Low velocity shocks as signatures of turbulent dissipation in diffuse irradiated gas

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Outline

- Two paths for molecules formation
- Turbulence dissipation
- Molecules production and excitation in shocks
- The example of the Stephan's Quintet
- Future prospects and ongoing work

ISM molecular gas chemistry for the dummies like me

- Form H_2 molecules on grains. Then:

- $H_2 + H_2^+ \rightarrow H_3^+ + X \rightarrow XH^+ + H_2$

- $H_2 + X \rightarrow XH + H$

where X is in {C, O, S, Si}.

(N is an exception..)

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Needs ionisation (Cosmic rays, Irradiation)

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Needs ionisation (Cosmic rays, Irradiation)

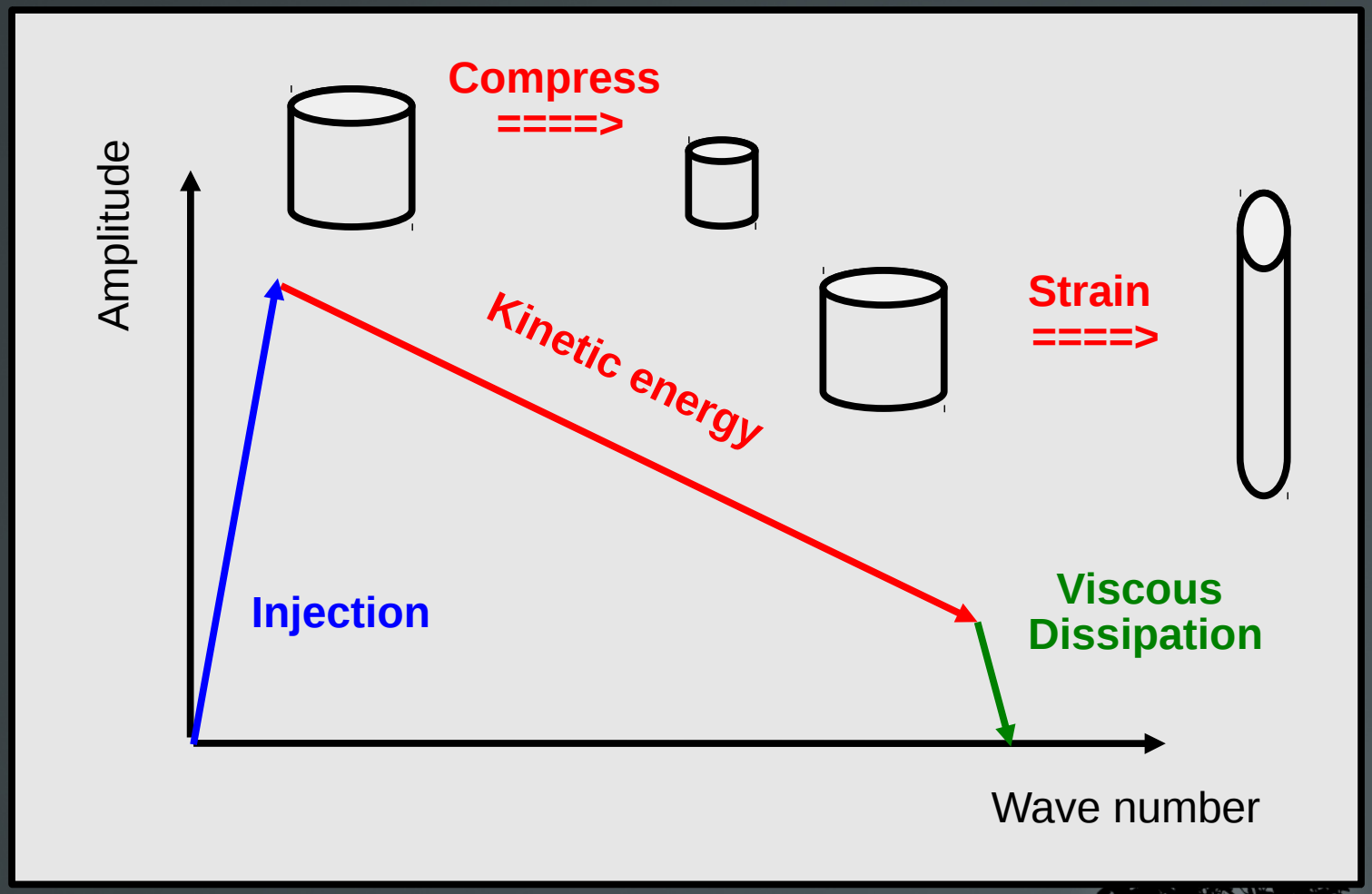
* $H_2 + X\ (\rightarrow)\ XH + H$

Needs thermal energy (Turbulence dissipation, mixing)

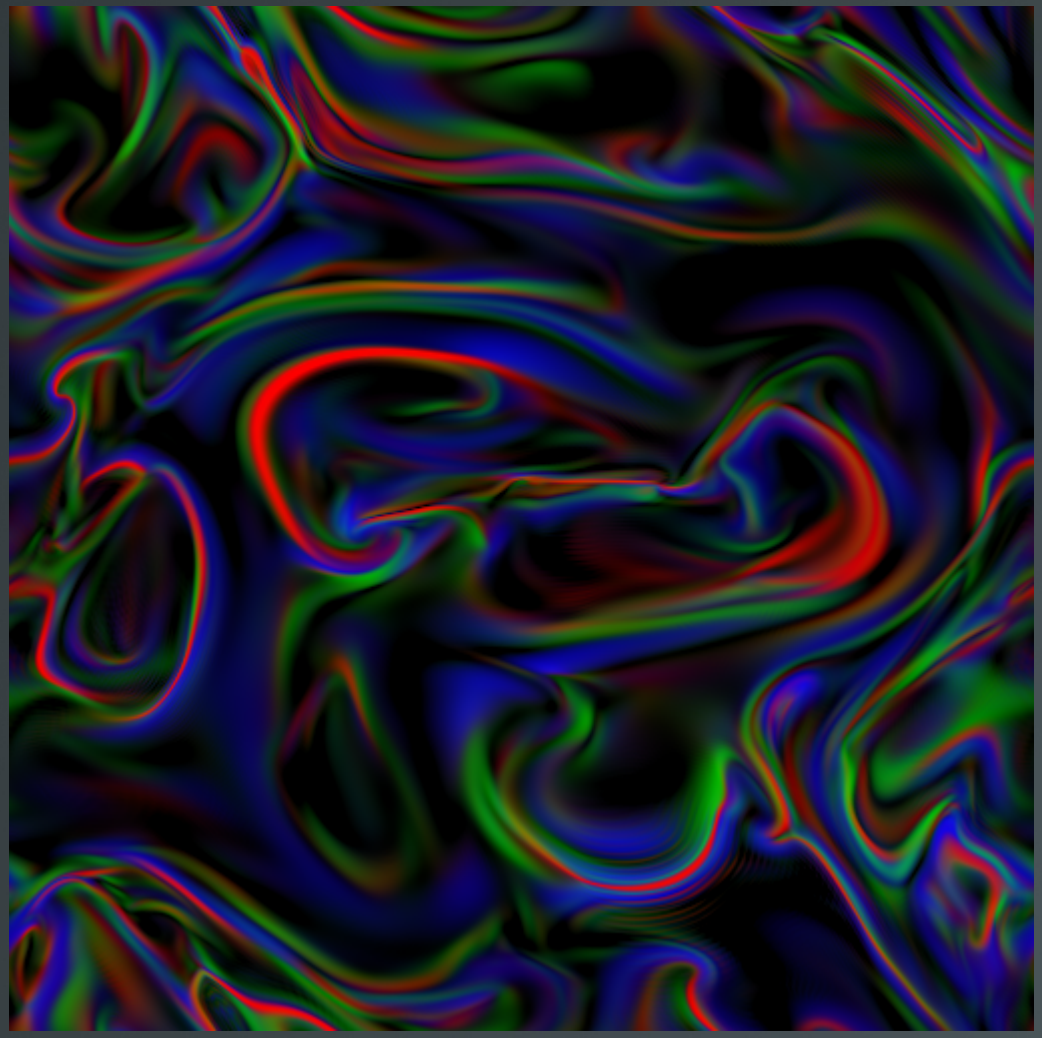
where X is in {C, O, S, Si}.

(N is an exception..)

The Kolmogorov cascade



Nature of the dissipation



$$\varepsilon_t = \varepsilon_v + \varepsilon_o + \varepsilon_a$$

Dissipative heatings:

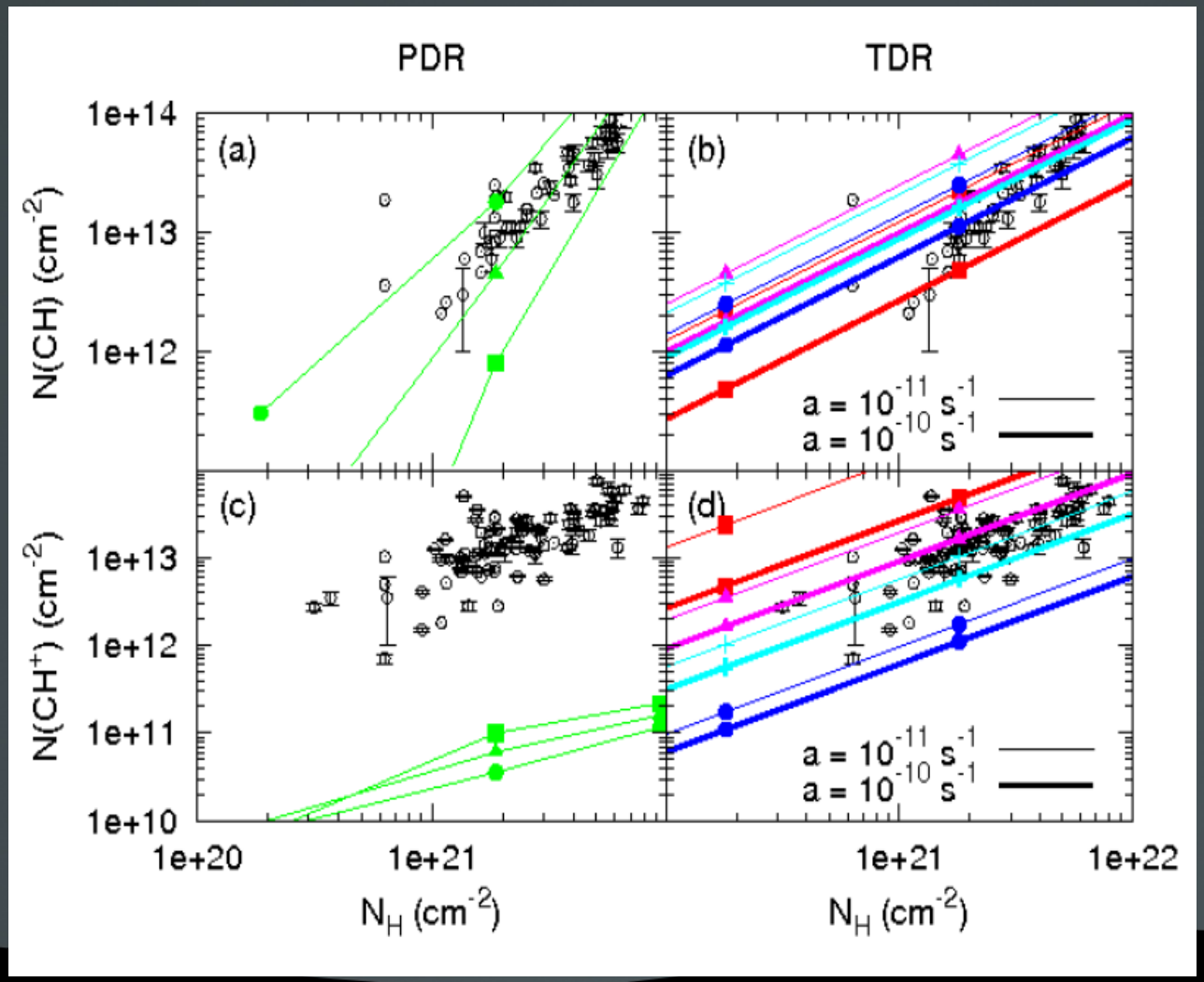
- **Green**: viscous
- **Red**: ohmic
- Blue: ion-neutral drift

2D Slice of a 512^3 pseudo-spectral 3D incomressible MHD + A.D. Decaying turbulence from an Orzag-Tang vortex.
Snapshot at peak dissipation.

