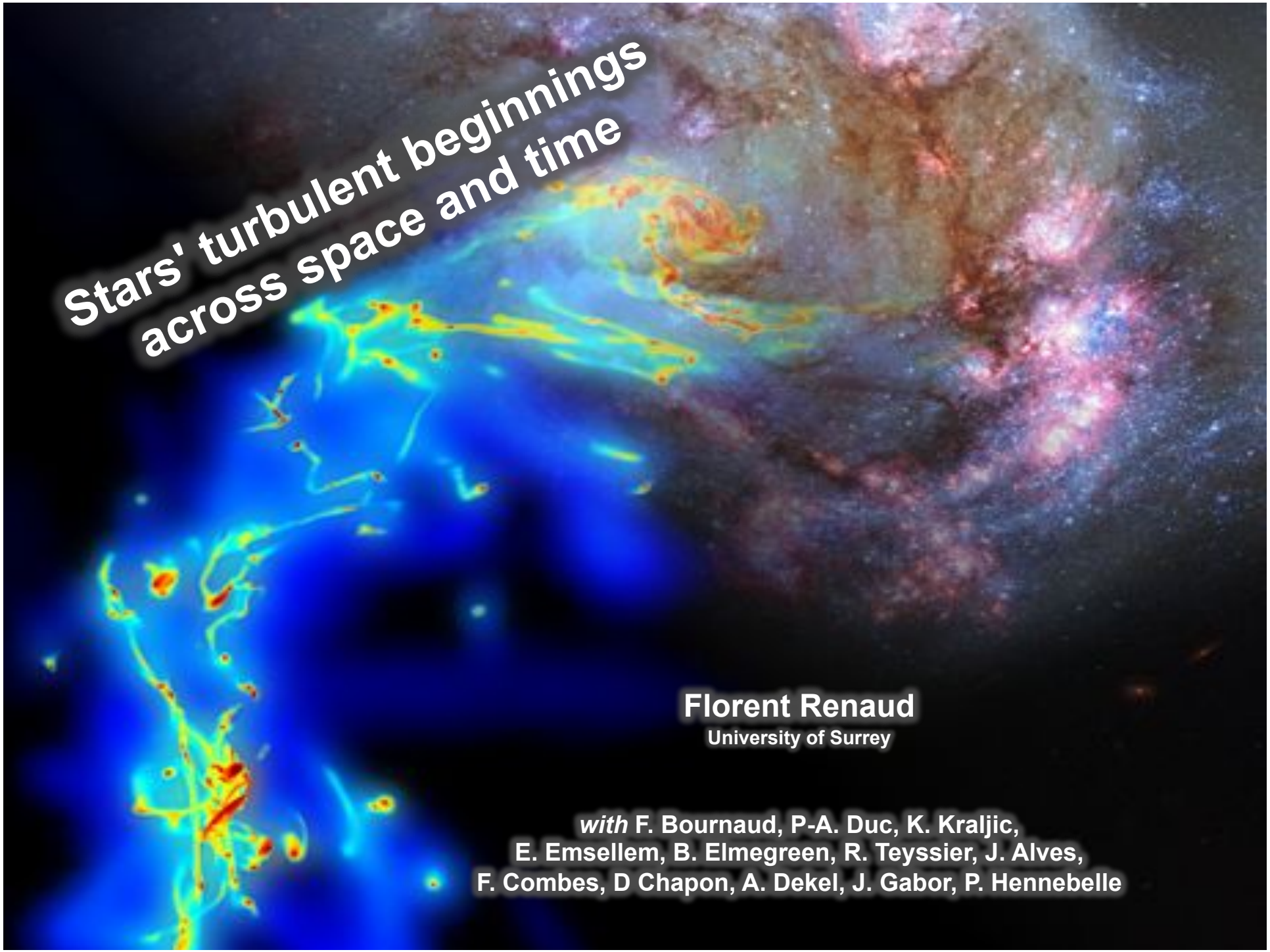
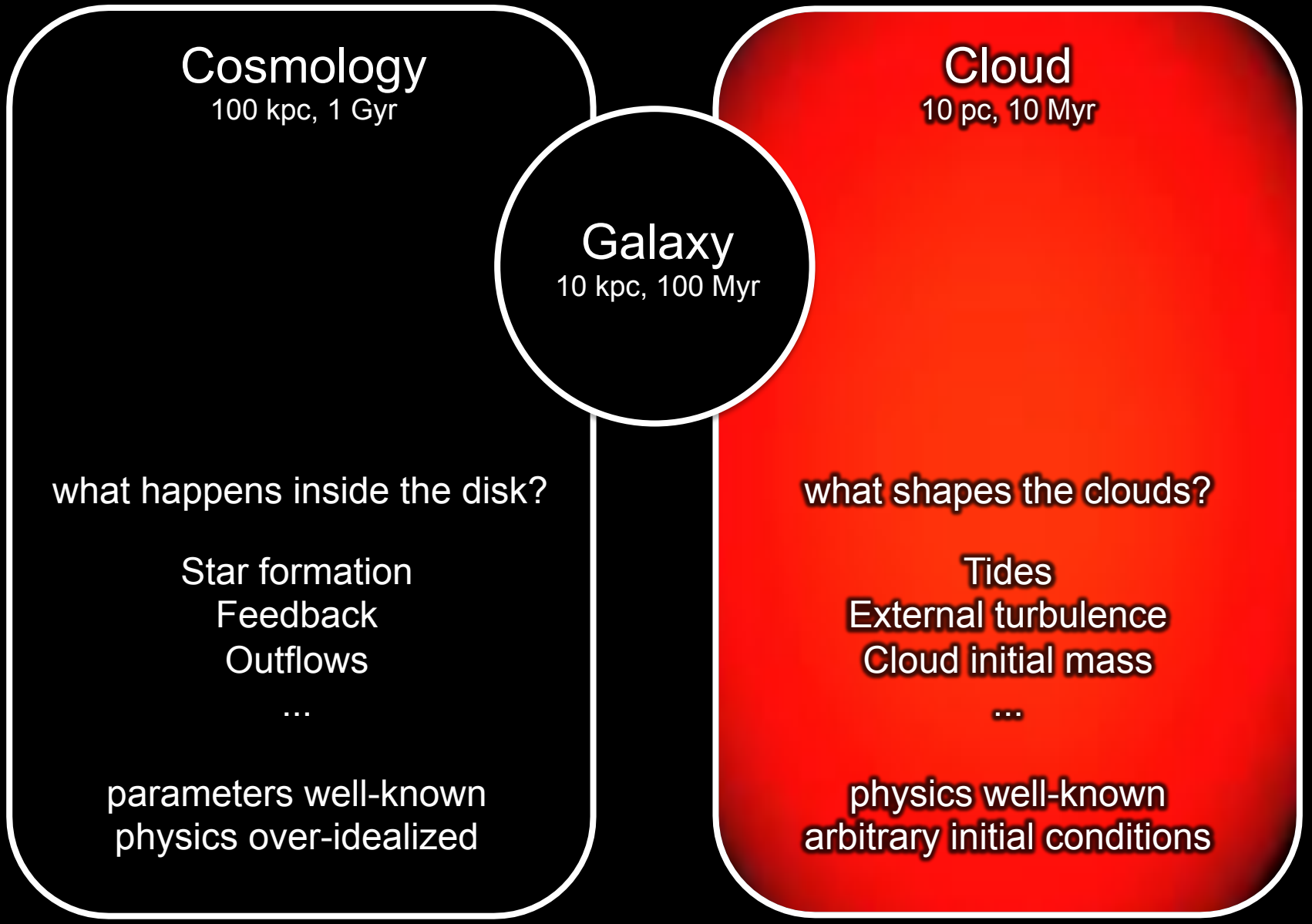
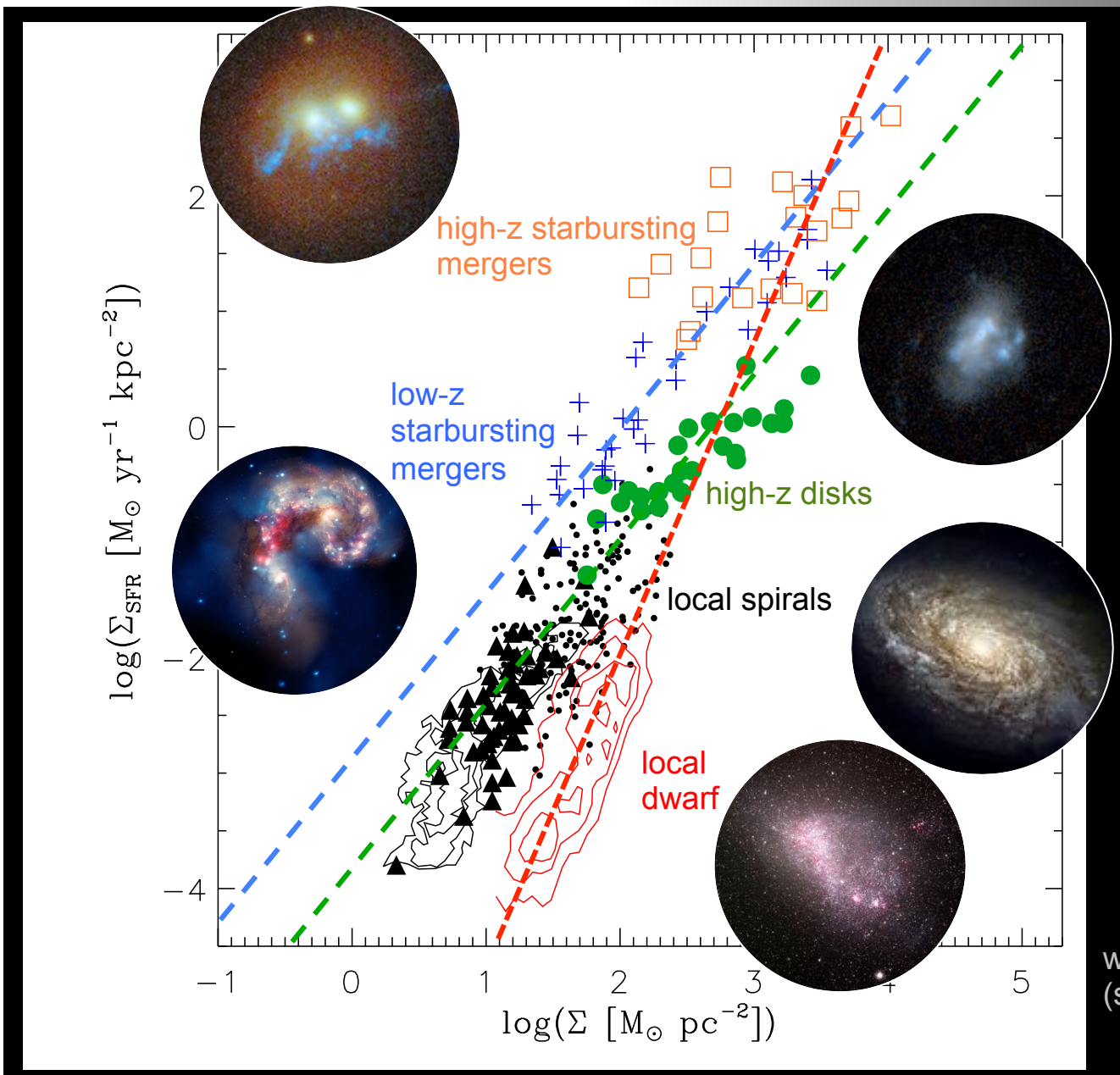

Stars' turbulent beginnings
across space and time
Florent Renaud
University of Surrey
with F. Bournaud, P-A. Duc, K. Kraljic,
E. Emsellem, B. Elmegreen, R. Teyssier, J. Alves,
F. Combes, D Chapon, A. Dekel, J. Gabor, P. Hennebelle

Problems in Simulations



UNIVERSALITY OF STAR FORMATION?



