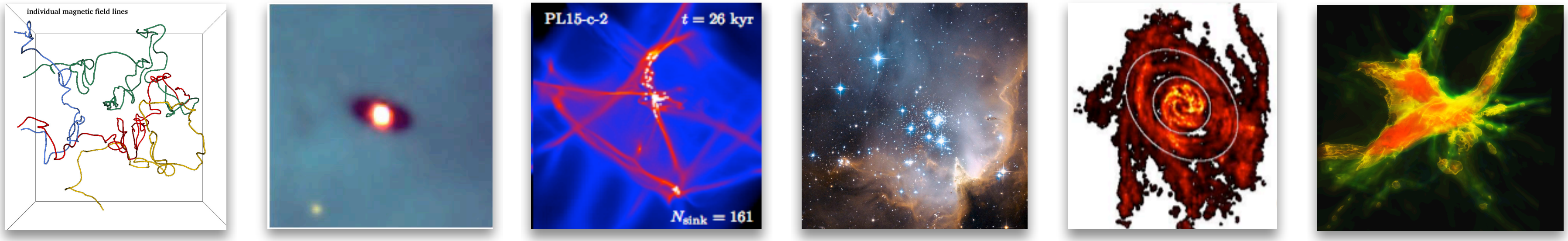
ISM Dynamics and Star Formation



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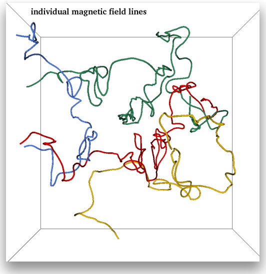
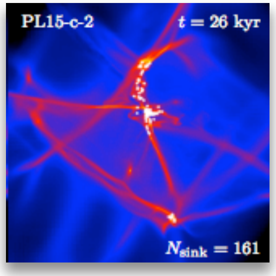
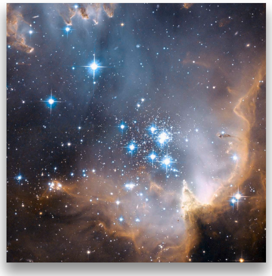
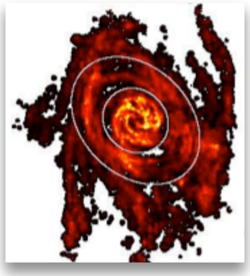
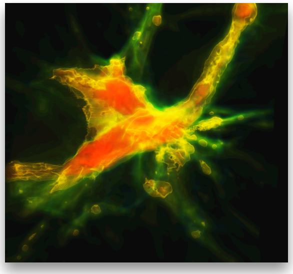
ISM Dynamics and SF: Chemistry & Thermodynamics











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ISM Dynamics and
Chemistry & The ics

DISCLAIMER

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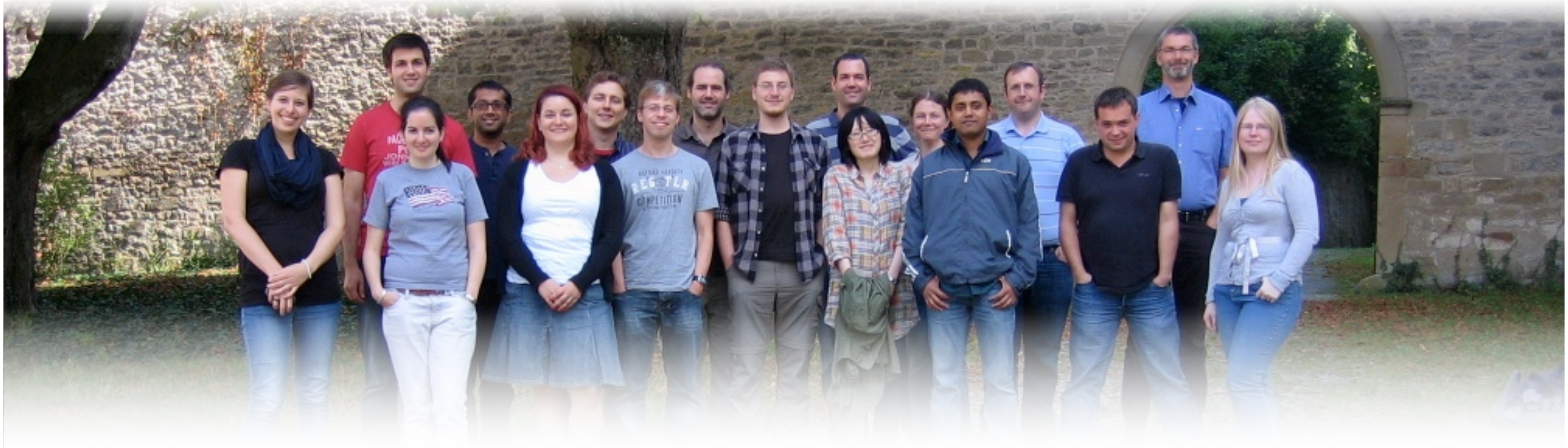
thanks to ...



... people in the group in Heidelberg:

Christian Baczynski, Erik Bertram, Frank Bigiel, Rachel Chicharro, Roxana Chira, Paul Clark, Gustavo Dopcke, Jayanta Dutta, Volker Gaibler, Simon Glover, Lukas Konstandin, Faviola Molina, Mei Sasaki, Jennifer Schober, Rahul Shetty, Rowan Smith, László Szűcs, Svitlana Zhukovska

... former group members:

Robi Banerjee, Ingo Berentzen, Christoph Federrath, Philipp Girichidis, Thomas Greif, Milica Micic, Thomas Peters, Dominik Schleicher, Stefan Schmeja, Sharanya Sur

... many collaborators abroad!

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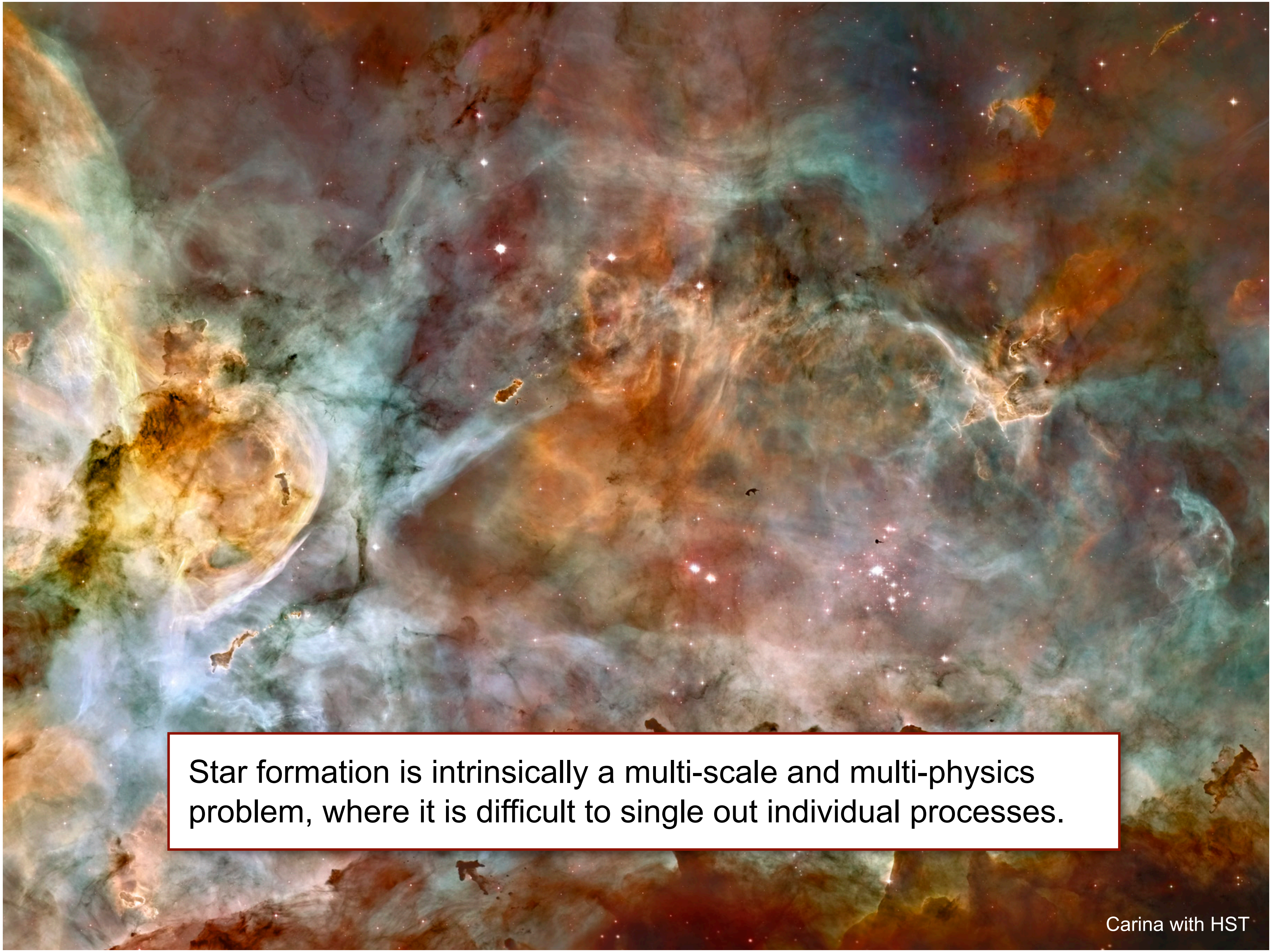
STIFTUNG
Wir stiften Zukunft

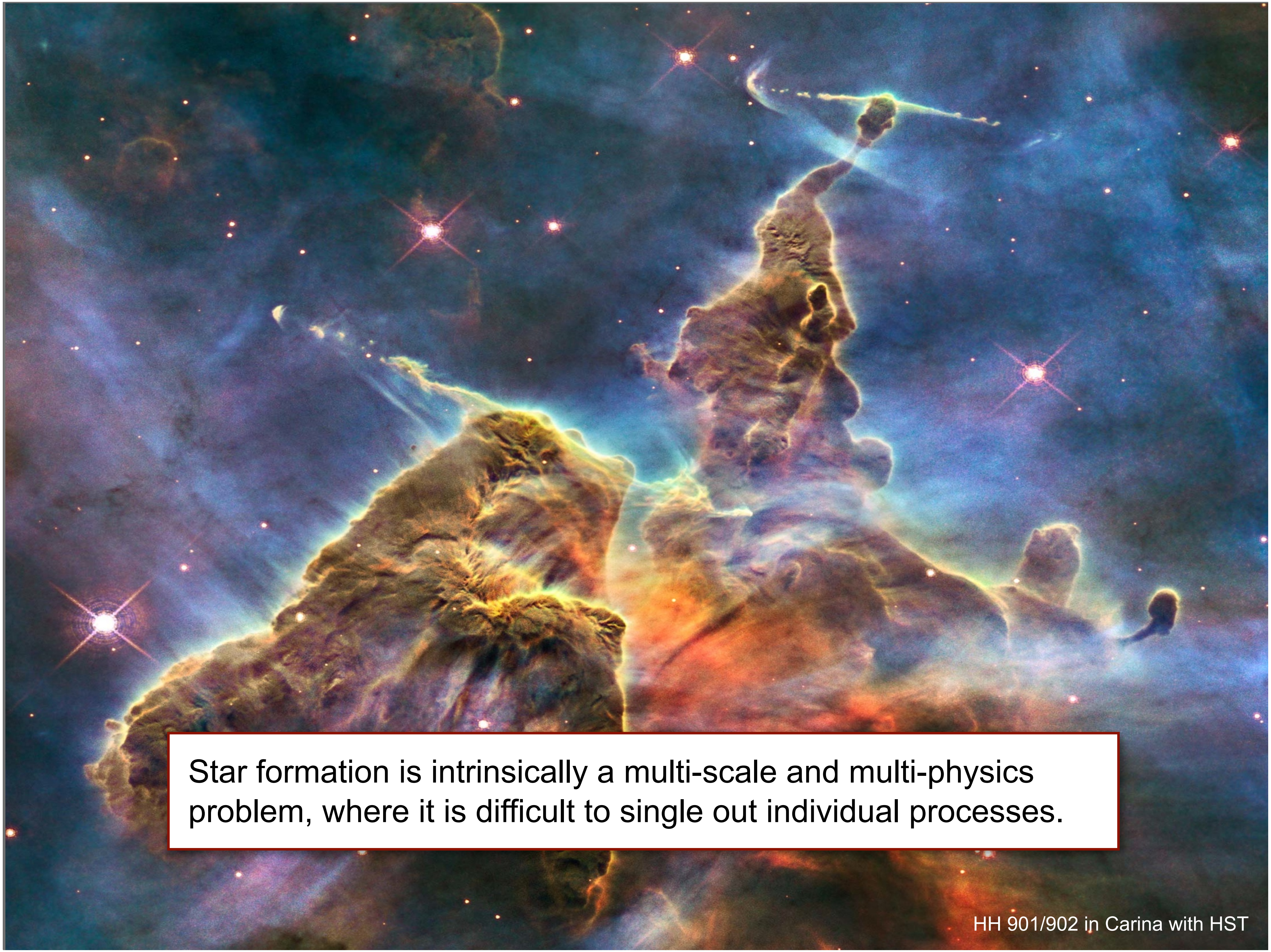
HGSFP

IMPRS



Star formation is intrinsically a multi-scale and multi-physics problem, where it is difficult to single out individual processes.

Carina with HST

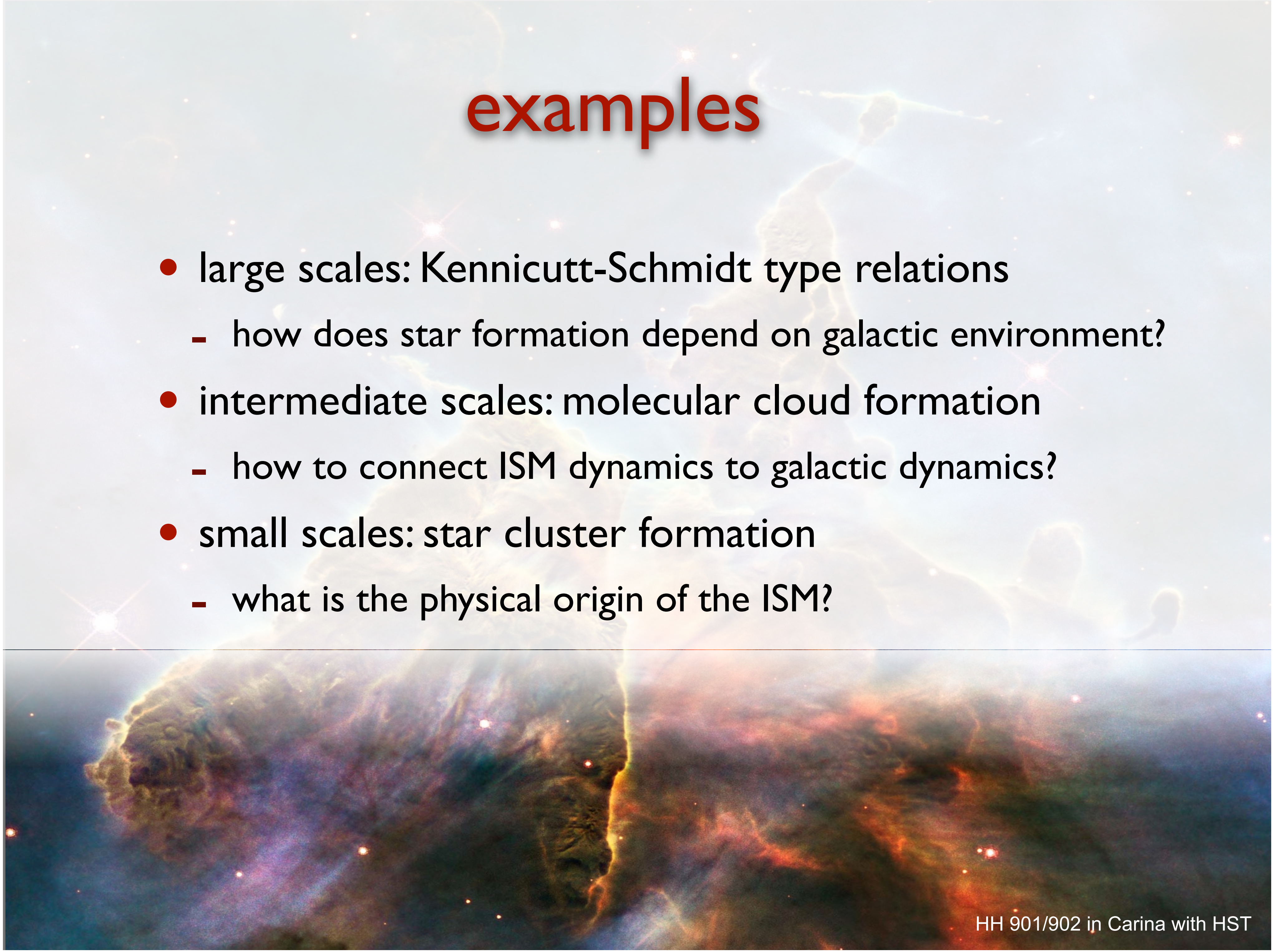


Star formation is intrinsically a multi-scale and multi-physics problem, where it is difficult to single out individual processes.

HH 901/902 in Carina with HST

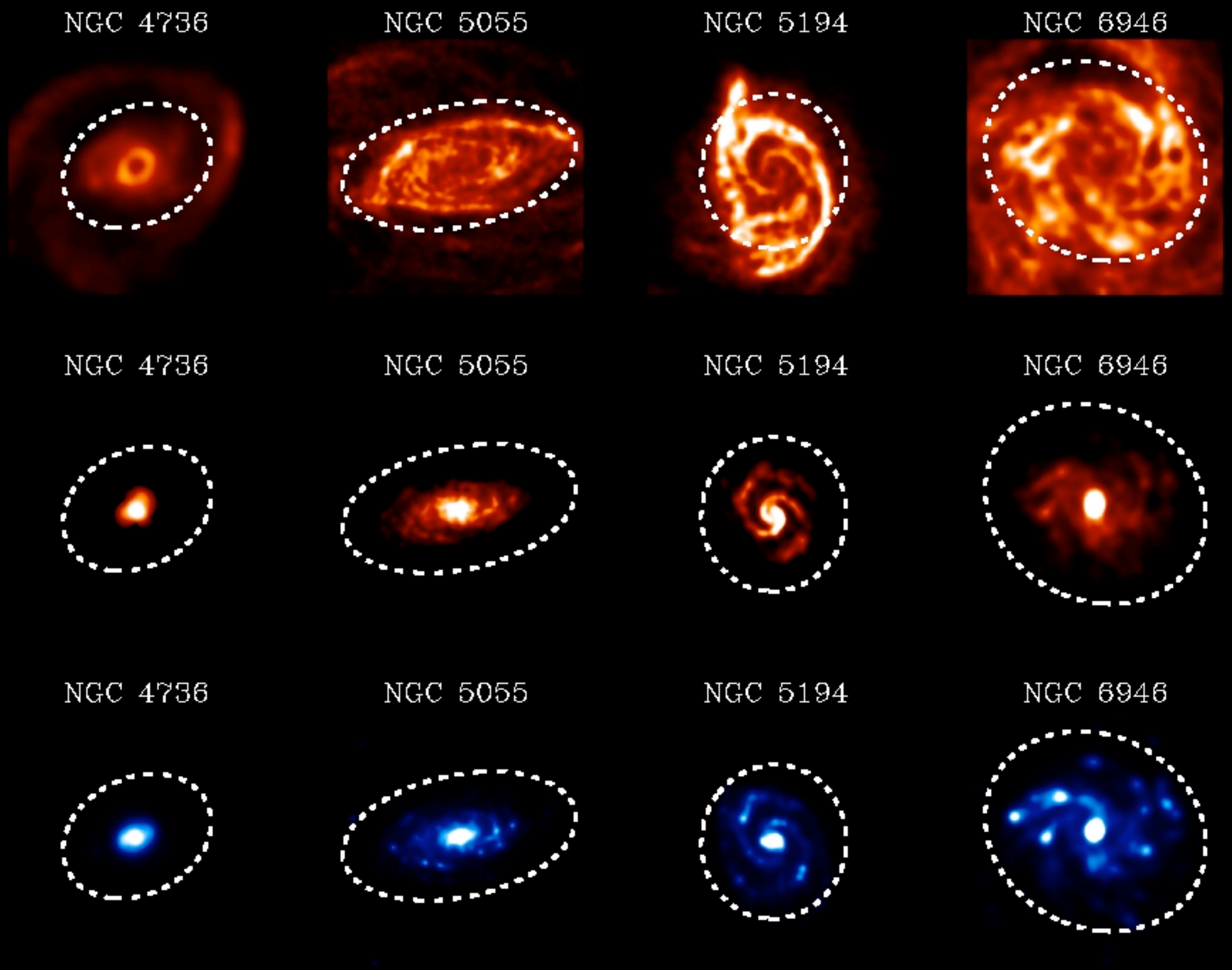
examples

- large scales: Kennicutt-Schmidt type relations
  - how does star formation depend on galactic environment?
- intermediate scales: molecular cloud formation
  - how to connect ISM dynamics to galactic dynamics?
- small scales: star cluster formation
  - what is the physical origin of the ISM?



HH 901/902 in Carina with HST

global SF relations



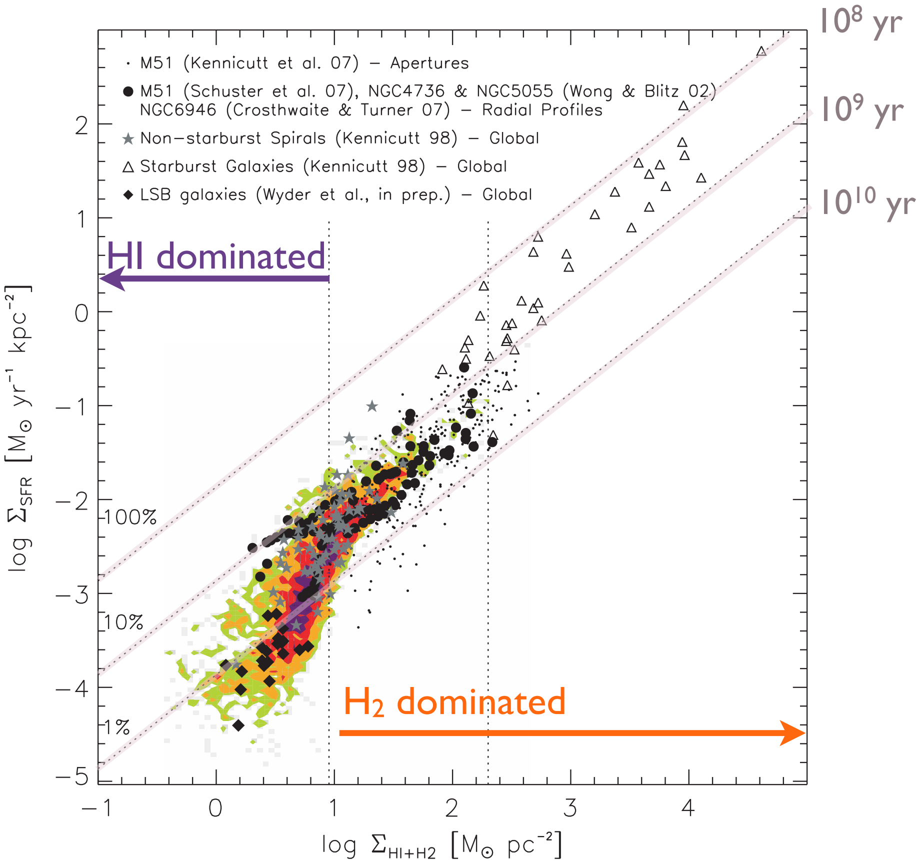
atomic hydrogen

molecular hydrogen

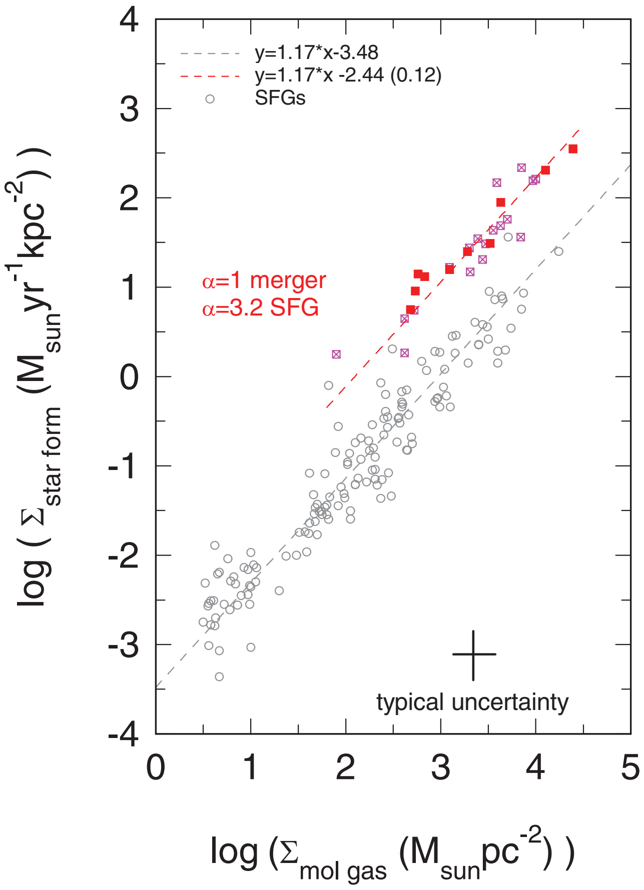
star formation

- HI gas more extended
- H2 and SF well correlated

galaxies from THINGS and HERACLES survey
(images from Frank Bigiel, ZAH/ITA)



