galaxy formation theory

lecture 3

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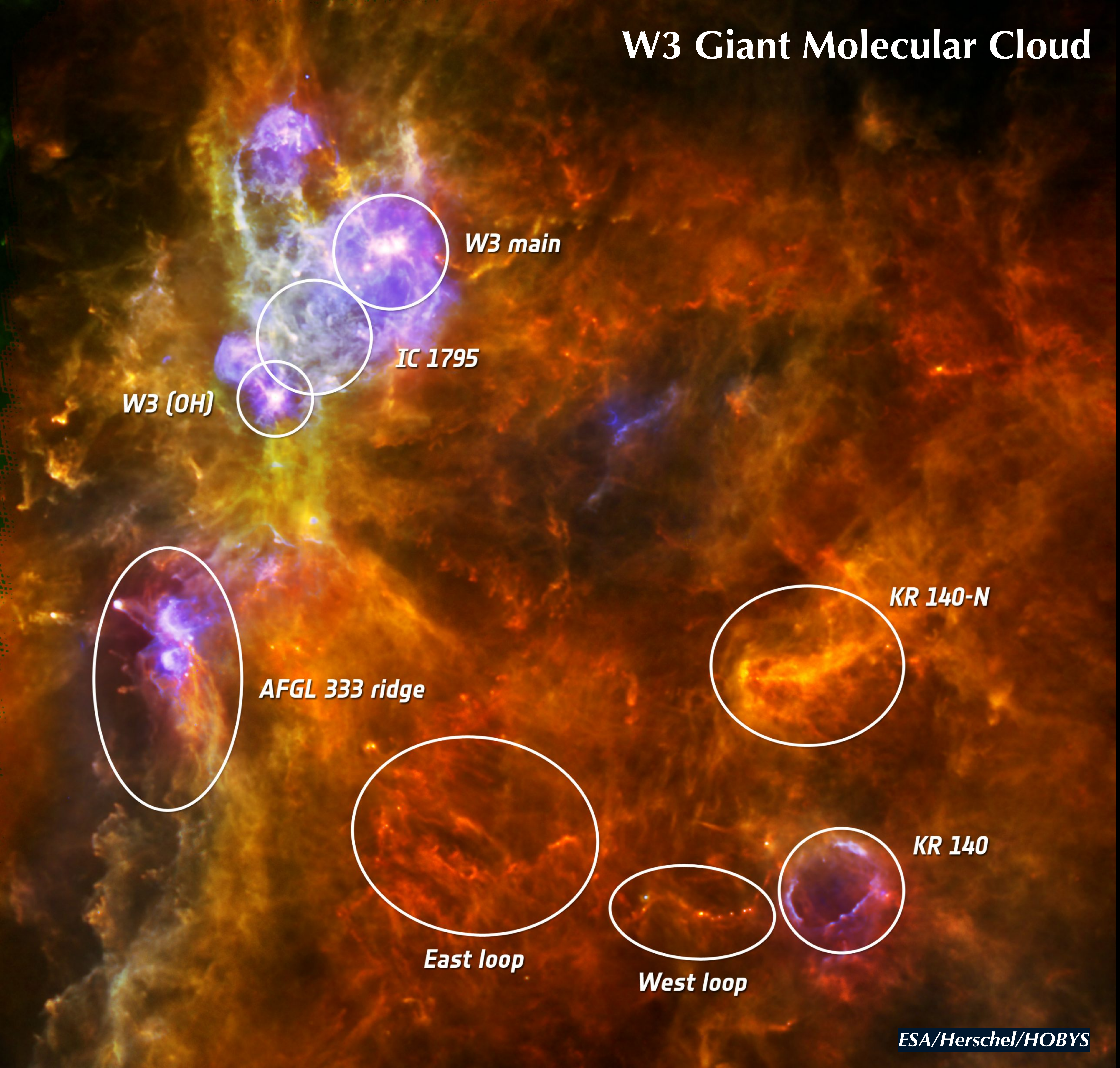
outline of the course

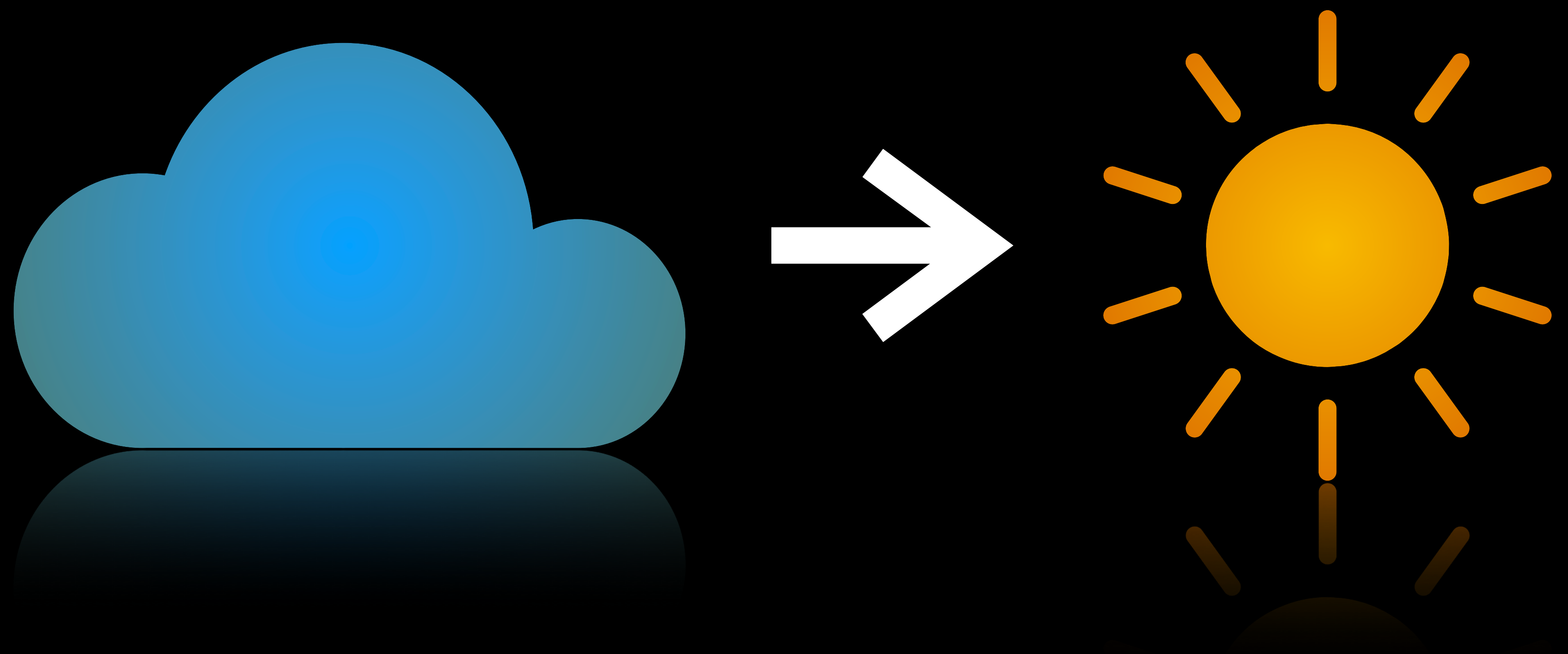
- a brief review of the observational background
- assembly of dark matter haloes
- gas cooling
- angular momentum
- star formation
- feedback
- galaxy mergers & morphology
- evolution of supermassive black holes

5. star formation

W3 Giant Molecular Cloud



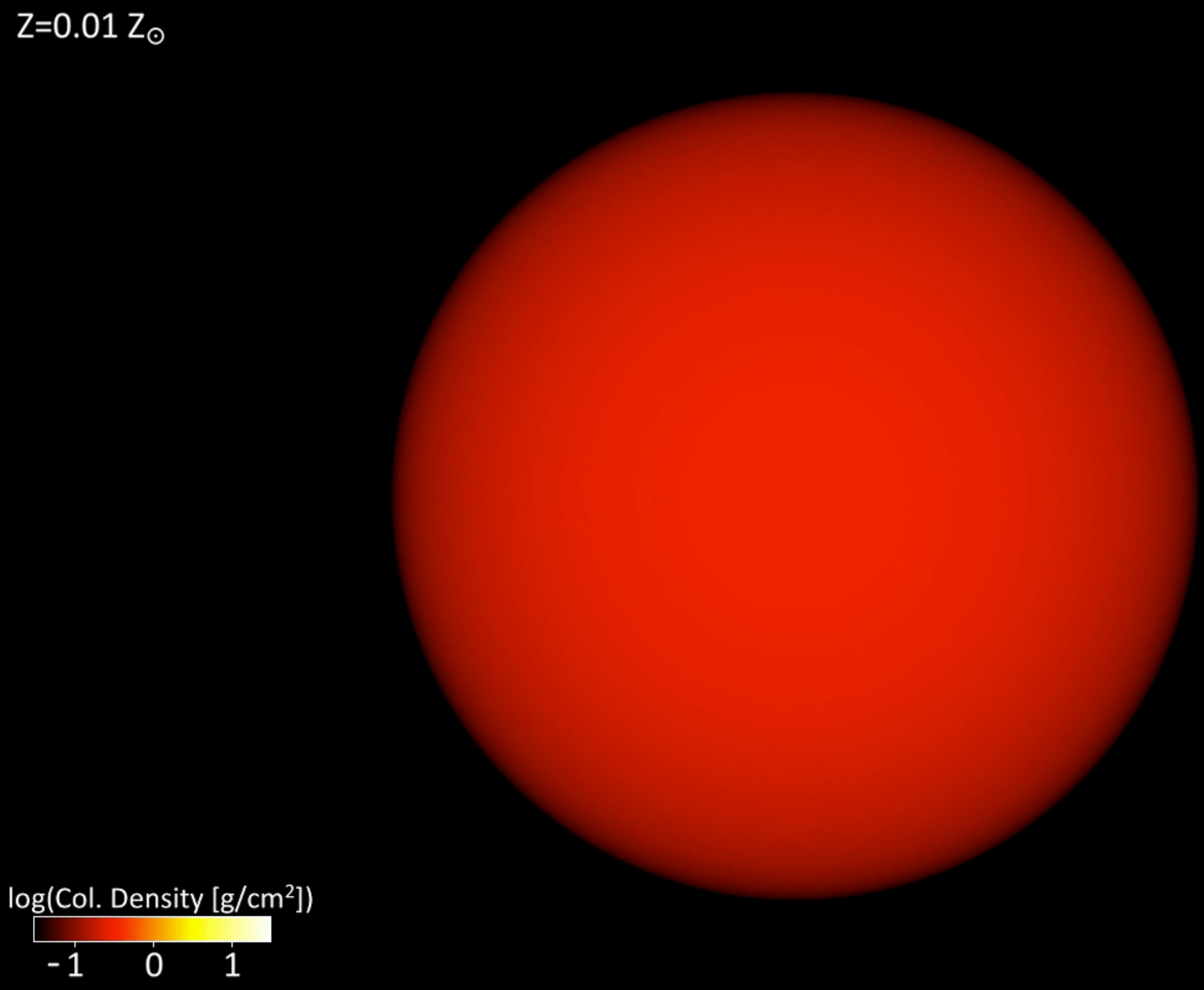
stars, universally, are formed out of cold, dense gas in galaxies, specifically in regions known as Giant Molecular Clouds (GMCs)



$n_{\mathrm{H}} \sim 10 - 1000\,\mathrm{cm}^{-3}$
$r \sim \mathcal{O}\,(10)$ pc

$\rho \sim 1\,\mathrm{gcm}^{-3}$
$r \sim \mathcal{O}\left(10^{-7}\right)$ pc

during the process of star formation, typical densities have to increase by several orders of magnitude



a roughly 2-stage process: (i) the **large-scale aggregation/ collapse** of the **interstellar medium** into GMCs followed by (ii) the **gravitational collapse** and **fragmentation** of GMCs into **protostellar cores** which collapse to form stars

inefficient: only a small % of gas converted to stars due to feedback from young massive stars, turbulence etc.

