EFFECTS OF X-RAYS ON BLACK HOLE GROWTH & STELLAR POPULATION

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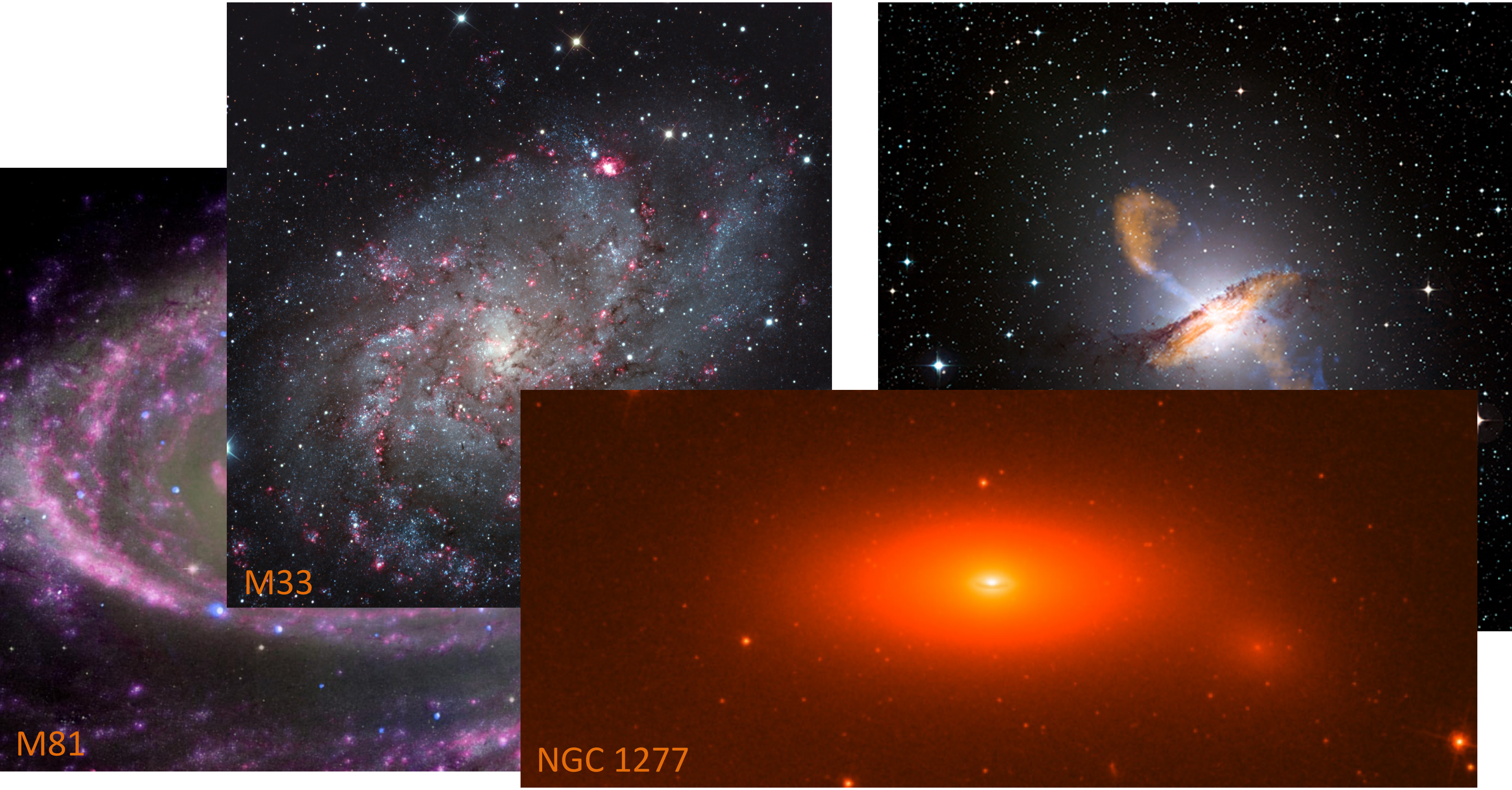
Guillermo Haro, 9 July 2015

OUTLINE

- Black Holes
- Black Hole Growth
- Simulations
  - Part I: Relevance of X-rays & Metals
  - Part II: Effects of X-rays on BH Growth & Stellar Population
- Open Questions

Observations of Local Universe

- All massive galaxies host a central black hole

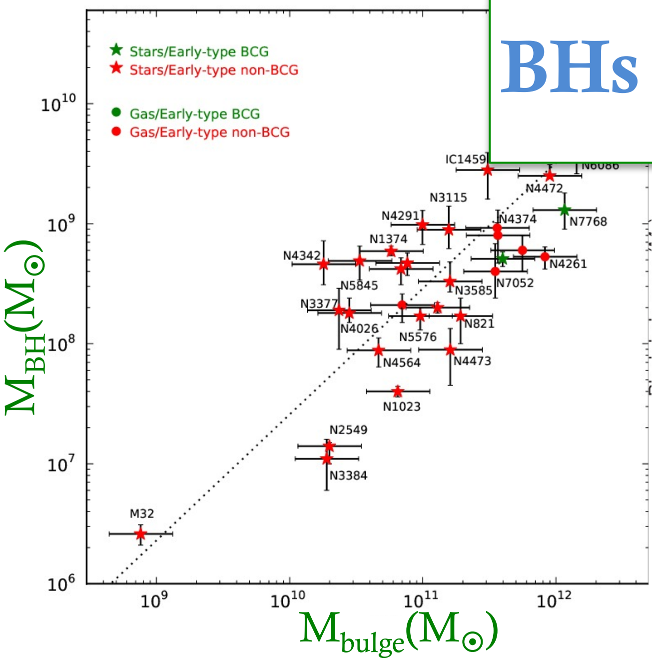


- Correlations exist between the M_{BH} and the host galaxy properties

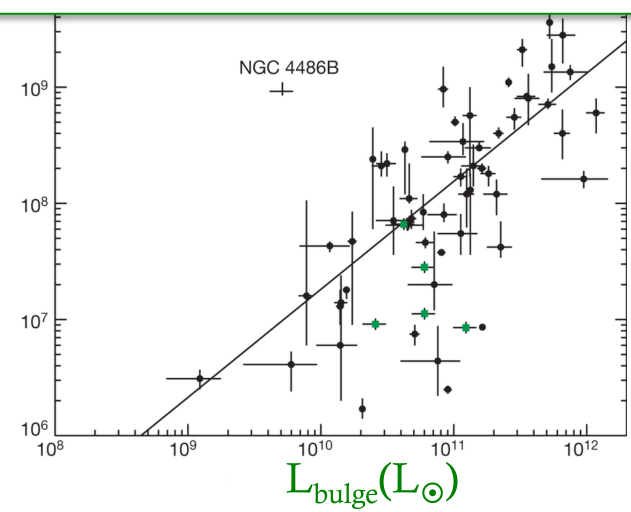
Correlations Between M_{BH}-Host Galaxy Properties

- Galaxy bulge mass ($M_{BH} \sim 10^{-3}\ M_{bulge}$; Dressler ‘89; Magorrian et al. ‘98)
- Galaxy bulge luminosity (M_{BH}-$L^{1.0\pm0.1}$; Kormendy ‘93; Kormendy & Richstone ‘95)
- Stellar velocity dispersion ($M_{BH} \sim \sigma^4$; Gebhardt et al. ‘00; Ferrarese & Merritt ‘00)

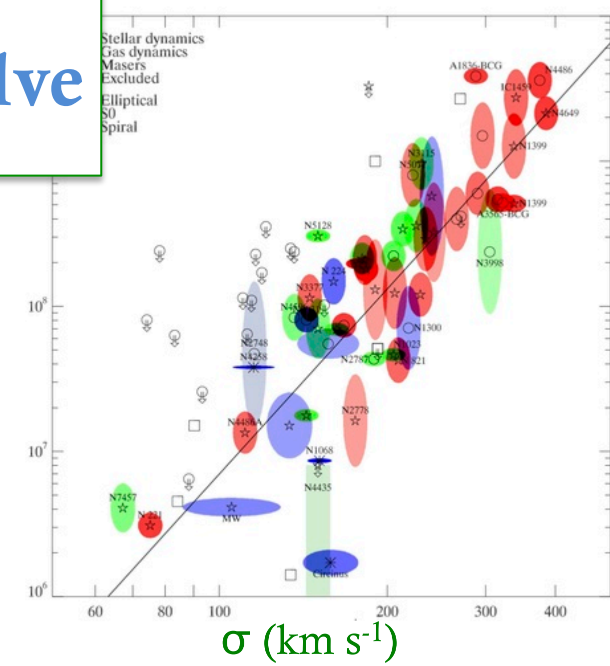
BHs & Galaxies Co-Evolve



McConnell & Ma ‘13



van den Bosch et al. ‘12

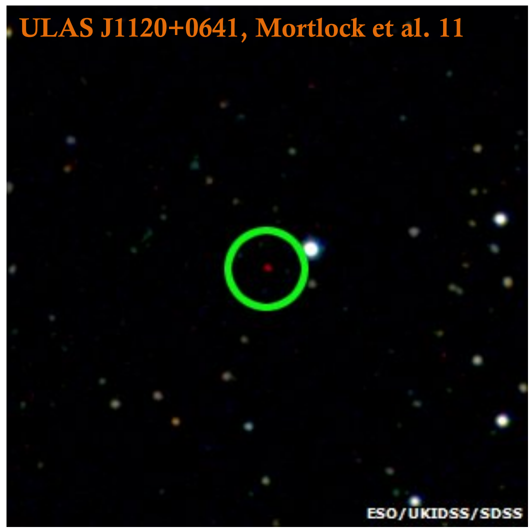


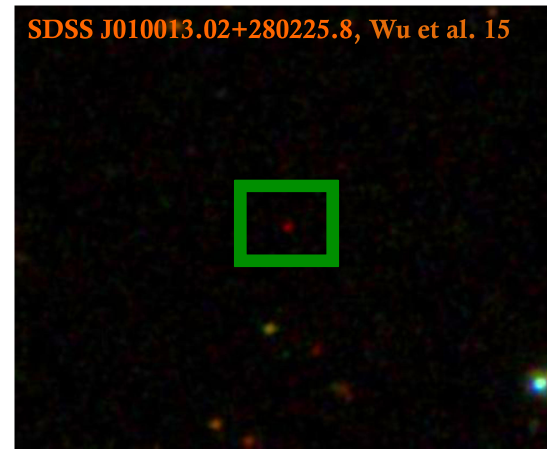
Gültekin et al. ‘09

Observations of High-z Quasars

4-8 orders of magnitude in mass in only ~700 Myr!!!

Seed BH





$M_{BH} = 10^2\text{-}10^6\ M_\odot$, $z = 20\text{-}15$

$M_{BH} = 2 \times 10^9\ M_\odot$, $z = 7.085$

$M_{BH} = 1.2 \times 10^{10}\ M_\odot$, $z = 6.3$

In order to grow $10^{10}\ M_\odot$ SMBH by z=6.3, assuming Edd. Accretion, the seed BH should be at least $10^4\ M_\odot$ @ z=20 !!!

