theory of star formation

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this talk contains strong personal biases and selection effects

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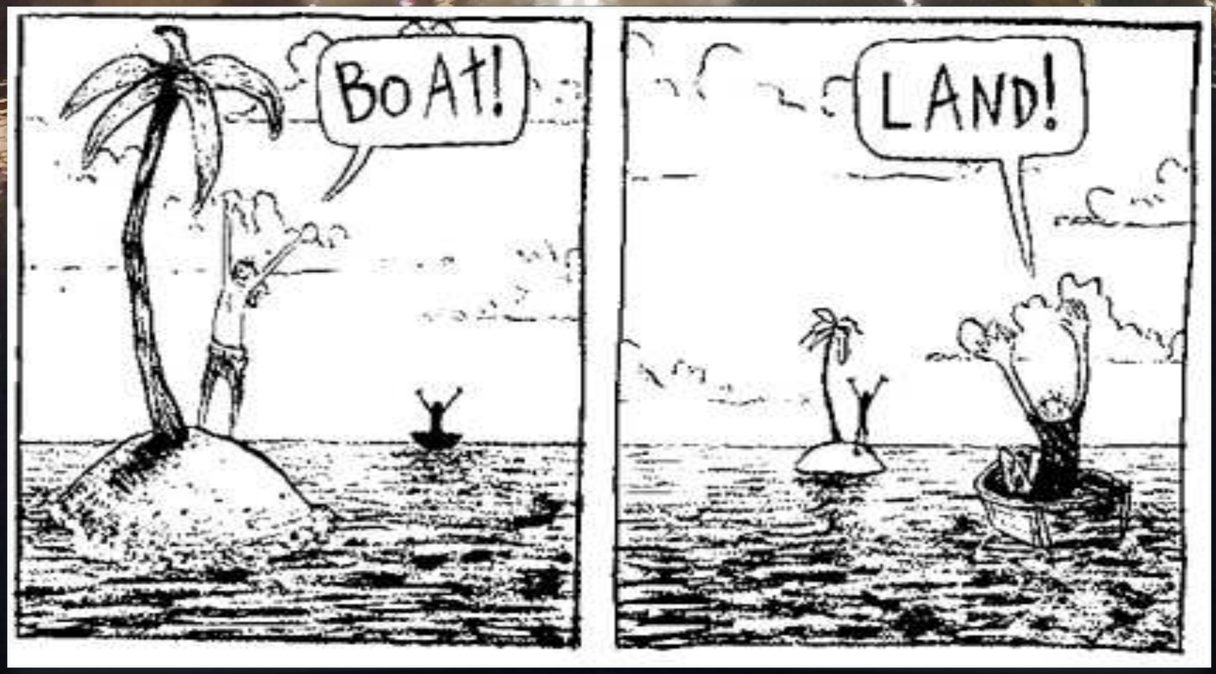
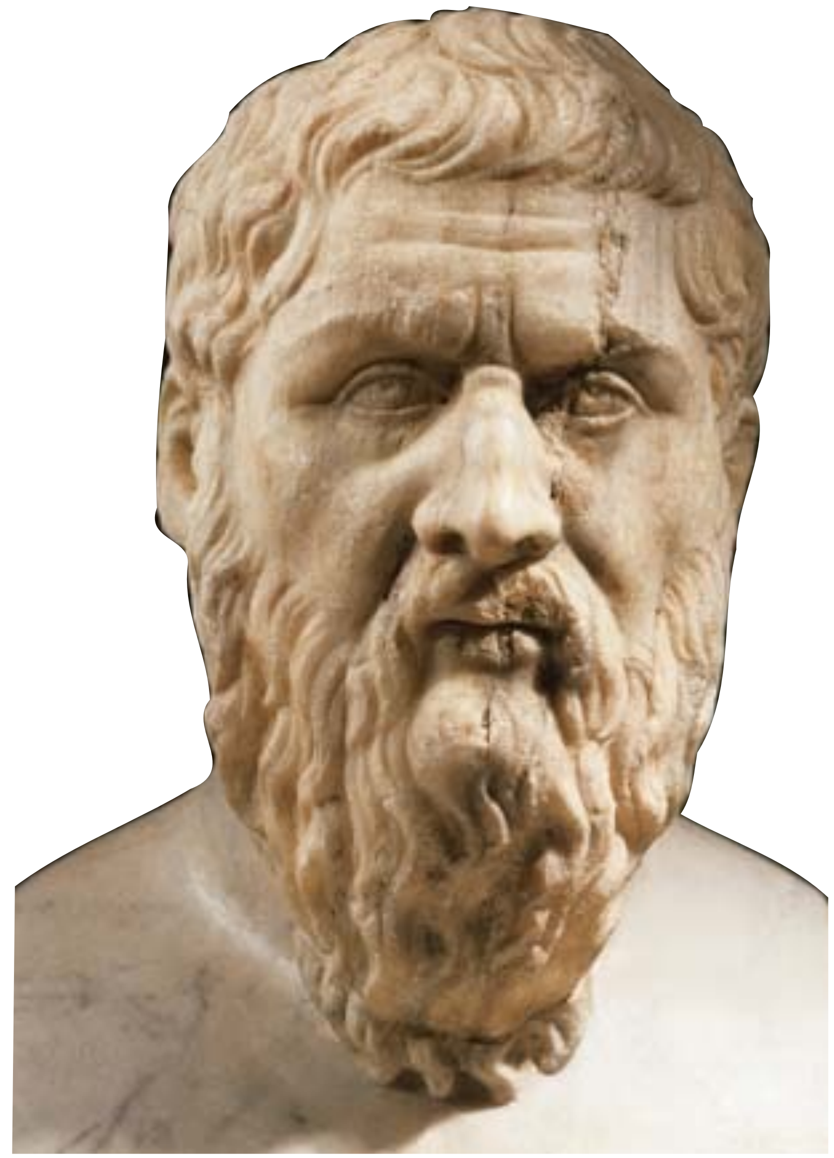


agenda

- prolegomenon
- theoretical remarks
- ISM dynamics and star formation on large scales
- some thoughts about the future

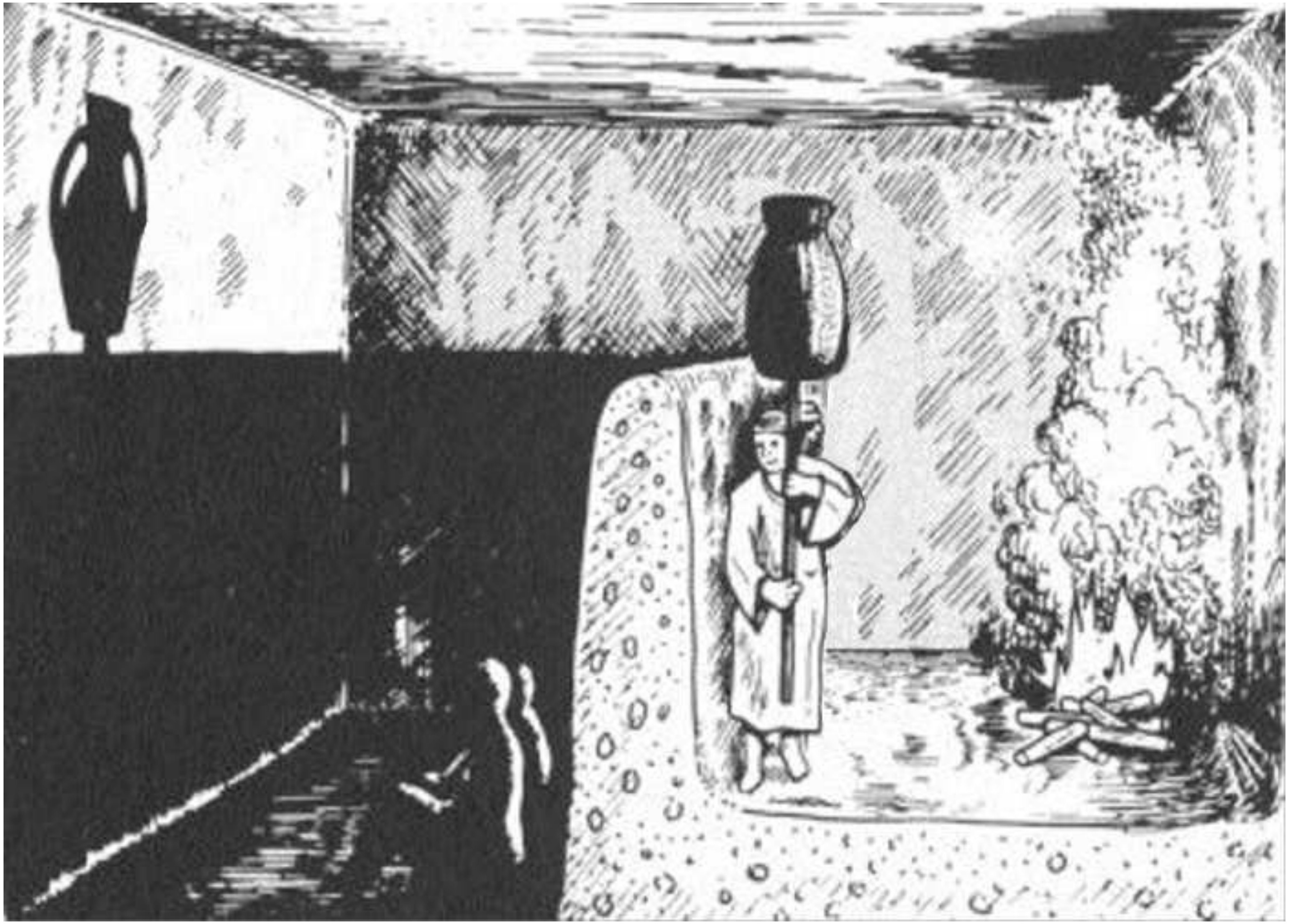

prolegomenon



Platon
428/427 – 348/347 BC

Capitoline Museum, Rome.

Plato's allegory of the cave*



* The Republic
(514a-520a)

Laszlo Szücs, image from criticalthinking-mc205.wikispaces.com

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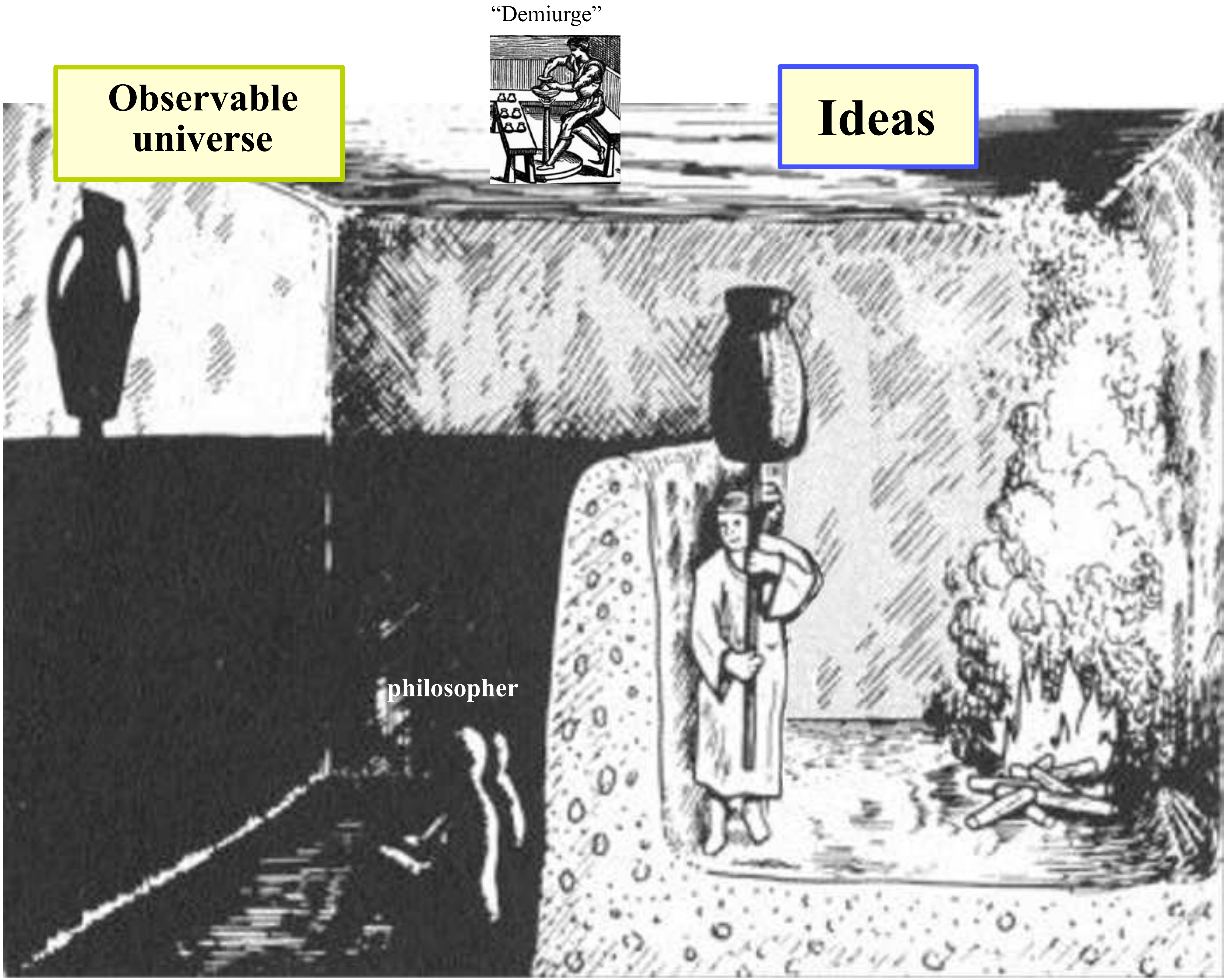

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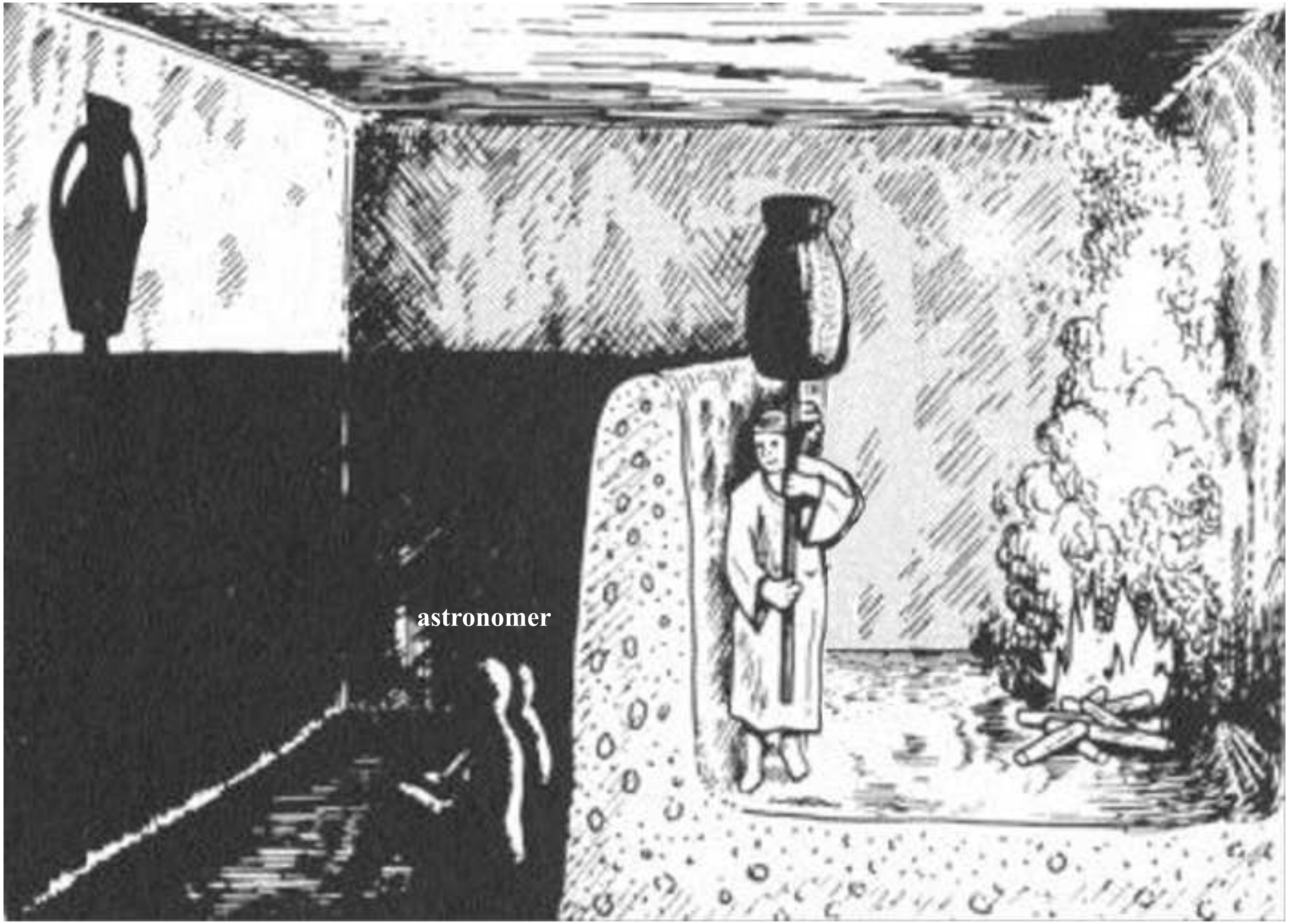
Plato's allegory of the cave* ↔ Astronomical observations



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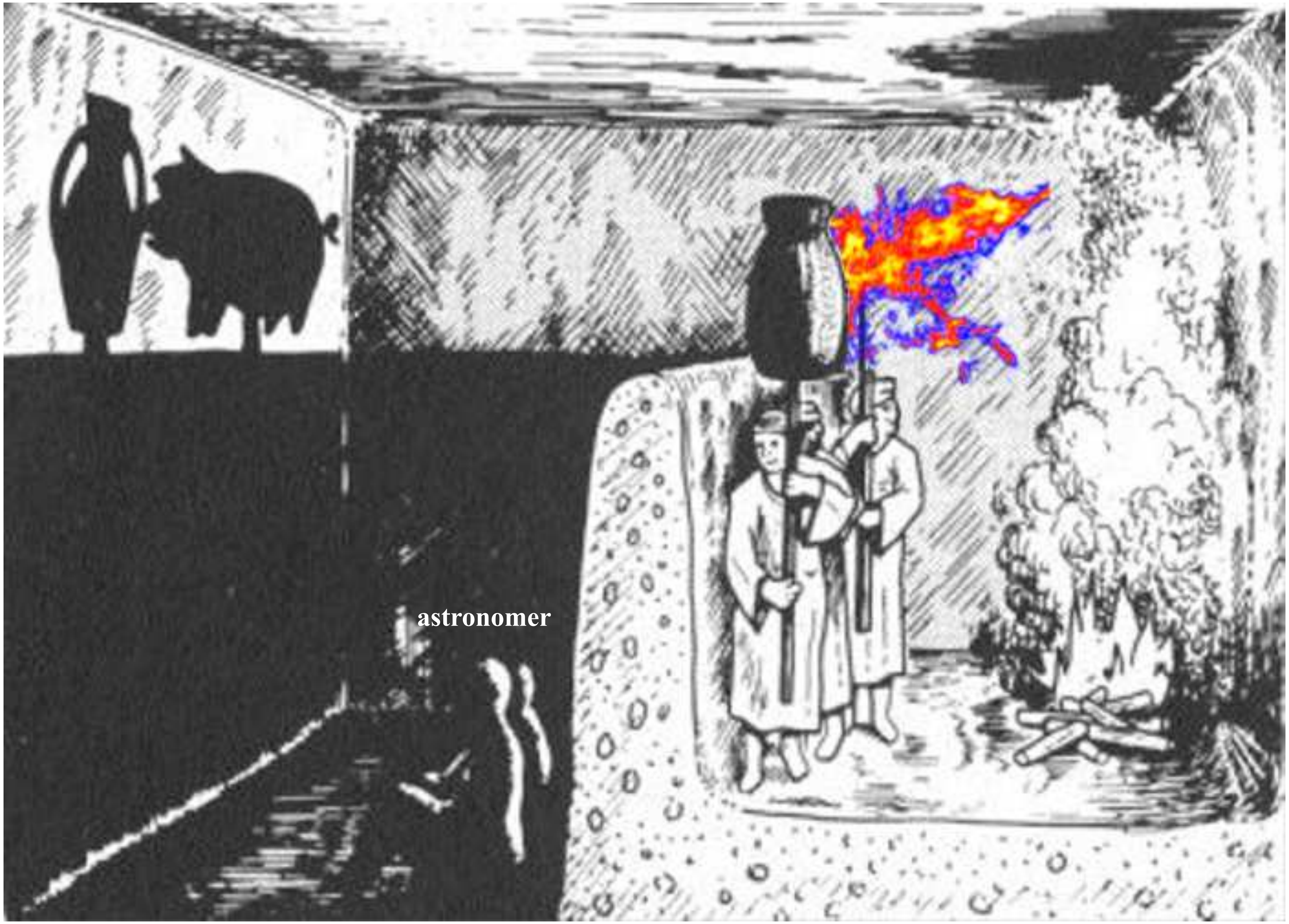

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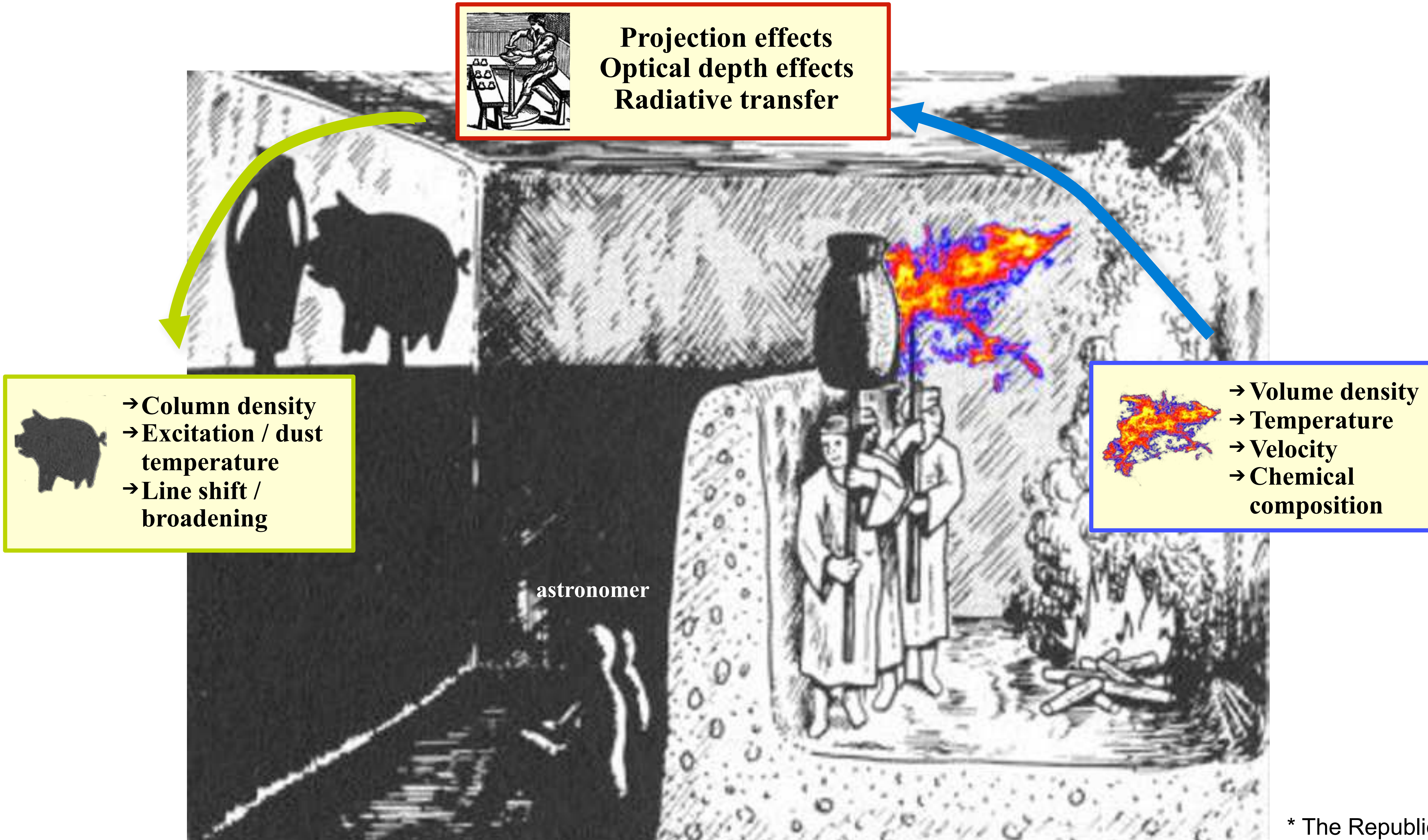

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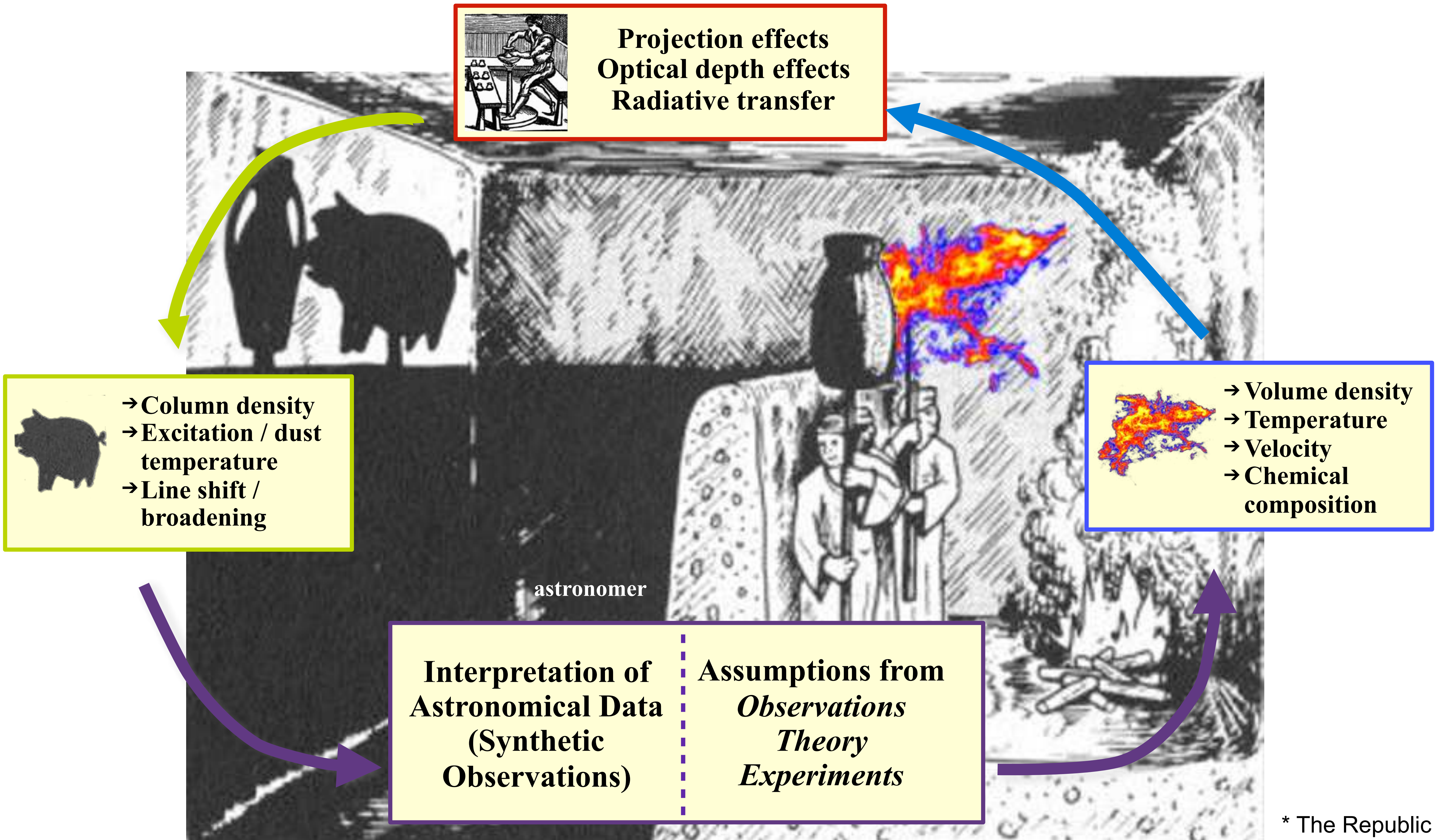

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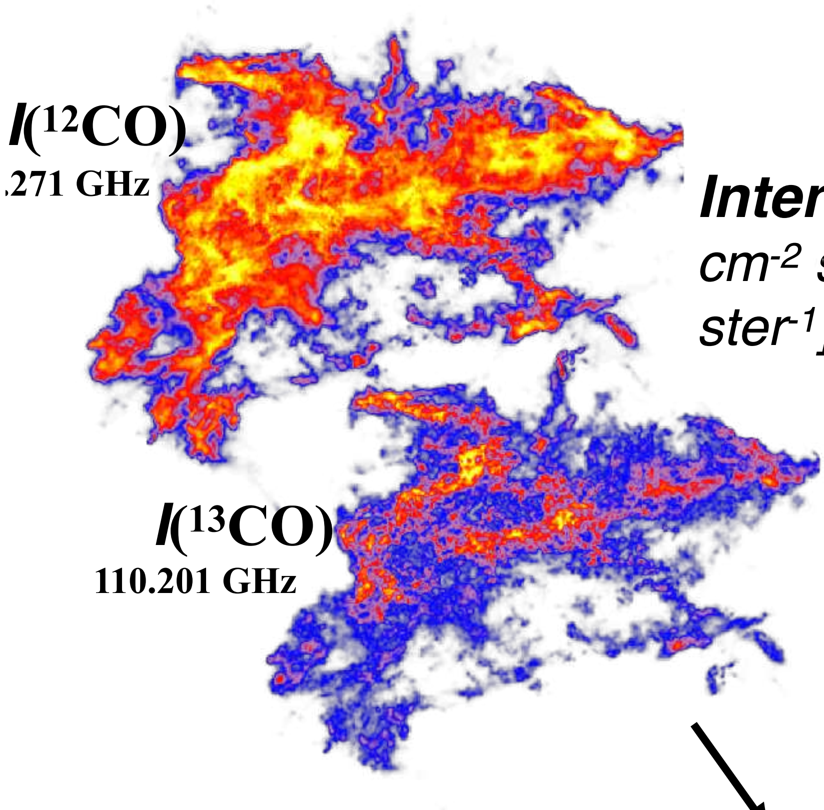
Example: from CO emission to total column density



Intensity *[erg cm^{-2} s^{-1} Hz^{-1} ster^{-1}]*

Brightness temperature *[K]*

T_B^{12}

T_B^{13}

Following Wilson et al. 2009

Assumptions I.

$I(^{12}CO)$ is optically thick

$I(^{13}CO)$ is optically thin

Along a line of sight uniform T_{ex} and same for ^{12}CO and ^{13}CO

$$T_{\rm ex} = 5.5/\ln\left(1 + \frac{5.5}{T_B^{12} + 0.82}\right)$$

$$\tau_{13}(v) = -\ln\left[1 - \frac{T_{\rm B}^{13}}{5.3}\left\{\exp\left(\frac{5.3}{T_{\rm ex}} - 1\right)^{-1} - 0.16\right\}^{-1}\right],$$

LTE

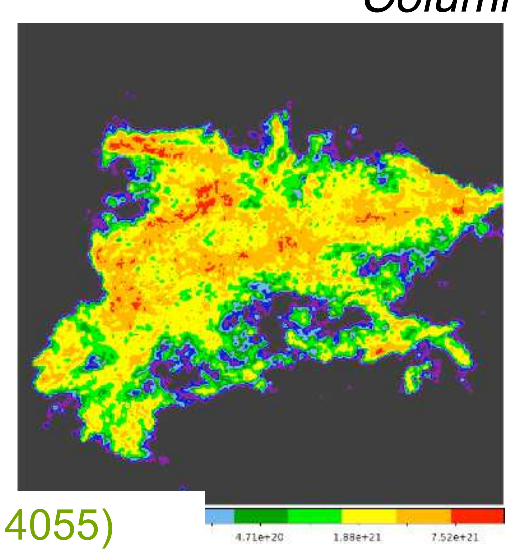
$$N(^{13}{\rm CO}) = 3.0\times10^{14}\,\frac{T_{\rm ex}\int\tau_{13}(v)dv}{1-\exp(-5.3/T_{\rm ex})}$$

Assumptions II.