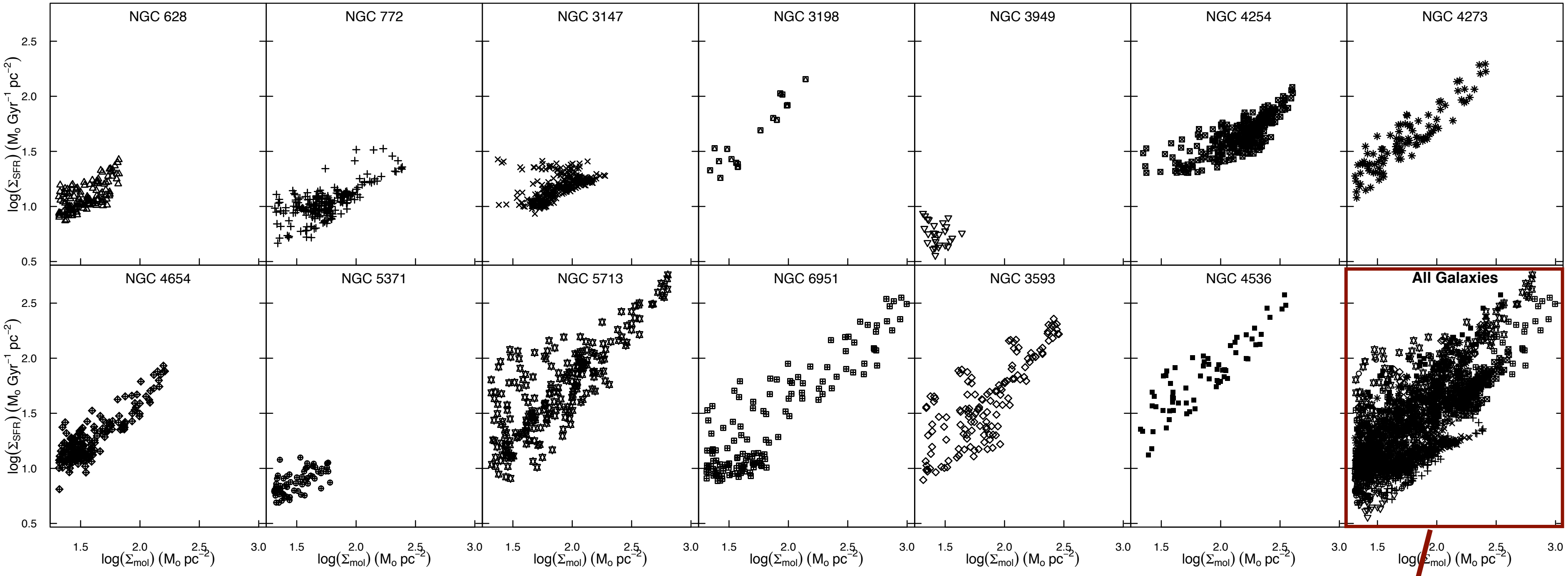
Bigiel et al. (2008, AJ, 136, 2846)



Genzel et al. (2010, MNRAS, AJ, 407, 2091)

- standard model: roughly linear relation between H_2 and SFR
- standard model: roughly constant depletion time: few x 10^9 yr
- super linear relation between total gas and SFR

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

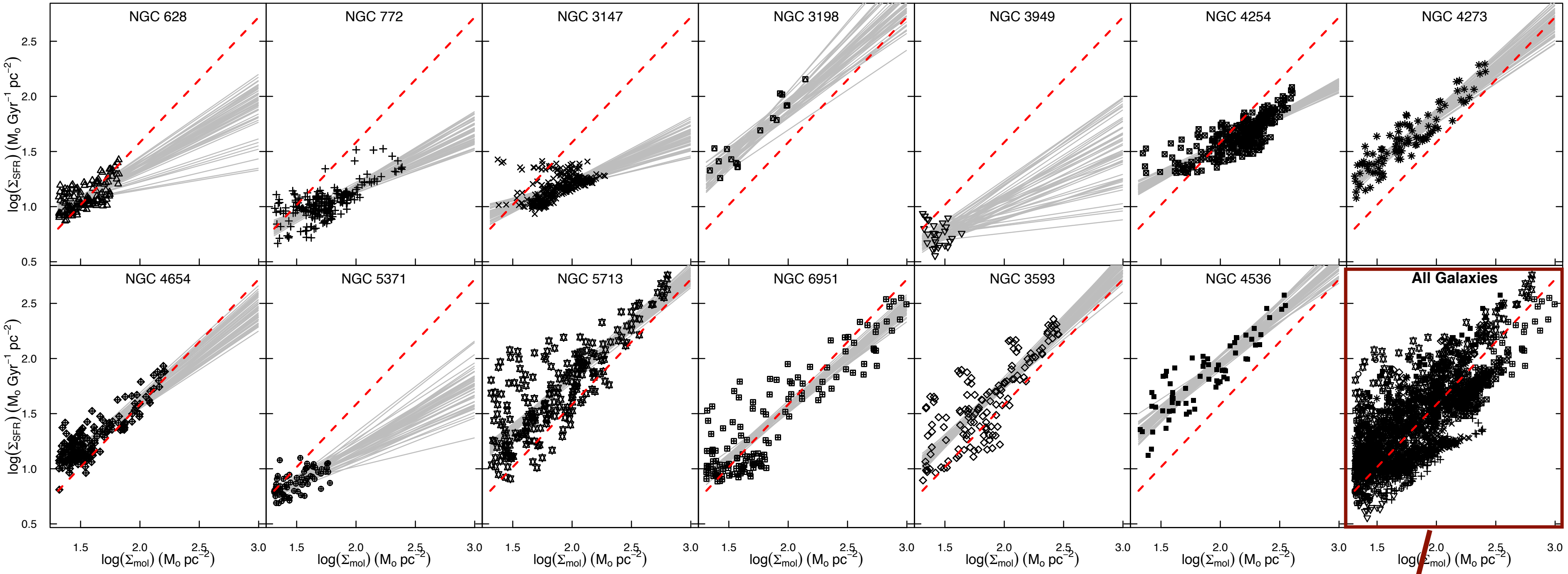


all galaxies

- QUIZ: do you see a universal Σ_{H2} - Σ_{SFR} relation?

Shetty et al. (2013, MNRAS submitted, arXiv:1306.2951, see also Shetty, Kelly, Bigiel, 2013, MNRAS, 430, 288)

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

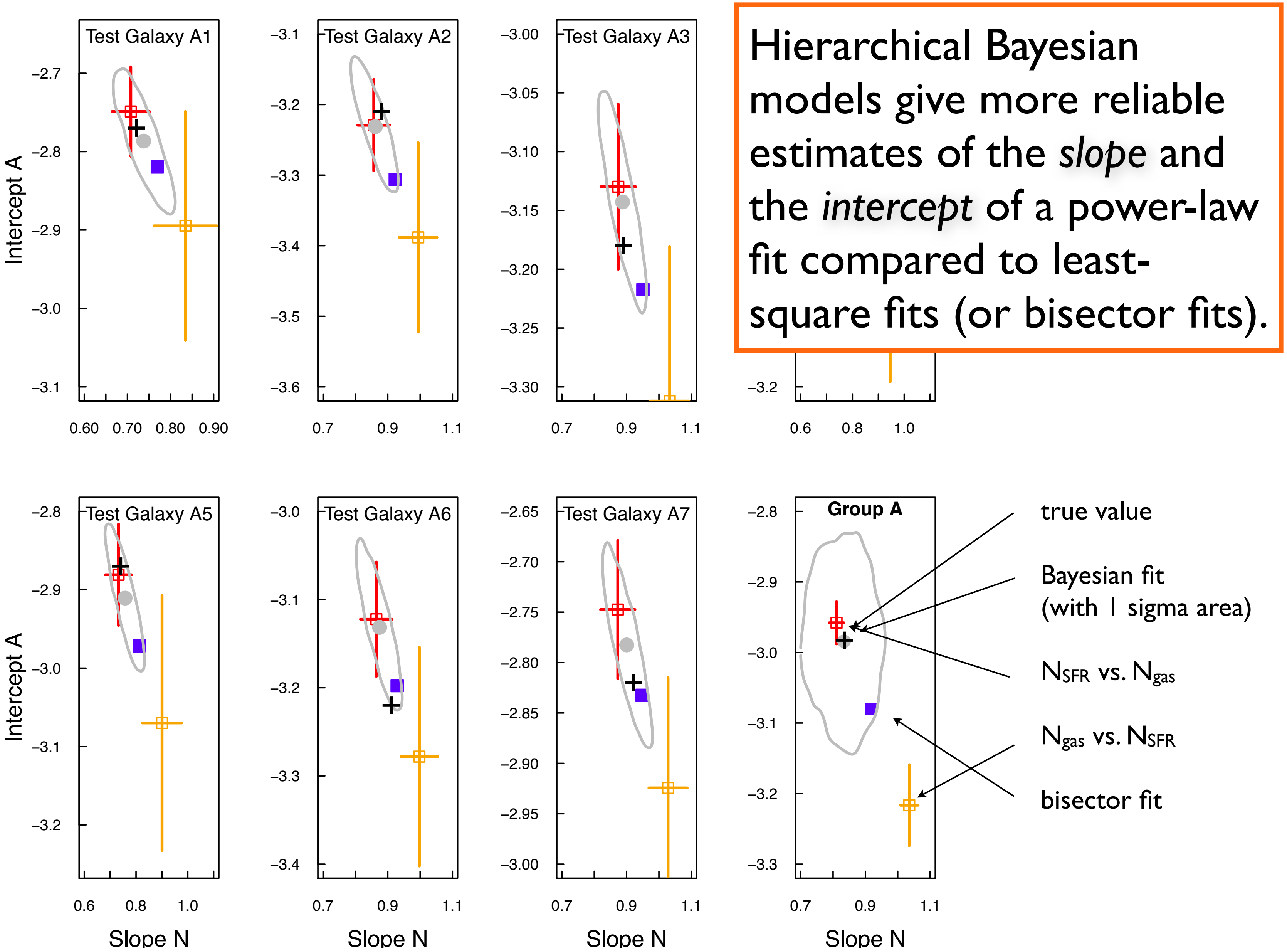


all galaxies

- QUIZ: do you see a universal Σ_{H2} - Σ_{SFR} relation?
- ANSWER: - probably not
  - in addition, the relation often is sublinear

Shetty et al. (2013, MNRAS submitted, arXiv:1306.2951, see also Shetty, Kelly, Bigiel, 2013, MNRAS, 430, 288)

Hierarchical Bayesian models give more reliable estimates of the *slope* and the *intercept* of a power-law fit compared to least-square fits (or bisector fits).



true value

Bayesian fit
(with 1 sigma area)

N_{SFR} vs. N_{gas}

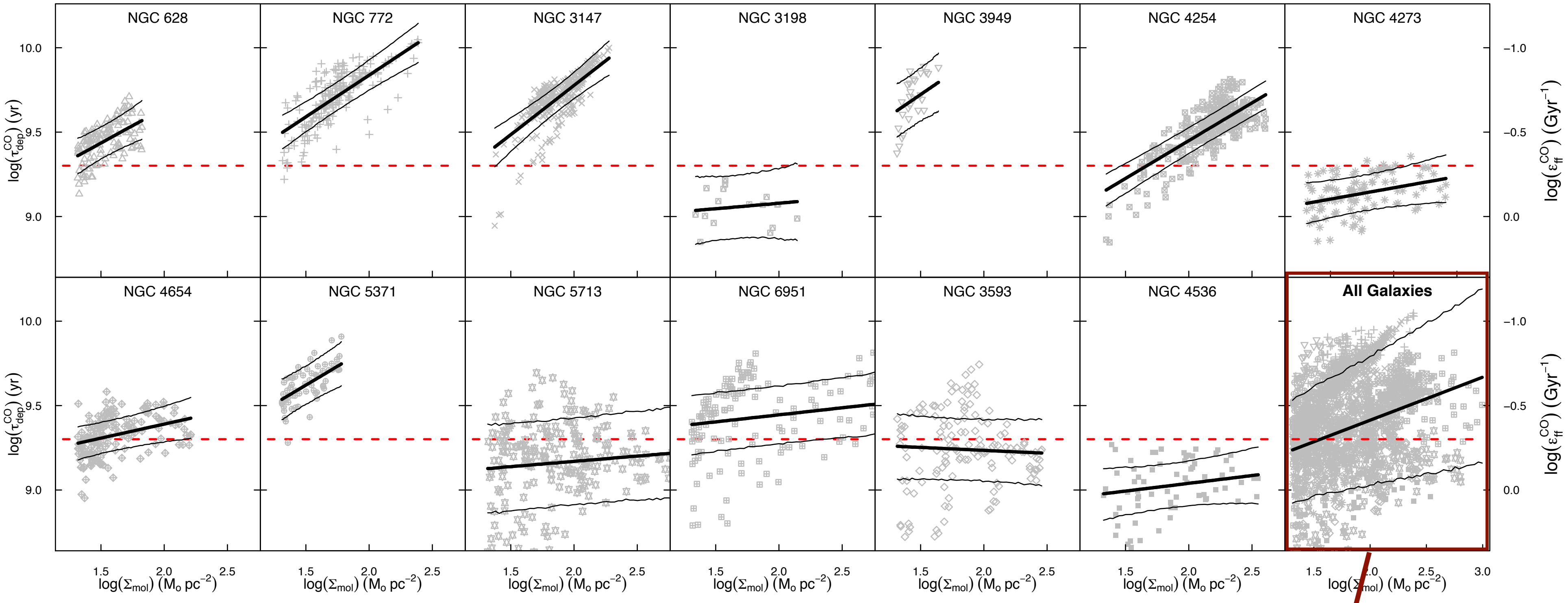
N_{gas} vs. N_{SFR}

bisector fit

Figure 1. Slope and intercept of test galaxies in Group A. Black cross shows the true values. Red and orange squares show the OLS($\Sigma_{\rm SFR}|\Sigma_{\rm mol}$) and OLS($\Sigma_{\rm mol}|\Sigma_{\rm SFR}$) results, with their 1σ uncertainties, respectively. The gray circles indicate the estimate provided by the median of hierarchical Bayesian posterior result, and the contours mark the 1σ deviation. The filled blue squares mark the bisector estimates. The last panel on the bottom row shows the group parameters and fit estimates.

Shetty et al. (2013, MNRAS, 430, 288)

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

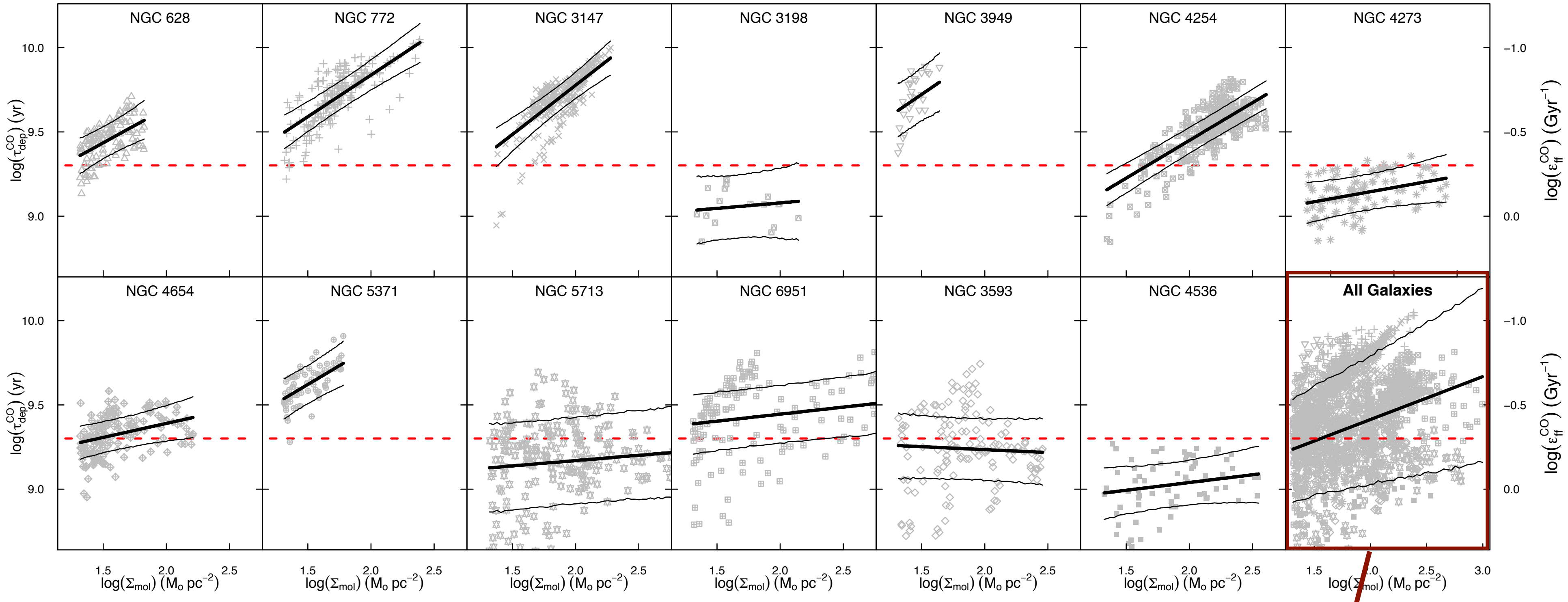


all galaxies

Hierarchical Bayesian model for STING galaxies indicate *varying depleting times*.

Shetty et al. (2013, arXiv:1306.2951)

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 (i.e. high extinctions)...

Shetty et al. (2013, MNRAS submitted, arXiv:1306.2951, see also Shetty, Kelly, Bigiel, 2013, MNRAS, 430, 288)

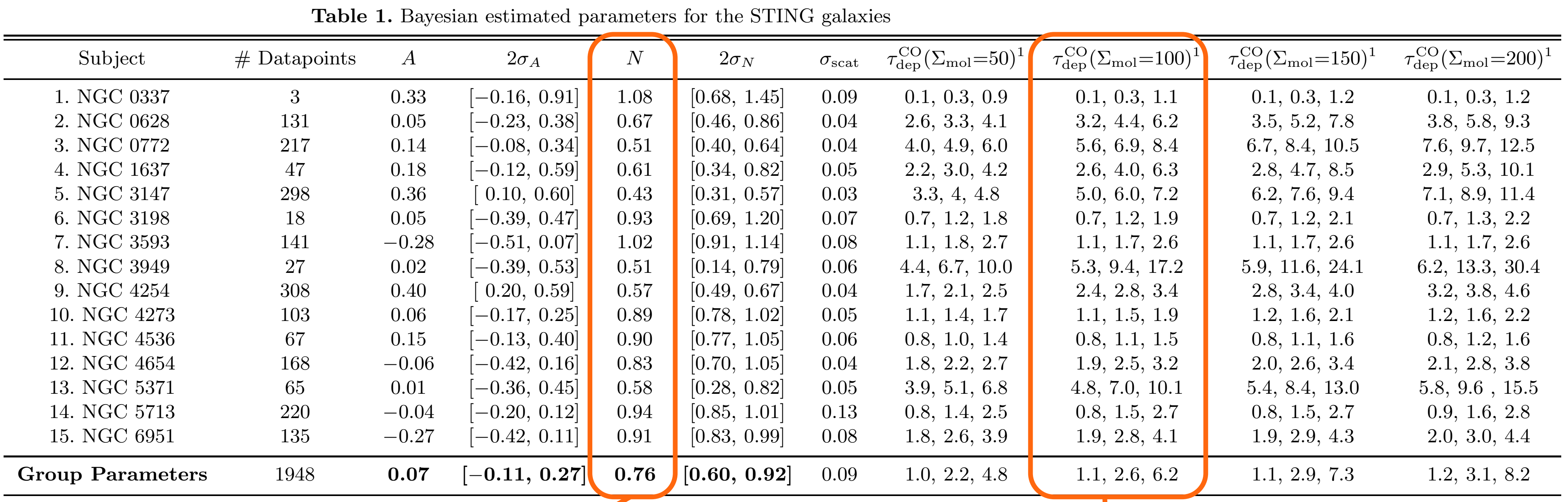


Table 1. Bayesian estimated parameters for the STING galaxies

Subject	# Datapoints	A	$2\sigma_A$	N	$2\sigma_N$	$\sigma_{\rm scat}$	$\tau^{\rm CO}_{\rm dep}(\Sigma_{\rm mol}{=}50)^1$	$\tau^{\rm CO}_{\rm dep}(\Sigma_{\rm mol}{=}100)^1$	$\tau^{\rm CO}_{\rm dep}(\Sigma_{\rm mol}{=}150)^1$	$\tau^{\rm CO}_{\rm dep}(\Sigma_{\rm mol}{=}200)^1$
1. NGC 0337	3	0.33	[−0.16, 0.91]	1.08	[0.68, 1.45]	0.09	0.1, 0.3, 0.9	0.1, 0.3, 1.1	0.1, 0.3, 1.2	0.1, 0.3, 1.2
2. NGC 0628	131	0.05	[−0.23, 0.38]	0.67	[0.46, 0.86]	0.04	2.6, 3.3, 4.1	3.2, 4.4, 6.2	3.5, 5.2, 7.8	3.8, 5.8, 9.3
3. NGC 0772	217	0.14	[−0.08, 0.34]	0.51	[0.40, 0.64]	0.04	4.0, 4.9, 6.0	5.6, 6.9, 8.4	6.7, 8.4, 10.5	7.6, 9.7, 12.5
4. NGC 1637	47	0.18	[−0.12, 0.59]	0.61	[0.34, 0.82]	0.05	2.2, 3.0, 4.2	2.6, 4.0, 6.3	2.8, 4.7, 8.5	2.9, 5.3, 10.1
5. NGC 3147	298	0.36	[0.10, 0.60]	0.43	[0.31, 0.57]	0.03	3.3, 4, 4.8	5.0, 6.0, 7.2	6.2, 7.6, 9.4	7.1, 8.9, 11.4
6. NGC 3198	18	0.05	[−0.39, 0.47]	0.93	[0.69, 1.20]	0.07	0.7, 1.2, 1.8	0.7, 1.2, 1.9	0.7, 1.2, 2.1	0.7, 1.3, 2.2
7. NGC 3593	141	−0.28	[−0.51, 0.07]	1.02	[0.91, 1.14]	0.08	1.1, 1.8, 2.7	1.1, 1.7, 2.6	1.1, 1.7, 2.6	1.1, 1.7, 2.6
8. NGC 3949	27	0.02	[−0.39, 0.53]	0.51	[0.14, 0.79]	0.06	4.4, 6.7, 10.0	5.3, 9.4, 17.2	5.9, 11.6, 24.1	6.2, 13.3, 30.4
9. NGC 4254	308	0.40	[0.20, 0.59]	0.57	[0.49, 0.67]	0.04	1.7, 2.1, 2.5	2.4, 2.8, 3.4	2.8, 3.4, 4.0	3.2, 3.8, 4.6
10. NGC 4273	103	0.06	[−0.17, 0.25]	0.89	[0.78, 1.02]	0.05	1.1, 1.4, 1.7	1.1, 1.5, 1.9	1.2, 1.6, 2.1	1.2, 1.6, 2.2
11. NGC 4536	67	0.15	[−0.13, 0.40]	0.90	[0.77, 1.05]	0.06	0.8, 1.0, 1.4	0.8, 1.1, 1.5	0.8, 1.1, 1.6	0.8, 1.2, 1.6
12. NGC 4654	168	−0.06	[−0.42, 0.16]	0.83	[0.70, 1.05]	0.04	1.8, 2.2, 2.7	1.9, 2.5, 3.2	2.0, 2.6, 3.4	2.1, 2.8, 3.8
13. NGC 5371	65	0.01	[−0.36, 0.45]	0.58	[0.28, 0.82]	0.05	3.9, 5.1, 6.8	4.8, 7.0, 10.1	5.4, 8.4, 13.0	5.8, 9.6 , 15.5
14. NGC 5713	220	−0.04	[−0.20, 0.12]	0.94	[0.85, 1.01]	0.13	0.8, 1.4, 2.5	0.8, 1.5, 2.7	0.8, 1.5, 2.7	0.9, 1.6, 2.8
15. NGC 6951	135	−0.27	[−0.42, 0.11]	0.91	[0.83, 0.99]	0.08	1.8, 2.6, 3.9	1.9, 2.8, 4.1	1.9, 2.9, 4.3	2.0, 3.0, 4.4
Group Parameters	1948	**0.07**	**[−0.11, 0.27]**	**0.76**	**[0.60, 0.92]**	0.09	1.0, 2.2, 4.8	1.1, 2.6, 6.2	1.1, 2.9, 7.3	1.2, 3.1, 8.2

