Physics of Groups, IAP, Dec 12-15

A *shocking* group!

Turbulent dissipation and star formation in Stephan's Quintet

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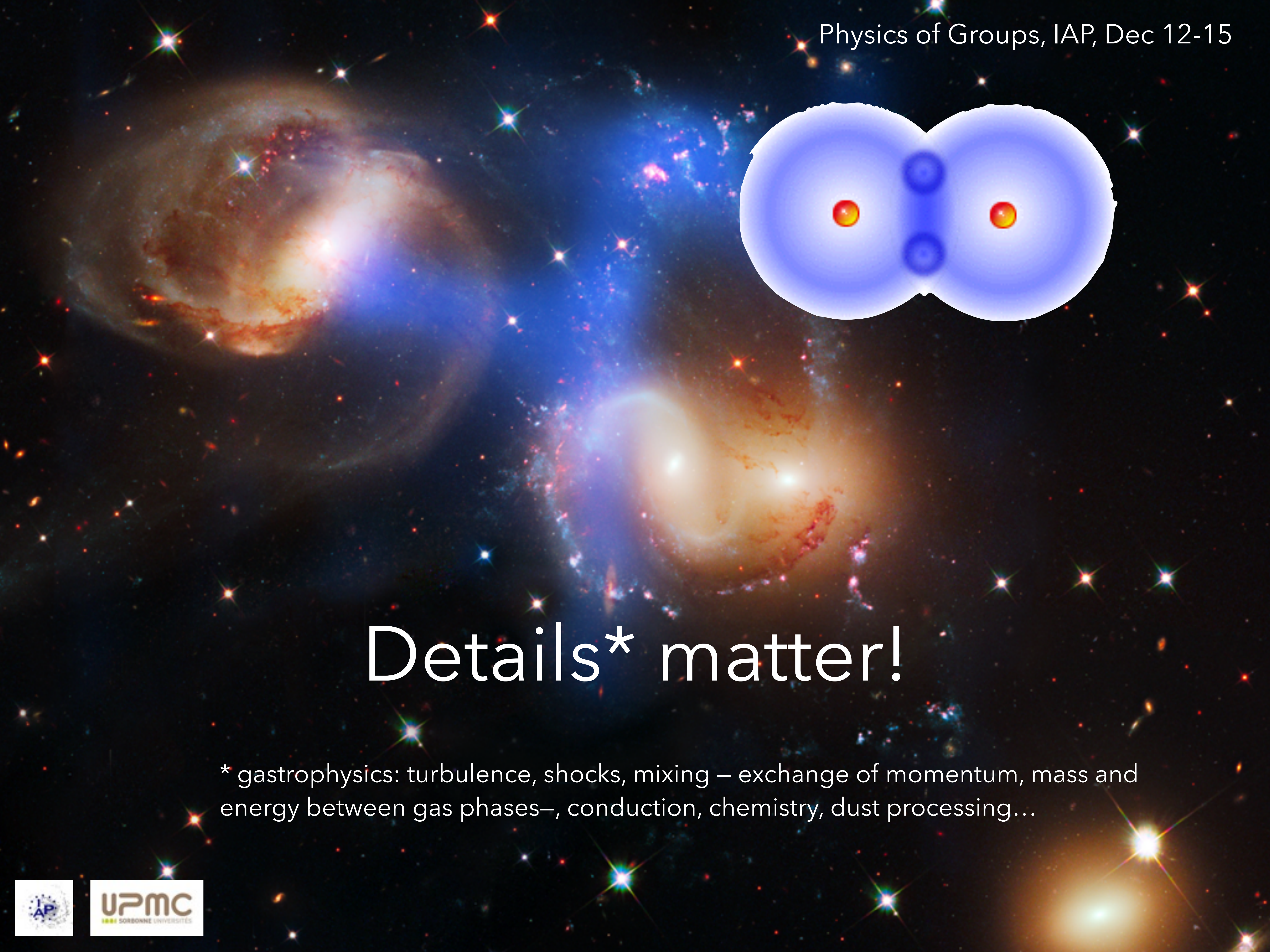
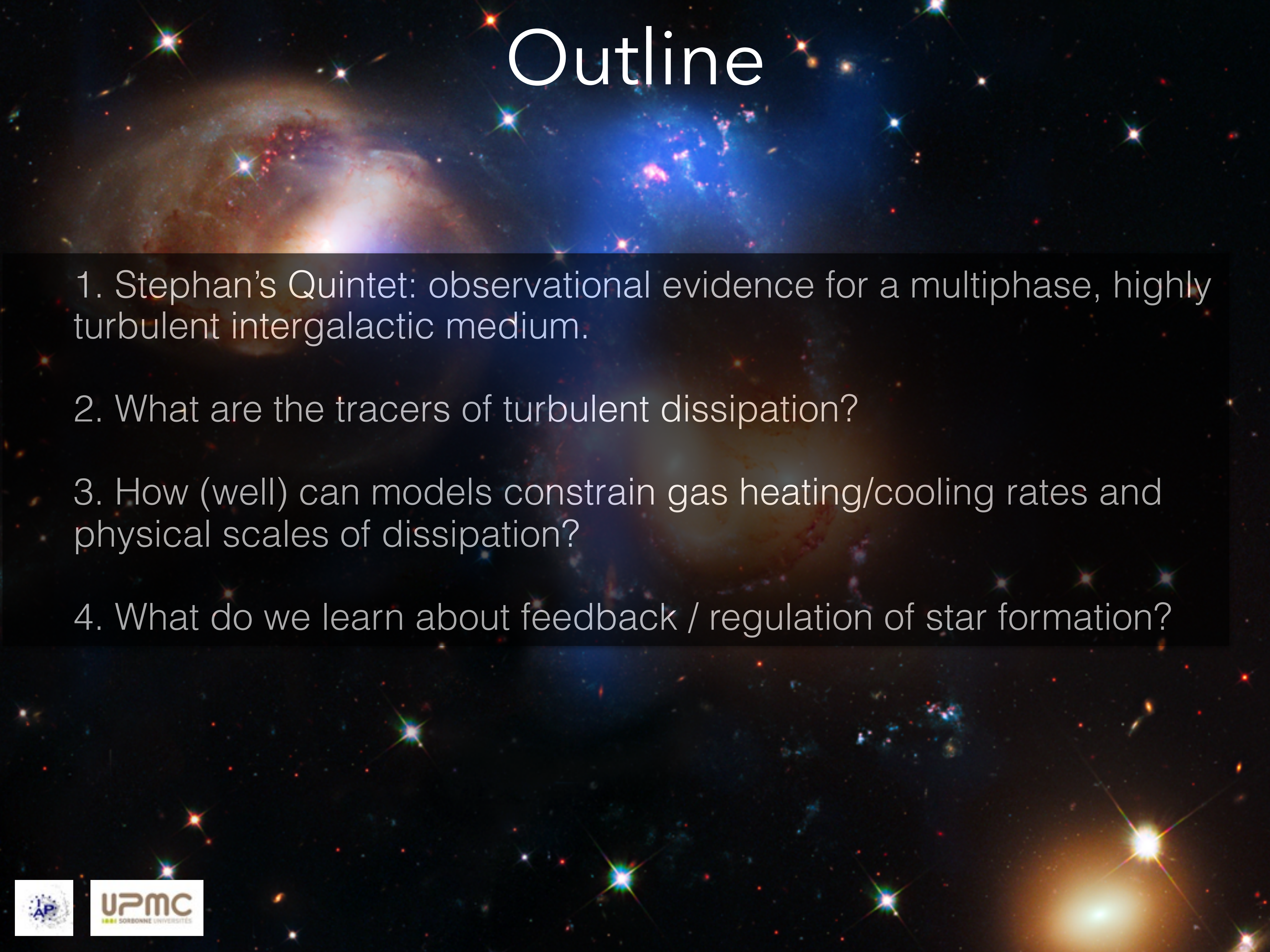


Details* matter!

* gastrophysics: turbulence, shocks, mixing – exchange of momentum, mass and energy between gas phases–, conduction, chemistry, dust processing…



Outline

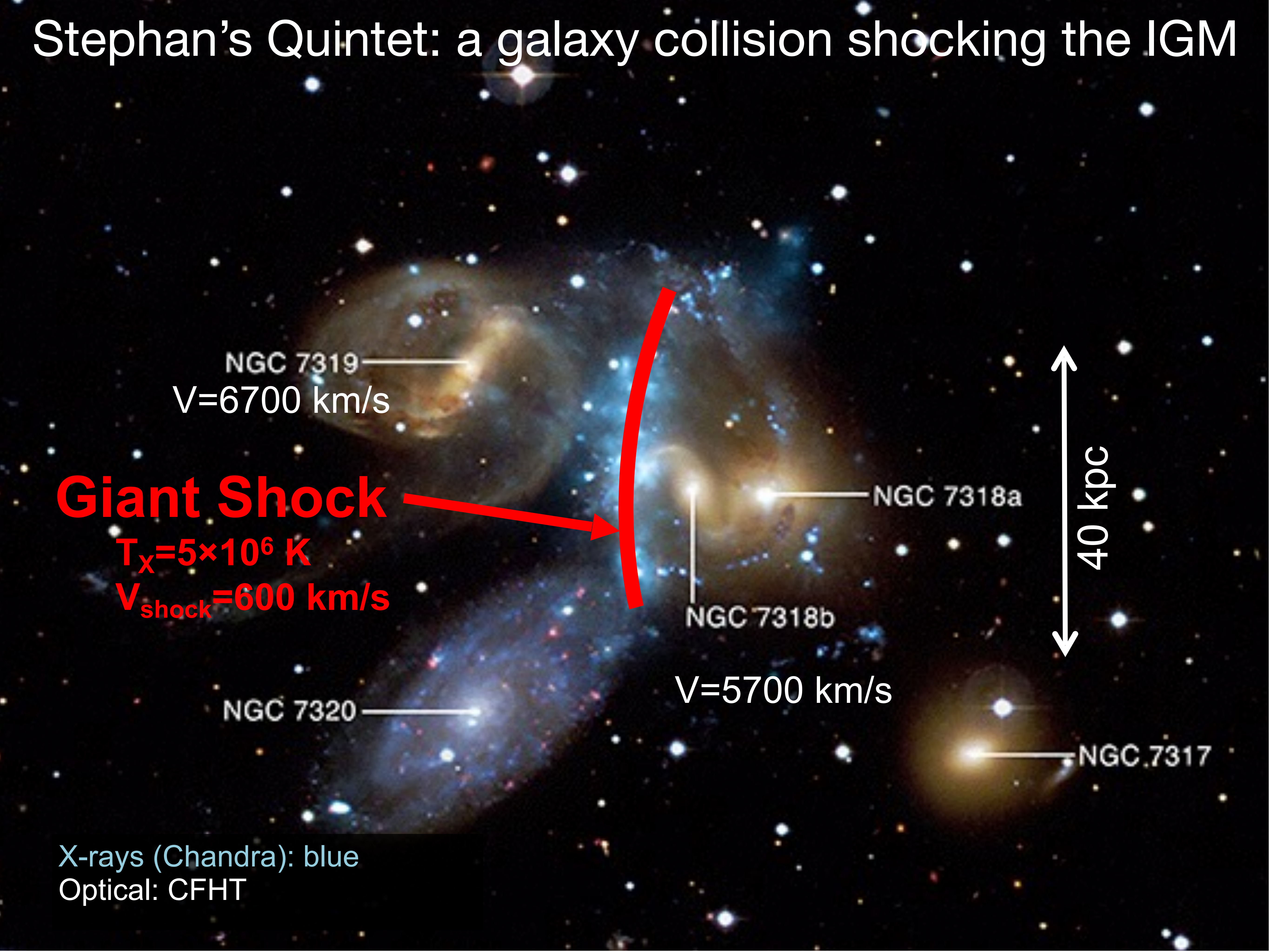
1. Stephan's Quintet: observational evidence for a multiphase, highly turbulent intergalactic medium.