Kennicutt+1998

Kennicutt+2007

Bigiel+2008

Tacconi+2010 ; Daddi+2010a

Kennicutt+1998

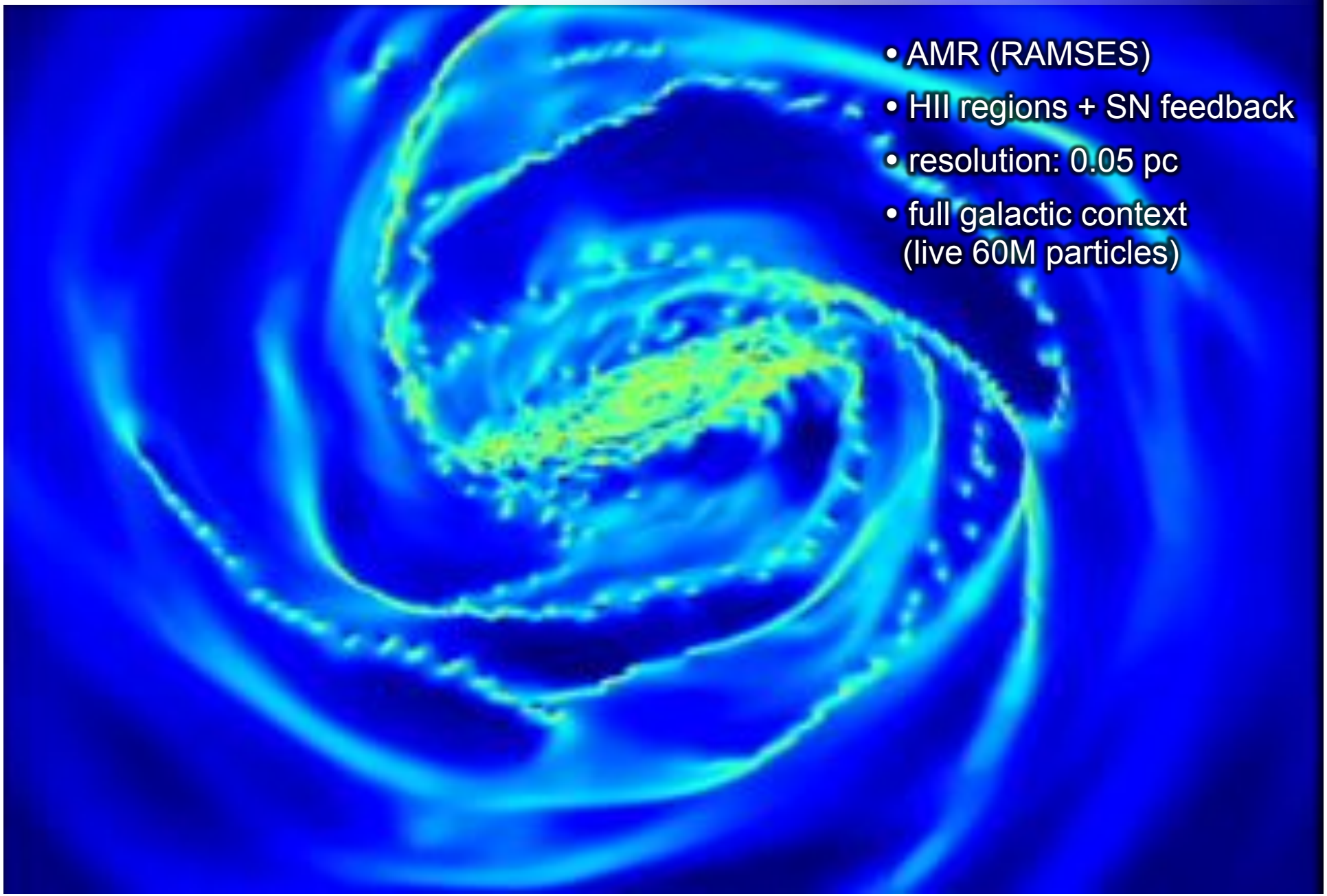
Bouché+2007 ; Bothwell+2009

Bolatto+2011

widely inspired by Daddi+2010b
(see also Genzel+2010)

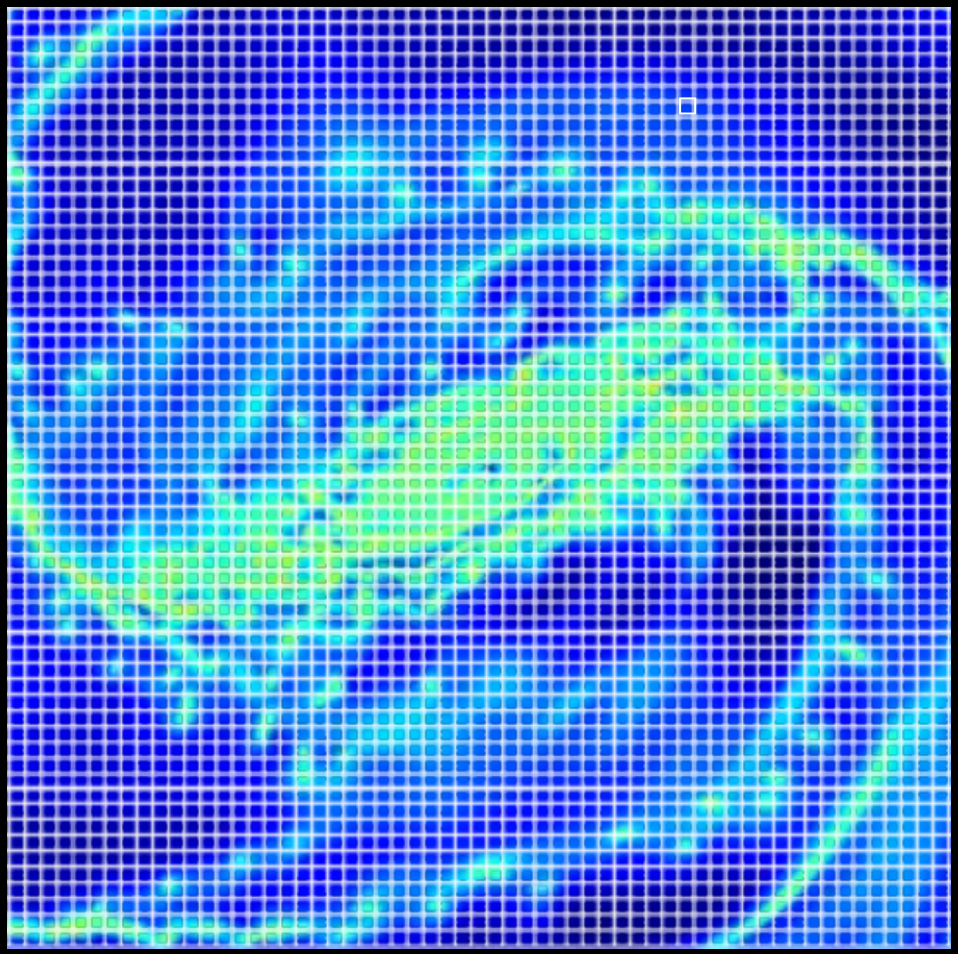
The Milky Way

Renaud et al. (2013)



SF at 100 pc Scale

Kraljic, Renaud et al. (2014)



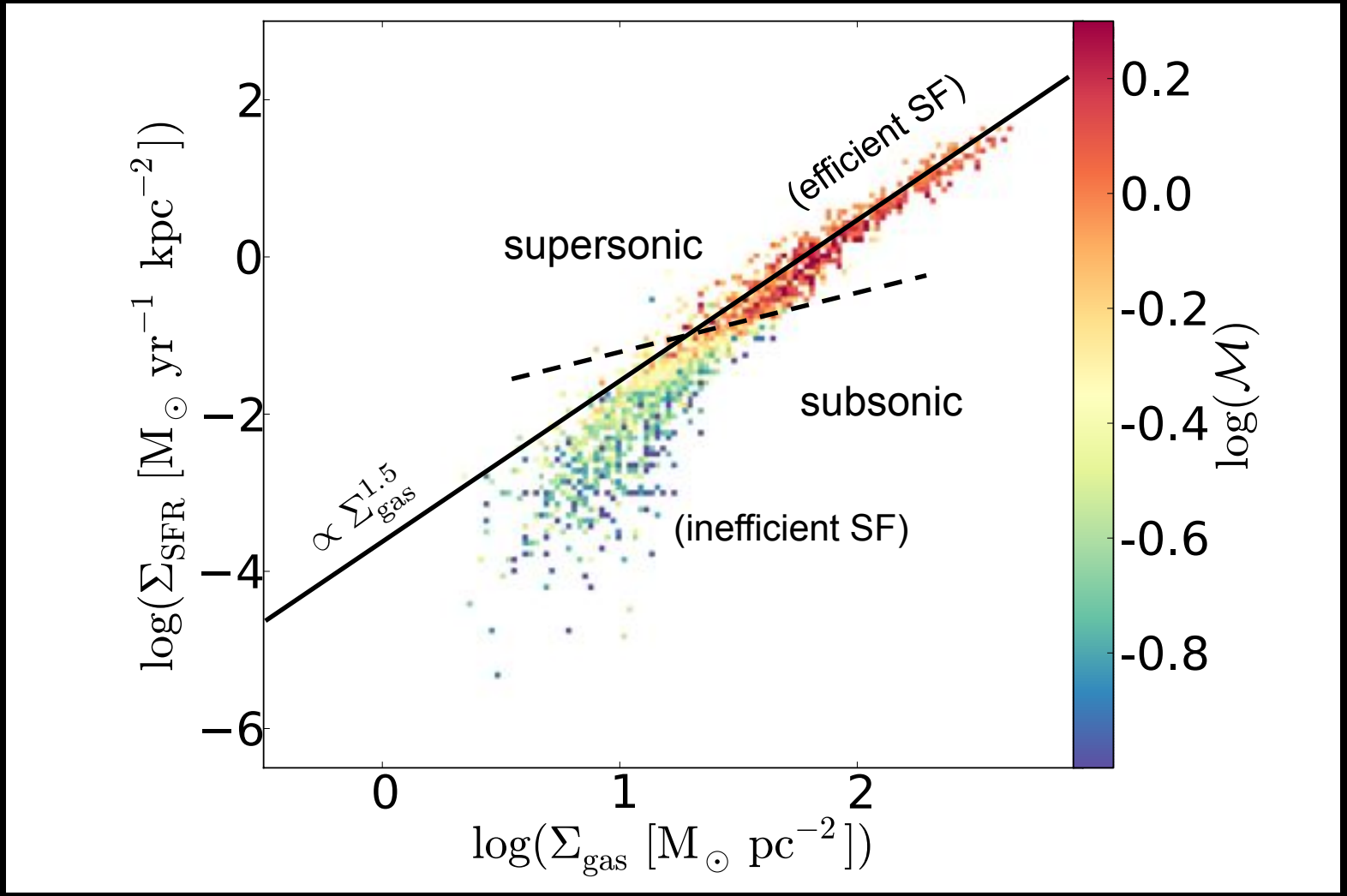
= 100 pc * 100 pc

Σ_{gas}

Σ_{SFR}

SCHMIDT-KENNICUTT RELATION

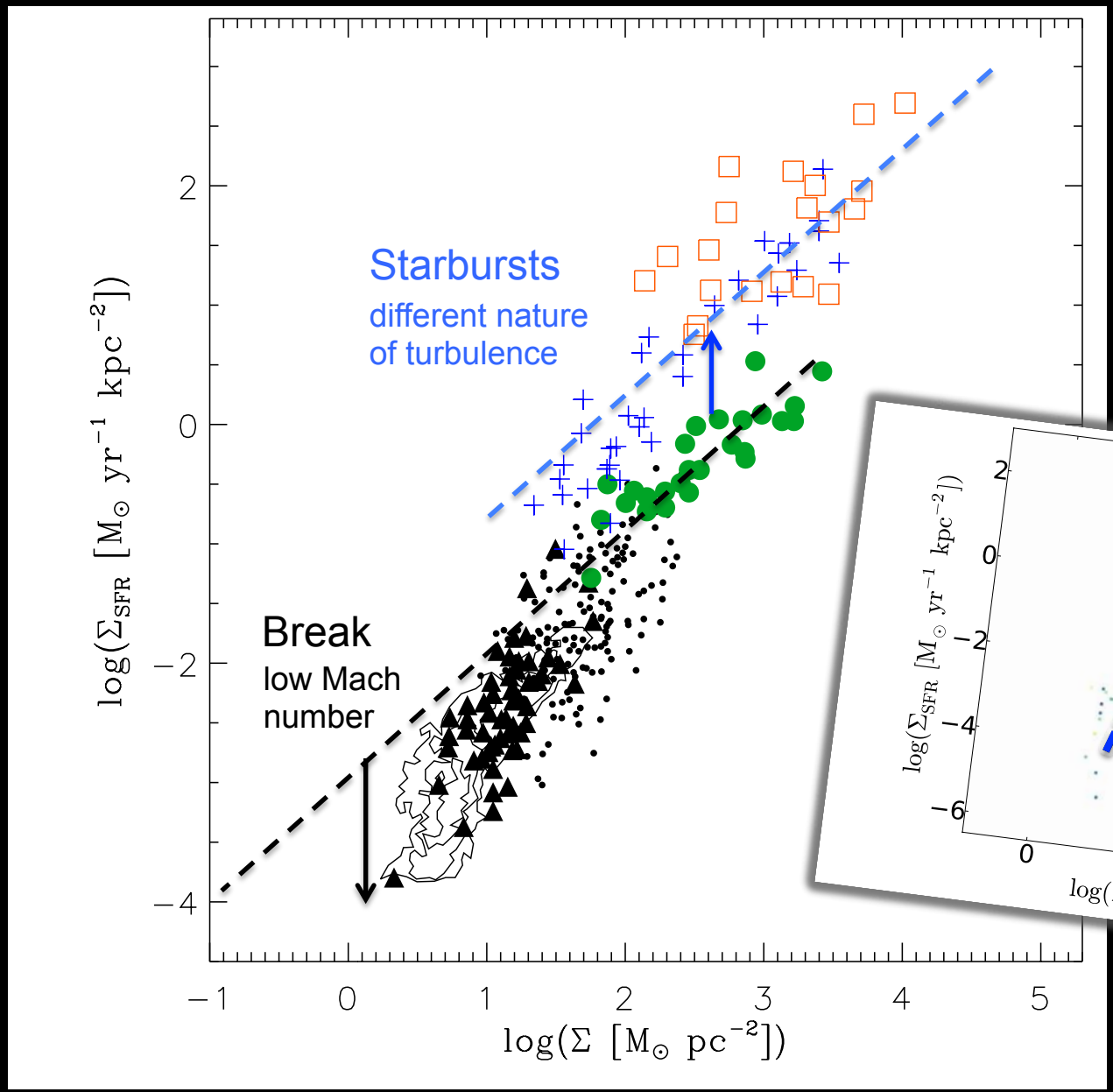
Kraljic, Renaud et al. (2014)

