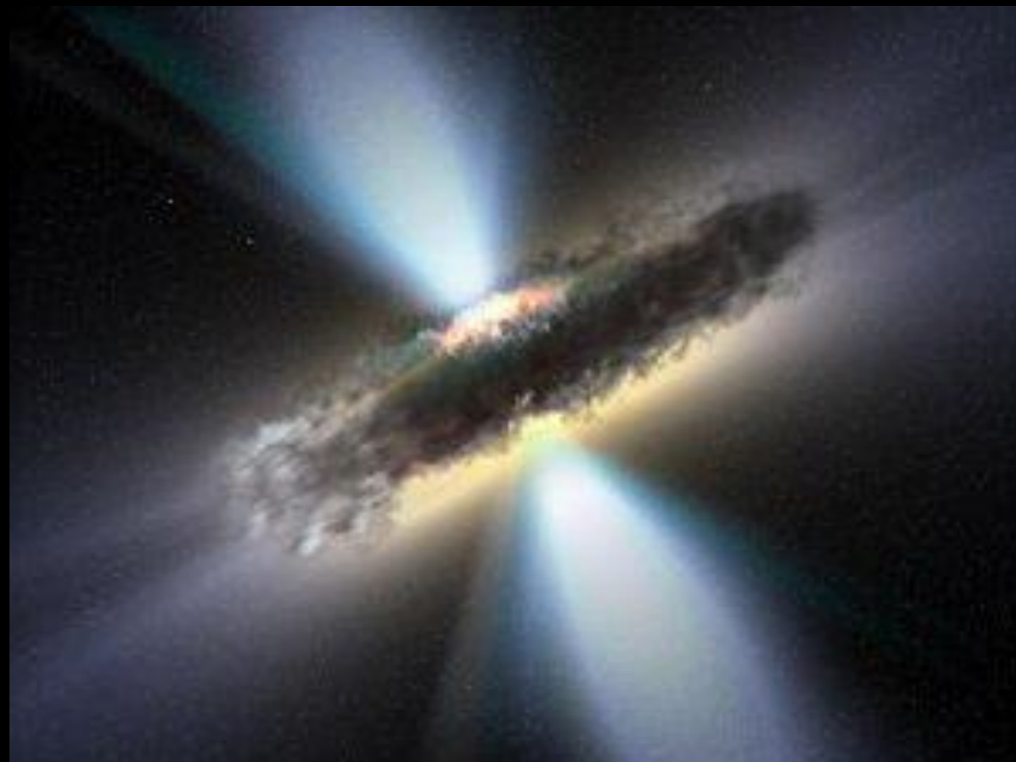
Modeling the link between AGN and star formation in primeval galaxies



Orianne ROOS – CEA-Saclay

Collaborators : F. Bournaud, J. Gabor, S. Juneau

Education

- Bachelor of Physics, Master of Astrophysics
  Université de Strasbourg
- PhD, Université Paris-Diderot

- How did I end up here ? M2 internship in SAp, then PhD

PhD thesis

- **Do AGNs kill galaxies ?**

- Primeval/high-redshift galaxies
- AGN, AGN feedback
- Link with star formation
- HPC, simulations
- Stellar feedback

Cosmic crimes : who killed the galaxy ?

- Some galaxies suddenly stop forming stars (they get “quenched” and then they “die”) : why ?

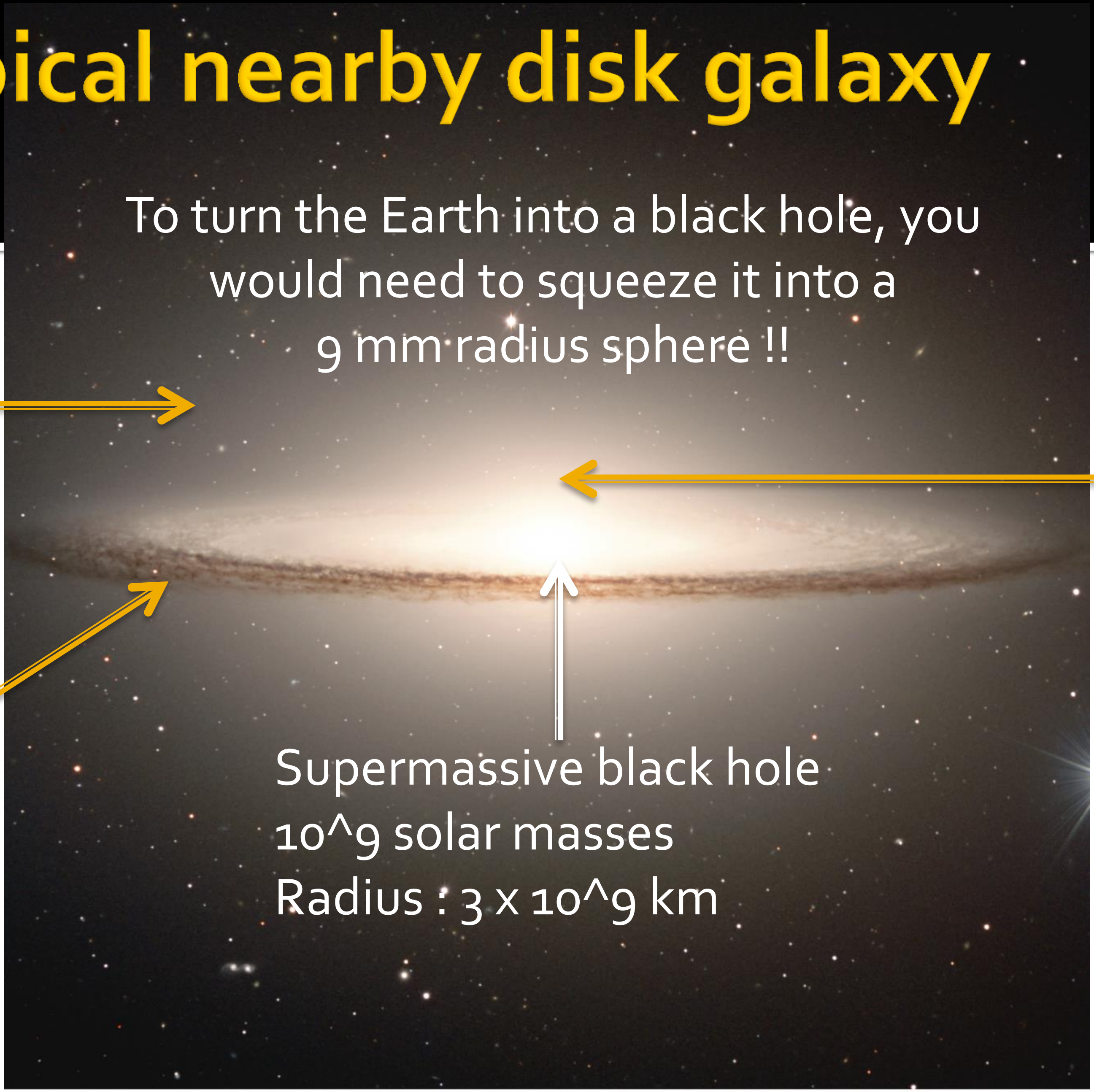
- Ideal culprit : central supermassive black hole
  - SMBH mass related to bulge mass -> co-evolution ?
  - Energy generated by SMBHs in active phases (AGNs) theoretically able to blow away all gas of the host
  - AGNs needed to reproduce observed number of stars in simulations

=> Link between AGN feedback and SF quenching ?

A typical nearby disk galaxy

Halo
(gas and
globular
clusters)

Disk
(gas, stars,
dust, ...)

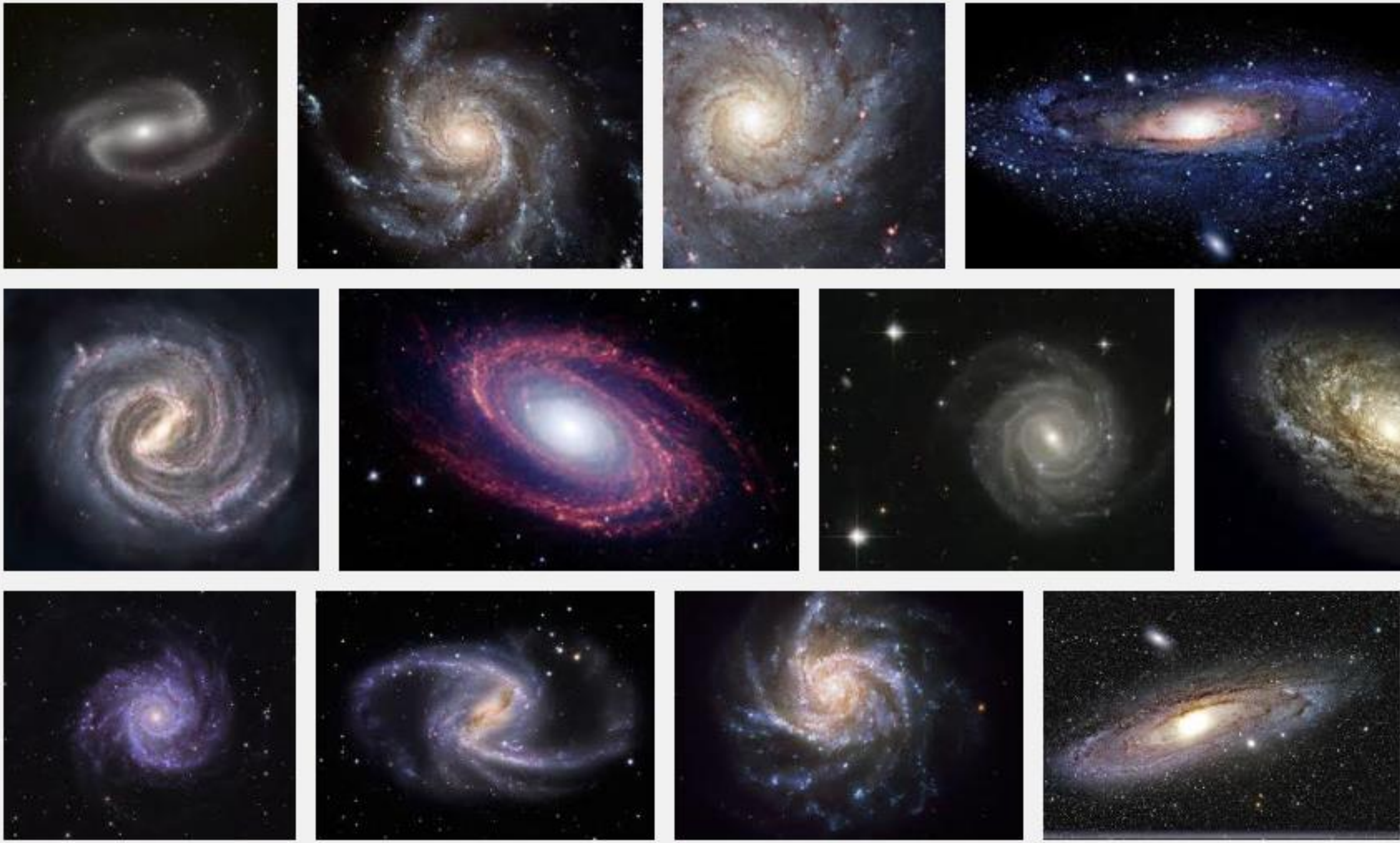


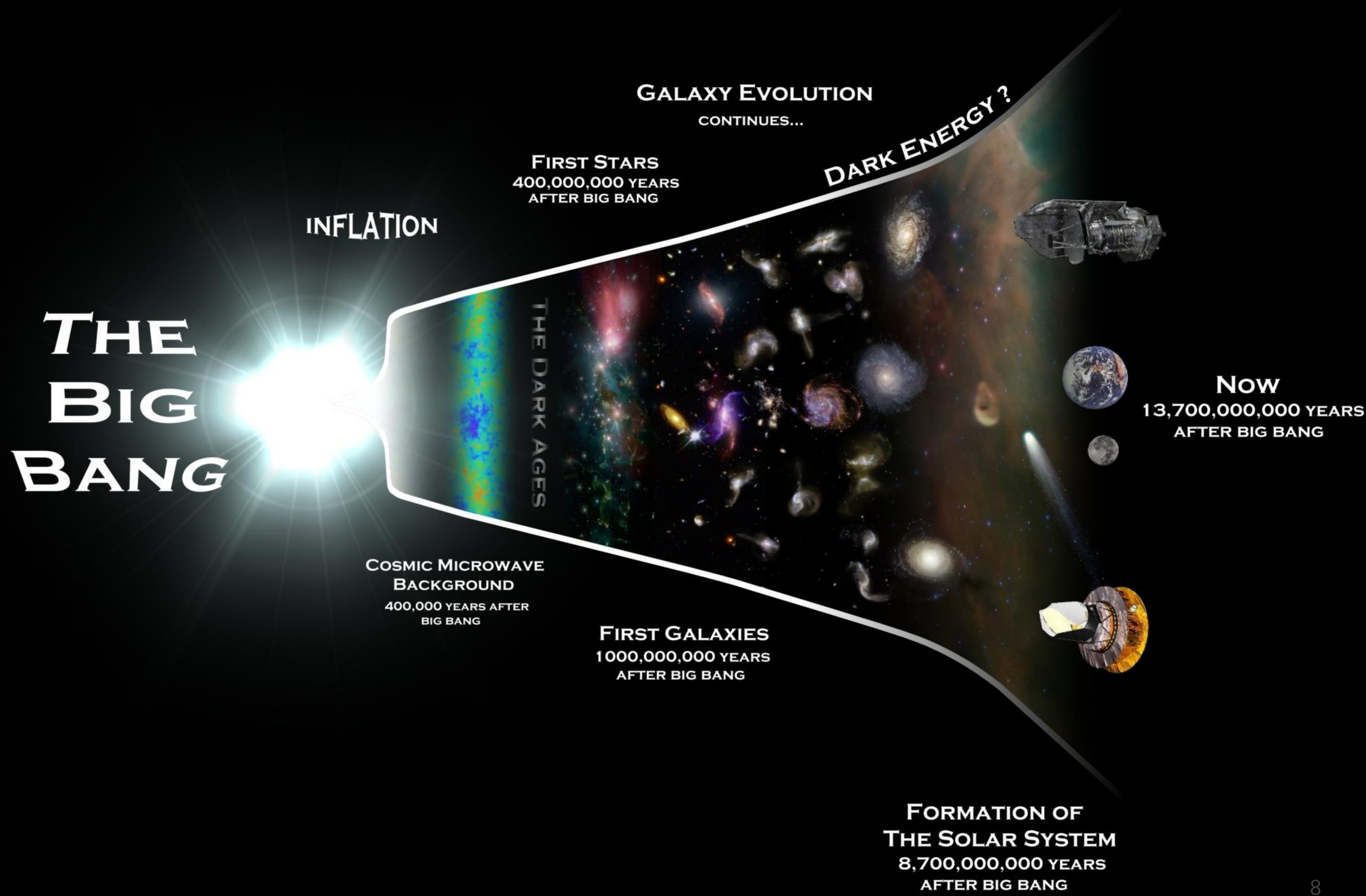
Bulge
(stars)

