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Stirred Up: The Impact of Outflows on Star Formation Efficiency in Quenching Galaxies

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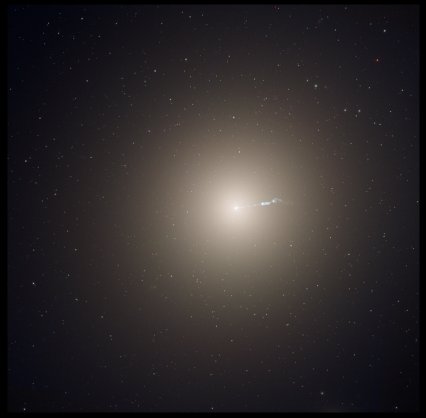

Image credit: Hubble Heritage

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Tess Stewart (Stanford)
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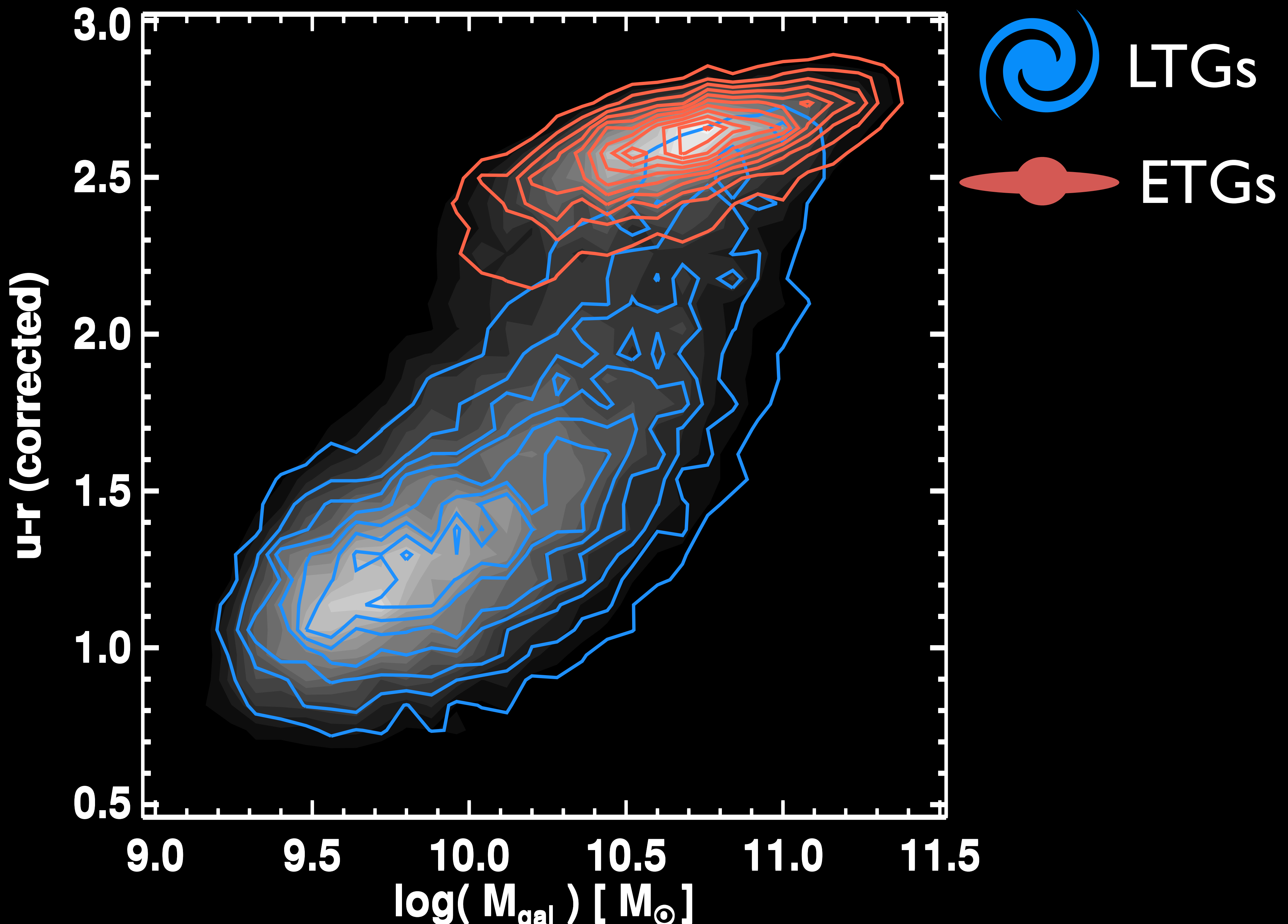
The ATLAS^{3D} team

