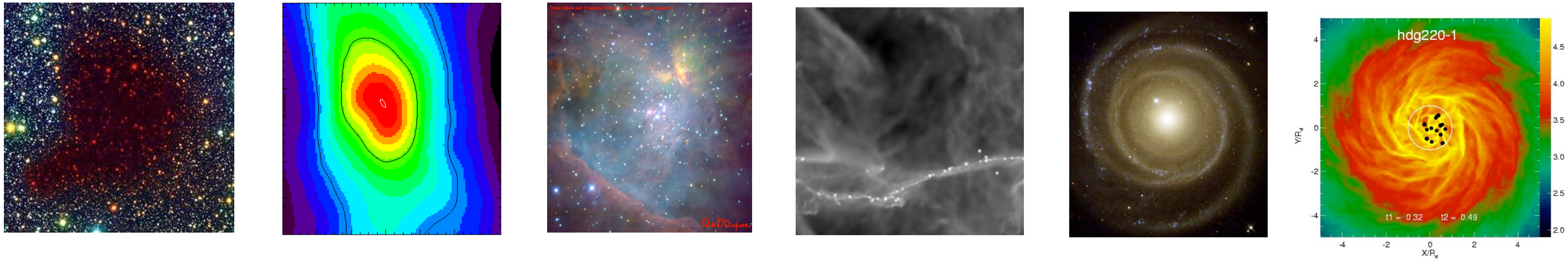
ISM Turbulence (and Star Formation)



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ARI+ITA+LSW

thanks to ...

Volker Bromm (Austin), Dennis Duffin (McMaster), Patrick Hennebelle (ENS),Thomas Greif (MPA), Eric Keto (CfA), Mordecai Mac Low (AMNH), Roberto Galvan-Madrid (CfA, UNAM), Ralph Pudritz (McMaster), Dominik Schleicher (ESO), Enrique Vazquez-Semadeni (UNAM)

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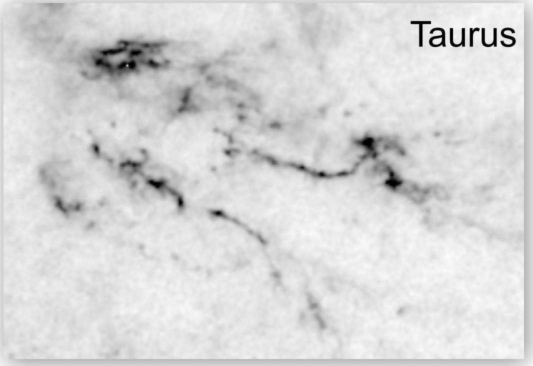
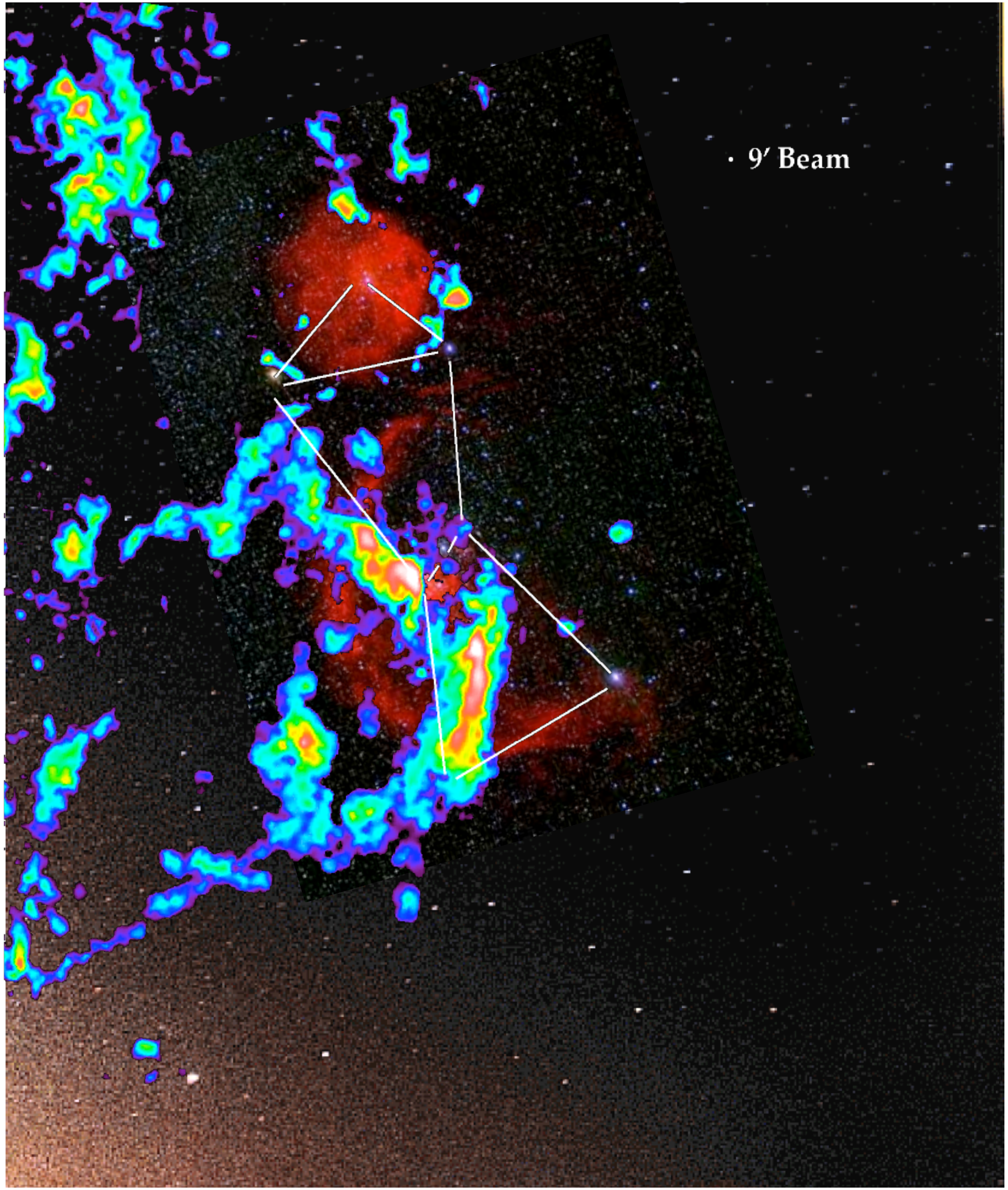
Agenda



- some phenomenology
  - what we know
  - what we need to explain
- turbulence in the ISM
  - some basic properties
  - statistics of turbulence (solenoidal vs. dilatational modes)
  - including more physics: time-dependent chemistry
    ---> formation of molecular clouds
  - the first (strong) magnetic fields in the universe
- summary

Star formation in Orion



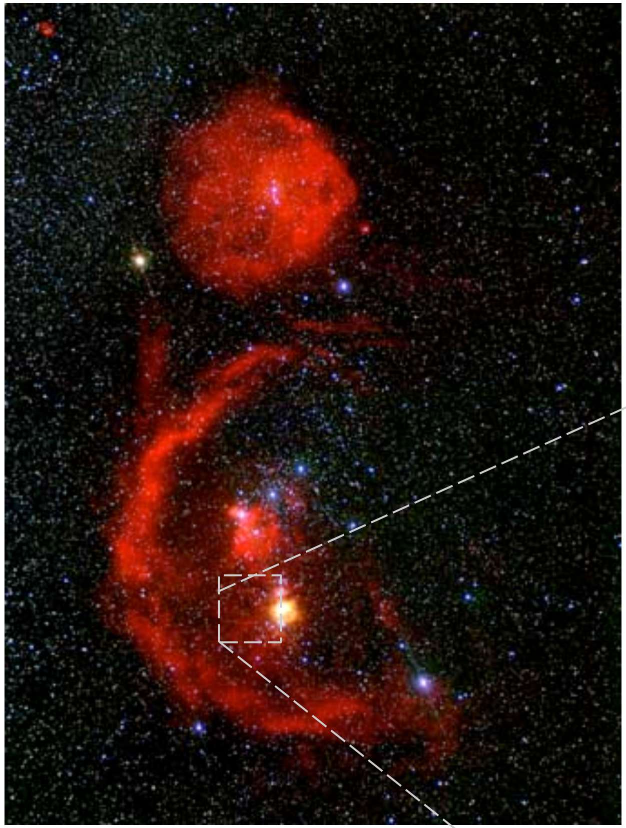
We see

- *Stars* (in visible light)
- Atomic hydrogen (in Hα -- red)
- Molecular hydrogen H_2 (radio emission -- color coded)

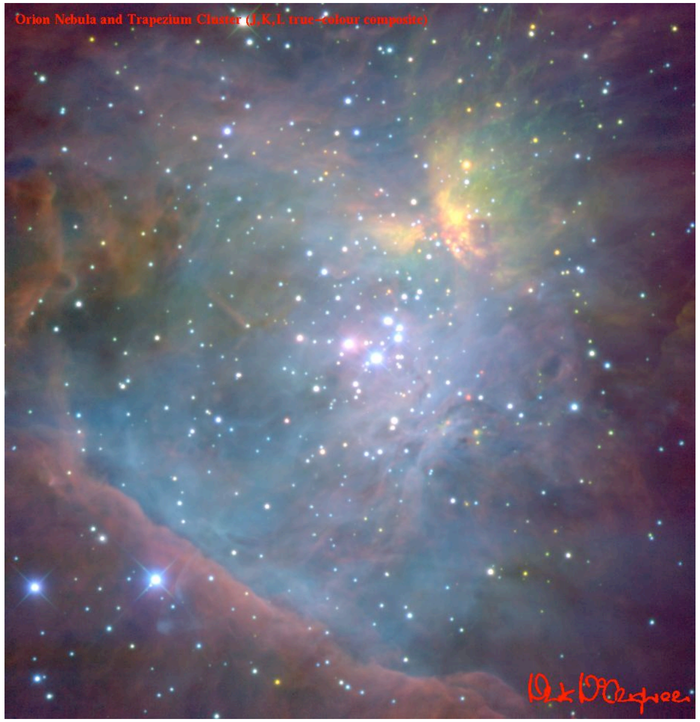
Local star forming region: The Trapezium Cluster in Orion

The Orion molecular cloud is the birth- place of several young embedded star clusters.

The Trapezium cluster is only visible in the IR and contains about 2000 newly born stars.

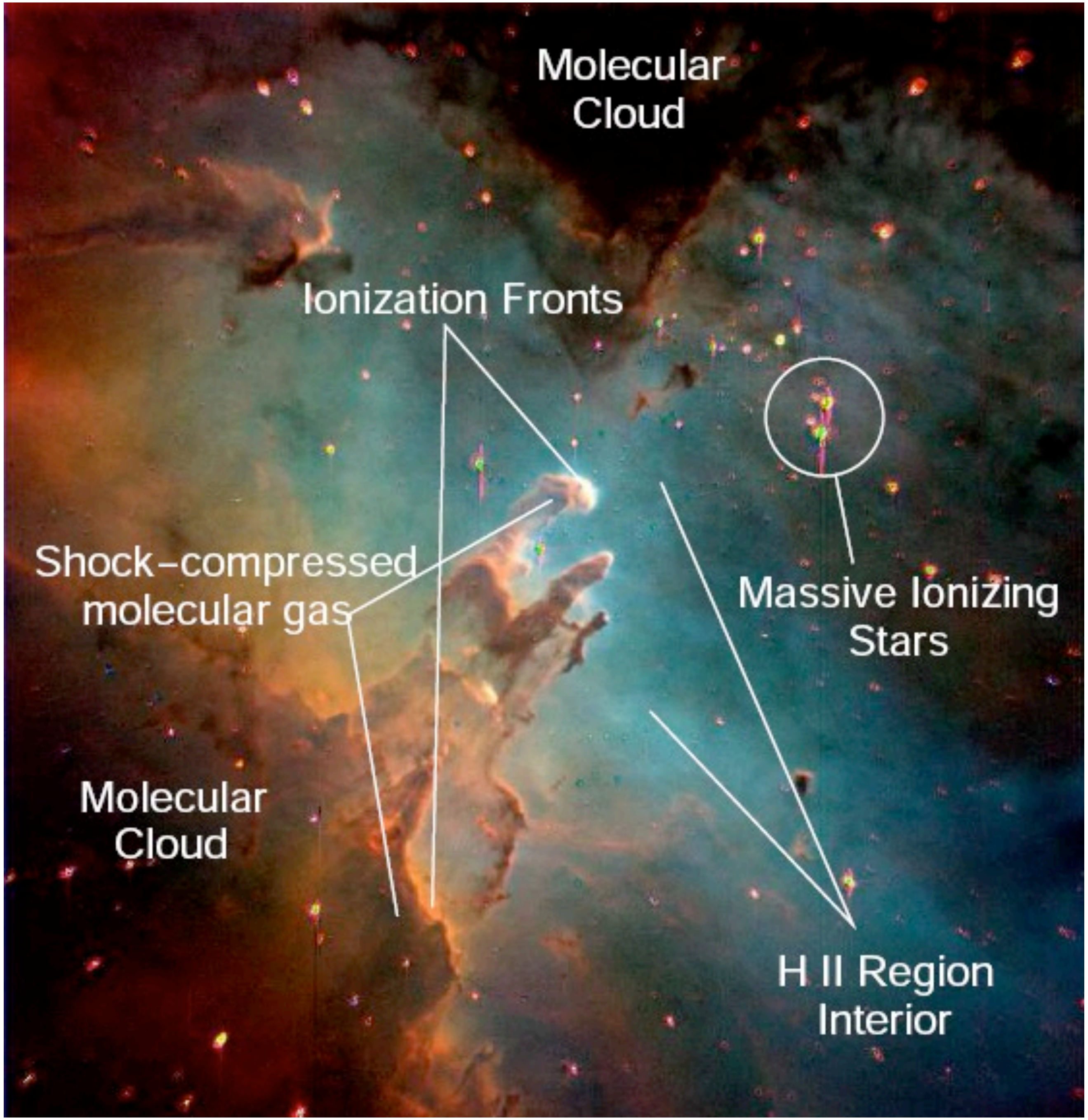


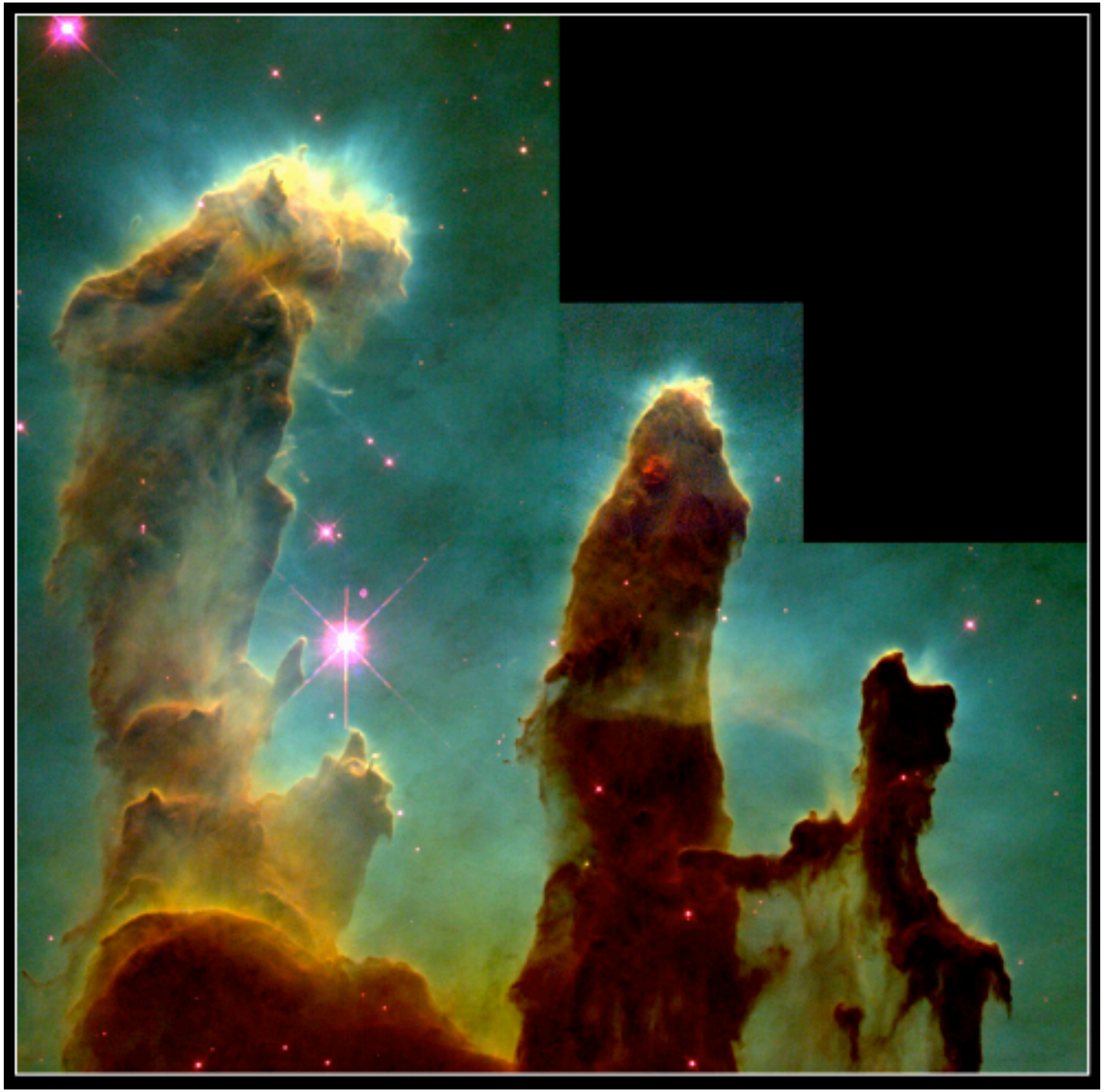
Orion molecular cloud



Trapezium cluster

alles in einem Bild





HST Aufnahme

Pillars of God (in Eagle Nebula): Formation of small groups of young stars in the tips of the columns of gas and dust ….

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Infrared
observation

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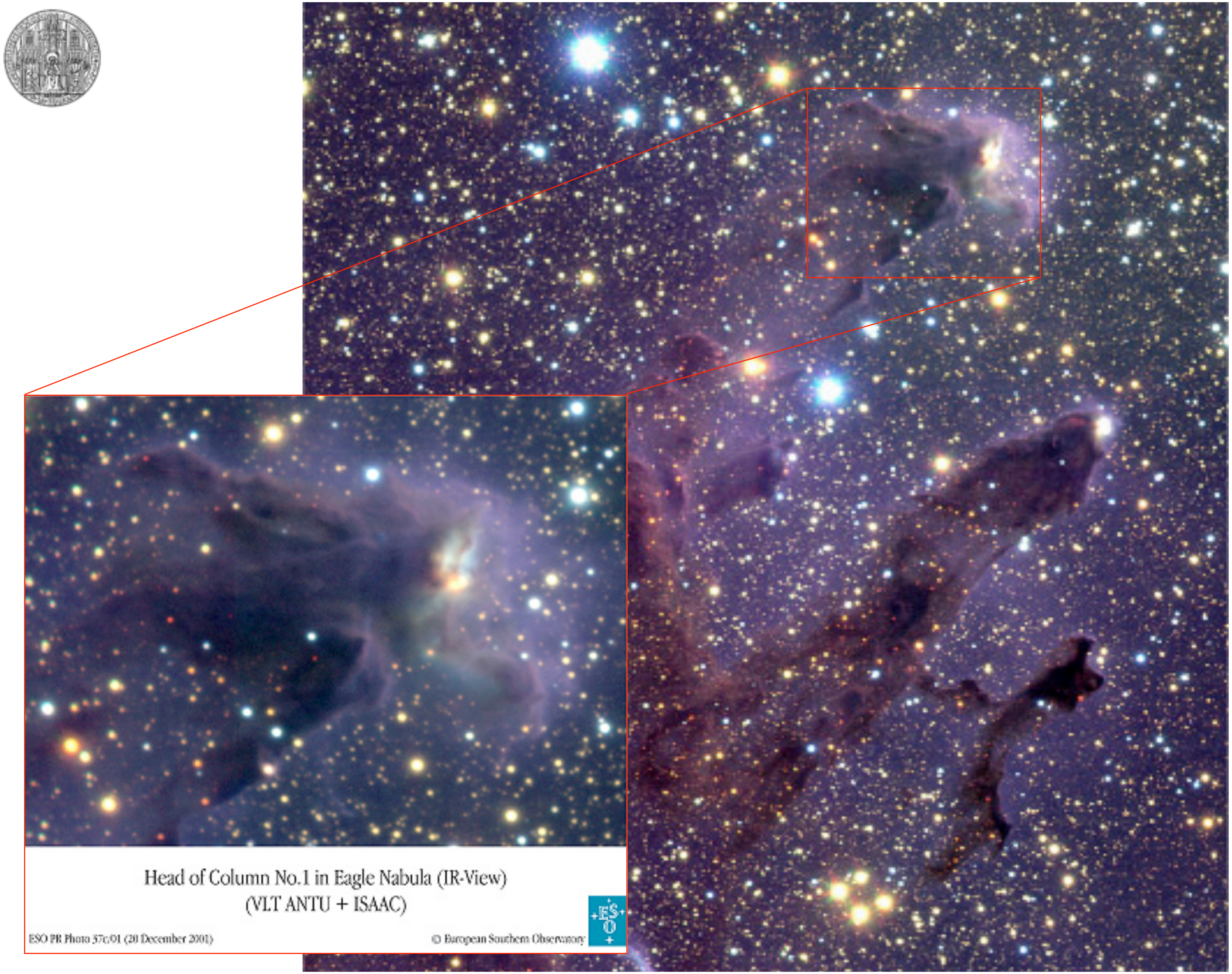
of



Head of Column No.1 in Eagle Nabula (IR-View)
(VLT ANTU + ISAAC)

ESO PR Photo 57c/01 (20 December 2001)

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IR observation with ESO-VLT

Pillars of God (in Eagle Nebula): Formation of small groups of young stars in the tips of the columns of gas and dust ….

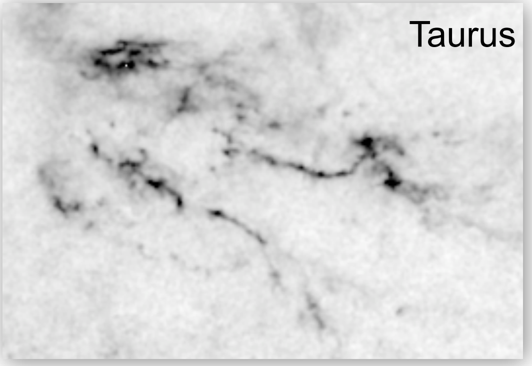
IR observation with ESO-VLT

Pillars of God (in Eagle Nebula): Formation of small groups of young stars in the tips of the columns of gas and dust ….

Interstellar Matter: ISM

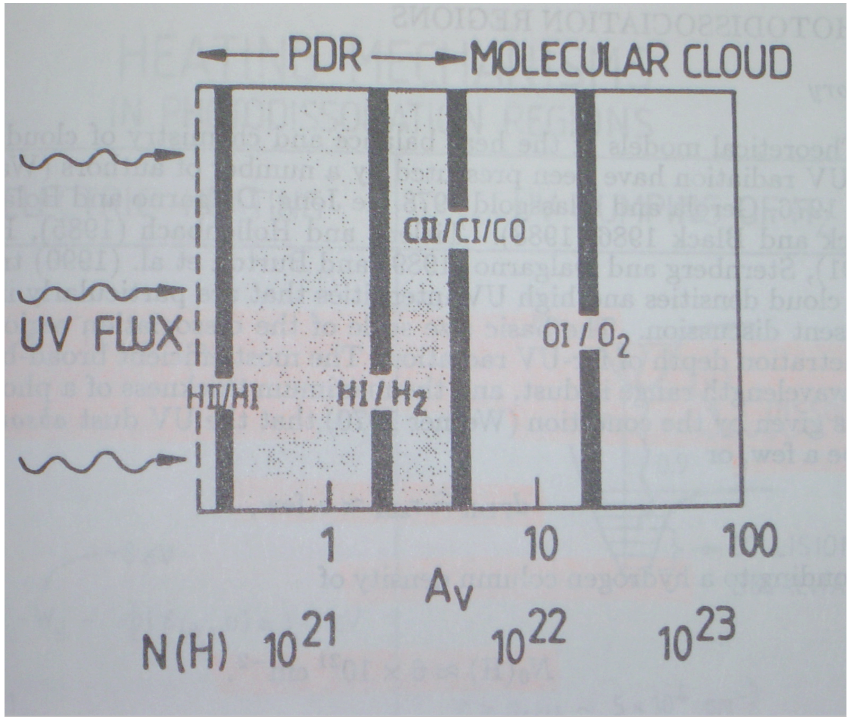
Abundances, scaled to 1.000.000 H atoms

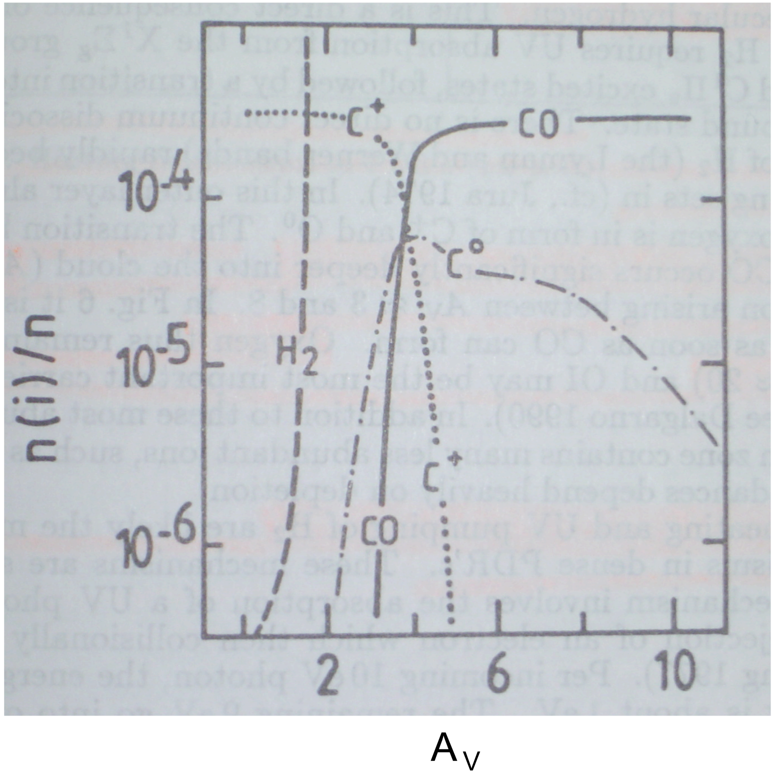
element		atomic number	abundance
hydrogen	H	1	1.000.000
deuterium	$_1H^2$	1	16
helium	He	2	68.000
carbon	C	6	420
nitrogen	N	7	90
oxygen	O	8	700
neon	Ne	10	100
sodium	Na	11	2
magnesium	Mg	12	40
aluminium	Al	13	3
silicium	Si	14	38
sulfur	S	16	20
calcium	Ca	20	2
iron	Fe	26	34
nickel	Ni	28	2



hydrogen is by far the most abundant element (more than 90% in number).