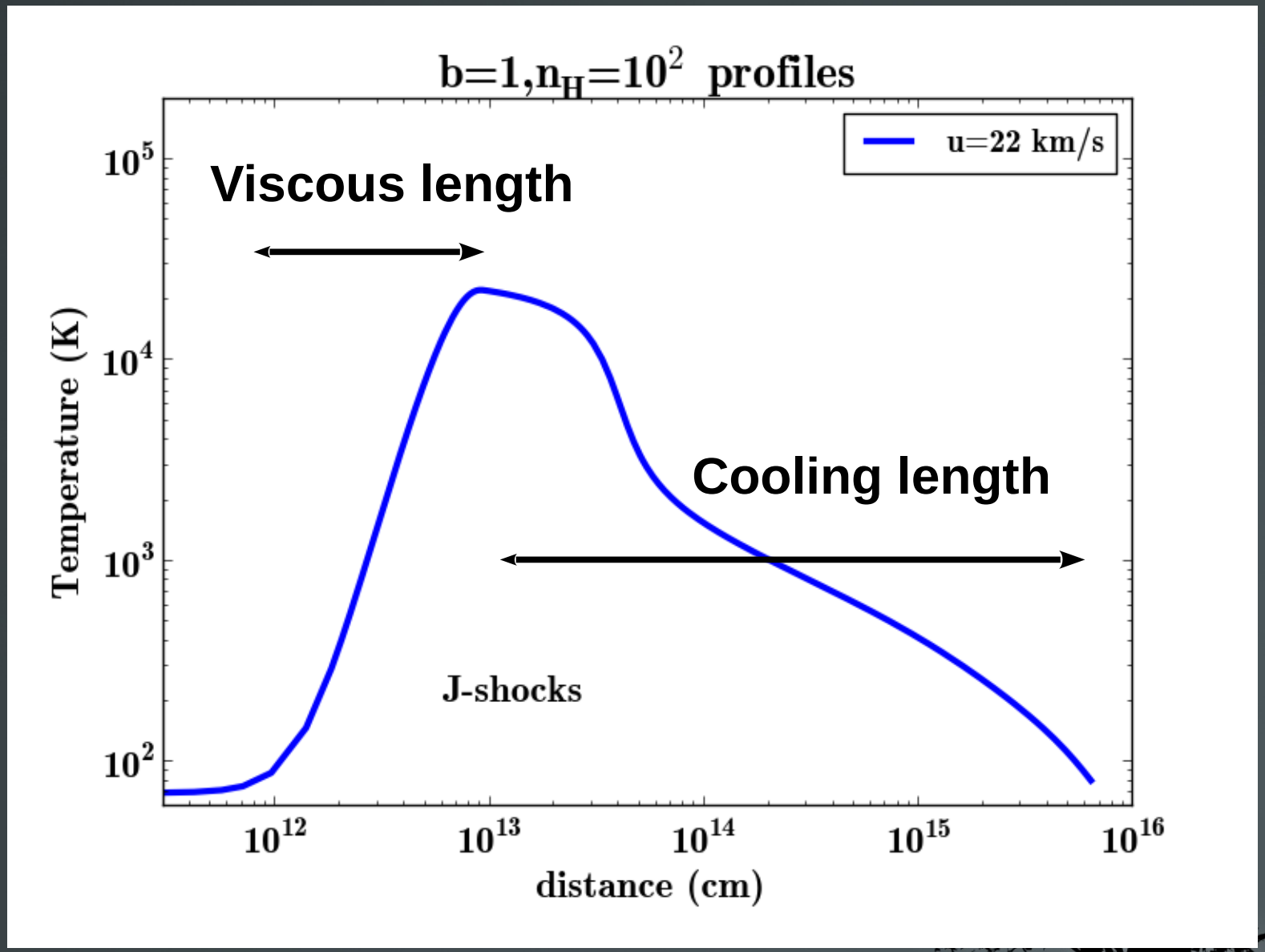
G. Momferratos

Dissipation in vortices

B. Godard, E. Falgarone, G. Pineau des Forêts (2009)



Dissipation in shocks



The Paris-Durham code (?) (soon online thanks to A. Gusdorf)

- Follow a fluid parcel through a steady shock structure :

J-shock : trigger viscous jump

C-shock : charge and neutral velocities free to differ

- Cooling / Heating

- Chemical network : 140 species, 1000 reactions

- 150 H_2 levels followed

=> Temperature and chemical structure, line emissivities...

Models of *Irradiated* shocks

- Include basic PDR physics:

  * Integrate Av extinction throughout the shock

  * Include relevant photo-reactions

  * H_2 and CO self-shielding functions

- Check PDR models are recovered for slowly moving fluid parcel.

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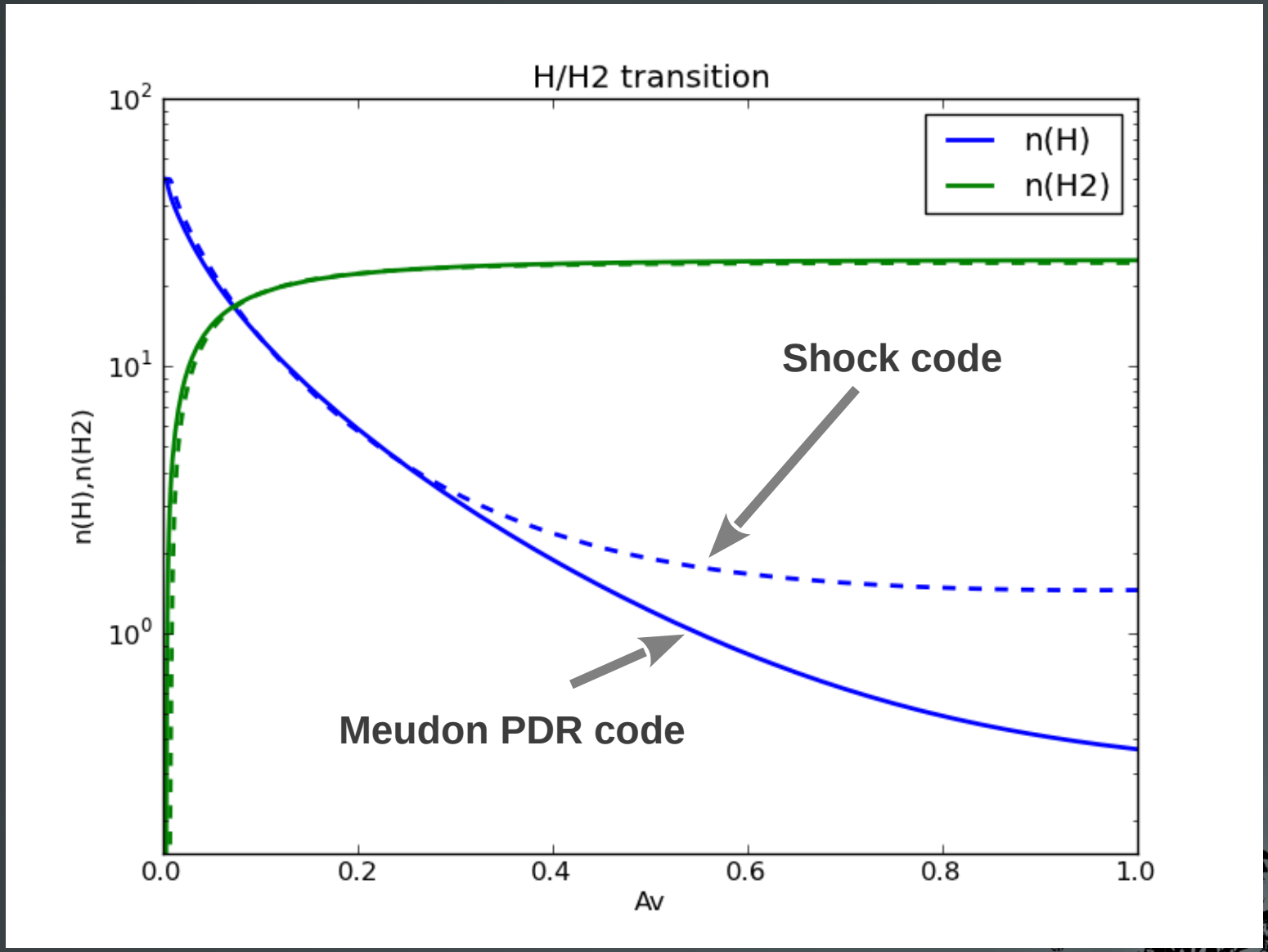
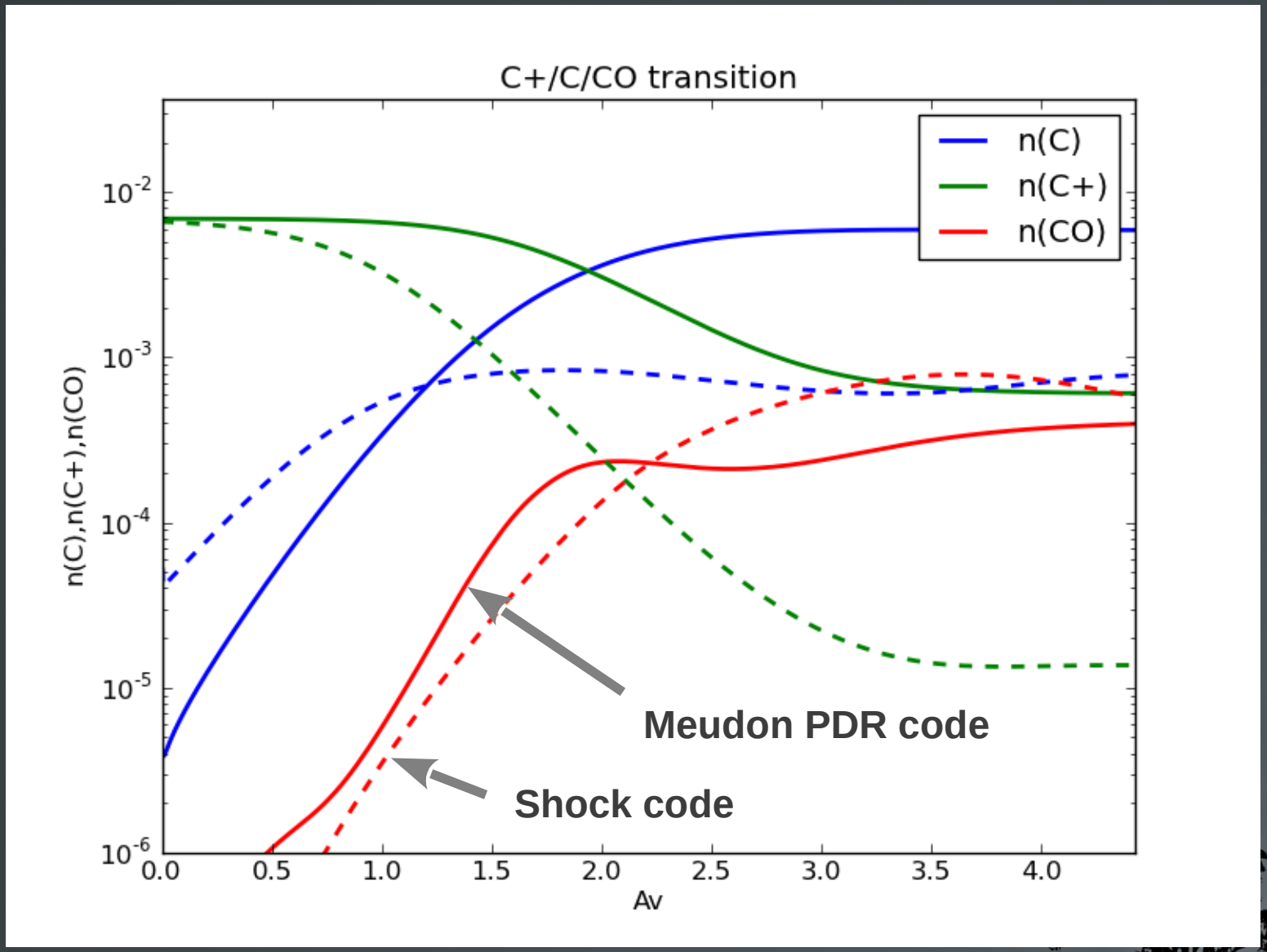
Comparison with PDR models