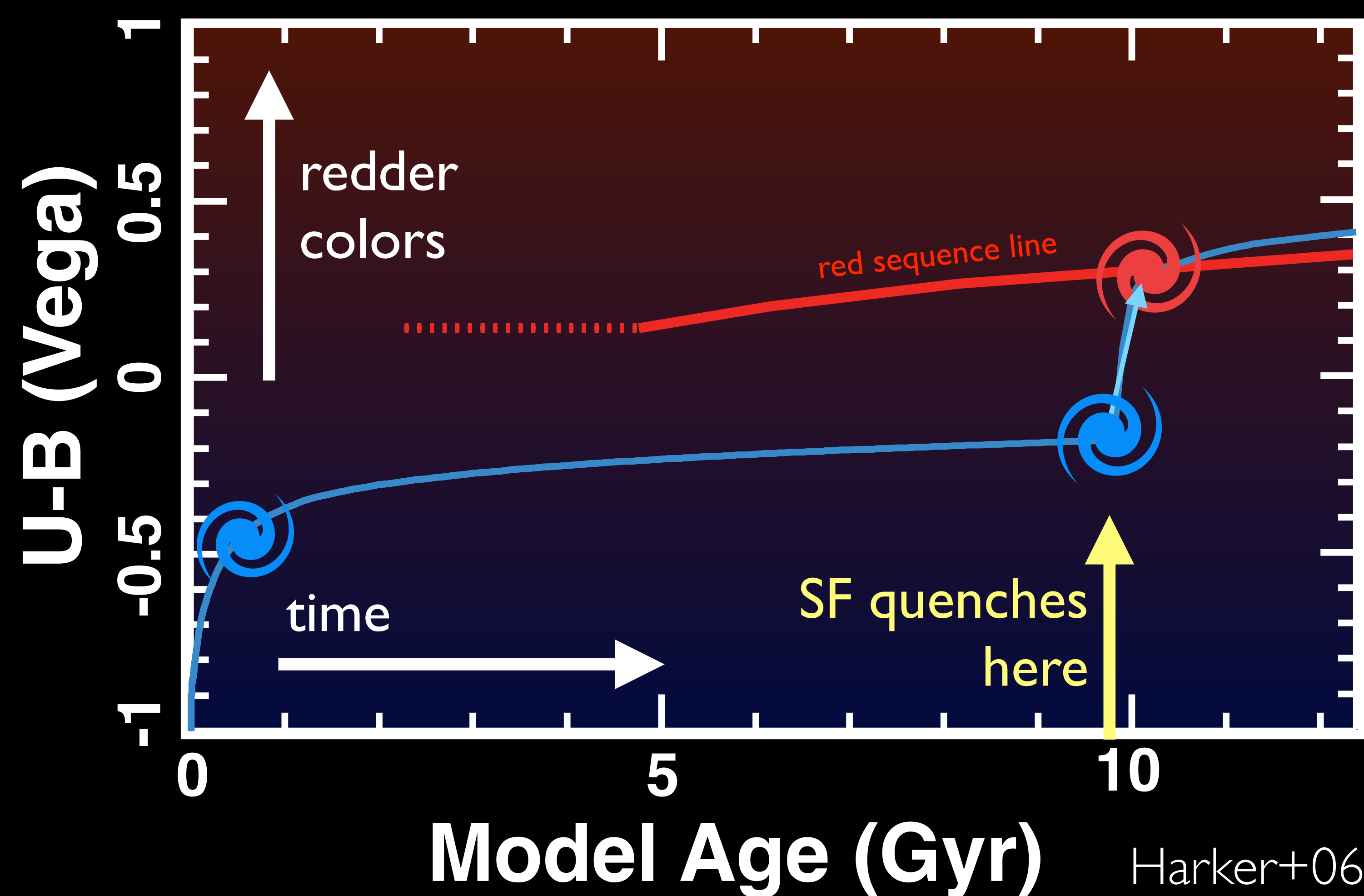
Optical color bimodality



Schawinski+14, Alatalo+14c

Observables to physics

answer: yes



Harker+06

ceasing star formation rapidly changes a galaxy's colors from blue to red

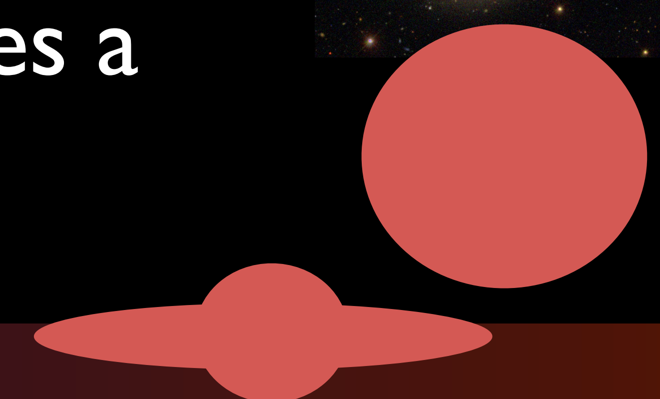


Image Credit: David W. Hogg, SDSS

The road from blue to red

(is paved with gas)

transition trigger

the event that ignited the galaxy's transformation.

(often of external origin)

star-forming fuel is removed

the gas in the galaxy that was forming stars must be rendered incapable of doing so.

stellar population fades

the average stellar age in the galaxy becomes older, thus the galaxy becomes redder.

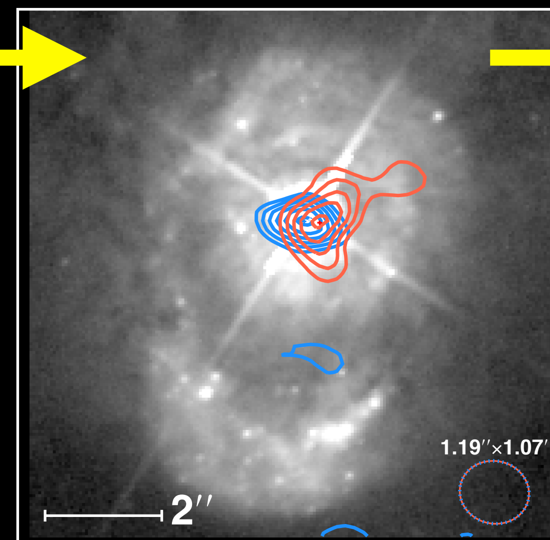
a galaxy's gas serves as the lynchpin to understanding its evolution

Image Credit: David W. Hogg, SDSS

Revising the “standard framework”