Phases of the ISM





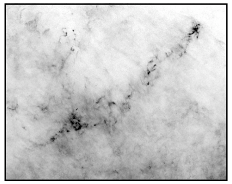
HII **HI** **H_2**

density / column density increases

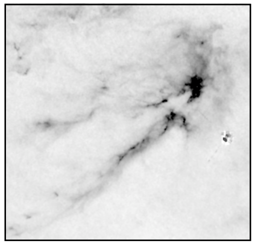
A_V denotes the extinction, the attenuation of radiation due to absorption (mostly on dust grains)

nearby molecular clouds

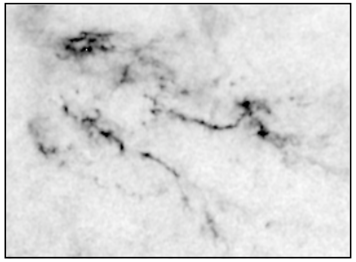
-Pipe



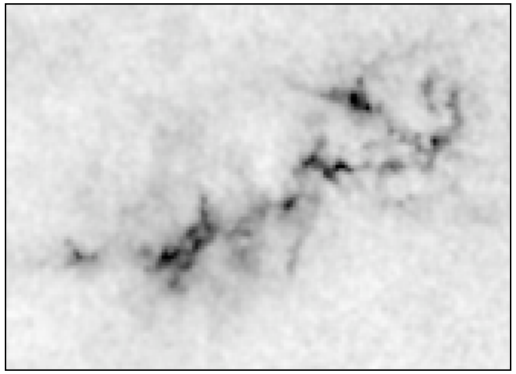
-Ophiuchus



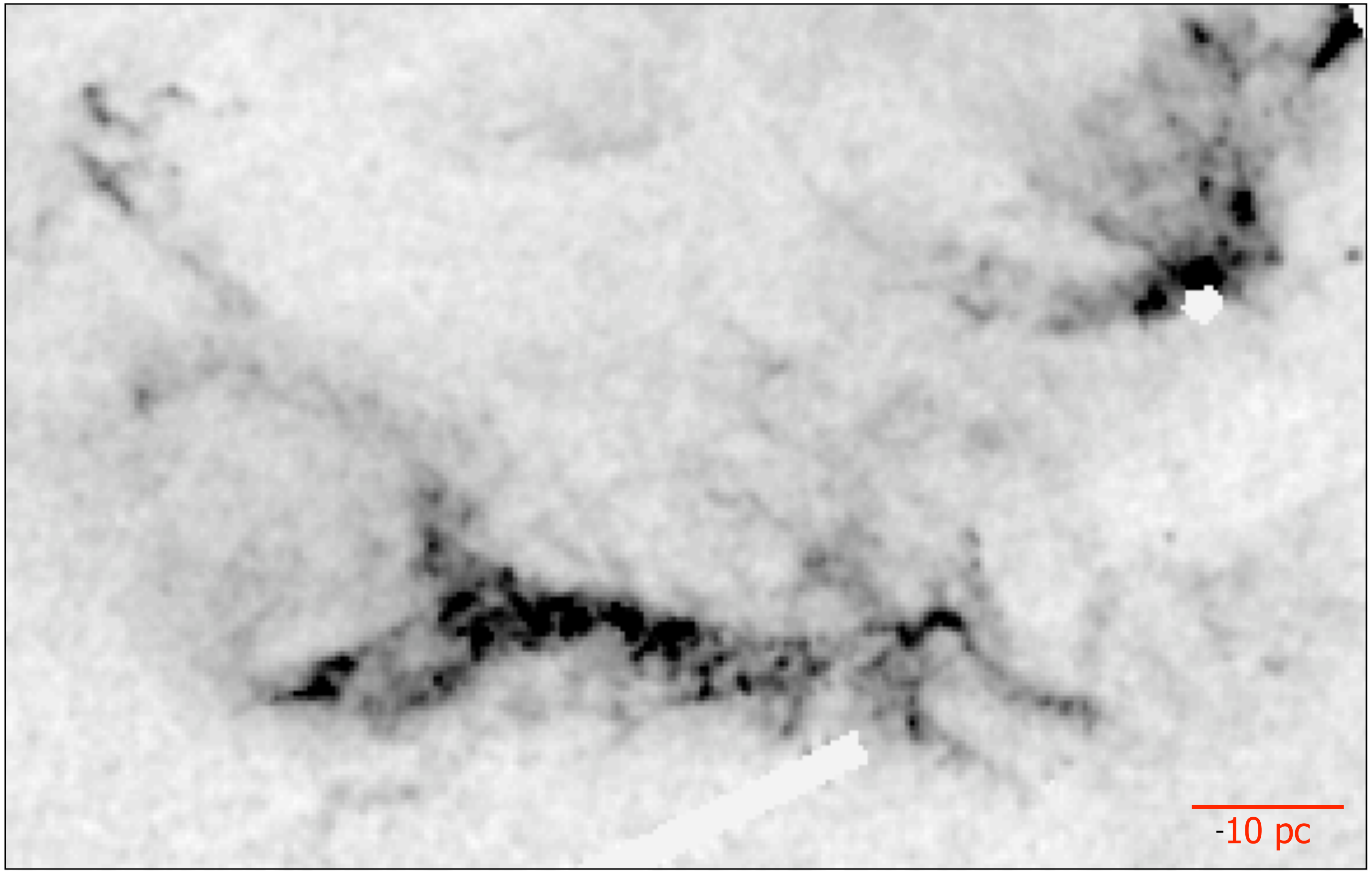
-Taurus



-Perseus



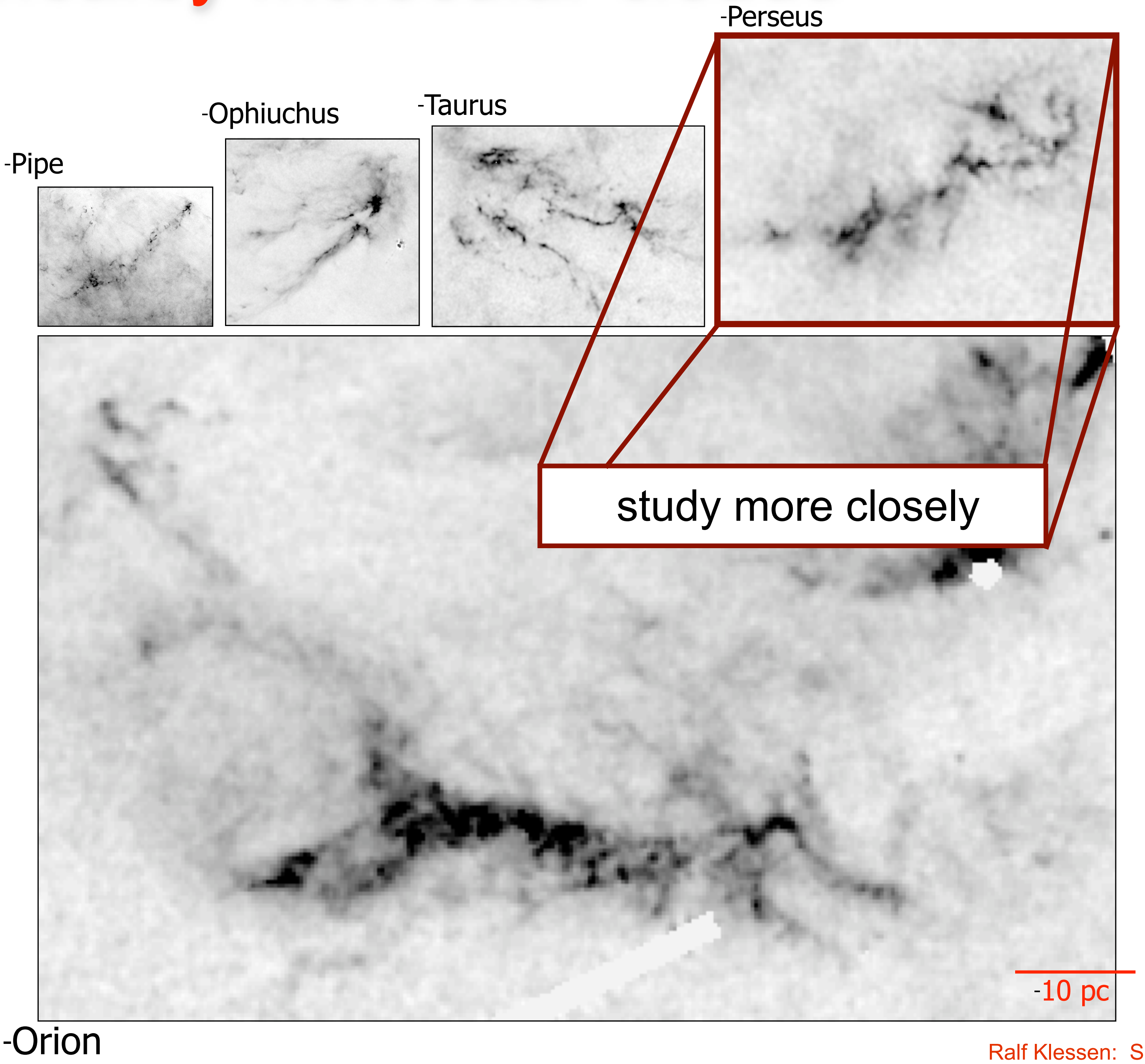
scales to same scale



-Orion

(from A. Goodman)

nearby molecular clouds



study more closely

scales to same scale

(from A. Goodman)

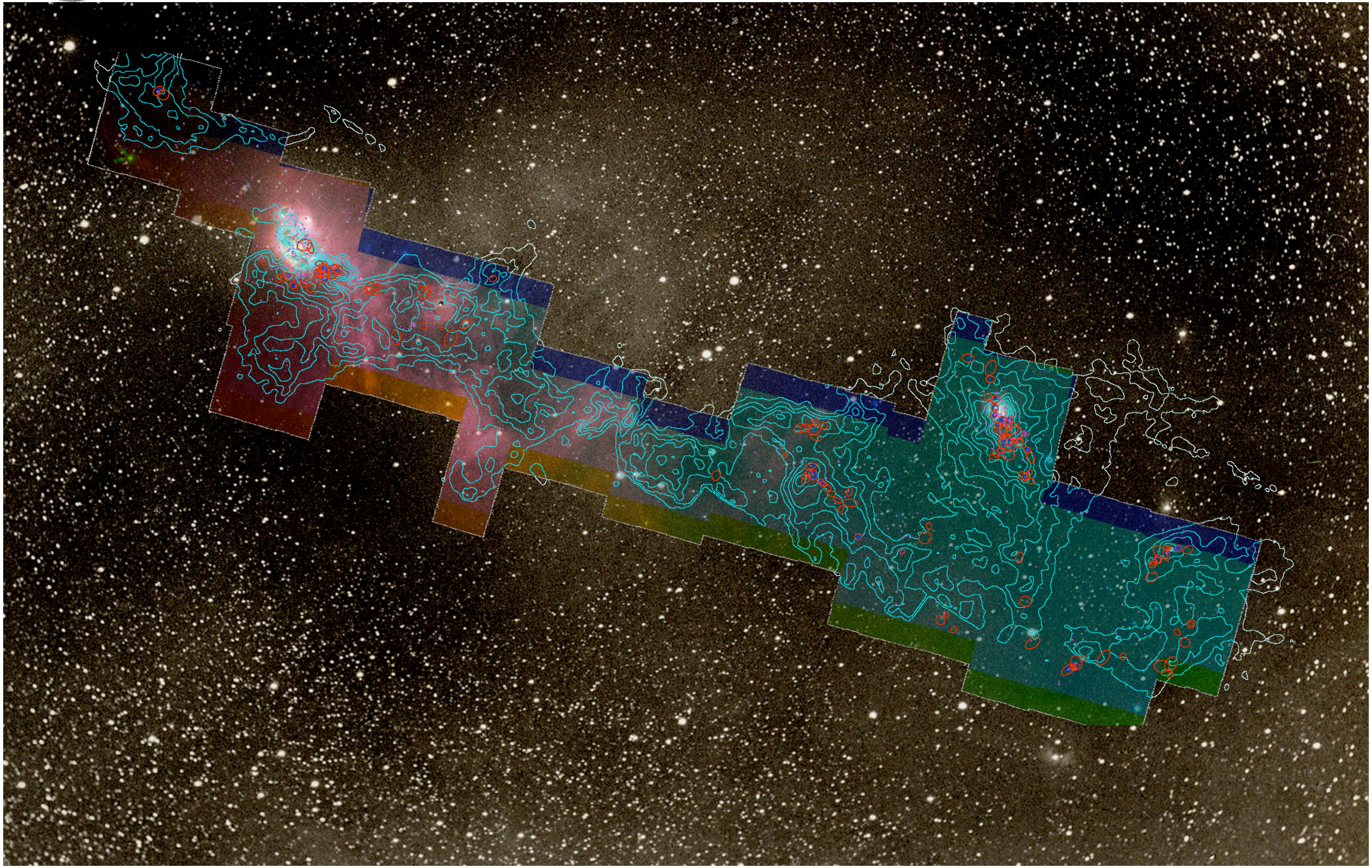
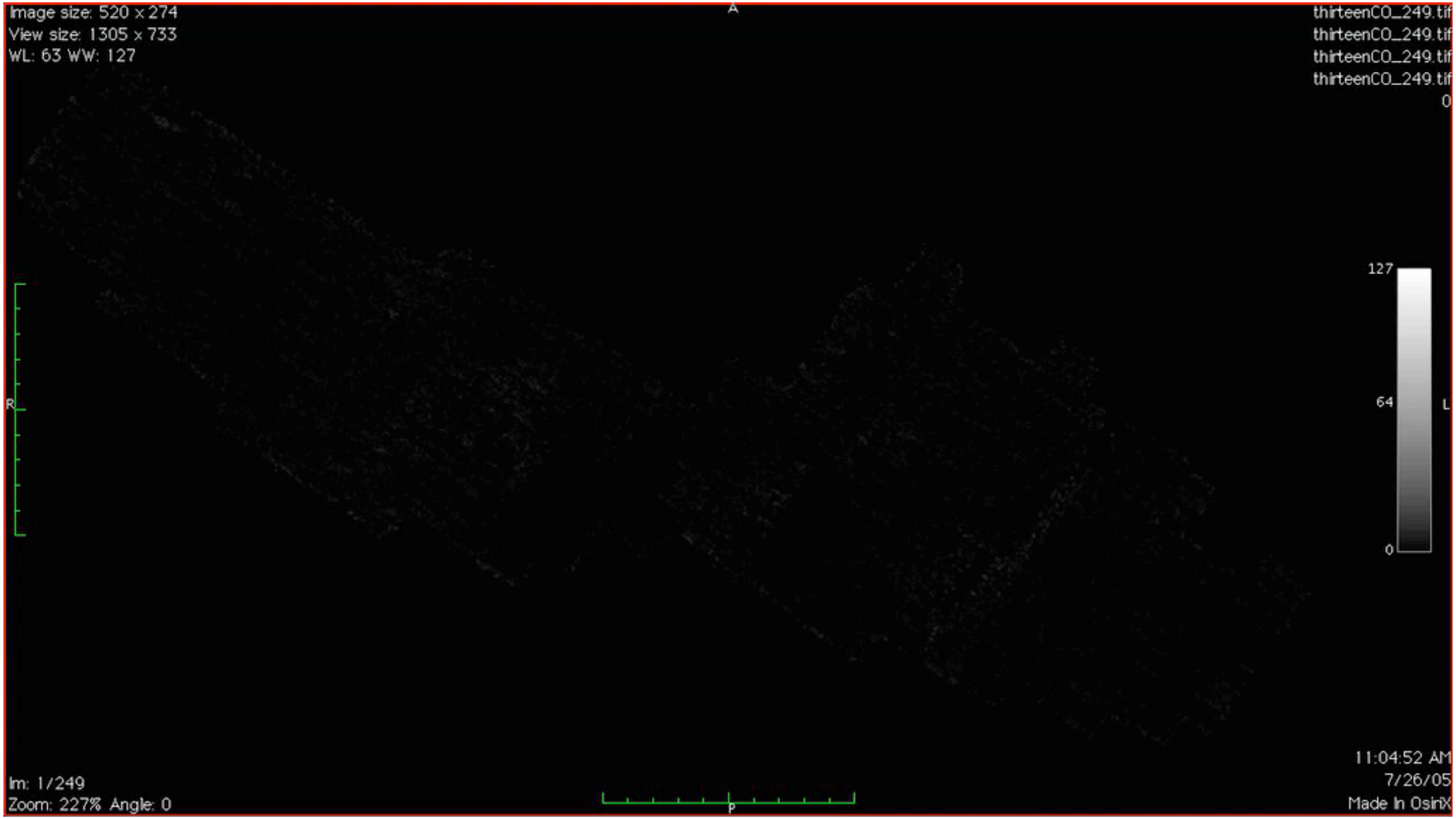
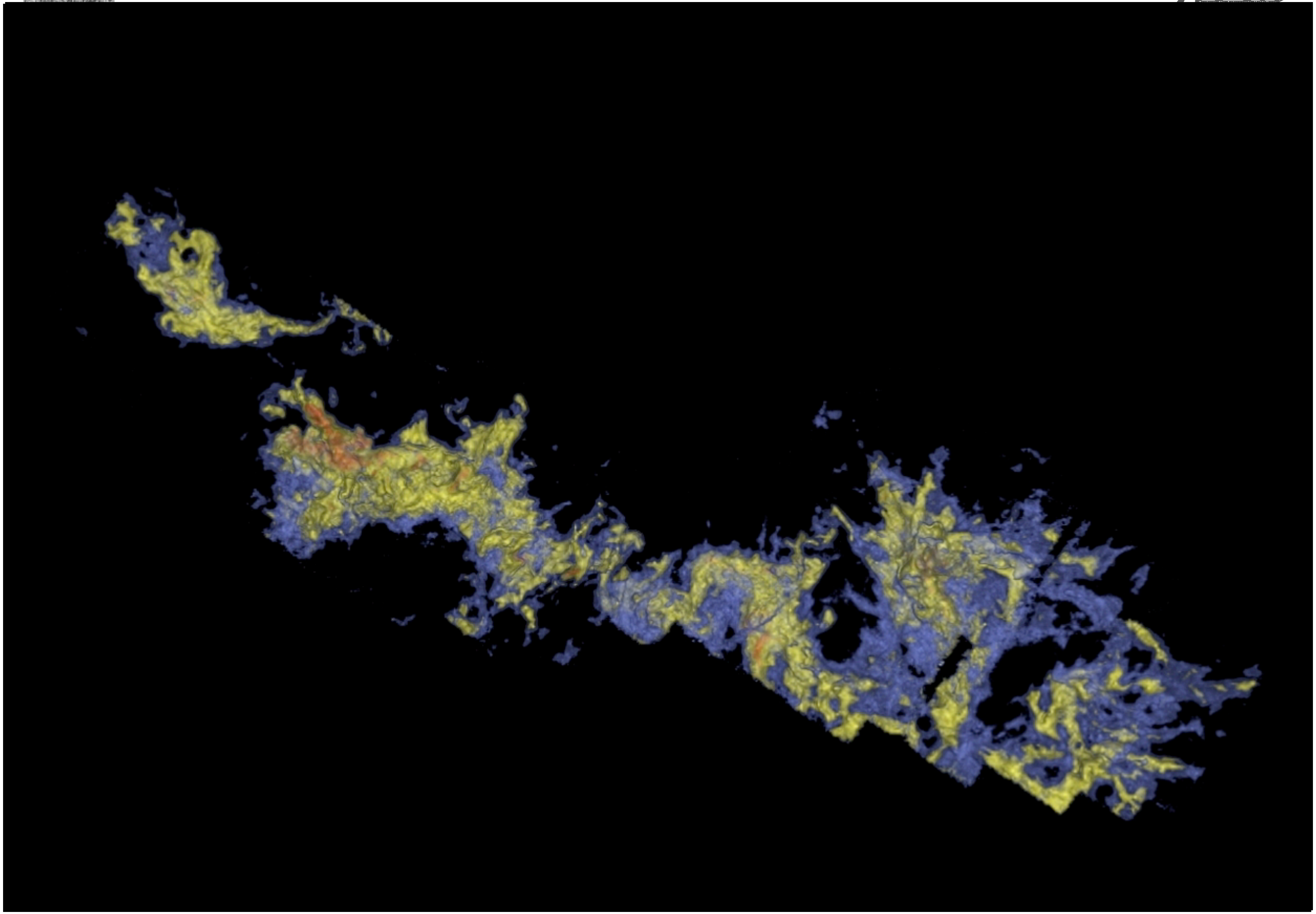


image from Alyssa Goodman: COMPLETE survey



velocity distribution in Perseus

velocity cube from Alyssa Goodman: COMPLETE survey



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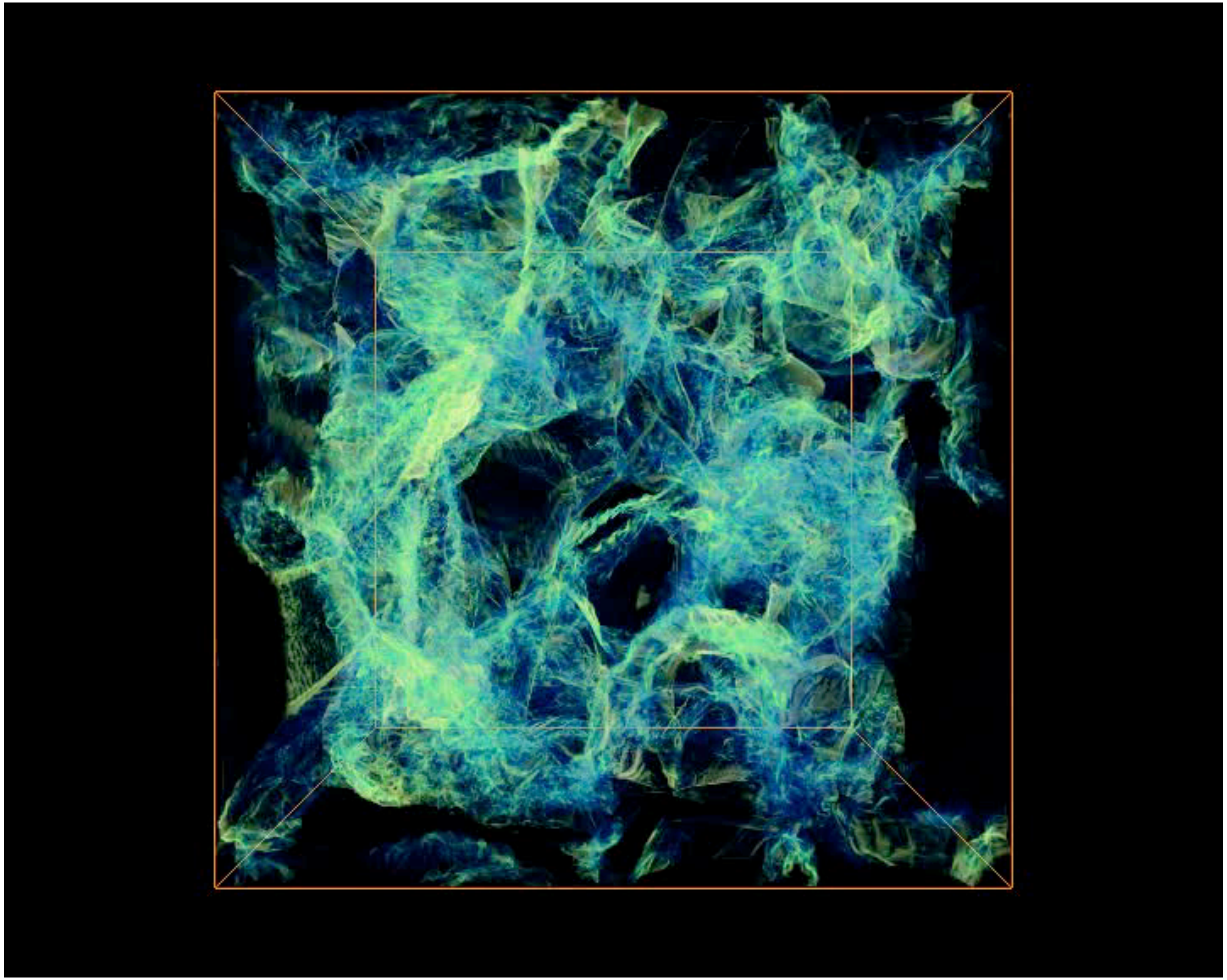
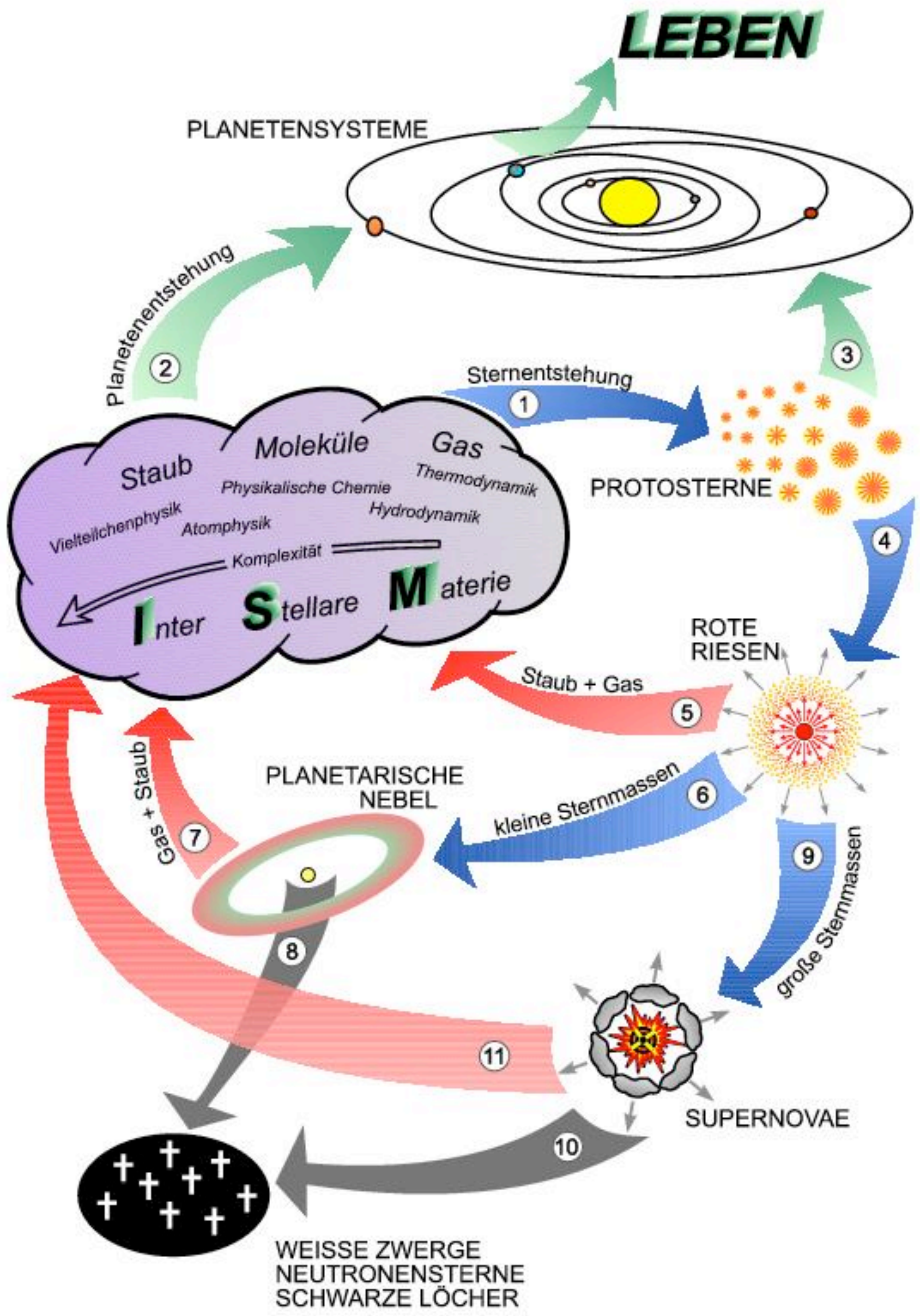


(movie from Christoph Federrath)

what we want



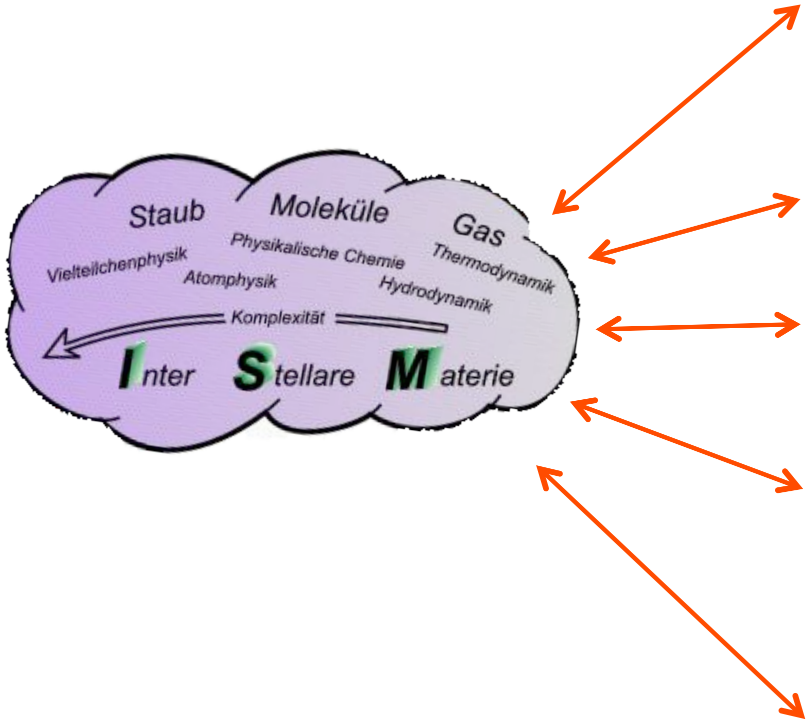
(from AG meeting in Berlin 2002)

it is this complex matter cycle that we want to model

feedback loops on virtually all scales

multi-scale and multi-physics problem

What do we need to study ISM?



magneto-hydrodynamics
(multi-phase, non-ideal MHD,
turbulence)

chemistry (gas + dust, heating + cooling)

radiation (continuum + lines)

stellar dynamics
(collisional: star clusters,
collisionless: galaxies, DM)

stellar evolution
(feedback: radiation, winds, SN)

\+ **laboratory work**
(reaction rates, cross sections,
dust coagulation properties, etc.)

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- massive parallel codes
- particle-based: SPH with improved algorithms (XSPH with turb. subgrid model, GPM, particle splitting, MHD-SPH?)
- grid-based: AMR (FLASH, ENZO, RAMSES, Athena, Nirvana3, etc), subgrid-scale models (FEARLESS)
- BGK methods

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(reaction rates, cross sections, dust coagulation properties, etc.)

