AGN feedback, quiescence and CGM metal enrichment in early-type galaxies

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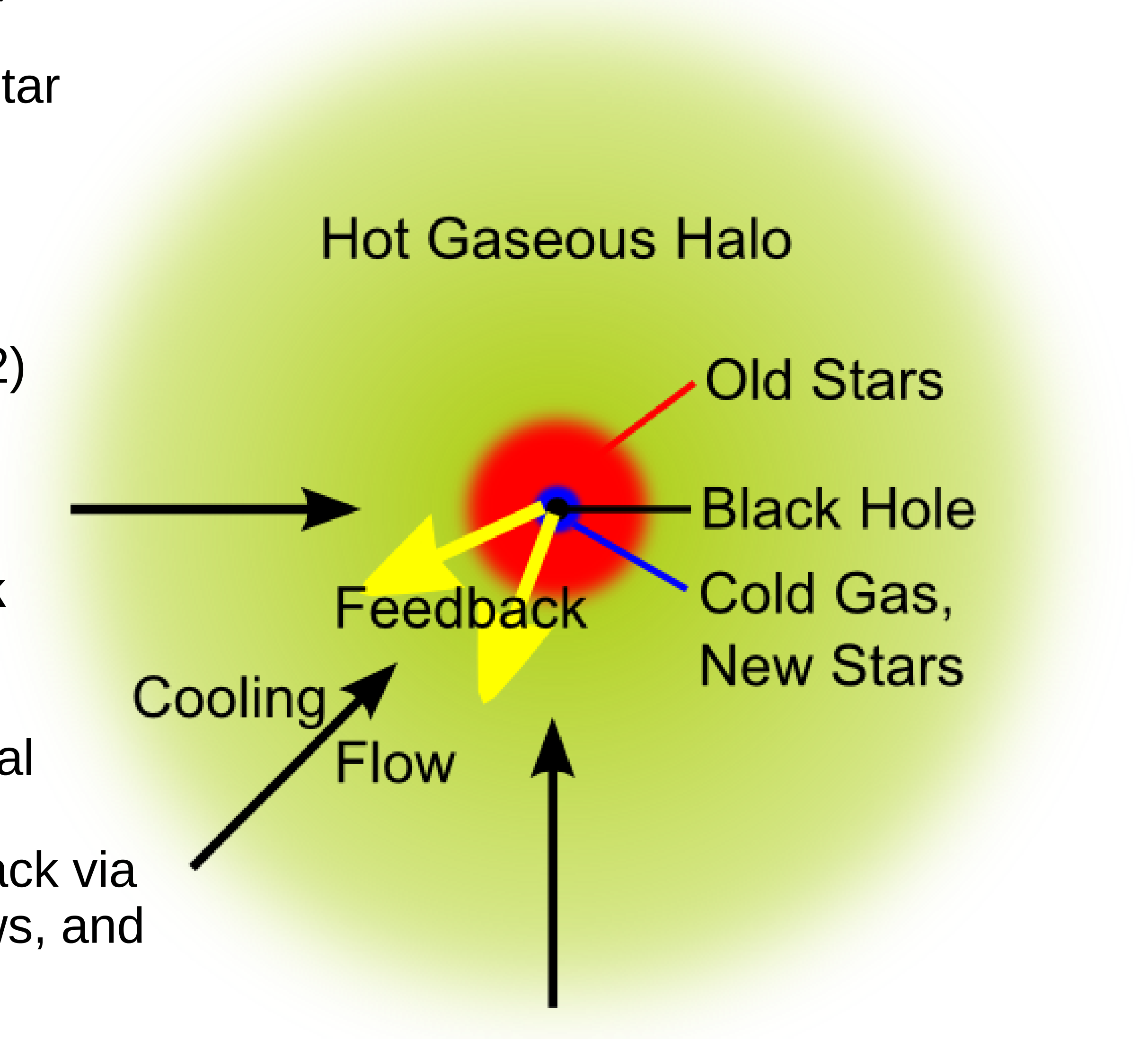
ETGs, their gas, and AGN feedback

- Predominantly red, old (~10 Gyr) stellar systems
- **Quiescent**: little to no ongoing star formation
- **ISM**:
  - Hot ($10^6 - 10^7$ K) gaseous halo
  - No/little cold gas (e.g. Young+2011, Serra+2012)

- **Central SMBH:**
  - Likely preventing permanent cooling flow through **feedback** (**keeping galaxy quiescent**)
  - Potentially large impact on morphology, kinematics & metal distribution of the ISM
  - Investigate influence of feedback via SFR, metal distribution/outflows, and X-ray properties



Simulation Code

- **Hydrodynamic simulations**:
  "modern SPH": modified version of GADGET-3 (Springel 2005)
  with numerical improvements (**SPHGal**, Hu+2014)

- **Cooling, star formation & stellar feedback models**
  (Scannapieco+2005/06, Aumer+2013):

  - Metal-dependent **gas cooling** (11 elemental species)

  - **star formation** (stochastic, density- and temperature-dependent)

  - **stellar feedback** (**SNIa, SNII, AGB** winds) including metal enrichment

Simulation Code

Black hole accretion & feedback model (based on Choi+2012):

- Bondi-Hoyle-Lyttleton accretion with modifications (Eddington-limited)

$$\dot{M}_{\rm BHL} = \left\langle \frac{4\pi G^2 M_{\rm BH}^2 \rho}{(c_{\rm s}^2 + v^2)^{3/2}} \right\rangle$$

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- **Mechanical**-thermal **wind feedback**:
  - Gas particles kicked || to rotation axis around SMBH
  - **Free parameters**: $v_{\rm w} = 10,000 \text{ km s}^{-1}$ $\quad \dot{E}_{\rm w} \equiv \epsilon_{\rm w} \dot{M}_{\rm acc} c^2 = \frac{1}{2} \dot{M}_{\rm outf} v_{\rm w}^2$

    $\epsilon_{\rm w} = 0.005$ $\quad \dot{p} = \dot{M}_{\rm outf} v_{\rm w},$
  - 90% of gas flowing towards SMBH ejected in wind, 10% accreted
  - Ejected gas particles share momentum with two neighbours
  - Rest of feedback energy distributed as thermal energy

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- **Radiative (X-ray) feedback** using Sazonov+2005 formulae (Compton scattering):
  - Isotropic, distance-dependent heating & outward acceleration (pressure)
  - **Free parameter:** $\epsilon_{\rm r} = 0.1$