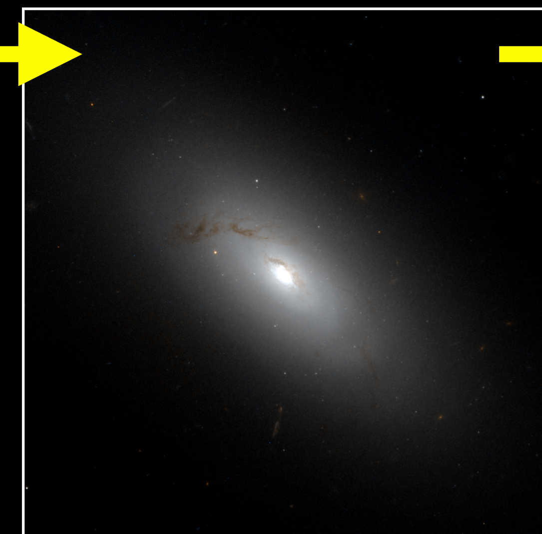
quenching trigger

~100 Myr



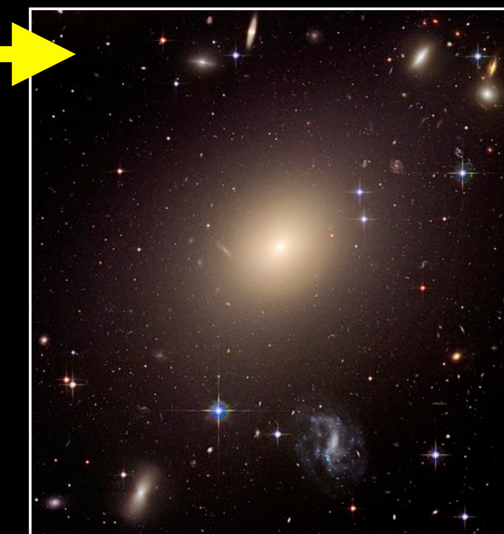
AGN active

~few Myr



post-starburst

~100s Myr

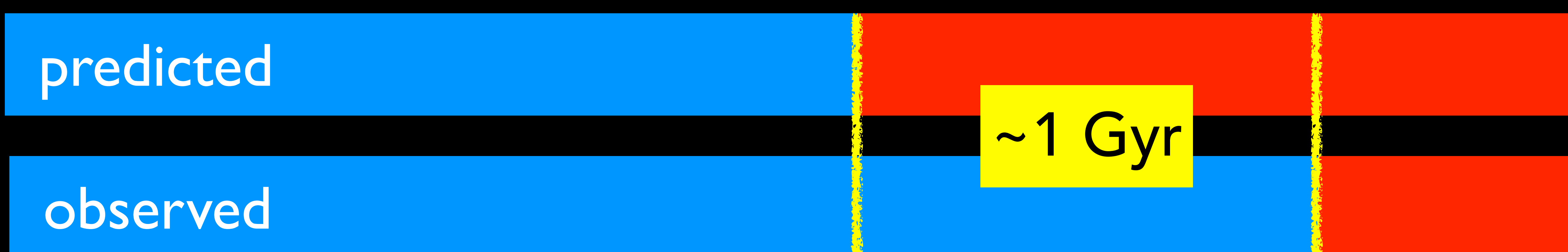


quiescent

~Gyrs

molecular gas

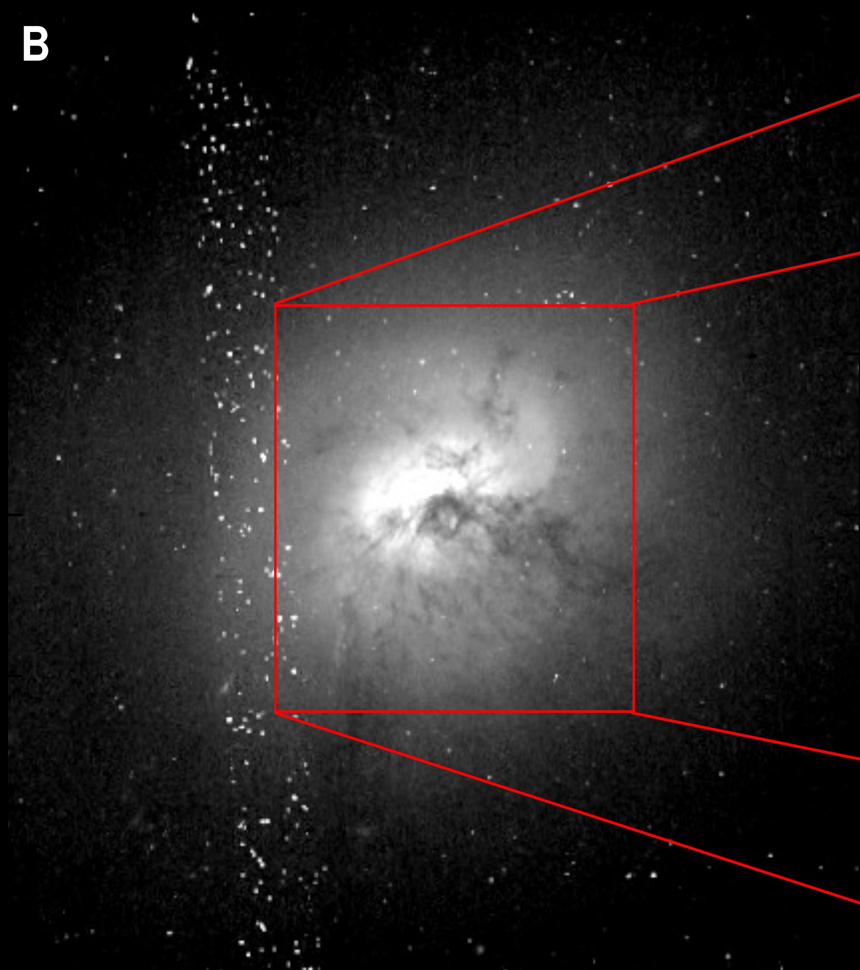
no molecular gas

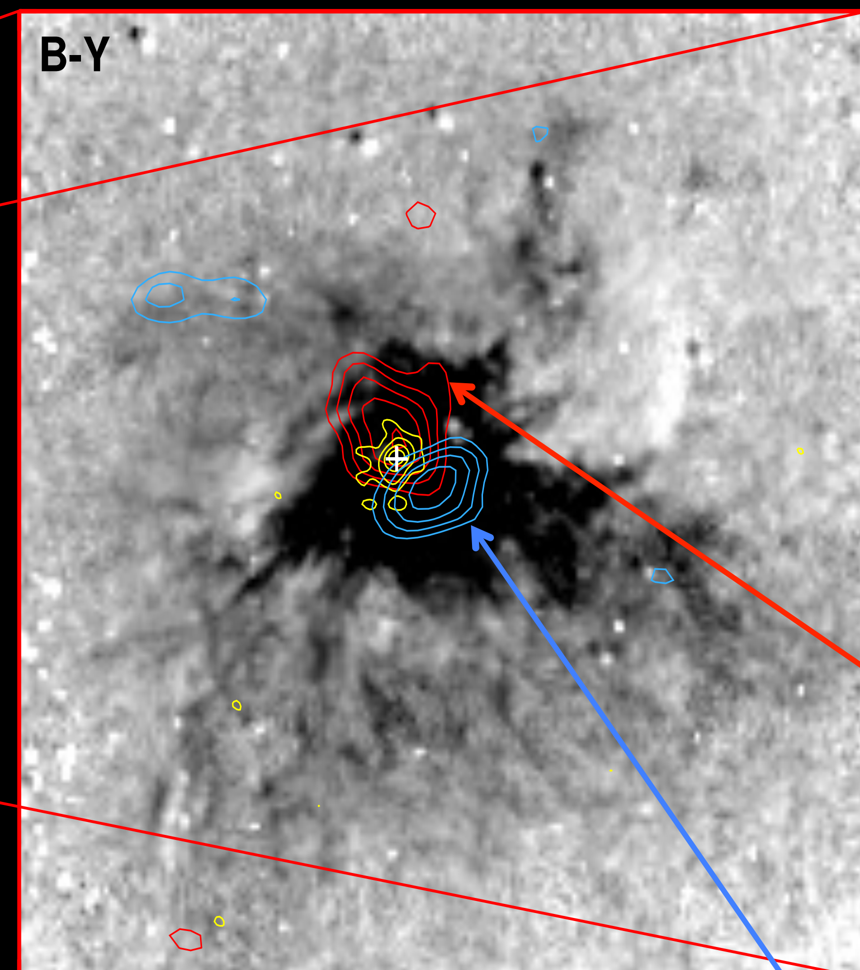


time →

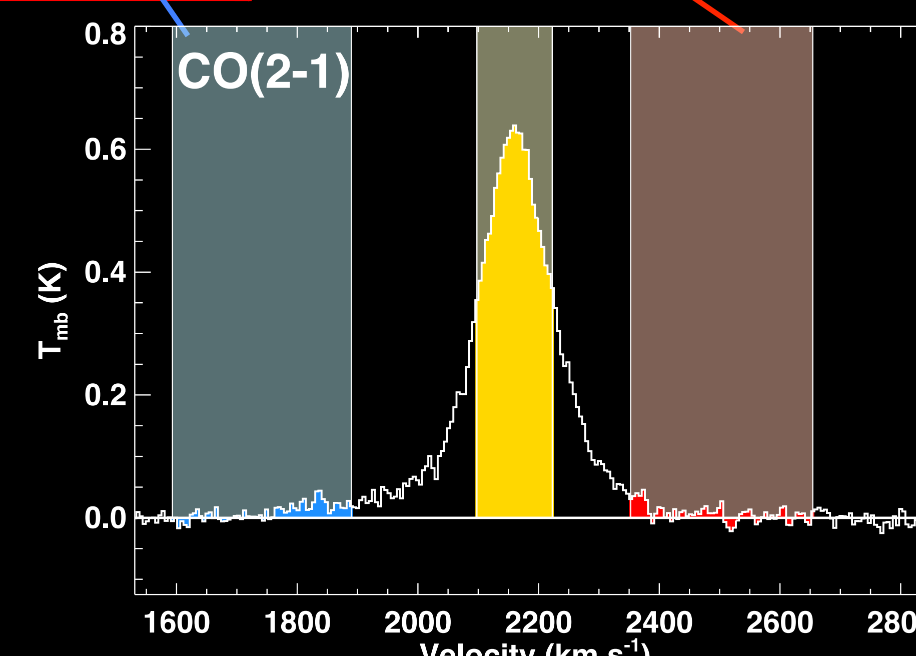