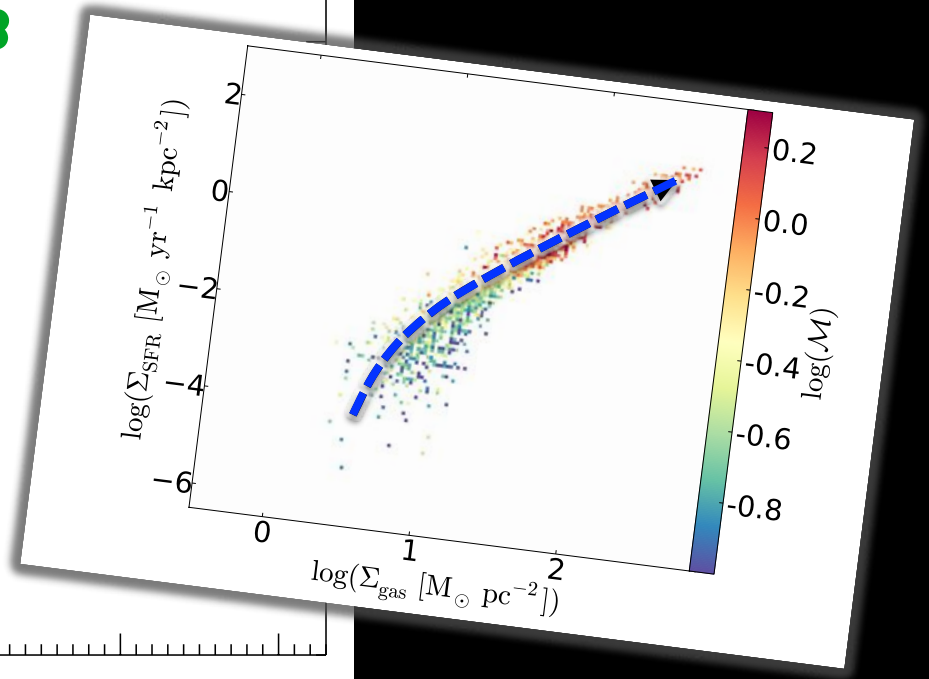


→ Variations of turbulence within the disk explain the break at low Σ_{gas}.

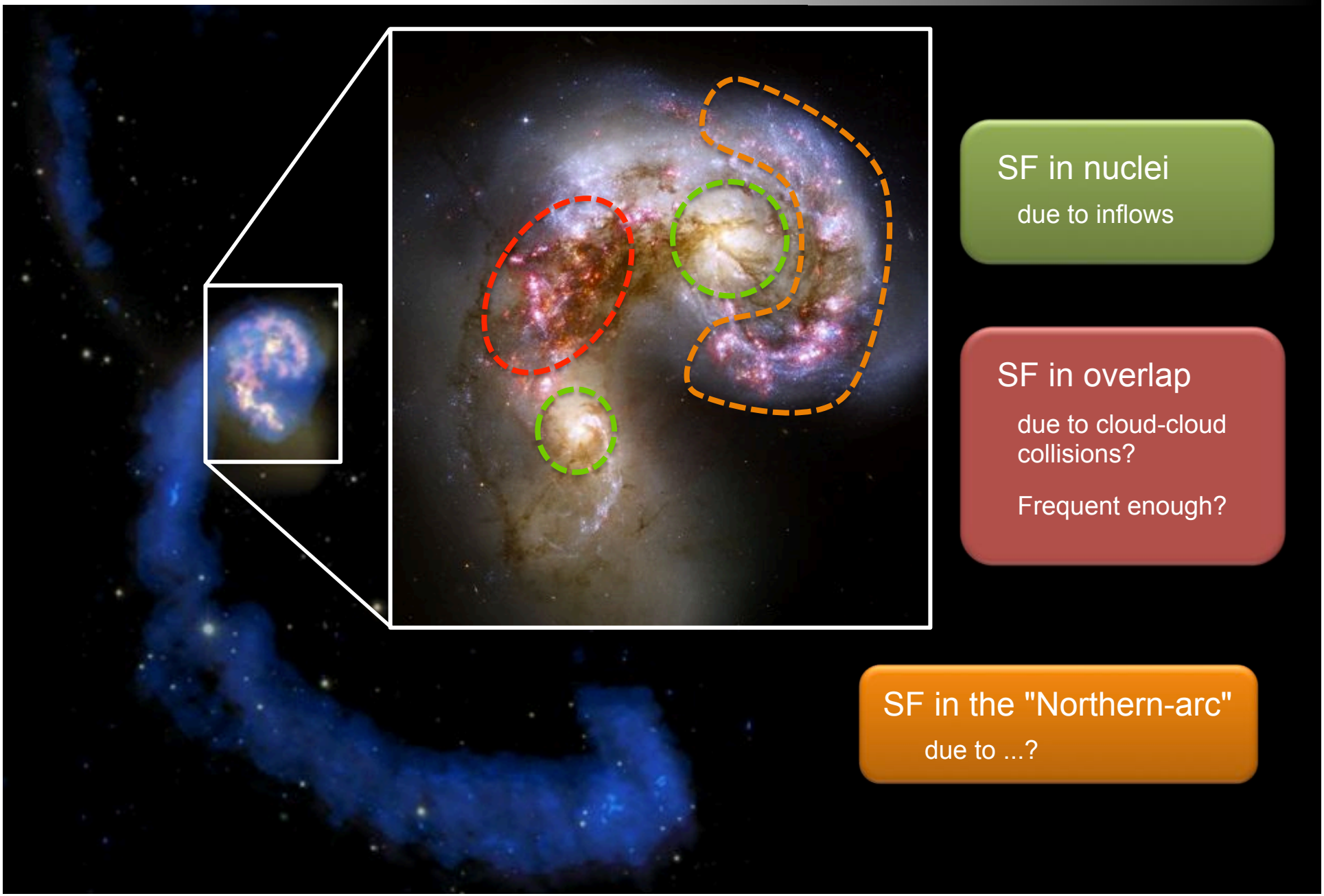
see also Padoan & Nordlund 2011, Hennebelle & Chabrier 2011

What about Starbursts?





Extended Starbursts



SF in nuclei

due to inflows

SF in overlap

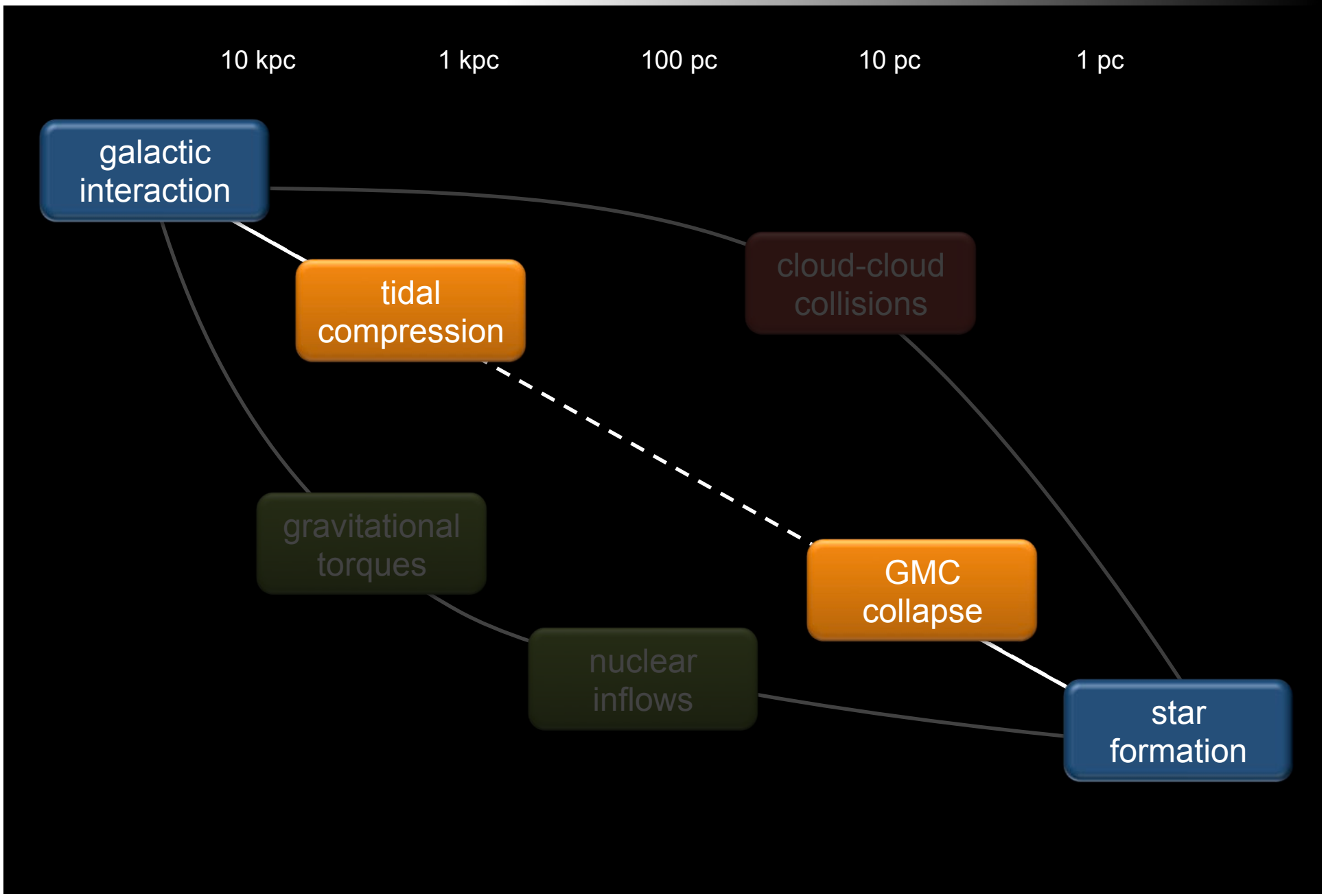
due to cloud-cloud collisions?

Frequent enough?

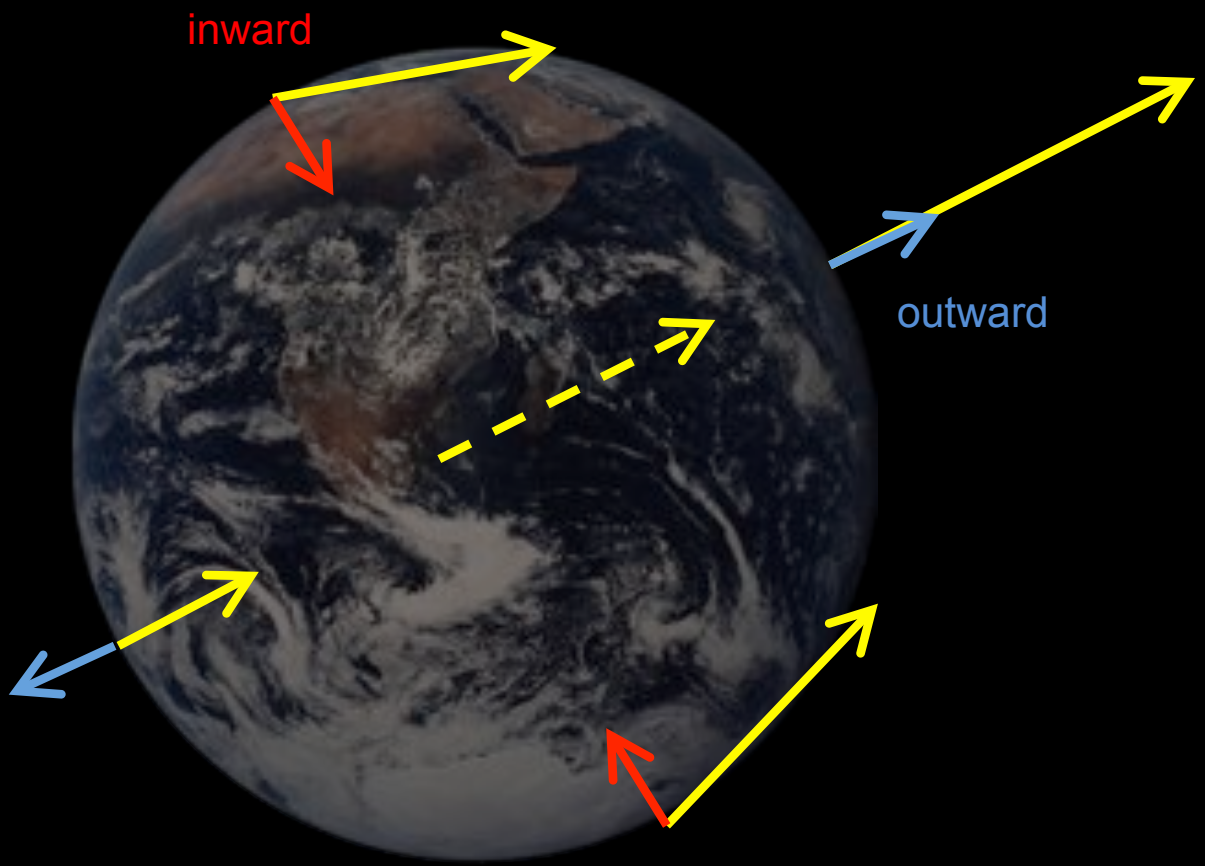
SF in the "Northern-arc"

due to ...?