2. What are the tracers of turbulent dissipation?

3. How (well) can models constrain gas heating/cooling rates and physical scales of dissipation?

4. What do we learn about feedback / regulation of star formation?

Stephan's Quintet: a galaxy collision shocking the IGM



V=6700 km/s

Giant Shock

$T_X=5\times10^6$ K

$V_{shock}=600$ km/s

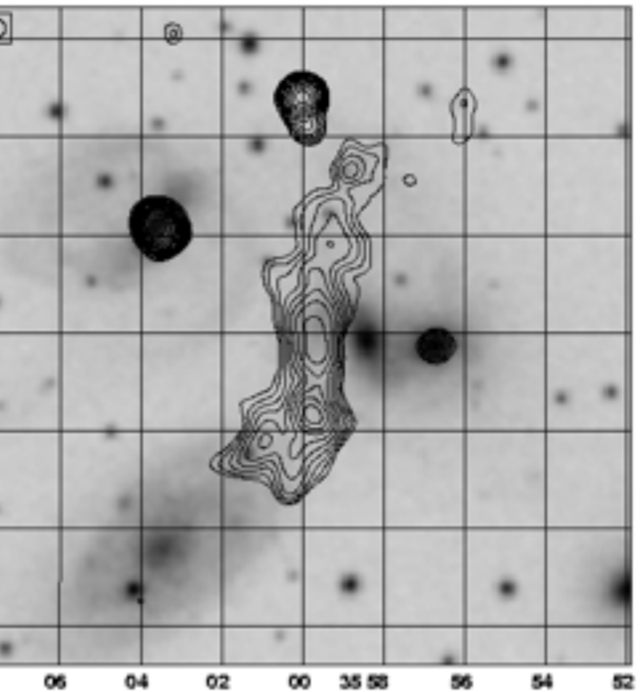
V=5700 km/s

X-rays (Chandra): blue
Optical: CFHT

Stephan’s Quintet: a galaxy collision shocking the IGM

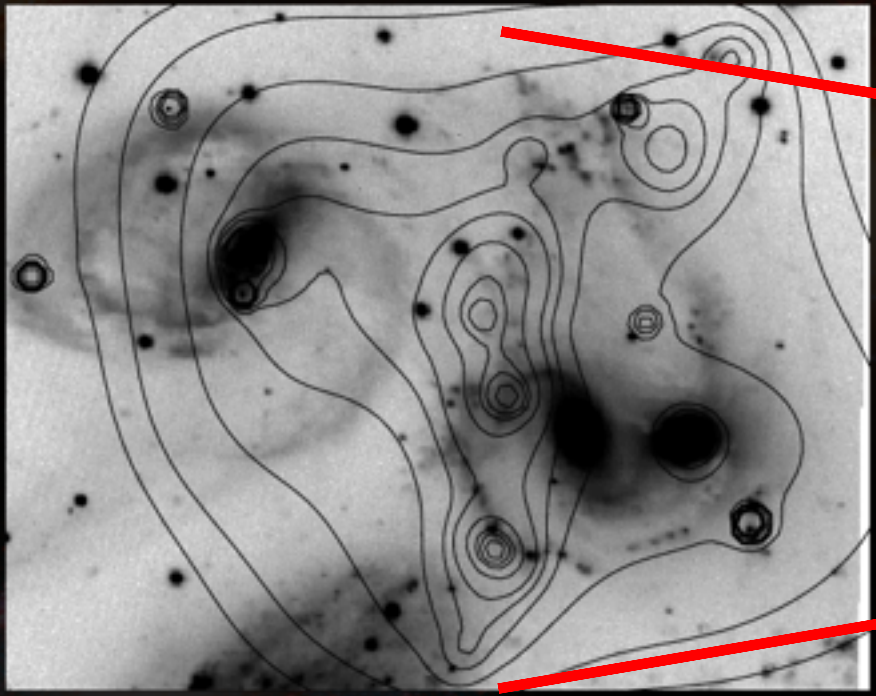
NGC 7318b is crashing into the rest of the group at V ~ 800 km/s : interloper

VLA Observations (20 cm)



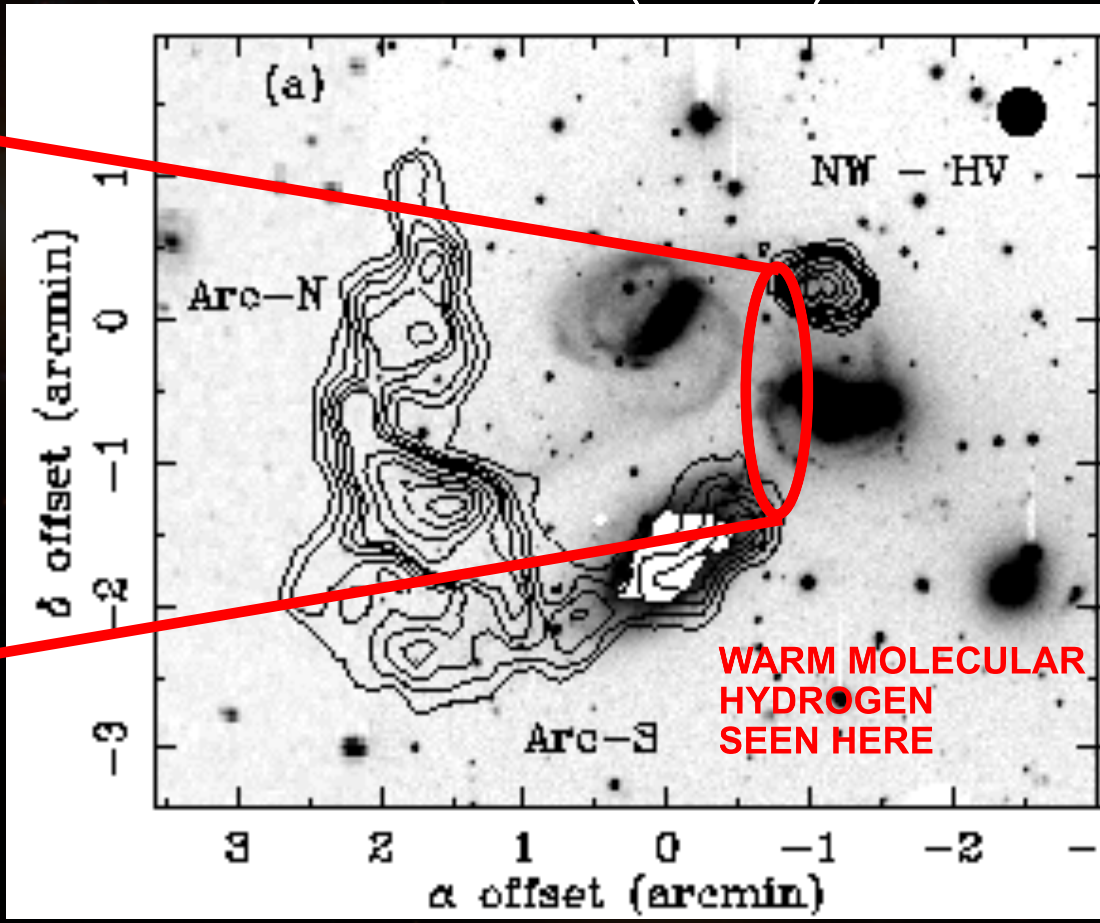
20 cm Radio emission from between galaxies suggested an intergalactic shock (Allen & Hartzuiker 1972)

Hα + Chandra contours



Hot X-ray gas indicating a 600 km/s shock wave (Trinchieri et al. 2003)

VLA Observations (HI line)



WARM MOLECULAR HYDROGEN SEEN HERE

Neutral hydrogen Observations show “gap” in HI where the shock is observed

Isolating the physics of turbulent dissipation against the dark sky!

Pure H_2 spectrum!

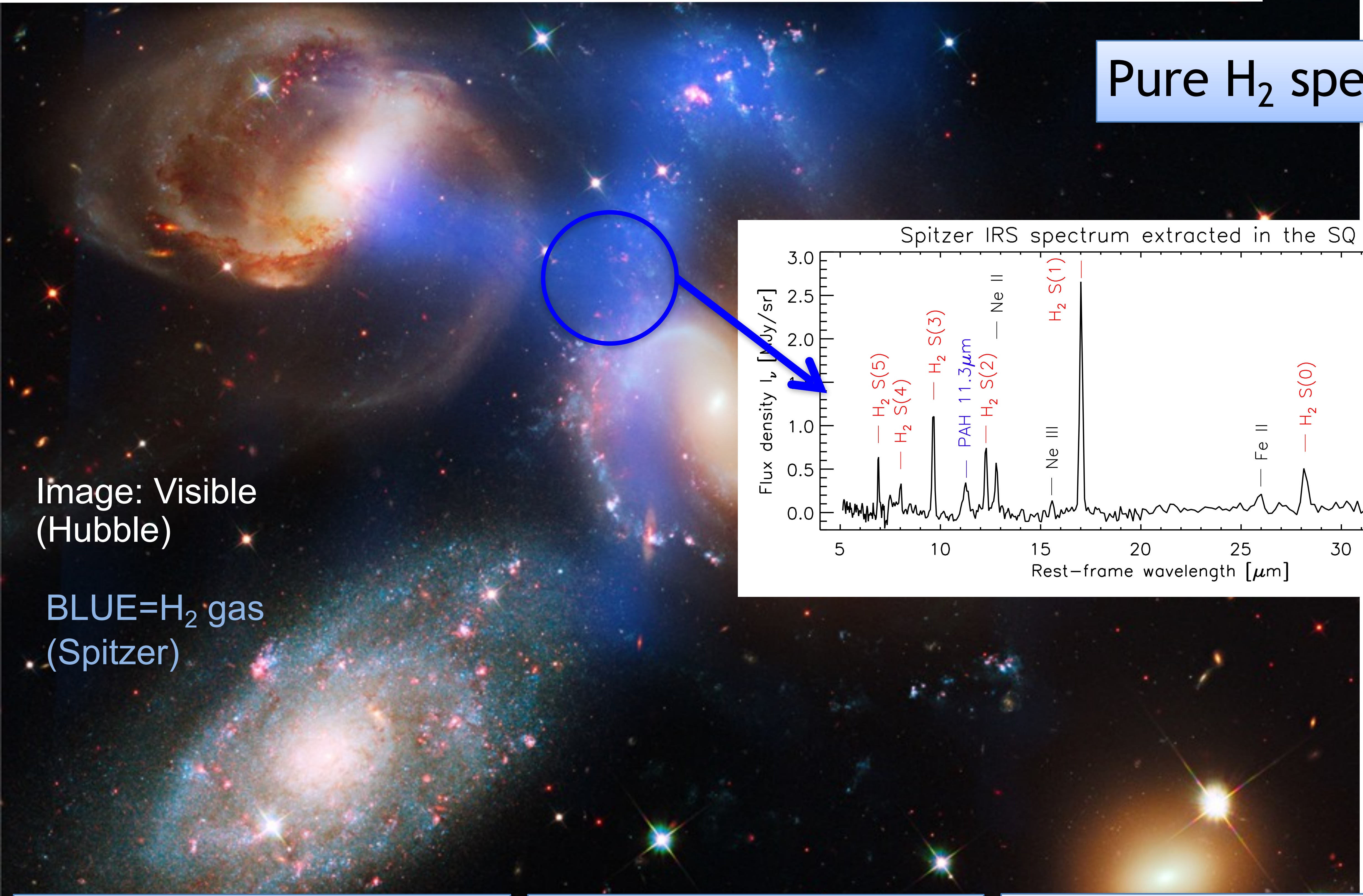


Image: Visible (Hubble)

BLUE=H_2 gas (Spitzer)