Alatalo15, Rowlands+15, French+15, **Alatalo+16**, Smercina+18

NGC 1266: the canonical case study





NGC 1266 hosts a molecular outflow and suppressed star formation



M_{gas} ~ 4×10^9 $M_\odot$ (Young+KA+11; Alatalo+11,15a)

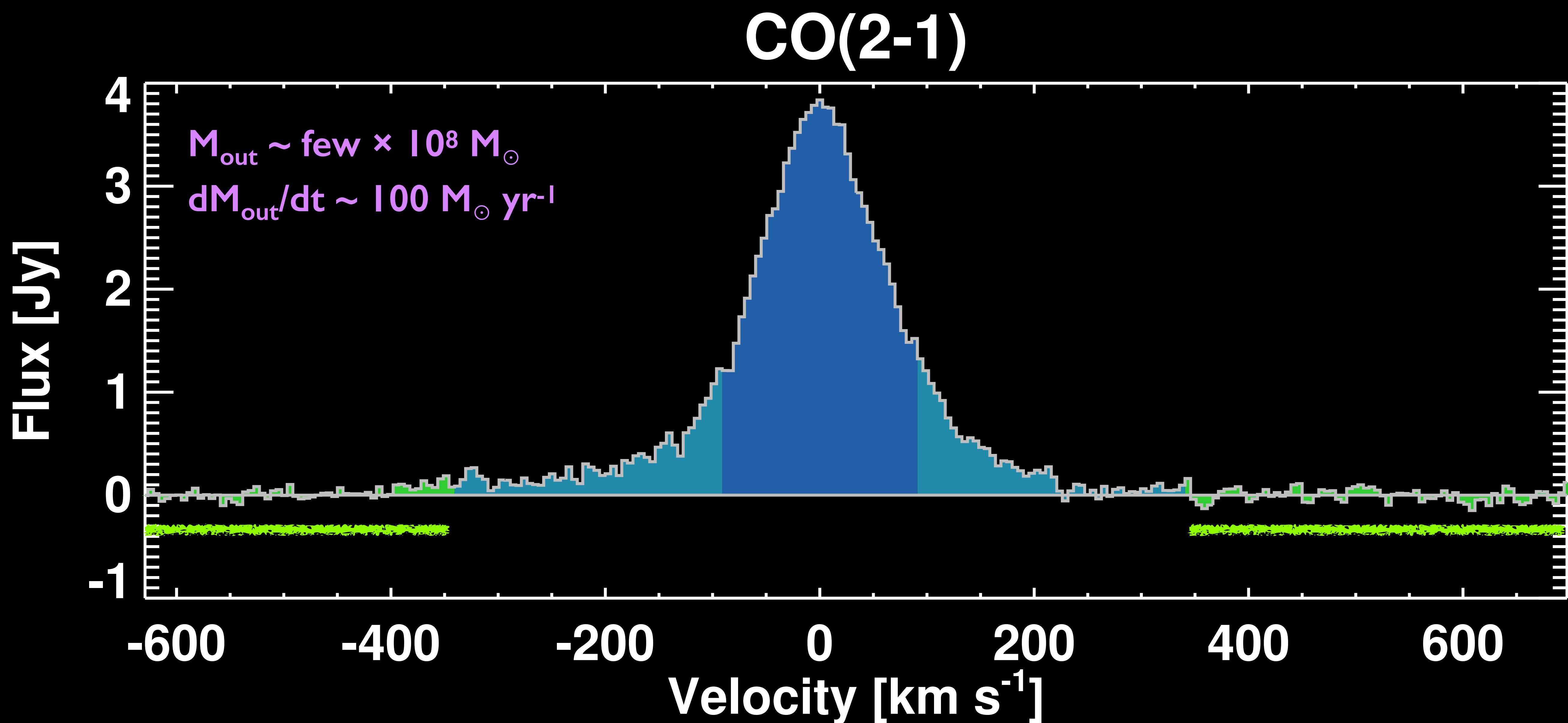
$M_{outflow}$ ~ few×10^8 $M_\odot$ (Alatalo+11,14a)

Outflow mass flux ≈ 110 $M_\odot$ yr^{-1} (Alatalo+15a)

Outflow dynamical time < 3 Myr (Alatalo+11)