Triggered, Enhanced Star Formation

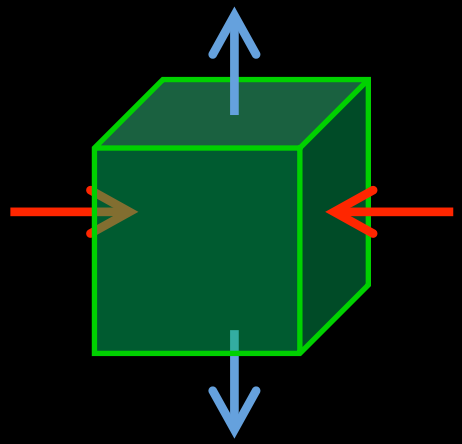


A Quick Reminder about Tides



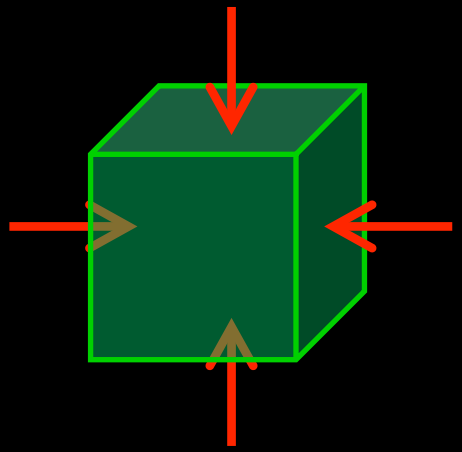
Tidal Modes

extensive mode



- Earth-Moon
- Dominant in galaxies

compressive mode



- Galactic cores
- Important in mergers

see also Avishai's talk

COMPRESSIVE TIDES

Renaud et al. (2008, 2009)

Simulation of the Antennae (no hydro yet ...)

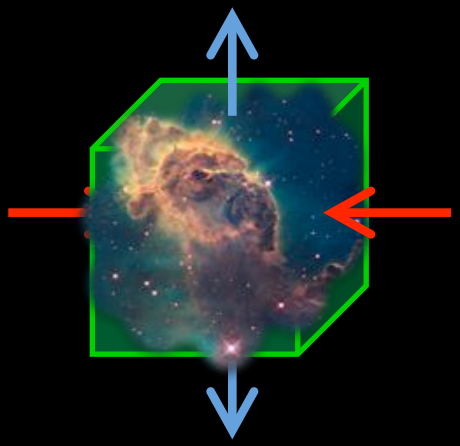
- triggered by the collisions
- Over large volumes
- Valid for all mergers

red = compressive tides

TIDES AND ISM STABILITY

Renaud et al. (2008, 2009)

extensive mode



- Earth-Moon
- Dominant in galaxies

$$\lambda > 0$$

$$M'_{\rm Jeans} > M_{\rm Jeans}$$

no tides

$$\lambda = 0$$

$$M'_{\rm Jeans} = M_{\rm Jeans}$$

compressive mode

- Galactic cores
- Important in mergers

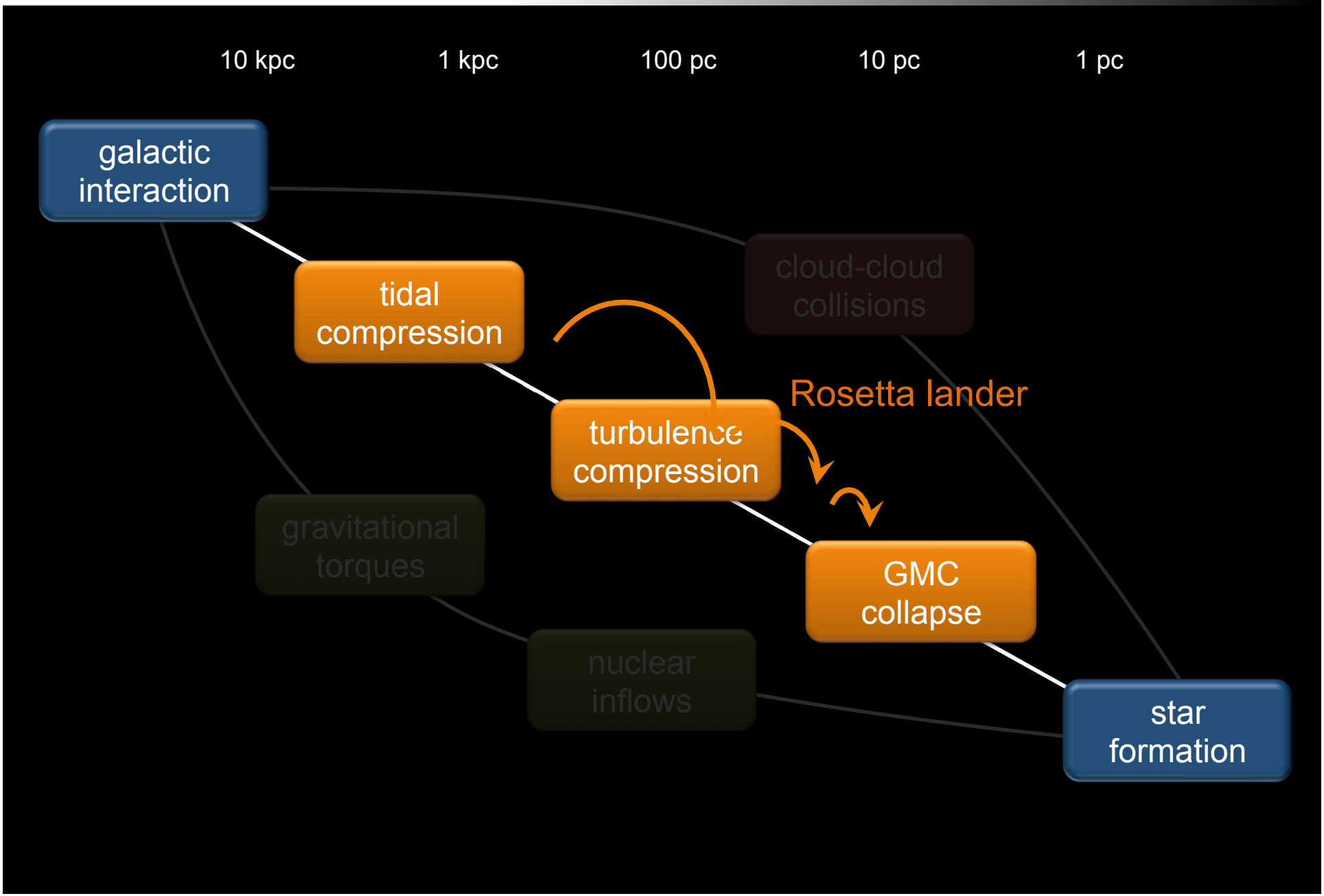
$$\lambda < 0$$

$$M'_{\rm Jeans} < M_{\rm Jeans}$$

$$M'_{\rm Jeans} = \frac{M_{\rm Jeans}}{(1-\lambda)^{3/2}}$$

Jog (2013,2014)

Triggered, Enhanced Star Formation



A Quick Reminder about Turbulence

Local velocity field =

net motion
(*average*)

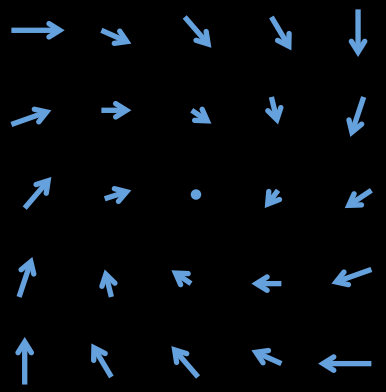
$\langle v \rangle$

Move it!

+

solenoidal
turbulence
(*curl*)

$\nabla \times v$

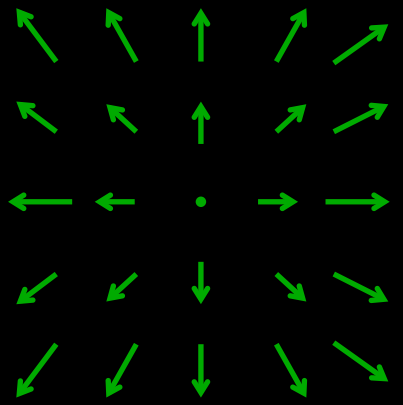


Mix it!

+

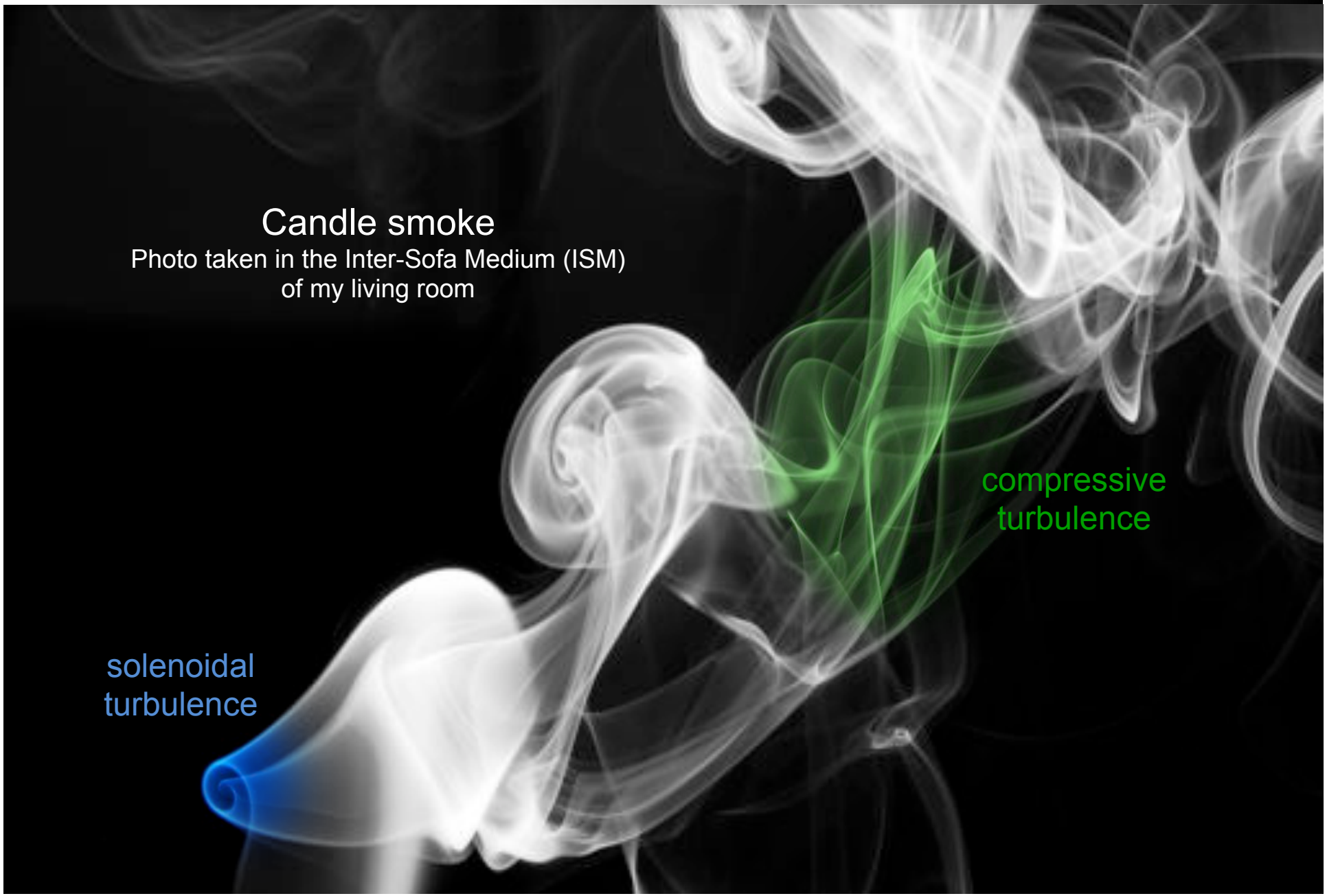
compressive
turbulence
(*divergence*)