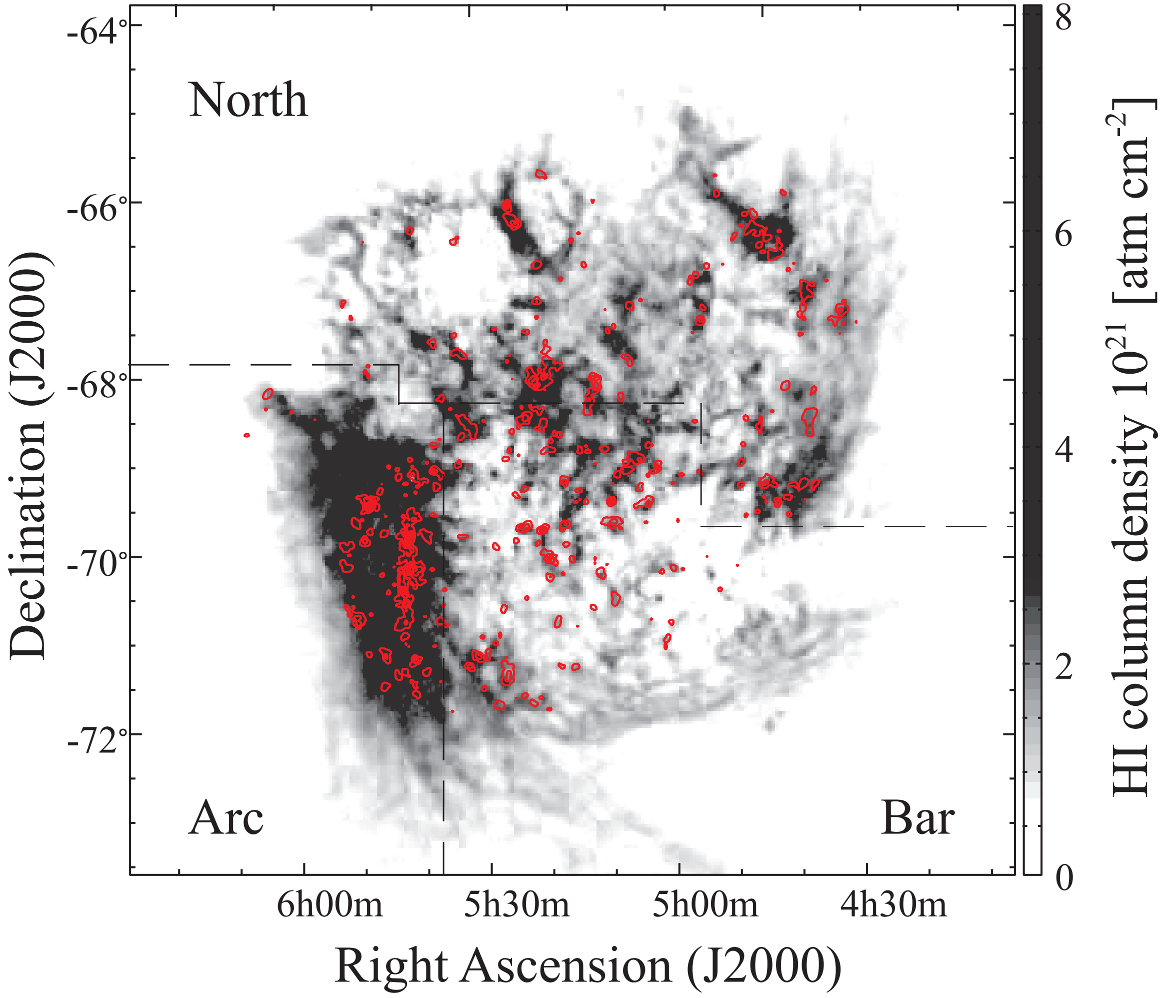
slope of KS relation

depletion times

Shetty et al. (2013, arXiv:1306.2951)

molecular cloud formation

molecular cloud formation



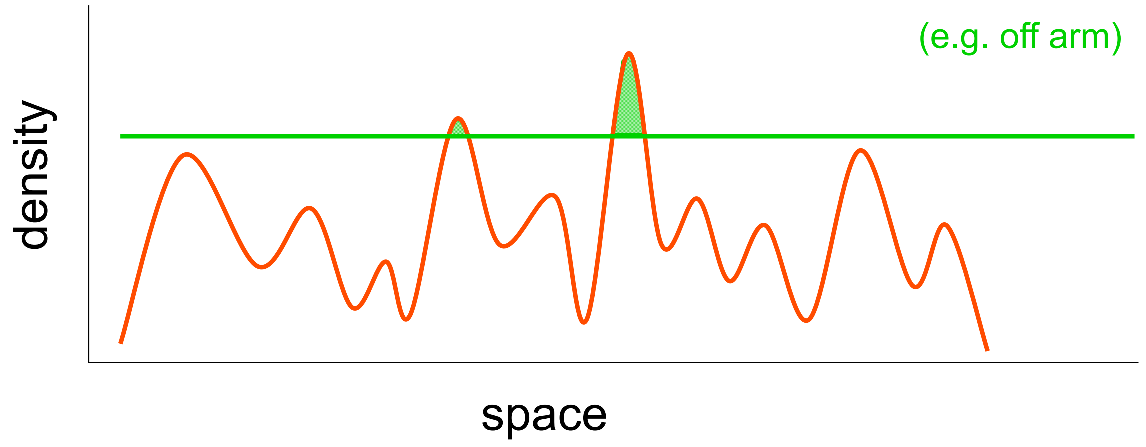
Idea:

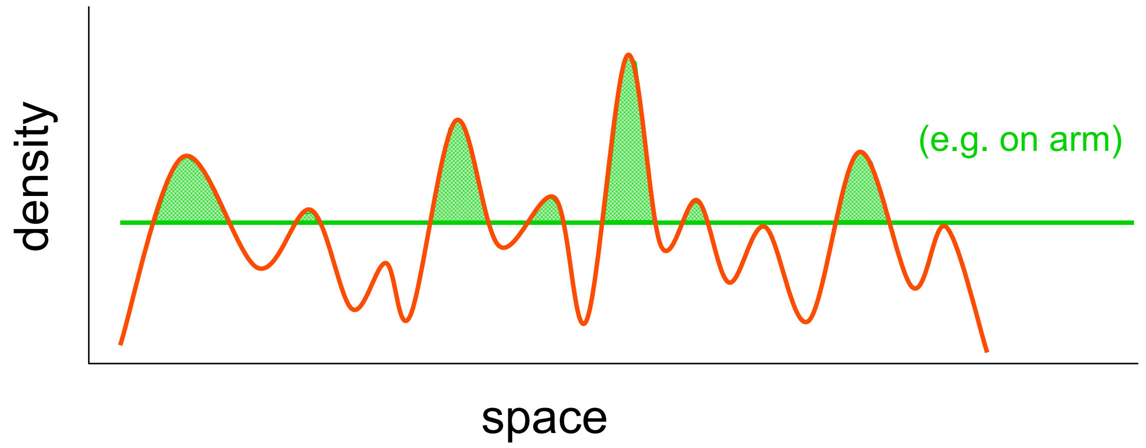
Molecular clouds form at *stagnation points* of large-scale convergent flows, mostly triggered by global (or external) perturbations. Their internal turbulence is driven by accretion, i.e. by the process of cloud formation

- molecular clouds grow in mass
- this is inferred by looking at molecular clouds in different evolutionary phases in the LMC (Fukui et al. 2008, 2009)

Fukui et al. (2009)

correlation with large-scale perturbations





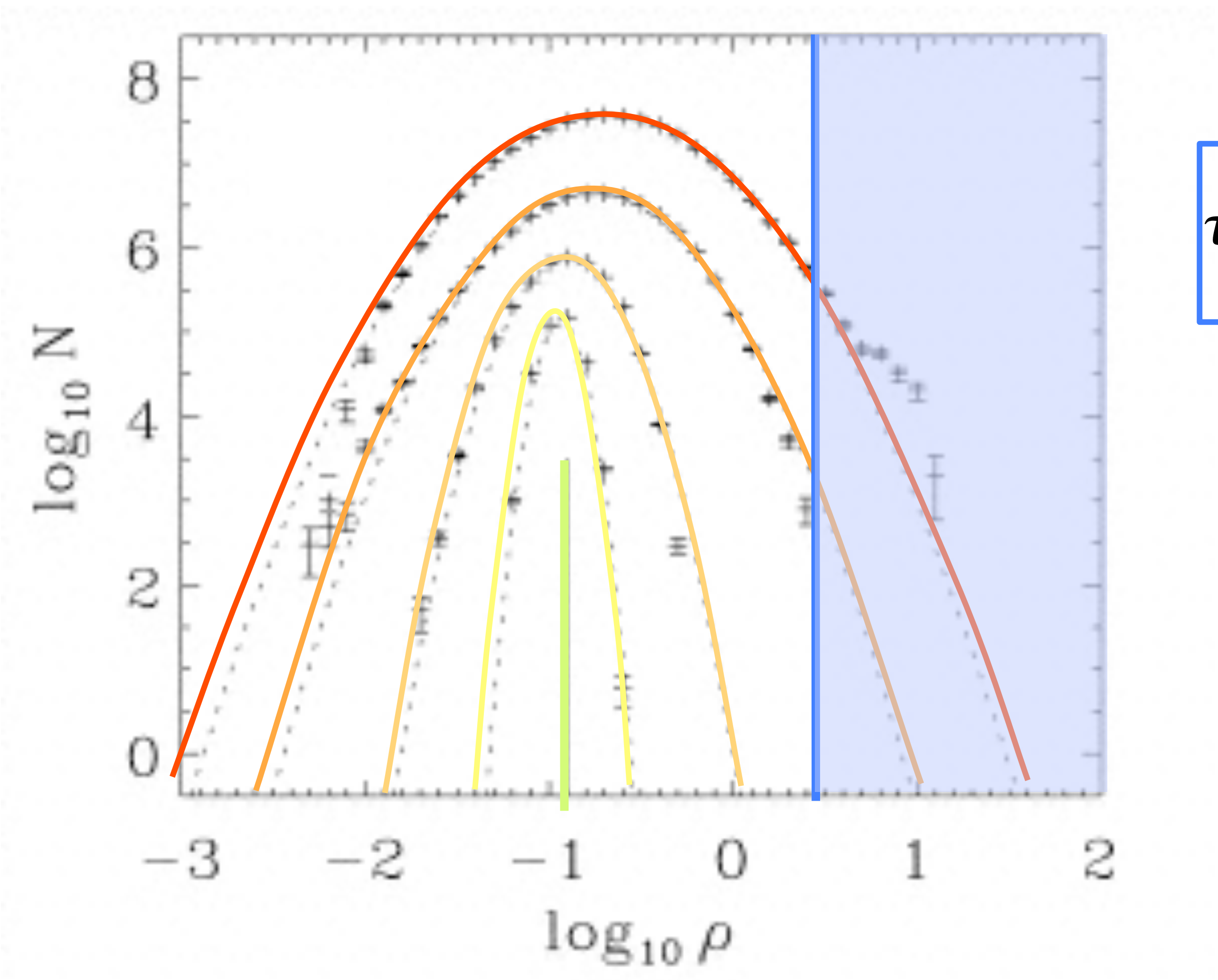
density/temperature fluctuations in warm atomar ISM are caused by *thermal/ gravitational instability* and/ or *supersonic turbulence*

some fluctuations are *dense* enough to *form* H_2 within “*reasonable time*”

→ *molecular cloud*

external perturbuations (i.e. potential changes) *increase* likelihood

star formation on *global* scales



mass weighted ρ-pdf, each shifted by ΔlogN=1

(rate from Hollenback, Werner, & Salpeter 1971)

H_2 formation rate:

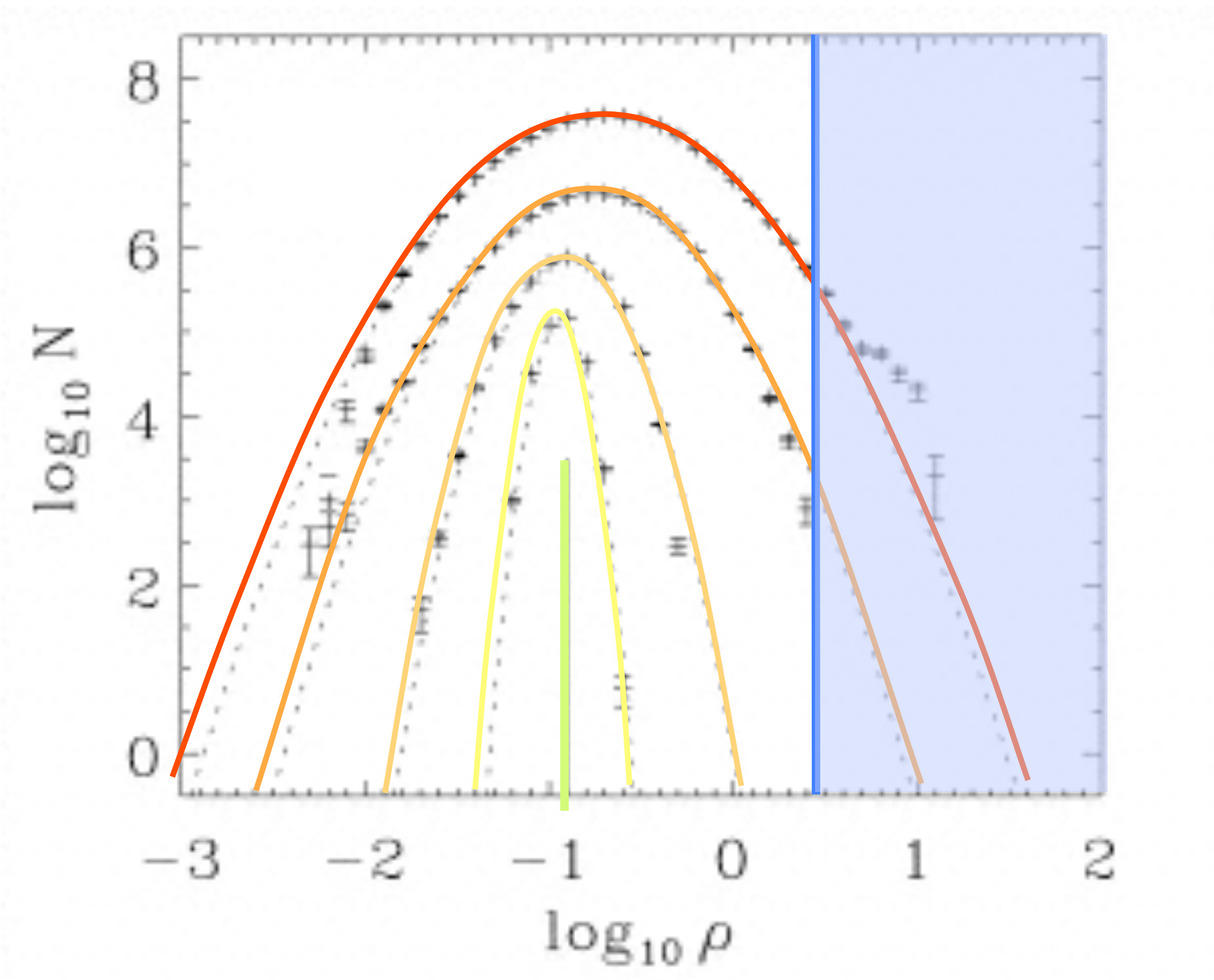
$$\boxed{\tau_{H_2} \approx \frac{1.5\,\mathrm{Gyr}}{n_H / 1\mathrm{cm}^{-3}}}$$

for $n_H \geq 100$ cm^{-3}, H_2 forms within 10 Myr, this is about the lifetime of typical MC’s.

in turbulent gas, the H_2 fraction can become very high on short timescale

(for models with coupling between cloud dynamics and time-dependent chemistry, see Glover & Mac Low 2007a,b)

star formation on *global* scales



mass weighted ρ-pdf, each shifted by $\Delta \log N = 1$

(rate from Hollenback, Werner, & Salpeter 1971)

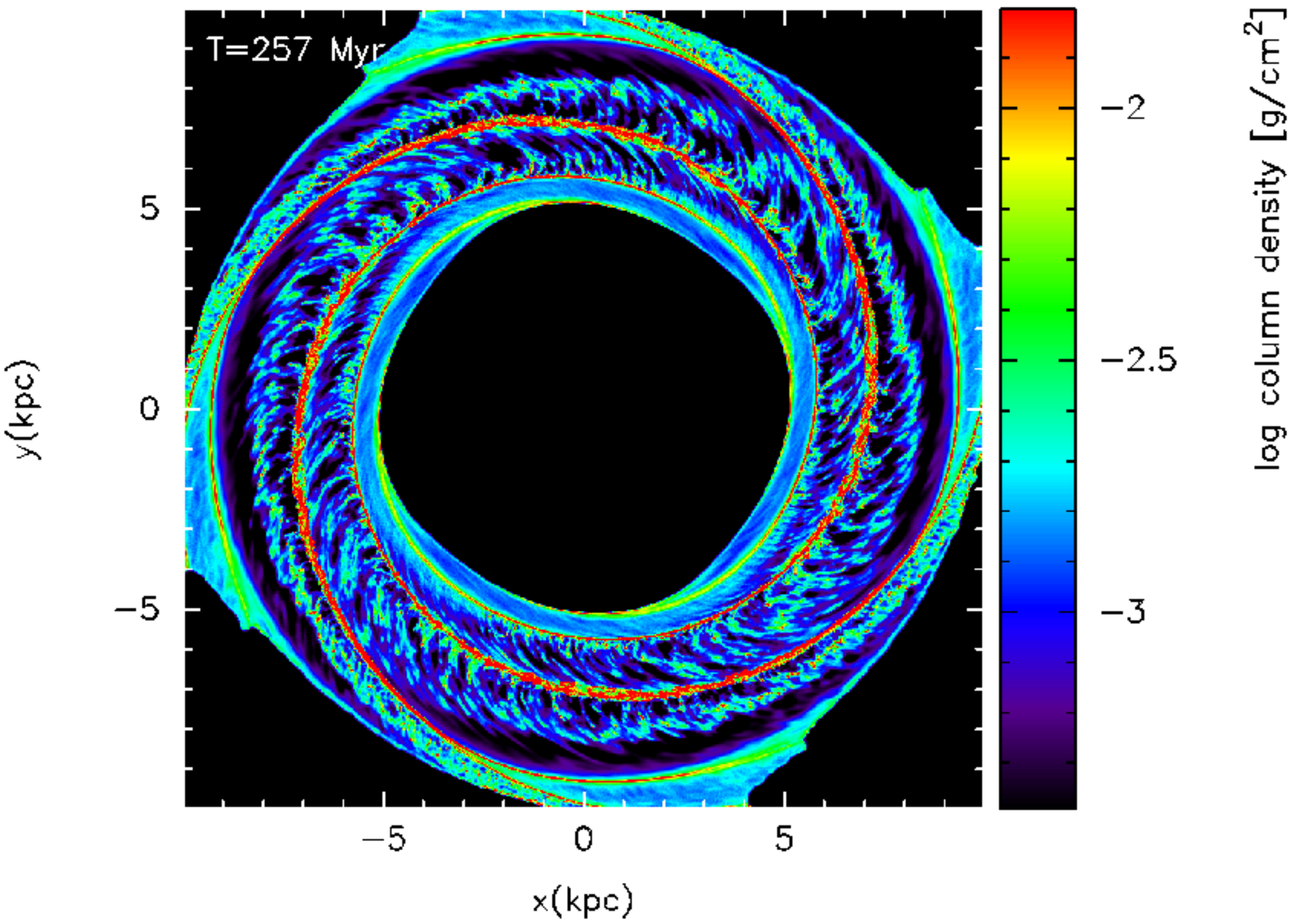
BUT: *it doesn't work*
(at least not so easy):

Chemistry has a memory effect!

H2 forms more quickly in high-density regions as it gets destroyed in low-density parts.

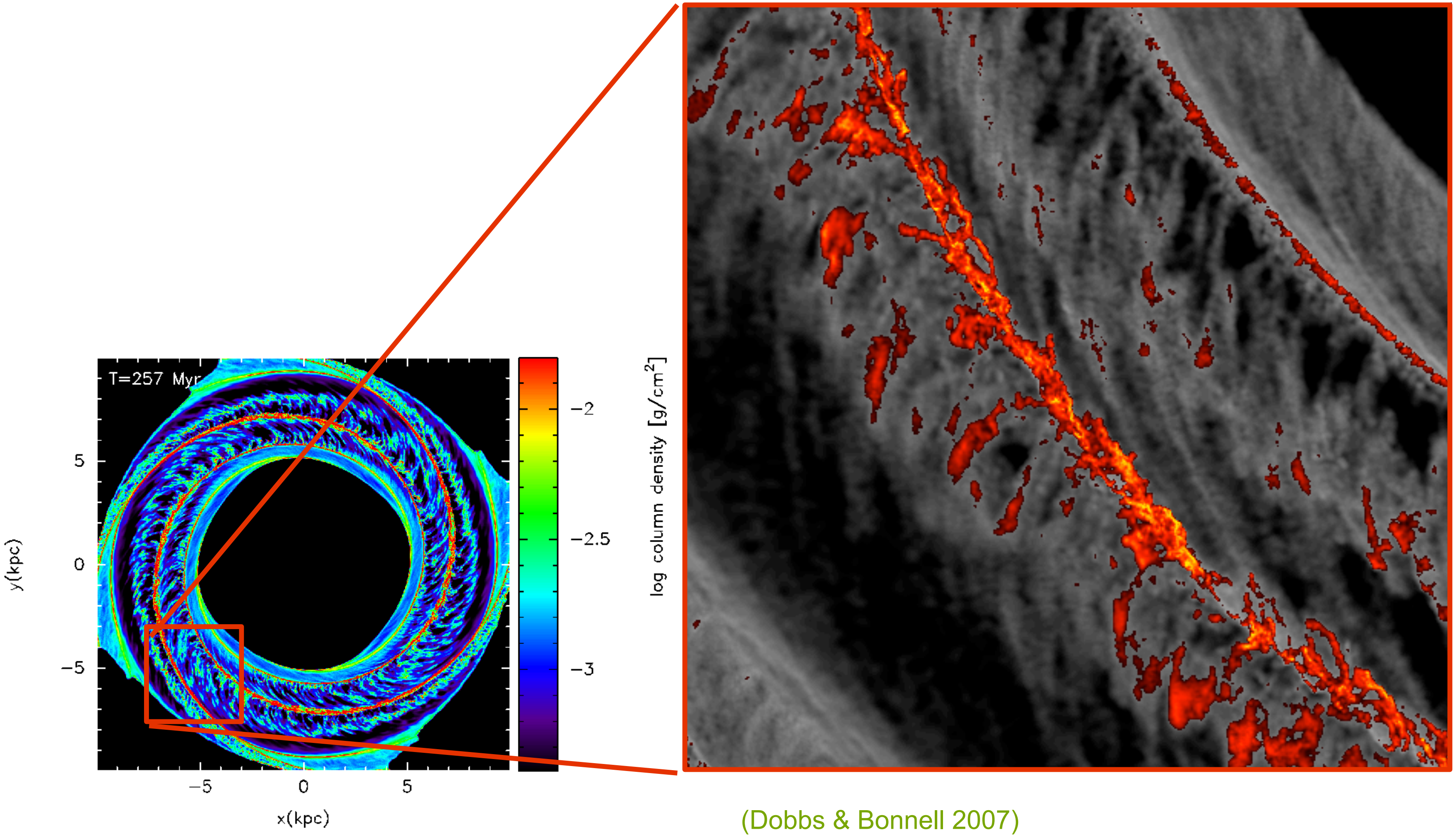
(for models with coupling between cloud dynamics and time-dependent chemistry, see Glover & Mac Low 2007a,b)

molecular cloud formation



(from Dobbs et al. 2008)