Alatalo+11,14a,15a, Nyland,KA+13

$\dot{M}_{out} \neq \dot{M}_{depletion}$



the outflow rate does not reflect how much mass is **escaping.**

the **mass escape rate** is closer to **2 $M_\odot$ yr^{-1}**

Alatalo+15a

Star formation regulation

star formation is determined by the balance of energy

$$Q_{\mathrm{gas}} = \frac{c_s \kappa}{\pi G \Sigma}$$

Kinetic energy

c_s gas dispersion

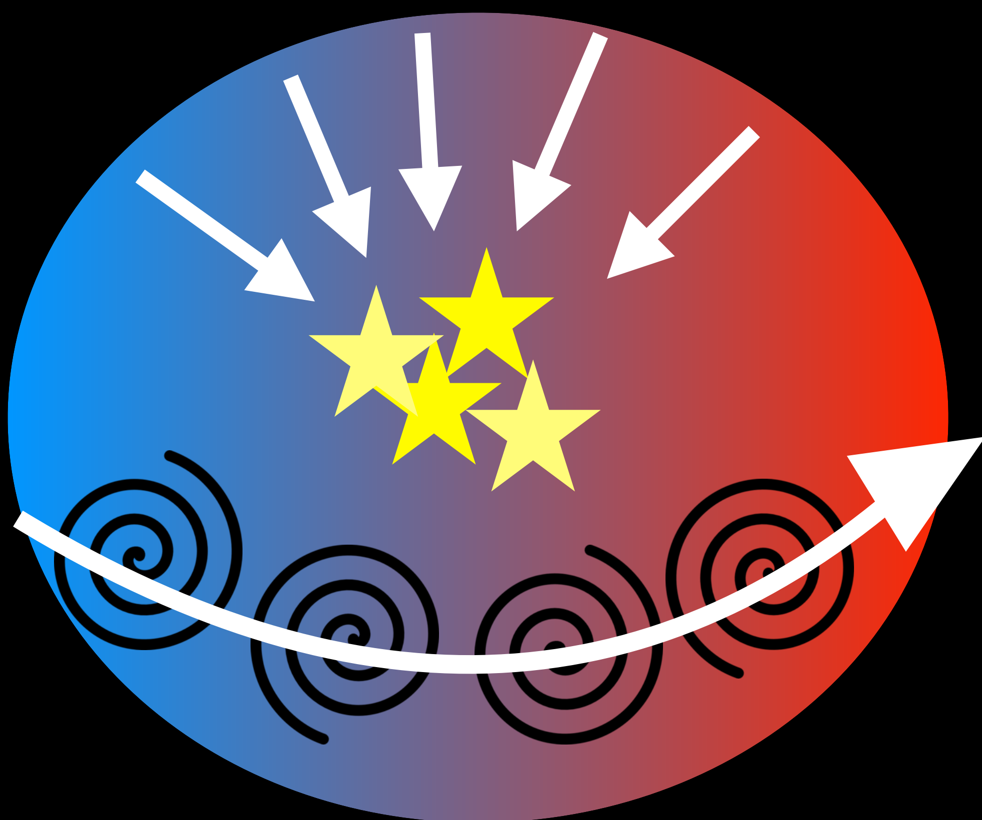
κ gas rotation

Q ↑

Gravitational binding energy

Σ gas surface density Q ↓

molecular gas blob



$Q > 1$ gas is stable against collapse

$Q \leq 1$ gas is gravitationally unstable will form stars

Safranov 60, Toomre 64

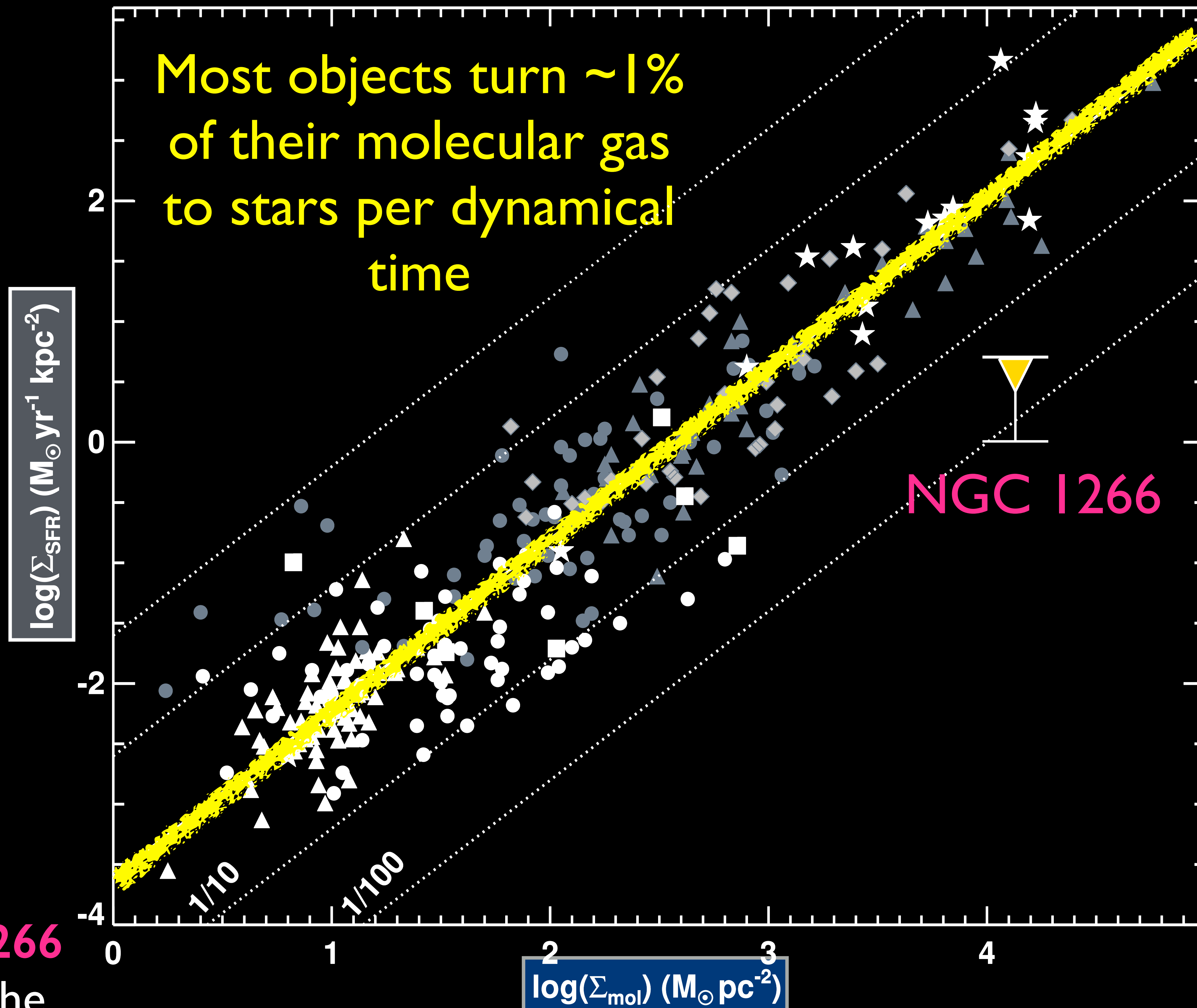
The Kennicutt-Schmidt relation

Star formation surface density

The amount of star formation per unit surface area

Molecular gas surface density

The amount of molecular gas per unit surface area



AGN & molecular outflow host NGC1266 falls 50-100× below the relation (Alatalo+15a)