Uniform $N(^{12}CO)/N(^{13}CO) \sim 60$ *

$N(H_2)/N(^{12}CO)$ ratio $\sim 6.6\times10^3$ **

Column density [cm^{-2}]



Astrophysical interpretation

Laszlo Szücs et al. (2014, MNRAS, 445, 4055)

* Langer & Penzias (1990)

** Pineda et al. (2009)

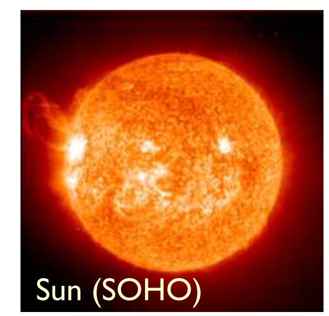

thoughts on theory

decrease in spatial scale / increase in density


Andromeda (R. Gendler)


NGC 602 in LMC (Hubble)


Proplyd in Orion (Hubble)


Sun (SOHO)


Earth

- density
  - density of ISM: few particles per cm^3
  - density of molecular cloud: few 100 particles per cm^3
  - density of Sun: 1.4 g/cm^3
- spatial scale
  - size of molecular cloud: few 10s of pc
  - size of young cluster: ~ 1 pc
  - size of Sun: 1.4×10^{10} cm

decrease in spatial scale / increase in density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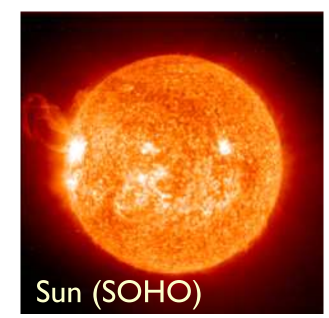
Sun (SOHO)


Earth

- contracting force
  - only force that can do this compression is ***GRAVITY***
- opposing forces
  - there are several processes that can oppose gravity
  - ***GAS PRESSURE***
  - ***TURBULENCE***
  - ***MAGNETIC FIELDS***
  - ***RADIATION PRESSURE***

decrease in spatial scale / increase in density


Andromeda (R. Gendler)


NGC 602 in LMC (Hubble)


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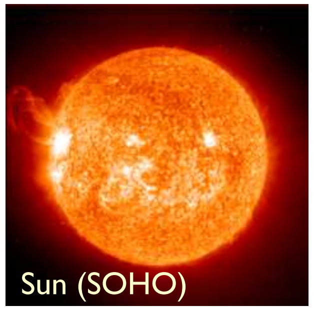
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  - ***GAS PRESSURE***
  - ***TURBULENCE***
  - ***MAGNETIC FIELDS***
  - ***RADIATION PRESSURE***

Modern star formation theory is based on the complex interplay between *all* these processes.

early theoretical models

- *Jeans (1902):* Interplay between self-gravity and thermal pressure
  - stability of homogeneous spherical density enhancements against gravitational collapse
  - dispersion relation:

$$\omega^2 = c_s^2 k^2 - 4\pi G \rho_0$$

  - instability when $\omega^2 < 0$
  - minimal mass: $M_J = \frac{1}{6}\pi^{-5/2} G^{-3/2} \rho_0^{-1/2} c_s^3 \propto \rho_0^{-1/2} T^{+3/2}$

Sir James Jeans, 1877 - 1946

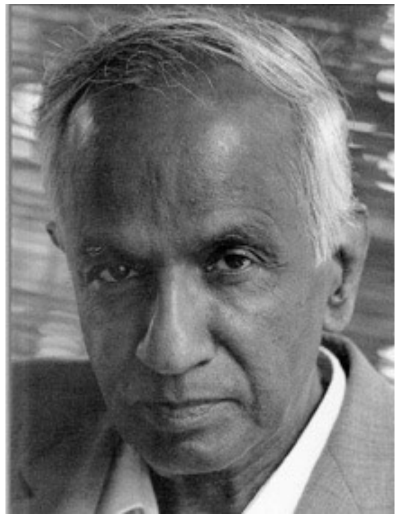
first approach to turbulence

- *von Weizsäcker (1943, 1951)* and *Chandrasekhar (1951):* concept of ***MICROTURBULENCE***
  - BASIC ASSUMPTION: separation of scales between dynamics and turbulence

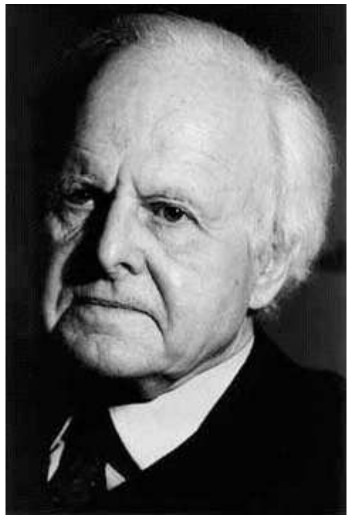
    $l_{turb} \ll l_{dyn}$
  - then turbulent velocity dispersion contributes to effective sound speed:

    $$c_c^2 \mapsto c_c^2 + \sigma_{rms}^2$$
  - → Larger effective Jeans masses → more stability
  - BUT: *(1) turbulence depends on k:* $\sigma_{rms}^2(k)$

    (2) supersonic turbulence usually → $\sigma_{rms}^2(k) >> c_s^2$



S. Chandrasekhar, 1910 - 1995



C.F. von Weiszäcker, 1912 - 2007

problems of early dynamical theory

- molecular clouds are *highly Jeans-unstable,*
  yet, they do *NOT* form stars at high rate
  and with high efficiency (Zuckerman & Evans 1974 conundrum)
  (the observed global SFE in molecular clouds is *~5%*)
  → *something prevents large-scale collapse.*
- all throughout the early 1990's, molecular clouds had been thought to be long-lived quasi-equilibrium entities.
- molecular clouds are *magnetized*

magnetic star formation

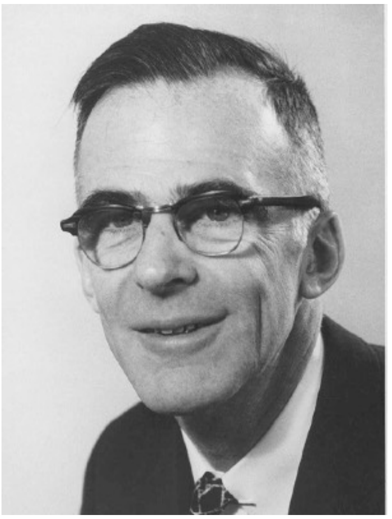
- *Mestel & Spitzer (1956):* Magnetic fields can prevent collapse*!!!*
  - Critical mass for gravitational collapse in presence of B-field

$$M_{cr} = \frac{5^{3/2}}{48\pi^2}\frac{B^3}{G^{3/2}\rho^2}$$

  - Critical mass-to-flux ratio (Mouschovias & Spitzer 1976)

$$\left[\frac{M}{\Phi}\right]_{cr} = \frac{\zeta}{3\pi}\left[\frac{5}{G}\right]^{1/2}$$

  - Ambipolar diffusion can initiate collapse

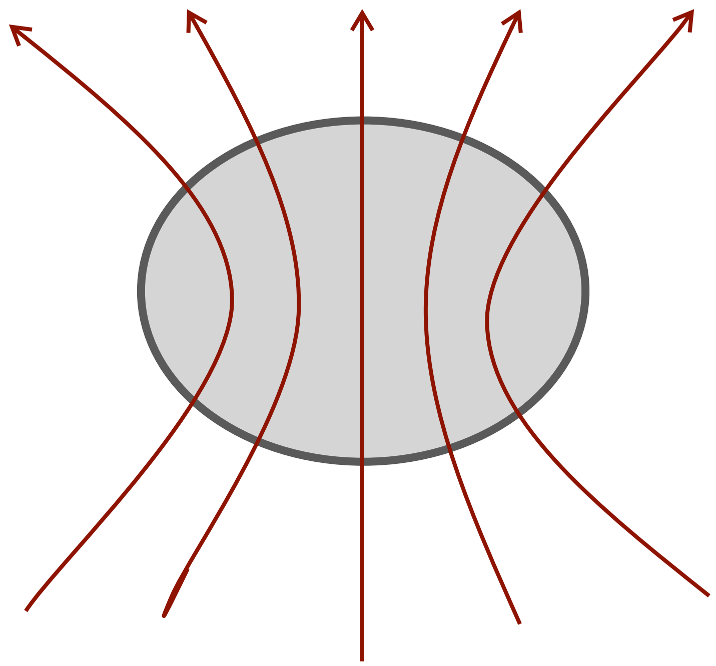


Lyman Spitzer, Jr., 1914 - 1997

“standard theory” of star formation

- BASIC ASSUMPTION: Stars form from magnetically highly subcritical cores
- Ambipolar diffusion slowly increases (M/Φ): $\tau_{AD} \approx 10\tau_{ff}$
- Once $(M/\Phi) > (M/\Phi)_{crit}$: dynamical collapse of SIS
    - Shu (1977) collapse solution
    - $dM/dt = 0.975\ c_s{}^3/G = \text{const.}$
- Was (in principle) only intended for isolated, low-mass stars

Frank Shu, 1943 -



problems of "standard theory"

- Observed B-fields are weak, at most marginally critical (Crutcher 1999, Bourke et al. 2001)
- Magnetic fields cannot prevent decay of turbulence (Mac Low et al. 1998, Stone et al. 1998, Padoan & Nordlund 1999)
- Structure of prestellar cores (e.g. Bacman et al. 2000, Alves et al. 2001)
- Strongly time varying dM/dt (e.g. Hendriksen et al. 1997, André et al. 2000)
- More extended infall motions than predicted by the standard model (Williams & Myers 2000, Myers et al. 2000)
- Most stars form as binaries (e.g. Lada 2006)
- As many prestellar cores as protostellar cores in SF regions (e.g. André et al 2002)
- Molecular cloud clumps are chemically young (Bergin & Langer 1997, Pratap et al 1997, Aikawa et al 2001)
- Stellar age distribution small ($\tau_{ff} << \tau_{AD}$) (Ballesteros-Paredes et al. 1999, Elmegreen 2000, Hartmann 2001)
- Strong theoretical criticism of the SIS as starting condition for gravitational collapse (e.g. Whitworth et al 1996, Nakano 1998, as summarized in Klessen & Mac Low 2004)
- Standard AD-dominated theory is incompatible with observations (Crutcher et al. 2009, 2010ab, Bertram et al. 2011)

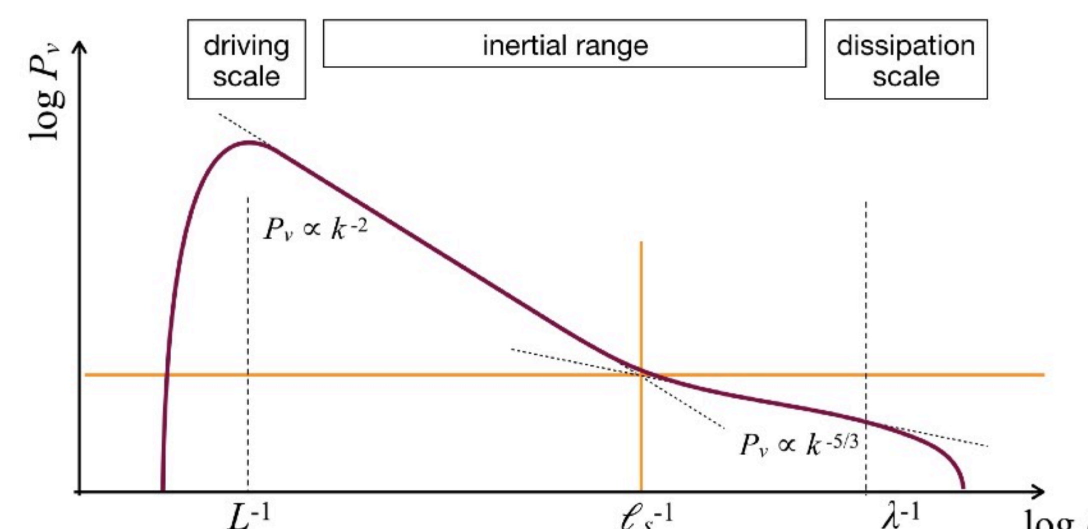
(see e.g. Mac Low & Klessen, 2004, Rev. Mod. Phys., 76, 125-194
Klessen & Glover, 2016, Saas Fee Lecture, 43, 85)

gravoturbulent star formation

- BASIC ASSUMPTION:

  star formation is controlled by interplay between supersonic turbulence and self-gravity

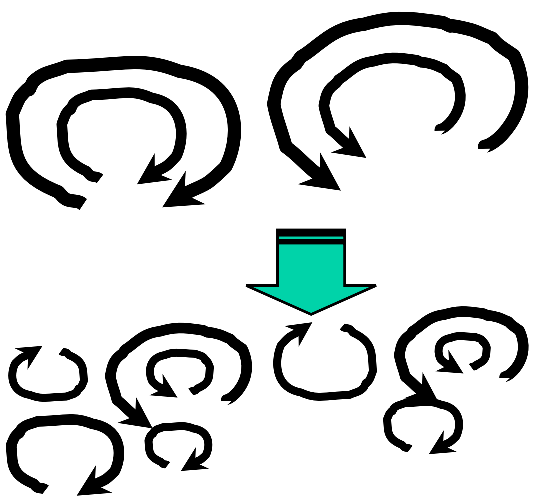
- turbulence plays a *dual role*:
  - on *large scales* it *provides support*
  - on *small scales* it can *trigger collapse*
- some predictions:
  - dynamical star formation timescale τ_{ff}
  - high binary fraction
  - complex spatial structure of embedded star clusters
  - and many more . . .



Mac Low & Klessen, 2004, Rev. Mod. Phys., 76, 125-194
McKee & Ostriker, 2007, ARAA, 45, 565
Klessen & Glover, 2016, Saas Fee Lecture, 43, 85

properties of turbulence

- laminar flows turn *turbulent* at *high* *Reynolds* numbers



$$Re = \frac{\text{advection}}{\text{dissipation}} = \frac{V\,L}{\nu}$$

V= typical velocity on scale L, ν = *η*/*ρ* = kinematic viscosity,
turbulence for Re > 1000 → typical values in ISM 10^8-10^{10}

- Navier-Stokes equation (transport of momentum)

$$\rho\frac{d\vec{v}}{dt} = \rho\left(\frac{\partial\vec{v}}{\partial t} + (\vec{v}\cdot\vec{\nabla})\vec{v}\right) = -\vec{\nabla}P + \eta\,\vec{\nabla}^2\vec{v} + \left(\frac{\eta}{3} + \zeta\right)\vec{\nabla}(\vec{\nabla}\cdot\vec{v})$$

shear viscosity

bulk viscosity

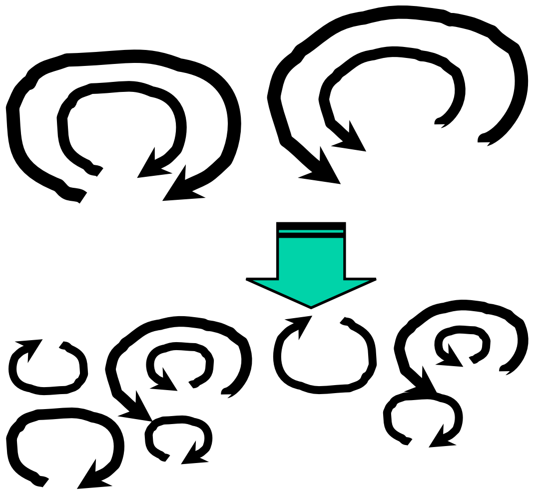
$$\sigma_{ij} \equiv \eta\left(\frac{\partial v_i}{\partial x_j} + \frac{\partial v_j}{\partial x_i} - \frac{2}{3}\,\delta_{ij}\frac{\partial v_k}{\partial x_k}\right) + \zeta\delta_{ij}\frac{\partial v_k}{\partial x_k}$$

viscous stress tensor

properties of turbulence

- laminar flows turn *turbulent* at *high* *Reynolds* numbers

$$Re = \frac{\text{advection}}{\text{dissipation}} = \frac{VL}{\nu}$$



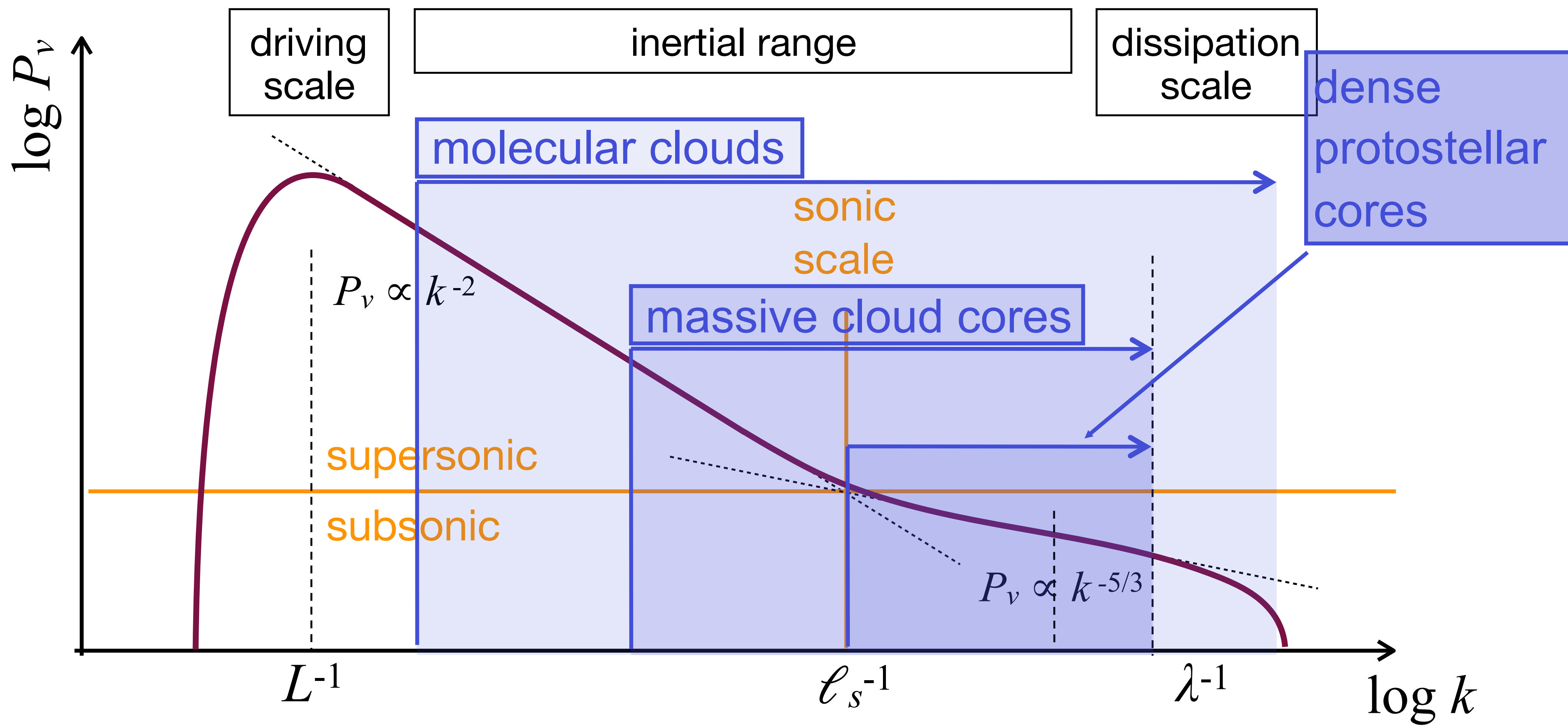
V= typical velocity on scale L, $\nu = \eta/\rho$ = kinematic viscosity,
turbulence for Re > 1000 → typical values in ISM 10^8-10^{10}

- vortex streching --> turbulence is intrinsically anisotropic
(only on large scales you may get
homogeneity & isotropy in a statistical sense;
see Landau & Lifschitz, Chandrasekhar, Taylor, etc.)

Tornado over Portofino

(ISM turbulence: shocks & B-field
cause additional inhomogeneity)

turbulent cascade in the ISM



power spectrum

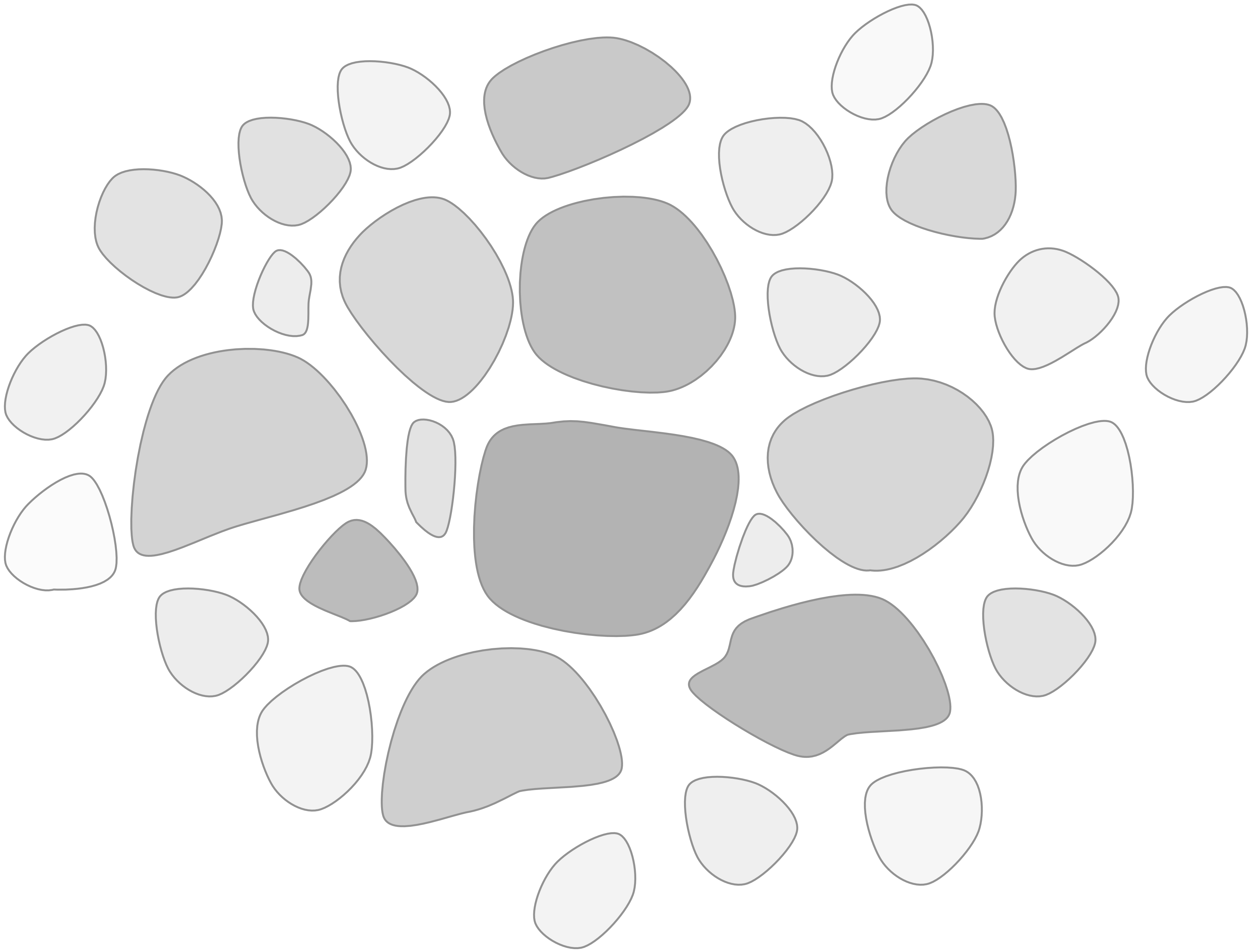
energy source & scale *NOT known* (supernovae, winds, spiral density waves?)

σ_{rms} << 1 km/s

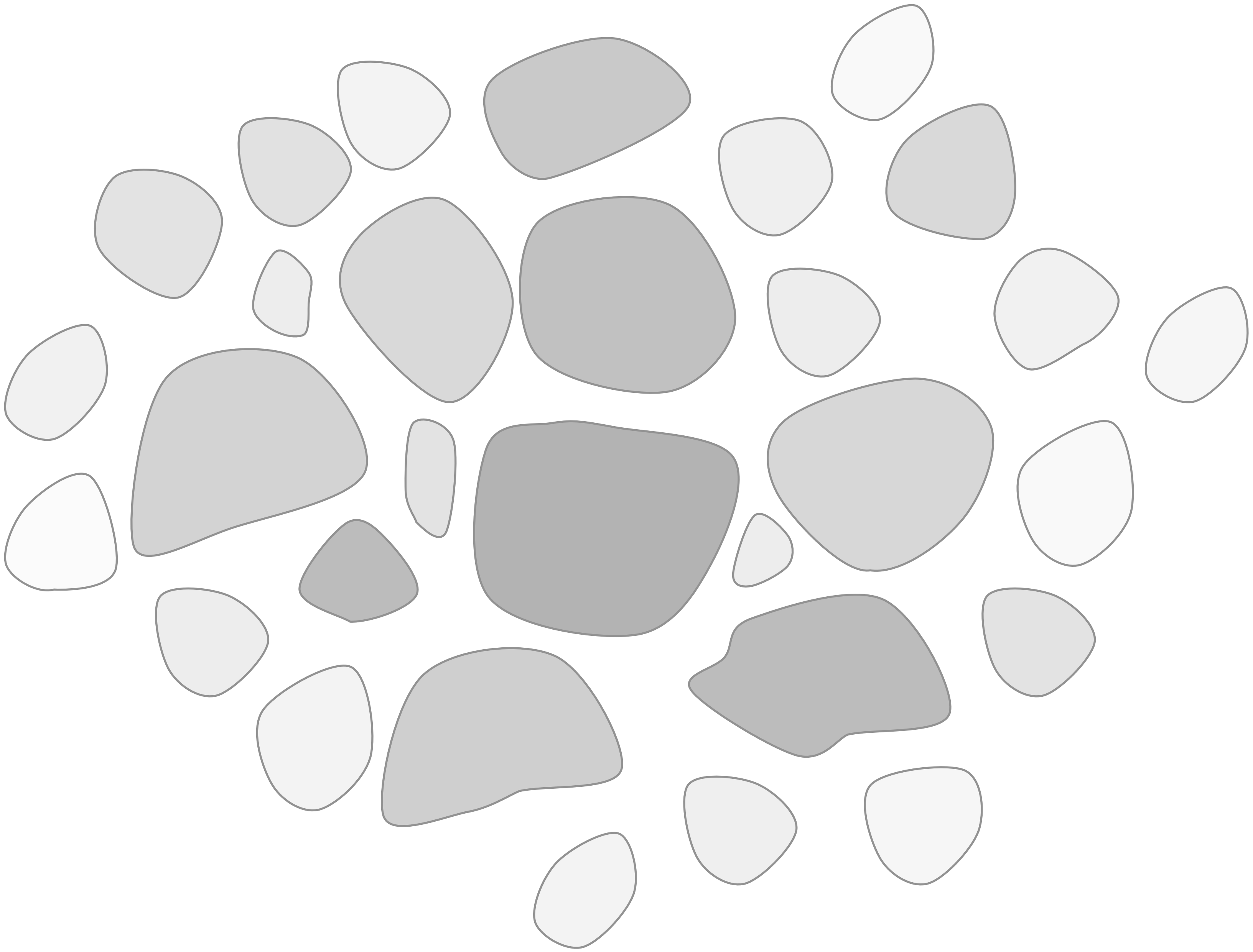
$M_{rms} \leq 1$

L ≈ 0.1 pc

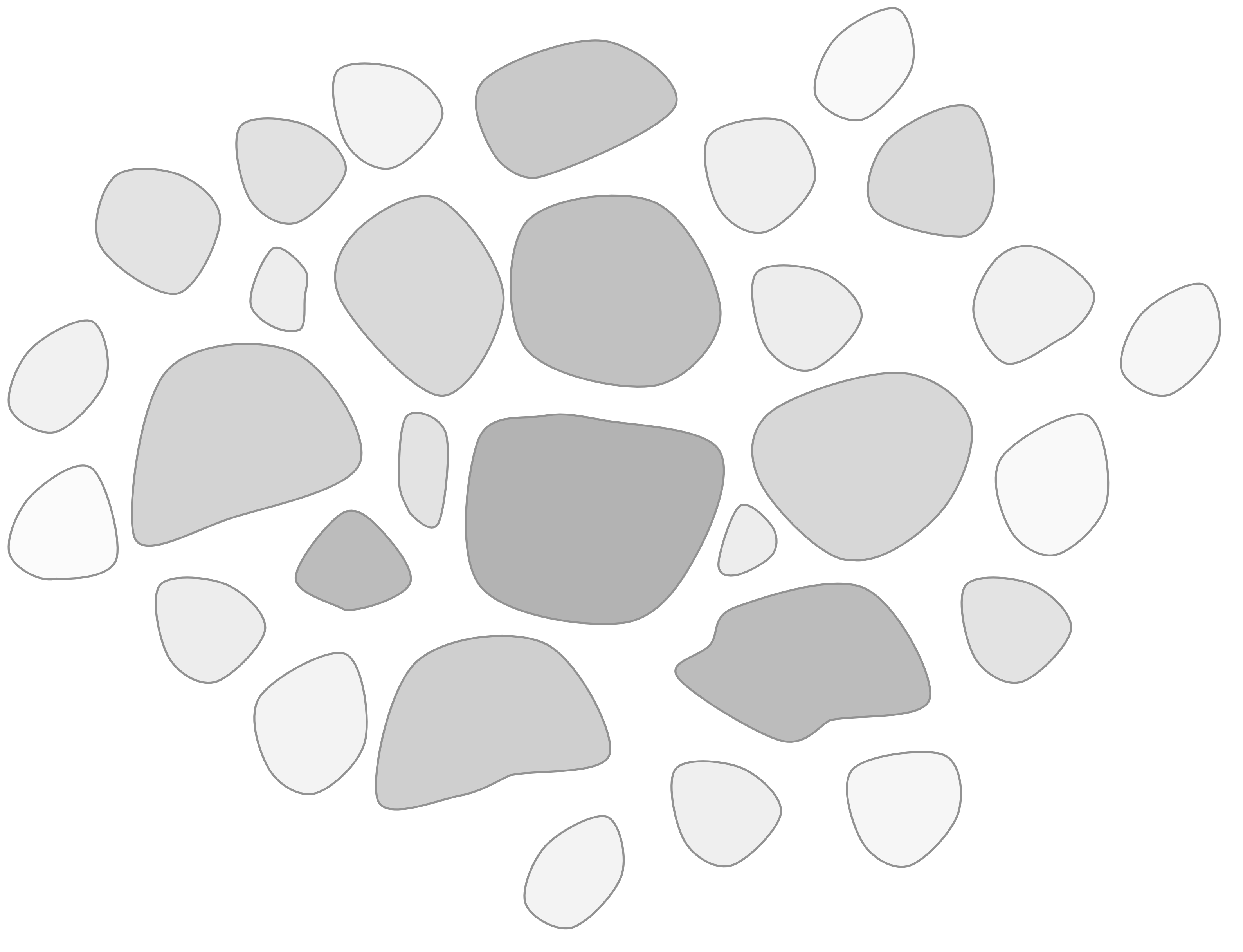
dissipation scale not known (ambipolar diffusion, molecular diffusion?)



turbulence creates a hierarchy of clumps



as turbulence decays locally, contraction sets in



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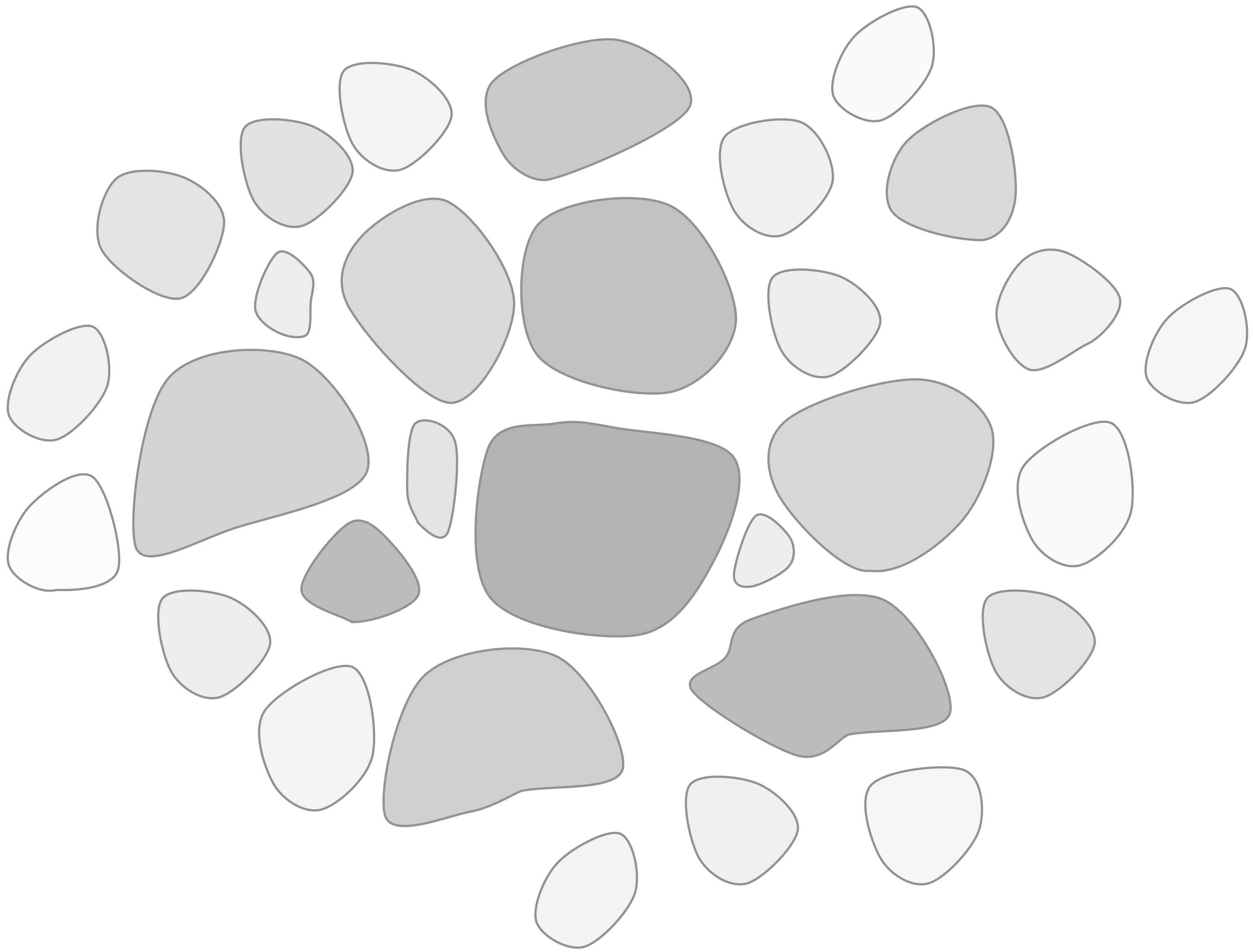
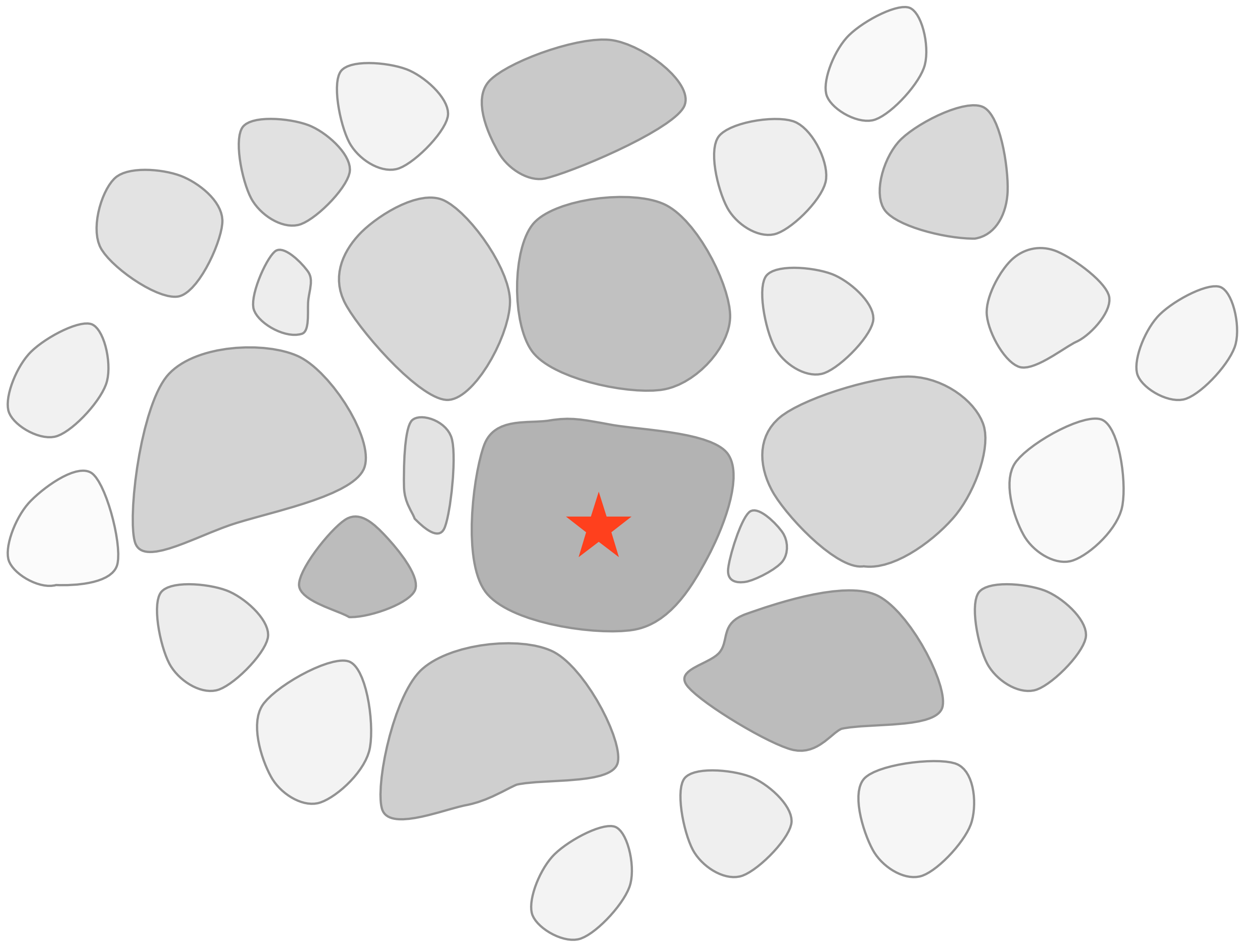


while region contracts, individual clumps collapse to form stars



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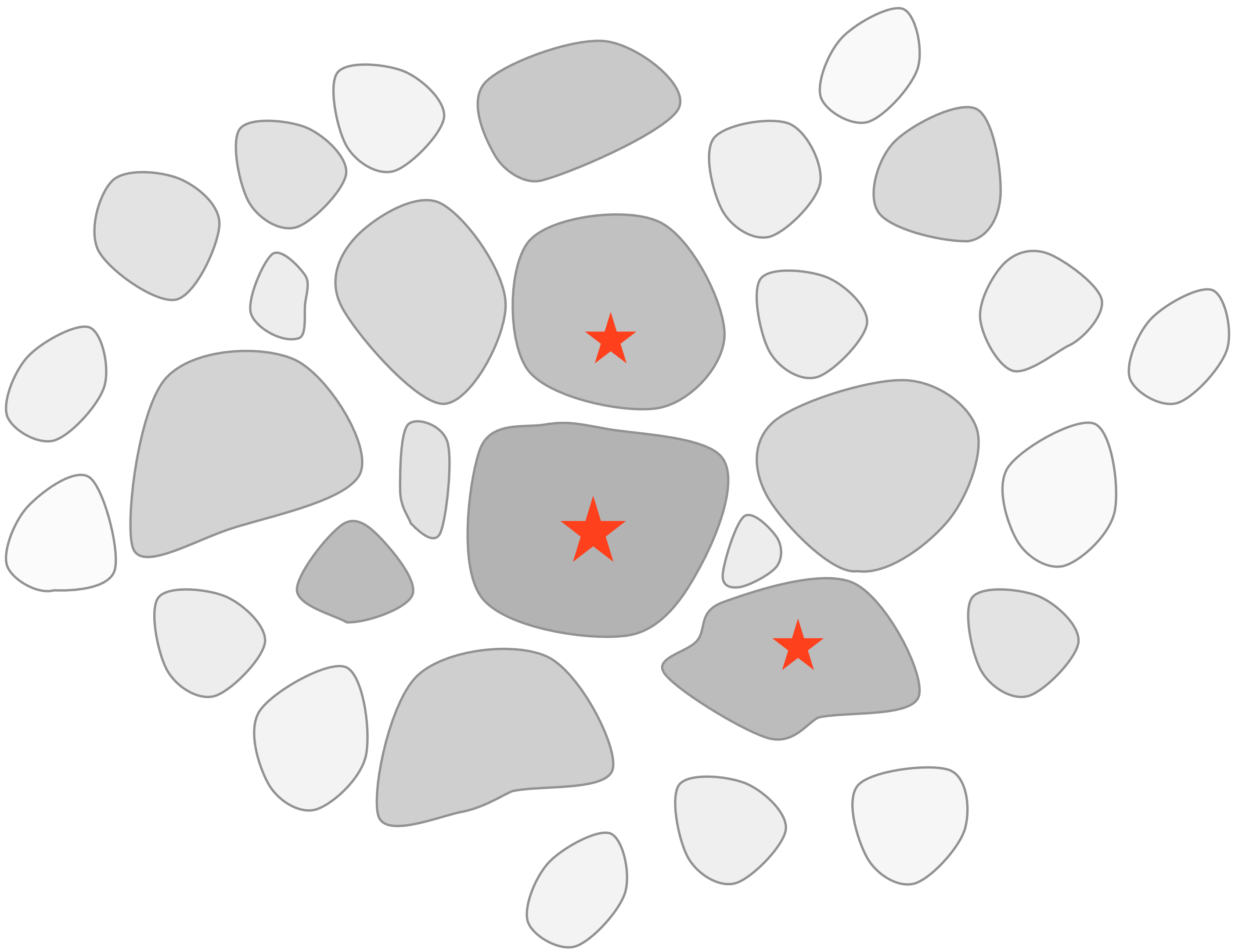

