thanks for ...

... bringing us to such a beautiful place
thanks to …

… people in the star formation group at Heidelberg University:

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… many collaborators abroad!
Magnetic field amplification by gravity-driven turbulence

Fig. 3.—Spherical slice of the gas density inside the Jeans volume at \( t_\text{final} = 128 \text{ cells per Jeans length} \). Velocity streamlines on a linear color scale ranging from dark blue \( 0 \text{ km s}^{-1} \) to high gray \( 5 \text{ km s}^{-1} \). Magnetic field lines showing a highly tangled and twisted magnetic field structure typical of the small-scale dynamo; yellow: \( \mu = 0.5 \mu \text{G} \), green: \( \mu = 1 \mu \text{G} \). Four randomly chosen individual field lines. The green one in particular is extremely tangled close to the center of the Jeans volume. Contours of the vorticity modulus \( |\vec{\omega}| \) show elongated filamentary structure typical of subsonic turbulence (Frisch 1995). Spherical slice of the divergence of the velocity field \( \nabla \cdot \vec{v} \); white: compression, red: expansion.
ISM dynamics & star formation

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connecting theory with observations

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more on observations in Charlie Lada’s talk
prolegomenon
Platon
428/427–348/347 BC

Capitoline Museum, Rome.
Plato's allegory of the cave*

* The Republic (514a-520a)
Plato’s allegory of the cave*

 observable universe

 “Demiurge”

 ideas

 philosopher

* The Republic (514a-520a)

Laszlo Szücs, image from criticalthinking-mc205.wikispaces.com
Plato's allegory of the cave* ↔ Astronomical observations

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Projection effects
Optical depth effects
Radiative transfer

→ Column density
→ Excitation / dust temperature
→ Line shift / broadening

→ Volume density
→ Temperature
→ Velocity
→ Chemical composition

Interpretation of Astronomical Data (Synthetic Observations)
Assumptions from Observations Theory Experiments

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

* The Republic (514a-520a)
Example: from CO emission to total column density

Assumptions I.

\( k^{(12) \text{CO}} \) is optically thick

\( k^{(13) \text{CO}} \) is optically thin

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

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

\[
\tau_{13}(v) = -\ln \left[ 1 - \frac{T_B^{13}}{5.3} \left\{ \exp \left( \frac{5.3}{T_{\text{ex}}} - 1 \right) - 0.16 \right\}^{-1} \right]^{-1}
\]

\[
N^{(13) \text{CO}} = 3.0 \times 10^{14} \frac{T_{\text{ex}} \int \tau_{13}(v) dv}{1 - \exp(-5.3/T_{\text{ex}})}
\]

Assumptions II.

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

\( N(\text{H}_2)/N^{(12) \text{CO}} \) ratio \( \sim 6.6 \times 10^3 \)

* Langer & Penzias (1990)

** Pineda et al. (2009)
global SF relations
galaxies from THINGS and HERACLES survey
(images from Frank Bigiel, ZAH/ITA)
• HI gas more extended
• H2 and SF well correlated
when considering galaxies as a whole, there seems to be a super-linear relation between total gas ($H_2+H$) and the star formation rate ($SFR$) with slope $\sim 1.4$:

$$\Sigma_{SFR} = (2.5 \pm 0.7) \times 10^{-4} \left( \frac{\Sigma_{gas}}{1 \ M_\odot \ pc^{-2}} \right)^{1.4\pm0.15} \ M_\odot \ year^{-1} \ kpc^{-2}$$
• for “resolved” galaxies on scales of 0.5-1 kpc, there seems to be a **linear relation** between $H_2$ and SFR
• implying a roughly **constant depletion time** of a few $\times 10^9$ yr
• for “resolved” galaxies on scales of 0.5-1 kpc, there seems to be a linear relation between $H_2$ and SFR
• implying a roughly constant depletion time of a few $\times 10^9$ yr
• but with different normalization for starburst galaxies compared to normal ones
true physical behavior may be (much) more complicated than simple models assume!


Kennicutt (1998, ARAA, 36, 189)
data from STING survey (Rahman et al. 2011, 2012)

• QUIZ: do you see a universal $\Sigma_{H2} - \Sigma_{SFR}$ relation?
QUIZ: do we really see a universal $\Sigma_{H2} - \Sigma_{SFR}$ relation?