- ever increasing chemical networks
- working reduced networks for time-dependent chemistry in combination with hydrodynamics
- improved data on reaction rates (laboratory + quantum mechanical calculations)

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(reaction rates, cross sections,
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- continuum vs. lines
- Monte Carlo, characteristics
- approximative methods
- combine with hydro

What do we need to study ISM?

- statistics: number of stars (collisional: 10^6, collisionless: 10^{10})
- transition from gas to stars
- binary orbits
- long-term integration

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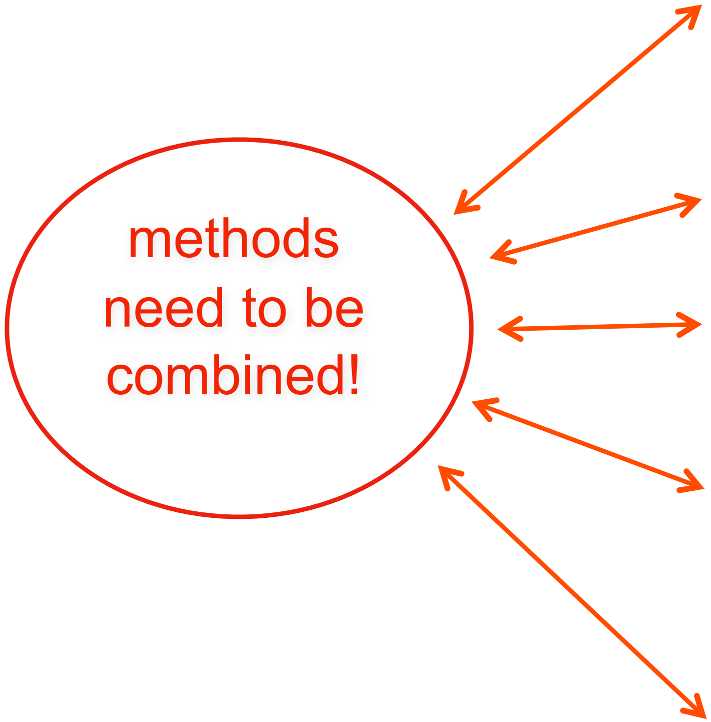
- very early phases (pre main sequence tracks)
- massive stars at late phases
- role of rotation
- primordial star formation

What do we need to study ISM?



methods
need to be
combined!

magneto-hydrodynamics
(multi-phase, non-ideal MHD,
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chemistry (gas + dust, heating + cooling)

radiation (continuum + lines)

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(collisional: star clusters,
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stellar evolution
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\+ **laboratory work**
(reaction rates, cross sections,
dust coagulation properties, etc.)

challenges

- Problem of star formation is very complex. It involves many scales (10^7 in length, and 10^{20} in density) and many physical processes → *NO* analytic solution
  → NUMERICAL APPROACH
- BUT, we need to…
  - solve the MHD equations in 3 dimensions
  - solve Poisson's equation (self-gravity)
  - follow the full turbulent cascade (from galactic scales to stellar surface)
  - follow chemical evolution (time-dependent chemical network)
  - include heating / cooling processes (internal degrees of freedom)
  - treat radiation transfer

IMPOSSIBLE

approach

- Simplify!
  Divide problem into little bits and pieces….
- **GRAVOTURBULENT CLOUD FRAGMENTATION**
- We try to…
  - solve the HD equations in 3 dimensions
  - solve Poisson's equation (self-gravity)
  - include a (humble) approach to supersonic turbulence
  - include simple chemical network & tabulated cooling functions
  - follow collapse: include "sink particles"
    (this will "handle" our subgrid-scale physics)

LARGE-EDDY SIMULATIONS

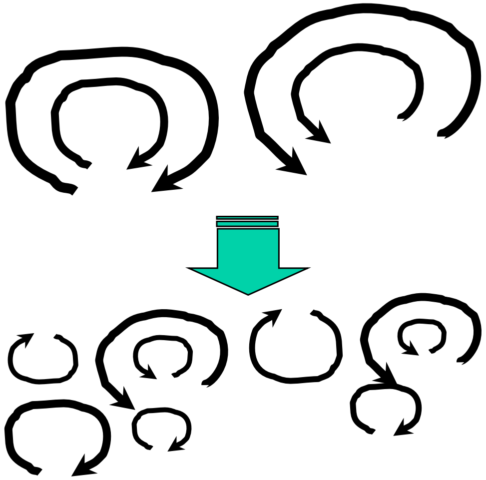
turbulence

Properties of turbulence

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

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

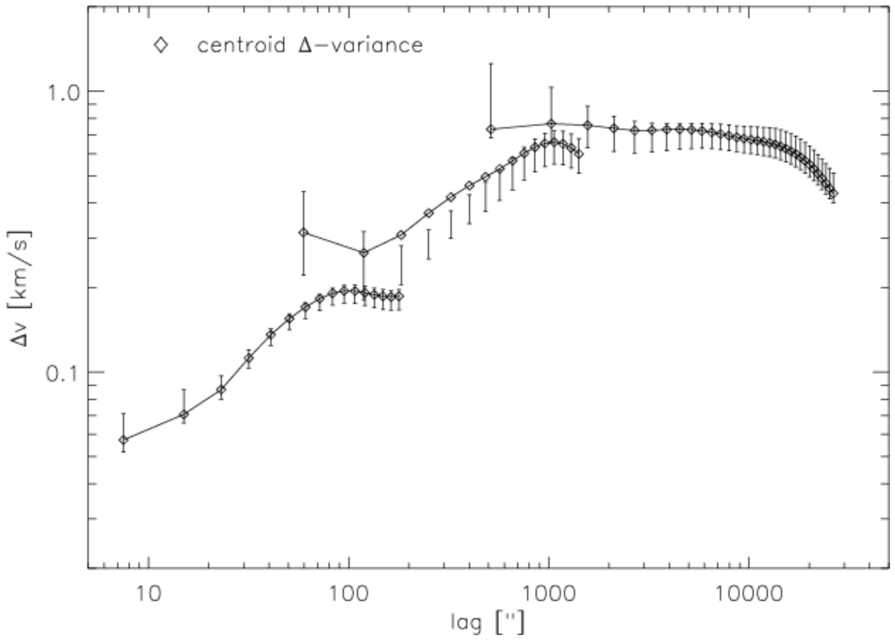
V= typical velocity on scale L, ν = viscosity, Re > 1000



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

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

what drives turbulence?

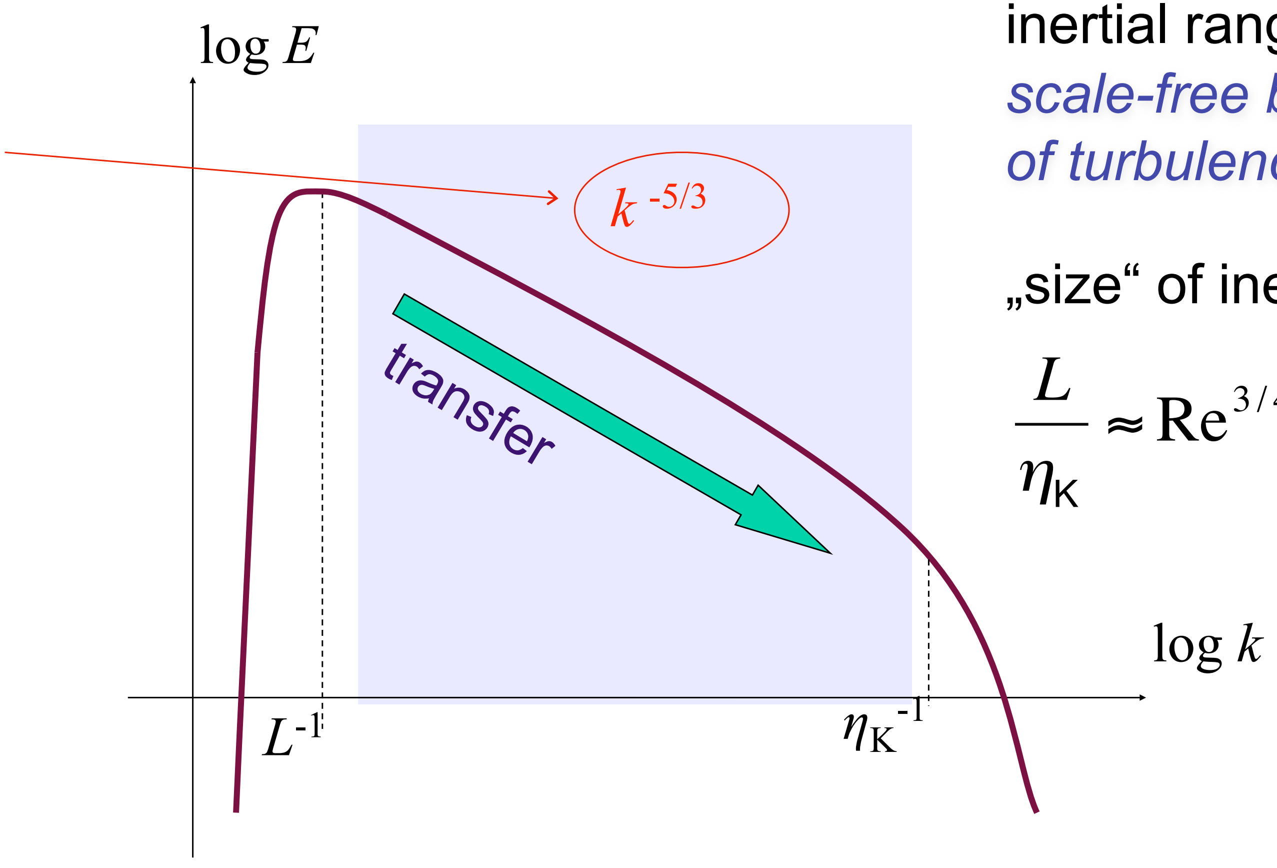


Polaris flare (from Ossenkopf & Mac Low 2002)

- turbulence characteristics
  - molecular cloud turbulence seems to be dominated by large-scale models
  - consistent with external driving
  - convergent flows?
    → the same process that creates the cloud supplies internal turbulence ...
  - alternative mechanisms:
    - gravity (spiral shocks), supernovae, HII regions?
    - internal sources: jets, outflows?

Turbulent cascade

Kolmogorov (1941) theory
incompressible turbulence



energy
input
scale

energy
dissipation
scale

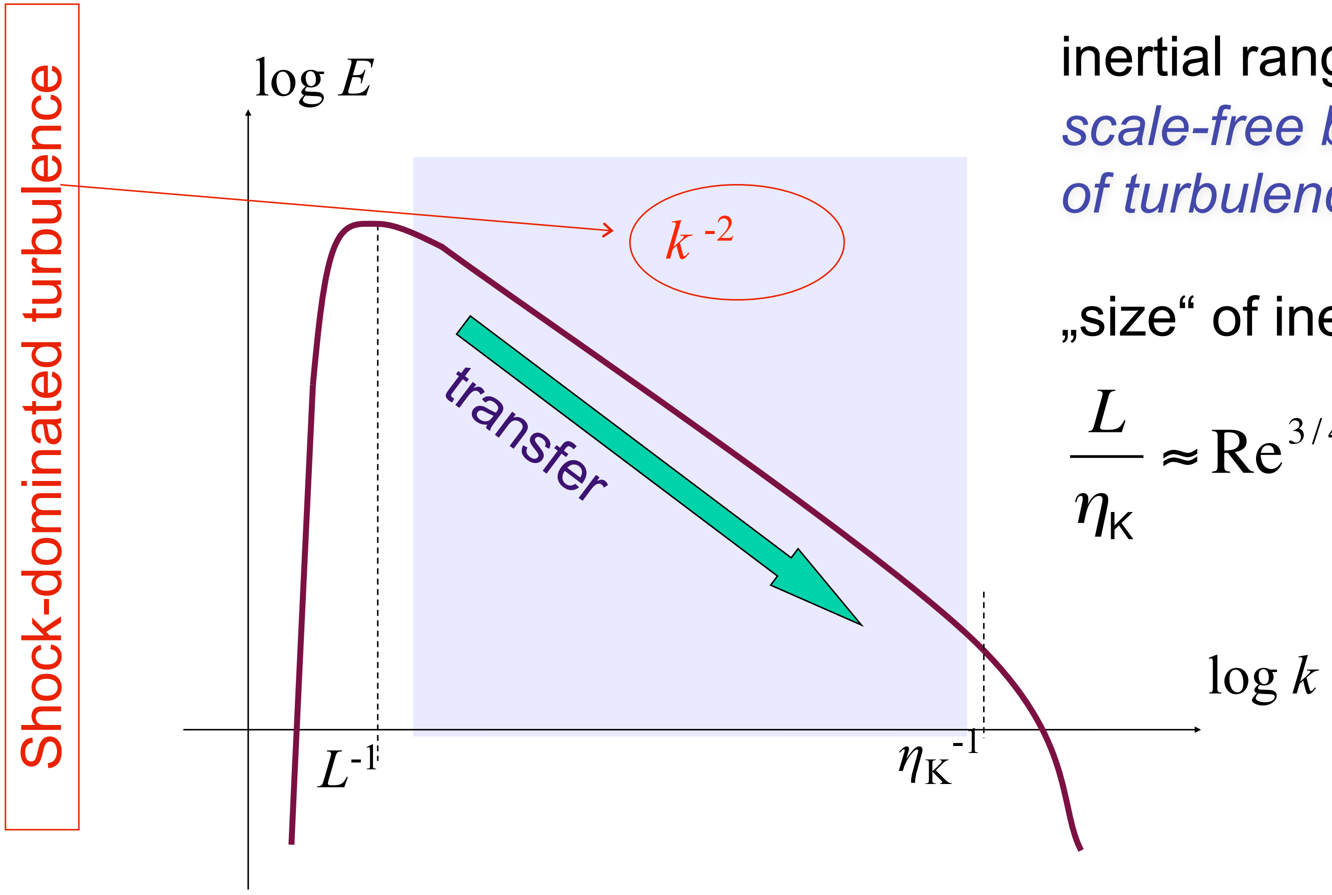
inertial range:

scale-free behavior of turbulence

„size“ of inertial range:

$$\frac{L}{\eta_K} \approx \mathrm{Re}^{3/4}$$

Turbulent cascade



inertial range:

scale-free behavior of turbulence

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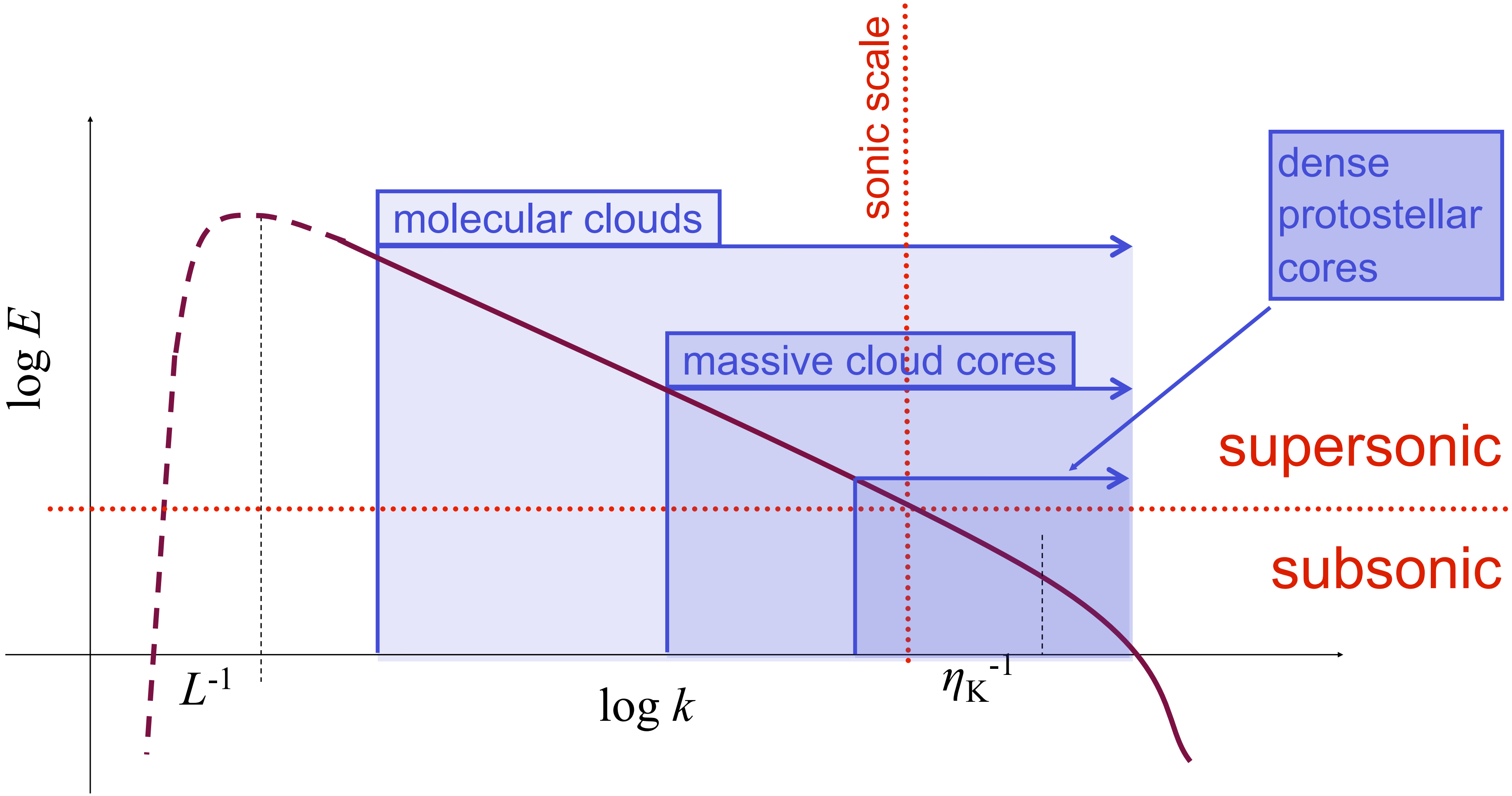
$$\frac{L}{\eta_K} \approx \mathrm{Re}^{3/4}$$

energy
input
scale

energy
dissipation
scale

Turbulent cascade in ISM



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

$\sigma_{rms} << 1$ km/s

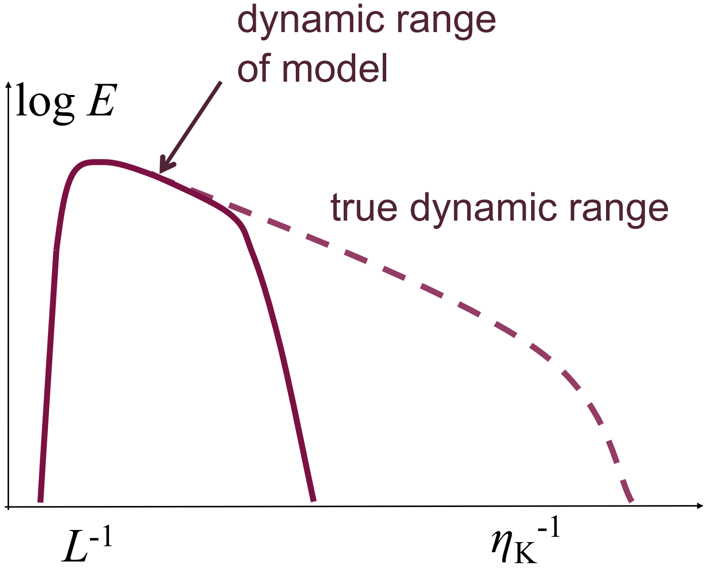
$\mathcal{M}_{rms} \leq 1$

$L \approx 0.1$ pc

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

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?



See also talks by Norman, Kritsuk, Müller, and others

three examples

- statistics of ISM turbulence
  - rotational vs dilatational modes
- formation of molecular cloud in the turbulent ISM
  - combining MHD with time-dependent chemistry
- the first (strong) B-fields in the universe
  - the turbulent dynamo in action

statistics

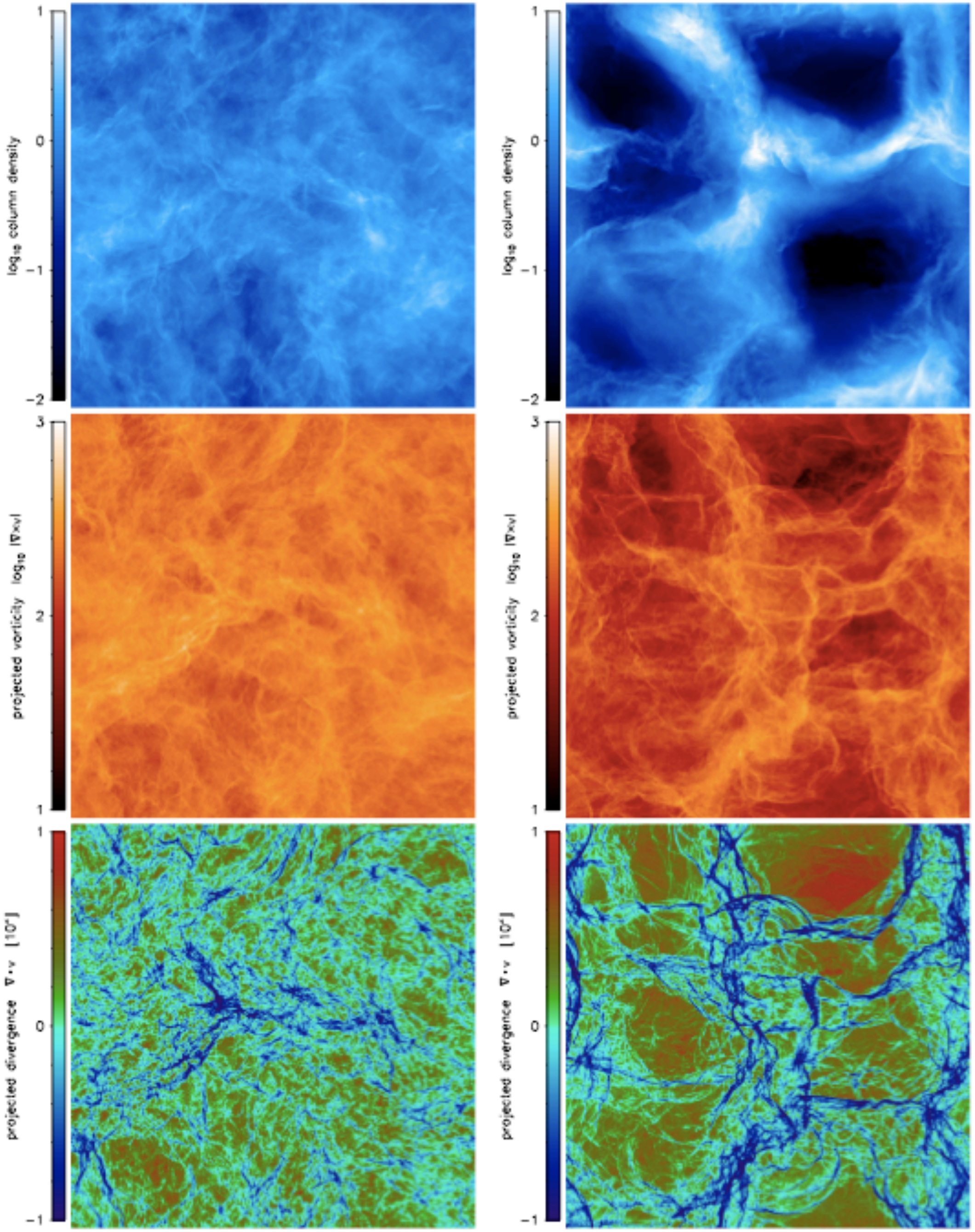
dilatational vs. solenoidal

density as function of time / cut through 1024^3 cube simulation (FLASH)

compressive
larger structures, higher ρ-contrast

rotational
smaller structures, small ρ-pdf

Federrath, Klessen, Schmidt (2008a,b)



column density

projected vorticity

projected divergence

Fig. 1. Maps showing density, vorticity and divergence in projection along the z-axis at time $t = 2\,T$ as an example for the regime of statistically fully developed compressible turbulence for solenoidal forcing (*left*) and compressive forcing (*right*). *Top panels:* Column density fields in units of the mean column density. Both maps show three orders of magnitude in column density with the same scaling and magnitudes for direct comparison. *Middle panels:* Projections of the modulus of the vorticity $|\nabla \times v|$. Regions of intense vorticity appear to be elongated filamentary structures often coinciding with positions of intersecting shocks. *Bottom panels:* Projections of the divergence of the velocity field $\nabla \cdot v$ showing the positions of shocks. Negative divergence corresponds to compression, while positive divergence corresponds to rarefaction.

dilatational vs. solenoidal

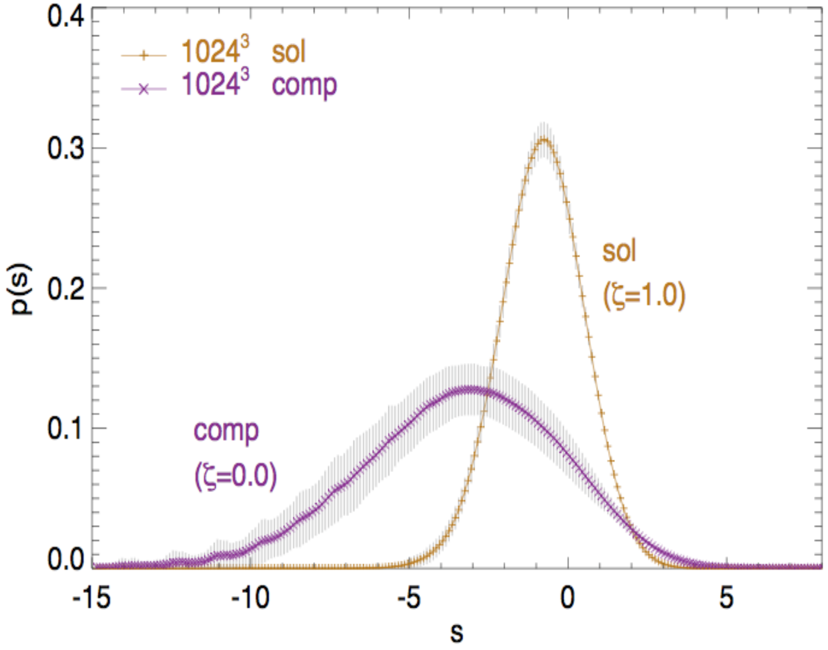


FIG. 2.— Volume-weighted density PDFs $p_s(s)$ in linear scaling where $s = \ln(\rho/\rho_0)$. The PDF obtained by compressive forcing (comp, $\zeta = 0.0$) is much broader compared to the solenoidal one (sol, $\zeta = 1.0$) at the same rms Mach number. The peak is shifted due to mass conservation (Vázquez-Semadeni 1994). Gray error bars indicate 1-sigma temporal fluctuations of the PDF. A sample of $\sim 10^{11}$ datapoints contribute to each PDF.

- density pdf depends on “dimensionality” of driving
    - relation between width of pdf and Mach number

$$\boxed{\sigma_\rho/\rho_0 = b\mathcal{M}}$$

    - with b depending on ζ via

$$\boxed{b = 1 + \left[\frac{1}{D} - 1\right]\zeta = \begin{cases} 1 - \frac{2}{3}\zeta & \text{, for } D = 3 \\ 1 - \frac{1}{2}\zeta & \text{, for } D = 2 \\ 1 & \text{, for } D = 1 \end{cases}}$$

    - with ζ being the ratio of dilatational vs. solenoidal modes:

$$\mathcal{P}_{ij}^{\zeta} = \zeta\mathcal{P}_{ij}^{\perp} + (1-\zeta)\mathcal{P}_{ij}^{\parallel} = \zeta\delta_{ij} + (1-2\zeta)\frac{k_i k_j}{|k|^2}$$

Federrath, Klessen, Schmidt (2008a)

dilatational vs. solenoidal

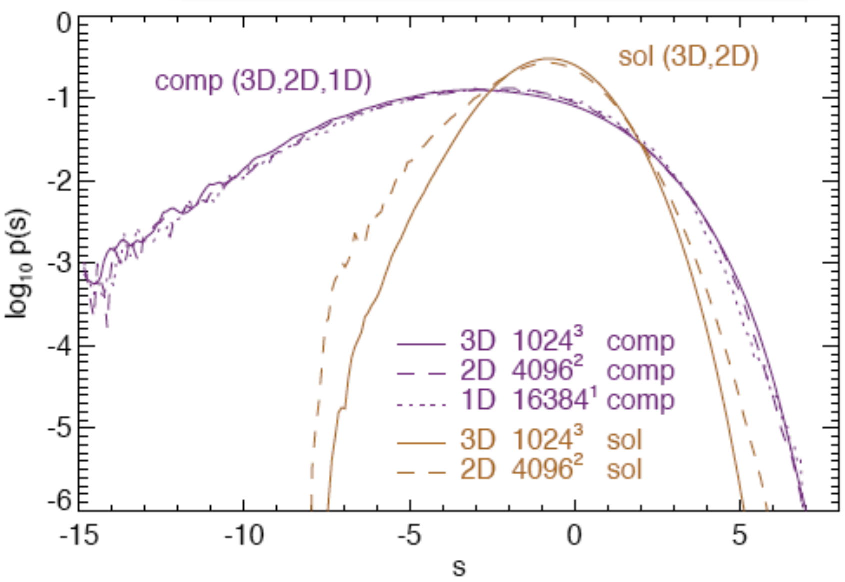


FIG. 3.— Volume-weighted density PDFs $p(s)$ obtained from 3D, 2D and 1D simulations with compressive forcing and from 3D and 2D simulations using solenoidal forcing. Note that in 1D, only compressive forcing is possible as in the study by Passot & Vázquez-Semadeni (1998). As suggested by eq. (5), compressive forcing yields almost identical density PDFs in 1D, 2D and 3D with $b\sim1$, whereas solenoidal forcing leads to a density PDF with $b\sim1/2$ in 2D and with $b\sim1/3$ in 3D.