nH=50/cm3
u=10^{-4} km/s
G0=1

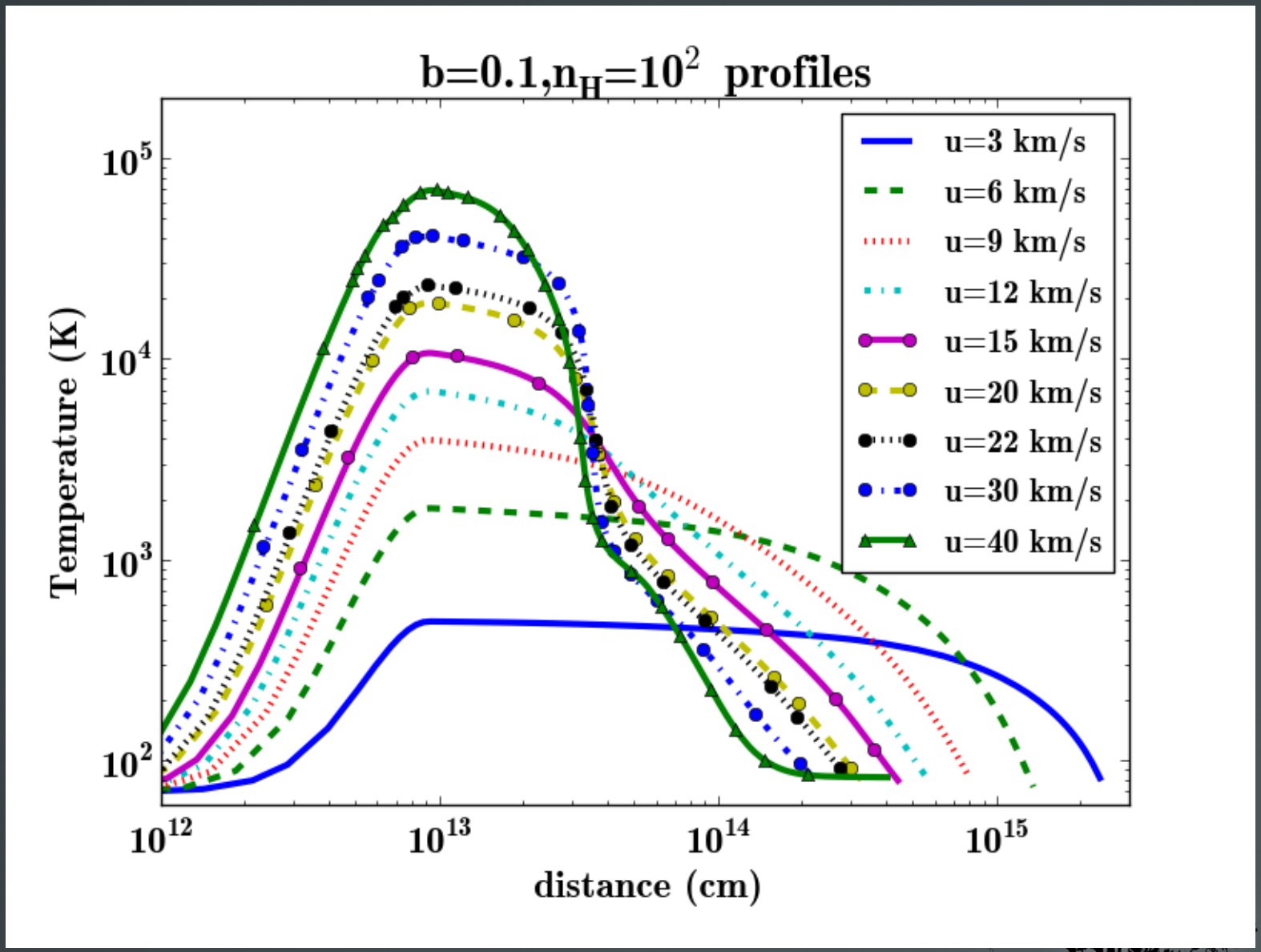
Comparison with PDR models



nH=50/cm3
u=10^{-4} km/s
G0=1

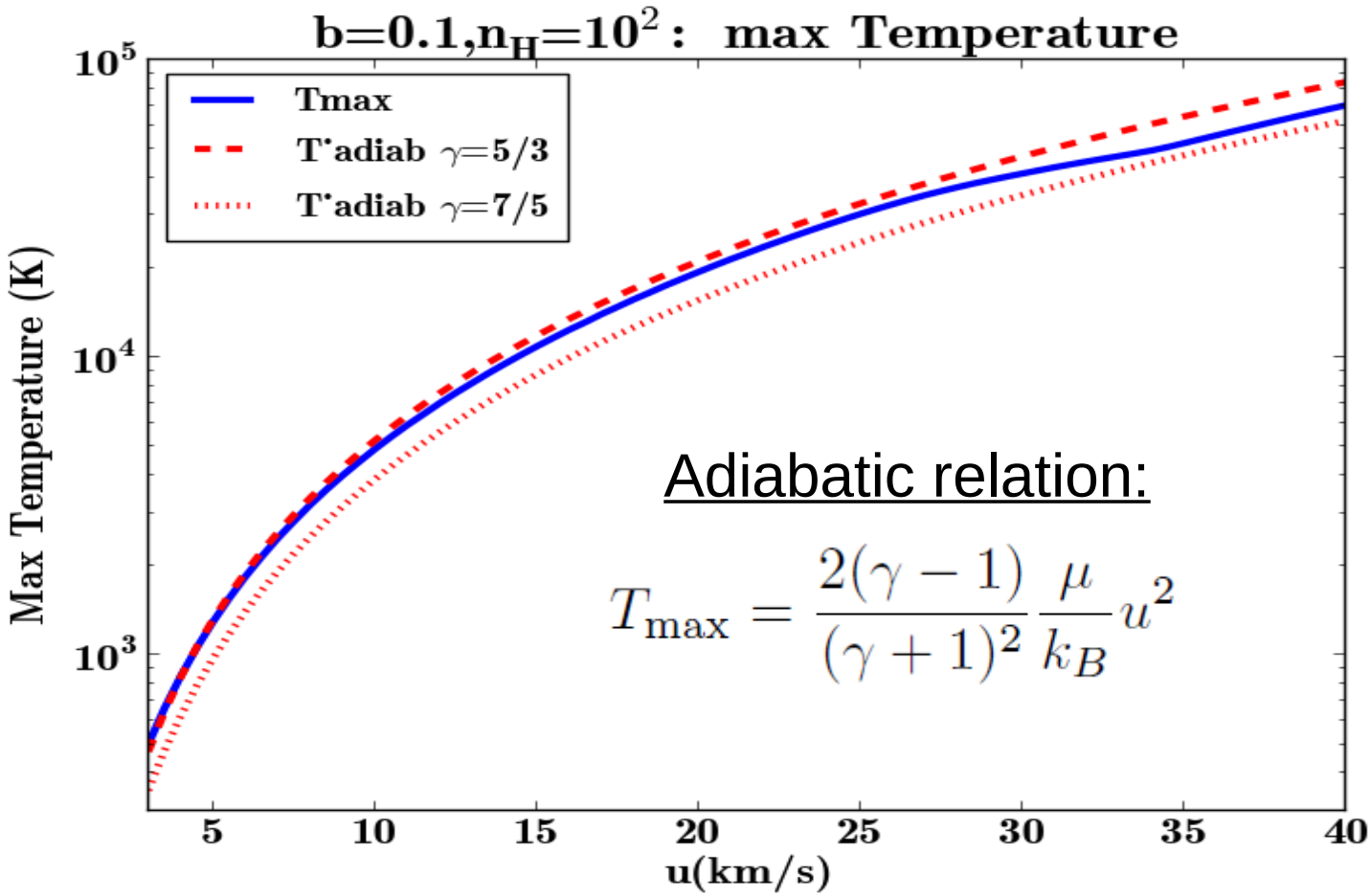
G_0=1
Av=0.1
$N(H_2)=10^{20}/cm^2$

Full grid of models: http://cemag.ens.fr



Molecule production in shocks

Reaction	Temperature barrier	Velocity
$O + H_2 \rightarrow OH + H$	2980 K	7.5 km.s^{-1}



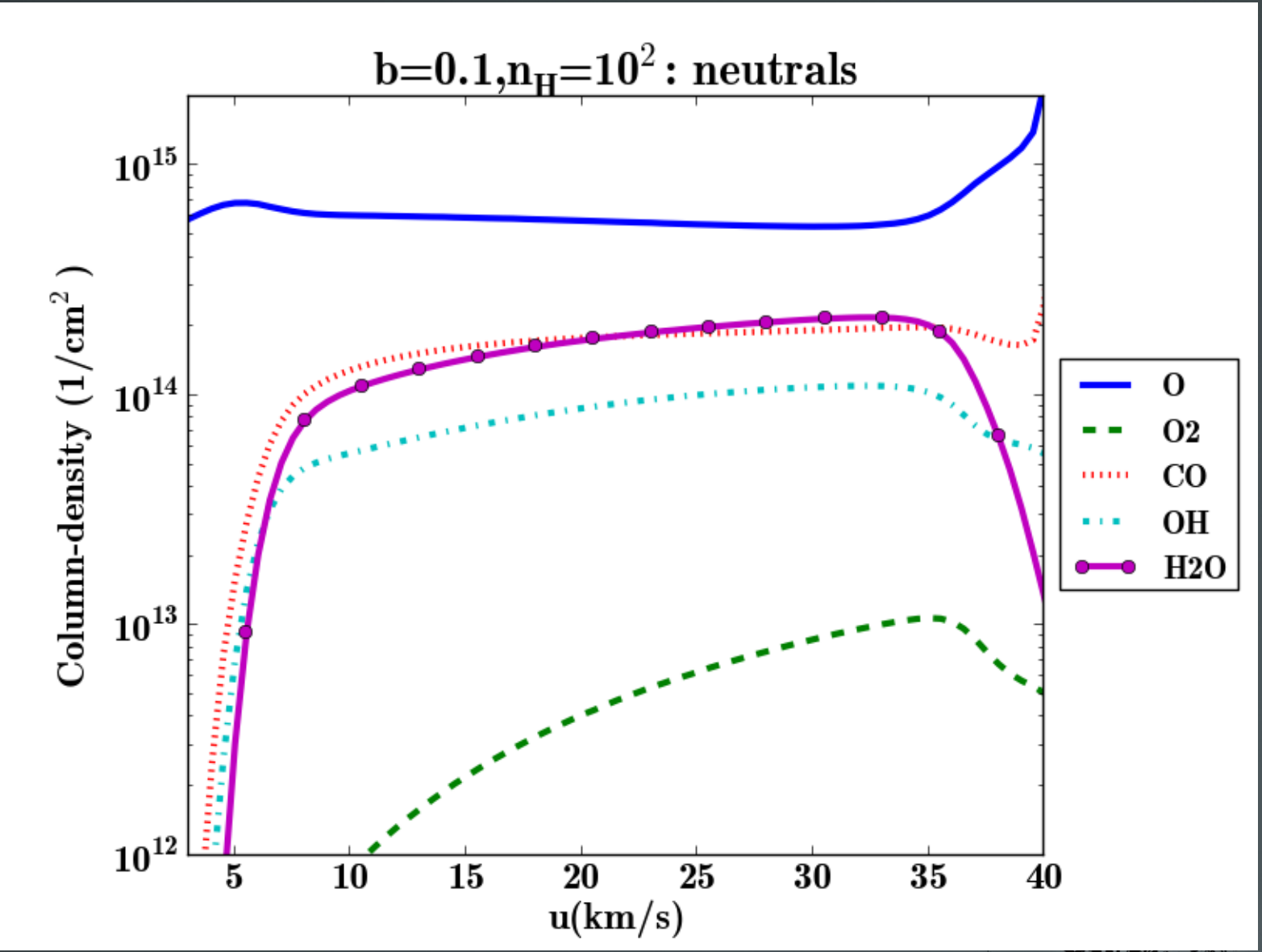
Adiabatic relation:

$$T_{\max} = \frac{2(\gamma - 1)}{(\gamma + 1)^2} \frac{\mu}{k_B} u^2$$

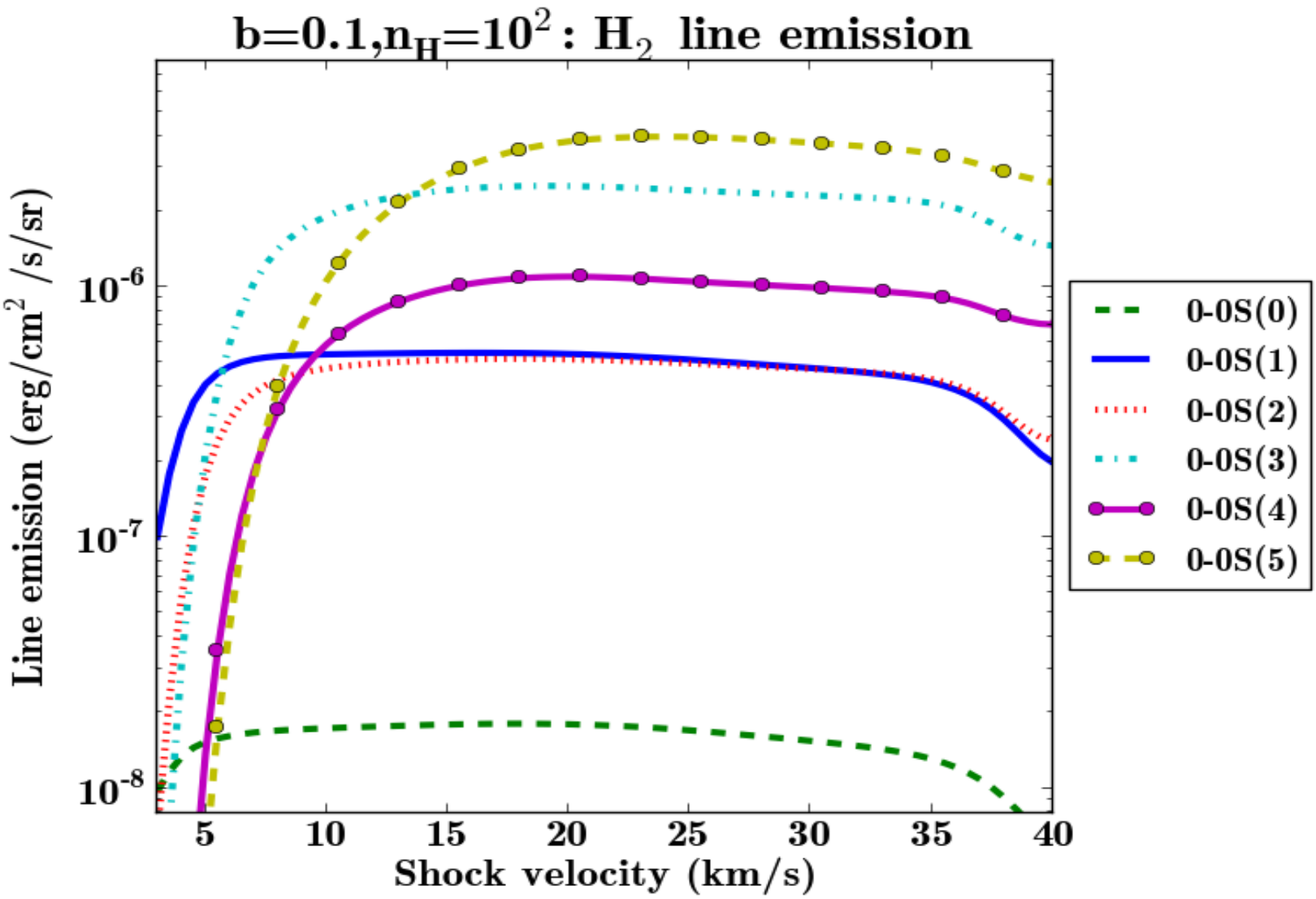
Molecule production in shocks

Reaction	Temperature barrier	Velocity
$O + H_2 \rightarrow OH + H$	2980 K	7.5 $km.s^{-1}$
$C^+ + H_2 \rightarrow CH^+ + H$	4640 K	9.4 $km.s^{-1}$
$S + H_2 \rightarrow SH + H$	9620 K	13.5 $km.s^{-1}$
$S^+ + H_2 \rightarrow SH^+ + H$	9860 K	13.6 $km.s^{-1}$
$C + H_2 \rightarrow CH + H$	14100 K	16.3 $km.s^{-1}$
$Si^+ + H_2 \rightarrow SiH^+ + H$	14310 K	16.4 $km.s^{-1}$
$N + H_2 \rightarrow NH + H$	14600 K	16.6 $km.s^{-1}$
H_2 dissociation energy	52000 K	31.3 $km.s^{-1}$

