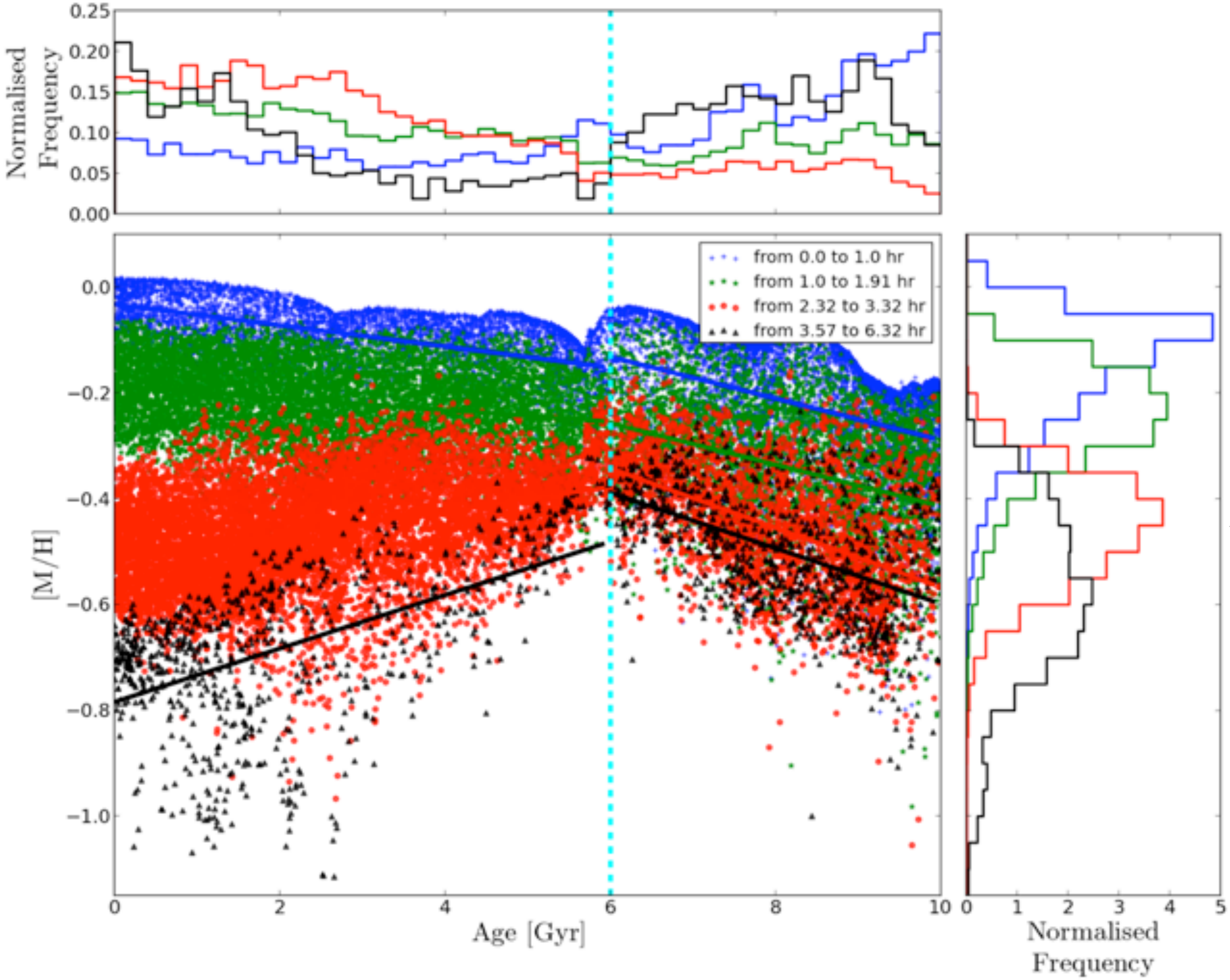


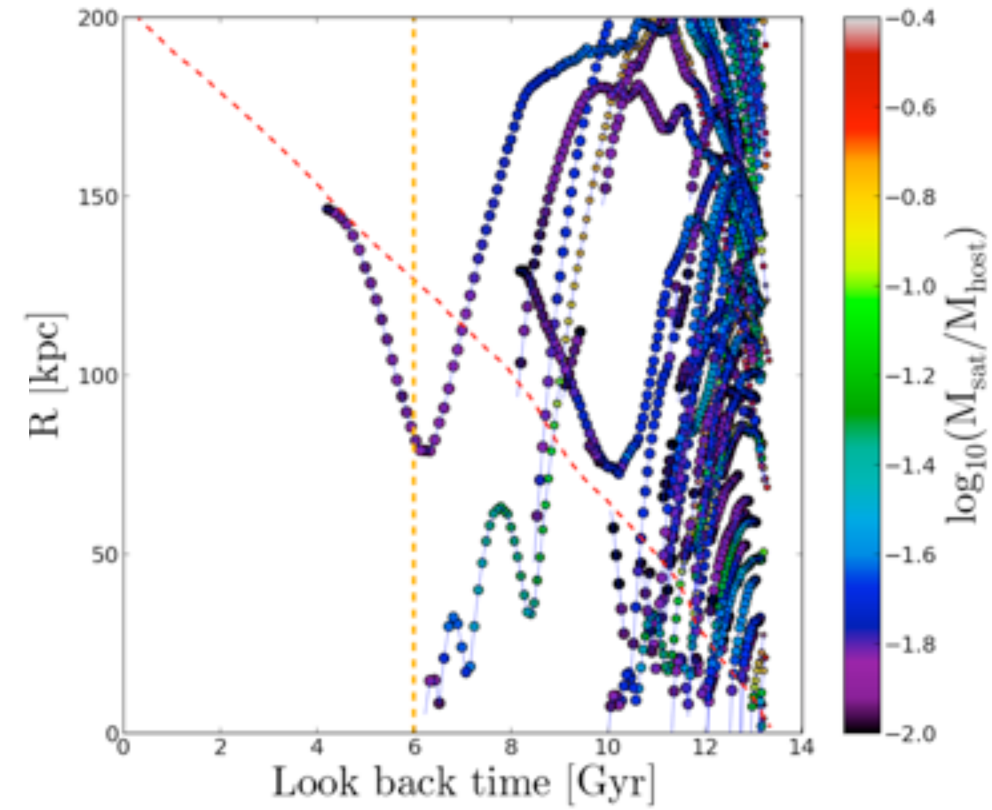
A better kind of merger analysis

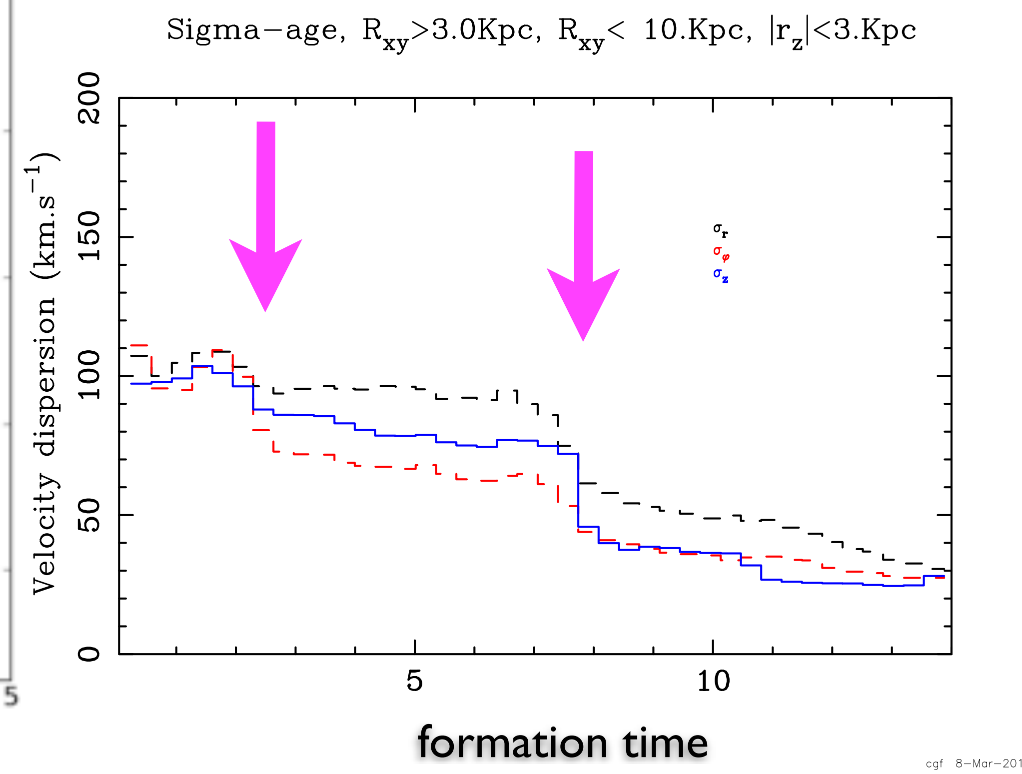




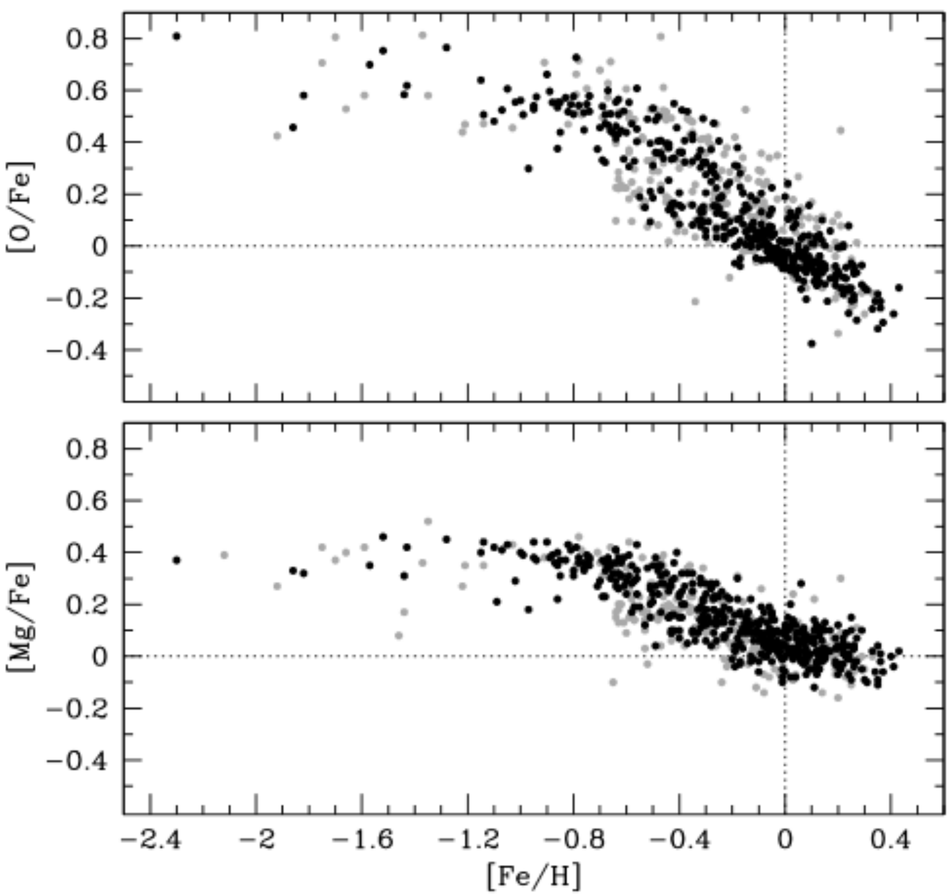
Interactions and the age-metallicity relation