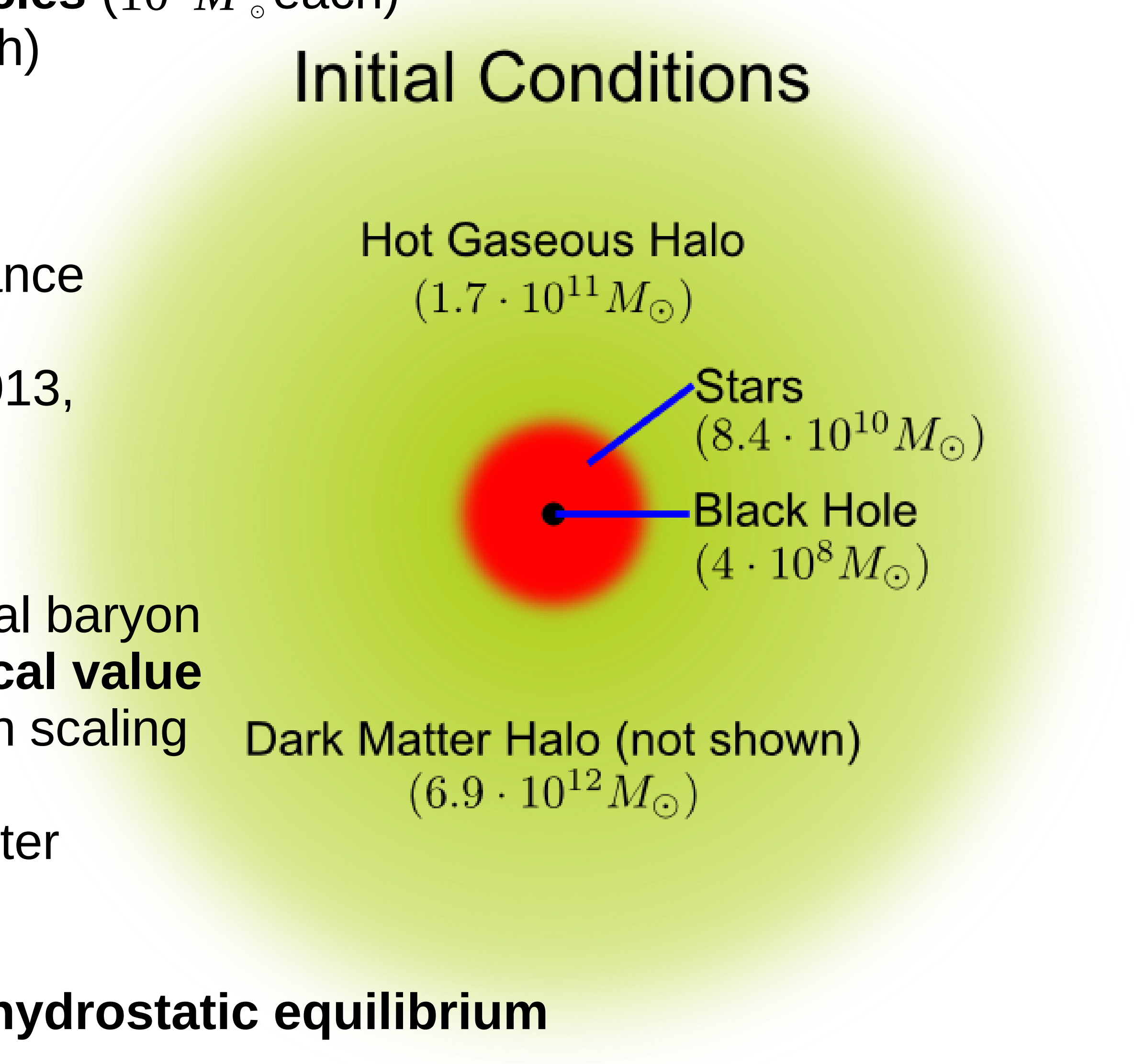
- **Eddington force** (Thompson scattering):
  - Isotropic, distance-dependent outward acceleration

Initial Conditions

- **Resolution**:
  - **2.12 million gas**, 841k star **particles** ($10^5 M_\odot$ each)
  - 1 million DM particles ($10^7 M_\odot$ each)

- **Dark matter, stars, black hole:**
  - Isolated, idealized ETG set up to follow observed scaling & abundance matching relations (Kormendy & Ho2013, Moster+2013, Williams+2010)

- **Hot gaseous halo:**
  - Mass determined by choosing total baryon fraction to be **20% of cosmological value**
  - Resulting X-ray luminosity fits with scaling relation by Kim & Fabbiano 2013
  - Spin parameter equal to dark matter (λ=0.033)
  - **Density: beta-profile** (beta=2/3)
  - Temperature profile follows from **hydrostatic equilibrium**



Set of Simulations

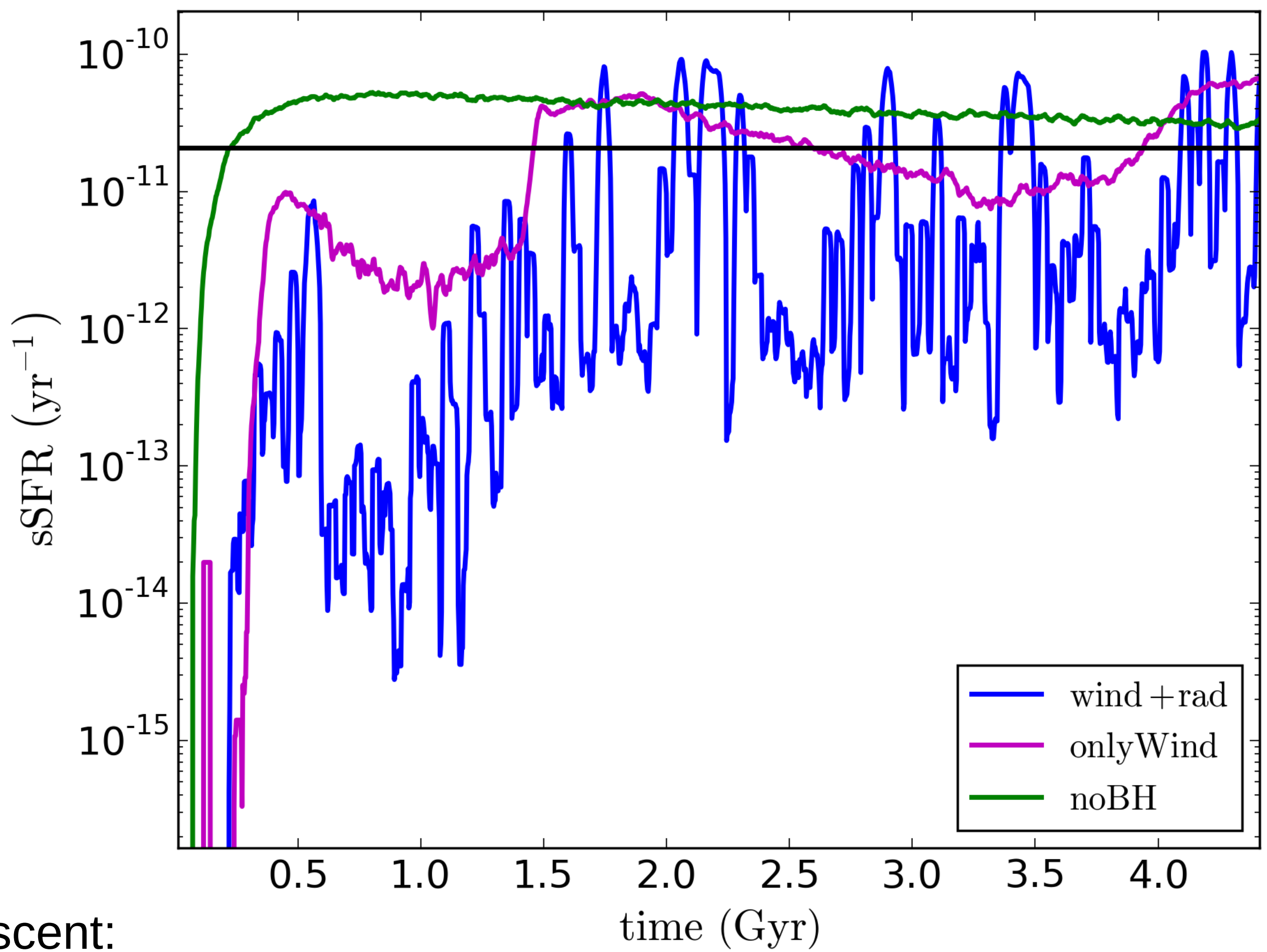
- Comparison of three models:
  - No black hole accretion & feedback (noBH)
  - Pure wind feedback from SMBH (onlyWind)
  - Combined wind & radiative feedback (wind+rad)

	Black hole accretion	Black hole wind feedback	Black hole radiative feedback
Model 1: **noBH**	✗	✗	✗
Model 2: **onlyWind**	✓	✓	✗
Model 3: **wind+rad**	✓	✓	✓