Molecule production in shocks



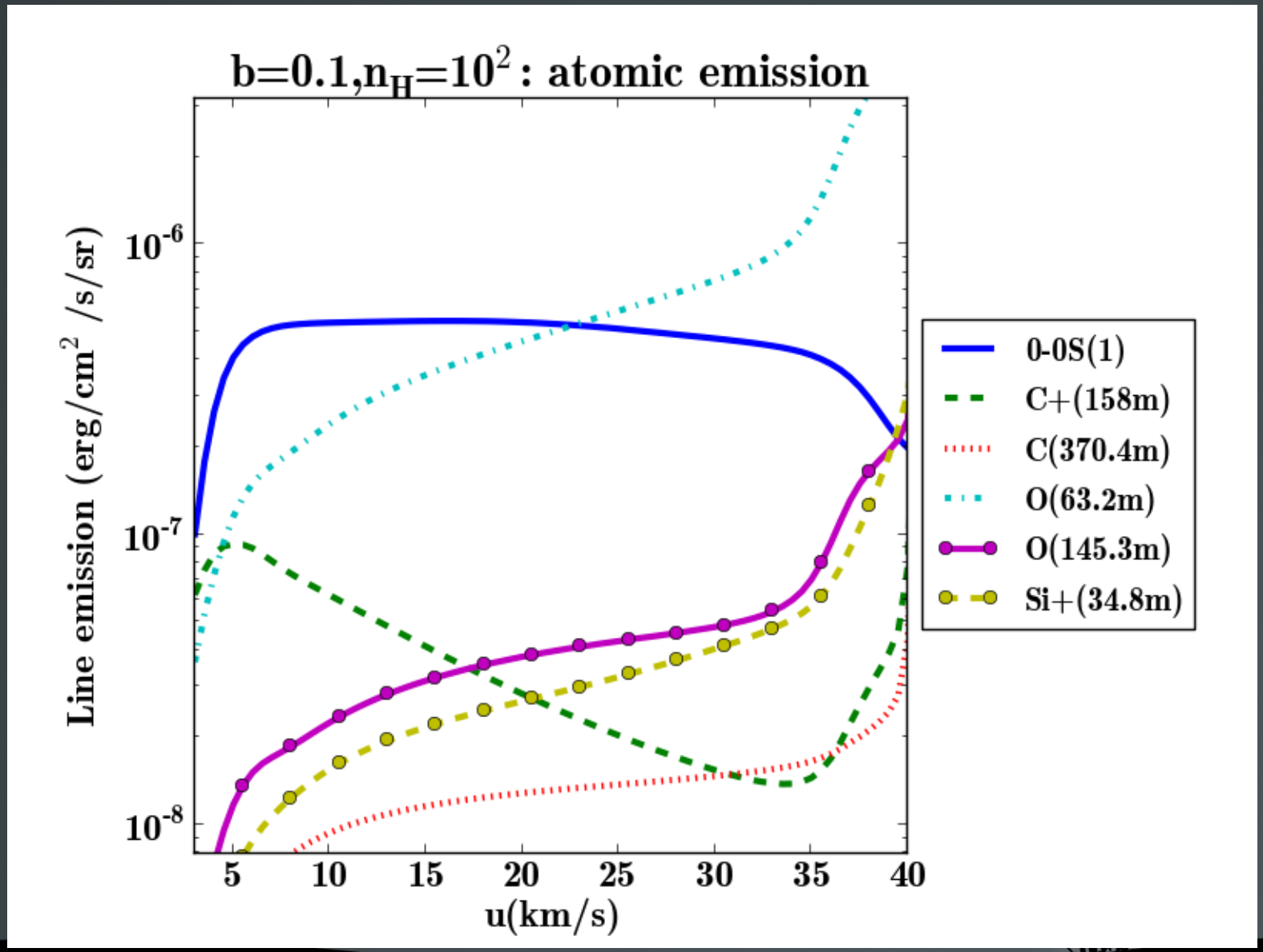
Excitation in shocks
H_2 lines



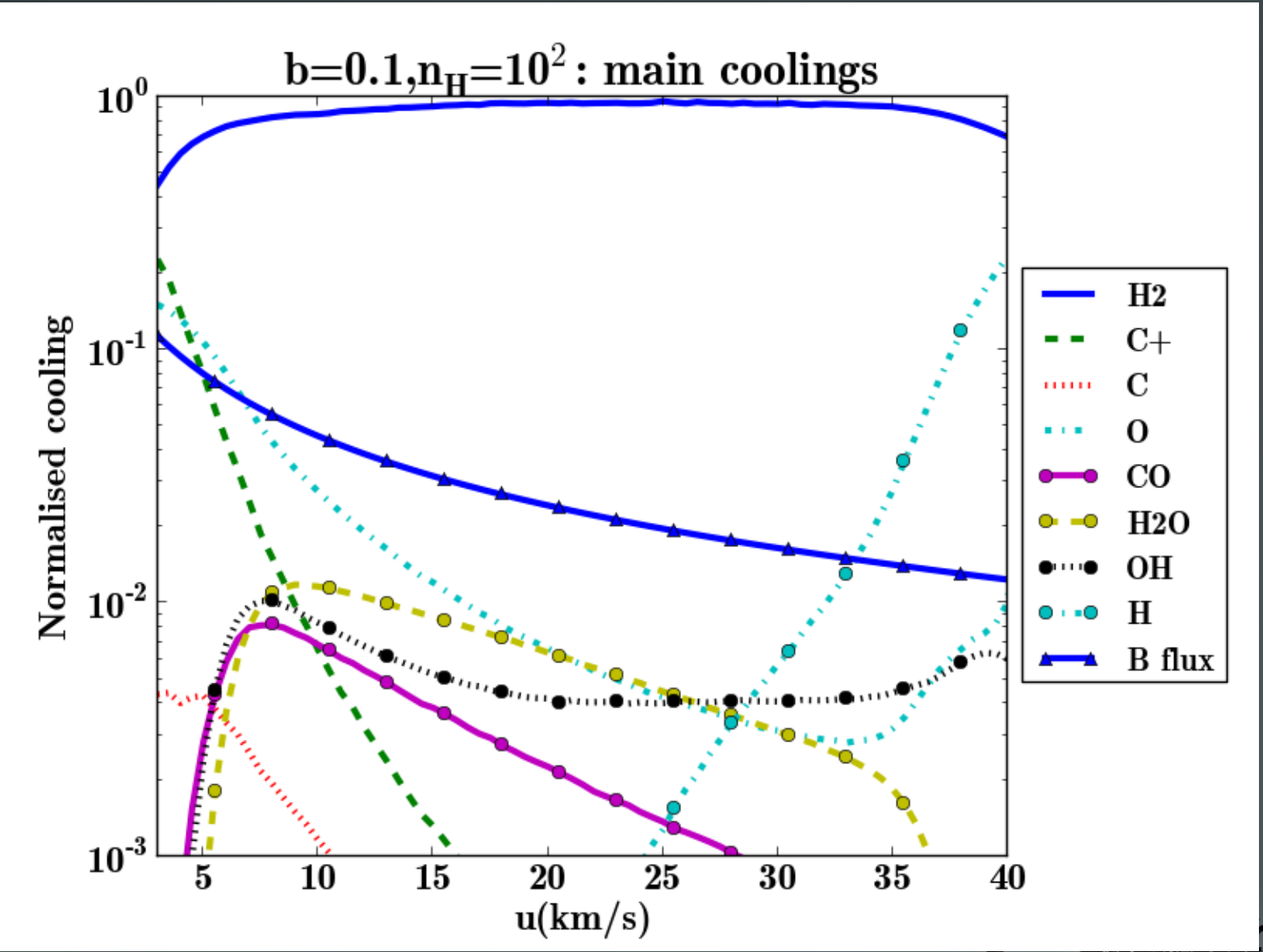
T (K)