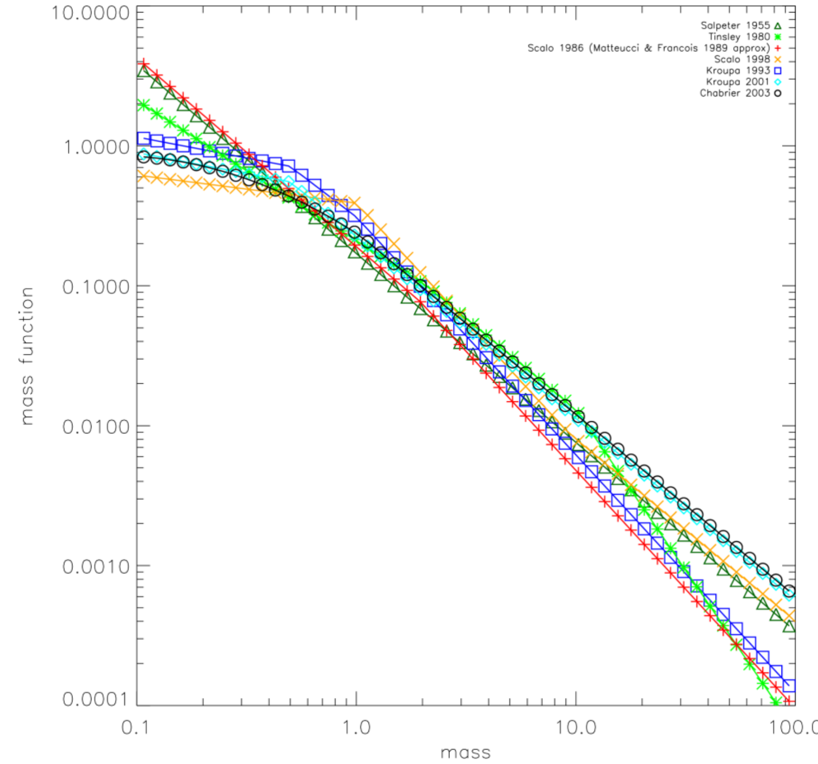


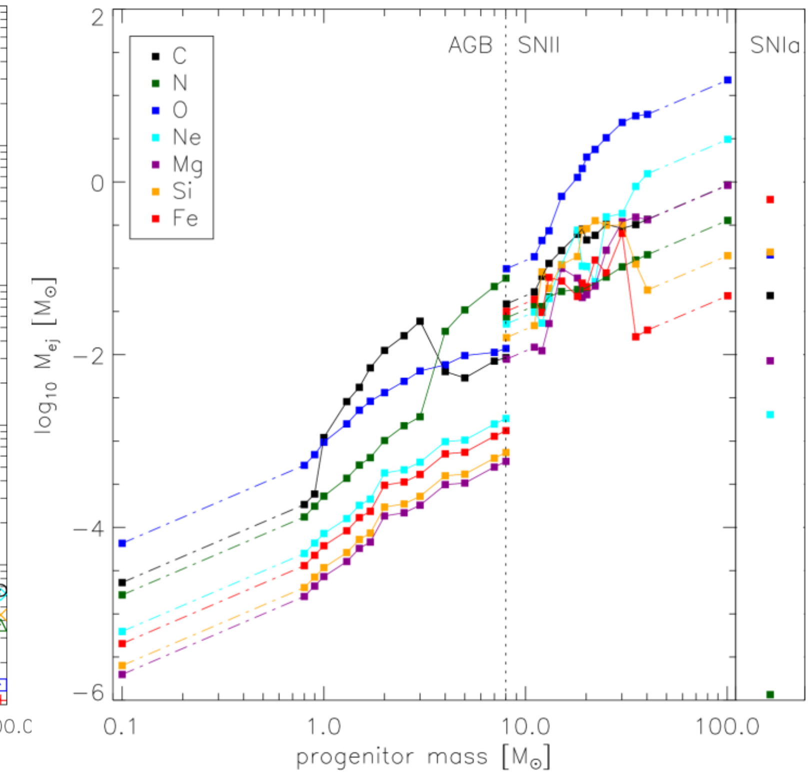


RAMSES-CH - chemodynamics

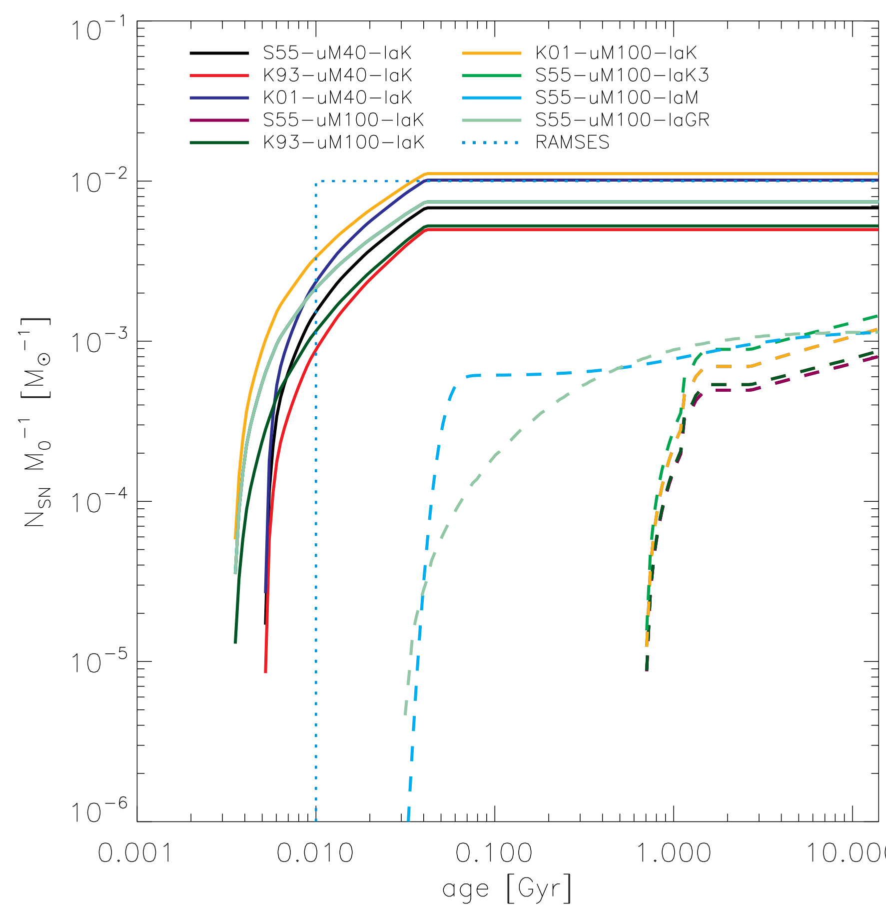


Bensby, Feltzing & Oey (2013)



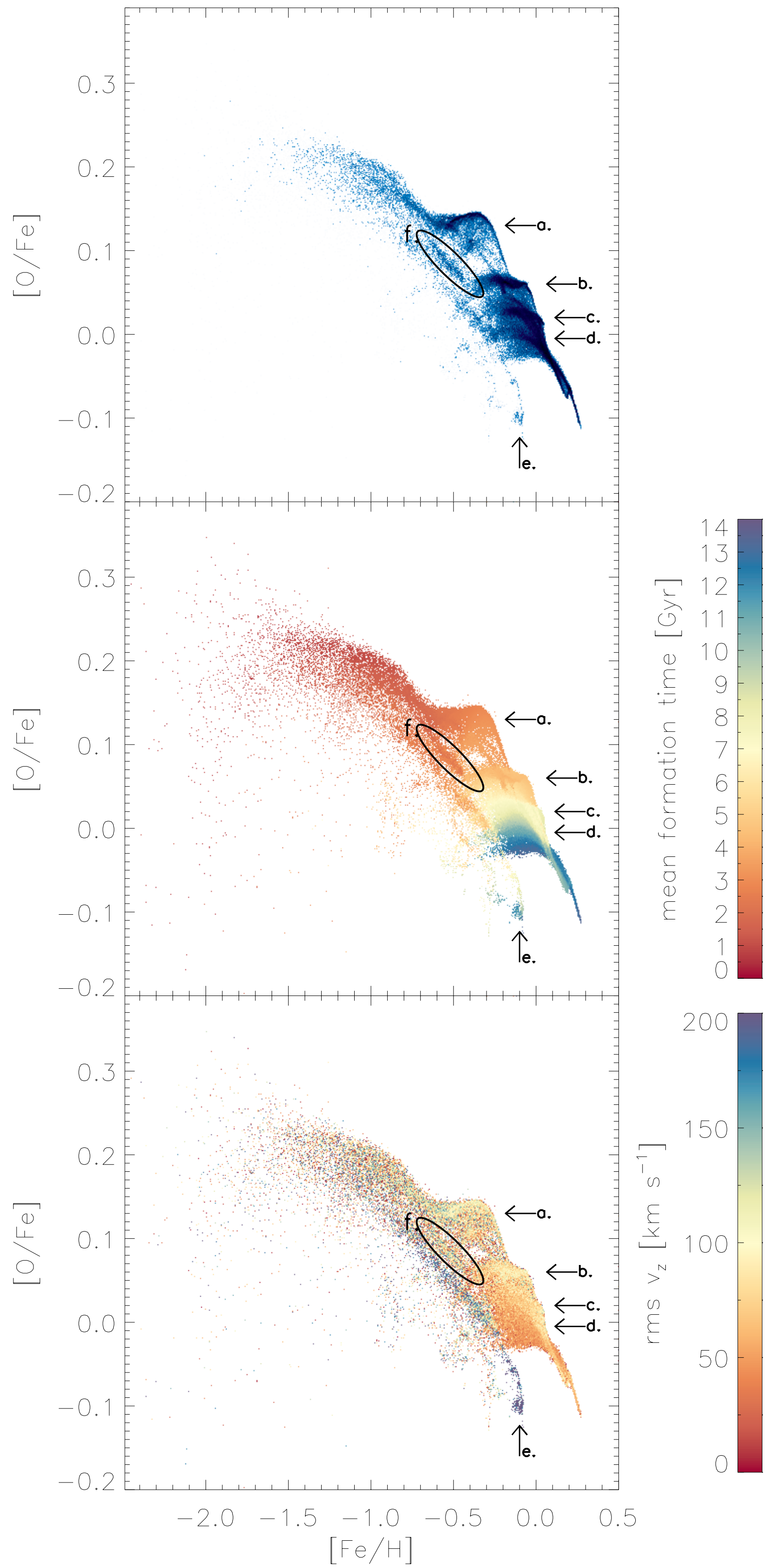


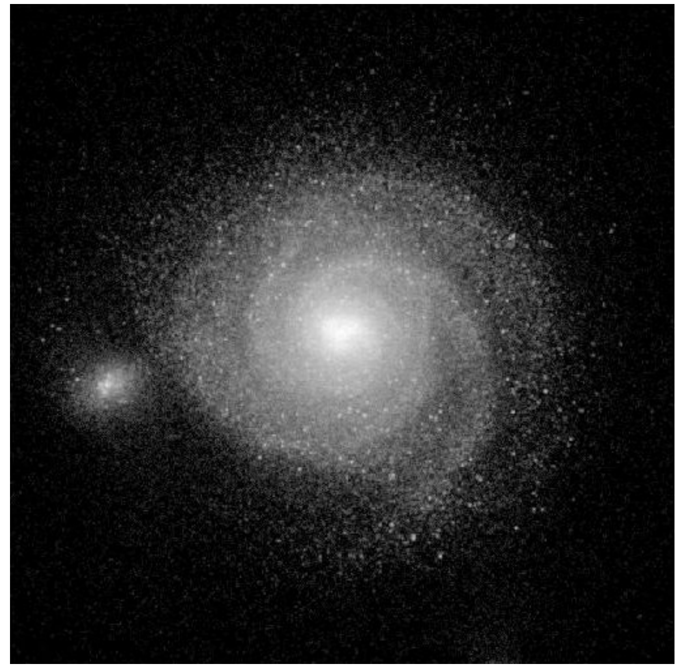
$$N_{\rm SNIa}(\tau_*) = M_0 \int_{m_{\rm P,u}}^{m_{\rm P,l}} \frac{\varphi(m)}{m} {\rm d}m \times \left[b_{\rm MS} \frac{\int_{MAX(m_{\rm MS,l}, m_{\rm TO})}^{m_{\rm MS,u}} \frac{\varphi(m)}{m} {\rm d}m}{\int_{m_{\rm MS,l}}^{m_{\rm MS,u}} \frac{\varphi(m)}{m} {\rm d}m} + b_{\rm RG} \frac{\int_{MAX(m_{\rm RG,l}, m_{\rm TO})}^{m_{\rm RG,u}} \frac{\varphi(m)}{m} {\rm d}m}{\int_{m_{\rm RG,l}}^{m_{\rm RG,u}} \frac{\varphi(m)}{m} {\rm d}m} \right]$$