- Simulation time each: ~4.4 Gyr

Quiescence

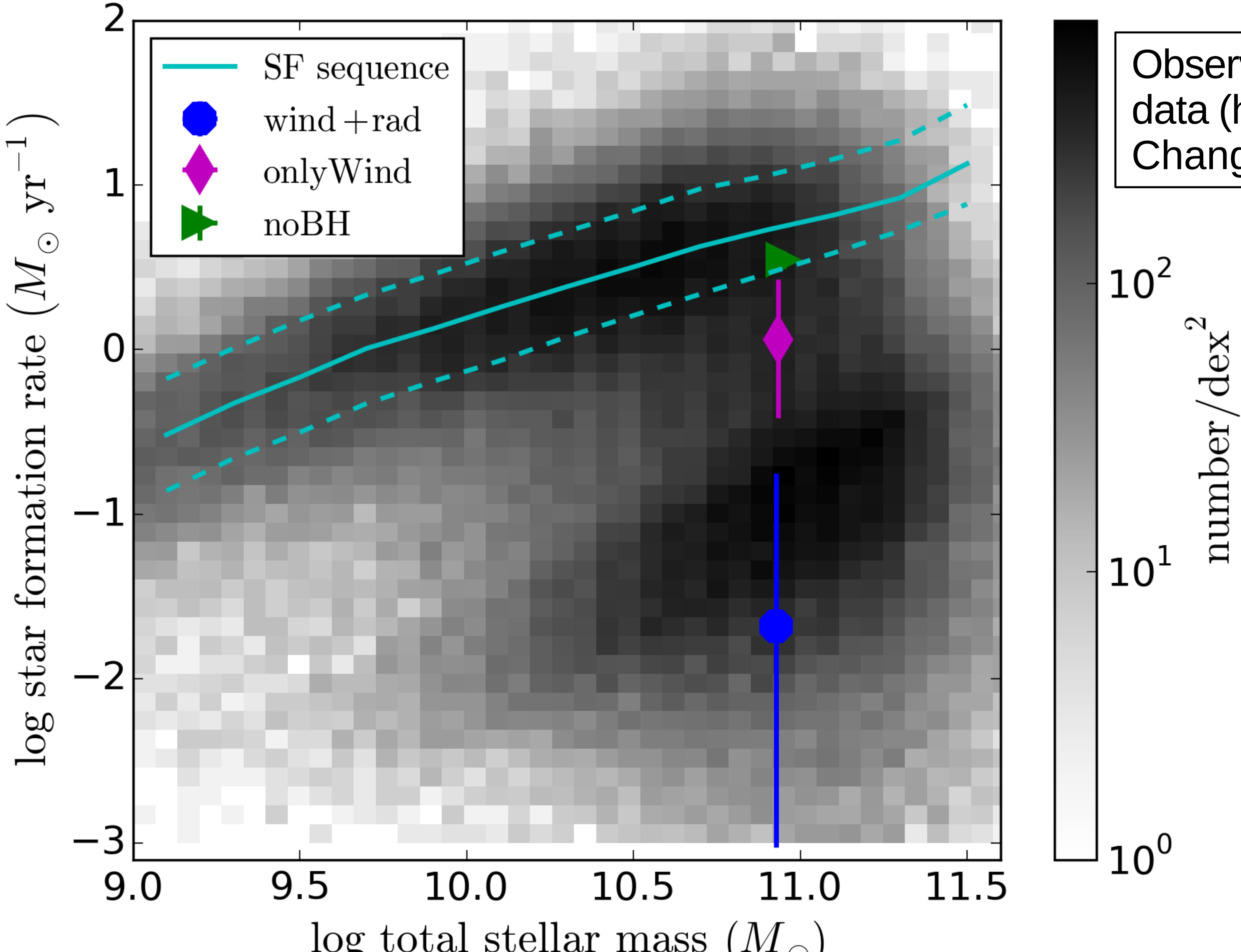
- Black horizontal line: quiescence limit (Franx+2008)
- **noBH**: always actively star-forming
- BH feedback reduces overall star formation significantly
- **onlyWind**: alternating long periods of SF and quiescence
- **wind+rad:** most quiescent, fast oscillation with some peaks of comparatively high sSFR



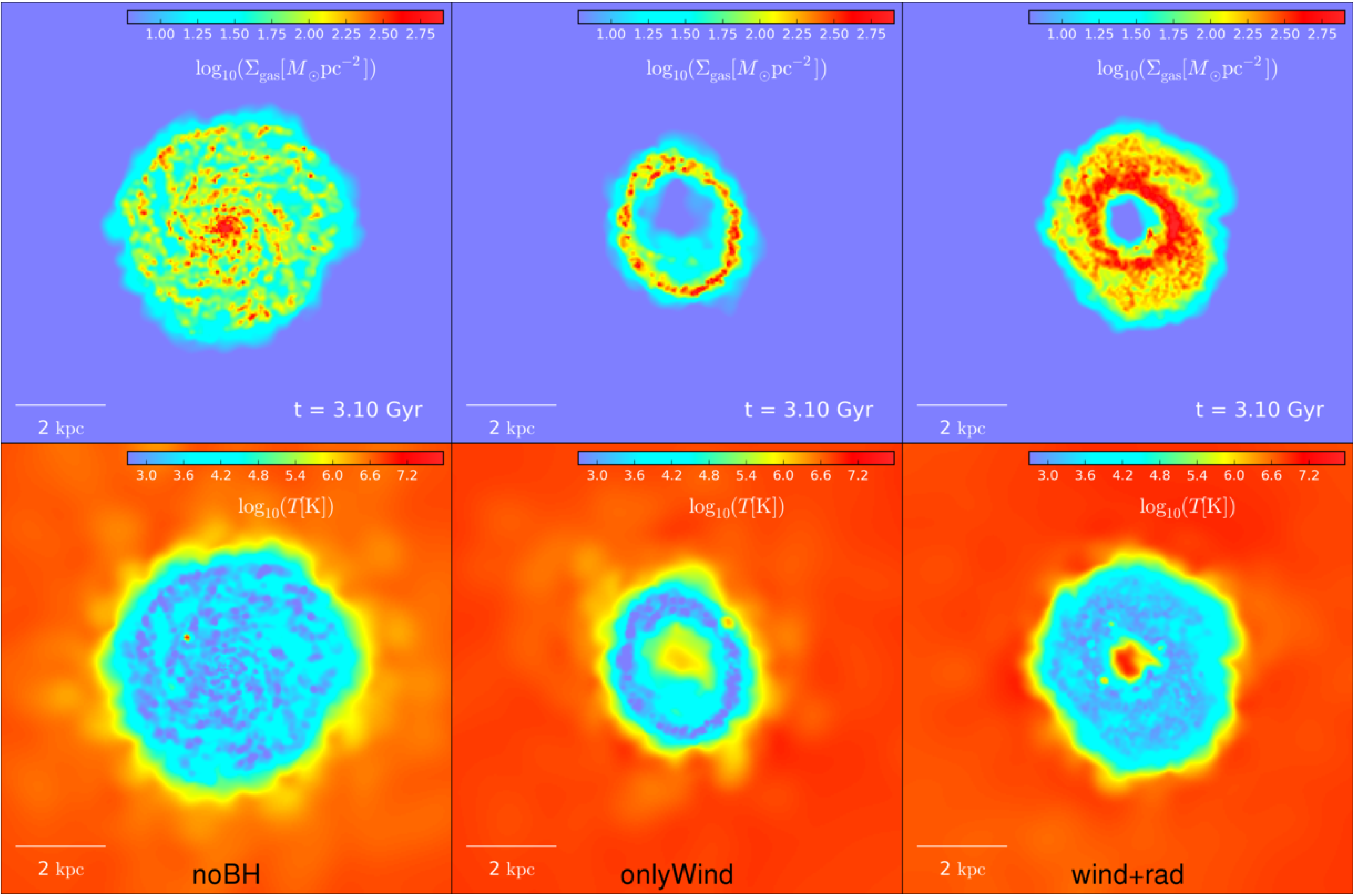
Percentage of time quiescent:

noBH	onlyWind	wind+rad
5%	63%	87%

Quiescence



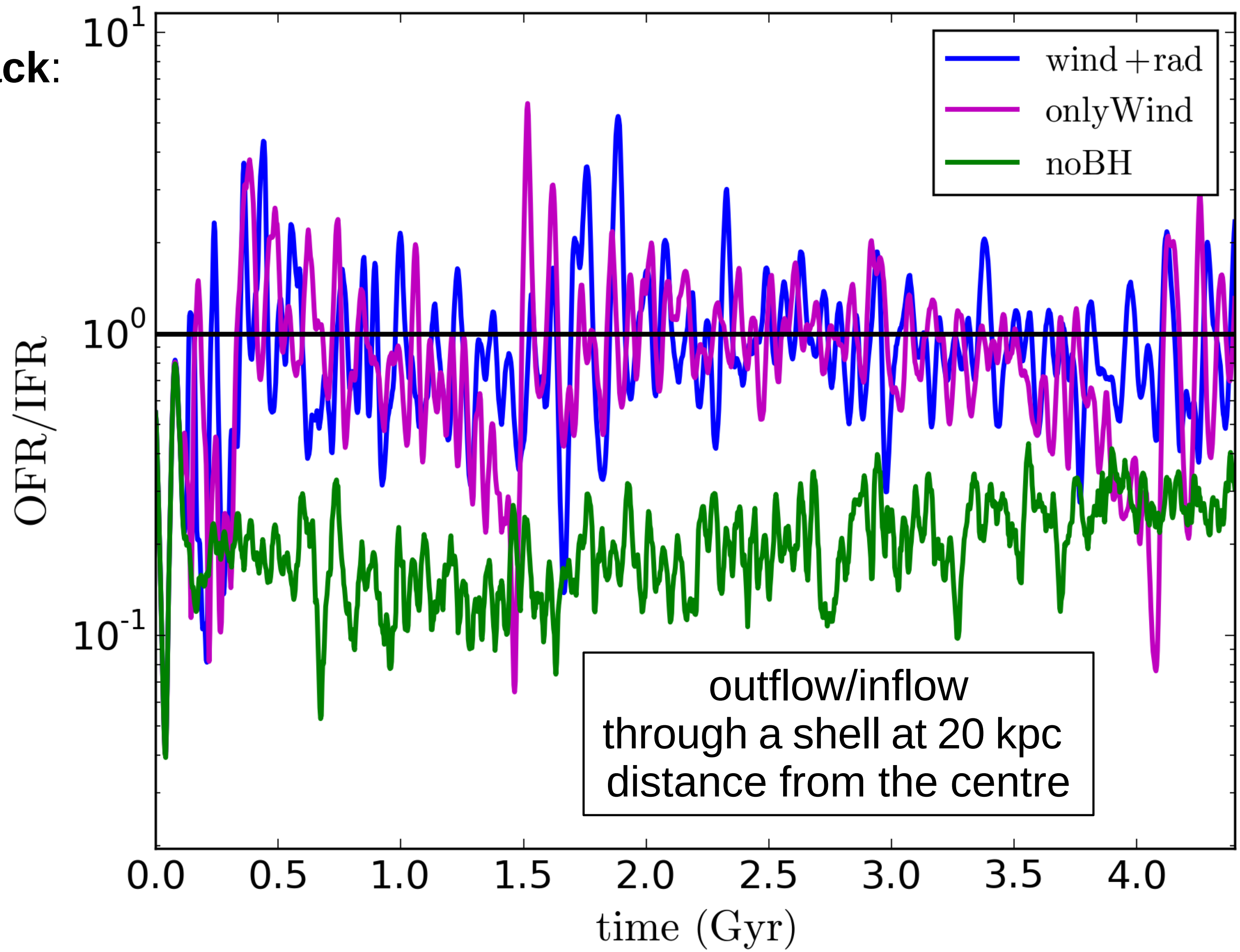
Observational data (histogram): Chang+2015

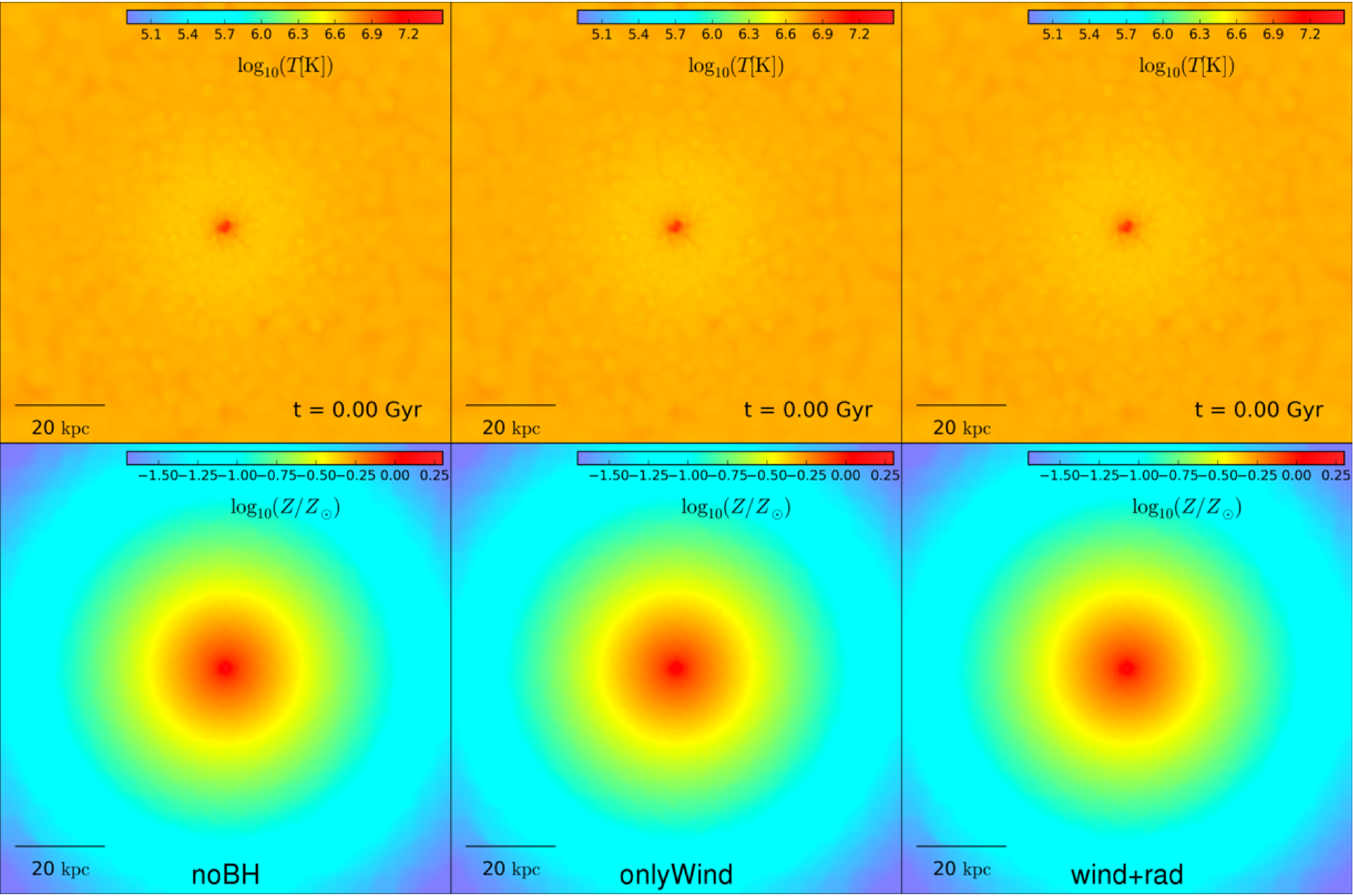


Images created using **pygad**
(https://bitbucket.org/broett/pygad)