Matthew Bate
University of Exeter

star formation in the present-day Universe

on galaxy-wide scales, there appear to be two distinct modes of star formation

quiescent

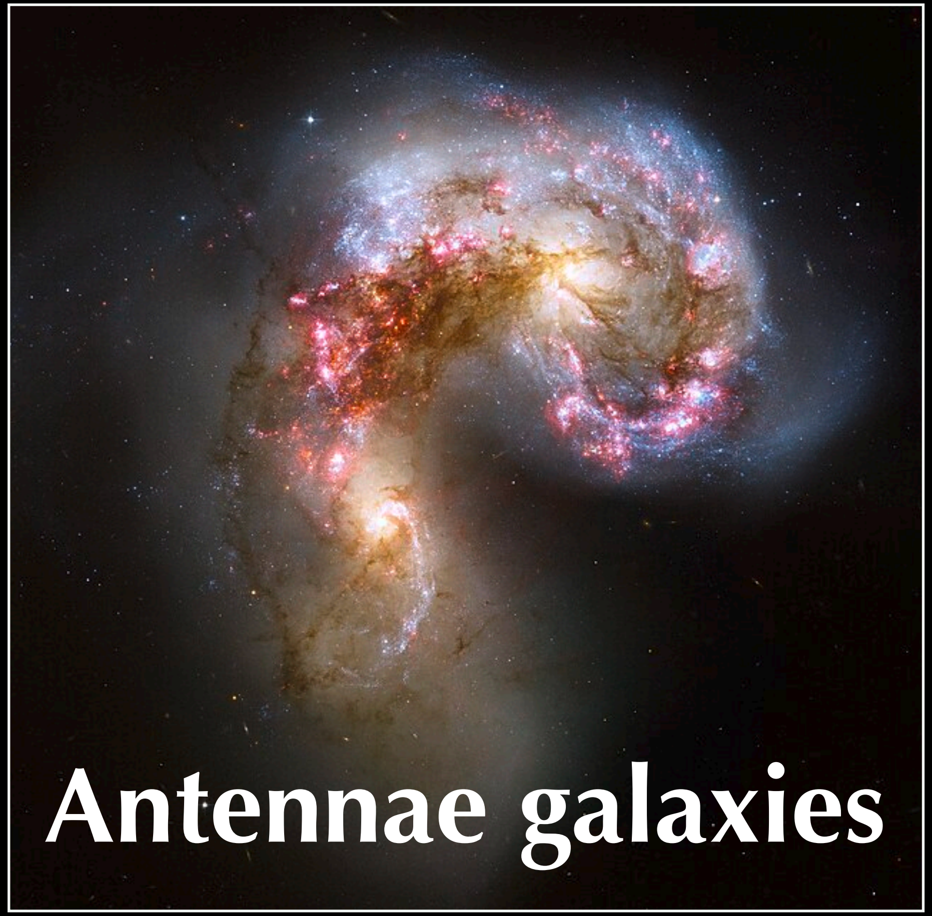
in the discs of spiral & irregular galaxies

$$\tau_\star = M_{\rm gas}/{\rm SFR} \sim 10^9 - 10^{10}\,{\rm yr}$$

starbursts

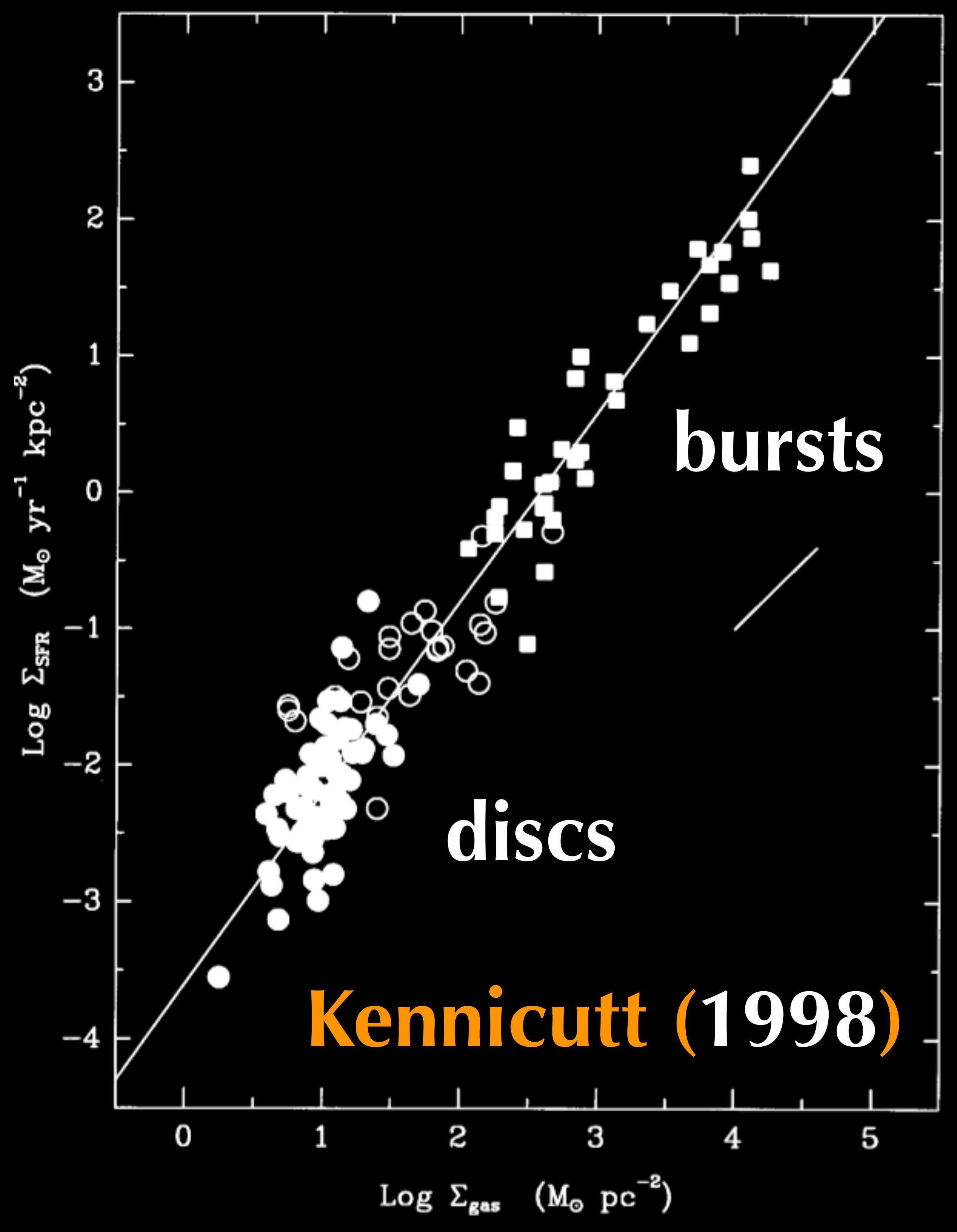
usually triggered by major dynamical disturbances — galaxy mergers, tidal interactions, galactic bars

$$\tau_\star \sim 10^7 - 10^8\,{\rm yr}$$



modelling star formation on galactic scales

there is no good *ab initio* model for star formation. furthermore, the state-of-the-art for modelling processes in individual GMCs are very separated spatially from the scales (~kpc) resolved in simulations. galaxy formation models therefore resort to phenomenological or empirical relations to calculate star formation. the most well-known of these is the Kennicutt-Schmidt relation



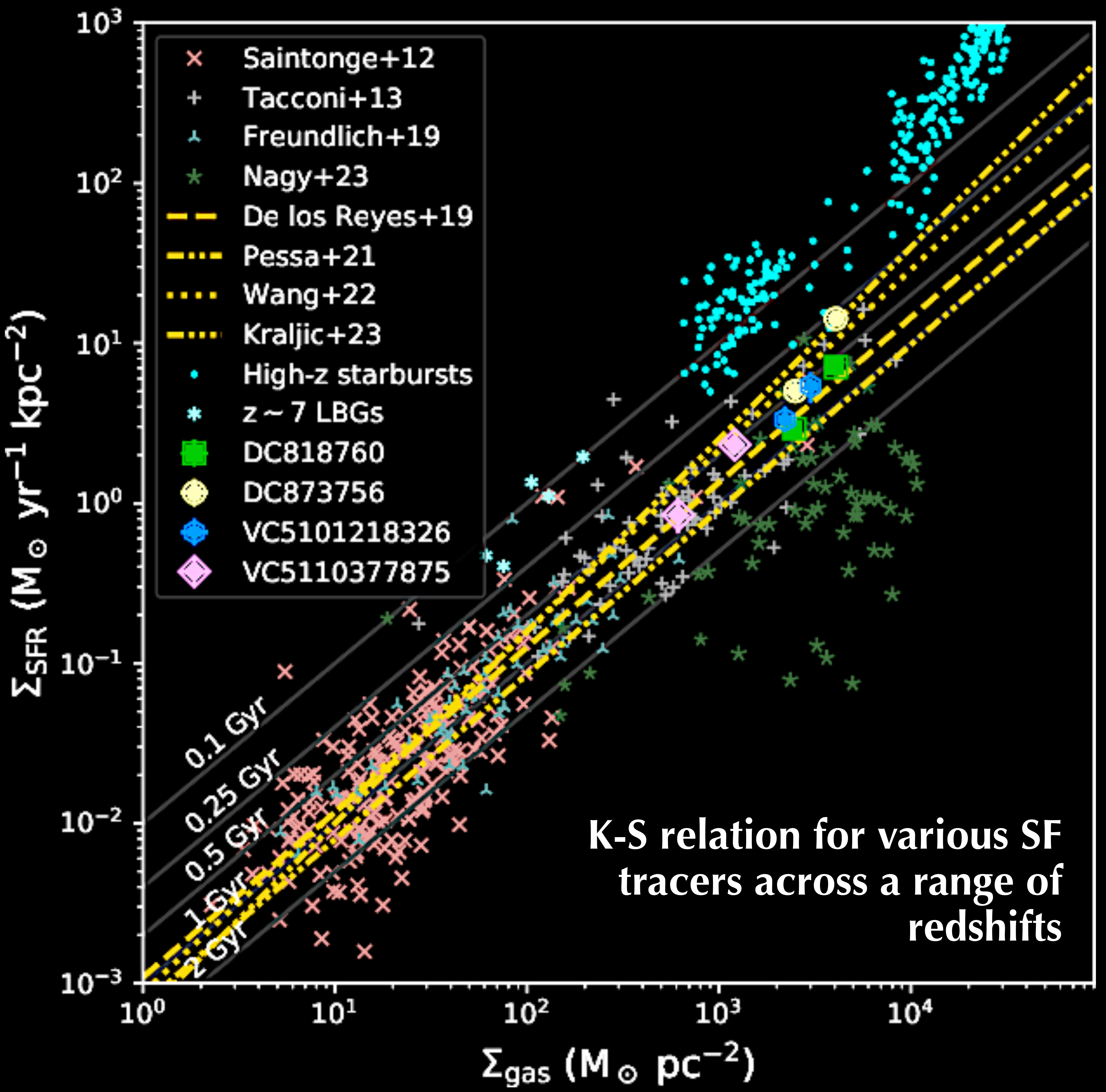
this relates the surface densities of star formation with the total ($HI+H_2$) gas content of galaxies. importantly, both quiescent and starburst galaxies appear follow the same scaling law:

$$\dot{\Sigma}_\star = K\,\Sigma_{\rm gas}^N \qquad \text{where } N \approx 1.4$$

this is consistent with what one would estimate theoretically:

$$\tau_\star \propto \tau_{\rm ff} \propto 1/\left(G\rho_{\rm gas}\right)^{1/2} \Rightarrow \rho_{\rm SFR} \propto \rho_{\rm gas}^{3/2}$$

