3rd Chinese German
Star Formation Meeting

ISM Dynamics and Star Formation

Ralf Klessen

Zentrum für Astronomie der Universität Heidelberg
Institut für Theoretische Astrophysik

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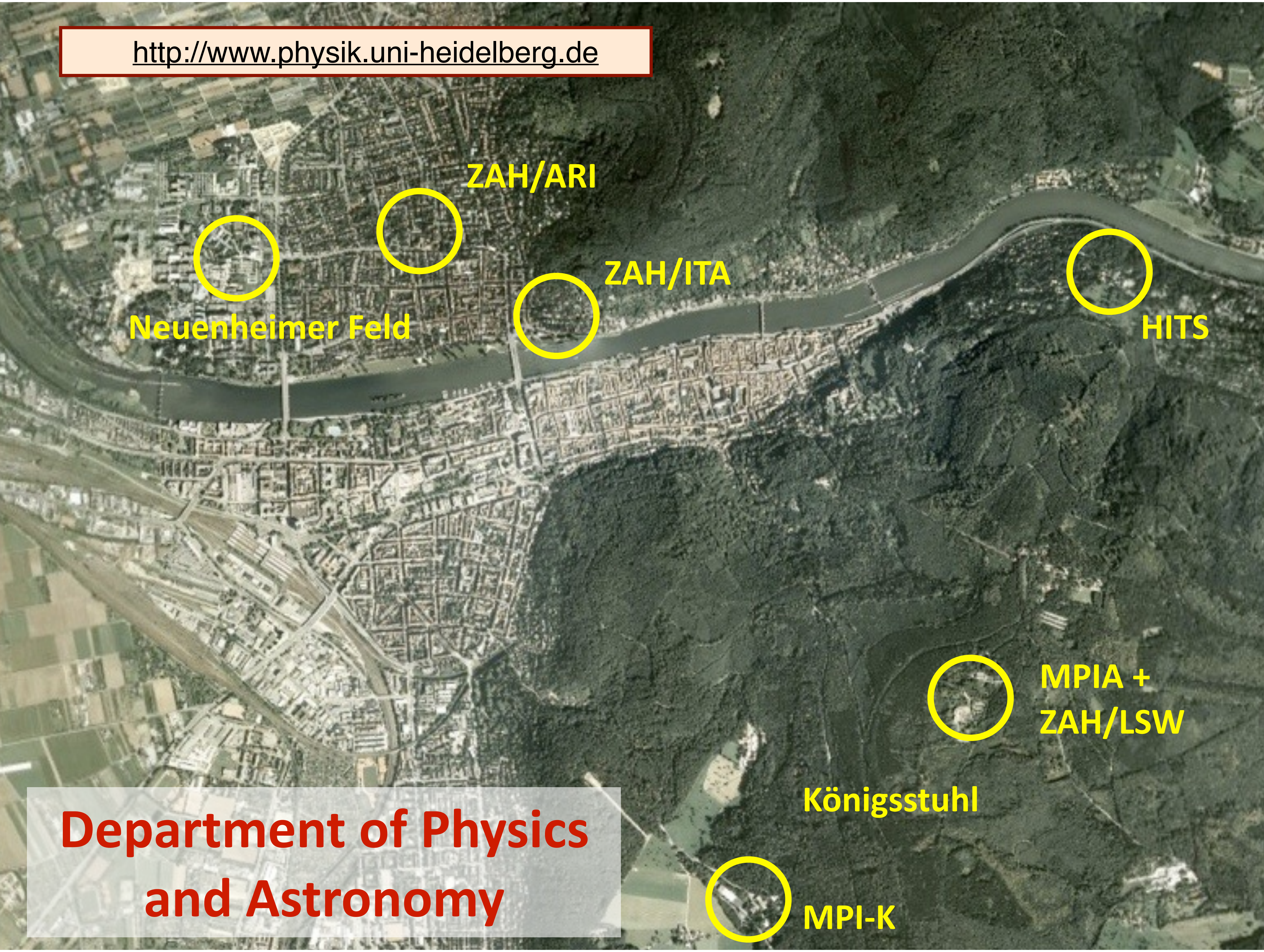
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http://www.ita.uni-heidelberg.de/research/klessen/index.shtml

Institut für Theoretische Astrophysik

ITA

Matthias Bartelmann
(cosmology, lensing)

Cornelis Dullemond
(planet formation, accretion disks)

Ralf Klessen
(star formation, ISM dynamics)

Björn-Malte Schäfer
(cosmology, lensing)

http://www.ita.uni-heidelberg.de/research/klessen/index.shtml

University > ZAH > ITA > Research >

Star-Formation Group

We work on different aspects of star formation in the Galaxy as well as in the early universe. We study interstellar turbulence and formation and evolution of molecular clouds. We are also interested in the dynamical evolution of the Milky Way and its satellite galaxies. As our work relies heavily on computer simulations, we also work on developing and improving numerical methods for astrophysics.

Group Members

Head:	Ralf S. Klessen
Scientific Staff:	Simon C. O. Glover
Emmy Noether Group Leader:	Frank Bigiel
Postdocs:	*Daniel Ceverino (starting December 2015)* Diane Cormier (Emmy Noether Group) Dimitrios Gouliermis Sacha Hony (long term guest) Jan-Pieter Paardekooper *Eric Pellegrini (starting June 2015)* *Stefan Reißl (starting August 2015)* Jennifer Schober Daniel Whalen
PhD Students:	Christian Baczynski Erik Bertram Carla June Carroll Juan Ibanez Mejia (mostly AMNH, New York) Anna Schauer Katharina Wollenberg
BSc / MSc Students:	Andre Bubel Mattis Magg Robin Gopala Treb

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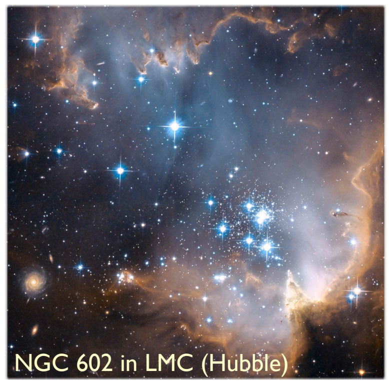
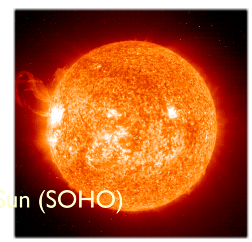
decrease in spatial scale / increase in density


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 x 10^{10} cm

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decrease in spatial scale / increase in density


Andromeda (R. Gendler)


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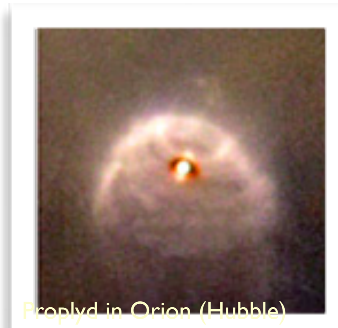
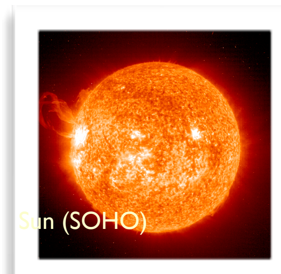
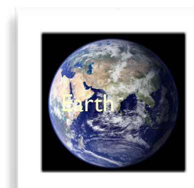

Proplyd in Orion (Hubble)


Sun (SOHO)

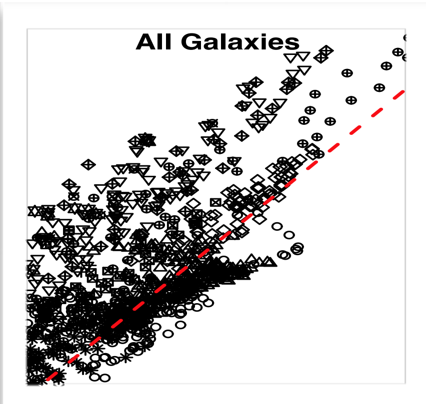

Earth

- 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*

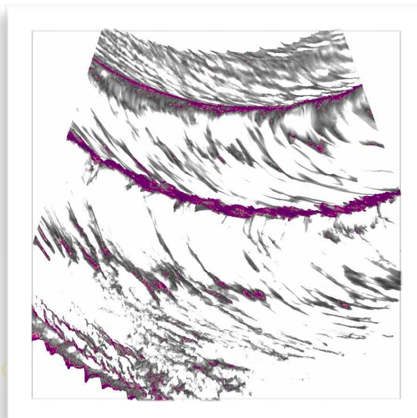
Modern star formation theory is based on the complex interplay between *all* these processes.

http://www.ita.uni-heidelberg.de/research/klessen/index.shtml

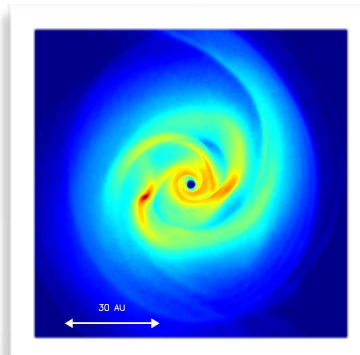
decrease in spatial scale / increase in density



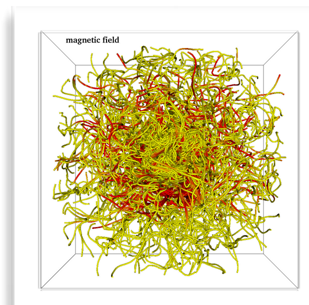
galactic scale star formation relations
(with Bigiel etc.)



ISM dynamics and chemistry
(with Glover, etc.)



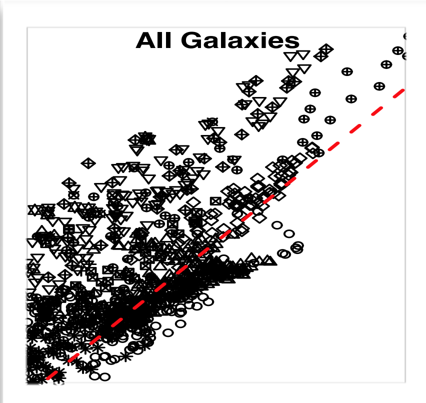
primordial star formation
(with Glover, Whalen, Paardekooper, ERC team)



turbulence and magnetic fields dynamics
(with Schober, etc.)

http://www.ita.uni-heidelberg.de/research/klessen/index.shtml

decrease in spatial scale / increase in density



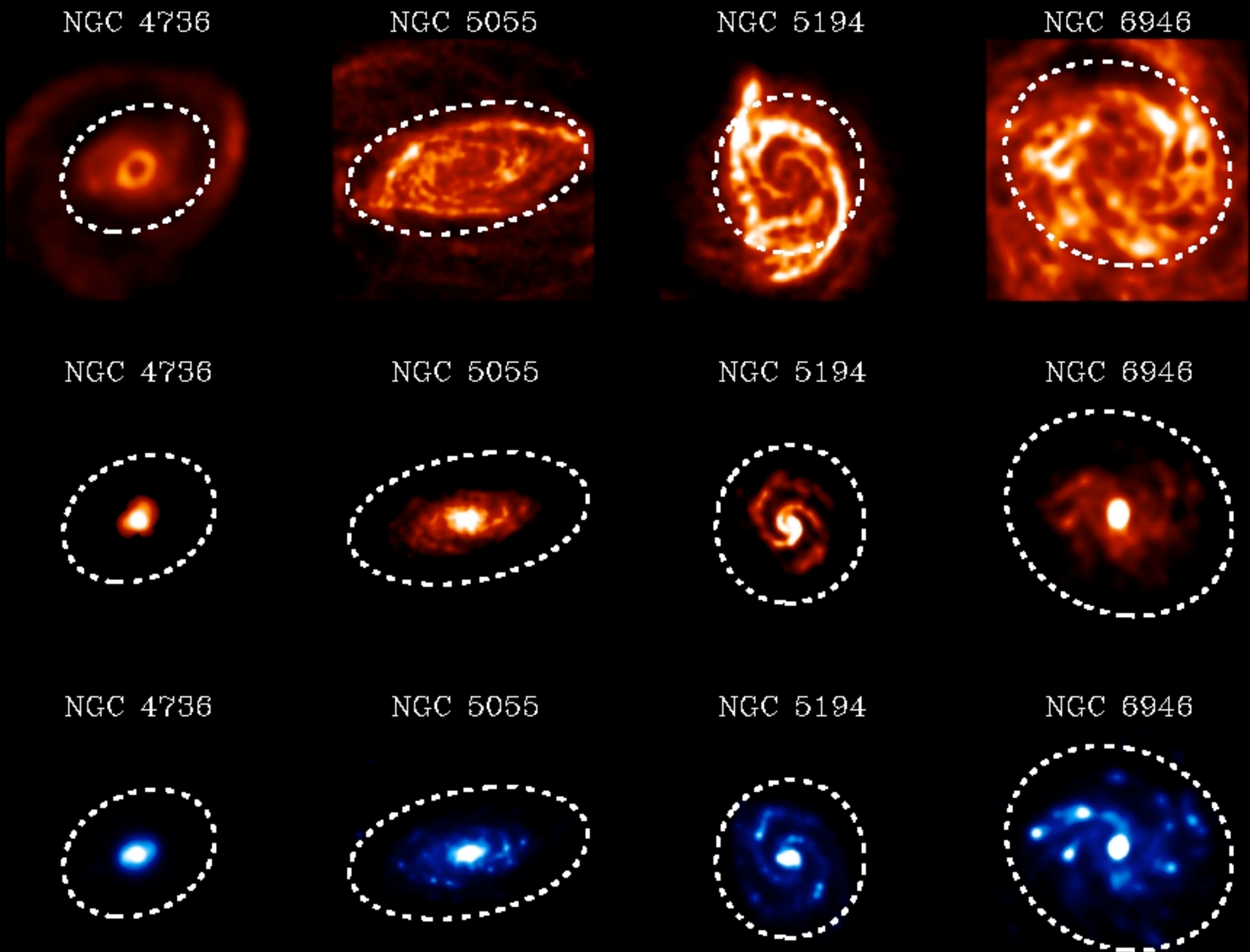
galactic scale star formation relations
(with Shetty, Bigiel, etc.)