- density pdf depends on "dimensionality" of driving
  - relation between width of pdf and Mach number

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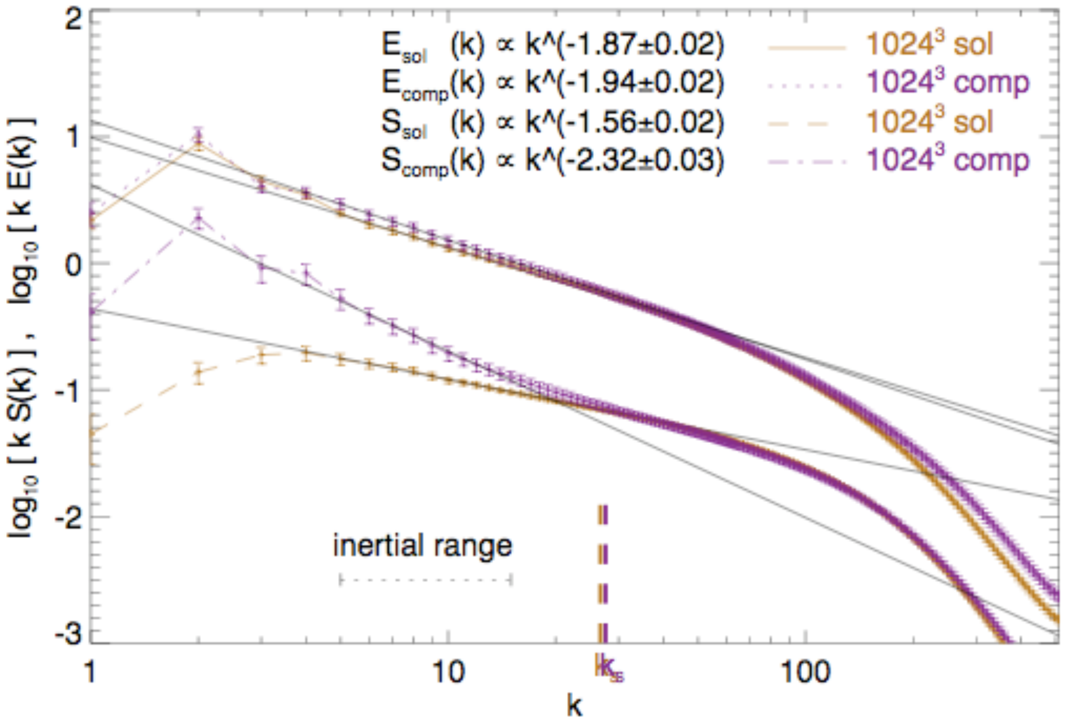
Federrath, Klessen, Schmidt (2008a)

dilatational vs. solenoidal



compensated density spectrum kS(k) shows clear break at sonic scale. below that shock compression no longer is important in shaping the power spectrum ...

- density power spectrum differs between dilatational and solenoidal driving!

→ dilatational driving leads to break at sonic scale!

- can we use that to determine driving sources from observations ?

Federrath, Klessen, Schmidt (2008b)

dilatational vs. solenoidal

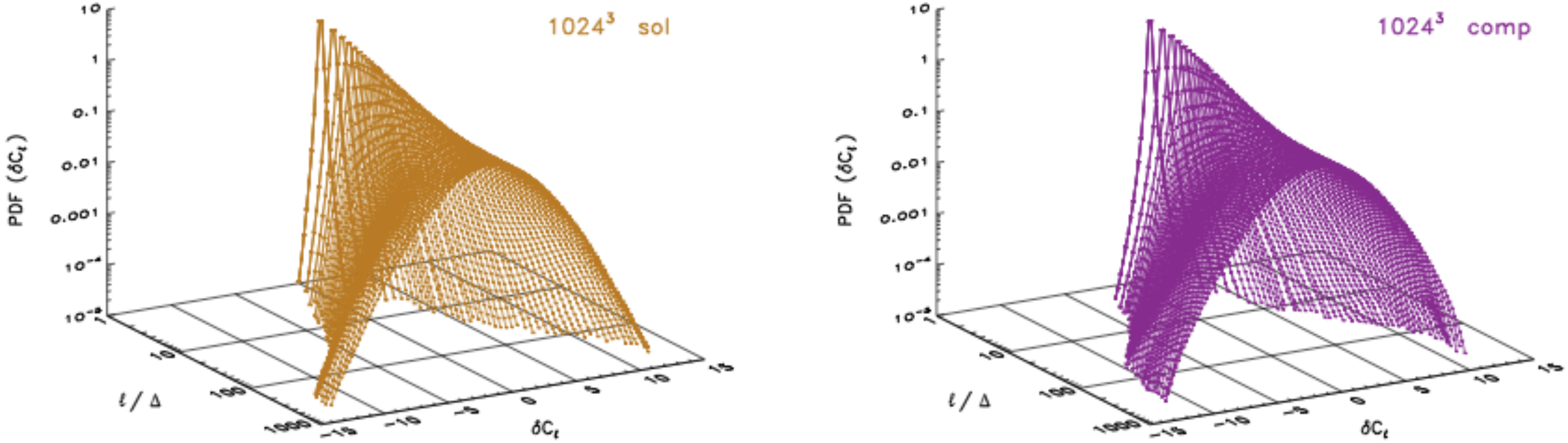
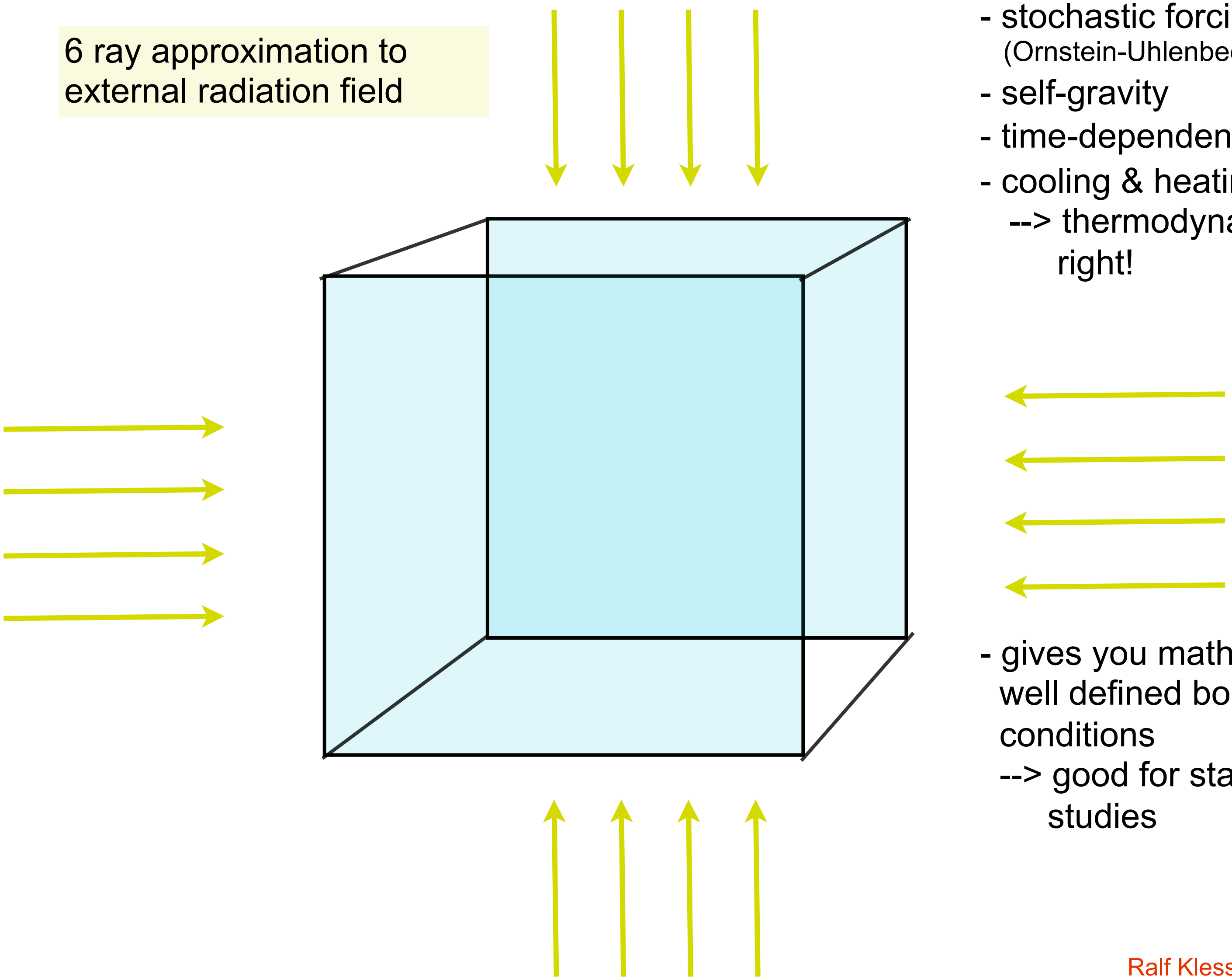


Fig. 7. PDFs of centroid velocity increments computed using equations (18) and (19) are shown as a function of the lag ℓ in units of grid cells $\Delta = L/1024$ for solenoidal forcing (*left*) and compressive forcing (*right*). The PDFs are very close to Gaussian distributions for large lags ℓ, whereas for small lags, they develop exponential tails, which is a manifestation of intermittency (e.g., Hily-Blant et al. 2008).

Federrath, et al. (2009)

molecular clouds

experimental set-up



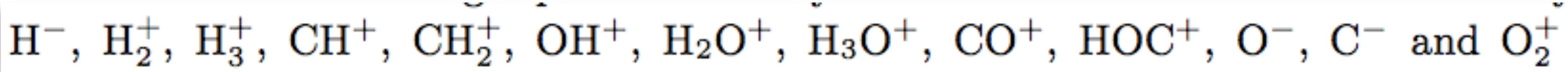
6 ray approximation to
external radiation field

- AMR MHD (B = 2 muG)
- stochastic forcing
  (Ornstein-Uhlenbeck)
- self-gravity
- time-dependent chemistry
- cooling & heating processes
  --> thermodynamics done
  right!

- gives you mathematically well defined boundary conditions
  --> good for statistical studies

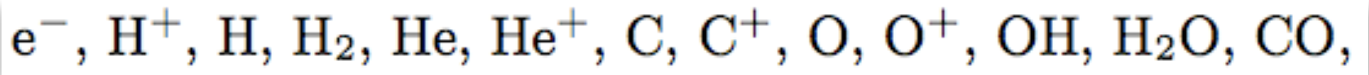
chemical model 0

- 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

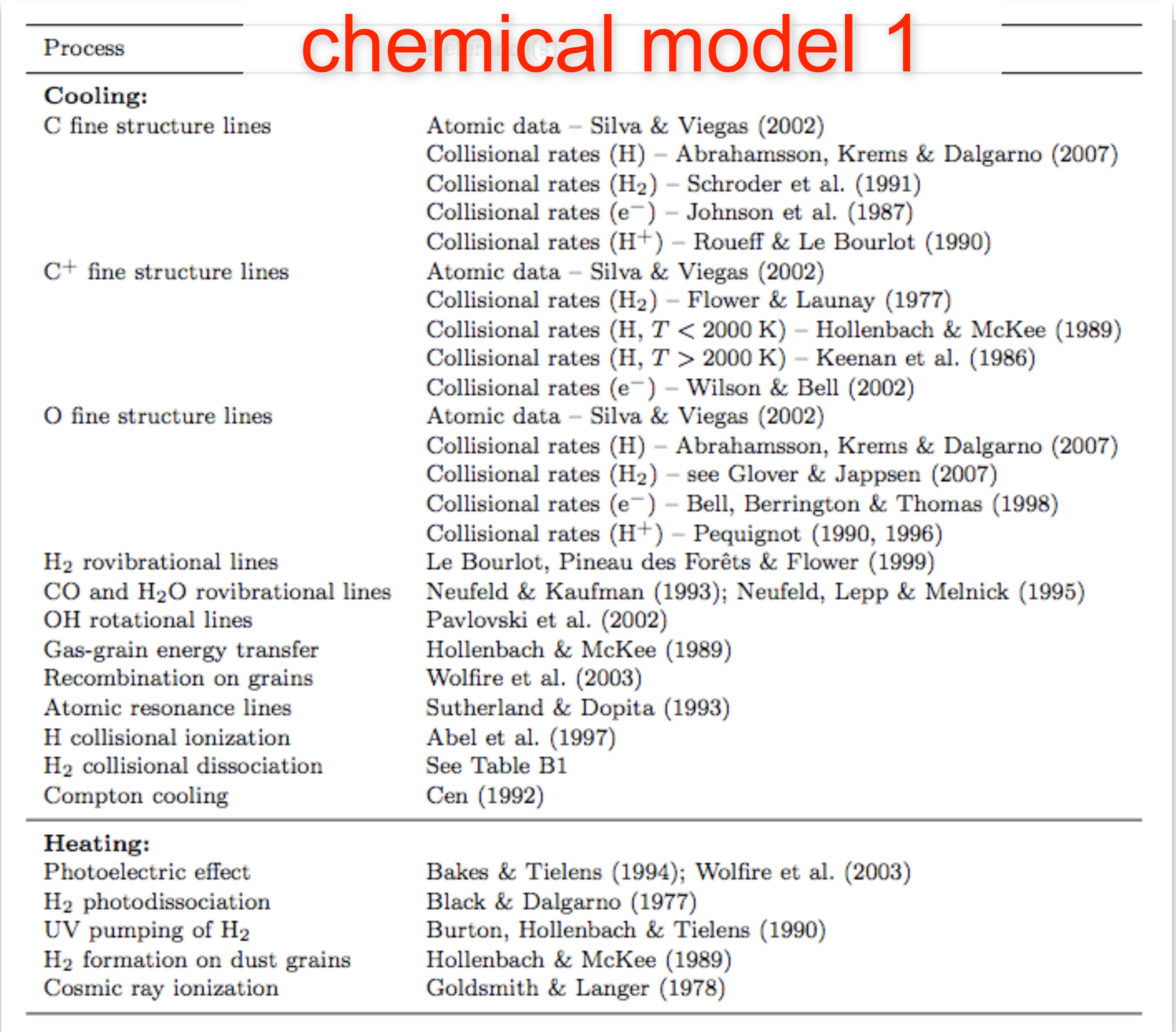


e^-, H^+, H, H_2, He, He^+, C, C^+, O, O^+, OH, H_2O, CO,

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

- 218 reactions, 17+ heating / cooling processes
- operator-split, implicit method: DVODE
  (Brown, Byrne & Hindmarsh 1989)
- extension of consistent multi-fluid advection scheme
  (Plewa & Müller 1999)

chemical model 1



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, Federrath, Mac Low, Klessen, 2010, MNRS, 404, 2)

chemical model 2

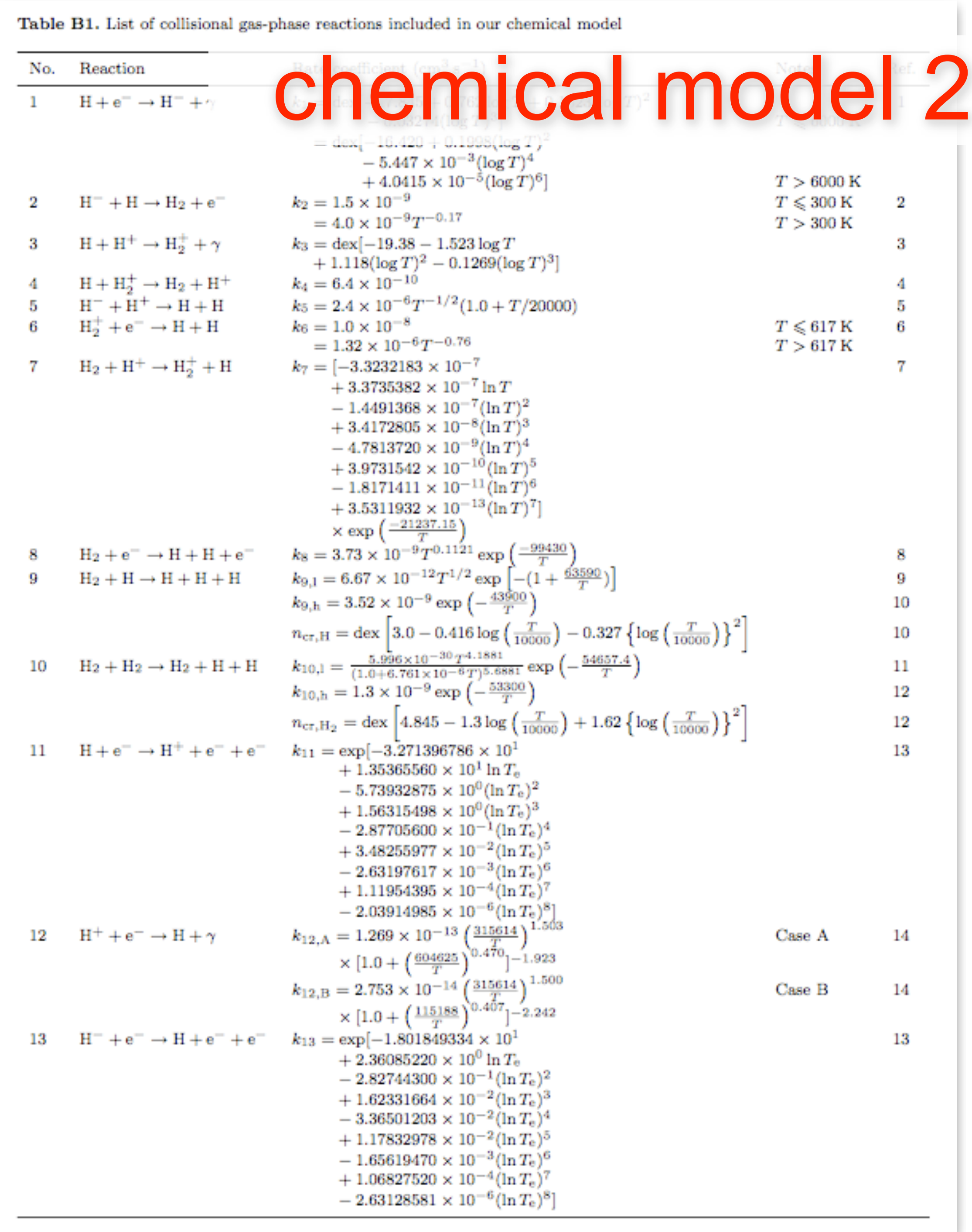


Table B1. List of collisional gas-phase reactions included in our chemical model

No.	Reaction	Rate coefficient ($cm^3 s^{-1}$)	Notes	Ref.
1	$H + e^- \rightarrow H^- + \gamma$	$k_1 = \mathrm{dex}[-17.845 + 0.762 \log T + 0.1523 (\log T)^2$ $- 0.03274 (\log T)^3]$	$T \leqslant 6000$ K	1
		$= \mathrm{dex}[-16.420 + 0.1998 (\log T)^2$ $- 5.447 \times 10^{-3} (\log T)^4$ $+ 4.0415 \times 10^{-5} (\log T)^6]$	$T > 6000$ K	
2	$H^- + H \rightarrow H_2 + e^-$	$k_2 = 1.5 \times 10^{-9}$	$T \leqslant 300$ K	2
		$= 4.0 \times 10^{-9} T^{-0.17}$	$T > 300$ K	
3	$H + H^+ \rightarrow H_2^+ + \gamma$	$k_3 = \mathrm{dex}[-19.38 - 1.523 \log T$ $+ 1.118 (\log T)^2 - 0.1269 (\log T)^3]$		3
4	$H + H_2^+ \rightarrow H_2 + H^+$	$k_4 = 6.4 \times 10^{-10}$		4
5	$H^- + H^+ \rightarrow H + H$	$k_5 = 2.4 \times 10^{-6} T^{-1/2} (1.0 + T/20000)$		5
6	$H_2^+ + e^- \rightarrow H + H$	$k_6 = 1.0 \times 10^{-8}$	$T \leqslant 617$ K	6
		$= 1.32 \times 10^{-6} T^{-0.76}$	$T > 617$ K	
7	$H_2 + H^+ \rightarrow H_2^+ + H$	$k_7 = [-3.3232183 \times 10^{-7}$ $+ 3.3735382 \times 10^{-7} \ln T$ $- 1.4491368 \times 10^{-7} (\ln T)^2$ $+ 3.4172805 \times 10^{-8} (\ln T)^3$ $- 4.7813720 \times 10^{-9} (\ln T)^4$ $+ 3.9731542 \times 10^{-10} (\ln T)^5$ $- 1.8171411 \times 10^{-11} (\ln T)^6$ $+ 3.5311932 \times 10^{-13} (\ln T)^7]$ $\times \exp\left(\frac{-21237.15}{T}\right)$		7
8	$H_2 + e^- \rightarrow H + H + e^-$	$k_8 = 3.73 \times 10^{-9} T^{0.1121} \exp\left(\frac{-99430}{T}\right)$		8
9	$H_2 + H \rightarrow H + H + H$	$k_{9,l} = 6.67 \times 10^{-12} T^{1/2} \exp\left[-\left(1 + \frac{63590}{T}\right)\right]$		9
		$k_{9,h} = 3.52 \times 10^{-9} \exp\left(-\frac{43900}{T}\right)$		10
		$n_{cr,H} = \mathrm{dex}\left[3.0 - 0.416 \log\left(\frac{T}{10000}\right) - 0.327 \left\{\log\left(\frac{T}{10000}\right)\right\}^2\right]$		10
10	$H_2 + H_2 \rightarrow H_2 + H + H$	$k_{10,l} = \frac{5.996 \times 10^{-30} T^{4.1881}}{(1.0 + 6.761 \times 10^{-6} T)^{5.6881}} \exp\left(-\frac{54657.4}{T}\right)$		11
		$k_{10,h} = 1.3 \times 10^{-9} \exp\left(-\frac{53300}{T}\right)$		12
		$n_{cr,H_2} = \mathrm{dex}\left[4.845 - 1.3 \log\left(\frac{T}{10000}\right) + 1.62 \left\{\log\left(\frac{T}{10000}\right)\right\}^2\right]$		12
11	$H + e^- \rightarrow H^+ + e^- + e^-$	$k_{11} = \exp[-3.271396786 \times 10^1$ $+ 1.35365560 \times 10^1 \ln T_e$ $- 5.73932875 \times 10^0 (\ln T_e)^2$ $+ 1.56315498 \times 10^0 (\ln T_e)^3$ $- 2.87705600 \times 10^{-1} (\ln T_e)^4$ $+ 3.48255977 \times 10^{-2} (\ln T_e)^5$ $- 2.63197617 \times 10^{-3} (\ln T_e)^6$ $+ 1.11954395 \times 10^{-4} (\ln T_e)^7$ $- 2.03914985 \times 10^{-6} (\ln T_e)^8]$		13
12	$H^+ + e^- \rightarrow H + \gamma$	$k_{12,A} = 1.269 \times 10^{-13} \left(\frac{315614}{T}\right)^{1.503}$ $\times \left[1.0 + \left(\frac{604625}{T}\right)^{0.470}\right]^{-1.923}$	Case A	14
		$k_{12,B} = 2.753 \times 10^{-14} \left(\frac{315614}{T}\right)^{1.500}$ $\times \left[1.0 + \left(\frac{115188}{T}\right)^{0.407}\right]^{-2.242}$	Case B	14
13	$H^- + e^- \rightarrow H + e^- + e^-$	$k_{13} = \exp[-1.801849334 \times 10^1$ $+ 2.36085220 \times 10^0 \ln T_e$ $- 2.82744300 \times 10^{-1} (\ln T_e)^2$ $+ 1.62331664 \times 10^{-2} (\ln T_e)^3$ $- 3.36501203 \times 10^{-2} (\ln T_e)^4$ $+ 1.17832978 \times 10^{-2} (\ln T_e)^5$ $- 1.65619470 \times 10^{-3} (\ln T_e)^6$ $+ 1.06827520 \times 10^{-4} (\ln T_e)^7$ $- 2.63128581 \times 10^{-6} (\ln T_e)^8]$		13

(Glover, Federrath, Mac Low, Klessen, 2010, MNRS, 404, 2)