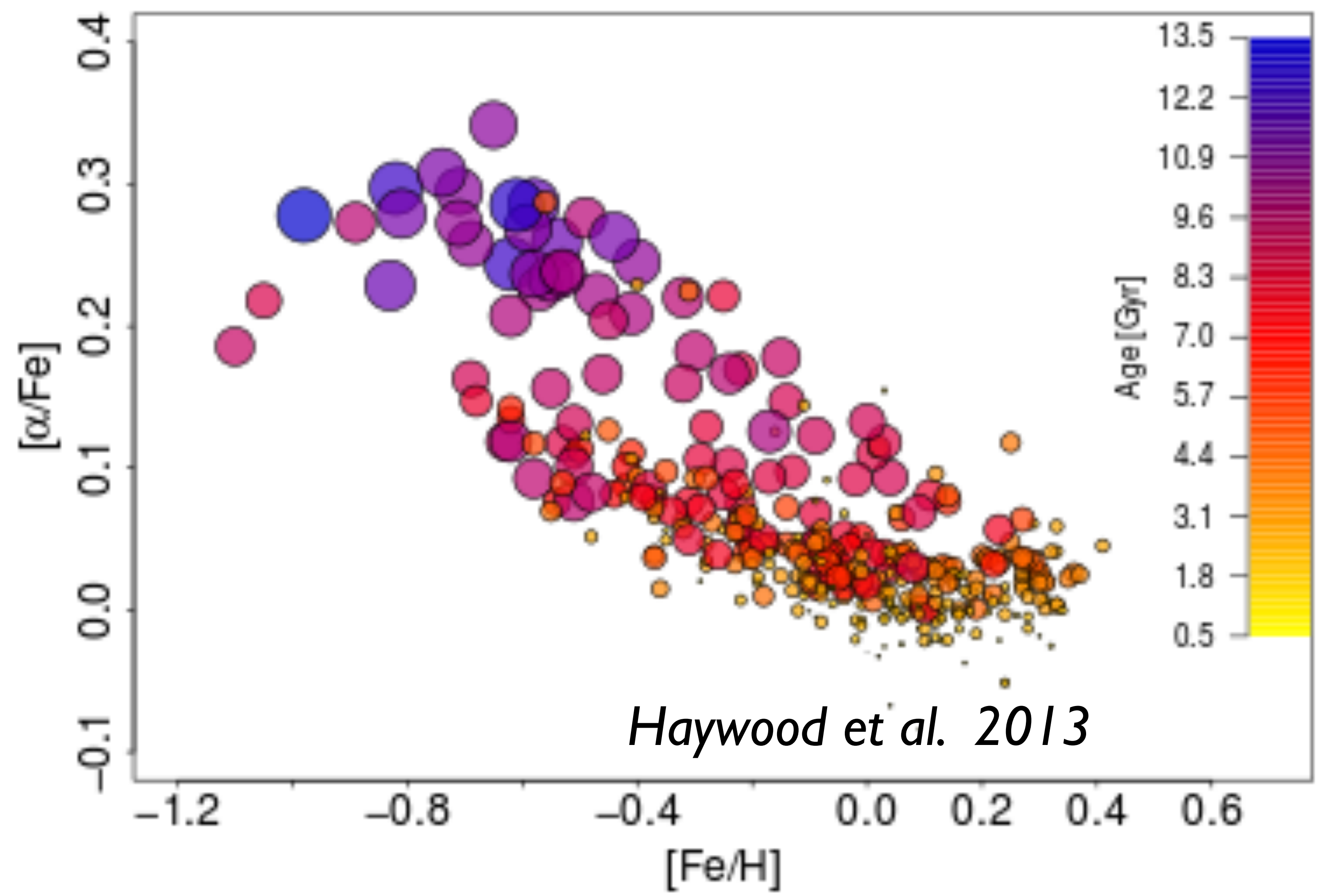
- Incorporated chemical evolution model into RAMSES
- Stellar populations now produce SNIa and AGB ejecta in addition to SNII
- Elements produced on differing timescales give rise to observed chemical evolution
- Used to probe uncertainties in the models