- How do BHs and the host galaxy know about each other
- Do these scaling relations evolve through cosmic time
- How do the relative contributions of AGN and SN feedback on the host galaxy evolve with time
- How do seed BHs grow
- How do seed BHs form ✔

Direct Collapse Seed BH Formation

Fragmentation of collapsing gas needs to be prevented

Lyman Werner (LW, 11.2-13.6 eV)

Formation of H_2 should be avoided

Otherwise, $T \sim 100$ K and for $n = 10^4$ cm^{-3}

$M_J \sim 10^6 (T/10^4)^{3/2}$, $M_{BH} = 100\ M_\odot$

For $T_{vir} > 10^4$ K, high LW background is required

($J_{21} = 10^{2-5}$, Omukai et al. '01, Shang et al. '10, Latif et al. '14, Glover '15)

($J_{21} = 10^{-21}$ erg cm^{-2} sr^{-1} s^{-1} Hz^{-1})

Lyman α Trapping

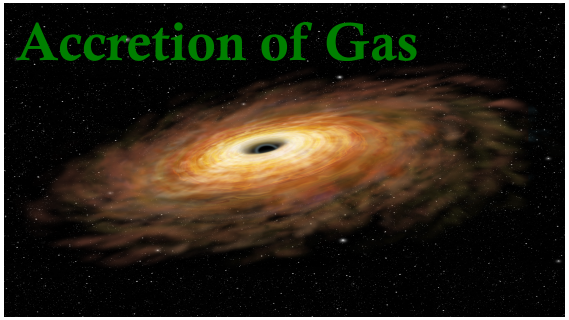
No H_2 & very low metallicity $Z < 10^{-4}\ Z_\odot$

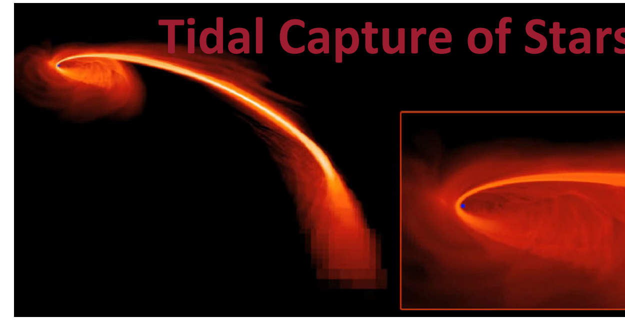
Lyα trapping keeps gas temperature $T > 10^4$ K

$t_{ff} < t_{lyes}$ a DCBH with a mass of 10^{-2}-10^{-3} M_H forms

(Spaans & Silk '06)

How Do Black Holes Grow?





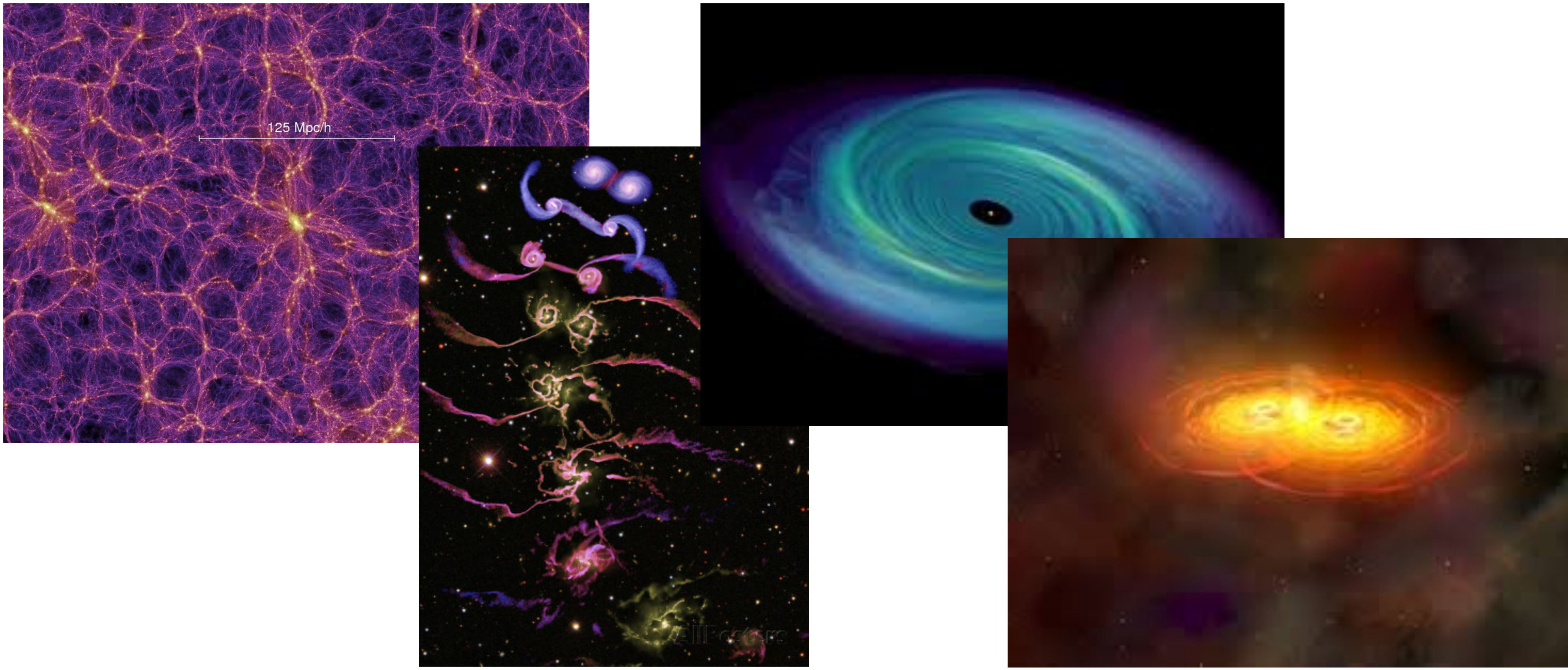
Efficiency of these channels depends on:

- black hole seed masses and cosmic time
- occurrence of merger events
- properties of the central region and of the host galaxy
- larger scale environment of the host dark matter halo
- stellar and black hole feedback processes

Large dyn. range
10 kpc - 0.01 pc

Angular Momentum Problem

How cosmic gas from large scales fall into accretion disks and feed BHs?

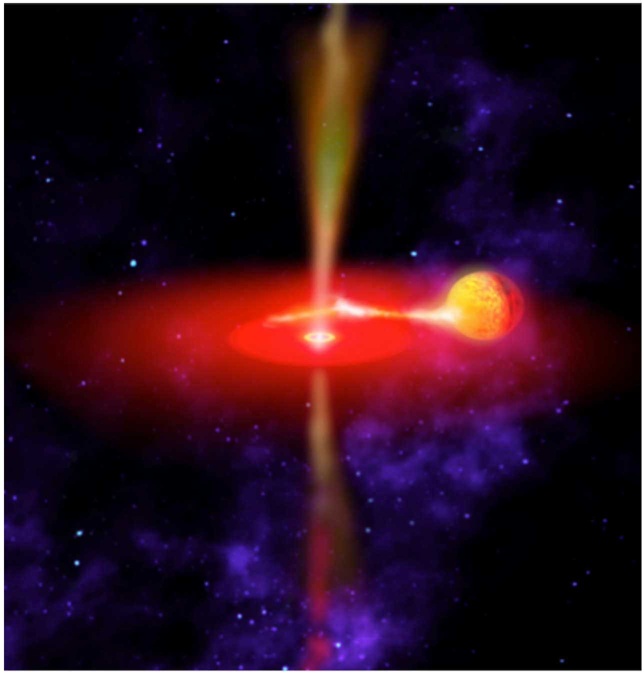


Angular momentum acts as an ‘accretion barrier’: Gas parcel starts out at ~10 kpc needs to lose ~99.9% of its angular momentum, **without forming stars!**

For rapid BH growth, an efficient mechanism is needed to transport angular momentum.

X-rays

- Accretion of gas onto the central BH yields a luminous source of UV (90%) and X-ray (10%) photons



- Thermodynamics of the gas in the inner region of AGN is dominated by the X-ray radiation (Wada et al. '09, Aykutalp et al. '13)

- Absorption cross-section, $\sigma \sim E^{-3}$
  e.g. 1 keV photon ➡ 10^{22} cm^{-2}

- X-rays ionise and drive the ion-molecule chemistry, hence the **H_2 formation**

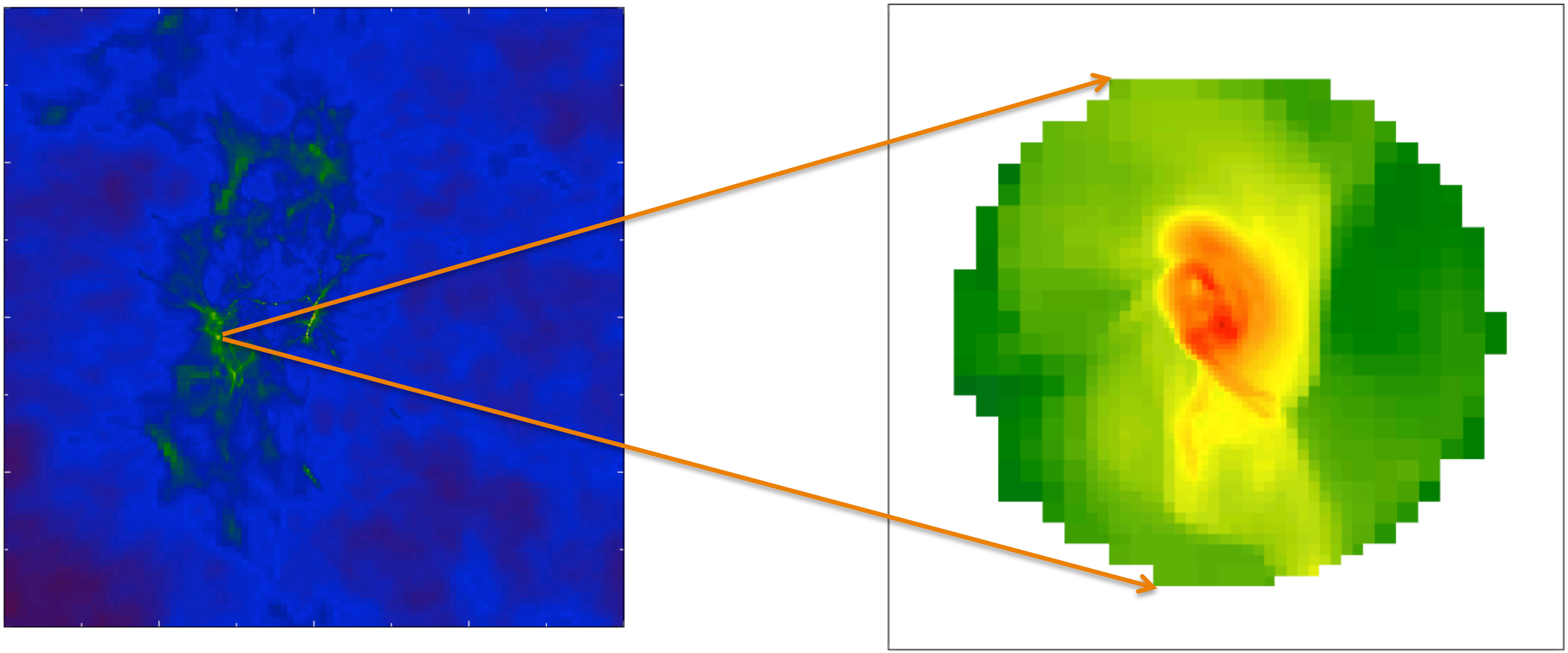
- X-rays couple to metal rich gas due to high cross-section