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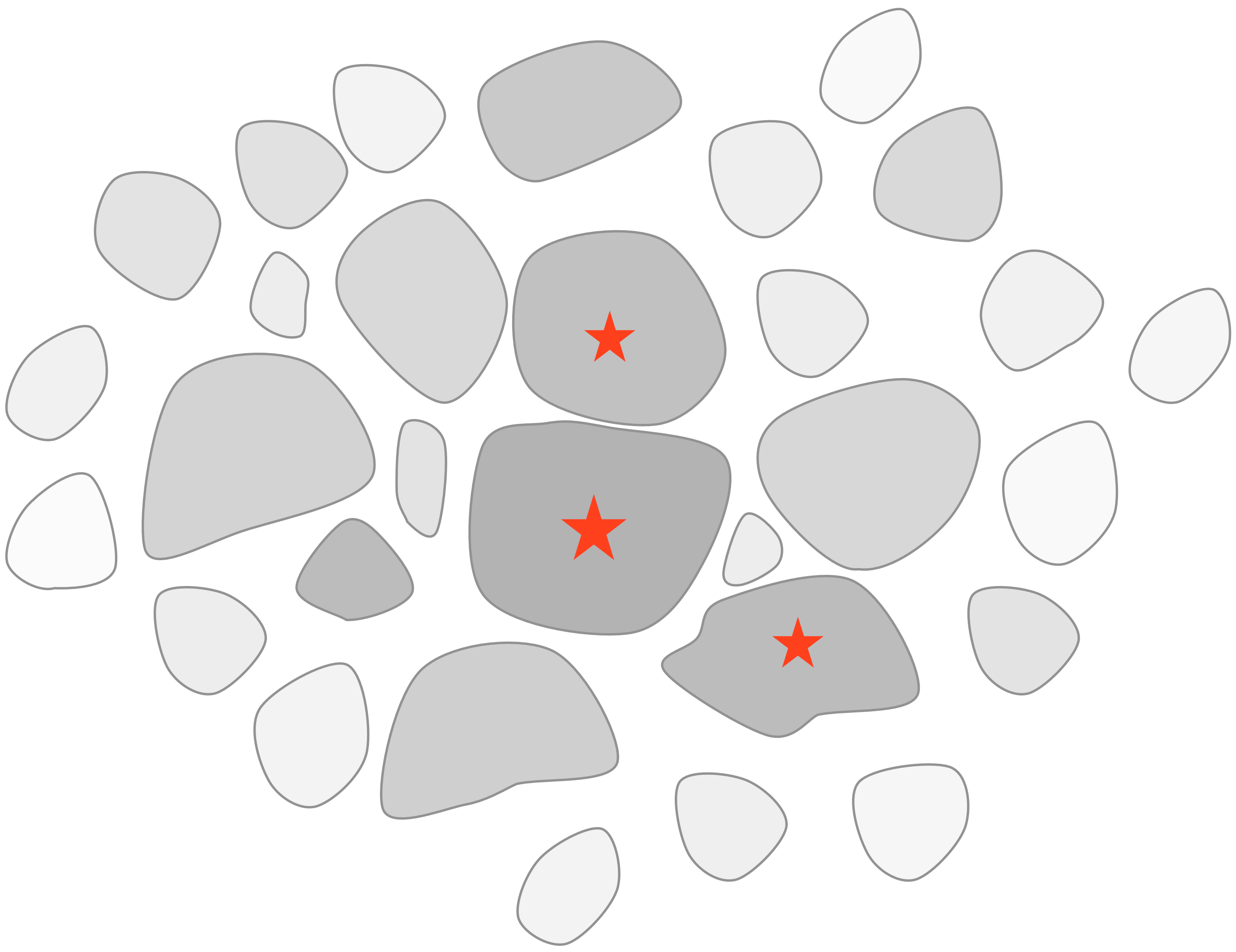

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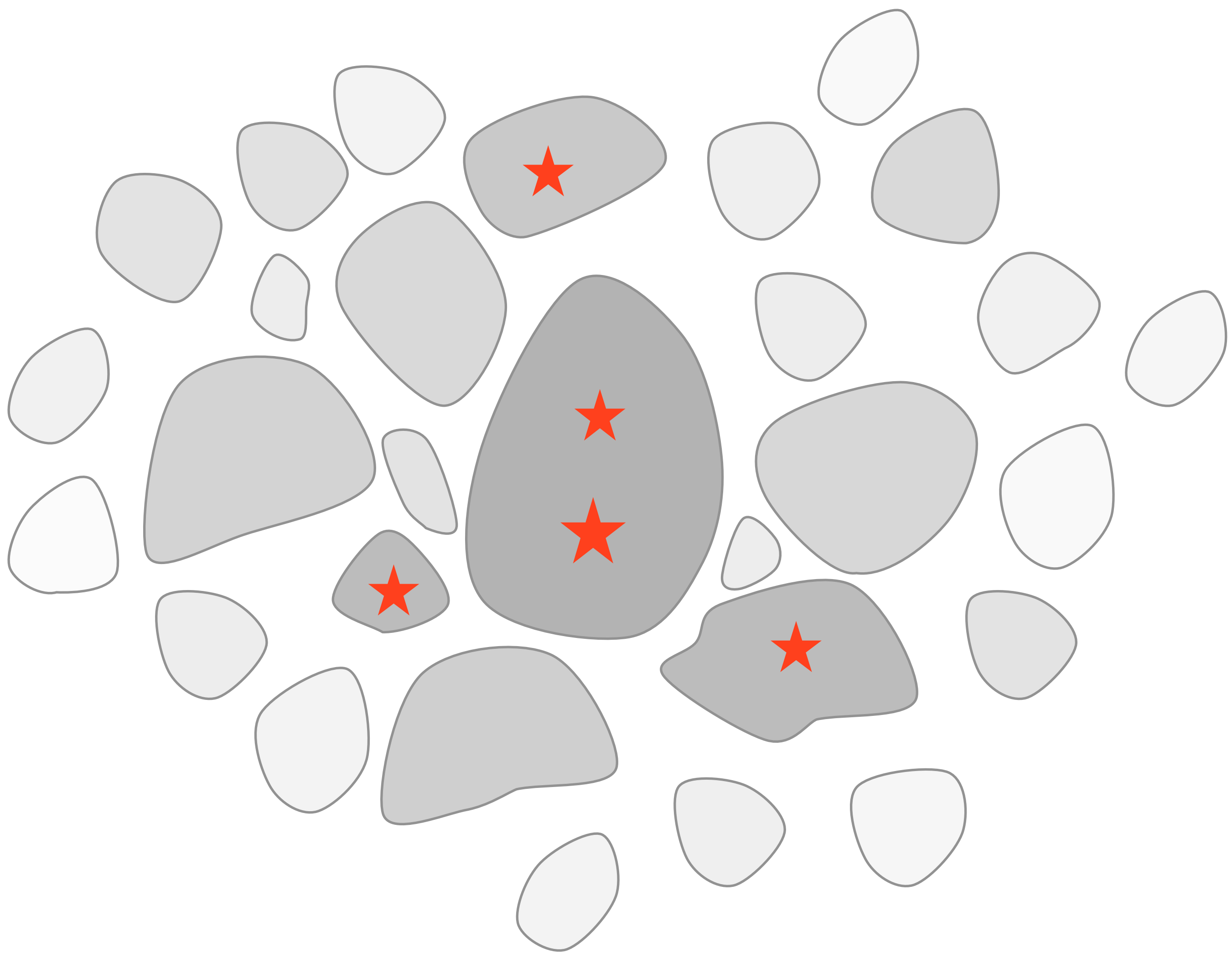
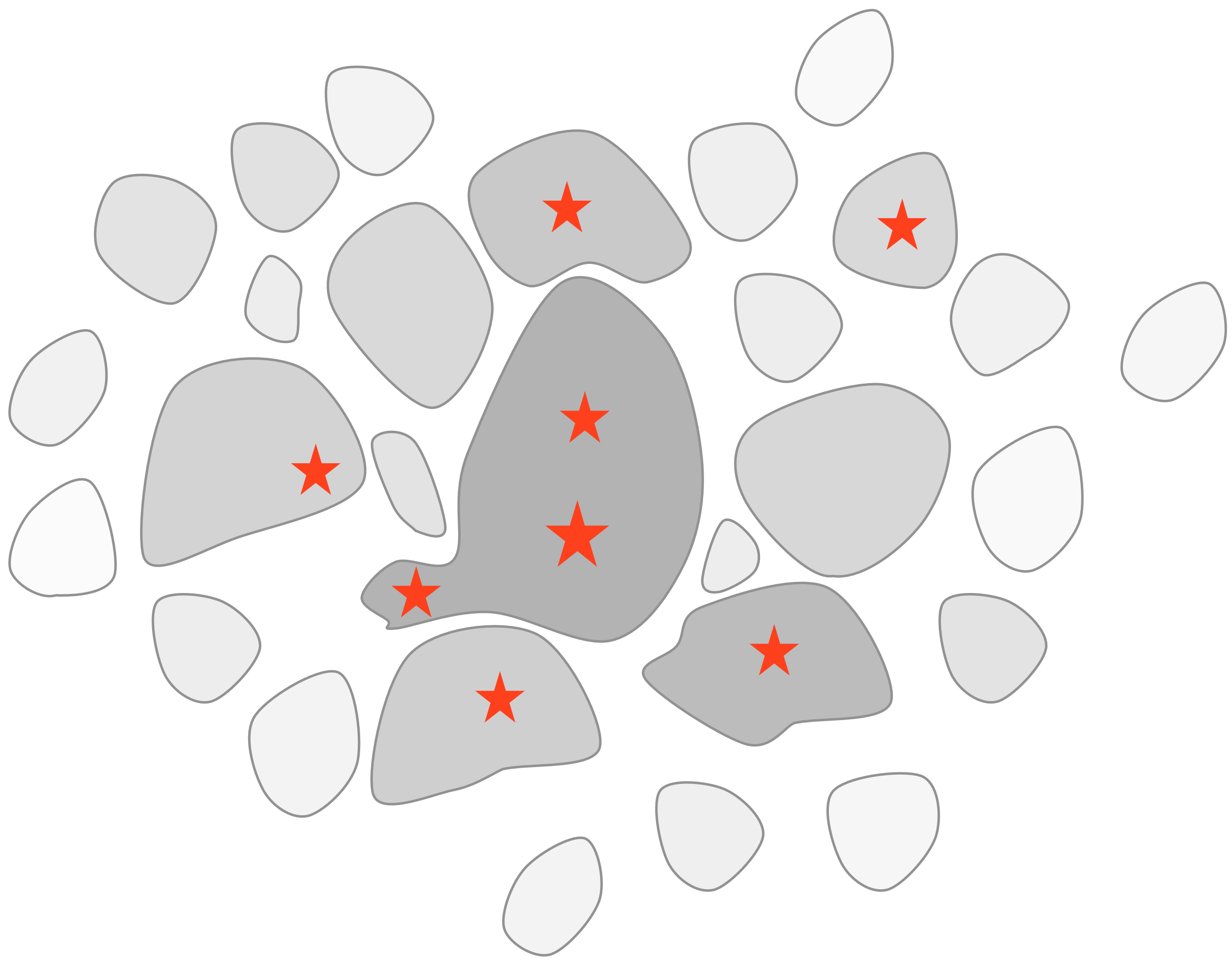


$\alpha = E_{kin}/|E_{pot}| < 1$

in *dense clusters*, clumps may merge while collapsing
--> then contain multiple protostars



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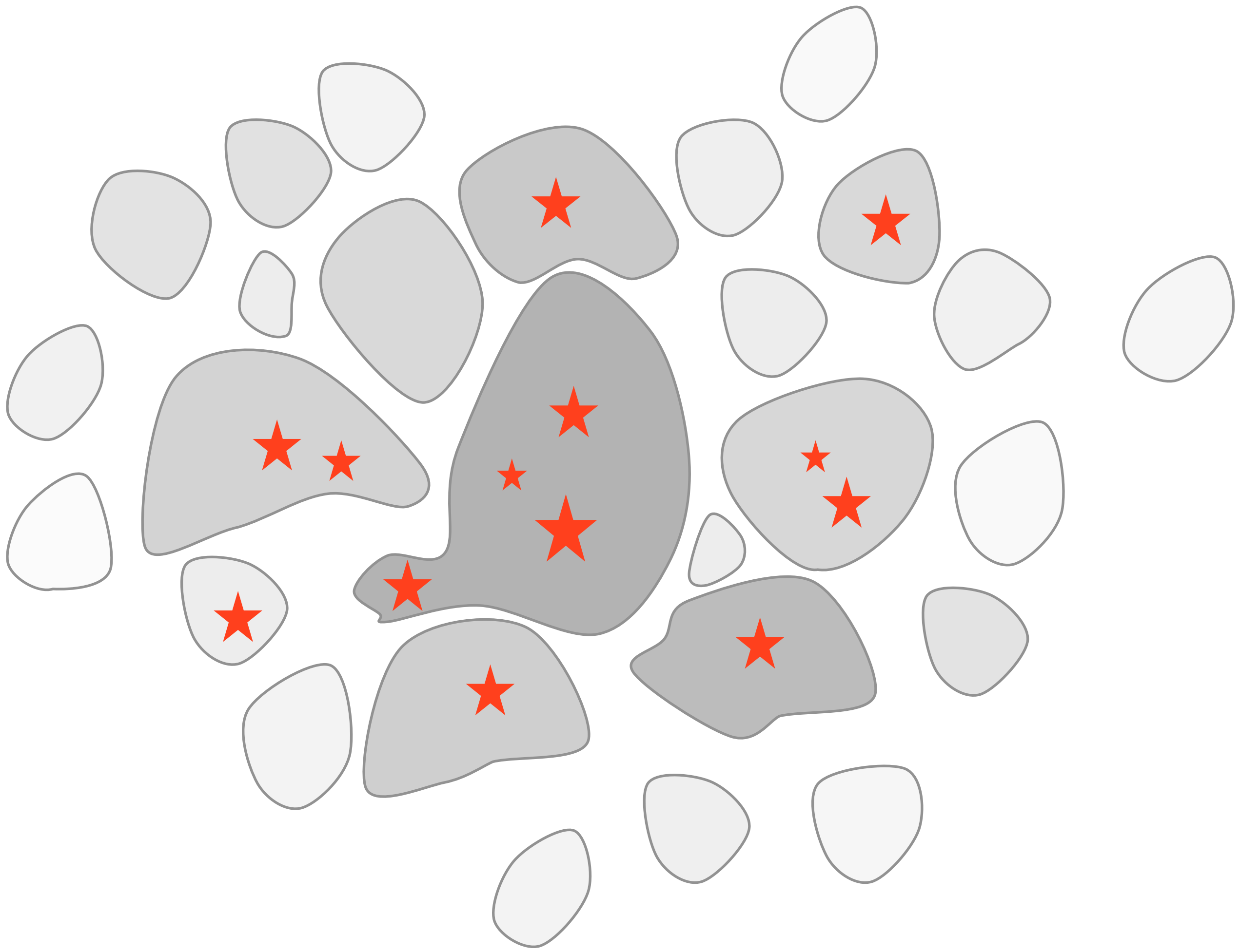

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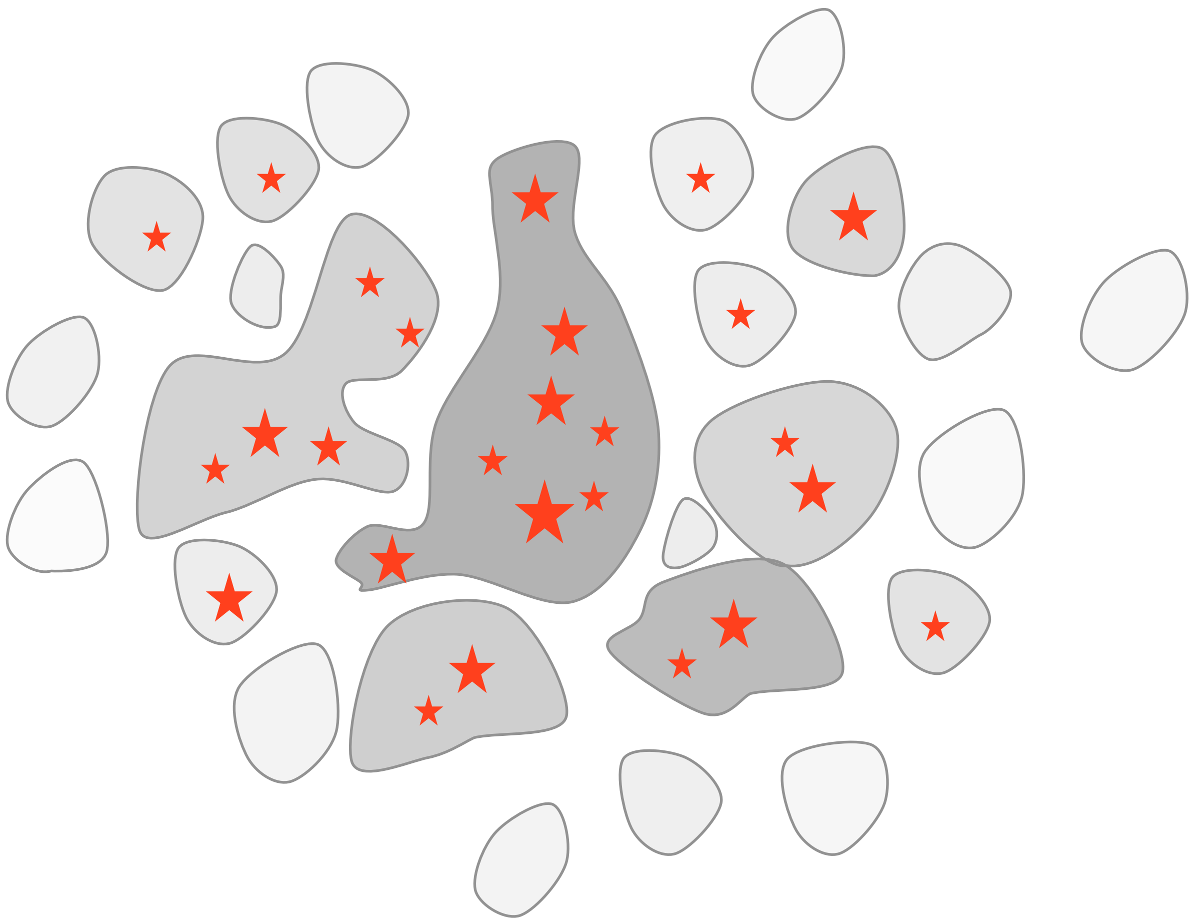
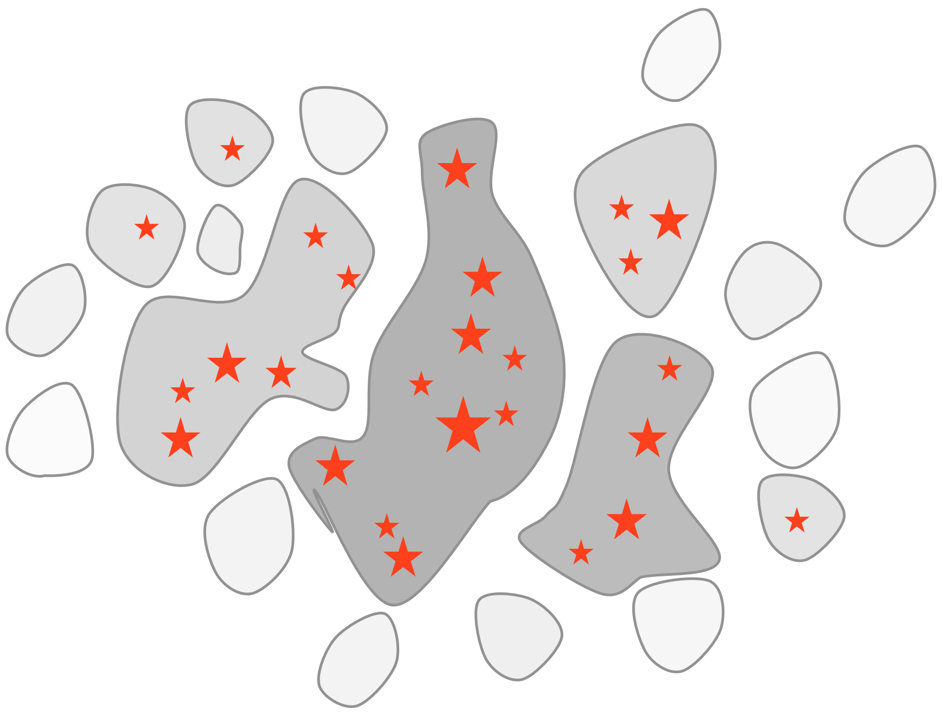


in *dense clusters*, competitive mass growth becomes important



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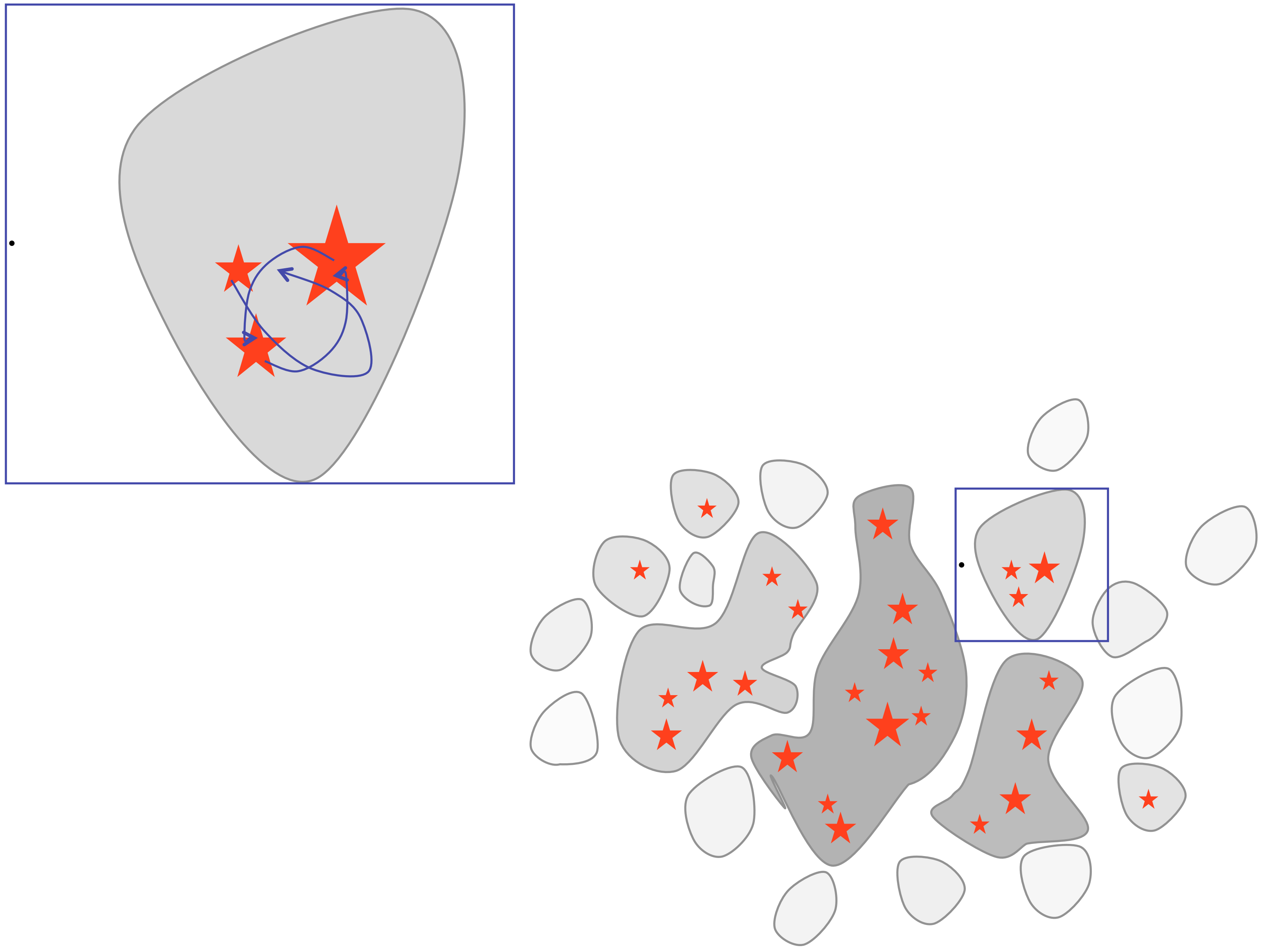
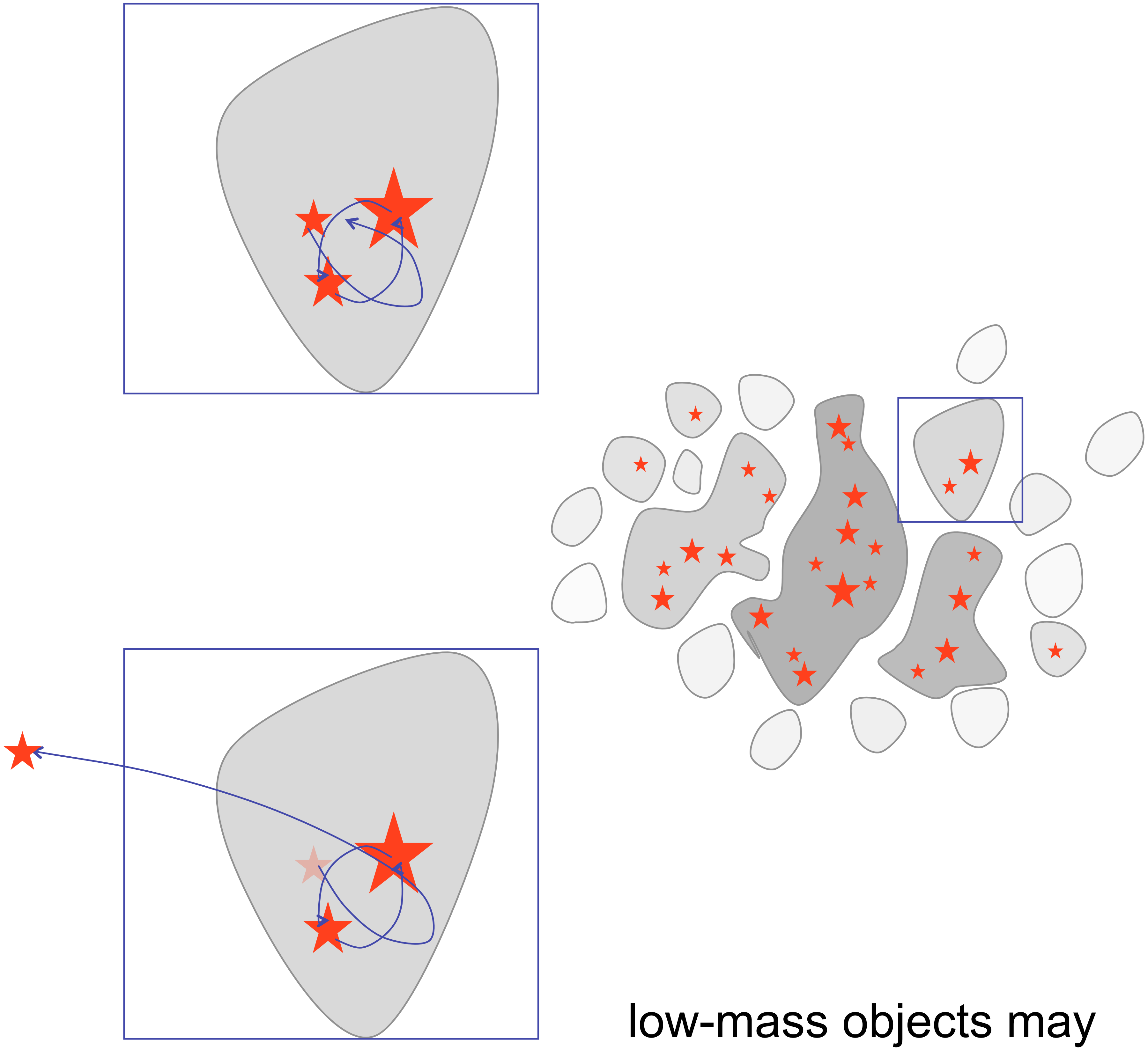
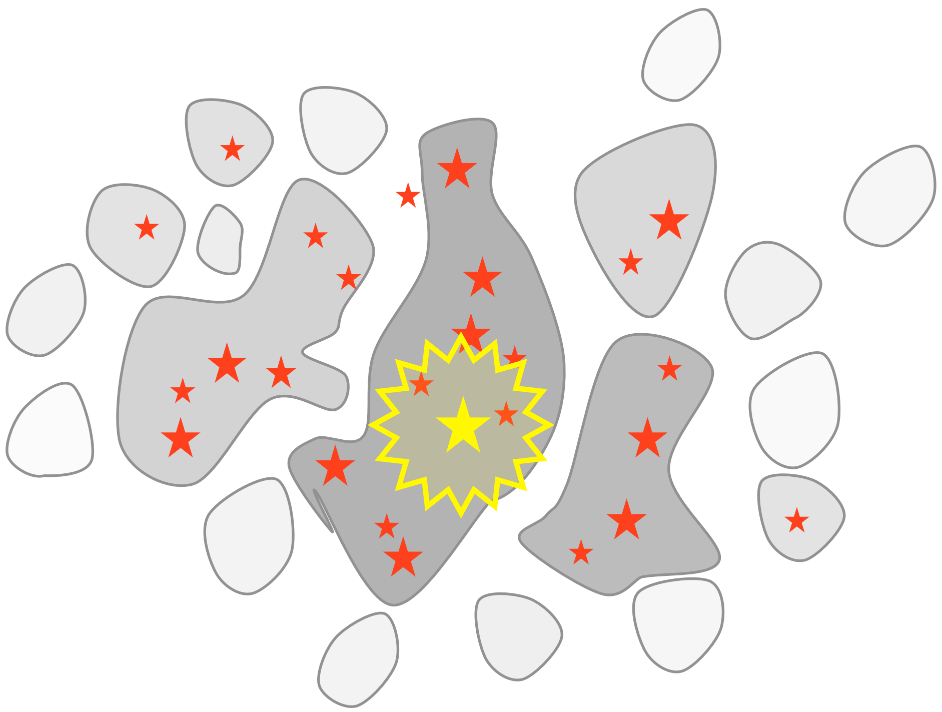