$\nabla \cdot v$

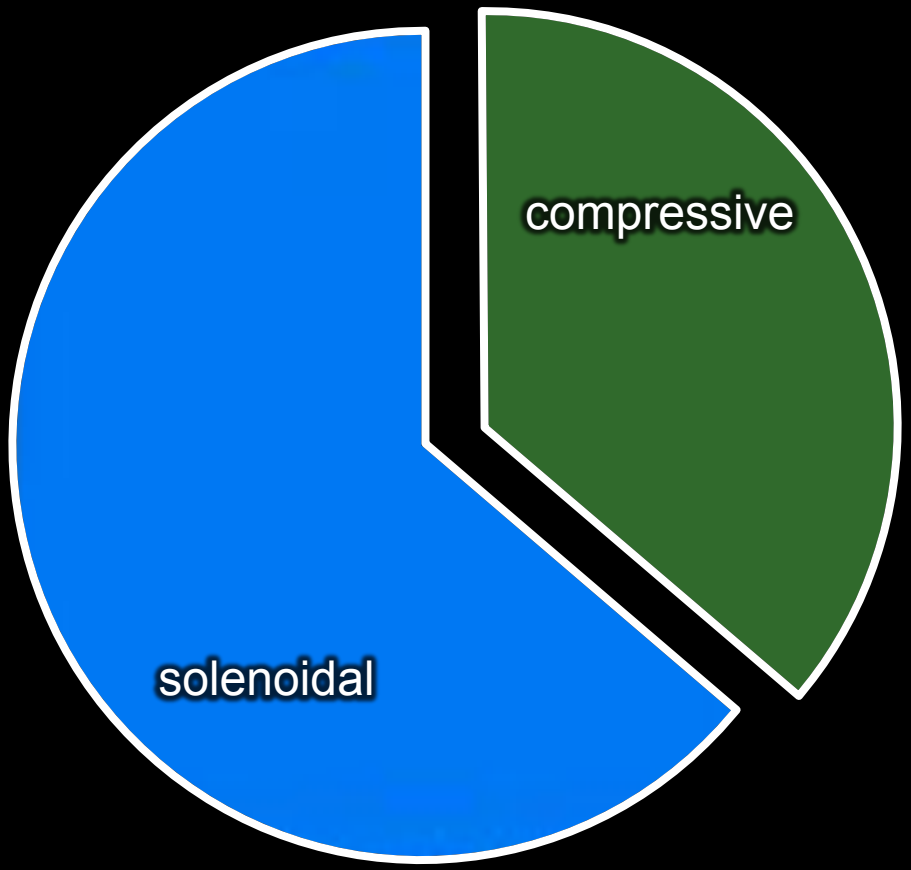


Pinch it!

Solenoidal and Compressive Turbulence



Solenoidal and Compressive Turbulence

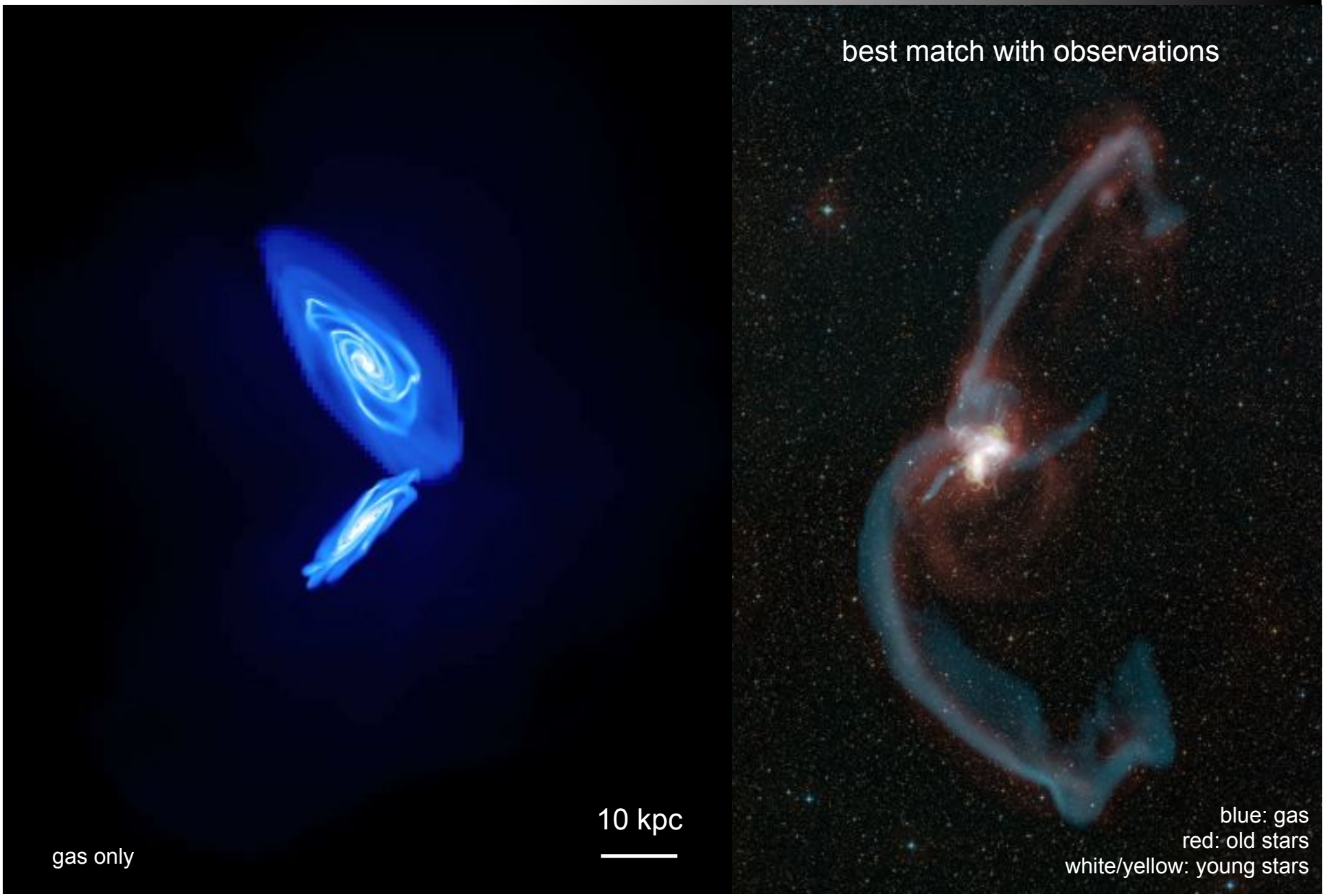


"Natural" turbulence energy budget
(i.e. with no external forcing)

Federrath et al. (2010)

YET ANOTHER SIMULATION OF THE ANTENNAE

Renaud, Bournaud & Duc (2014)



THE ANTENNAE

Renaud, Bournaud & Duc (2014)

gas

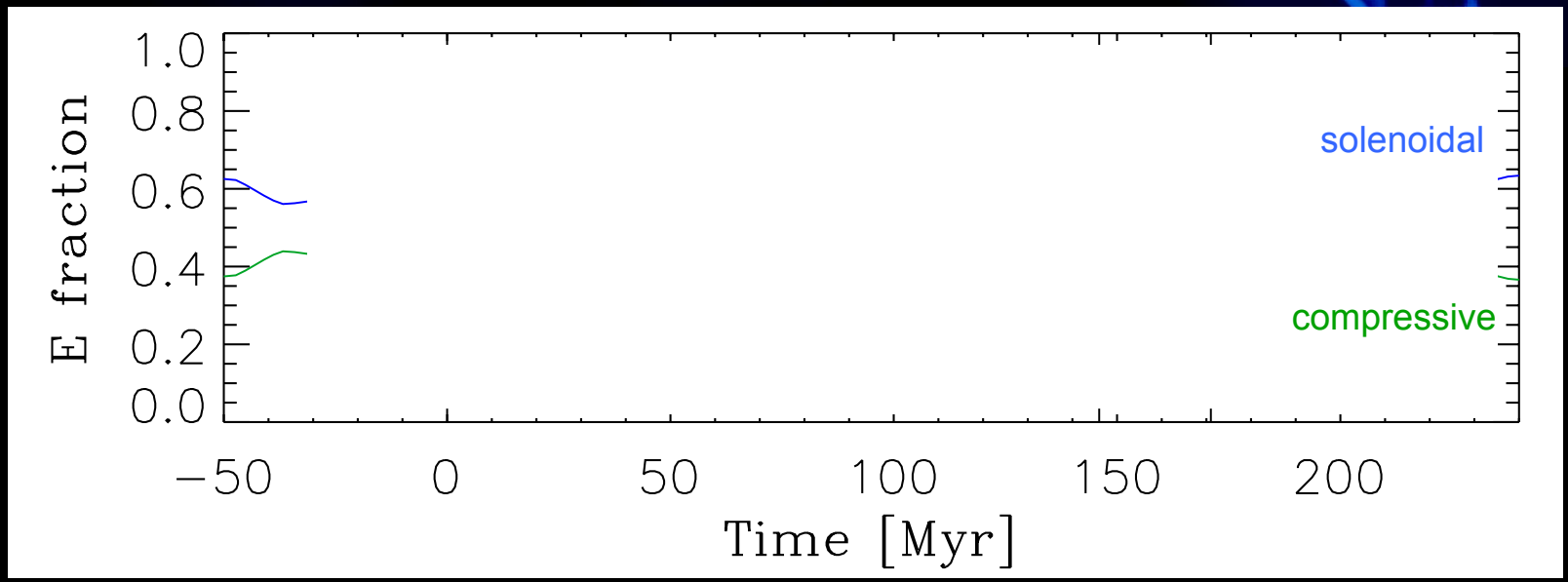
new stars

2 kpc

Numerical method comparable to the Milky Way simulation (but only parsec resolution)

In a Merger

Renaud et al. (2014)

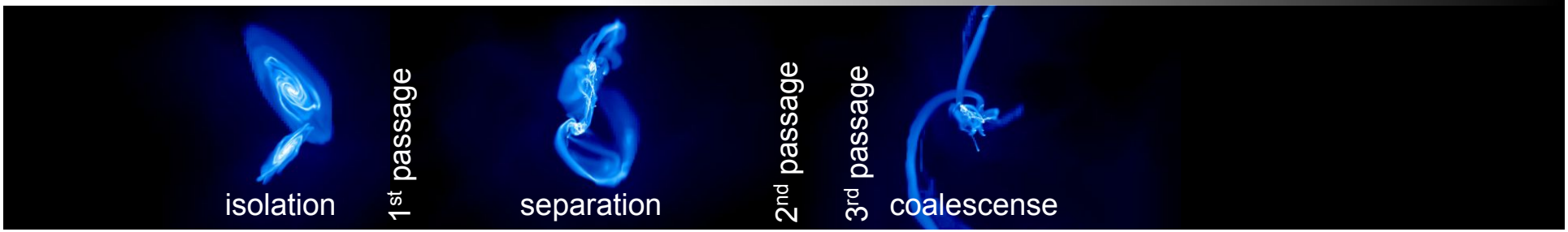


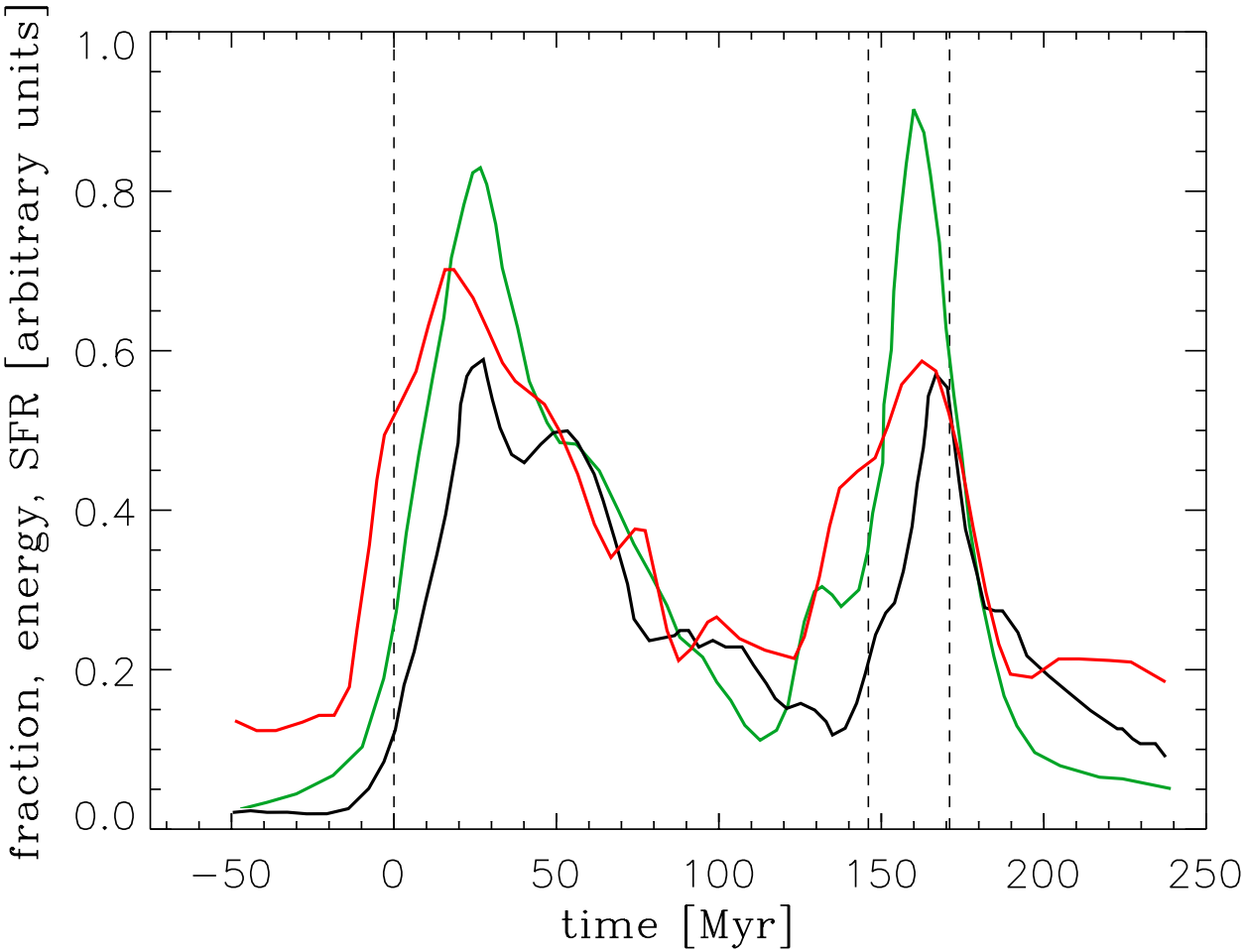
- Change the nature of turbulence
- Change how the ISM fragments
- Change the IMF (→ bottom-heavy)

