ENV 2022

Simulating Jellyfish Galaxies
-A Case Study for a Gas-Rich Dwarf Galaxy-

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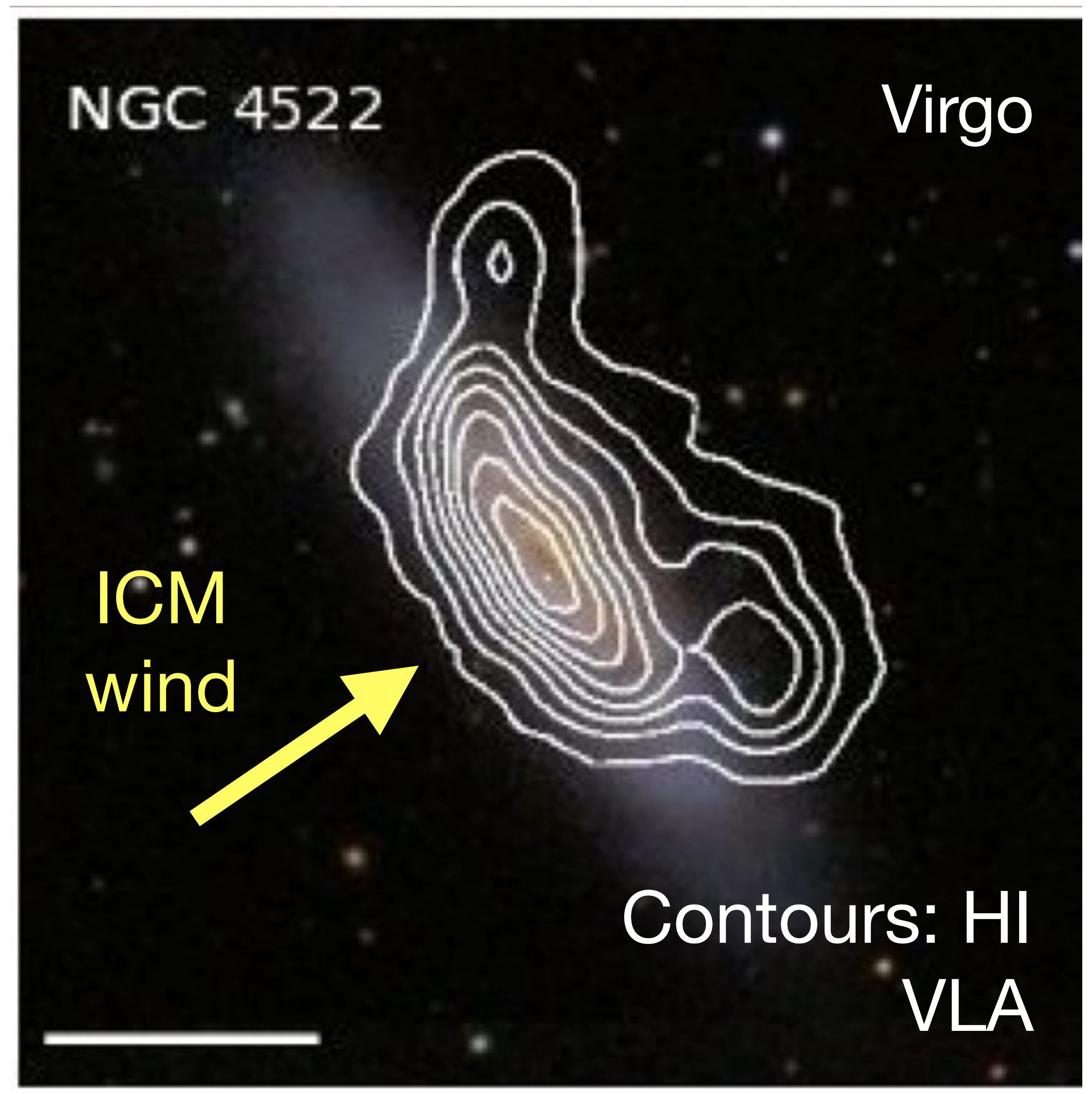
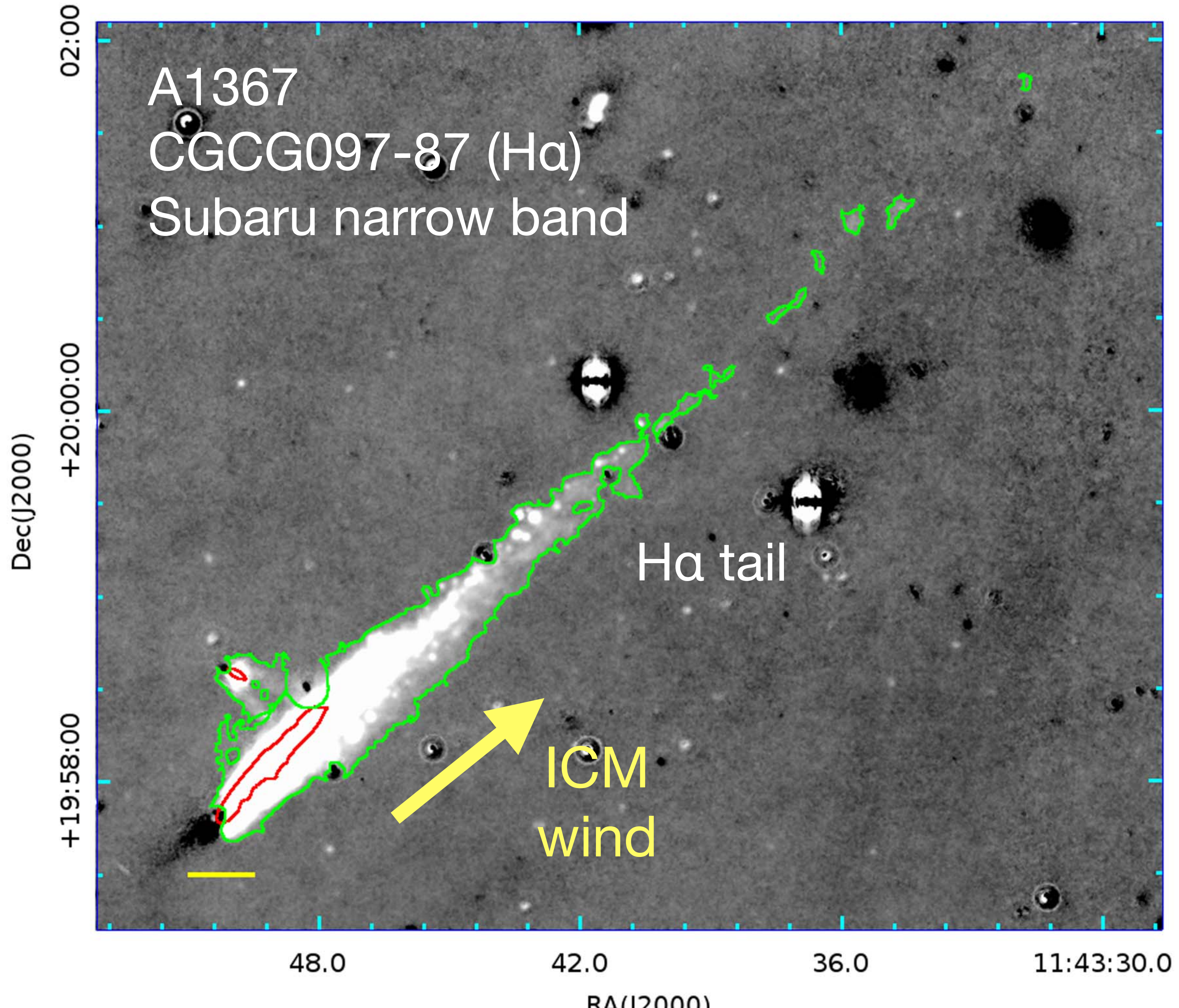
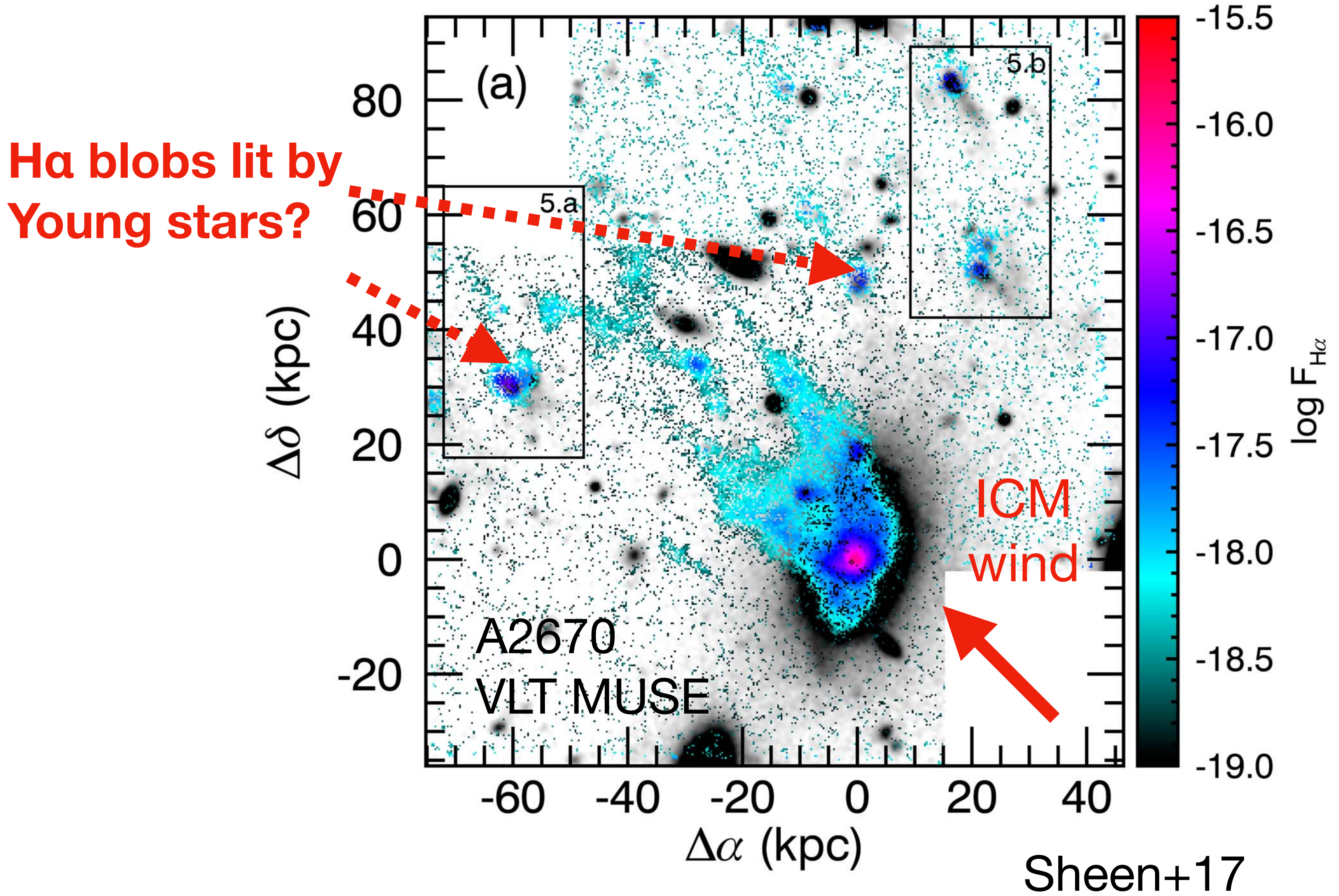
- Ram pressure stripping
  - Hydrodynamical process that can directly blow the ISM away from galaxies
    $$P_{\rm ram} \sim \rho_{\rm ICM} v^2$$ (Gunn&Gott 72)
  - Stronger in denser environments => mainly effective in galaxy clusters
  - Characteristic tails are observed in multiple bands
  - Young stars are detected in the wakes of some ram pressure stripped (RPS) galaxies => evidencing the presence of molecular clumps?