Kennicutt 98, Krumholz+12, Alatalo+15a (and references therein)

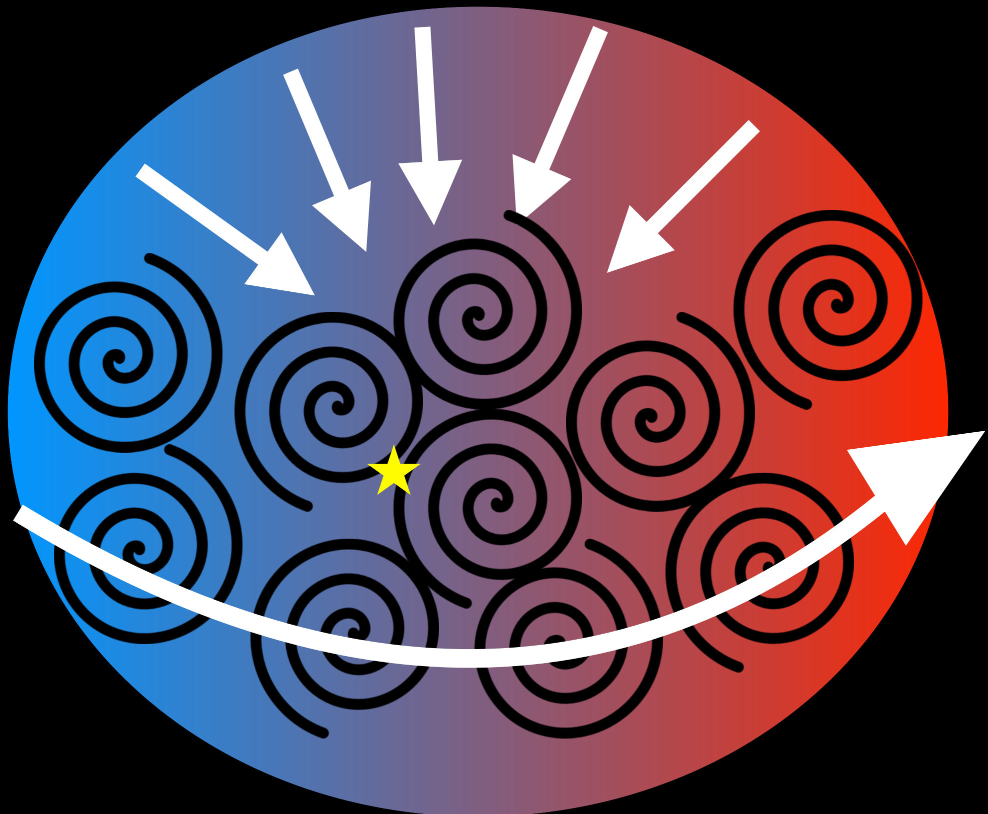
Star formation relation

how to suppress star formation

$$Q_{\rm gas} = \frac{c_s \kappa}{\pi G \Sigma}$$

Q > 1 gas is stable against collapse

Q ≤ 1 gas is gravitationally unstable will form stars



Injecting turbulence (c_s↑) into the gas rebalances the energy equation & combats gravitational collapse

but… fine structure lines also turn on and cool the turbulent gas (Λ↑ c_s↓), so the injection of turbulence must be sustained to observe the star formation suppression