SIMULATIONS PART -I-

Relevance of X-rays & Metals

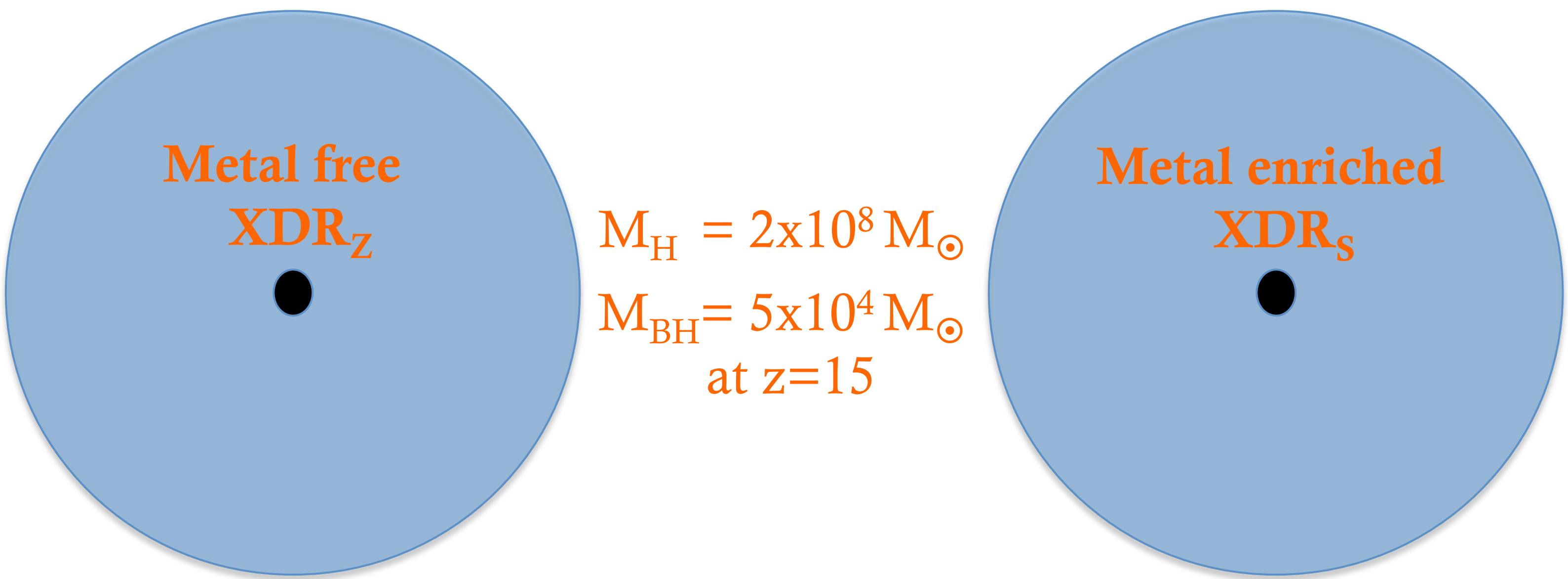
Simulation Ingredients -1-

- Include X-ray chemistry (Meijerink & Spaans '05): dust & ion-molecule chemistry, heating, cooling; pre-computed tables in n_H, N_H, F_X, $Z/Z_\odot$ (176 species, more than 1000 reac.)
- Utilize Moray (Wise et al. '12): X-ray radiation transport (polychromatic spectrum) around the seed BH

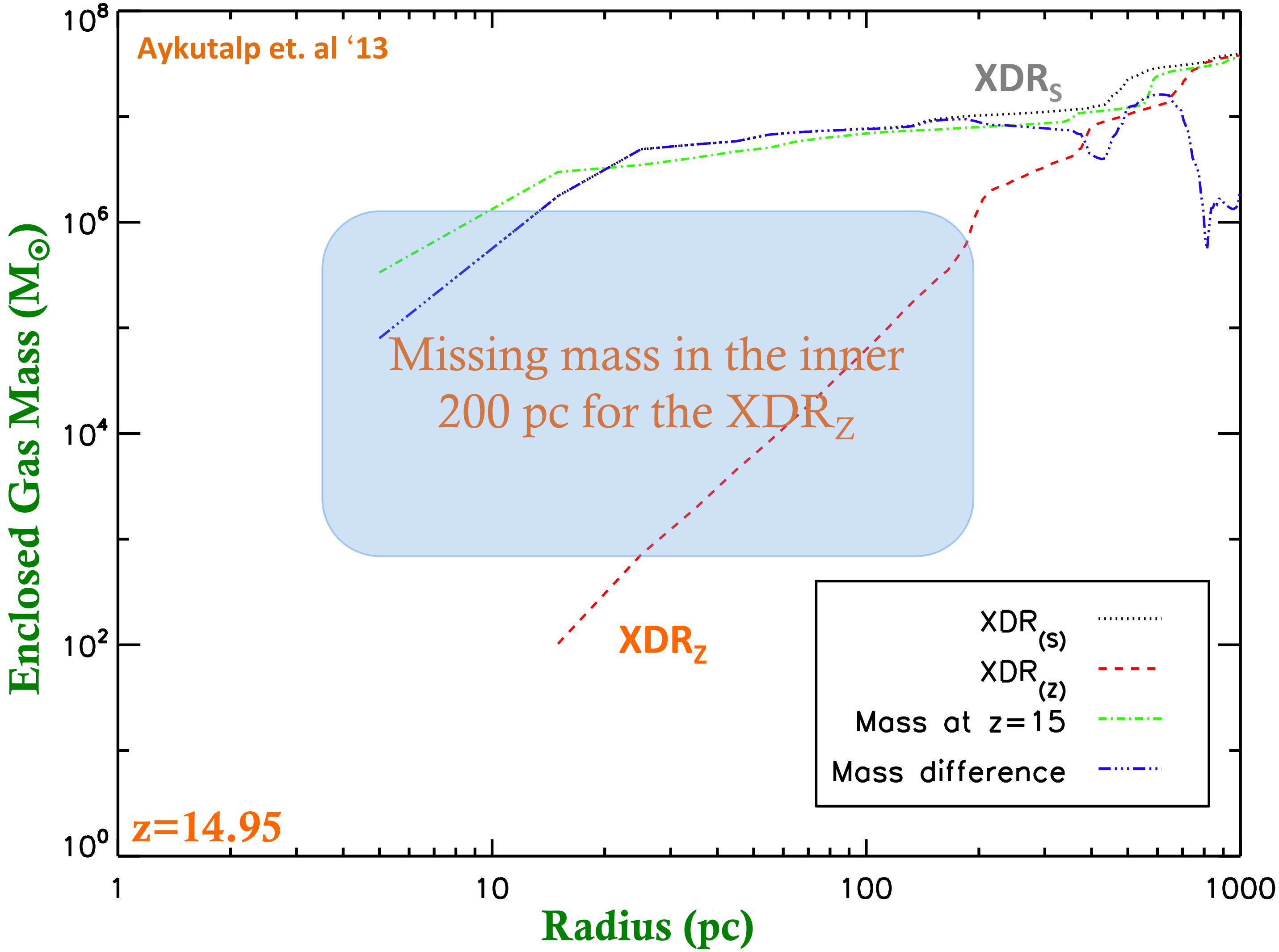


Enzo Simulations -1-

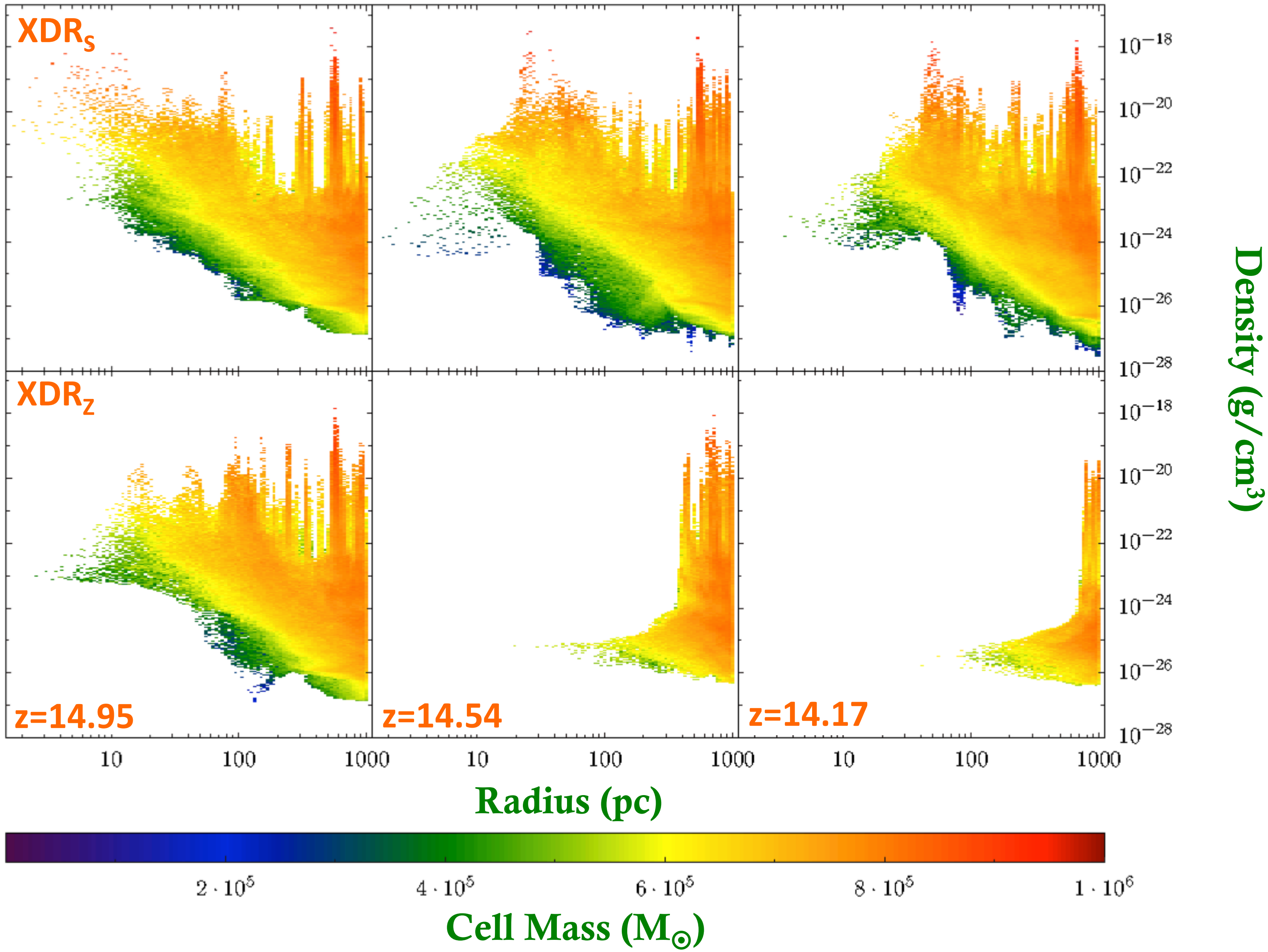
- Simulation box: 3 Mpc/h, highest resolution: 3.6 pc
- Perform two cosmological simulations for halos with a solar (XDR_S) and zero (XDR_Z) metallicity