The Sombrero Galaxy (VLT ANTU + FORS1)

ESO PR Photo 07a/00 (22 February 2000)

A typical nearby disk galaxy



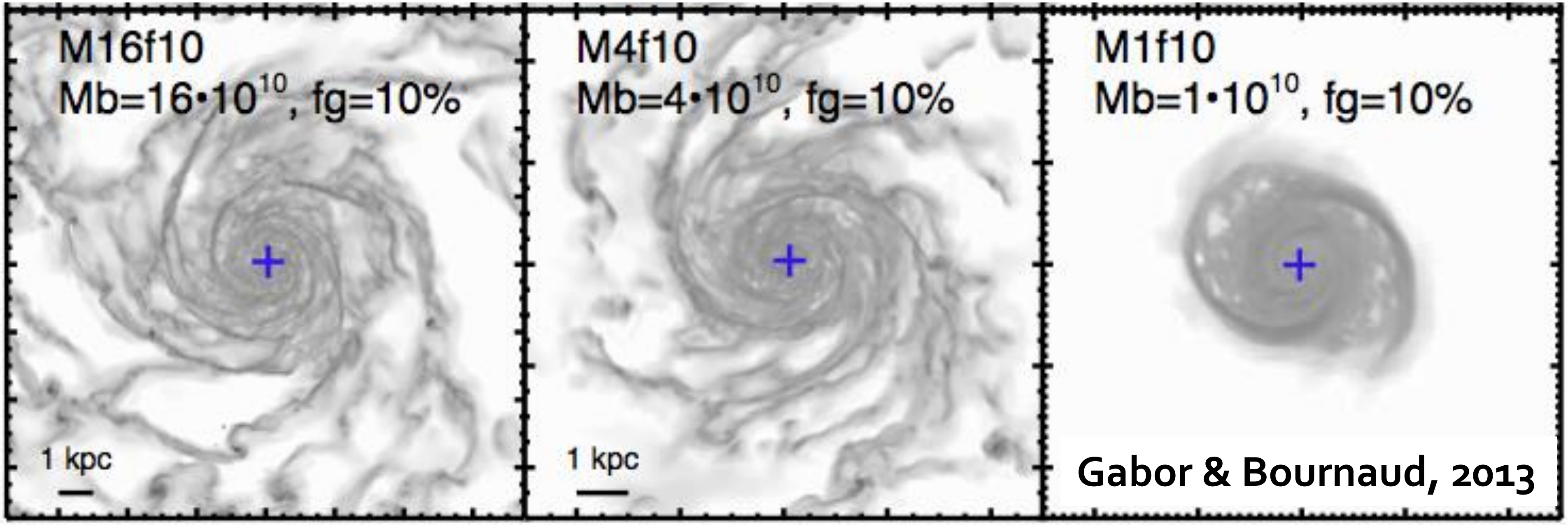


The Big Bang
Inflation
First Stars
400,000,000 years after Big Bang
Galaxy Evolution continues...
Dark Energy ?
The Dark Ages
Cosmic Microwave Background
400,000 years after Big Bang
First Galaxies
1000,000,000 years after Big Bang
Now
13,700,000,000 years after Big Bang
Formation of The Solar System
8,700,000,000 years after Big Bang

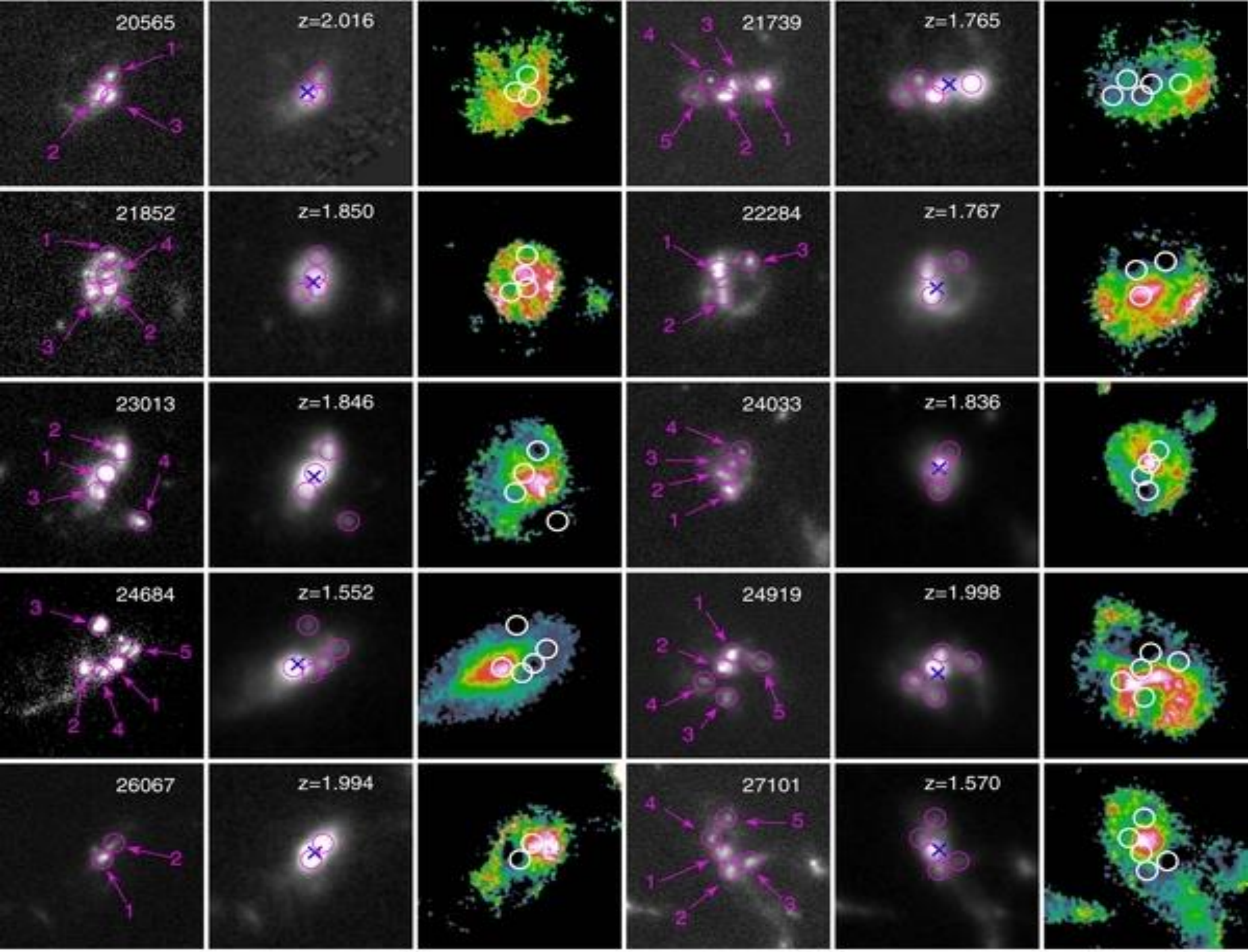
Simulated high-redshift disk galaxies

Local disk galaxies look like spirals…

Clumpy, gas-rich high-redshift disk-galaxies



Gabor & Bournaud, 2013



z band H band z - H z band H band z - H

Typical star-forming galaxies at *z* ~ 2. (Guo et al 2012)

Progress bar

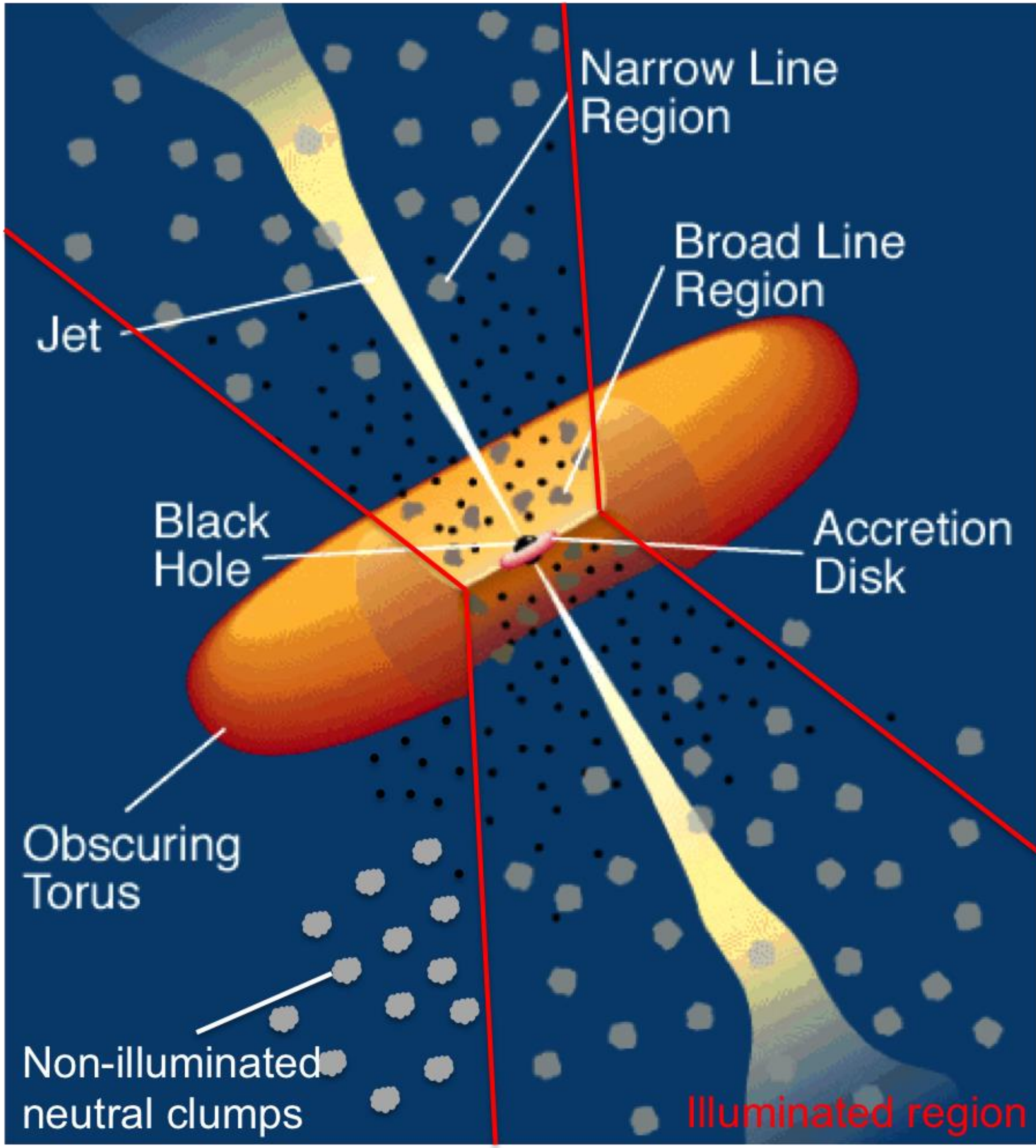
- Primeval/high-redshift galaxies ☑
- AGN
- AGN feedback
- Link with star formation
- HPC
- To kill or not to kill ?
- Stellar feedback

(Schematic) Structure of an AGN :

Active
Galactic
Nucleus

Unified AGN Model :