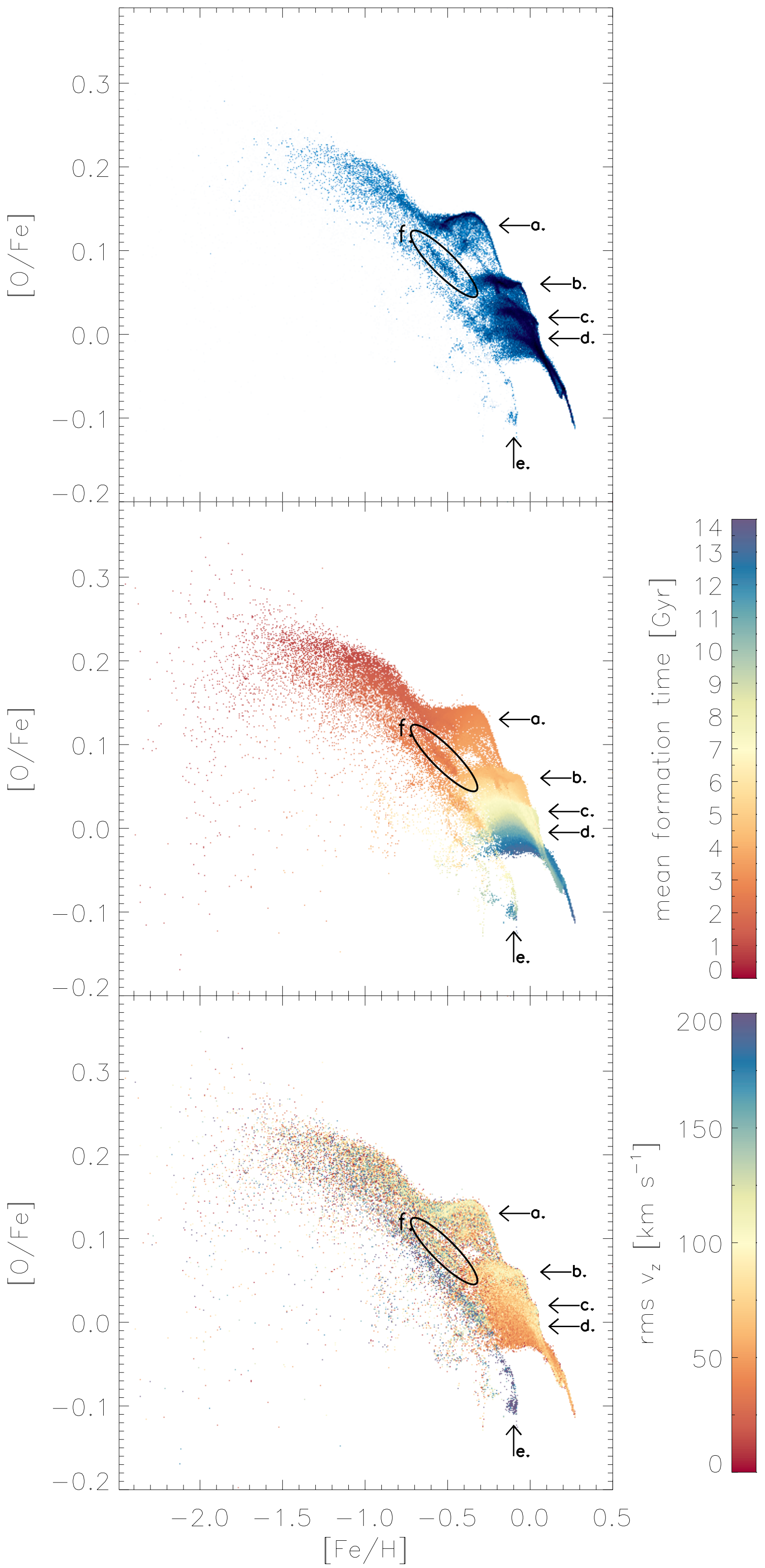
109 - numerical chemical evolution

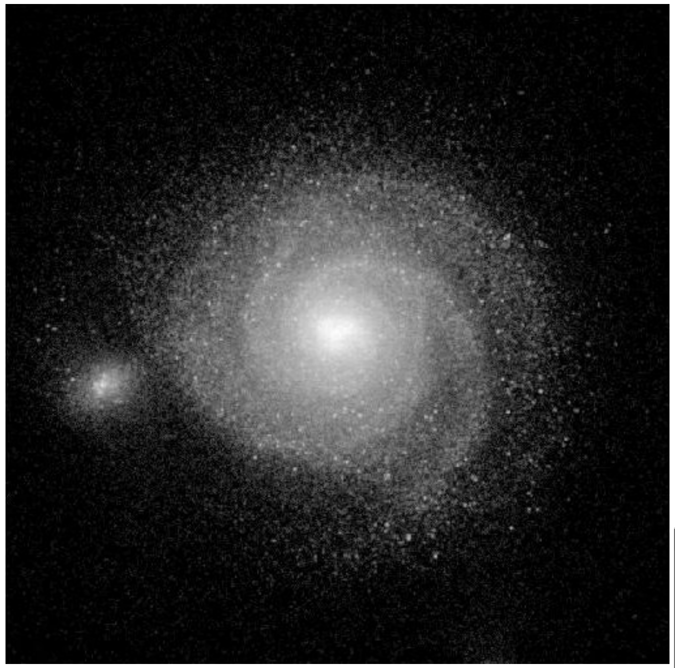




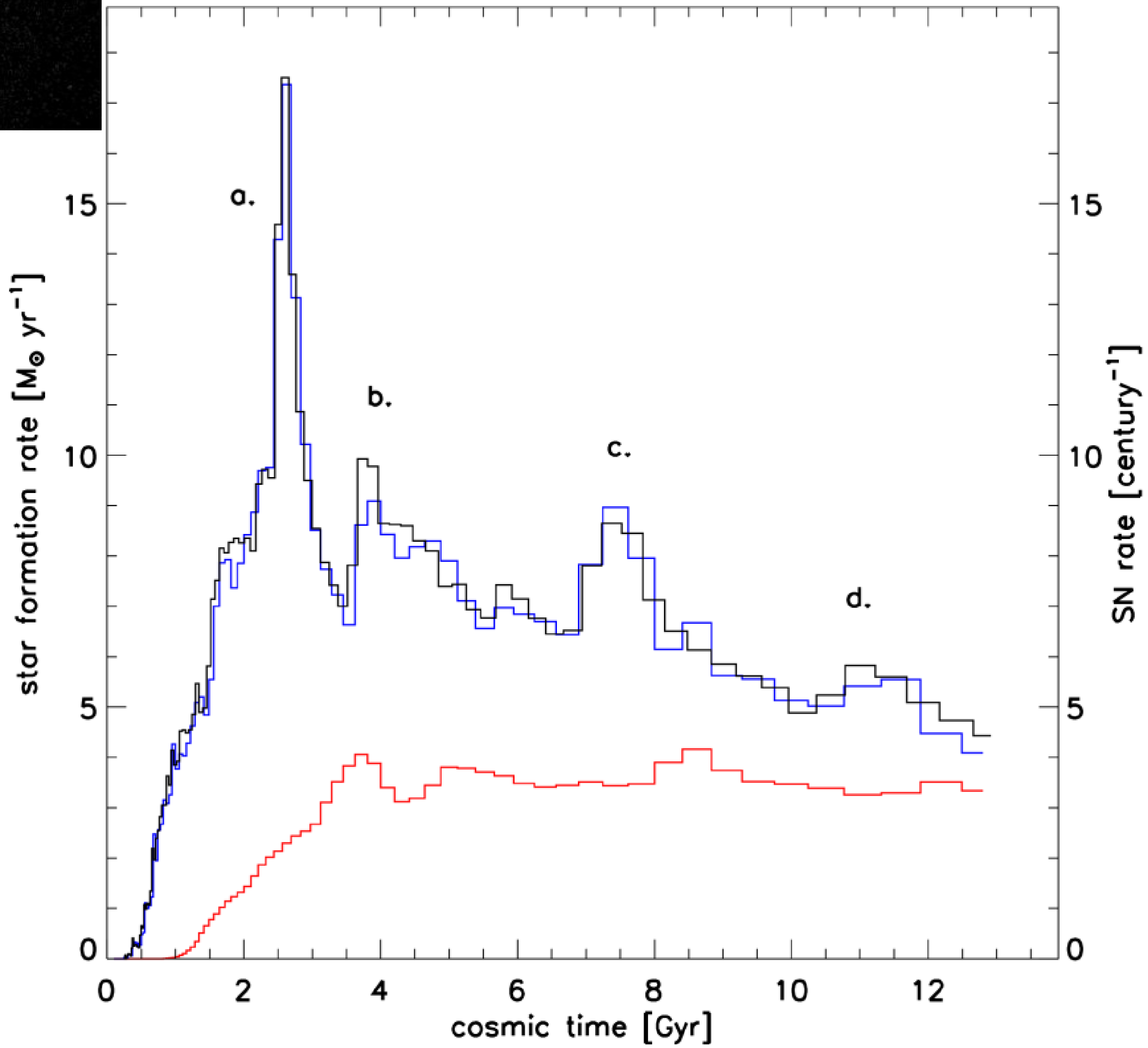
- Chemical evolution trends are followed
- Alpha-rich, Fe poor regions is older and kinematically hotter
- There is substructure in this plot...