ANSWER: - large galaxy-to-galaxy variations
- relation is often sublinear
many galaxies show sublinear KS-type relation

Image from R. Shetty / thanks to Adam Leroy for providing the THINGS/HERACLES data.
• **HOWEVER:** there seems to be a relation between SFR tracers and dense gas tracers that extends over many orders of magnitude!!

• this includes many different objects

![Graph showing a linear relationship between IR luminosity and HCN luminosity](figure from Frank Bigiel (ZAH/ITA))

**New data:**
- Disk pointings (Usero et al.)
- EMPIRE pilot: M51 pixels
- Antenna pointings
• **HOWEVER:** there seems to be a relation between SFR tracers and dense gas tracers that extends over many orders of magnitude!!

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![Diagram with annotations](image-url)

**New data:**
- Disk pointings (Usero et al.)
- EMPIRE pilot: M51 pixels
- Antenna pointings

More details on this plot can be provided by Frank Bigiel and Diane Cormier at this conference.
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?*
• **EMPIRE Survey (PI Frank Bigiel):**
• 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)

![Graphs showing correlations]

- **different galaxies in survey**

• **EMPIRE Survey (PI Frank Bigiel):**
• 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)

![Graph showing the relationship between IR luminosity and dense gas (HCN) across the disk of M51.](image)

- **resolved data in M51**

Figure 1. Distribution of dense gas and SF activity tracers as a function of Galactic latitude and longitude. Black circles mark the positions of H\textsuperscript{II} regions, blue crosses show methanol masers and red plus symbols mark water masers. Regions of sky not covered in these surveys are shaded in grey. NH\textsubscript{3} (1, 1) (bottom) and H\textsubscript{69}\textalpha (second-bottom) integrated intensity emission is displayed using a square-root image stretch. The tracers and their function as either a dense gas or SF activity tracer are labelled at the right-hand edge of the bottom row. The CMZ can be seen as bright, extended NH\textsubscript{3} (1, 1) emission from longitudes of roughly 358\degree to 4\degree.

- similar holds for Galactic Center:
  - dense gas in Central Molecular Zone (CMZ) seems relative inefficient in forming stars
more Galactic Center in review talk by Mark Morris

- similar holds for Galactic Center:
- dense gas in Central Molecular Zone (CMZ) seems relative inefficient in forming stars
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 $A_V \sim 1$, CO needs $A_V \sim 2$,)…

Figure 2. 

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

physical origin of this behavior?

SEARCH FOR CO-dark H$_2$ GAS
here SOFIA can provide major input

more on CO-dark gas in talks by Paul Goldsmith and Diane Cormier

physical origin of this behavior?

SEARCH FOR CO-dark H$_2$ GAS here SOFIA can provide major input

dense vs. diffuse CO-traced $\text{H}_2$ gas

in addition:

• maybe a large fraction of $\text{H}_2$ (even if traced by CO) may not be in dense clouds, but in a diffuse state!

average Galactic surface density of molecular gas in the Milky Way. The variations in the luminosity ratio. Other possible effects that could explain the variations in the density and/or the abundance of excited gas, which could be consistent with the variations in mass. The mass fraction of dense gas decreases with decreasing surface density or luminosity ratio include more sub-thermally excited gas.

Between 50% and 80%, and is anti-correlated with surface density and/or the abundance of excited gas. The mass fraction of dense gas decreases with decreasing surface density and/or the abundance of excited gas. The mass fraction of dense gas decreases with decreasing surface density and/or the abundance of excited gas. The mass fraction of dense gas decreases with decreasing surface density and/or the abundance of excited gas. The mass fraction of dense gas decreases with decreasing surface density and/or the abundance of excited gas.

In the Outer Galaxy, the mass fraction of dense gas varies between 50% and 80%, and is anti-correlated with surface density. The mass fraction of dense gas decreases from very dense 2.8 to 4.8 — 4.8, dense 4.5 to 1.1, very dense 4.8 to 2.8, total 5.3 to 1.3, and diffuse 8.5 to 2.1.

Note: CO/\(^12\)CO decreases with decreasing surface density.

Masses are given in units of \(10^8 \) \(M_\odot\) and \(10^{12} \) \(M_\odot\). Systematic uncertainties are \(\sim 30\%\)

TABLE 4

<table>
<thead>
<tr>
<th></th>
<th>Inner</th>
<th>Outer</th>
<th>Total</th>
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</thead>
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<td>(\Sigma)</td>
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<td>3.8</td>
<td>3.4</td>
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<tr>
<td>(M_{\odot} )</td>
<td>10^8</td>
<td>10^8</td>
<td>10^8</td>
</tr>
<tr>
<td>(M_{\odot} )</td>
<td>10^12</td>
<td>10^12</td>
<td>10^12</td>
</tr>
</tbody>
</table>

observational approach:

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

INNER GALAXY: Galactic Ring Survey (GRS)

OUTER GALAXY: Exeter Fife College survey

dense gas fraction as function of radius

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).