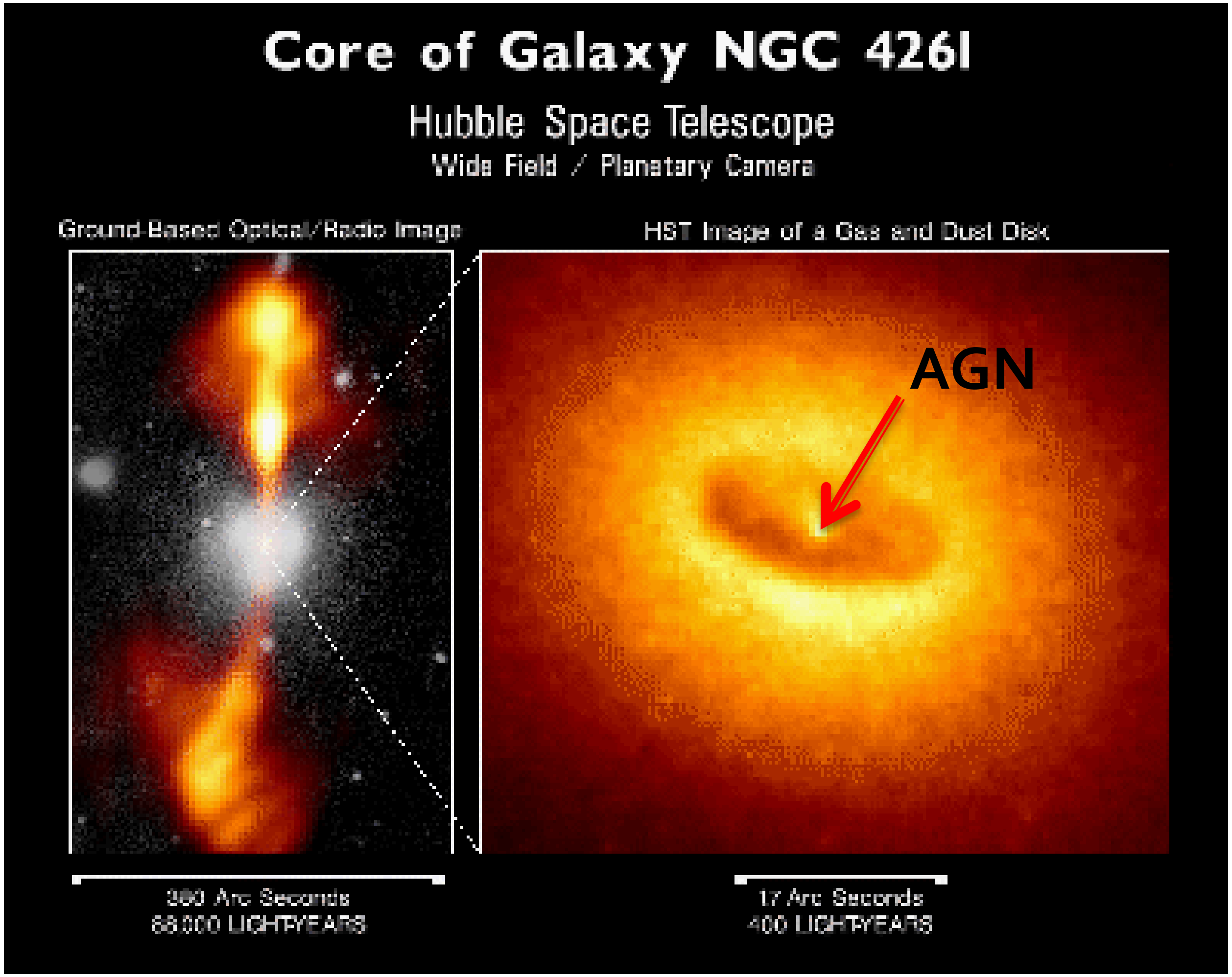
- BLR (< 3 ly)
- NLR (> 300 ly)
- Radio jets (>>3 kly)
- Emission cone



From Urry & Padovani 1995, modified

Observations of AGN

Ground-based Optical/Radio image



HST image

Progress bar++

- Primeval/high-redshift galaxies ☑
- AGN ☑
- AGN feedback
- Link with star formation
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- To kill or not to kill ?
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AGN feedback

A clump of gas falls onto the AGN…

- Thermal feedback : ← **in the simulation**

  = **HEATING**

  - AGN absorbs energy due to accretion and re-emits fraction of it, heating central region
  - Creation of a hot and diffuse outflow of gas
- Radiative feedback :

  = **IONIZATION** ← **added a posteriori**

  - Energy of photons emitted by AGN is so high that encountered gas is ionized

Structure of an AGN :

Active
Galactic
Nucleus

Unified AGN Model :

- BLR (< 3 ly)
- NLR (> 300 ly)
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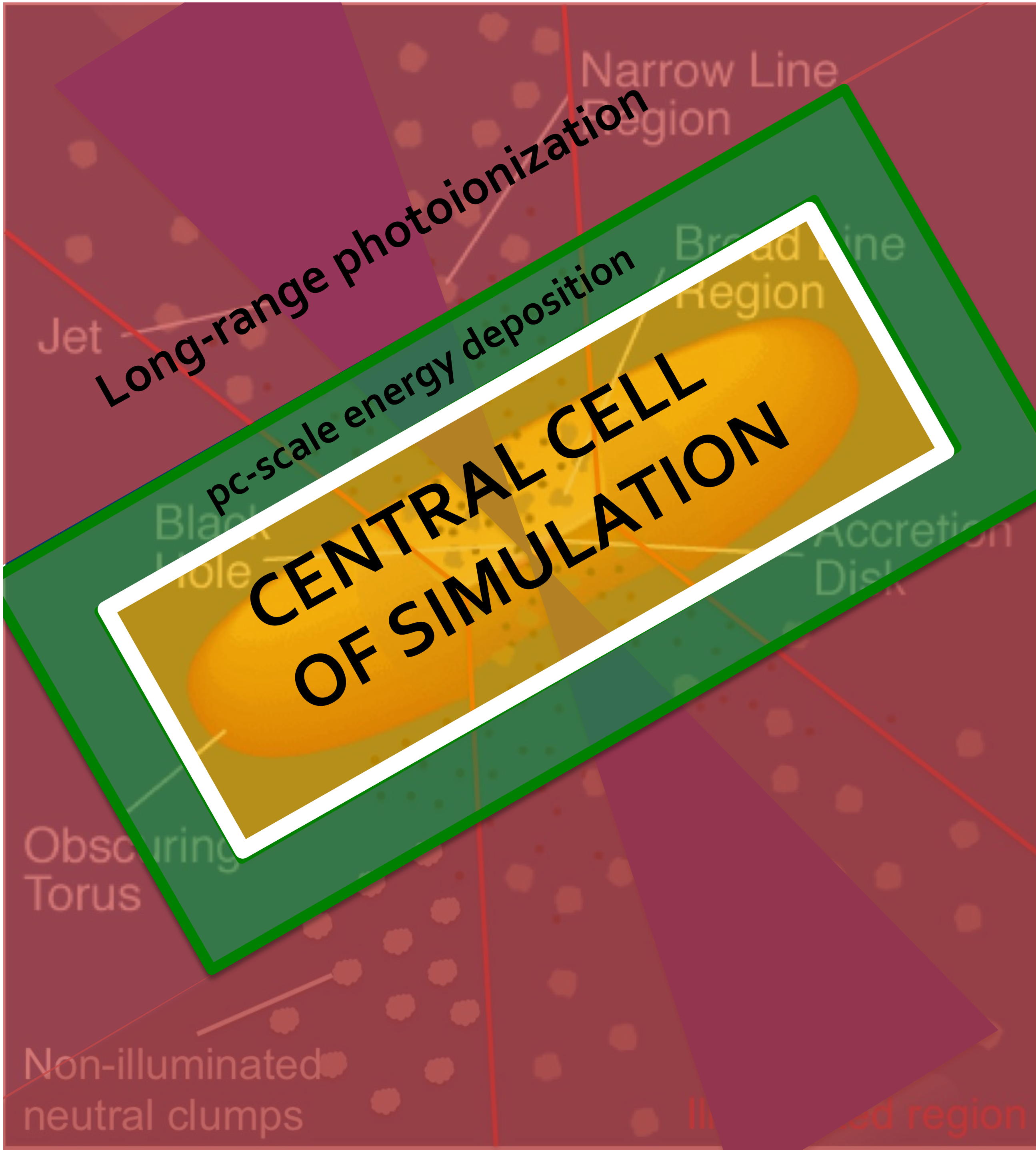
- Emission cone



From Urry & Padovani 1995, modified

Hang on !

- Primeval/high-redshift galaxies ☑
- AGN ☑
- AGN feedback ☑
- Link with star formation
- HPC
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AGN feedback vs star formation :

- Stars form into cold and dense clumps of gas…

WHEREAS

- AGN feedback dilutes and heats gas…

Is there an impact on star formation ?

Wake up… Awesome things coming !

- Primeval/high-redshift galaxies
- AGN
- AGN feedback
- Link with star formation
- HPC
- To kill or not to kill ?
- Stellar feedback

The Curie super-computer @TGCC

High
Performance
Computing

More than 5000 computation nodes

5 PB of disks (100 GB/s of bandwith)
10 PB of bands
1 PB of cache

Let's investigate

- Primeval/high-redshift galaxies ☑
- AGN ☑
- AGN feedback ☑
- Link with star formation ☑
- HPC ☑
- To kill or not to kill ?
- Stellar feedback

Do AGN (outflows) quench SF ?

Gas temperature

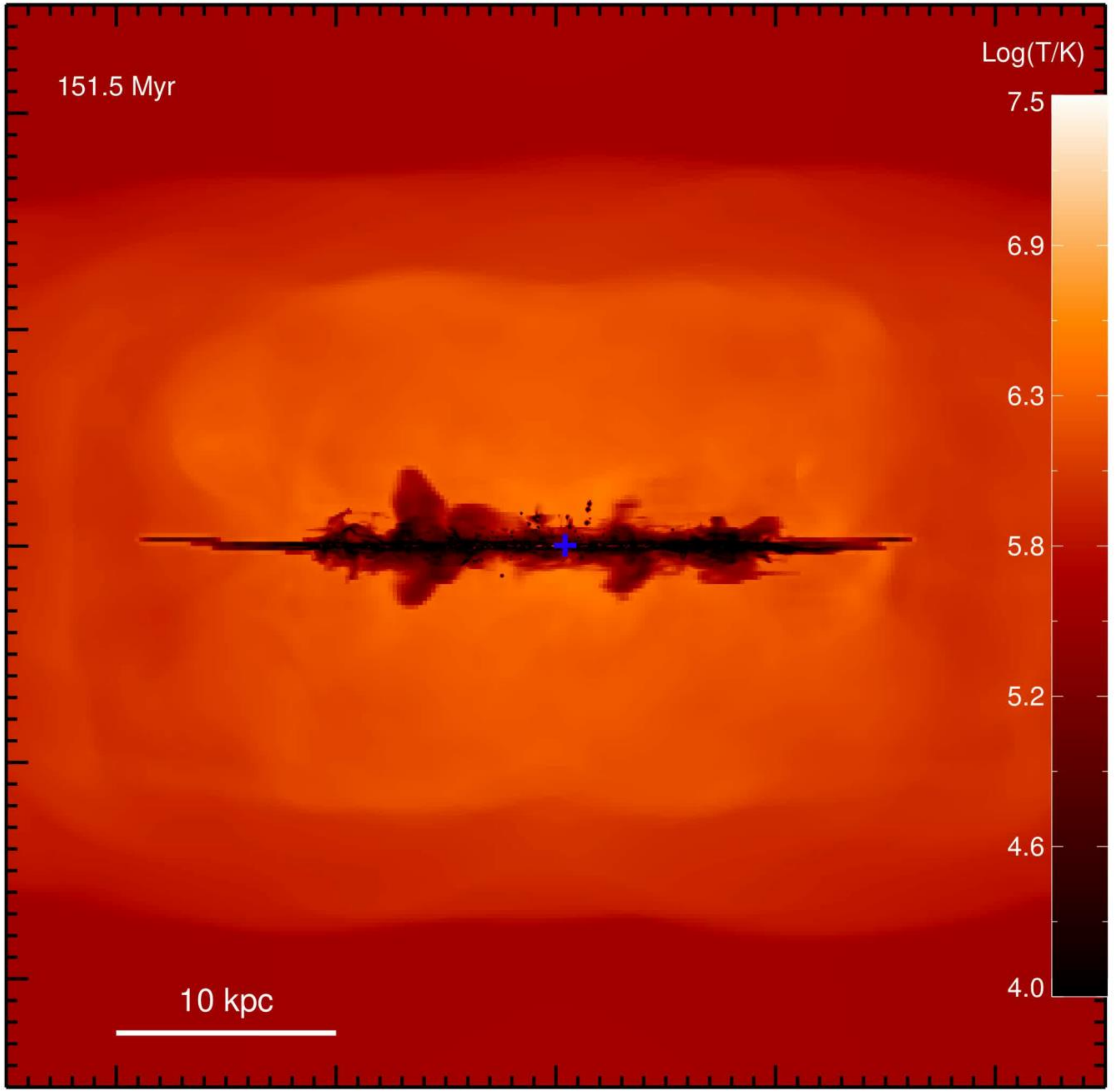
Max. resolution : 6 pc
GMCs are resolved.

High-velocity
AGN-driven outflows

Mass outflow rates :
~ 10 - 100 % of SFR
(~ 30 M_sun/yr).