Enclosed Gas Mass



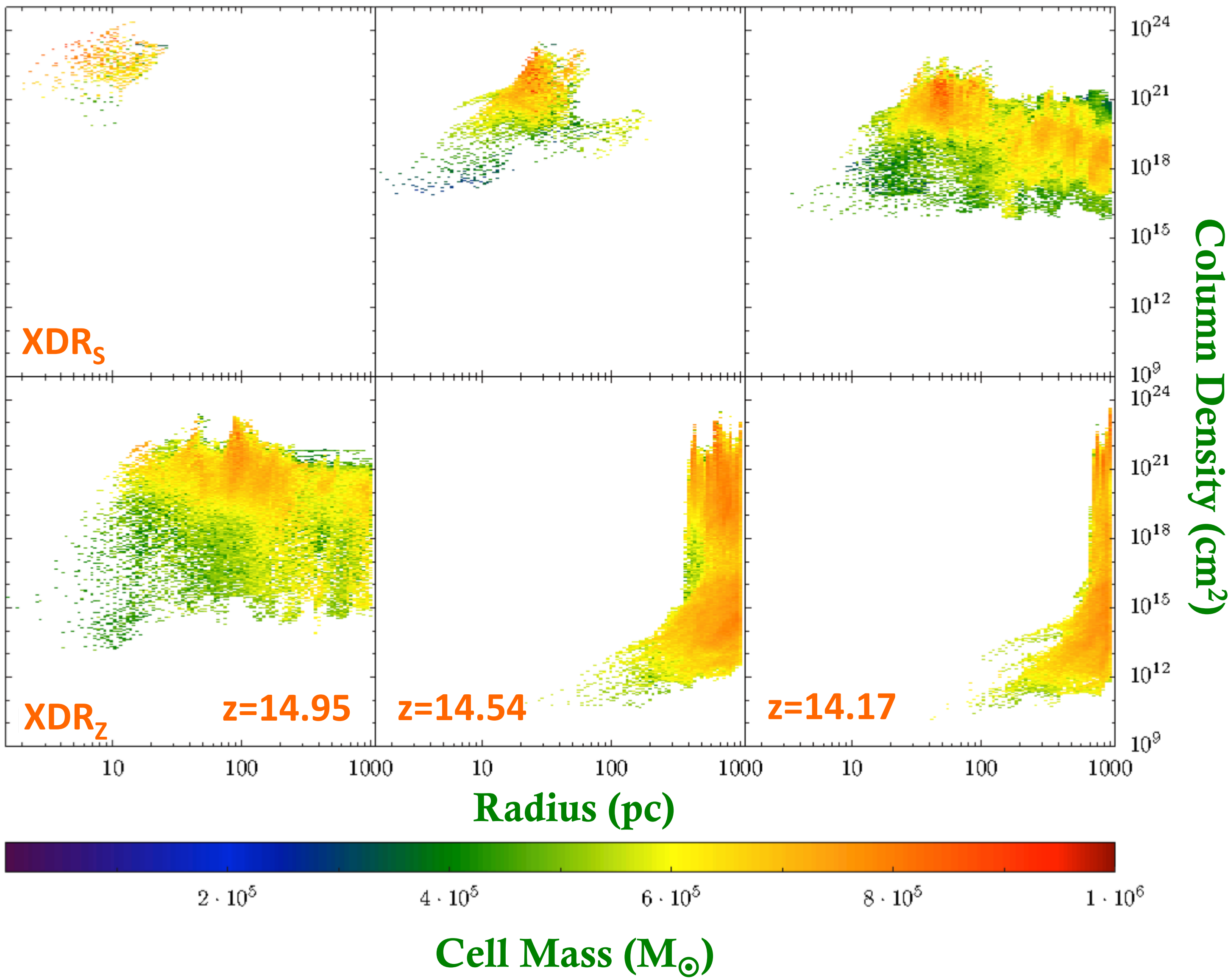
Density vs Radius



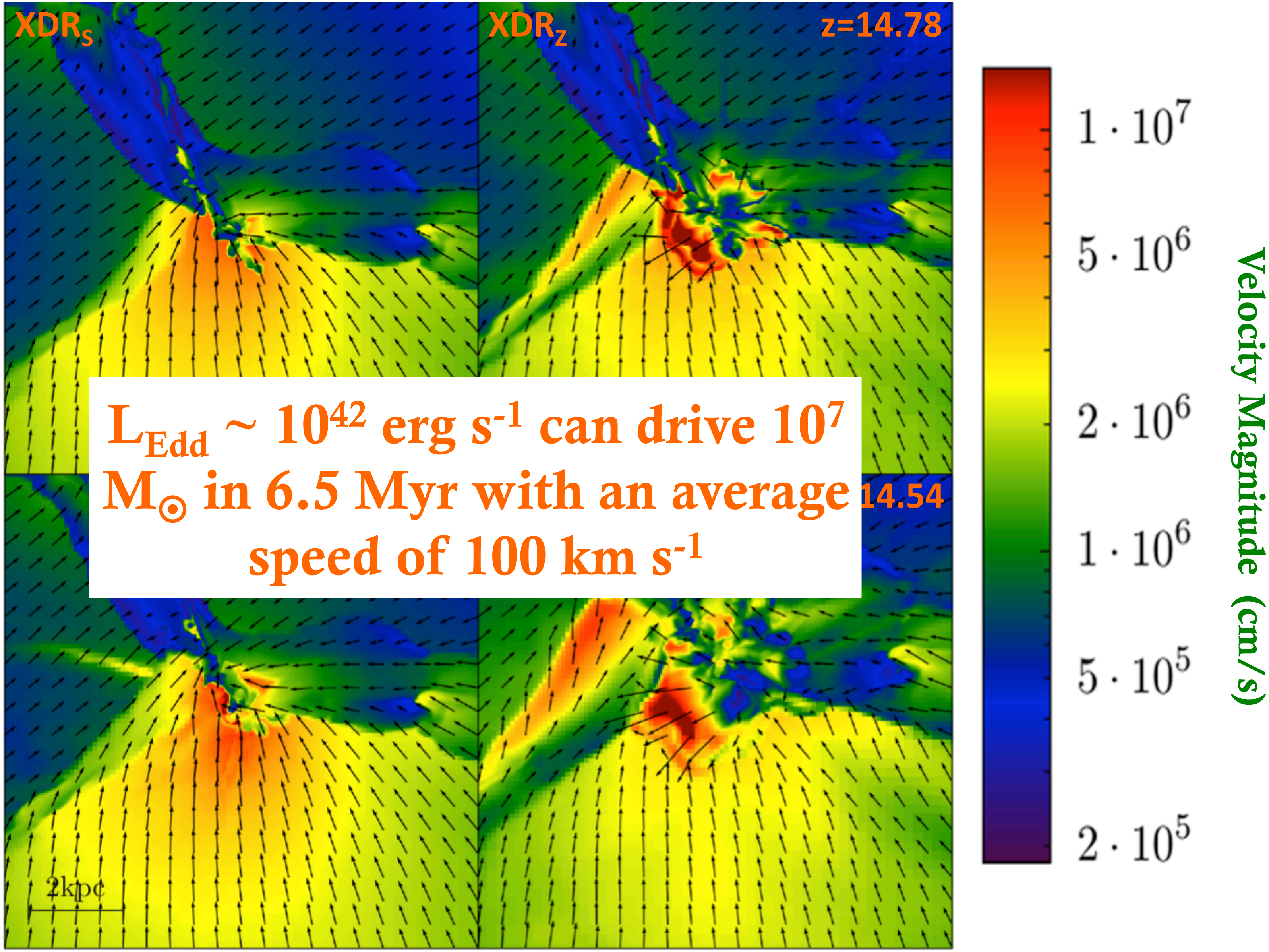
Column Density vs Radius

For $N_H > 10^{22}$ cm^{-2} opacity wall forms and X-ray power dissipated only locally

X-rays penetrate to larger columns and X-ray power dissipated globally

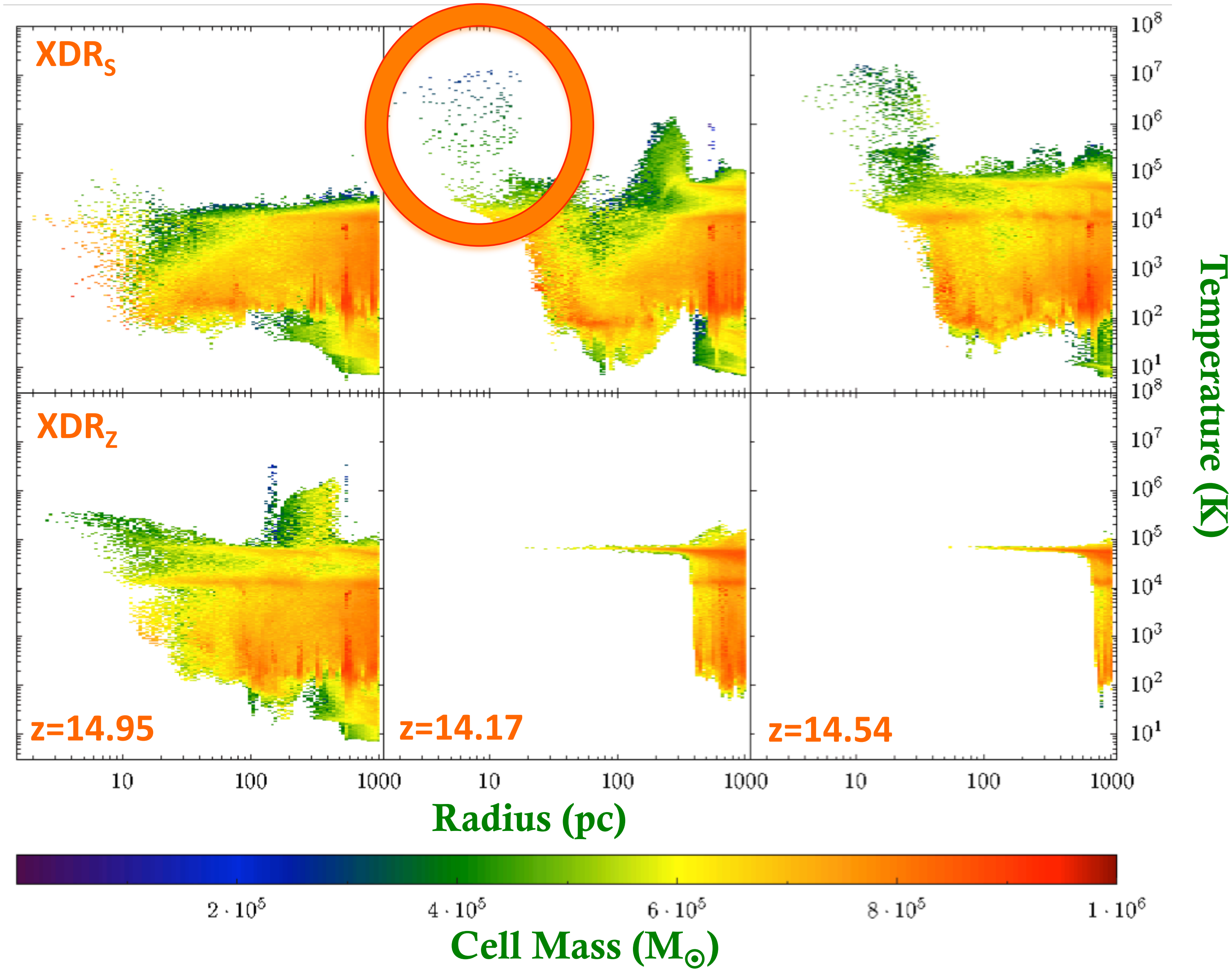


X-ray Induced H II Region



L_{Edd} ~ 10^{42} erg s^{-1} can drive 10^7 $M_\odot$ in 6.5 Myr with an average speed of 100 km s^{-1}

Temperature vs Radius



Results -Part I-

- In the XDR_Z case, X-ray induced H II region forms and blows away the ambient gas, self-limiting the growth of the central BH.

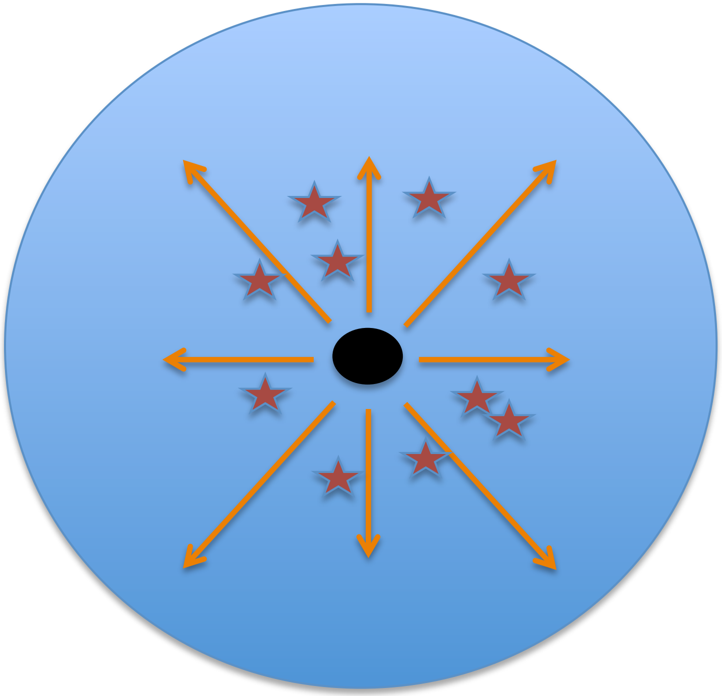
- In the XDR_S case, due to the efficient cooling, the ambient gas initially has higher column/densities and lower temperatures.

- In the XDR_S case, X-rays are captured by the metals in the inner 10 pc and heats the gas. However, gas at larger radius stays unaffected hence continue accreted onto the central BH.