Chung+09

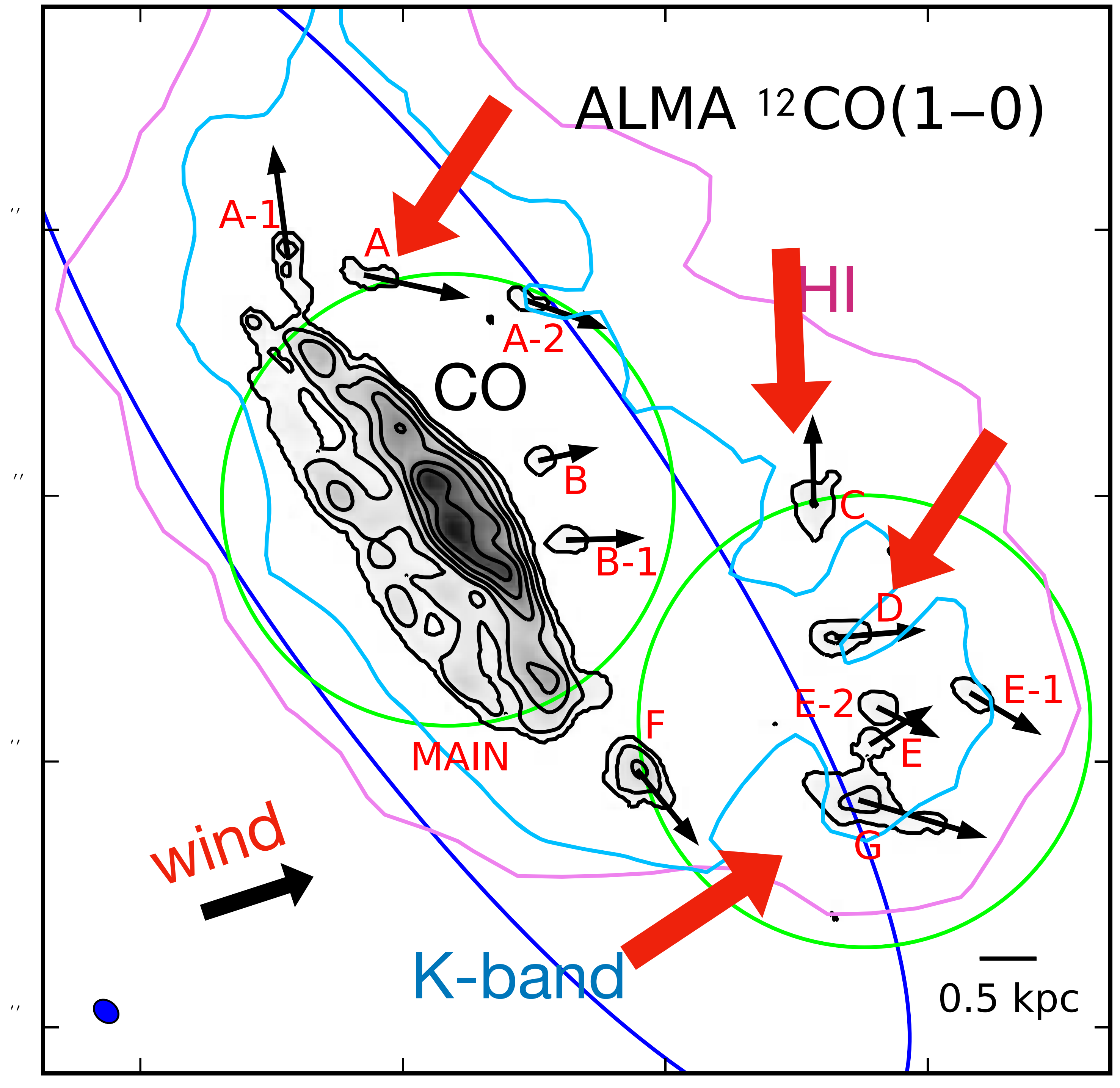


Yagi+17

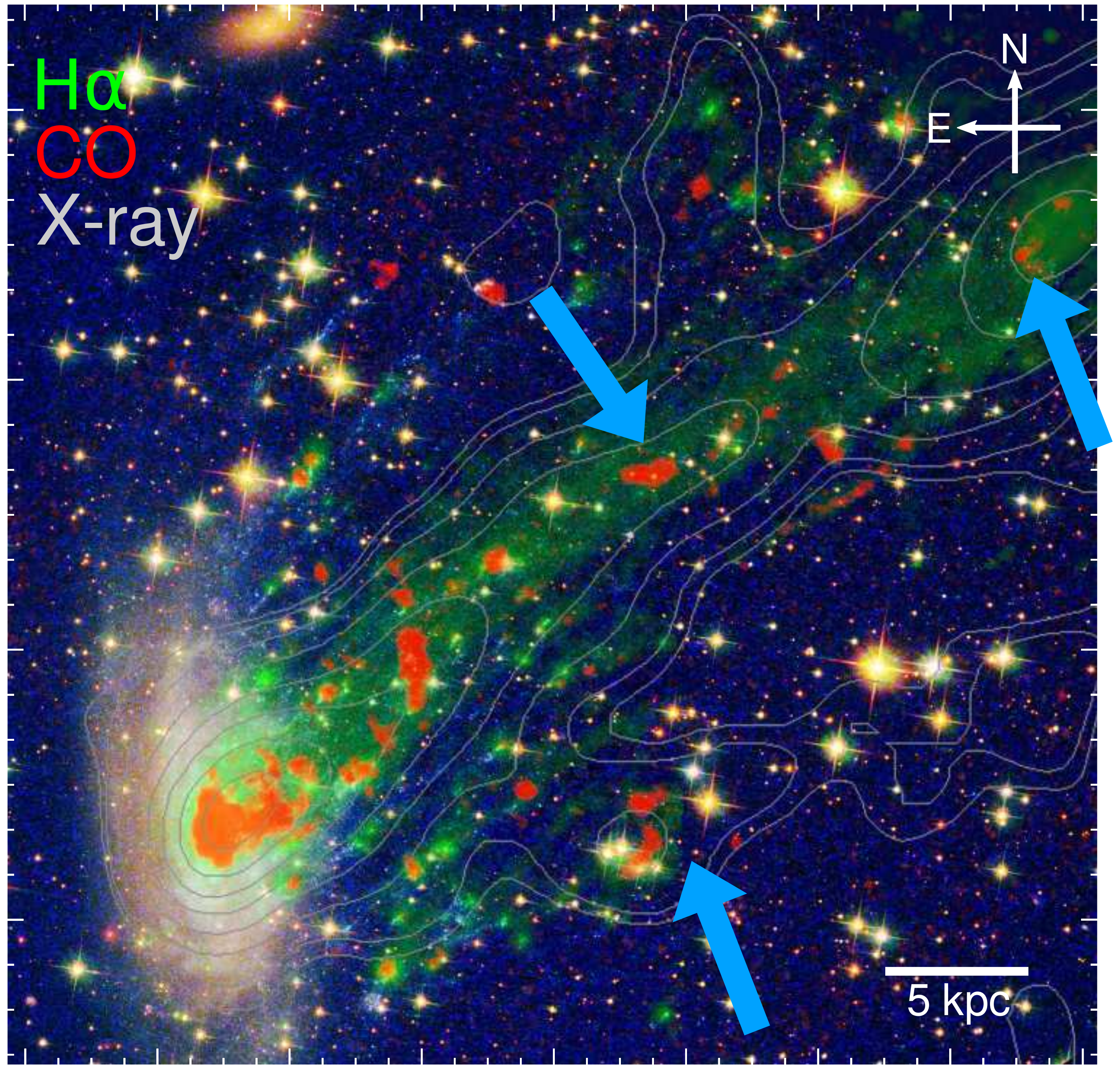


Sheen+17

- Multiphase nature of RPS galaxies
  - Extra-planar features are detected both in HI and CO
  - RPS tails are also multiphase (HI, CO, Hα, and X-ray)
    - A few RPS galaxies have $M_{H_2} \sim 10^9 M_\odot$ in their tails