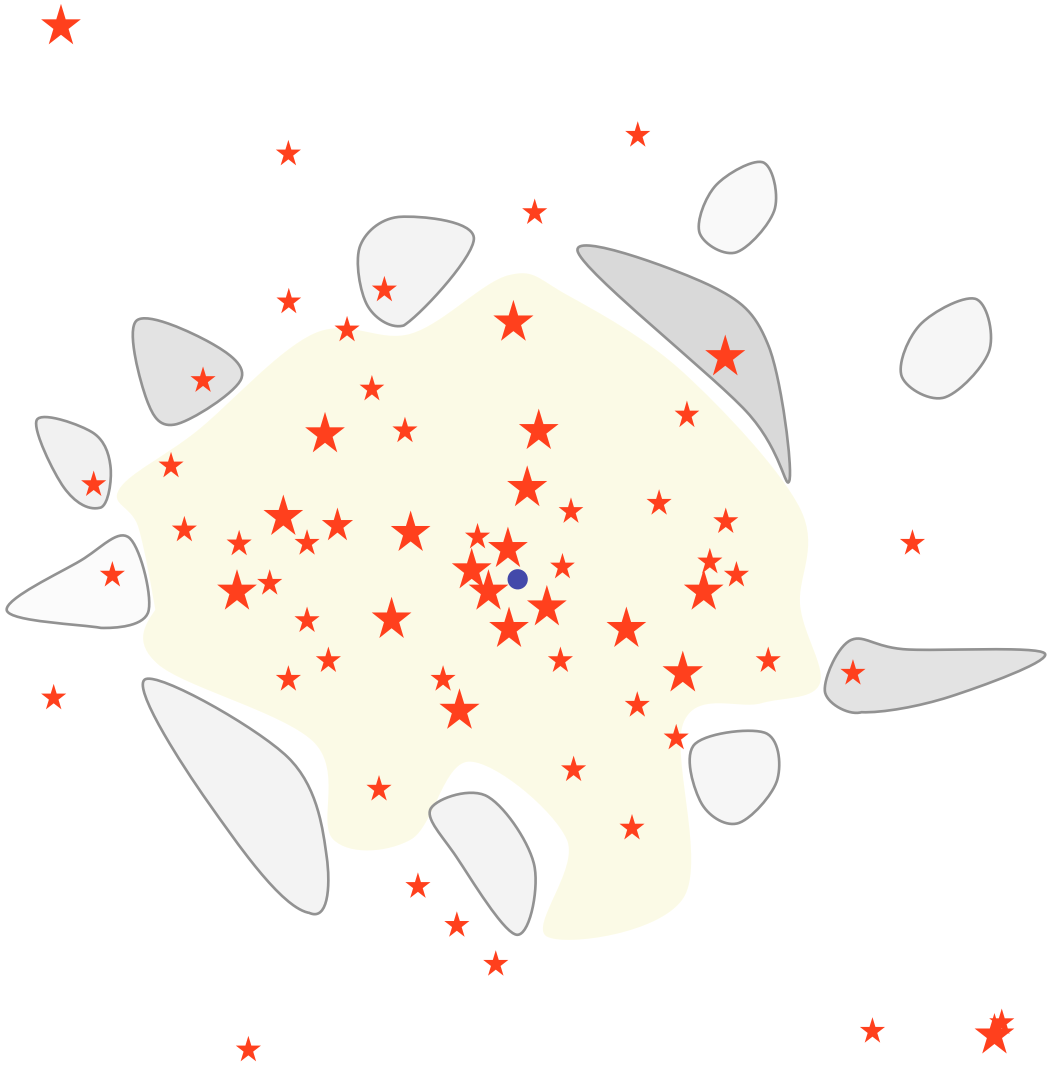
in *dense clusters*, *N*-body effects influence mass growth



low-mass objects may
become ejected --> accretion stops



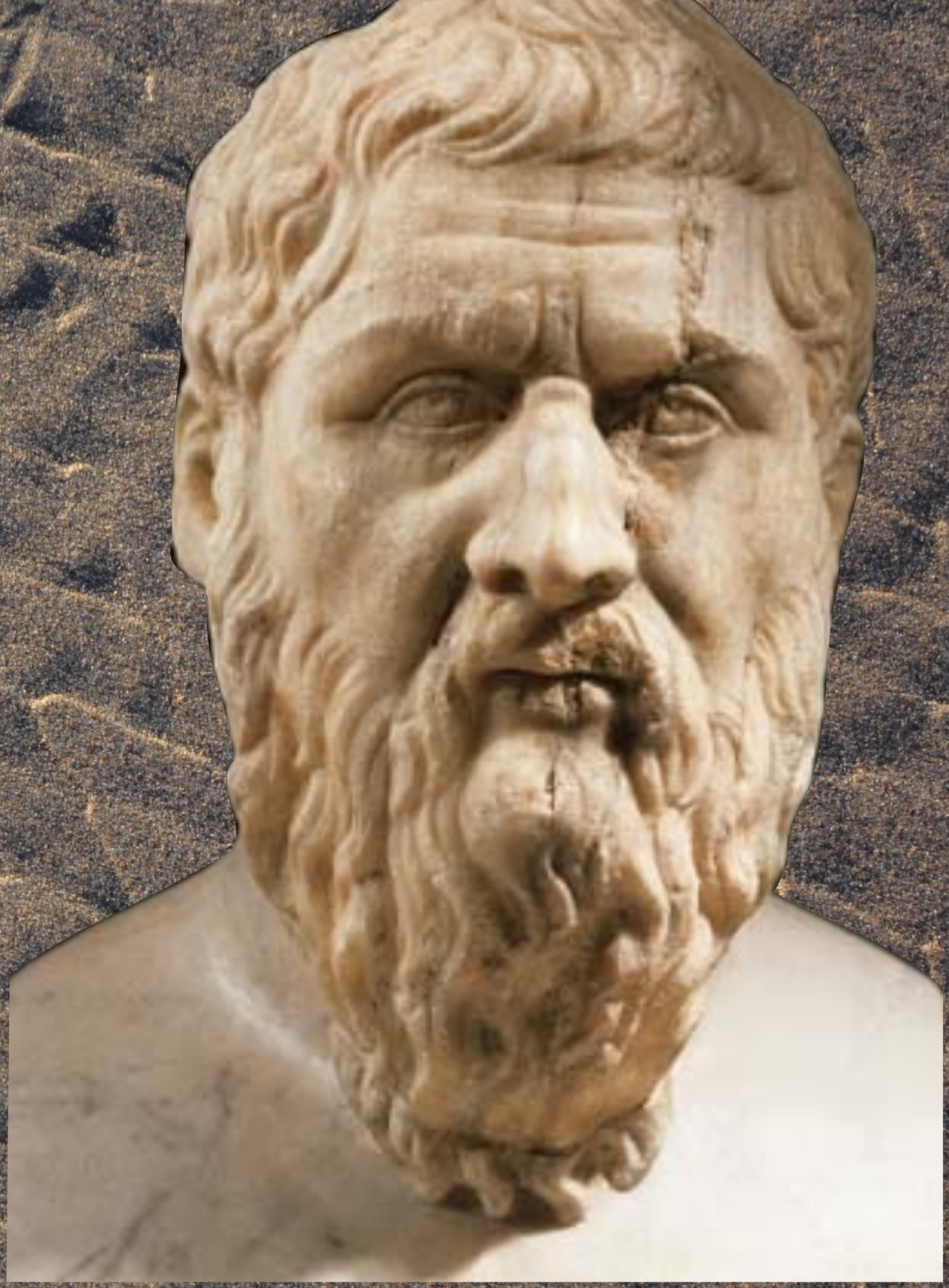
feedback terminates star formation



result: *star cluster*, possibly with HII region

NGC 602 in the LMC: Hubble Heritage Image


relation between
ISM dynamics and star formation



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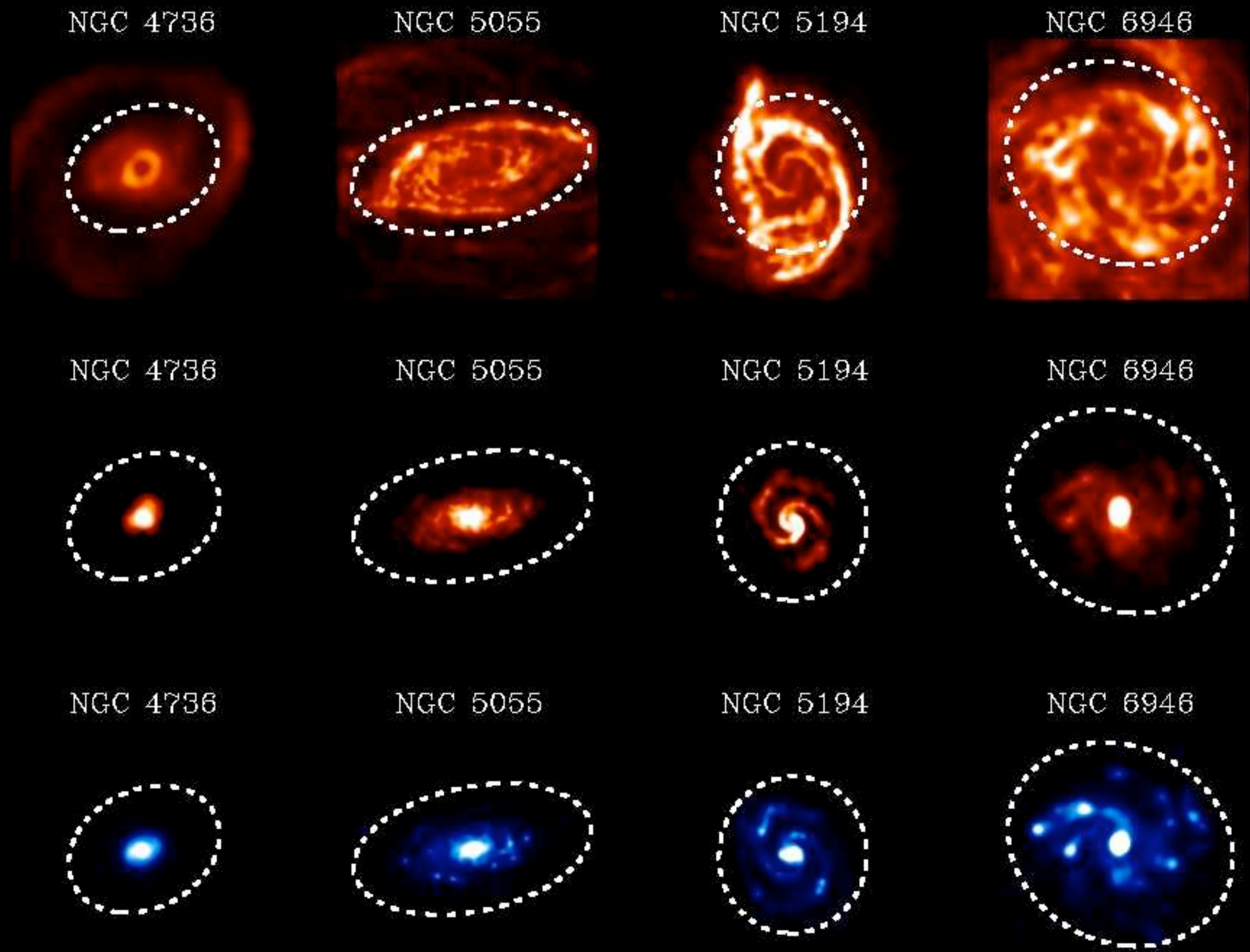
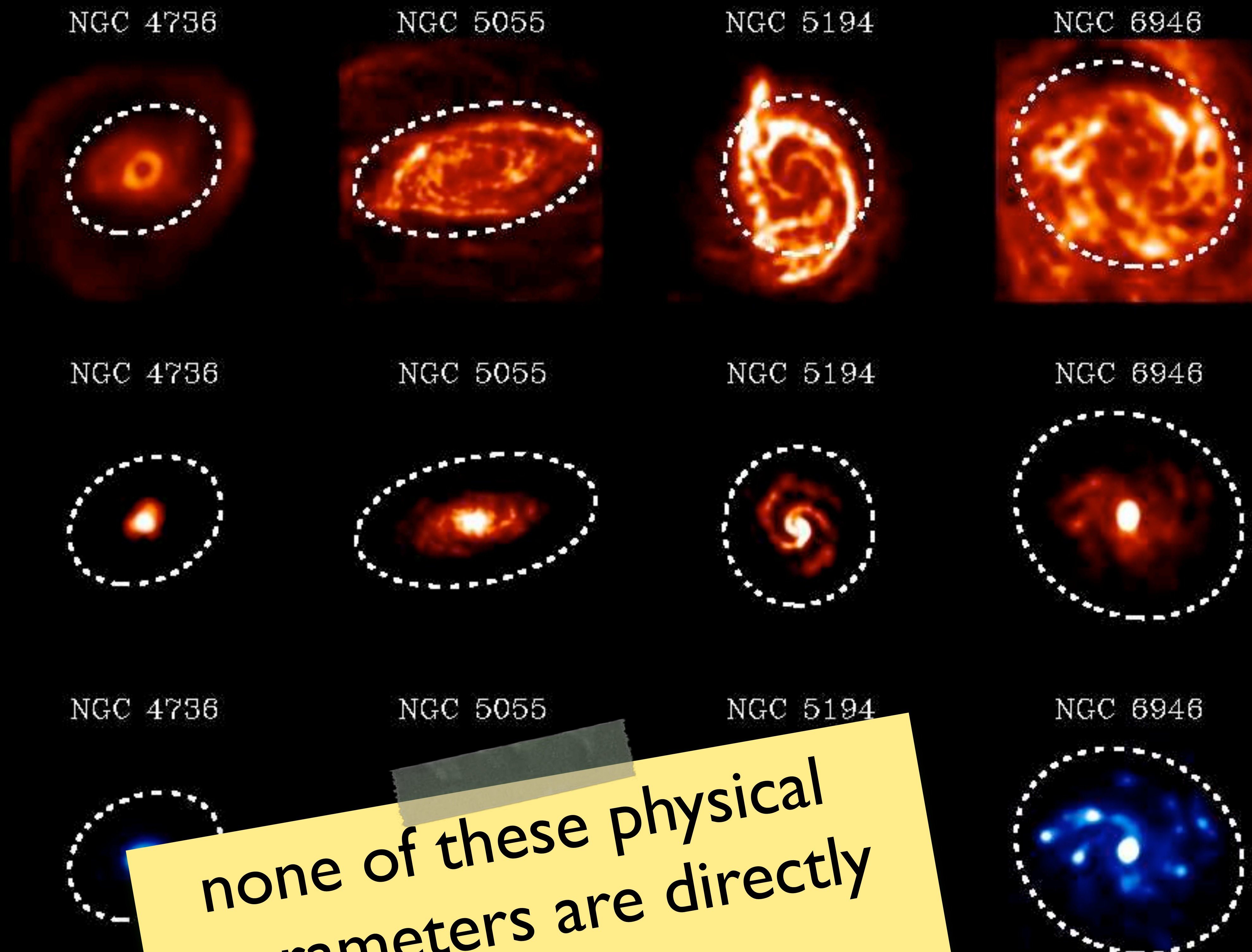


atomic hydrogen

molecular hydrogen

star formation

galaxies from THINGS and HERACLES survey



atomic hydrogen

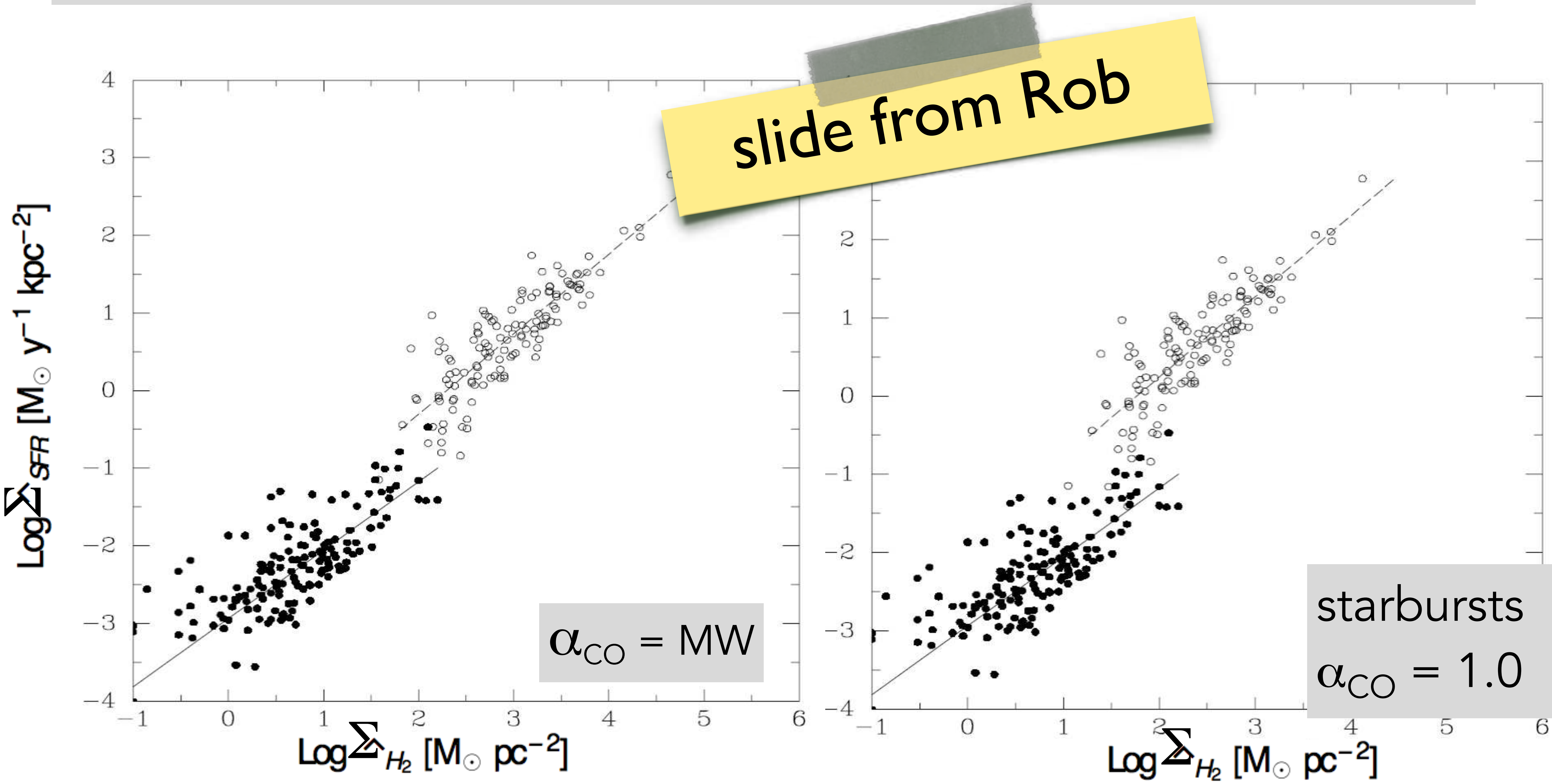
molecular hydrogen

star formation

none of these physical parameters are directly measured

galaxies from THINGS and HERACLES survey

Considering the molecular gas SF law alone does not change matters…



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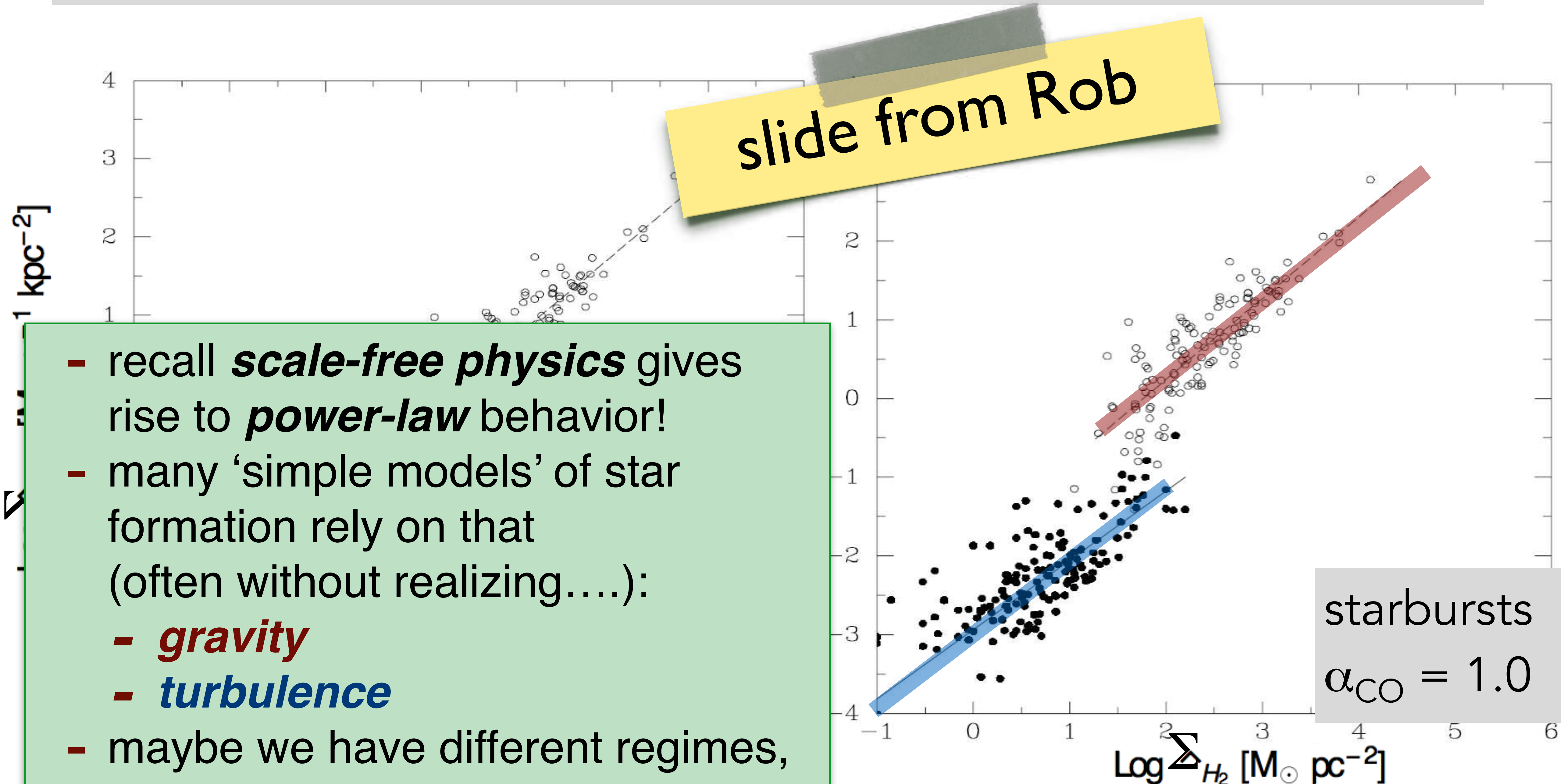
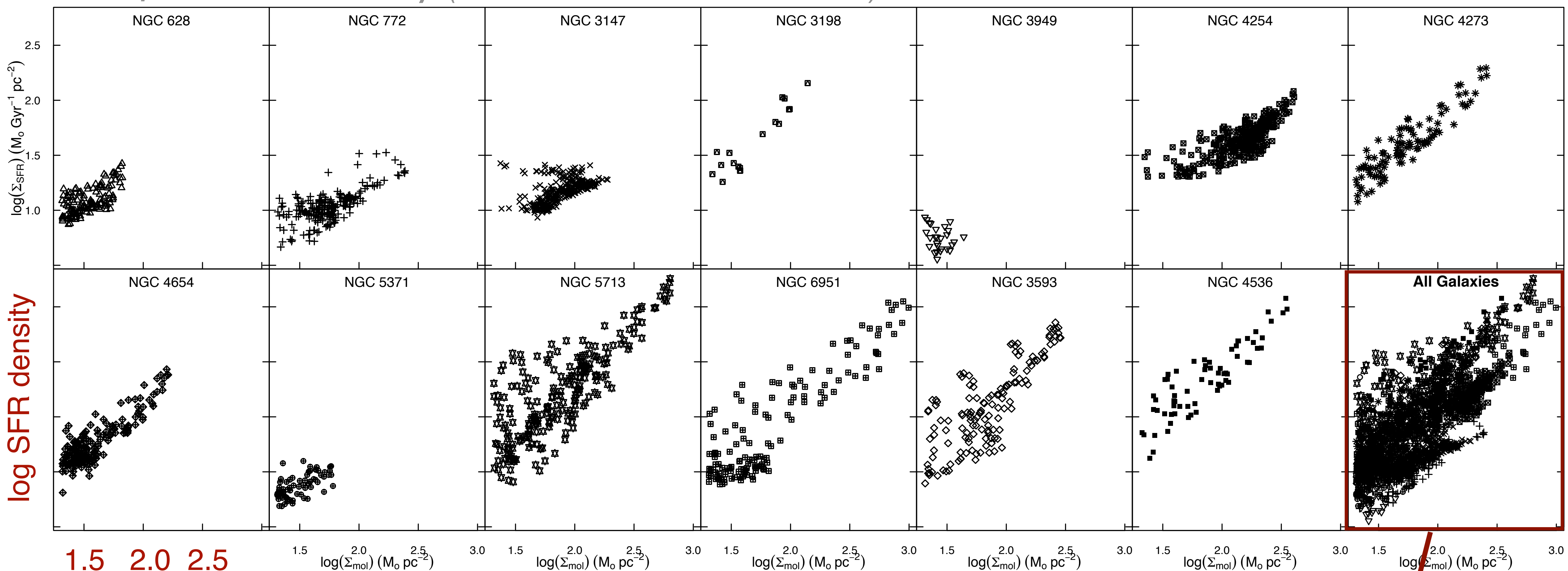


- recall ***scale-free physics*** gives rise to ***power-law*** behavior!
- many ‘simple models’ of star formation rely on that (often without realizing….):
  - ***gravity***
  - ***turbulence***
- maybe we have different regimes, in which different processes dominate star formation …

data from STING survey (Rahman et al. 2011, 2012)



log SFR density

1.5 2.0 2.5

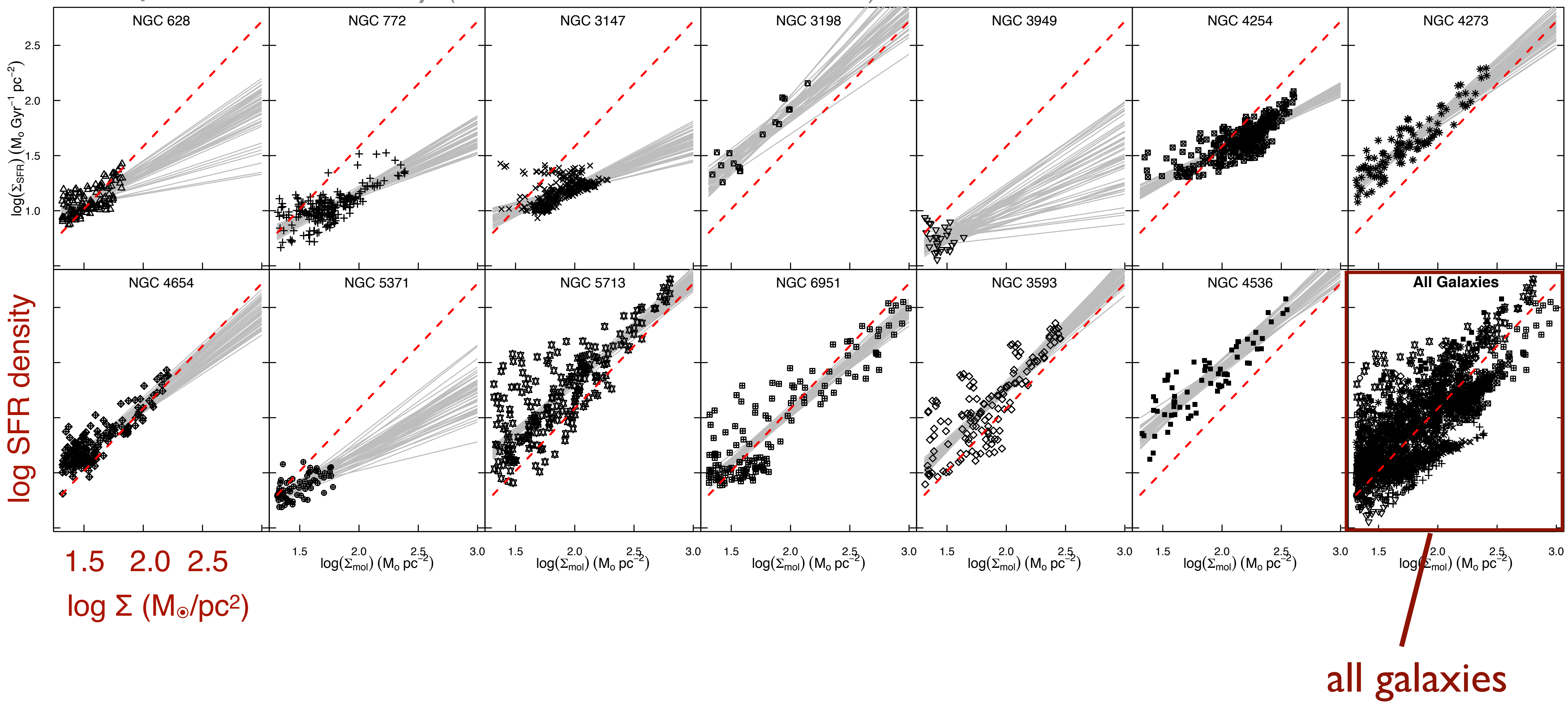
log Σ ($M_\odot/pc^2$)

all galaxies

- is there really a universal Σ_{H2} - Σ_{SFR} relation?

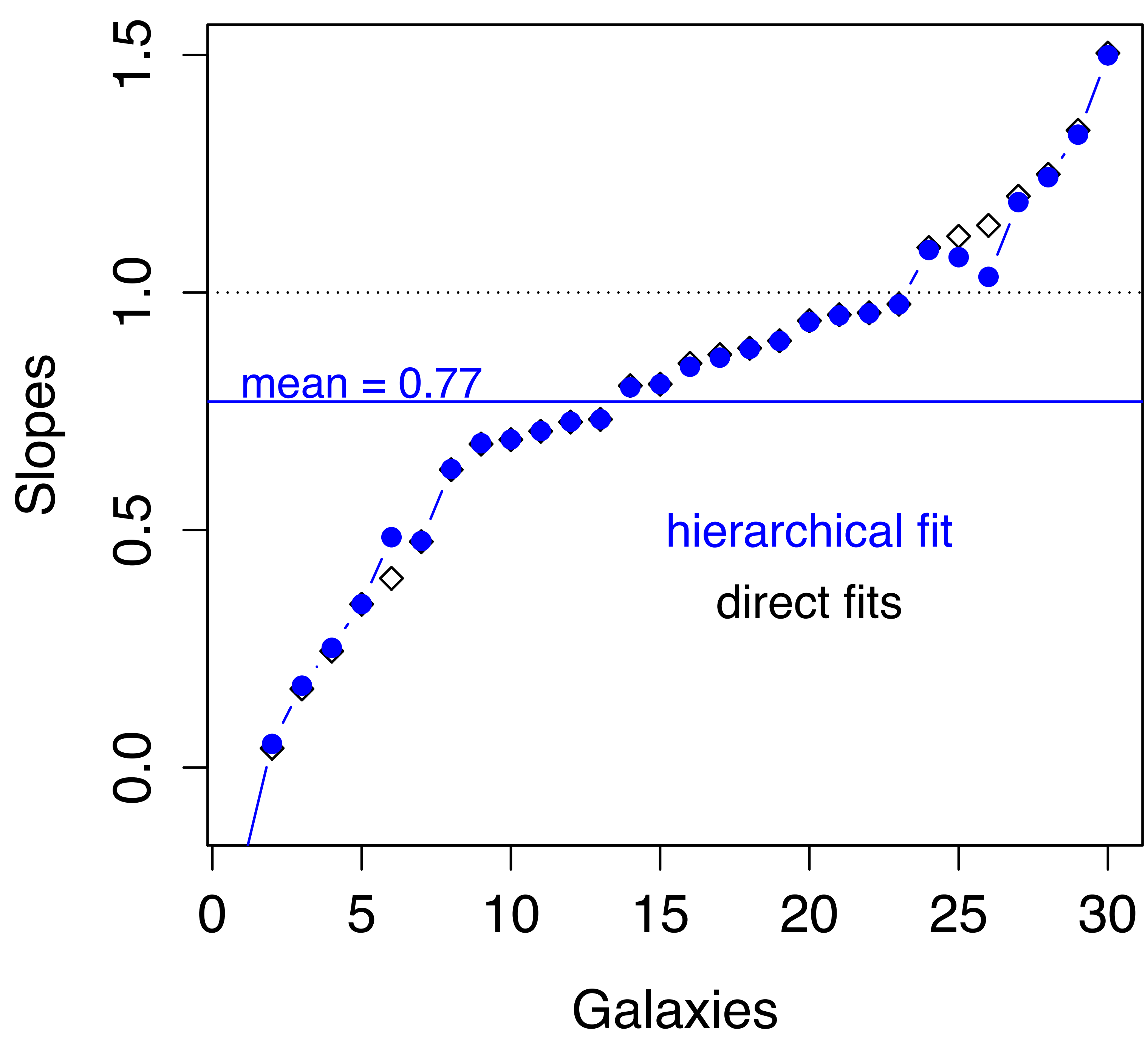
Shetty et al. (2014, MNRAS, 437, L61, see also Shetty, Kelly, Bigiel, 2013, MNRAS, 430, 288)

data from STING survey (Rahman et al. 2011, 2012)



- is there really a universal Σ_{H2} - Σ_{SFR} relation?
- there seem to be - large galaxy-to-galaxy variations
  - relation is often sublinear

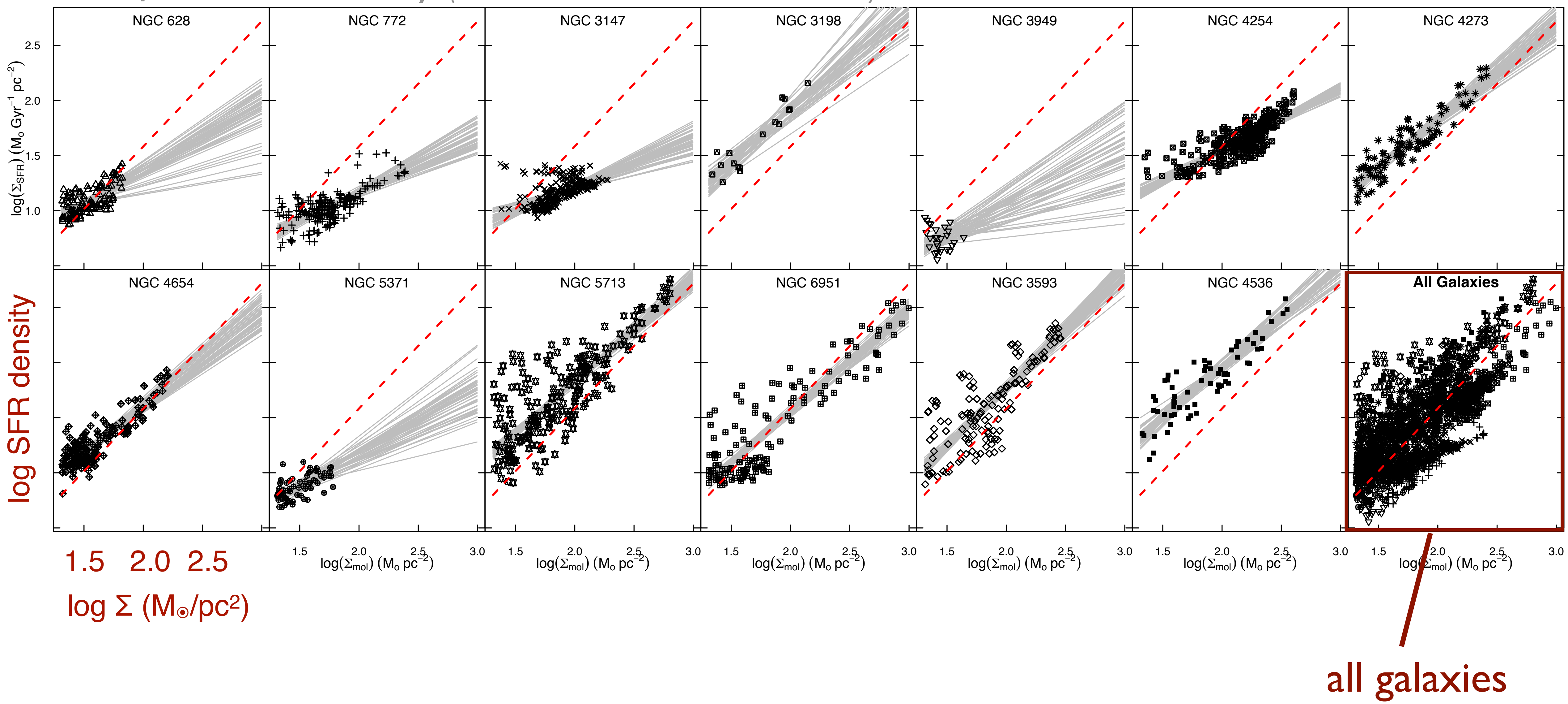
Shetty et al. (2014, MNRAS, 437, L61, see also Shetty, Kelly, Bigiel, 2013, MNRAS, 430, 288)



- analysis of THINGS/ HERACLES data
- many galaxies show sublinear KS-type relation