Flow Rates

- **Without BH-feedback**:
  - Always net-inflow
- **With BH-feedback:**
  - Balanced in- and outflow




5.1 5.4 5.7 6.0 6.3 6.6 6.9 7.2
$\log_{10}(T[\mathrm{K}])$
20 kpc
t = 0.00 Gyr
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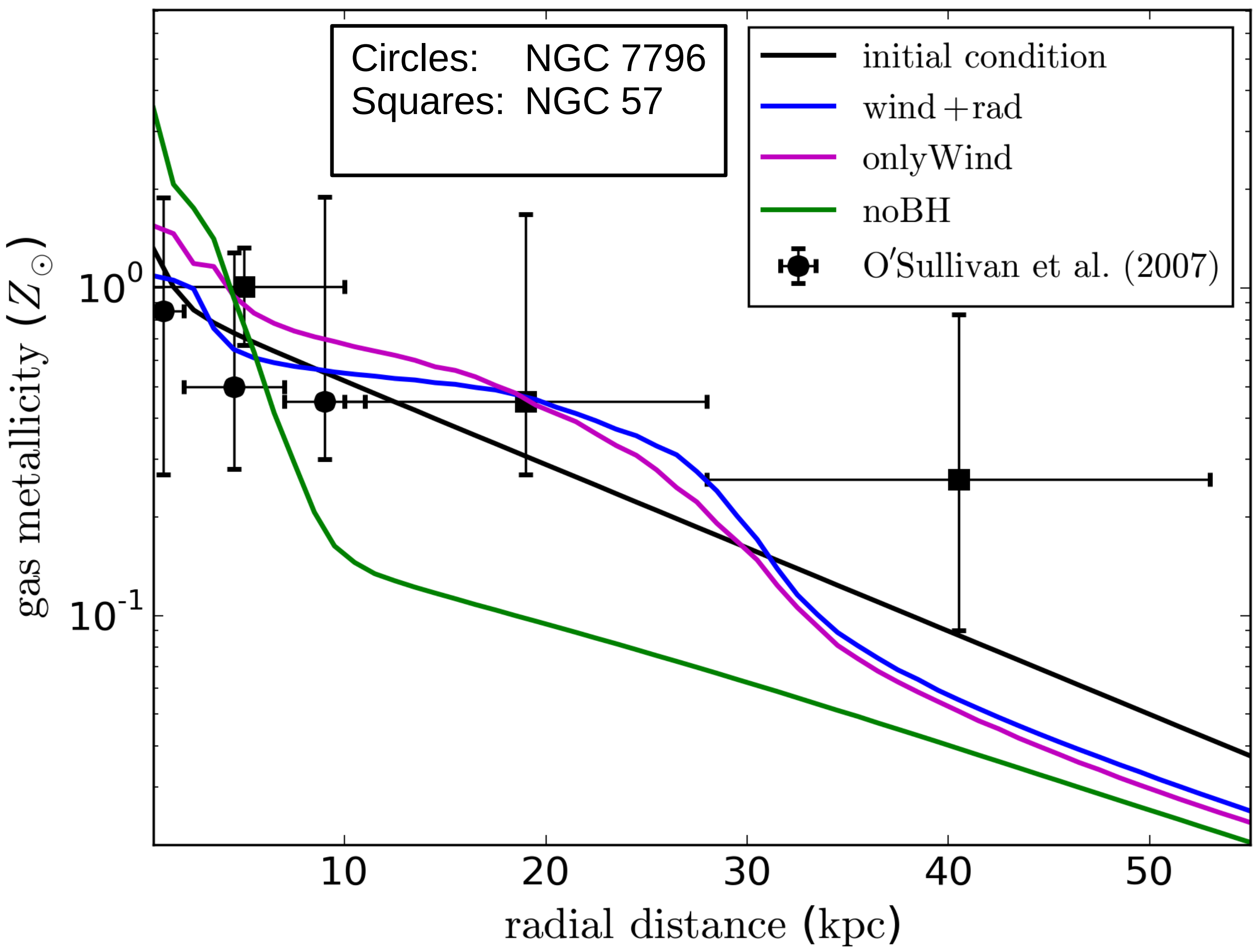
$\log_{10}(T[\mathrm{K}])$
20 kpc
t = 0.00 Gyr
−1.50 −1.25 −1.00 −0.75 −0.50 −0.25 0.00 0.25
$\log_{10}(Z/Z_\odot)$
20 kpc
noBH
−1.50 −1.25 −1.00 −0.75 −0.50 −0.25 0.00 0.25
$\log_{10}(Z/Z_\odot)$
20 kpc
onlyWind
−1.50 −1.25 −1.00 −0.75 −0.50 −0.25 0.00 0.25
$\log_{10}(Z/Z_\odot)$
20 kpc
wind+rad