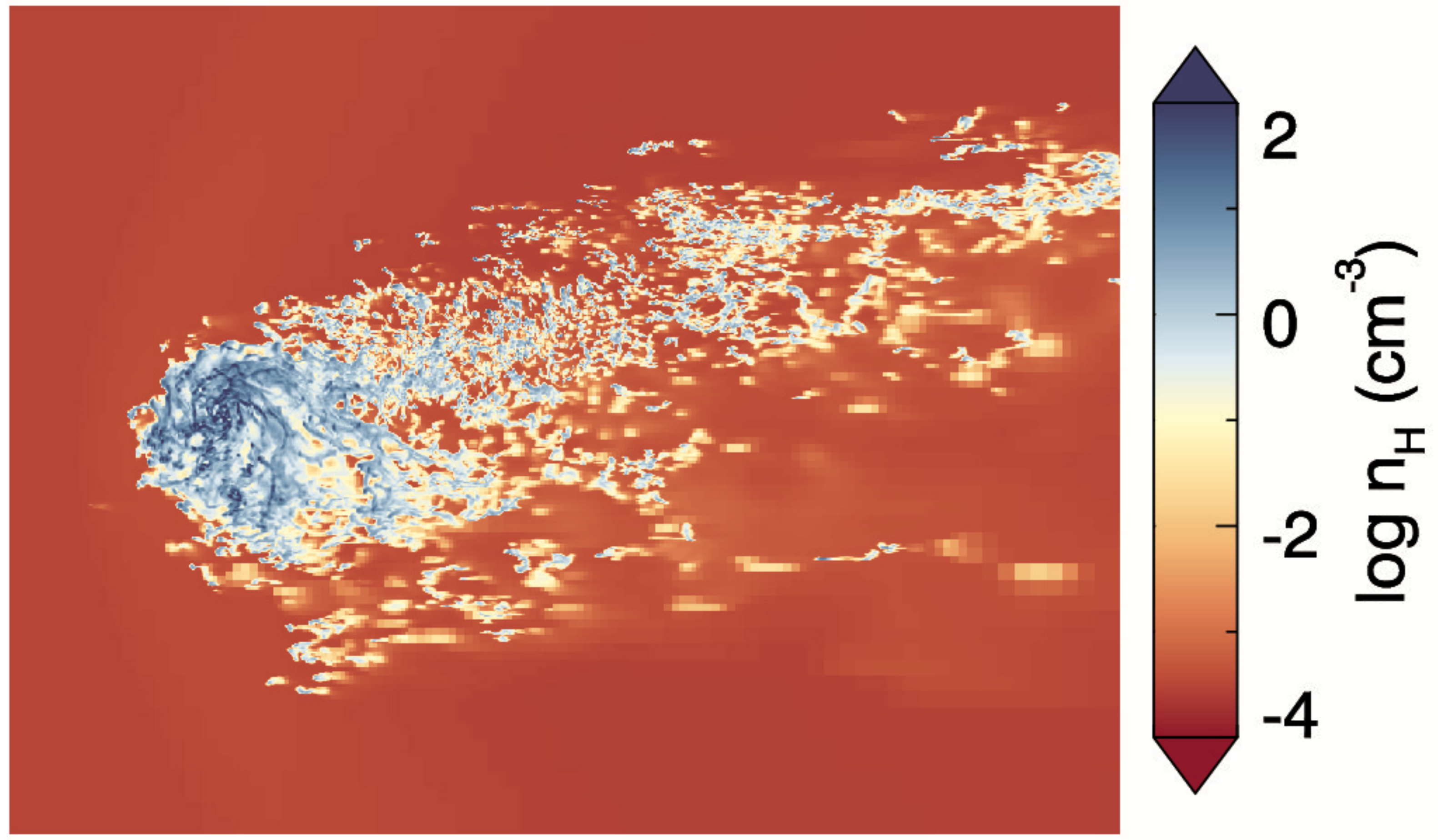


NGC4522 in Virgo cluster
Lee & Chung 18

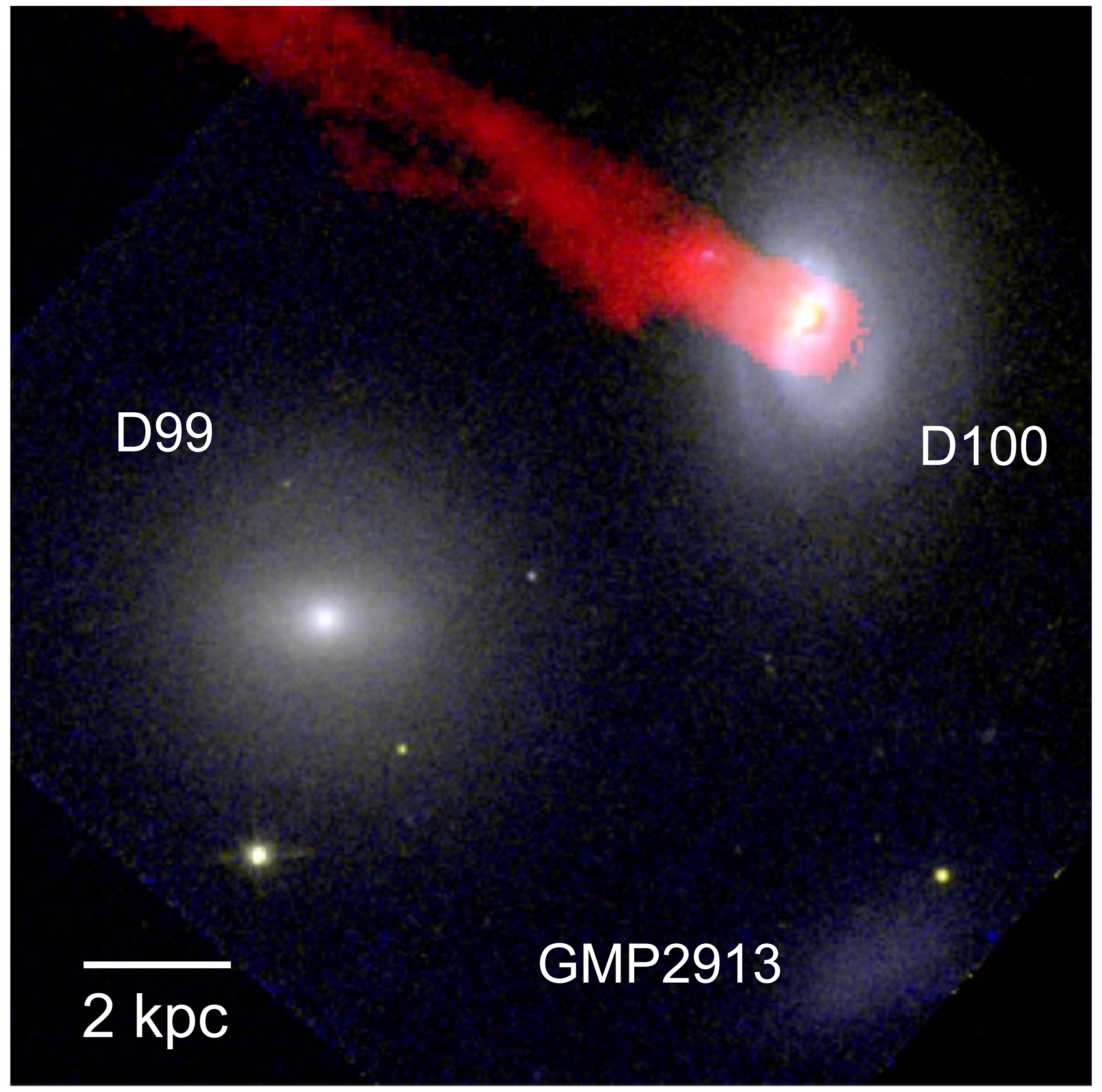


ESO137-001 in Norma cluster
Jachym+19

- Impact of ram pressure on multi-phase disks
    - Lee+20 attempted to examine the origin of jellyfish features using Radiation-Hydrodynamic (RHD) simulations
    - No molecular clumps form in the RPS tails of typical dwarf galaxies
- RPS galaxies with abundant molecular tails
    - ESO137-001 (Jachym+19), D100 (Jachym+17), JO201, JO204, JO206, JW100 (Moretti+18) : $M_{H_2} \sim 10^9 M_\odot$ estimated in their tails
    - Stellar mass varies (2×10^9-3×10^{10} $M_\odot$), but they are commonly gas-rich in their disks



RPS galaxy in an RHD simulation
Lee+20



D100 in the Coma cluster
Jachym+17

- Key motivation
  - Molecular-rich tails are found behind gas-rich disks
    - Does the plenty ISM play a critical role in the development of multiphase tails after stripping?

- Methodology
  - RHD simulations for a gas-rich galaxy experiencing strong ram pressure in an idealized environment

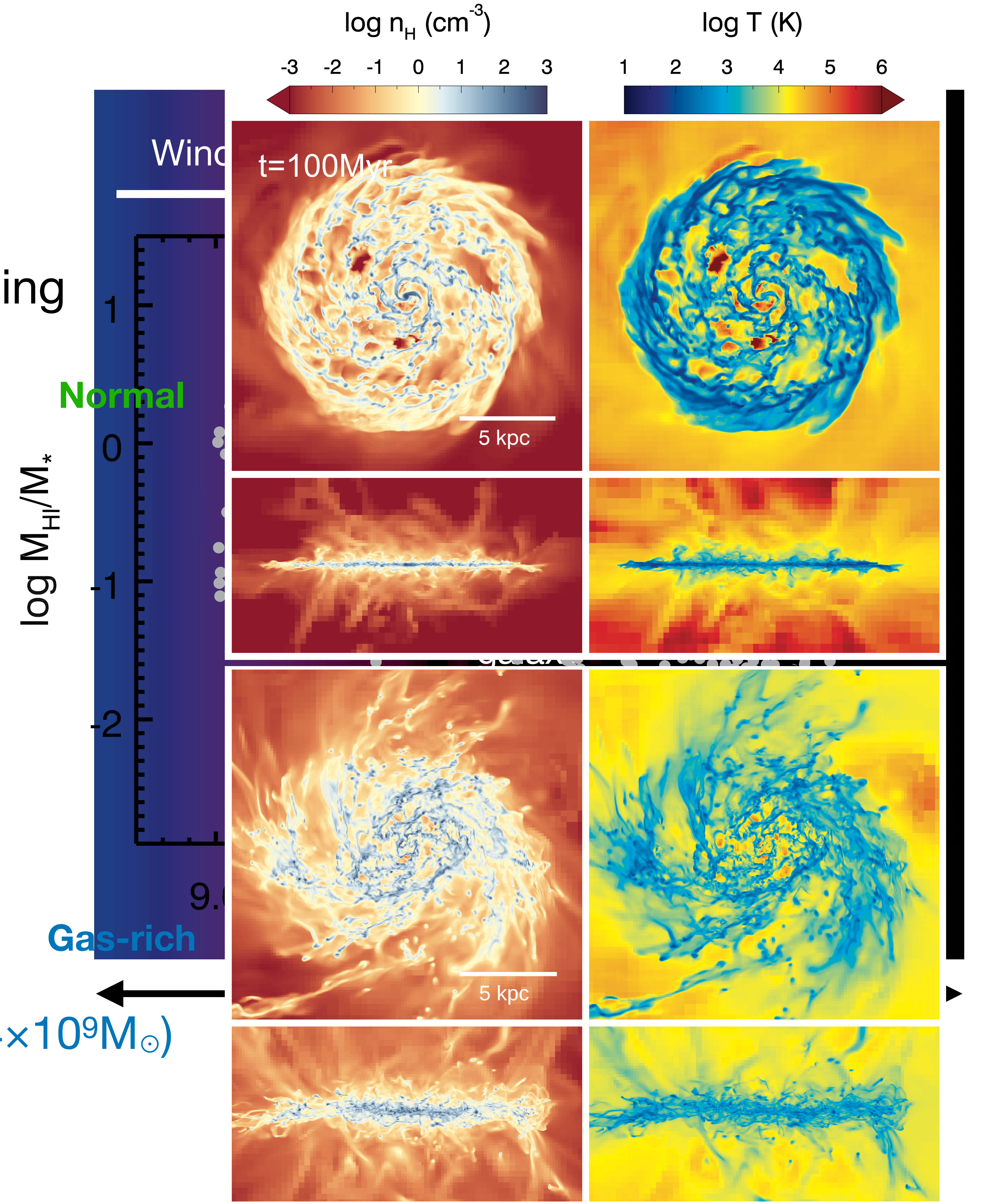
- RAMSES-RT
  - Developed by Teyssier 02; Rosdahl+13; Rosdahl & Teyssier 15
    - Based on an adaptive-mesh refinement code, RAMSES
    - Tracing 8 photon groups, from extreme ultraviolet (UV) to infra-red (IR)
    - Computing non-equilibrium chemistry and cooling of HI, HII, HeI, HeII, HeIII and e^-
  - Updated by Katz+17; Kimm+17, 18
    - H_2 formation and dissociation is included based on a modified photochemistry model
    - Star formation efficiency (SFE) computed based on a thermo-turbulent model
      - SFE can vary, depending on the turbulent condition of the ISM
    - Mechanical and radiative SN feedback

- RAMSES-RT
  - Tracing gas phase transition based on 8 photon groups
    - Chemical species traced : H_2, HI, HII, HeI, HeII, HeIII, and e^-
    - Formation of H_2 via dust and H^- channels
    - Destruction of H_2 via photo-dissociation and collisional ionisation

Photon group	ϵ_0 (eV)	ϵ_1 (eV)	κ ($cm^2\,g^{-1}$)	Main function
IR	0.1	1.0	5	Radiation pressure (RP)
Optical	1.0	5.6	10^3	Direct RP
FUV	5.6	11.2	10^3	Photoelectric heating
LW	11.2	13.6	10^3	H_2 dissociation
$EUV_{H\,I,1}$	13.6	15.2	10^3	H I ionization
$EUV_{H\,I,2}$	15.2	24.59	10^3	H I and H_2 ionization
$EUV_{He\,I}$	24.59	54.42	10^3	He I ionization
$EUV_{He\,II}$	54.42	∞	10^3	He II ionization