Bethermin+ (2023)



$$\dot{\Sigma}_\star \simeq 2.5\times 10^{-4}\left(\frac{\Sigma_{\rm gas}}{\rm M_\odot\,pc^{-2}}\right)^{1.4}\ \rm M_\odot\,yr^{-1}\,kpc^{-2}$$

equivalently, these data also suggest a tight correlation between $\dot{\Sigma}_\star$ and $\Sigma_{\rm gas}/t_{\rm dyn}$

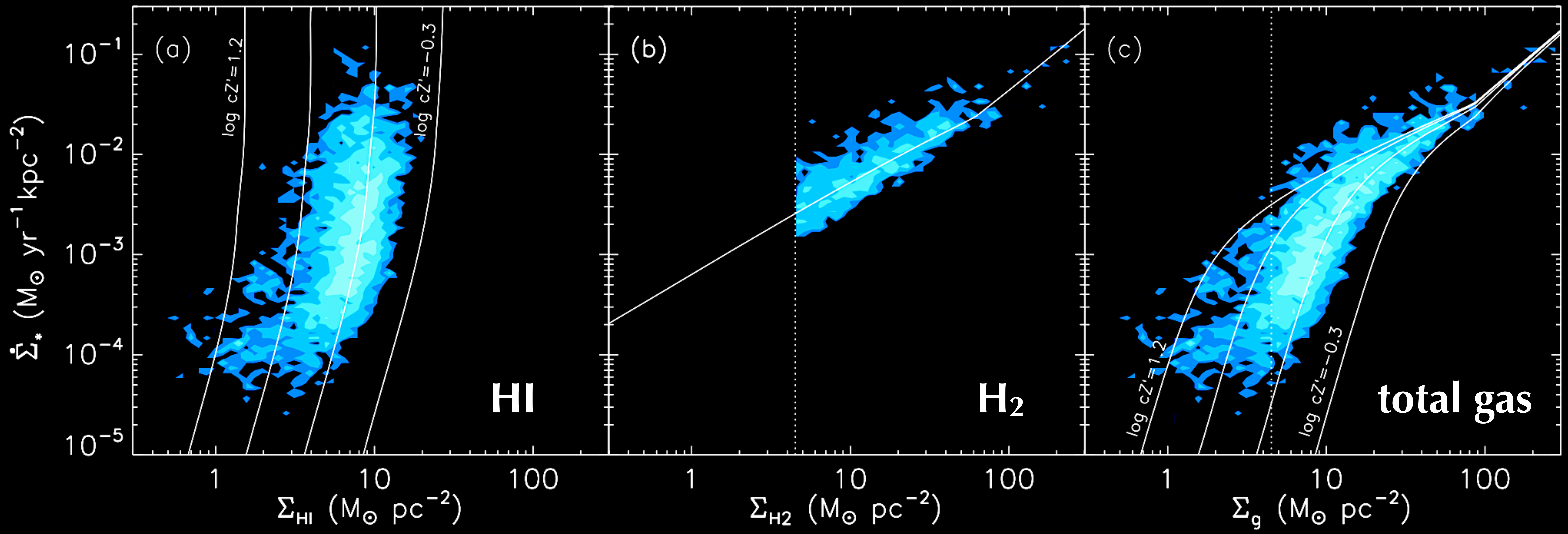
defining $t_{\rm dyn} = t_{\rm orb} = 2\pi R/V_{\rm rot}(R)$, where R is the outer radius of the star forming disc:

$$\dot{\Sigma}_\star \simeq 0.017\,\Sigma_{\rm gas}\,\Omega$$

where $\Omega \equiv V_{\rm rot}(R)/R$ is the orbital frequency

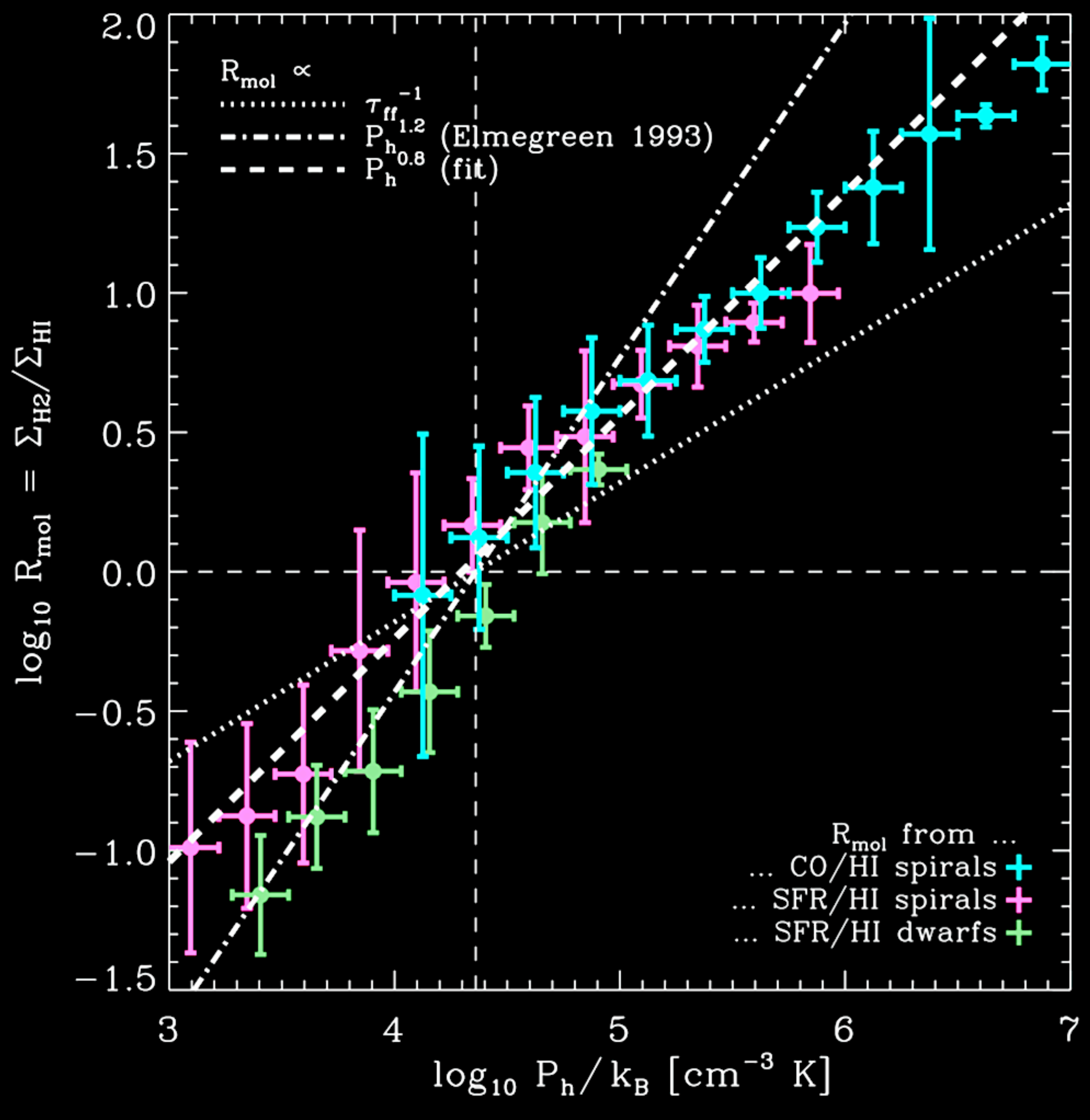
per free-fall time, $\mathcal{O}\left(1 - 10\,\%\right)$ of gas is consumed by star formation

Krumholz+ (2009)



recent measurements of star formation on sub-kpc scales of local galaxies suggest that SFR has NO correlation with HI surface density, a LINEAR relation with H_2, and a non-linear, non-power law relation with total gas surface density

what determines the ratio between HI and H_2?



Leroy+ (2008)

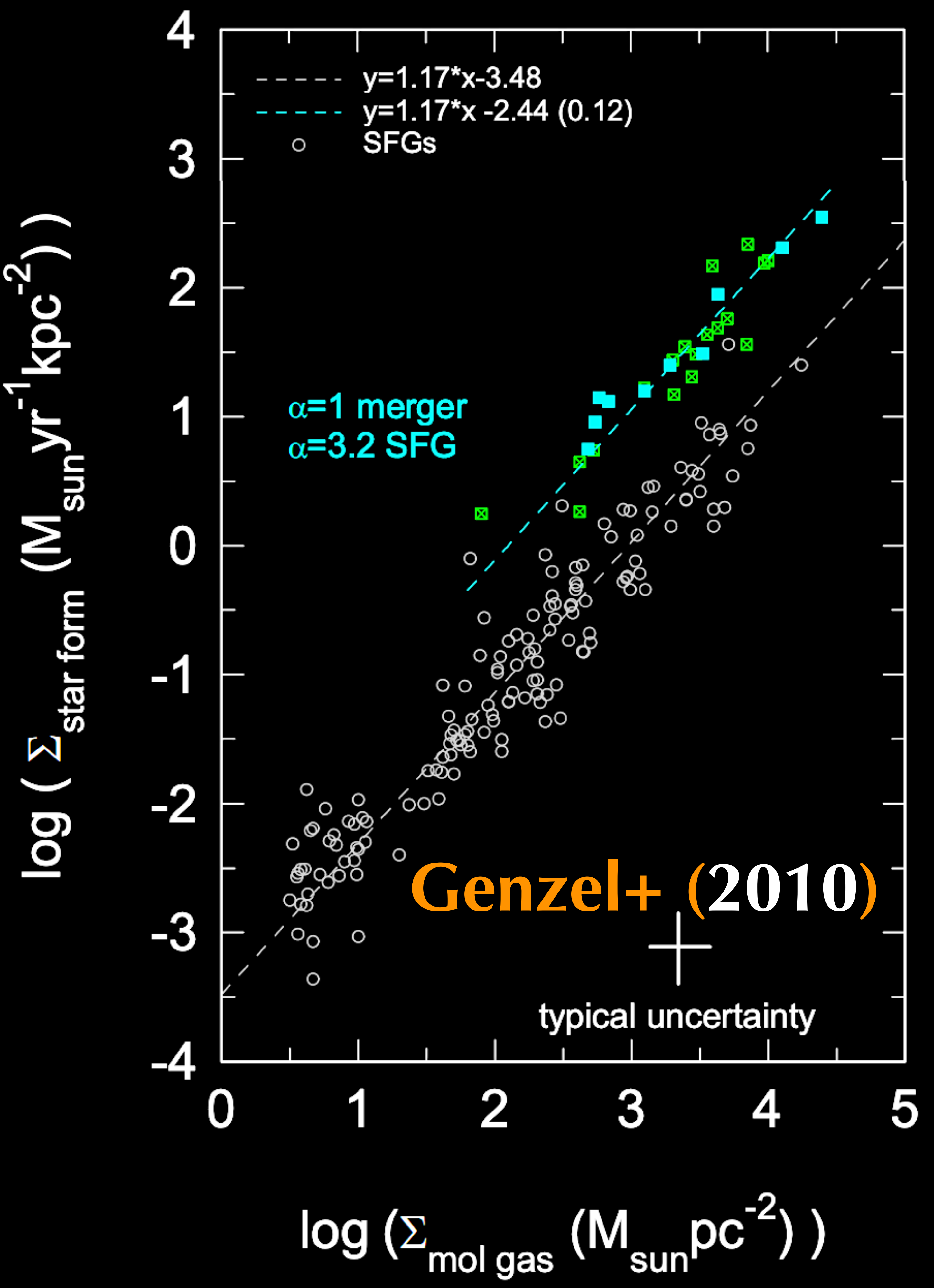
observations of nearby spiral galaxies seem to be well fit by:

$$R_{\rm mol} = \Sigma_{\rm H_2}/\Sigma_{\rm HI} = \left(P_{\rm gas}/P_0\right)^{\alpha}$$

where $\alpha = 0.8$, $P_0/k_B = 1700\,{\rm cm}^{-3}\,K$, and $P_{\rm gas}$ is the midplane gas pressure (c.f. Blitz & Rosolowsky 2006)

the idea is that pressure, which is directly proportional to the gas density, should affect the rate of H_2 formation/destruction and the ability for a gravitationally unstable overdensity to condense out of a turbulent ISM. but, theoretically, it is not obvious that pressure is the real physical variable driving this relation.

a different SF law in starbursts?



looking at galaxies at slightly higher redshift (z ~ 1-3), there are some tentative hints that starburst galaxies are somewhat offset from the average K-S relation

however, an important caveat is that one does not measure all the molecular gas directly at these redshifts — uses only e.g. CO emission line, which is then converted to gas mass using an uncertain CO-to-H_2 conversion factor, as well as assumptions for the assumed initial mass function (IMF)

different works will make use of different tracers for measuring SFR and will predict integrated properties (e.g. stellar mass) using different IMFs… bear these in mind when comparing works with one another and with theoretical models!