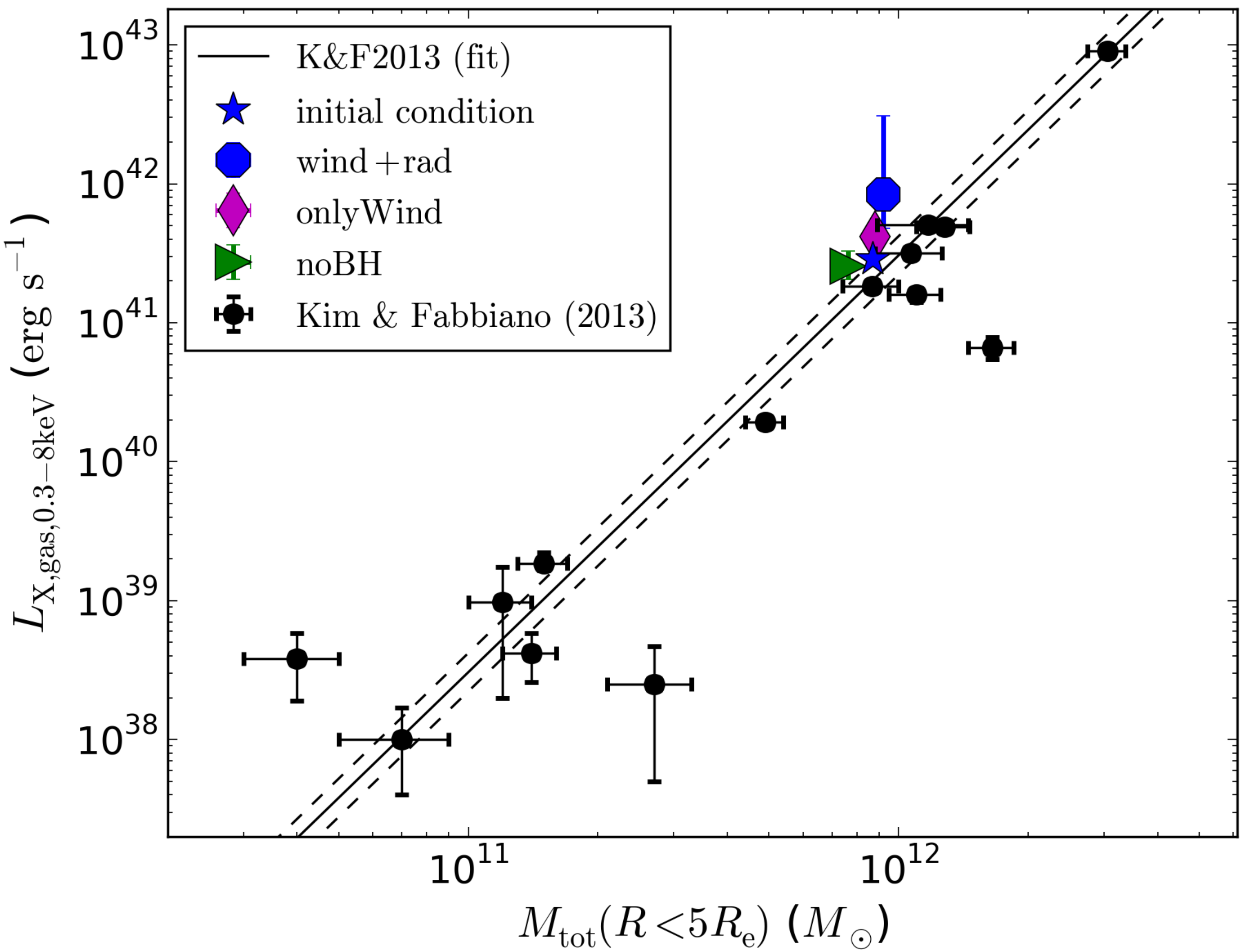
Metal distribution

- **Without feedback**:
  - Galaxy deprived of metals outside of central disk

- **With feedback**:
  - Enrichment of CGM out to ~30 kpc by feedback-driven large-scale outflows



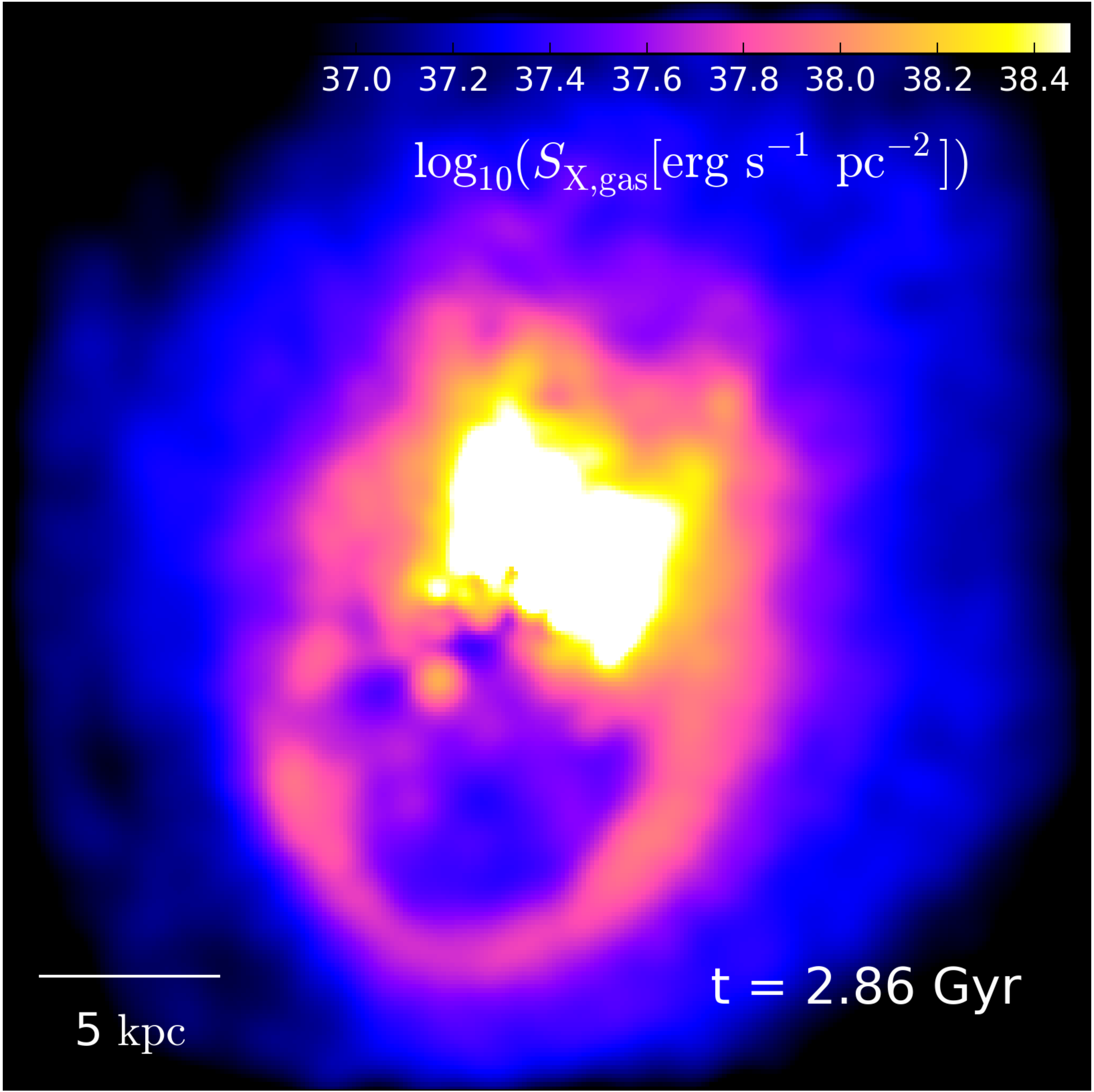
X-ray luminosity



Soft X-ray band (0.3-8 kev) emission, including metal-lines, calculated using XSPEC

Excluded:
Dense gas in star-forming regions

- All models fit reasonably well to observations
- X-ray luminosity is not a good indicator for influence of black-hole feedback



37.0 37.2 37.4 37.6 37.8 38.0 38.2 38.4
$\log_{10}(S_{\mathrm{X,gas}}[\mathrm{erg\ s^{-1}\ pc^{-2}}])$
5 kpc
t = 2.86 Gyr