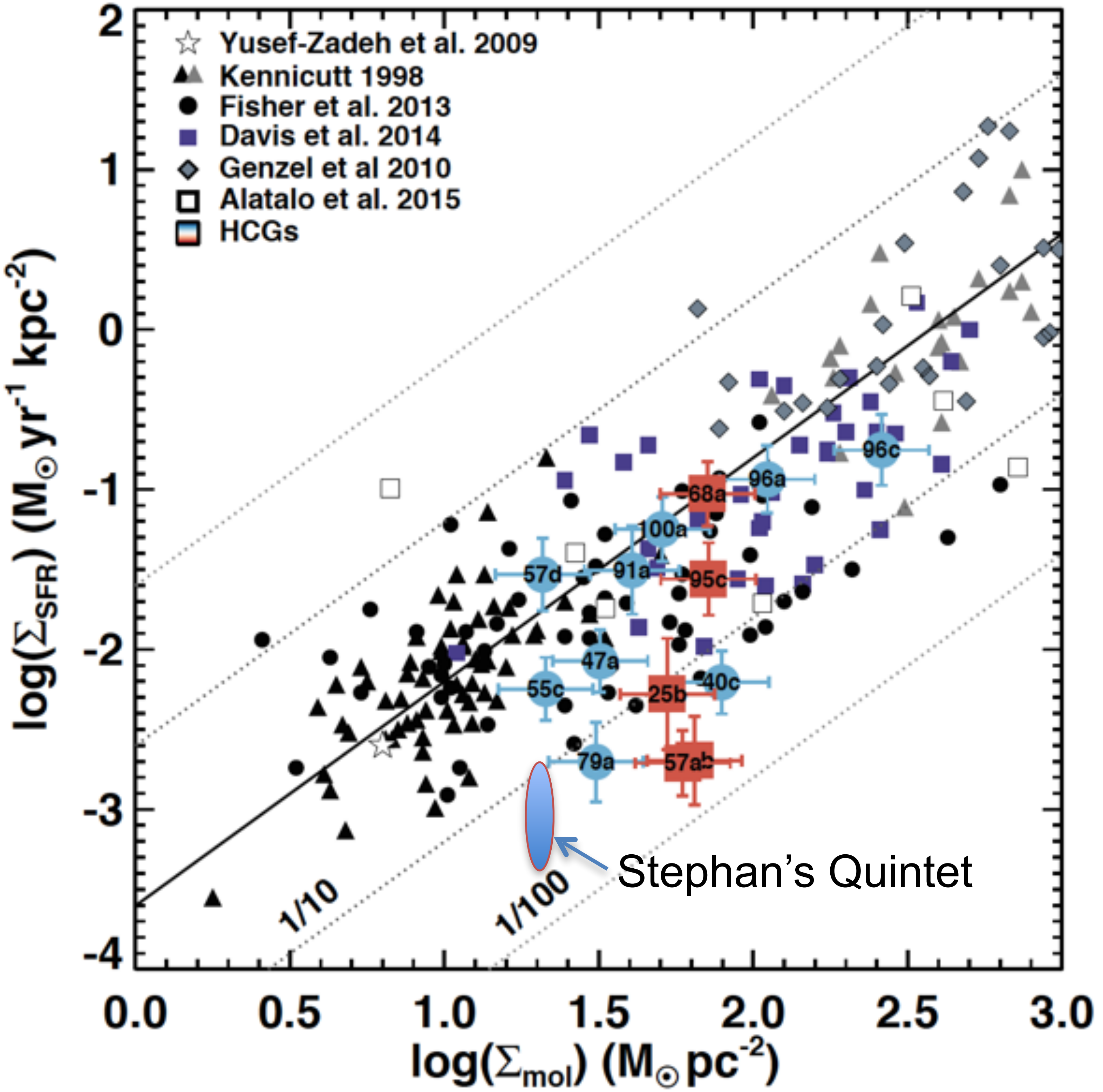
$L(H_2) = 3 \times L(\text{X-rays})$

$M(H_2) = 5 \times 10^9\ M_\odot$

$SFR < 0.07\ M_\odot/yr$

Appleton et al. 2006, Guillard et al. 2009; Guillard et al. 2012b; Cluver et al. 2013

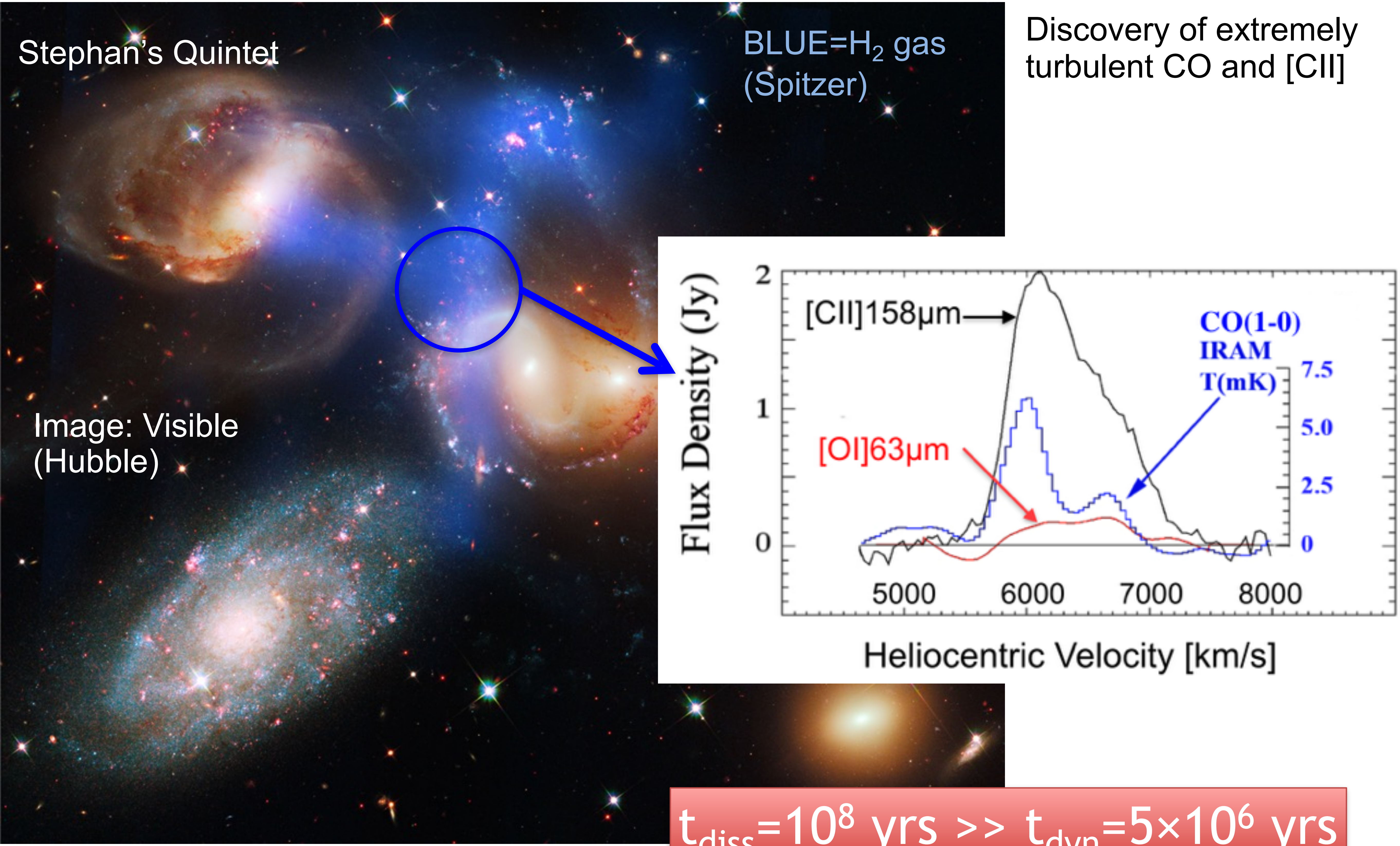
One example amongst other "SF-suppressed" HCGs (cf. Katey's talk + Ute's poster)



Stephan's Quintet

updated from Alatalo et al.
Guillard et al. 2012b, Cluver et al. 2013; Alatalo et al. 2014b, 2015c

The energy of the galaxy collision is not thermalized

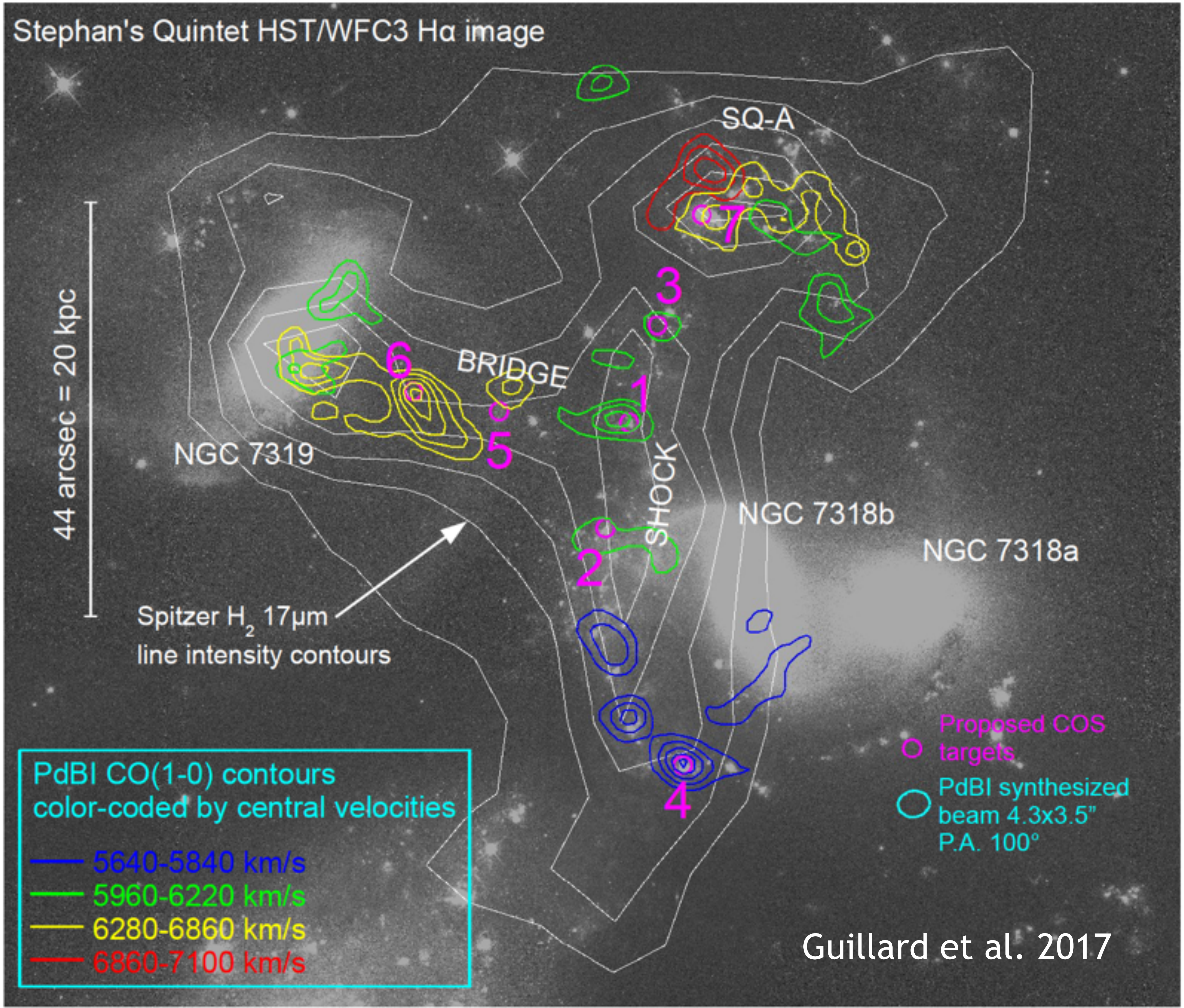


Discovery of extremely turbulent CO and [CII]