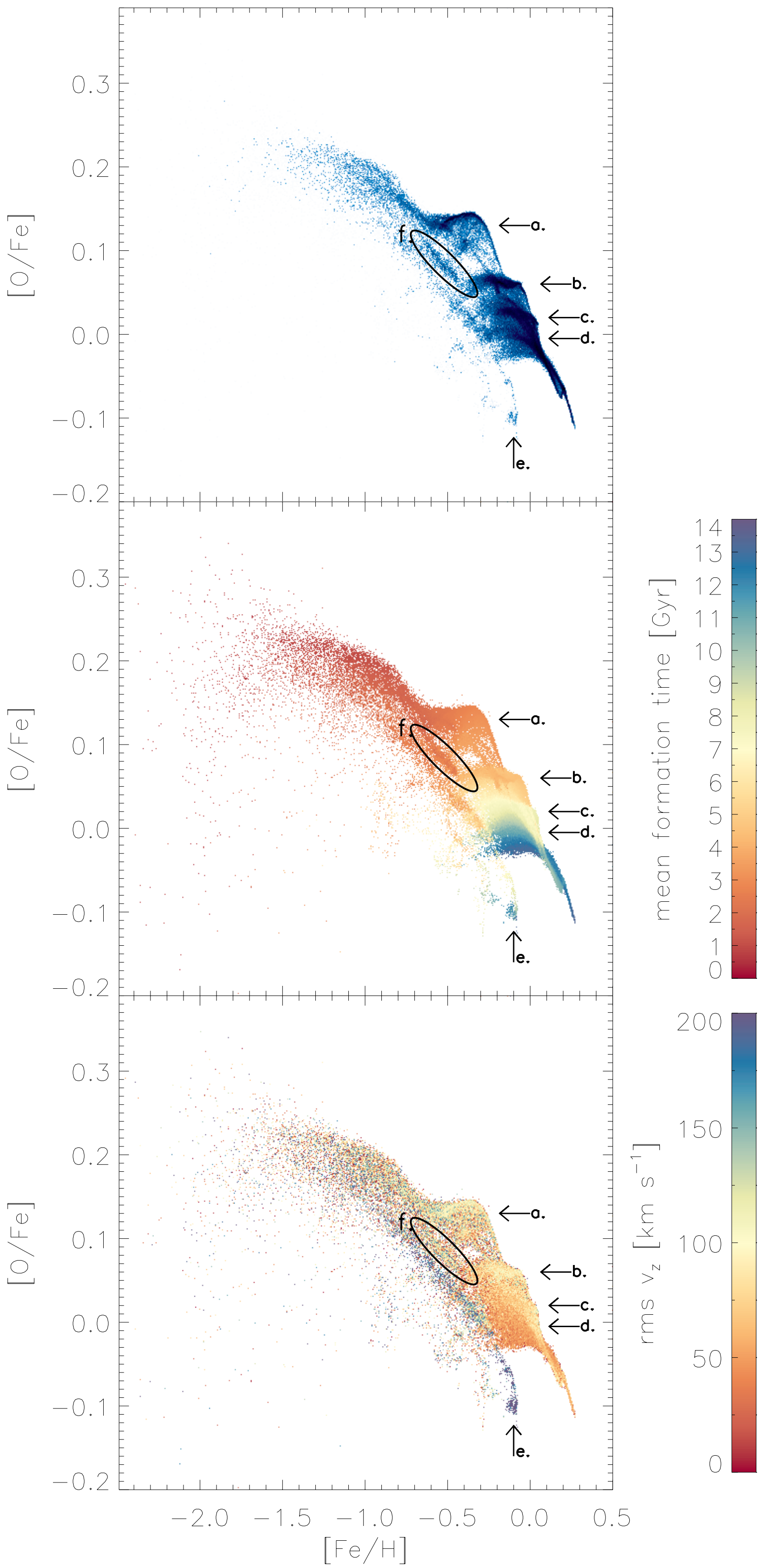


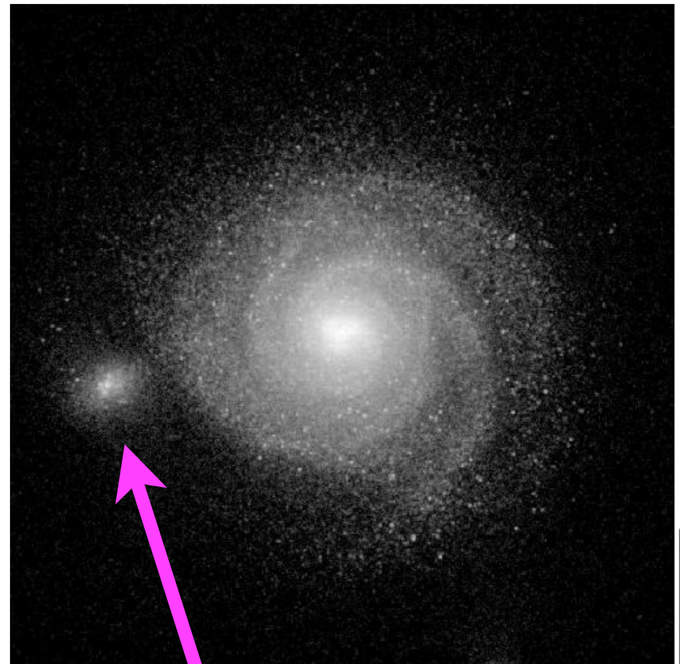




a, b, c, d are all peaks in star formation (minor mergers) which create abundance 'strata' (increasingly older and hotter)