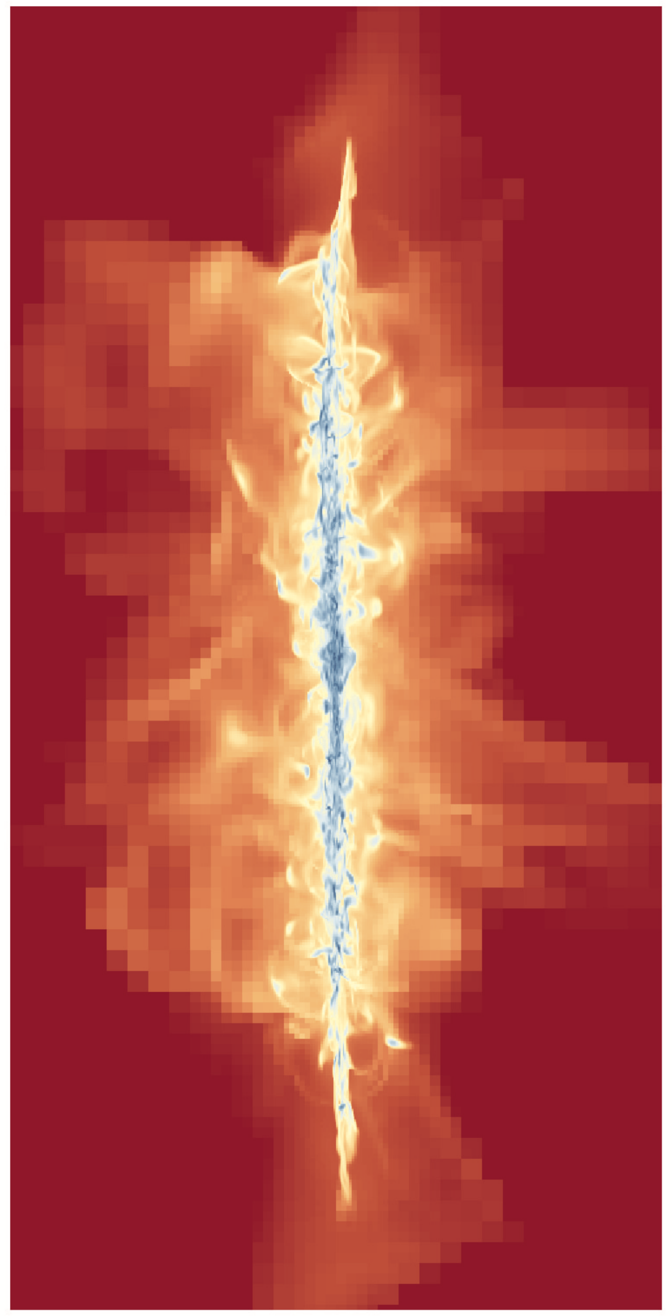
Kimm+17

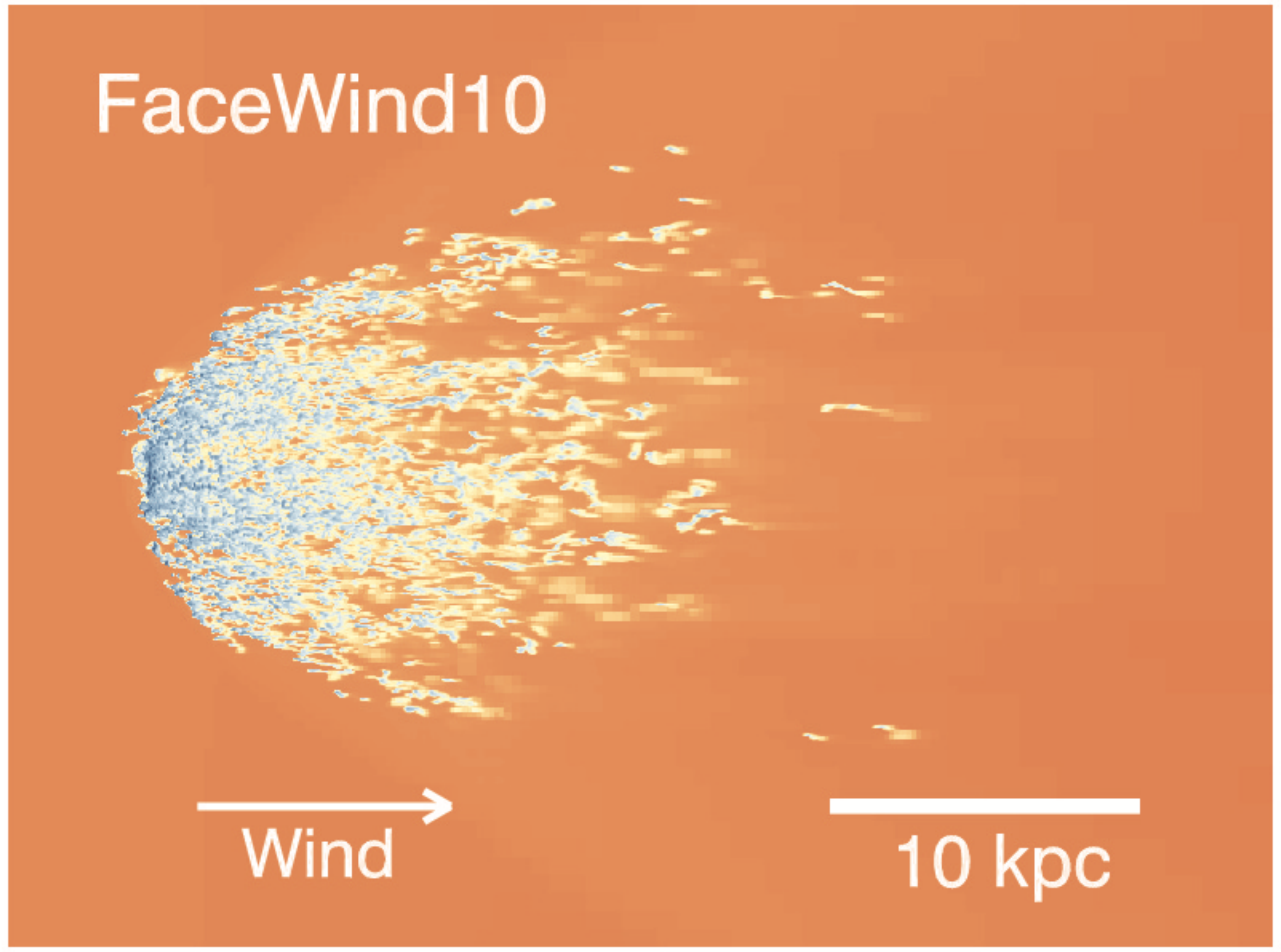
- Simulation setup - galaxies
  - Idealized wind-tunnel experiments
  - Initial condition (G9) generated by Rosdahl+15 using MakeDisk (Springel+05)
    - Box size: 300kpc on a side
    - $M_{halo} \sim 10^{11} M_{\odot}$, $R_{vir} = 89$ kpc
    - $M_{\star} \sim 2.1 \times 10^{9} M_{\odot}$ ($R_{1/2} \sim 2.4$kpc)
  - Gas content
    - Normal gas fraction : $M_{HI}/M_{\star} \sim 0.54$ ($1.1 \times 10^{9} M_{\odot}$)
    - High gas fraction (5x of normal) : $M_{HI}/M_{\star} \sim 2.6$ ($5.4 \times 10^{9} M_{\odot}$)
  - Cell resolution down to 18pc



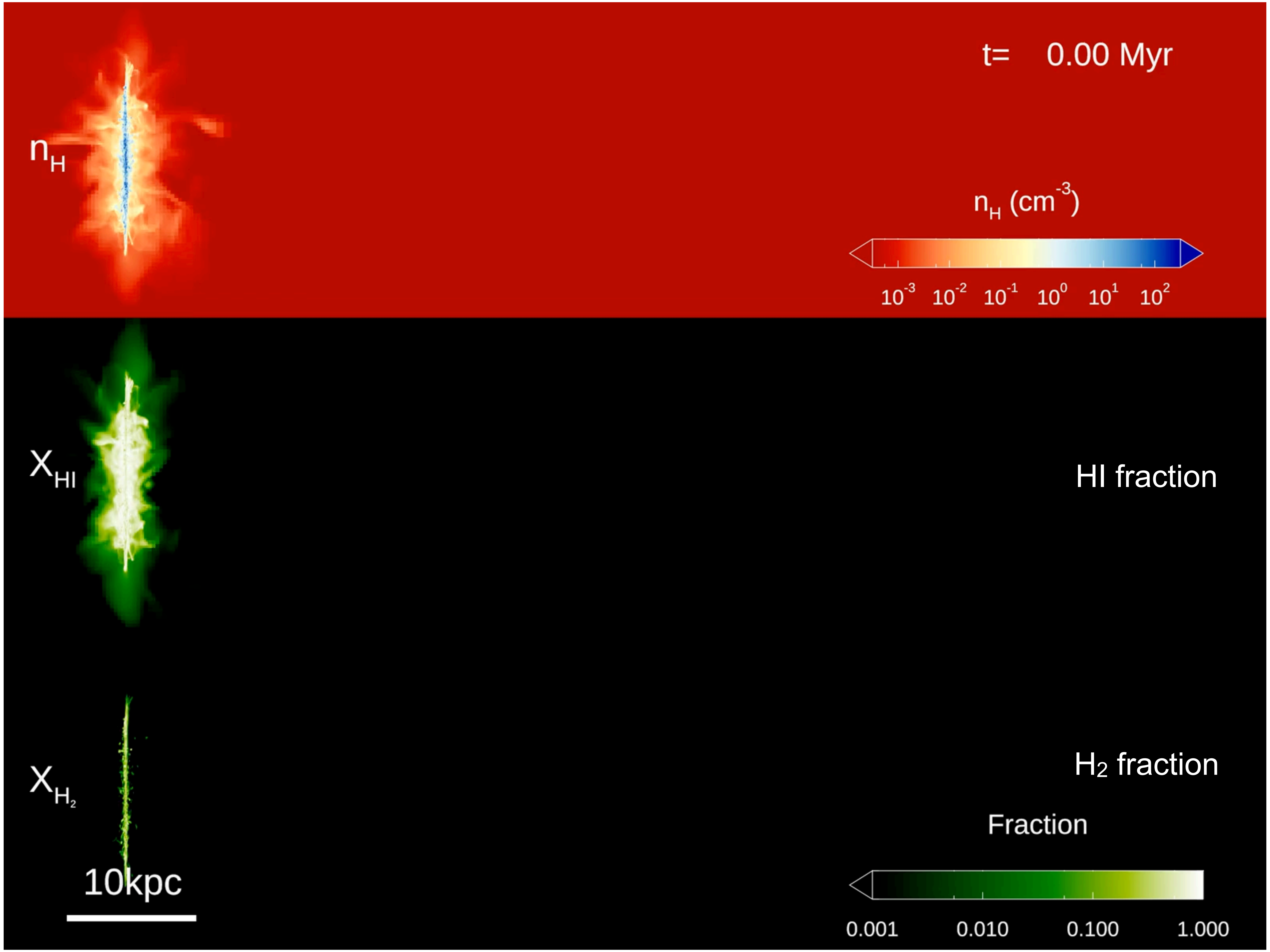
- Simulations
  - Isolated environment - no wind (control sample)
    - Gas-rich (NoWind_rich)
  - Strong face-on winds to mimic ram pressure at the cluster center (v_{wind}=1,000km s^{-1}, T_{ICM} ~10^7K, $n_H=3\times10^{-3}cm^{-3}$)
    - Normal (FaceWind10, Lee+20)
    - Gas-rich (FaceWind10_rich)
  - Metal enrichment from SNe is turned off
    - To enable us to trace the medium origin
      - ISM : 0.75 $Z_\odot$, ICM: 0.3 $Z_\odot$