508
844
1682
2332
3474
4415

Excitation in shocks atomic lines



Main coolants in shocks, b=0.1



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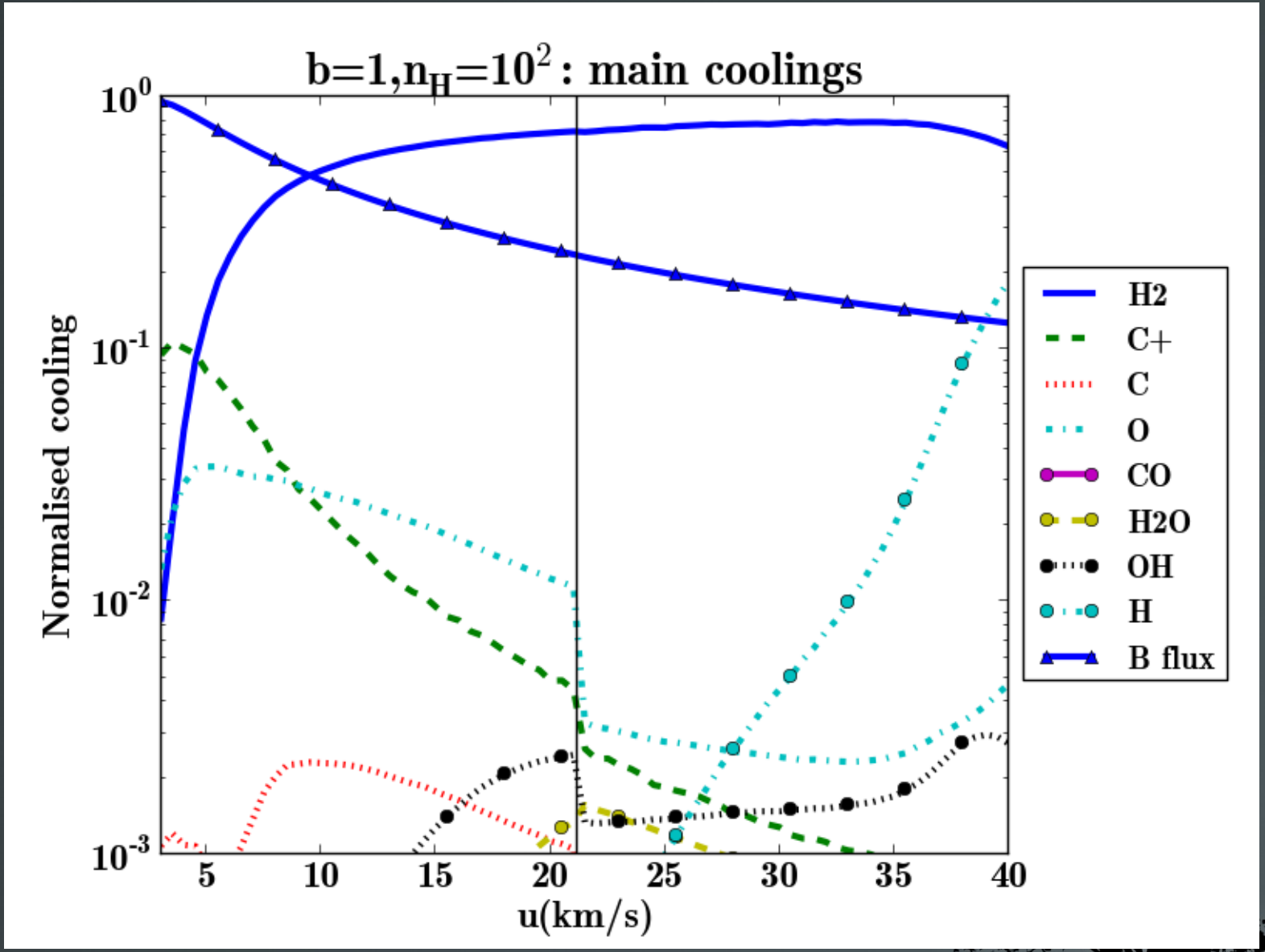
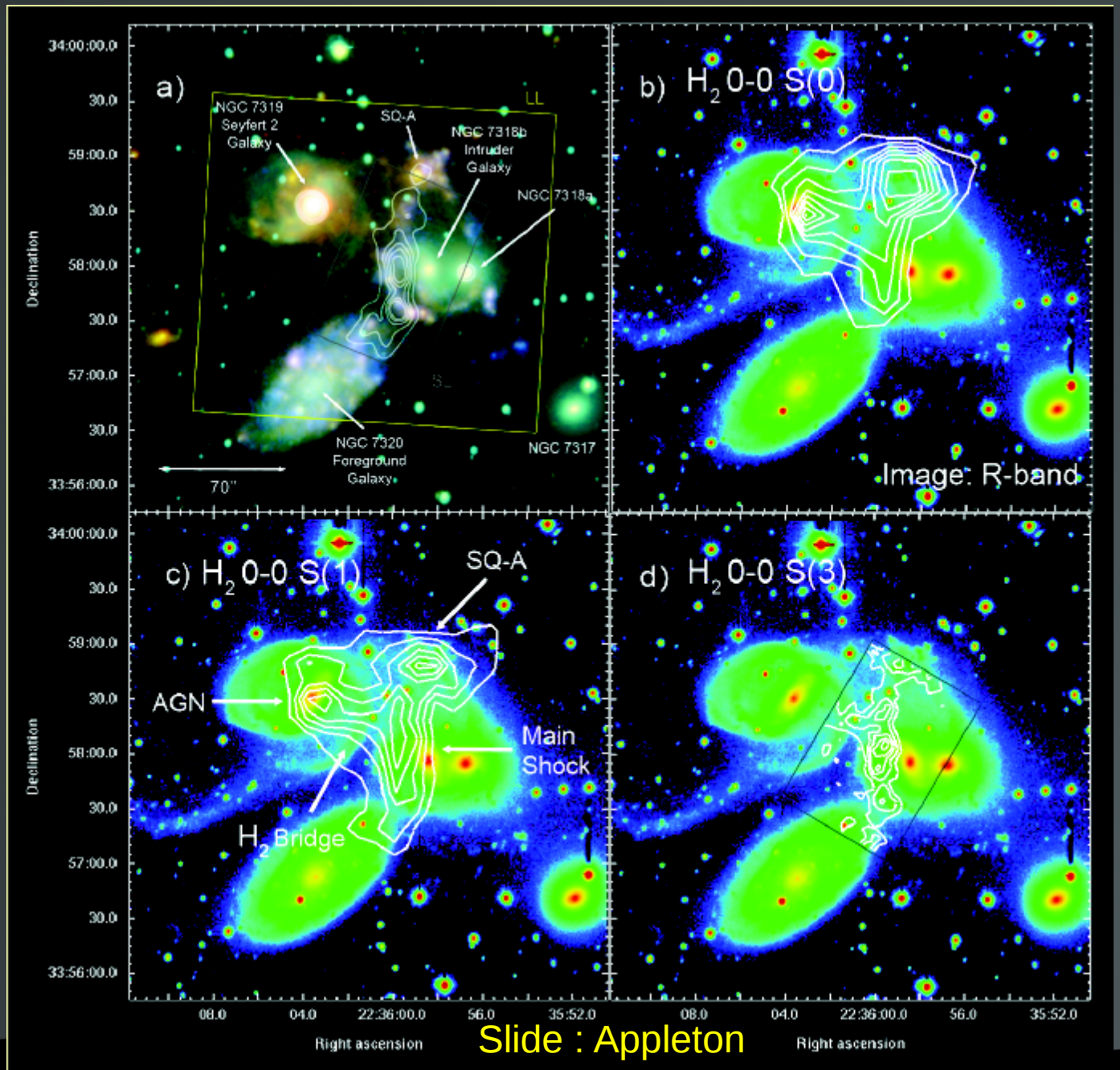


Ex : Stephan's Quintett



Slide : Appleton

Cluver, Appleton et al. (2010)

Guillard et al. (2009)

$L(H_2) \sim 10^{42}$ erg/s

$L(H_2) \sim 3\ L(X)$

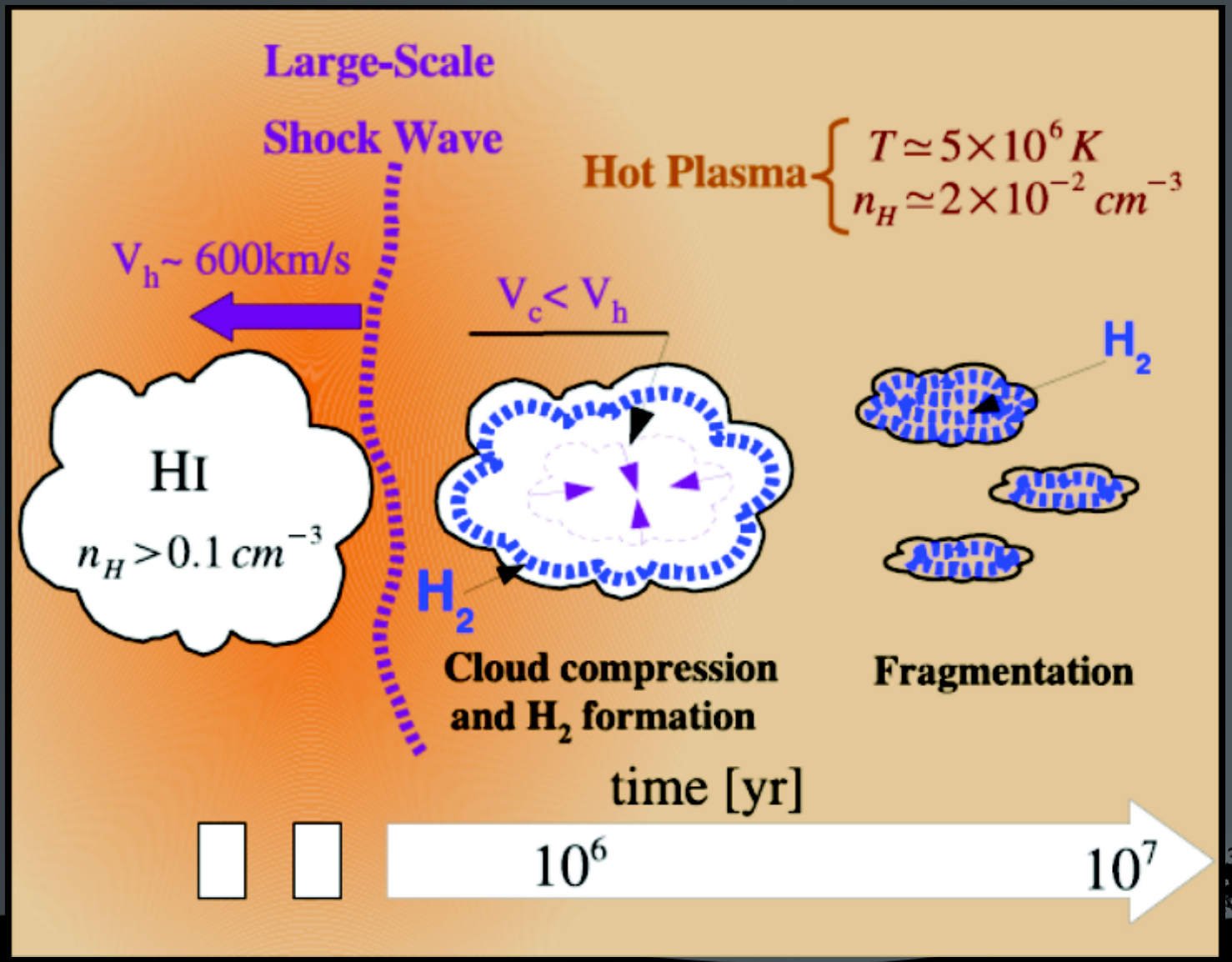
$L(H_2) \sim 0.3\ L(IR)$

$L(H_2) \sim 2\ L(CII)$

UV : $G_0 \sim 1$

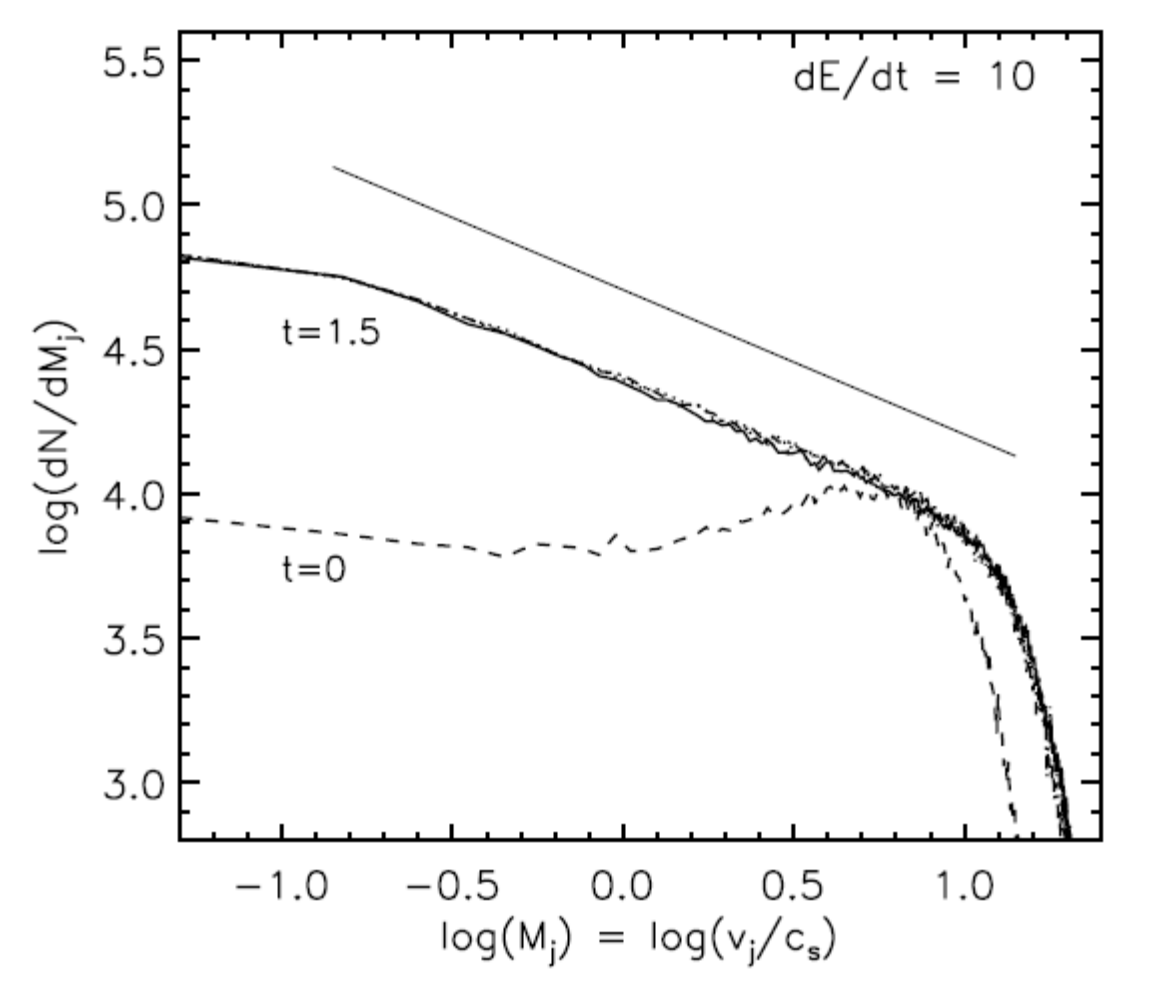
Shock driven turbulence

Guillard et al. (2010)



Shocks distribution in driven turbulence

Smith, Mac Low & Heitsch (2000) : power-law PDF



Adjust PDF of shocks to observed H_2 emission

Chi square table:

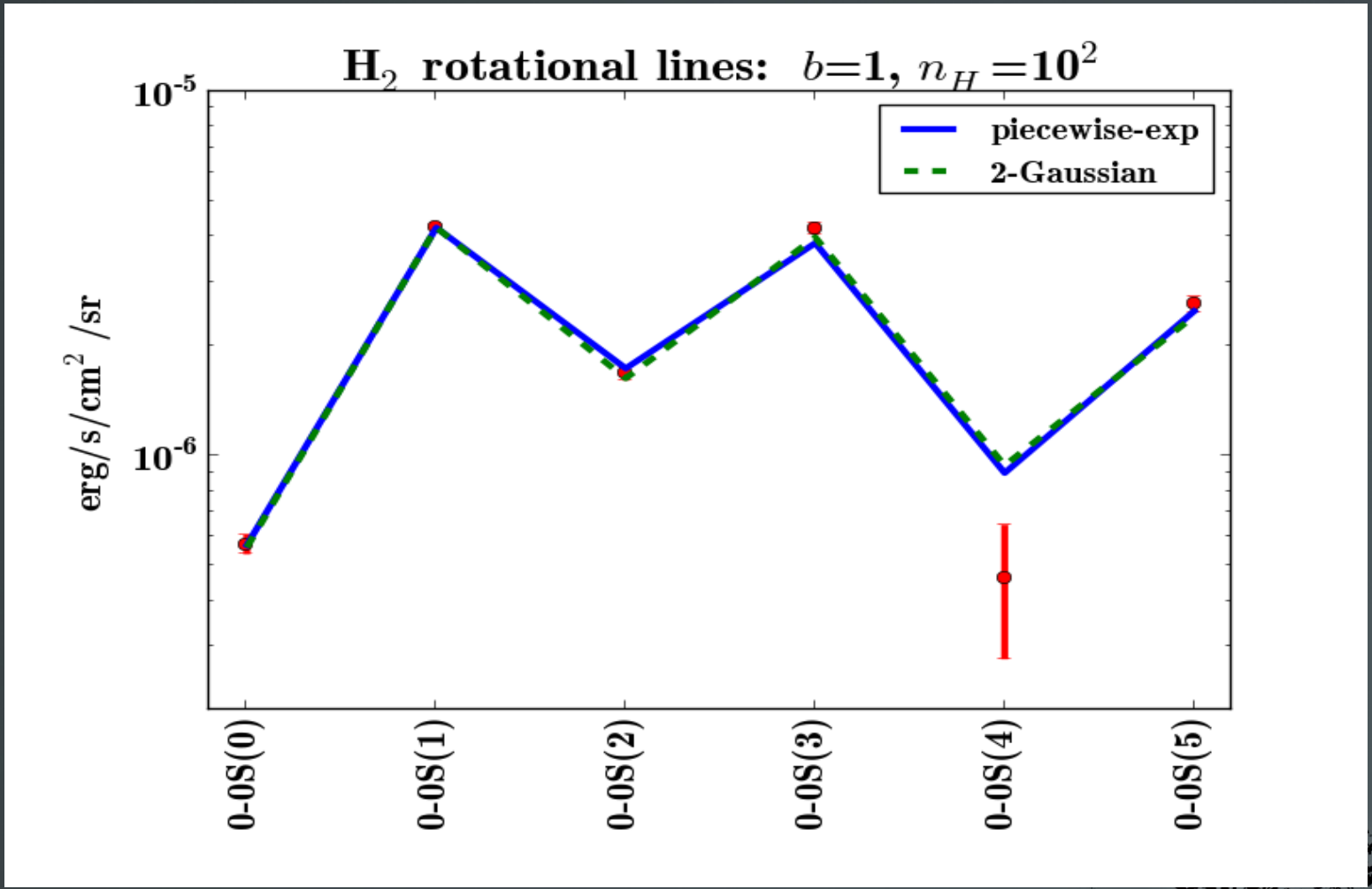
b	n_H	1-Gauss	pow-law	exp.	pw-exp.	2-Gauss
0.1	10^2	371.8	2307.0	54.3	60.8	11.2
0.1	10^3	504.0	1650.4	152.4	61.1	105.6
0.1	10^4	416.1	2139.9	174.3	580.8	155.3
1	10^2	1628.5	184.2	598.5	**2.6**	**2.0**
1	10^3	139.3	175.1	35.9	5.0	13.8
1	10^4	130.3	1648.0	12.6	6.3	15.8

Generic PDF shapes:

PDF	formula	N
Power-Law	u^{-p_1}	1
Exponential	$\exp(-p_1 u)$	1
Piece-wise exponential	at $u = 3, 10, 20, 40$ $f(u) = 1, p_1, p_2, p_3$	3
1-Gaussian	$e^{-(u-p_1)^2}$	1
2-Gaussian	$e^{-(u-p_1)^2} + p_3 e^{-(u-p_2)^2}$	3

Adjust PDF of shocks to observed H_2 emission

The two best fits:



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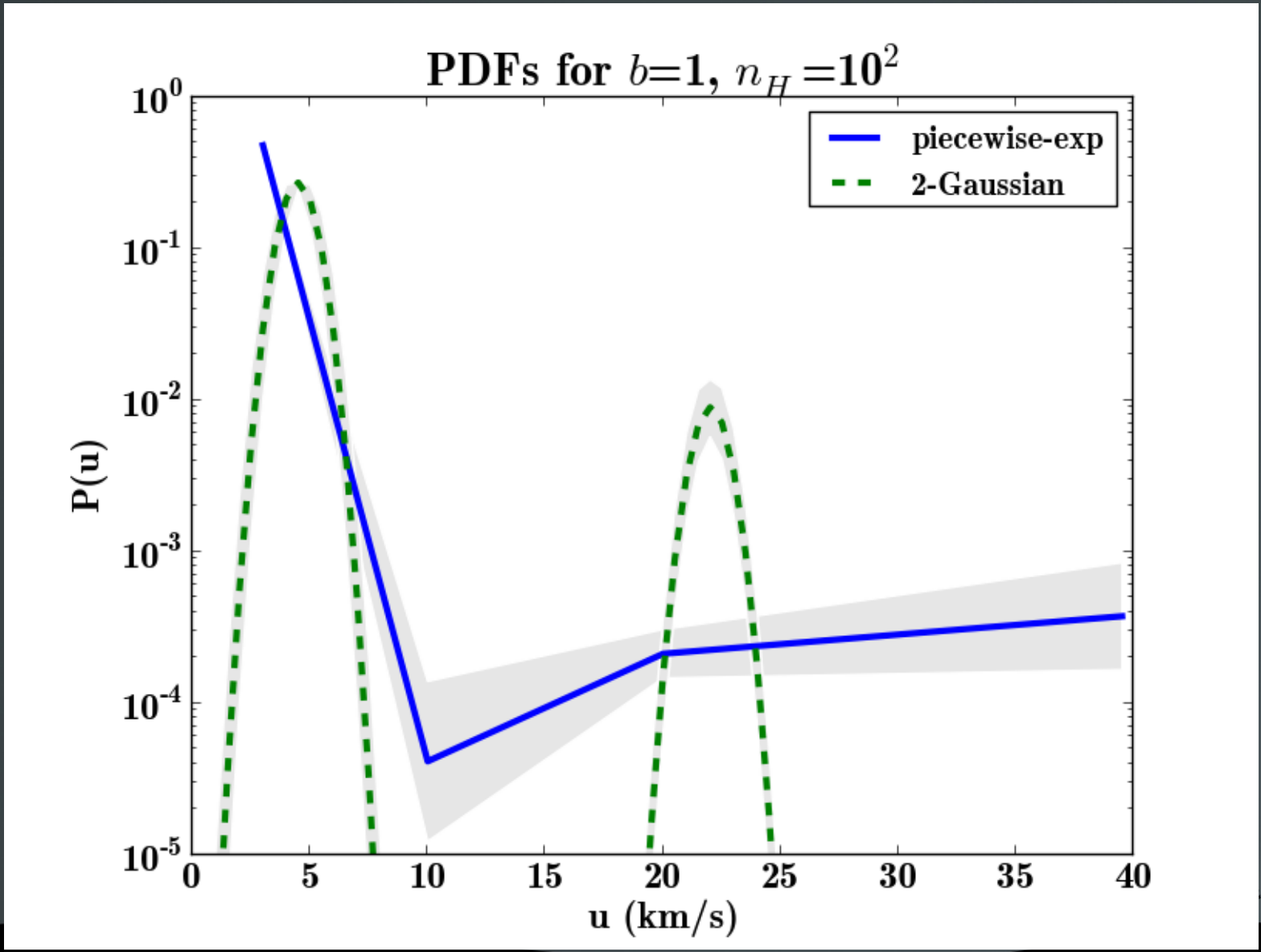
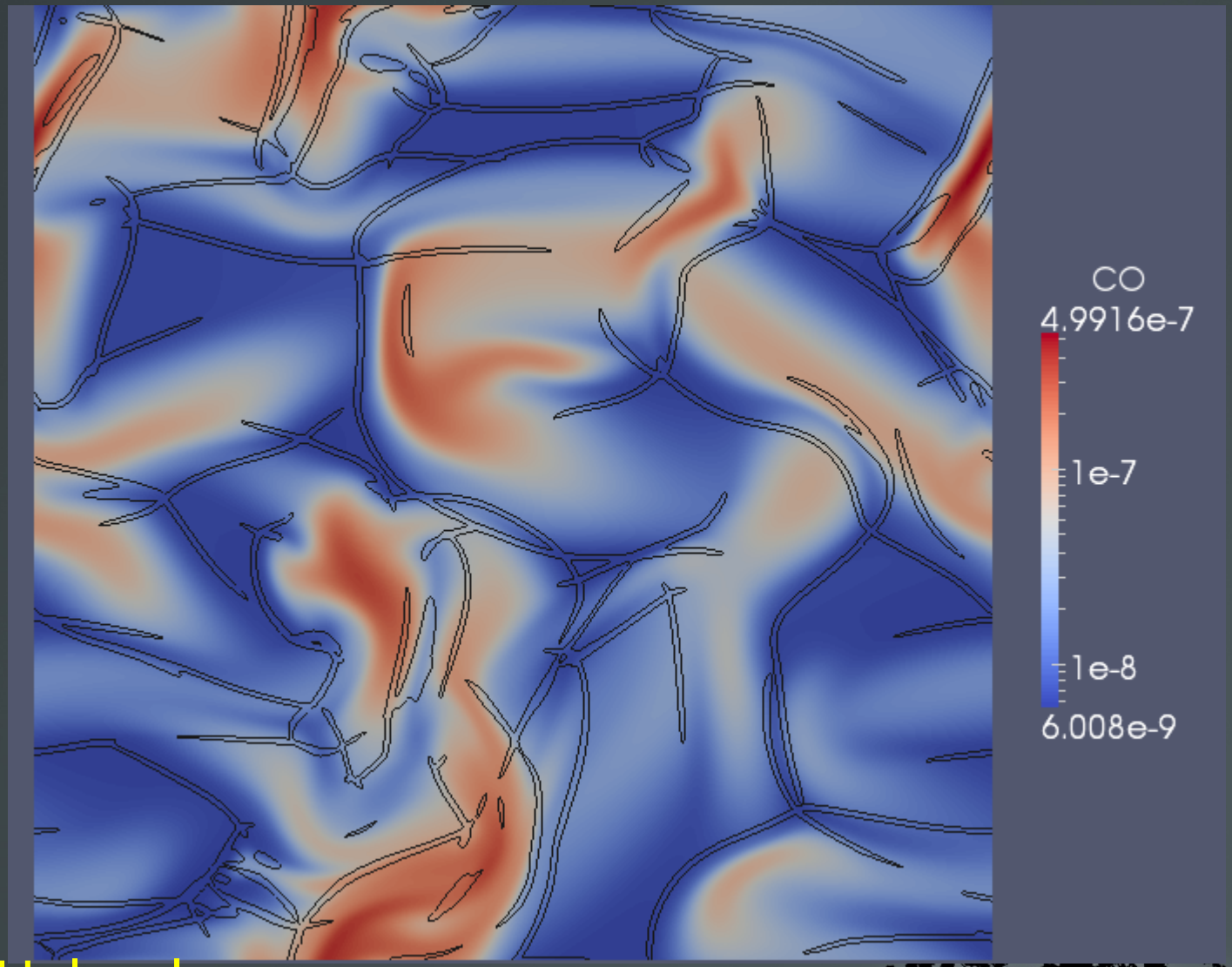


Conclusions

- A new grid of irradiated shock models: http://cemag.ens.fr
- Molecules are enhanced in low velocity shocks
- Molecular observations probe shock statistics
- We find a bi-modal distribution in both the SQ and the Chamaeleon line of sight
- A significant fraction of the material on these line of sight is shocked
- CO column-densities and CII emission can be significantly affected by low velocity shocks
- Read more in Lesaffre et al. (2012)