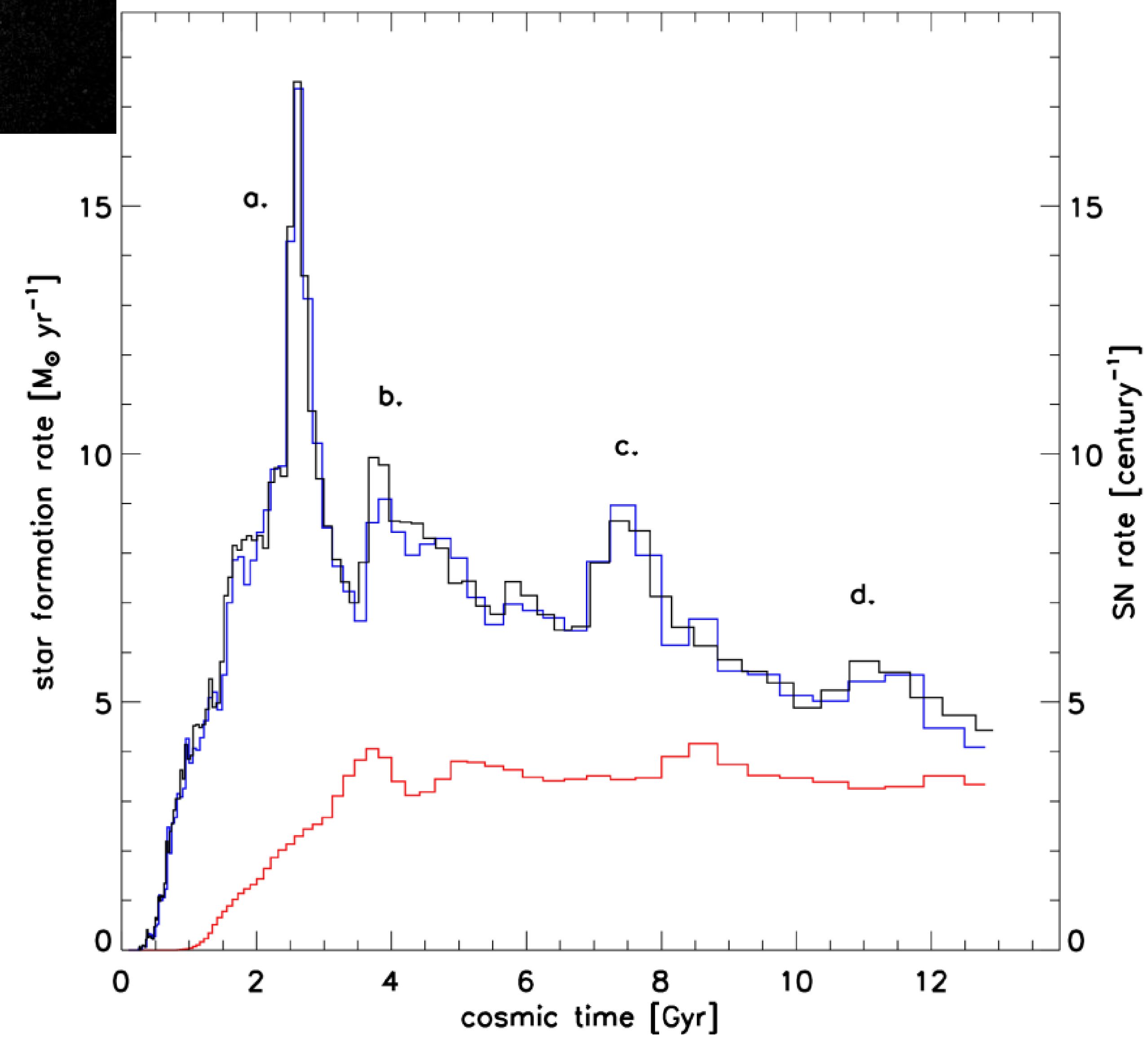




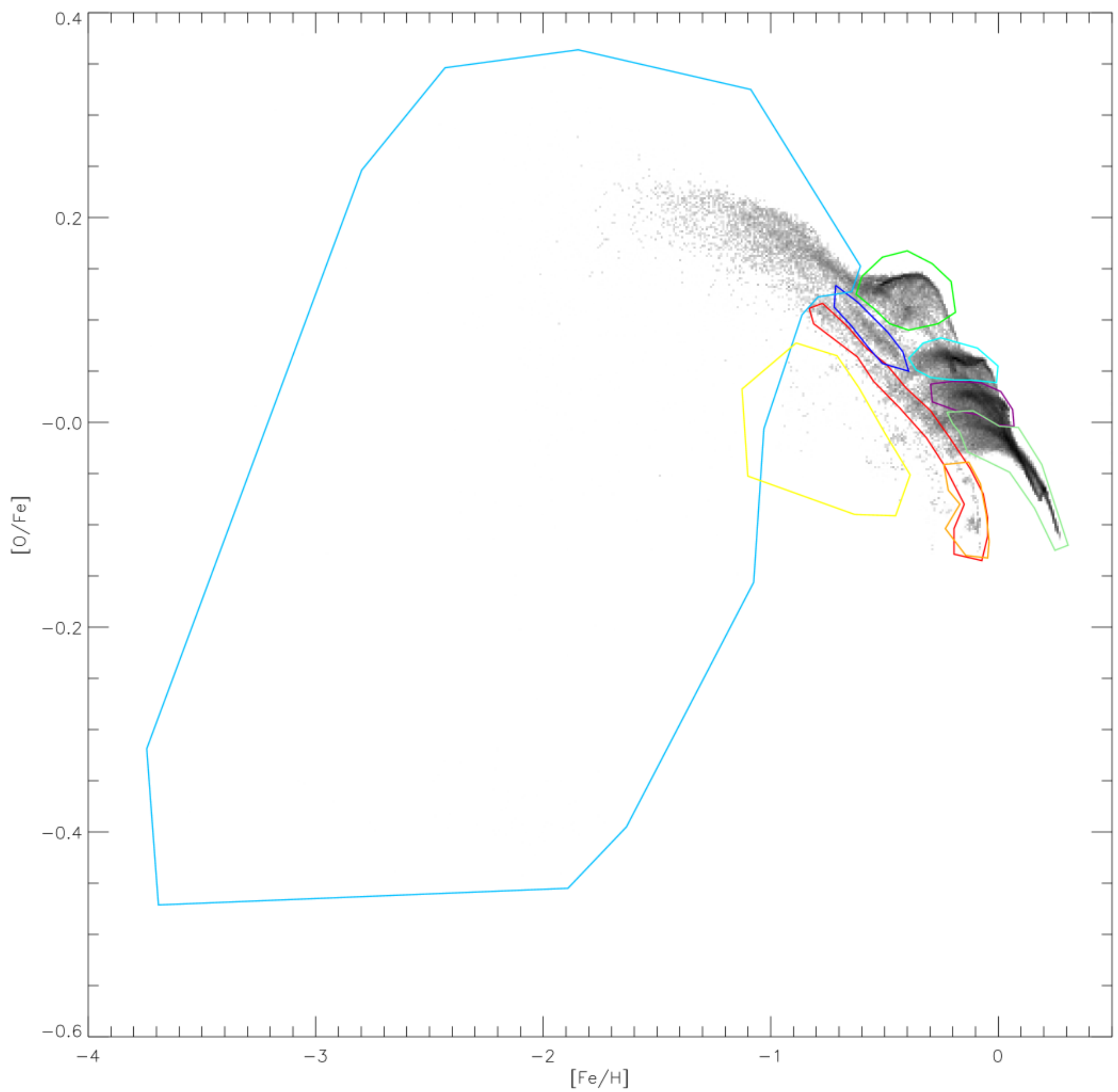


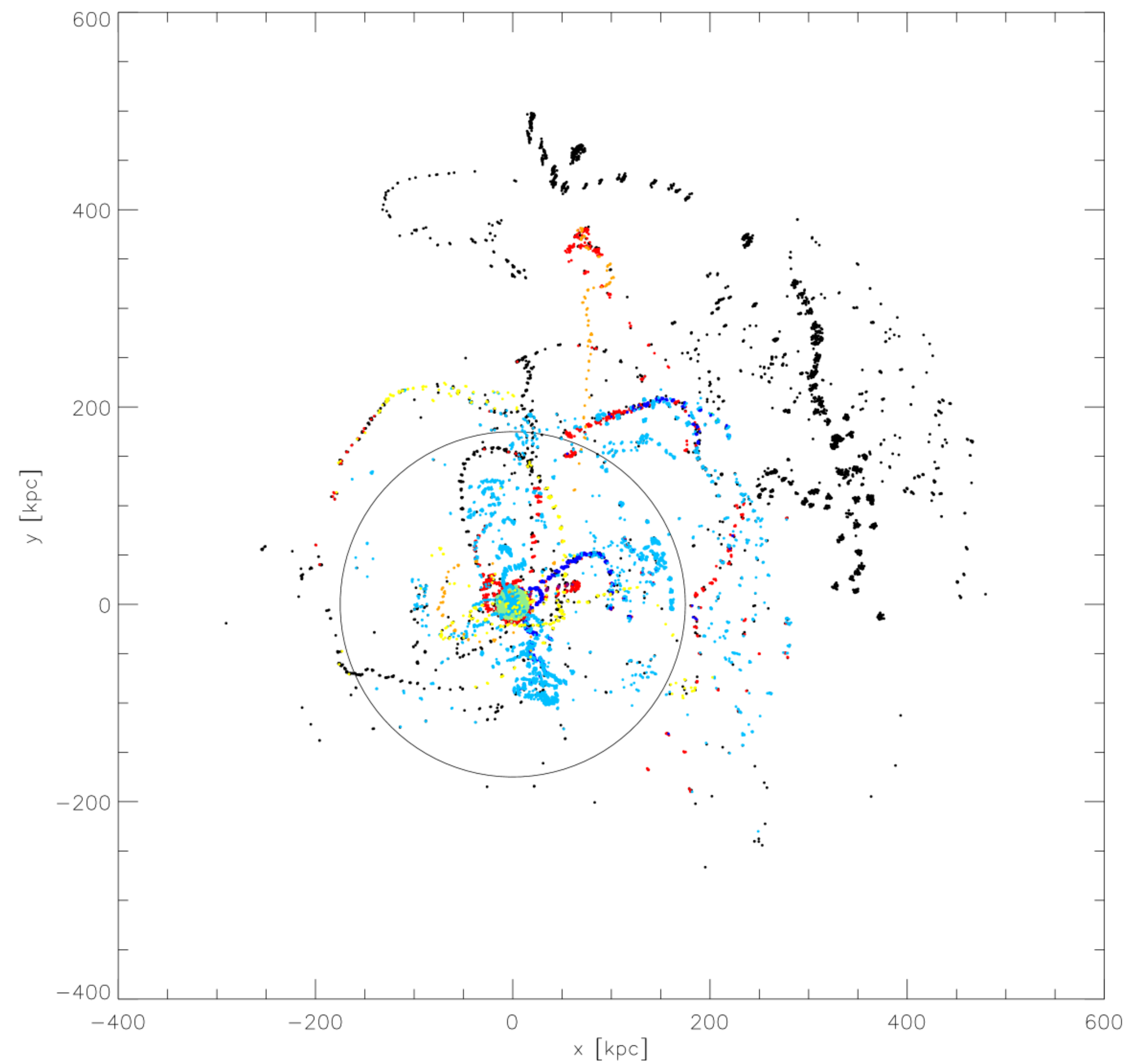
Feature e. is the satellite
It will one day merge but it's chemical abundance signature will remain the same

a, b, c, d are all peaks in star formation (minor mergers) which create abundance 'strata' (increasingly older and hotter)