chemical model 2

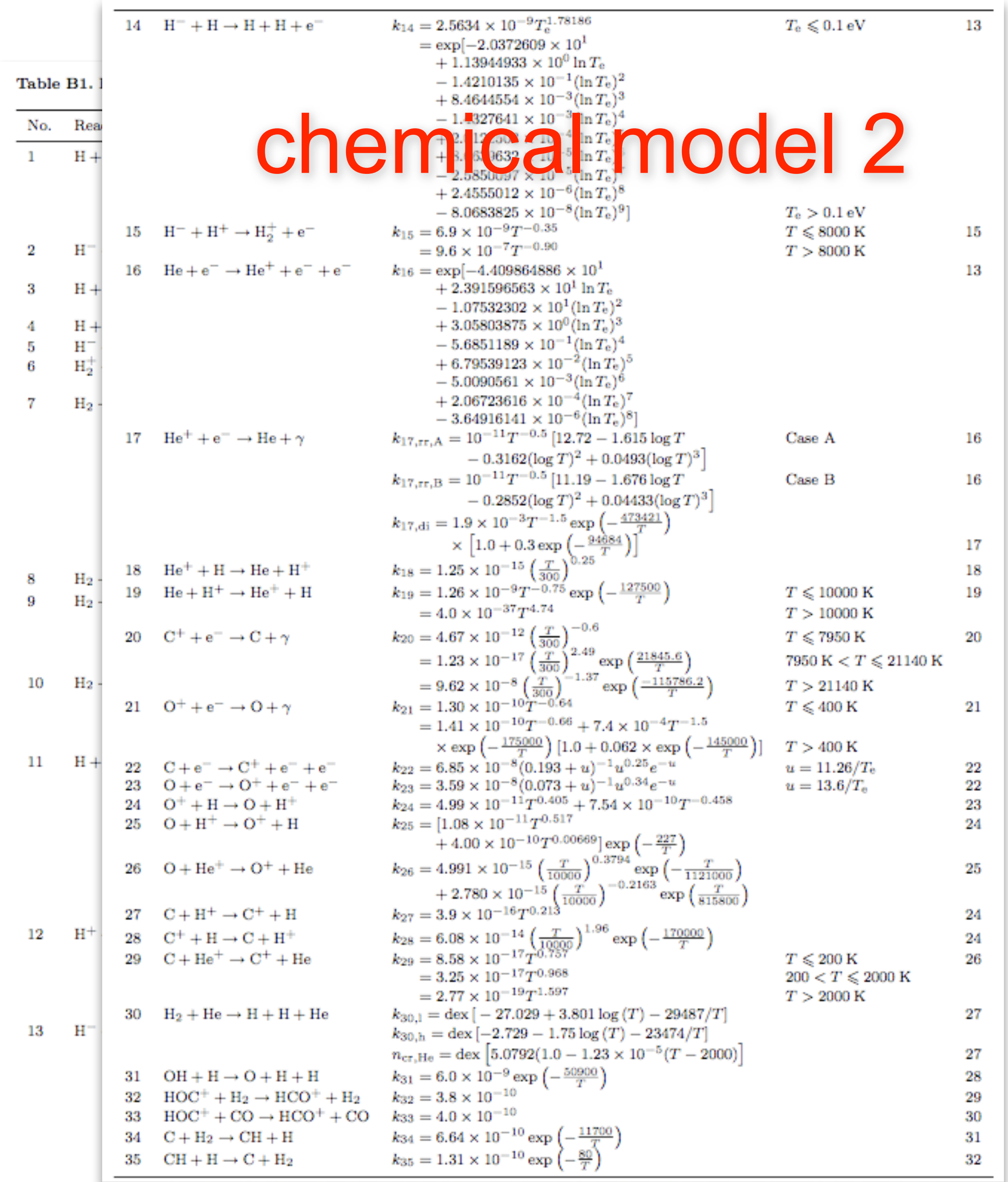


Table B1. I

No.	Rea
1	H +
2	H^-
3	H +
4	H +
5	H^-
6	H_2^+
7	H_2
8	H_2
9	H_2
10	H_2
11	H +
12	H^+
13	H^-

14	$H^- + H \rightarrow H + H + e^-$	$k_{14} = 2.5634 \times 10^{-9} T_e^{1.78186}$	$T_e \leqslant 0.1$ eV	13
		$= \exp[-2.0372609 \times 10^1$ $+ 1.13944933 \times 10^0 \ln T_e$ $- 1.4210135 \times 10^{-1} (\ln T_e)^2$ $+ 8.4644554 \times 10^{-3} (\ln T_e)^3$ − 1.[illegible]327641 × 10^{-3} [illegible] $\ln T_e)^4$ + 2.12[illegible] × [illegible] $\ln T_e$ [illegible] + 8.6[illegible]9632 × [illegible] $\ln T_e$ [illegible] − 2.5850097 × [illegible] $(\ln T_e)$ [illegible] $+ 2.4555012 \times 10^{-6} (\ln T_e)^8$ $- 8.0683825 \times 10^{-8} (\ln T_e)^9]$	$T_e > 0.1$ eV	
15	$H^- + H^+ \rightarrow H_2^+ + e^-$	$k_{15} = 6.9 \times 10^{-9} T^{-0.35}$	$T \leqslant 8000$ K	15
		$= 9.6 \times 10^{-7} T^{-0.90}$	$T > 8000$ K	
16	$He + e^- \rightarrow He^+ + e^- + e^-$	$k_{16} = \exp[-4.409864886 \times 10^1$ $+ 2.391596563 \times 10^1 \ln T_e$ $- 1.07532302 \times 10^1 (\ln T_e)^2$ $+ 3.05803875 \times 10^0 (\ln T_e)^3$ $- 5.6851189 \times 10^{-1} (\ln T_e)^4$ $+ 6.79539123 \times 10^{-2} (\ln T_e)^5$ $- 5.0090561 \times 10^{-3} (\ln T_e)^6$ $+ 2.06723616 \times 10^{-4} (\ln T_e)^7$ $- 3.64916141 \times 10^{-6} (\ln T_e)^8]$		13
17	$He^+ + e^- \rightarrow He + \gamma$	$k_{17,\mathrm{rr,A}} = 10^{-11} T^{-0.5} [12.72 - 1.615 \log T$ $- 0.3162 (\log T)^2 + 0.0493 (\log T)^3]$	Case A	16
		$k_{17,\mathrm{rr,B}} = 10^{-11} T^{-0.5} [11.19 - 1.676 \log T$ $- 0.2852 (\log T)^2 + 0.04433 (\log T)^3]$	Case B	16
		$k_{17,\mathrm{di}} = 1.9 \times 10^{-3} T^{-1.5} \exp\left(-\frac{473421}{T}\right)$ $\times \left[1.0 + 0.3 \exp\left(-\frac{94684}{T}\right)\right]$		17
18	$He^+ + H \rightarrow He + H^+$	$k_{18} = 1.25 \times 10^{-15} \left(\frac{T}{300}\right)^{0.25}$		18
19	$He + H^+ \rightarrow He^+ + H$	$k_{19} = 1.26 \times 10^{-9} T^{-0.75} \exp\left(-\frac{127500}{T}\right)$	$T \leqslant 10000$ K	19
		$= 4.0 \times 10^{-37} T^{4.74}$	$T > 10000$ K	
20	$C^+ + e^- \rightarrow C + \gamma$	$k_{20} = 4.67 \times 10^{-12} \left(\frac{T}{300}\right)^{-0.6}$	$T \leqslant 7950$ K	20
		$= 1.23 \times 10^{-17} \left(\frac{T}{300}\right)^{2.49} \exp\left(\frac{21845.6}{T}\right)$	$7950 \mathrm{K} < T \leqslant 21140$ K	
		$= 9.62 \times 10^{-8} \left(\frac{T}{300}\right)^{-1.37} \exp\left(\frac{-115786.2}{T}\right)$	$T > 21140$ K	
21	$O^+ + e^- \rightarrow O + \gamma$	$k_{21} = 1.30 \times 10^{-10} T^{-0.64}$	$T \leqslant 400$ K	21
		$= 1.41 \times 10^{-10} T^{-0.66} + 7.4 \times 10^{-4} T^{-1.5}$ $\times \exp\left(-\frac{175000}{T}\right) [1.0 + 0.062 \times \exp\left(-\frac{145000}{T}\right)]$	$T > 400$ K	
22	$C + e^- \rightarrow C^+ + e^- + e^-$	$k_{22} = 6.85 \times 10^{-8} (0.193 + u)^{-1} u^{0.25} e^{-u}$	$u = 11.26/T_e$	22
23	$O + e^- \rightarrow O^+ + e^- + e^-$	$k_{23} = 3.59 \times 10^{-8} (0.073 + u)^{-1} u^{0.34} e^{-u}$	$u = 13.6/T_e$	22
24	$O^+ + H \rightarrow O + H^+$	$k_{24} = 4.99 \times 10^{-11} T^{0.405} + 7.54 \times 10^{-10} T^{-0.458}$		23
25	$O + H^+ \rightarrow O^+ + H$	$k_{25} = [1.08 \times 10^{-11} T^{0.517}$ $+ 4.00 \times 10^{-10} T^{0.00669}] \exp\left(-\frac{227}{T}\right)$		24
26	$O + He^+ \rightarrow O^+ + He$	$k_{26} = 4.991 \times 10^{-15} \left(\frac{T}{10000}\right)^{0.3794} \exp\left(-\frac{T}{1121000}\right)$ $+ 2.780 \times 10^{-15} \left(\frac{T}{10000}\right)^{-0.2163} \exp\left(\frac{T}{815800}\right)$		25
27	$C + H^+ \rightarrow C^+ + H$	$k_{27} = 3.9 \times 10^{-16} T^{0.213}$		24
28	$C^+ + H \rightarrow C + H^+$	$k_{28} = 6.08 \times 10^{-14} \left(\frac{T}{10000}\right)^{1.96} \exp\left(-\frac{170000}{T}\right)$		24
29	$C + He^+ \rightarrow C^+ + He$	$k_{29} = 8.58 \times 10^{-17} T^{0.757}$	$T \leqslant 200$ K	26
		$= 3.25 \times 10^{-17} T^{0.968}$	$200 < T \leqslant 2000$ K	
		$= 2.77 \times 10^{-19} T^{1.597}$	$T > 2000$ K	
30	$H_2 + He \rightarrow H + H + He$	$k_{30,\mathrm{l}} = \mathrm{dex}[-27.029 + 3.801 \log(T) - 29487/T]$ $k_{30,\mathrm{h}} = \mathrm{dex}[-2.729 - 1.75 \log(T) - 23474/T]$		27
		$n_{\mathrm{cr,He}} = \mathrm{dex}\left[5.0792(1.0 - 1.23 \times 10^{-5}(T - 2000)\right]$		27
31	$OH + H \rightarrow O + H + H$	$k_{31} = 6.0 \times 10^{-9} \exp\left(-\frac{50900}{T}\right)$		28
32	$HOC^+ + H_2 \rightarrow HCO^+ + H_2$	$k_{32} = 3.8 \times 10^{-10}$		29
33	$HOC^+ + CO \rightarrow HCO^+ + CO$	$k_{33} = 4.0 \times 10^{-10}$		30
34	$C + H_2 \rightarrow CH + H$	$k_{34} = 6.64 \times 10^{-10} \exp\left(-\frac{11700}{T}\right)$		31
35	$CH + H \rightarrow C + H_2$	$k_{35} = 1.31 \times 10^{-10} \exp\left(-\frac{80}{T}\right)$		32

(Glover, Federrath, Mac Low, Klessen, 2010, MNRS, 404, 2)

chemical model 2

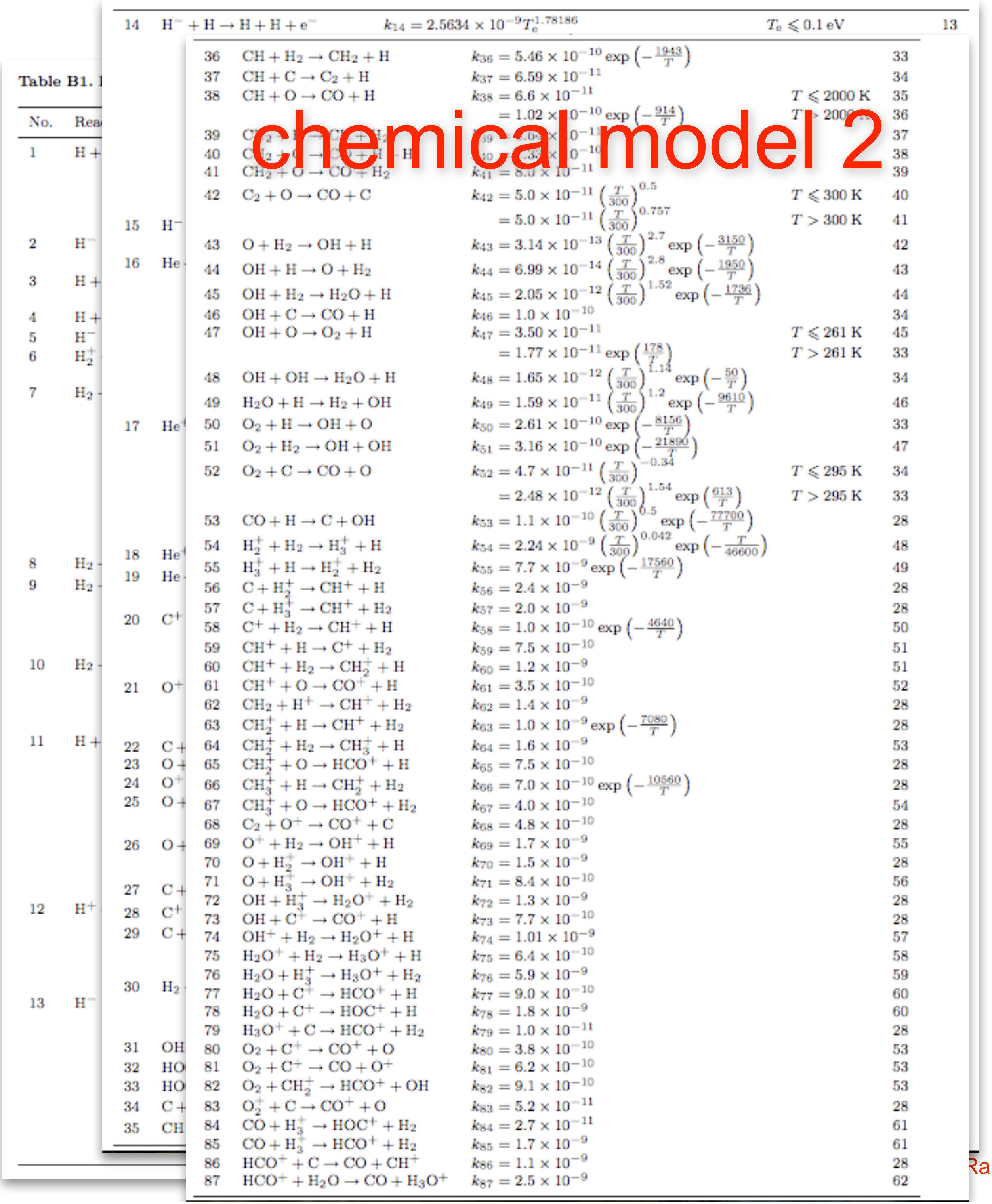


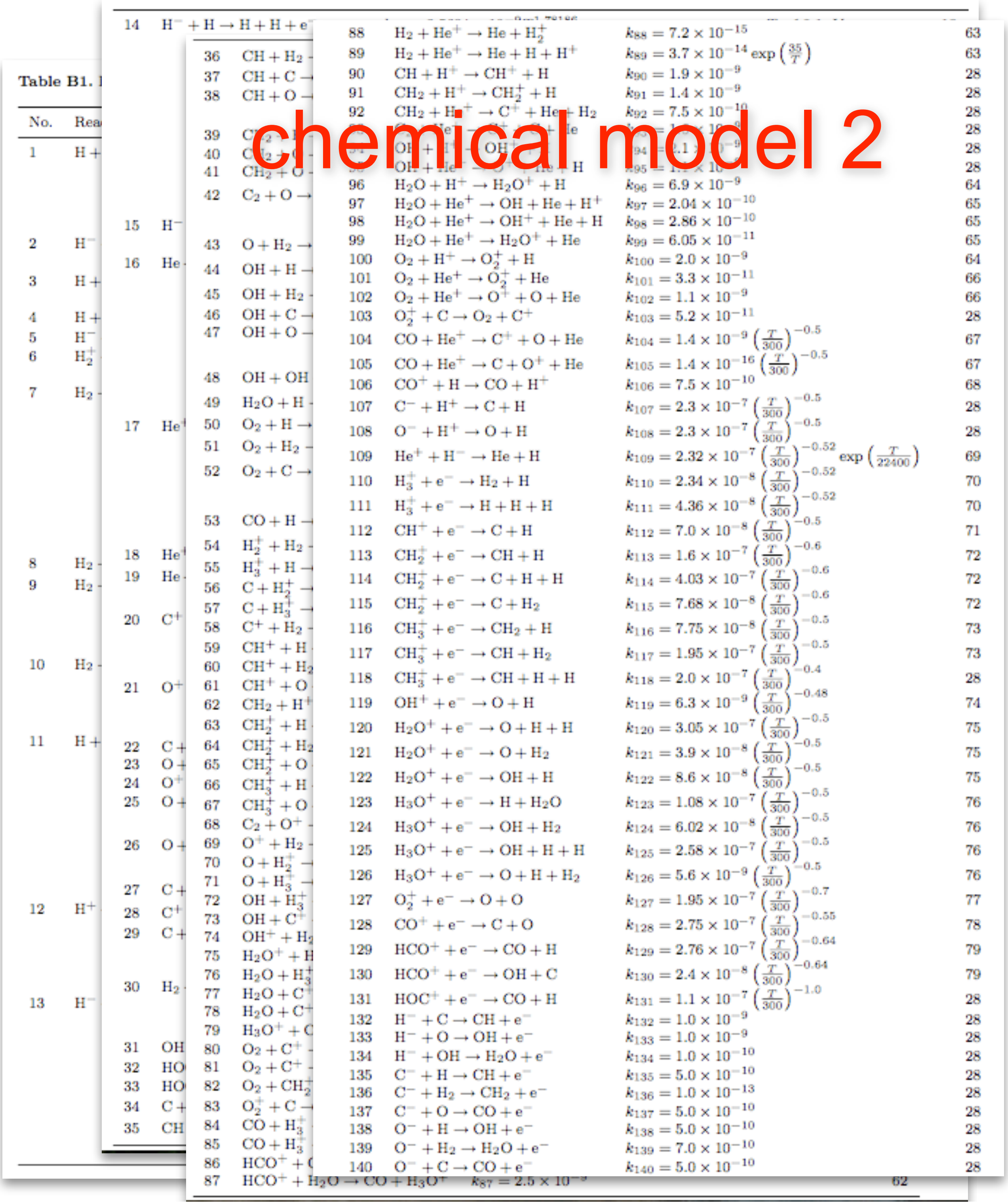
Table B1.

14 $H^- + H \rightarrow H + H + e^-$ $k_{14} = 2.5634 \times 10^{-9} T_e^{1.78186}$ $T_e \leqslant 0.1$ eV 13

36	$CH + H_2 \rightarrow CH_2 + H$	$k_{36} = 5.46 \times 10^{-10} \exp\left(-\frac{1943}{T}\right)$		33
37	$CH + C \rightarrow C_2 + H$	$k_{37} = 6.59 \times 10^{-11}$		34
38	$CH + O \rightarrow CO + H$	$k_{38} = 6.6 \times 10^{-11}$	$T \leqslant 2000$ K	35
		$= 1.02 \times 10^{-10} \exp\left(-\frac{914}{T}\right)$	$T > 2000$ K	36
39	$CH_2 + H \rightarrow CH + H_2$	$k_{39} =$ [illegible] $\times 10^{-11}$		37
40	$CH_2 + C \rightarrow C_2 + H + H$	$k_{40} =$ [illegible] $\times 10^{-10}$		38
41	$CH_2 + O \rightarrow CO + H_2$	$k_{41} = 8.0 \times 10^{-11}$		39
42	$C_2 + O \rightarrow CO + C$	$k_{42} = 5.0 \times 10^{-11} \left(\frac{T}{300}\right)^{0.5}$	$T \leqslant 300$ K	40
		$= 5.0 \times 10^{-11} \left(\frac{T}{300}\right)^{0.757}$	$T > 300$ K	41
43	$O + H_2 \rightarrow OH + H$	$k_{43} = 3.14 \times 10^{-13} \left(\frac{T}{300}\right)^{2.7} \exp\left(-\frac{3150}{T}\right)$		42
44	$OH + H \rightarrow O + H_2$	$k_{44} = 6.99 \times 10^{-14} \left(\frac{T}{300}\right)^{2.8} \exp\left(-\frac{1950}{T}\right)$		43
45	$OH + H_2 \rightarrow H_2O + H$	$k_{45} = 2.05 \times 10^{-12} \left(\frac{T}{300}\right)^{1.52} \exp\left(-\frac{1736}{T}\right)$		44
46	$OH + C \rightarrow CO + H$	$k_{46} = 1.0 \times 10^{-10}$		34
47	$OH + O \rightarrow O_2 + H$	$k_{47} = 3.50 \times 10^{-11}$	$T \leqslant 261$ K	45
		$= 1.77 \times 10^{-11} \exp\left(\frac{178}{T}\right)$	$T > 261$ K	33
48	$OH + OH \rightarrow H_2O + H$	$k_{48} = 1.65 \times 10^{-12} \left(\frac{T}{300}\right)^{1.14} \exp\left(-\frac{50}{T}\right)$		34
49	$H_2O + H \rightarrow H_2 + OH$	$k_{49} = 1.59 \times 10^{-11} \left(\frac{T}{300}\right)^{1.2} \exp\left(-\frac{9610}{T}\right)$		46
50	$O_2 + H \rightarrow OH + O$	$k_{50} = 2.61 \times 10^{-10} \exp\left(-\frac{8156}{T}\right)$		33
51	$O_2 + H_2 \rightarrow OH + OH$	$k_{51} = 3.16 \times 10^{-10} \exp\left(-\frac{21890}{T}\right)$		47
52	$O_2 + C \rightarrow CO + O$	$k_{52} = 4.7 \times 10^{-11} \left(\frac{T}{300}\right)^{-0.34}$	$T \leqslant 295$ K	34
		$= 2.48 \times 10^{-12} \left(\frac{T}{300}\right)^{1.54} \exp\left(\frac{613}{T}\right)$	$T > 295$ K	33
53	$CO + H \rightarrow C + OH$	$k_{53} = 1.1 \times 10^{-10} \left(\frac{T}{300}\right)^{0.5} \exp\left(-\frac{77700}{T}\right)$		28
54	$H_2^+ + H_2 \rightarrow H_3^+ + H$	$k_{54} = 2.24 \times 10^{-9} \left(\frac{T}{300}\right)^{0.042} \exp\left(-\frac{T}{46600}\right)$		48
55	$H_3^+ + H \rightarrow H_2^+ + H_2$	$k_{55} = 7.7 \times 10^{-9} \exp\left(-\frac{17560}{T}\right)$		49
56	$C + H_2^+ \rightarrow CH^+ + H$	$k_{56} = 2.4 \times 10^{-9}$		28
57	$C + H_3^+ \rightarrow CH^+ + H_2$	$k_{57} = 2.0 \times 10^{-9}$		28
58	$C^+ + H_2 \rightarrow CH^+ + H$	$k_{58} = 1.0 \times 10^{-10} \exp\left(-\frac{4640}{T}\right)$		50
59	$CH^+ + H \rightarrow C^+ + H_2$	$k_{59} = 7.5 \times 10^{-10}$		51
60	$CH^+ + H_2 \rightarrow CH_2^+ + H$	$k_{60} = 1.2 \times 10^{-9}$		51
61	$CH^+ + O \rightarrow CO^+ + H$	$k_{61} = 3.5 \times 10^{-10}$		52
62	$CH_2 + H^+ \rightarrow CH^+ + H_2$	$k_{62} = 1.4 \times 10^{-9}$		28
63	$CH_2^+ + H \rightarrow CH^+ + H_2$	$k_{63} = 1.0 \times 10^{-9} \exp\left(-\frac{7080}{T}\right)$		28
64	$CH_2^+ + H_2 \rightarrow CH_3^+ + H$	$k_{64} = 1.6 \times 10^{-9}$		53
65	$CH_2^+ + O \rightarrow HCO^+ + H$	$k_{65} = 7.5 \times 10^{-10}$		28
66	$CH_3^+ + H \rightarrow CH_2^+ + H_2$	$k_{66} = 7.0 \times 10^{-10} \exp\left(-\frac{10560}{T}\right)$		28
67	$CH_3^+ + O \rightarrow HCO^+ + H_2$	$k_{67} = 4.0 \times 10^{-10}$		54
68	$C_2 + O^+ \rightarrow CO^+ + C$	$k_{68} = 4.8 \times 10^{-10}$		28
69	$O^+ + H_2 \rightarrow OH^+ + H$	$k_{69} = 1.7 \times 10^{-9}$		55
70	$O + H_2^+ \rightarrow OH^+ + H$	$k_{70} = 1.5 \times 10^{-9}$		28
71	$O + H_3^+ \rightarrow OH^+ + H_2$	$k_{71} = 8.4 \times 10^{-10}$		56
72	$OH + H_3^+ \rightarrow H_2O^+ + H_2$	$k_{72} = 1.3 \times 10^{-9}$		28
73	$OH + C^+ \rightarrow CO^+ + H$	$k_{73} = 7.7 \times 10^{-10}$		28
74	$OH^+ + H_2 \rightarrow H_2O^+ + H$	$k_{74} = 1.01 \times 10^{-9}$		57
75	$H_2O^+ + H_2 \rightarrow H_3O^+ + H$	$k_{75} = 6.4 \times 10^{-10}$		58
76	$H_2O + H_3^+ \rightarrow H_3O^+ + H_2$	$k_{76} = 5.9 \times 10^{-9}$		59
77	$H_2O + C^+ \rightarrow HCO^+ + H$	$k_{77} = 9.0 \times 10^{-10}$		60
78	$H_2O + C^+ \rightarrow HOC^+ + H$	$k_{78} = 1.8 \times 10^{-9}$		60
79	$H_3O^+ + C \rightarrow HCO^+ + H_2$	$k_{79} = 1.0 \times 10^{-11}$		28
80	$O_2 + C^+ \rightarrow CO^+ + O$	$k_{80} = 3.8 \times 10^{-10}$		53
81	$O_2 + C^+ \rightarrow CO + O^+$	$k_{81} = 6.2 \times 10^{-10}$		53
82	$O_2 + CH_2^+ \rightarrow HCO^+ + OH$	$k_{82} = 9.1 \times 10^{-10}$		53
83	$O_2^+ + C \rightarrow CO^+ + O$	$k_{83} = 5.2 \times 10^{-11}$		28
84	$CO + H_3^+ \rightarrow HOC^+ + H_2$	$k_{84} = 2.7 \times 10^{-11}$		61
85	$CO + H_3^+ \rightarrow HCO^+ + H_2$	$k_{85} = 1.7 \times 10^{-9}$		61
86	$HCO^+ + C \rightarrow CO + CH^+$	$k_{86} = 1.1 \times 10^{-9}$		28
87	$HCO^+ + H_2O \rightarrow CO + H_3O^+$	$k_{87} = 2.5 \times 10^{-9}$		62

(Glover, Federrath, Mac Low, Klessen, 2010, MNRS, 404, 2)

chemical model 2



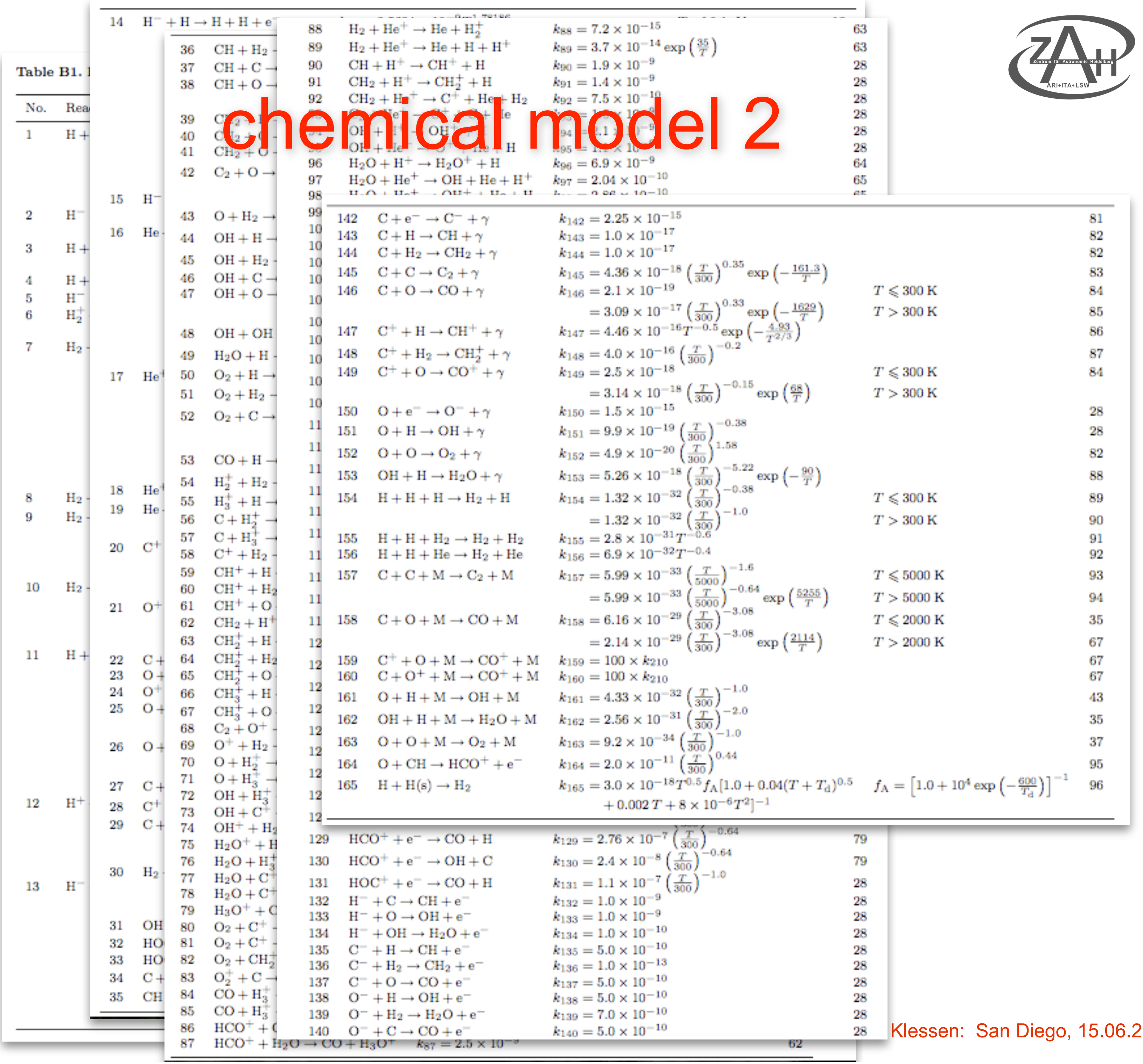
87 $HCO^+ + H_2O \rightarrow CO + H_3O^+$ $k_{87} = 2.5 \times 10^{-9}$ 62