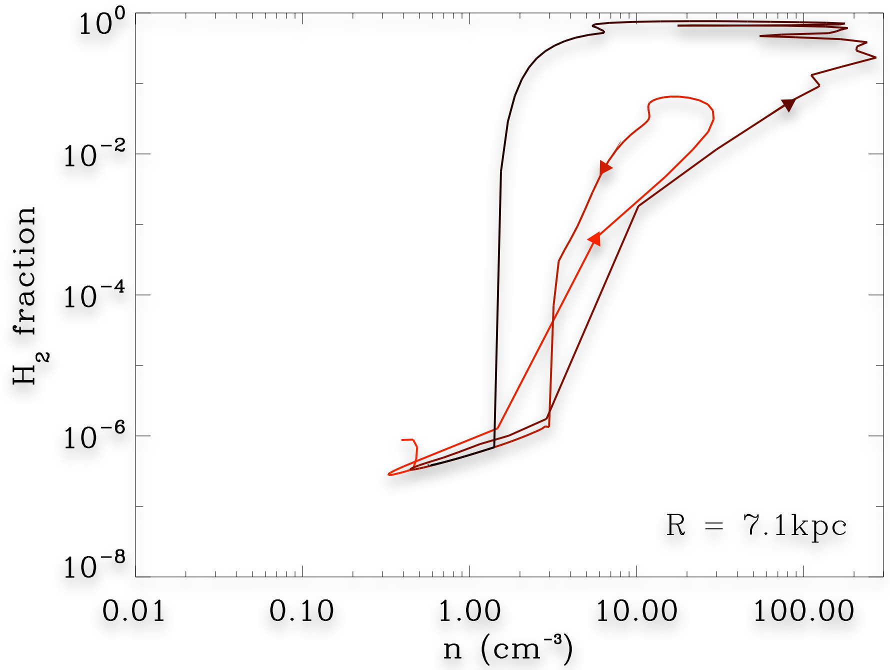
molecular cloud formation



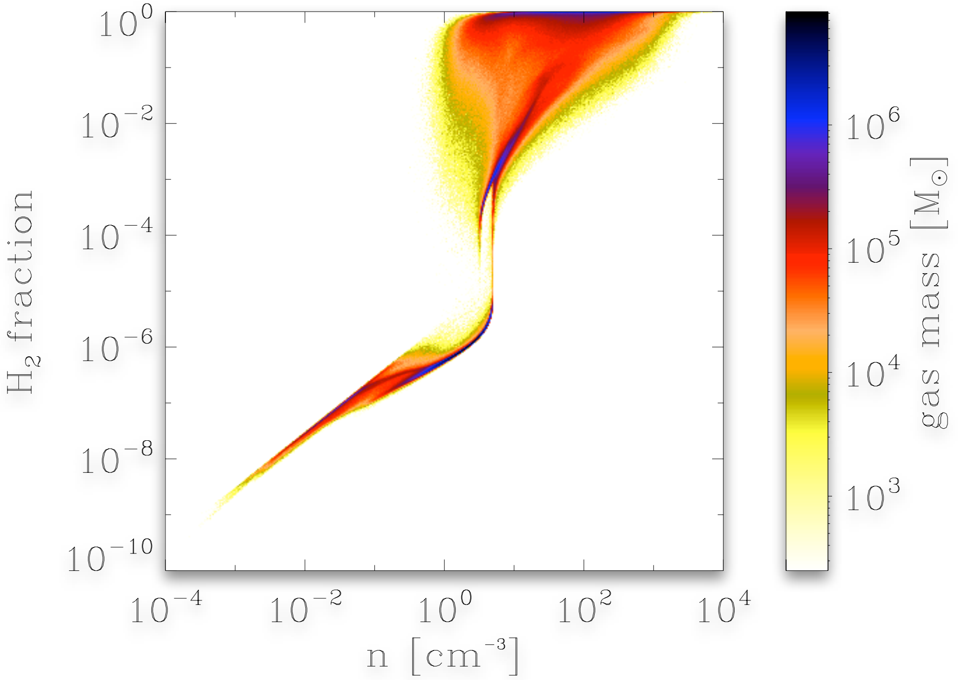
(Dobbs & Bonnell 2007)

molecular cloud formation

molecular gas fraction of fluid element as function of time

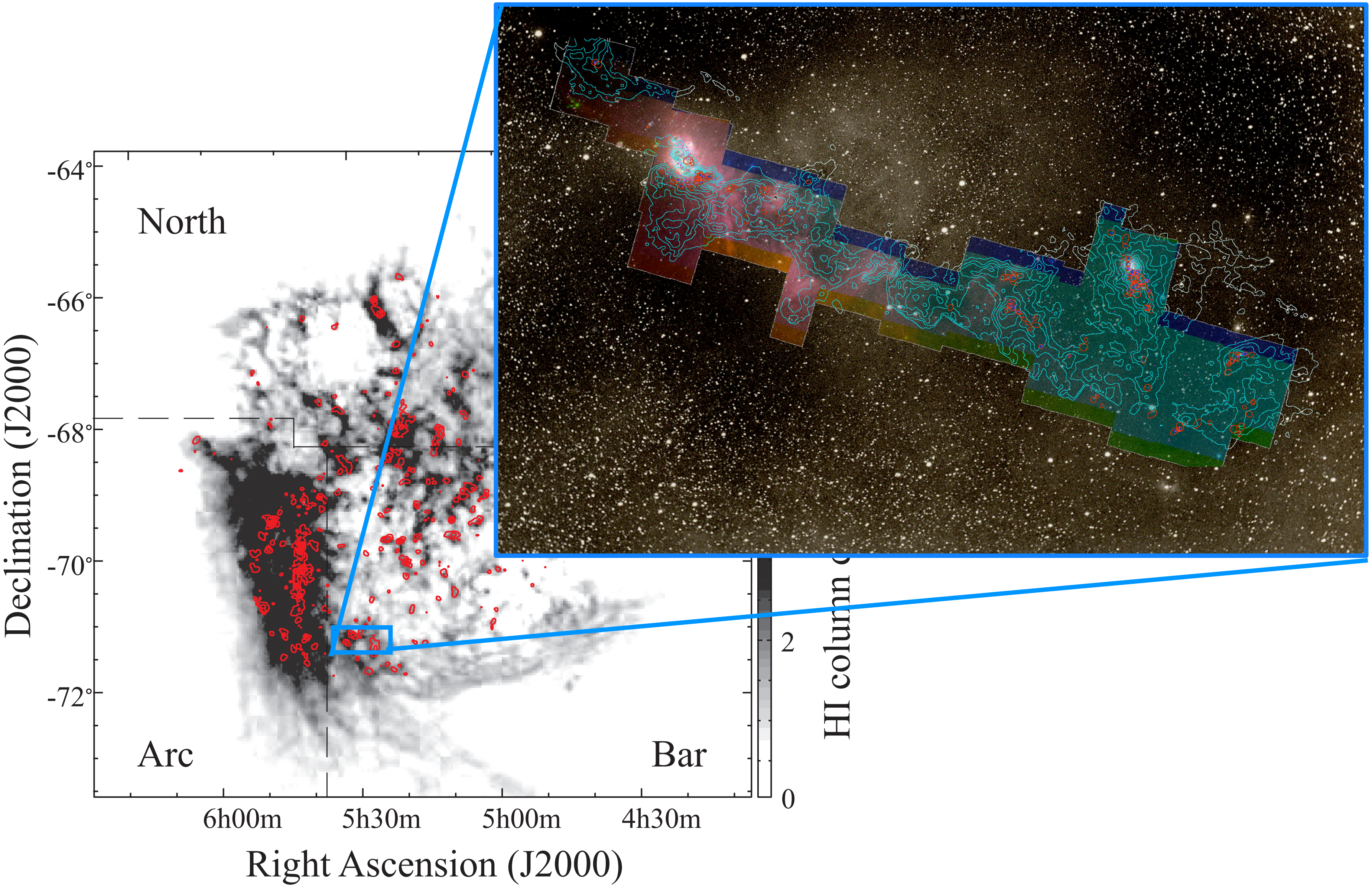


molecular gas fraction as function of density



(Dobbs et al. 2008)

zooming in ...


-64°
-66°
-68°
-70°
-72°
North
Arc
Bar
6h00m
5h30m
5h00m
4h30m
Right Ascension (J2000)
Declination (J2000)
HI column
2
0

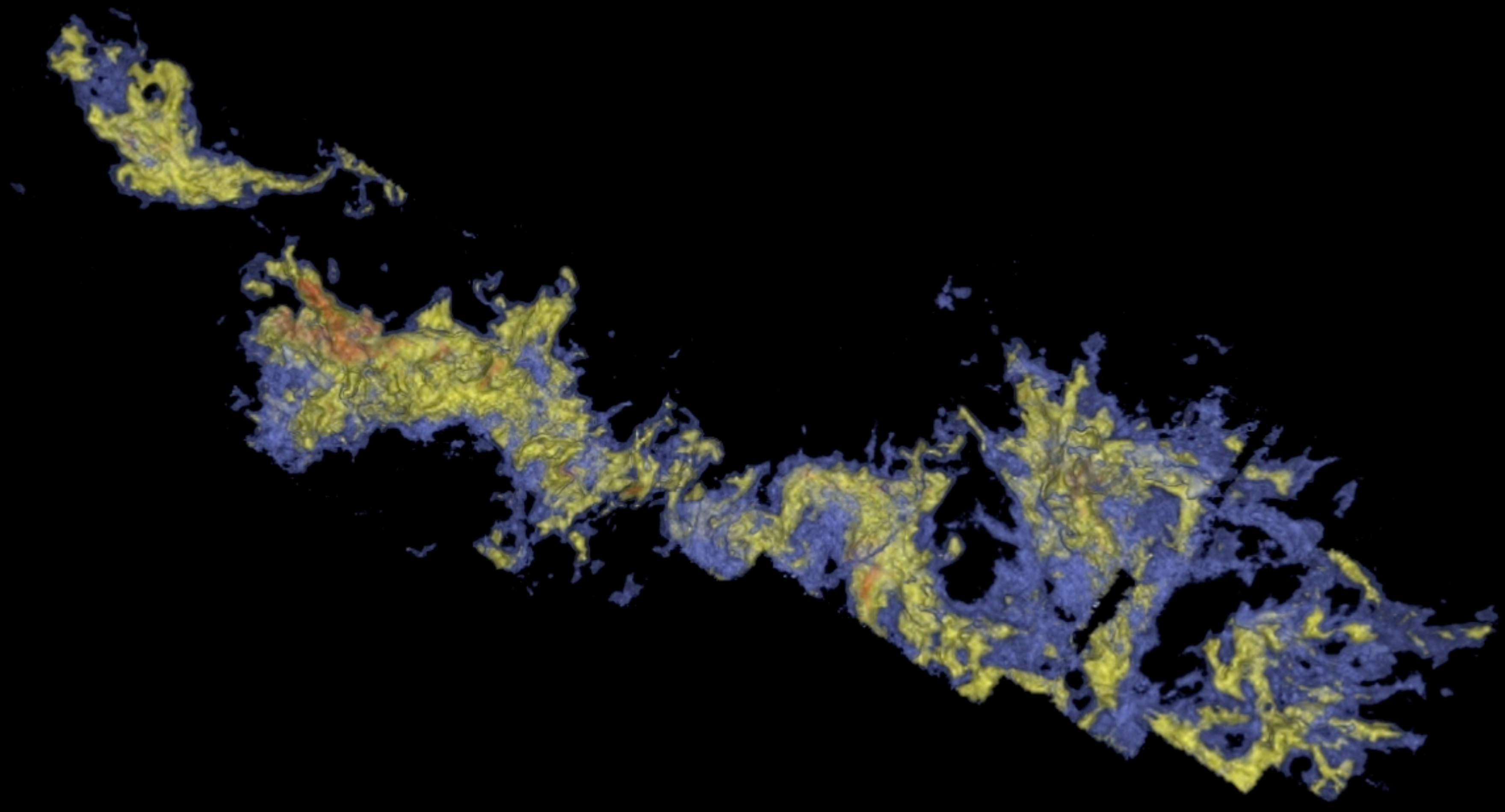
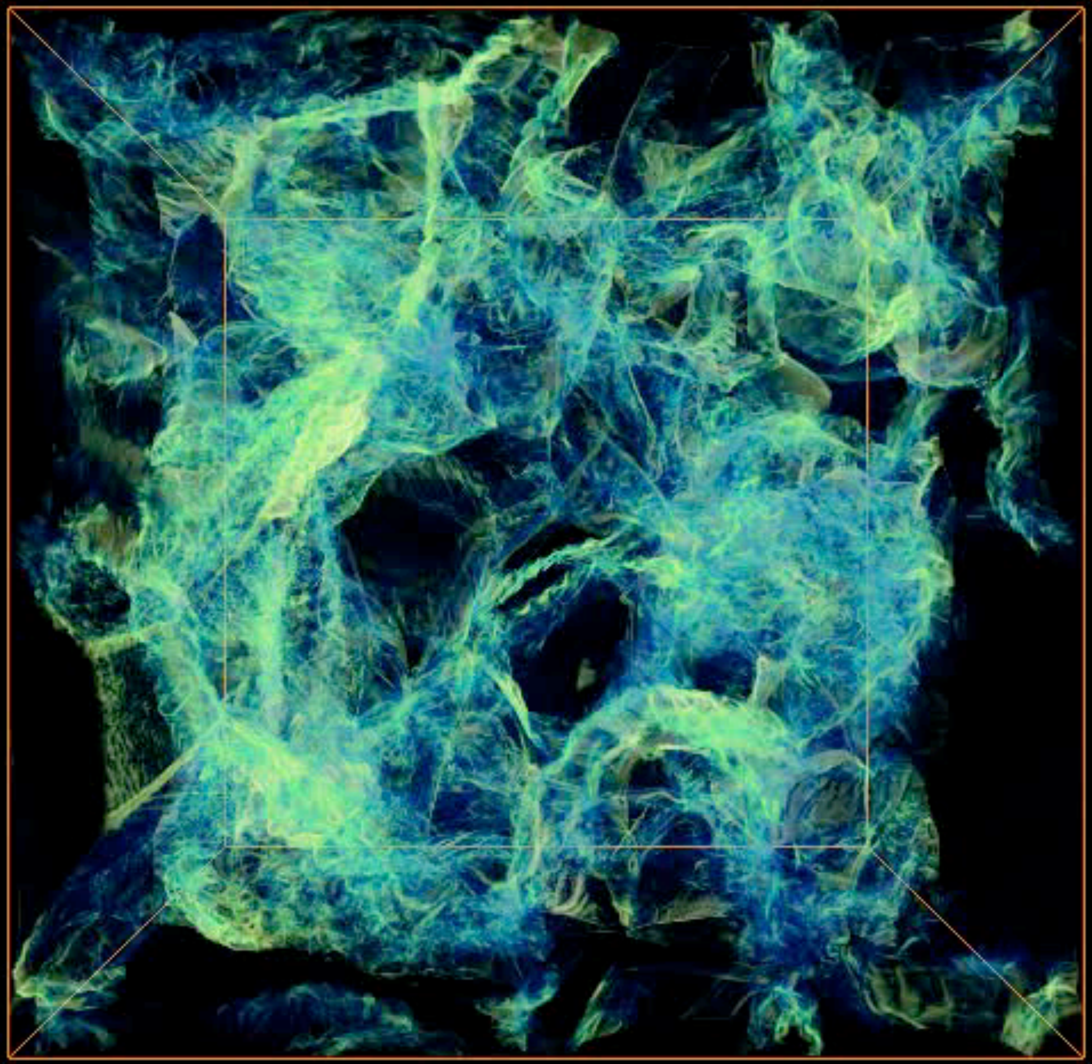


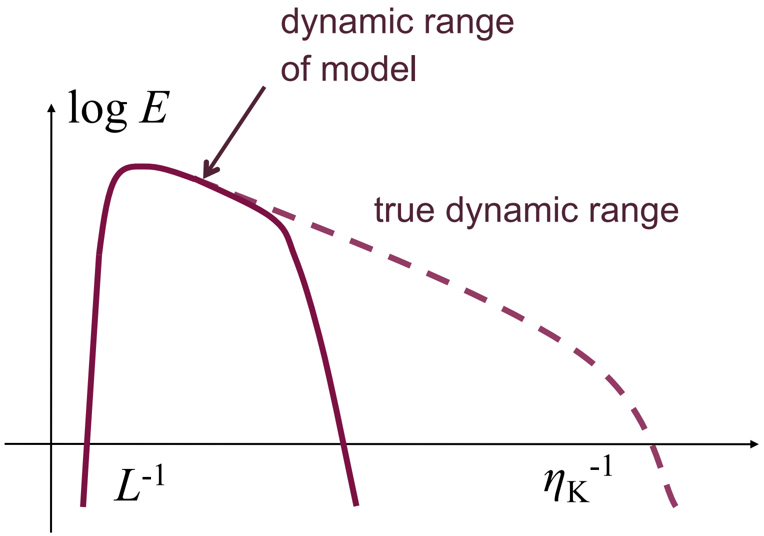
image from Alyssa Goodman: COMPLETE survey



(movie from Christoph Federrath, see his talk tomorrow)

Large-eddy simulations

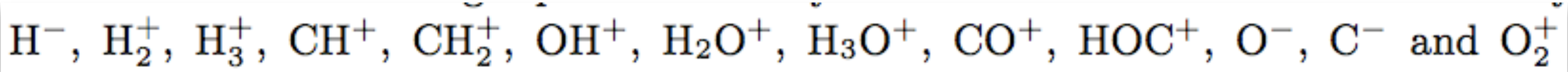
- We use ***LES*** to model the large-scale dynamics
- Principal problem: only large scale flow properties
  - Reynolds number: Re = LV/ν ***($Re_{nature} >> Re_{model}$)***
  - dynamic range much smaller than true physical one
  - need *subgrid model* (in our case simple: only dissipation)
  - but what to do for more complex when processes on subgrid scale determine large-scale dynamics (chemical reactions, nuclear burning, etc)
  - Turbulence is "space filling" --> difficulty for AMR (don't know what criterion to use for refinement)
- How *large* a Reynolds number do we need to catch basic dynamics right?



including detailed
chemistry

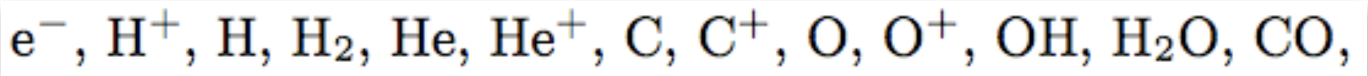
chemical model

- 32 chemical species
  - 17 in instantaneous equilibrium:

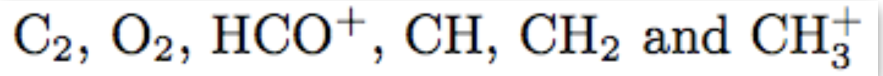


H^-, H_2^+, H_3^+, CH^+, CH_2^+, OH^+, H_2O^+, H_3O^+, CO^+, HOC^+, O^-, C^- and O_2^+

  - 19 full non-equilibrium evolution



e^-, H^+, H, H_2, He, He^+, C, C^+, O, O^+, OH, H_2O, CO,

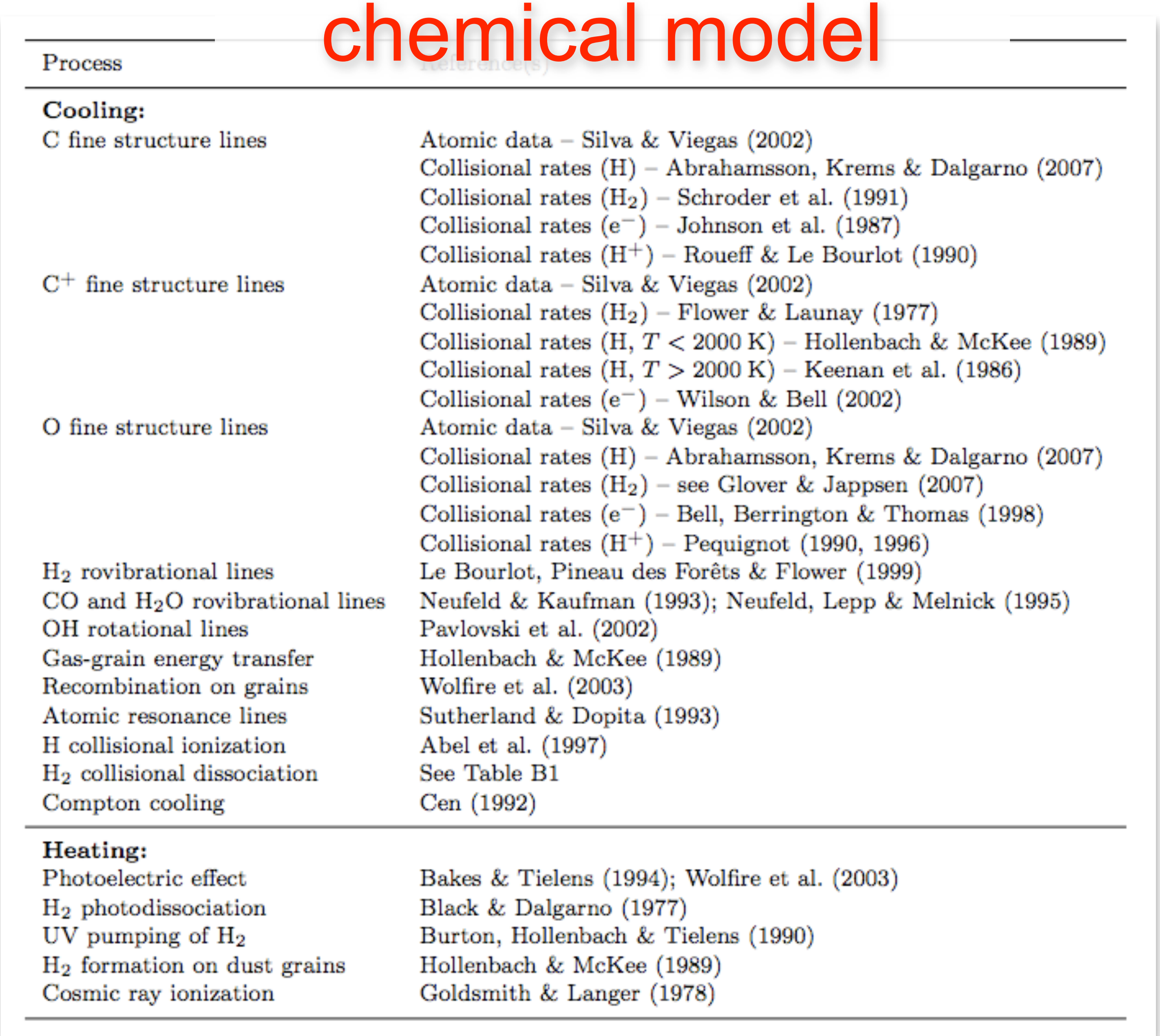


C_2, O_2, HCO^+, CH, CH_2 and CH_3^+

- 218 reactions
- various heating and cooling processes

long series of publications by Simon Glover and collaborators, e.g. Glover & Mac Low (2007ab), Glover, Federrath, Mac Low, Klessen (2010), Glover & Clark (2012, 2013), Clark & Clover (2012, 2013)

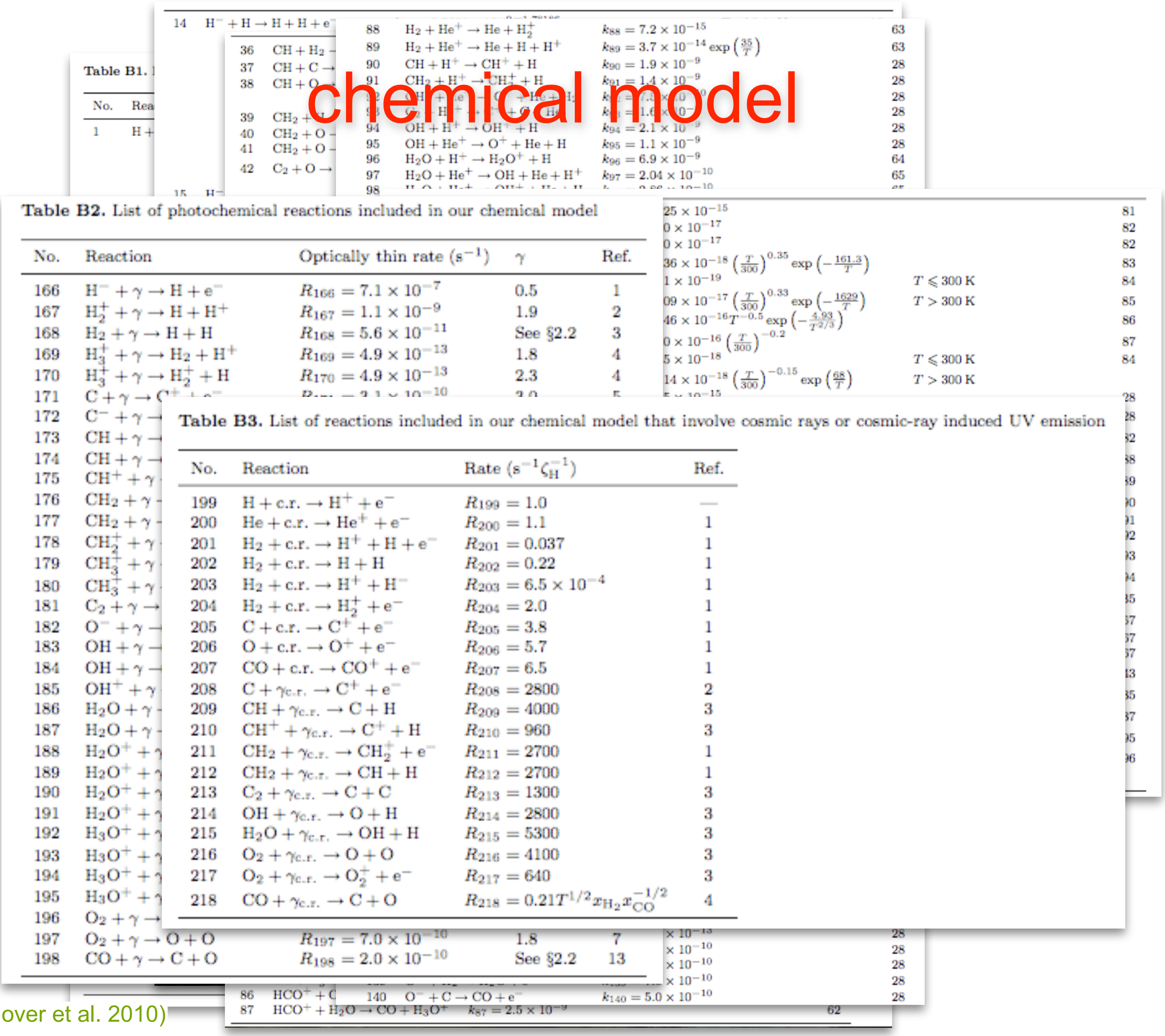
chemical model



Process	Reference(s)
Cooling:	
C fine structure lines	Atomic data – Silva & Viegas (2002)
	Collisional rates (H) – Abrahamsson, Krems & Dalgarno (2007)
	Collisional rates (H_2) – Schroder et al. (1991)
	Collisional rates (e^-) – Johnson et al. (1987)
	Collisional rates (H^+) – Roueff & Le Bourlot (1990)
C^+ fine structure lines	Atomic data – Silva & Viegas (2002)
	Collisional rates (H_2) – Flower & Launay (1977)
	Collisional rates (H, $T < 2000$ K) – Hollenbach & McKee (1989)
	Collisional rates (H, $T > 2000$ K) – Keenan et al. (1986)
	Collisional rates (e^-) – Wilson & Bell (2002)
O fine structure lines	Atomic data – Silva & Viegas (2002)
	Collisional rates (H) – Abrahamsson, Krems & Dalgarno (2007)
	Collisional rates (H_2) – see Glover & Jappsen (2007)
	Collisional rates (e^-) – Bell, Berrington & Thomas (1998)
	Collisional rates (H^+) – Pequignot (1990, 1996)
H_2 rovibrational lines	Le Bourlot, Pineau des Forêts & Flower (1999)
CO and H_2O rovibrational lines	Neufeld & Kaufman (1993); Neufeld, Lepp & Melnick (1995)
OH rotational lines	Pavlovski et al. (2002)
Gas-grain energy transfer	Hollenbach & McKee (1989)
Recombination on grains	Wolfire et al. (2003)
Atomic resonance lines	Sutherland & Dopita (1993)
H collisional ionization	Abel et al. (1997)
H_2 collisional dissociation	See Table B1
Compton cooling	Cen (1992)
Heating:	
Photoelectric effect	Bakes & Tielens (1994); Wolfire et al. (2003)
H_2 photodissociation	Black & Dalgarno (1977)
UV pumping of H_2	Burton, Hollenbach & Tielens (1990)
H_2 formation on dust grains	Hollenbach & McKee (1989)
Cosmic ray ionization	Goldsmith & Langer (1978)