Ongoing work:
CHEMSES = DUMSES + chemistry

10^{16} cm

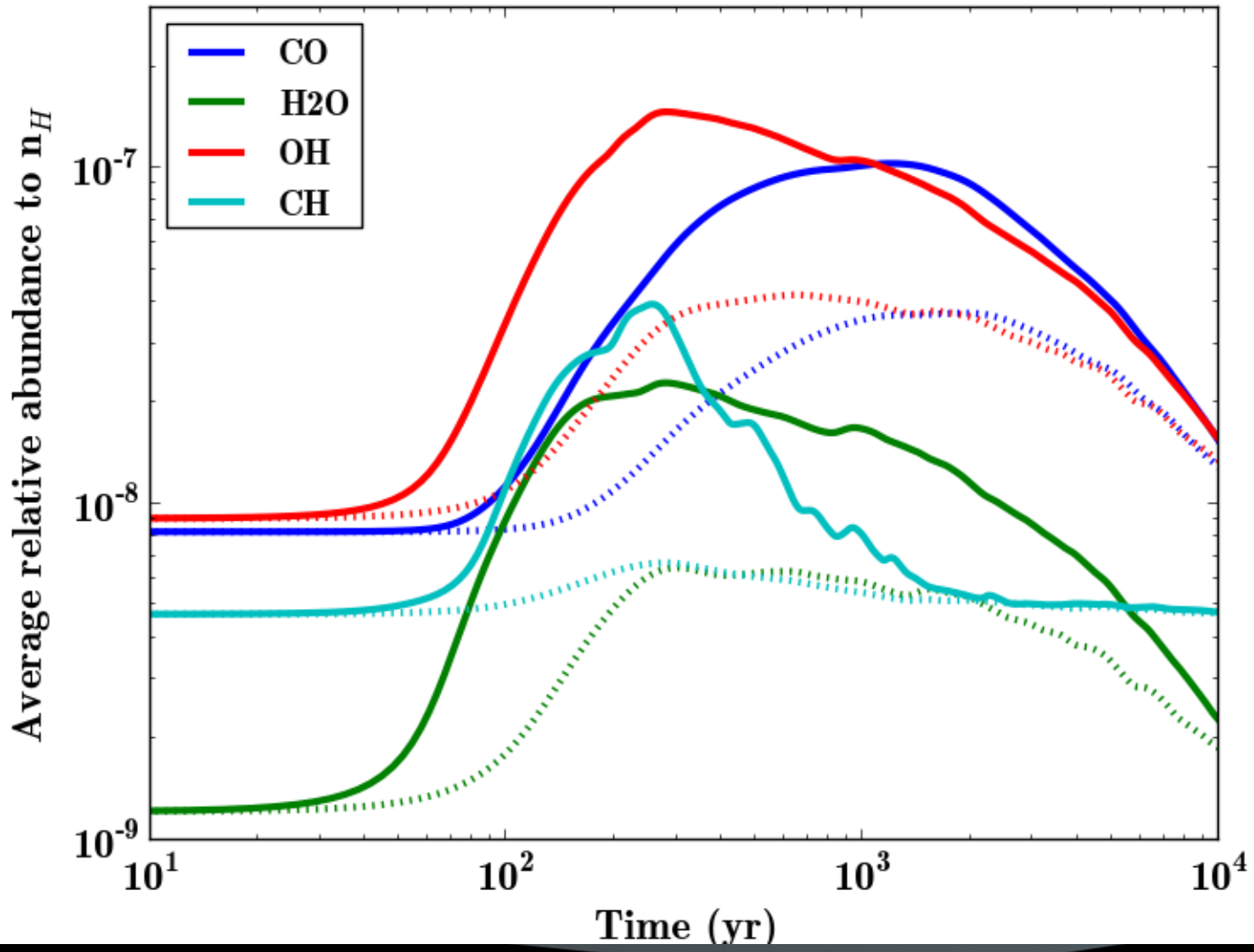


32 species, 7 H_2 levels

1024^2 pixels, decaying 2D turbulence, U_{rms} ~2 km/s

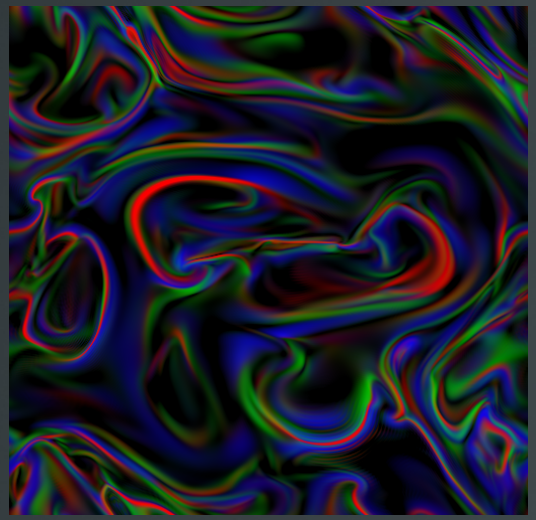
Molecules enhanced by dissipation of 2D turbulence

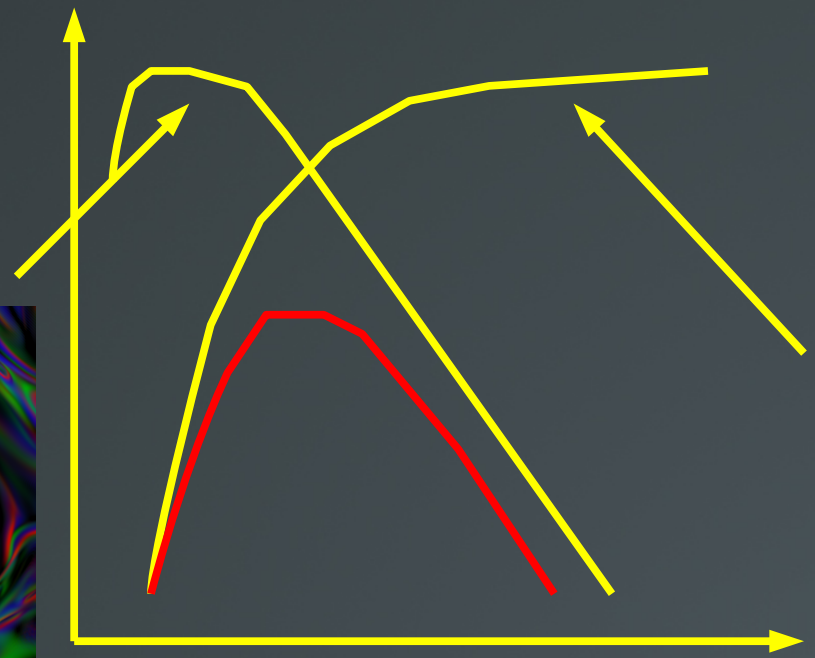
G_0=1
Av=0.1



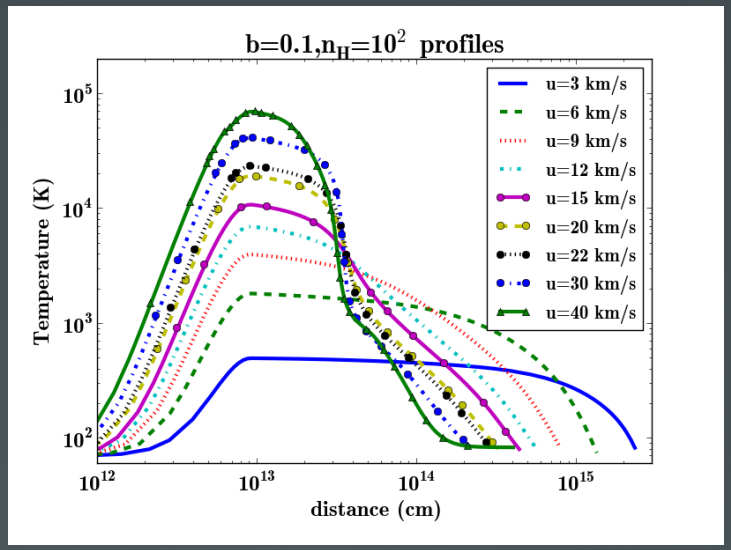
The cunning plan..

Intermittent statistics of the dissipation



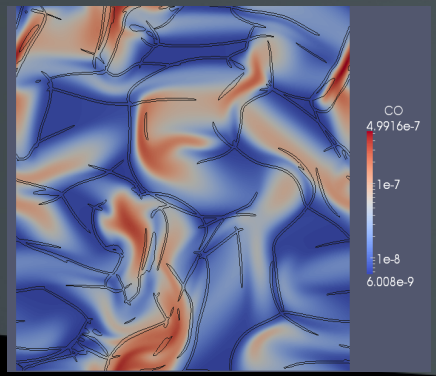


Molecular yields from Shocks (for example)