1 snapshot = 1 moment
in the simulation

Gabor & Bournaud 2014

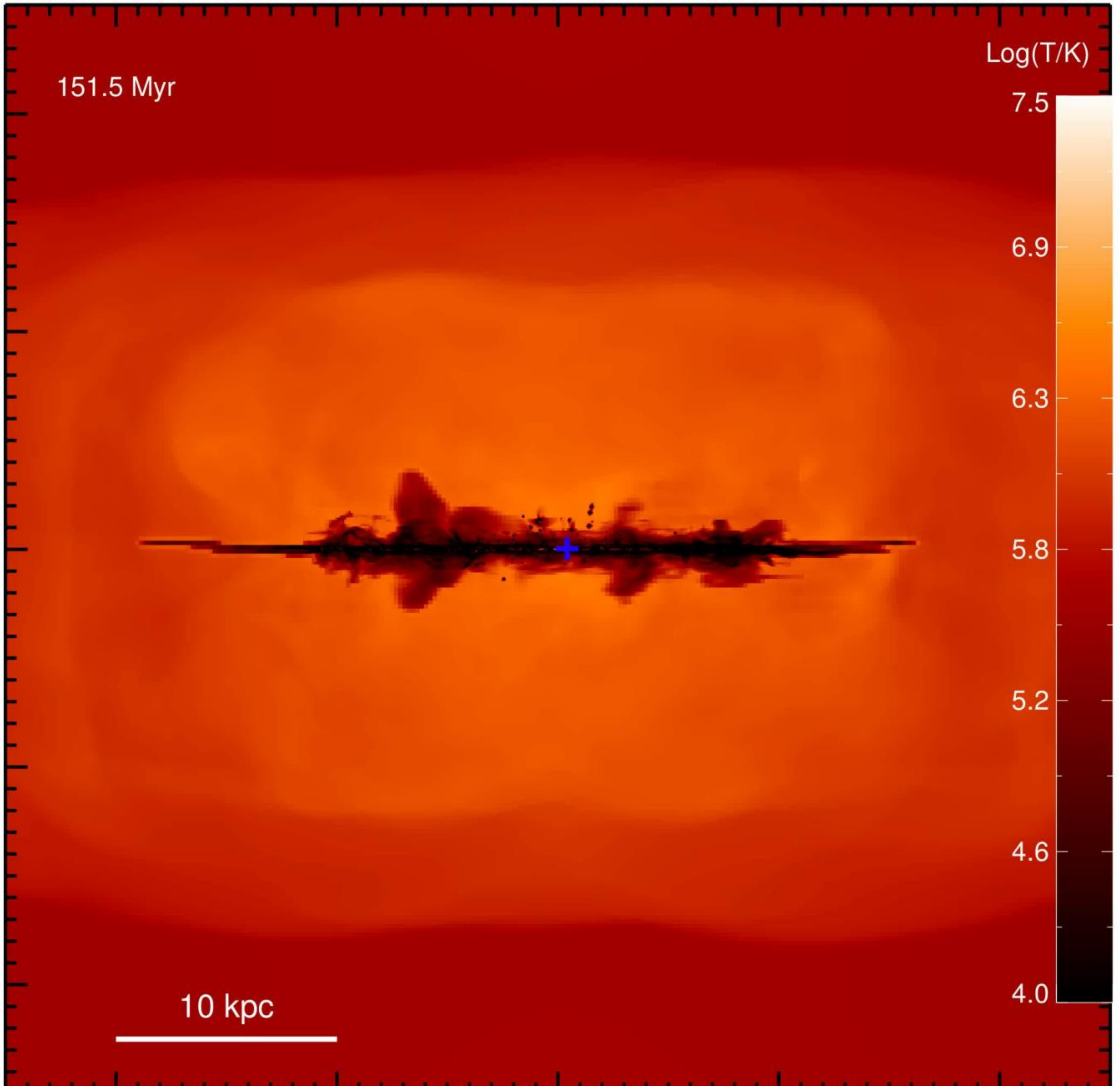


Do AGN (outflows) quench SF ?

AGN *outflows* do not quench star formation.

... but :
Do AGNs quench SF ?

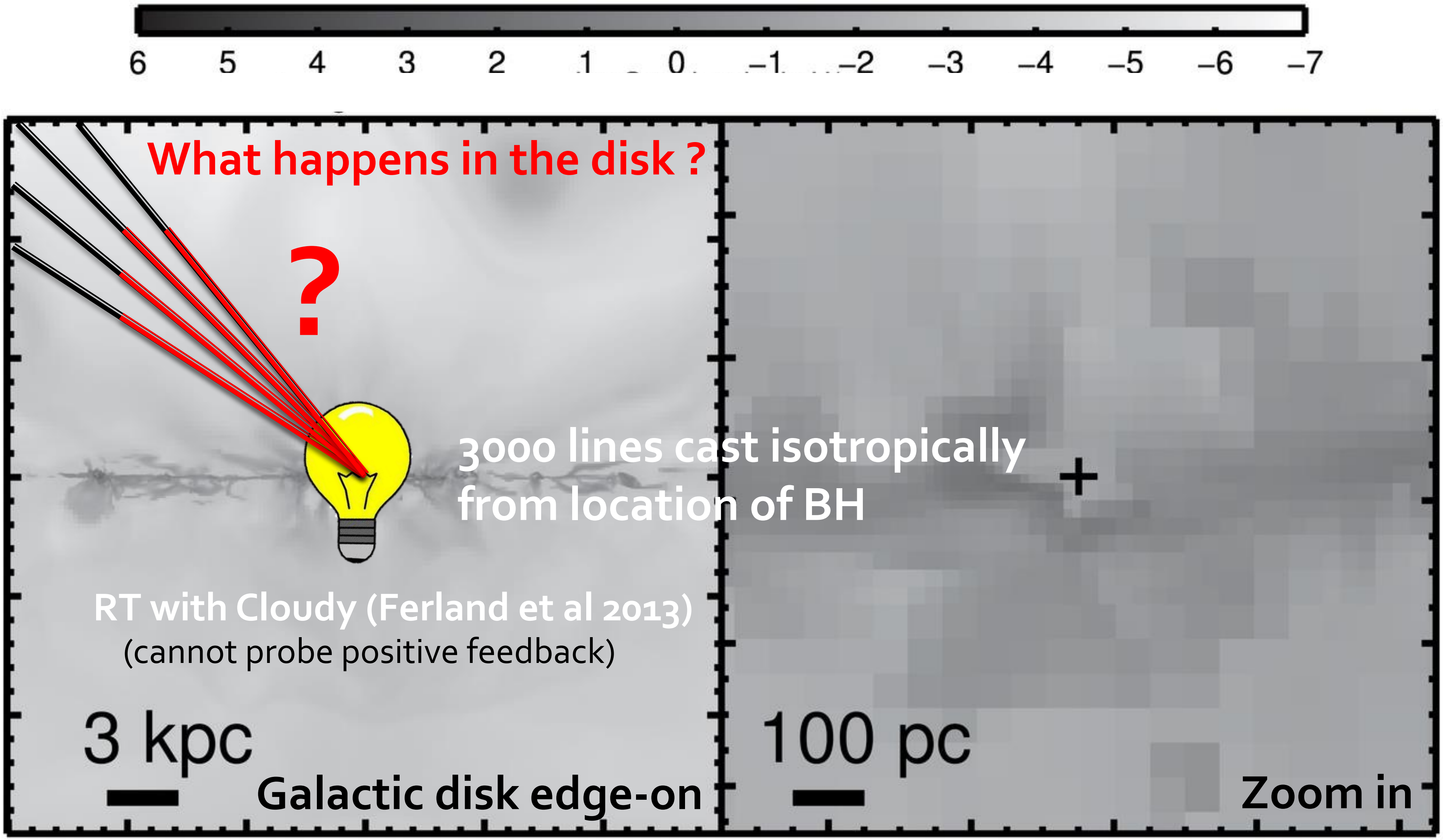
AGN photoionization



Gabor & Bournaud 2014

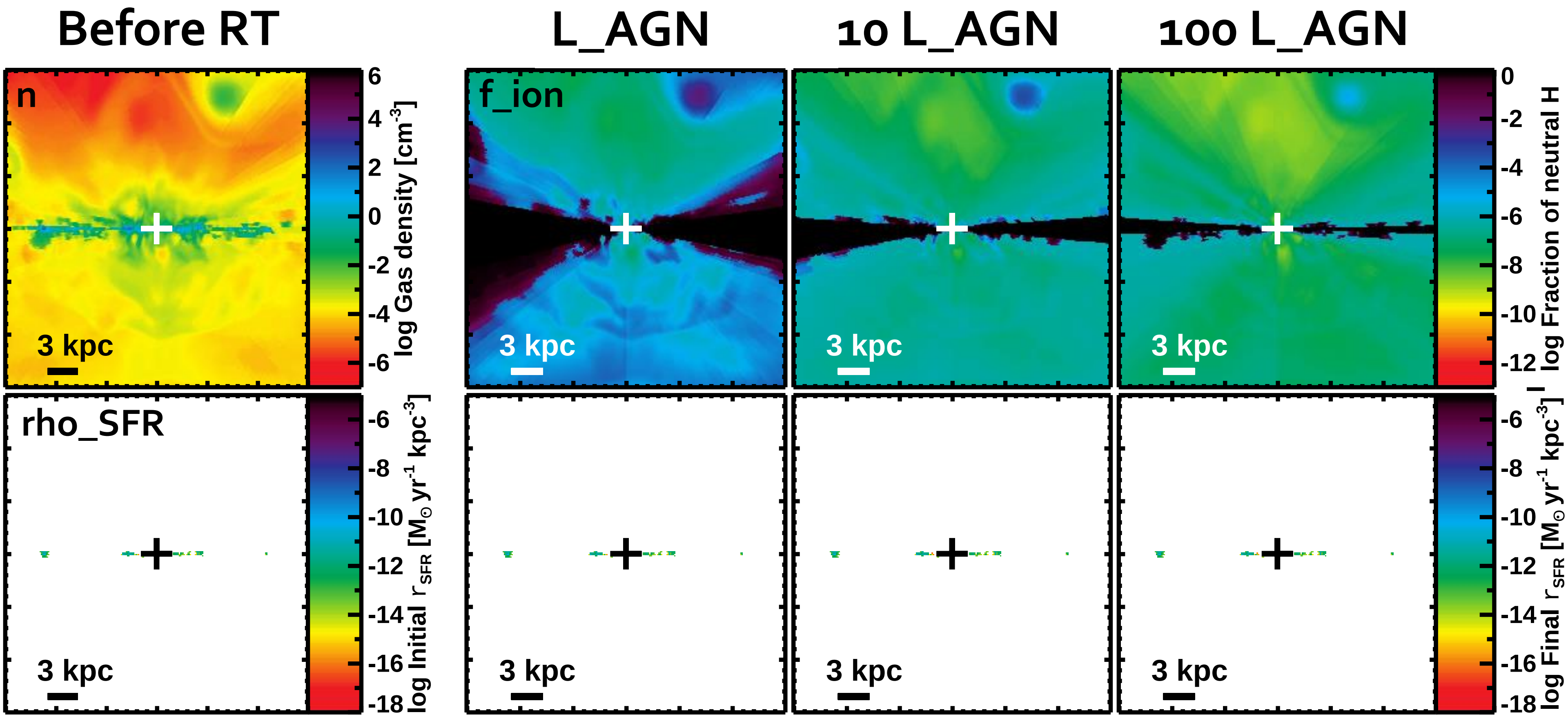
Does AGN radiation quench SF ?

Gas density map of the disk seen edge-on



Simulation with standard thermal AGN feedback (Gabor & Bournaud 2013)

+ RT post-processing (Roos *et al.* 2015 *ApJ* **800** 19)



Even at a QSO luminosity, the galactic disk remains completely neutral !

super-powerful AGN

Edge-on view

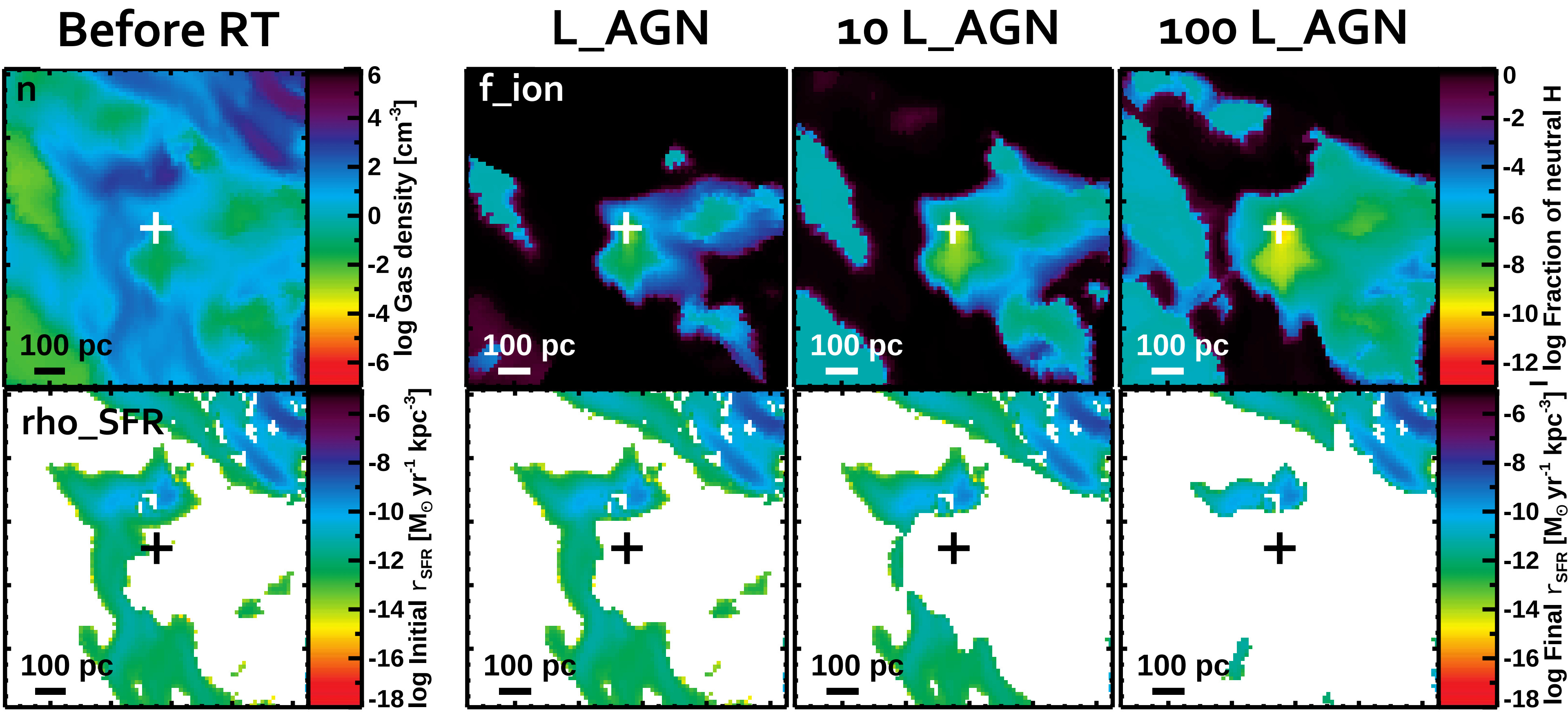
L_AGN = 10^44.5 erg/s

Is the impact of AGN feedback luminosity-dependent ?