Table 5

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

<table>
<thead>
<tr>
<th></th>
<th>Inner</th>
<th>Outer</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>L($^{12}$CO)</td>
<td>Diffuse</td>
<td>2.0 $\times$ 10$^1$</td>
<td>4.0</td>
</tr>
<tr>
<td></td>
<td>Dense</td>
<td>1.1 $\times$ 10$^2$</td>
<td>3.8</td>
</tr>
<tr>
<td></td>
<td>Very dense</td>
<td>4.8</td>
<td>...</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>1.3 $\times$ 10$^2$</td>
<td>7.7</td>
</tr>
<tr>
<td>M($H_2$)</td>
<td>Diffuse</td>
<td>9.3 $\times$ 10$^7$</td>
<td>6.0 $\times$ 10$^7$</td>
</tr>
<tr>
<td></td>
<td>Dense</td>
<td>4.6 $\times$ 10$^8$</td>
<td>3.9 $\times$ 10$^7$</td>
</tr>
<tr>
<td></td>
<td>Very dense</td>
<td>2.9 $\times$ 10$^7$</td>
<td>...</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>5.5 $\times$ 10$^8$</td>
<td>9.9 $\times$ 10$^7$</td>
</tr>
</tbody>
</table>

fraction CO-traced H2 gas in Milky Way:
~1/4 diffuse
~3/4 dense
~1/20 in known molecular clouds only !!!

dense gas fraction as function of radius

more on diffuse gas in talk by Julia Roman-Duval

fraction CO-traced H2 gas in Milky Way:
~1/4 diffuse
~3/4 dense
~1/20 in known molecular clouds only !!!

• star formation is a multi-scale multi-physics problem
• progress requires the combination of many different physical/chemical processes (often included as ‘sub-grid scale’ models’)
• analytic theories fail (*much too simplified*), numerical simulations are needed to face this complexity
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progress requires the combination of many different physical/chemical processes (often included as ‘sub-grid scale’ models’)
analytic theories fail (much too simplified), numerical simulations are needed to face this complexity
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:

$$M_J = \frac{1}{6} \pi^{-5/2} G^{-3/2} \rho_0^{-1/2} c_s^3 \propto \rho_0^{-1/2} T^{3/2}$$
first approach to turbulence

- von Weizsäcker (1943, 1951) and Chandrasekhar (1951): concept of MICRO TURBULENCE

  - BASIC ASSUMPTION: separation of scales between dynamics and turbulence
    \[ \ell_{\text{turb}} \ll \ell_{\text{dyn}} \]
  
  - then turbulent velocity dispersion contributes to effective soundspeed:
    \[
    c_c^2 \rightarrow c_c^2 + \sigma_{\text{rms}}^2
    \]
  
  - \( \rightarrow \) Larger effective Jeans masses \( \rightarrow \) more stability
  
  - BUT: (1) turbulence depends on \( k \): \( \sigma_{\text{rms}}^2(k) \)

    (2) supersonic turbulence \( \rightarrow \sigma_{\text{rms}}^2(k) >> c_s^2 \) usually
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 \( \sim 5\% \))
  \( \rightarrow \) *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*
Mestel & Spitzer (1956): Magnetic fields can prevent collapse!!!

- Critical mass for gravitational collapse in presence of B-field

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

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

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

- Ambipolar diffusion can initiate collapse
"standard theory" of star formation

- **BASIC ASSUMPTION:** Stars form from magnetically highly subcritical cores

- Ambipolar diffusion slowly increases \( (M/\Phi) : \tau_{AD} \approx 10\tau_{ff} \)

- 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 -

magnetic field
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, 2014, Saas Fee Lecture, arXiv:1412.5182 )
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 $\tau_{\text{ff}}$
  - 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
properties of turbulence

• laminar flows turn turbulent at high Reynolds numbers

\[ \textit{Re} = \frac{\text{advection}}{\text{dissipation}} = \frac{V L}{\nu} \]

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

• Navier-Stokes equation (transport of momentum)