ISM dynamics and chemistry
(with Glover, Smith, Clark, etc.)

primordial star formation
(with Glover, soon Whalen, Paardekooper, ERC team)

turbulence and magnetic fields dynamics
(with Konstandin, Schober, etc.)

global SF relations



atomic hydrogen

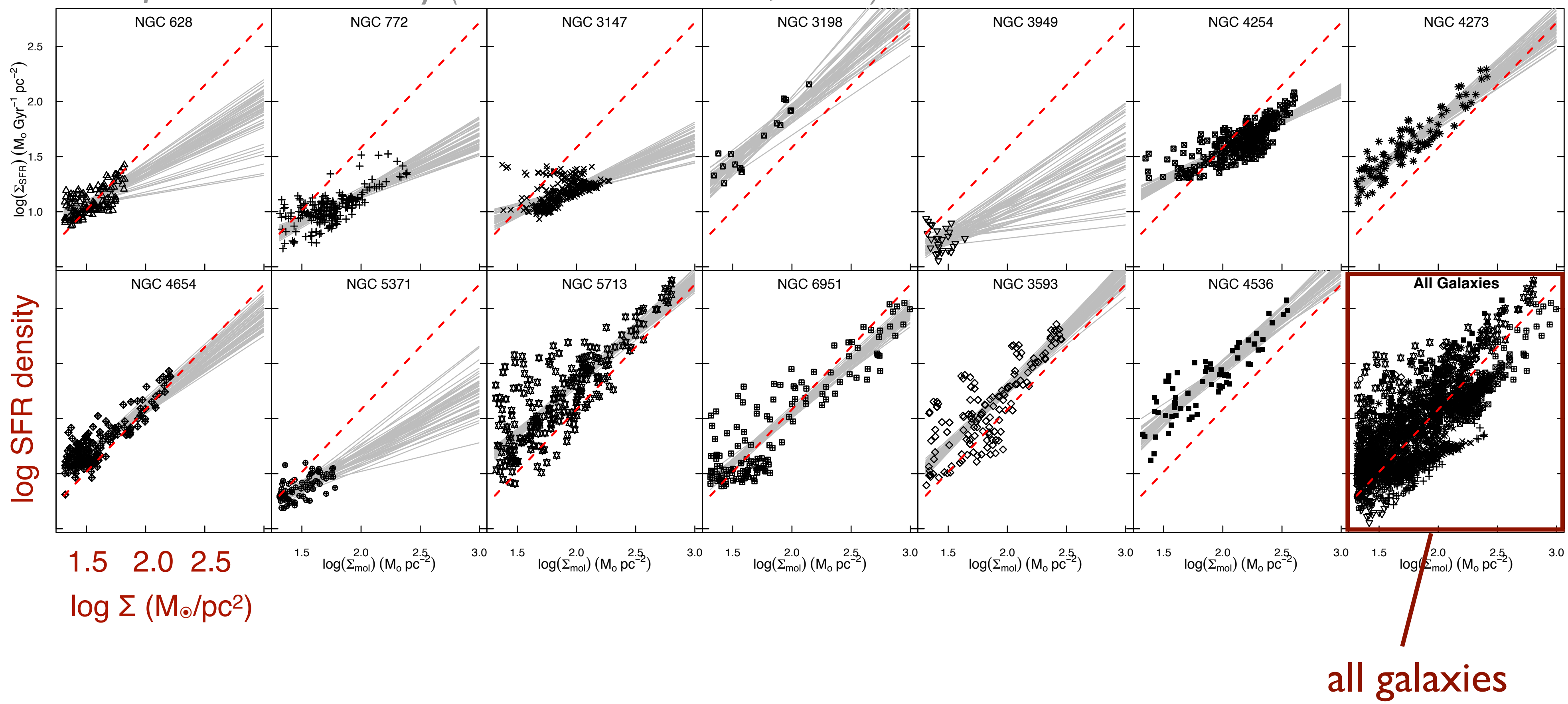
molecular hydrogen

star formation

- HI gas more extended
- H2 and SF well correlated

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

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



- QUIZ: do you see a universal
- ANSWER: - probably not

  - in addition, the relation often is sublinear

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

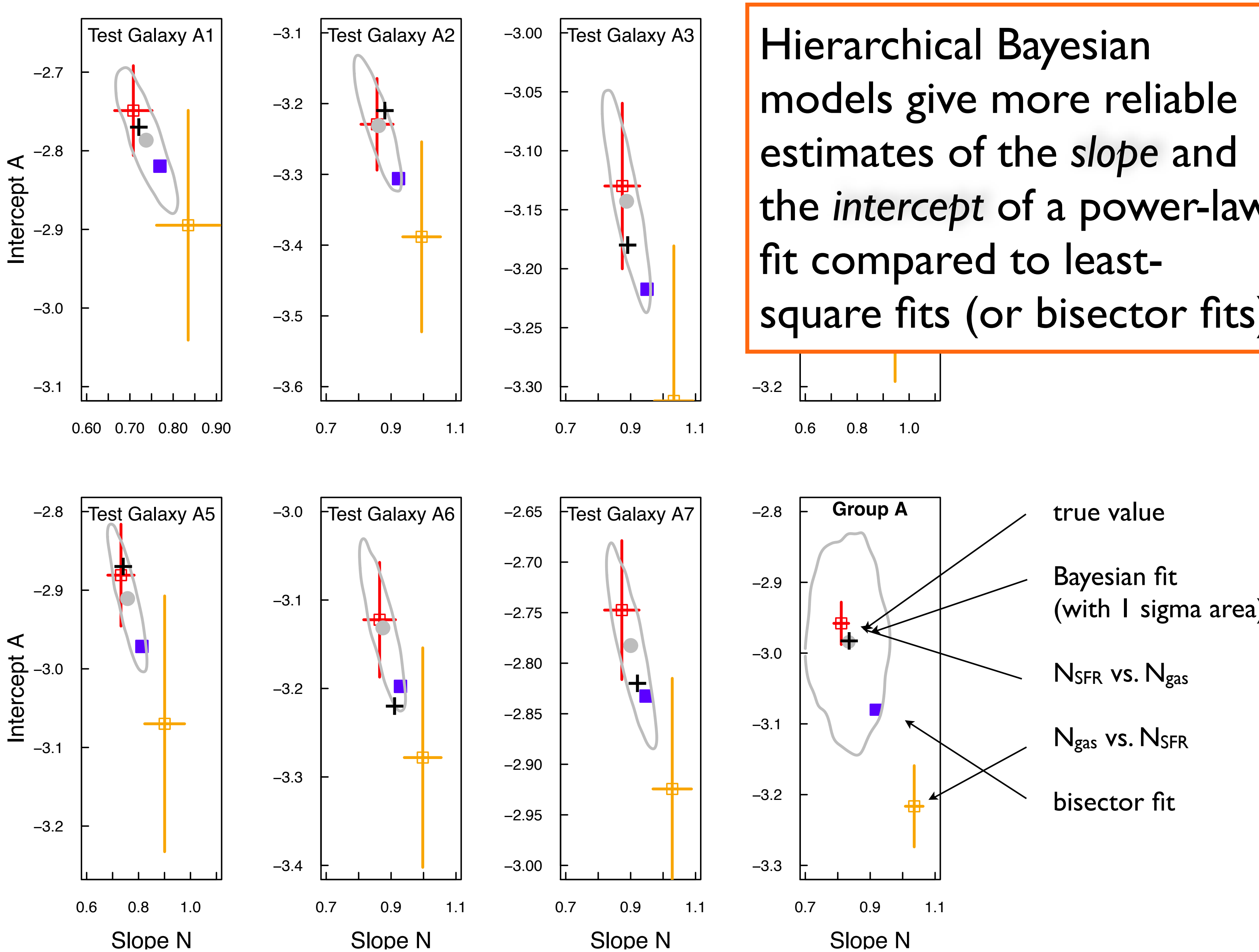
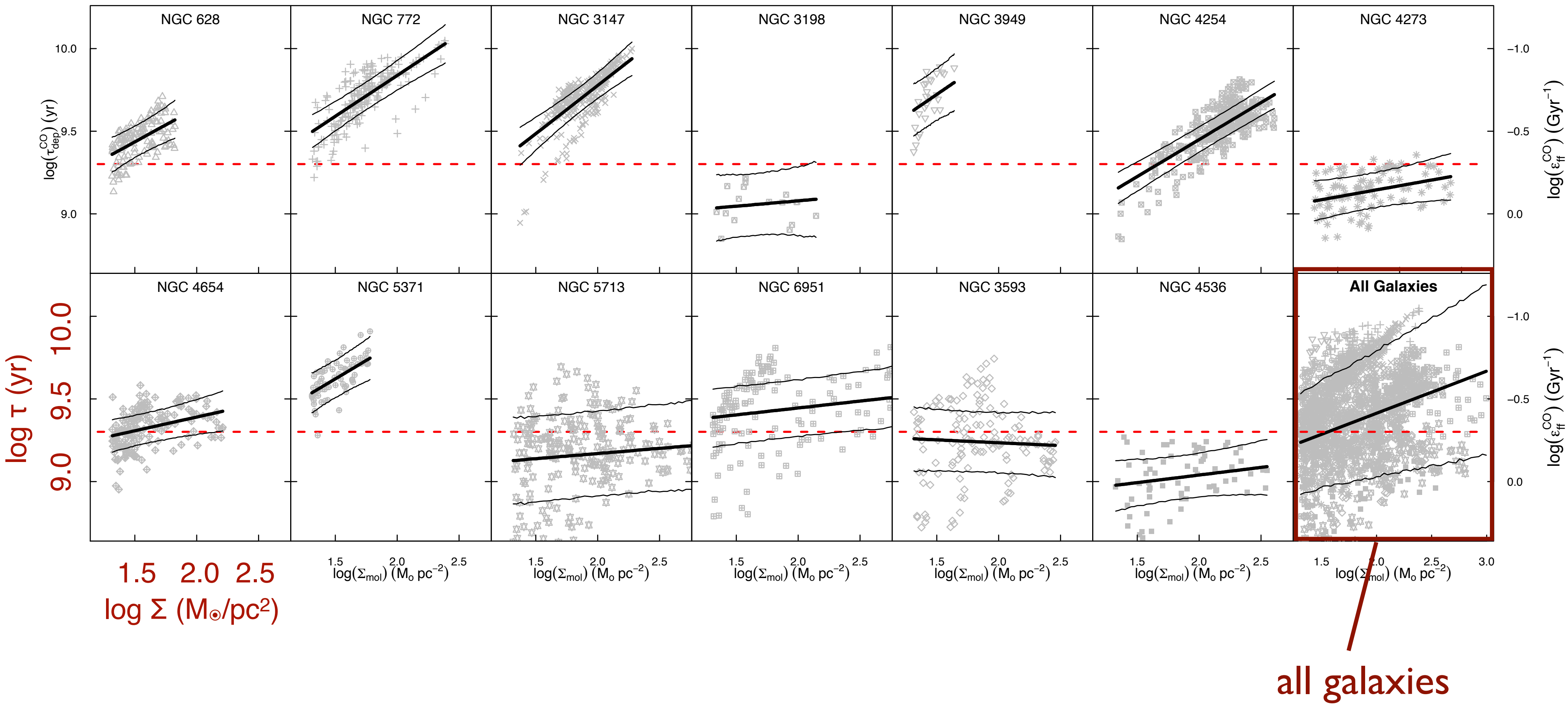


Figure 1. Slope and intercept of test galaxies in Group A. Black cross shows the true values. Red and orange squares show the OLS($\Sigma_{\rm SFR}|\Sigma_{\rm mol}$) and OLS($\Sigma_{\rm mol}|\Sigma_{\rm SFR}$) results, with their 1σ uncertainties, respectively. The gray circles indicate the estimate 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)