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
92	$CH_2 + H^+ \rightarrow C^+ + He + H_2$	$k_{92} = 7.5 \times 10^{-10}$	28
[illegible]	[illegible] $He^+ \rightarrow C^+ + C + He$	[illegible]	28
[illegible]	$OH + H^+ \rightarrow OH^+ + H$	$k_{94} = 2.1 \times 10^{-9}$	28
[illegible]	$OH + He^+ \rightarrow O^+ + He + H$	$k_{95} = 1.1 \times 10^{-9}$	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
98	$H_2O + He^+ \rightarrow OH^+ + He + H$	$k_{98} = 2.86 \times 10^{-10}$	65
99	$H_2O + He^+ \rightarrow H_2O^+ + He$	$k_{99} = 6.05 \times 10^{-11}$	65
100	$O_2 + H^+ \rightarrow O_2^+ + H$	$k_{100} = 2.0 \times 10^{-9}$	64
101	$O_2 + He^+ \rightarrow O_2^+ + He$	$k_{101} = 3.3 \times 10^{-11}$	66
102	$O_2 + He^+ \rightarrow O^+ + O + He$	$k_{102} = 1.1 \times 10^{-9}$	66
103	$O_2^+ + C \rightarrow O_2 + C^+$	$k_{103} = 5.2 \times 10^{-11}$	28
104	$CO + He^+ \rightarrow C^+ + O + He$	$k_{104} = 1.4 \times 10^{-9} \left(\frac{T}{300}\right)^{-0.5}$	67
105	$CO + He^+ \rightarrow C + O^+ + He$	$k_{105} = 1.4 \times 10^{-16} \left(\frac{T}{300}\right)^{-0.5}$	67
106	$CO^+ + H \rightarrow CO + H^+$	$k_{106} = 7.5 \times 10^{-10}$	68
107	$C^- + H^+ \rightarrow C + H$	$k_{107} = 2.3 \times 10^{-7} \left(\frac{T}{300}\right)^{-0.5}$	28
108	$O^- + H^+ \rightarrow O + H$	$k_{108} = 2.3 \times 10^{-7} \left(\frac{T}{300}\right)^{-0.5}$	28
109	$He^+ + H^- \rightarrow He + H$	$k_{109} = 2.32 \times 10^{-7} \left(\frac{T}{300}\right)^{-0.52} \exp\left(\frac{T}{22400}\right)$	69
110	$H_3^+ + e^- \rightarrow H_2 + H$	$k_{110} = 2.34 \times 10^{-8} \left(\frac{T}{300}\right)^{-0.52}$	70
111	$H_3^+ + e^- \rightarrow H + H + H$	$k_{111} = 4.36 \times 10^{-8} \left(\frac{T}{300}\right)^{-0.52}$	70
112	$CH^+ + e^- \rightarrow C + H$	$k_{112} = 7.0 \times 10^{-8} \left(\frac{T}{300}\right)^{-0.5}$	71
113	$CH_2^+ + e^- \rightarrow CH + H$	$k_{113} = 1.6 \times 10^{-7} \left(\frac{T}{300}\right)^{-0.6}$	72
114	$CH_2^+ + e^- \rightarrow C + H + H$	$k_{114} = 4.03 \times 10^{-7} \left(\frac{T}{300}\right)^{-0.6}$	72
115	$CH_2^+ + e^- \rightarrow C + H_2$	$k_{115} = 7.68 \times 10^{-8} \left(\frac{T}{300}\right)^{-0.6}$	72
116	$CH_3^+ + e^- \rightarrow CH_2 + H$	$k_{116} = 7.75 \times 10^{-8} \left(\frac{T}{300}\right)^{-0.5}$	73
117	$CH_3^+ + e^- \rightarrow CH + H_2$	$k_{117} = 1.95 \times 10^{-7} \left(\frac{T}{300}\right)^{-0.5}$	73
118	$CH_3^+ + e^- \rightarrow CH + H + H$	$k_{118} = 2.0 \times 10^{-7} \left(\frac{T}{300}\right)^{-0.4}$	28
119	$OH^+ + e^- \rightarrow O + H$	$k_{119} = 6.3 \times 10^{-9} \left(\frac{T}{300}\right)^{-0.48}$	74
120	$H_2O^+ + e^- \rightarrow O + H + H$	$k_{120} = 3.05 \times 10^{-7} \left(\frac{T}{300}\right)^{-0.5}$	75
121	$H_2O^+ + e^- \rightarrow O + H_2$	$k_{121} = 3.9 \times 10^{-8} \left(\frac{T}{300}\right)^{-0.5}$	75
122	$H_2O^+ + e^- \rightarrow OH + H$	$k_{122} = 8.6 \times 10^{-8} \left(\frac{T}{300}\right)^{-0.5}$	75
123	$H_3O^+ + e^- \rightarrow H + H_2O$	$k_{123} = 1.08 \times 10^{-7} \left(\frac{T}{300}\right)^{-0.5}$	76
124	$H_3O^+ + e^- \rightarrow OH + H_2$	$k_{124} = 6.02 \times 10^{-8} \left(\frac{T}{300}\right)^{-0.5}$	76
125	$H_3O^+ + e^- \rightarrow OH + H + H$	$k_{125} = 2.58 \times 10^{-7} \left(\frac{T}{300}\right)^{-0.5}$	76
126	$H_3O^+ + e^- \rightarrow O + H + H_2$	$k_{126} = 5.6 \times 10^{-9} \left(\frac{T}{300}\right)^{-0.5}$	76
127	$O_2^+ + e^- \rightarrow O + O$	$k_{127} = 1.95 \times 10^{-7} \left(\frac{T}{300}\right)^{-0.7}$	77
128	$CO^+ + e^- \rightarrow C + O$	$k_{128} = 2.75 \times 10^{-7} \left(\frac{T}{300}\right)^{-0.55}$	78
129	$HCO^+ + e^- \rightarrow CO + H$	$k_{129} = 2.76 \times 10^{-7} \left(\frac{T}{300}\right)^{-0.64}$	79
130	$HCO^+ + e^- \rightarrow OH + C$	$k_{130} = 2.4 \times 10^{-8} \left(\frac{T}{300}\right)^{-0.64}$	79
131	$HOC^+ + e^- \rightarrow CO + H$	$k_{131} = 1.1 \times 10^{-7} \left(\frac{T}{300}\right)^{-1.0}$	28
132	$H^- + C \rightarrow CH + e^-$	$k_{132} = 1.0 \times 10^{-9}$	28
133	$H^- + O \rightarrow OH + e^-$	$k_{133} = 1.0 \times 10^{-9}$	28
134	$H^- + OH \rightarrow H_2O + e^-$	$k_{134} = 1.0 \times 10^{-10}$	28
135	$C^- + H \rightarrow CH + e^-$	$k_{135} = 5.0 \times 10^{-10}$	28
136	$C^- + H_2 \rightarrow CH_2 + e^-$	$k_{136} = 1.0 \times 10^{-13}$	28
137	$C^- + O \rightarrow CO + e^-$	$k_{137} = 5.0 \times 10^{-10}$	28
138	$O^- + H \rightarrow OH + e^-$	$k_{138} = 5.0 \times 10^{-10}$	28
139	$O^- + H_2 \rightarrow H_2O + e^-$	$k_{139} = 7.0 \times 10^{-10}$	28
140	$O^- + C \rightarrow CO + e^-$	$k_{140} = 5.0 \times 10^{-10}$	28

(Glover, Federrath, Mac Low, Klessen, 2010, MNRS, 404, 2)

chemical model 2

(Glover, Federrath, Mac Low, Klessen, 2010, MNRS, 404, 2)



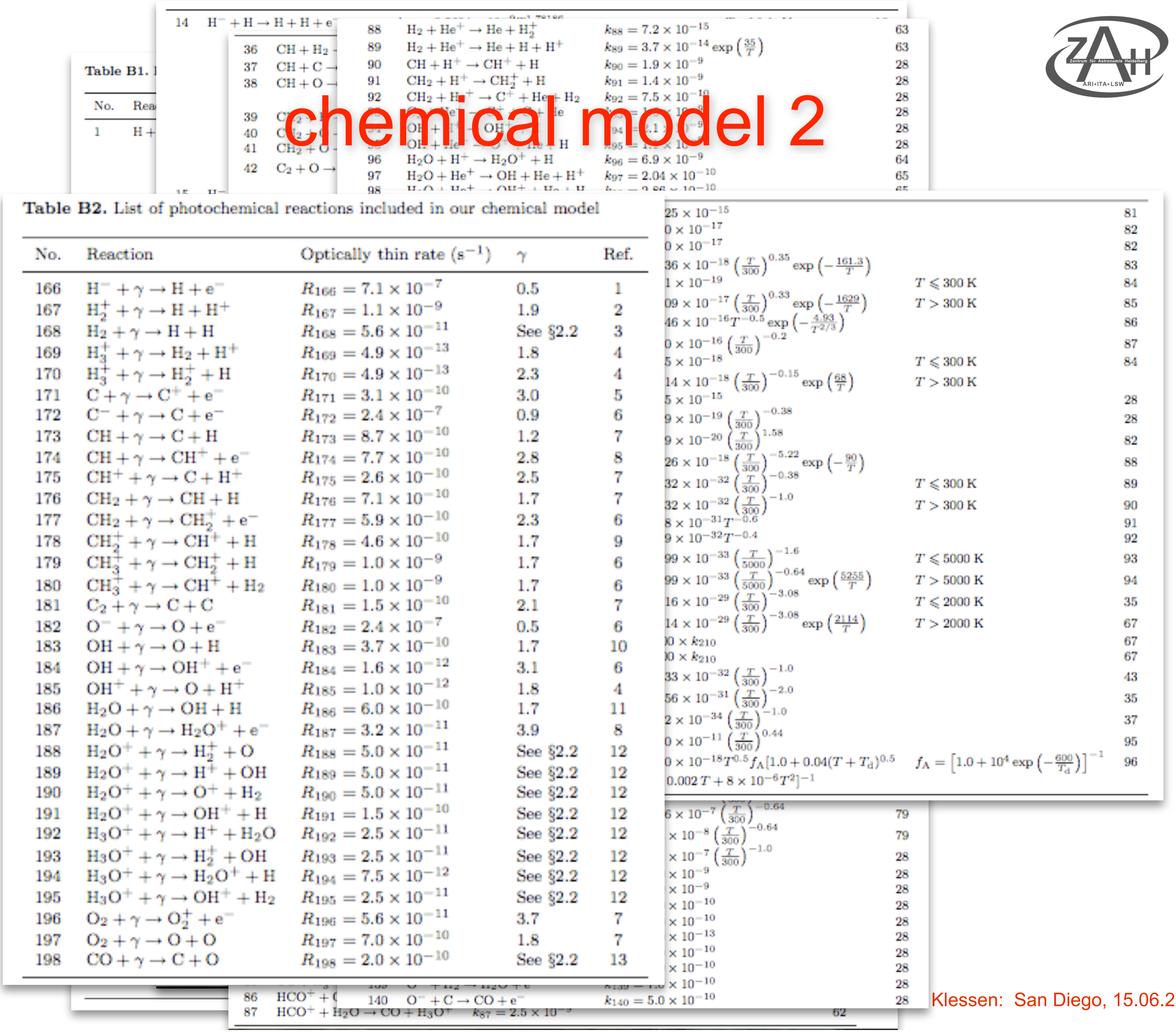
88	$H_2 + He^+ \rightarrow He + H_2^+$	$k_{88} = 7.2 \times 10^{-15}$		63
89	$H_2 + He^+ \rightarrow He + H + H^+$	$k_{89} = 3.7 \times 10^{-14} \exp\left(\frac{35}{T}\right)$		63
90	$CH + H^+ \rightarrow CH^+ + H$	$k_{90} = 1.9 \times 10^{-9}$		28
91	$CH_2 + H^+ \rightarrow CH_2^+ + H$	$k_{91} = 1.4 \times 10^{-9}$		28
92	$CH_2 + He^+ \rightarrow C^+ + He + H_2$	$k_{92} = 7.5 \times 10^{-10}$		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

142	$C + e^- \rightarrow C^- + \gamma$	$k_{142} = 2.25 \times 10^{-15}$		81
143	$C + H \rightarrow CH + \gamma$	$k_{143} = 1.0 \times 10^{-17}$		82
144	$C + H_2 \rightarrow CH_2 + \gamma$	$k_{144} = 1.0 \times 10^{-17}$		82
145	$C + C \rightarrow C_2 + \gamma$	$k_{145} = 4.36 \times 10^{-18} \left(\frac{T}{300}\right)^{0.35} \exp\left(-\frac{161.3}{T}\right)$		83
146	$C + O \rightarrow CO + \gamma$	$k_{146} = 2.1 \times 10^{-19}$	$T \leqslant 300$ K	84
		$= 3.09 \times 10^{-17} \left(\frac{T}{300}\right)^{0.33} \exp\left(-\frac{1629}{T}\right)$	$T > 300$ K	85
147	$C^+ + H \rightarrow CH^+ + \gamma$	$k_{147} = 4.46 \times 10^{-16} T^{-0.5} \exp\left(-\frac{4.93}{T^{2/3}}\right)$		86
148	$C^+ + H_2 \rightarrow CH_2^+ + \gamma$	$k_{148} = 4.0 \times 10^{-16} \left(\frac{T}{300}\right)^{-0.2}$		87
149	$C^+ + O \rightarrow CO^+ + \gamma$	$k_{149} = 2.5 \times 10^{-18}$	$T \leqslant 300$ K	84
		$= 3.14 \times 10^{-18} \left(\frac{T}{300}\right)^{-0.15} \exp\left(\frac{68}{T}\right)$	$T > 300$ K	
150	$O + e^- \rightarrow O^- + \gamma$	$k_{150} = 1.5 \times 10^{-15}$		28
151	$O + H \rightarrow OH + \gamma$	$k_{151} = 9.9 \times 10^{-19} \left(\frac{T}{300}\right)^{-0.38}$		28
152	$O + O \rightarrow O_2 + \gamma$	$k_{152} = 4.9 \times 10^{-20} \left(\frac{T}{300}\right)^{1.58}$		82
153	$OH + H \rightarrow H_2O + \gamma$	$k_{153} = 5.26 \times 10^{-18} \left(\frac{T}{300}\right)^{-5.22} \exp\left(-\frac{90}{T}\right)$		88
154	$H + H + H \rightarrow H_2 + H$	$k_{154} = 1.32 \times 10^{-32} \left(\frac{T}{300}\right)^{-0.38}$	$T \leqslant 300$ K	89
		$= 1.32 \times 10^{-32} \left(\frac{T}{300}\right)^{-1.0}$	$T > 300$ K	90
155	$H + H + H_2 \rightarrow H_2 + H_2$	$k_{155} = 2.8 \times 10^{-31} T^{-0.6}$		91
156	$H + H + He \rightarrow H_2 + He$	$k_{156} = 6.9 \times 10^{-32} T^{-0.4}$		92
157	$C + C + M \rightarrow C_2 + M$	$k_{157} = 5.99 \times 10^{-33} \left(\frac{T}{5000}\right)^{-1.6}$	$T \leqslant 5000$ K	93
		$= 5.99 \times 10^{-33} \left(\frac{T}{5000}\right)^{-0.64} \exp\left(\frac{5255}{T}\right)$	$T > 5000$ K	94
158	$C + O + M \rightarrow CO + M$	$k_{158} = 6.16 \times 10^{-29} \left(\frac{T}{300}\right)^{-3.08}$	$T \leqslant 2000$ K	35
		$= 2.14 \times 10^{-29} \left(\frac{T}{300}\right)^{-3.08} \exp\left(\frac{2114}{T}\right)$	$T > 2000$ K	67
159	$C^+ + O + M \rightarrow CO^+ + M$	$k_{159} = 100 \times k_{210}$		67
160	$C + O^+ + M \rightarrow CO^+ + M$	$k_{160} = 100 \times k_{210}$		67
161	$O + H + M \rightarrow OH + M$	$k_{161} = 4.33 \times 10^{-32} \left(\frac{T}{300}\right)^{-1.0}$		43
162	$OH + H + M \rightarrow H_2O + M$	$k_{162} = 2.56 \times 10^{-31} \left(\frac{T}{300}\right)^{-2.0}$		35
163	$O + O + M \rightarrow O_2 + M$	$k_{163} = 9.2 \times 10^{-34} \left(\frac{T}{300}\right)^{-1.0}$		37
164	$O + CH \rightarrow HCO^+ + e^-$	$k_{164} = 2.0 \times 10^{-11} \left(\frac{T}{300}\right)^{0.44}$		95
165	$H + H(s) \rightarrow H_2$	$k_{165} = 3.0 \times 10^{-18} T^{0.5} f_A [1.0 + 0.04(T + T_d)^{0.5}$	$f_A = \left[1.0 + 10^4 \exp\left(-\frac{600}{T_d}\right)\right]^{-1}$	96
		$+ 0.002\,T + 8 \times 10^{-6} T^2]^{-1}$		

129	$HCO^+ + e^- \rightarrow CO + H$	$k_{129} = 2.76 \times 10^{-7} \left(\frac{T}{300}\right)^{-0.64}$	79
130	$HCO^+ + e^- \rightarrow OH + C$	$k_{130} = 2.4 \times 10^{-8} \left(\frac{T}{300}\right)^{-0.64}$	79
131	$HOC^+ + e^- \rightarrow CO + H$	$k_{131} = 1.1 \times 10^{-7} \left(\frac{T}{300}\right)^{-1.0}$	28
132	$H^- + C \rightarrow CH + e^-$	$k_{132} = 1.0 \times 10^{-9}$	28
133	$H^- + O \rightarrow OH + e^-$	$k_{133} = 1.0 \times 10^{-9}$	28
134	$H^- + OH \rightarrow H_2O + e^-$	$k_{134} = 1.0 \times 10^{-10}$	28
135	$C^- + H \rightarrow CH + e^-$	$k_{135} = 5.0 \times 10^{-10}$	28
136	$C^- + H_2 \rightarrow CH_2 + e^-$	$k_{136} = 1.0 \times 10^{-13}$	28
137	$C^- + O \rightarrow CO + e^-$	$k_{137} = 5.0 \times 10^{-10}$	28
138	$O^- + H \rightarrow OH + e^-$	$k_{138} = 5.0 \times 10^{-10}$	28
139	$O^- + H_2 \rightarrow H_2O + e^-$	$k_{139} = 7.0 \times 10^{-10}$	28
140	$O^- + C \rightarrow CO + e^-$	$k_{140} = 5.0 \times 10^{-10}$	28

chemical model 2

(Glover, Federrath, Mac Low, Klessen, 2010, MNRS, 404, 2)



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
92	$CH_2 + He^+ \rightarrow C^+ + He + H_2$	$k_{92} = 7.5 \times 10^{-10}$	28
[illegible]	[illegible]	[illegible]	28
[illegible]	[illegible]	[illegible]	28
[illegible]	[illegible]	[illegible]	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

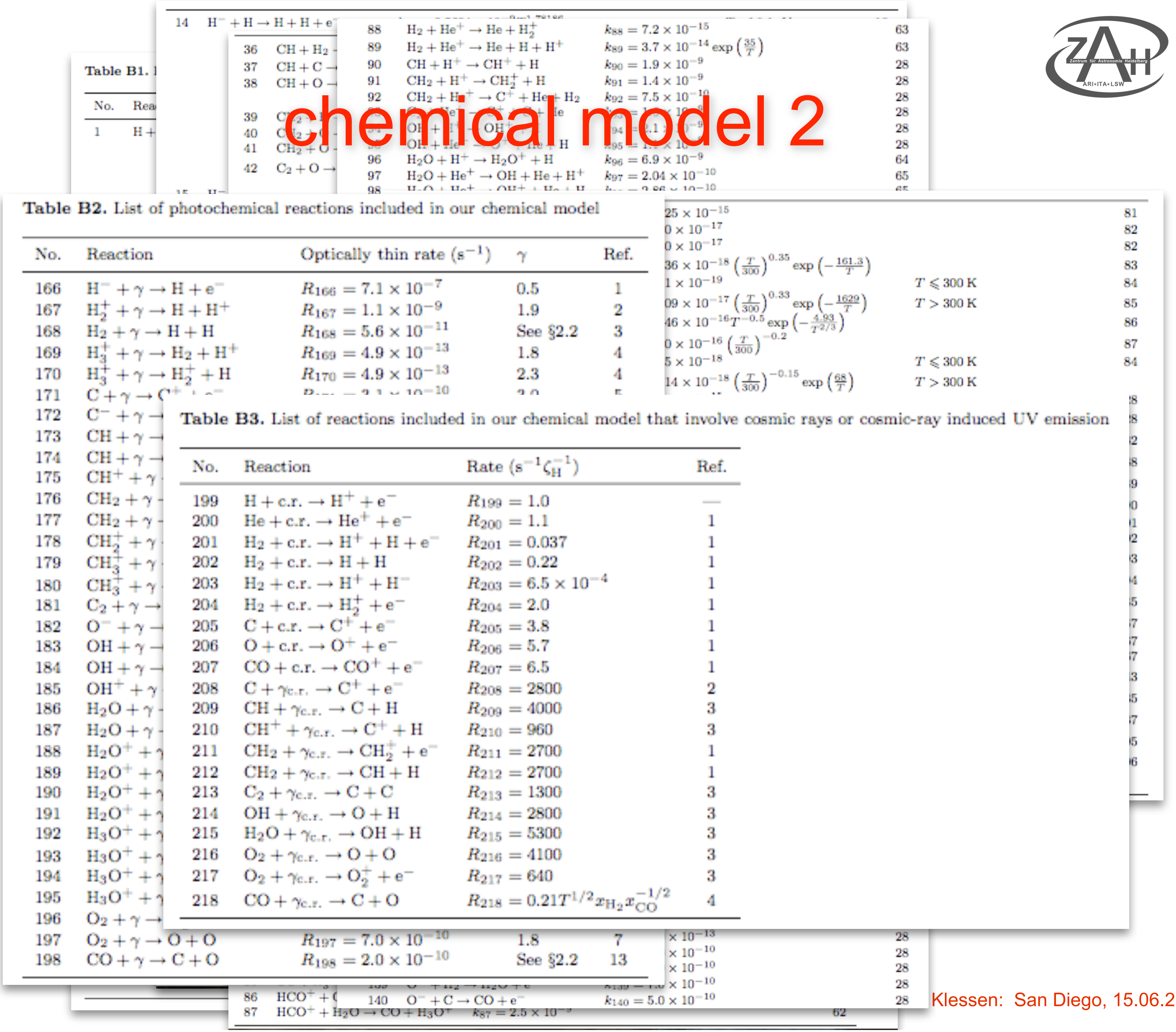
Table B2. List of photochemical reactions included in our chemical model

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
171	$C + \gamma \rightarrow C^+ + e^-$	$R_{171} = 3.1 \times 10^{-10}$	3.0	5
172	$C^- + \gamma \rightarrow C + e^-$	$R_{172} = 2.4 \times 10^{-7}$	0.9	6
173	$CH + \gamma \rightarrow C + H$	$R_{173} = 8.7 \times 10^{-10}$	1.2	7
174	$CH + \gamma \rightarrow CH^+ + e^-$	$R_{174} = 7.7 \times 10^{-10}$	2.8	8
175	$CH^+ + \gamma \rightarrow C + H^+$	$R_{175} = 2.6 \times 10^{-10}$	2.5	7
176	$CH_2 + \gamma \rightarrow CH + H$	$R_{176} = 7.1 \times 10^{-10}$	1.7	7
177	$CH_2 + \gamma \rightarrow CH_2^+ + e^-$	$R_{177} = 5.9 \times 10^{-10}$	2.3	6
178	$CH_2^+ + \gamma \rightarrow CH^+ + H$	$R_{178} = 4.6 \times 10^{-10}$	1.7	9
179	$CH_3^+ + \gamma \rightarrow CH_2^+ + H$	$R_{179} = 1.0 \times 10^{-9}$	1.7	6
180	$CH_3^+ + \gamma \rightarrow CH^+ + H_2$	$R_{180} = 1.0 \times 10^{-9}$	1.7	6
181	$C_2 + \gamma \rightarrow C + C$	$R_{181} = 1.5 \times 10^{-10}$	2.1	7
182	$O^- + \gamma \rightarrow O + e^-$	$R_{182} = 2.4 \times 10^{-7}$	0.5	6
183	$OH + \gamma \rightarrow O + H$	$R_{183} = 3.7 \times 10^{-10}$	1.7	10
184	$OH + \gamma \rightarrow OH^+ + e^-$	$R_{184} = 1.6 \times 10^{-12}$	3.1	6
185	$OH^+ + \gamma \rightarrow O + H^+$	$R_{185} = 1.0 \times 10^{-12}$	1.8	4
186	$H_2O + \gamma \rightarrow OH + H$	$R_{186} = 6.0 \times 10^{-10}$	1.7	11
187	$H_2O + \gamma \rightarrow H_2O^+ + e^-$	$R_{187} = 3.2 \times 10^{-11}$	3.9	8
188	$H_2O^+ + \gamma \rightarrow H_2^+ + O$	$R_{188} = 5.0 \times 10^{-11}$	See §2.2	12
189	$H_2O^+ + \gamma \rightarrow H^+ + OH$	$R_{189} = 5.0 \times 10^{-11}$	See §2.2	12
190	$H_2O^+ + \gamma \rightarrow O^+ + H_2$	$R_{190} = 5.0 \times 10^{-11}$	See §2.2	12
191	$H_2O^+ + \gamma \rightarrow OH^+ + H$	$R_{191} = 1.5 \times 10^{-10}$	See §2.2	12
192	$H_3O^+ + \gamma \rightarrow H^+ + H_2O$	$R_{192} = 2.5 \times 10^{-11}$	See §2.2	12
193	$H_3O^+ + \gamma \rightarrow H_2^+ + OH$	$R_{193} = 2.5 \times 10^{-11}$	See §2.2	12
194	$H_3O^+ + \gamma \rightarrow H_2O^+ + H$	$R_{194} = 7.5 \times 10^{-12}$	See §2.2	12
195	$H_3O^+ + \gamma \rightarrow OH^+ + H_2$	$R_{195} = 2.5 \times 10^{-11}$	See §2.2	12
196	$O_2 + \gamma \rightarrow O_2^+ + e^-$	$R_{196} = 5.6 \times 10^{-11}$	3.7	7
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

25×10^{-15}		81
0×10^{-17}		82
0×10^{-17}		82
$36 \times 10^{-18} \left(\frac{T}{300}\right)^{0.35} \exp\left(-\frac{161.3}{T}\right)$		83
1×10^{-19}	$T \leqslant 300$ K	84
$09 \times 10^{-17} \left(\frac{T}{300}\right)^{0.33} \exp\left(-\frac{1629}{T}\right)$	$T > 300$ K	85
$46 \times 10^{-16} T^{-0.5} \exp\left(-\frac{4.93}{T^{2/3}}\right)$		86
$0 \times 10^{-16} \left(\frac{T}{300}\right)^{-0.2}$		87
5×10^{-18}	$T \leqslant 300$ K	84
$14 \times 10^{-18} \left(\frac{T}{300}\right)^{-0.15} \exp\left(\frac{68}{T}\right)$	$T > 300$ K	
5×10^{-15}		28
$9 \times 10^{-19} \left(\frac{T}{300}\right)^{-0.38}$		28
$9 \times 10^{-20} \left(\frac{T}{300}\right)^{1.58}$		82
$26 \times 10^{-18} \left(\frac{T}{300}\right)^{-5.22} \exp\left(-\frac{90}{T}\right)$		88
$32 \times 10^{-32} \left(\frac{T}{300}\right)^{-0.38}$	$T \leqslant 300$ K	89
$32 \times 10^{-32} \left(\frac{T}{300}\right)^{-1.0}$	$T > 300$ K	90
$8 \times 10^{-31} T^{-0.6}$		91
$9 \times 10^{-32} T^{-0.4}$		92
$99 \times 10^{-33} \left(\frac{T}{5000}\right)^{-1.6}$	$T \leqslant 5000$ K	93
$99 \times 10^{-33} \left(\frac{T}{5000}\right)^{-0.64} \exp\left(\frac{5255}{T}\right)$	$T > 5000$ K	94
$16 \times 10^{-29} \left(\frac{T}{300}\right)^{-3.08}$	$T \leqslant 2000$ K	35
$14 \times 10^{-29} \left(\frac{T}{300}\right)^{-3.08} \exp\left(\frac{2114}{T}\right)$	$T > 2000$ K	67
$0 \times k_{210}$		67
$0 \times k_{210}$		67
$33 \times 10^{-32} \left(\frac{T}{300}\right)^{-1.0}$		43
$56 \times 10^{-31} \left(\frac{T}{300}\right)^{-2.0}$		35
$2 \times 10^{-34} \left(\frac{T}{300}\right)^{-1.0}$		37
$0 \times 10^{-11} \left(\frac{T}{300}\right)^{0.44}$		95
$0 \times 10^{-18} T^{0.5} f_A [1.0 + 0.04(T + T_d)^{0.5}$	$f_A = \left[1.0 + 10^4 \exp\left(-\frac{600}{T_d}\right)\right]^{-1}$	96
$0.002\,T + 8 \times 10^{-6} T^2]^{-1}$		

140	$O^- + C \rightarrow CO + e^-$	$k_{140} = 5.0 \times 10^{-10}$	28
87	$HCO^+ + H_2O \rightarrow CO + H_3O^+$	$k_{87} = 2.5 \times 10^{-9}$	62

chemical model 2



No.	Reaction	Rate	Ref.
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
92	$CH_2 + He^+ \rightarrow C^+ + He + H_2$	$k_{92} = 7.5 \times 10^{-10}$	28
[illegible]	[illegible]	[illegible]	28
[illegible]	$OH + H^+ \rightarrow OH^+ + H$	$k_{94} = 2.1 \times 10^{-9}$	28
[illegible]	$OH + He^+ \rightarrow O^+ + He + H$	[illegible]	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
171	$C + \gamma \rightarrow C^+ + e^-$	[illegible]	[illegible]	[illegible]
172	$C^- + \gamma \rightarrow$			
173	$CH + \gamma \rightarrow$			
174	$CH + \gamma \rightarrow$			
175	$CH^+ + \gamma$			
176	$CH_2 + \gamma$			
177	$CH_2 + \gamma$			
178	$CH_2^+ + \gamma$			
179	$CH_3^+ + \gamma$			
180	$CH_3^+ + \gamma$			
181	$C_2 + \gamma \rightarrow$			
182	$O^- + \gamma \rightarrow$			
183	$OH + \gamma \rightarrow$			
184	$OH + \gamma \rightarrow$			
185	$OH^+ + \gamma$			
186	$H_2O + \gamma$			
187	$H_2O + \gamma$			
188	$H_2O^+ + \gamma$			
189	$H_2O^+ + \gamma$			
190	$H_2O^+ + \gamma$			
191	$H_2O^+ + \gamma$			
192	$H_3O^+ + \gamma$			
193	$H_3O^+ + \gamma$			
194	$H_3O^+ + \gamma$			
195	$H_3O^+ + \gamma$			
196	$O_2 + \gamma \rightarrow$			
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, Federrath, Mac Low, Klessen, 2010, MNRS, 404, 2)

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*

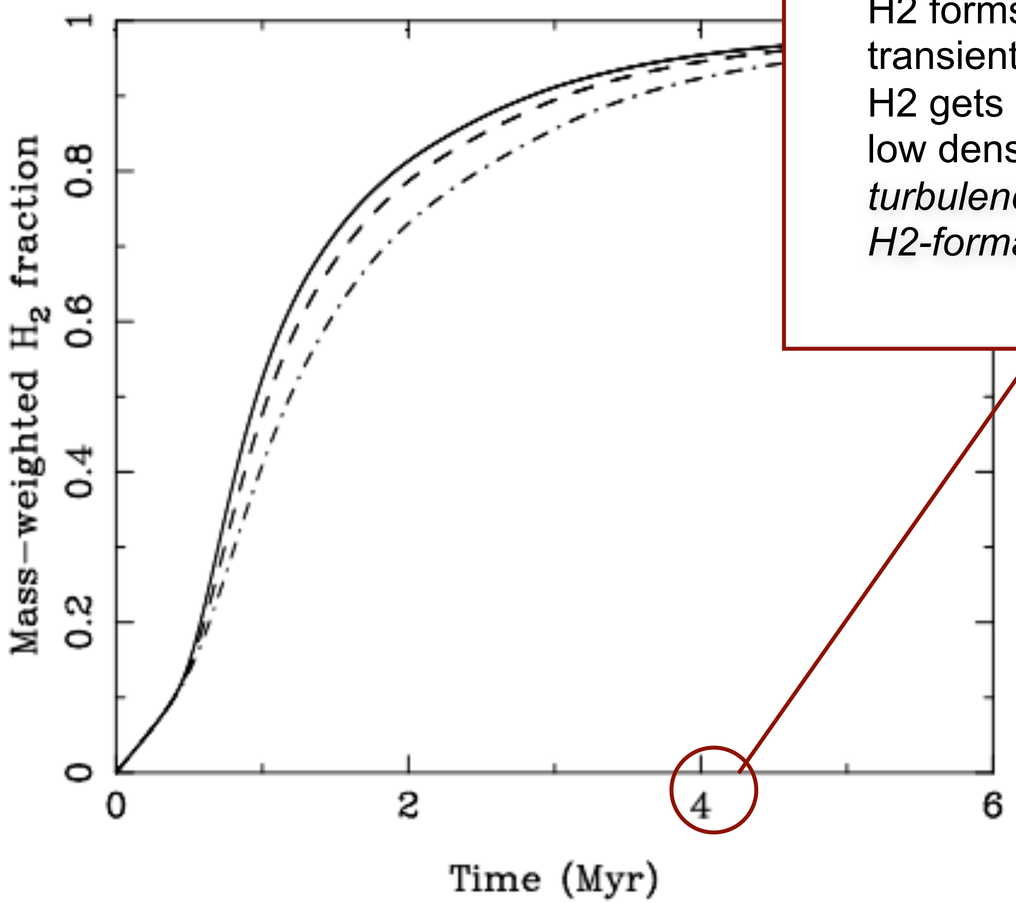


Figure 4. Time evolution of the mass-weighted H_2 abundance in simulations R1, R2 and R3, which have numerical resolutions of 64^3 zones (dot-dashed), 128^3 zones (dashed) and 256^3 zones (solid), respectively.