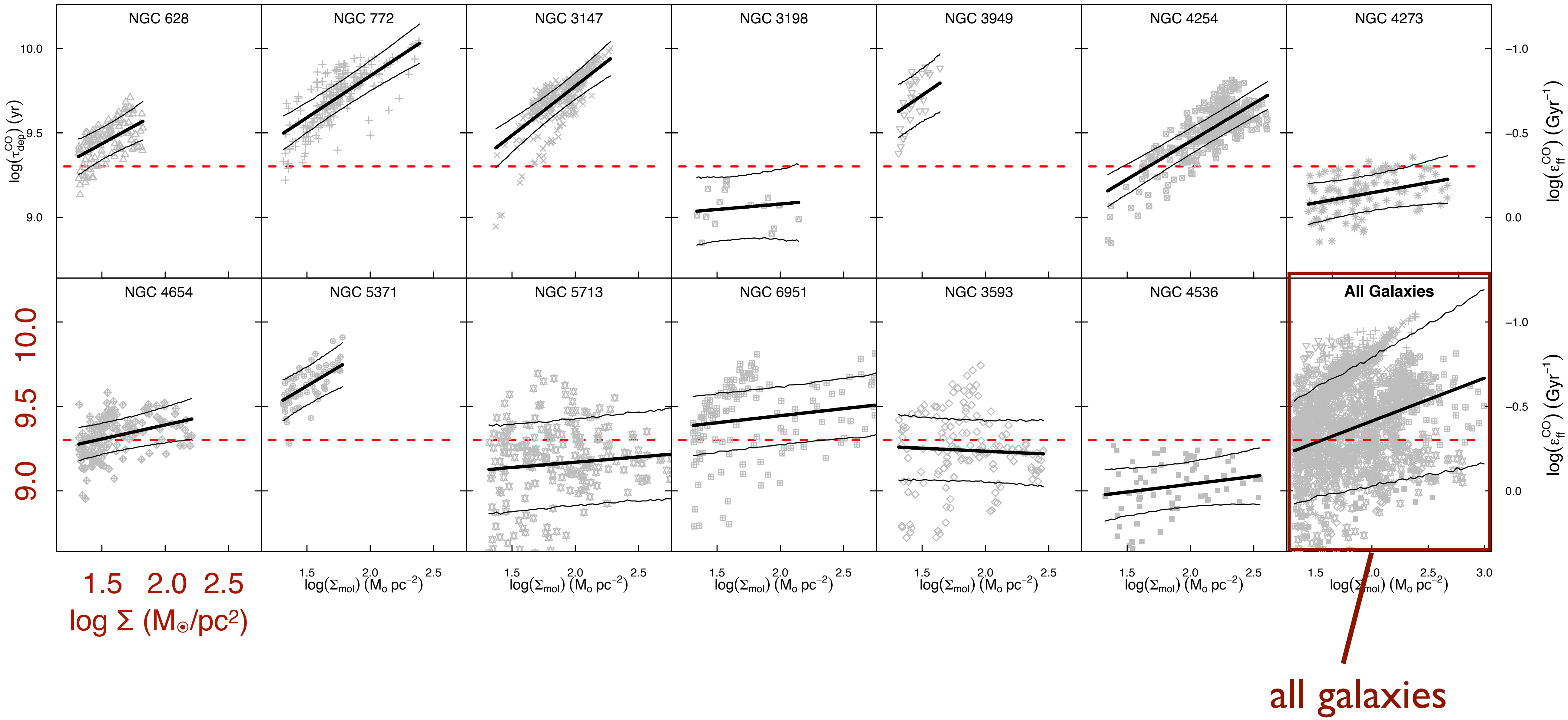
Image from R. Shetty / thanks to THINGS/HERACLES collaboration for providing the data.

data from STING survey (Rahman et al. 2011, 2012)



Shetty et al. (2014, MNRAS, 437, L61, see also Shetty, Kelly, Bigiel, 2013, MNRAS, 430, 288)

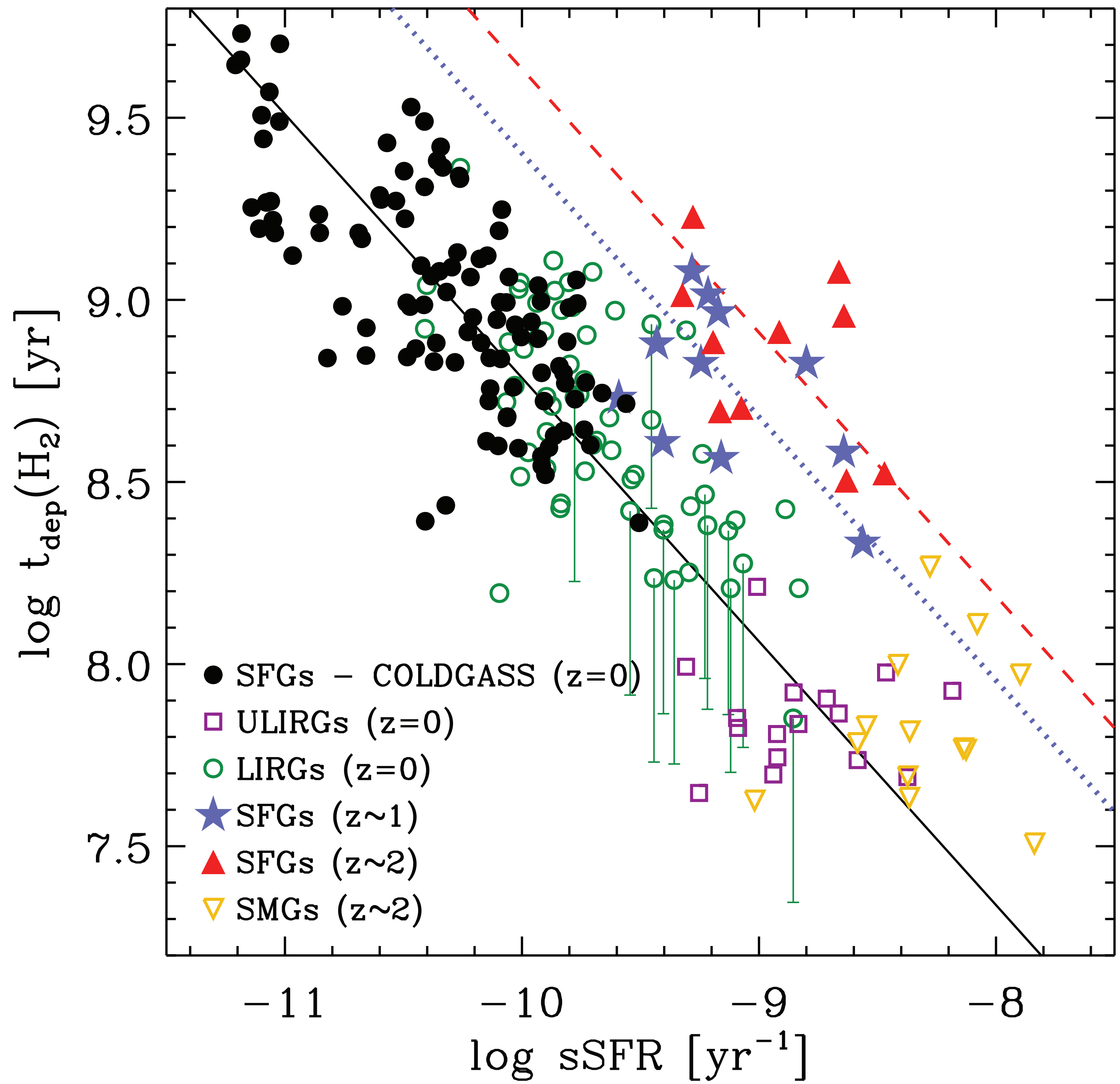
data from STING survey (Rahman et al. 2011, 2012)



Hierarchical Bayesian model for STING galaxies indicate *varying depleting times*. Depletion time *increases* with increasing density. *Why ??*

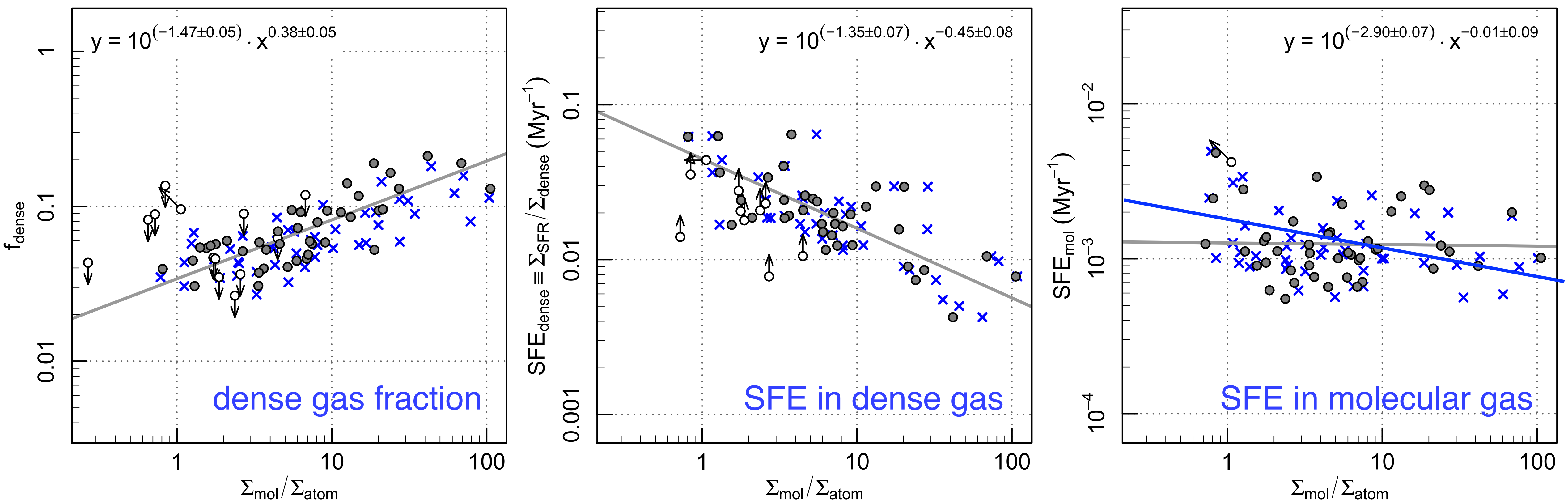
Shetty et al. (2014, MNRAS, 437, L61)

- ***COLD GASS survey***
- large number of different galaxies
- depletion times vary widely across different types of galaxies.

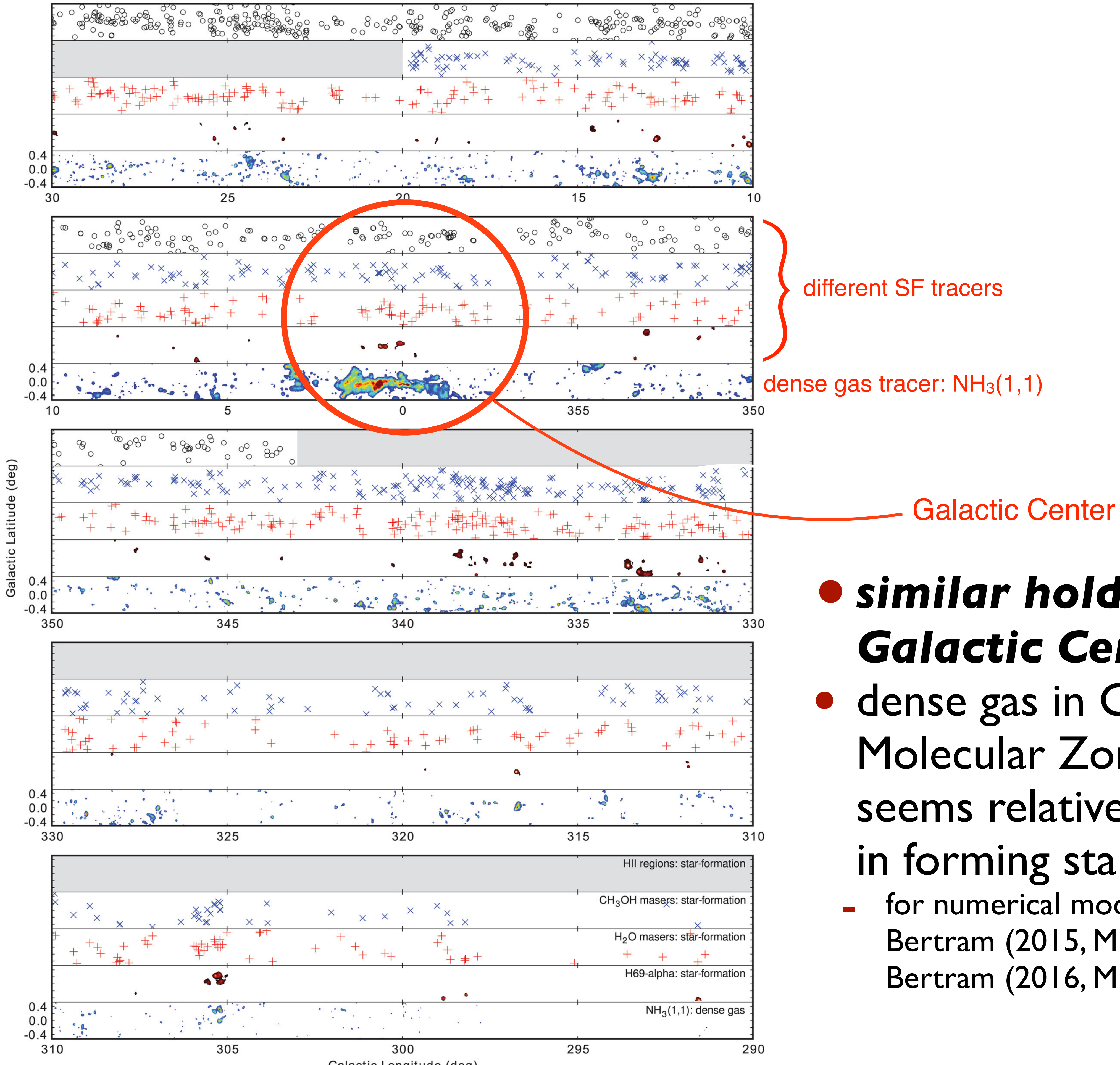


Saintonge et al. (2011, MNRAS, 415, 61)

- ***EMPIRE survey***
- IR-to-HCN ratio varies systematically as function of local disk structure (here stellar surface density)
- dense gas is less good in forming stars in overall dense regions (longer depletion time)



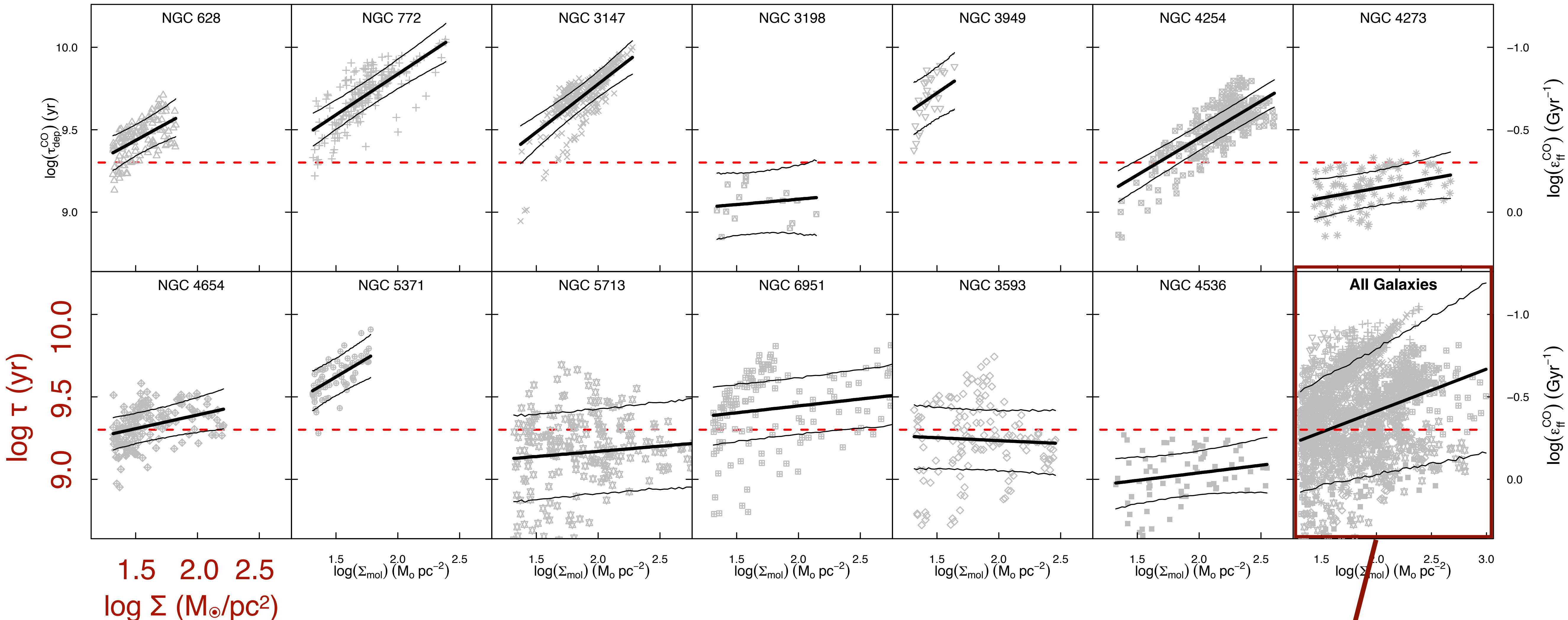
Usero (2015, ApJ, 150, 115)



- ***similar holds for Galactic Center:***
- dense gas in Central Molecular Zone (CMZ) seems relative inefficient in forming stars
  - for numerical modeling see Bertram (2015, MNRAS, 451, 3679), Bertram (2016, MNRAS, 455, 3763)

Longmore et al. (2013, MNRAS 429, 987)

data from STING survey (Rahman et al. 2011, 2012)



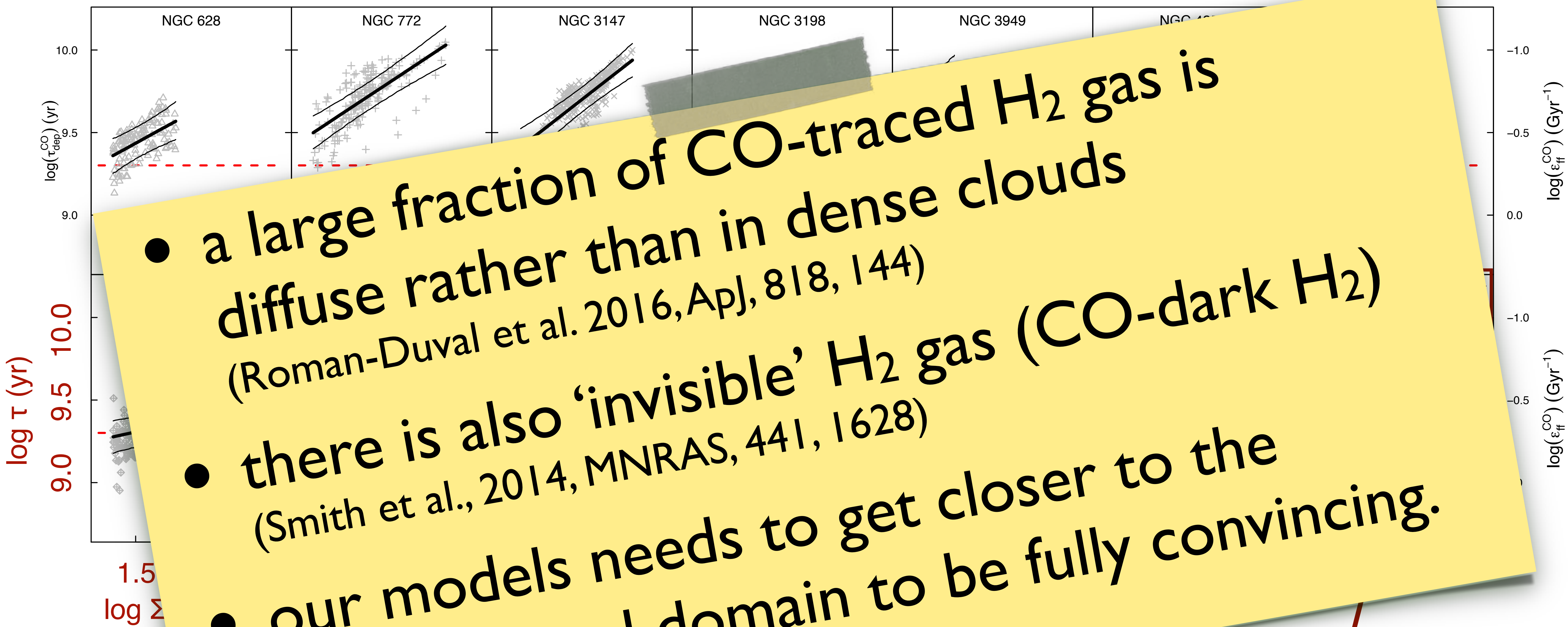
all galaxies

physical origin of this behavior?

- maybe strong shear in dense arms (example M51, Meidt et al. 2013)...
- maybe non-star forming H_2 gas becomes traced by CO at high column densities (recall H_2 needs A_V~1, CO needs A_V~2,)…

Shetty et al. (2013, MNRAS, 437, L61, see also Shetty, Kelly, Bigiel, 2013, MNRAS, 430, 288)

data from STING survey (Rahman et al. 2011, 2012)



- a large fraction of CO-traced H_2 gas is diffuse rather than in dense clouds (Roman-Duval et al. 2016, ApJ, 818, 144)
- there is also 'invisible' H_2 gas (CO-dark H_2) (Smith et al., 2014, MNRAS, 441, 1628)
- our models needs to get closer to the observational domain to be fully convincing.

physi... ...or?

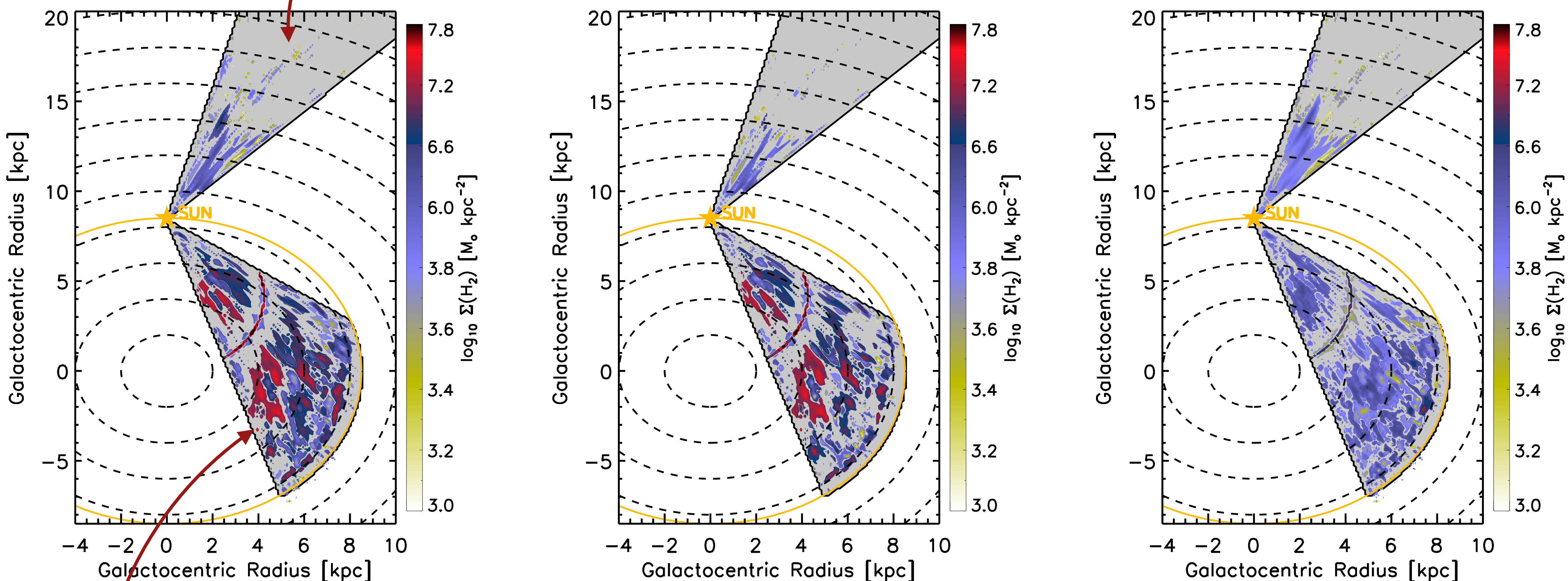
- mayb... ...ng shear in dense arms (example M51, Meidt et al. 2013)...
- maybe non-star forming H_2 gas becomes traced by CO at high column densities (recall H_2 needs $A_V \sim 1$, CO needs $A_V \sim 2$,)...

Shetty et al. (2013, MNRAS, 437, L61, see also Shetty, Kelly, Bigiel, 2013, MNRAS, 430, 288)

observational approach

OUTER GALAXY:
EXEF survey

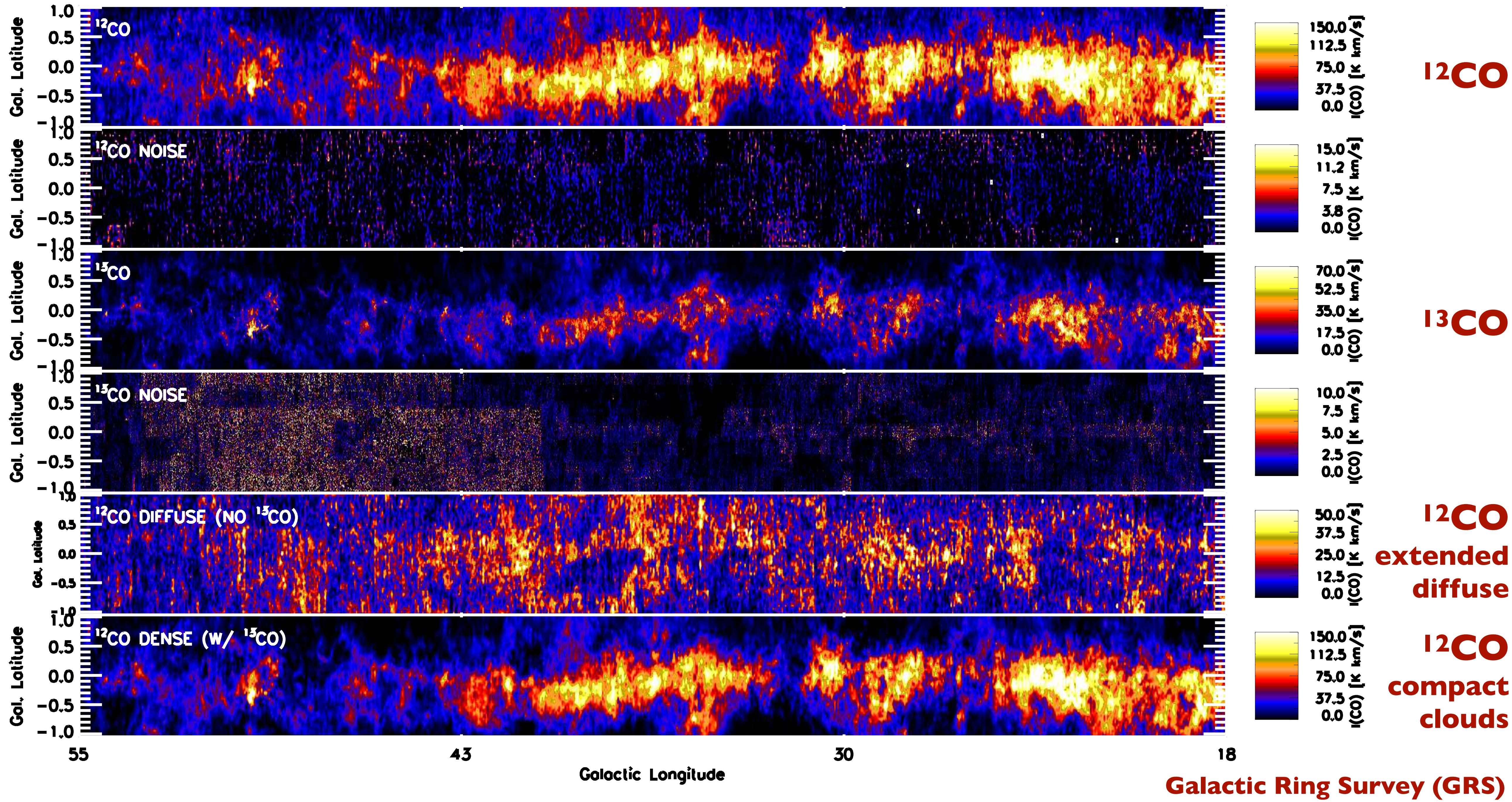
total gas | **dense clouds** | **diffuse gas**



INNER GALAXY:
Galactic Ring Survey (GRS)

Exeter-Five College Radio Astronomy Observatory (EXFC)
Galactic Ring Survey (GRS)

Roman-Duval et al. (2016, ApJ, 818, 144)

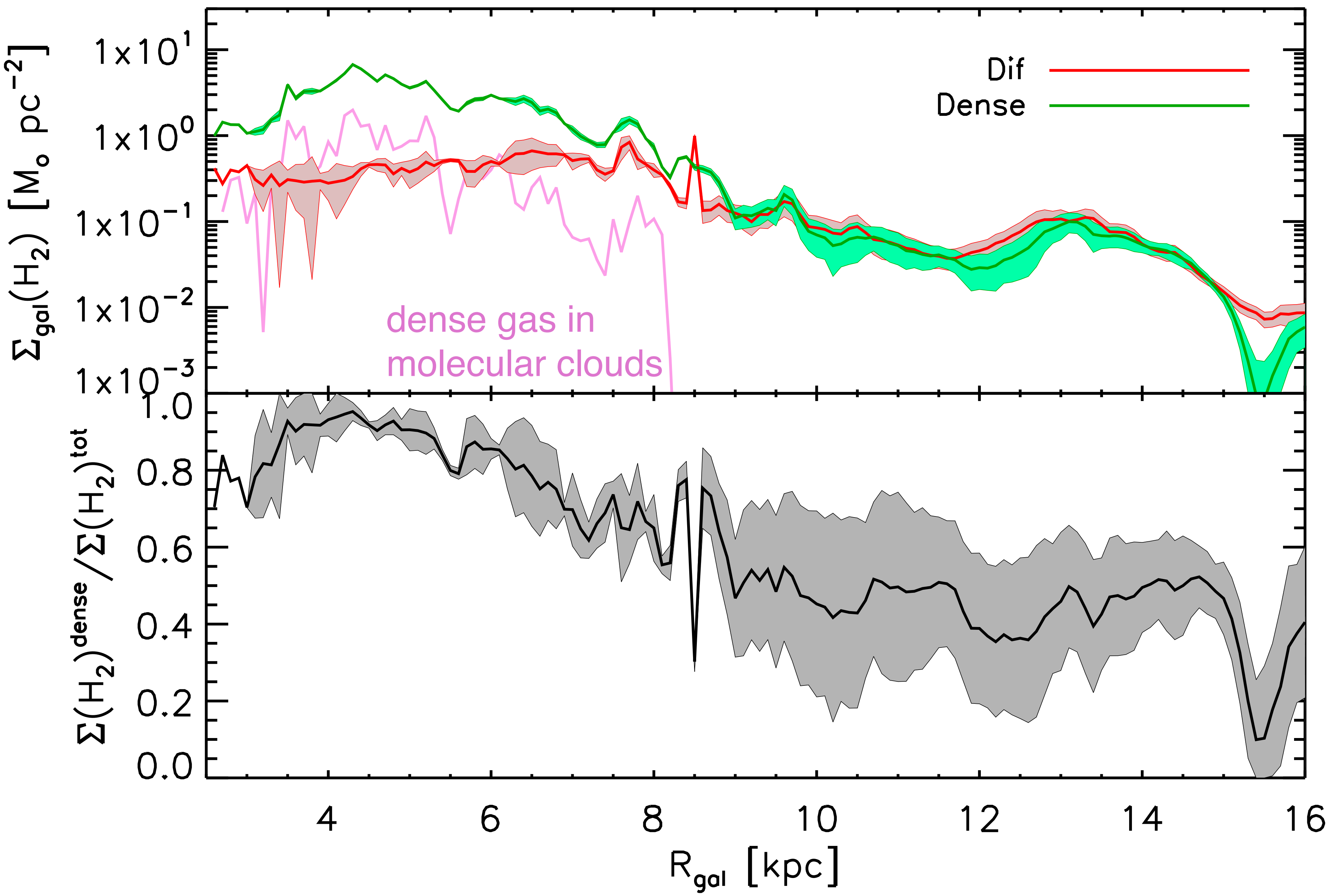


observational approach:

- comparison of ^{13}CO (tracing mostly dense clouds) and ^{12}CO tracing all the gas (including the more diffuse component)

Roman-Duval et al. (2016, ApJ, 818, 144)

dense gas fraction as function of radius

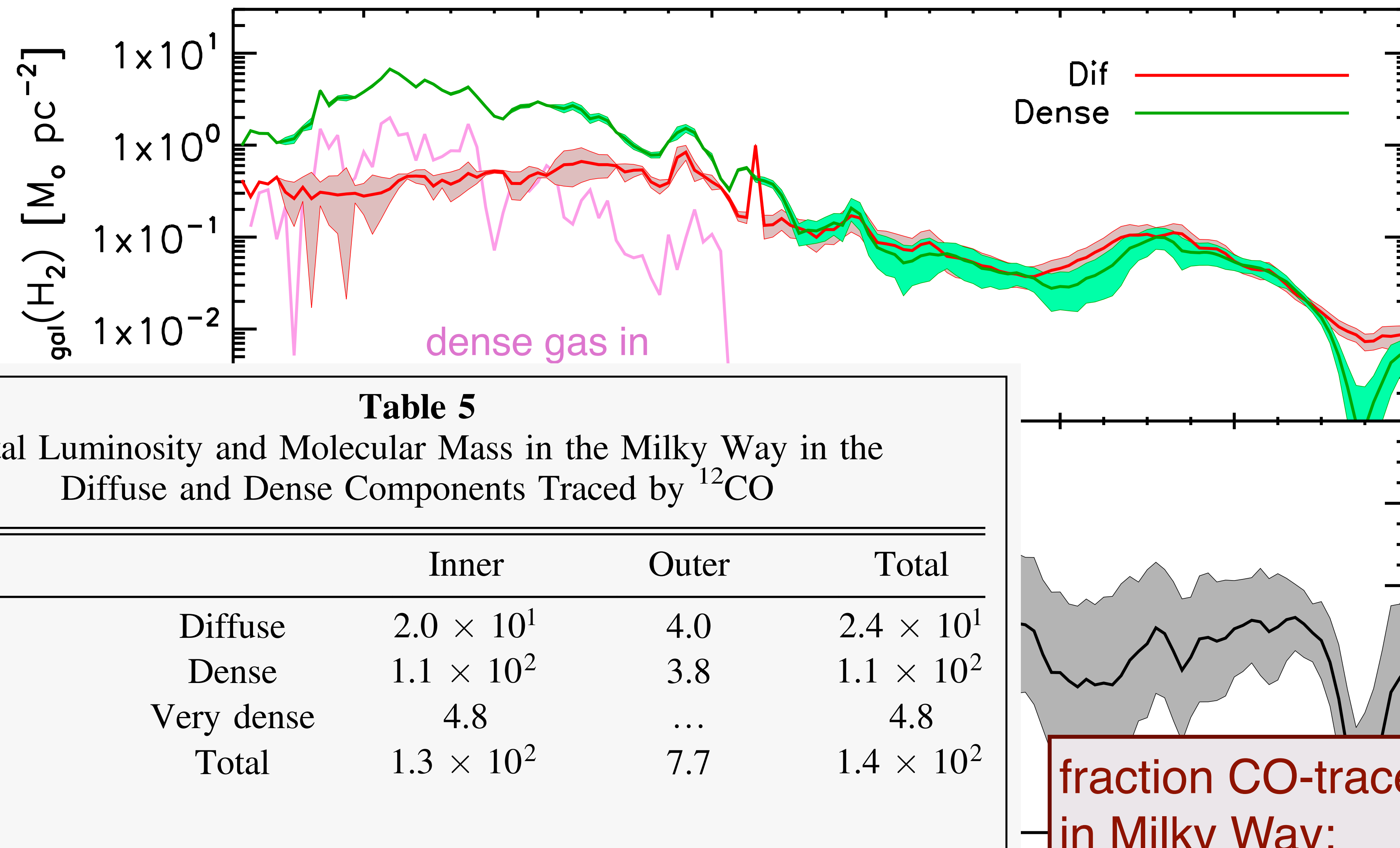


- inner Galaxy: GRS/UMSB
- outer Galaxy: EXFC

Figure 13. Average Galactic H_2 surface densities of the diffuse (red, detected in ^{12}CO, undetected in ^{13}CO) and dense (green, detected in ^{12}CO and ^{13}CO) components as a function of Galactocentric radius (in bins of width 0.1 kpc), in logarithmic scale, combining all data sets. In the inner Galaxy, the pink line indicates the surface density of H_2 in molecular clouds identified in Roman-Duval et al. (2010).