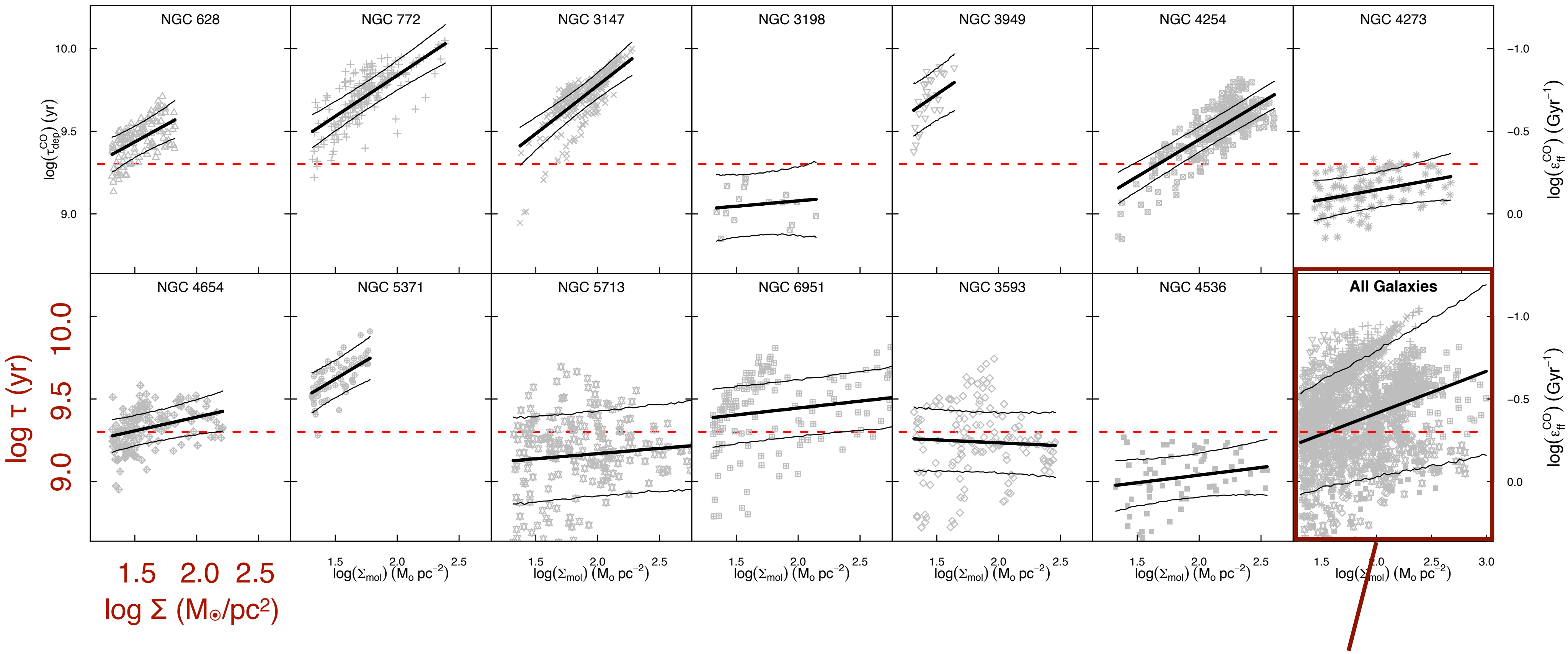
data from STING survey (Rahman et al. 2011, 2012)



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

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

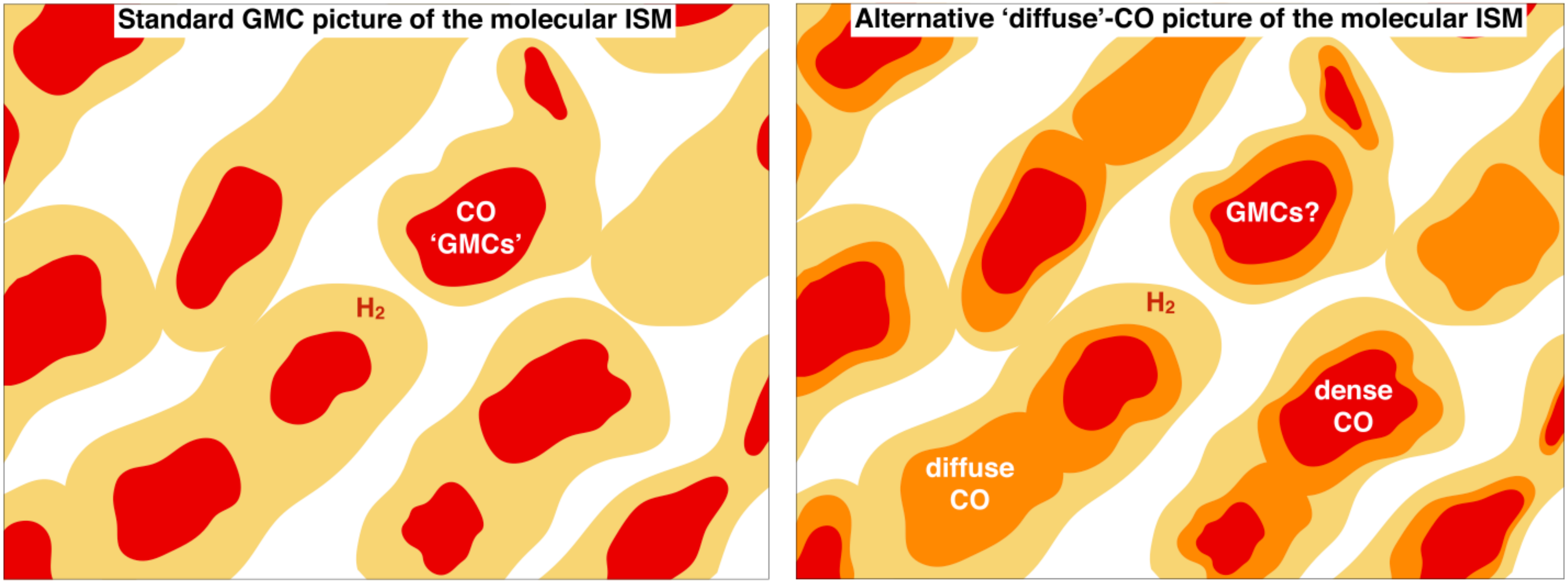
data from STING survey (Rahman et al. 2011, 2012)



physical origin of this behavior?

- maybe strong shear in dense arms (example M51, Meidt et al. 2013)...
- maybe non-star forming H
  densities (recall H

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



in addition:

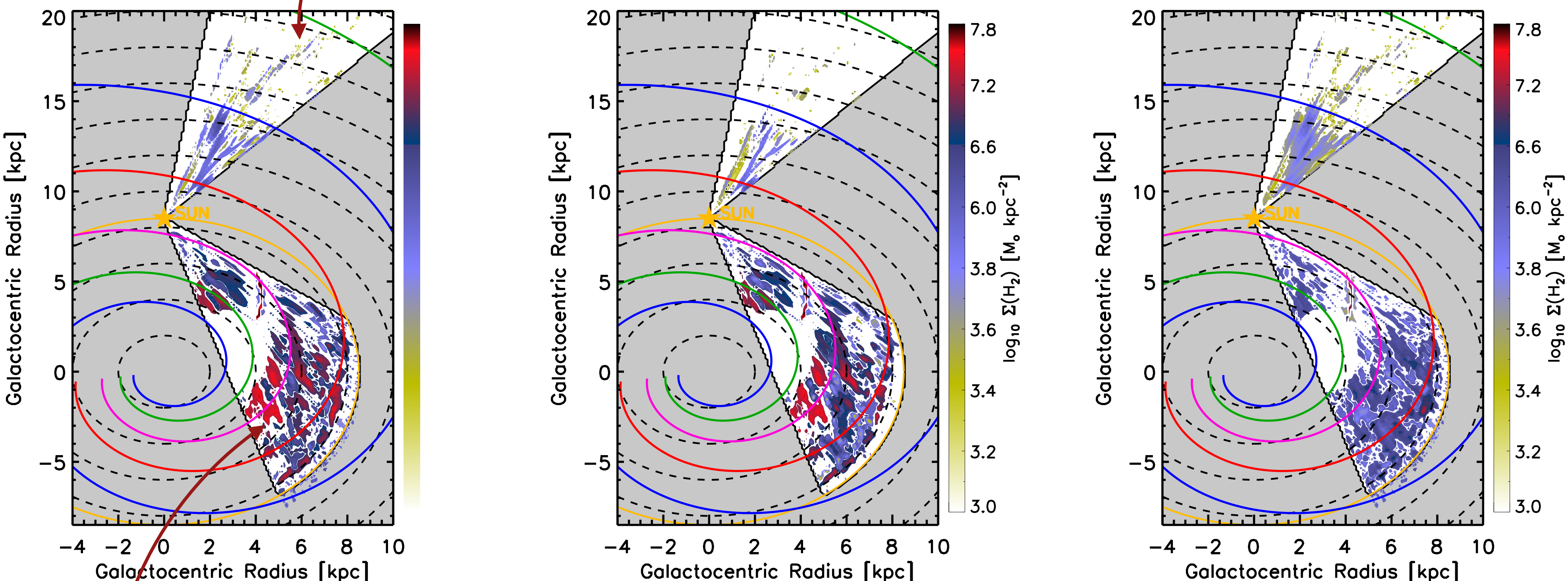
- maybe a large fraction of H
  dense clouds, but in a diffuse state!

Shetty et al. (2014, MNRAS, 422, 2208)

Spacial distribution

OUTER GALAXY:
Mark Heyer's survey

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



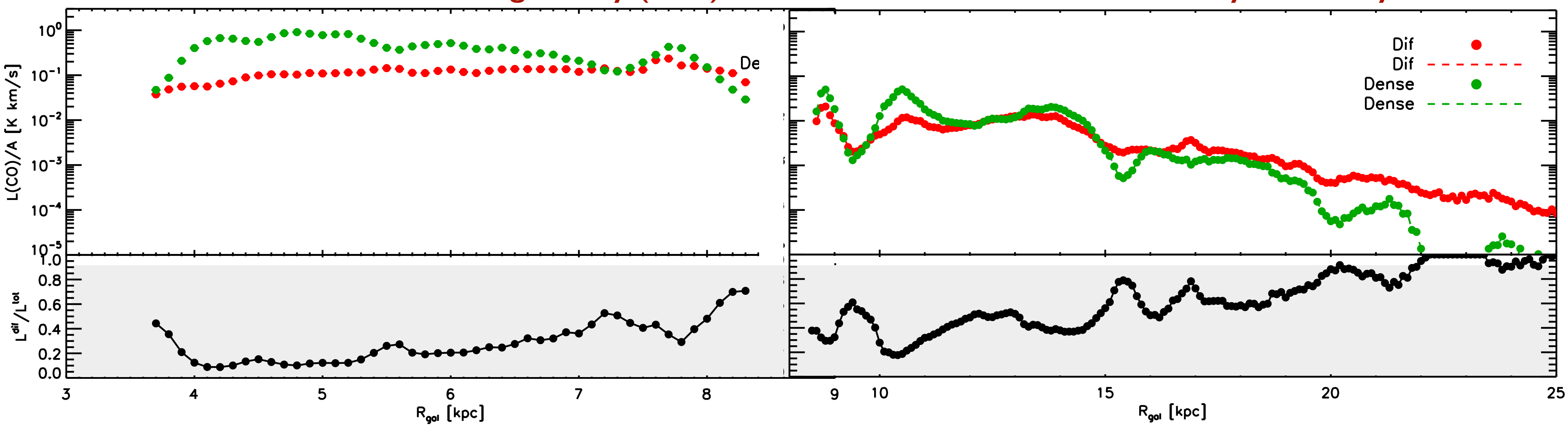
INNER GALAXY:
Galactic Ring Survey (GRS)

Roman-Duval et al. (2015, in prep.)

Diffuse gas fraction as function of Galactic radius.

INNER GALAXY: Galactic Ring Survey (GRS)

OUTER GALAXY: Mark Heyer's survey



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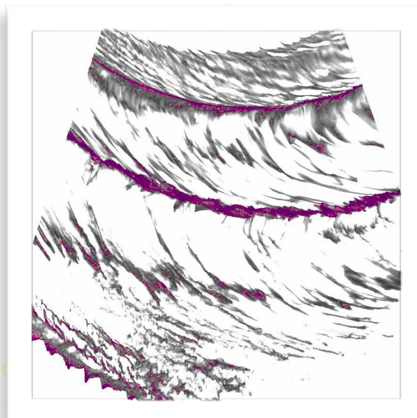
decrease in spatial scale / increase in density

galactic scale star formation relations
(with Shetty, Bigiel, etc.)