SIMULATIONS PART -II-

Effects of X-rays on BH Growth

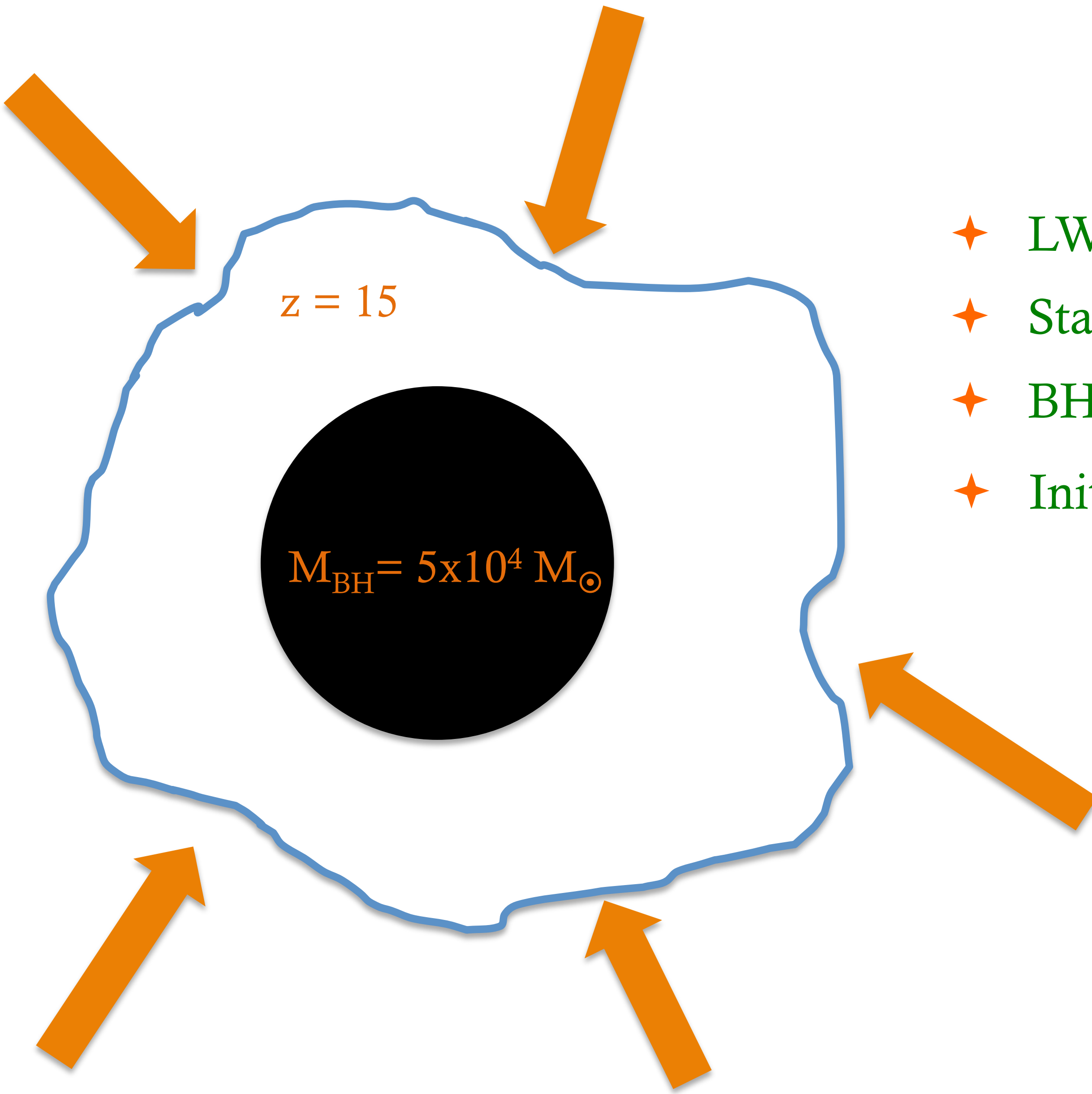
Simulation Ingredients -2-



- M_H: $2x10^8\ M_\odot$, M_{BH}: $5x10^4\ M_\odot$
- BH Acc.: Eddington-Lim. Spherical Bondi-Hoyle
- Star Formation Prescription: $f_{H2} > 5x10^{-4}$,
  $Z<10^{-3.5}\ Z_\odot$,
  $t_{cool} < t_{dyn}$
- Feedback: X-rays from the BH,
  SNe (radiative, mechanical & chemical)
- H_2 self-shielding
- Uniform LW background

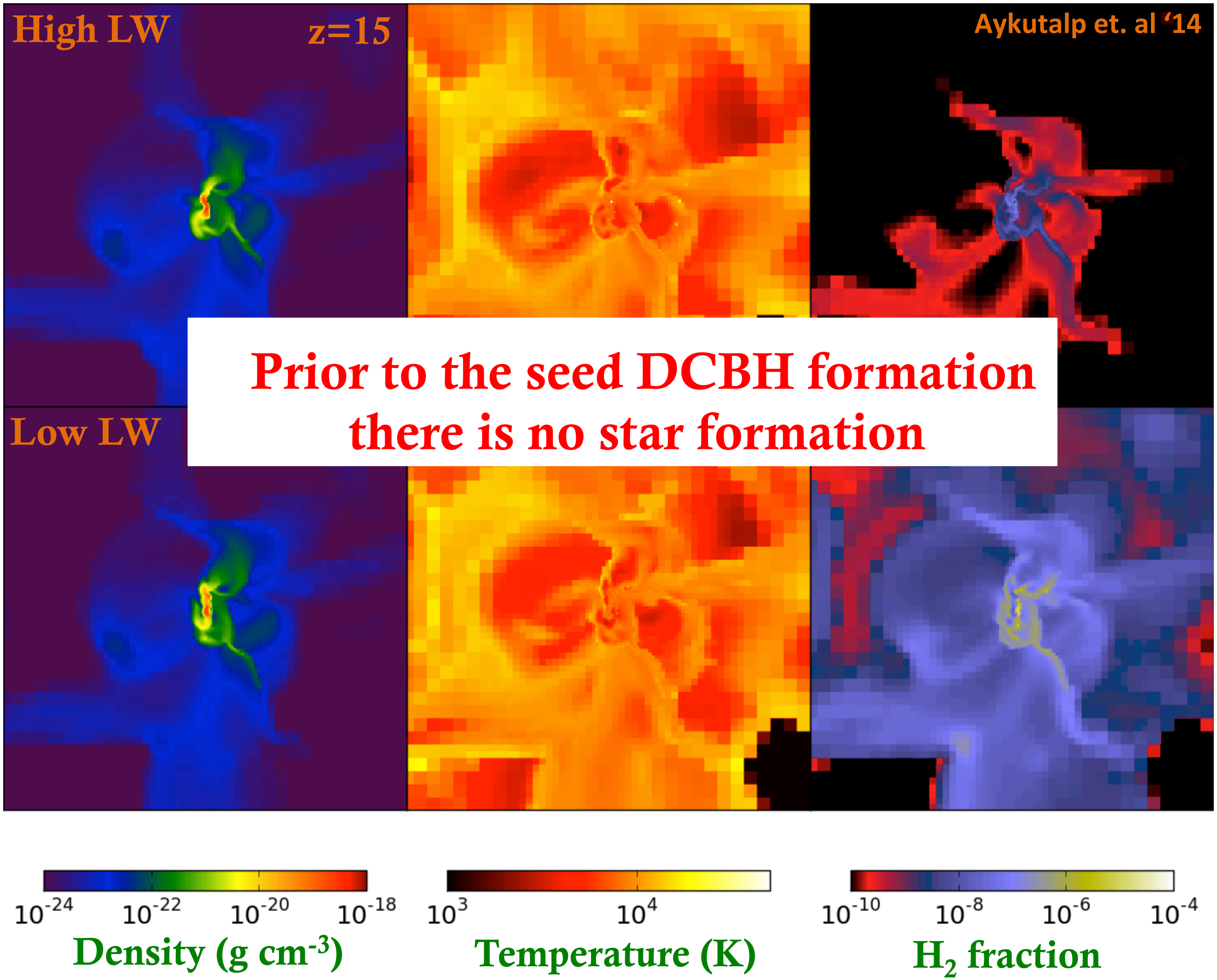
Enzo Simulations -2-

Perform 2 cosmological simulations for a LW background of 10^3 & 10^5 J_{21}

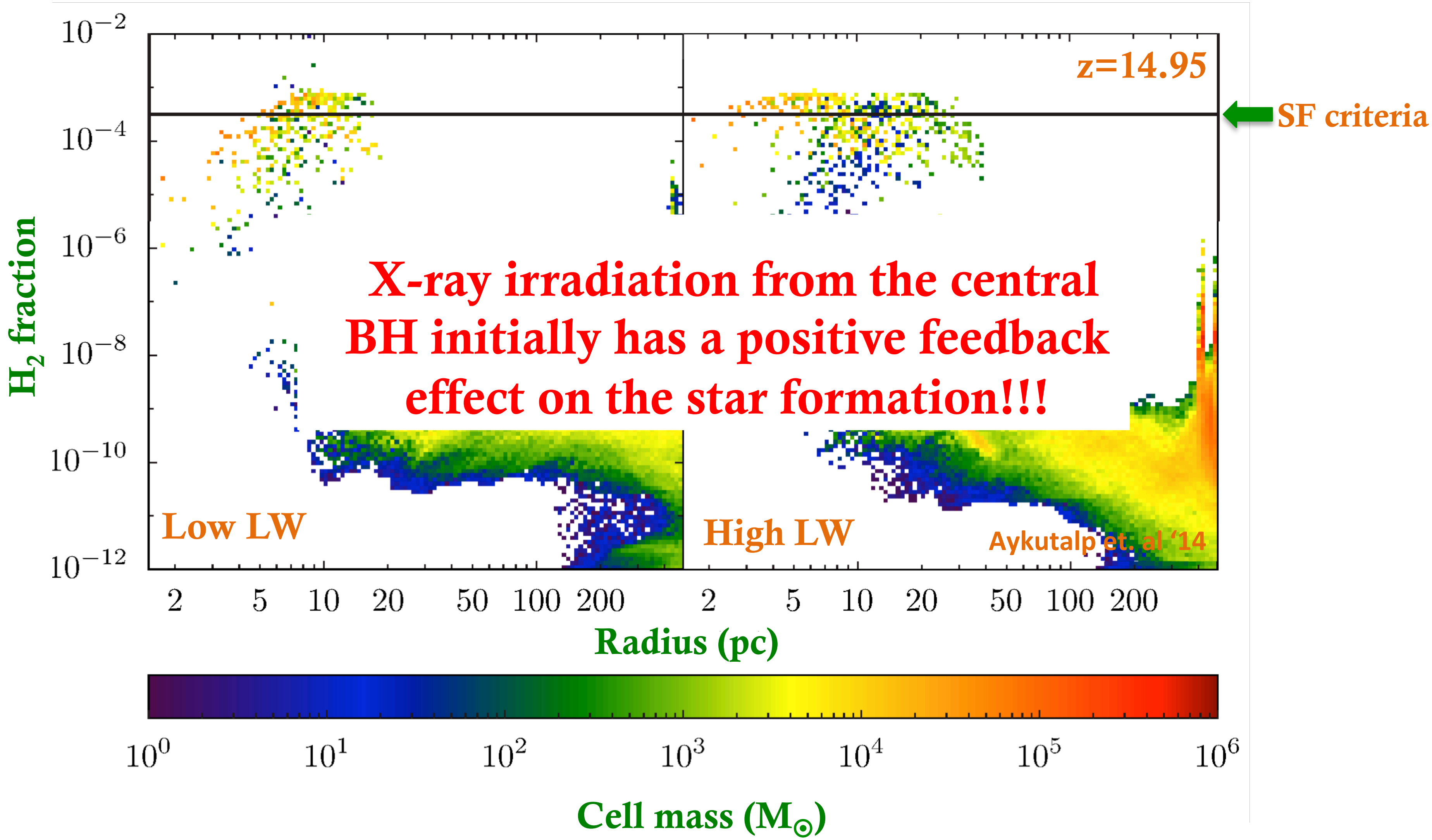


- LW background turned on @ z=30
- Star formation turned on @ z=30
- BH inserted @ z=15
- Initial metallicity $Z/Z_{\odot} = 0$