$t_{diss}=10^8$ yrs >> $t_{dyn}=5\times10^6$ yrs

Guillard et al. 2009; Guillard et al. 2012b
Appleton, Guillard et al. 2013

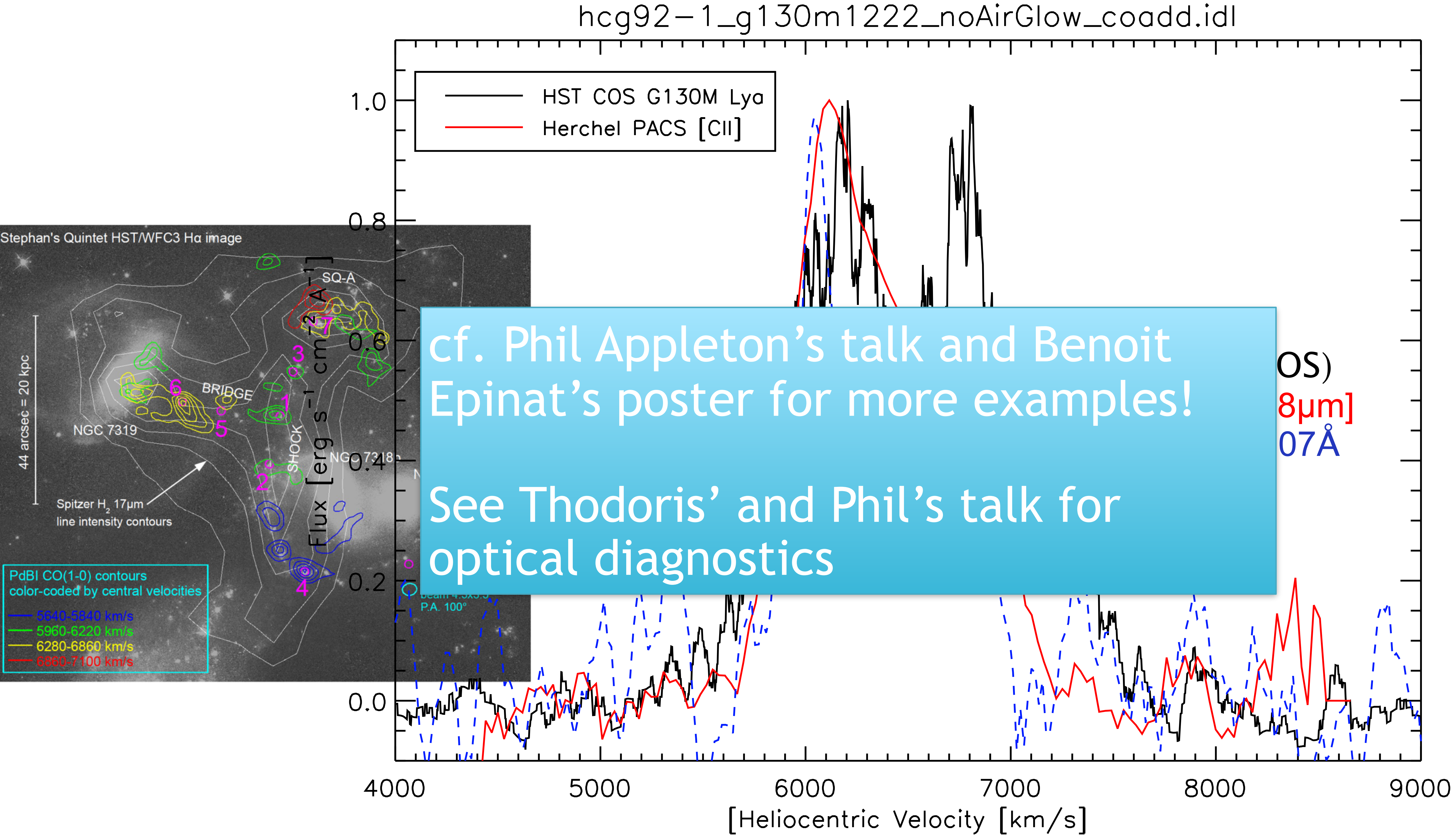
Large CO complexes along the ridge



Guillard et al. 2017

Detection of Ly-α with COS/HST

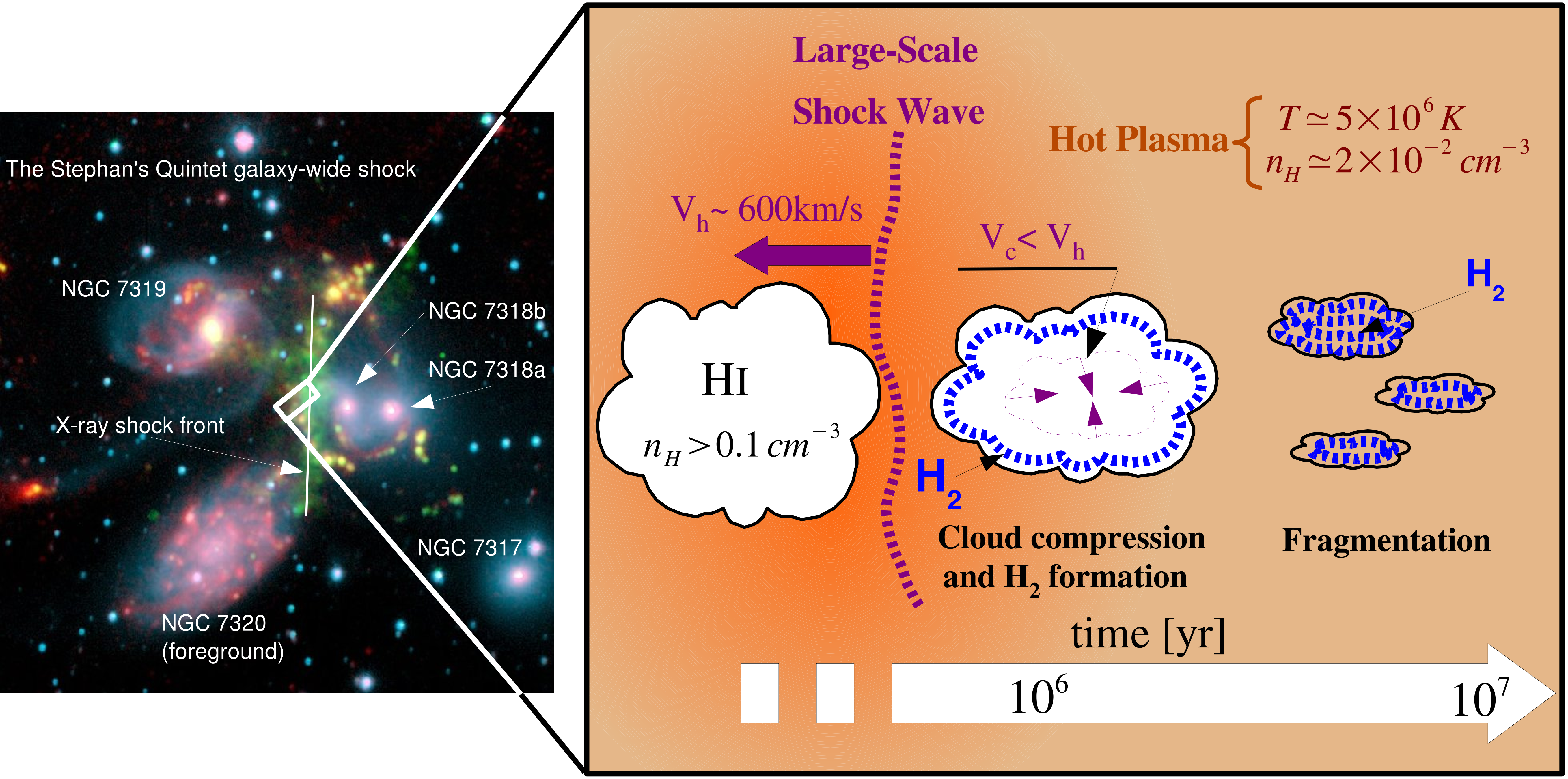
dynamically coupled gas phases at all scales!



cf. Phil Appleton's talk and Benoit Epinat's poster for more examples!