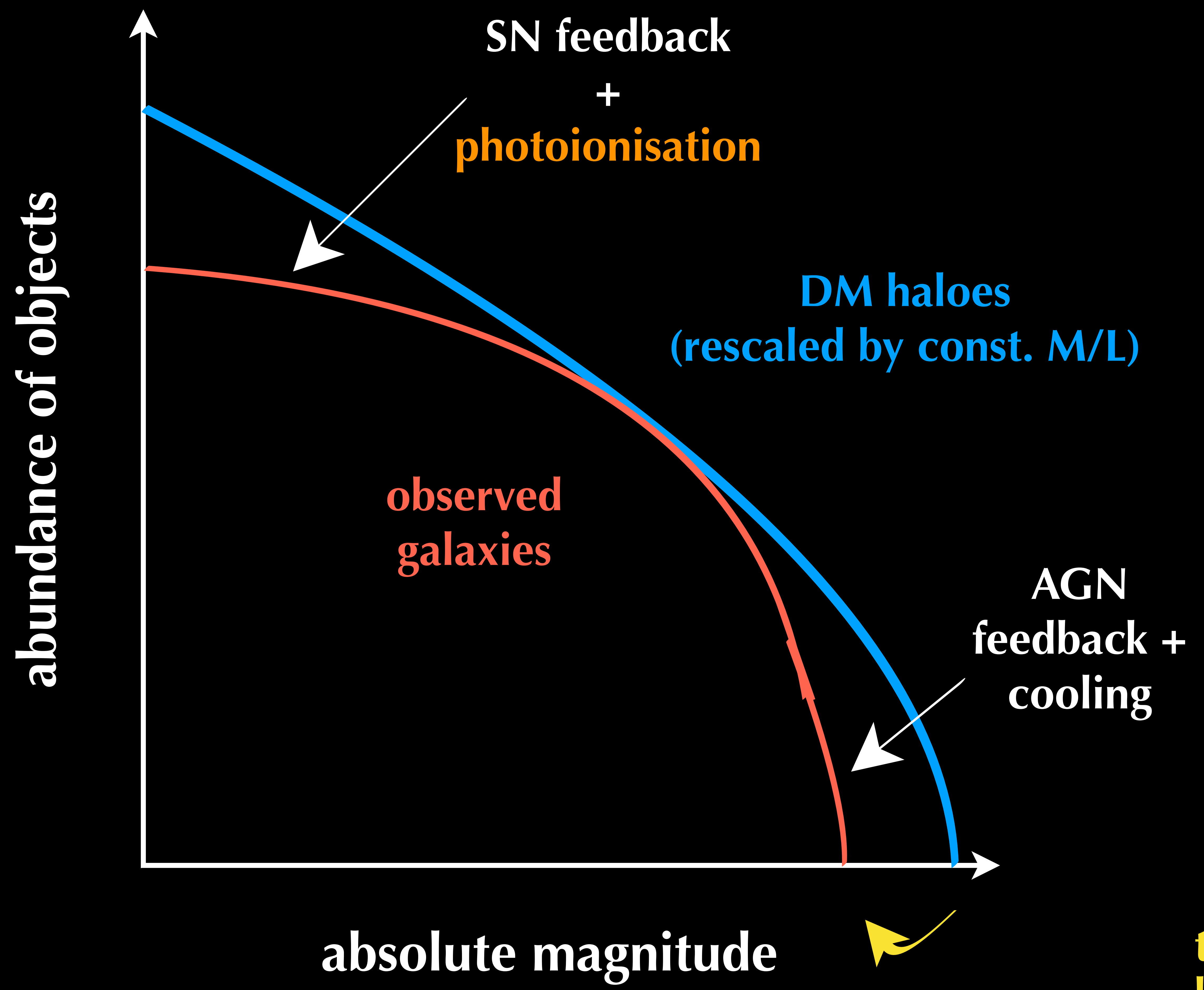
because of the lack of a good *ab initio* model for star formation, most models of galaxy formation calibrate their prescriptions based on observations of (mostly) local galaxies. these are (i) not unique and (ii) not clear over what range of physical conditions or redshifts they are valid.

in particular, star formation models remain an important uncertainty in galaxy formation models, particularly at high redshift

6. feedback processes

a process (energy input) that has a net negative impact on the amount of baryons that are able to condense into galaxies (either as cold gas or as stars)

why is feedback needed?



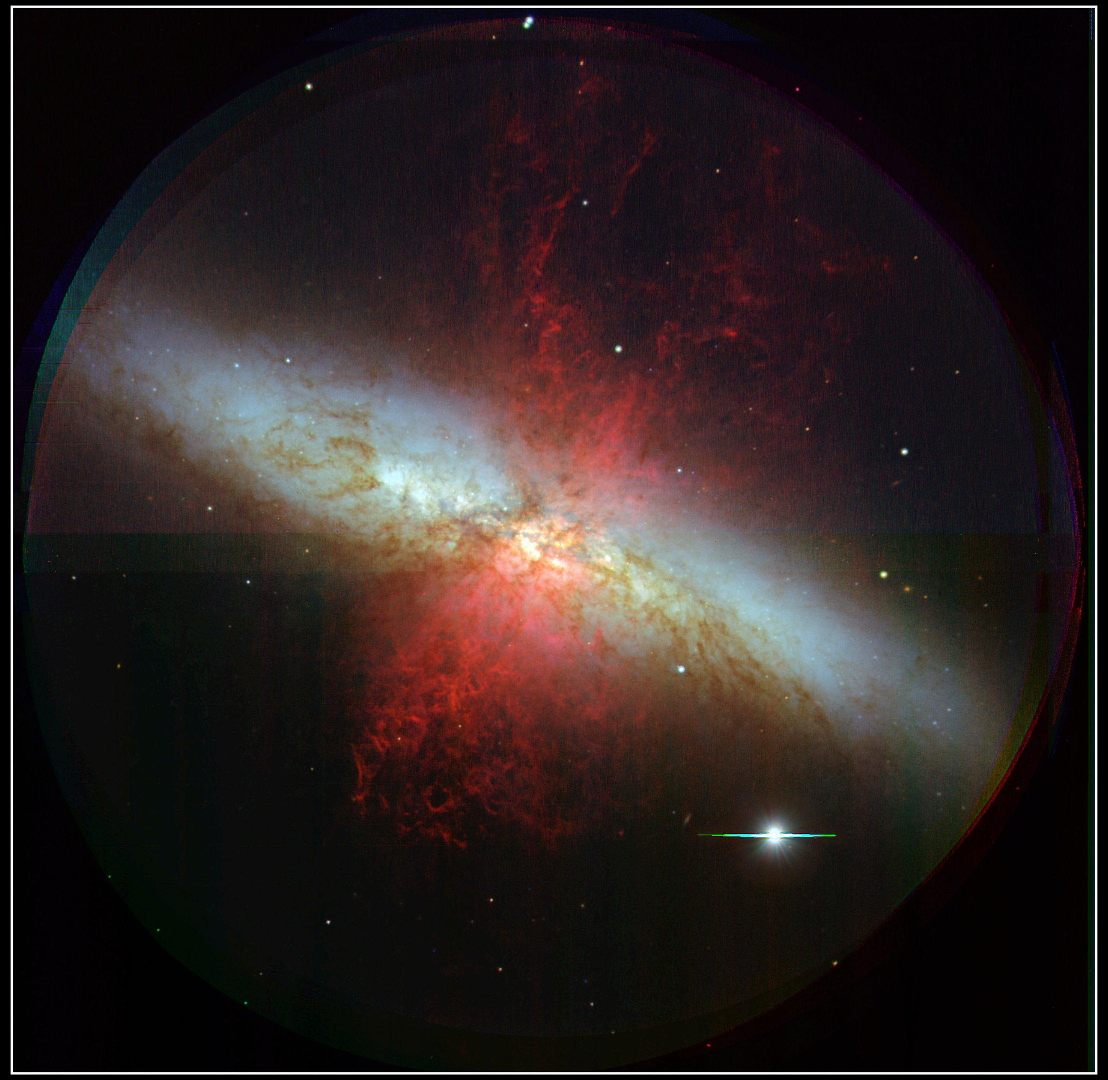
we have previously discussed (Lecture 2) the overcooling problem: in a hierarchical model of galaxy formation, where all progenitors, at some point, are in the efficient cooling regime, one should expect 80-90% of the baryons to be condensed into galaxies.

but, in reality, we observe that only 5% of the baryons are condensed at z=0 (of which 90% are stars)

this also suggests that the efficiency with which haloes convert baryons into stars varies as function of halo mass

sources of feedback

stars

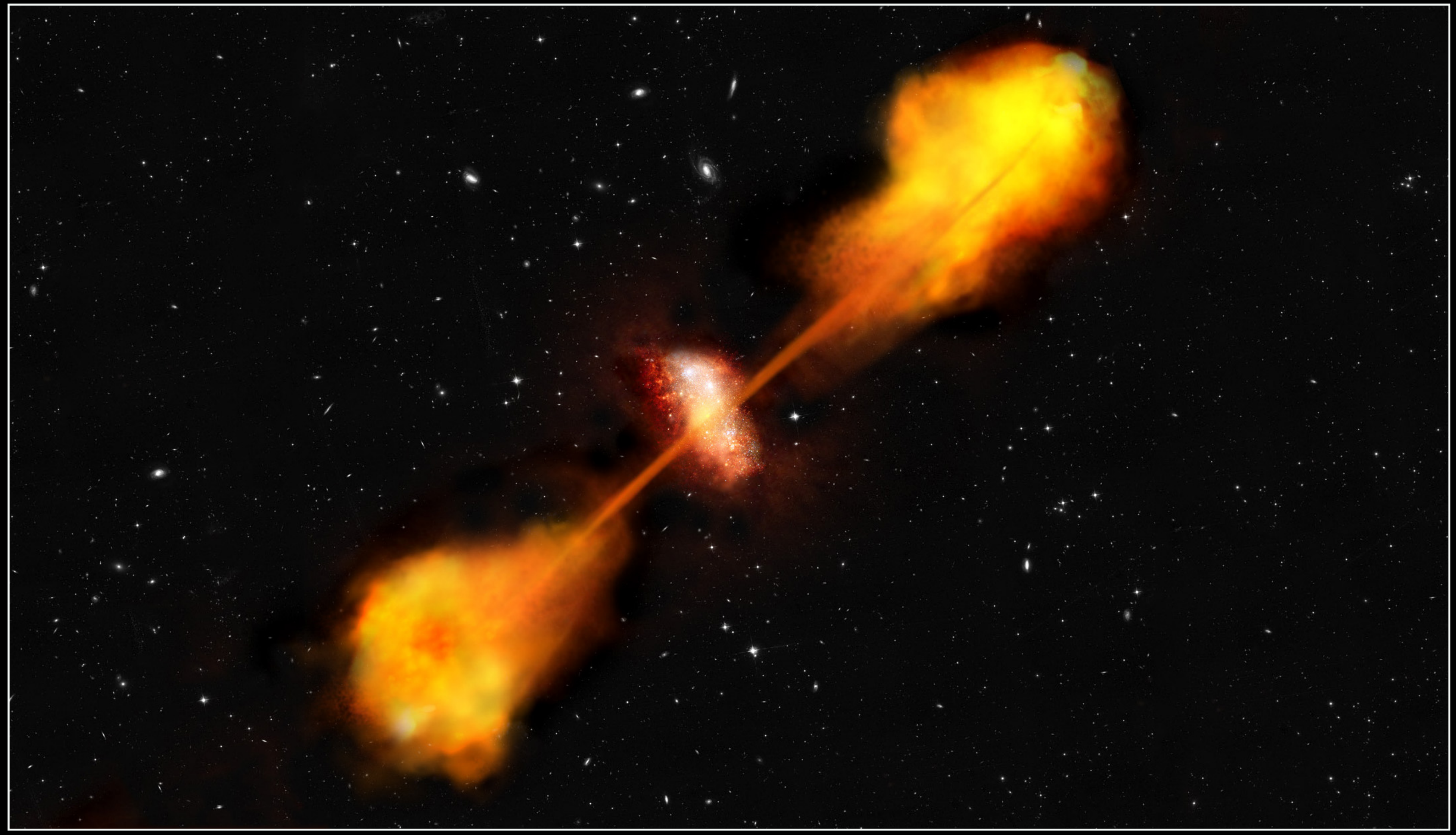


M 82 (NGC 3034) FOCAS (B, V, Hα)