With a higher AGN luminosity :

- Regions ionized by AGN enlarged
- Most heated gas is in the gaseous halo
- Galactic disk remains neutral even for QSO luminosity

→**Let's focus on the central region :** 600 x 600 pc **(face-on view)**



Even at a QSO luminosity, the bulk of the star forming clumps is not affected !

super-powerful AGN

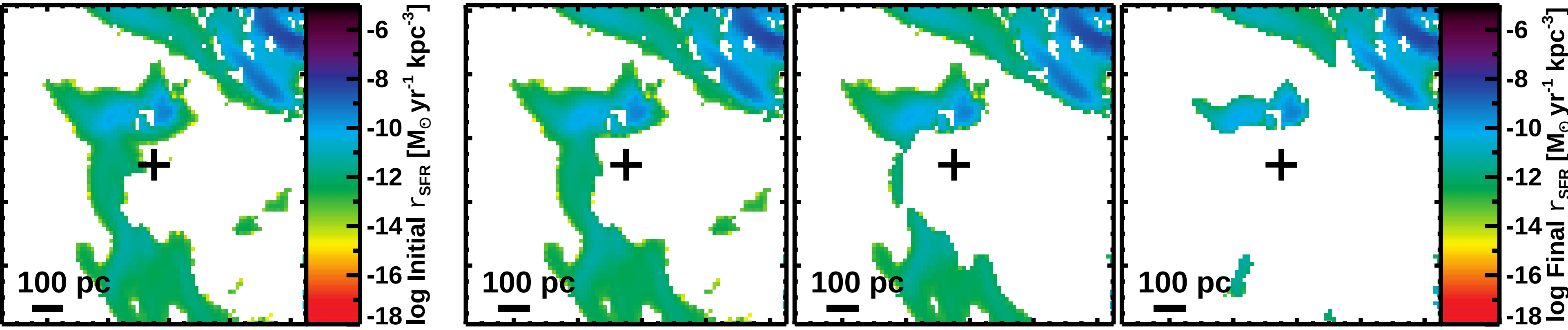
Face-on view – zoom in

L_AGN = 10^44.5 erg/s

Does AGN radiation quench SF ?

- Diffuse star-forming regions are prevented from forming stars
- The stronger the AGN, the more efficiently gas is heated/ionized

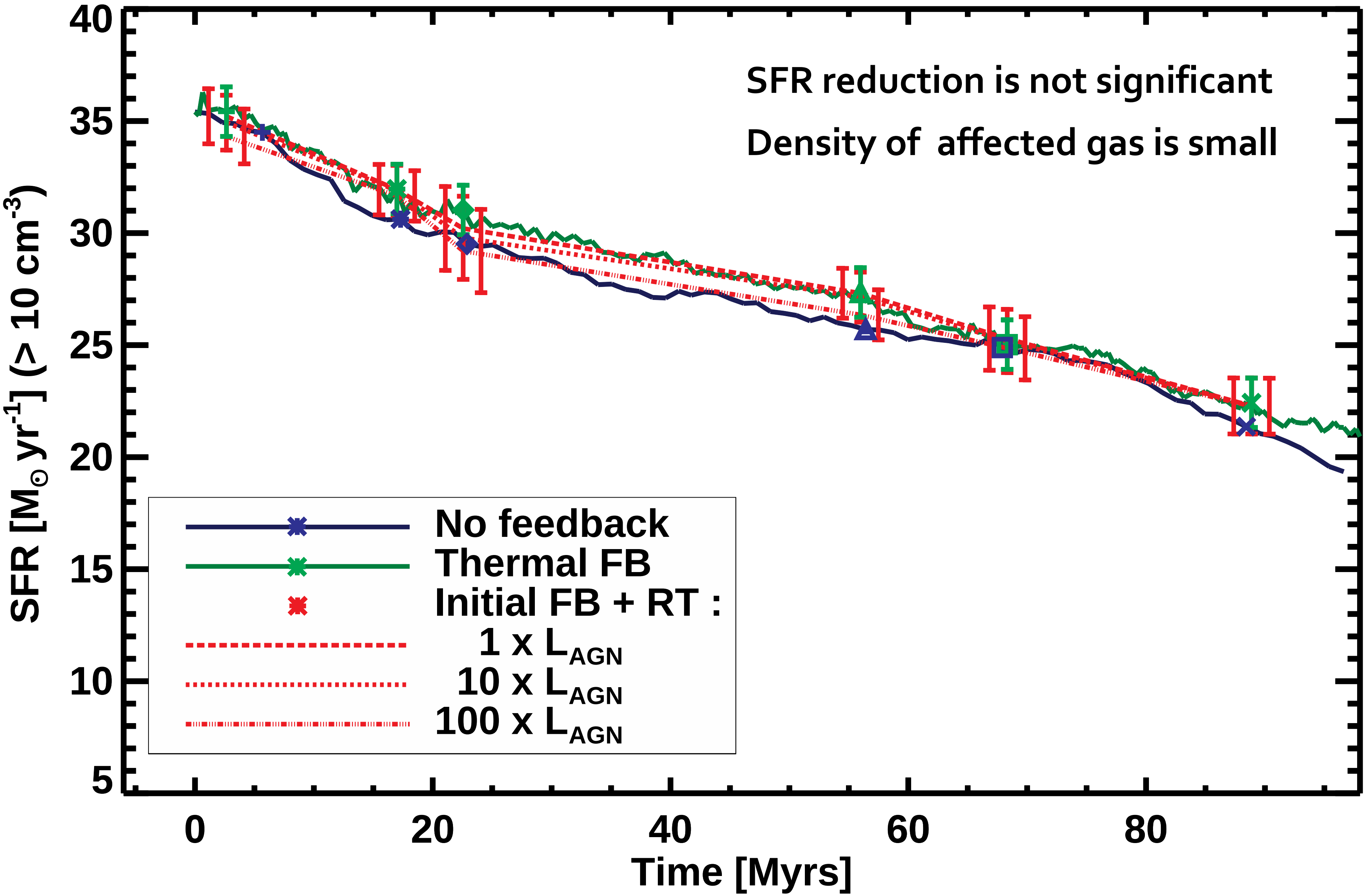
- But dense star-forming clumps shield themselves



-> **Major contributors to the total SFR are not affected.**

Roos *et al.* 2015 *ApJ* **800** 19

Instantaneous reduction of the total SFR due to AGN photo-ionization



Almost there !

- Primeval/high-redshift galaxies ☑
- AGN ☑
- AGN feedback ☑
- Link with star formation ☑
- HPC ☑
- To kill or not to kill ? ☑
- Stellar feedback

The POGO project

Physical Origins of Galactic Outflows

Do AGN+stellar outflows quench star formation ?

in z~2 star-forming galaxies

Work in progress !

11 Mh of computation time, very high resolution (1.5 pc), AGN feedback + stellar feedback, suite of 7 simulations

Qualitative properties of outflows

- Stars-driven outflows :
  - High mass outflow rate
  - Limited velocity (100 - 500 km/s)
  - Multiple SNe and young stars per galaxy

  Bournaud et al. 2014, …

- AGN-driven outflows :
  - Low outflow density
  - High velocity (3 000 - 30 000 km/s)
  - 1 AGN in the center of the galaxy (usually)

  Gabor & Bournaud 2014, …

Outflows in simulations

Example :

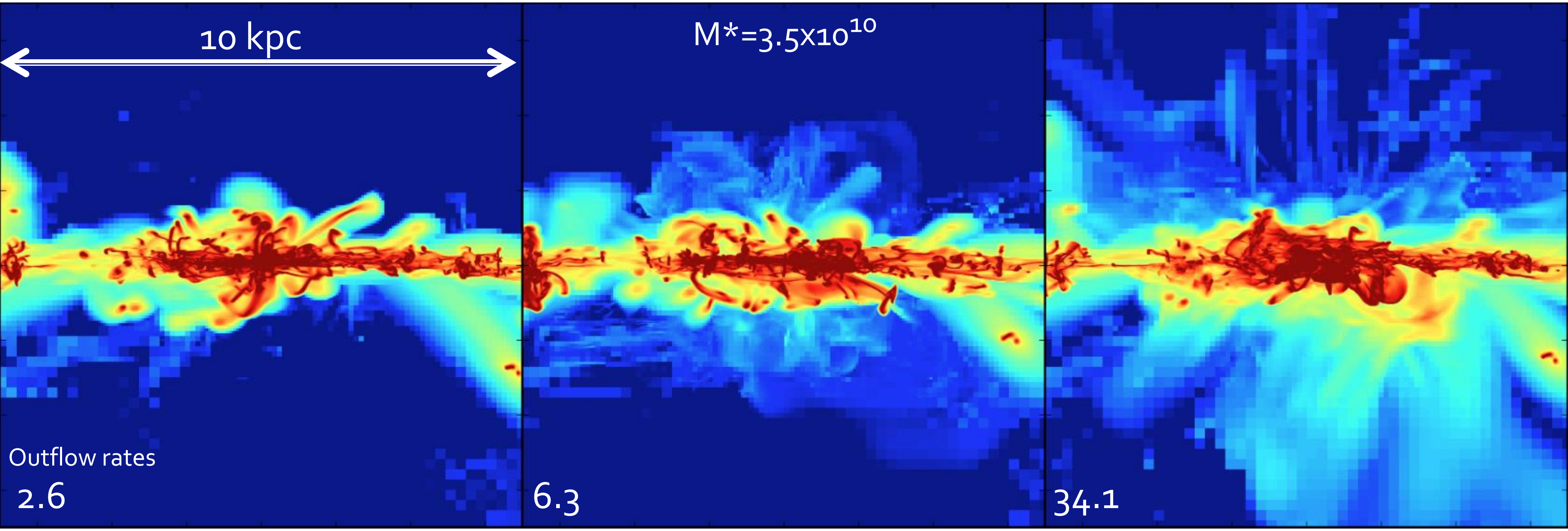
Outflows generated by :
- Supernovae (kin. energy)
- Young stars (rad. pressure)
- Both

(no AGN)

Non-linear coupling of stellar feedback models (at dx > 1.5 pc)

Three runs with different feedback processes, all evolved for 80 Myr.

Supernovae | OB stars | SNe + OB stars



Outflows from SNe + OB stars >> Outflows from SNe + Outflows from OB stars

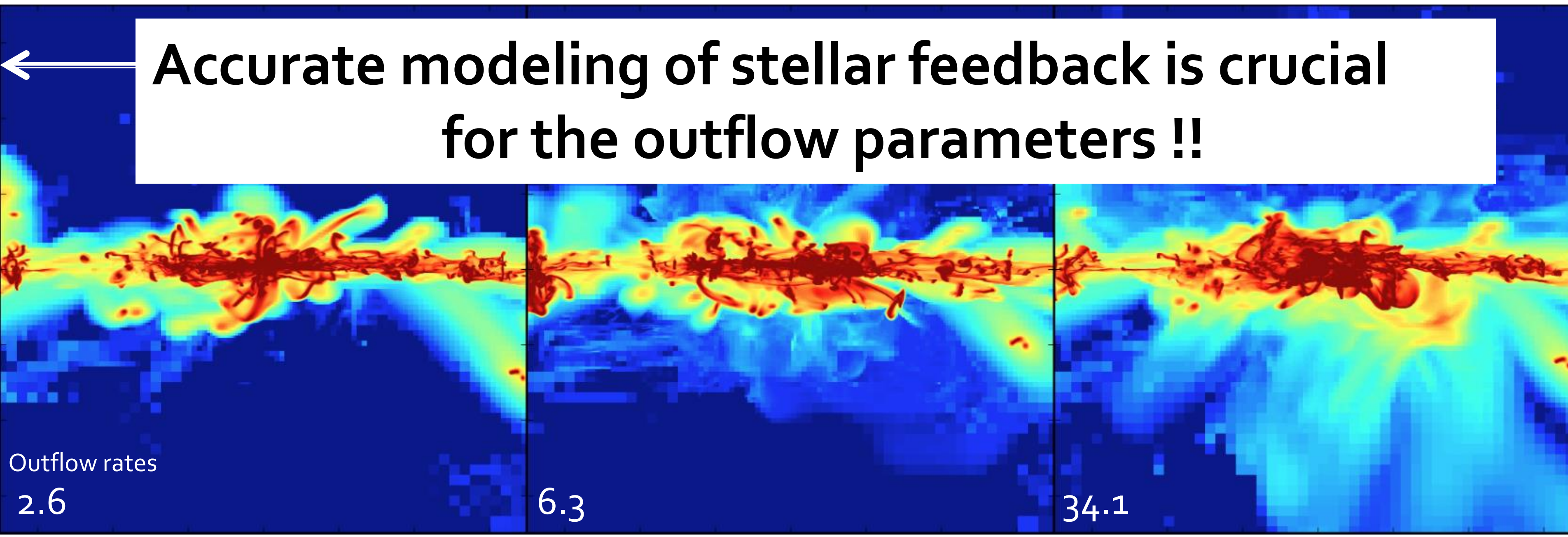
See also Hopkins+14

Gas density of simulated disk seen edge-on

Non-linear coupling of stellar feedback models (at dx > 1.5 pc)

Three runs with different feedback processes, all evolved for 80 Myr.