Roman-Duval et al. (2016, ApJ, 818, 144)

dense gas fraction as function of radius



- inner Galaxy: GRS/UMSB
- outer Galaxy: EXFC

Table 5
Total Luminosity and Molecular Mass in the Milky Way in the Diffuse and Dense Components Traced by ^{12}CO

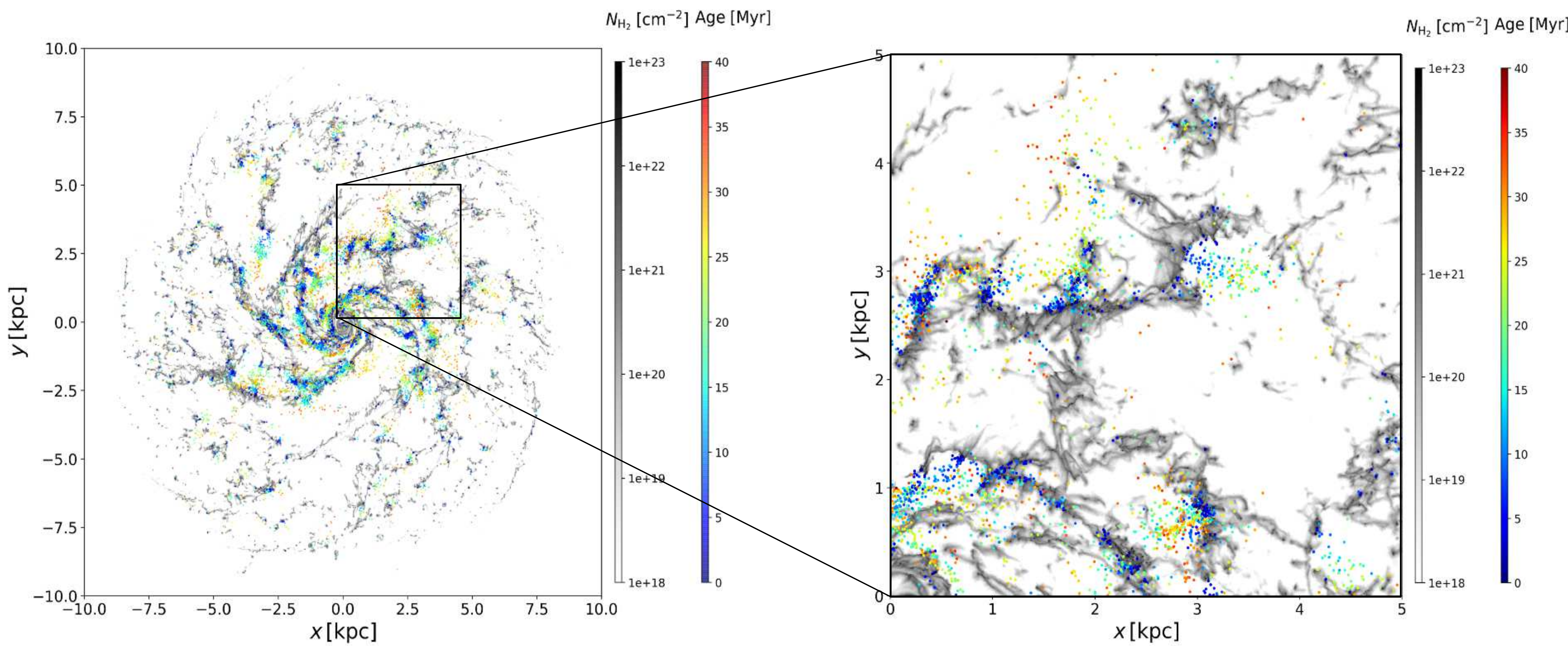
		Inner	Outer	Total
L(^{12}CO)	Diffuse	2.0×10^1	4.0	2.4×10^1
	Dense	1.1×10^2	3.8	1.1×10^2
	Very dense	4.8	…	4.8
	Total	1.3×10^2	7.7	1.4×10^2
$M(H_2)$	Diffuse	9.3×10^7	6.0×10^7	1.5×10^8
	Dense	4.6×10^8	3.9×10^7	4.9×10^8
	Very dense	2.9×10^7	…	2.9×10^7
	Total	5.5×10^8	9.9×10^7	6.5×10^8

fraction CO-traced H_2 gas in Milky Way:
~1/4 diffuse
~3/4 dense
~1/20 in known molecular clouds only !!!

Roman-Duval et al. (2016, ApJ, 818, 144)


modeling the
galactic ecosystem

modeling the multi-phase ISM



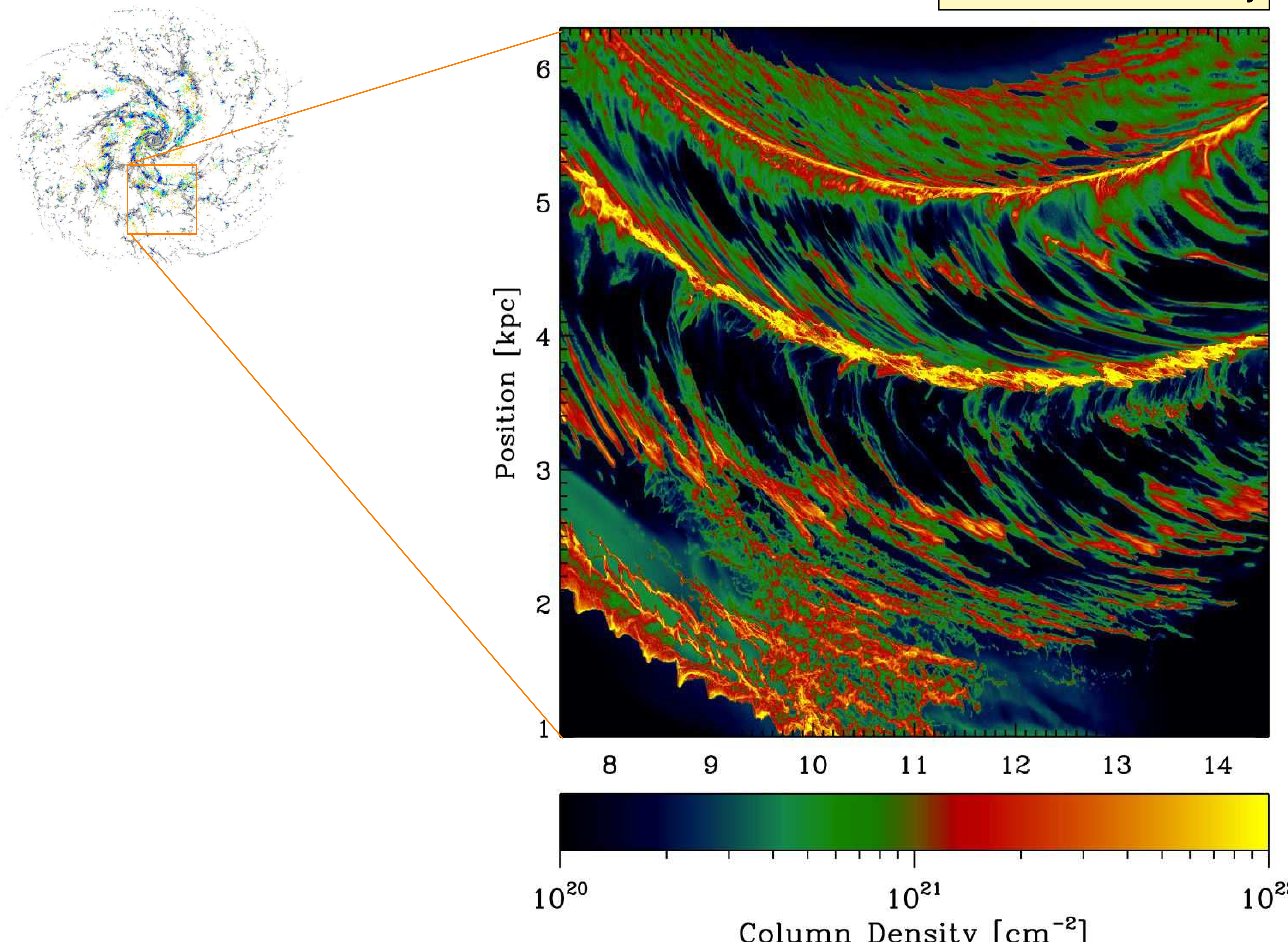
Simulation of a spiral galaxy with time-dependent chemistry, star formation, SN feedback.

Molecular gas indicated in grey, stellar ages color codes.

- Arepo moving mesh code *(Springel 2010)*
- more realistic potential (better disk scale height)
- with self-gravity and supernovae feedback!
- star formation
- full-chemistry
- possibility to define zoom-in regions

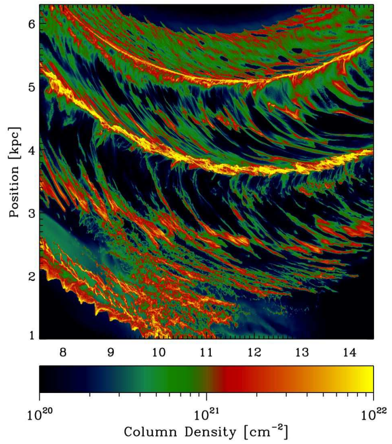
(Smith et al. (2014, MNRAS, 441, 1628), Glover & Smith (2016, 462, 3011), Tress et al. (2018, in prep.)

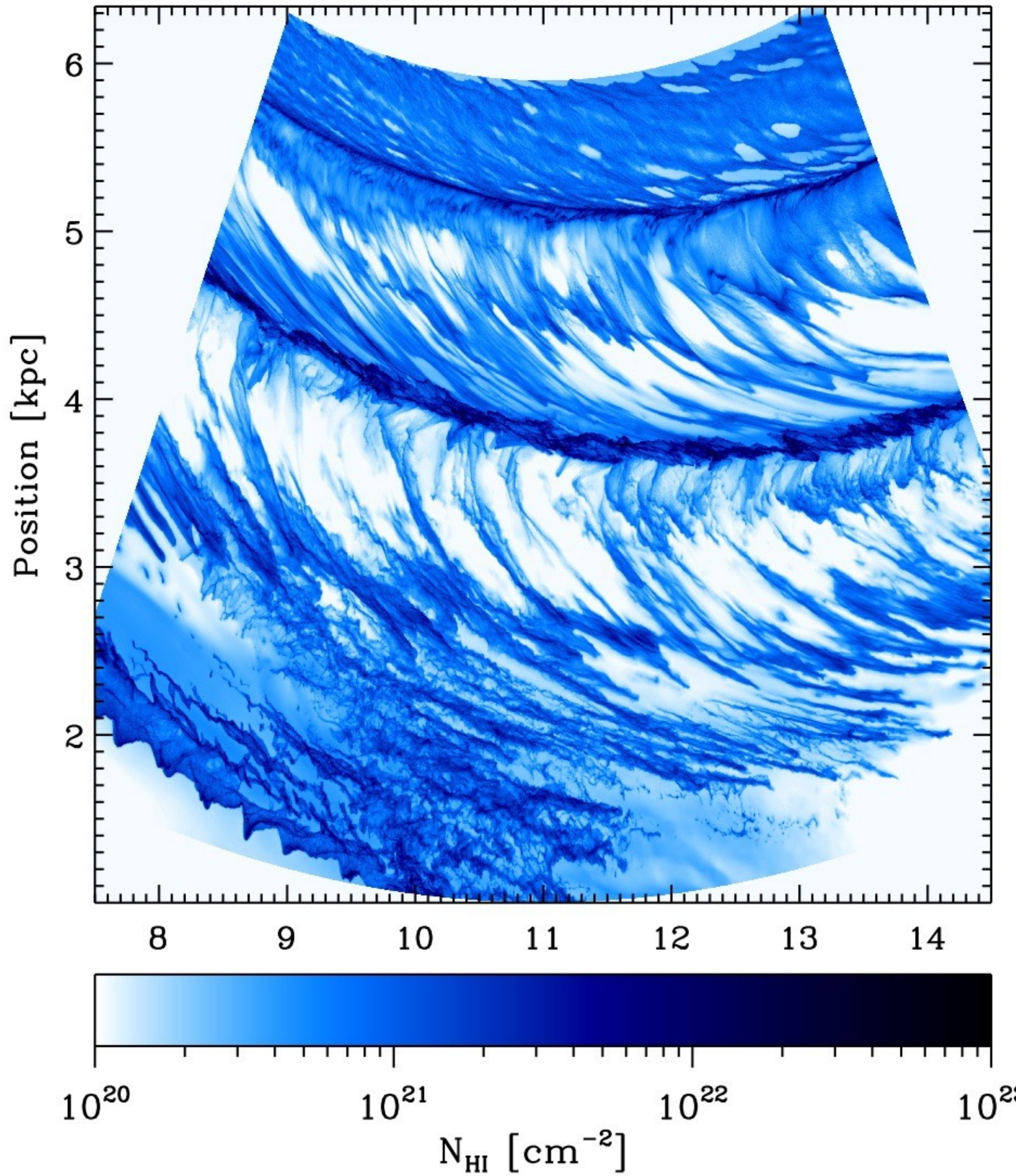
total column density



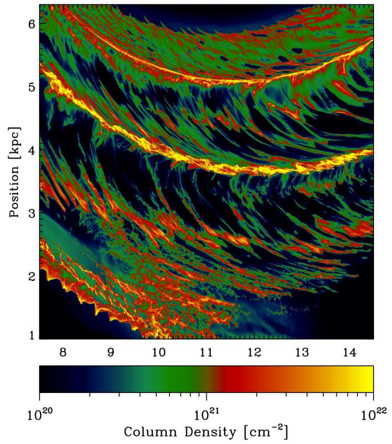
(Smith et al., 2014, MNRAS, 441, 1628)

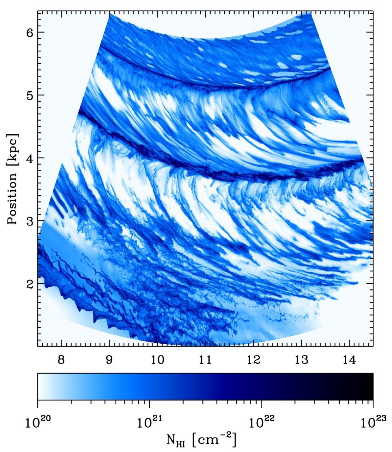
HI column density



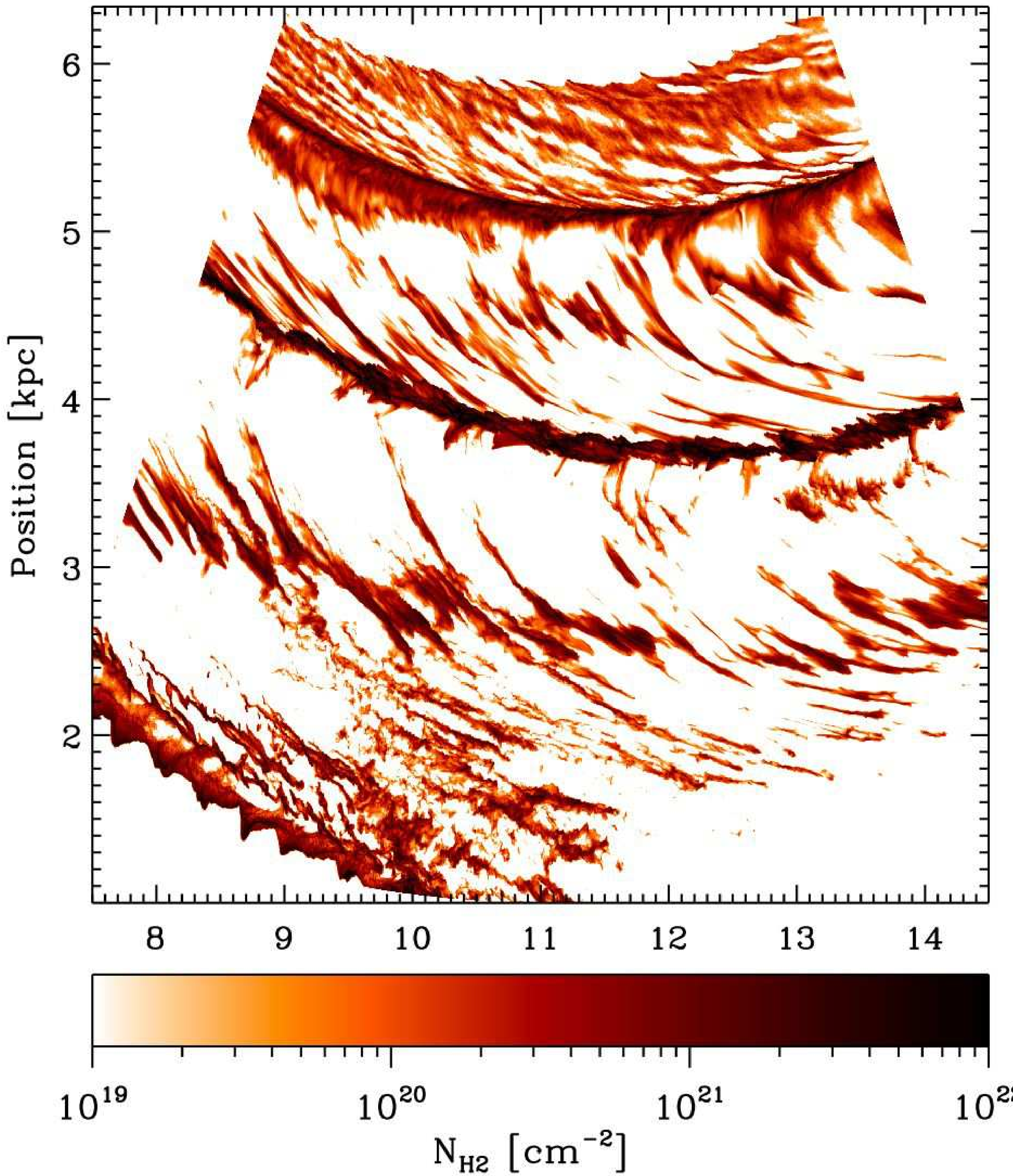


(Smith et al., 2014, MNRAS, 441, 1628)

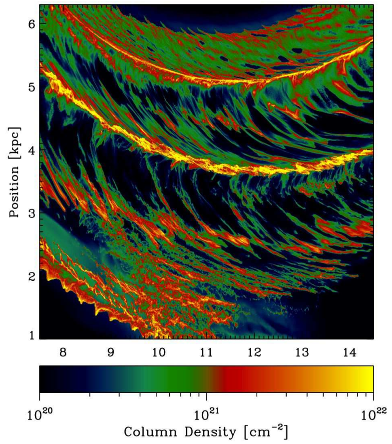


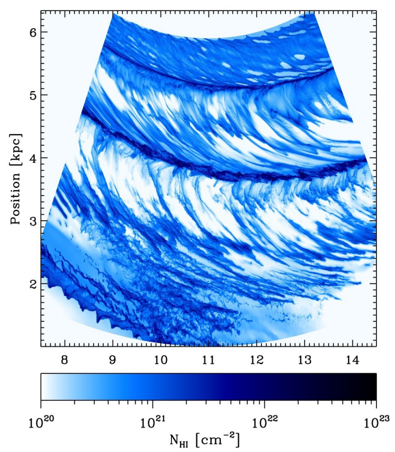


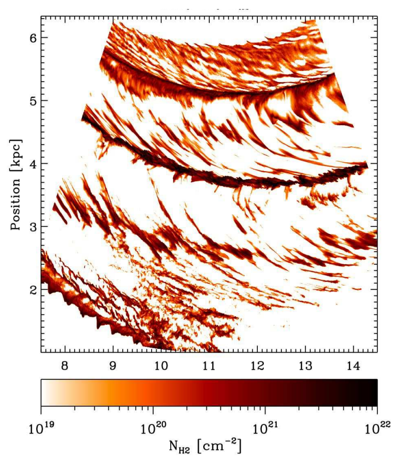
H_2 column density



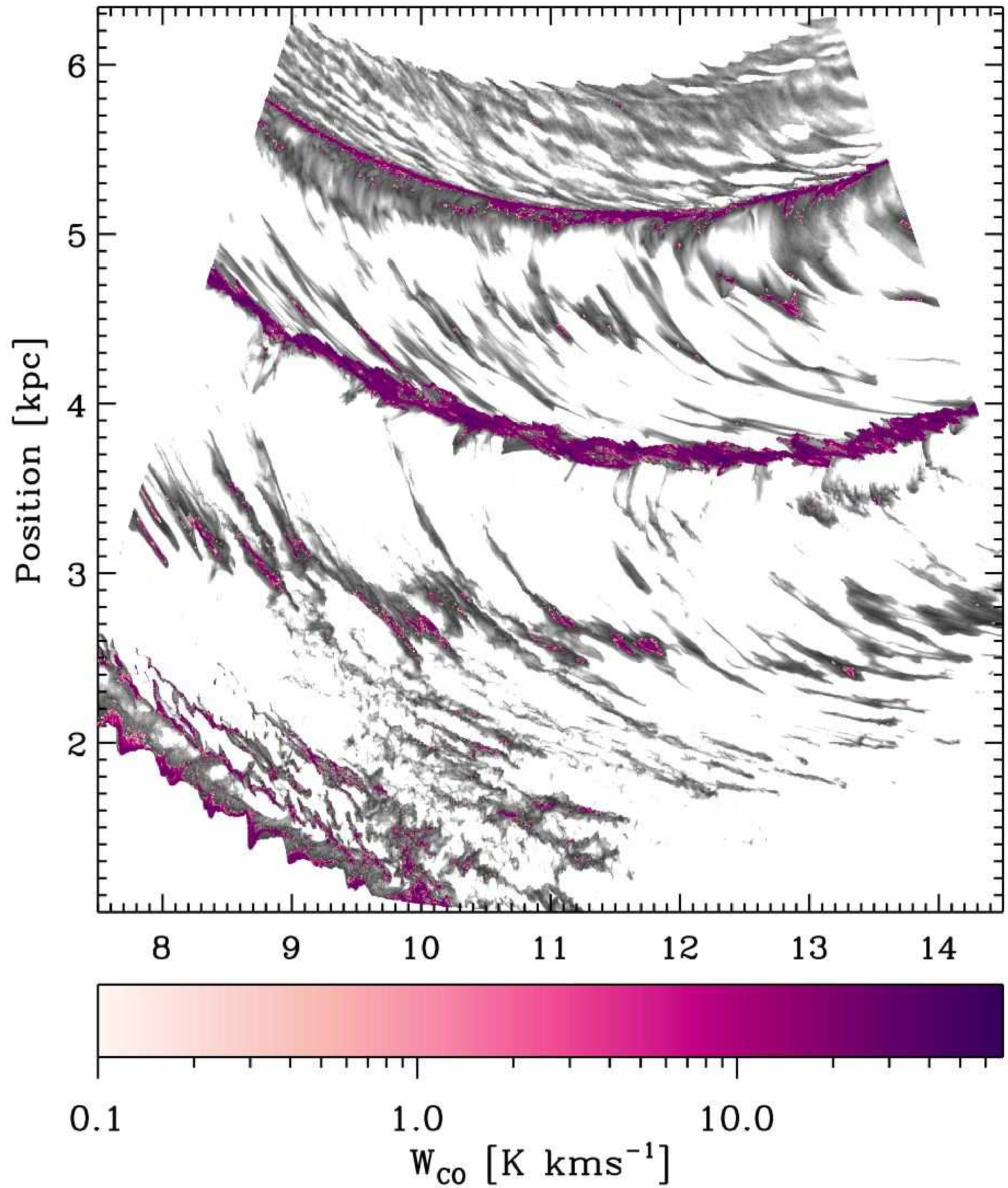
(Smith et al., 2014, MNRAS, 441, 1628)





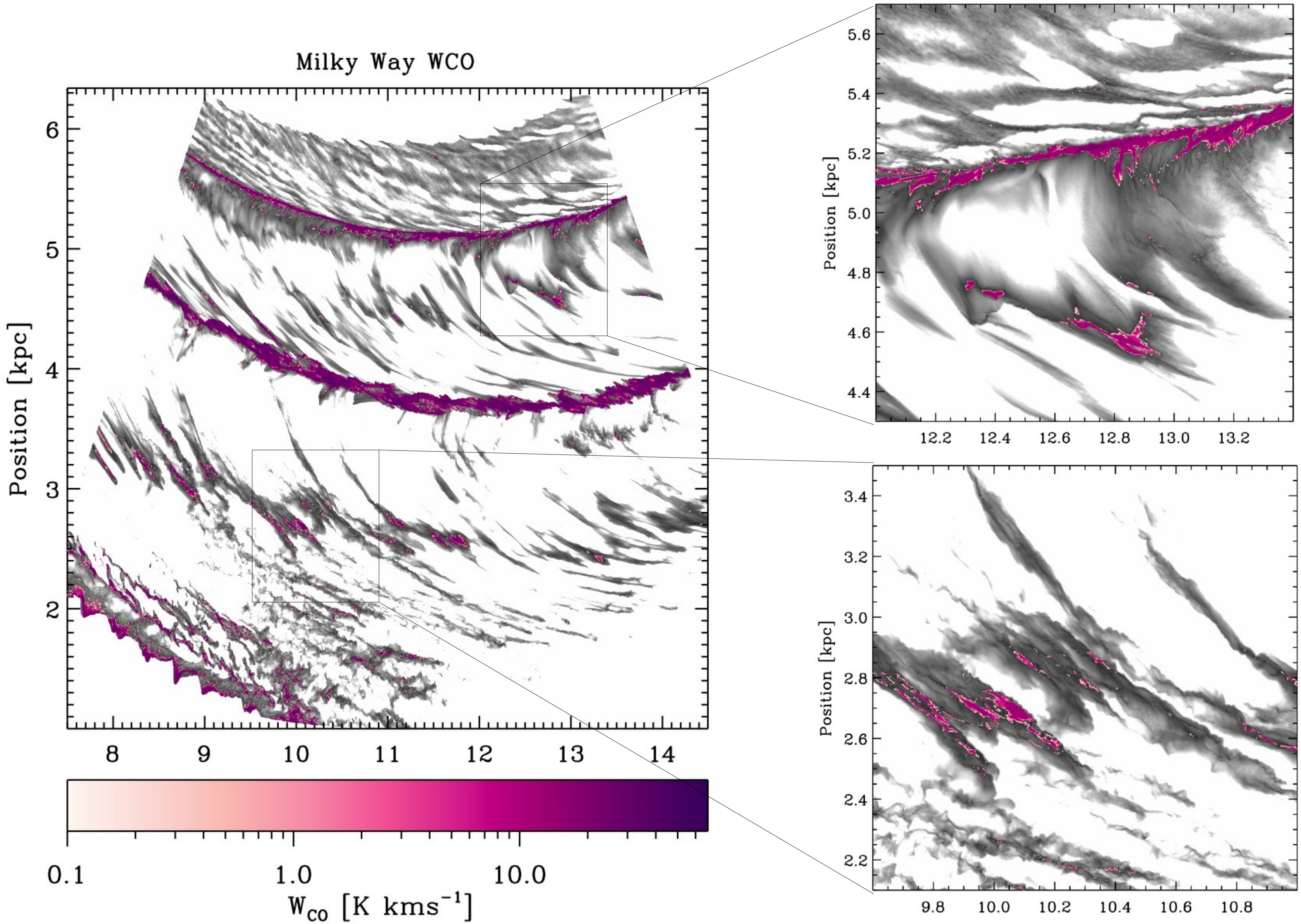


CO column density



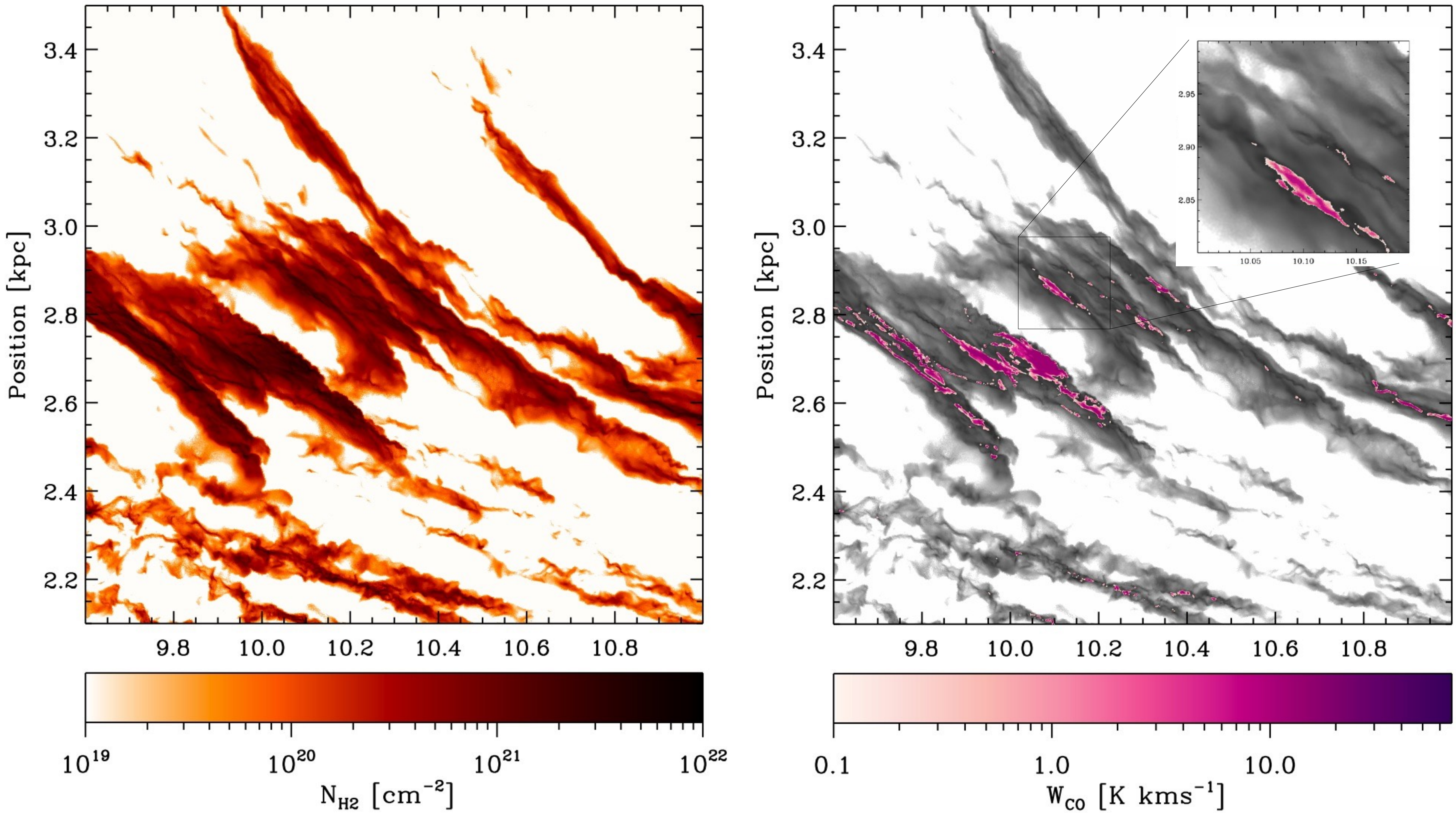
(Smith et al., 2014, MNRAS, 441, 1628)

relation between CO and H_2



(Smith et al., 2014, MNRAS, 441, 1628)

relation between CO and H_2



Filamentary molecular clouds in inter-arm regions are likely only the observable parts of much larger structures.

further evidence form detailed colliding flow calculations

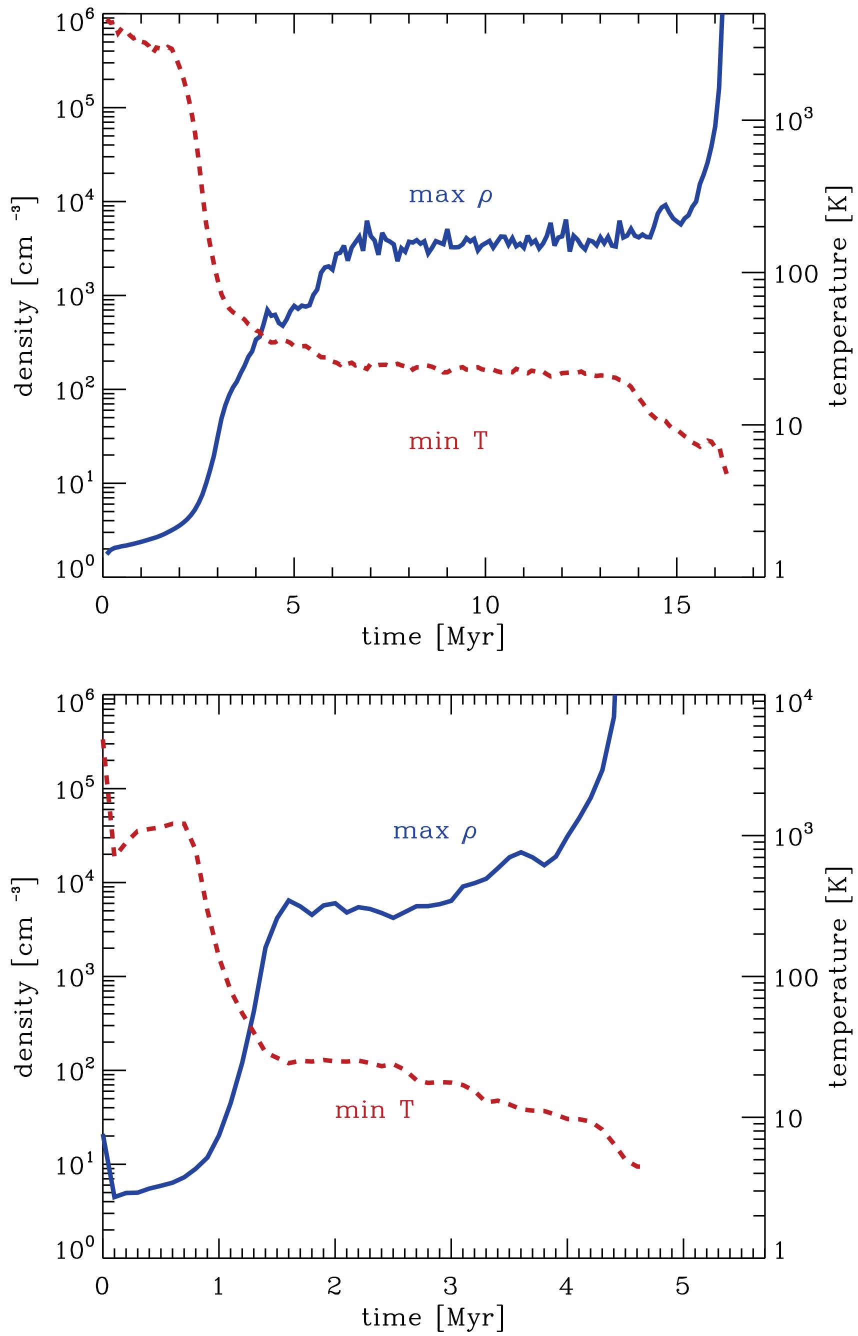


Figure 3. Evolution with time of the maximum density (blue, solid line) and minimum temperature (red, dashed line) in the slow flow (top panel) and the fast flow (bottom panel). Note that at any given instant, the coldest SPH particle is not necessarily the densest, and so the lines plotted are strictly independent of one another.