(Glover, Federrath, Mac Low, Klessen, 2010, MNRS, 404, 2)

CO, C$^+$ formation rates

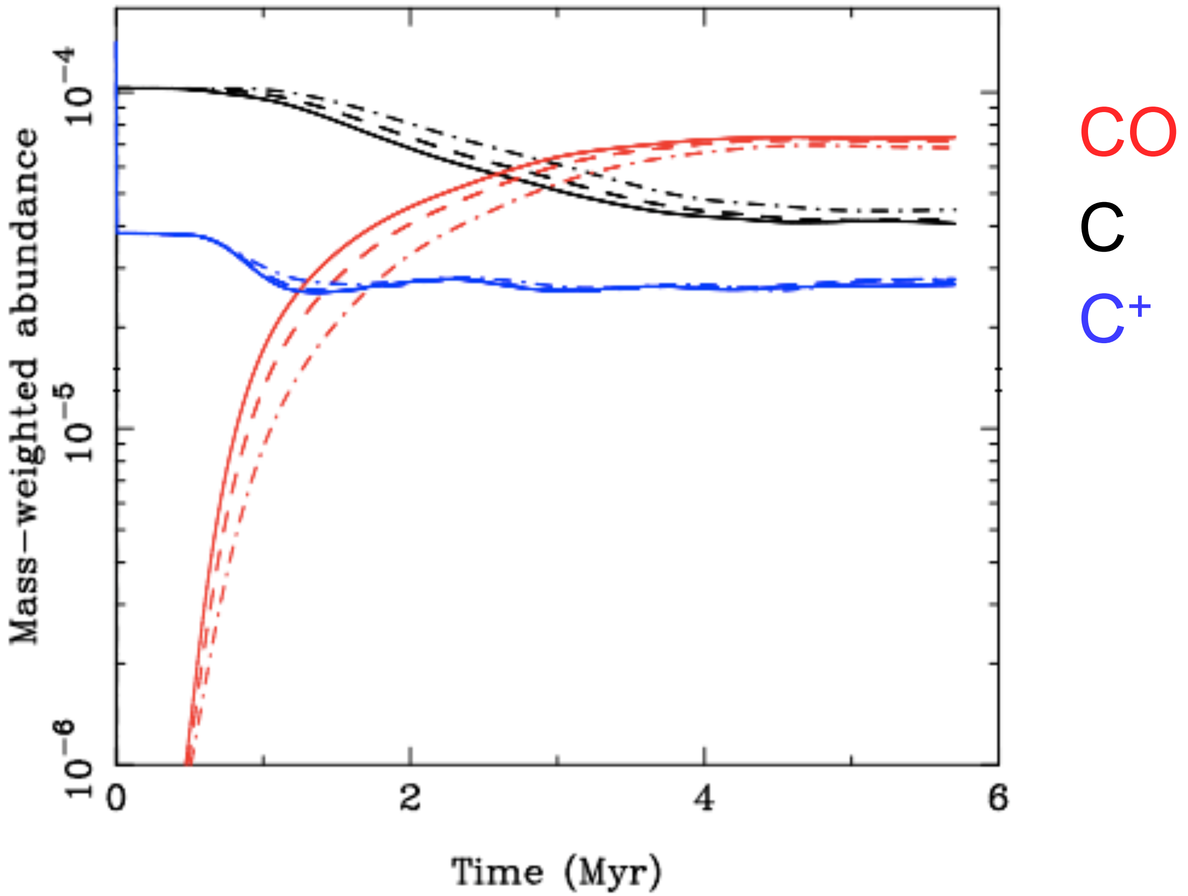
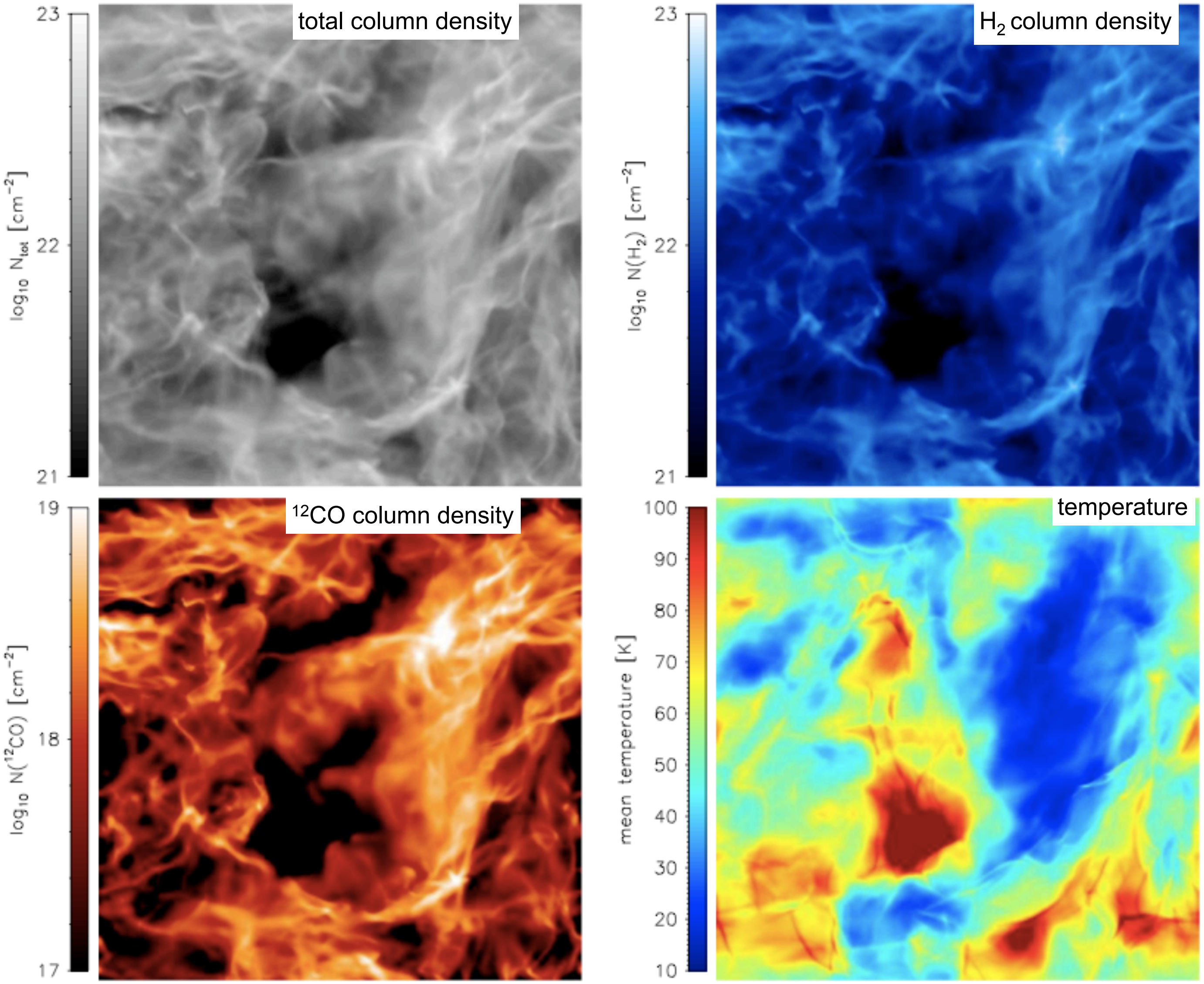


Figure 5. Time evolution of the mass-weighted abundances of atomic carbon (black lines), CO (red lines), and C$^+$ (blue lines) in simulations with numerical resolutions of 64^3 zones (dot-dashed), 128^3 zones (dashed) and 256^3 zones (solid).

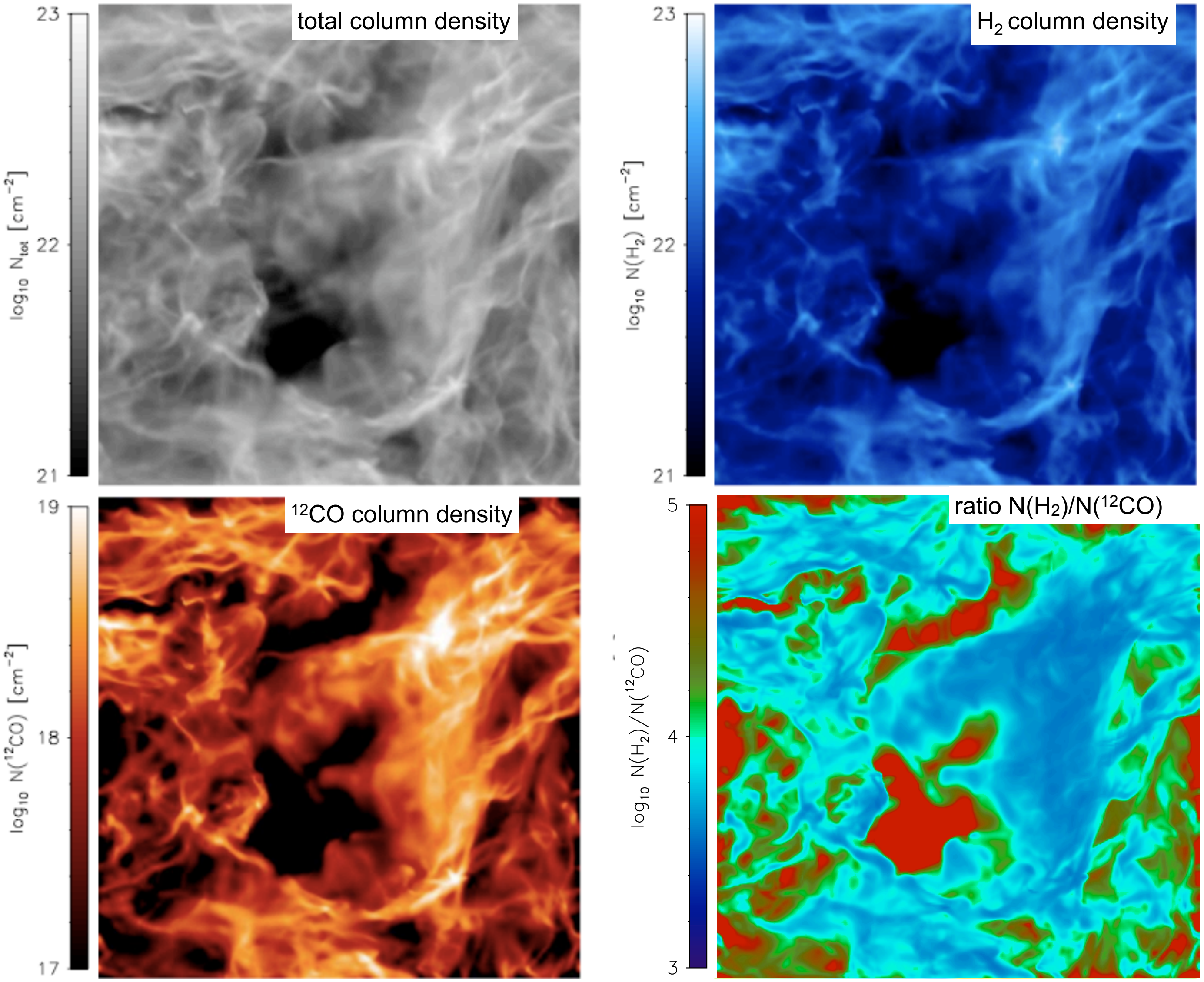
(Glover, Federrath, Mac Low, Klessen, 2010, MNRS, 404, 2)

effects of chemistry 1



(Glover, Federrath, Mac Low, Klessen, 2010, MNRS, 404, 2)

effects of chemistry 2

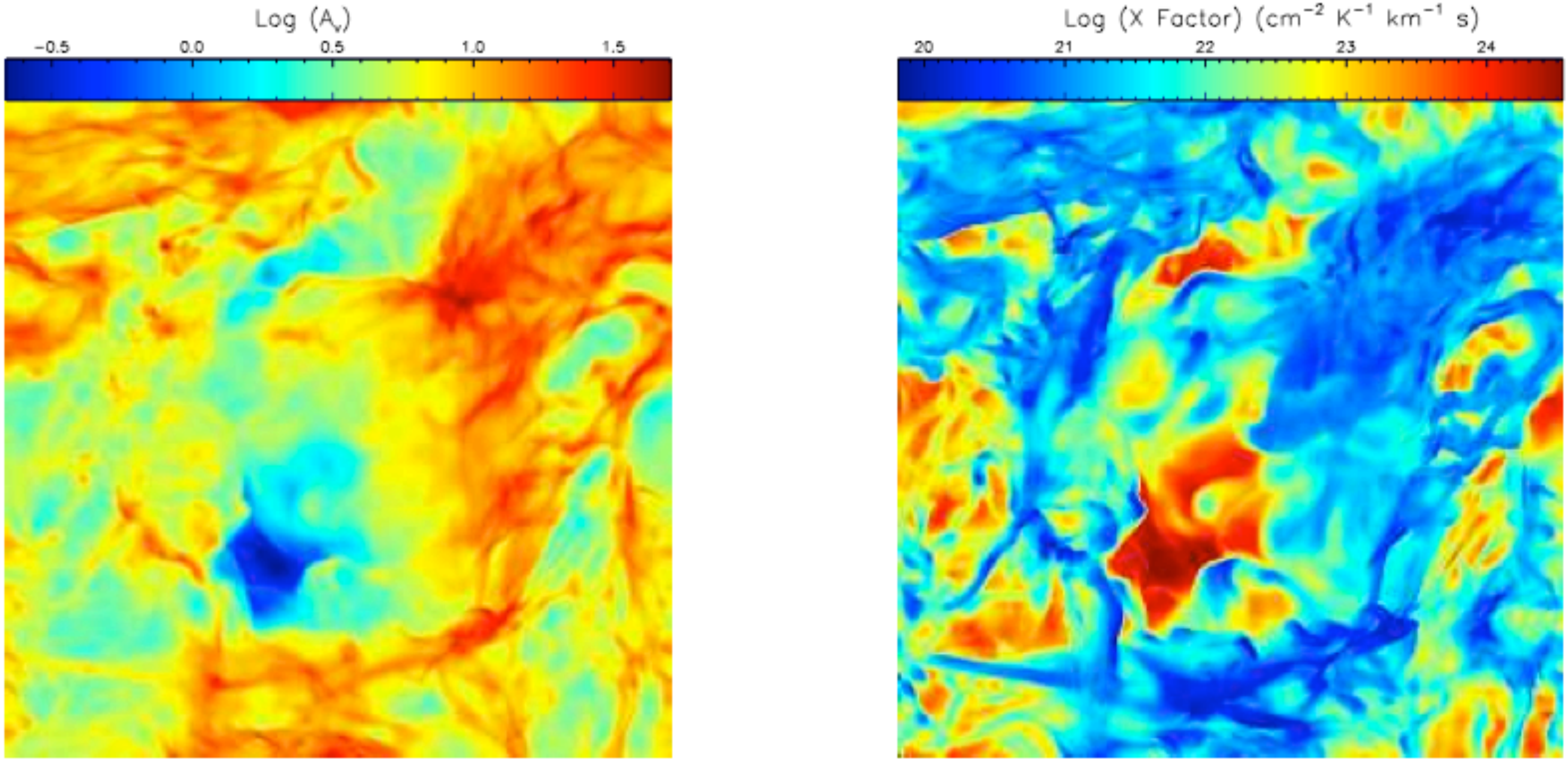


(Glover, Federrath, Mac Low, Klessen, 2010, MNRS, 404, 2)

effects of chemistry 3

- deliverables / predictions:
  - x-factor estimates (as function of environmental conditions)
  - synthetic line emission maps (in combination with line transfer)
  - pdf’s of density, velocity, emissivity / structure functions (to directly connect to observational regime)
  - *COMMENT:* density pdf is *NOT* lognormal!
    --> implications for analytical IMF theories

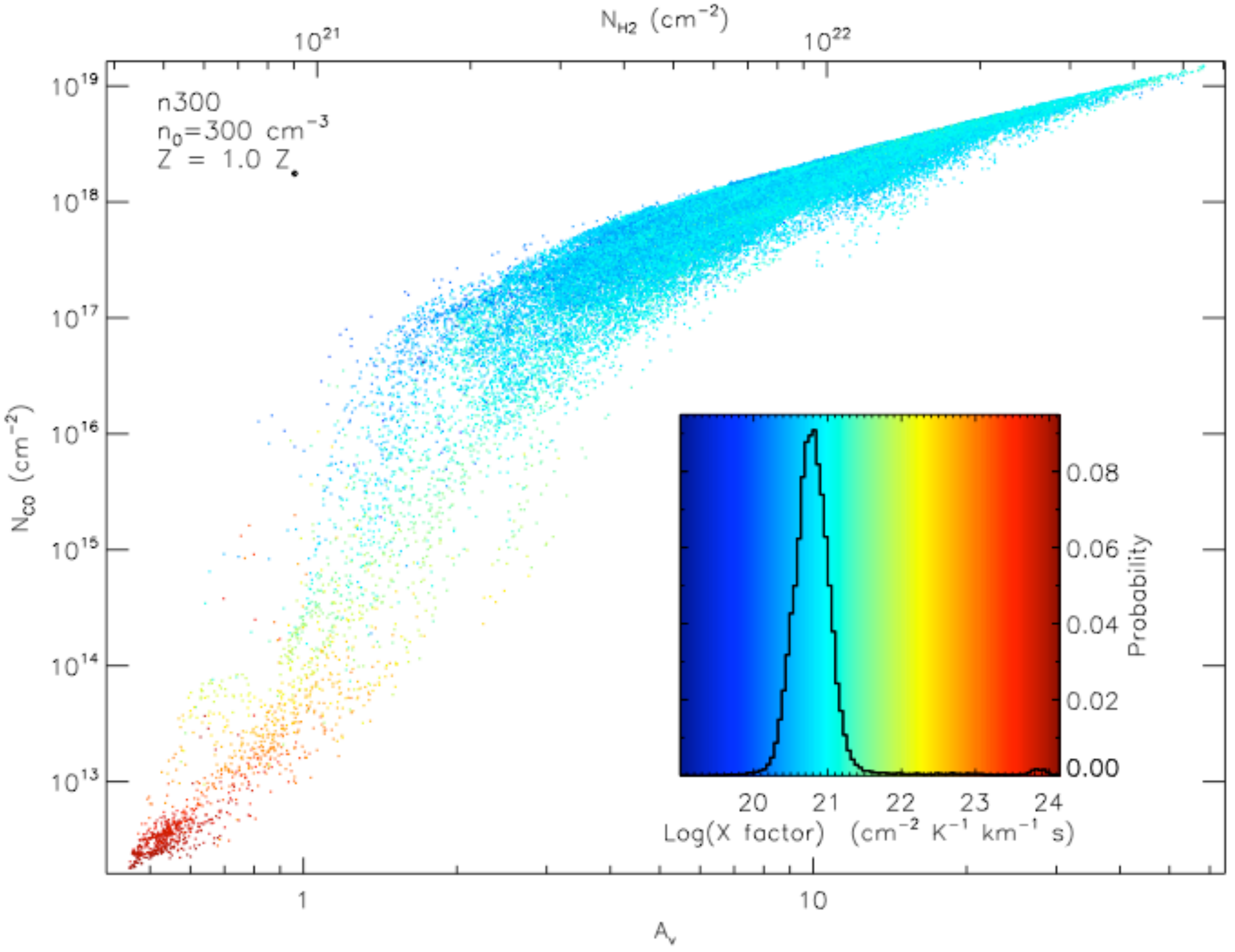
the x-factor



Images of A_v (left) and the X factor (right) of model n300-Z03.

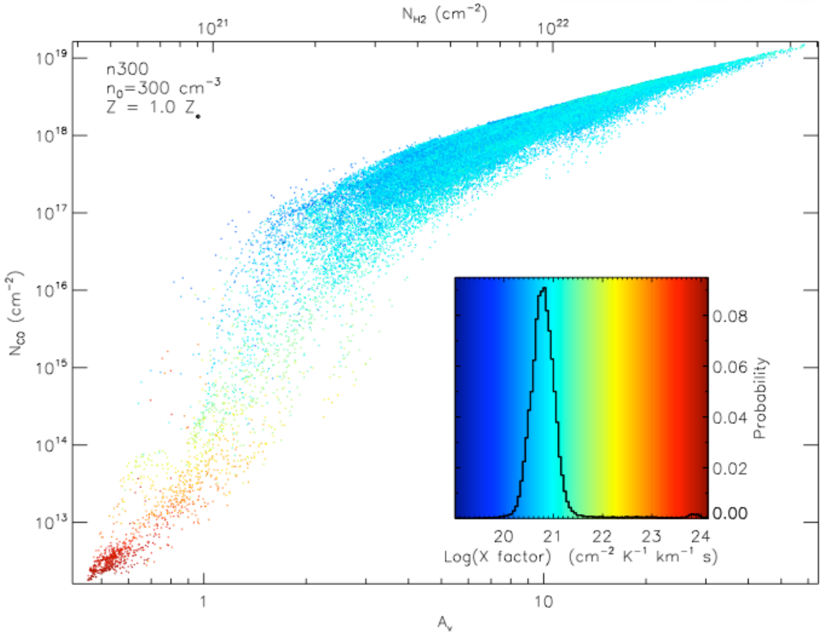
(Shetty, Glover, Dullemond, Klessen, in prep.)

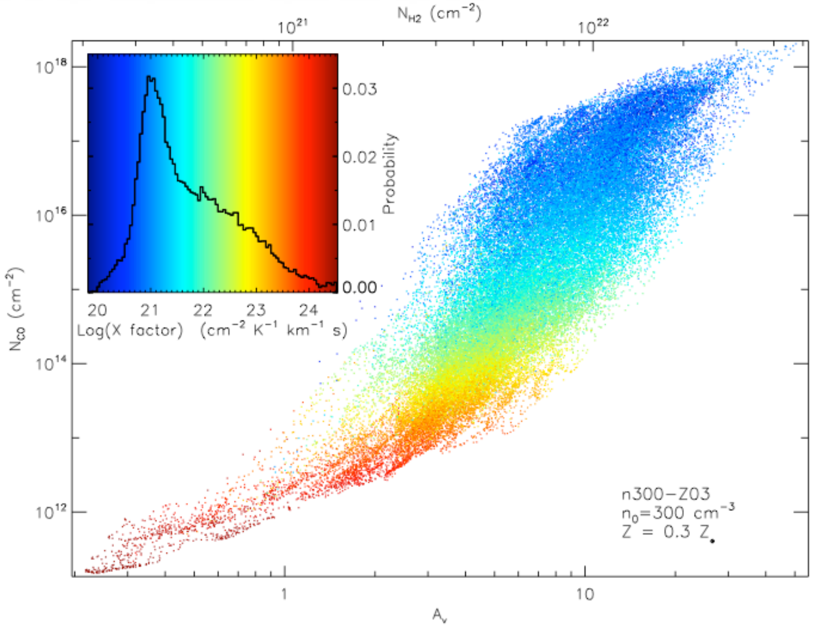
the x-factor

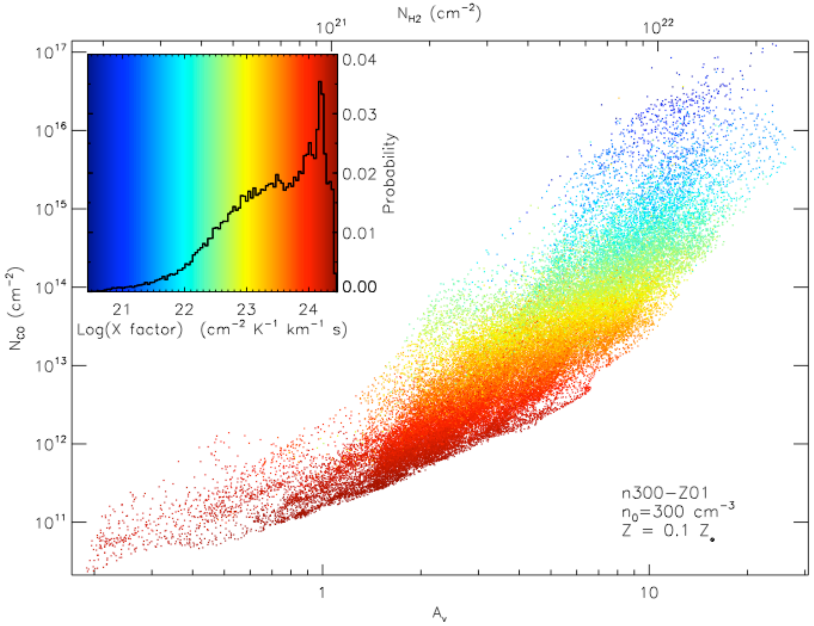


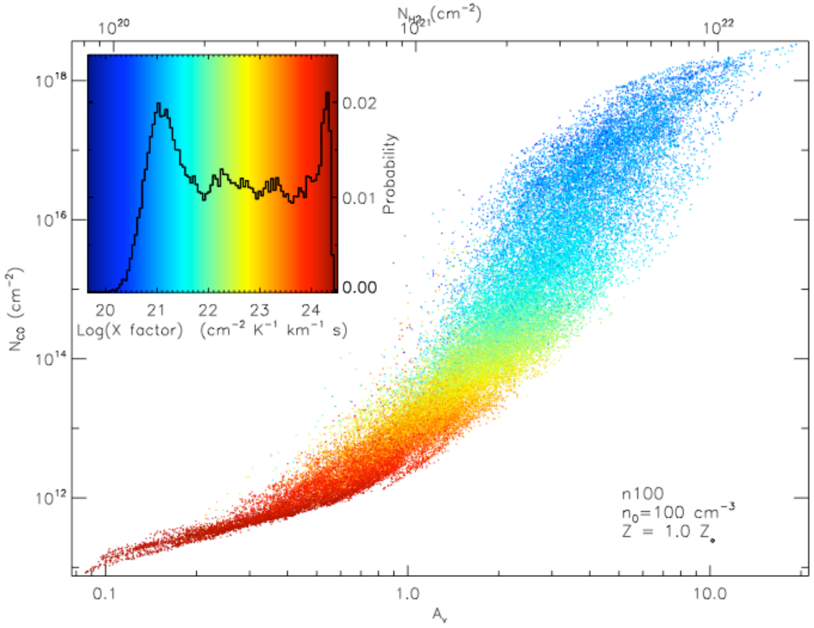
(Shetty, Glover, Dullemond, Klessen, in prep.)

different metallicities

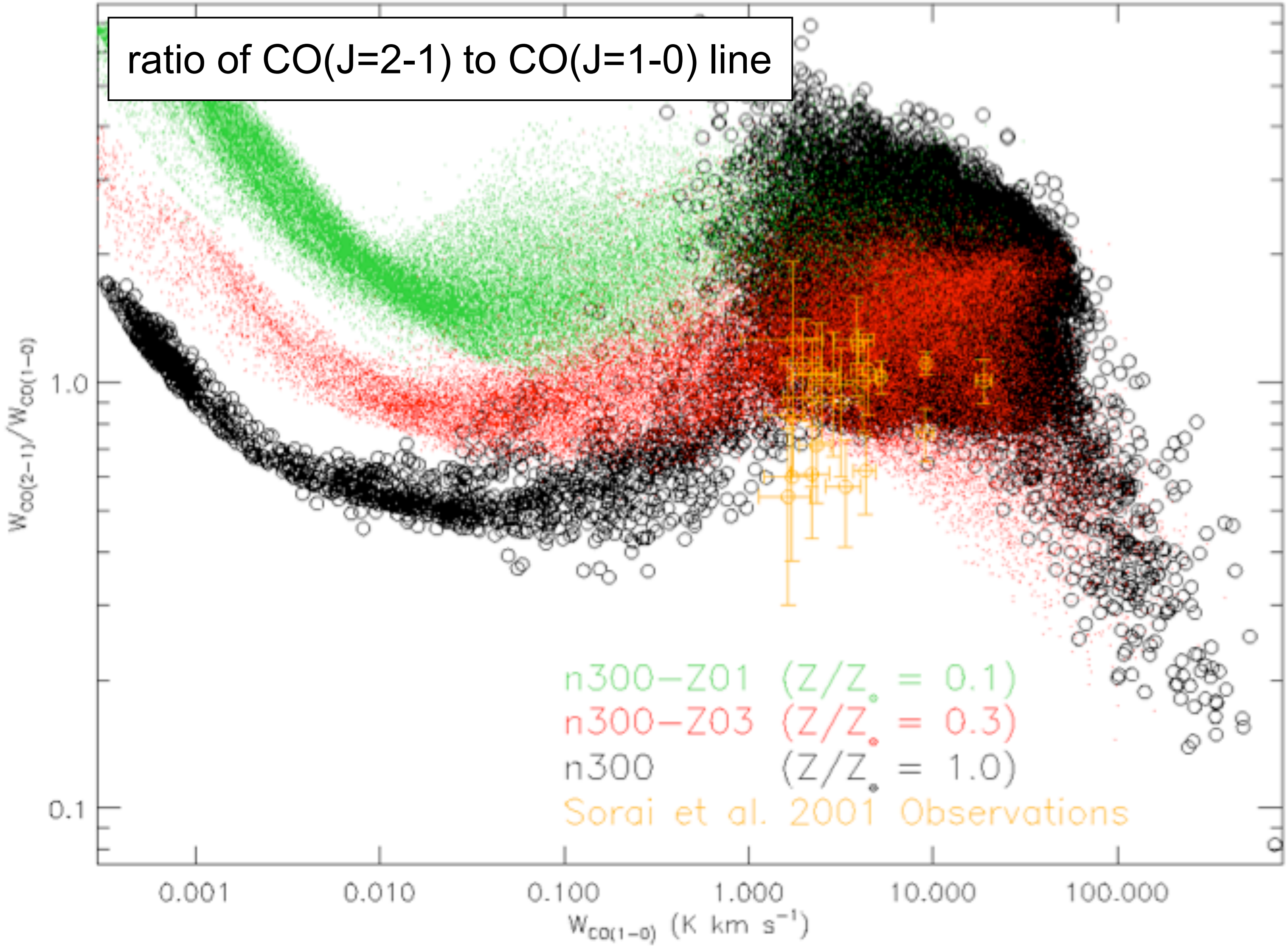








line ratios


ratio of CO(J=2-1) to CO(J=1-0) line

(Shetty, Glover, Dullemond, Klessen, in prep.)