Supernovae | OB stars | SNe + OB stars



Outflows from SNe + OB stars >> Outflows from SNe + Outflows from OB stars

See also Hopkins+14

Gas density of simulated disk seen edge-on

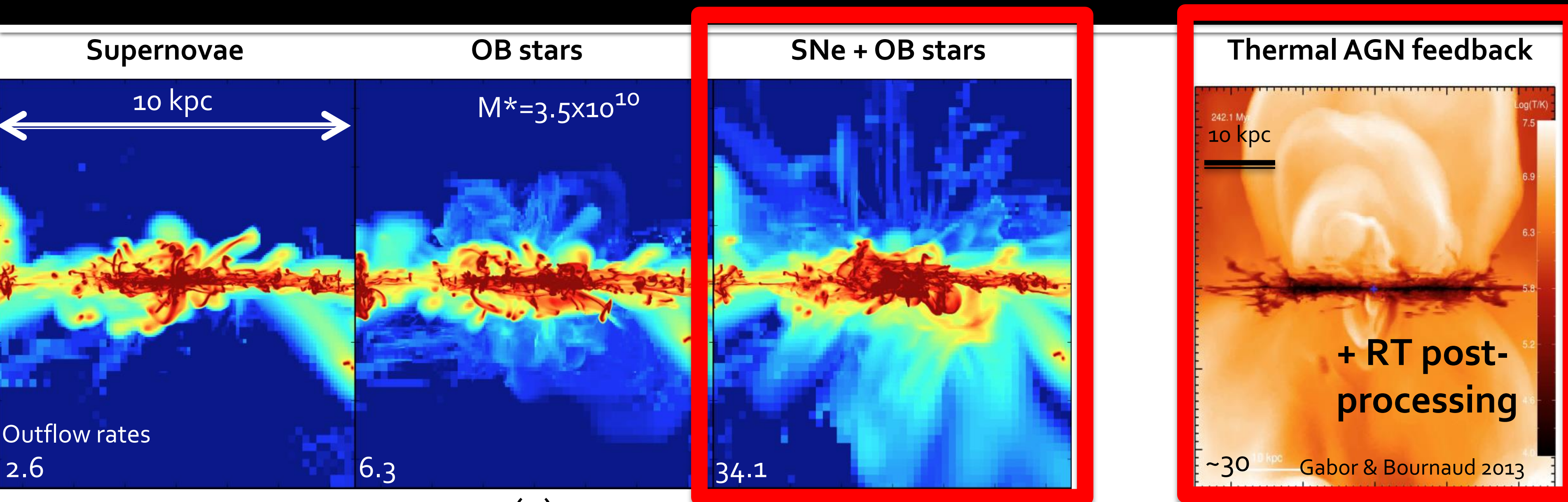
Can we model the multiple sources of winds *accurately* ?

- Thermal energy injection from AGN
- Ionization from AGN

- Thermal energy injection from SNe
- Kinetic energy injection from SNe
- Radiative pressure from OB stars

- **High space and mass resolution :** probe GMCs and avoid numerical coupling
- **+ half resolution :** check convergence

What if AGN+stellar FB also couple non-linearly ?



(a) (b)

First time ever. Let's POGO !

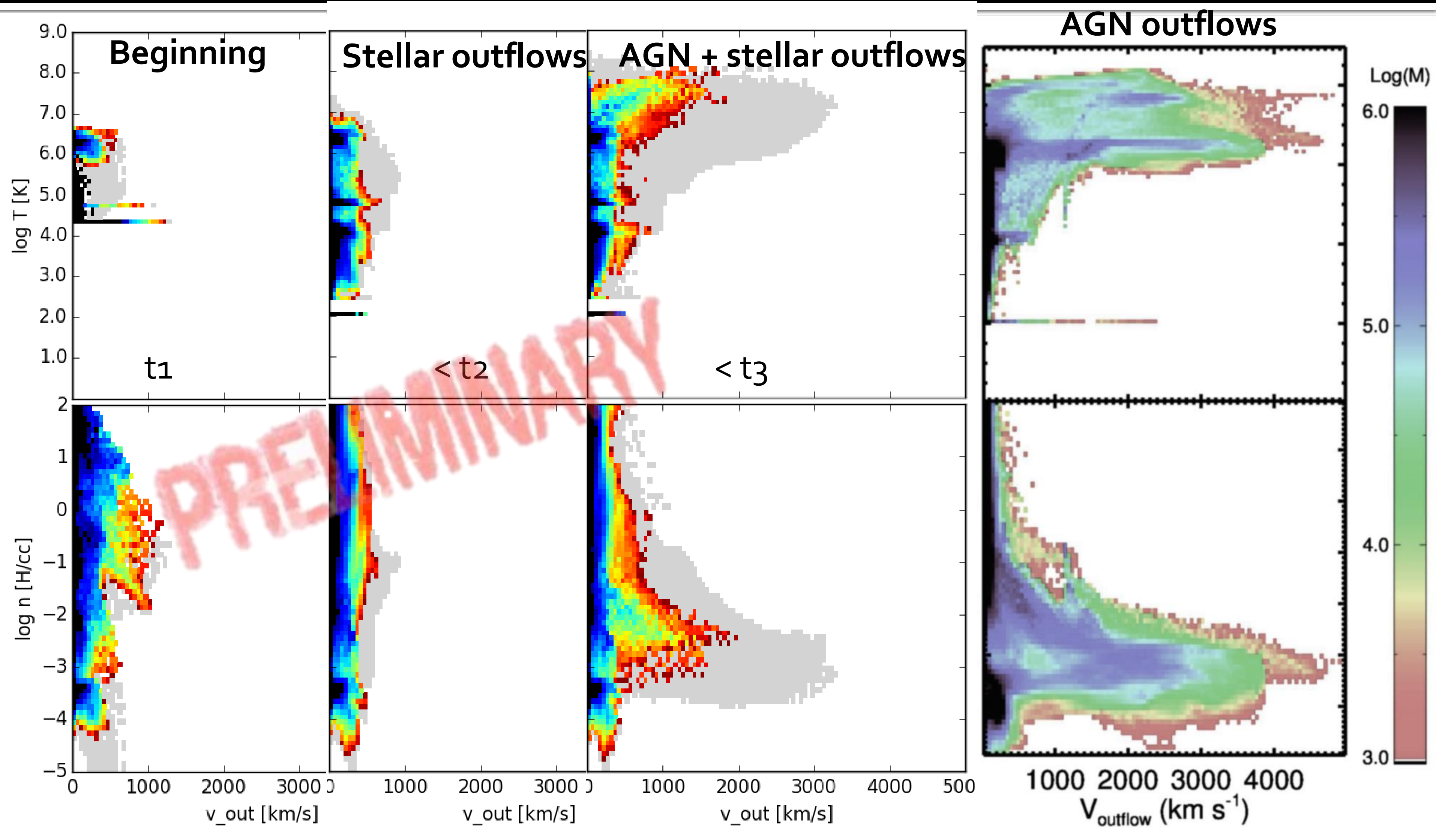
+

Combined effect of all feedback models may lead to very powerful and fast winds with high mass loading.

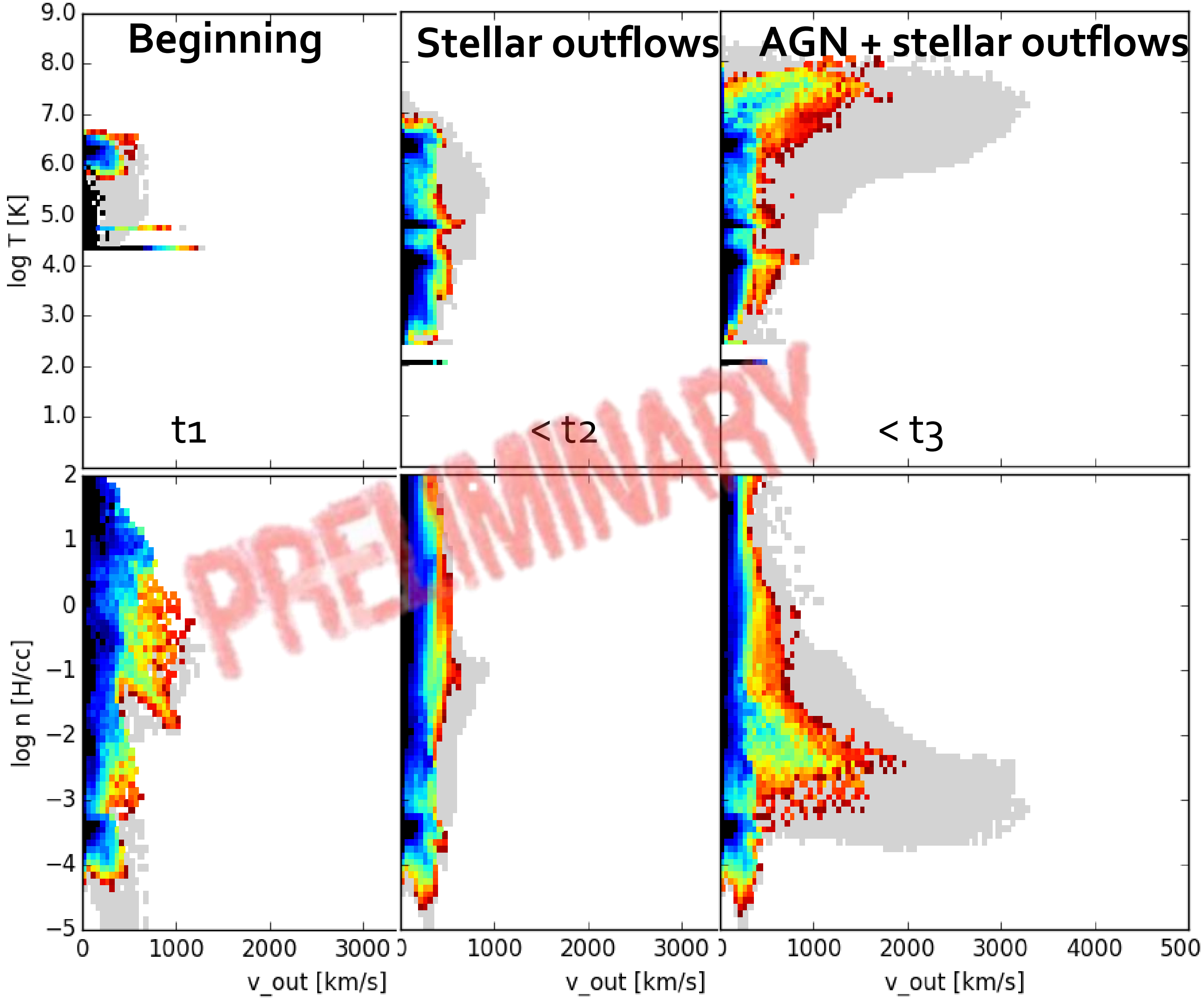
M1 : Mgas = 15 1E9 Msun
M2 : Mgas = 49 1E9 Msun
M3 : Mgas = 115 1E9 Msun

M3 : AGN + stellar FB
M1, M2 : AGN ; stellar FB ; AGN + stellar FB

How do AGN + stellar outflows couple ?



How do AGN + stellar outflows couple ?