See Thodoris' and Phil's talk for optical diagnostics

Modelling H_2 formation and excitation



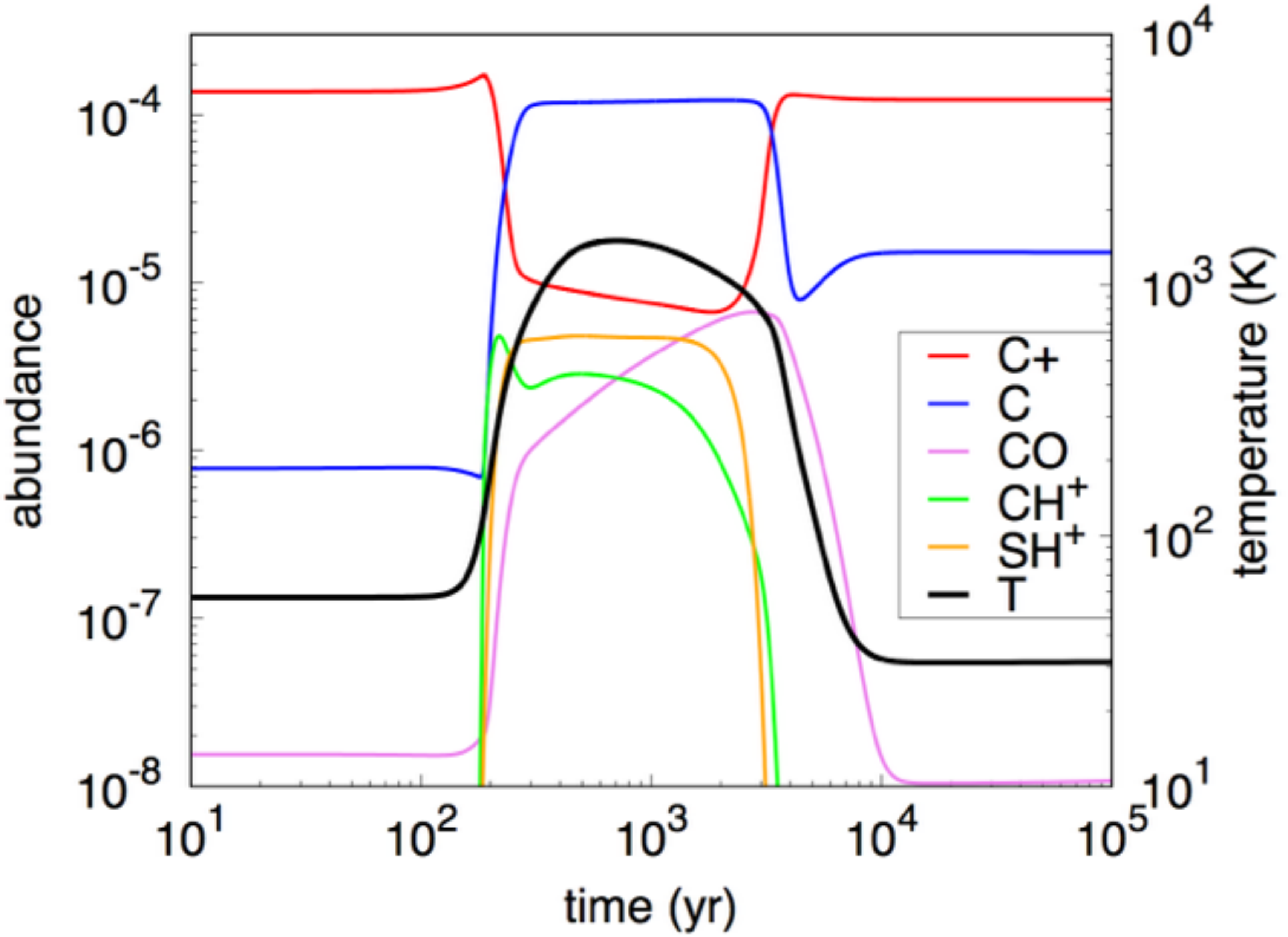
Guillard et al. 2009

Paris-Durham MHD shock model

input conditions

- wave velocity
- magnetic field
- density
- irradiation
- abundances

output - thermo-chemistry



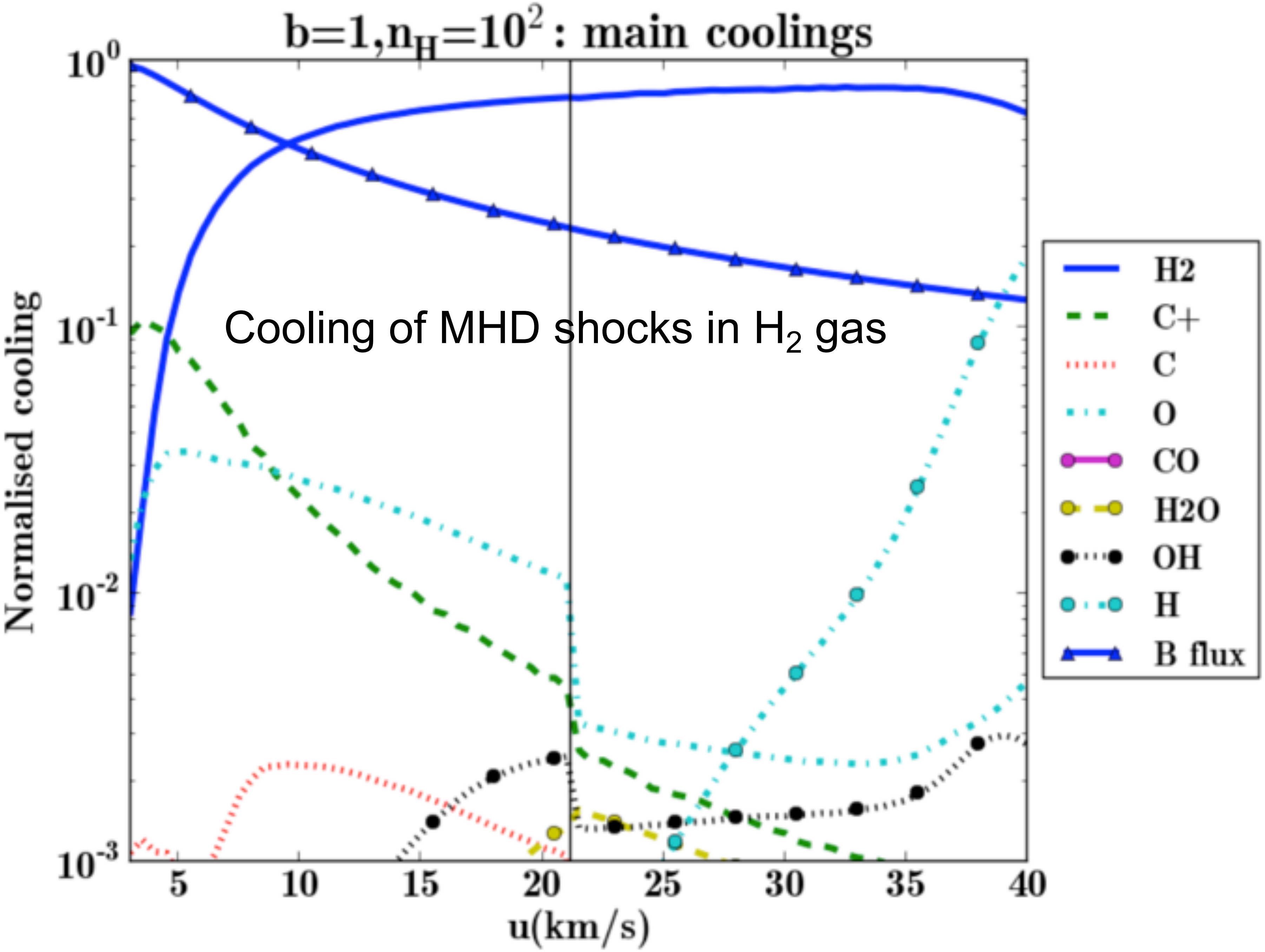
V_S = 20 km s^{-1} B = 20 μG
n_H = 10^4 cm^{-3} G_0 = 1, A_V = 0.1

Flower+03,+15, Guillard+09, Lesaffre+13

H_2 emission from shocks

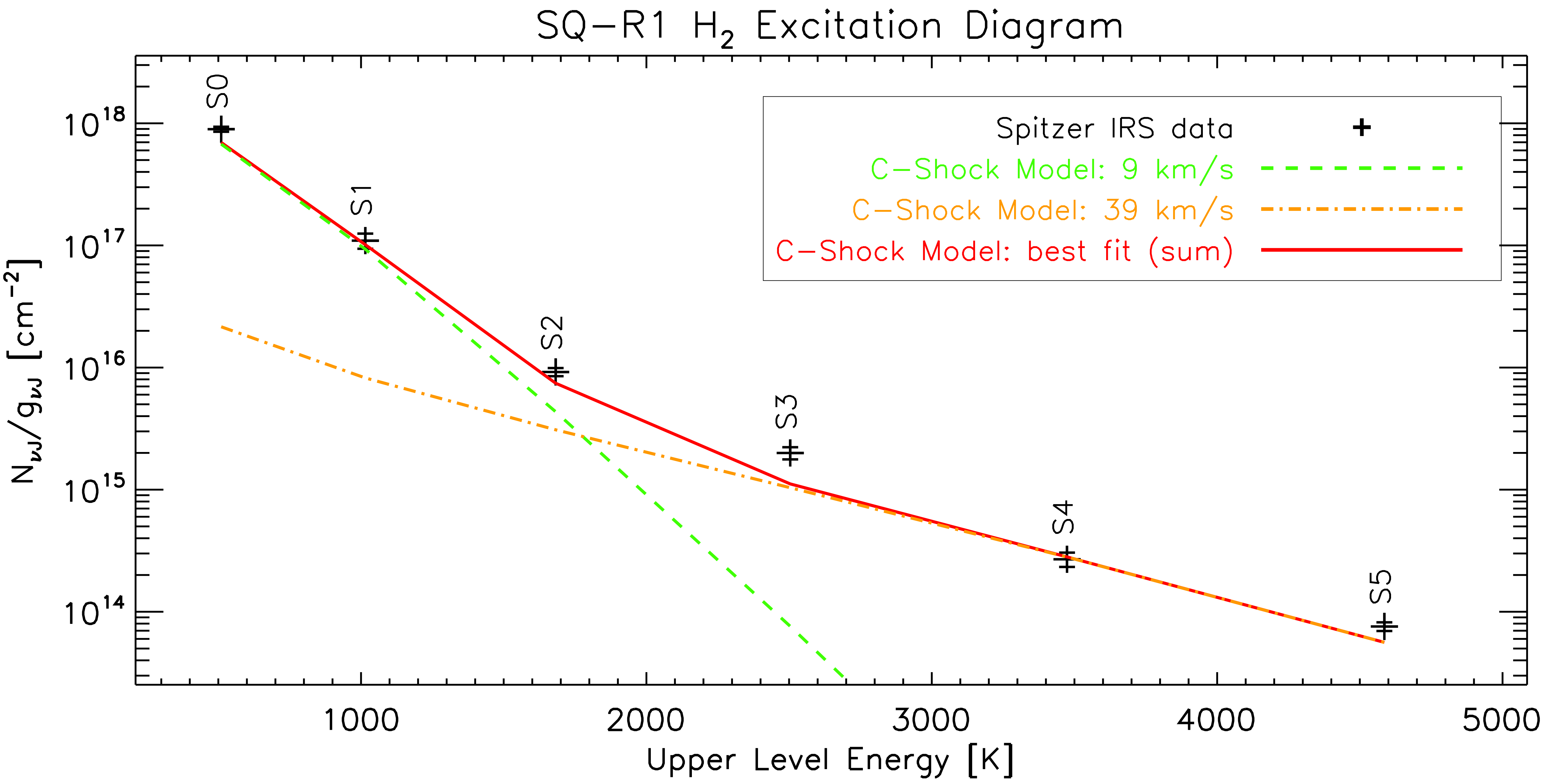
H_2 mid-IR lines are the main cooling lines of shocked molecular for $5 < V_s < 40$ km/s

Shocks trigger the formation of H_2 gas if the gas is initially atomic provided that there is dust (Bergin+2007, Guillard +2009)



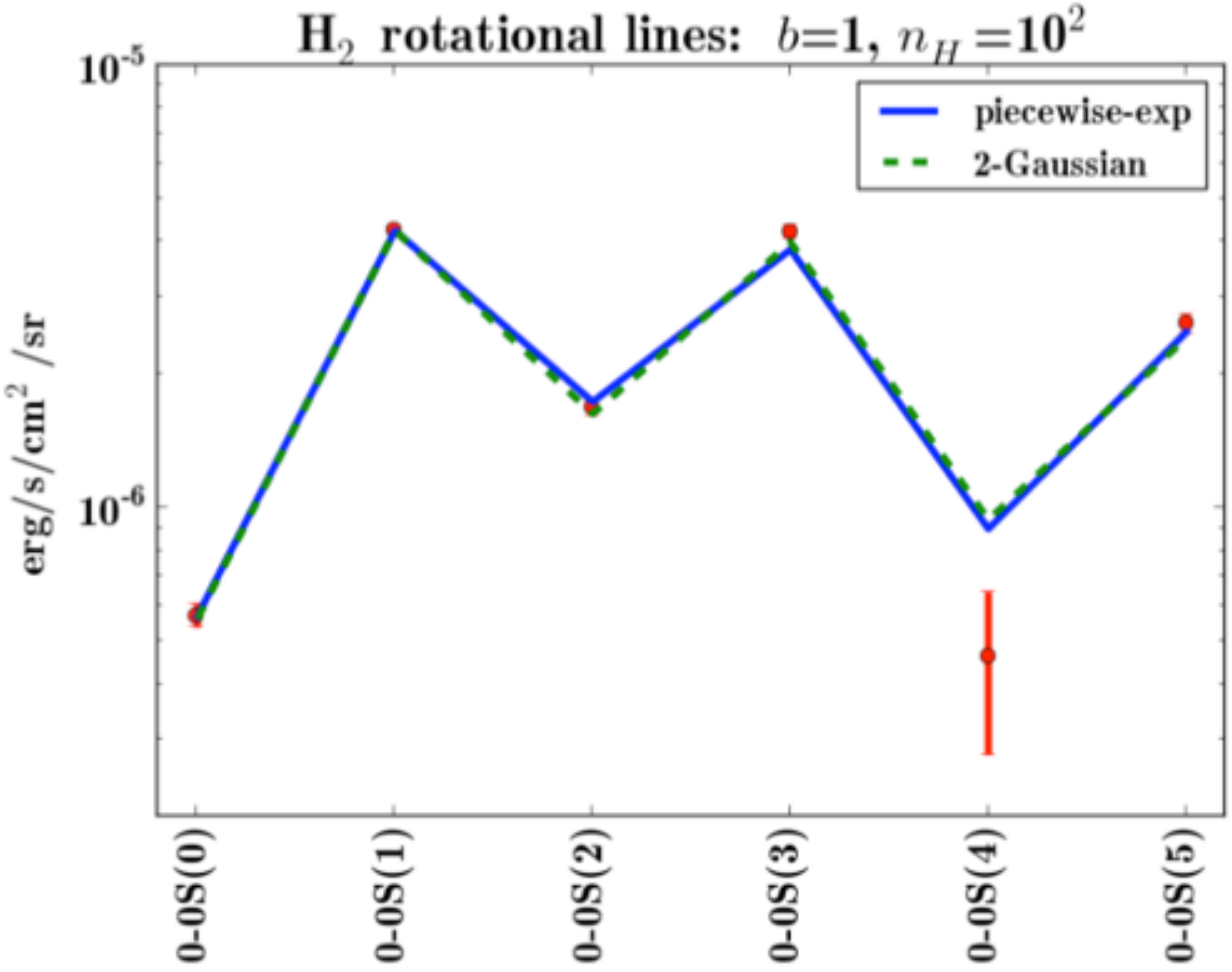
1D models of shocks within diffuse irradiated gas (Flower+15, Lesaffre+13)