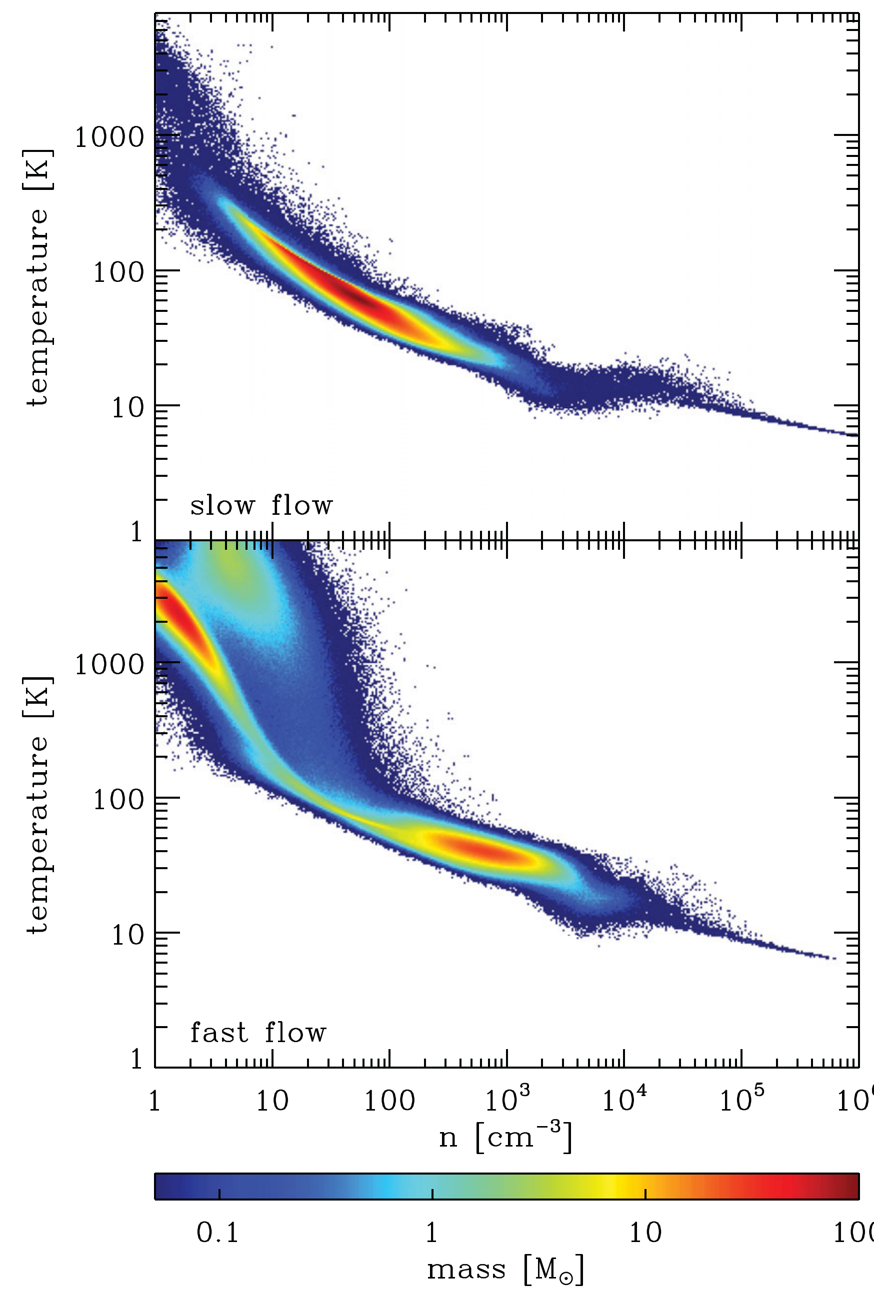


Figure 5. The gas temperature–density distribution in the flows at the onset of star formation.

Clark et al. (2012,MNRAS, 424, 2599)

see also Pringle, Allen, Lubov (2001), Hosokawa & Inutsuka (2007)

further evidence form detailed colliding flow calculations

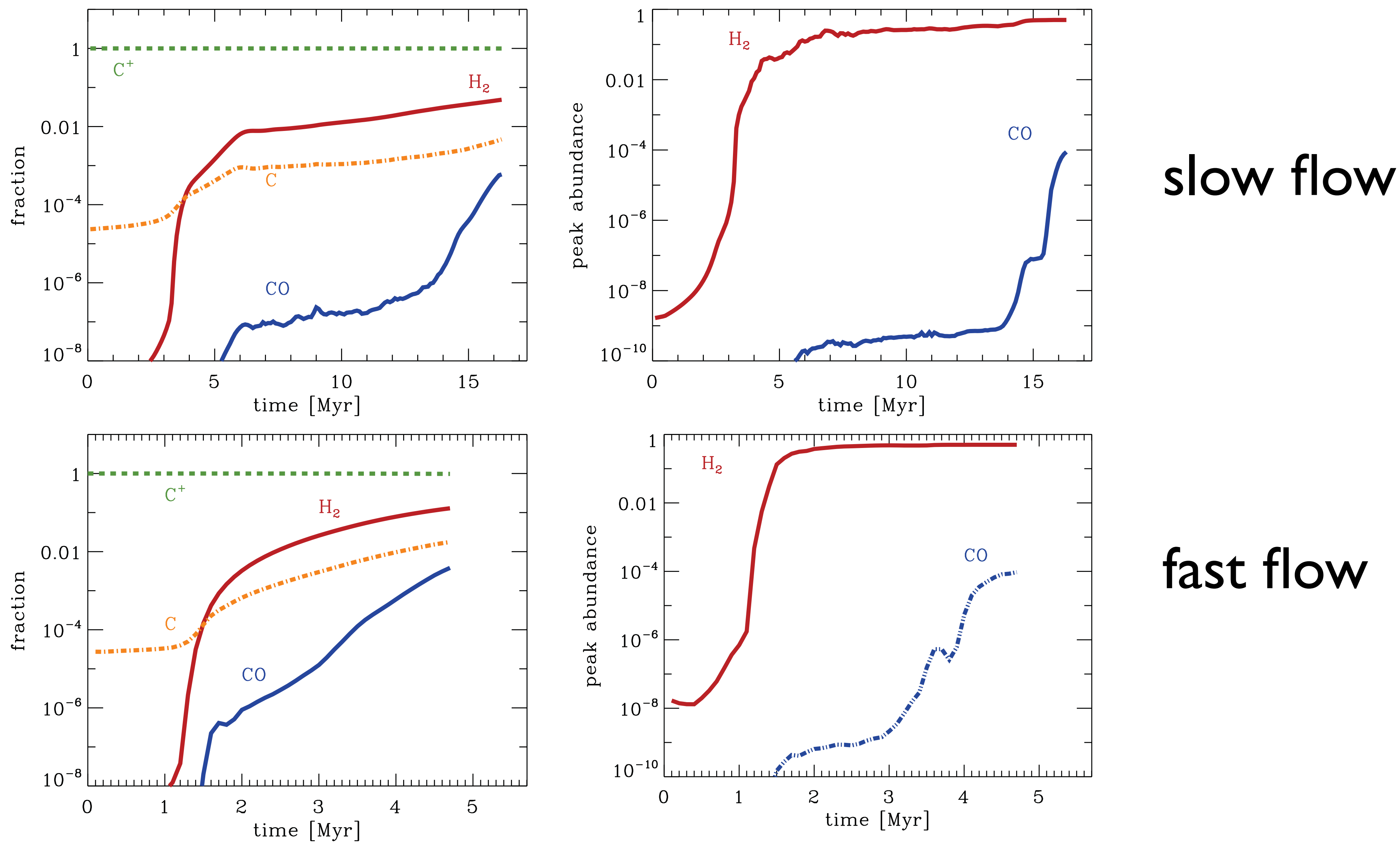
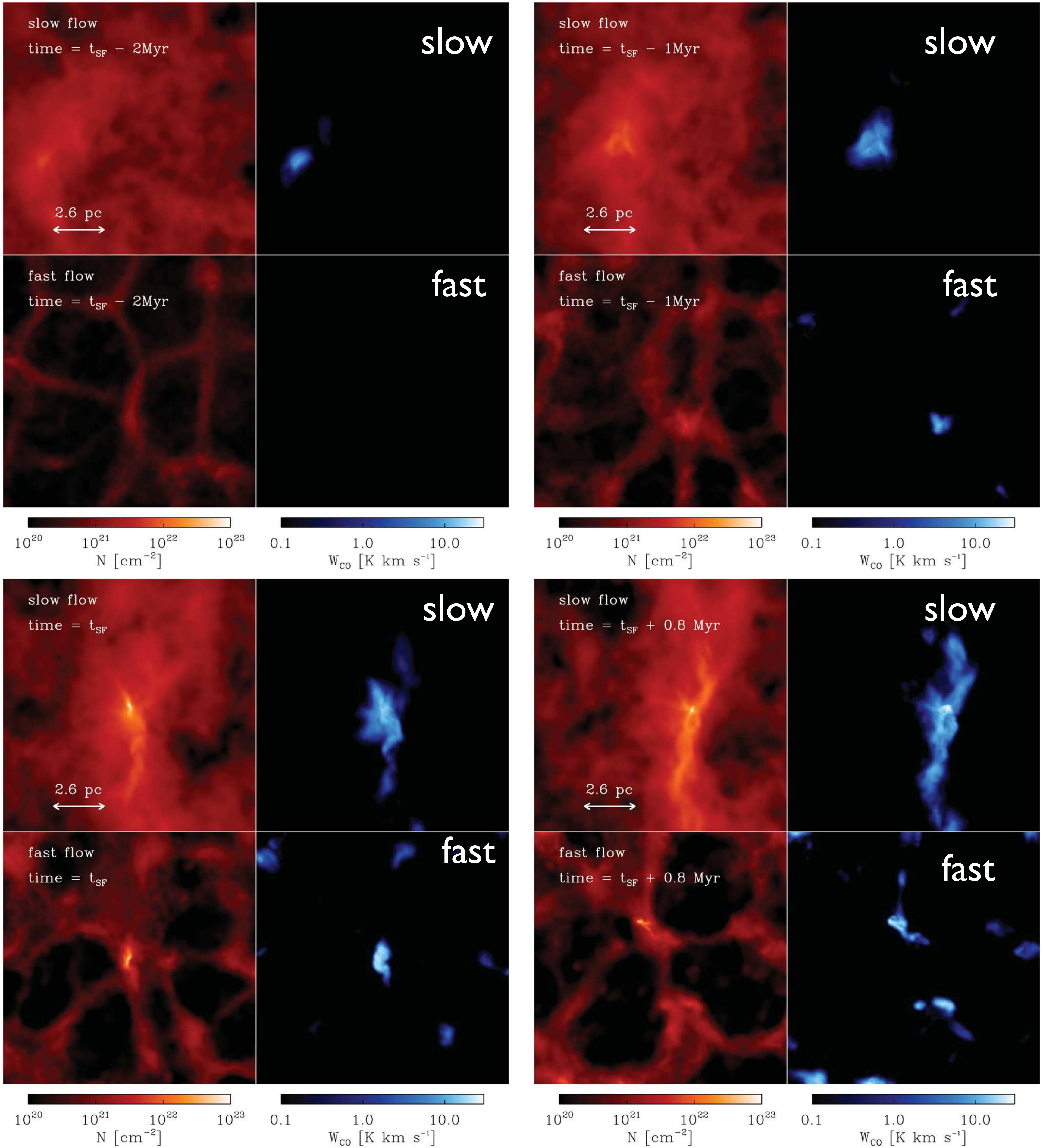


Figure 6. Chemical evolution of the gas in the flow. In the left-hand column, we show the time evolution of the fraction of the total mass of hydrogen that is in the form of H_2 (red solid line) for the 6.8 km s^{-1} flow (upper panel) and the 13.6 km s^{-1} flow (lower panel). We also show the time evolution of the fraction of the total mass of carbon that is in the form of C^+ (green dashed line), C (orange dot–dashed line) and CO (blue double-dot–dashed line). In the right-hand column, we show the peak values of the fractional abundances of H_2 and CO. These are computed relative to the total number of hydrogen nuclei, and so the maximum fractional abundances of H_2 and CO are 0.5 and 1.4×10^{-4}, respectively. Again, we show results for the 6.8 km s^{-1} flow in the upper panel and the 13.6 km s^{-1} flow in the lower panel. Note that the scale of the horizontal axis differs between the upper and lower panels.

Clark et al. (2012,MNRAS, 424, 2599)

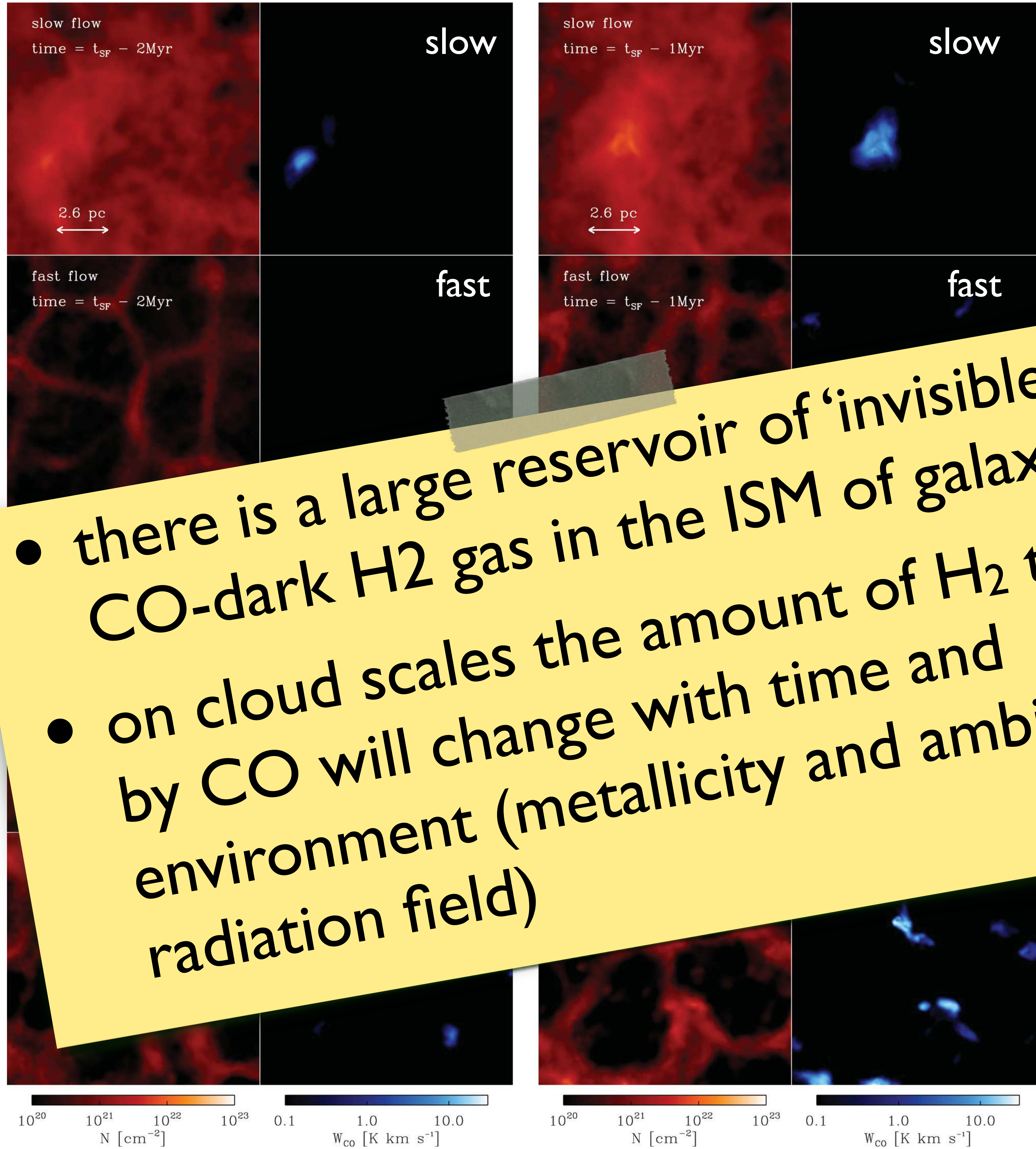
see also Pringle, Allen, Lubov (2001), Hosokawa & Inutsuka (2007)



H_2 column

CO emission

Clark et al. (2012,MNRAS, 424, 2599)



H_2 column

CO emission

- there is a large reservoir of ‘invisible’ CO-dark H2 gas in the ISM of galaxies!
- on cloud scales the amount of H_2 traced by CO will change with time and environment (metallicity and ambient radiation field)

Clark et al. (2012,MNRAS, 424, 2599)


some tools

Polaris

RT tool

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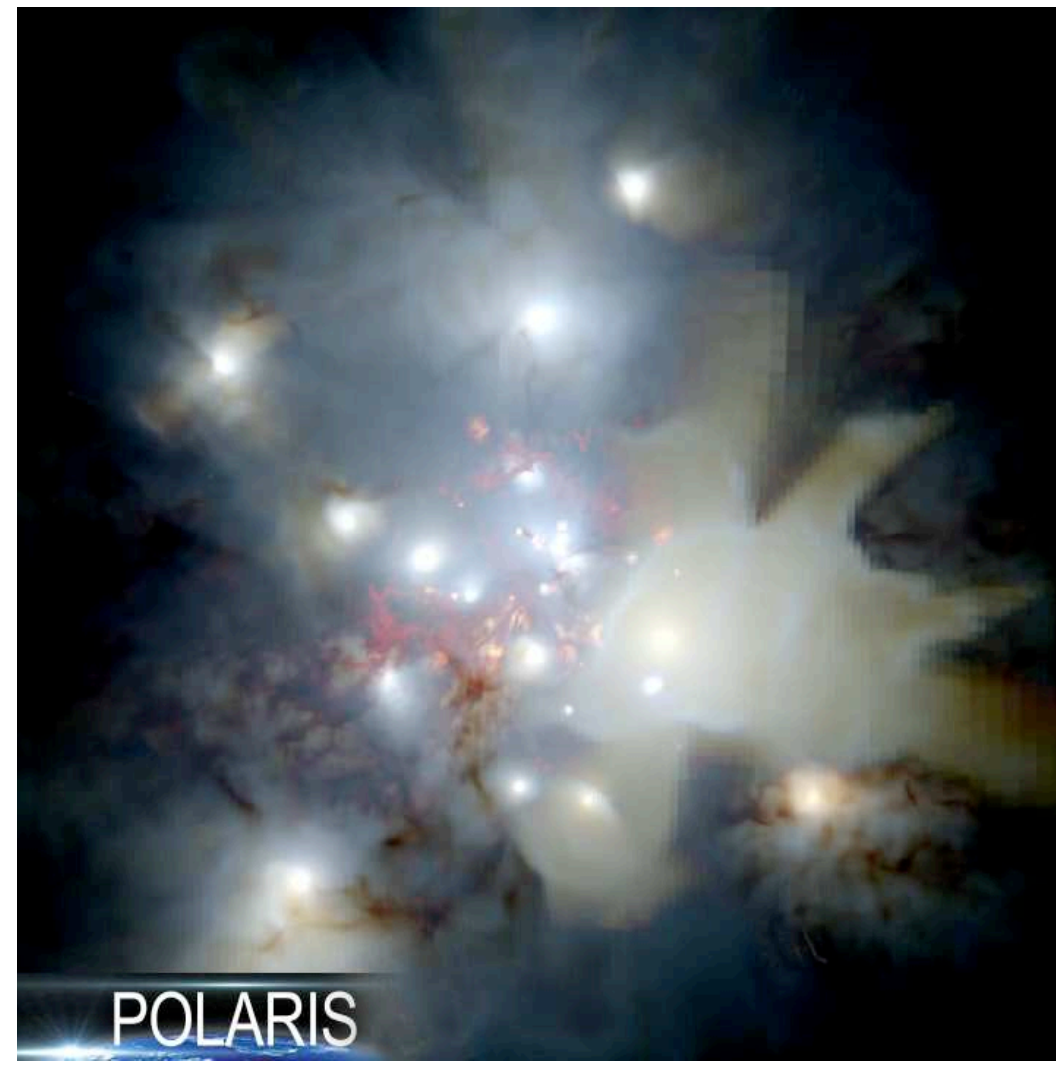
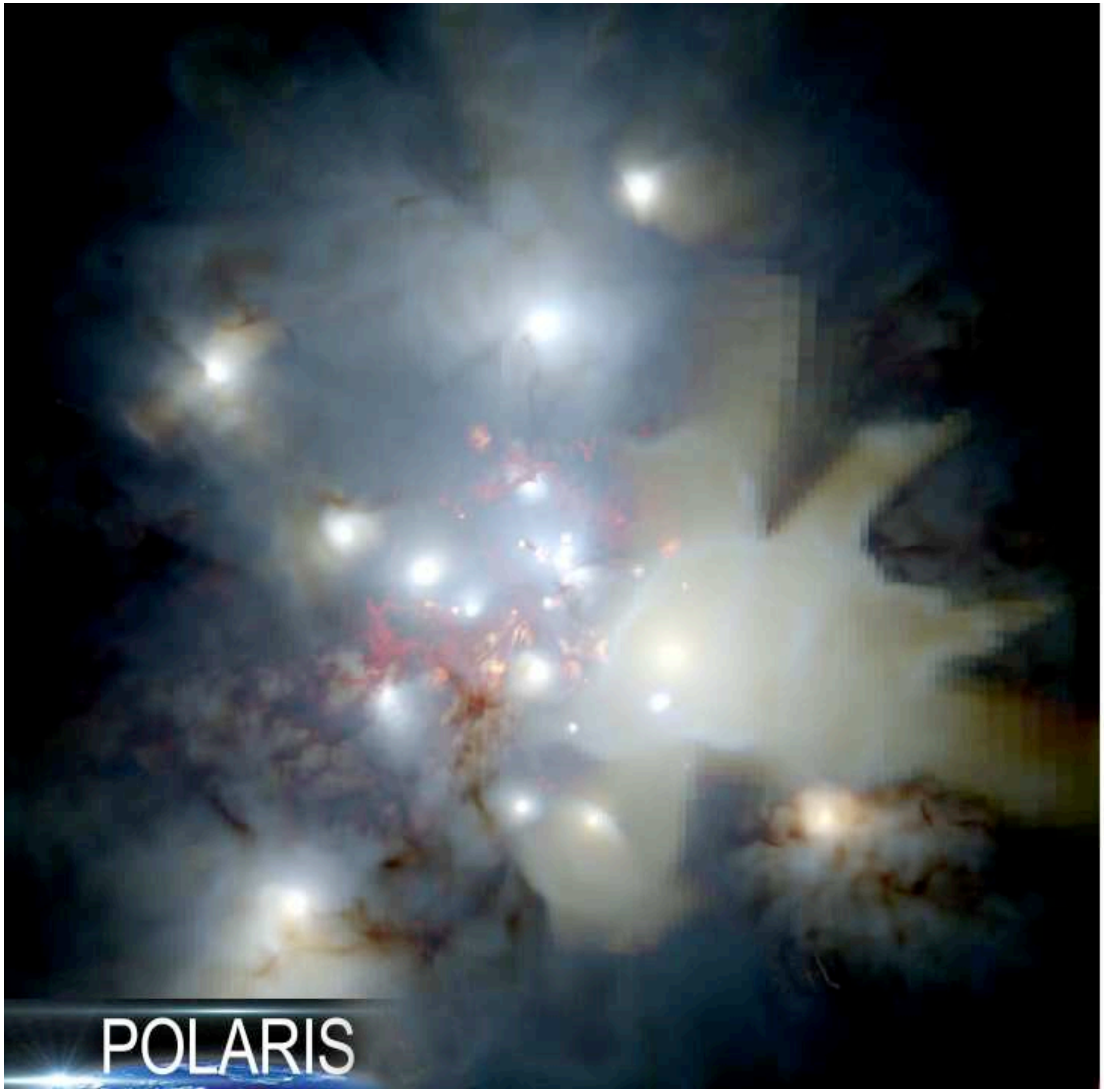
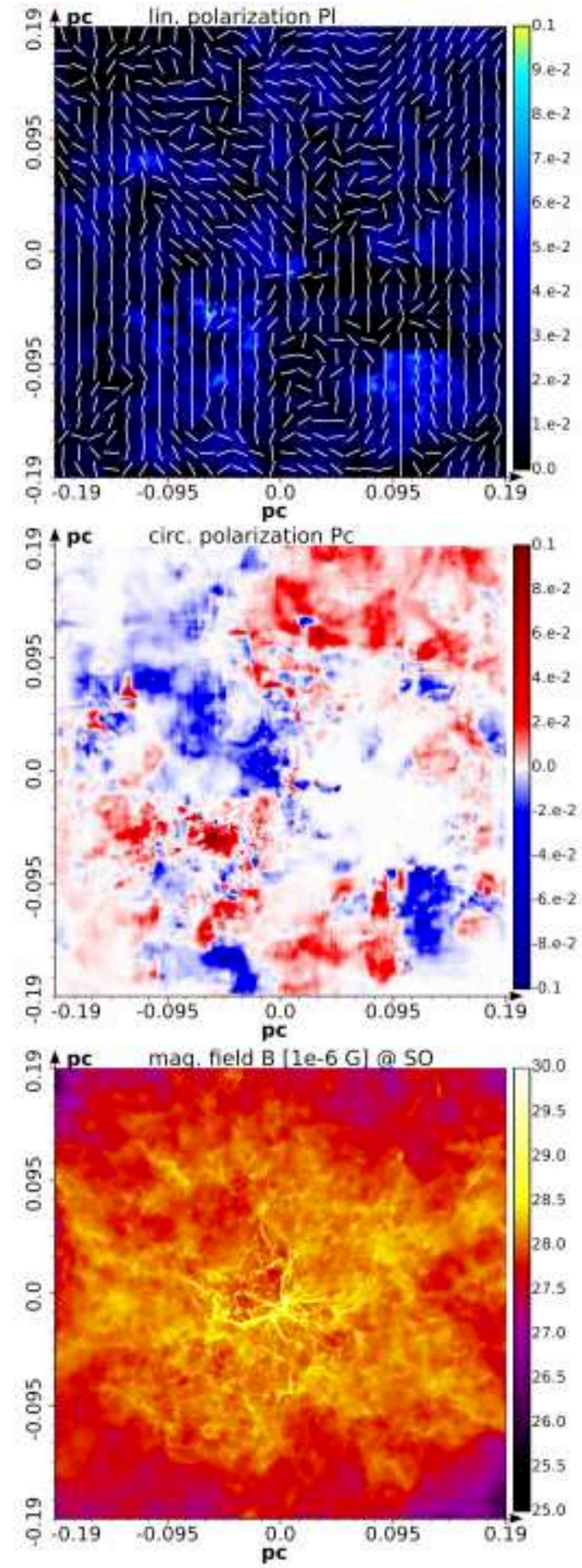
- MC dust heating: Combined heating algorithm of continuous absorption and immediate temperature correction
- Grid: Octree-grid with adaptive refinement
- Polarization mechanism: Dichroic extinction, thermal reemission, and scattering
- Dust grain alignment mechanisms:
  - Imperfect Davis-Greenstein (IDG)
  - Radiative torques (RAT)
  - Mechanical alignment (GOLD)
  - Imperfect internal alignement
  - Independent dust grain composition
- Optimization: Enforced scattering, wavelength range selection, and modified random walk



Polaris website in Kiel: http://www1.astrophysik.uni-kiel.de/~polaris/

Polaris postprocessing





Polaris website in Kiel: http://www1.astrophysik.uni-kiel.de/~polaris/

1D cloud/cluster model

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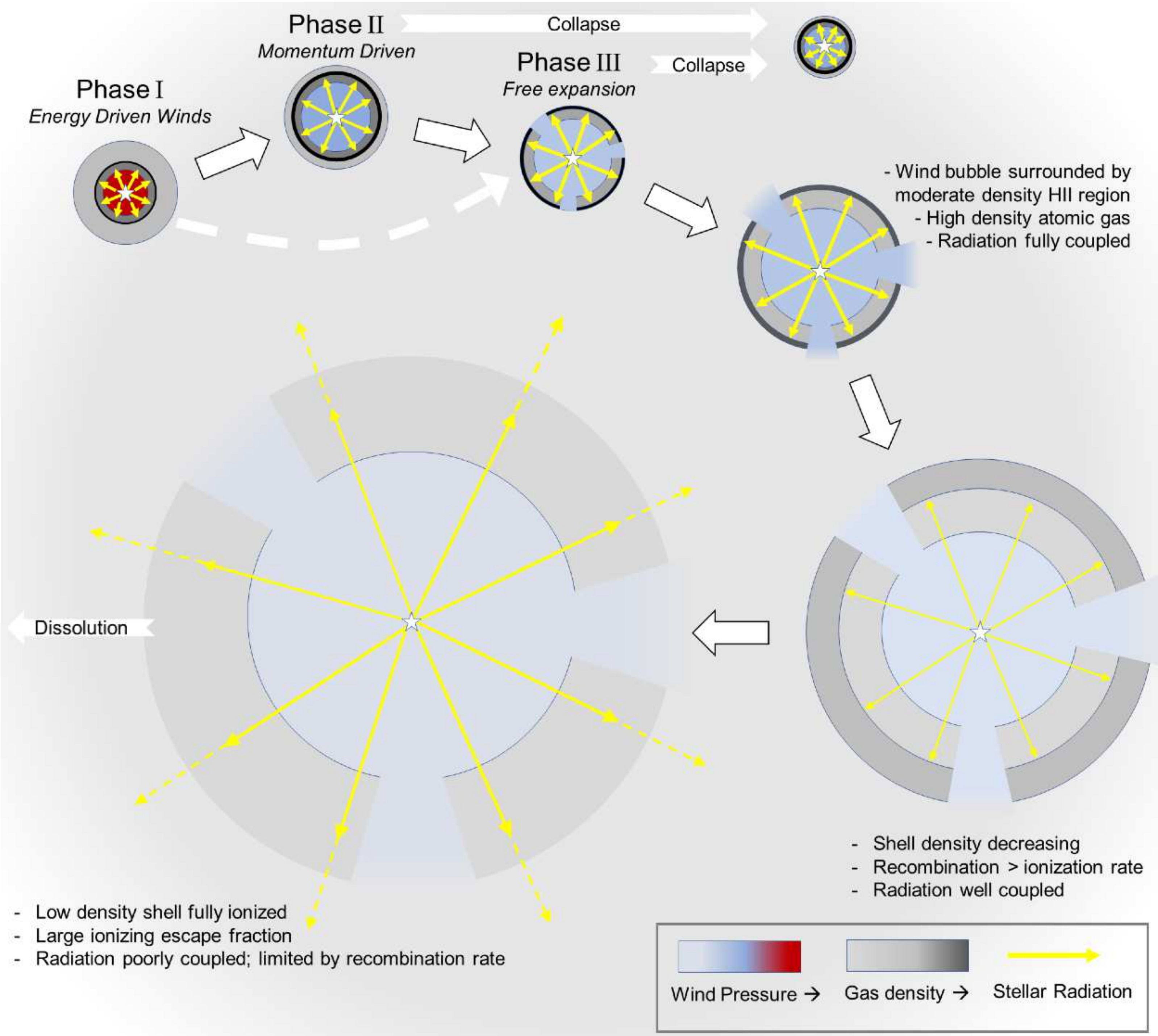
WARPFIELD:
- 1D model of cluster embedded in spherical cloud
- starburst99 cluster evolution
- dynamics of think shell is calculated consistently
- with all relevant forms of stellar feedback
- fast, allowing for large parameter studies



Rahner et al. (2017, MNRAS, 470, 4453)

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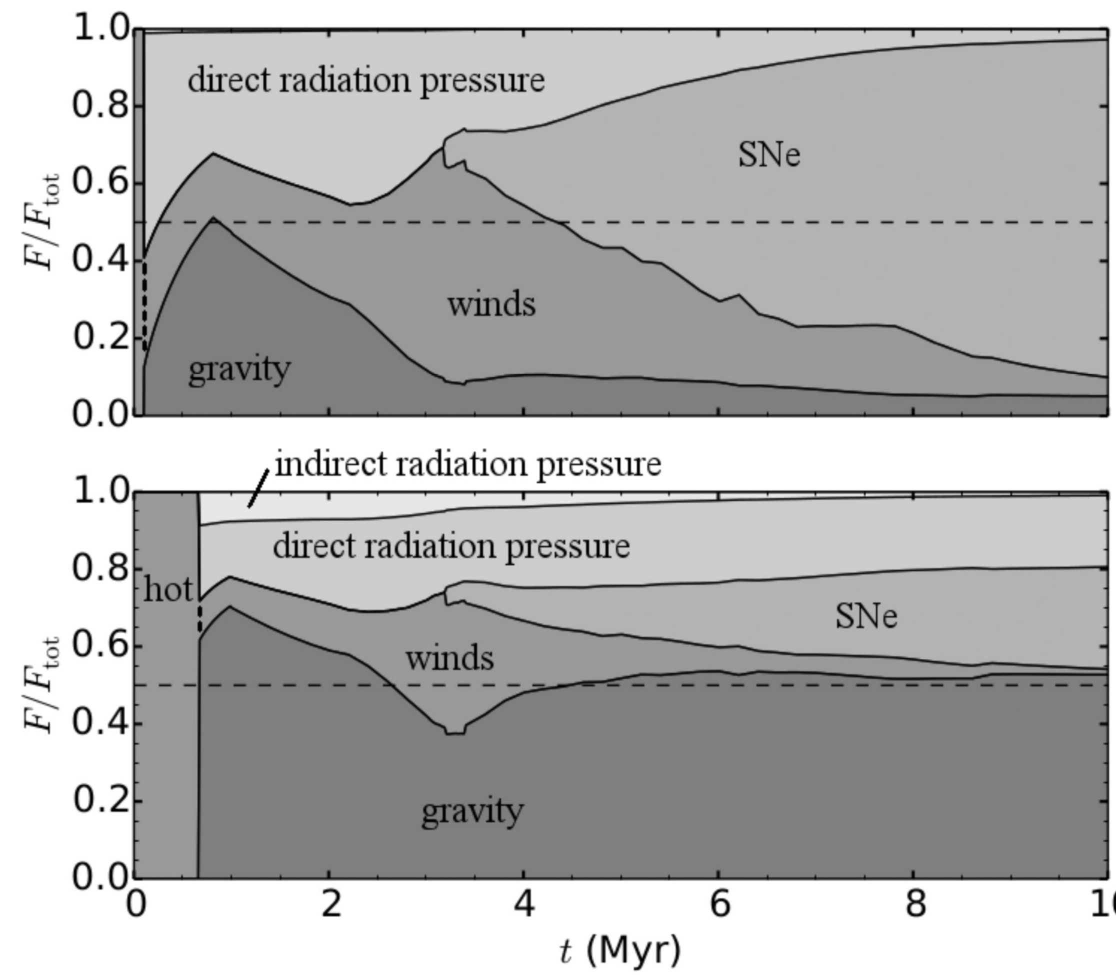


Figure 5. Comparison of relative forces from direct and indirect radiation pressure, winds, SNe, and gravity. If the contribution from gravity is above the 50 per cent margin (dashed horizontal line), the shell loses momentum. *Top*: $M_{cl} = 10^5\,M_\odot$, $\epsilon = 0.1$, $Z = Z_\odot$, and $n_{cl} = 1000\,cm^{-3}$ (same parameters as in Fig. 3). The contribution from indirect radiation pressure fraction is so small, it is barely visible (<1 per cent). *Bottom*: same n_{cl} and Z as in the top panel, but with a higher cloud mass and star formation efficiency ($M_{cl} = 3 \times 10^7\,M_\odot$ and $\epsilon = 0.25$). For more information see Section 5.