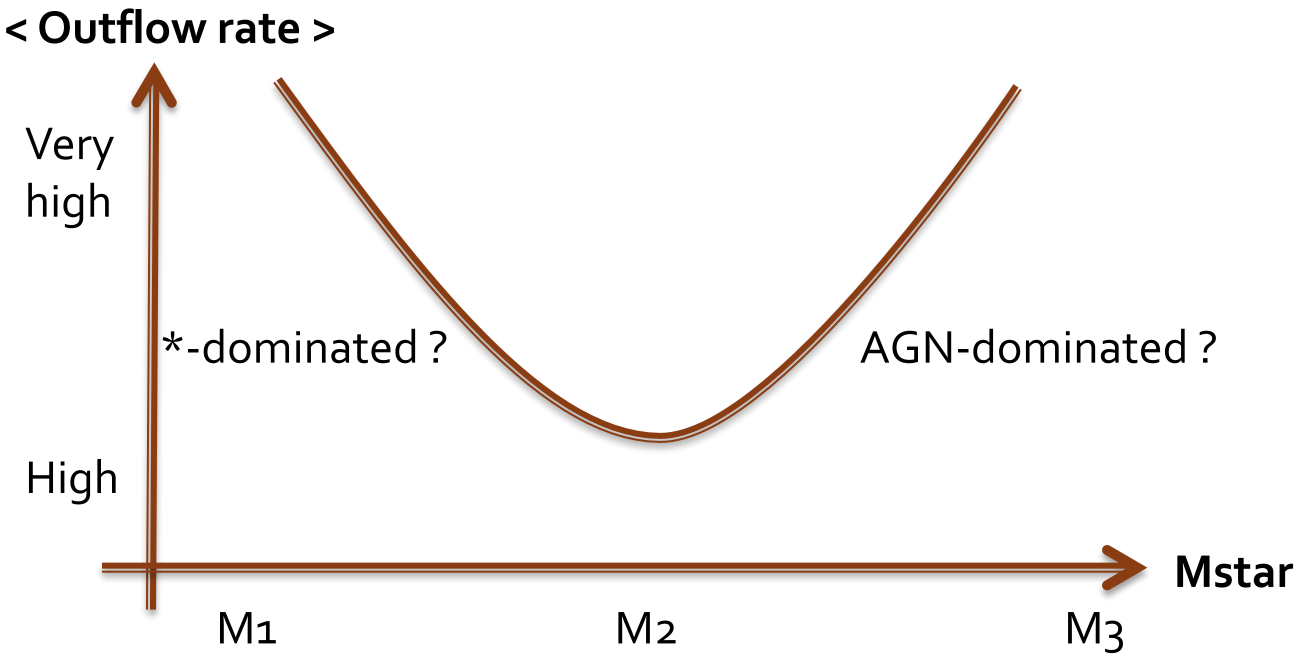
With M1 and M2 :

- **Study outflow characteristics as a function of time**
- **Identify outflow pattern for AGN FB only and stellar FB only**
- **Study outflow pattern for AGN + stellar FB :**
  - **= sum ?**
  - **> sum ?**
  - **< sum ?**

- **Nature of expelled gas : impact on SF ?**

What is the main outflow driver ?

Study 3 galaxy masses :



?

Mass loading compatible with observed IGM density ?

Missing baryons problem…

What if AGN+stellar FB also couple non-linearly ?

- If such dense UFOs are produced :
  - Evolve until steady state is reached
  - Study mass loading, expelled gas, …
  - Impact on star formation ?
  - Impact on IGM ?

UFO = ultra-fast outflow

What if they DON'T ?

- If such dense UFOs are NOT produced :
  - What other wind sources could produce UFOs ?
  - What kills them ?
  - What other non-linear effects are we missing ?

You're done !

- Primeval/high-redshift galaxies ☑
- AGN ☑
- AGN feedback ☑
- Link with star formation ☑
- HPC ☑
- To kill or not to kill ? ☑
- Stellar feedback ☑

SUMMARY : **For further details, see** Roos *et al.* 2015 *ApJ* **800** 19.

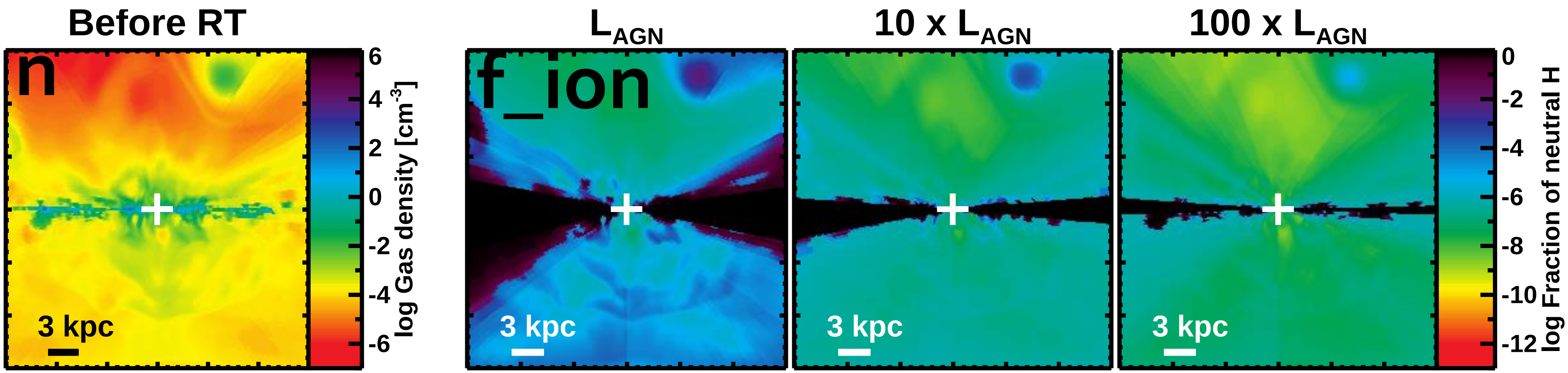
AGNs do not kill galaxies

Would this conclusion change with accurate modeling of stellar and AGN winds ?

Stay tuned for the POGO project !

Thank you for your attention.

Thermal and radiative AGN feedback in high-z galaxies..

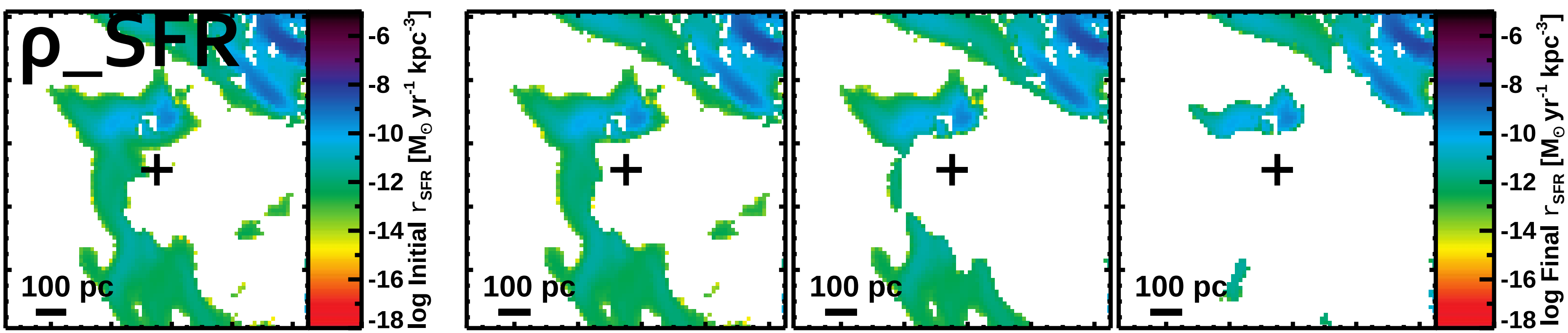


L_AGN = 10^44.5 erg/s

Edge-on view

.. mainly affect diffuse gas

Face-on view – zoom in



.. and have very little impact on the star-forming phase of the ISM.

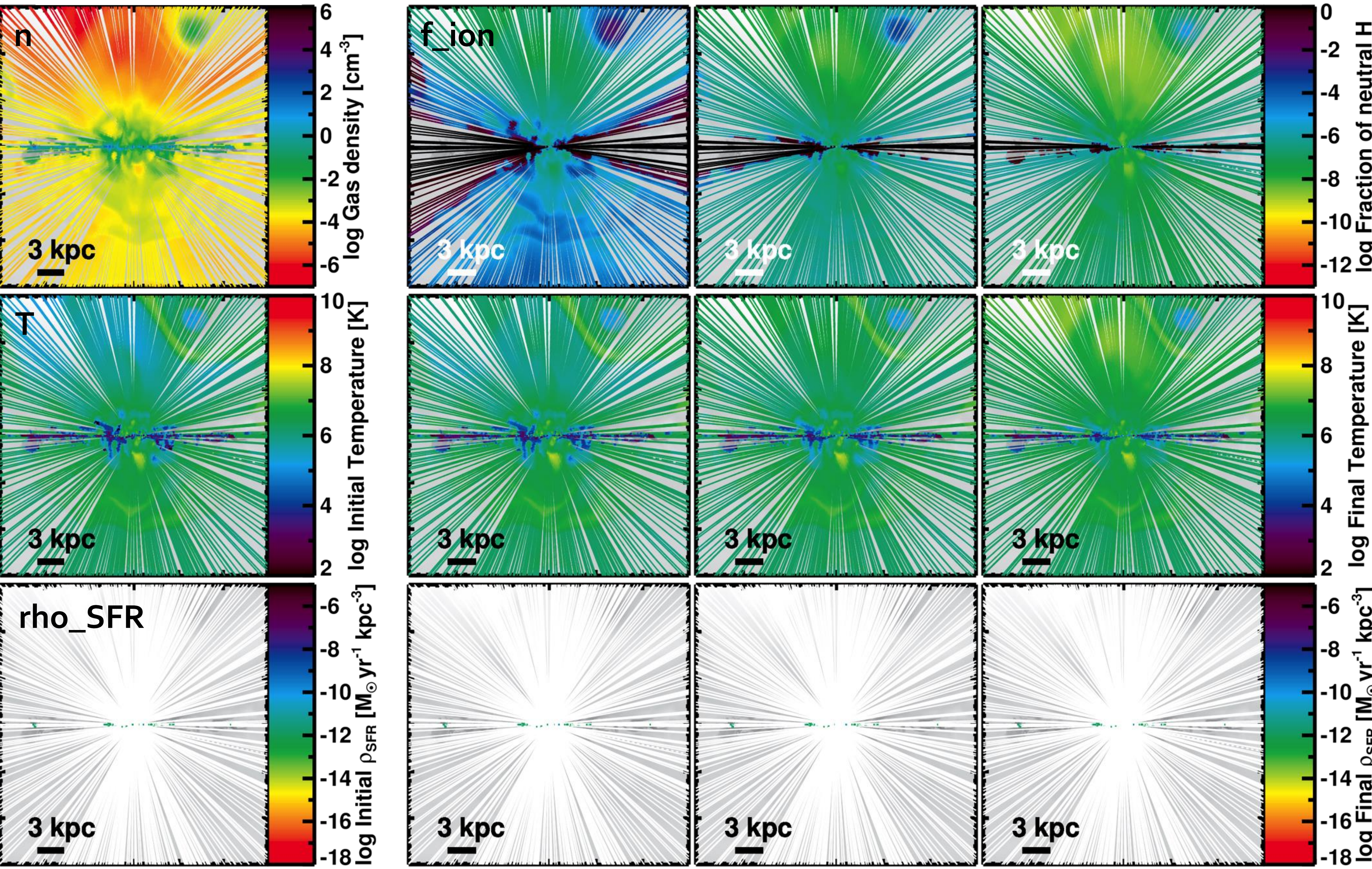
Reduction of SFR < 4%

Diffuse and extended star-forming regions around the AGN are suppressed, **but major contributors to the SFR are left unaffecte**

Orianne Roos, with S. Juneau, F. Bournaud and J. Gabor

see **Roos et al. 2015**

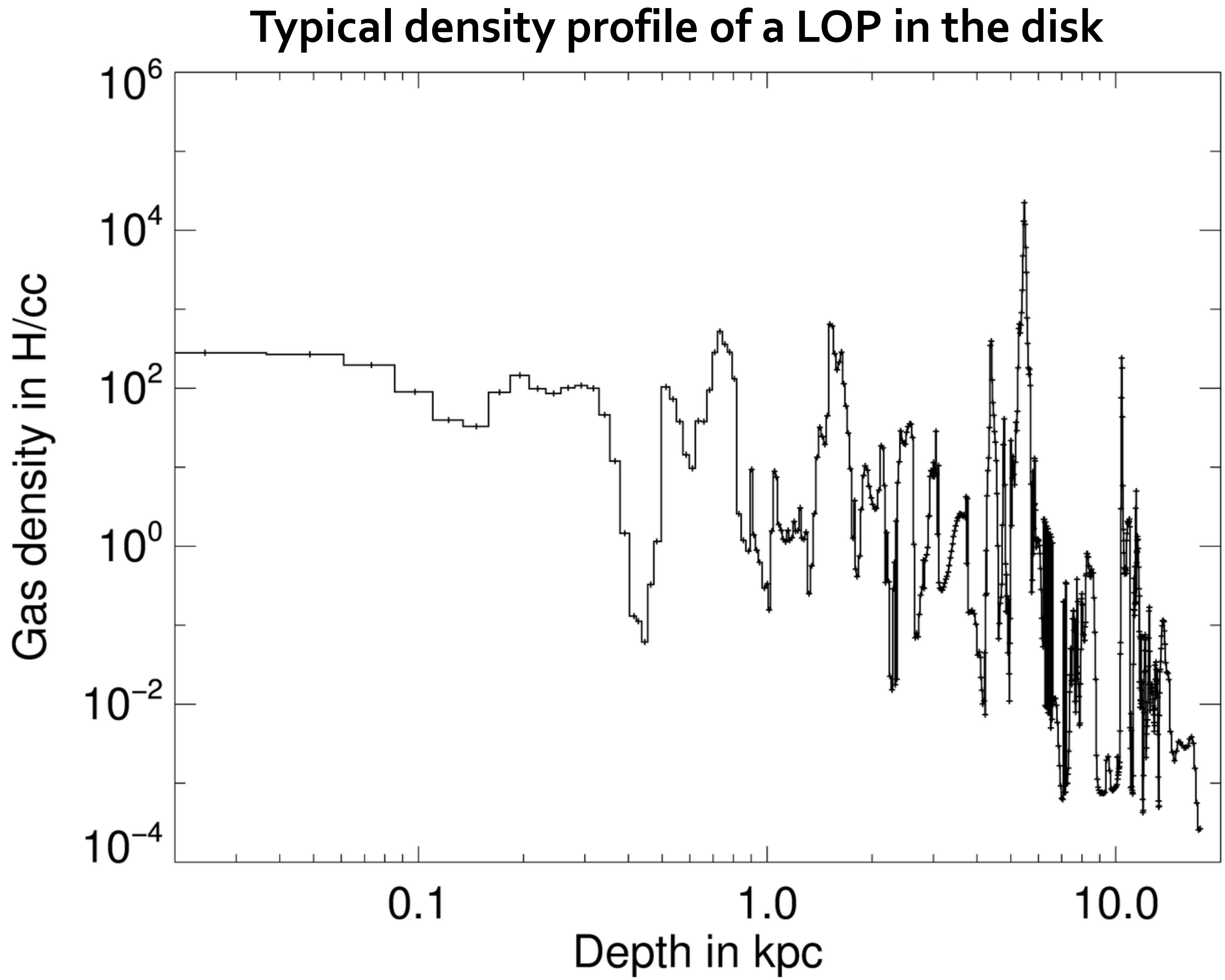
Before RT | L_AGN | 10 L_AGN | 100 L_AGN