Subaru Telescope, National Astronomical Observatory of Japan March 24, 2000

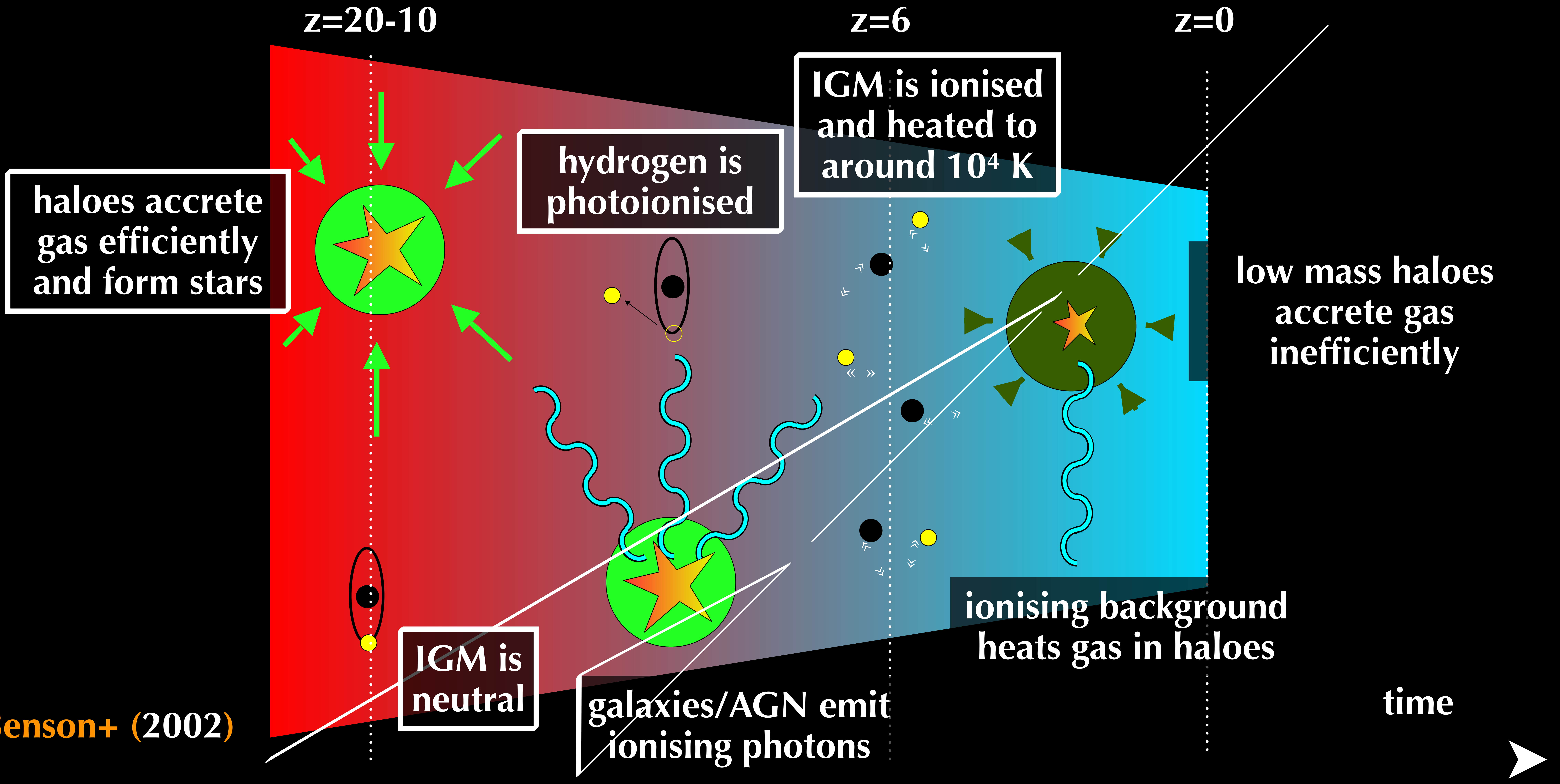
radiation (esp. ionising), supernovae + winds, cosmic rays

black holes



radiation, gas outflows, relativistic jets

photoionisation feedback



Benson+ (2002)

a simple model for photoionisation feedback

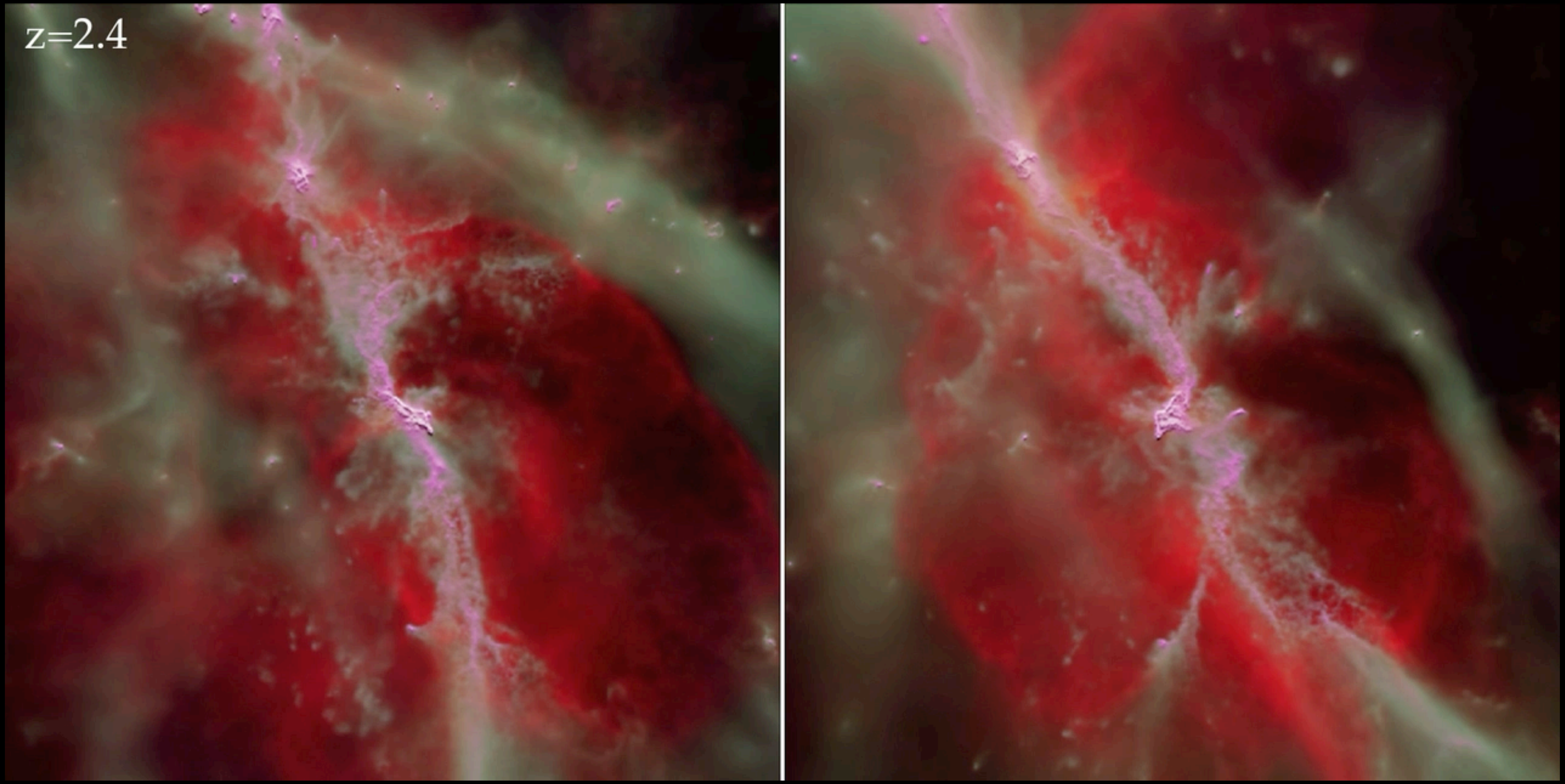
photoionisation typically heats gas to a temperature of $T \sim 2 \times 10^4 K$ — so, one would expect this to suppress collapse and cooling of gas in haloes with virial temperatures $T_{\rm vir} \lesssim 2 \times 10^4 K$

since $T_{\rm vir} = \left(\mu m_{\rm H}/2k_B\right) V_{\rm vir}^2$, this corresponds to $V_{\rm vir} \lesssim 20\,{\rm kms}^{-1}$

this picture is roughly supported by radiation hydrodynamic simulations, where the collapse of baryons is suppressed in haloes with $V_{\rm vir} \lesssim 20 - 30\,{\rm kms}^{-1}$, or haloes with $M_{\rm vir} = 10^8 - 10^{10}\,{\rm M}_\odot$ after reionisation (note: the $M_{\rm vir} - V_{\rm vir}$ relation depends on redshift)

photoionisation feedback is therefore relevant only to dwarf galaxies at the faint-end of the galaxy luminosity function

supernova feedback



cold/molecular gas (<1000 K)
warm ionised gas (10^4-10^5 K)
hot gas (>10^6 K)