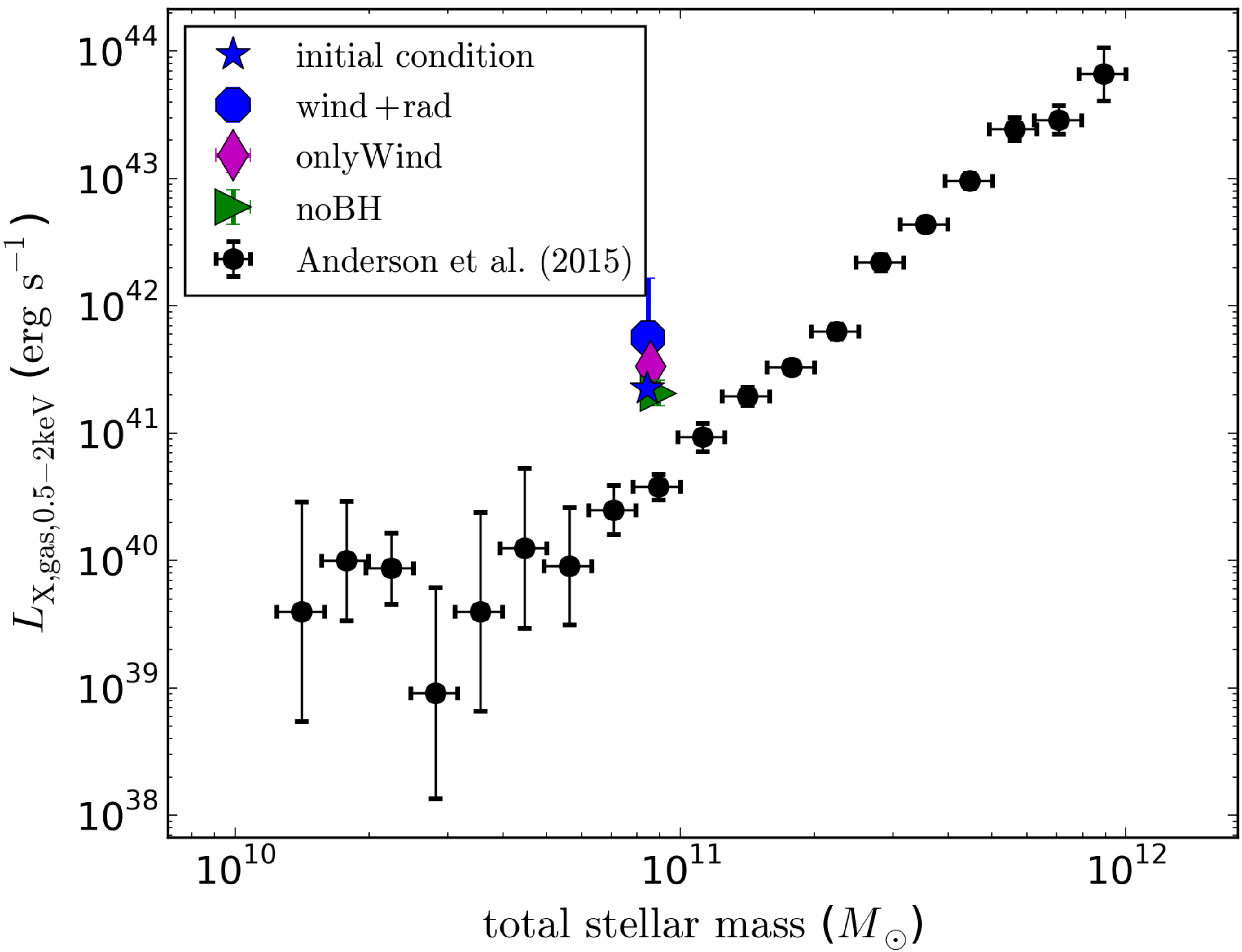
Conclusions

- SPH simulations of isolated ETGs comparing runs with and without accretion & feedback from the SMBH, with two different feedback models

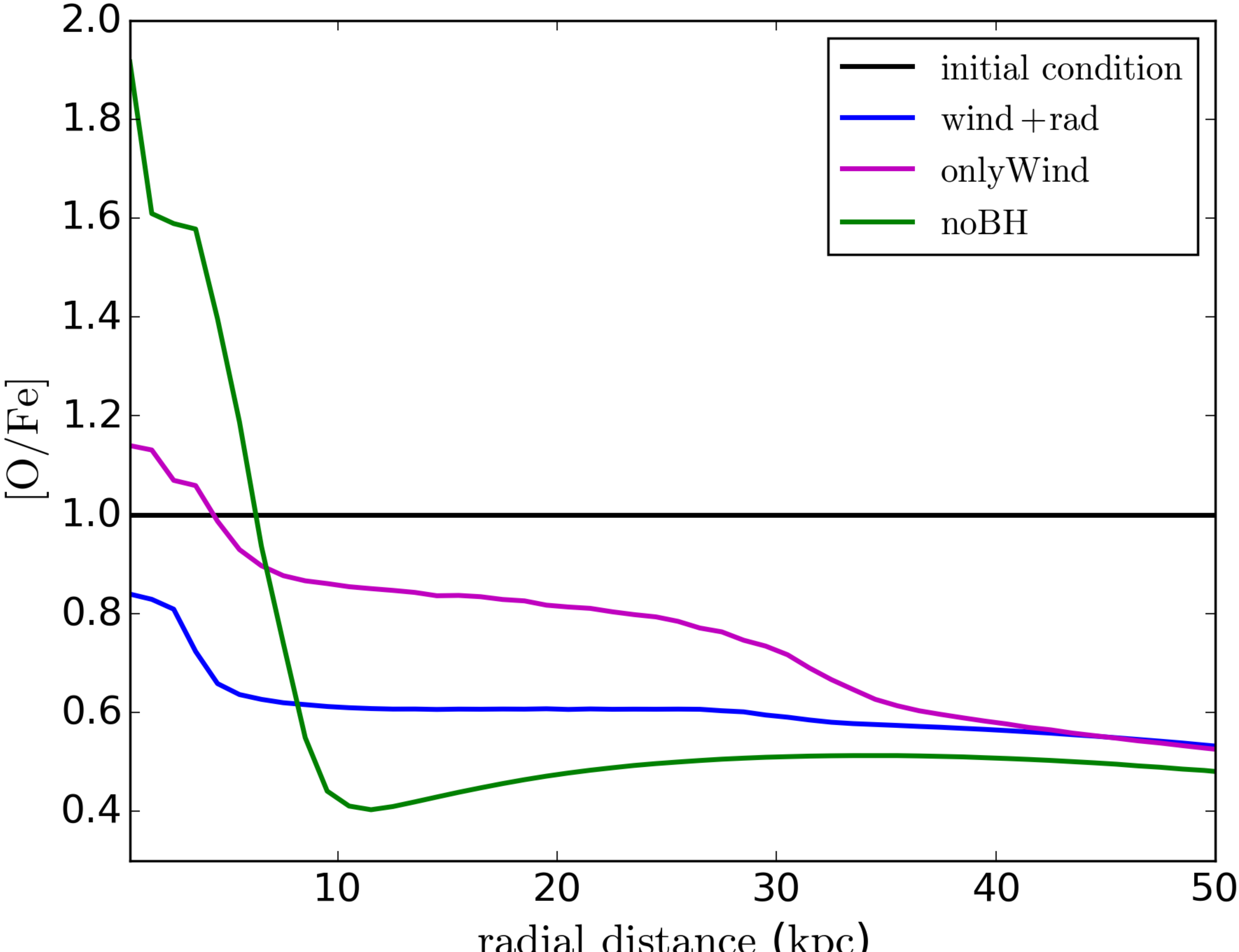
- **BH feedback necessary to and capable of keeping (isolated) ETG quiescent**
- Radiative feedback strongly reduces SFR compared to just wind feedback

- BH wind feedback creates **large-scale, metal-rich outflows** that enrich the CGM out to about 30 kpc
- No lasting enrichment or other influence farther out than 30 kpc