(Glover et al. 2010)

chemical model



88	$H_2 + He^+ \rightarrow He + H_2^+$	$k_{88} = 7.2 \times 10^{-15}$	63
89	$H_2 + He^+ \rightarrow He + H + H^+$	$k_{89} = 3.7 \times 10^{-14} \exp\left(\frac{35}{T}\right)$	63
90	$CH + H^+ \rightarrow CH^+ + H$	$k_{90} = 1.9 \times 10^{-9}$	28
91	$CH_2 + H^+ \rightarrow CH_2^+ + H$	$k_{91} = 1.4 \times 10^{-9}$	28
94	$OH + H^+ \rightarrow OH^+ + H$	$k_{94} = 2.1 \times 10^{-9}$	28
95	$OH + He^+ \rightarrow O^+ + He + H$	$k_{95} = 1.1 \times 10^{-9}$	28
96	$H_2O + H^+ \rightarrow H_2O^+ + H$	$k_{96} = 6.9 \times 10^{-9}$	64
97	$H_2O + He^+ \rightarrow OH + He + H^+$	$k_{97} = 2.04 \times 10^{-10}$	65

Table B2. List of photochemical reactions included in our chemical model

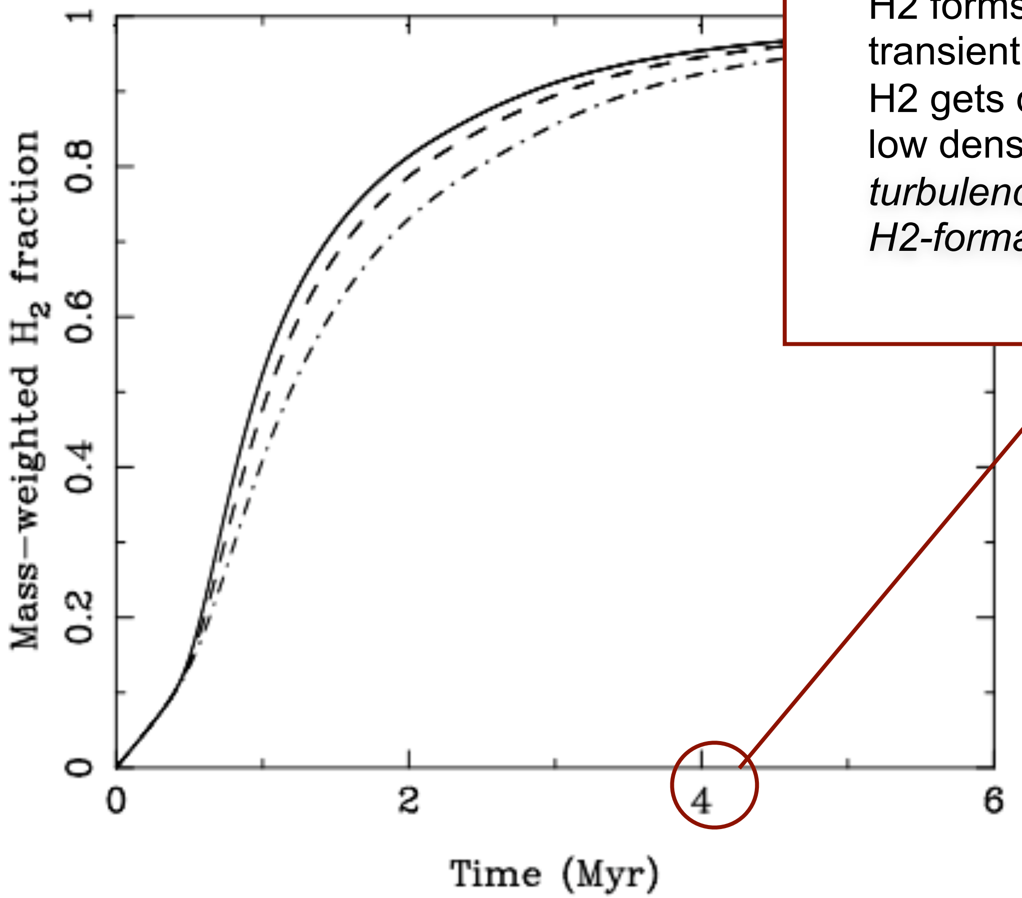
No.	Reaction	Optically thin rate (s^{-1})	γ	Ref.
166	$H^- + \gamma \rightarrow H + e^-$	$R_{166} = 7.1 \times 10^{-7}$	0.5	1
167	$H_2^+ + \gamma \rightarrow H + H^+$	$R_{167} = 1.1 \times 10^{-9}$	1.9	2
168	$H_2 + \gamma \rightarrow H + H$	$R_{168} = 5.6 \times 10^{-11}$	See §2.2	3
169	$H_3^+ + \gamma \rightarrow H_2 + H^+$	$R_{169} = 4.9 \times 10^{-13}$	1.8	4
170	$H_3^+ + \gamma \rightarrow H_2^+ + H$	$R_{170} = 4.9 \times 10^{-13}$	2.3	4
197	$O_2 + \gamma \rightarrow O + O$	$R_{197} = 7.0 \times 10^{-10}$	1.8	7
198	$CO + \gamma \rightarrow C + O$	$R_{198} = 2.0 \times 10^{-10}$	See §2.2	13

Table B3. List of reactions included in our chemical model that involve cosmic rays or cosmic-ray induced UV emission

No.	Reaction	Rate ($s^{-1}\zeta_H^{-1}$)	Ref.
199	$H + c.r. \rightarrow H^+ + e^-$	$R_{199} = 1.0$	—
200	$He + c.r. \rightarrow He^+ + e^-$	$R_{200} = 1.1$	1
201	$H_2 + c.r. \rightarrow H^+ + H + e^-$	$R_{201} = 0.037$	1
202	$H_2 + c.r. \rightarrow H + H$	$R_{202} = 0.22$	1
203	$H_2 + c.r. \rightarrow H^+ + H^-$	$R_{203} = 6.5 \times 10^{-4}$	1
204	$H_2 + c.r. \rightarrow H_2^+ + e^-$	$R_{204} = 2.0$	1
205	$C + c.r. \rightarrow C^+ + e^-$	$R_{205} = 3.8$	1
206	$O + c.r. \rightarrow O^+ + e^-$	$R_{206} = 5.7$	1
207	$CO + c.r. \rightarrow CO^+ + e^-$	$R_{207} = 6.5$	1
208	$C + \gamma_{c.r.} \rightarrow C^+ + e^-$	$R_{208} = 2800$	2
209	$CH + \gamma_{c.r.} \rightarrow C + H$	$R_{209} = 4000$	3
210	$CH^+ + \gamma_{c.r.} \rightarrow C^+ + H$	$R_{210} = 960$	3
211	$CH_2 + \gamma_{c.r.} \rightarrow CH_2^+ + e^-$	$R_{211} = 2700$	1
212	$CH_2 + \gamma_{c.r.} \rightarrow CH + H$	$R_{212} = 2700$	1
213	$C_2 + \gamma_{c.r.} \rightarrow C + C$	$R_{213} = 1300$	3
214	$OH + \gamma_{c.r.} \rightarrow O + H$	$R_{214} = 2800$	3
215	$H_2O + \gamma_{c.r.} \rightarrow OH + H$	$R_{215} = 5300$	3
216	$O_2 + \gamma_{c.r.} \rightarrow O + O$	$R_{216} = 4100$	3
217	$O_2 + \gamma_{c.r.} \rightarrow O_2^+ + e^-$	$R_{217} = 640$	3
218	$CO + \gamma_{c.r.} \rightarrow C + O$	$R_{218} = 0.21 T^{1/2} x_{H_2} x_{CO}^{-1/2}$	4

(Glover et al. 2010)

HI to H2 conversion rate



H2 forms rapidly in shocks / transient density fluctuations / H2 gets destroyed slowly in low density regions / *result: turbulence greatly enhances H2-formation rate*

Figure 4. Time evolution of the mass-weighted H_2 abundance in simulations R1, R2 and R3, which have numerical resolutions of 64^3 zones (dot-dashed), 128^3 zones (dashed) and 256^3 zones (solid), respectively.

(Glover et al. 2010)

CO, C^+ formation rates

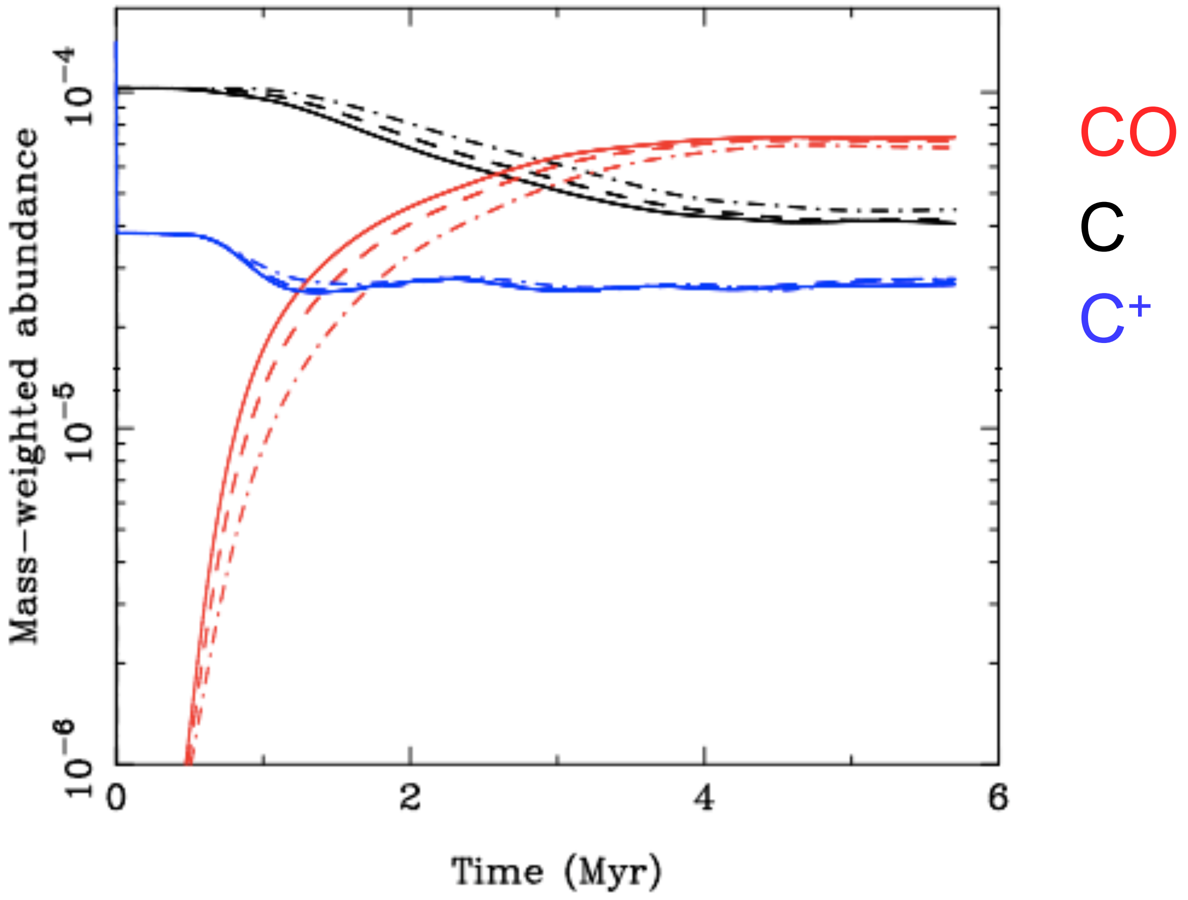
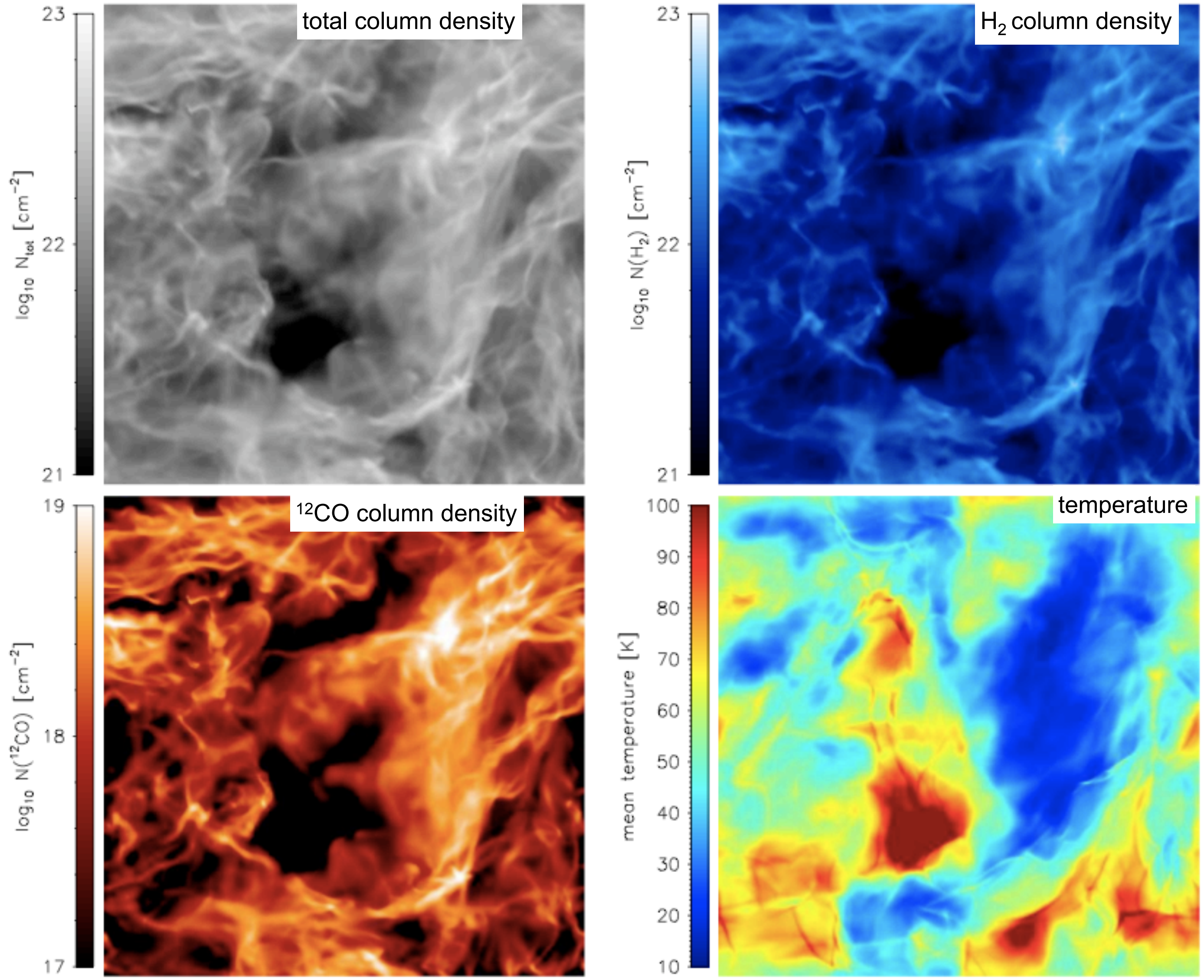


Figure 5. Time evolution of the mass-weighted abundances of atomic carbon (black lines), CO (red lines), and C^+ (blue lines) in simulations with numerical resolutions of 64^3 zones (dot-dashed), 128^3 zones (dashed) and 256^3 zones (solid).

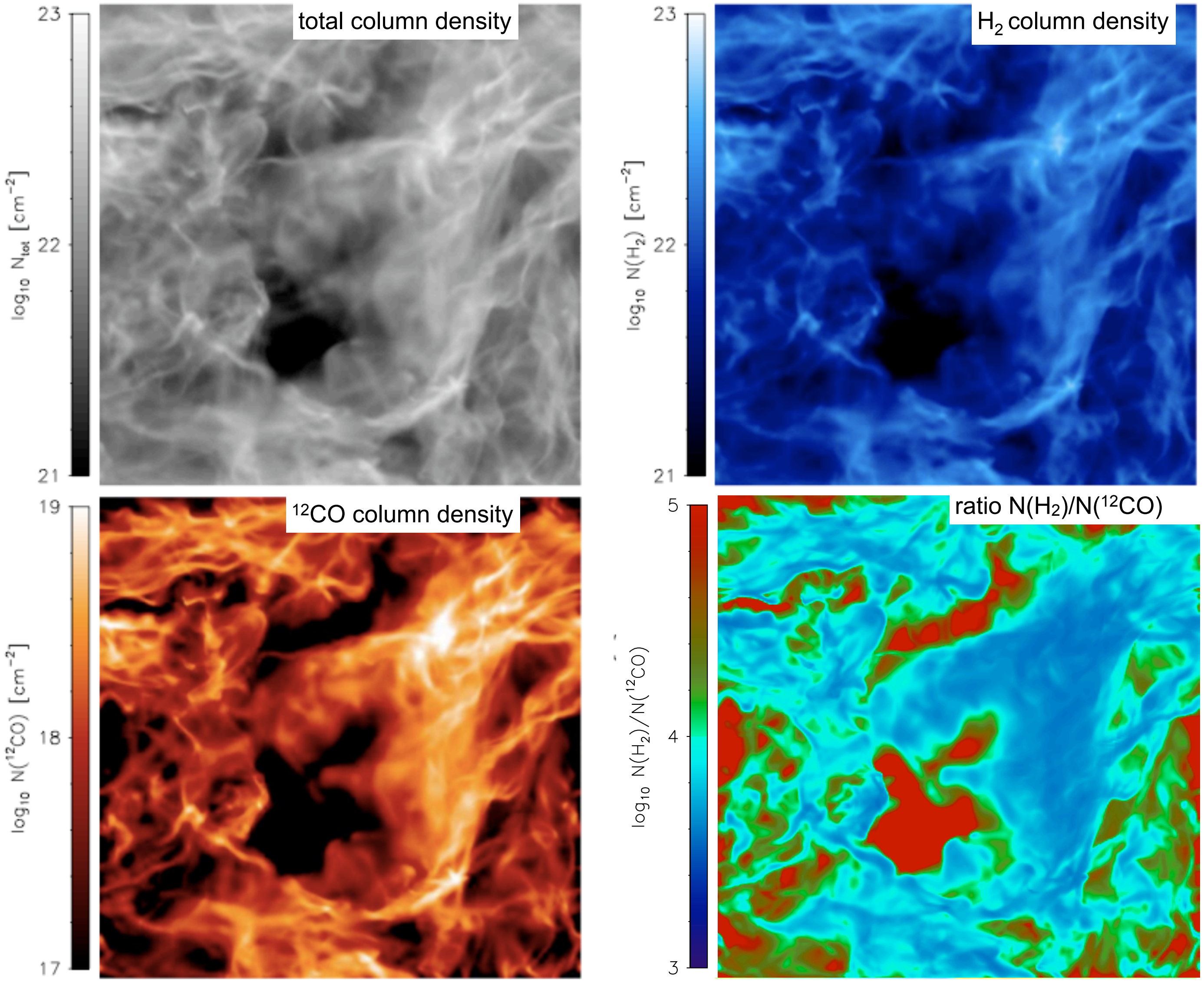
(Glover et al. 2010)

effects of chemistry



(Glover et al. 2010)

effects of chemistry



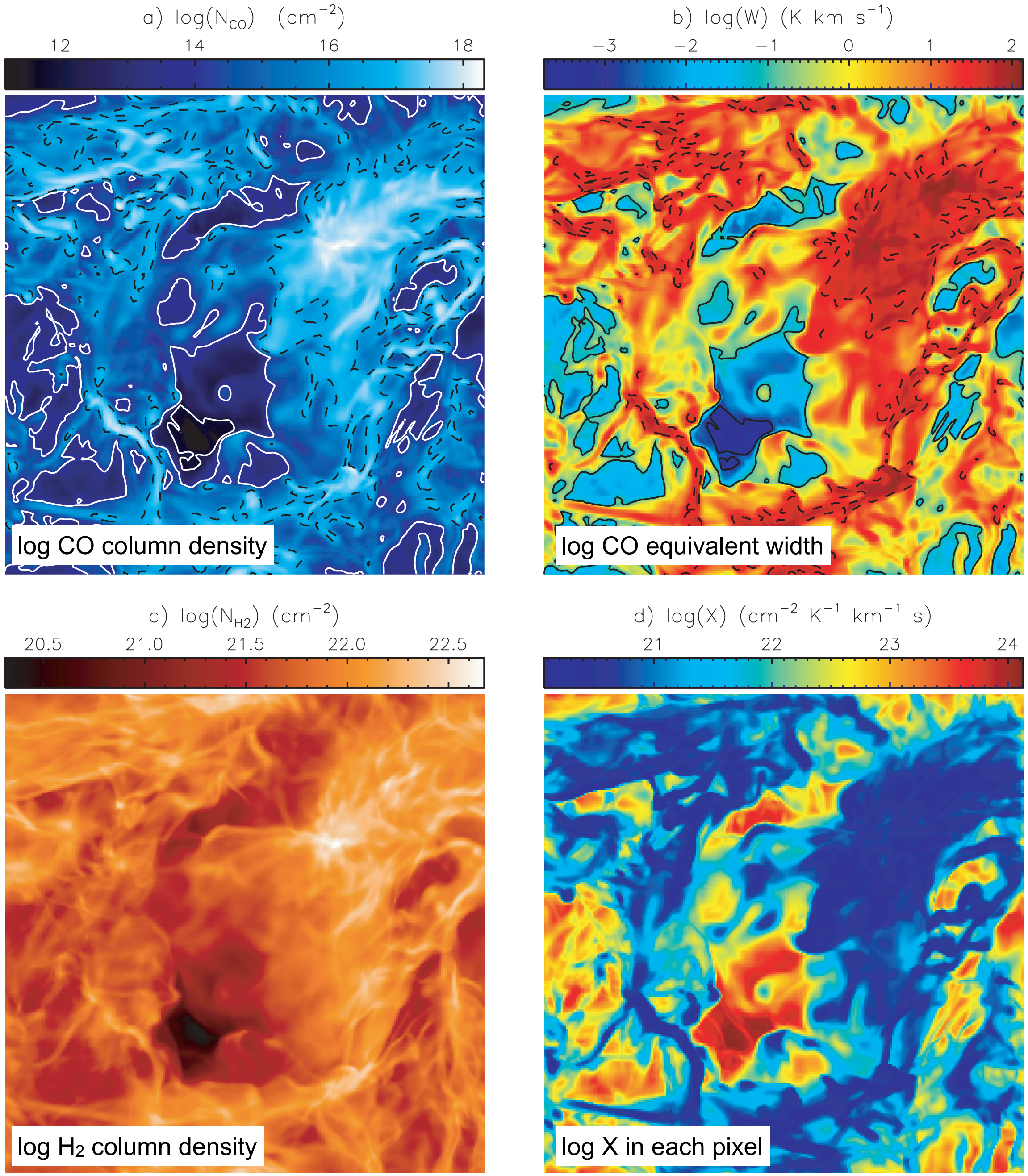
(Glover et al. 2010)