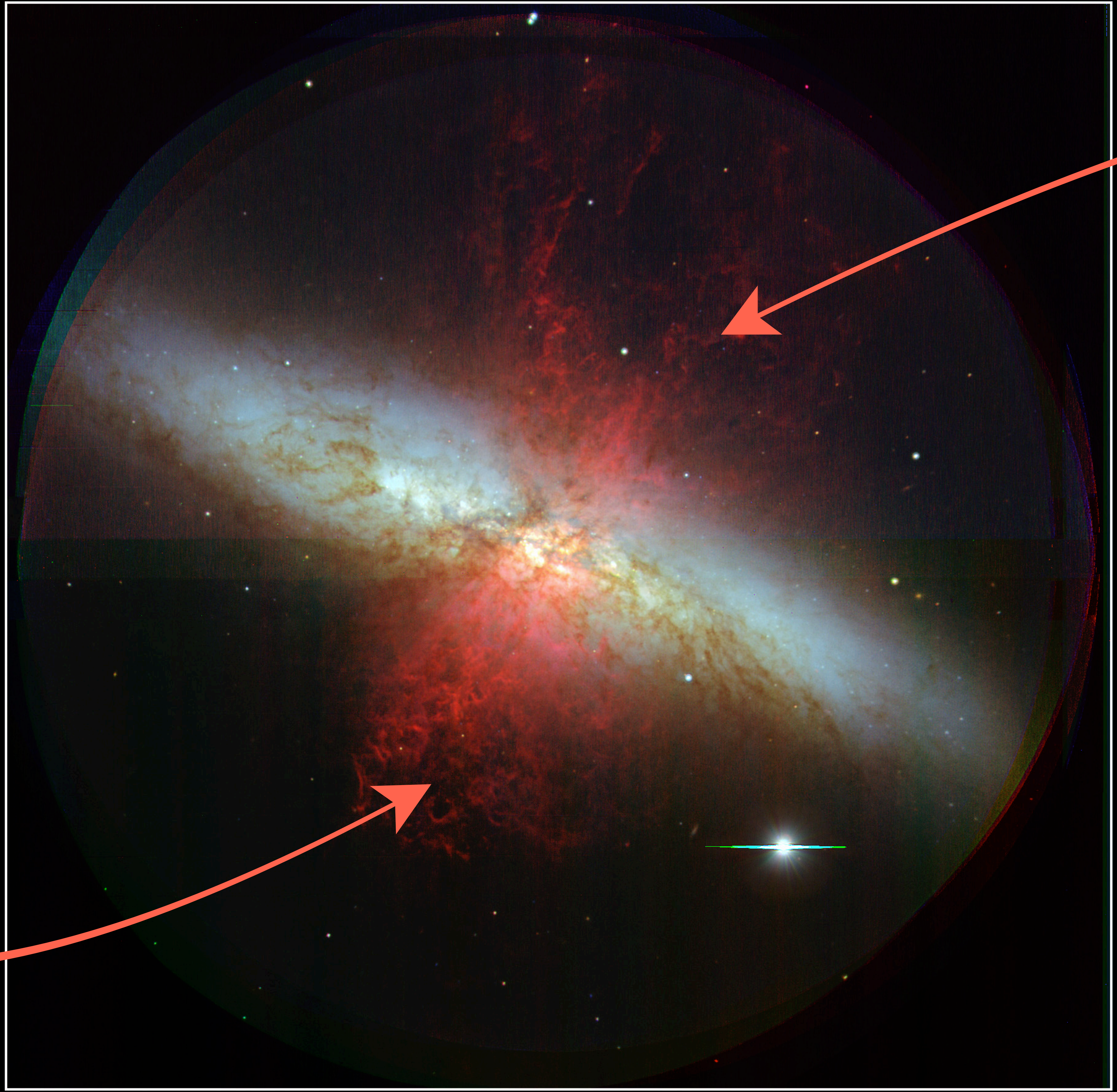
credit: the FIRE collaboration

observational evidence for SN outflows

outflow in a cone perpendicular to the disc

$V_{\mathrm{outflow}} > V_c$

with $\dot{M}_{\mathrm{outflow}} \propto \mathrm{SFR}$



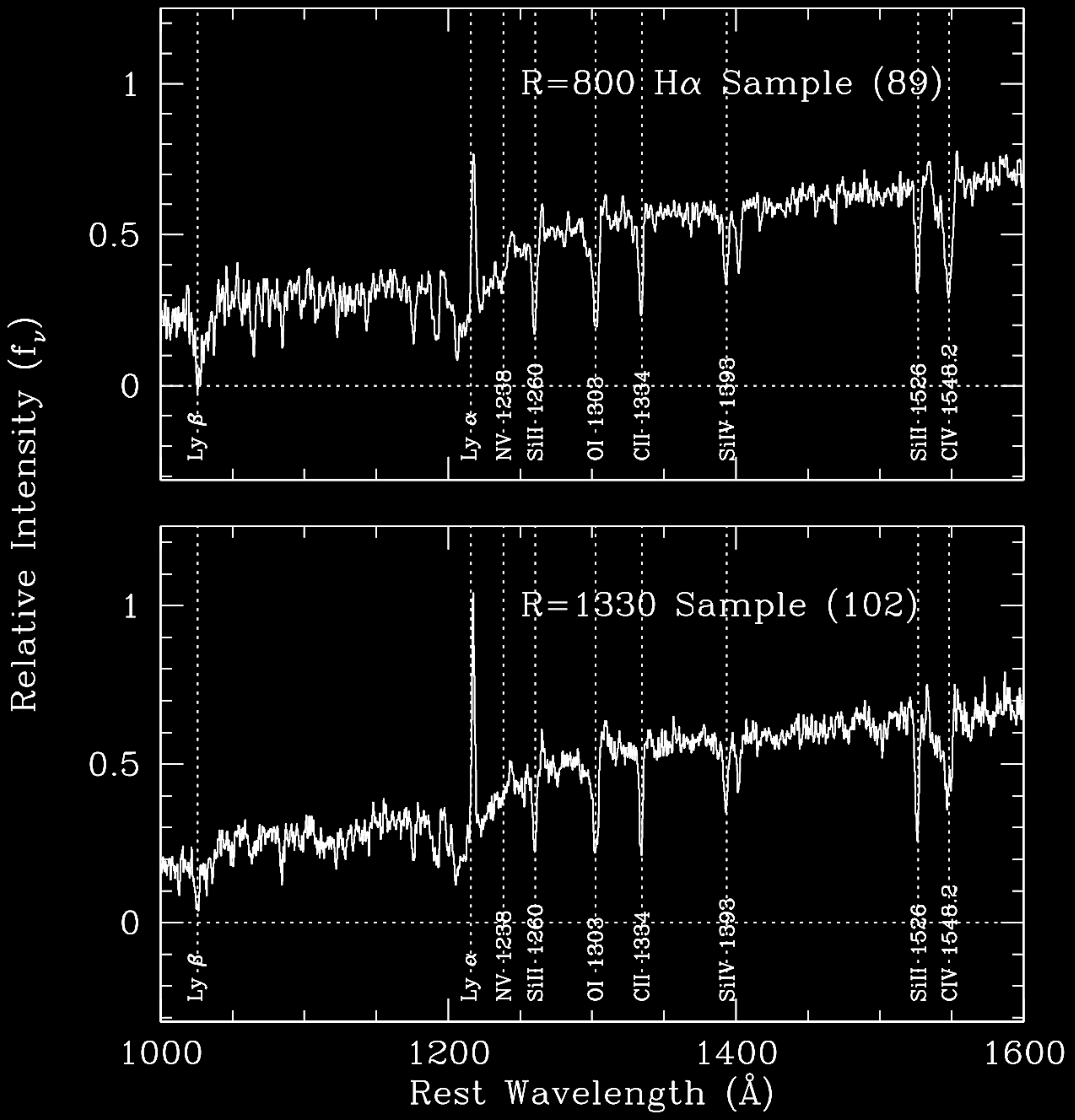
M 82 (NGC 3034) FOCAS (B, V, Hα)

Subaru Telescope, National Astronomical Observatory of Japan March 24, 2000

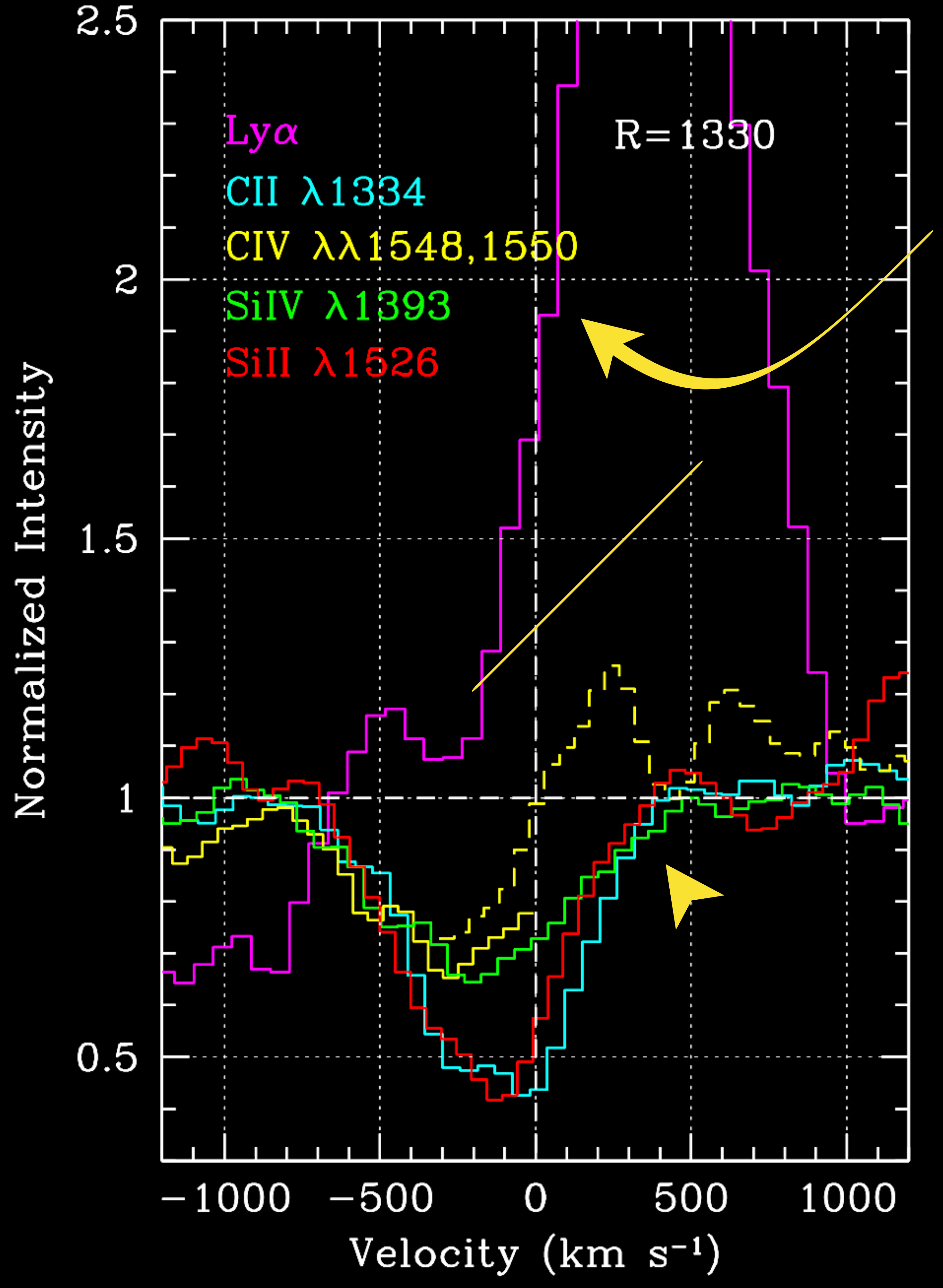
Hα filaments show outflowing gas to many kpc

(outflowing) hot gas seen in X-rays

observational evidence for SN outflows



Steidel+ (2010)



we observe **redshifted Lyα emission lines**

&

blueshifted absorption line features in the spectra of high-z star forming galaxies

outflows are ubiquitous in high-z galaxies

a simple estimate for the effect of SN feedback

let's assume we form a mass $M_\star$ of new stars following a star formation event. then, the total energy in (Type II) supernova explosions is $\eta M_\star E_{\rm SN}$, where $E_{\rm SN} = 10^{51}$ ergs, and $\eta = 1$ SN per 100 $M_\odot$ for a "normal" IMF

then, let's assume that some fraction $\varepsilon_{\rm ej}$ of this goes into driving outflows at the escape speed, $V_{\rm esc}$. the total mass ejected is:

$$\frac{1}{2} M_{\rm ej} V_{\rm esc}^2 = \varepsilon_{\rm ej}\, \eta\, M_\star\, E_{\rm SN}$$