No Wind

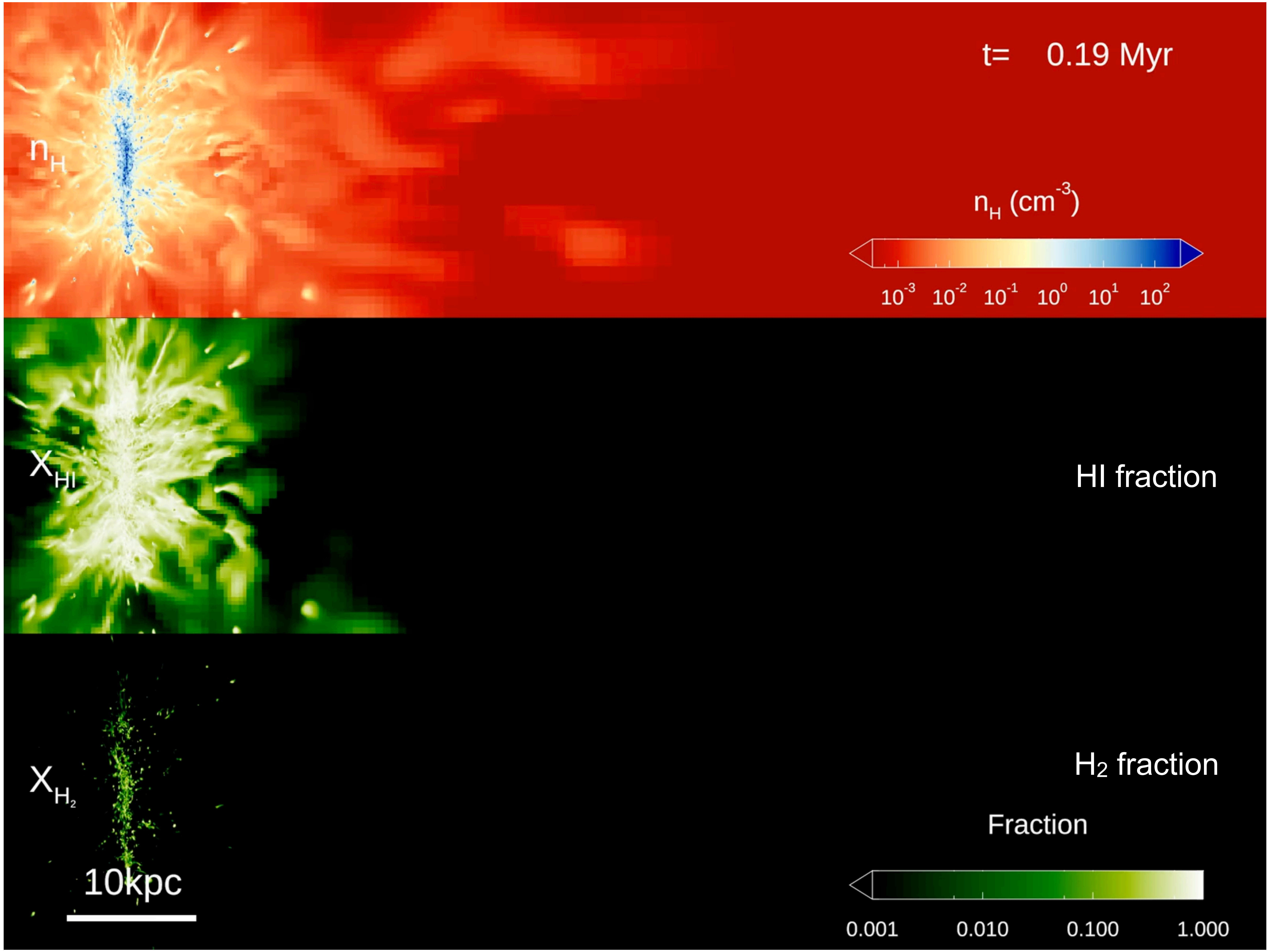




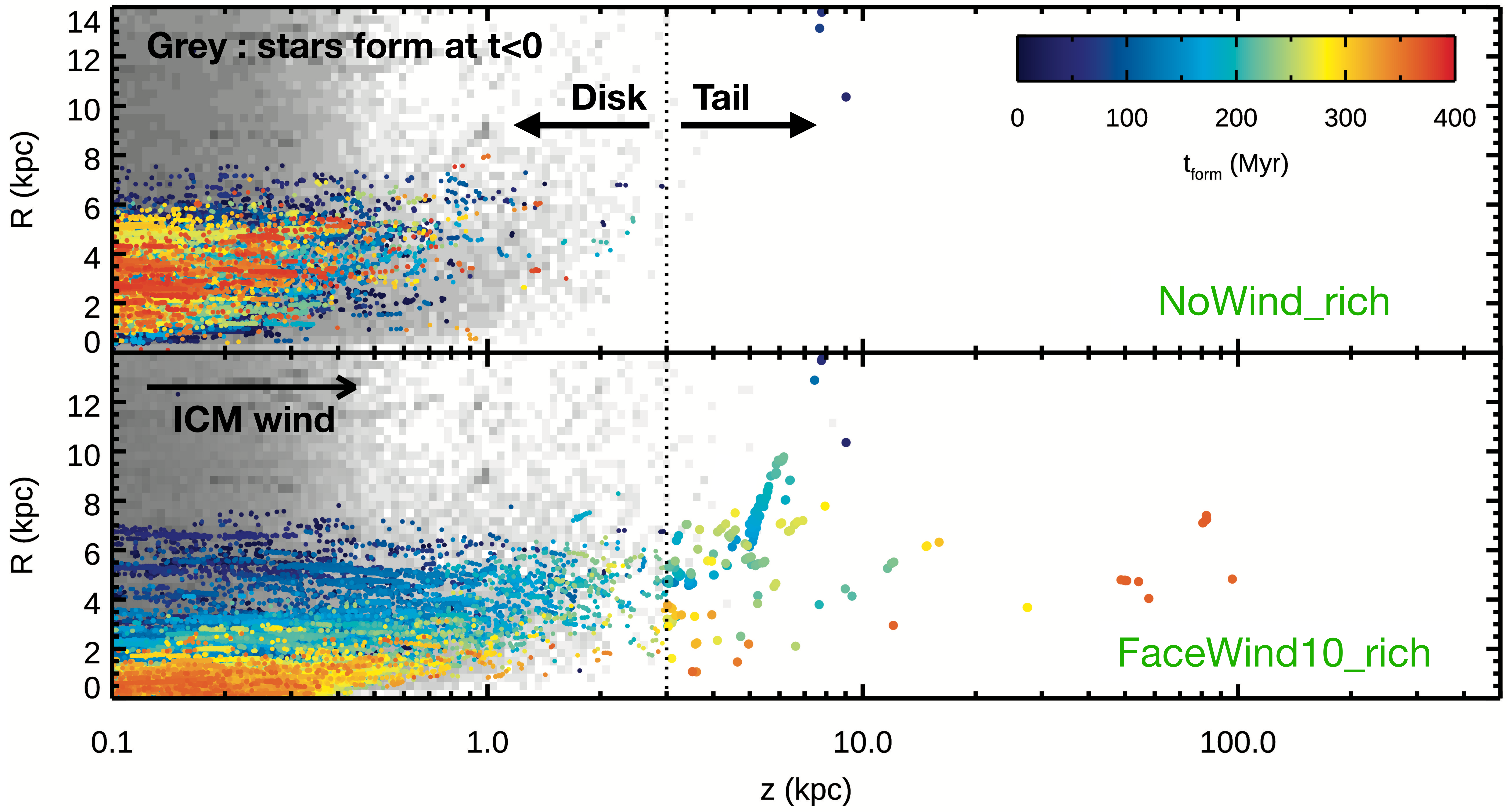
- FaceWind10 - a normal galaxy encountering a strong wind



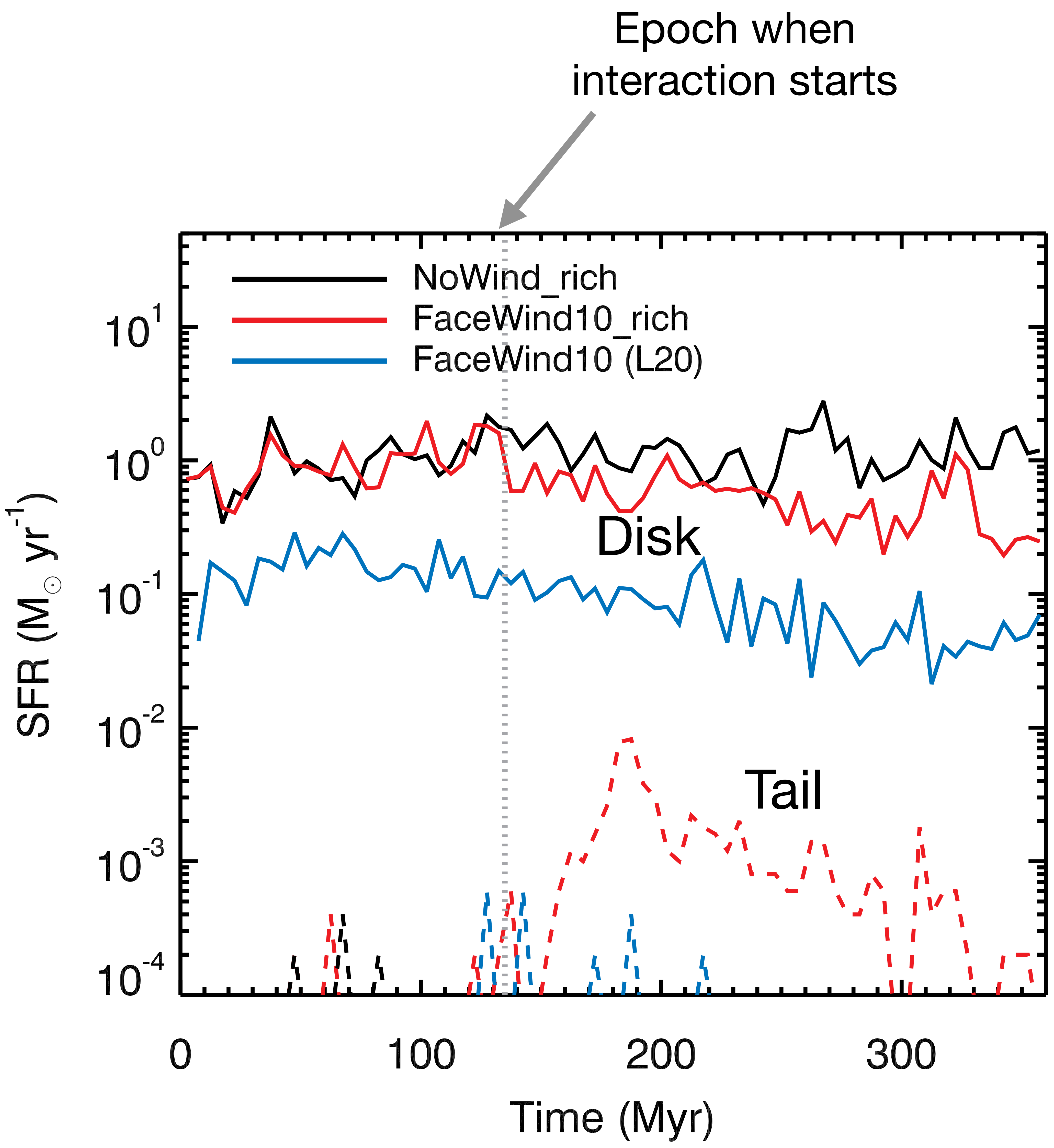
- FaceWind10_rich - gas-rich galaxy encountering a strong wind



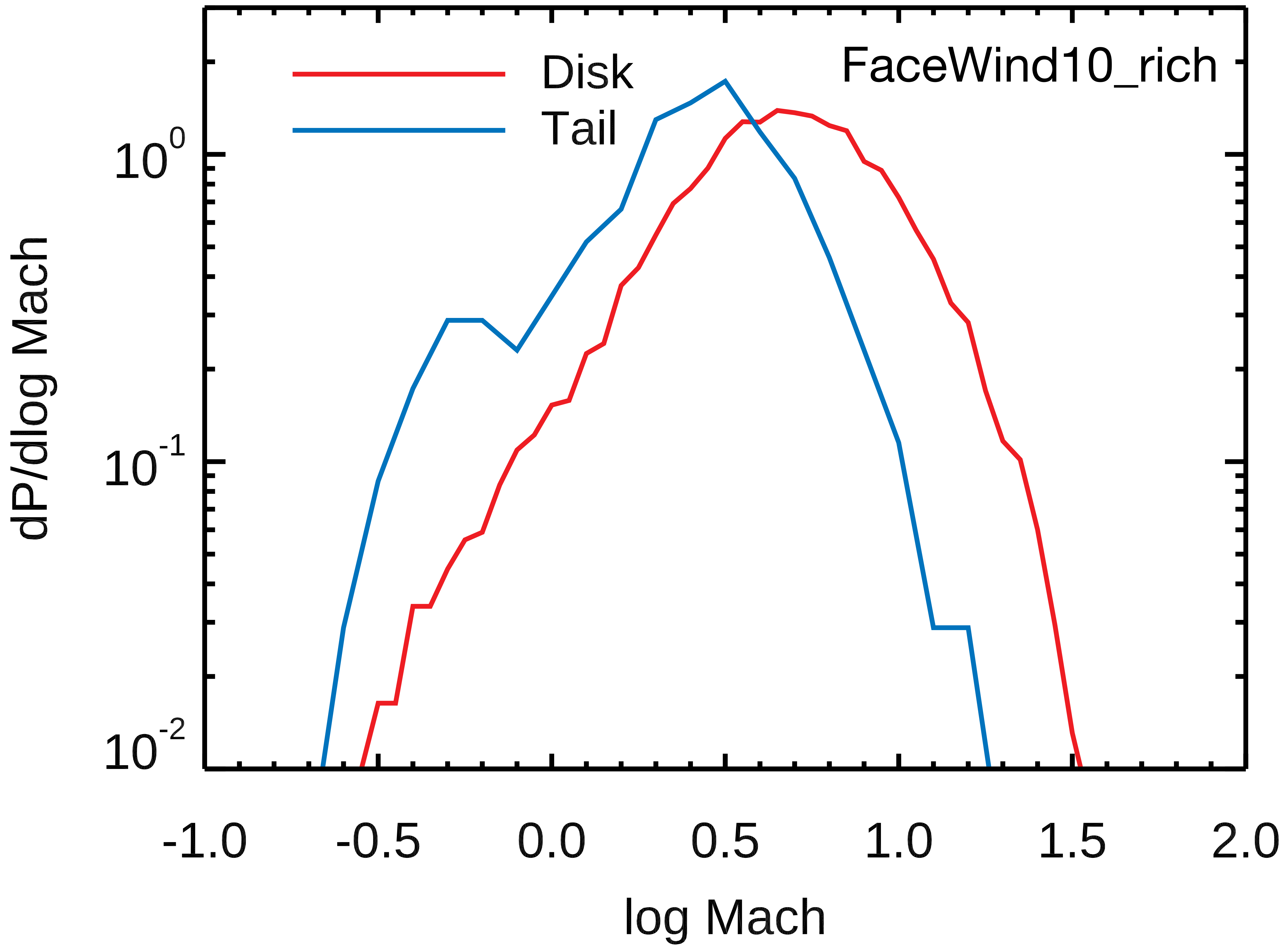
- Birthplace of stars in the gas-rich galaxy as a function of time
  - No stars form in z>3kpc after t~100Myr in the NoWind_rich galaxy
  - Stars form in the tail of the FaceWind10_rich galaxy after encountering the wind (t>130Myr)