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

\( \nabla \) is the gradient operator, \( \nabla^2 \) is the Laplacian operator, \( \nabla \cdot \vec{v} \) is the divergence of \( \vec{v} \), \( \nabla \vec{v} \) is the gradient of \( \vec{v} \)

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

\( \sigma_{ij} \) is the viscous stress tensor, \( \eta \) is the shear viscosity, \( \zeta \) is the bulk viscosity
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 \( L \), \( \nu = \eta/\rho = \) kinematic viscosity, turbulence for \( Re > 1000 \rightarrow \) typical values in ISM \( 10^8-10^{10} \)

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

(BUT: ISM turbulence: shocks & B-field cause additional inhomogeneity)
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 \( Re > 1000 \) \( \rightarrow \) typical values in ISM \( 10^8-10^{10} \)

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

more in talk by
Alex Lazarian
turbulent cascade in the ISM

- scale-free behavior of turbulence in the range $\frac{L}{\eta K} \approx Re^{3/4}$
- slope between $-5/3$ ... $-2$
- energy “flows” from large to small scales, where it turns into heat

energy source & scale \textit{NOT} known
(supernovae, winds, spiral density waves?)

dissipation scale not known
(ambipolar diffusion, molecular diffusion?)
molecular clouds \( \sigma_{\text{rms}} \approx \text{several km/s} \)

\[ M_{\text{rms}} > 10 \]

\[ L > 10 \text{ pc} \]

\[ \log L^{-1} \]

\[ \log k \]

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

\[ \eta_{K^{-1}} \]

energy source & scale \( NOT \text{ known} \)

(supernovae, winds, spiral density waves?)

\[ \sigma_{\text{rms}} << 1 \text{ km/s} \]

\[ M_{\text{rms}} \leq 1 \]

\[ L \approx 0.1 \text{ pc} \]

dense protostellar cores

supersonic

subsonic

turbulent cascade in the ISM
co-dark H₂ gas
modeling molecular cloud formation

- 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)

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Figure 2. Map of total column density of hydrogen nuclei for the highly resolved section of the disc in the Milky Way simulation. The gas has a range of morphologies, from dense spiral arms, to filamentary spurs, to diffuse inter-arm regions.

As an example of the results we obtain from our standard grid, we show in Figure 2 a map of the total column density in the high-resolution section of the Milky Way simulation. We see from the map that the gas exhibits very different morphologies, ranging from dense spiral arms, to filamentary spurs, to diffuse inter-arm regions. Each of these regions has a different degree of shielding to the ambient radiation field and consequently a different molecular hydrogen abundance.

Figure 3 shows the fractional abundance of molecular hydrogen relative to hydrogen in all forms as a function of column density. In this work, we define the fractional abundance of $\text{H}_2$ via the relationship $f_{\text{H}_2} \equiv \frac{n_{\text{H}_2}}{n_{\text{H}}}$, where $n_{\text{H}_2}$ is the number density of hydrogen molecules and $n_{\text{H}} \equiv 2n_{\text{H}_2} + n_{\text{H}^+} + n_{\text{H}_3}$ is the total number density of hydrogen nuclei. With this definition, the maximum value of the fractional abundance is $f_{\text{H}_2} = 0.5$, corresponding to fully molecular hydrogen. Between column densities of $10^{20} \text{ cm}^{-2}$ and $10^{21} \text{ cm}^{-2}$ the molecular hydrogen begins to self-shield and its abundance rises dramatically. A similar jump in molecular hydrogen abundance is seen observationally at similar total column densities, as shown by Leroy et al. (2007) and Wolfire et al. (2008).

Gnedin et al. (2009) presented a galactic scale model of molecular hydrogen formation in which these observations were used to calibrate a clumping factor, used to account for small-scale, unresolved density fluctuations, and tuned to ensure that the model matched observations. Our results in Figure 3 are a good match to the observed transition without us having to apply any calibration factors. There is some suggestion in Figure 3 that our column densities are slightly lower for a given value of $f_{\text{H}_2}$ than some of the observational data (e.g. Savage et al. 1977). However, these observations were taken along long sight-lines within the total column density (Smith et al., 2014, MNRAS, 441, 1628).
CO-dark gas in the Milky Way

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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)

(Smith et al., 2014, MNRAS, 441, 1628
Figure 4. Map of H$_2$ column density for the highly resolved section of the disc in the Milky Way simulation. H$_2$ is predominantly found in the spiral arms and in long filaments in the inter-arm regions.