take $V_{\rm esc} = 2V_c$

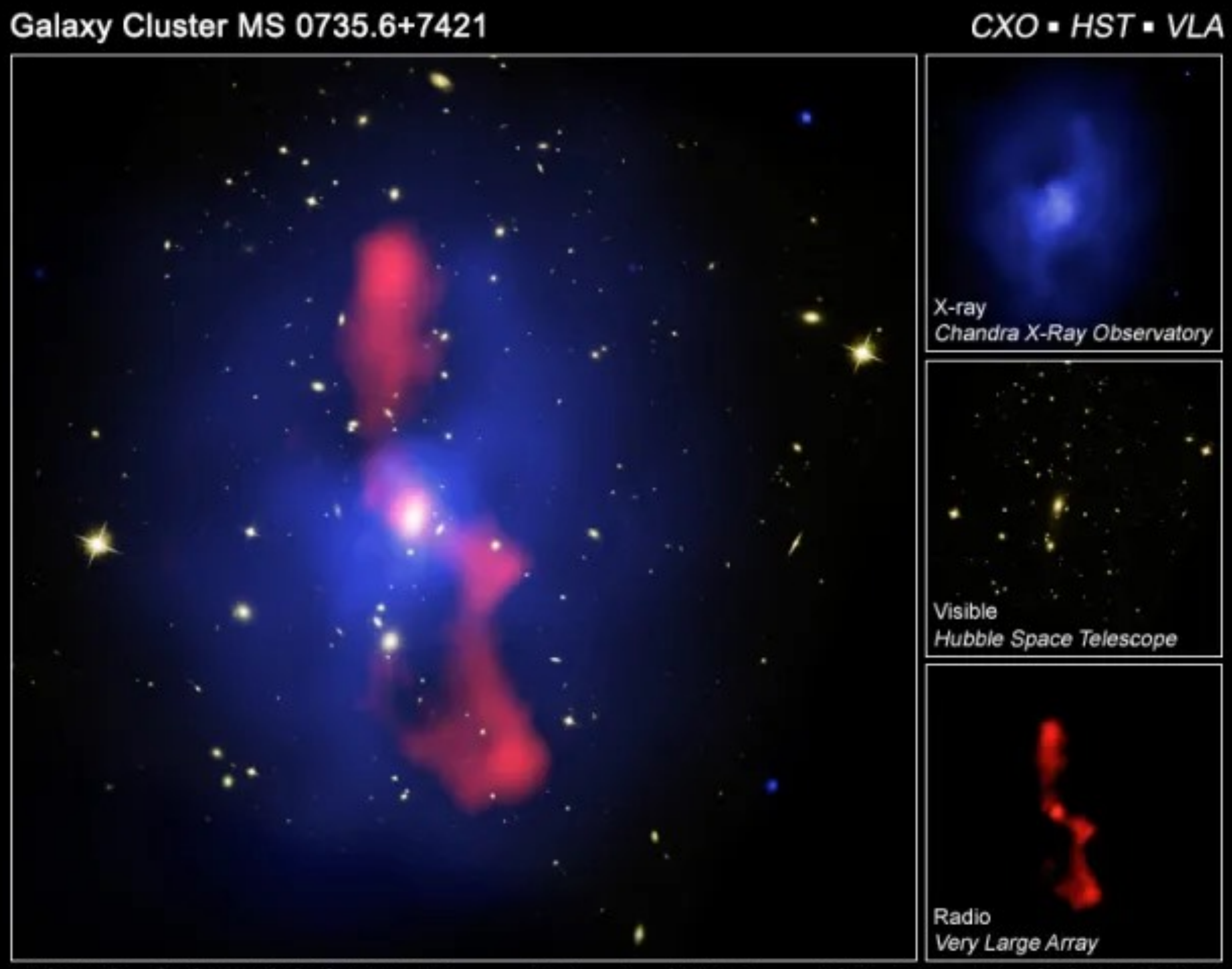
$$\Rightarrow M_{\rm ej} = M_\star \left(V_{\rm crit}/V_c\right)^2 \qquad \text{where } V_{\rm crit} = 500\, \varepsilon_{\rm ej}^{1/2}\, {\rm km s^{-1}}$$

Larson (1974)
Dekel & Silk (1987)

taking some plausible values: $\varepsilon_{\rm ej} \sim 0.1$, $V_{\rm crit} \sim 200\, {\rm km s^{-1}}$ $\Rightarrow$ a large effect on most galaxies

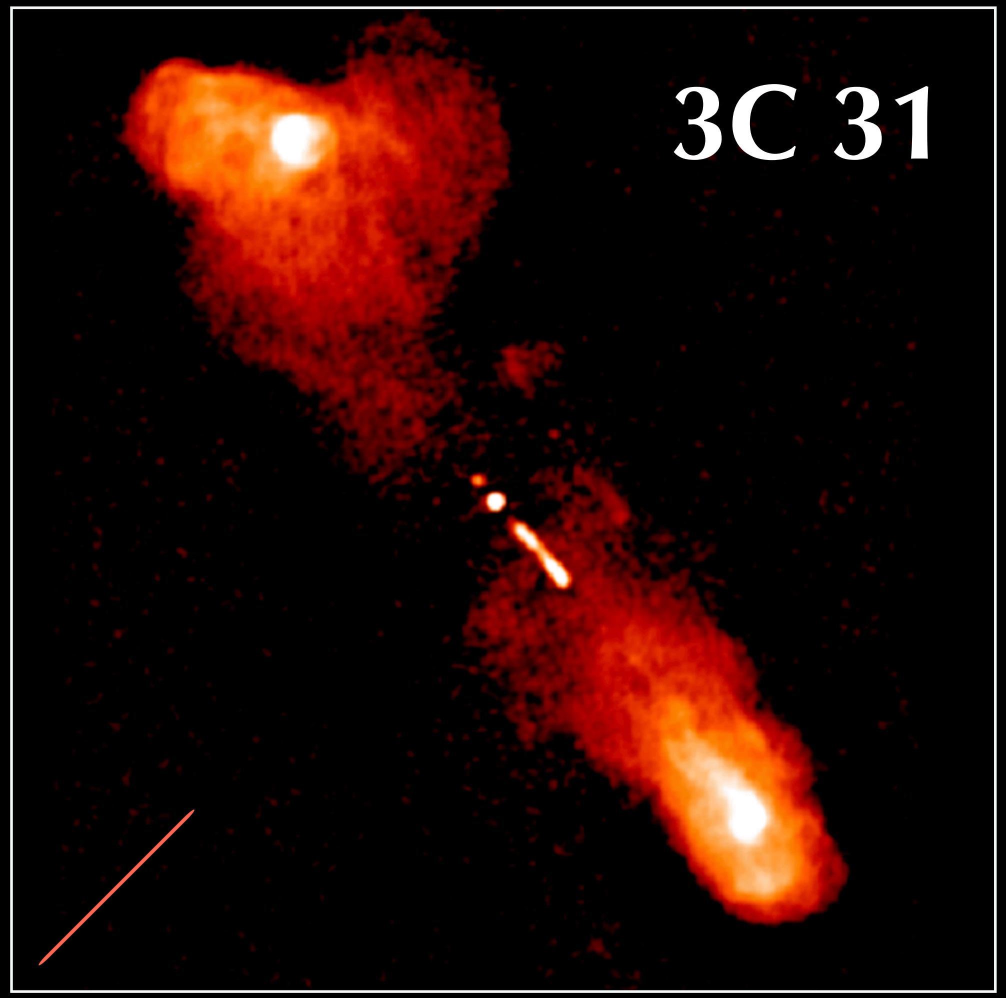
(in fact, $M_{\rm ej} > M_\star$ if $V_c < V_{\rm crit}$)

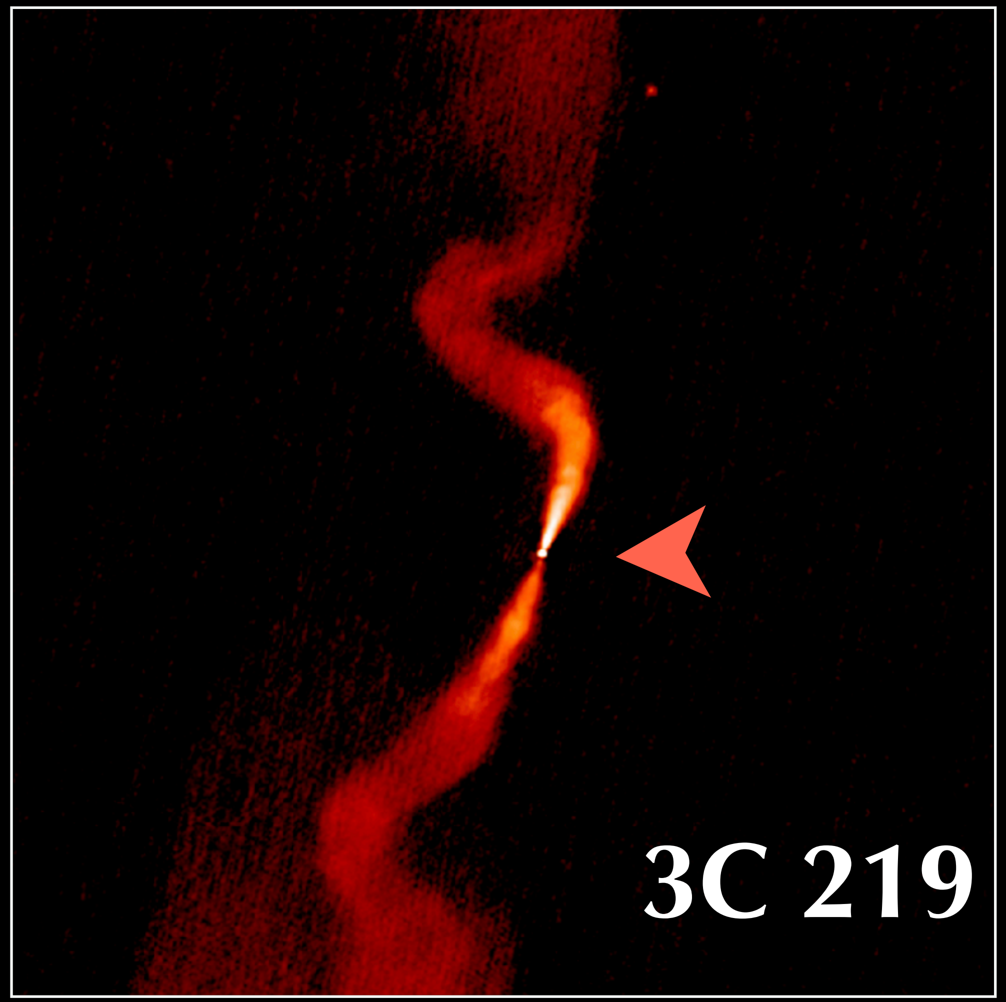
feedback from Active Galactic Nuclei (AGN)



NASA, ESA, CXC/NRAO/STScI, B. McNamara (University of Waterloo and Ohio University) STScI-PRC06-51