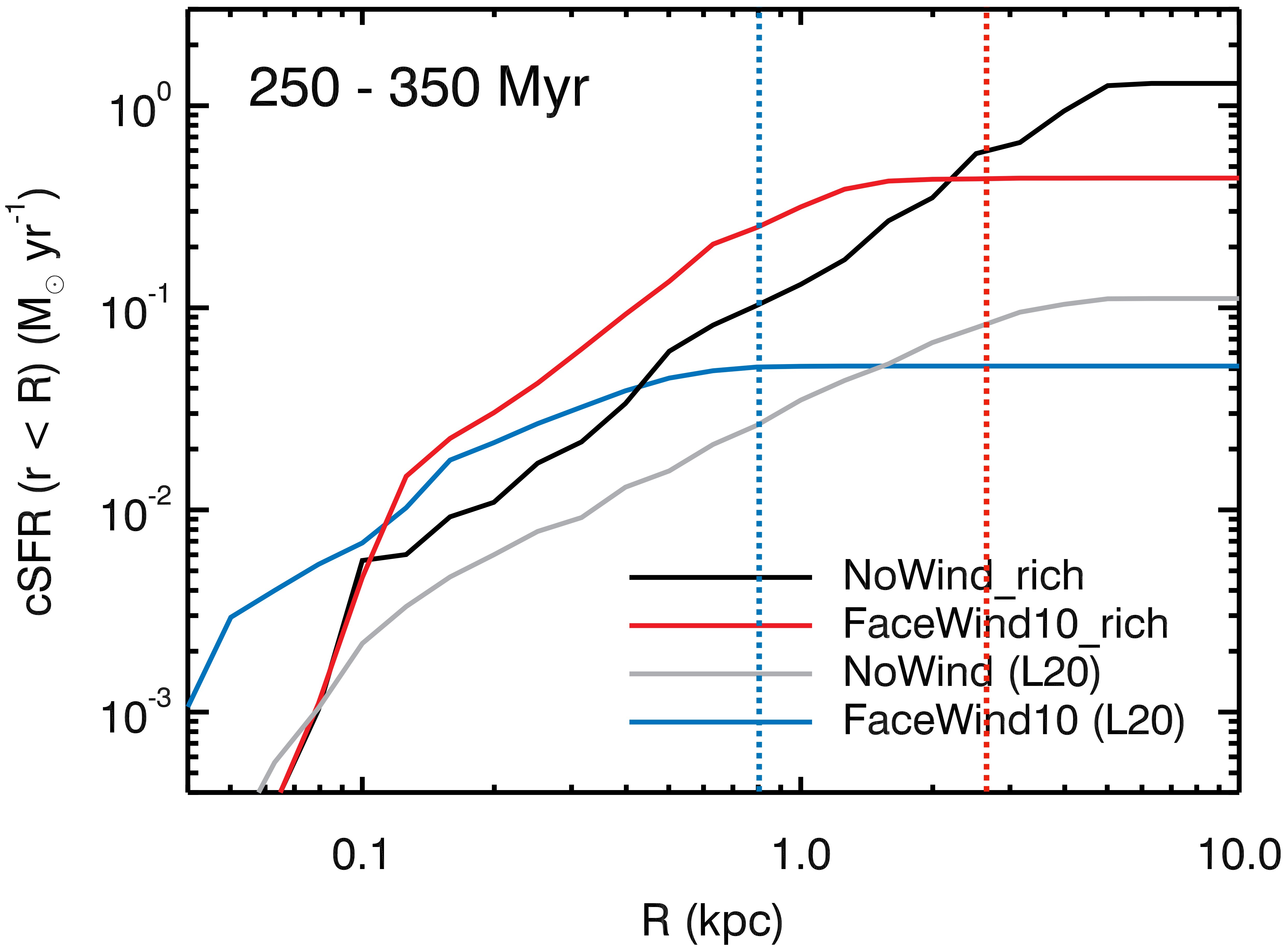
- Star formation rate (SFR) evolution
  - Disk star formation (SF) is quenched over time after encountering the ICM winds
    - SFRs decay similarly in the normal and gas-rich galaxies
    - SF is boosted at the center (r<<1kpc) due to gas compression by the ICM winds
  - Evident tail SF is observed in FaceWind10_rich
    - Tail SFR~10^{-3}-10^{-2} $M_\odot$/yr - comparable with observations (e.g. D100 in Coma)



- Are the tail clouds more turbulent than disk clouds?
  - Disk clouds are more turbulent mainly due to strong stellar feedback
  - Less gas reservoirs mainly account for the low SFR in the tail



- Star formation on the disk
  - Strong ram pressure truncates the disk, suppressing SF in R>1-2kpc
  - SF is rather boosted at the center (r<1kpc) due to gas compression by the wind

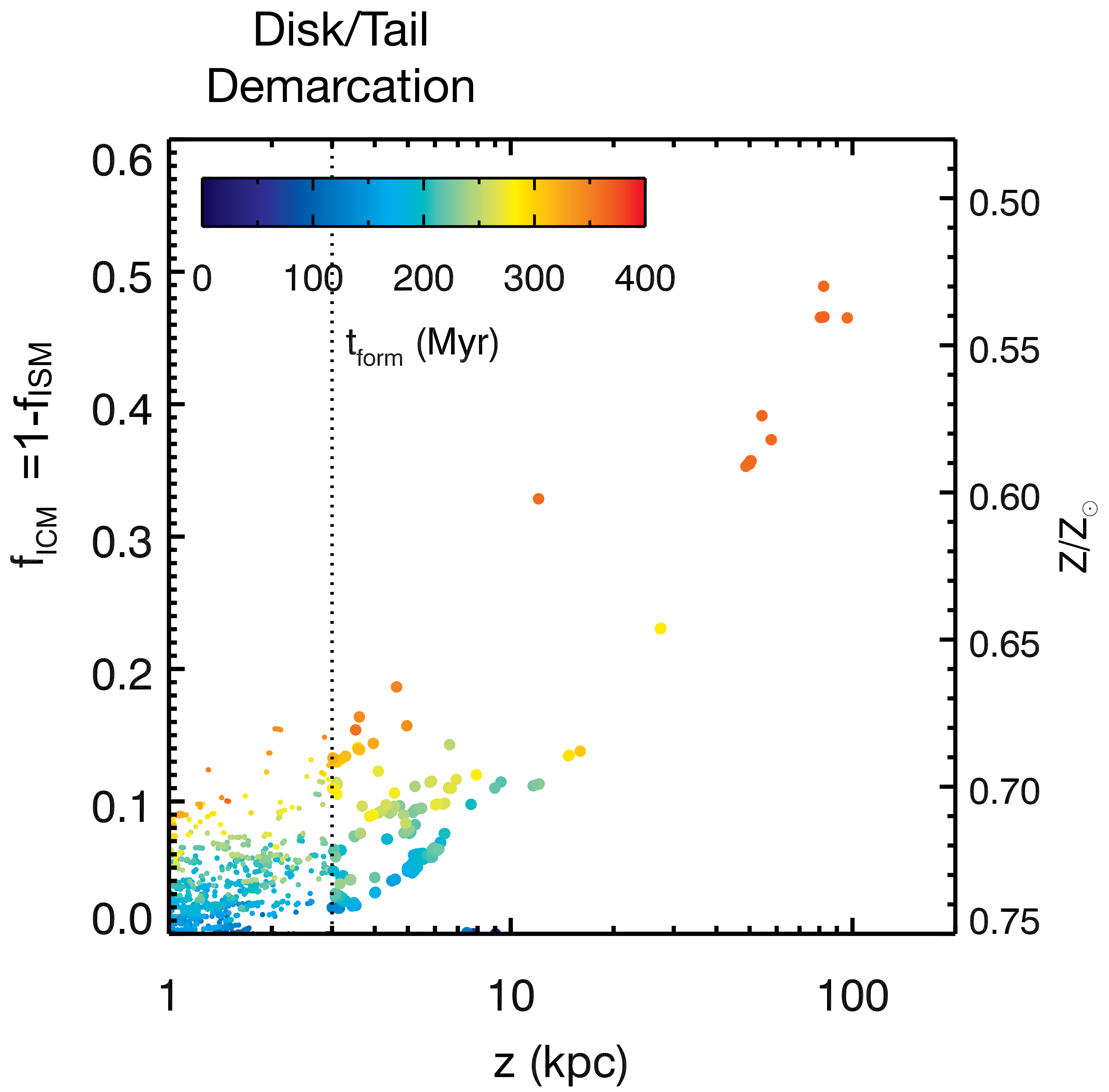


$$\rho_{\rm ICM} v_{\rm ICM}^2 = -\Sigma(r_{\rm c}) \partial\Phi(r_{\rm c}, z)/\partial z$$

(Gunn&Gott 72)

Truncated radius:
r_c~2.7 kpc in FaceWind10_rich
0.8 kpc in FaceWind10

- Star formation in the tail
  - Most (~90%) tail SF occurs in the near wake (z<10kpc) of the FaceWind10_rich galaxy
    - Their origin is mostly stripped ISM
  - Distant stars form in clouds that are mixed well with the ICM
    - Indicating the formation of molecular clumps in the RPS tail