Chabrier, Hennebelle & Charlot (2014)

TIME EVOLUTION

Renaud et al. (2014)





tides → turbulence → SF

20 – 30 Myr

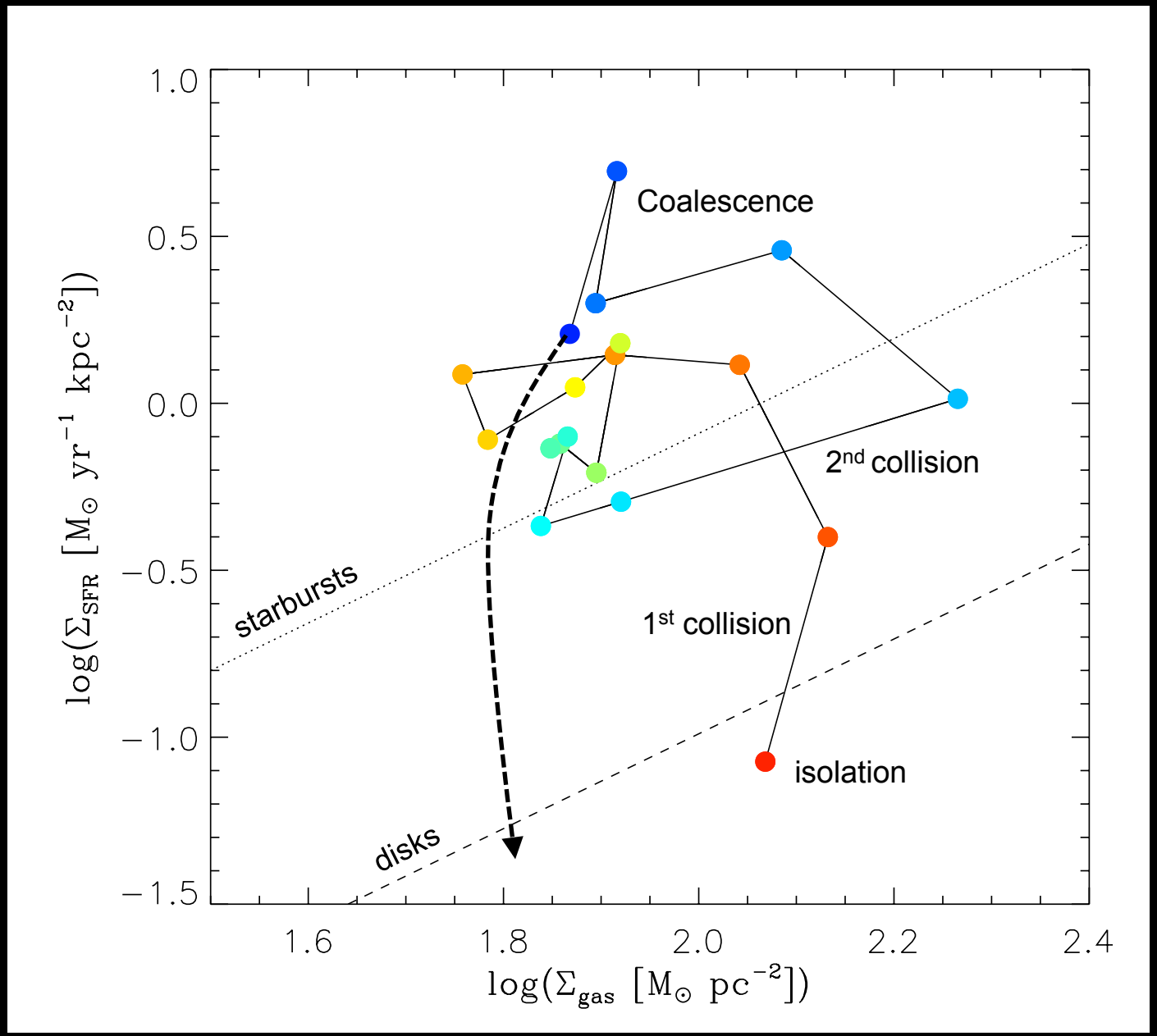
compressive tides (gas mass fraction)

compressive turbulence (energy)

SFR

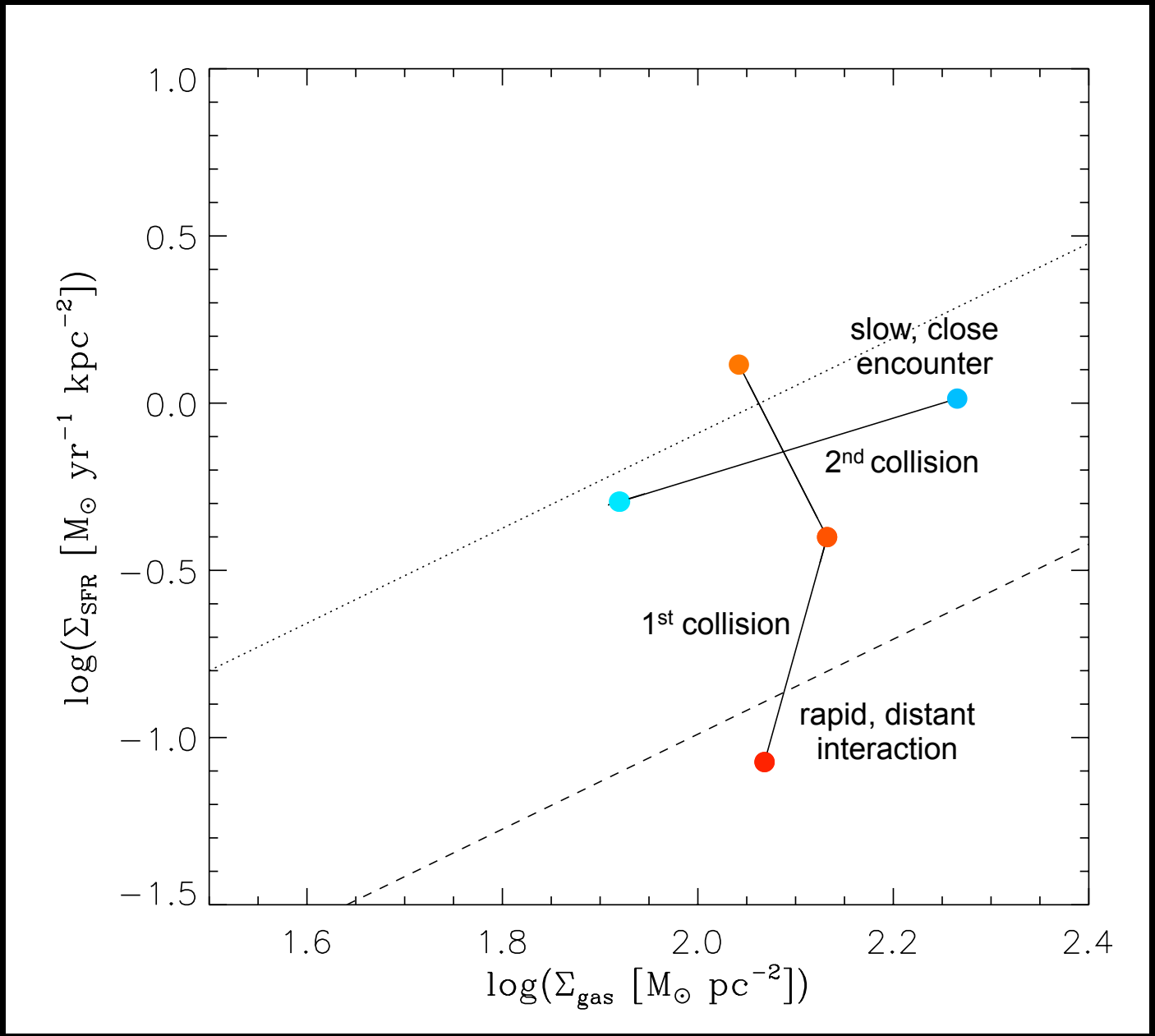
DISK VS MERGER

Renaud et al. (2014)



DISK VS MERGER

Renaud et al. (2014)

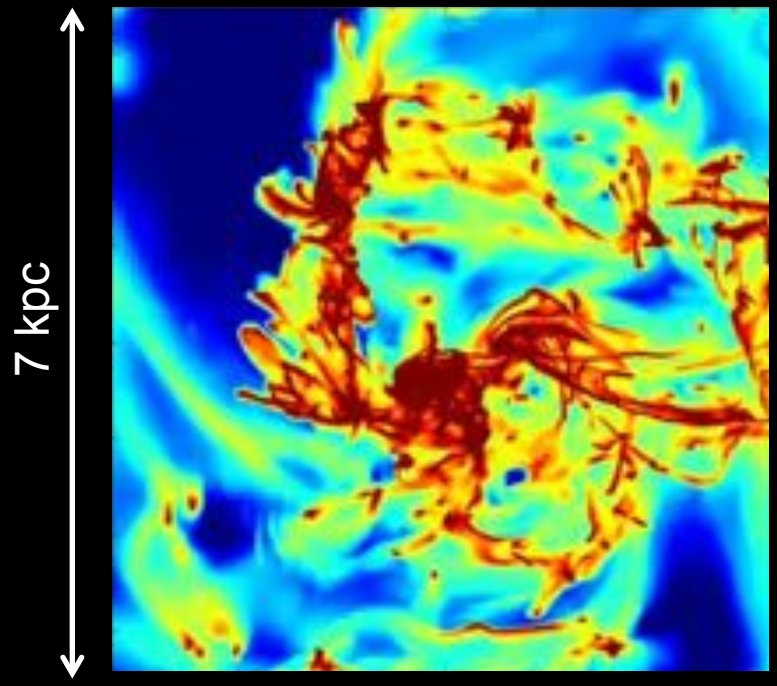


Different physical conditions

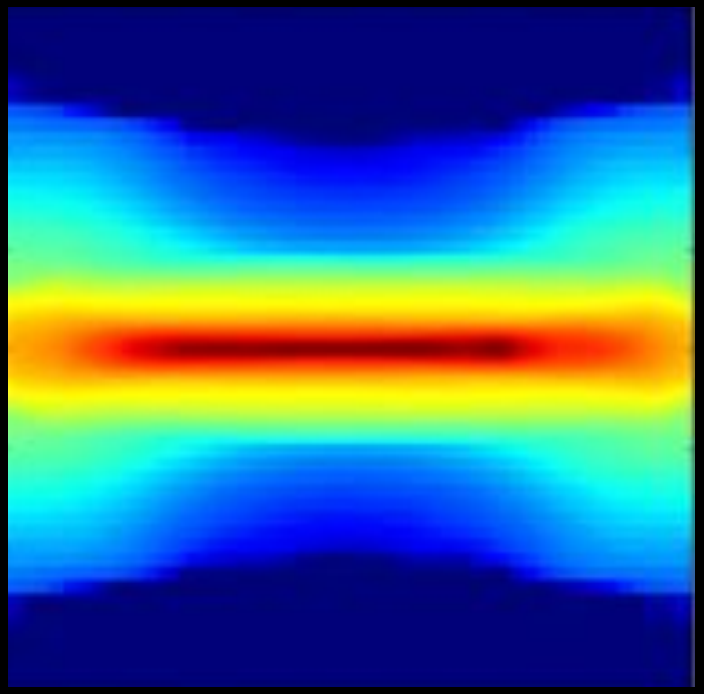
Different SF outcomes

CLUMPY DISK

Bournaud, Perret, Renaud et al. (2014)