a multi-wavelength view of galaxy clusters



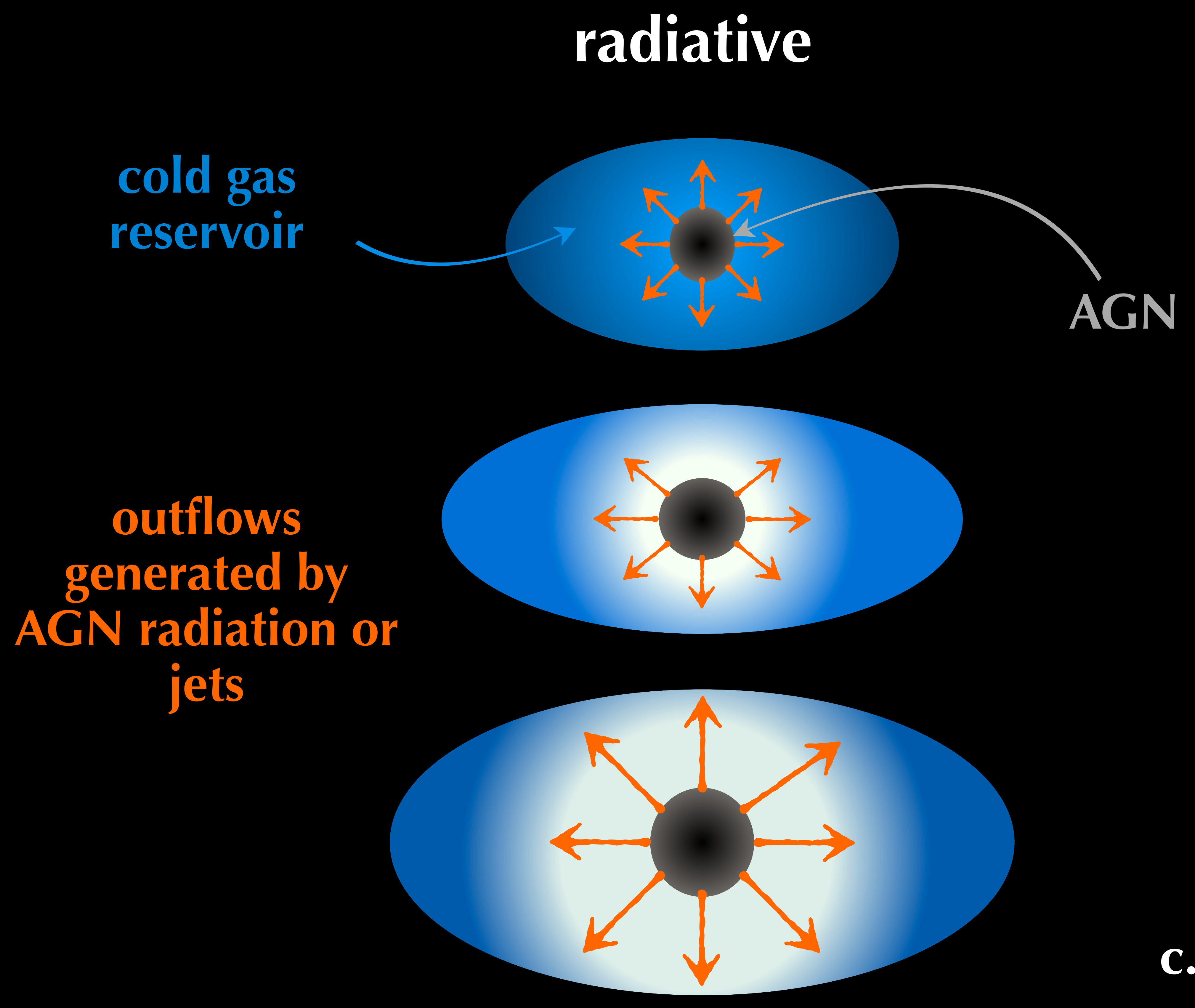


credit: Hardcastle & Croston (2020)

radio emission from relativistic particles

feedback from Active Galactic Nuclei (AGN)

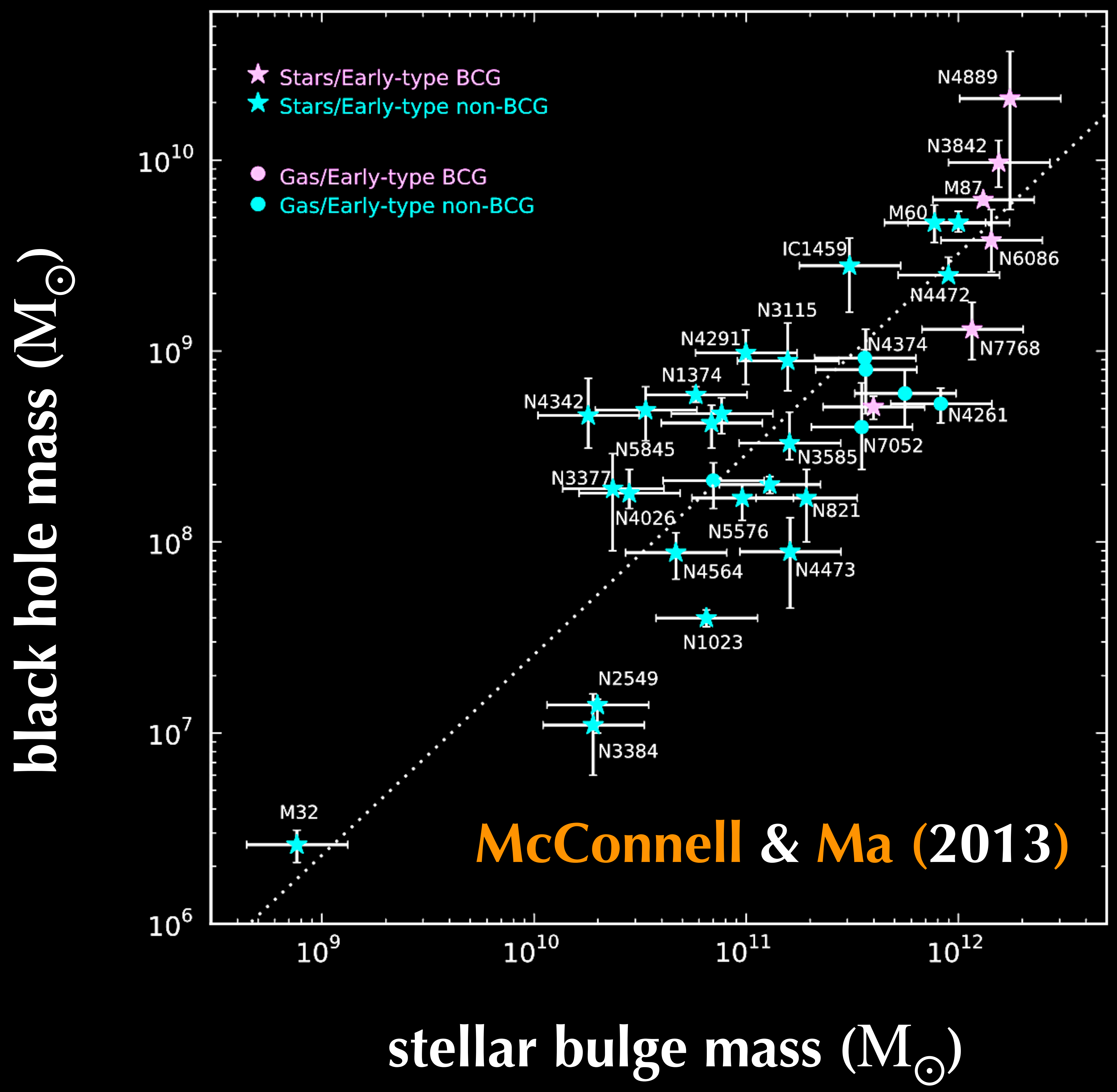
AGN are powered by the accretion of gas onto supermassive black holes in the centres of galaxies. their impact on the host galaxy can be categorised under two broad classes:



c.f. Fabian (2012)


600 kpc
$z = 2.1$
t_{age} = 3.11 Gyr
$\log M_{200c} = 14.01$ ($R_{200c} = 0.46$ Mpc)
$\log M_{\star} = 11.90$ (SFR = 2.8 $M_{\odot}\,yr^{-1}$)
$\log M_{BH} = 9.72$ ($\log \dot{M}_{BH} = -1.4$ $M_{\odot}\,yr^{-1}$)
$\dot{M}_{BH}$ [log $M_{\odot}$/yr]
0
-1
-2
-3
-4
6
5
4
3
2
1
0
Redshift

galaxy–SMBH co-evolution



stellar spheroids in nearly all galaxies are observed central supermassive black holes (SMBHs)

observationally, we find a correlation between the mass of the central SMBH and the stellar mass of the bulge/spheroid

$\Rightarrow M_{\rm BH} \propto M_{\rm bulge}$

this suggests a co-evolution between SMBHs and their host galaxies

the **energetics** of AGN feedback

observationally, we find that:

$$M_{\rm BH} \sim 10^{-3}\, M_\star^{\rm bulge}$$

for central black holes in galaxy spheroids (Magorrian+ 1998)

the formation of a BH through the accretion of gas should release energy of the order

$0.1\, M_{\rm BH}\, c^2 \sim 10^{-4}\, M_\star^{\rm bulge}\, c^2$, which is:

10x larger than the total supernova energy from stars
100x larger than the gravitational binding energy of a galaxy with $V_c \sim 200\,{\rm km s^{-1}}$

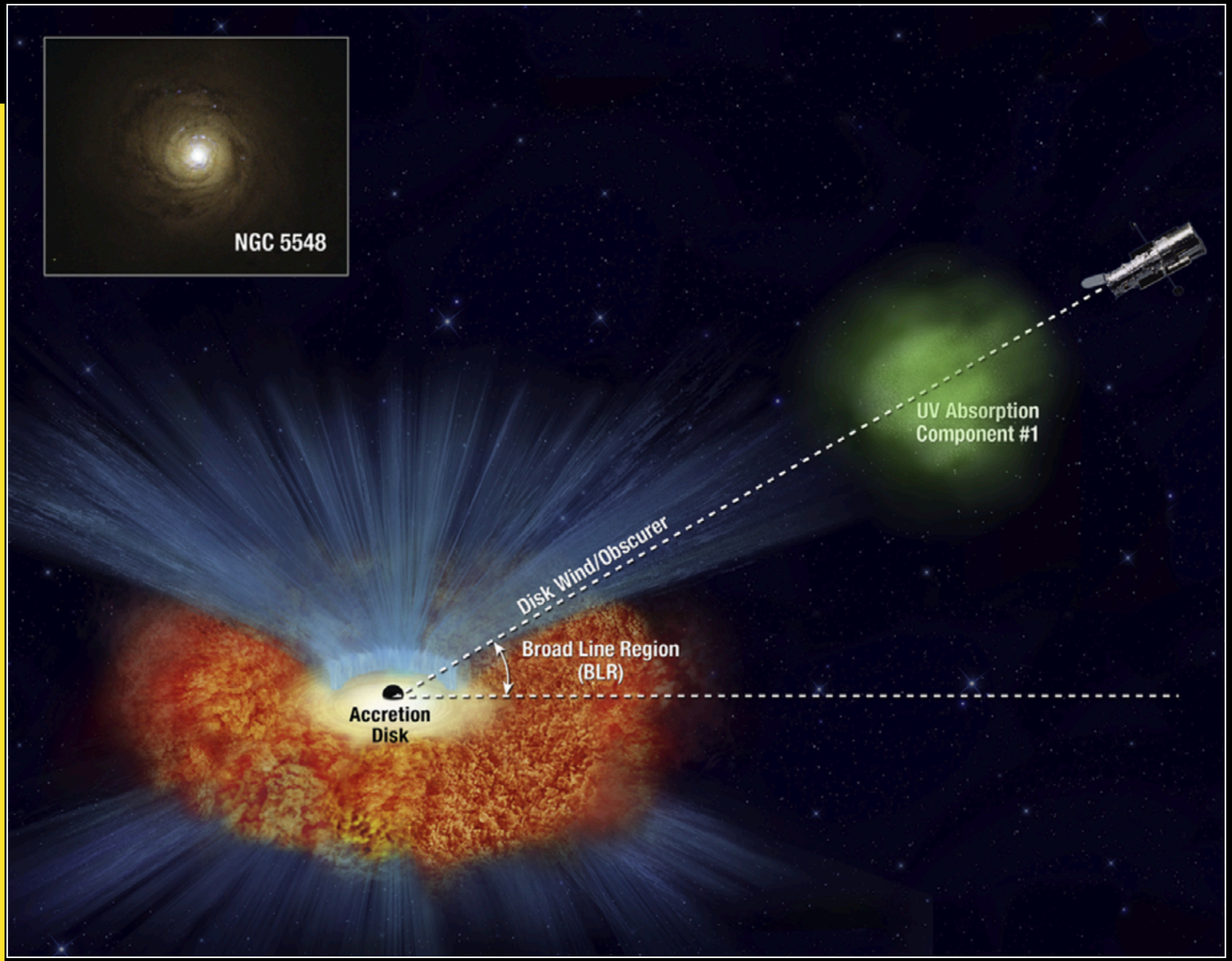
this means that IF a significant fraction of the energy released by accreting SMBHs (AGN) can couple effectively to gas in the galaxy or surrounding halo, we should expect important effects on the galaxy formation process

AGN winds

a further feedback channel exists through AGN-driven winds and outflows.
radiation from accretion disk can drive wind by radiation pressure:

- from accretion disc (electron scattering or UV absorption line opacity)
- from gas in galaxy (dust opacity)

these winds can blow gas out of galaxy



Dehghanian+ (2019)

observationally, optical/UV/X-ray absorption lines ⇒ outflows in central regions (~1-10 pc) of most AGN.
more extended ouflows seen in many host galaxies:

- ~kpc-scale outflows in cold molecular gas
- ~10 kpc-scale outflows in ionised gas