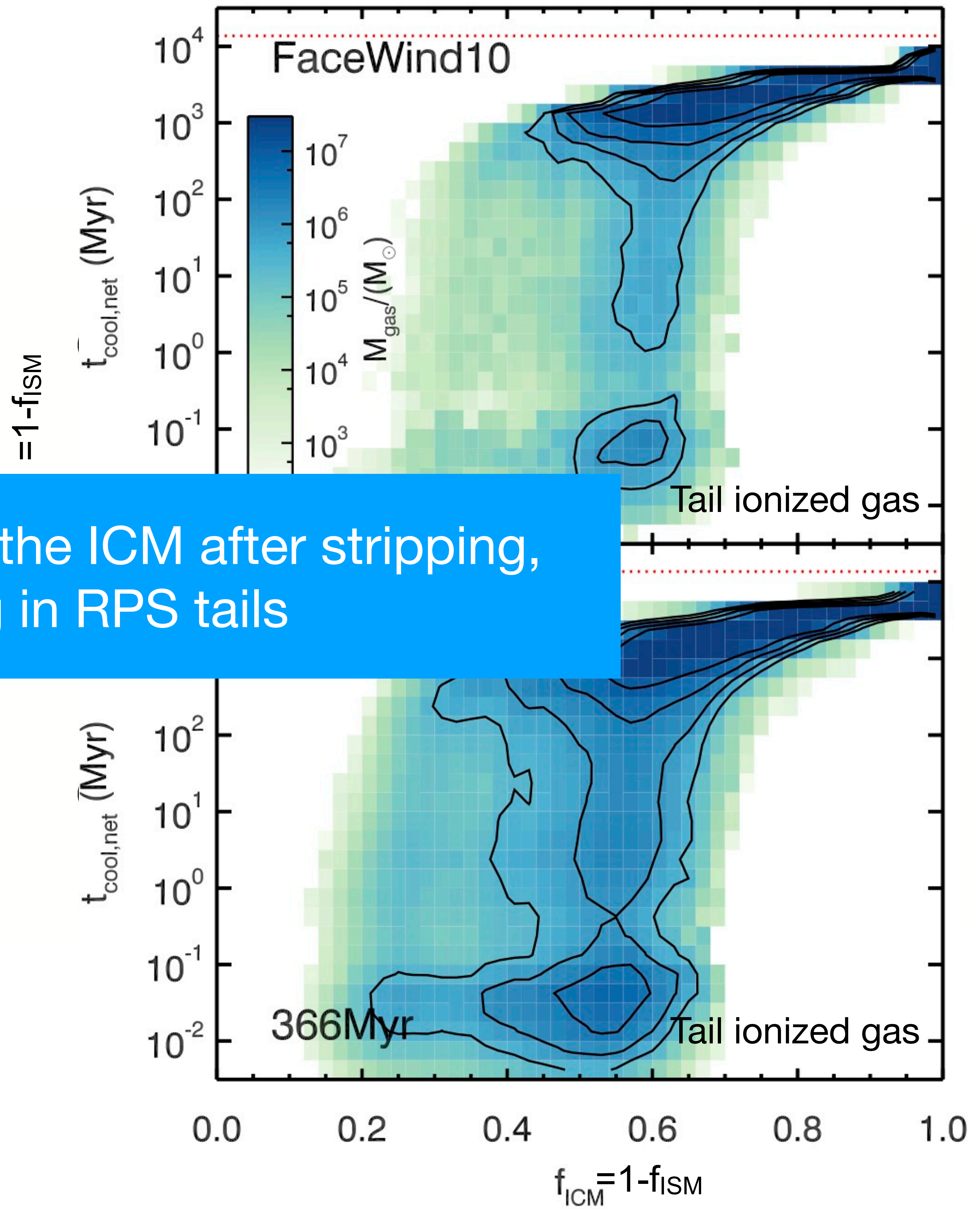
- Origin of tail molecular clumps

  - Molecular hydrogen clumps (n_H>100cm^{-3}) form far behind (z~60-80kpc) the galactic disk of the FaceWind10_rich galaxy

  - No dense [...] FaceWind [...]

  - Gas-rich galaxy (FaceWind10_rich) has warm ionized gas of t_{cool} <1Myr 20 times more than FaceWind10

The abundant ISM is mixed with the ICM after stripping, facilitating gas cooling in RPS tails

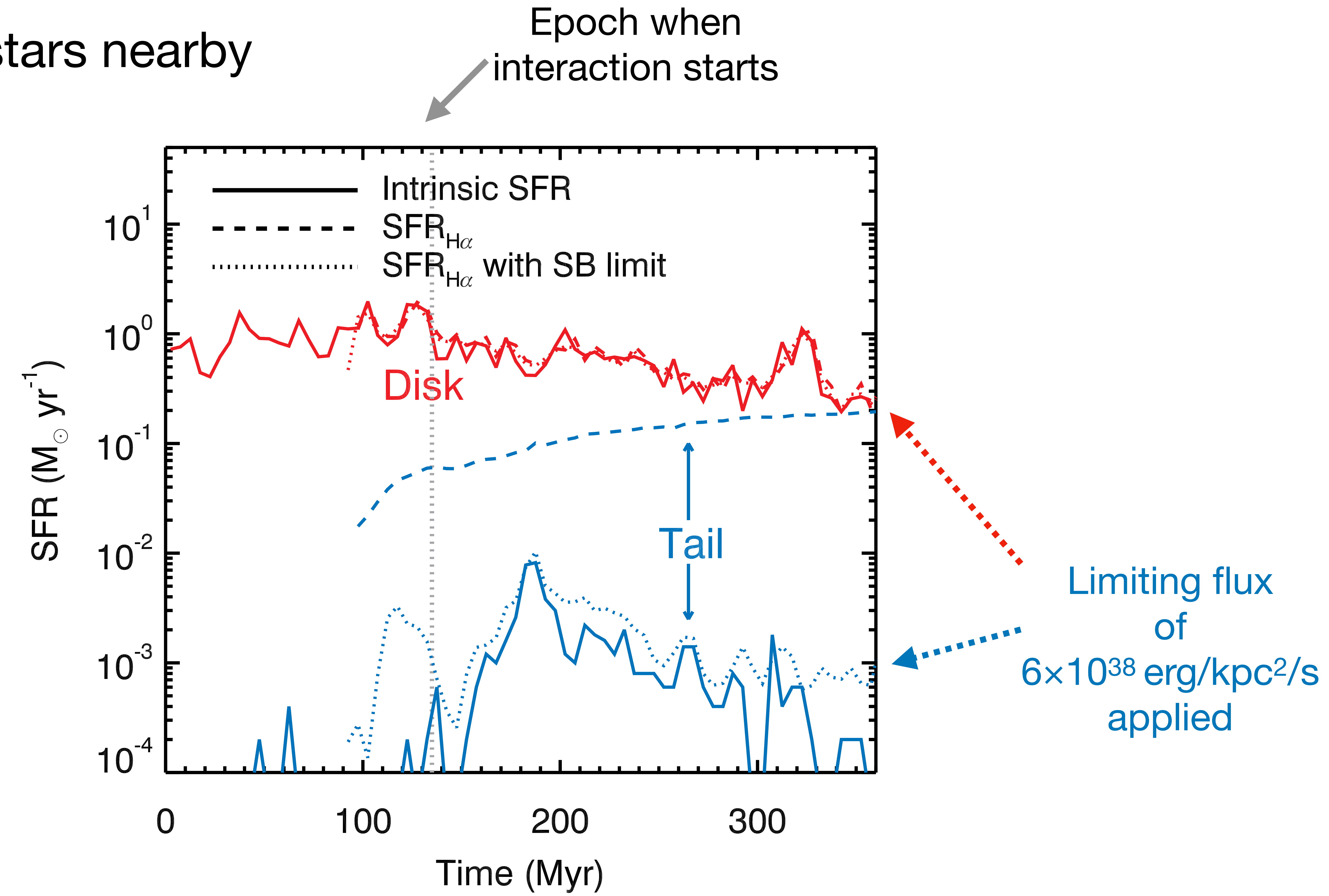


- Hα emissivity - Is SF the main origin of Hα emission in ram pressure stripped tails?
  - Hα emission is computed for recombinative and collisional processes
  - Local maxima of Hα strongly correlate with young stars in the tail

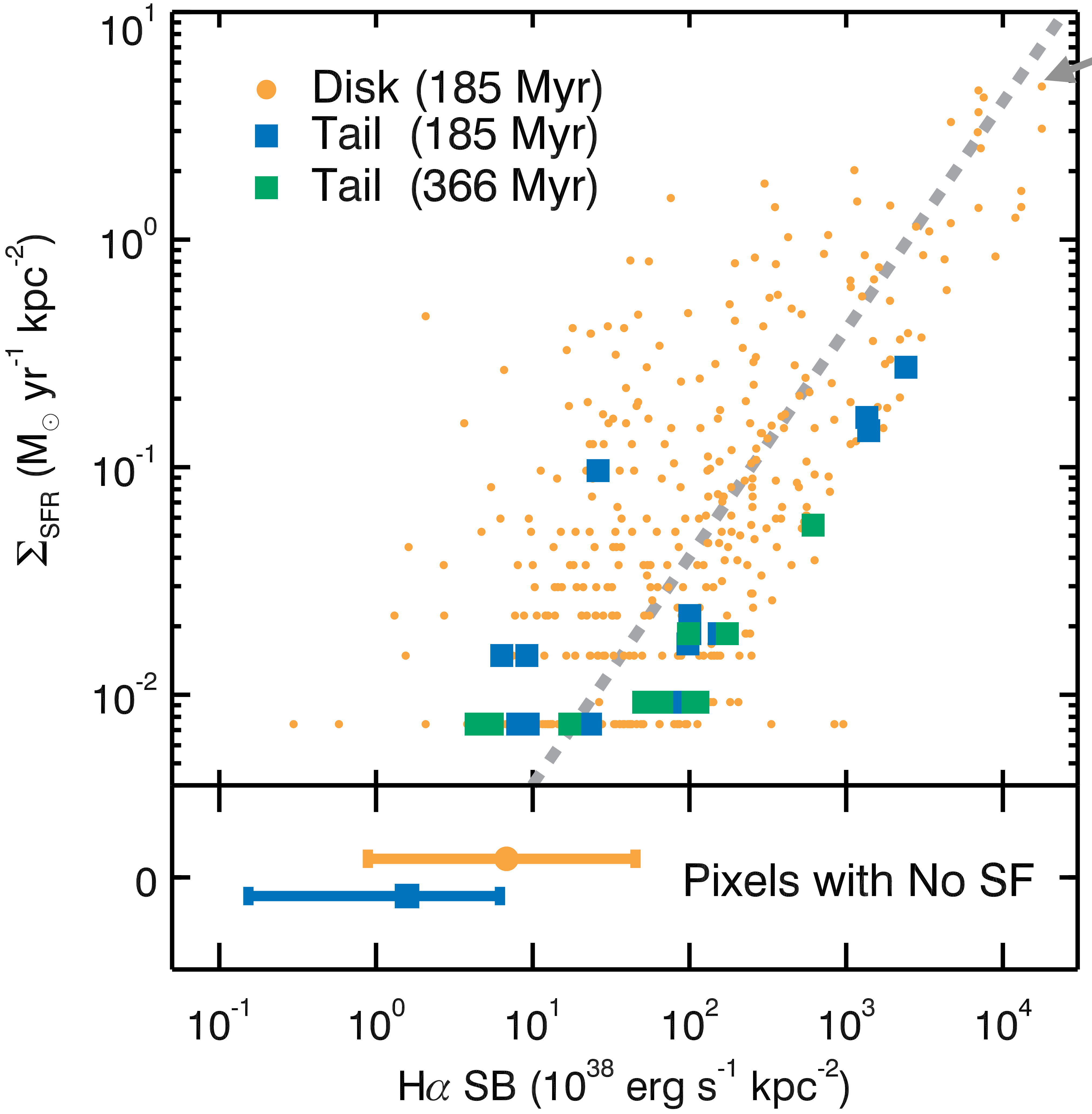
- Intrinsic SFR vs SFR derived from Hα
  - Total Hα luminosity is dominated by Hα photons emitted from diffuse clouds
    - A limiting flux of 6×10^{38}erg/s/kpc^2 largely reduces Hα luminosity in the tail
    - Bright sources are lit by young stars nearby

Hα -> SFR (BPASS 2.0)

$$\mathrm{SFR_{H\alpha}} \approx 4.0\,\mathrm{M_\odot\,yr^{-1}} \left(\frac{L_{\mathrm{H}\alpha}}{10^{42}\,\mathrm{erg\,s^{-1}}}\right)$$