Milky Way progenitor at z~2
gas fraction ~50%

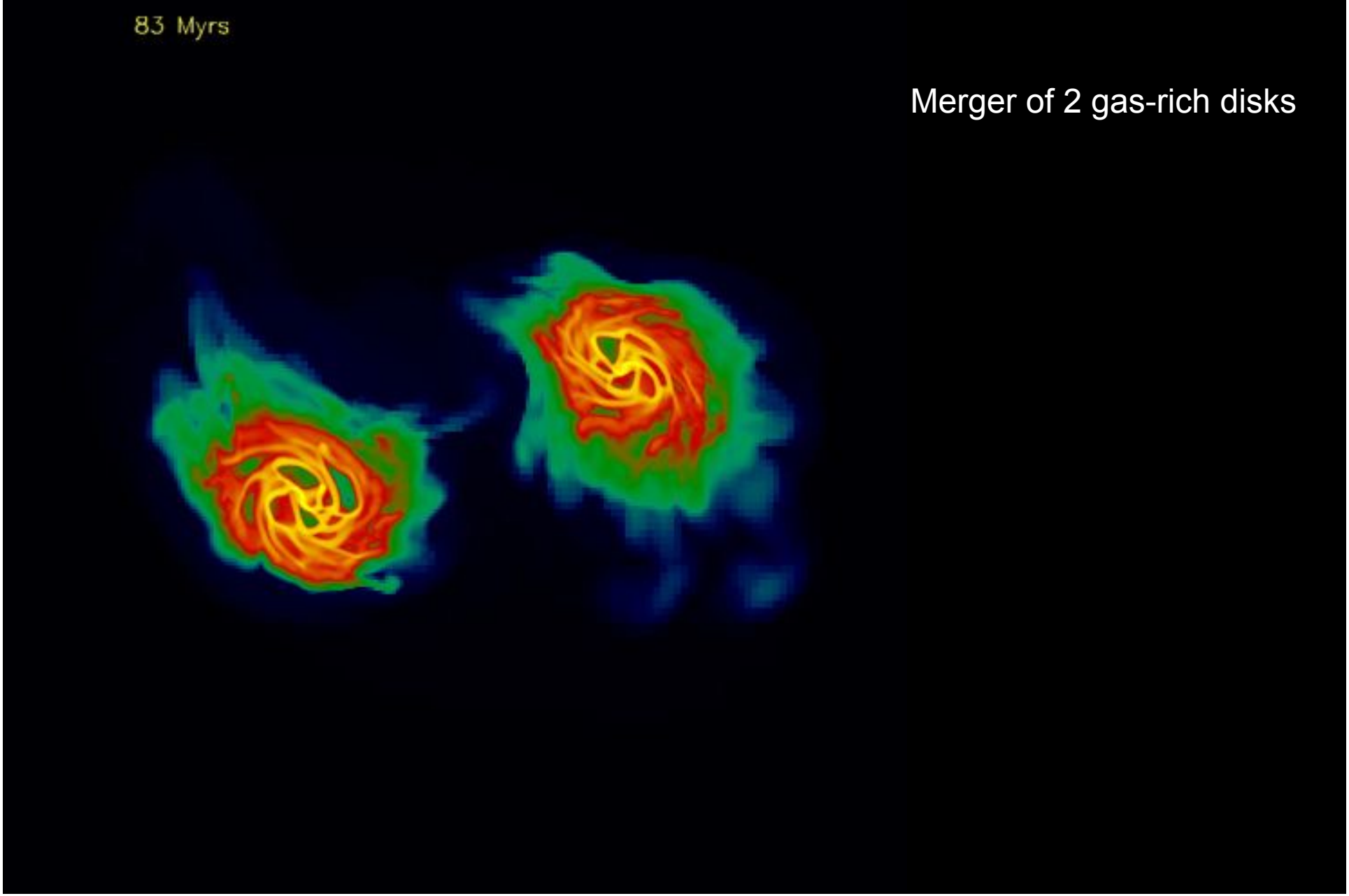


outflows

Formation of massive gas clumps (10^9 $M_\odot$)
High SFR (~50 $M_\odot$/yr)

High Redshift Mergers

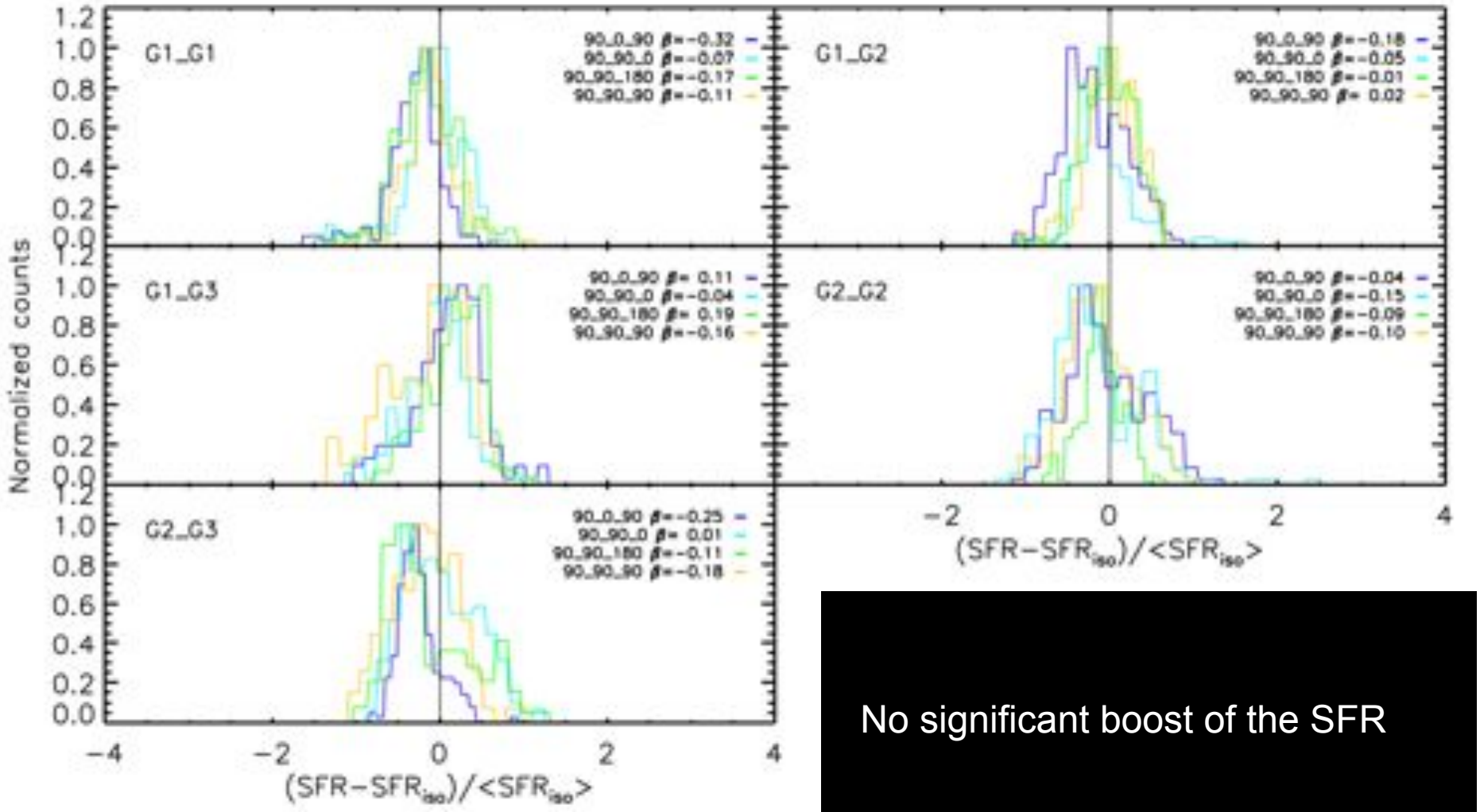
Perret, Renaud et al. (2014)



Merger of 2 gas-rich disks

HIGH REDSHIFT MERGERS

Perret, Renaud et al. (2014)



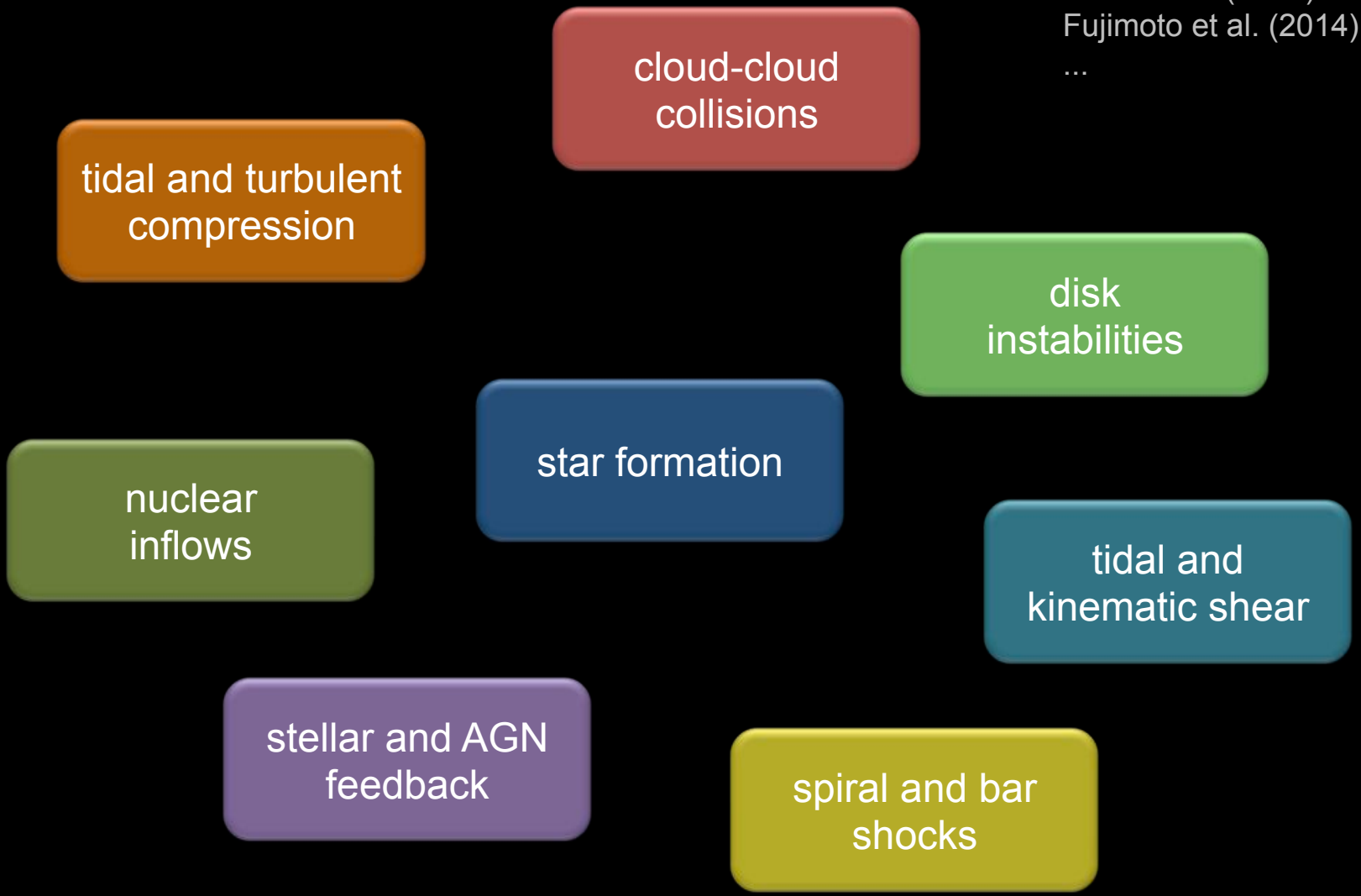
No significant boost of the SFR

Saturation due to the regulation by stellar feedback?