X_{CO} factor

- conversion rate between H_2 column density and CO emission (equivalent width W)

$$X = \frac{N_{H_2}}{W}\ (\mathrm{cm^{-2}\,K^{-1}\,km^{-1}\,s})$$

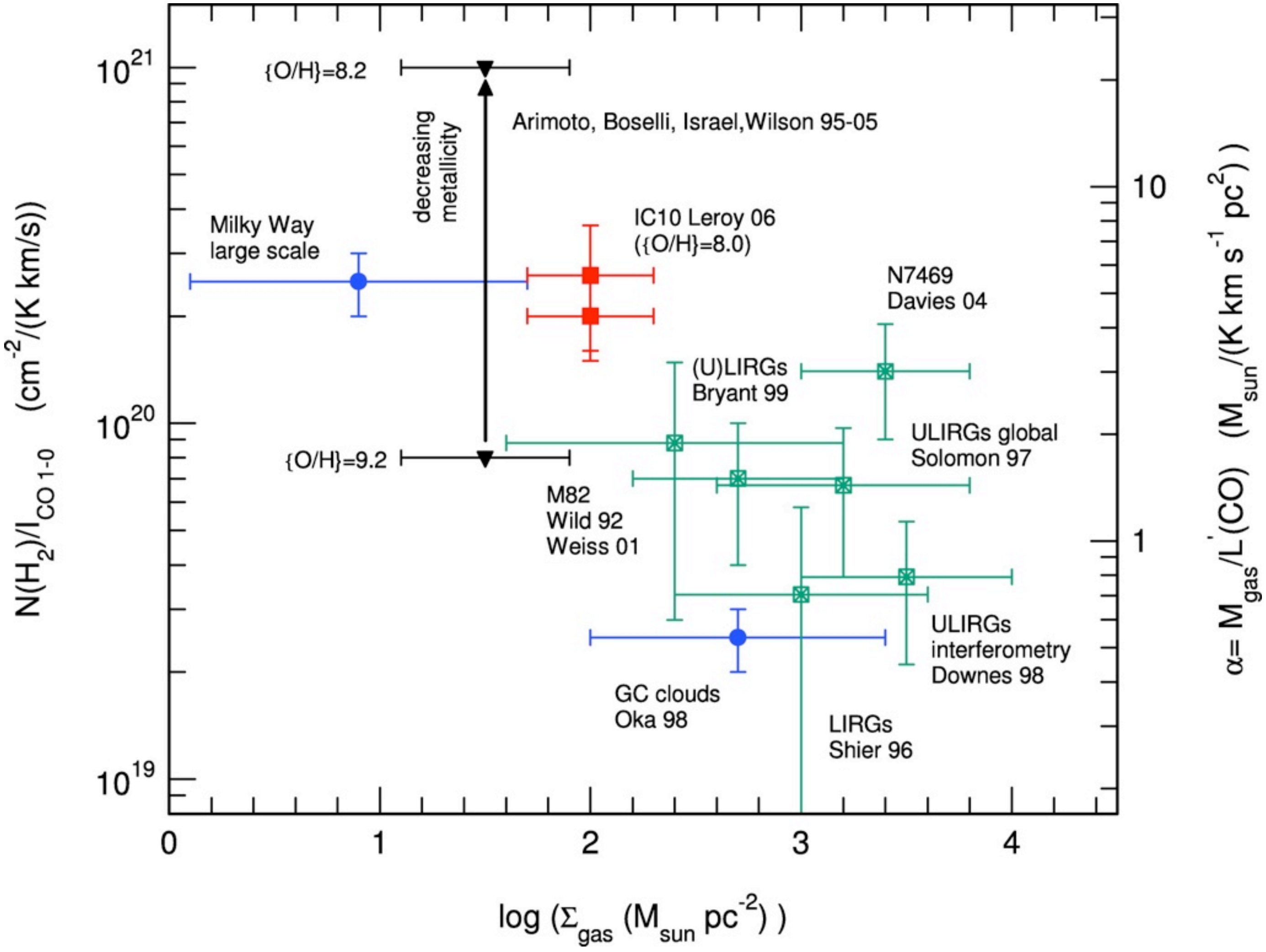
- most mass H_2 determinations depend on X*!*
- in Milky Way X ~ few x 10^{22} $\mathrm{cm^{-2}\,K^{-1}\,km^{-1}\,s}$ ~ const.
- how does it vary with environmental condition?
  - metallicity
  - density, radiation field, etc.
    ("normal" gal. vs star burst)



(Shetty, Glover, Dullemond, Klessen 2011)

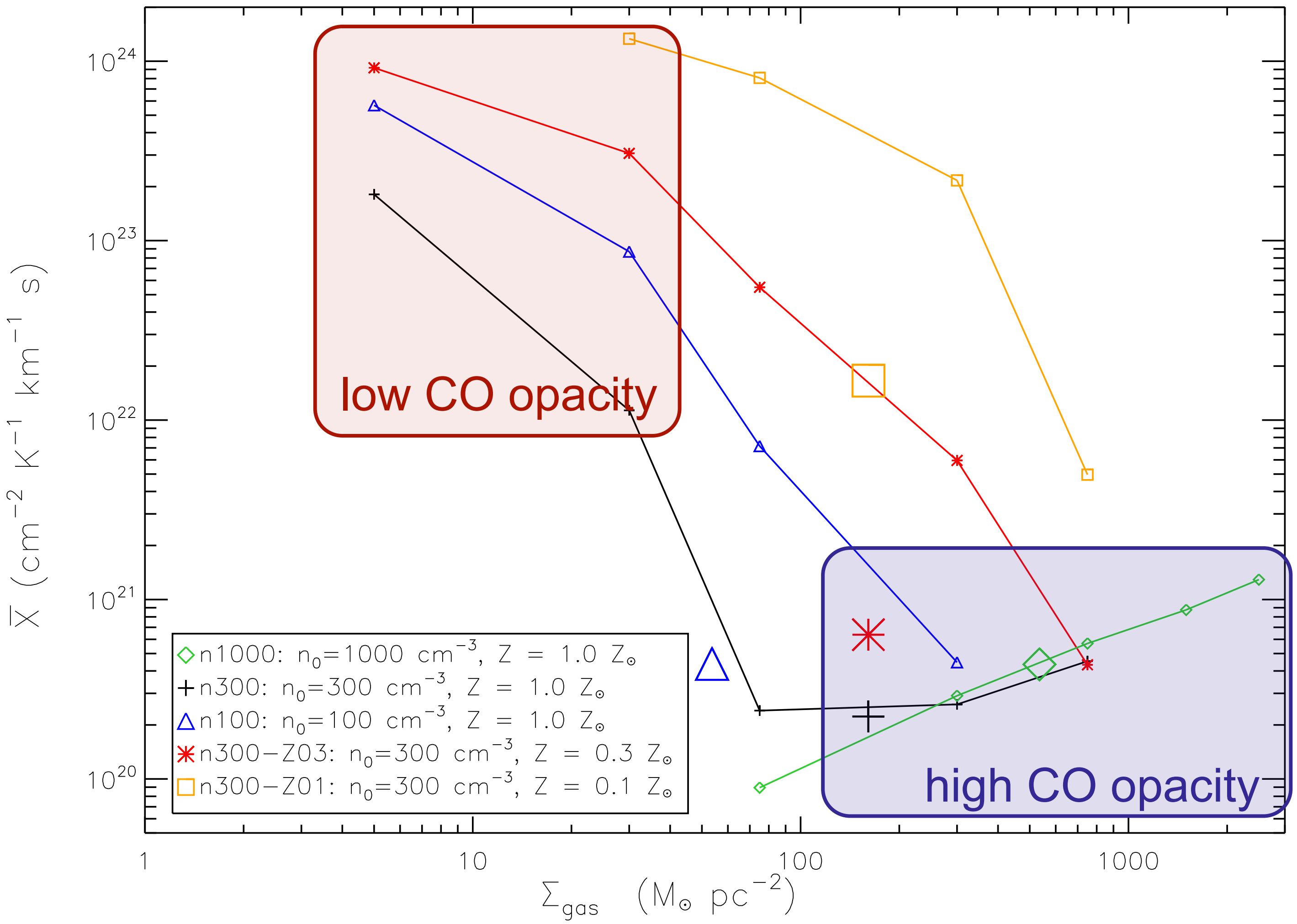
Figure 4. Images of (a) $N_{\rm CO}$, (b) W, (c) $N_{\rm H_2}$ and (d) the X factor of model n300-Z03. Each side has a length of 20 pc. In (a) and (b), solid contours indicate $\log(N_{\rm CO}) = 12$, 14 and $\log(W) = -3, -1$; dashed contours are $\log(N_{\rm CO}) = 16.5$ and $\log(W) = 1.5$ (see the text and Fig. 2d).

observed x-factor



Tacconi et al. (2008)

derived x-factor

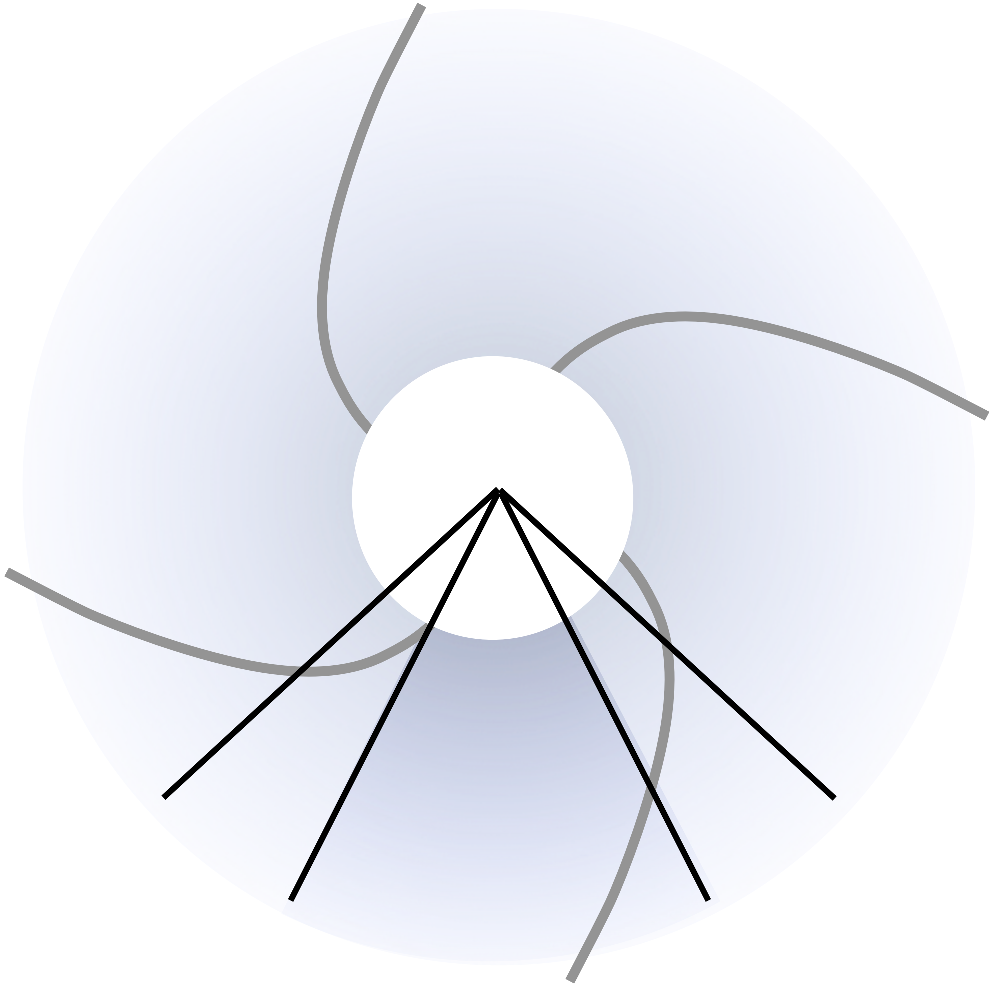


(Shetty, Glover, Dullemond, Klessen, MNRAS, 2011)

some applications

- large-scale galaxy simulations (work by Rowan Smith)
- ISM simulations (SILCC collaboration, lead by Steffi Walch)
- molecular cloud formation (work by Simon Glover and Paul Clark)

Modelling the galactic ISM dynamics



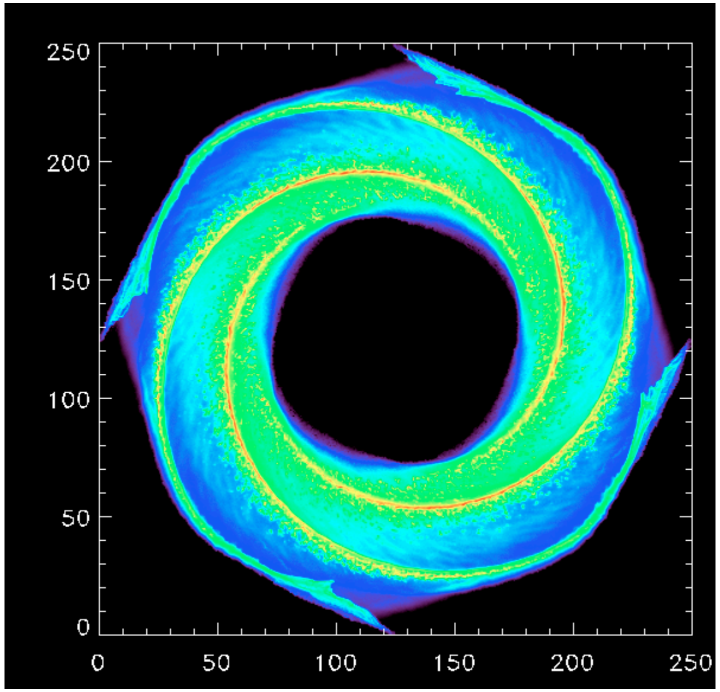
- use Arepo (Springel 2012)
- full-fledged H_2 and CO chemistry (Glover et al. 2010)
- external potential with 4-arm spiral (e.g. Dobbs et al. 2008)
- resolve down to 4 M_{sun}!

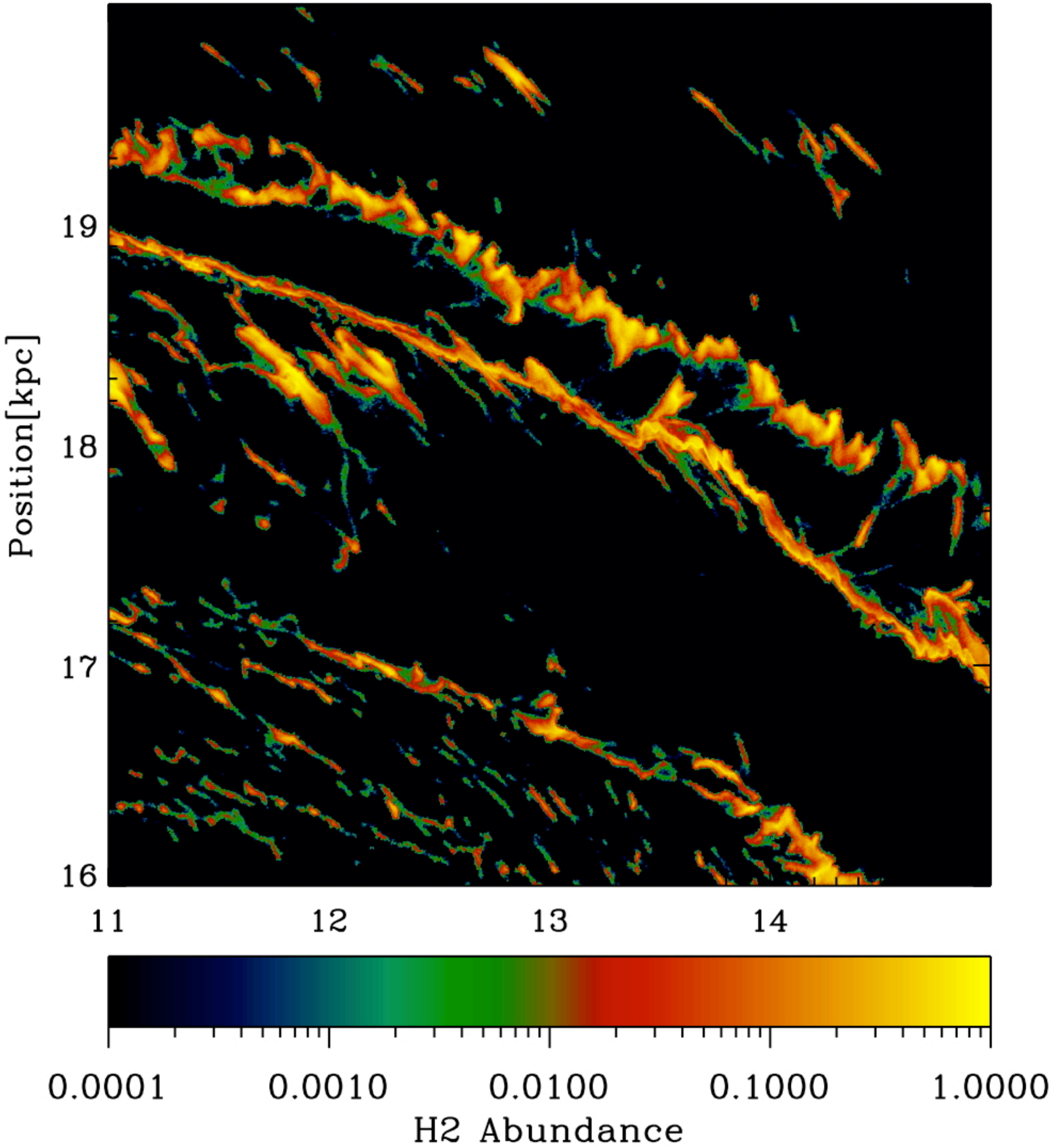
- produce synthetic maps in CO, HI, H_2, etc.
- include feedback

(Rowan Smith et al. in preparation)

Modelling the galactic ISM dynamics

H_2 formation in a spiral potential

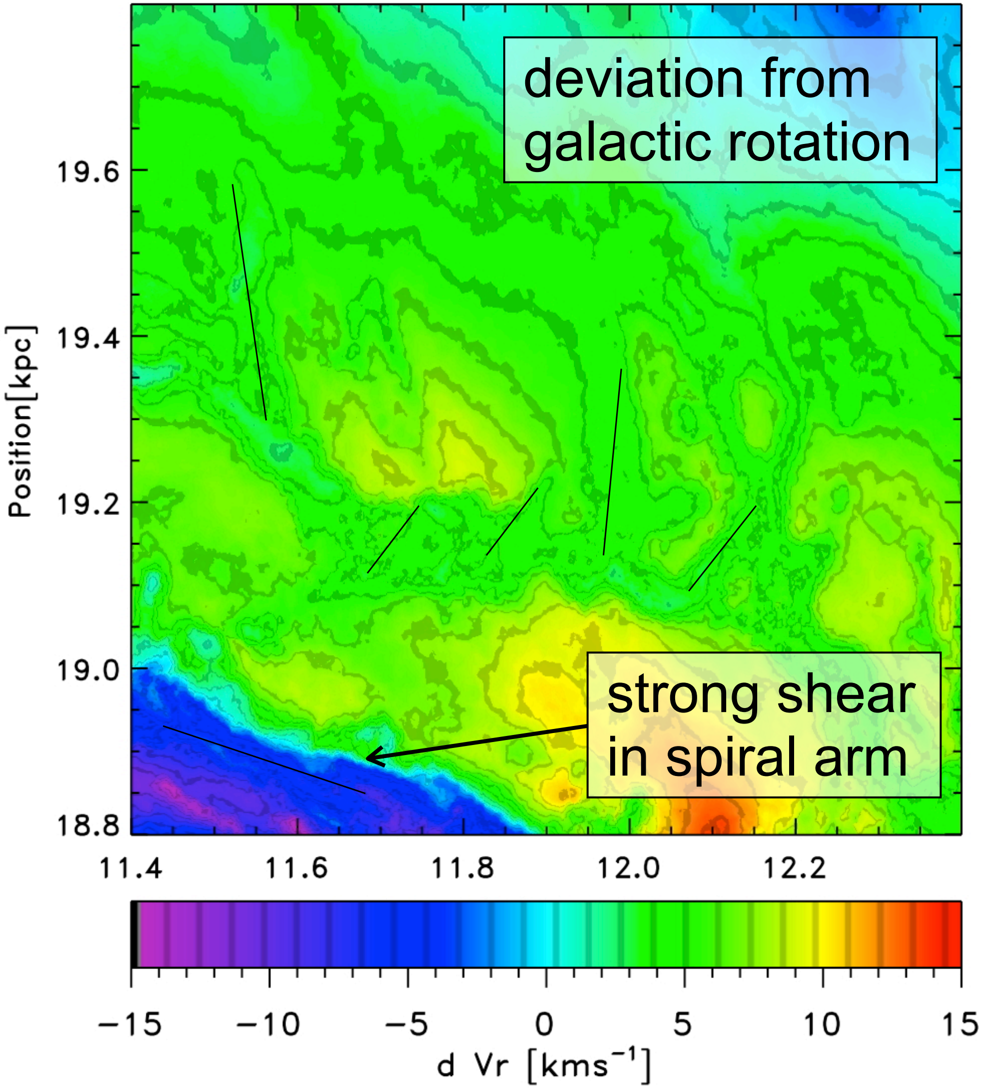




(Rowan Smith et al. in preparation)

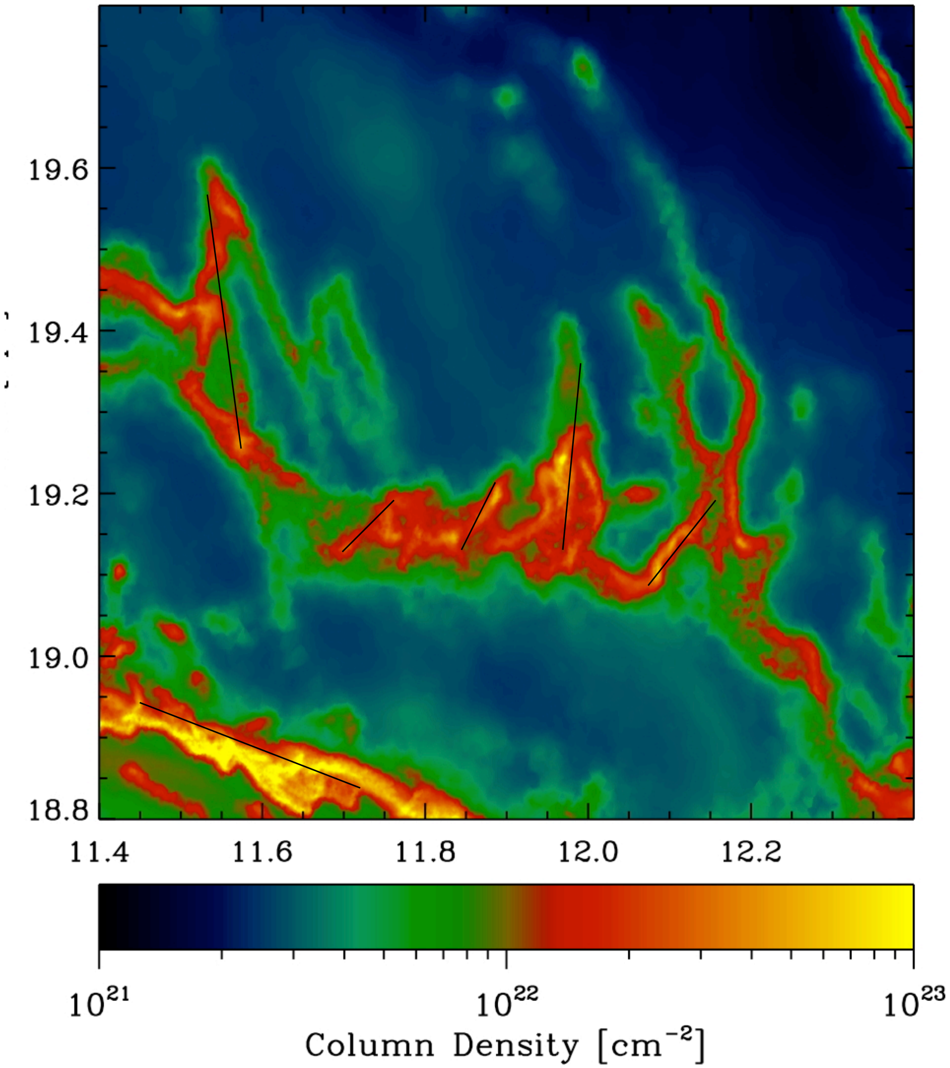
Modelling the galactic ISM dynamics

velocity


deviation from galactic rotation

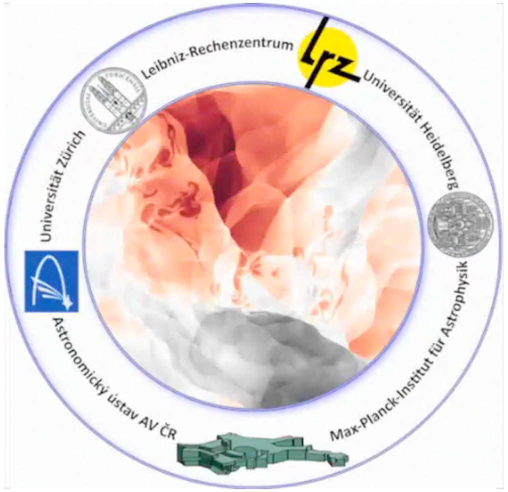
strong shear in spiral arm

density

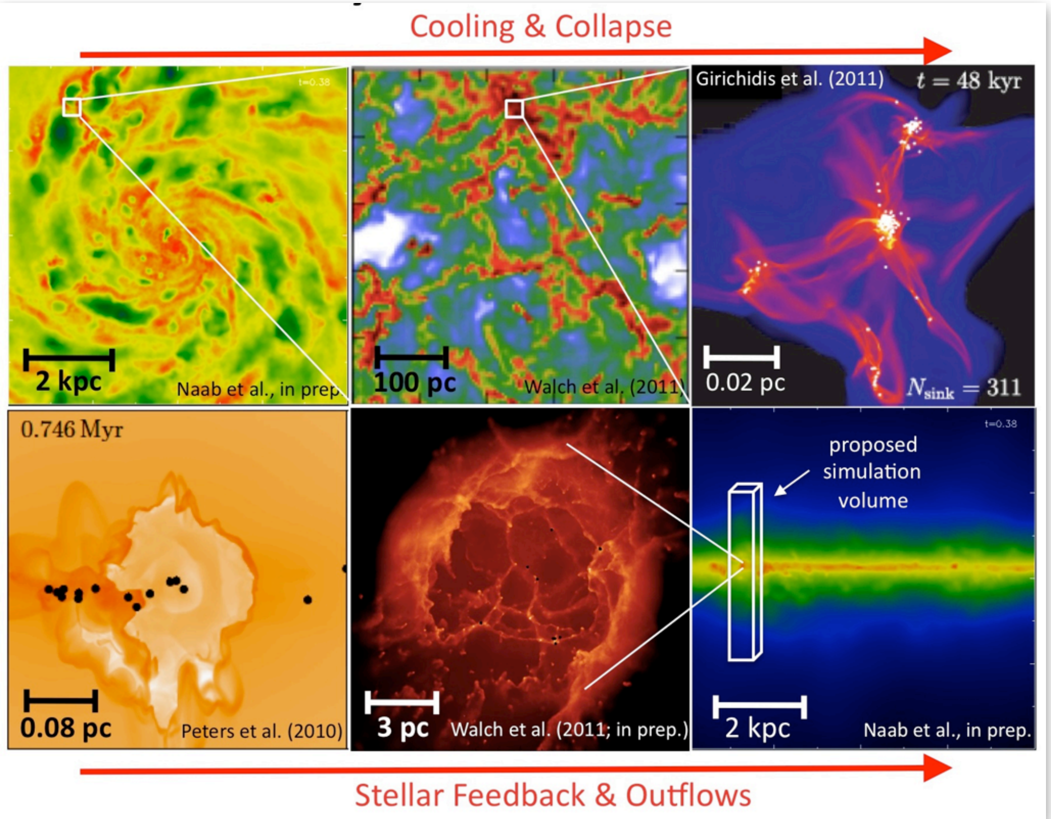


(Rowan Smith et al. in preparation)