ISM dynamics and chemistry
(with Glover etc.)

primordial star formation
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turbulence and magnetic fields dynamics
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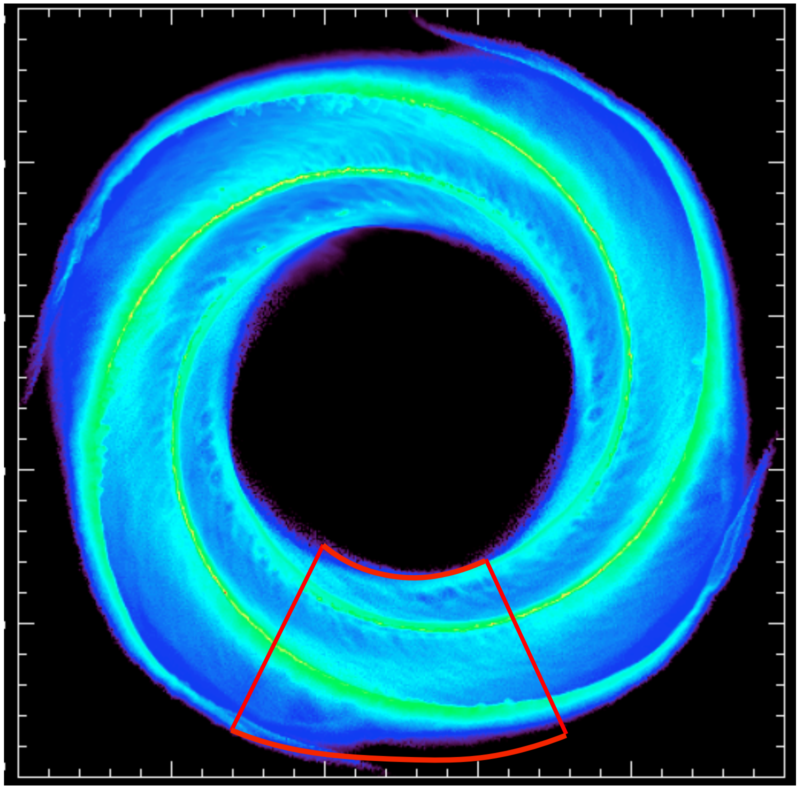
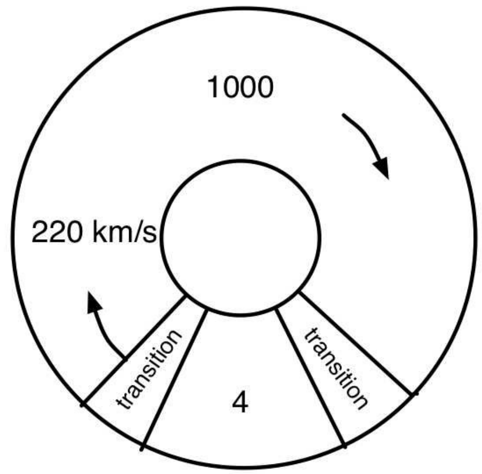
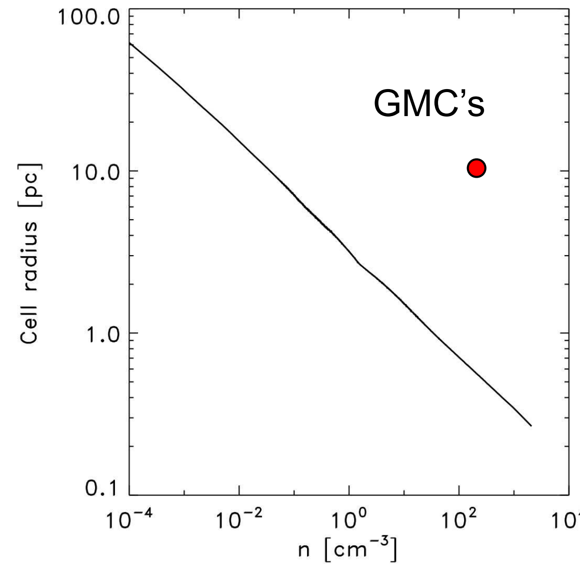
CO-dark gas

modeling molecular cloud formation



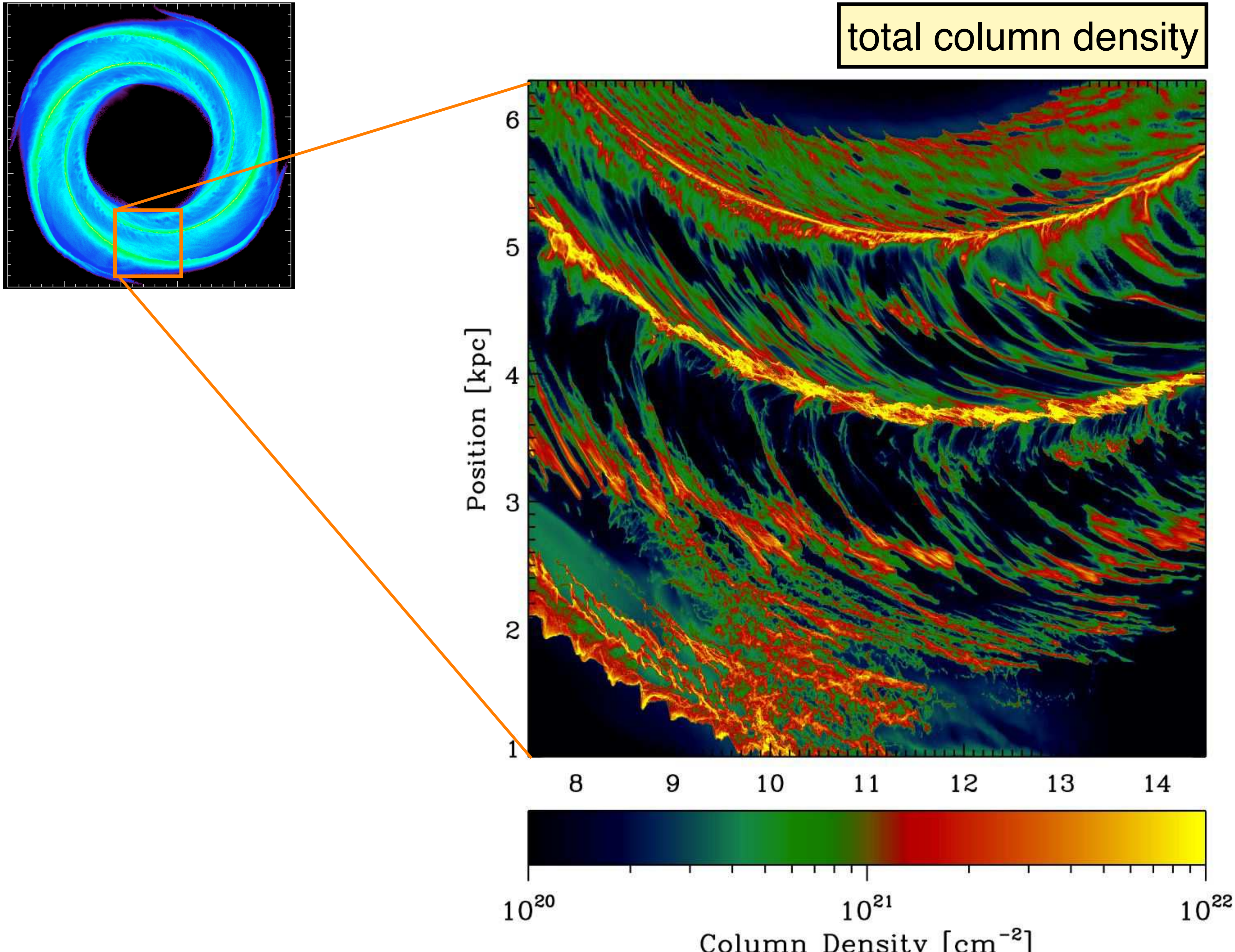




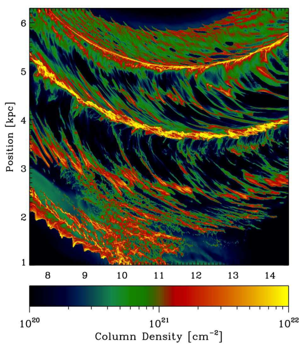
Simulation	Surface Density $M_\odot$ pc^{-2}	Radiation Field G_0
Milky Way	10	1
Low Density	4	1
Strong Field	10	10
Low & Weak	4	0.1

- Arepo moving mesh code *(Springel 2010)*
- time dependent chemistry *(Glover et al. 2007)* gives heating & cooling in a 2 phase medium
- two layers of refinement with mass resolution down to 4 $M_\odot$ in full Galaxy simulation
- UV field and cosmic rays
- TreeCol *(Clark et al. 2012)*
- external spiral potential *(Dobbs & Bonnell 2006)*
- no gas self-gravity, SN, or magnetic fields yet

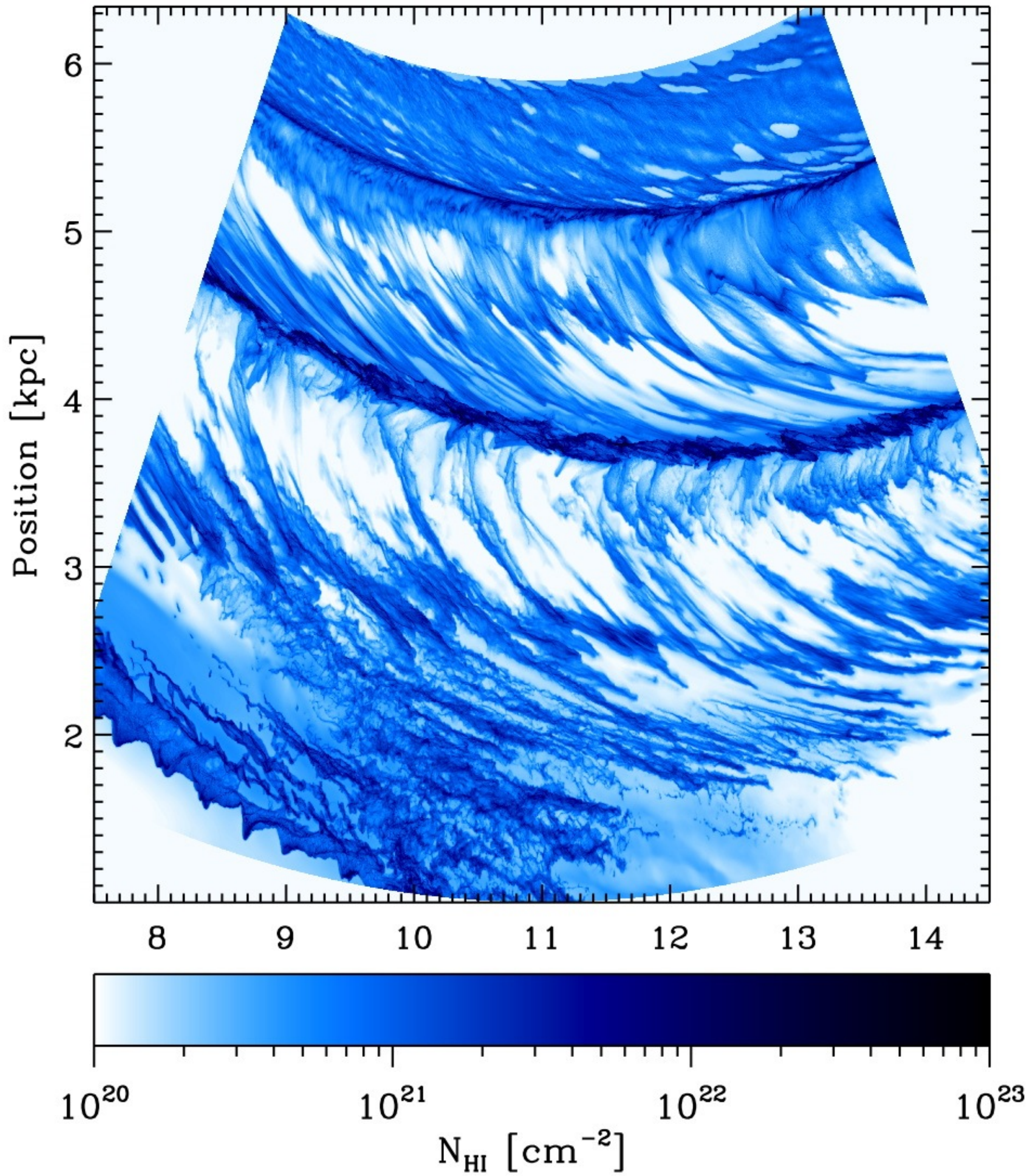
(Smith et al., 2014, MNRAS, 441, 1628)