Kinetic energy

c_s gas dispersion

K gas rotation

Gravitational binding energy

Σ gas surface density

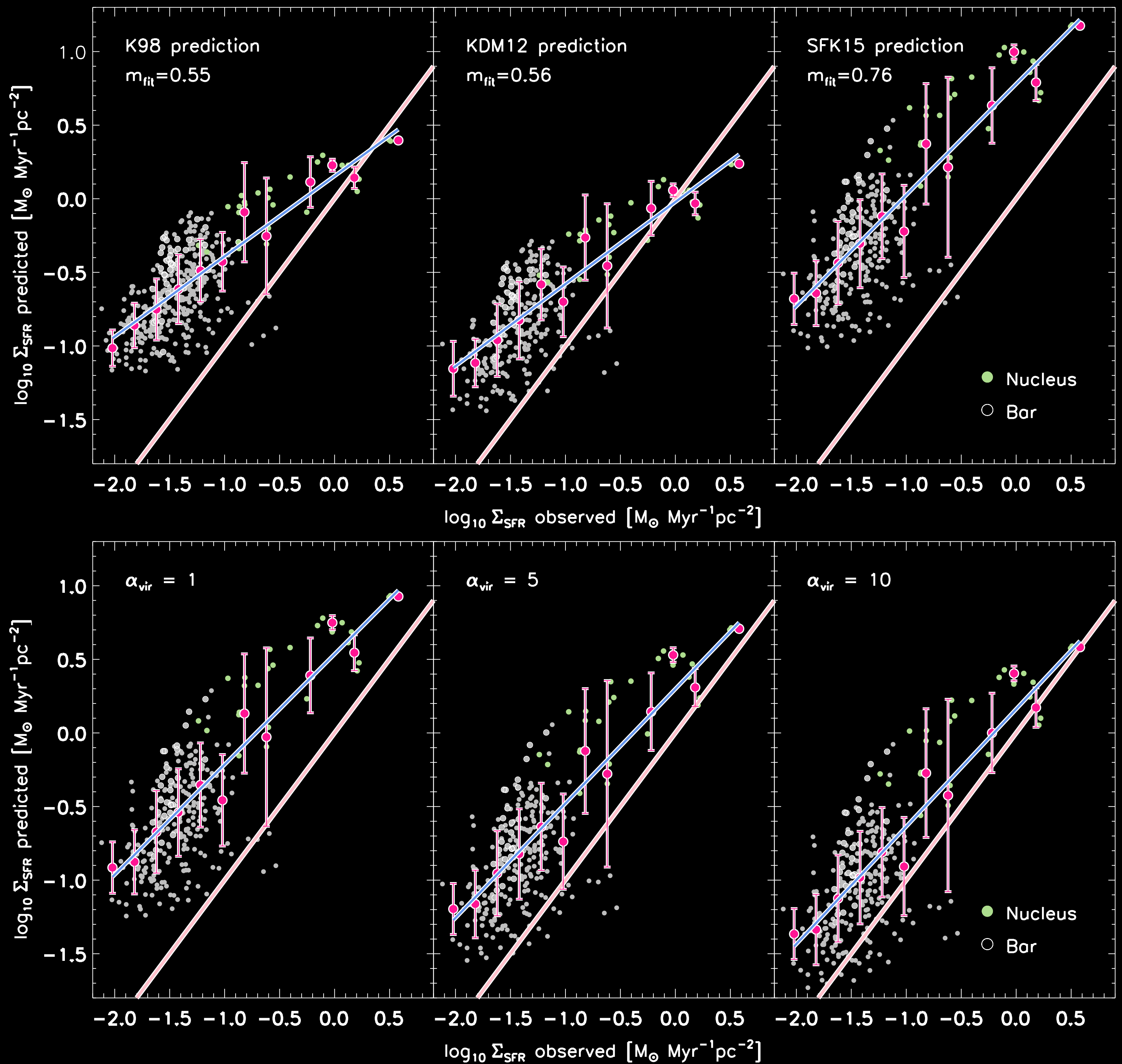
Safranov 60, Toomre 64

How to use turbulence to suppress star formation

Diane Salim, Rutgers

Using Hickson Compact Group galaxy HCG96, Salim, Alatalo+20 were able to show that the modification of the viral parameter (i.e. the balance between the kinetic and gravitational potential energy) is able to modify star formation efficiency.

Adding turbulence is able to suppress star formation.



The road from blue to red

An updated picture of the quenching sequence

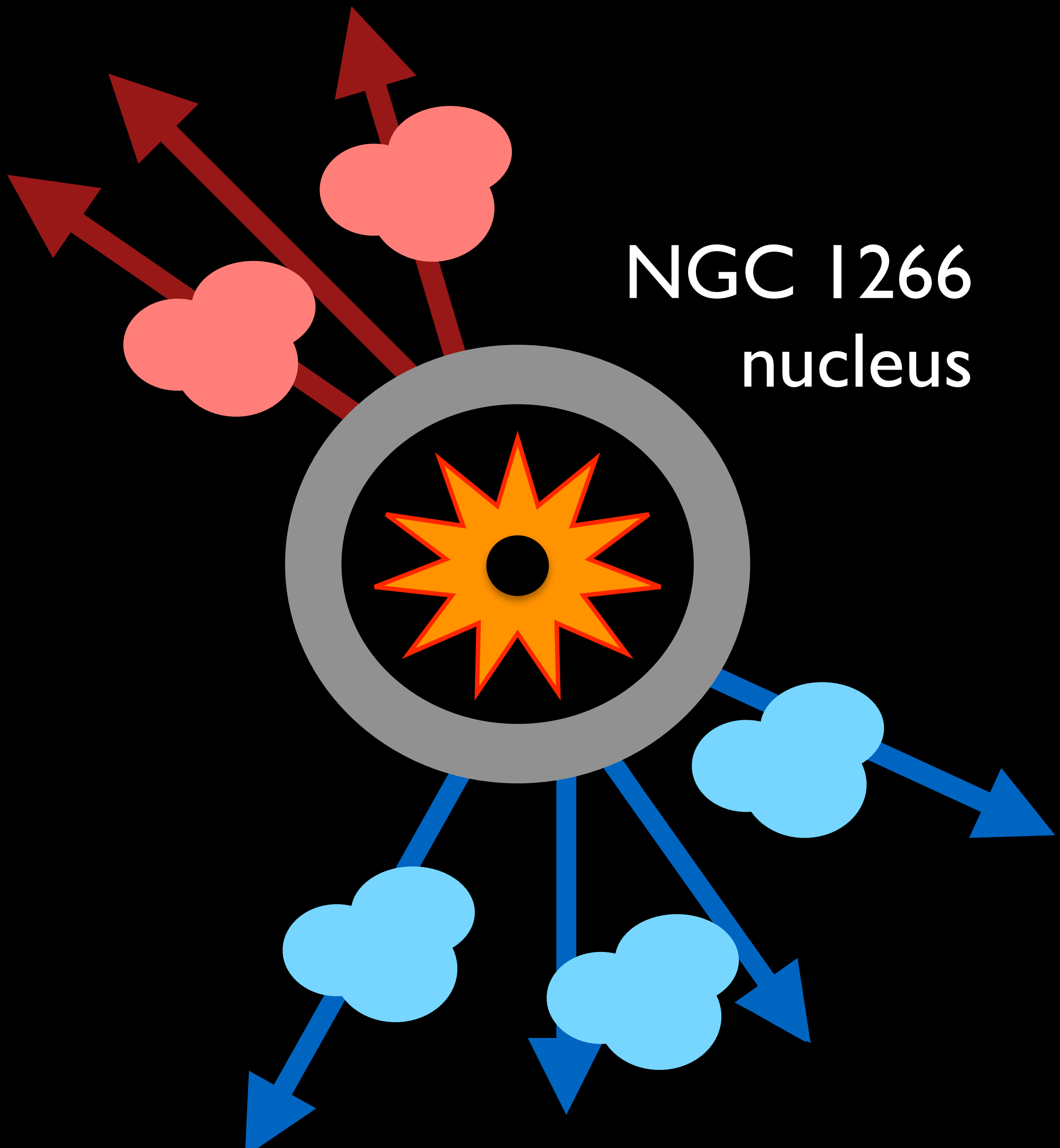
Rendering cold gas “infertile” by suppressing star formation allows it to survive through the galaxy’s transition from star-forming to passive.

A galaxy does not need to expel its cold gas to transform if there is an addition source of turbulence

Image Credit: David W. Hogg, SDSS

Is AGN feedback a duty cycle?