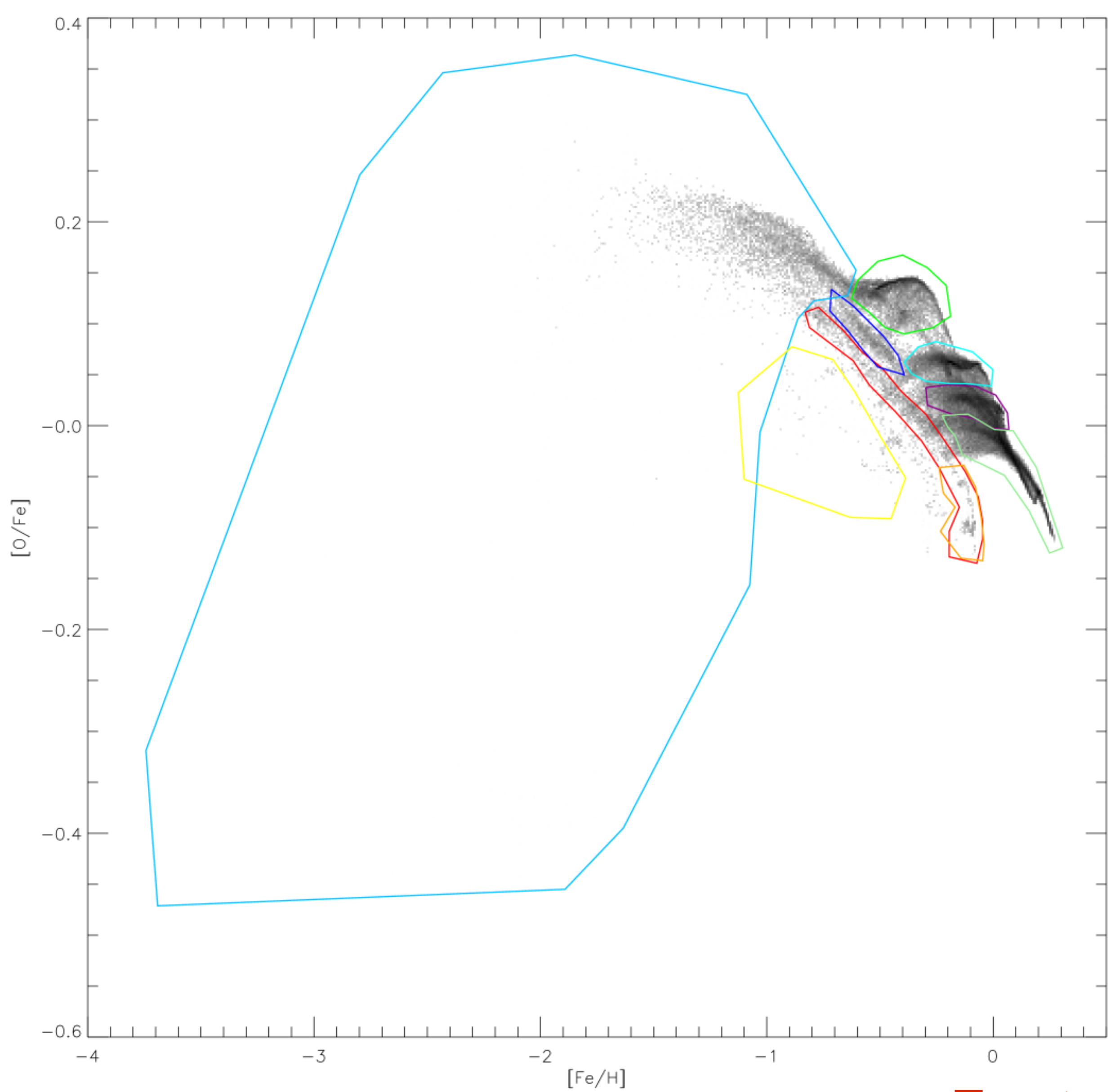
Decomposing abundance space

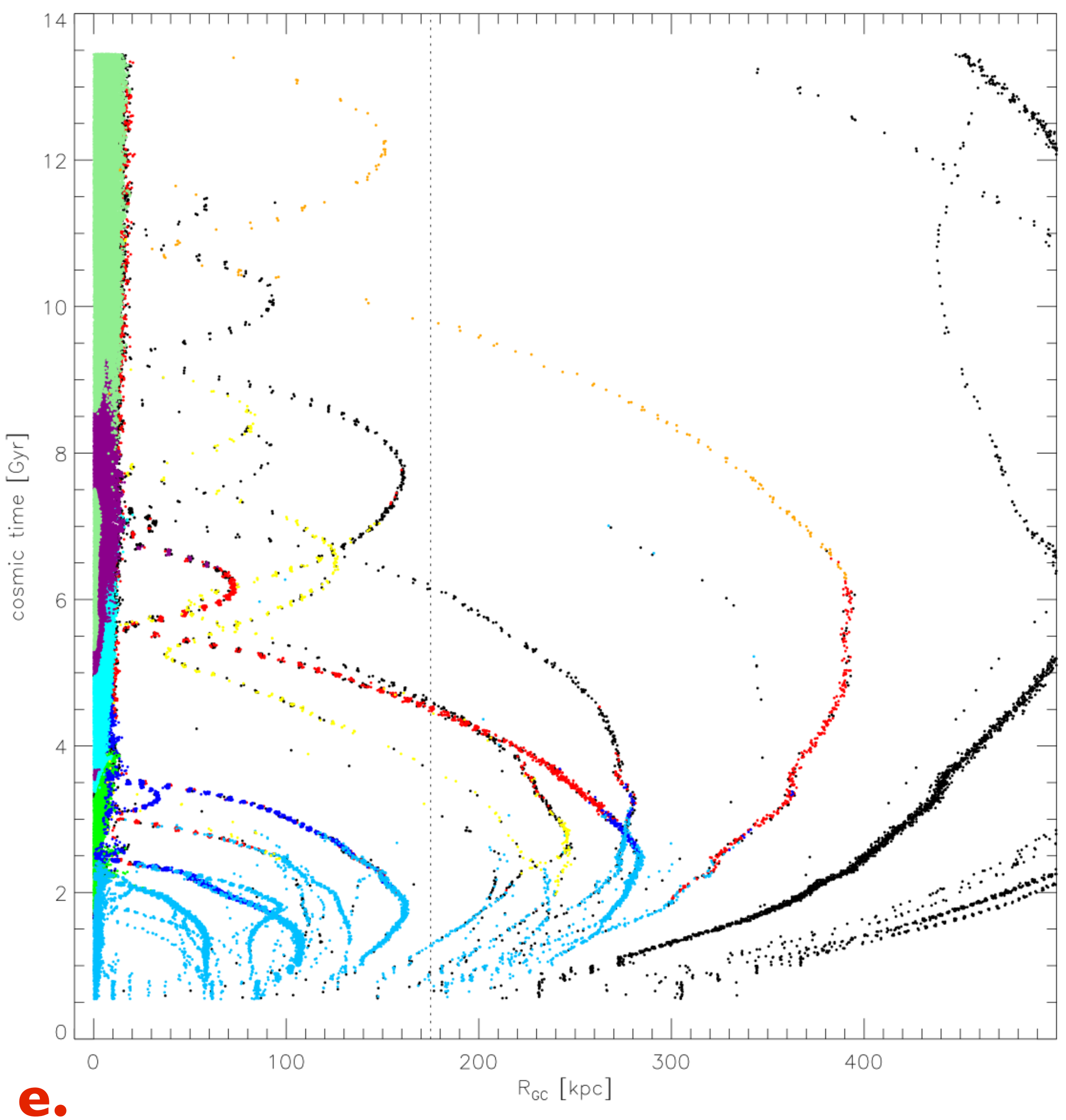




Decompose the abundance space into segments and trace those stars back to where they were born

Decomposing abundance space





Many of these weren't born in the galaxy

Stars born in satellites at later stages

Feature e. stars actual come from two accreted satellites

These are in-situ disk stars formed at different times

Very low mass satellites?

Conclusions

- Galaxies do form inside-out but a short period of extended star formation coupled with migration results in an old disk outside the young star-forming disk
- The edge of the young star forming disk results in a type-II break
- Small mergers can dilute metals (temporarily), increase SFR, excite kinematics and leave chemical imprint of accreted stars
- Star formed prior to mergers have well-mixed AMR in different radial bins, those formed after are more distinct
- The AMR can invert at greater radii: metal enrichments + migration overtakes inside-out formation
- We have a range of break types to look at and only really understand type-II right now
- Ruiz-Lara, Few, Gibson et al. (in prep)

Thank you for your time,
questions?
comments?
statements?

“true collaboration”

Image Credits
NGC2207: ESO
The Mice, Interacting Galaxies: NASA/HST
Reference map of local volume: Andrew Colvin

Selene movie: Ben Thompson, made using yt.