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

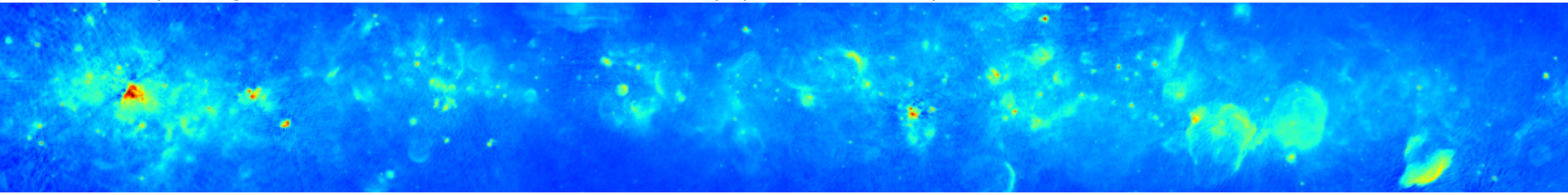


HI column density

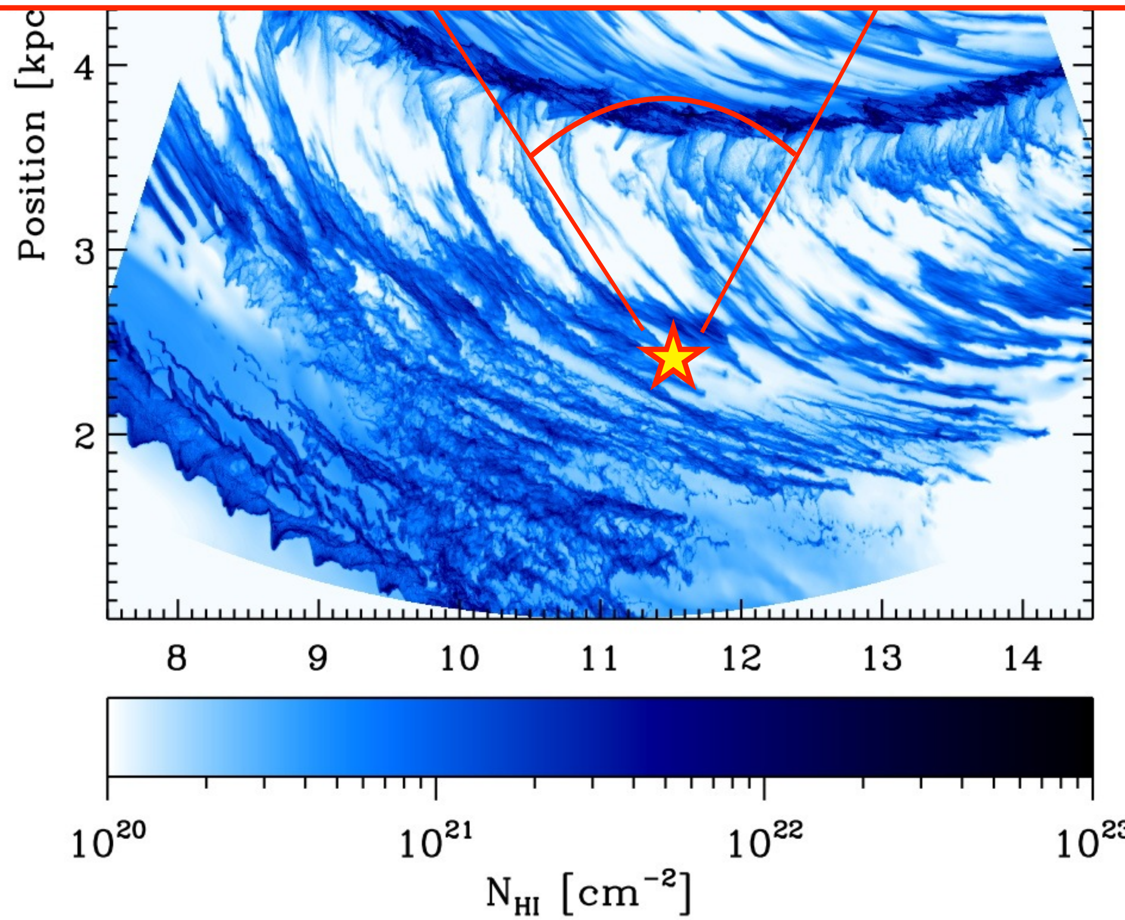


(Smith et al., 2014, MNRAS, 441, 1628)

preliminary image from THOR Galactic plane survey (PI H. Beuther): continuum emission around 21 cm



next step: produce all sky maps at various positions in the model galaxy (use RADMC-3D)



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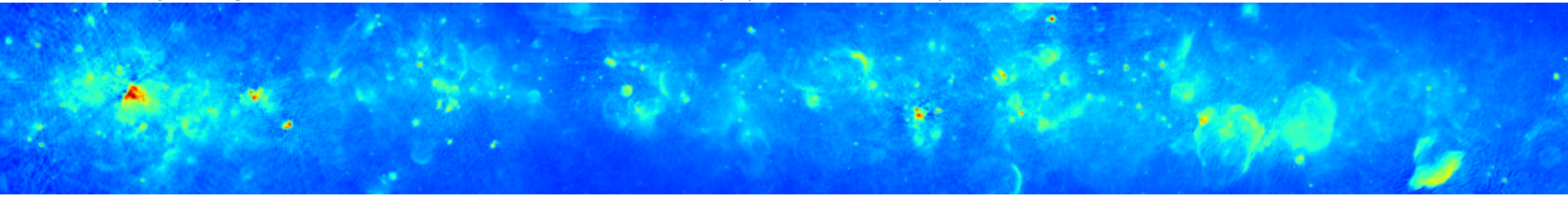

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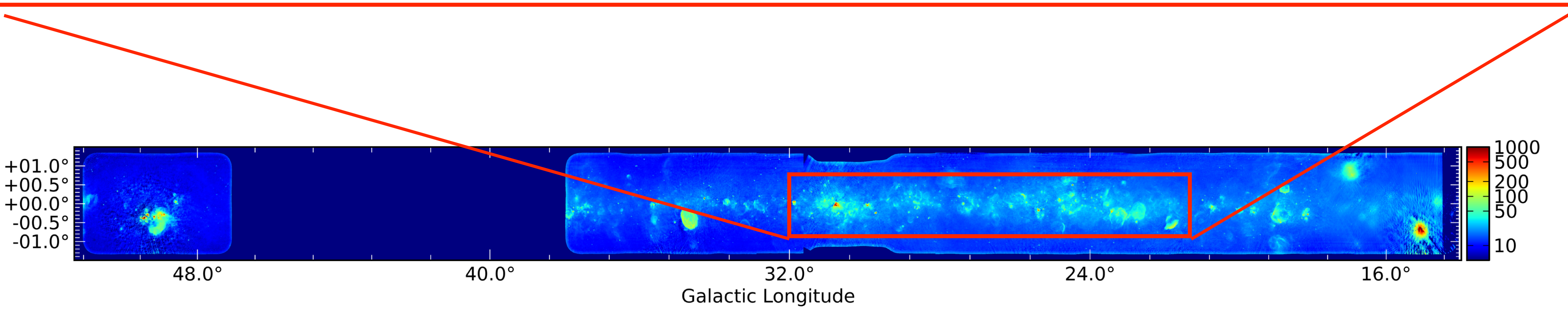
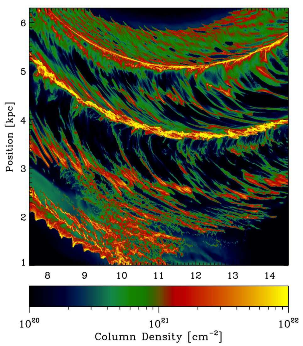
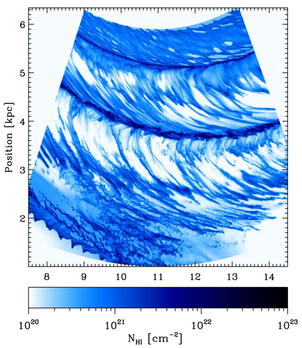
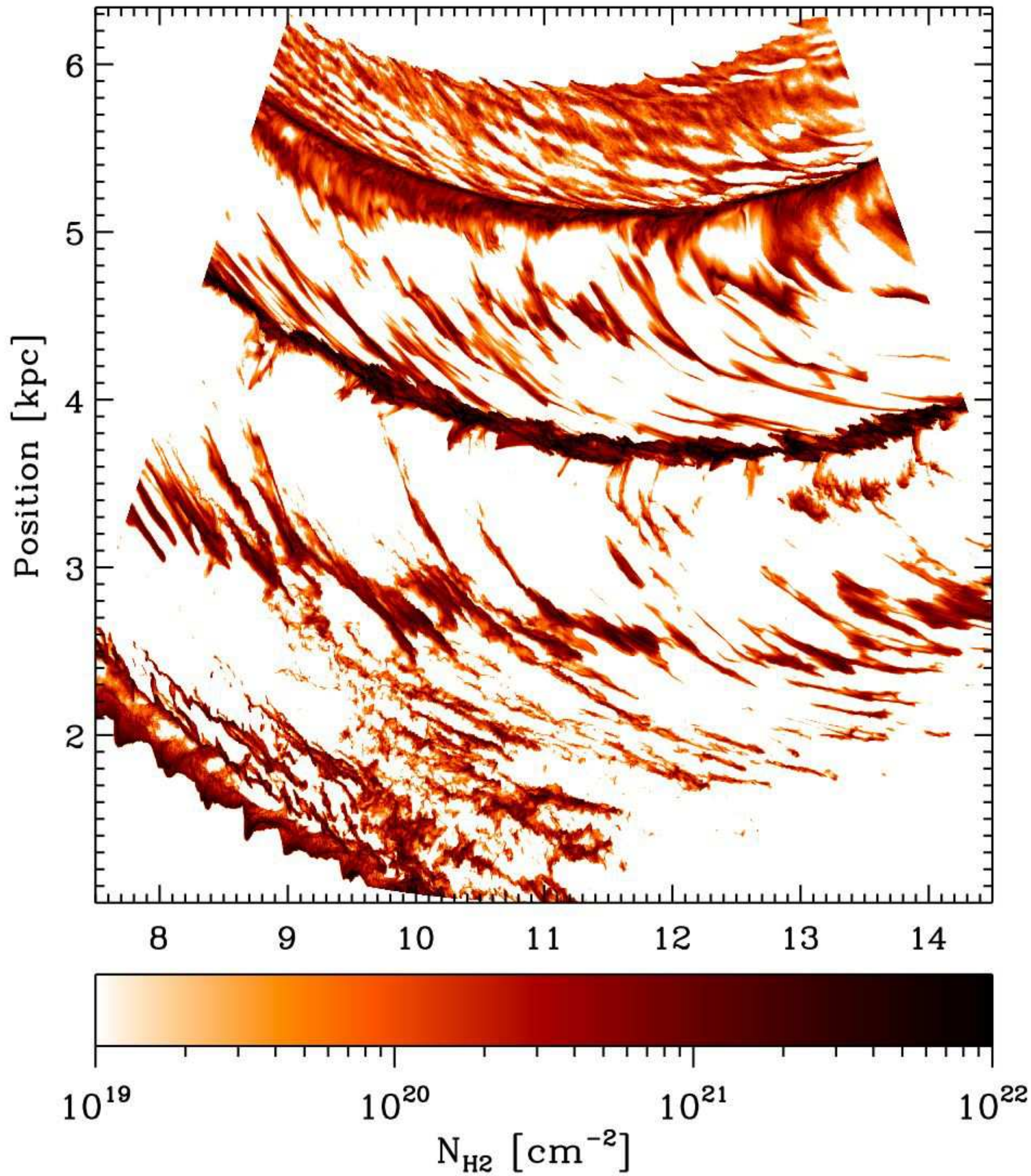