Galactic disc which will have higher column densities than in our face-on disc. The observations of Gillmon et al. (2006) along sight-lines perpendicular to the disc (shown by the bold diamonds in Figure 3) are in good agreement with our data. This gives us confidence that the small-scale galactic structure is sufficiently resolved to accurately describe its chemical makeup.

Figure 4 shows the column density of molecular hydrogen in the highly resolved disc segment. Molecular hydrogen is predominantly present in the spiral arms, but there is also molecular gas in inter-arm spurs and in the inner regions of the disc. In the inter-arm regions molecular hydrogen is often found in long filaments that were originally spurs connected to the spiral arms but that were sheared off as the disc rotated. Figure 5 shows the ratio of H$_2$ to CO column densities in the gas. There is considerable variation in the abundance of CO. In particular, the long inter-arm filaments, which are so apparent in Figure 4, are much less visible in CO. This can be attributed to their narrow filamentary geometry being inefficient at shielding the gas from the ambient radiation field. Due to the low abundance of CO in these regions, the molecular gas there is likely to appear 'dark' in observations of CO emission.

3.2 The relationship between CO and H$_2$ column densities

Although our simulations provide us with information on the full 3D distributions of the H$_2$ and CO abundances, in general these are not observable quantities. For comparison with observations, it is more useful to examine the correlation between the H$_2$ and CO column densities, and the column-averaged abundance of CO relative to H$_2$, $Z_{CO} = N_{CO}/N_{H_2}$.

The left panel of Figure 6 shows the relation between H$_2$ column density and CO-dark gas in the Milky Way.
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This gives us confidence that the small-scale galactic bold diamonds in Figure 3) are in good agreement with our observations, it is more useful to examine the correlation along sight-lines perpendicular to the disc (shown by the face-on disc. The observations of Gillmon et al. (2006) in the spiral arms and in long filaments in the inter-arm region.

In the high-resolution section of the Milky Way simulation. The greyscale background image shows the $H_2$ column density for the highly resolved section of the disc in the Milky Way simulation. H$_2$ the molecular hydrogen begins to self-shield and consequently a di different morphologies, ranging from dense spiral arms, to different molecular hydro-ff

Figure 7. Morphology of the molecular gas in our Milky Way simulation.

To quantify the amount of CO-dark molecular gas in our simulations, we define a dark gas fraction $f_{DG}$ as the mass of CO-dark H$_2$ with emission be-

$M_{DG} = M_{H_2}^{CO} X_{CO} \int N_{H_2} \, dV$ (4)

is the mass of CO-dark H$_2$ and thus would appear as $f_{DG}$, e s t i m a t e da sd e s c r i b di nt h e CO-bright H$_2$ other authors, who define the dark gas fraction relative to CO-dark gas in Wolfire et al. (2010), but di total molecular gas. This definition is equivalent to that us

To determine $f_{DG}$, we first need to estimate $M_{H_2}^{CO}$, which is the mass of CO-bright H$_2$ in our high-resolution region, including the CO-dark cloud.

In our high-resolution region, the total gas mass (i.e. the sum of the atomic and molecular other authors, who define the dark gas fraction relative to

In Wolfire et al. (2010), but di total molecular gas. This definition is equivalent to that us
In particular, the long inter-arm filaments, which contain molecular hydrogen, are seen in Figure 3. These filaments extend throughout the galactic disc, with a density that is significantly lower than that found in the spiral arms. The molecular gas in these inter-arm regions is predominantly found in long filaments that were originally spurs connected to the disc. In the inter-arm regions, molecular hydrogen is often intermixed with other forms of gas, contributing to a complex interplay of different morphologies. The fractional abundance of molecular hydrogen relative to hydrogen in all forms is observed to vary significantly across different regions of the disc. As an example of the results obtained from our simulations, we see a range of morphologies, from dense spiral arms, to filaments, and to inter-arm regions. Each of these regions exhibits a different degree of shielding to the ambient radiation field and consequently a different level of ionization. We see from the maps that the gas exhibits a range of morphologies, from dense spiral arms, to filaments, to inter-arm regions, with emission being more prominent in the spiral arms.