LW background suppresses H_2 formation

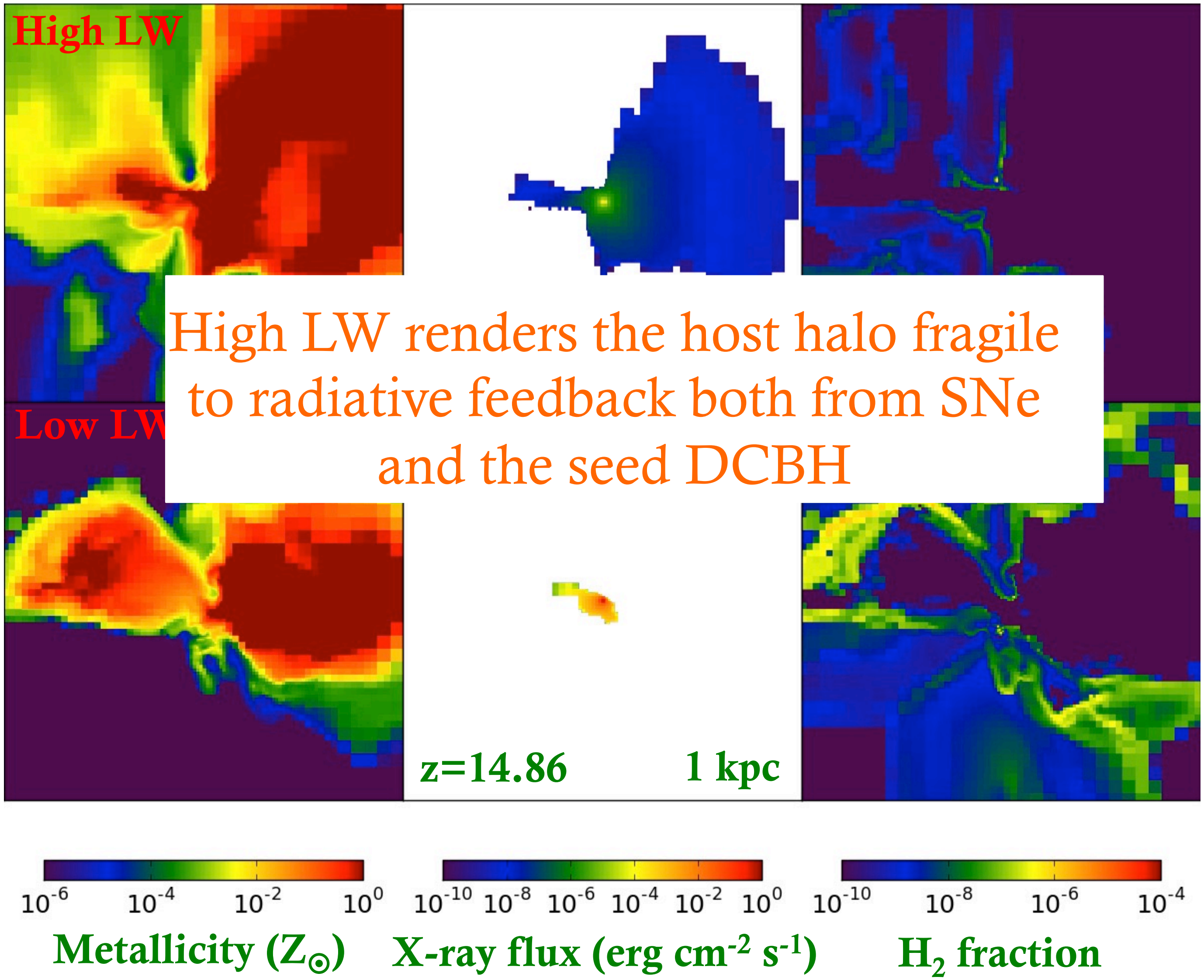


X-rays induce H_2 ➡ star formation



X-ray irradiation from the central BH initially has a positive feedback effect on the star formation!!!

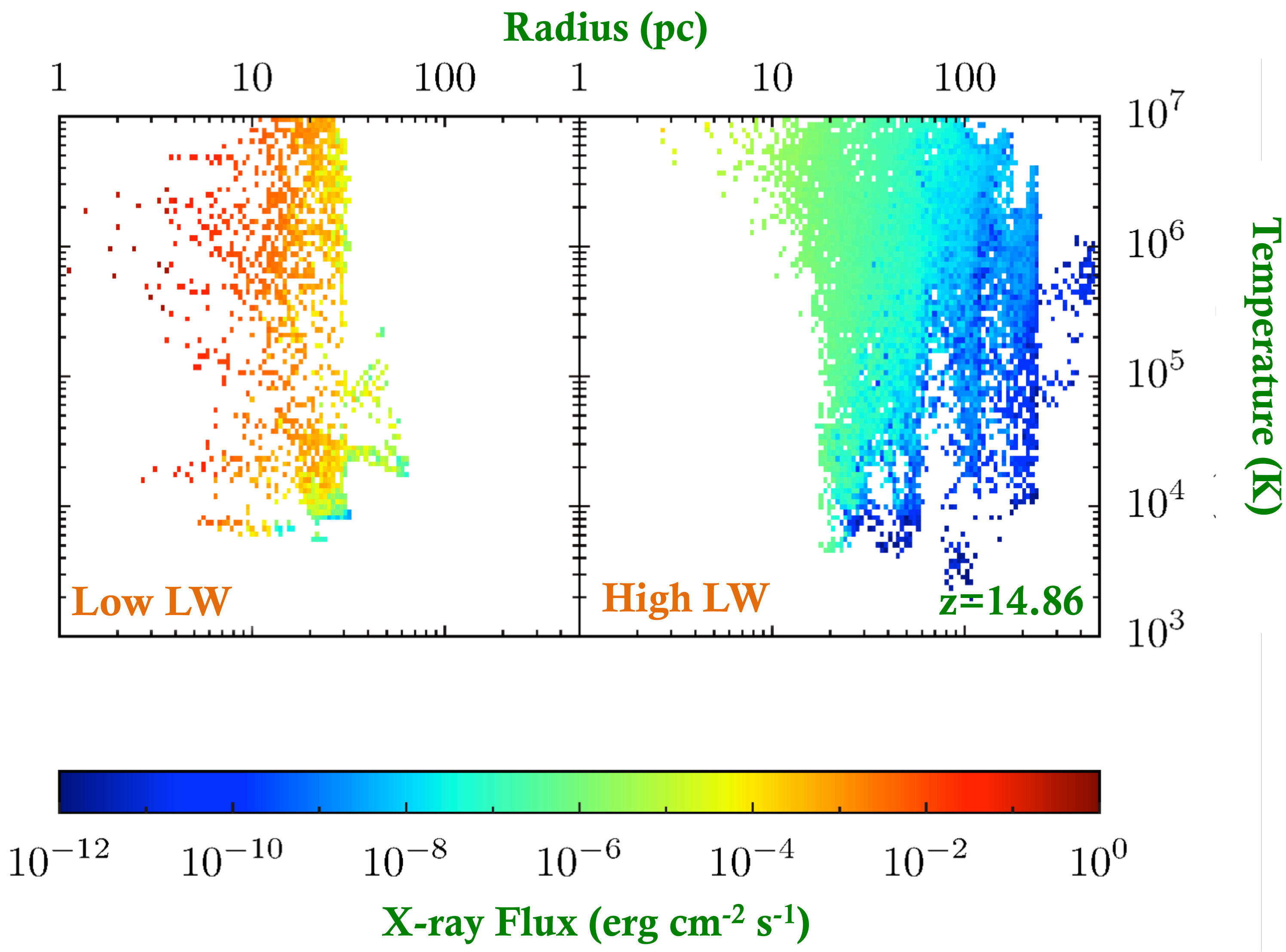
Metallicity, X-ray Flux & H_2 fraction



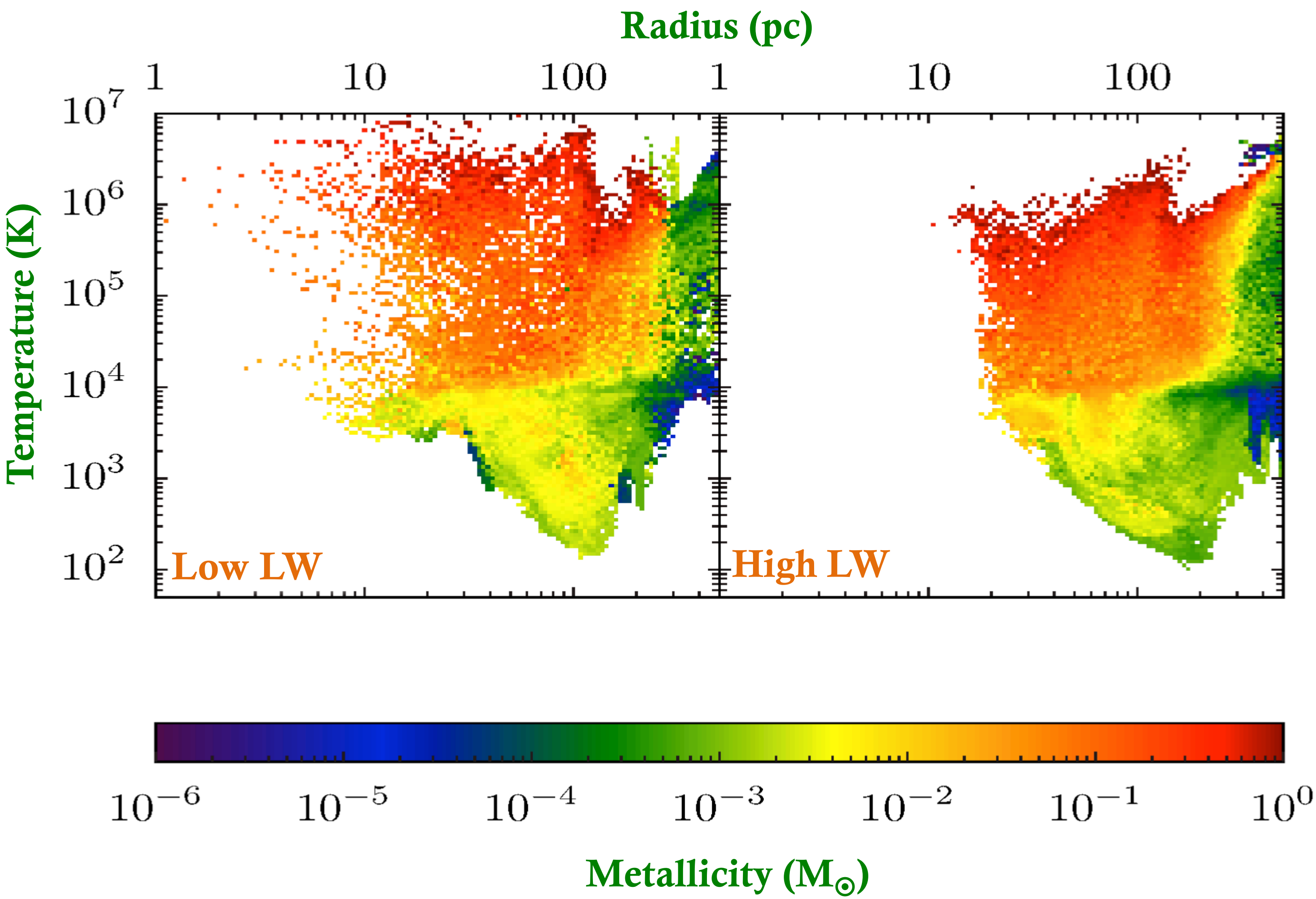
SNe form H II regions that propagate much faster in the High LW case due to the low column dens.

X-rays penetrates to larger distances in the High LW case compare to Low LW case due to the lack of gas.