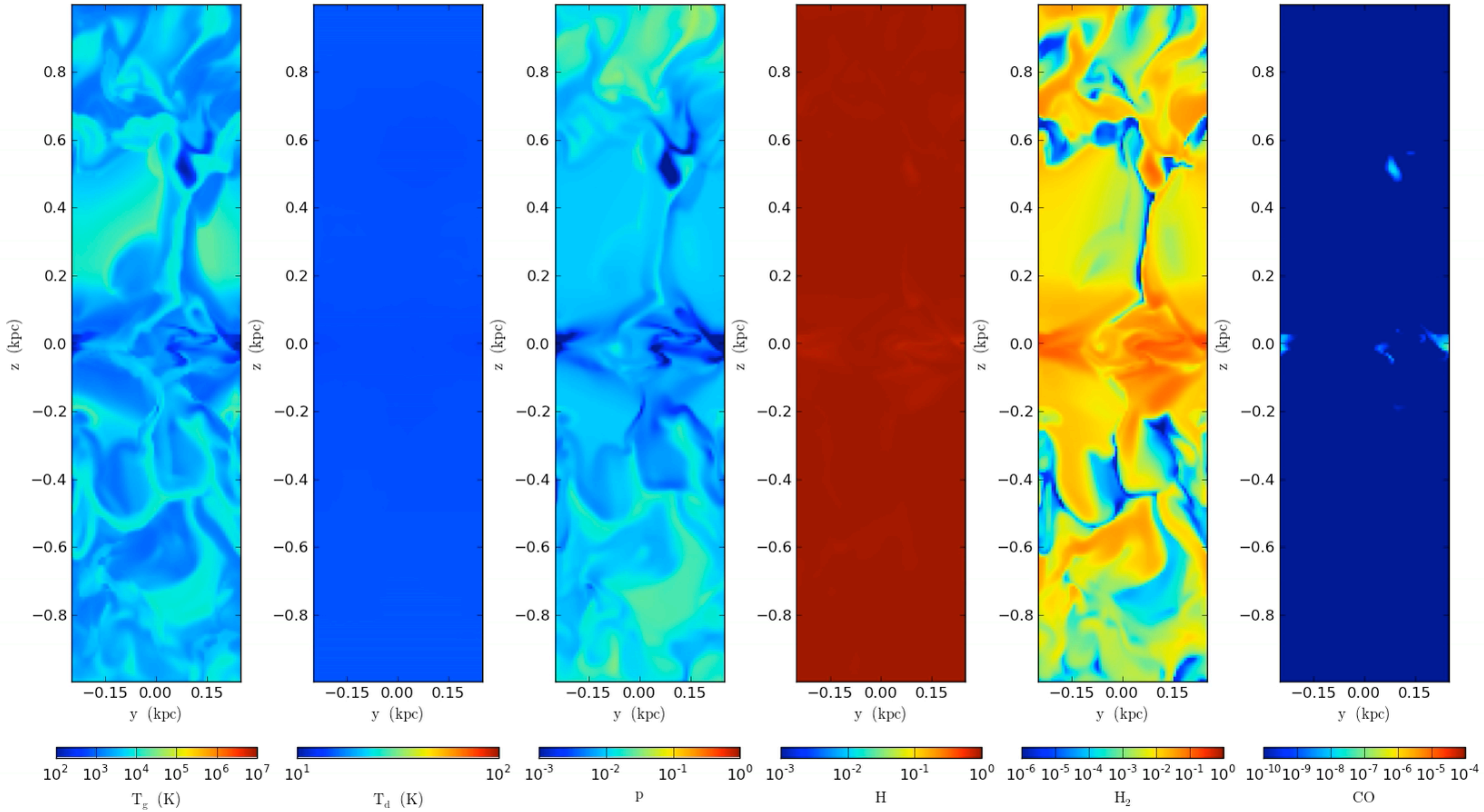
Modelling the ISM on 1 kpc scale:



- SILCC project (42 million CPU-h on Super-MUC, PI: Steffi Walch, MPA soon Cologne)
- model 1 x 1 x 4 kpc^3 region of Galactic ISM as consistently as possible
  - extremely high-resolution AMR MHD simulations (FLASH4)
  - SN driven turbulence
  - resolve star formation down to 500 AU
  - radiative + mechanical feedback from stars
  - time-dependent chemistry
  - Galactic potential
- goal is to better understand
  - formation and evolution of molecular clouds
  - larger-scale SF relations
  - Galactic fountains
  - Galactic matter cycle



Modelling the ISM on 1 kpc scale:



(Philipp Girichidis et al. in preparation)

are there “dark” clouds?

- there is increasing evidence, that a significant fraction of the H_2 gas in galaxies is not traced by CO (e.g. Pringle, Allen, Lubov 2001, Hosokawa & Inutsuka 2007, Clark et al. 2012)

- 3D simulations of colliding HI gas forming molecular clouds at the stagnation region performed by Paul Clark in Heidelberg
  - SPH (also with FLASH)
  - full fledged CO chemistry
  - TREECOL for calculating extinction
  - ‘standard’ dust model
  - sink particles to account for local collapse (star formation)
  - two models: slow and fast flow

are there “dark” clouds?

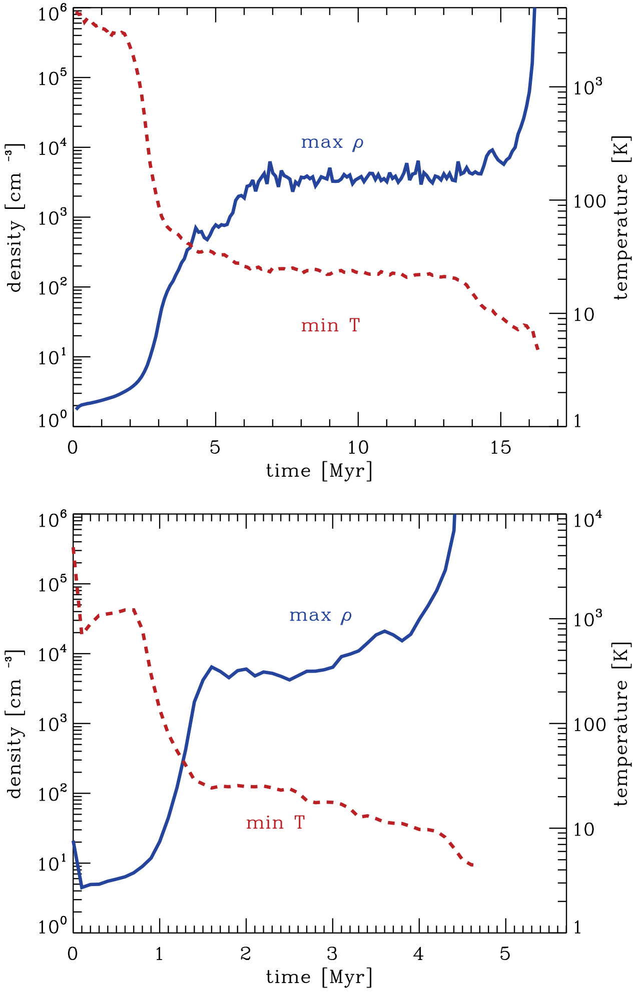
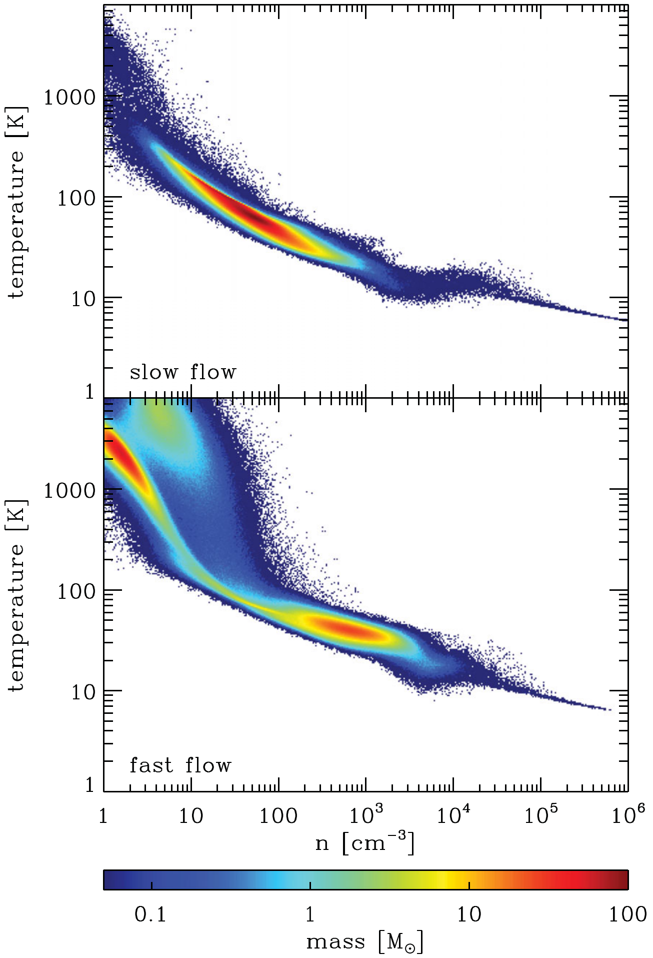


Figure 3. Evolution with time of the maximum density (blue, solid line) and minimum temperature (red, dashed line) in the slow flow (top panel) and the fast flow (bottom panel). Note that at any given instant, the coldest SPH particle is not necessarily the densest, and so the lines plotted are strictly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



slow flow

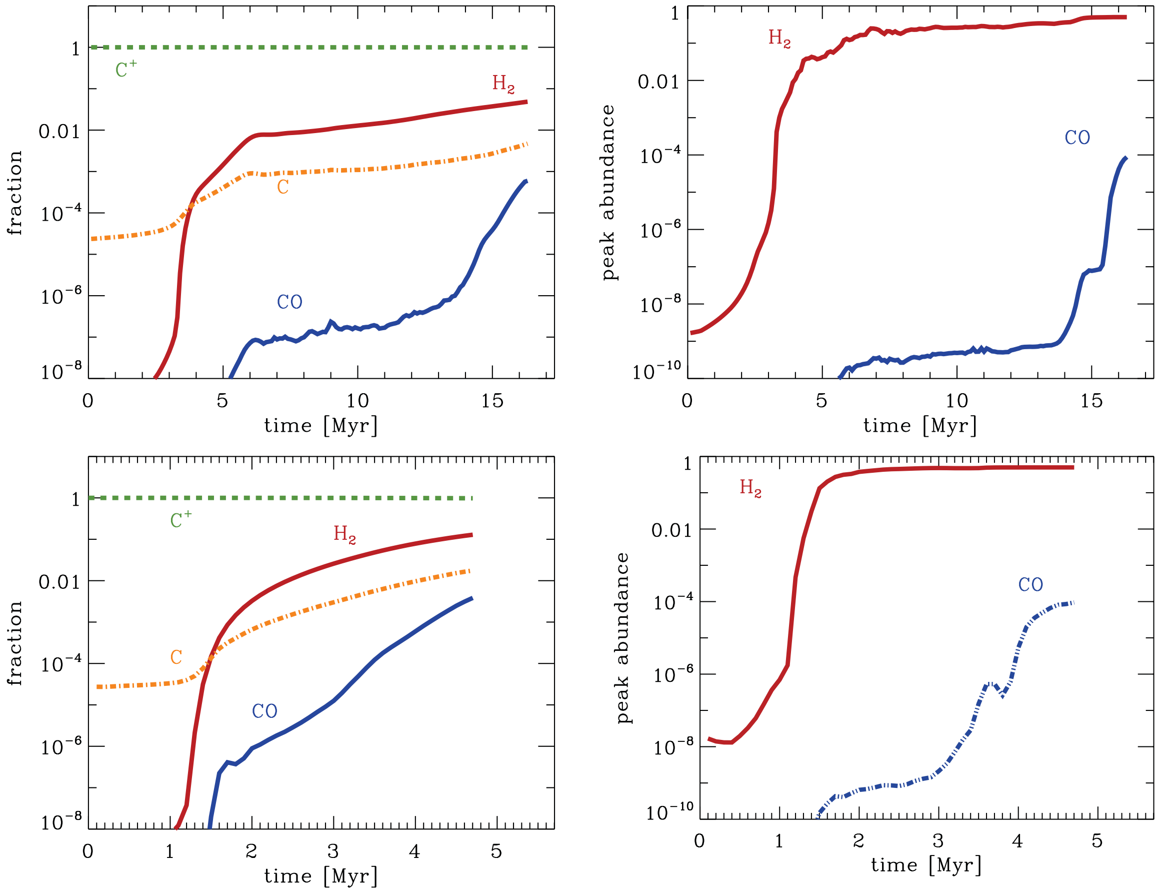
fast flow

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

Clark et al. (2012)

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

are there “dark” clouds?



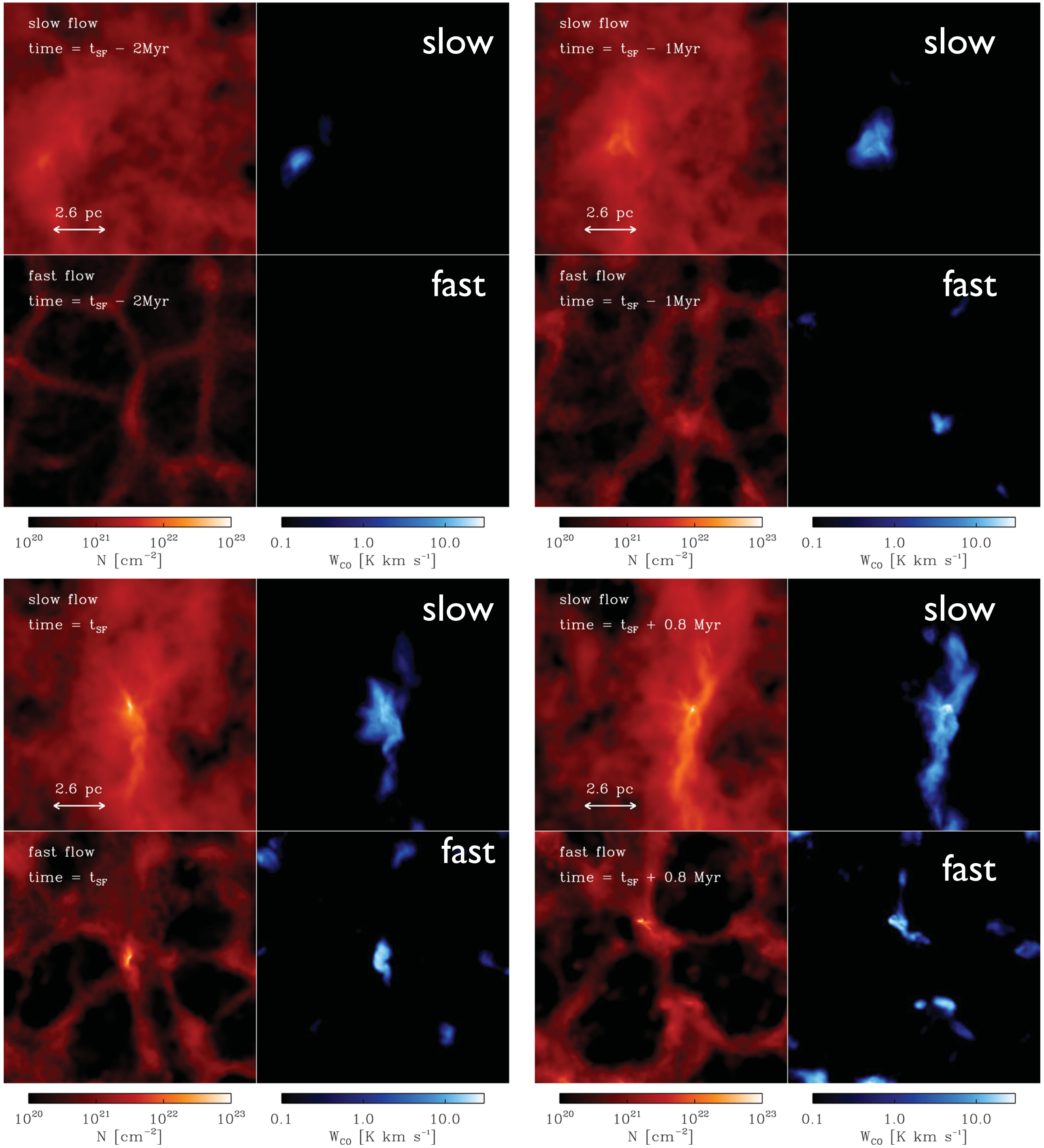
slow flow

fast flow

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)

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



H_2 column

CO emission

fraction of CO dark gas will also change with metallicity and with ambient radiation field

Clark et al. (2012)

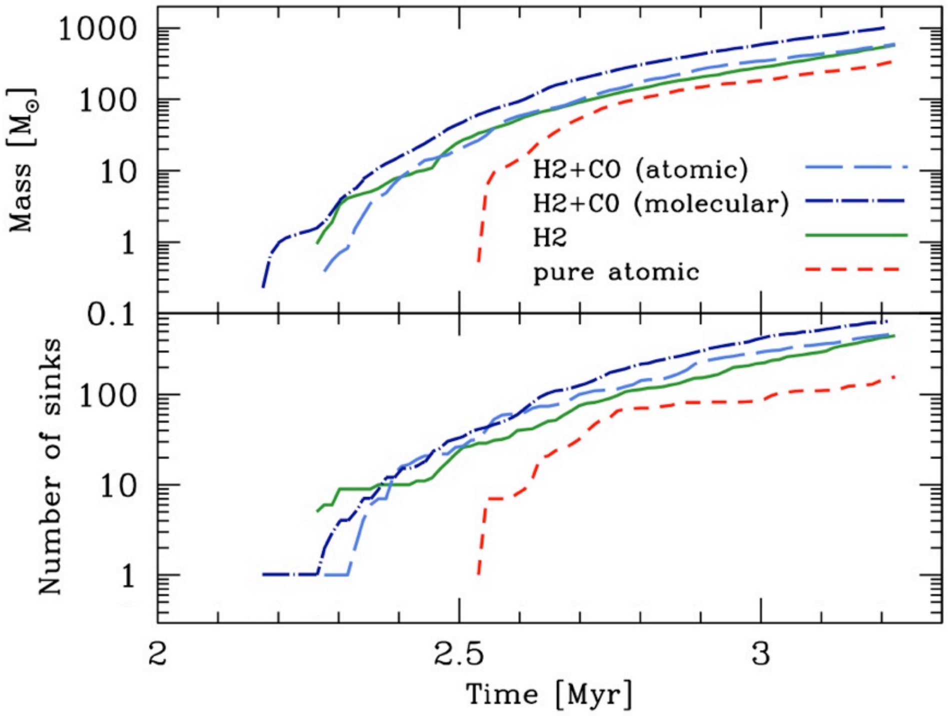
are molecules needed for star formation?

- it has been proposed that molecule formation (H_2, CO, etc.) is a prerequisite for star formation
(e.g. Schaye 2004; Krumholz & McKee 2005; Elmegreen 2007; Krumholz et al. 2009)
- the idea is that CO is a necessary coolant for collapse
- however, also C+ and C are very efficient coolants
- see what is needed for star formation, by artificially 'switching' of certain chemical pathways
(Glover & Clark 2011, 2012)

  - no shielding
  - no chemistry, gas remains atomic
  - H2 chemistry, but no CO
  - H2 and CO chemistry, hydrogen initially atomic
  - H2 and CO chemistry, hydrogen initially molecular

  - SPH (and FLASH) simulations of isolated, gravitational bound molecular cloud
  - column densities for H2 self-shielding, dust shielding determined using TreeCol (Clark et al. 2011)

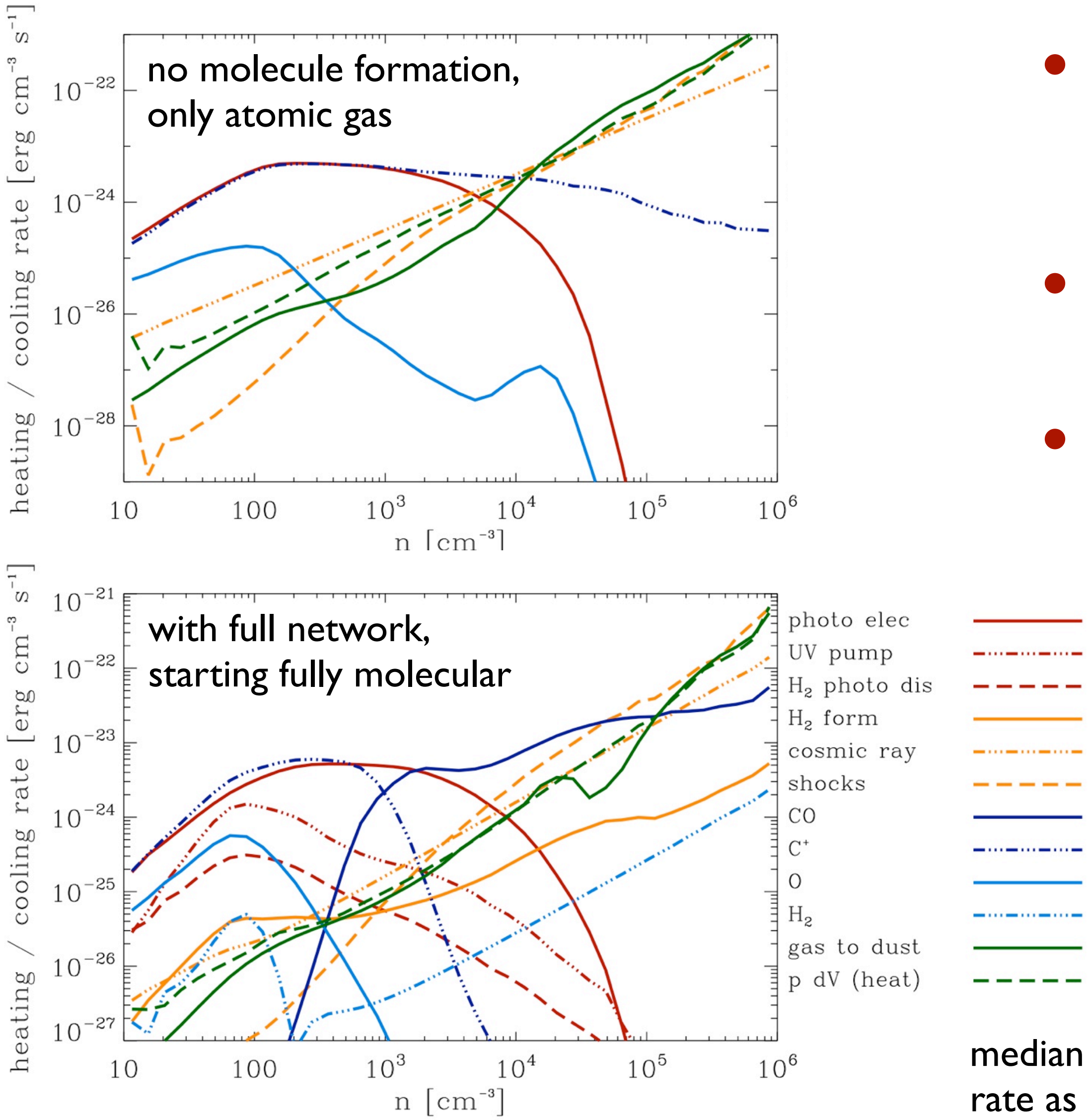
are molecules needed for star formation?



- presence of molecular gas has only very minor influence on ability of cloud to form stars

Glover & Clark (2011)

are molecules needed for star formation?