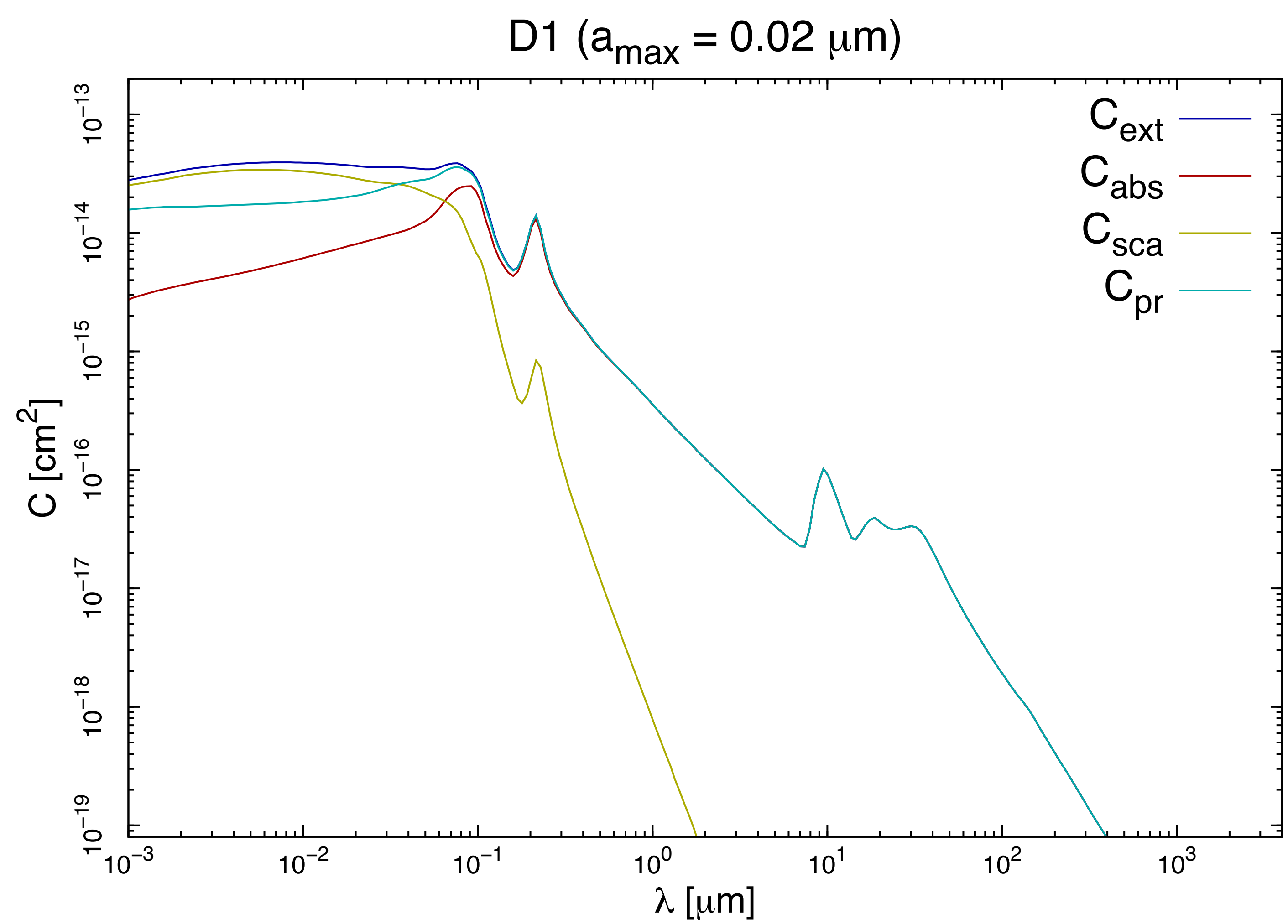
Rahner et al. (2017, MNRAS, 470, 4453)

WARPFIELD

Polaris for microphysics

1D cloud/cluster model

Polaris:
- detailed dust scattering and absorption model
- 120 frequency bin
- Monte Carlo RT



Reissl et al. (2018, A&A in press, arXiv171002854)

Polaris for microphysics

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1D cloud/cluster model

Polaris:
- detailed dust scattering and absorption model
- 120 frequency bin
- Monte Carlo RT

—> for Milky Way clouds, radiation pressure is not dominating over gravity!

red: gravity
blue: radiation pressure
purple: ratio

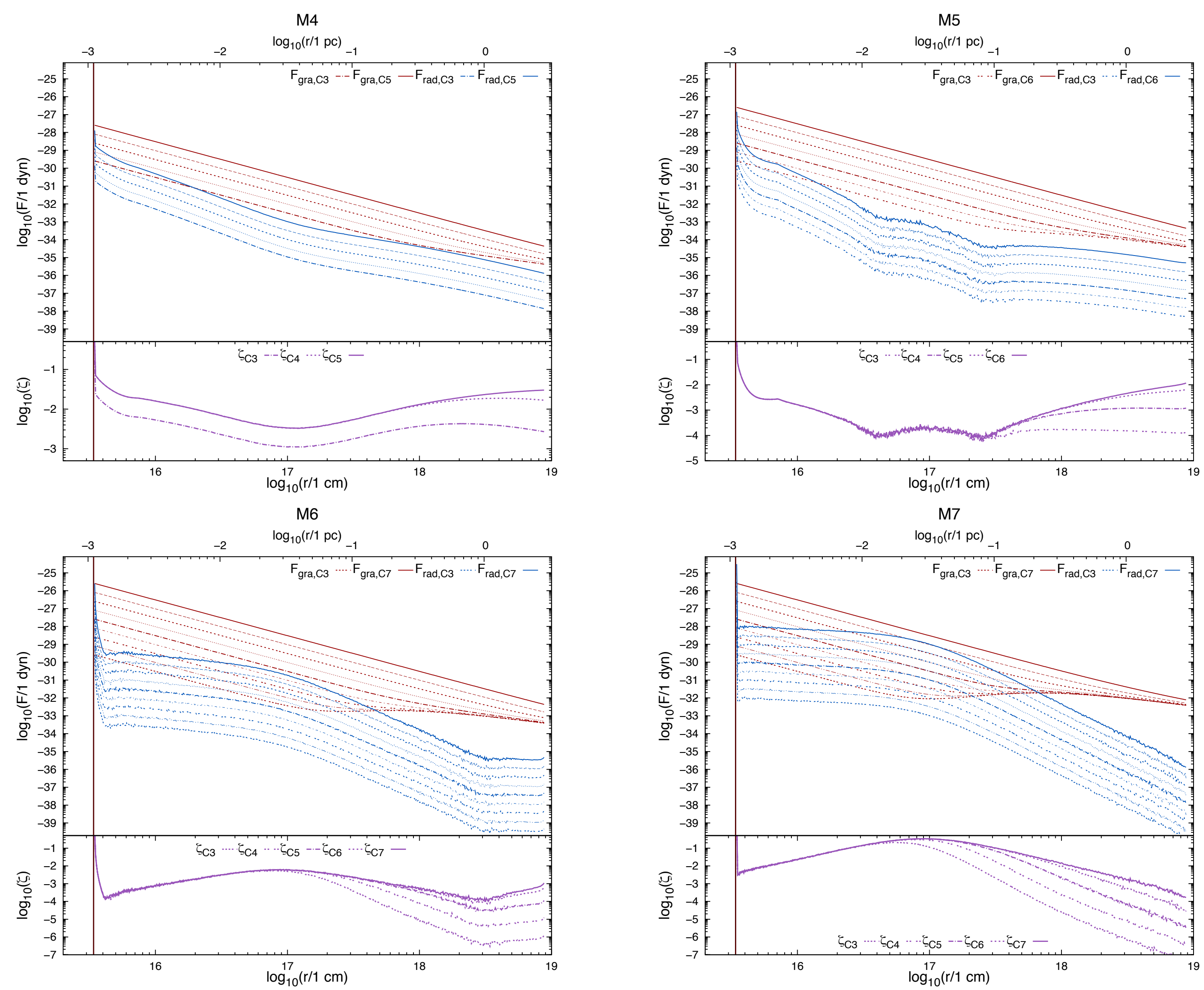

Fig. 5: Gravity ($F_{\rm gra}$, red lines) in comparison to radiative forces ($F_{\rm rad}$, blue lines) for models M4 (top left), M5 (top right left), M6 (bottom left), and M7 (bottom right). The ratio of forces is defined as $\zeta = F_{\rm rad}/F_{\rm gra}$ (purple lines). All cases have a *constant* dust temperature of $T_{\rm d} = 20$ K, an outer radius of $R_{\rm out} = 5$ pc and use dust model D2. Note that $\zeta < 1$ everywhere, implying that radiation pressure does not support the cloud against gravitational contraction. The vertical black line marks the sublimation radius.

Reissl et al. (2018, A&A in press, arXiv171002854)

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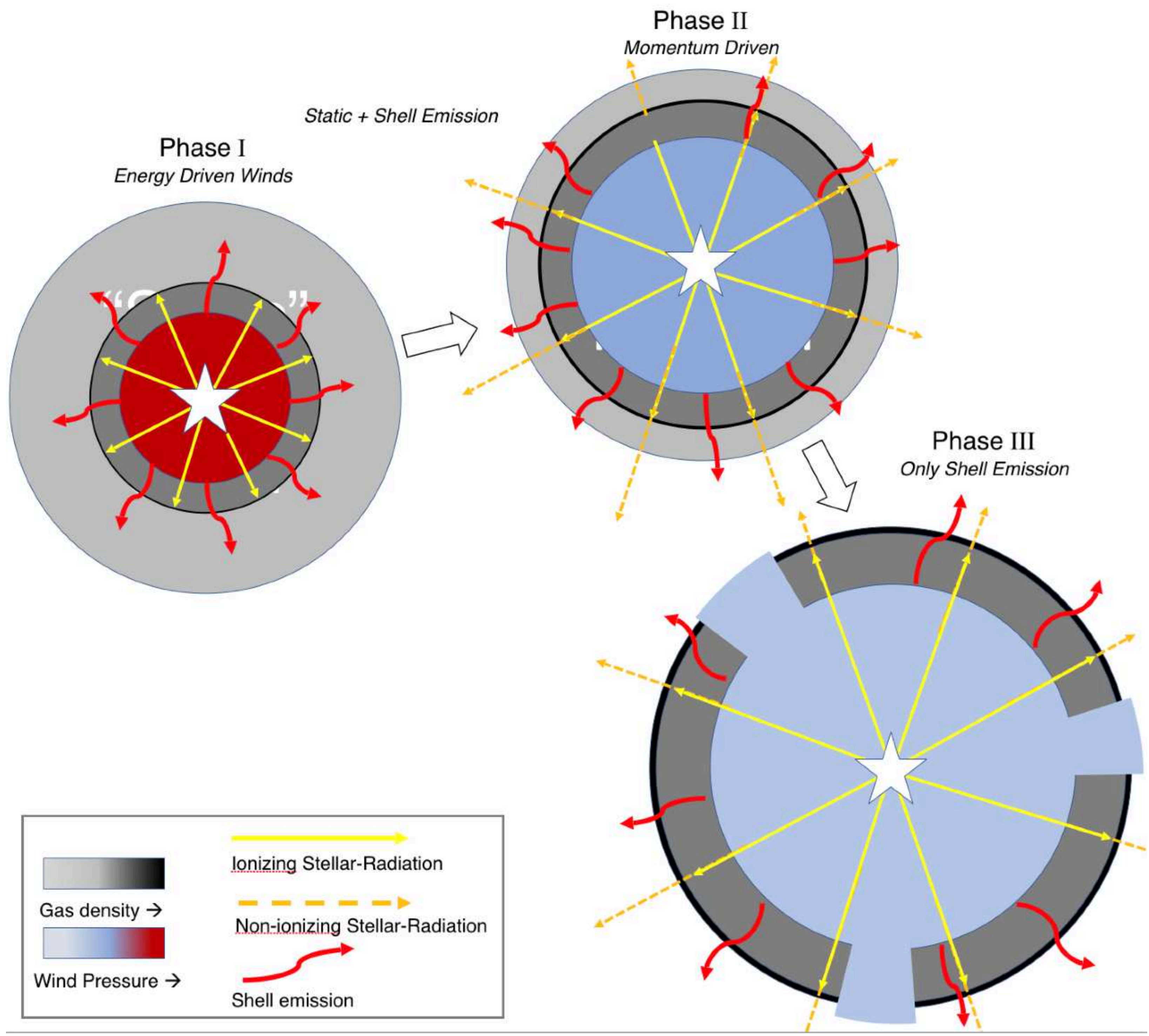
1D cloud/cluster model

WARPFIELD-EMP:

- 1D model of cluster embedded in spherical cloud
- starburst99 cluster evolution
- dynamics of think shell is calculated consistently
- with all relevant forms of stellar feedback
- fast, allowing for large parameter studies
- coupled to CLOUDY and 1D RT
- many different emission diagnostics

work by Daniel Rahner, Eric Pellegrini



Pellegrini et al. (2018, to be submitted)

WARPFIELD-EMP

synthetic BPT diagrams

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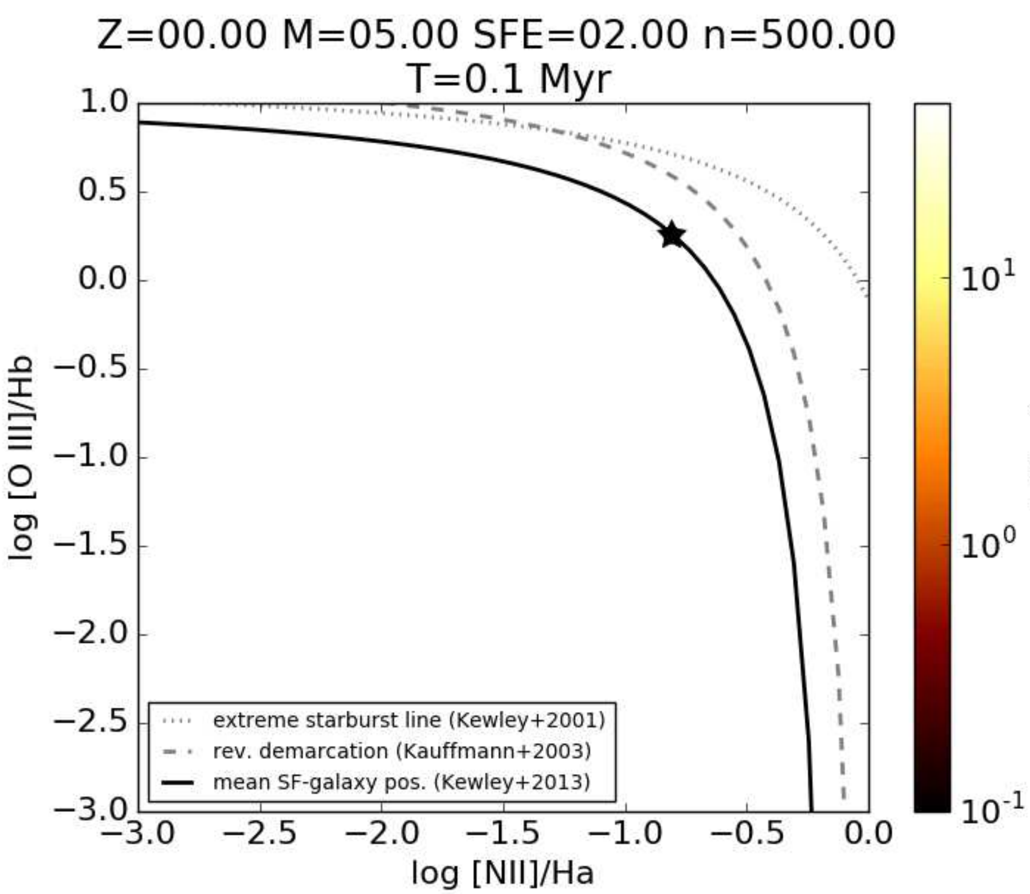
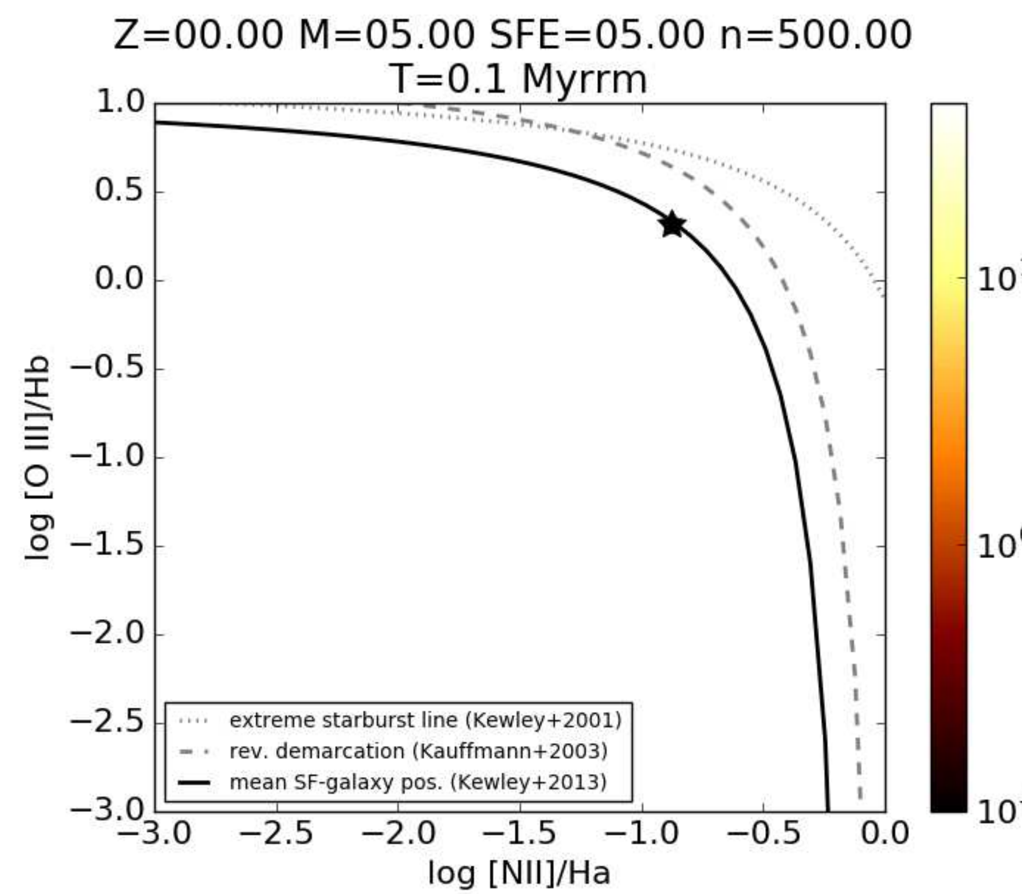
WARPFIELD-EMP:

- example synthetic BPT diagrams
- plans: extend to larger/ smaller clusters
- produce large statistical samples
- employ machine learning both as diagnostic and generative tool to produce database of emission measures

work by Daniel Rahner, Eric Pellegrini





synthetic BPT diagrams

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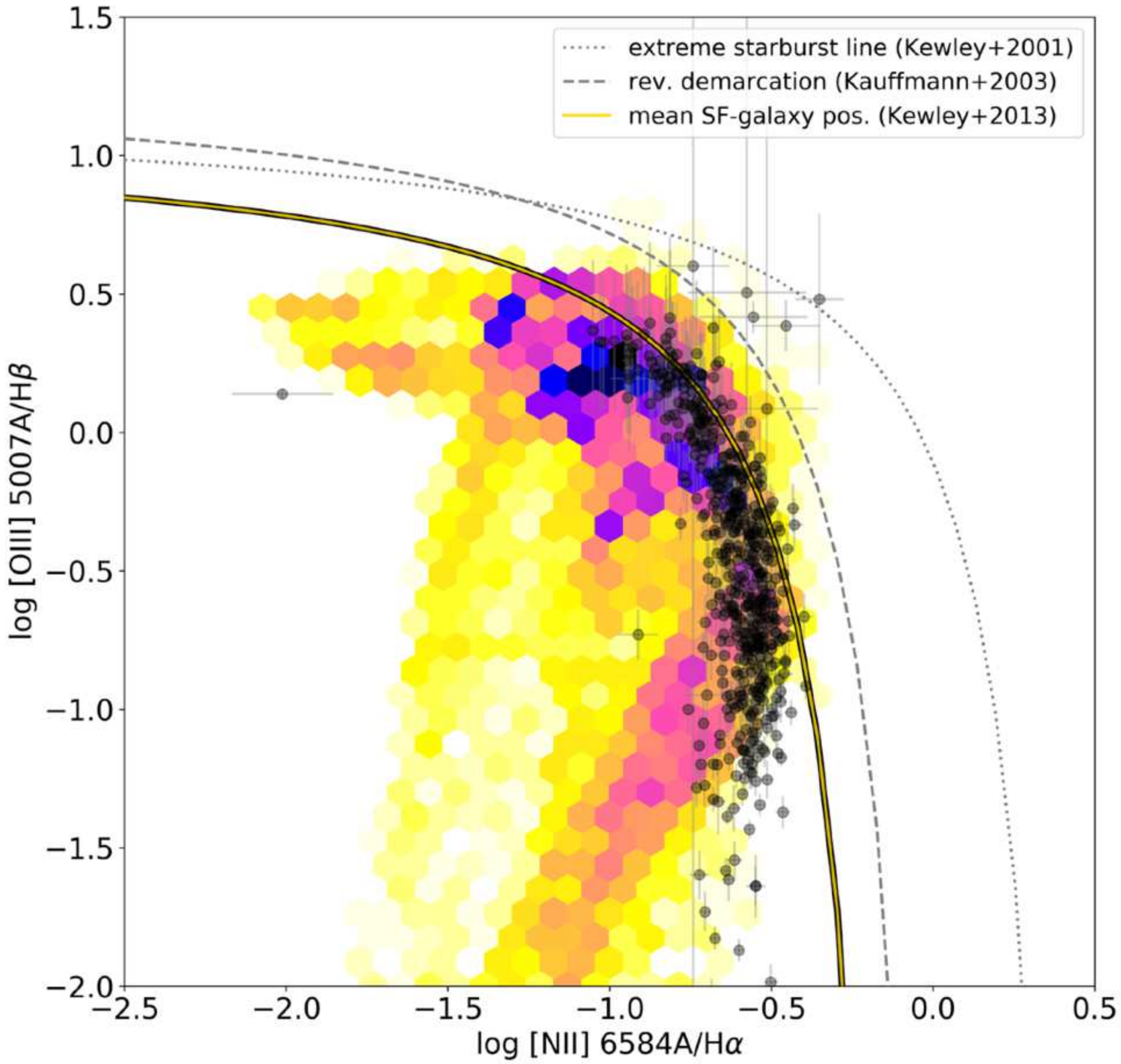

Pellegrini et al. (2018, to be submitted)

- synthetic population of cloud/cluster models in BPT diagram compared to data from SITELLE

NGC 628: data from Rousseau-Nepton et al. (2018)

WARPFIELD-EMP

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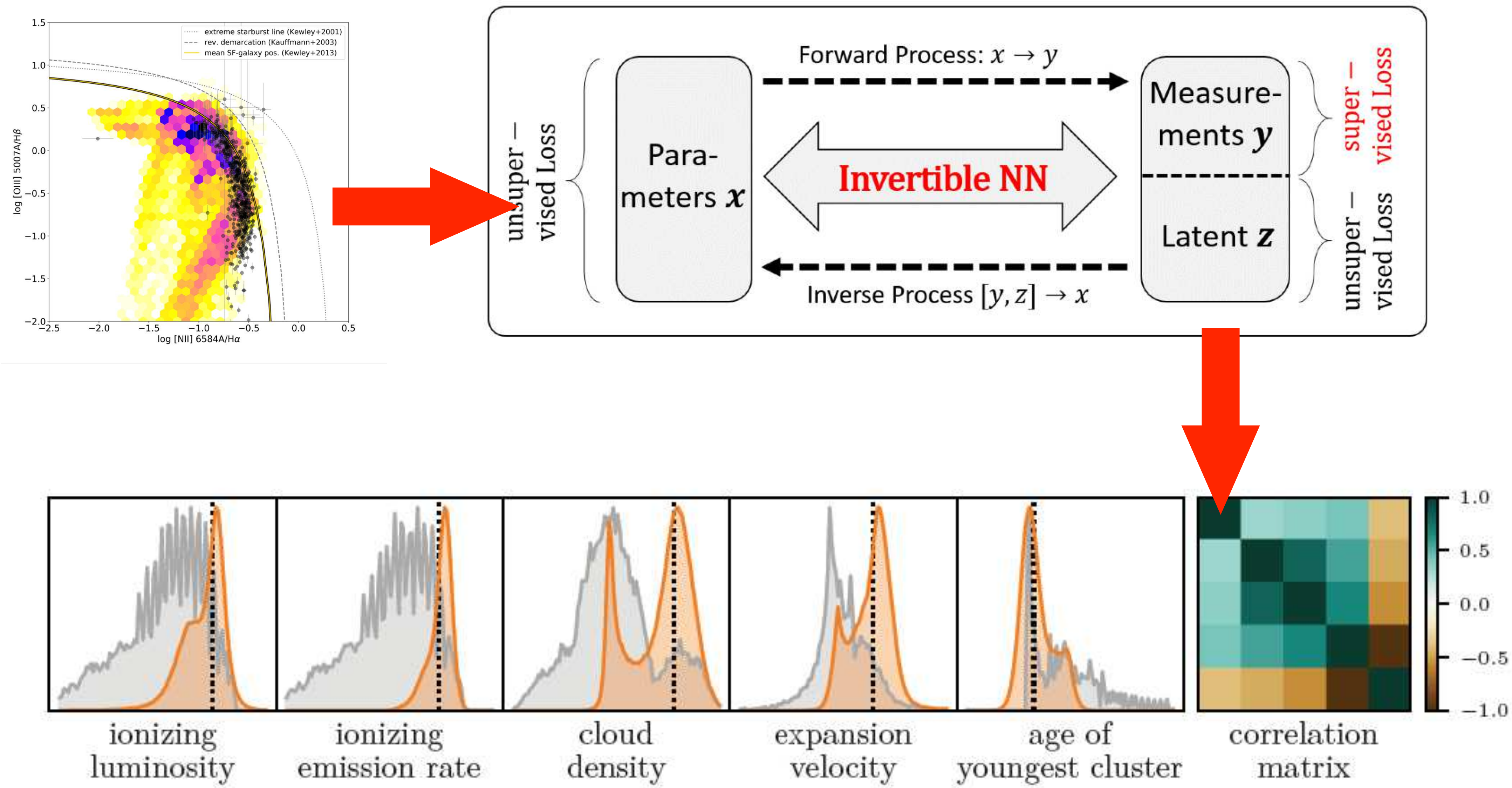
invertible neural networks



Ardizzone et al. (2018, arXiv:1808.04730)

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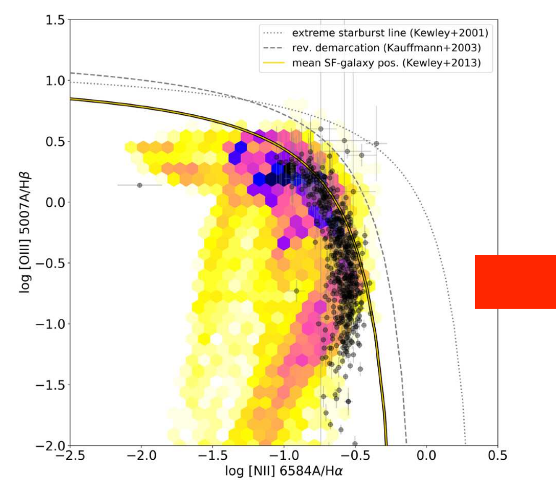

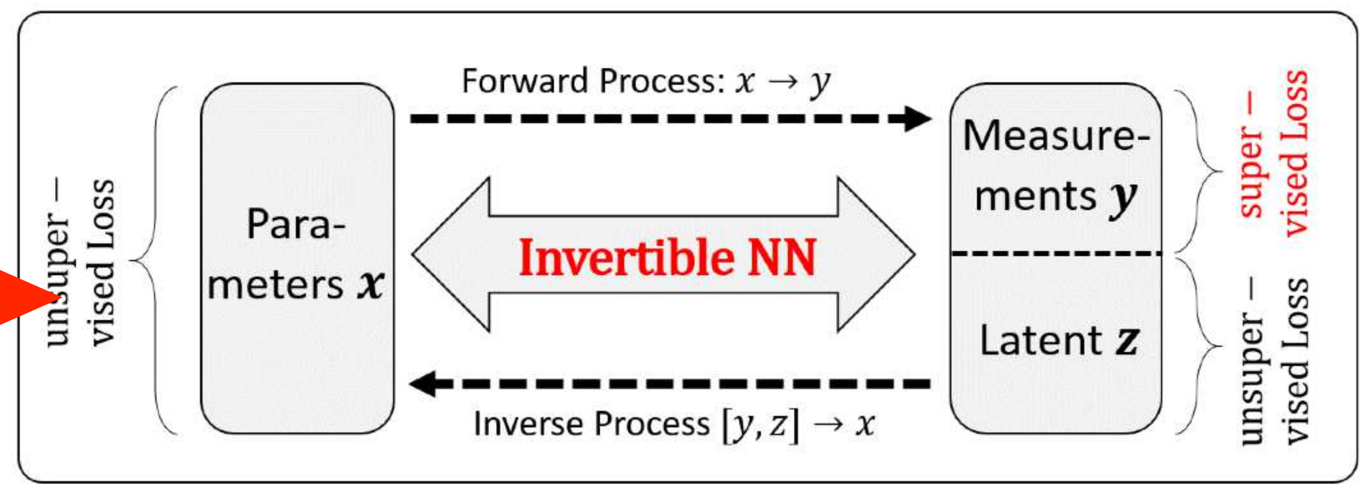

- new surveys
  - SDSS-V (Kollmeier/Rix): ***LVM*** (~25 million spectra in Milky Way)
  - CFHT: ***SIGNALS*** (Rousseau-Nepton) (~50.000 HI regions in different galaxies)
  - ***PHANGS*** (MUSE)

Ardizzone et al. (2018, arXiv:1808.04730)


summary
- prolegomenon
- theoretical remarks
- star formation
- tools

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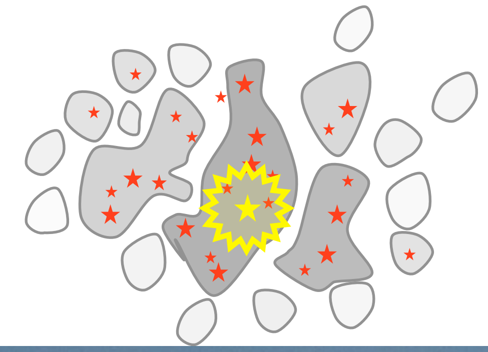
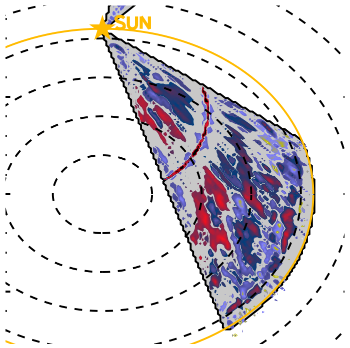
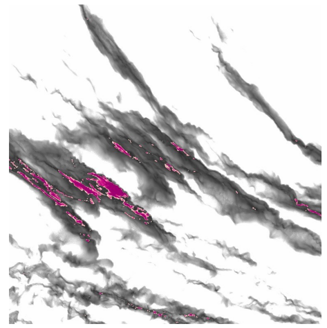
- stars form in competition between gravity and a large number of competing processes
- lots of CO-traced H_2 gas is in diffuse form
- larger reservoir of CO-dark H_2







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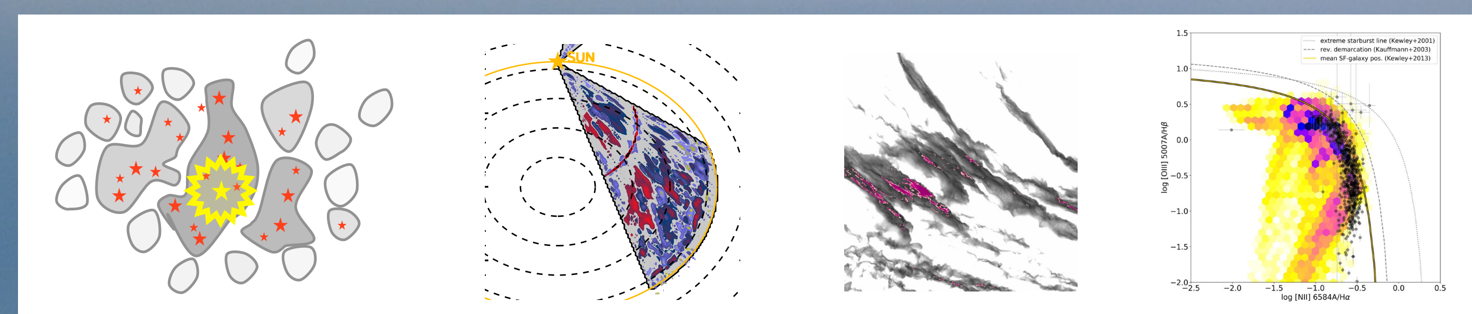

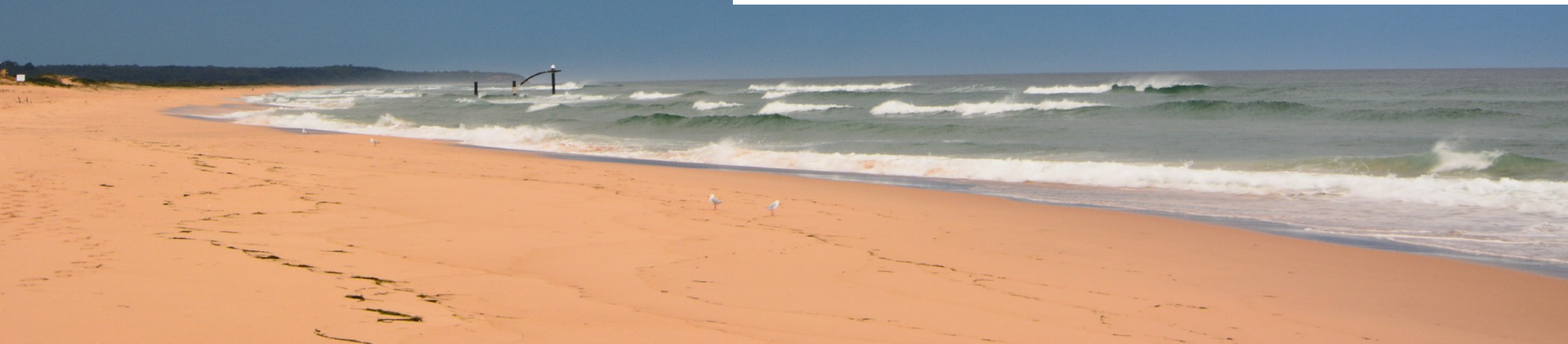

many thanks

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