Diversity of Processes

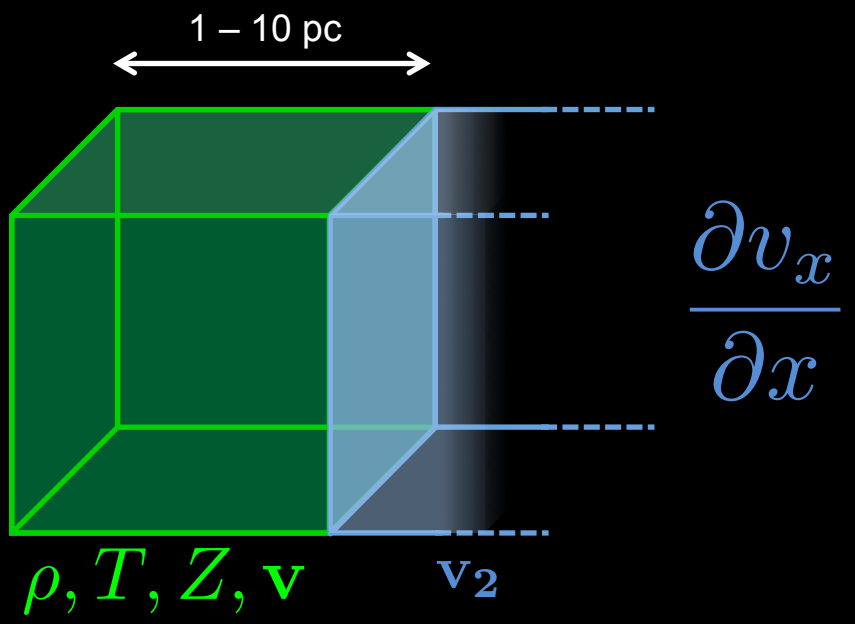
Many alternative, complementary mechanisms

Barnes (2004)
Dobbs et al. (2008)
Meidt et al. (2013)
Fujimoto et al. (2014)
...



LVG Method

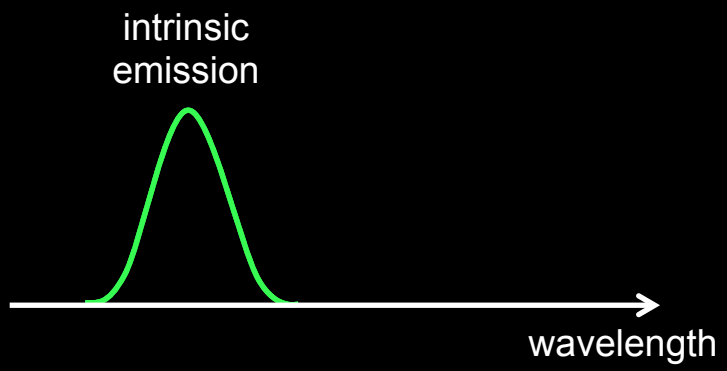
Bournaud, ... Renaud et al. (2014b)



Large Velocity Gradient

Intrinsic emission (tabulated)

Weiß et al. (2005)

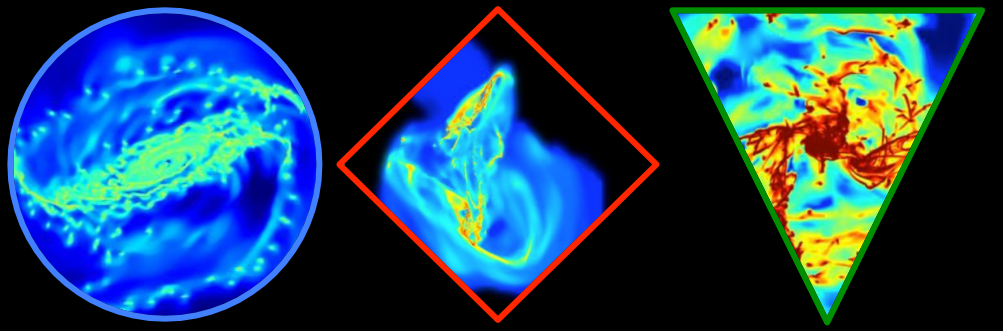


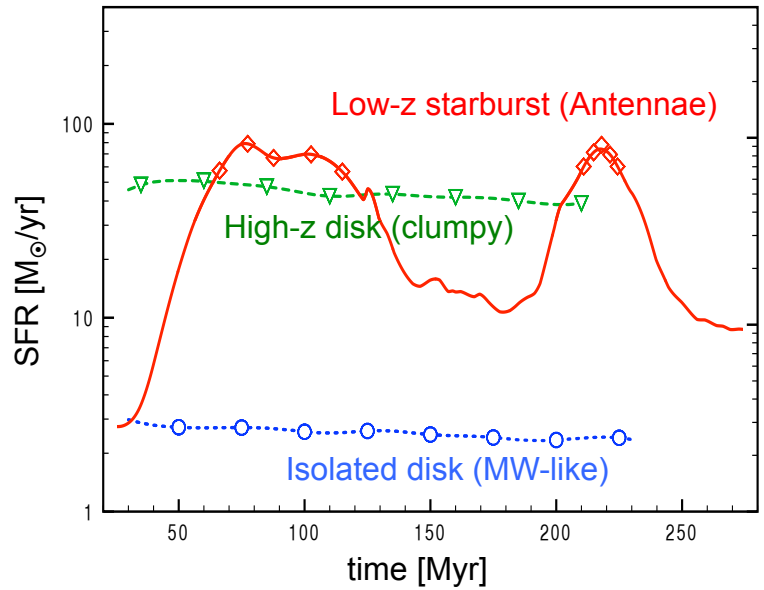
Velocity gradient along LOS

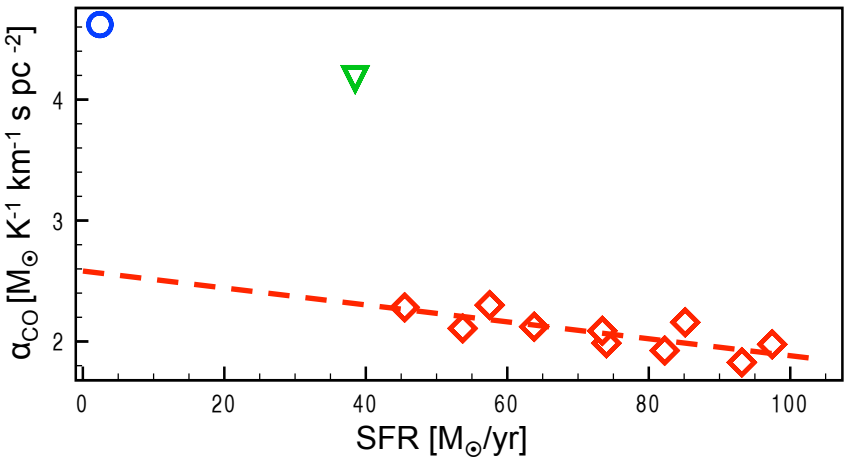
- Large gradient: transparent
- Small gradient: self-absorbtion

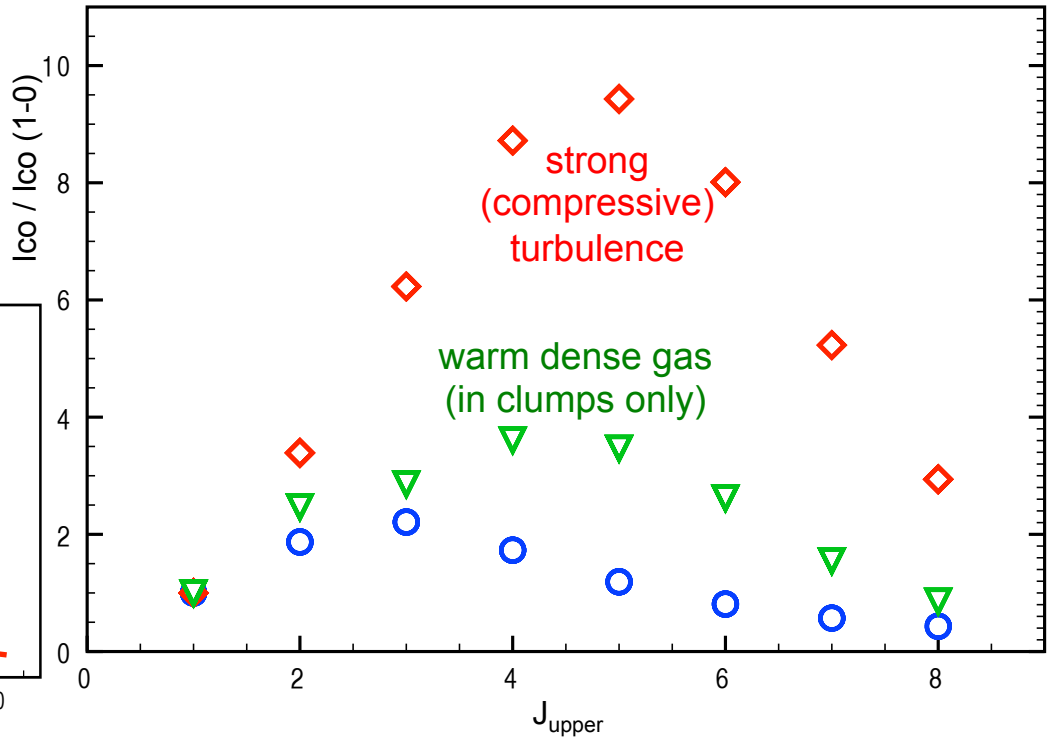
CO EMISSION

Bournaud, ... Renaud et al. (2014b)



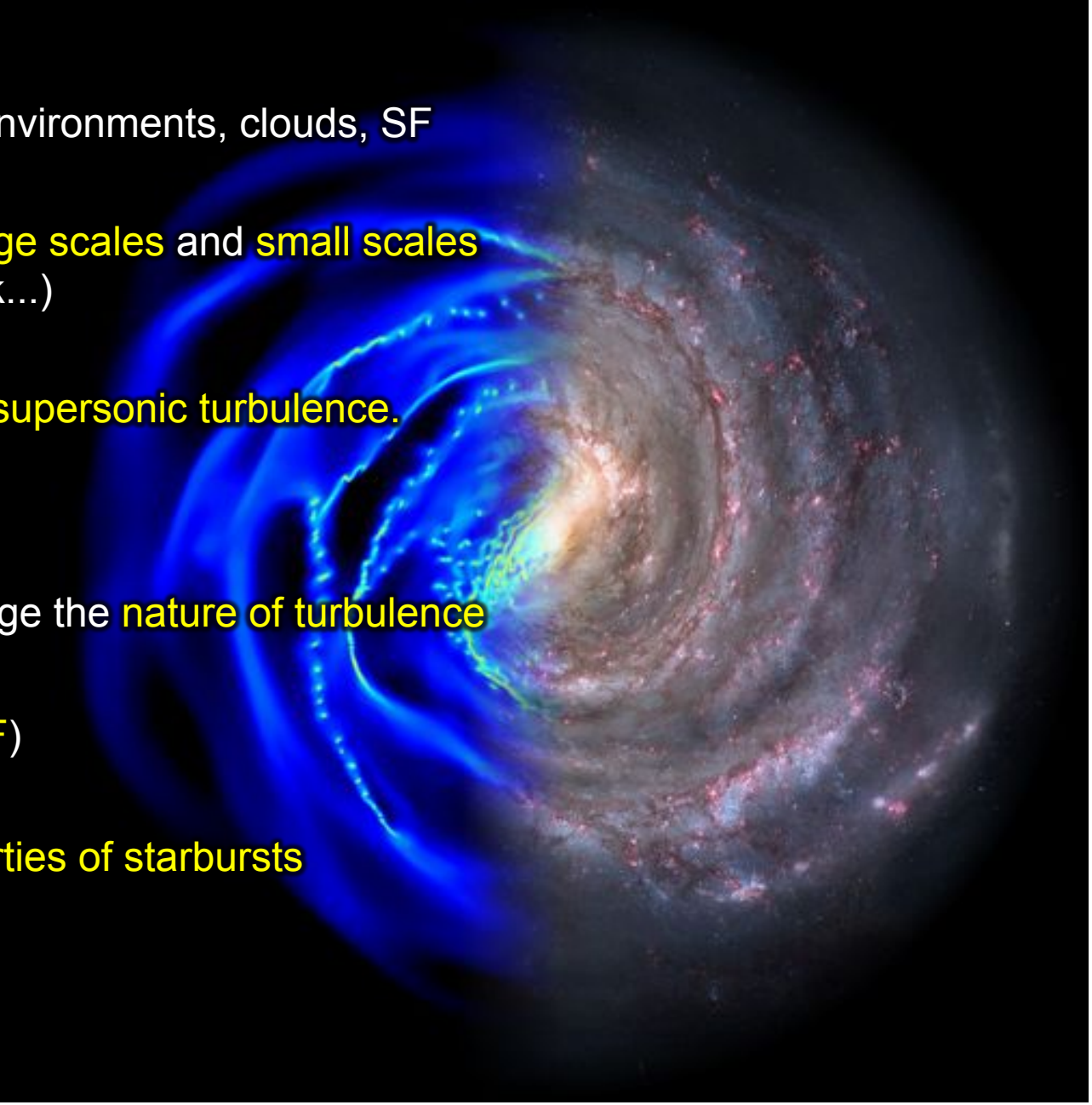






CONCLUSIONS

- Diversity of galactic environments, clouds, SF
- Coupling between large scales and small scales (turbulence, feedback...)
- SF closely related to supersonic turbulence.
- Galaxy mergers change the nature of turbulence
- (and probably the IMF)
- which explains properties of starbursts (e.g. off-nuclear SF)



What's the Connection between these Pictures?

What's the Connection between these Pictures?

Star formation is enhanced

by (compressive) turbulence

which is induced by (compressive) tides,

when two (Samsung) *galaxies meet.*