http://www.mpia.de/thor/Overview.html

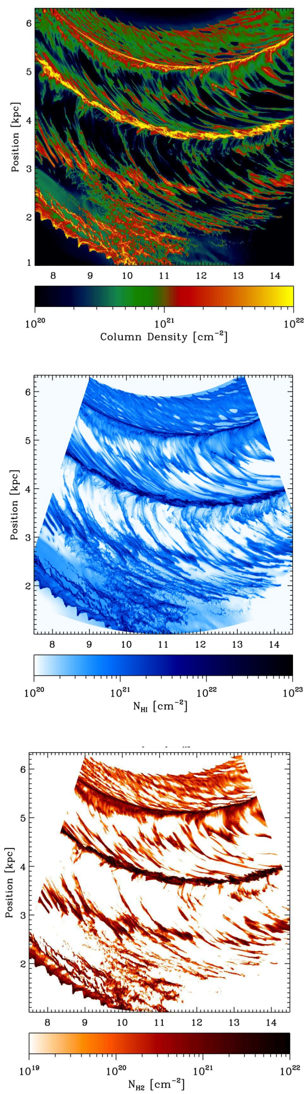


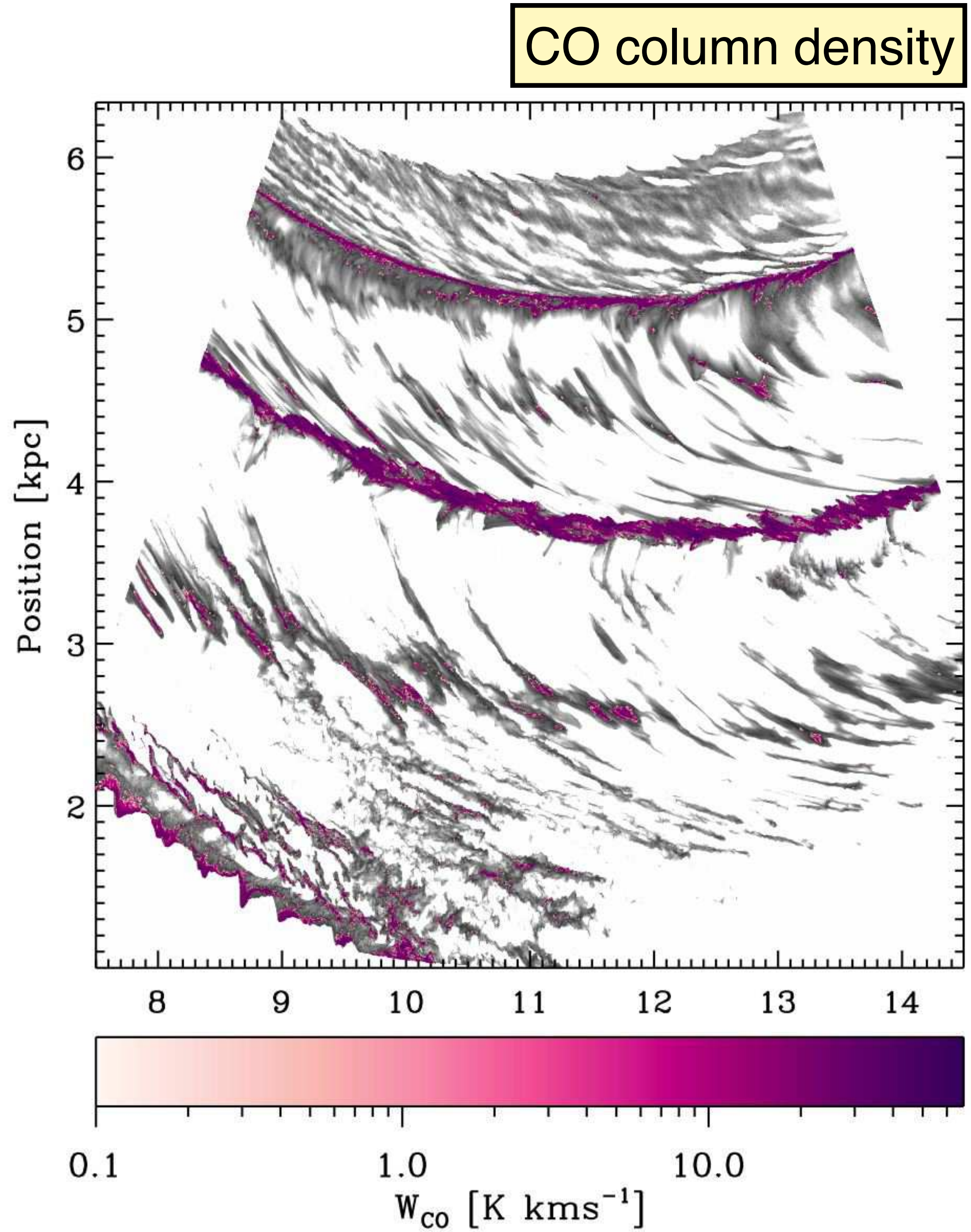


H_2 column density



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





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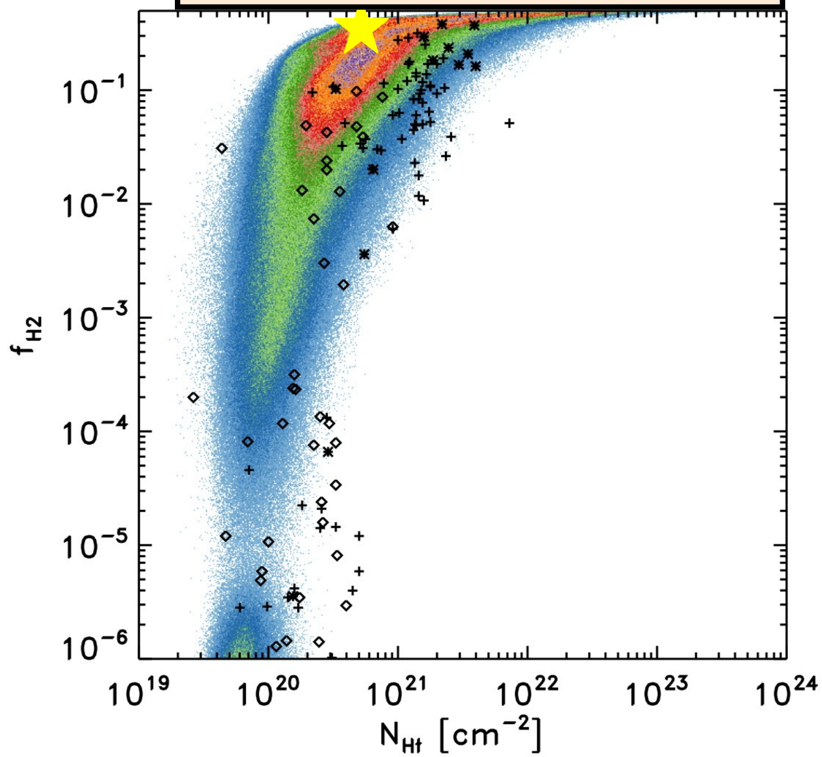
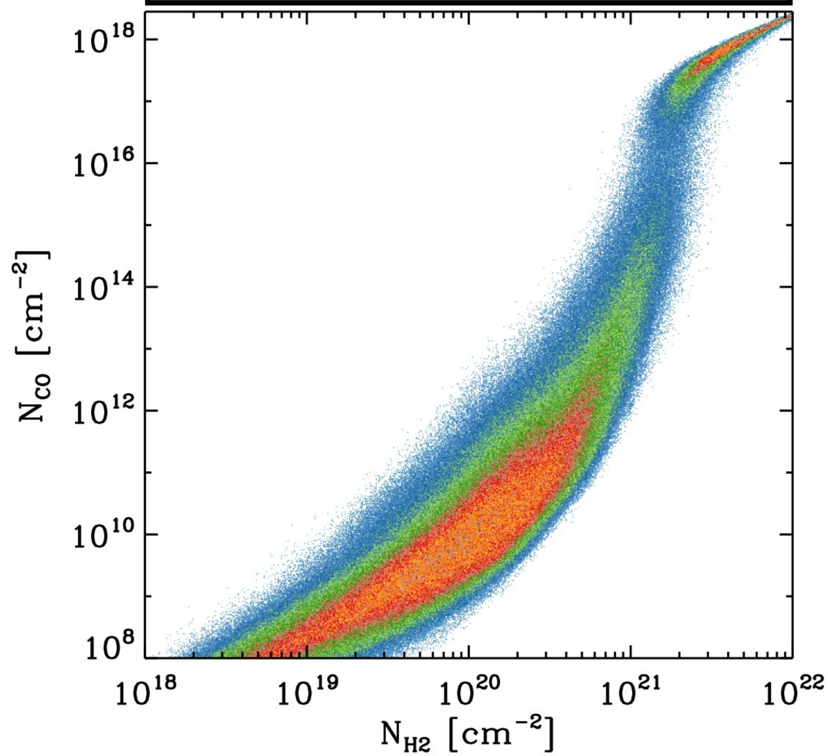
H$_2$ fraction vs. column density N

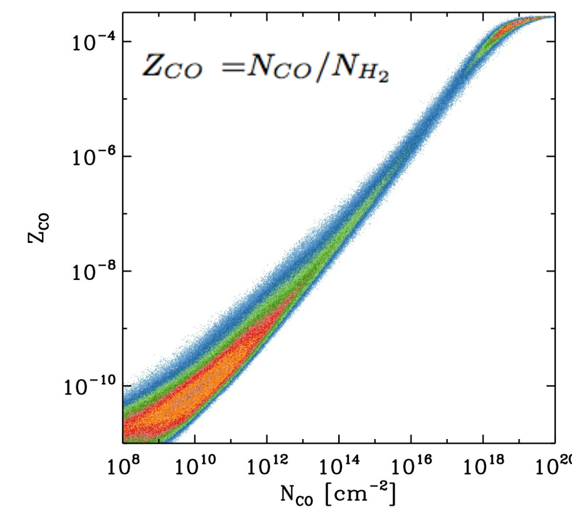


CO col. density vs. H$_2$ col. density



H$_2$ forms above column densities of 10^{20} cm^{-2}

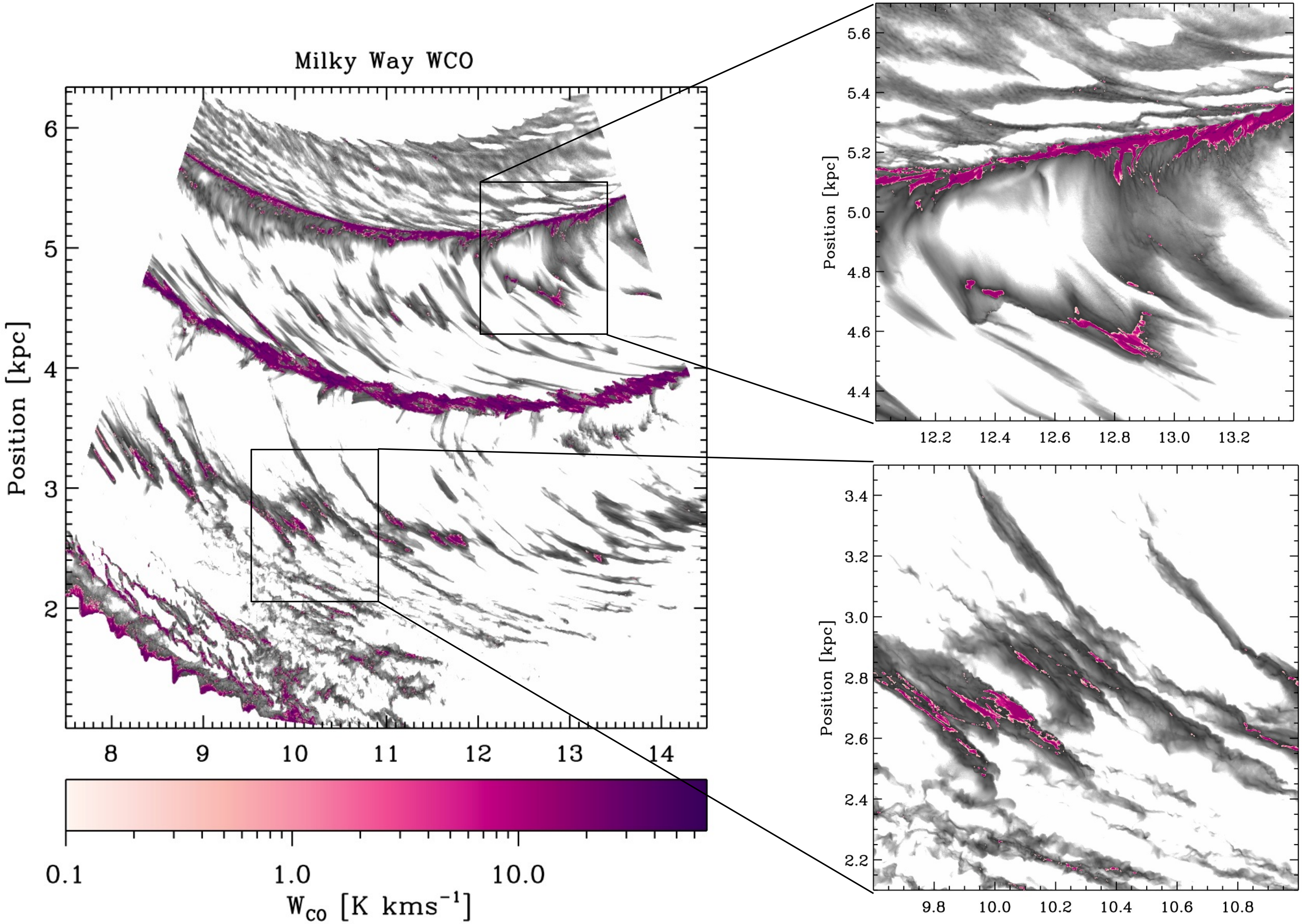
CO columns jump after $N_{H2} \sim 10^{21}$ cm^{-2}