NGC 1266 may be a case-study of slow black hole growth via gas expulsion duty cycle



Instead of a rapid process, every outflow “event” grows the black hole, increasing L_{Edd} ($\propto M_{BH}$) and stirring up gas (thus inhibiting SF)

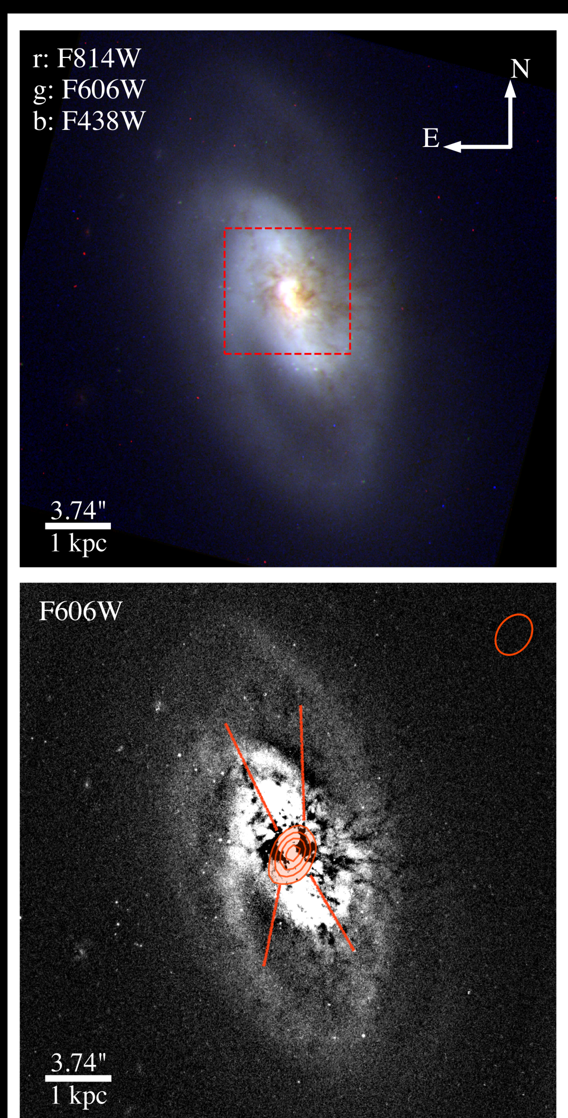
At some point, it will be massive enough to efficiently expel the remaining circumnuclear gas

Alatalo+14,15

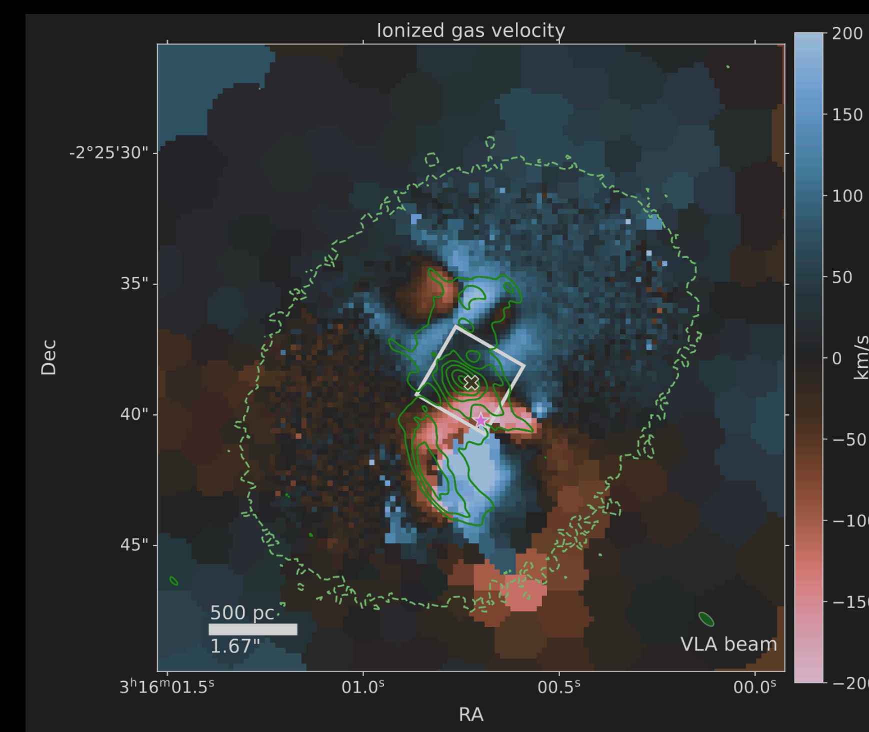
The hunt for exceptional case studies

Yuanze Luo, JHU

Justin Otter, JHU



Galaxies for which we can run these tests require exceptional ISM conditions, in which a turbulent energy source can be identified. Luo+22 showed that IC 860 was such a case, with an outflow directly impacting nuclear molecular gas. It makes an excellent candidate for further study.



NGC 1266 is another such source, with compact molecular gas being impacted by an AGN driven molecular outflow. Otter+in prep will apply the Salim framework to NGC1266 soon!

Summary

- The emergent bimodalities in galaxies underlies physics of how galaxies rapidly transition between blue, star-forming spirals and quiescent early-types.
- Outflows seem to be common (if not ubiquitous) during this phase
- NGC 1266, a well-determined molecular outflow host, demonstrates that cold gas does not need to leave a galaxy for it to transition
- Injection of energy into the dense molecular medium (boosting α_{vir}) is able to modify the star formation efficiency and suppress SF
- This could mean AGN feedback (at low z) is a duty cycle (but more examples are needed)

Image Credit: David W. Hogg, SDSS

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Outflows and quenching: death by a million pinpricks?

Thank you!

Questions?

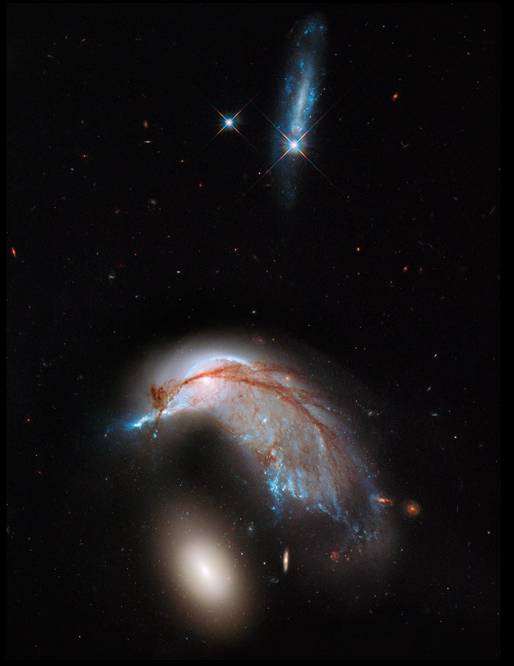

Image credit: Hubble Heritage