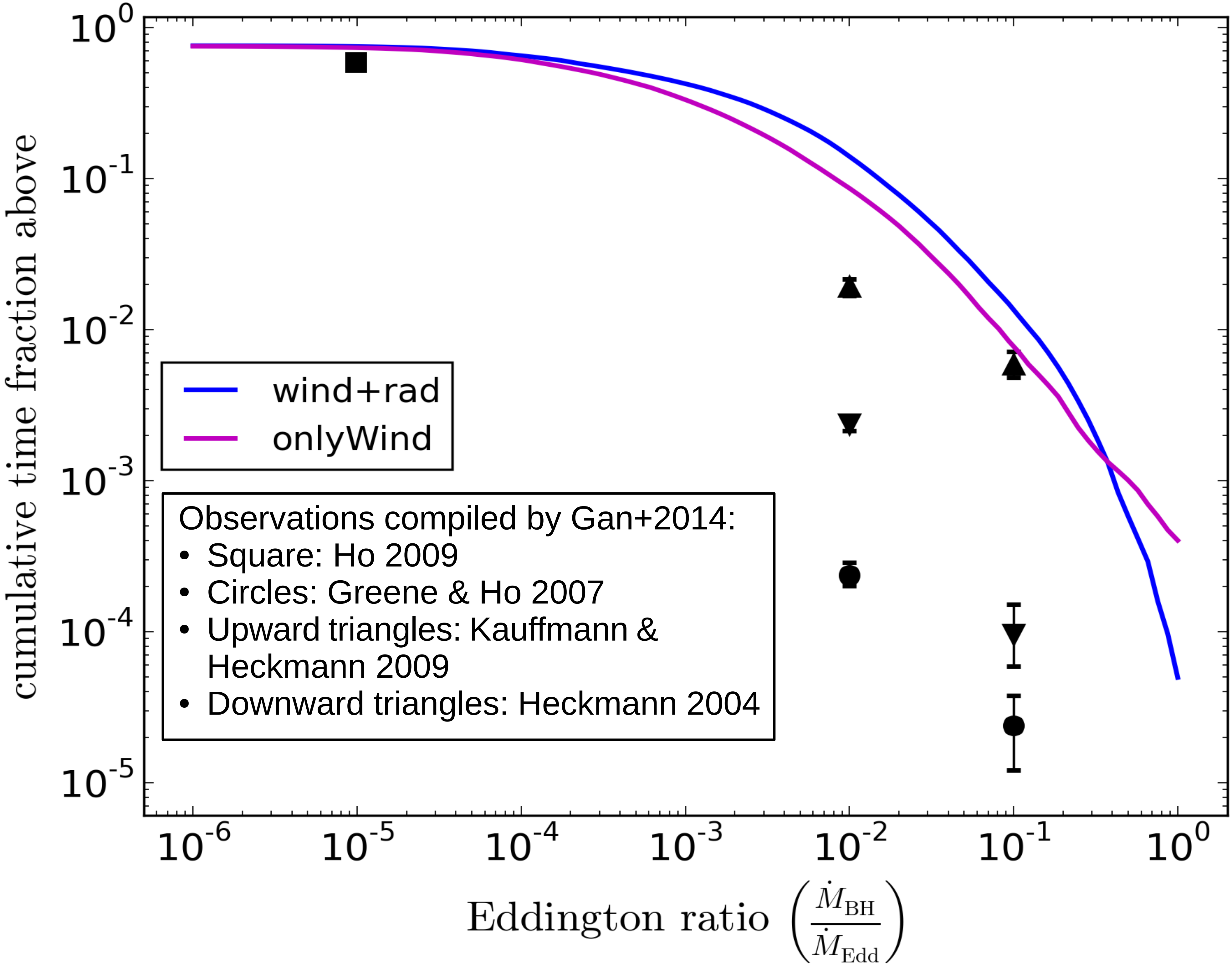
Extra Slides



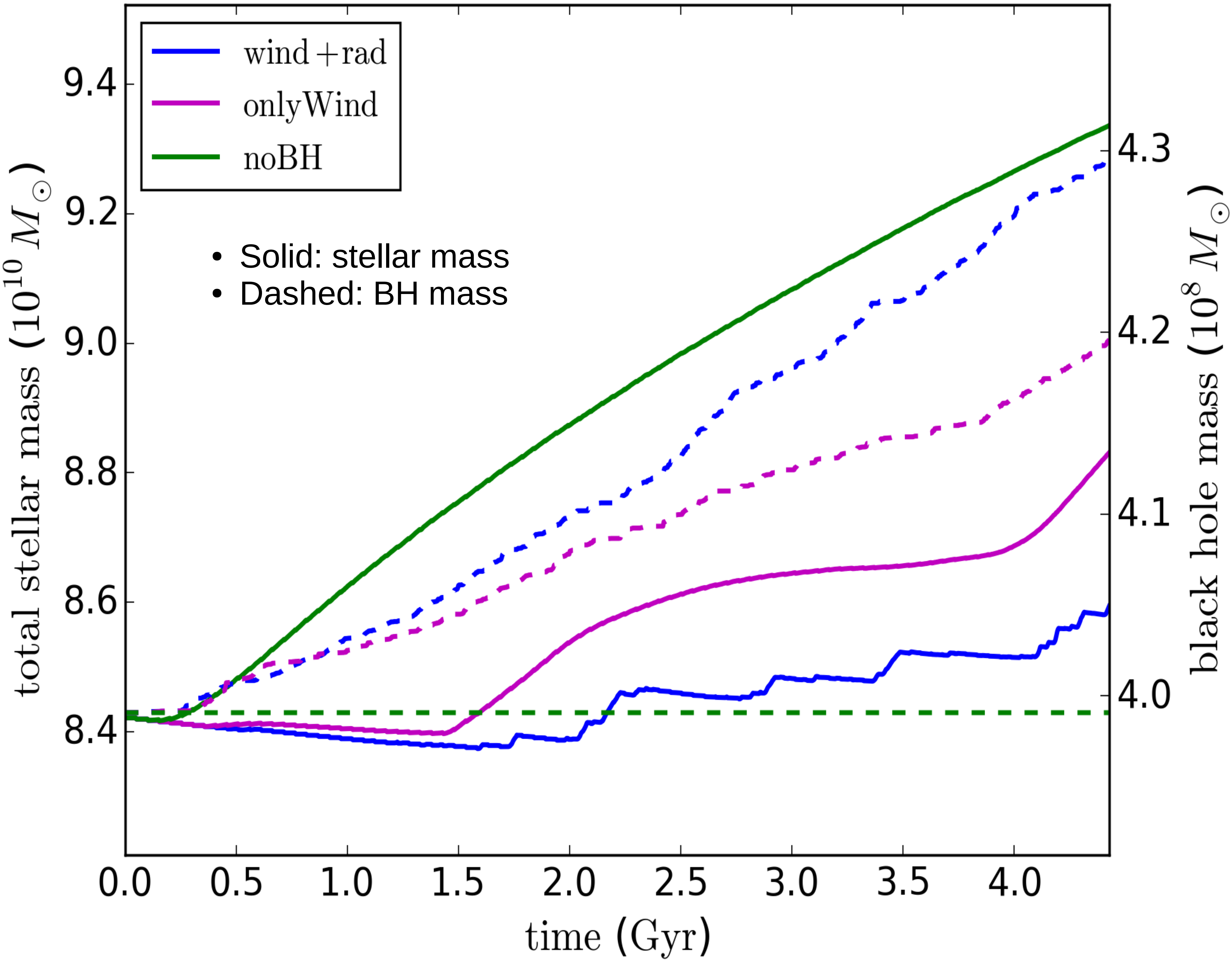
initial condition
wind+rad
onlyWind
noBH
Anderson et al. (2015)
$L_{\rm X,gas,0.5-2keV}$ (erg s^{-1})
10^{38}
10^{39}
10^{40}
10^{41}
10^{42}
10^{43}
10^{44}
10^{10}
10^{11}
10^{12}
total stellar mass ($M_\odot$)



initial condition
wind+rad
onlyWind
noBH
[O/Fe]
radial distance (kpc)
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
10
20
30
40
50



cumulative time fraction above
Eddington ratio $\left(\frac{\dot{M}_{\rm BH}}{\dot{M}_{\rm Edd}}\right)$
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
wind+rad
onlyWind
Observations compiled by Gan+2014:
• Square: Ho 2009
• Circles: Greene & Ho 2007
• Upward triangles: Kauffmann & Heckmann 2009
• Downward triangles: Heckmann 2004



wind+rad
onlyWind
noBH
• Solid: stellar mass
• Dashed: BH mass
total stellar mass ($10^{10} M_\odot$)
black hole mass ($10^8 M_\odot$)
time (Gyr)
9.4
9.2
9.0
8.8
8.6
8.4
4.3
4.2
4.1
4.0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0