Edge-on view

L_AGN = 10^44.5

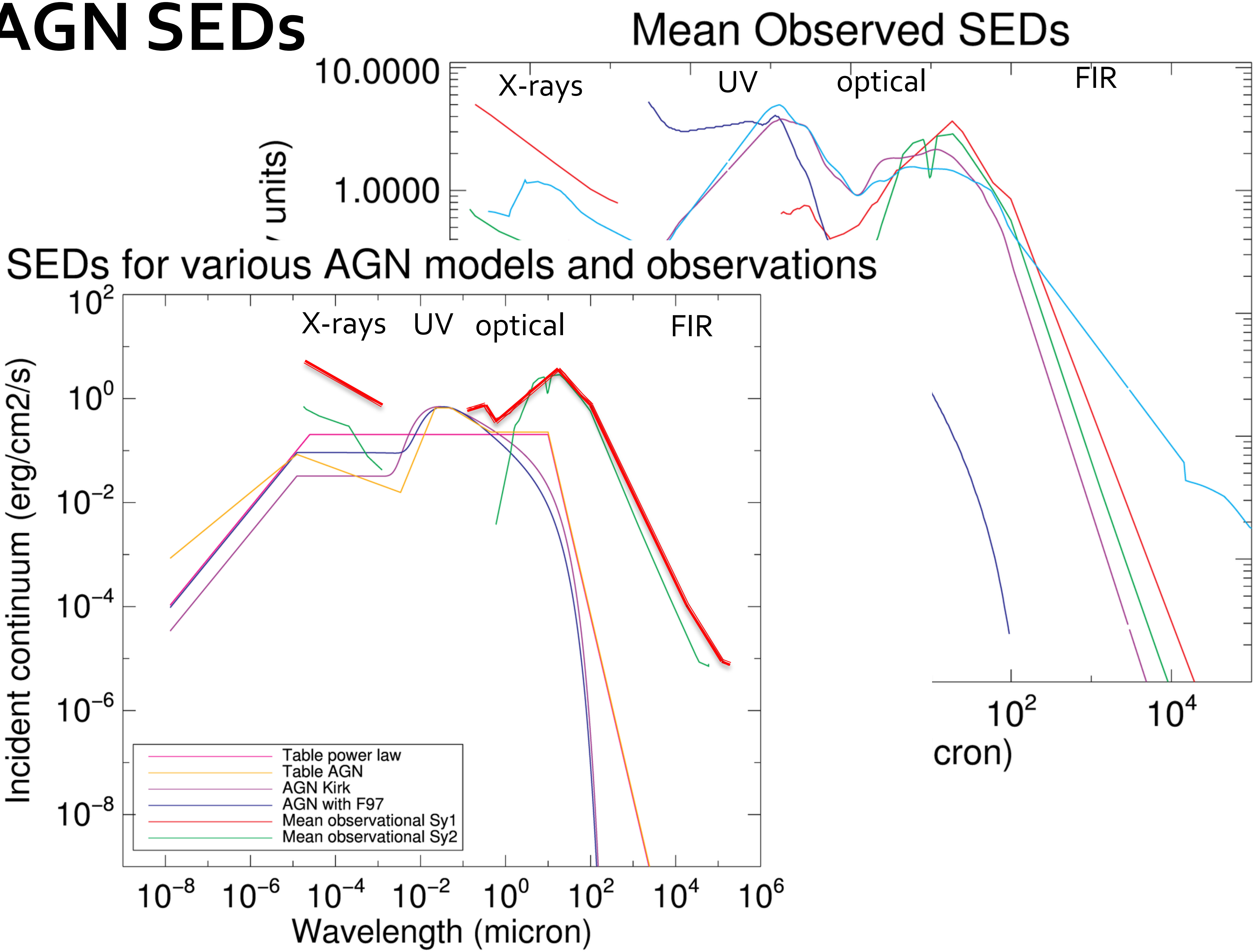
Simulation of a high-redshift disk galaxy



CLOUDY

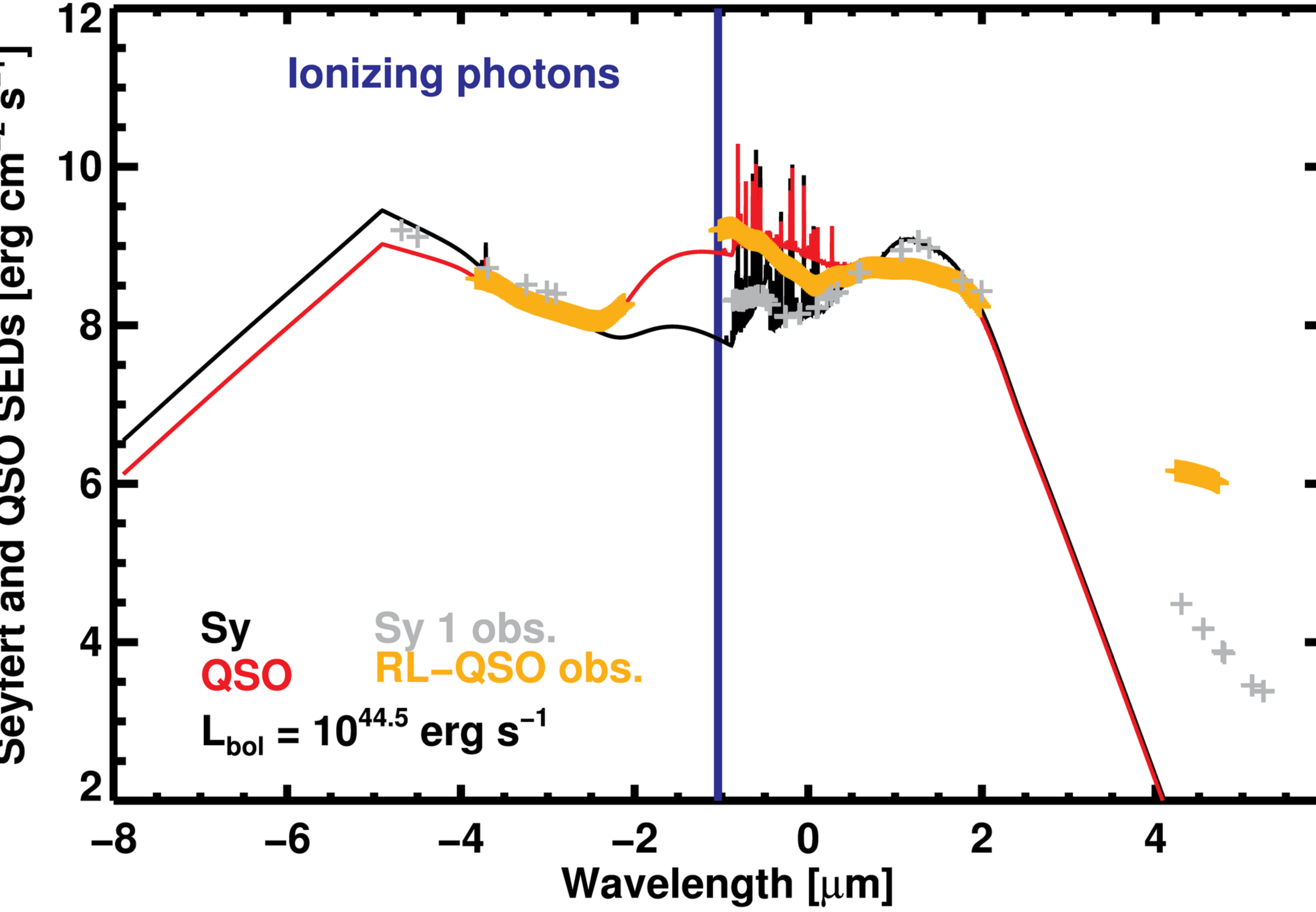
- Large-scale spectral synthesis code : Ferland et al, 2013
- Computes radiative transfer and molecular chemistry
  along 1D lines
- Divides each line into thin zones
- Balances recombination and ionization processes
- Input : ionization source and density profile
- Output : ionization fraction, temperature, line emission …

AGN SEDs

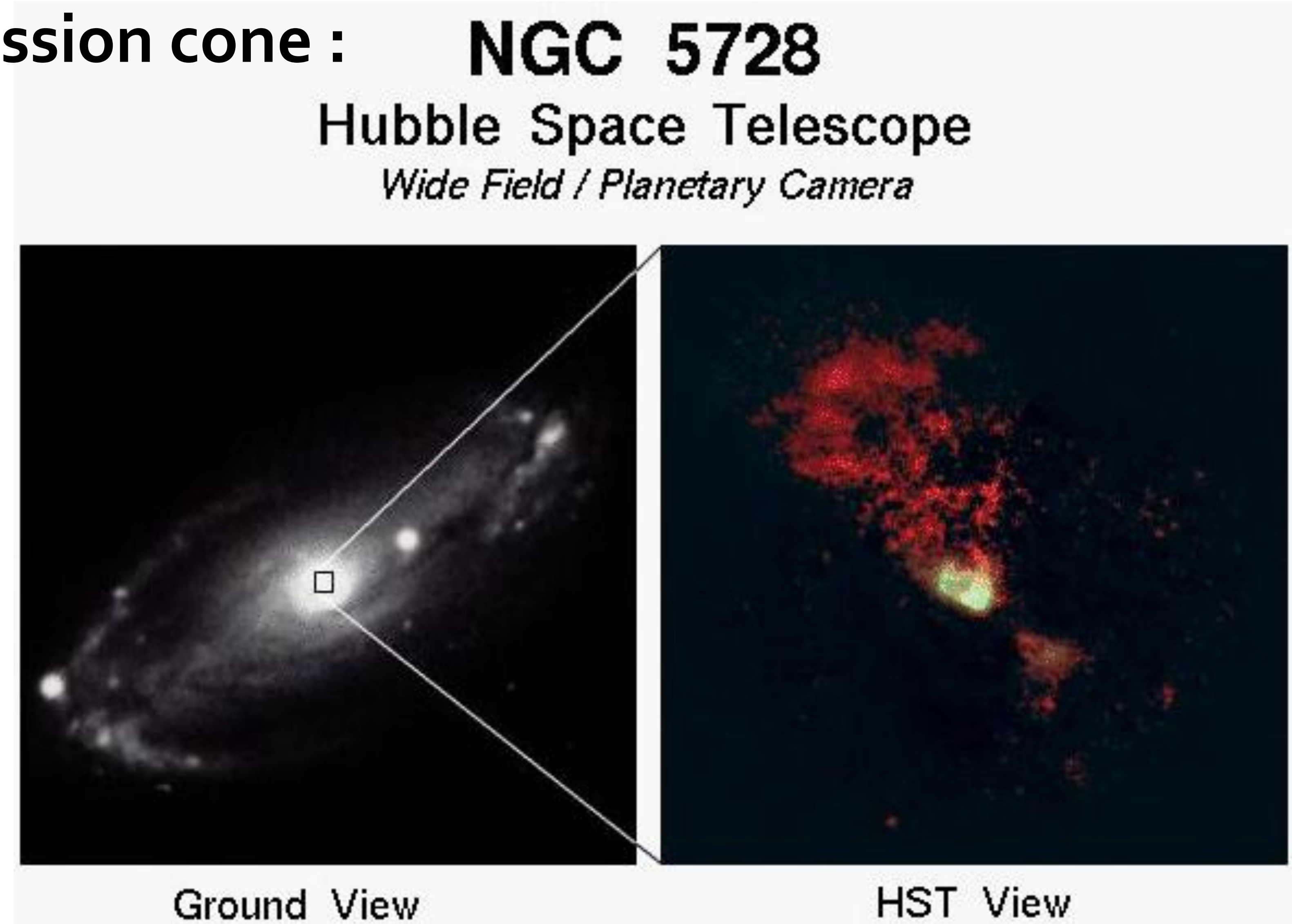


Mean Observed SEDs
10.0000
1.0000
X-rays
UV
optical
FIR
units)
10^2
10^4
cron)
SEDs for various AGN models and observations
X-rays
UV
optical
FIR
Incident continuum (erg/cm2/s)
10^2
10^0
10^-2
10^-4
10^-6
10^-8
10^-8
10^-6
10^-4
10^-2
10^0
10^2
10^4
10^6
Wavelength (micron)
Table power law
Table AGN
AGN Kirk
AGN with F97
Mean observational Sy1
Mean observational Sy2

Seyfert- and QSO-matched SEDs



Emission cone :



From STScI, modified by G. Rieke

Mean half-opening angle : ~ 30° at low-z (Müller-Sanchez+2011)