Figure 7. [CII] surface brightness map of the Milky Way disc. The map shows the density distribution of the disc, with the color scale indicating the column density. The map is a result of our simulation, and it demonstrates the correlation between the surface brightness of [CII] lines and the molecular hydrogen column density. The [CII] lines are used as a tracer of the CO-dark molecular component, and the map shows the distribution of this component across the disc. The results are consistent with theoretical predictions and observations of CO emission. The map is a valuable tool for understanding the structure and dynamics of the galactic disc, particularly in regions where CO emission is not particularly sensitive to the gas distribution.
- weak correlation between [CII] emission and H$_2$ column density (saturation at large columns)
- CO-bright component is cold (T $\lesssim$ 30 K) and gas is almost 100% molecular (clouds)
- CO-dark gas has range of temperatures (30 K $\lesssim$ T $\lesssim$ 100 K), H$_2$ fraction varies strongly
of the estimated...this line and the H...and consequently the correlation between the surface brightness of

illustrated clearly in Fig. 10. We see that even in...energy required to excite the fine-structure lines makes [O II] maps, but that doing so at high accuracy will be...challenging.

In Fig. 11, we show a map of the [CII] surface brightness in...Figure 14. Top panel: as Fig...2014, but for the Strong Field simulation. The...Field simulation (Fig. 13), we show a map of the [CII] surface brightness in...13. We see that it also strongly affects the [CII] surface brightness in the Strong...261.1 Myr. (b) As (a), but for the 145...the [CII] surface brightness in the Strong Field simulation at time $t = 261.1$ Myr. Comparing this with...$= 3011 – 3025$ (2016)

spatial distribution of the [CII] surface brightness...In this case, the greater difference in the CO brightness of these two regions, and...that much less dense structure formed in the interarm regions in the Low Density simulation than in the Milky Way simulation. This led...we see here that it also strongly affects the [CII] surface brightness in the Strong Field simulation (Fig. 14).

We have also investigated the behaviour of the [CII] of the interarm gas. We see similar behaviour if we look at the spatial distribution of the...extremely weak, on account of the low gas temperature, and is un...

detection thresholds of around...detection. The temperature and chemical composition of the gas from the interarm regions is much lower and is unlikely to be...Our Low Density simulation shows that...at University Heidelberg on September 16, 2016

standard MW case
dlow surface density
standard surface density with high radiation field ($G_0 = 17$)

(Glover & Smith, 2016, 462, 3011)
comparison with data from SOFIA large program on M51
new models (full disk)

same as in Smith et al. (2014), but improved:
• more realistic potential (better disk scale height)
• larger disk area
• with self-gravity and supernovae feedback!
• two types now:
  - high resolution (4 M☉) wedge as previously
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more information about the M51 SOFIA project in talk by Jorge Pineda

comparison with data from SOFIA large program on M51
details of CO emission

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

relation between $\text{H}_2$ and CO
Filamentary molecular clouds in inter-arm regions are likely only the observable parts of much larger structures.
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. \( f_{DG} \sim 0.5 \)
(in prep.)

* dust methods have large uncertainties.

\( f_{DG} = 0.42 \)

probably more on that in talk by Paul Goldsmith

what is coming ...
new models that include self-consistent star formation
new models that include self-consistent star formation
Girichidis et al.
current developments

recombination lines

... in further observables: HI, Hα, other radio

Figure 6 shows for each sink particle formed in the three

star formation by early feedback (see also Gatto et al. 2016).

reduced by one order of magnitude compared to run FSN.

events. As a result, the averaged SFR in these simulations is

runs FWSN and FRWSN display many fewer star formation

occur steadily from the onset of star formation at

some notable di

these stars provide a floor to the observed SFR.

a significant level after the first star formation event, since

the shape of the IMF, these stars at the lower end of the

lives for 35 Myr before it explodes as supernova. Because of

short lifetimes (less than 7 Myr). In contrast, a 9 M

SILCC collaboration: http://hera.ph1.uni-koeln.de/~silcc/
zoom-in calculations to provide better boundary conditions for star cluster formation simulations
ISM dynamics is intrinsically a multi-scale and multi-physics problem. Many different processes need to be considered simultaneously.
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• Example 1: hierarchical Bayesian statistics indicated complex relation between ISM properties and star formation on galactic scales (Kennicutt Schmidt relation).

• Example 2: detailed (M)HD calculations with time-dependent chemistry allow us to study the properties of CO-dark H2 gas.

(personal) WISH LIST for SOFIA:

• Help quantifying amount of CO-dark H2 in the Milky Way and in other galaxies.

• Identify and characterize convergent flows in turbulent ISM that form molecular clouds —> help determining initial conditions for star (cluster) formation.
thanks