$$log(Z_{CO}[cm^{-2}]) = -18.1 log(N_{CO}[cm^{-2}]) + 0.8.$$

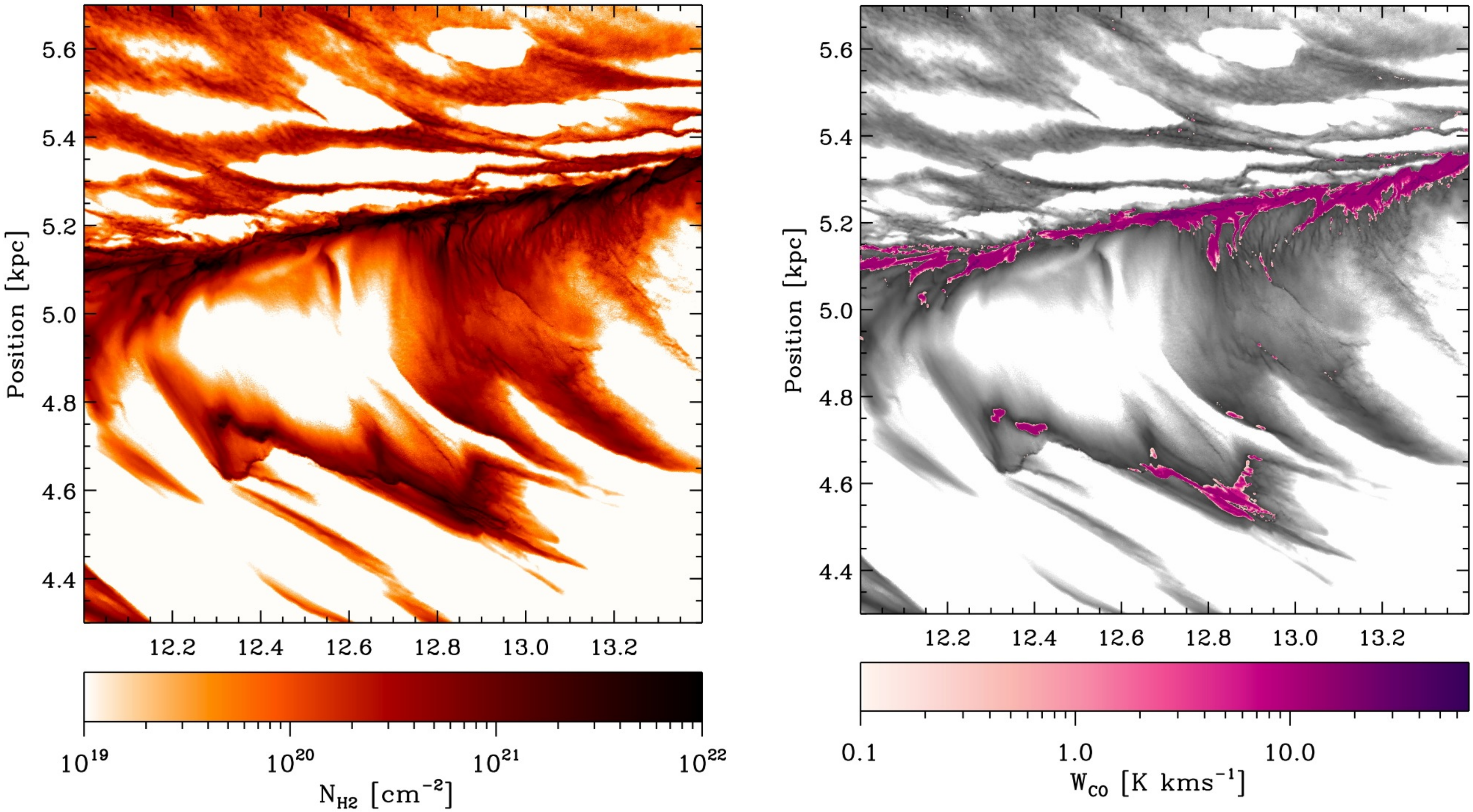
(Smith et al., 2014, MNRAS, 441, 1628)

details of CO emission



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

relation between CO and H_2



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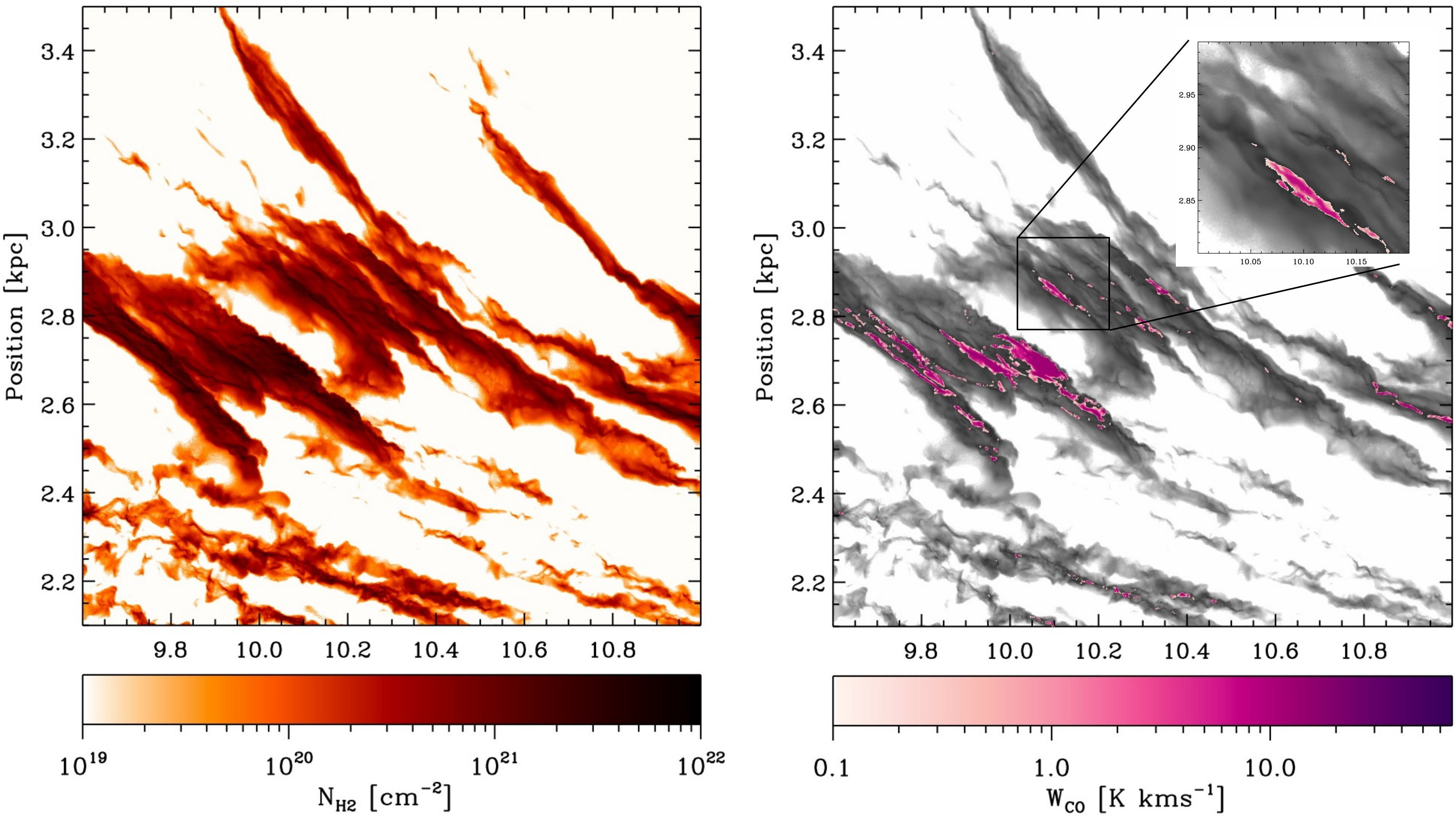
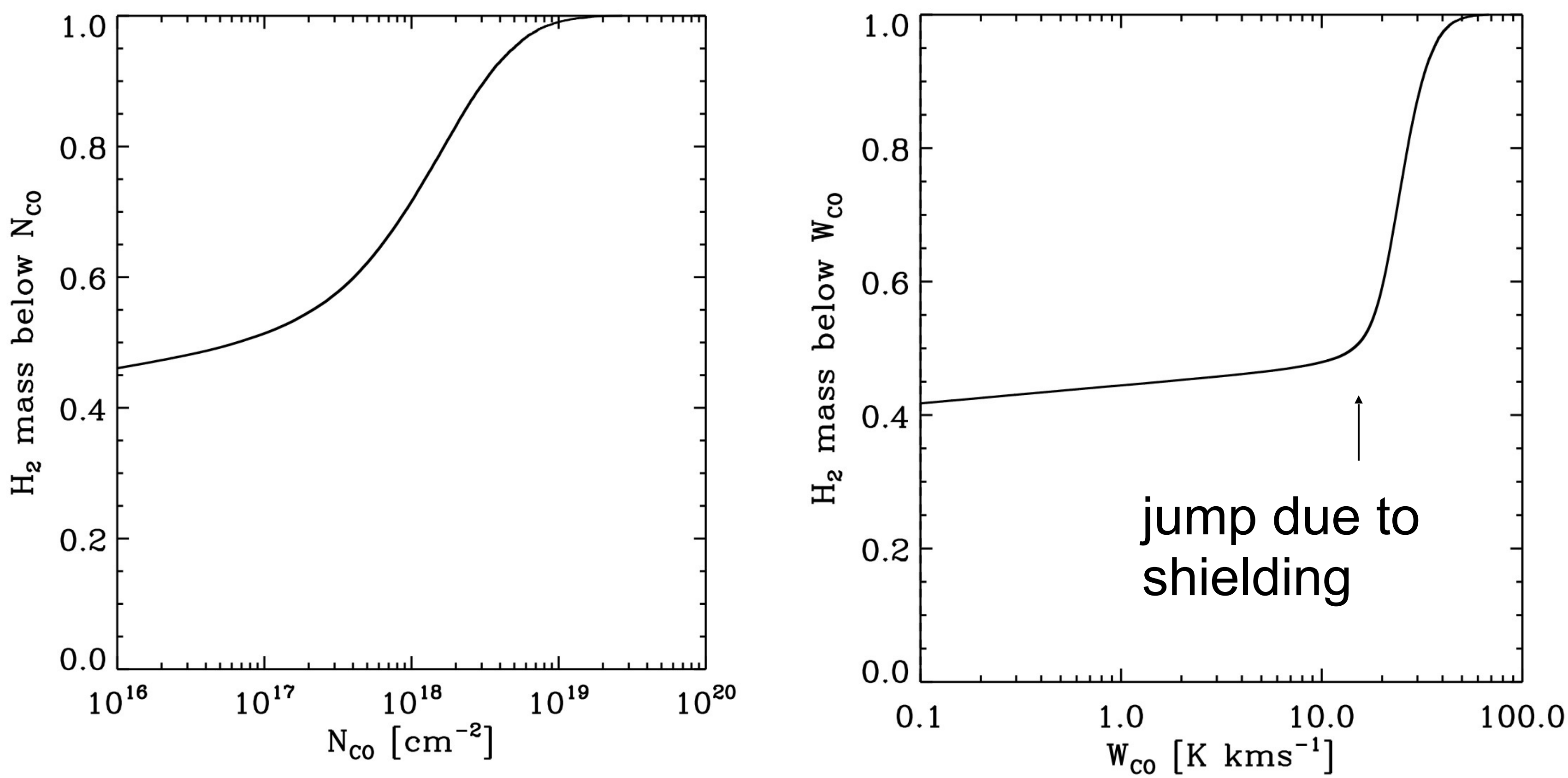


Filamentary molecular clouds in inter-arm regions are likely only the observable parts of much larger structures.

dark gas fraction



46% molecular gas below CO column densities of 10^{16} cm^{-2}

42% has an integrated CO emission of less than 0.1 K kms^{-1}

$f_{DG} = 0.42$ $X_{CO} = 2.2 \times 10^{20}\ cm^{-2}K^{-1}km^{-1}s$

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

dark gas fraction

Observational estimates:

Grenier et al. (2005) f_{DG} = 0.33-0.5

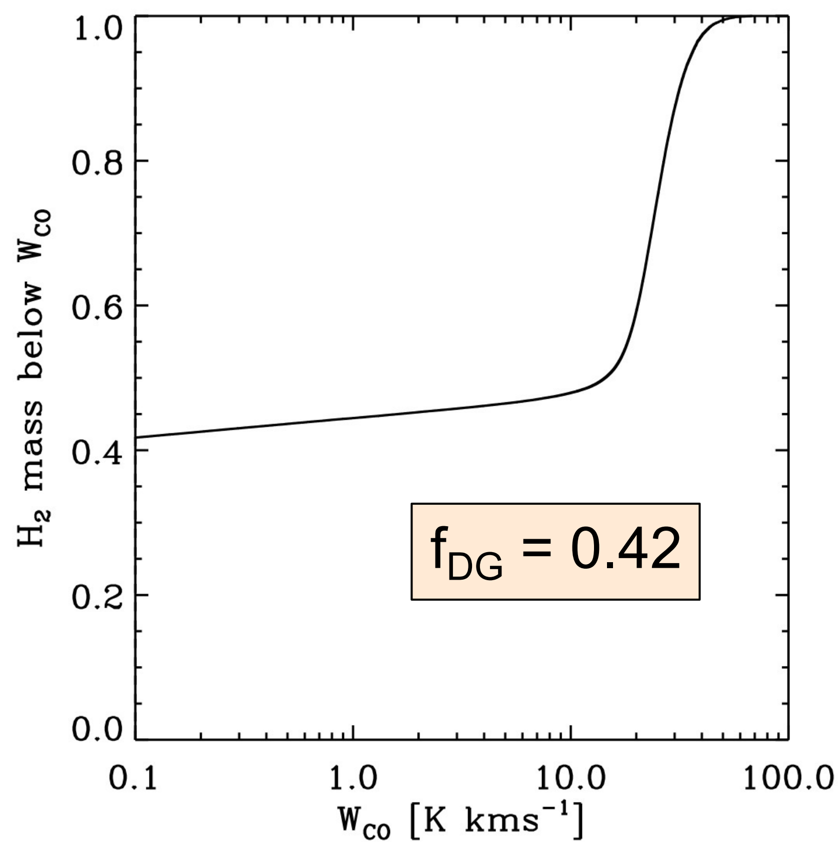
Planck coll. (2011)* f_{DG} = 0.54

Paradis et al. (2012)* f_{DG} = 0.62

(inner f_{DG} = 0.71, outer f_{DG} = 0.43)

Pineda et al. (2013) f_{DG}= 0.3

Roman-Duval et al. (in prep.) f_{DG} ~ 0.5



* dust methods have large uncertainties.

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

is there CO-dark H_2 gas?