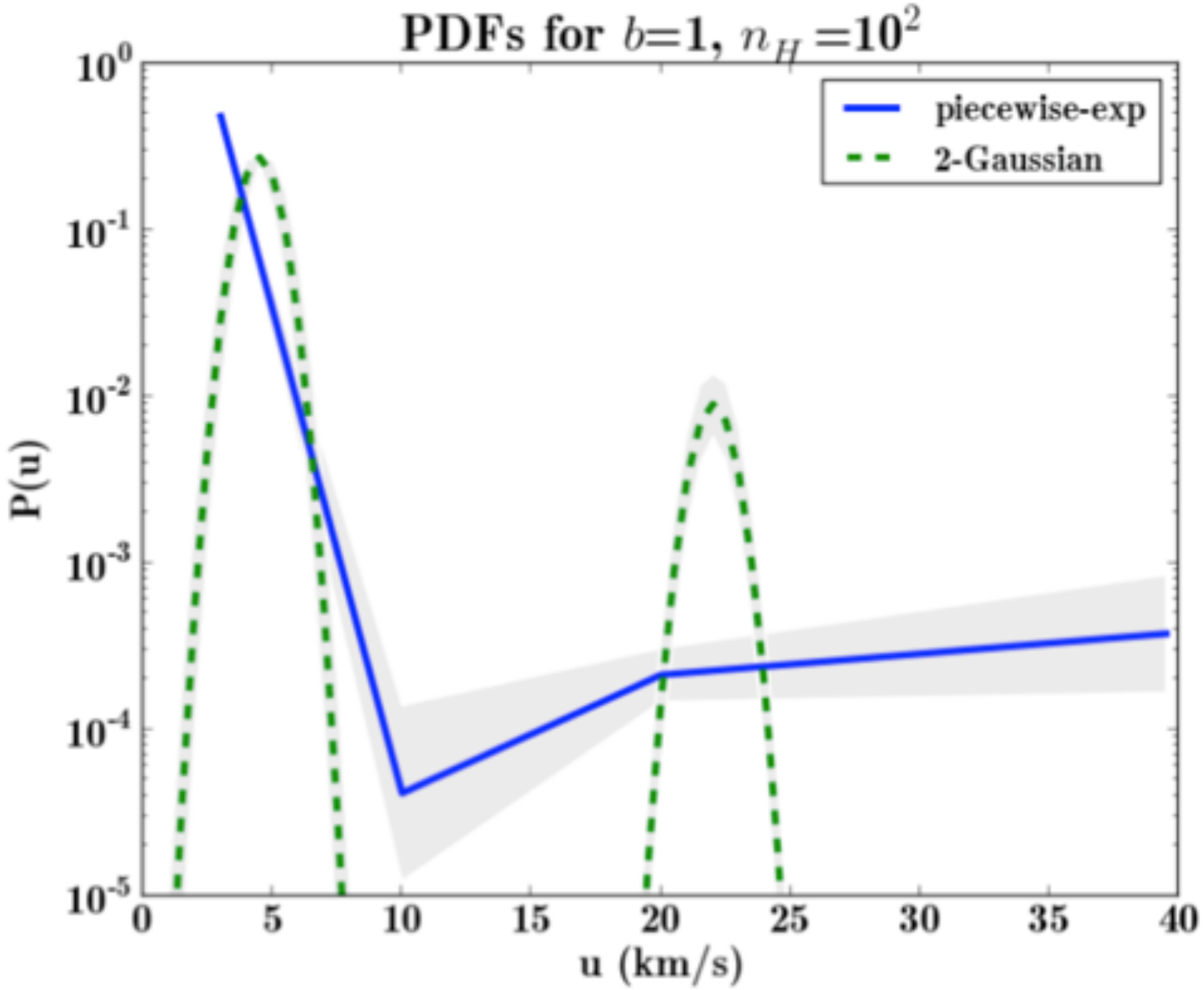
Modeling of H_2 shows that mechanical energy is cascading from large (40 kpc) to small scales (<0.1pc)



Guillard et al. 2009, Appleton et al. 2017

Modelling the H_2 excitation diagram constrains the distribution of turbulence dissipation structures





b	n_H	1-Gauss	pow-law	exp.	pw-exp.	2-Gauss
0.1	10^2	371.8	2307.0	54.3	60.8	11.2
0.1	10^3	504.0	1650.4	152.4	61.1	105.6
0.1	10^4	416.1	2139.9	174.3	580.8	155.3
1	10^2	1628.5	184.2	598.5	**2.6**	**2.0**
1	10^3	139.3	175.1	35.9	5.0	13.8
1	10^4	130.3	1648.0	12.6	6.3	15.8

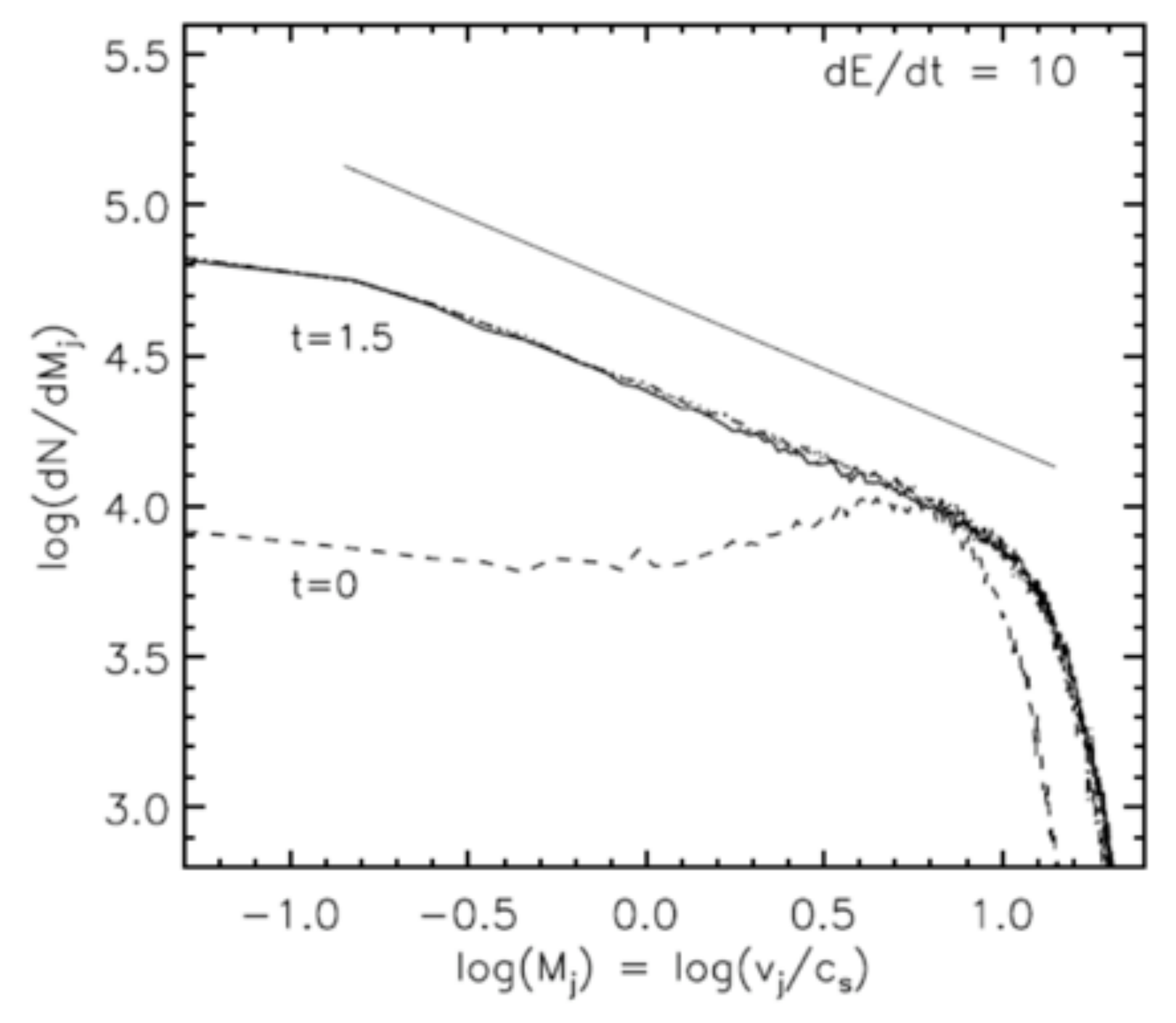
← chi^2 values (6 H_2 lines are fitted simultaneously)