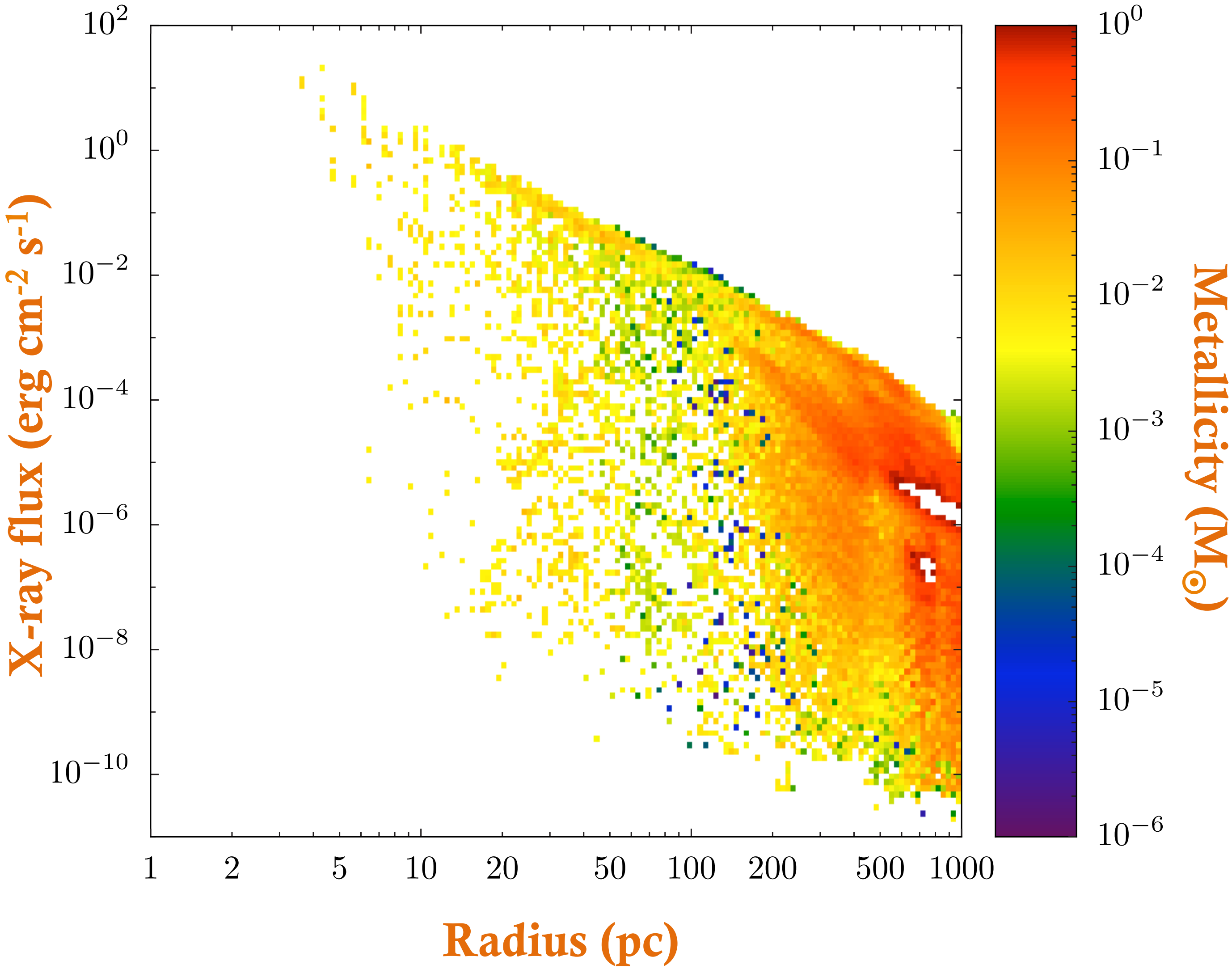
Temperature vs Radius



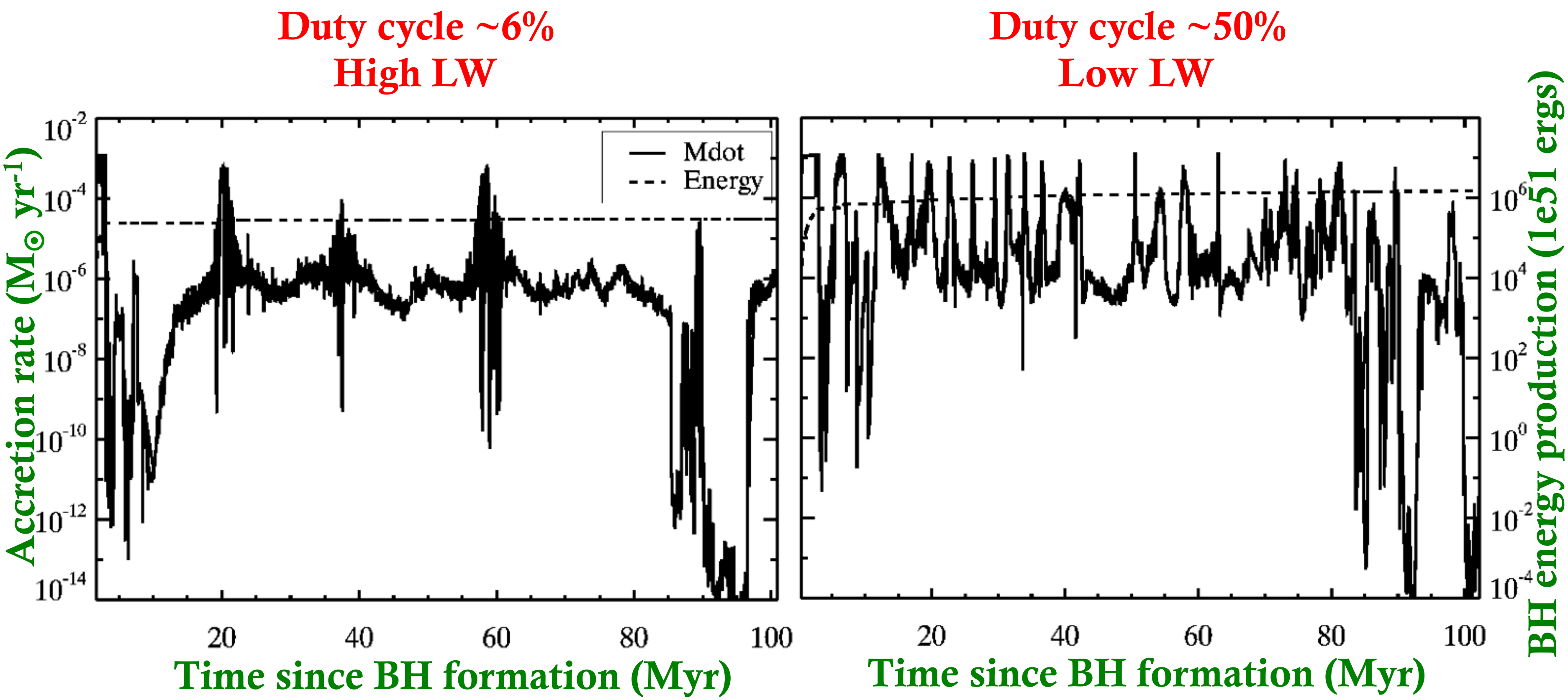
X-rays attenuated by metals ➡ high temp.