- 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

further evidence form detailed colliding flow calculations

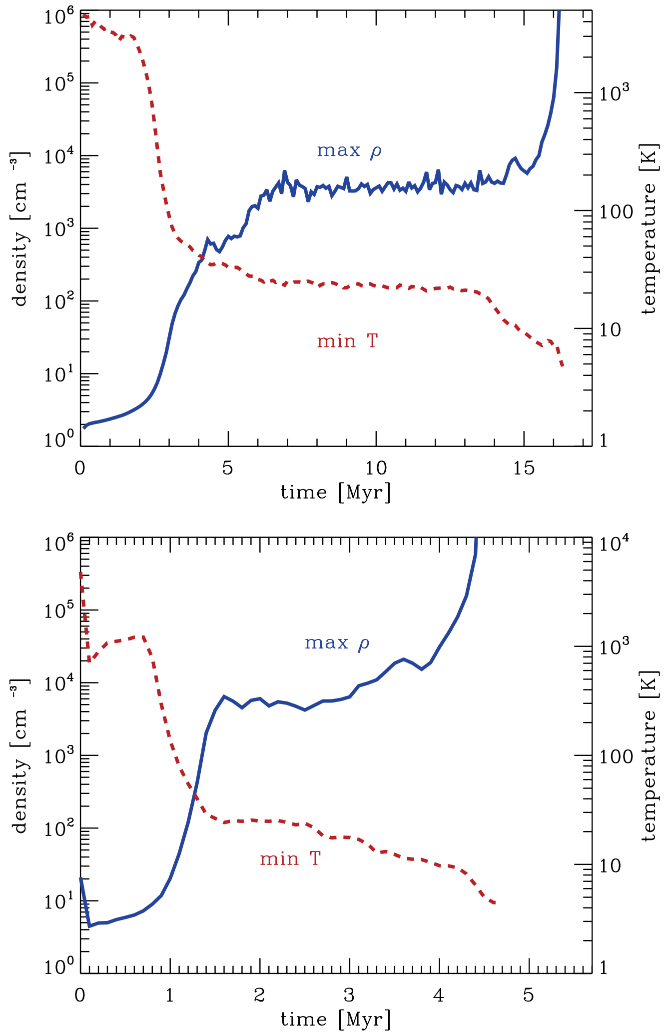
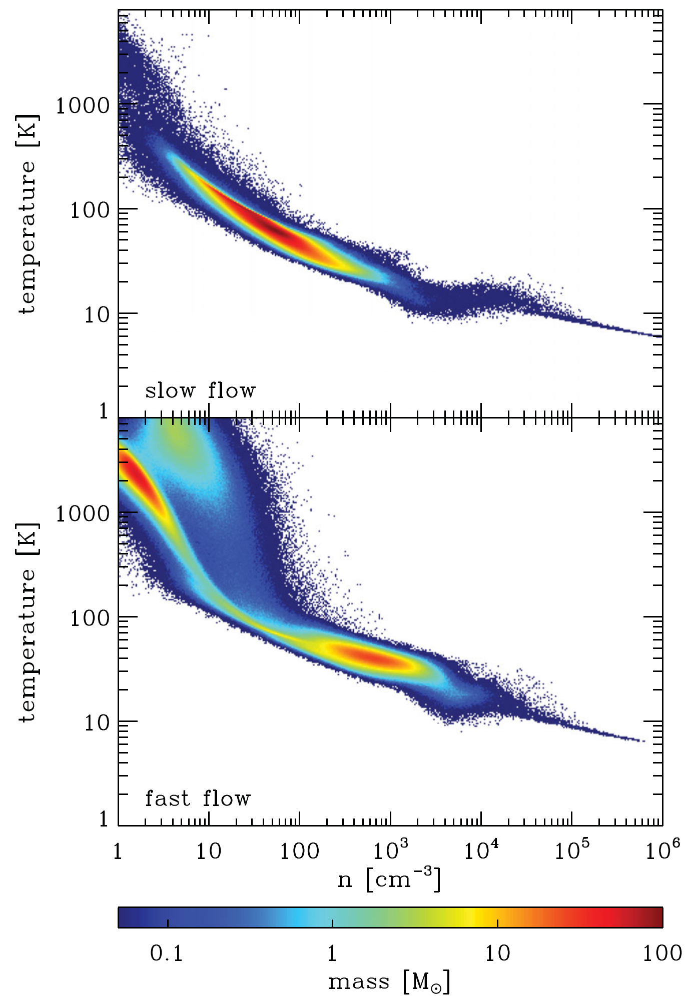


Figure 3. Evolution with time of the maximum density (blue, solid line) and minimum temperature (red, dashed line) in the slow flow (top panel) and the fast flow (bottom panel). Note that at any given instant, the coldest SPH particle is not necessarily the densest, and so the lines plotted are strictly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



slow flow

fast flow

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

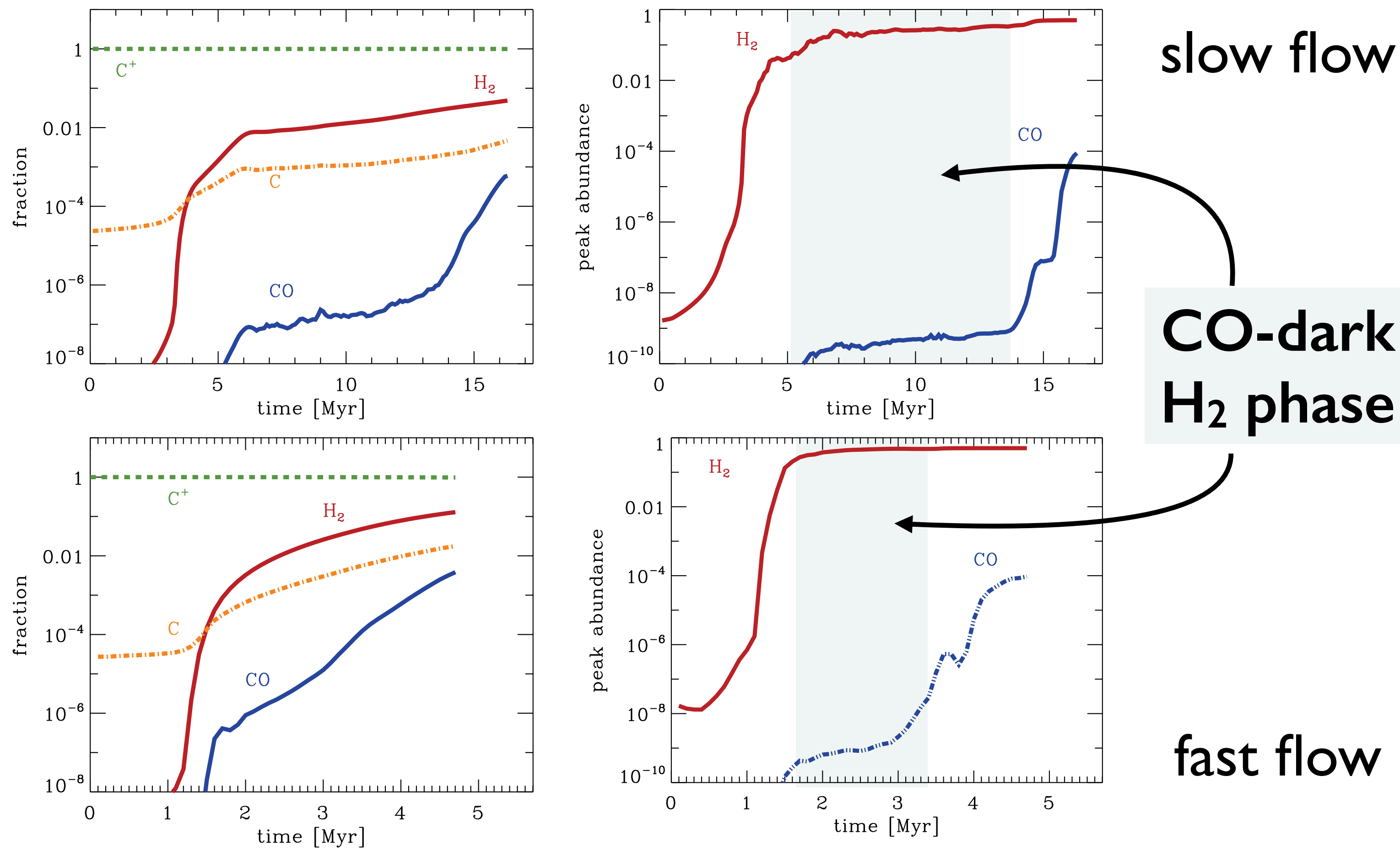
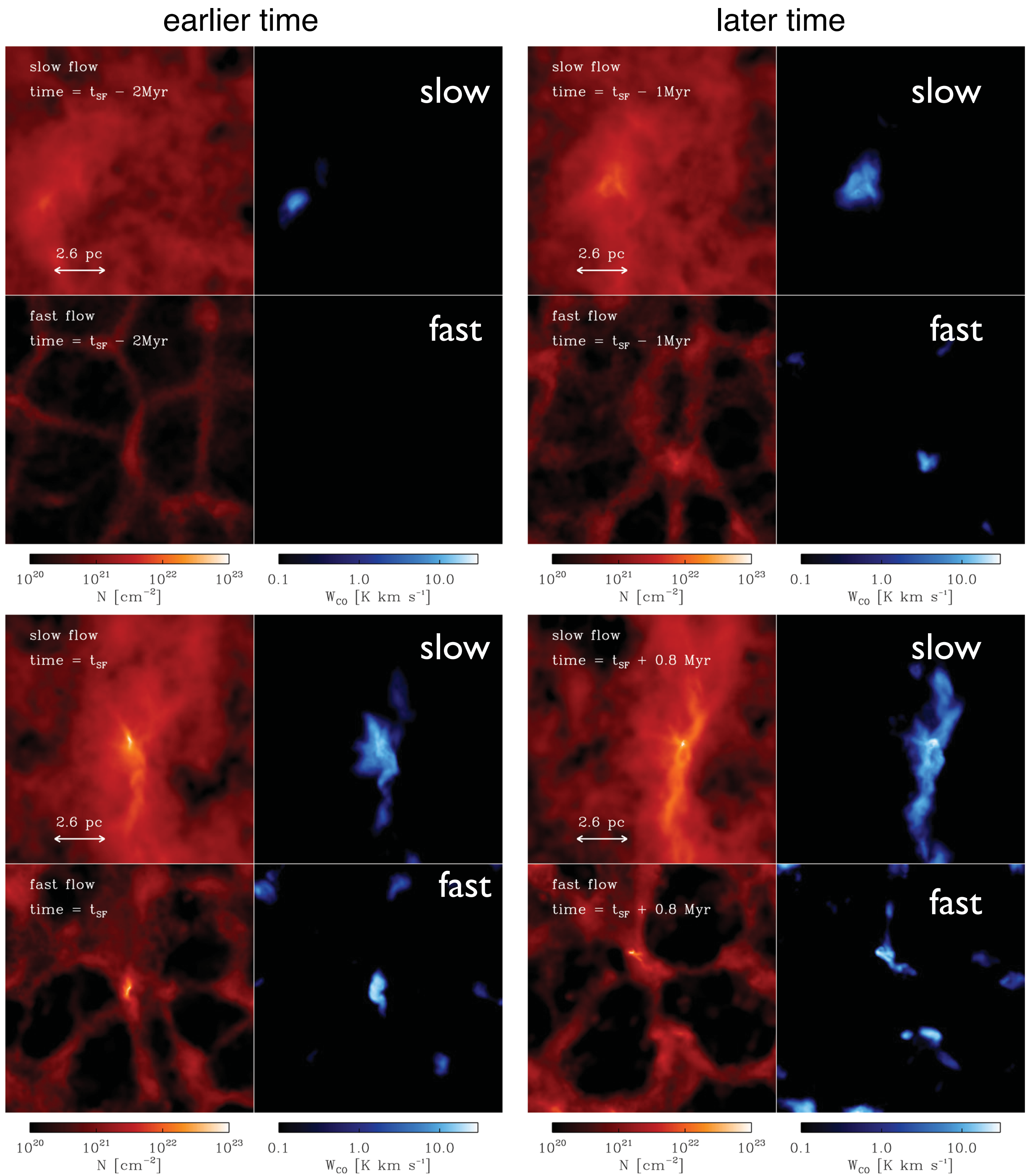


Figure 6. Chemical evolution of the gas in the flow. In the left-hand column, we show the time evolution of the fraction of the total mass of hydrogen that is in the form of H_2 (red solid line) for the 6.8 km s^{-1} flow (upper panel) and the 13.6 km s^{-1} flow (lower panel). We also show the time 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

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

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

summary

- the ***global SF*** relation may ***not*** be *universal* and *linear*, instead there seem to be galaxy-to-galaxy ***variations*** and often Σ_{SFR} vs. Σ_{gas} is ***sub-linear***
- there is a considerable ***diffuse*** and ***extended component*** of ***CO emitting gas*** in the Milky Way as well as in other disk galaxies
- in addition, there is a ***substantial fraction*** of ***CO-dark molecular gas*** typical $L_\star$ spirals


THANKS
… also to Chong Li for bringing me up here!