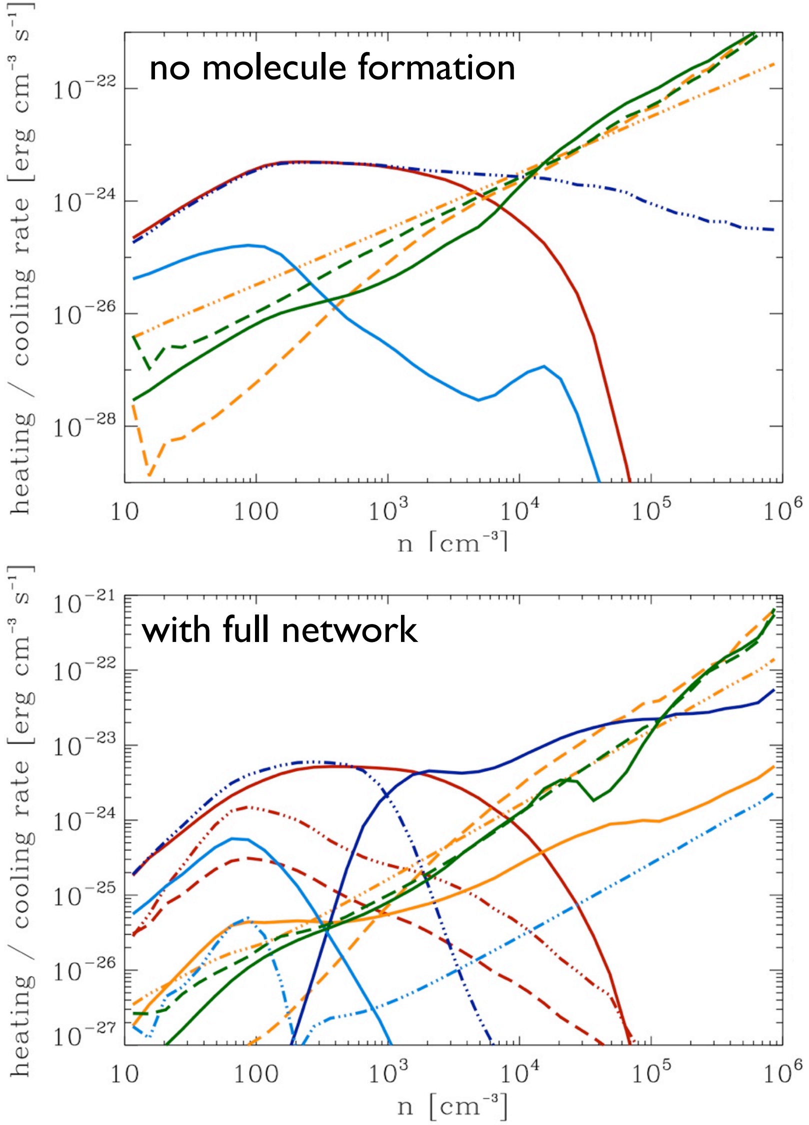


median heating and cooling rate as function of density

Glover & Clark (2011)

- presence of molecular gas has only very minor influence on ability of cloud to form stars
- C^+ is equally efficient coolant in atomic phase as CO in molecular
- shielding is important at high densities: photoelectric emission from dust grains is not longer dominant heating process

are molecules needed for star formation?

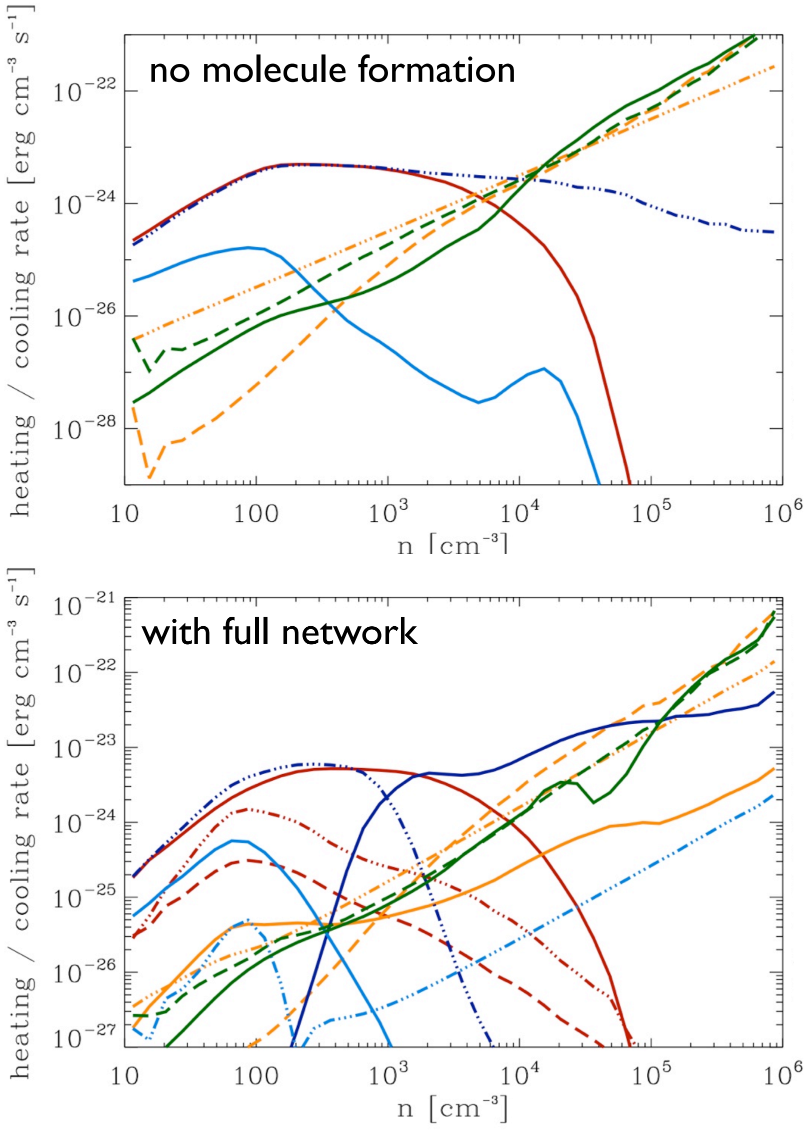


Glover & Clark (2011)

- presence of molecular gas has only very minor influence on ability of cloud to form stars
- C^+ is equally efficient coolant in atomic phase as CO in molecular
- what is crucial is the ability of cloud to shield itself from interstellar radiation field
- but clouds that are big/dense enough to shield themselves will be molecular!

this suggests that the correlation between H_2 and star formation is a coincidence

are molecules needed for star formation?



Glover & Clark (2011)

- presence of molecular gas has only very minor influence on ability of cloud to form stars
- C^+ is equally efficient coolant in atomic phase as CO in molecular
- what is crucial is the ability of cloud to shield itself from interstellar radiation field
- but clouds that are big/dense enough to shield themselves will be molecular!

more important is *extinction* (this introduces metallicity dependence)

metallicity dependence

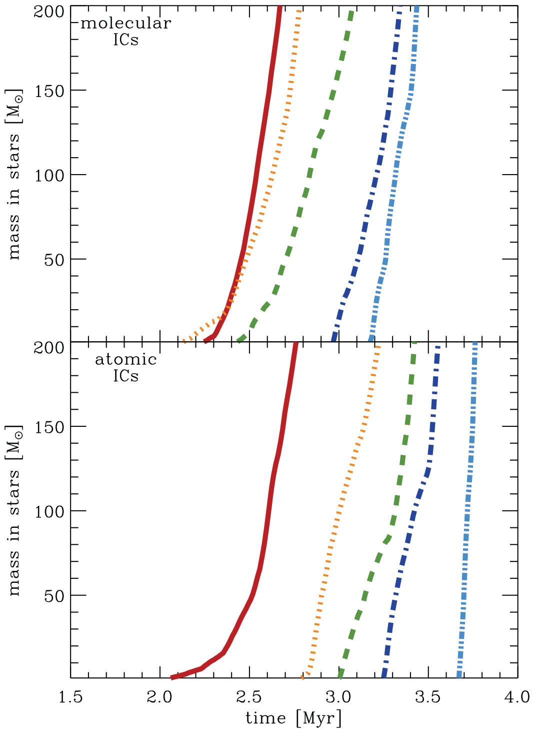
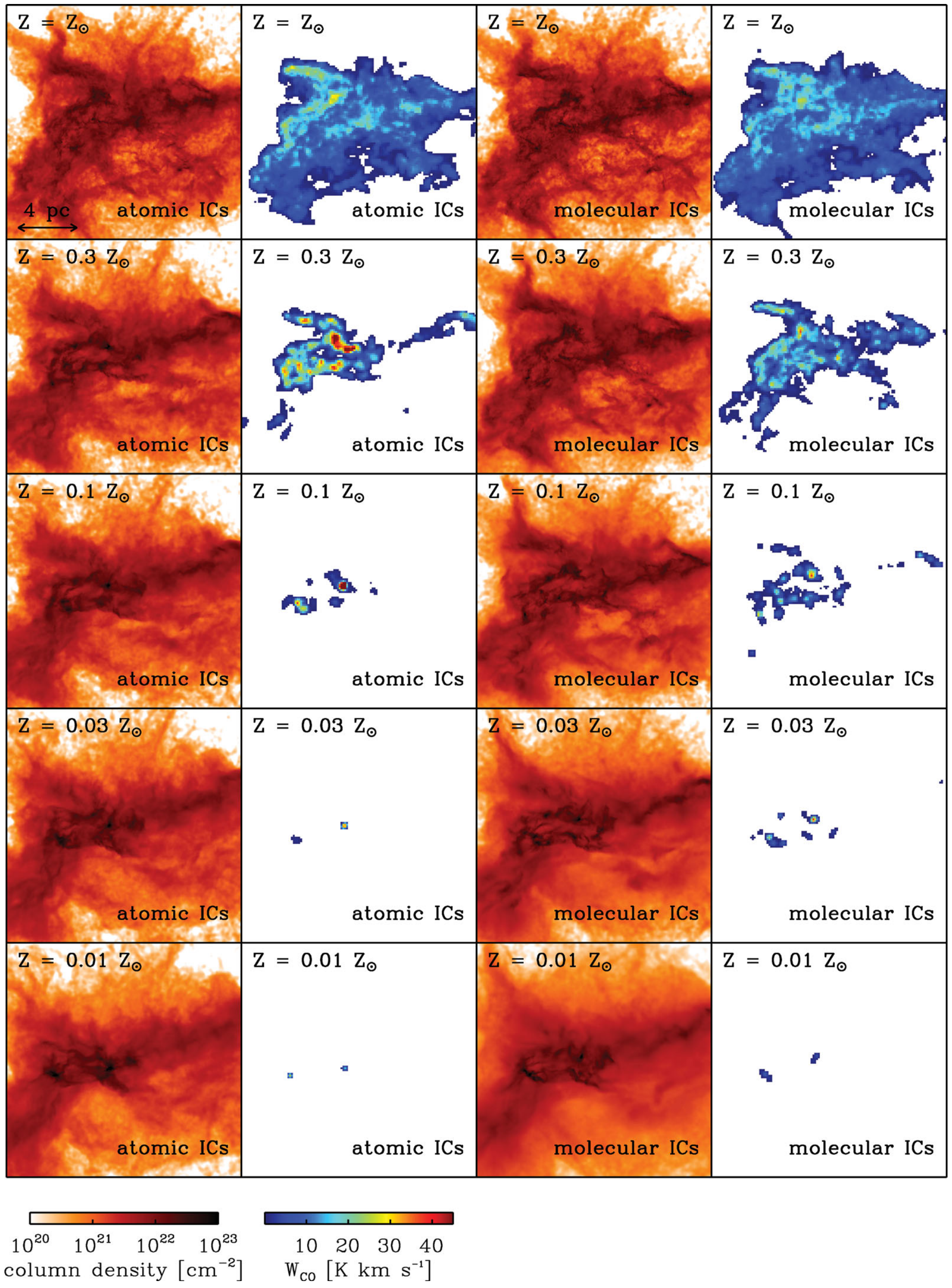


Figure 1. Upper panel: mass in sinks, plotted as a function of time, for runs Z1-M (solid line), Z03-M (dotted line), Z01-M (dashed line), Z003-M (dot–dashed line) and Z001-M (double-dot–dashed line). In these runs, hydrogen was initially in fully molecular form. Lower panel: the same quantity, but for runs Z1-A (solid line), Z03-A (dotted line), Z01-A (dashed line), Z003-A (dot–dashed line) and Z001-A (double-dot–dashed line). In these runs, hydrogen was initially fully atomic.



1.0

0.3

0.1

0.03

0.01

Figure 5. Maps of column density (first and third columns) and integrated intensity in the $J = 1$–0 rotational transition of ^{12}CO (second and fourth columns) for each of the simulations. The maps show a region of side length 16.2 pc that includes roughly 80 per cent of the total cloud mass, but almost all of the CO emission. The CO integrated intensity maps were produced using the RADMC-3D radiative transfer code, as described in the text.

Glover & Clark (2012)

BUT: at low metallicities, H2 and HD cooling may indeed matter!

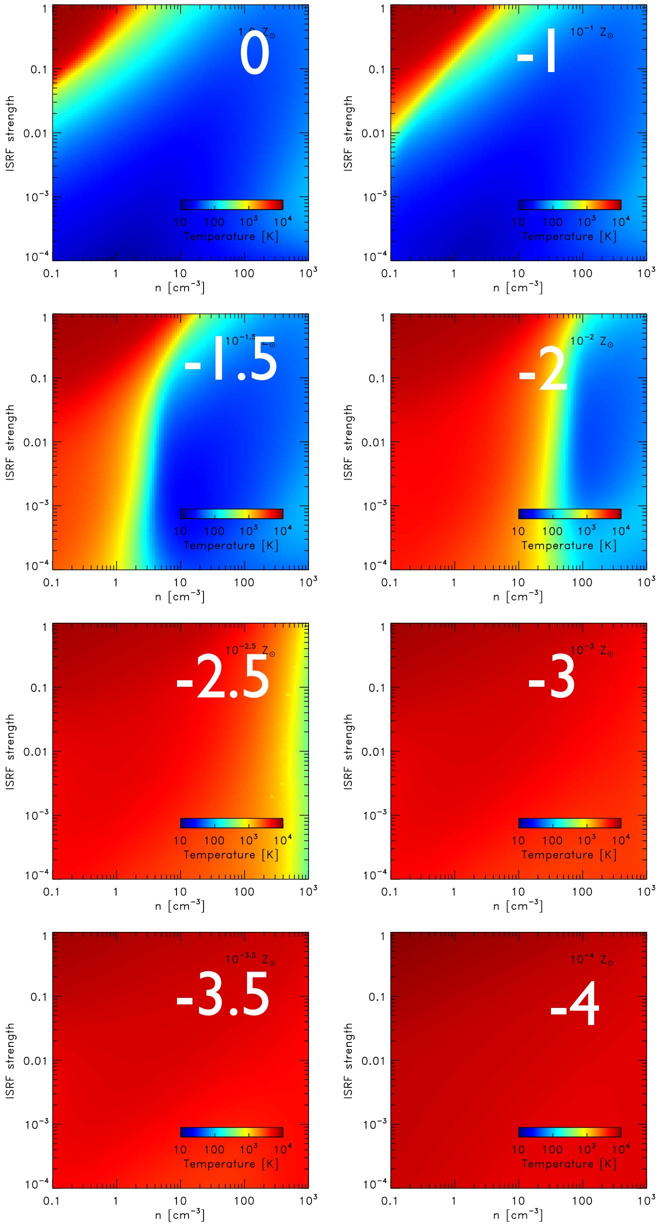


Figure 1. Gas temperature at $t = t_{\rm ff}$, computed as a function of the number density of hydrogen nuclei, n, and the strength of the interstellar radiation field in units of the standard value, G_0, for a set of runs covering a range of metallicities between $Z = Z_\odot$ and $Z = 10^{-4}$ Z$_\odot$. In these runs, the effects of H_2 and HD cooling were not included.

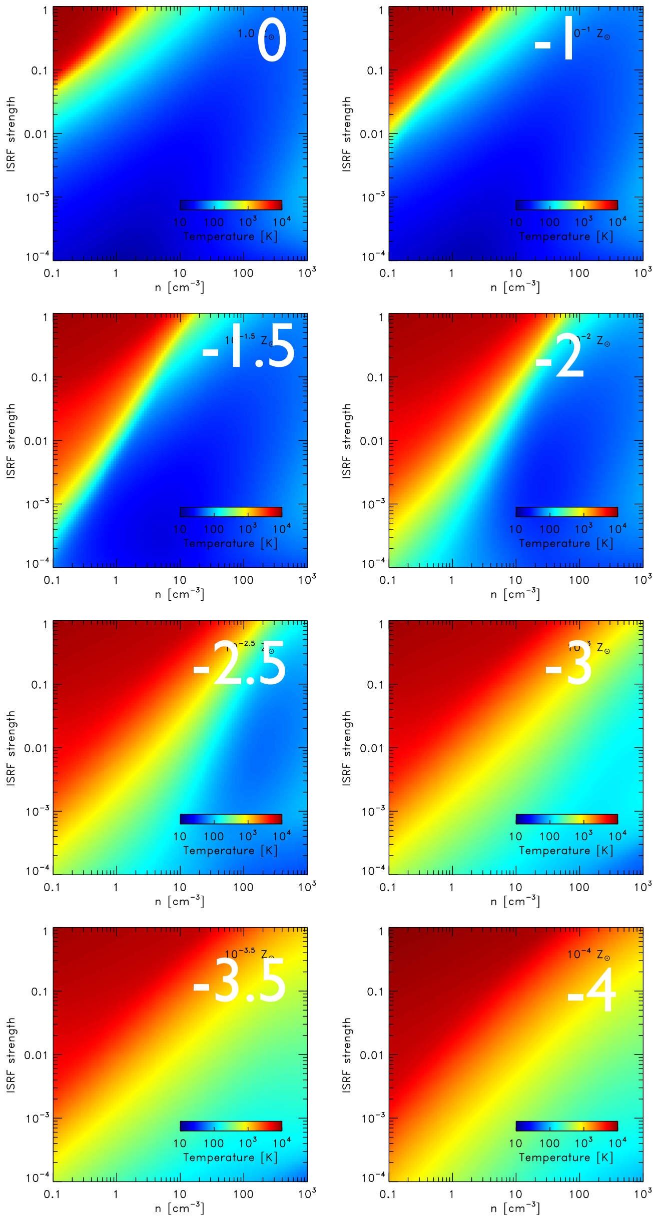
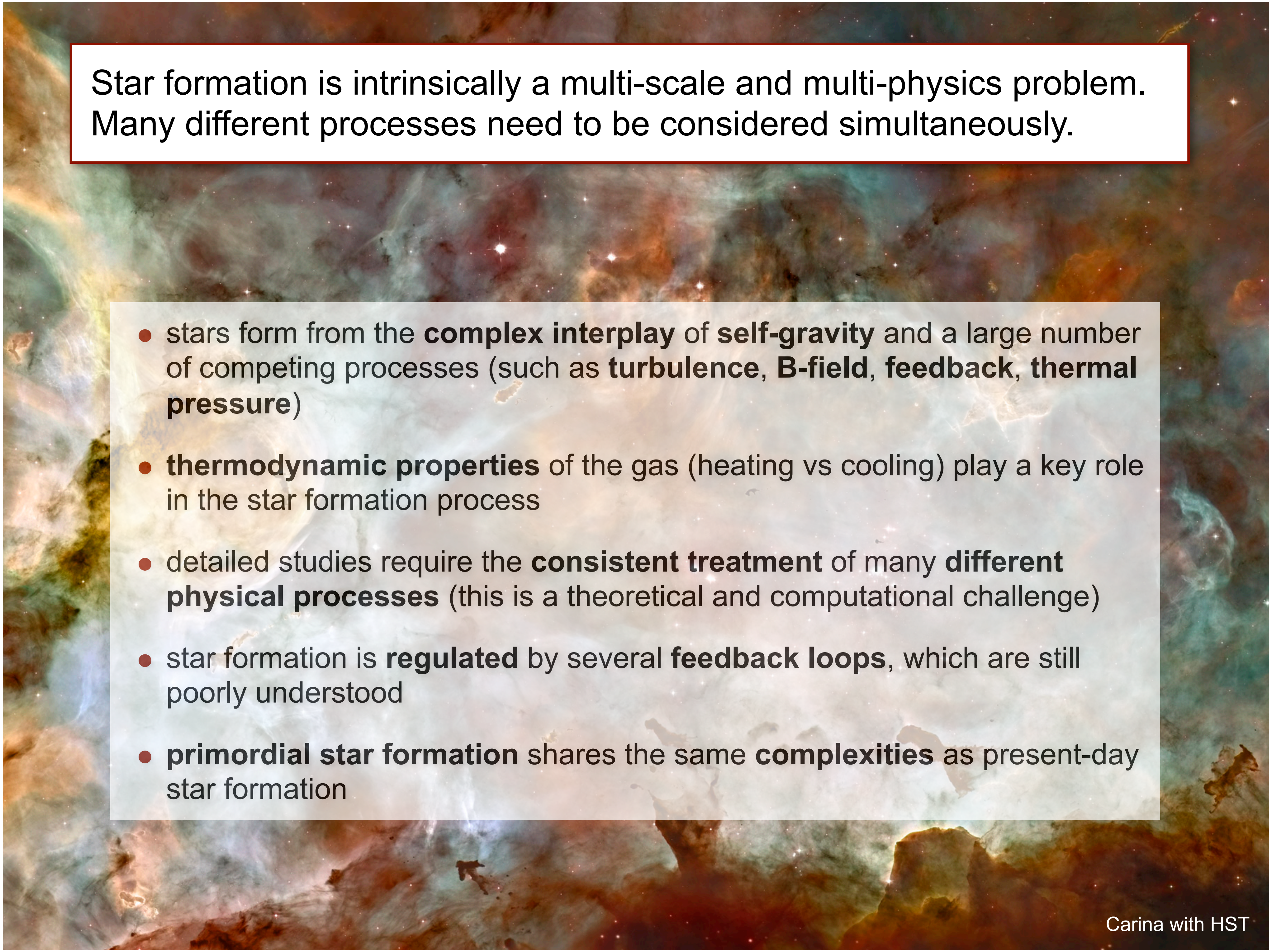


Figure 2. As Figure 1, but for a set of runs that included the effects of H_2 and HD cooling.

Glover & Clark (2013)


Carina with HST

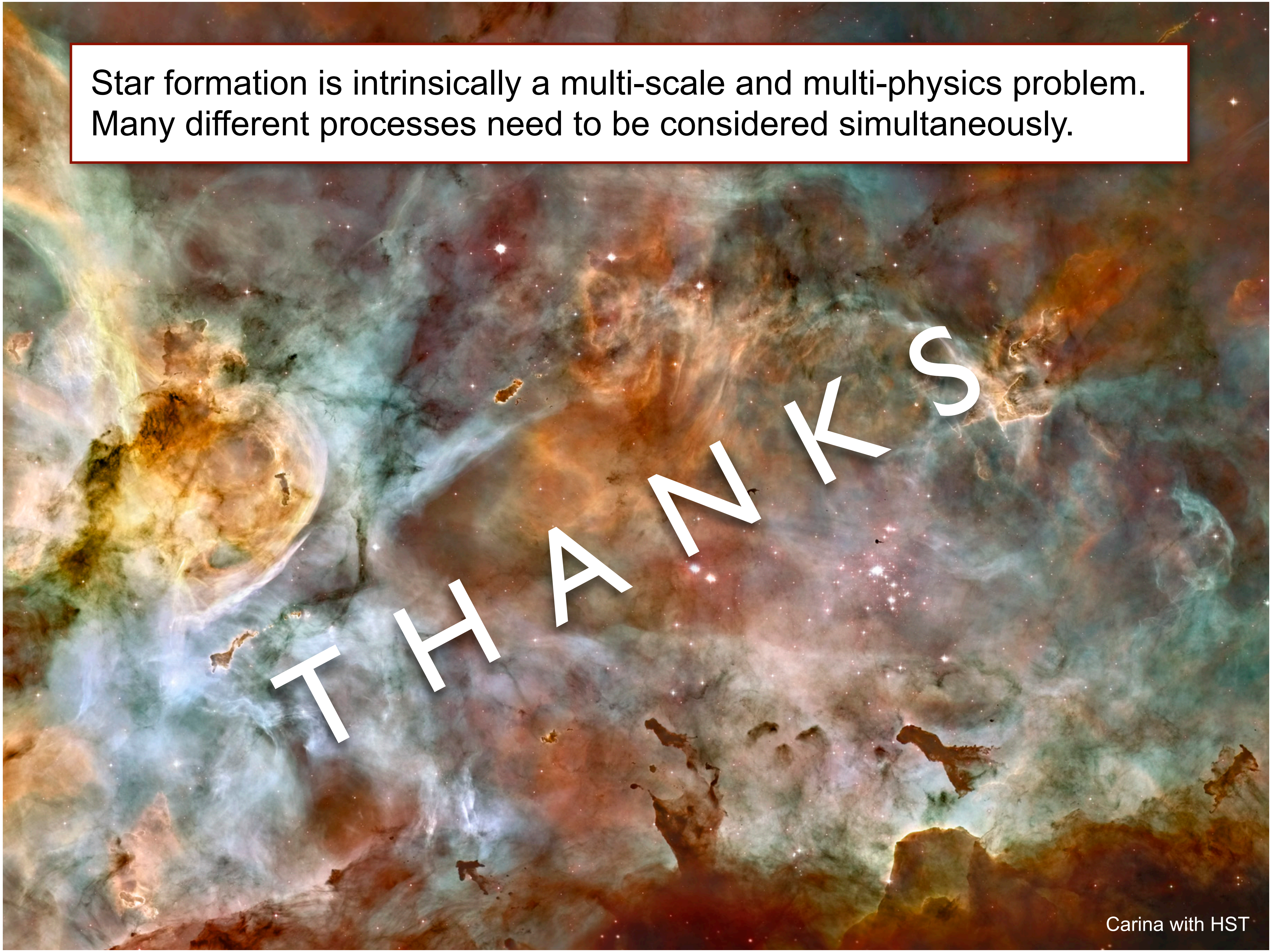
Star formation is intrinsically a multi-scale and multi-physics problem.
Many different processes need to be considered simultaneously.



- stars form from the **complex interplay** of **self-gravity** and a large number of competing processes (such as **turbulence**, **B-field**, **feedback**, **thermal pressure**)
- **thermodynamic properties** of the gas (heating vs cooling) play a key role in the star formation process
- detailed studies require the **consistent treatment** of many **different physical processes** (this is a theoretical and computational challenge)
- star formation is **regulated** by several **feedback loops**, which are still poorly understood
- **primordial star formation** shares the same **complexities** as present-day star formation

Carina with HST

Star formation is intrinsically a multi-scale and multi-physics problem. Many different processes need to be considered simultaneously.



THANKS

Carina with HST