B-fields

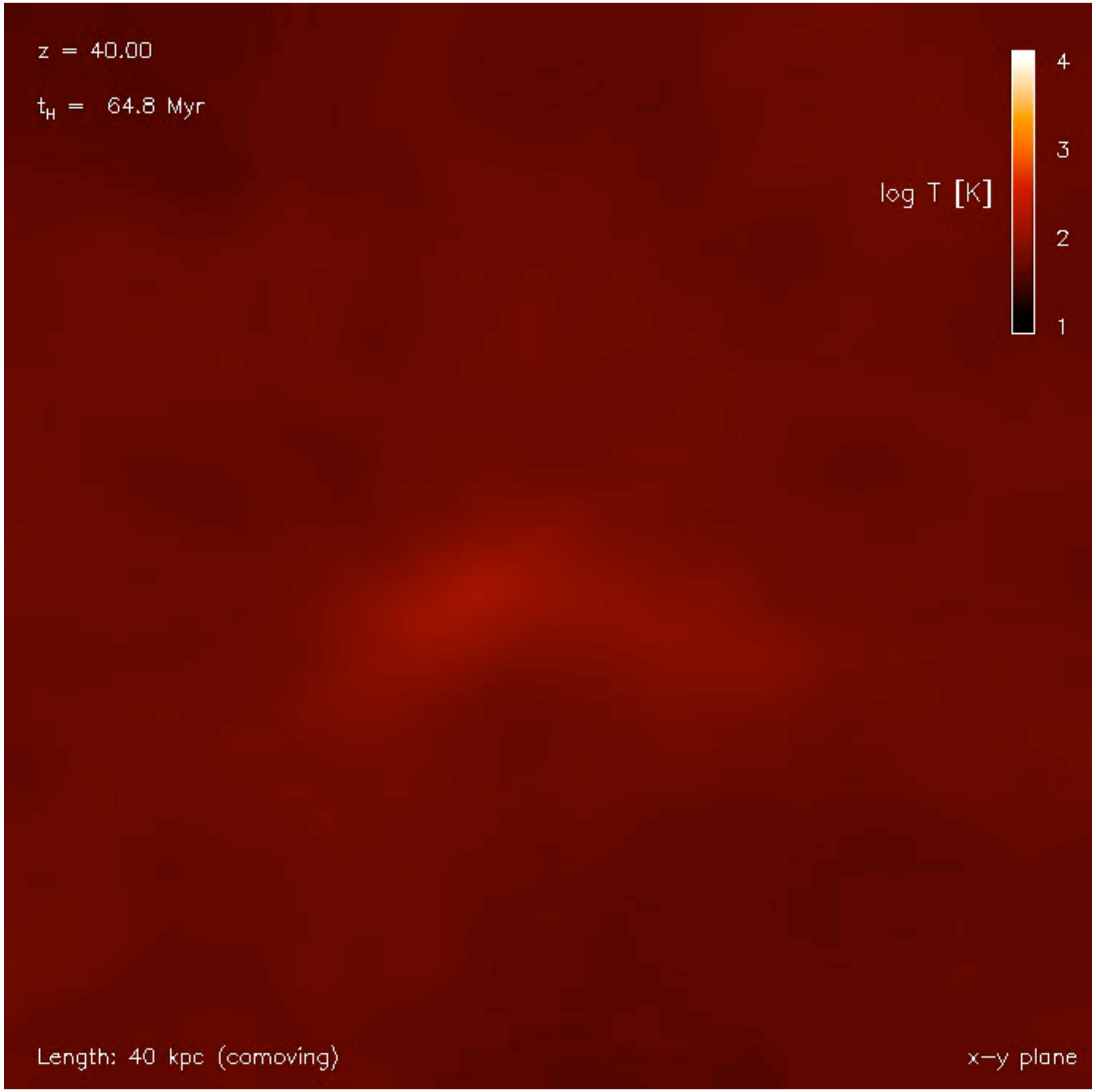
how to make strong B-fields

- we know the universe is magnetized (now)
- knowledge about B-fields in the high-redshift universe is extremely uncertain
  - inflation / QCD phase transition / Biermann battery / Weibel instability
- they are thought to be extremely small
- however, THIS MAY BE WRONG!

small-scale turbulent dynamo

- *idea:* the small-scale turbulent dynamo can generate strong magnetic fields from very small seed fields
- *approach:* model collapse of primordial gas ---> formation of the first stars in low-mass halo at redshift z ~ 20
- *method:* solve ideal MHD equations with very high resolution
  - grid-based AMR code FLASH
  - resolution up to 128^3 cells per Jeans volume (effective resolution 65536^3 cells)

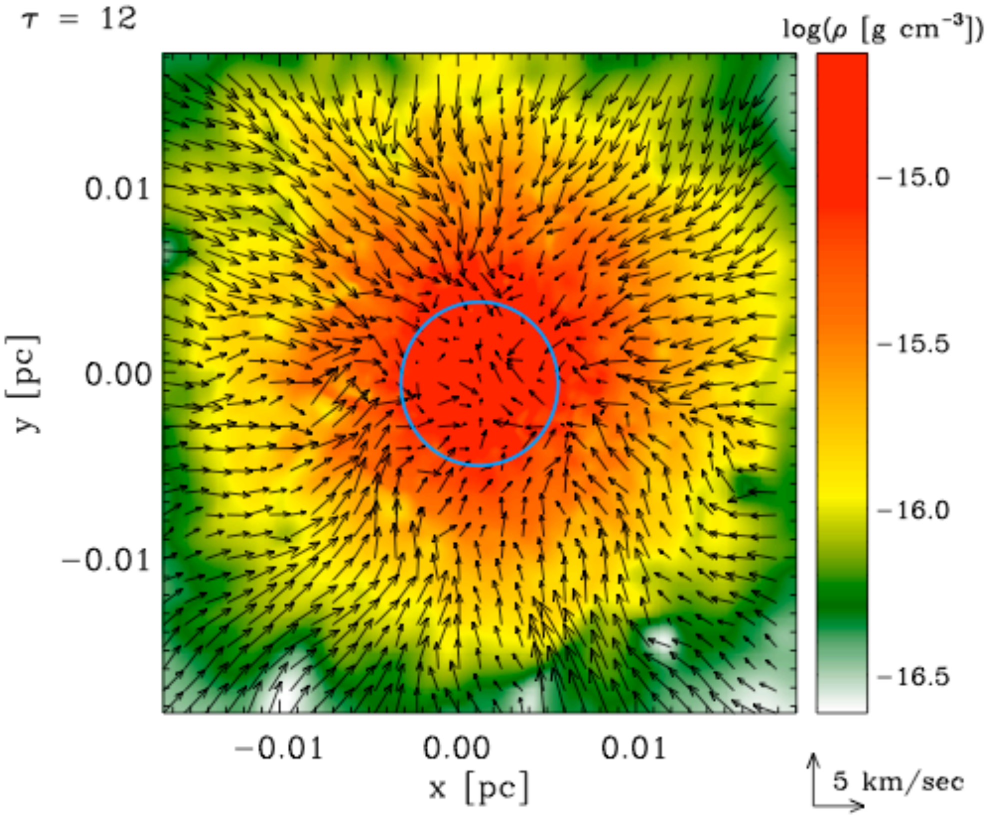
turbulence developing in an atomic cooling halo



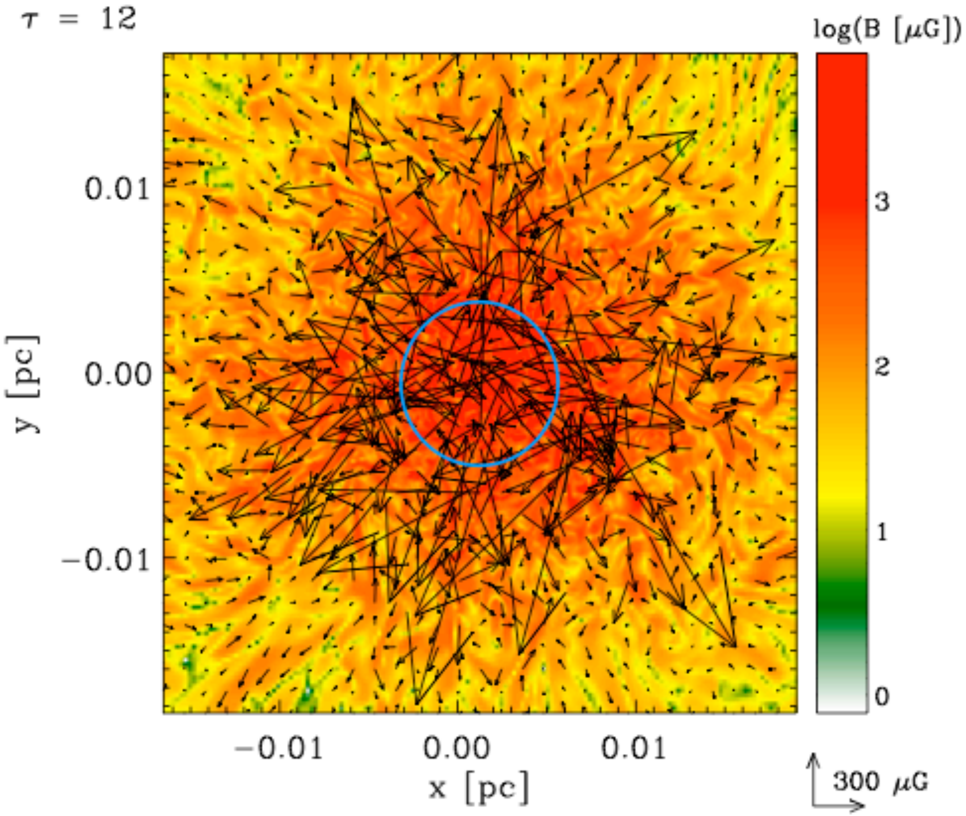
(Greif et al. 2008, MNRAS, 387, 1021, see also Wise & Abel 2007)

see also talk
by *Thomas Greif*

small-scale turbulent dynamo



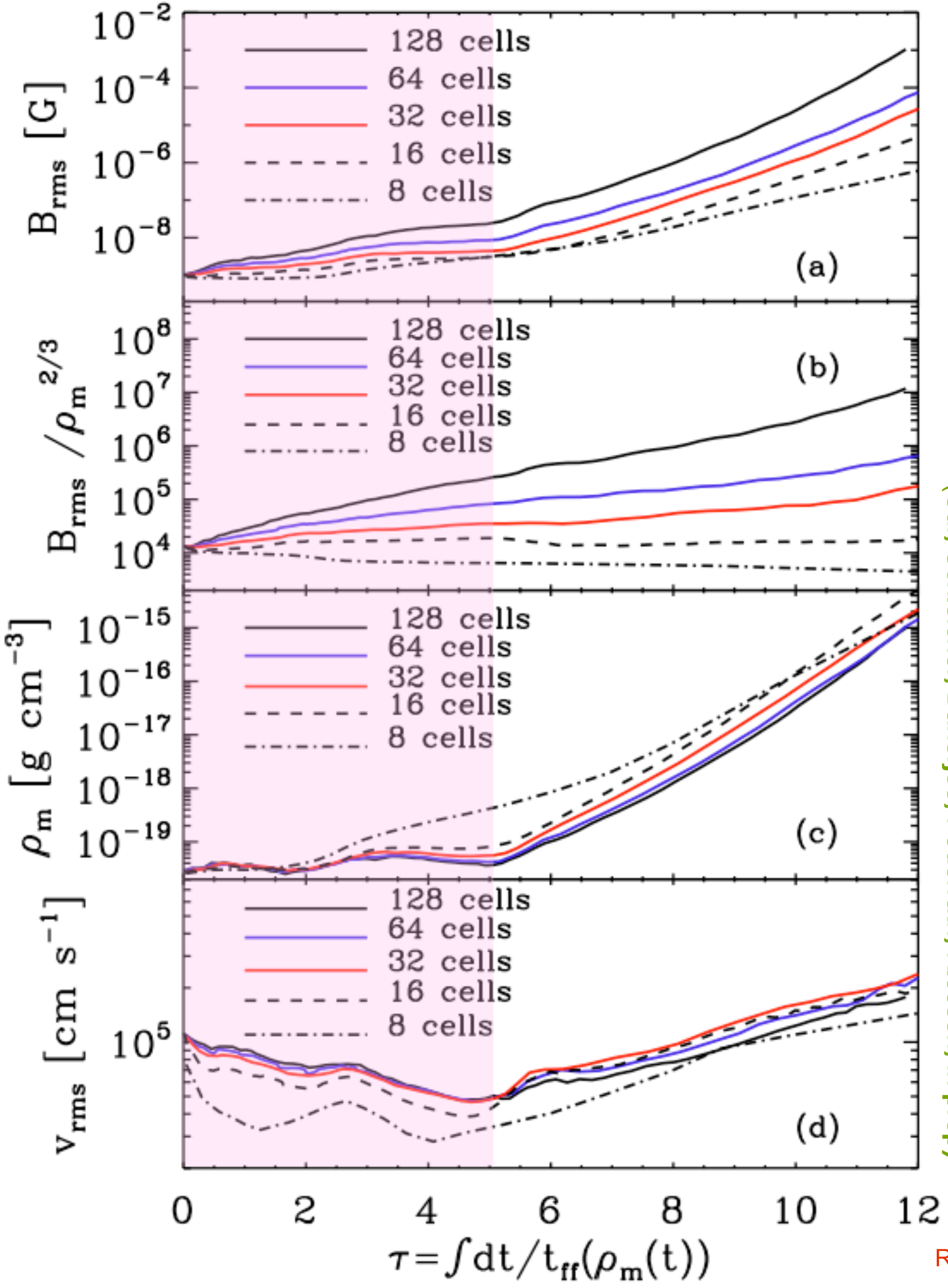
density, xy-velocity



B-field amplitude, xy-component

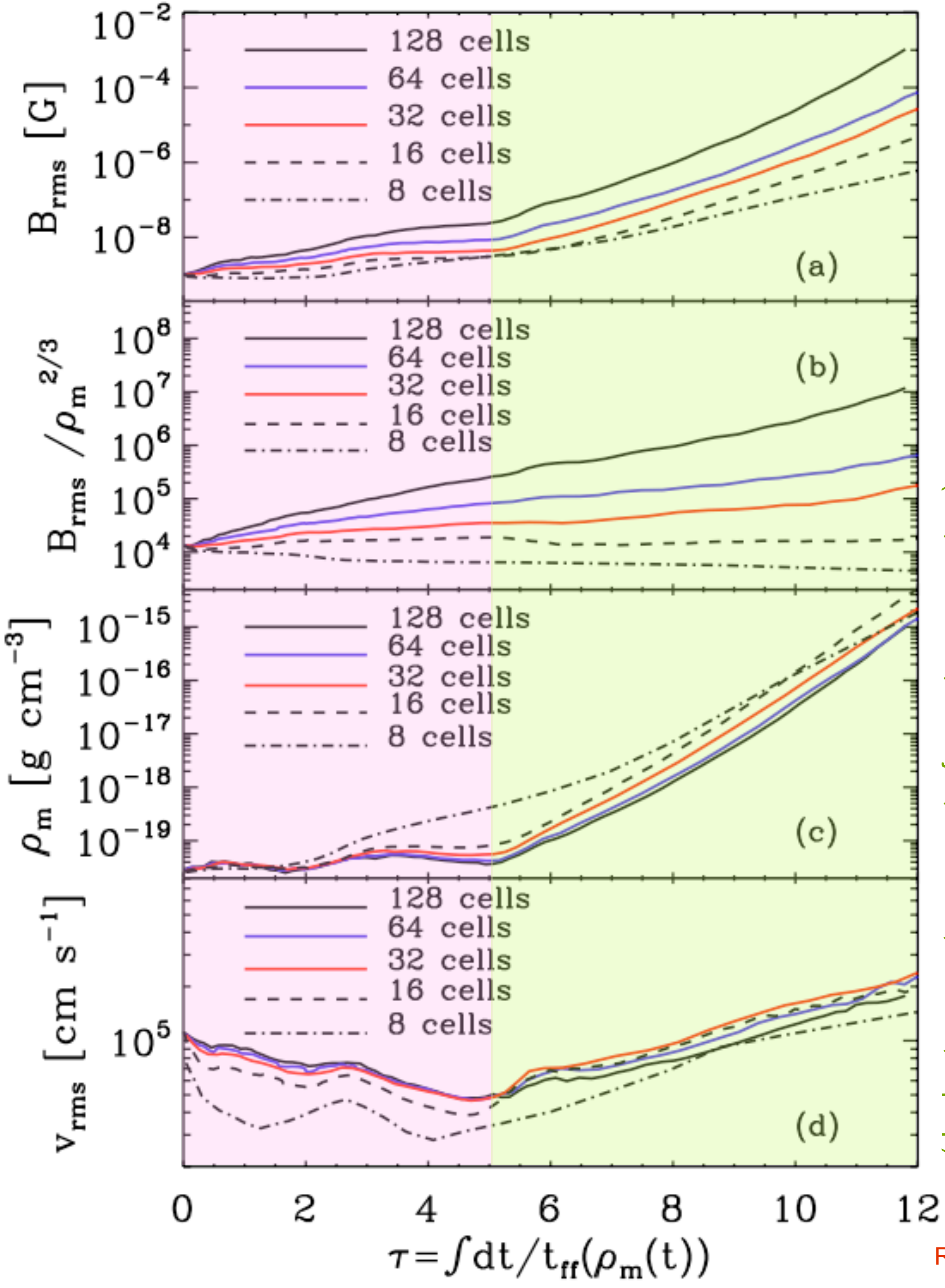
(Sur, Schleicher, Banerjee, Federrath, Klessen, in prep)

decay of turbulence



(Sur, Schleicher, Banerjee, Federrath, Klessen, in prep)

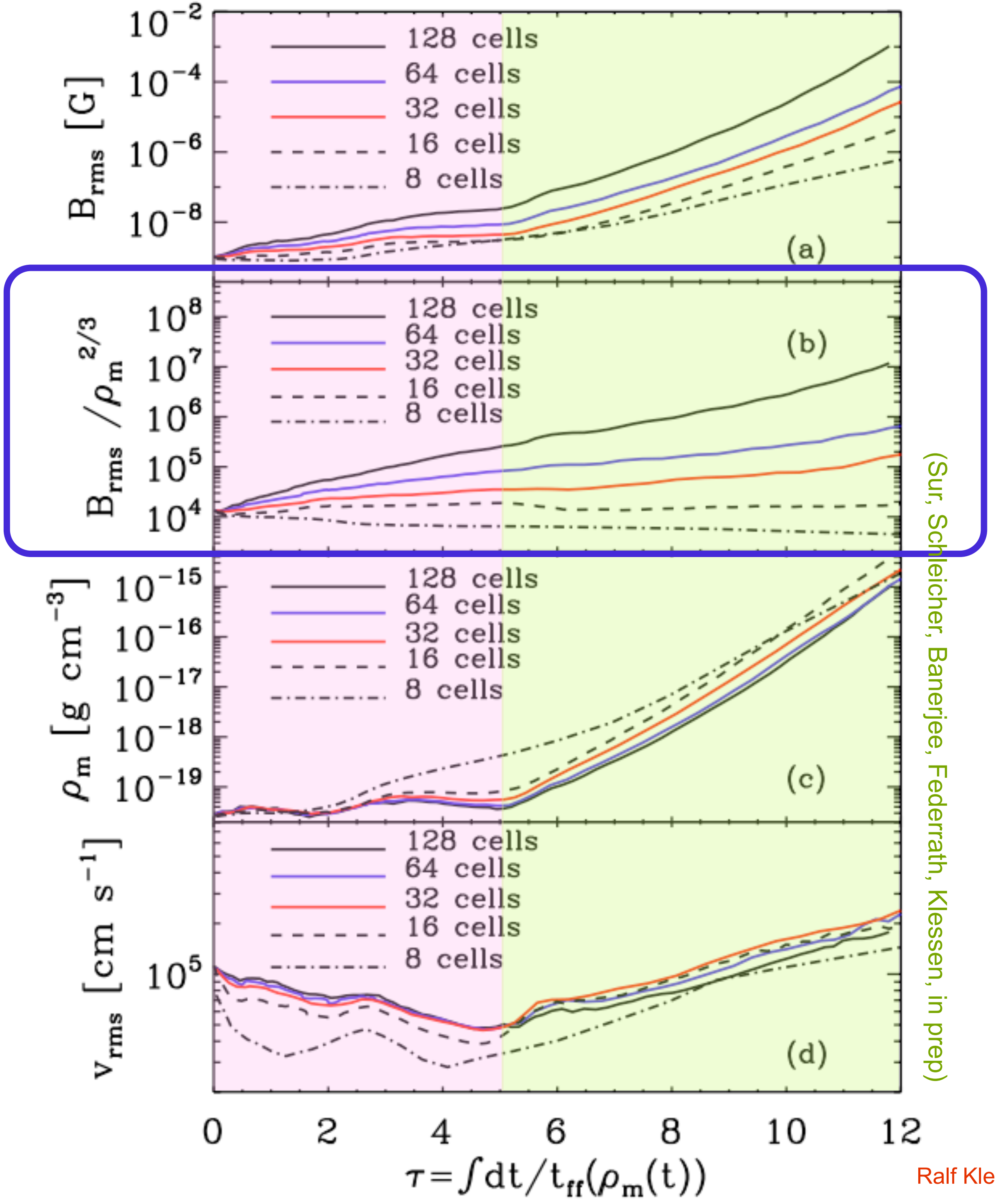
decay of turbulence



(Sur, Schleicher, Banerjee, Federrath, Klessen, in prep)

gravitational collapse,
accretion driven turbulence

decay of turbulence

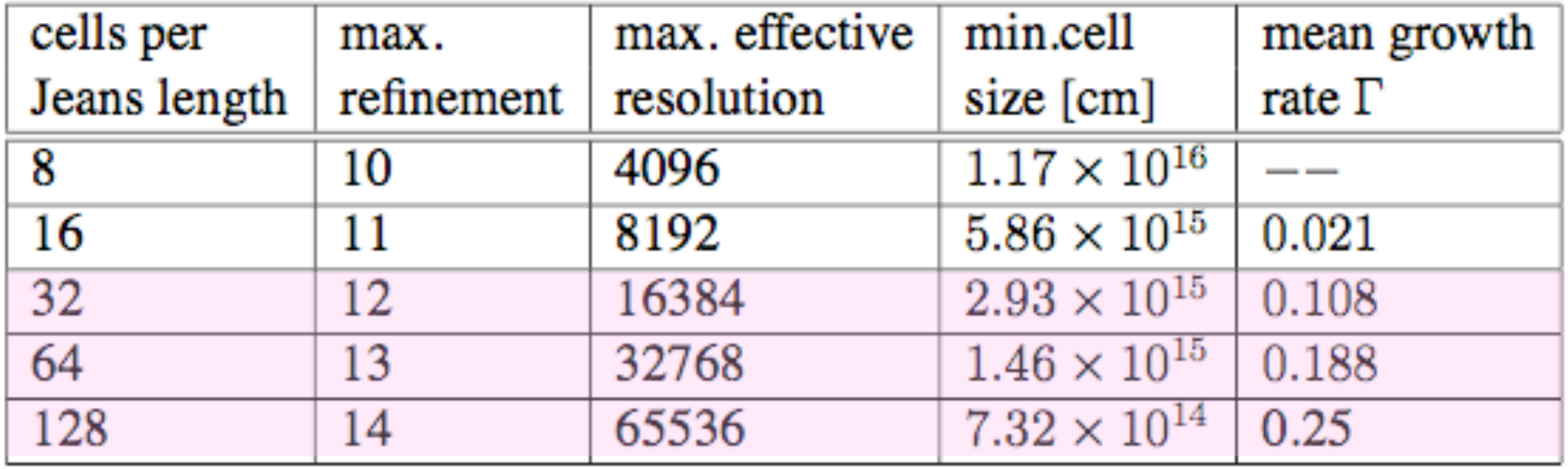


(Sur, Schleicher, Banerjee, Federrath, Klessen, in prep)

gravitational collapse,
accretion driven turbulence

small-scale turbulent dynamo

- small-scale turbulent dynamo can generate dynamically significant B-fields in the during first star formation!
- expected saturation level ~10% - 20% of equipartition value (Subramanian & Brandenburg 2005)
- needs very high resolution to be seen:



cells per Jeans length	max. refinement	max. effective resolution	min.cell size [cm]	mean growth rate Γ
8	10	4096	1.17×10^{16}	$--$
16	11	8192	5.86×10^{15}	0.021
32	12	16384	2.93×10^{15}	0.108
64	13	32768	1.46×10^{15}	0.188
128	14	65536	7.32×10^{14}	0.25

summary

summary

- modeling ISM turbulence and star formation is feasable
    - more physics is needed (chemistry, radiation field, realistic sources of turbulence, etc.)
- caveat: all LES of ISM turbulence model "crude oil" not interstellar gas
- examples
    - statistical properties of the turbulence
    - molecular cloud formation
    - generation of the first dynamically significant magnetic fields in the universe

thanks