X-ray Flux vs Radius



BH Accretion Rate



BH Accretion Rate

High LW

Hostile to both SNe and X-rays

↓

Lower column densities

↓

X-rays penetrates to larger distances

↓

Hence the metals

↓

Respond time of the ambient gas to both SNe and X-rays effect is longer

↓

Duty cycle ~6%

Low LW

Less fragile to both SNe and X-rays

↓

Higher column densities

↓

X-rays absorbed close by

↓

Metals are more centrally concentrated

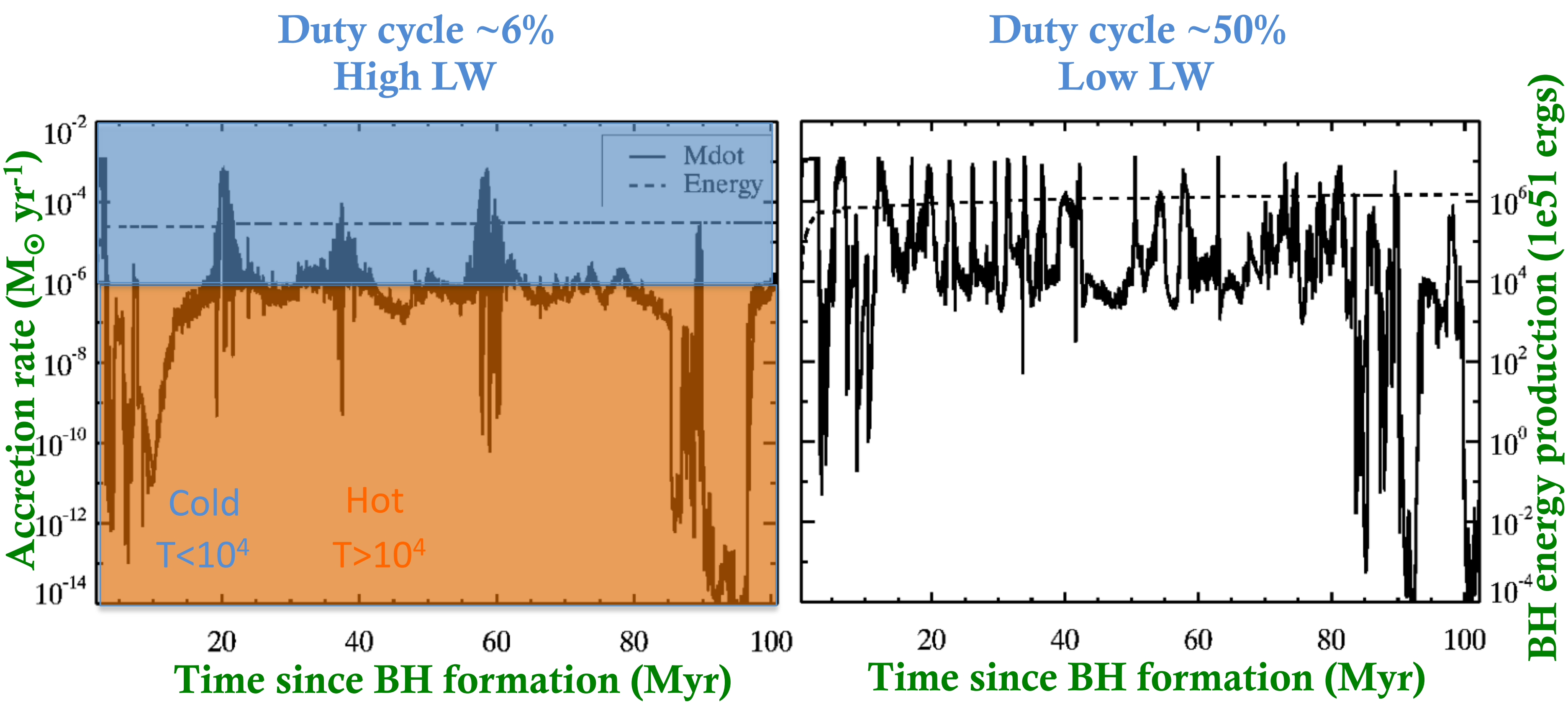
↓

Respond time of the ambient gas to both SNe and X-rays effect is shorter

↓

Duty cycle ~50%

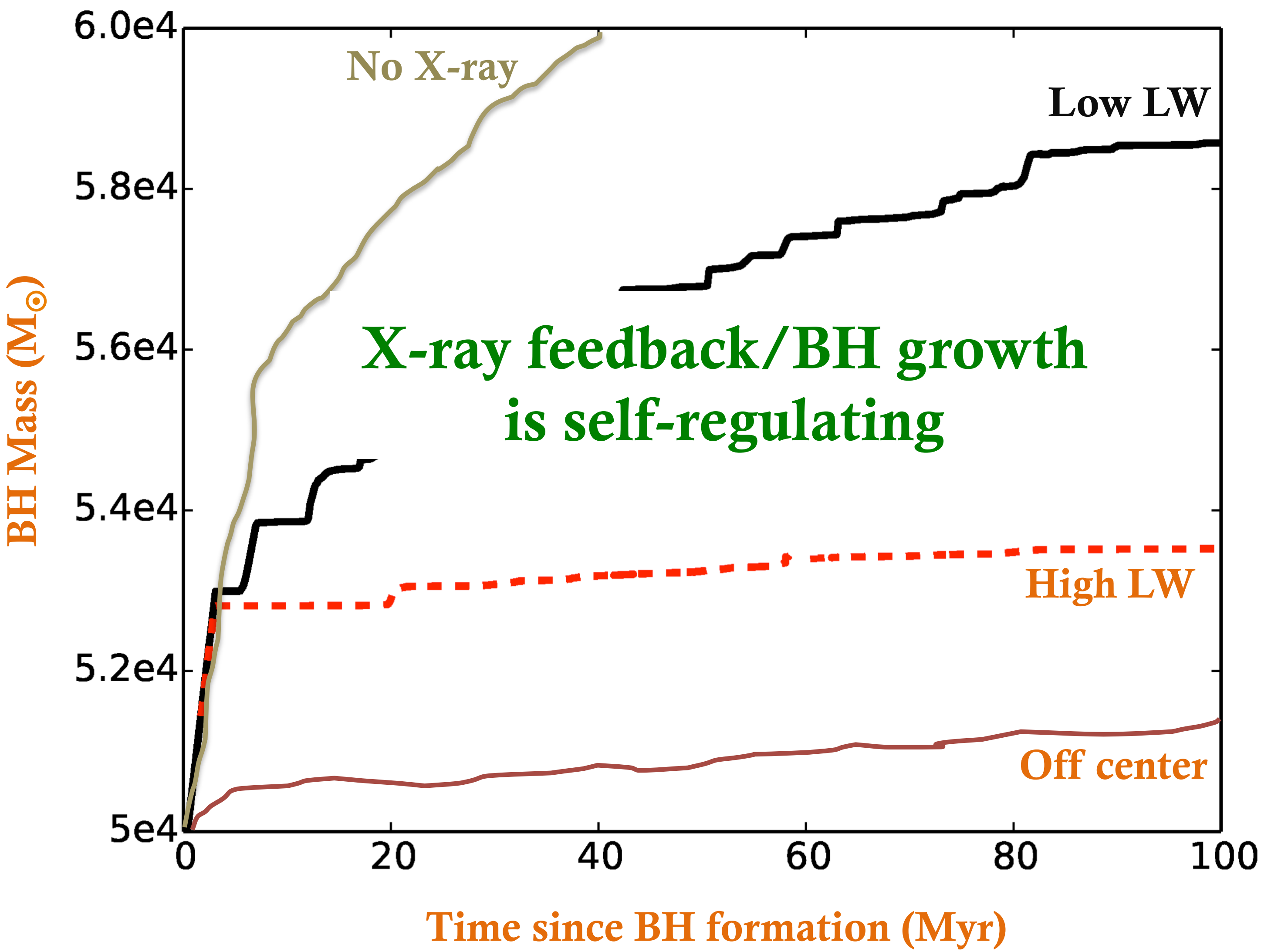
BH Accretion Rate



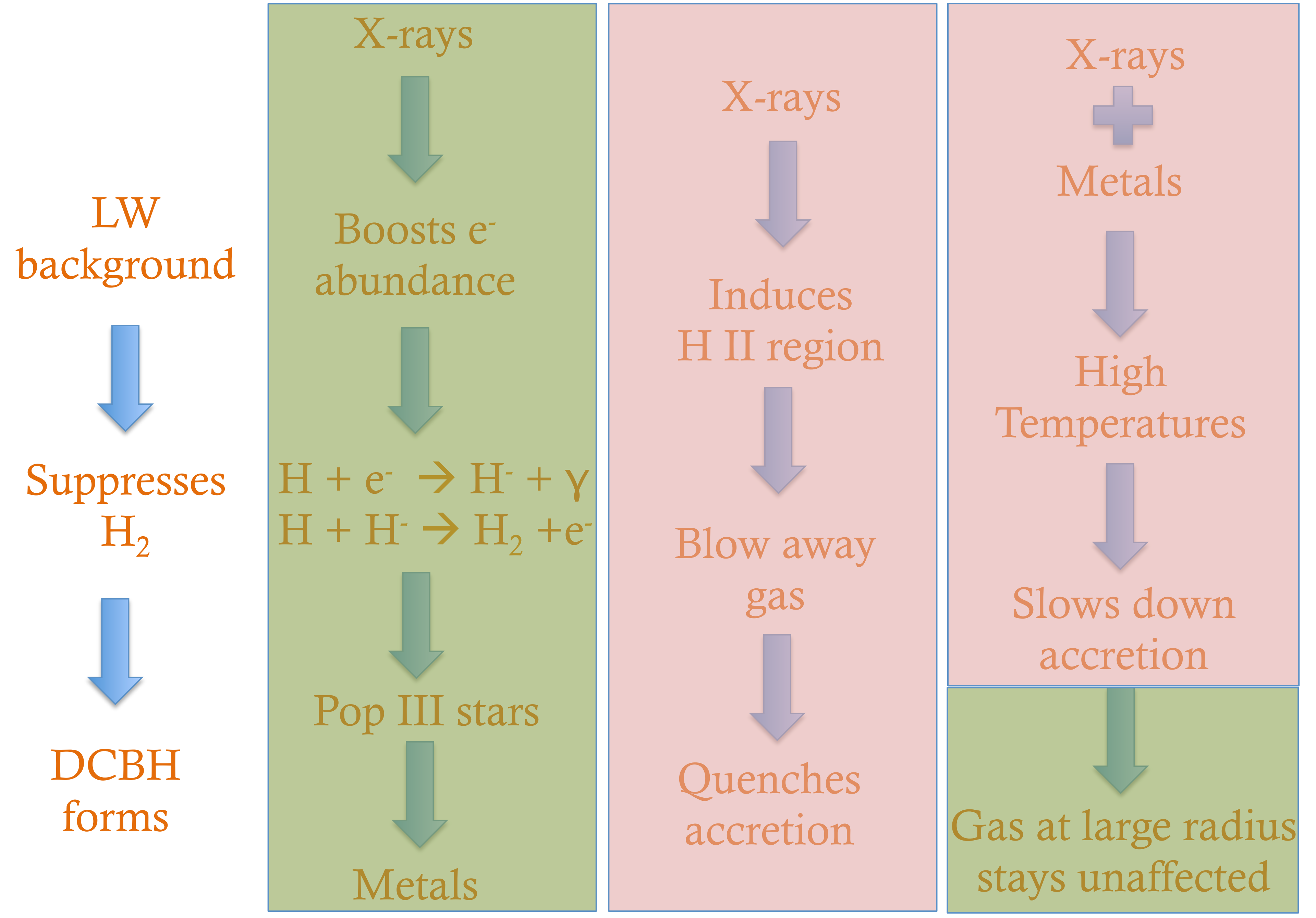
The peak of the accretion rate is determined by the local gas thermodynamics

Duty cycle is determined by the large scale gas dynamics

BH Growth



6.0e4
5.8e4
5.6e4
5.4e4
5.2e4
5e4
0
20
40
60
80
100
No X-ray
Low LW
X-ray feedback/BH growth
is self-regulating
High LW
Off center
BH Mass ($M_\odot$)
Time since BH formation (Myr)


LW background
Suppresses H_2
DCBH forms
X-rays
Boosts e^- abundance
$H + e^- \rightarrow H^- + \gamma$
$H + H^- \rightarrow H_2 + e^-$
Pop III stars
Metals
X-rays
Induces H II region
Blow away gas
Quenches accretion
X-rays
Metals
High Temperatures
Slows down accretion
Gas at large radius stays unaffected

Results -II-

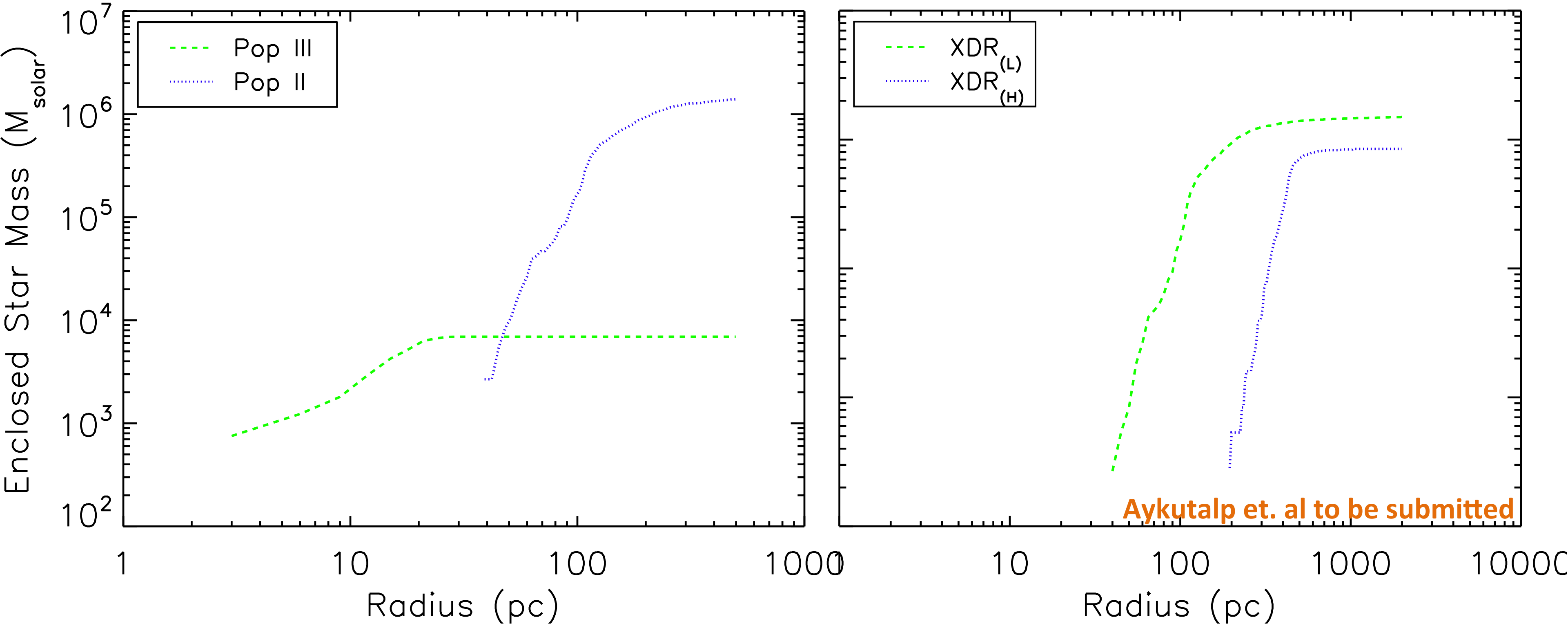
- X-rays initially have a positive effect on the star formation

- X-ray feedback/BH growth is self-regulating

- The peak of the accretion rate is determined by the local gas thermodynamics whereas **the duty cycle is determined by the large scale gas thermodynamics**

- **X-rays make it difficult for the BH to grow, which makes it even more challenging to explain the existence of SMBH in the early universe!**

Stellar Population



✦Pop II stars form at larger distances compare to Pop III stars

✦Effect of X-rays on the distribution of Pop II stellar population is more prominent in the High LW case

Open Questions

- Bondi-Hoyle estimate is limited, keeps the gas fragile for AGN feedback
- Angular momentum of infalling gas needs to be taken into account but how?
- Should star formation avoided to aid BH growth in the last pc or not ?
- X-rays might help preventing star formation, induce turbulence!
- Super Eddington accretion is needed but how long can it last and how often and under which circumstances can it occur?