Lesaffre et al. 2013

Probability Distribution Function (PDF) of shock velocities

Driven turbulence

- ➢ power-law PDF

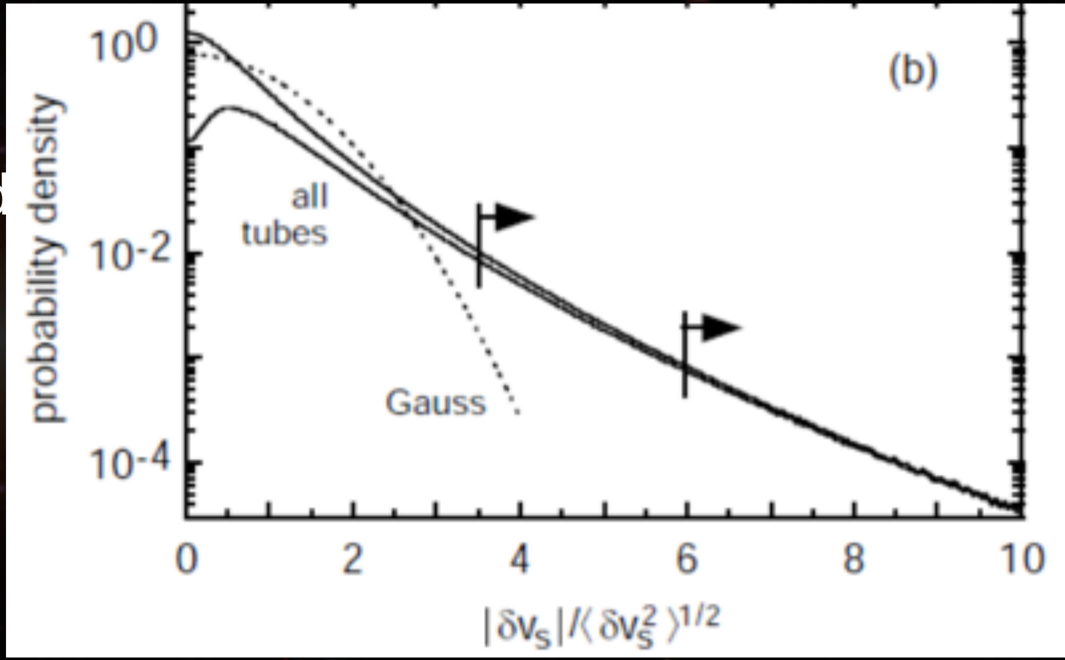


Smith, Mac Low & Heitsch 2000

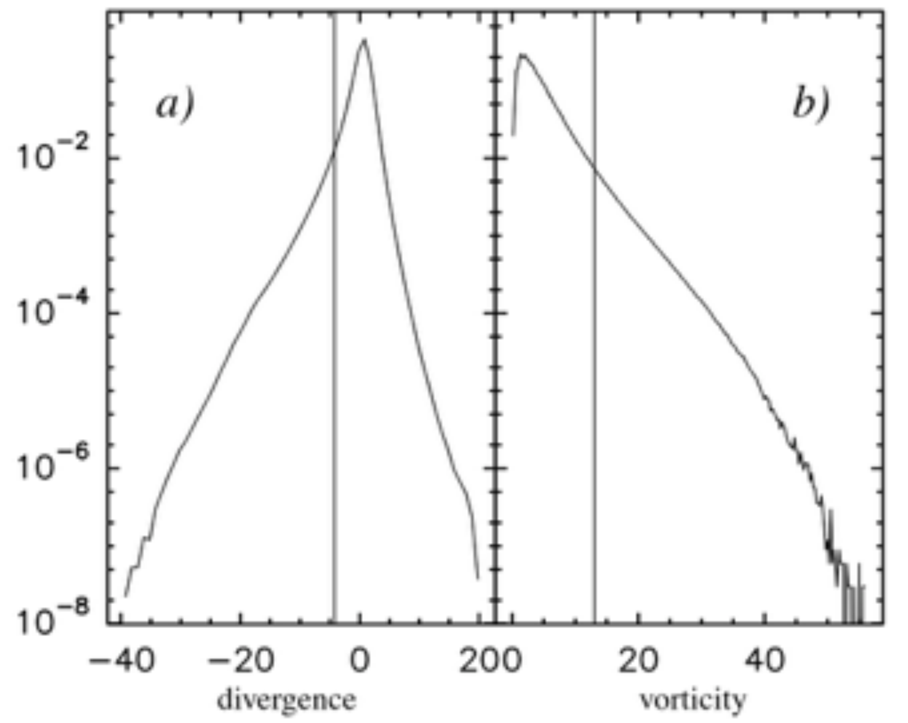
Decaying turbulence

- ➢ exponential PDF

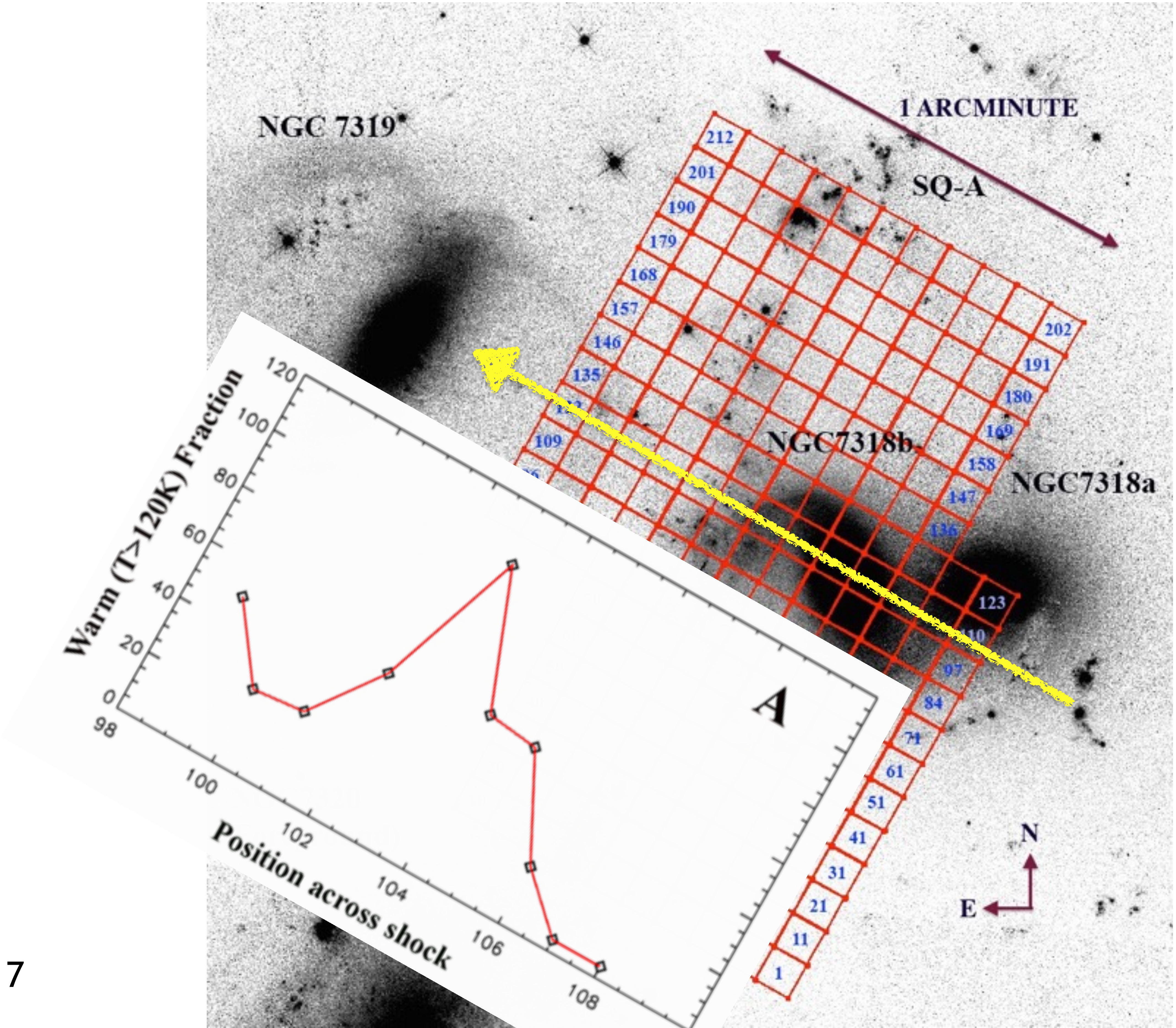
Subsonic wind tunnel experiments: Mouri & Hori 2008



Compressible supersonic turbulence: Pety & Falgarone 2000

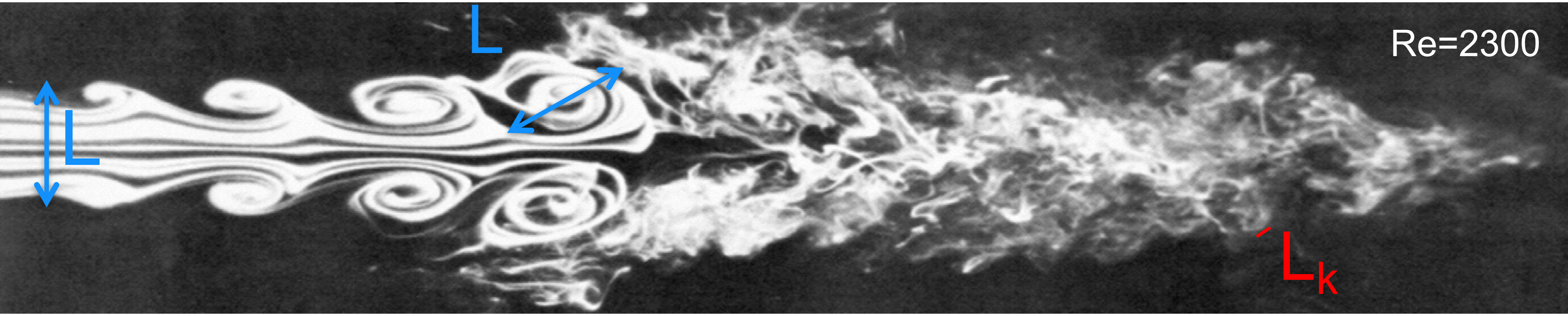


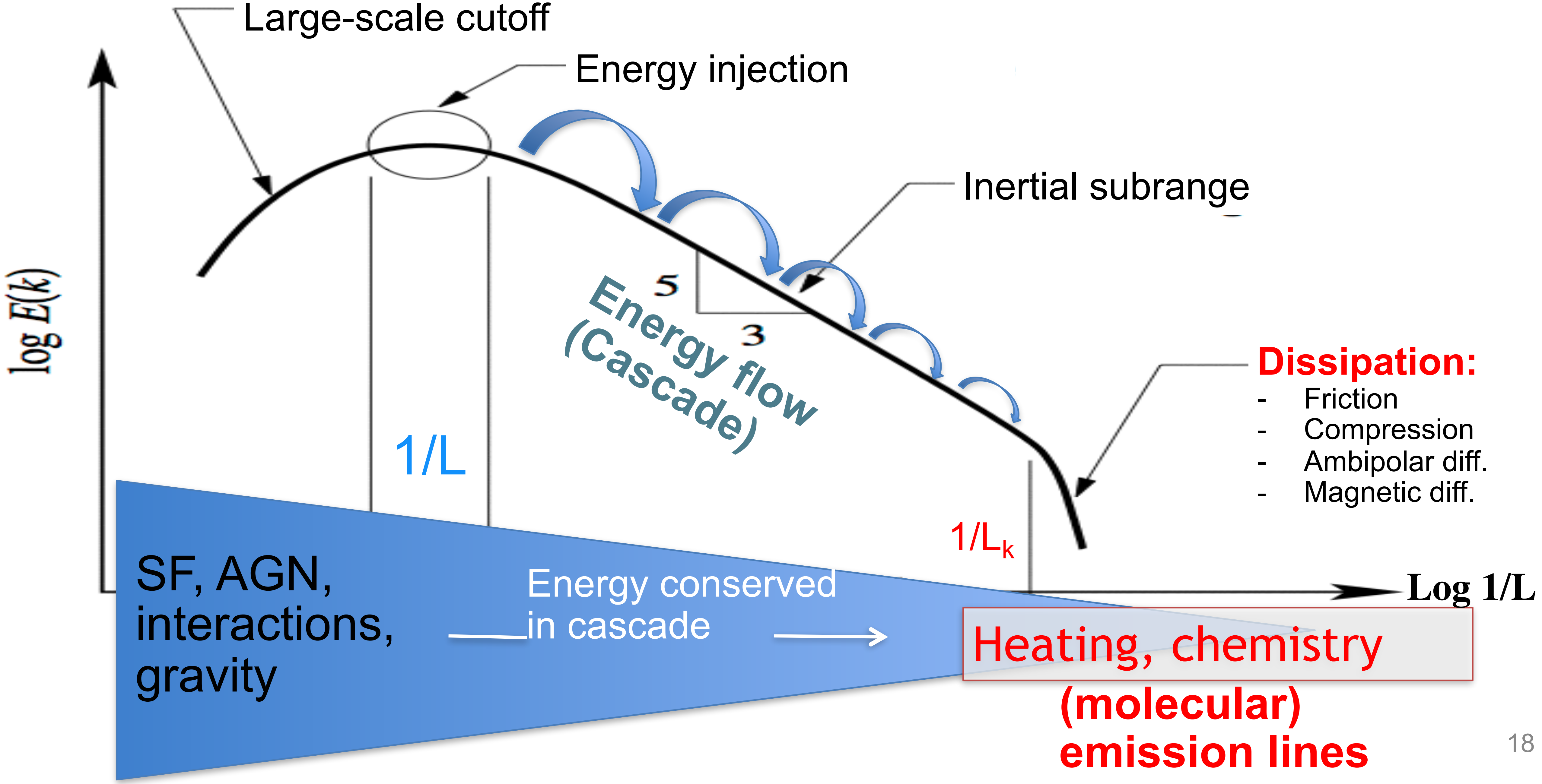
Change of shocked gas properties across the IGM



Appleton et al. 2017

Riding the turbulent energy cascade





Large-scale cutoff

Energy injection

Inertial subrange

Energy flow (Cascade)

Dissipation:

- Friction
- Compression
- Ambipolar diff.
- Magnetic diff.

SF, AGN, interactions, gravity

Energy conserved in cascade

Heating, chemistry

(molecular) emission lines

Let’s shake a small box of ISM gas….