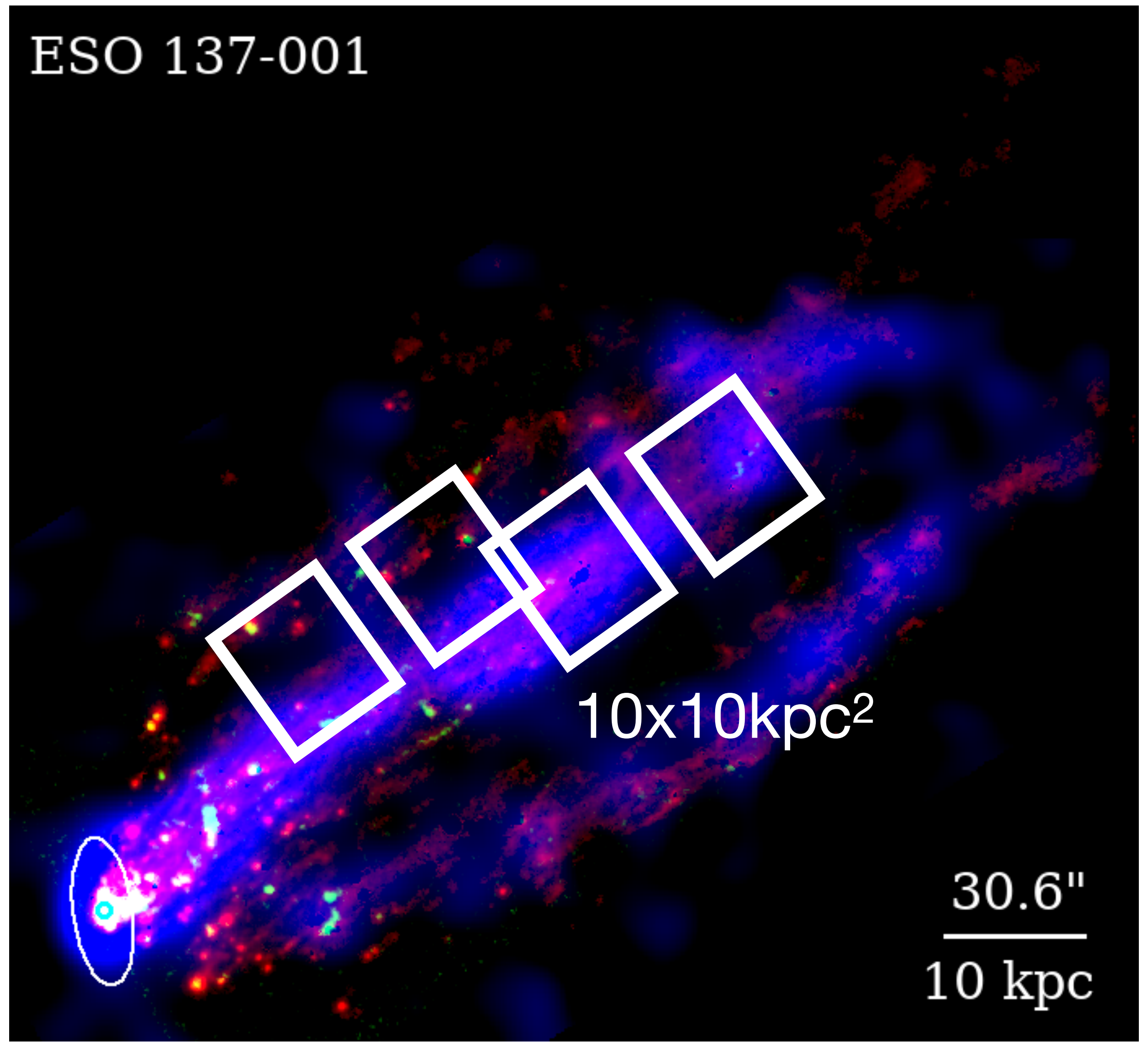
- Bright Hα cores lit by young stars
  - Non-star forming regions are dominated by diffuse Hα

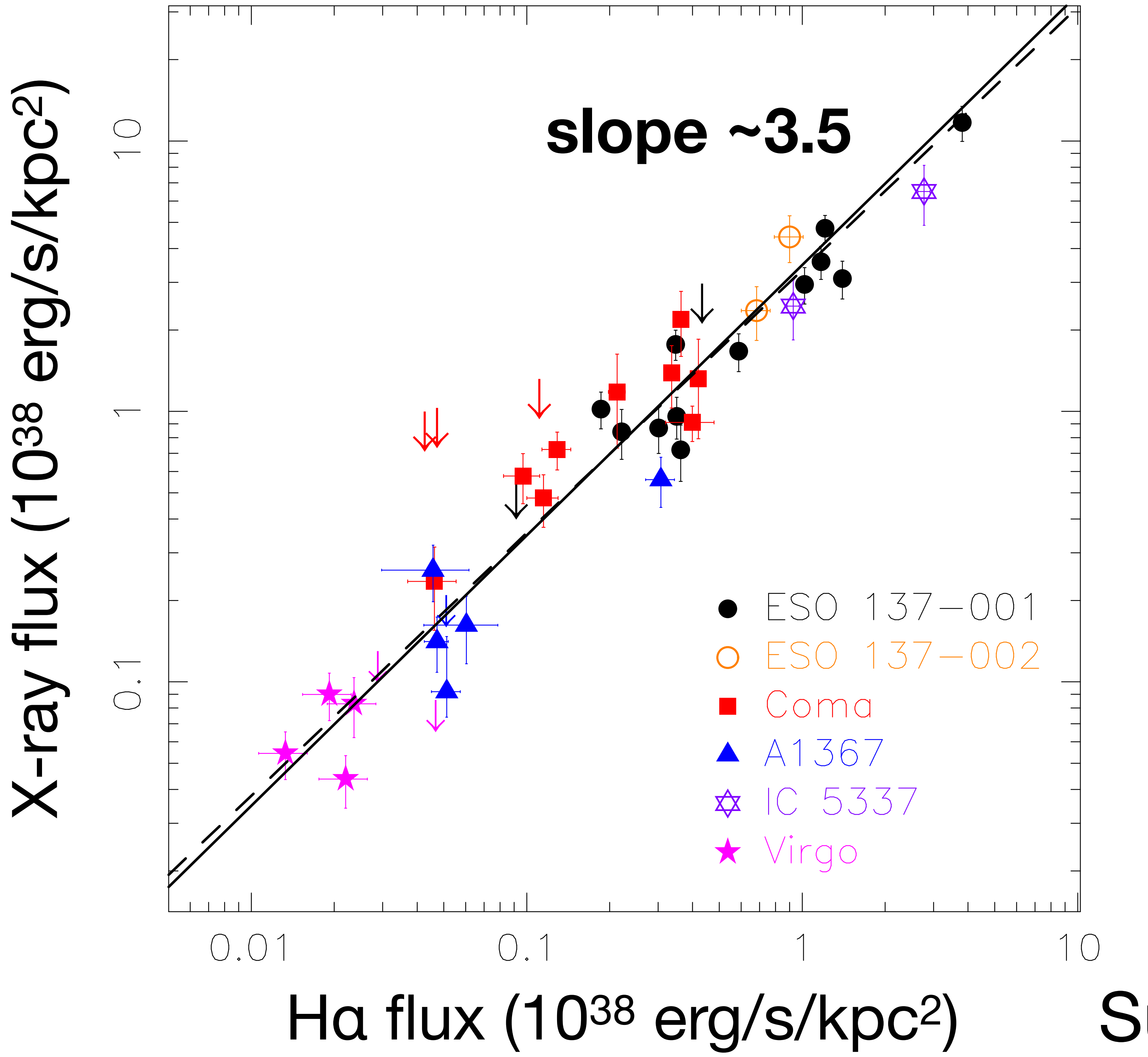


Hα -> SFR (BPASS 2.0)

$$\mathrm{SFR}_{\mathrm{H}\alpha} \approx 4.0\,\mathrm{M}_\odot\,\mathrm{yr}^{-1}\left(\frac{L_{\mathrm{H}\alpha}}{10^{42}\,\mathrm{erg\,s^{-1}}}\right)$$

- Hα - Xray flux correlation in RPS tails
  - A strong correlation is reported by Sun+21
    - $F_X/F_{H\alpha}$~3.5 in RPS tails, on average
      - Measured on a scale of 10×10kpc²
    - The source of the Hα and Xray photons are fundamentally different: T_{gas}~10^4K vs T_{gas}~10^7K
    - Strongly evidencing mixing between the ICM and stripped ISM in RPS tails?





Sun+21

- Hα and X-ray emissivity of the FaceWind10_rich galaxy
  - Hα: computed for recombinative and collisional excitation processes
  - X-ray: computed using Astrophysical Plasma Emission Code (Smith+01)

- Hα - Xray SB correlation in the RPS tail of the FaceWind10_rich galaxy

  - F_X measured in 0.4-7.5keV and converted into bolometric flux, following observations (Sun+21)

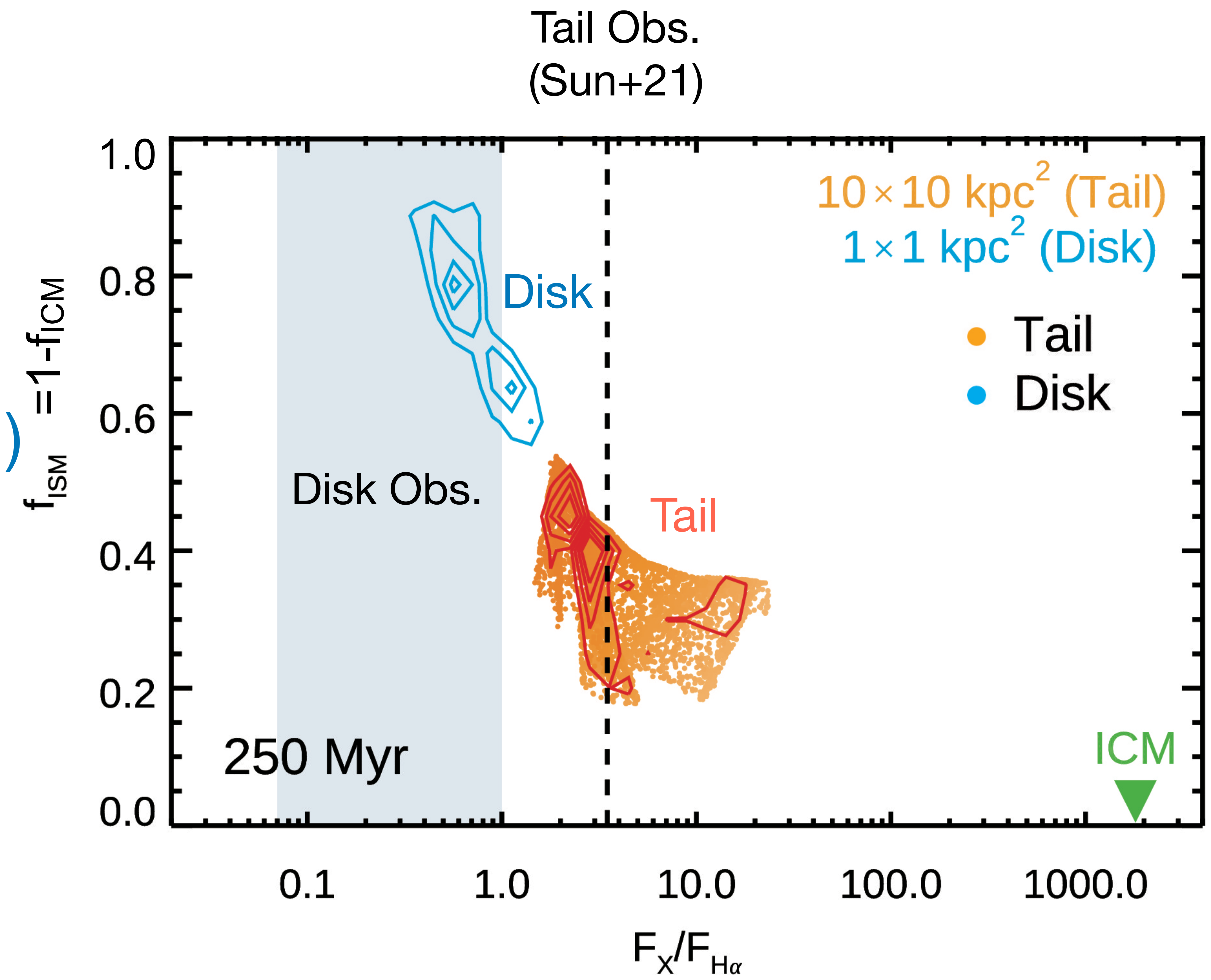
  - $F_X/F_{H\alpha}$~1800 in the ICM

    ~1.5-20 in the tail (c.f. $F_X/F_{H\alpha}$~3.5 in Sun+21)

    < 1.5 in the disk

  - F_{ISM} tightly correlates with $F_X/F_{H\alpha}$

    - $F_X/F_{H\alpha}$ increase with decreasing f_{ISM}



- Caveat (which will be investigated soon)
  - Missing or incomplete physics
    - Magnetic field
    - Thermal conduction
  - Live halo environments can make different tail features

- Summary
  - Strong ram pressure effectively suppresses star formation in the gas-rich galaxy
  - Evident tail SF presents in molecular clumps
  - Molecular clumps form in-situ in the RPS tail of the gas-rich galaxy
    - Mixing between the ICM and stripped ISM facilitates gas cooling in the tail
  - Bright Hα cores are lit by young stars
    - Most diffuse Hα photons are produced from processes other than star formation
  - Observed X-ray to Ha flux ratio is reproduced with moderate deviations
    - The flux ratio strongly correlates with the ISM fraction, which indicates the key role of mixing in the formation of RPS tails