Dissipation in decaying MHD turbulence

Isothermal 3D MHD, (Mach 4, ABC)

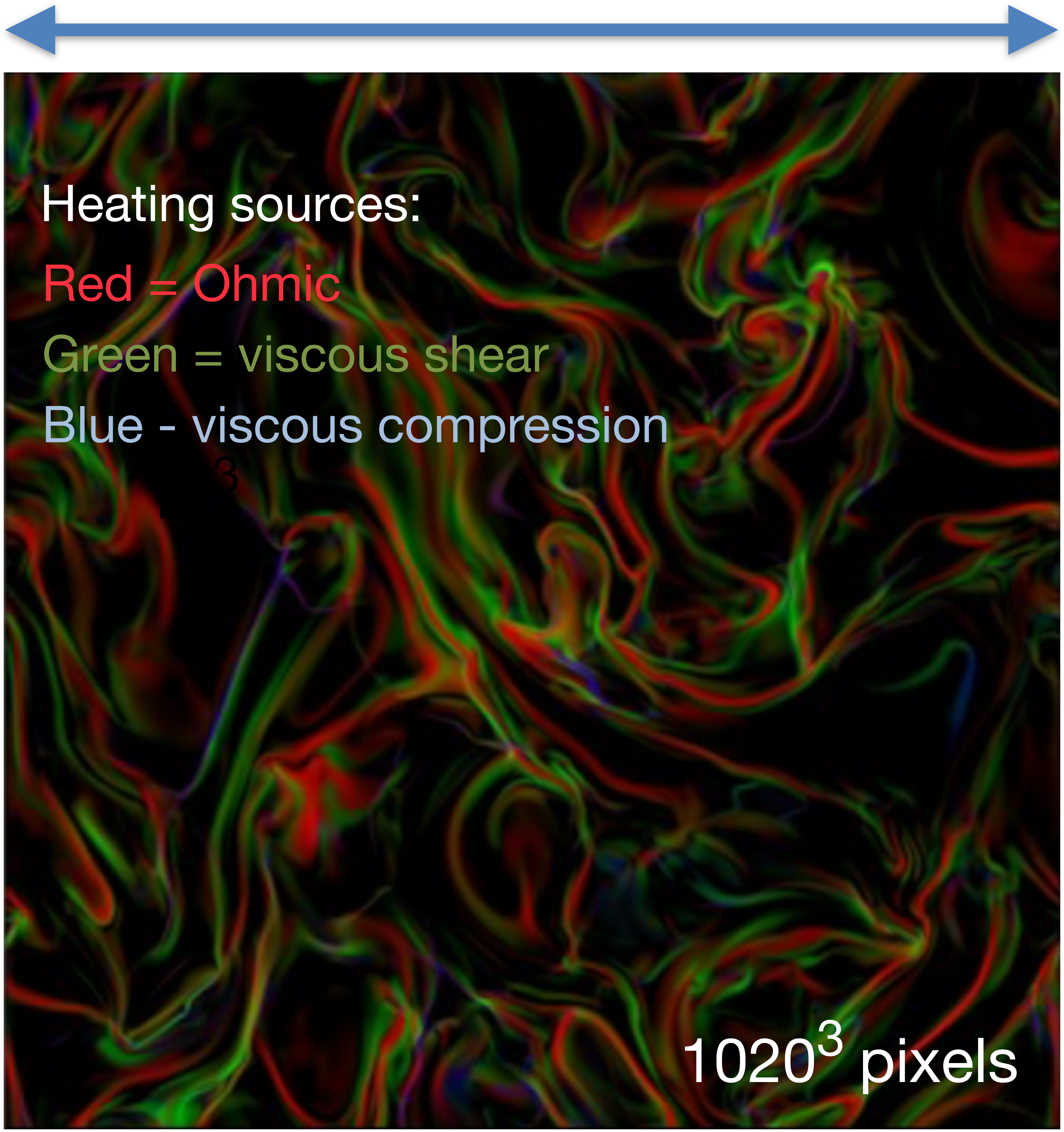
$n_H \sim 100 \text{cm}^3$

$<u^2>\sim<b^2/\rho>$

$\text{Re} \;=LU/\nu \sim \cancel{2.10^7}\;\; 10^3$

$\text{Re}_m=LU/\eta \sim \cancel{2.10^{17}}\;\; 10^3$

RAMSES simulations with careful treatment of viscous and resistive dissipation: DUMSES (Momferratos, PhD)



Heating sources:

Red = Ohmic

Green = viscous shear

Blue - viscous compression

Coupling chemistry and MHD

CHEMSES = RAMSES + DUMSES

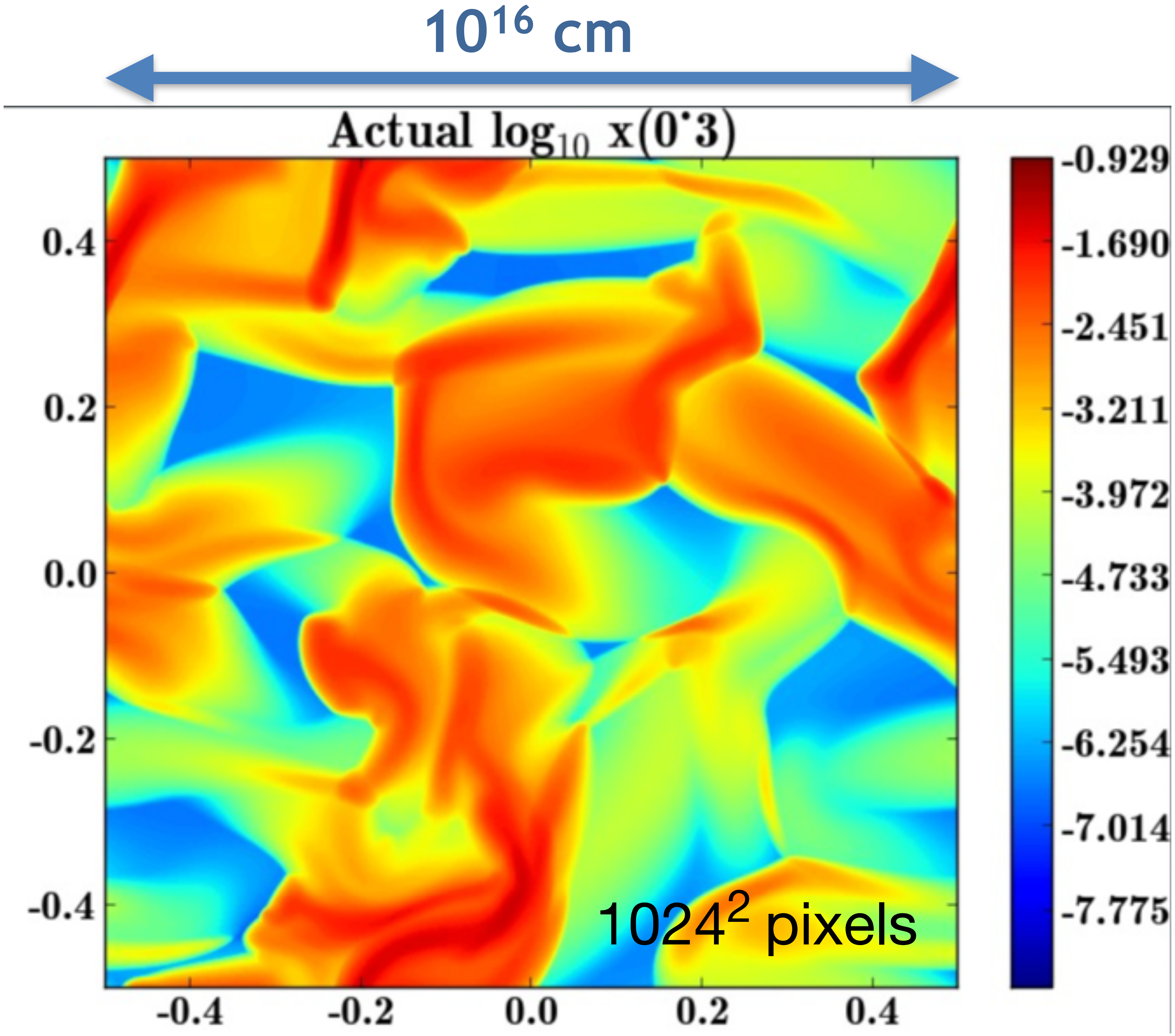
ACTUAL
viscous dissipation

32 species,
7 H_2 levels

Uniform Irradiation:
G_0=1, Av=0.1

$n_H \sim 100/cm^3$

=> molecular, but
without CO.

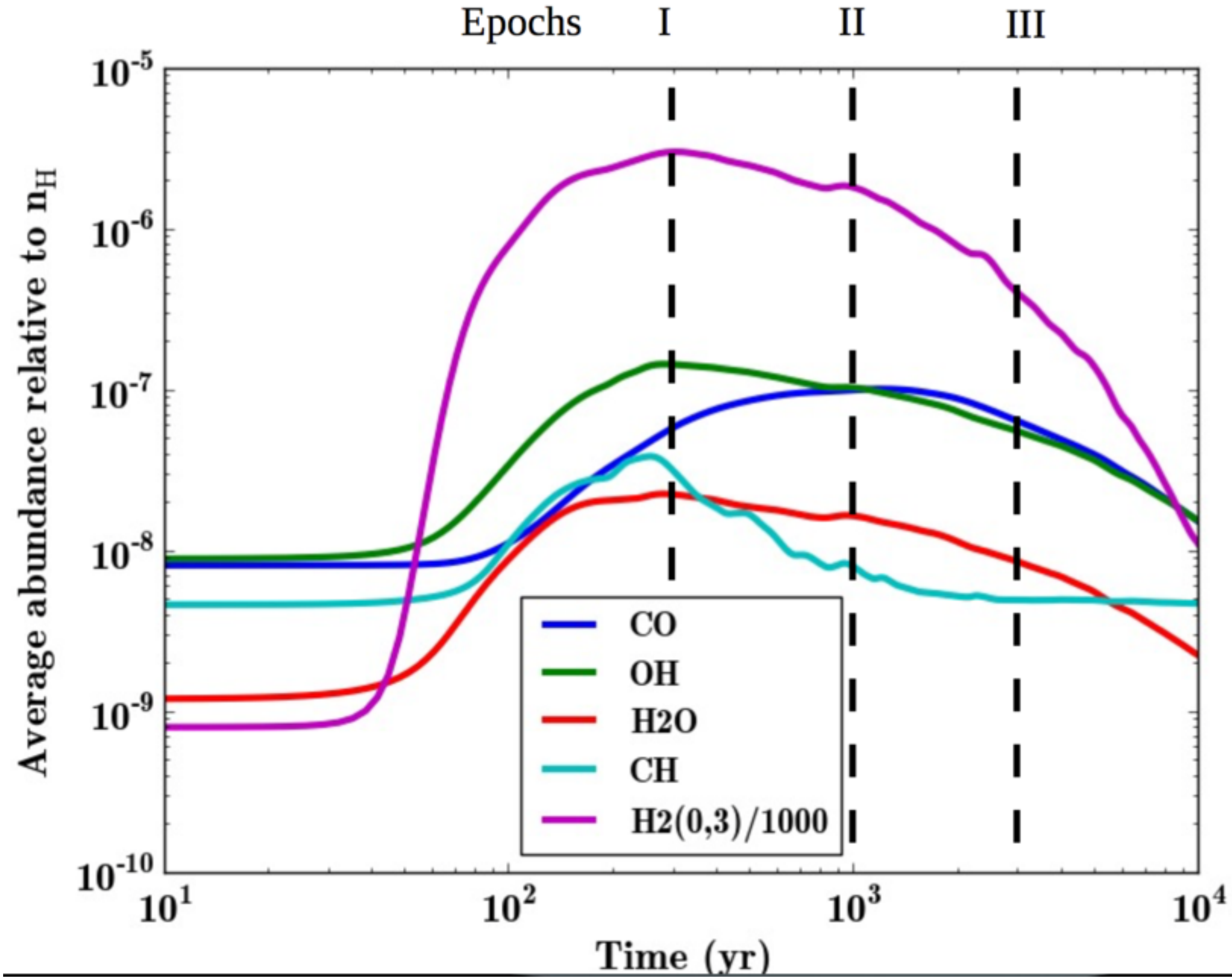


Map of H_2 v=0, J=3

Production of molecules and H_2 excitation by dissipation of turbulence

G_0=1

Av=0.1



Lessons learned

From line luminosities and energy balance arguments:

- Molecular cooling rate can be higher than X-ray cooling
- Gas cooling is controlled by the dissipation of turbulent energy
- Turbulent dissipation time >> dynamical time

From kinematics:

- Mechanical energy >> thermal energy
- The gas has to cool dynamically (not only thermally).
- The different gas phases are kinematically coupled

From shock models and simulations:

- Turbulence is supersonic in the dense phase
- Amplitude of turbulence is beyond what is explored in current models/simulations of star formation
- Large dynamical range of spatial scales: ~100 kpc — 0.01pc

Merci !

http://www.sensitivelight.com/smoke2/