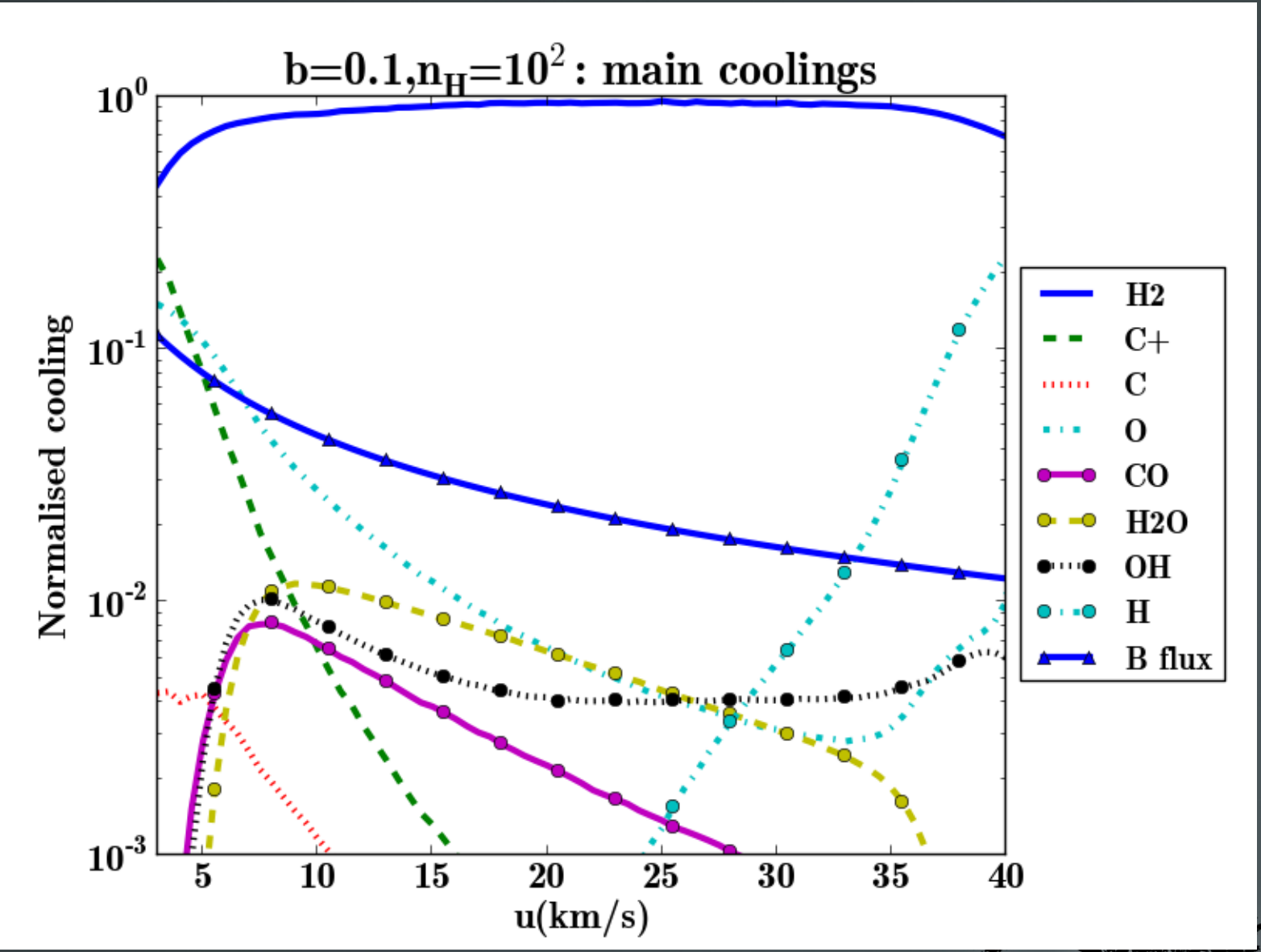


=> Molecules formation

G. Momferratos



Main coolants b=0.1



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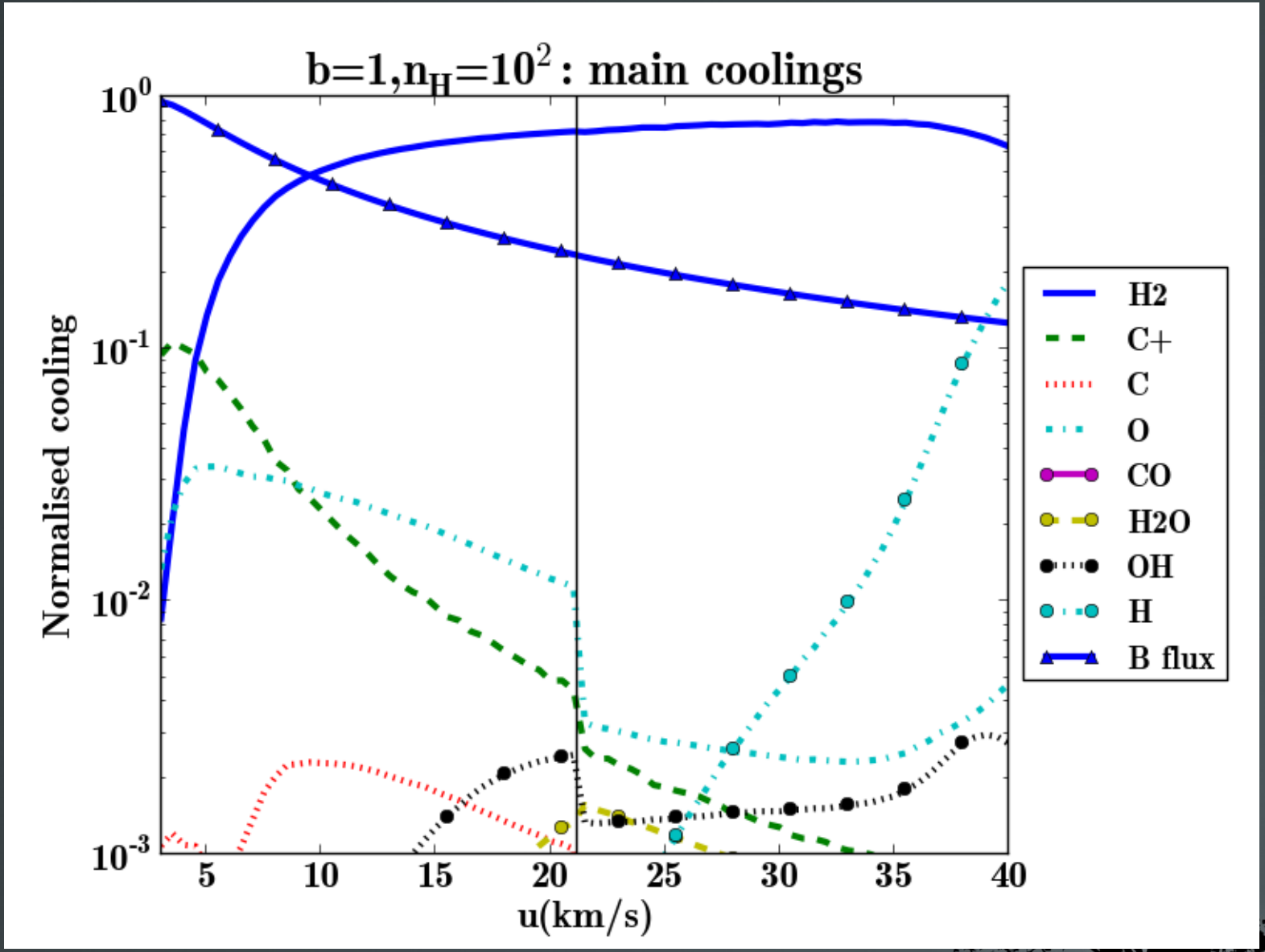
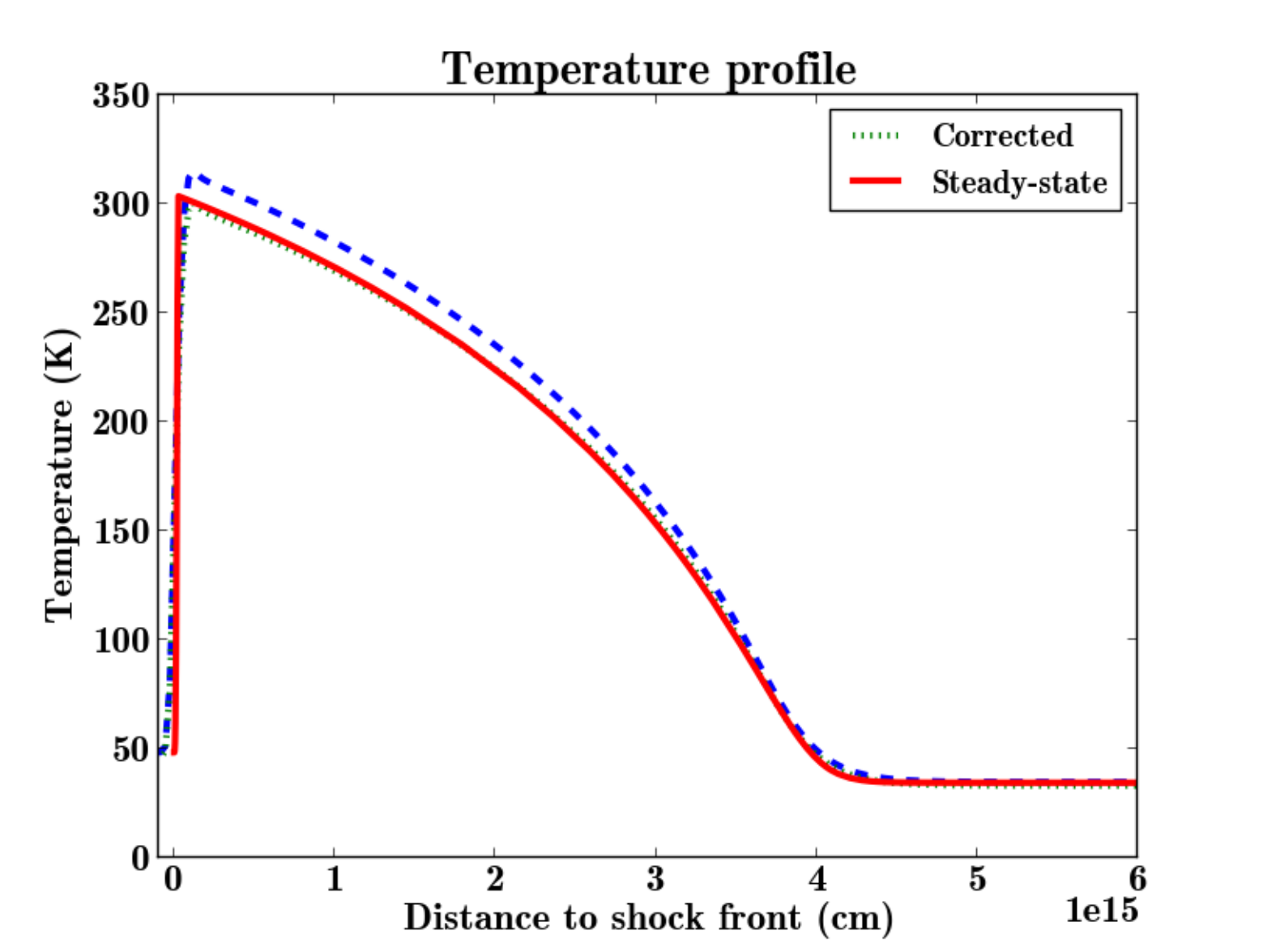


Code validation: steady-state shock at 3 km/s



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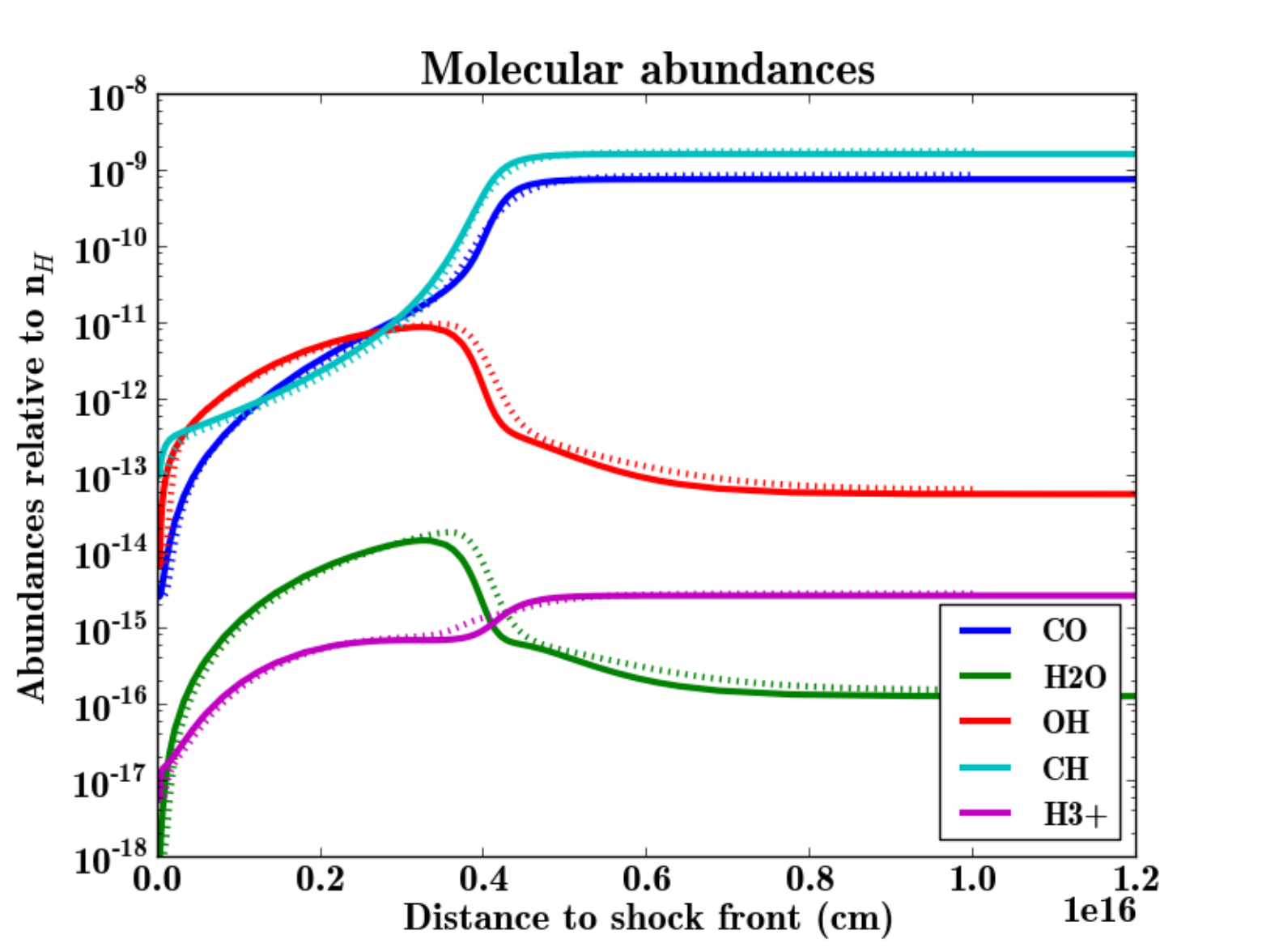

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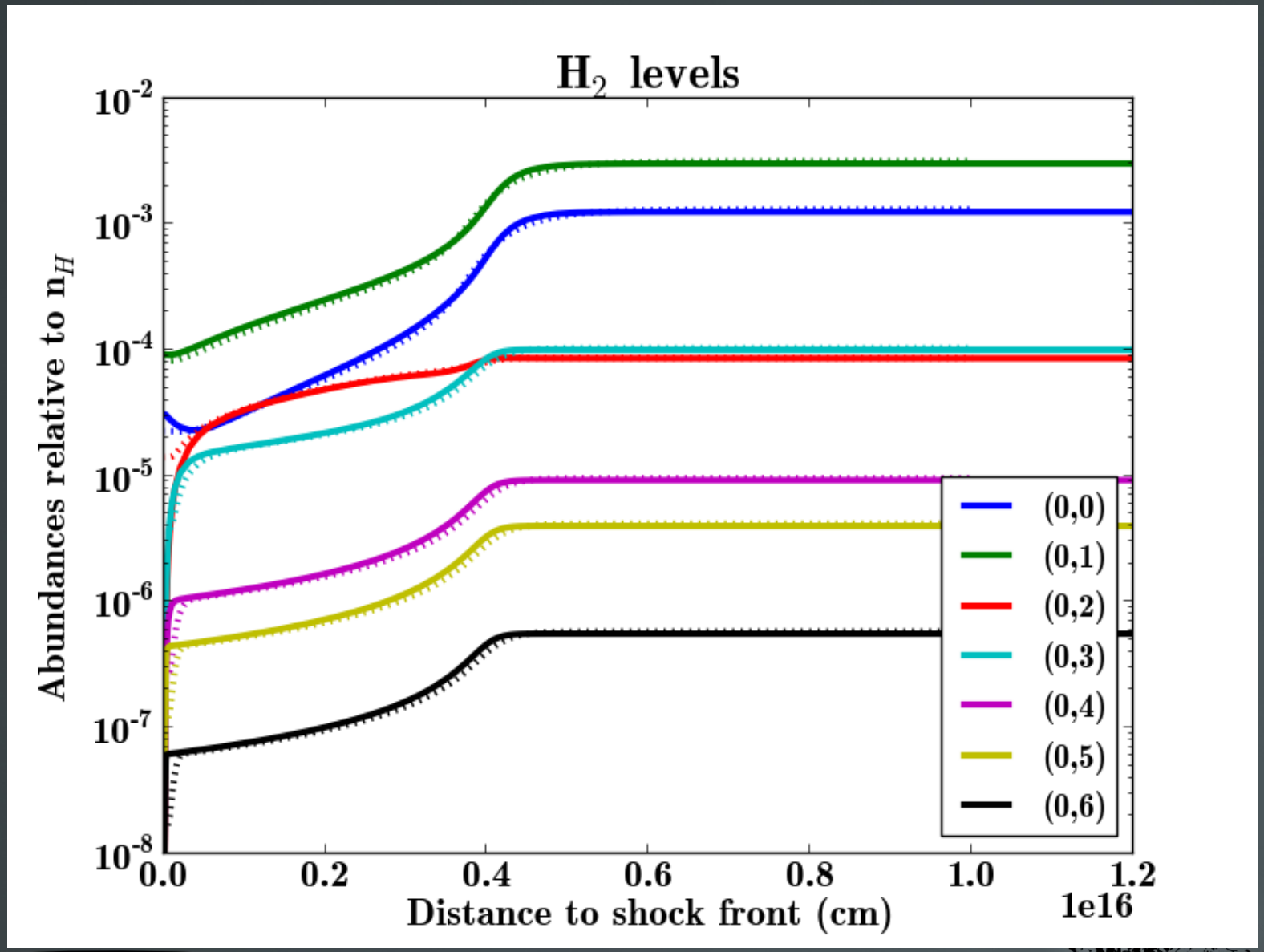
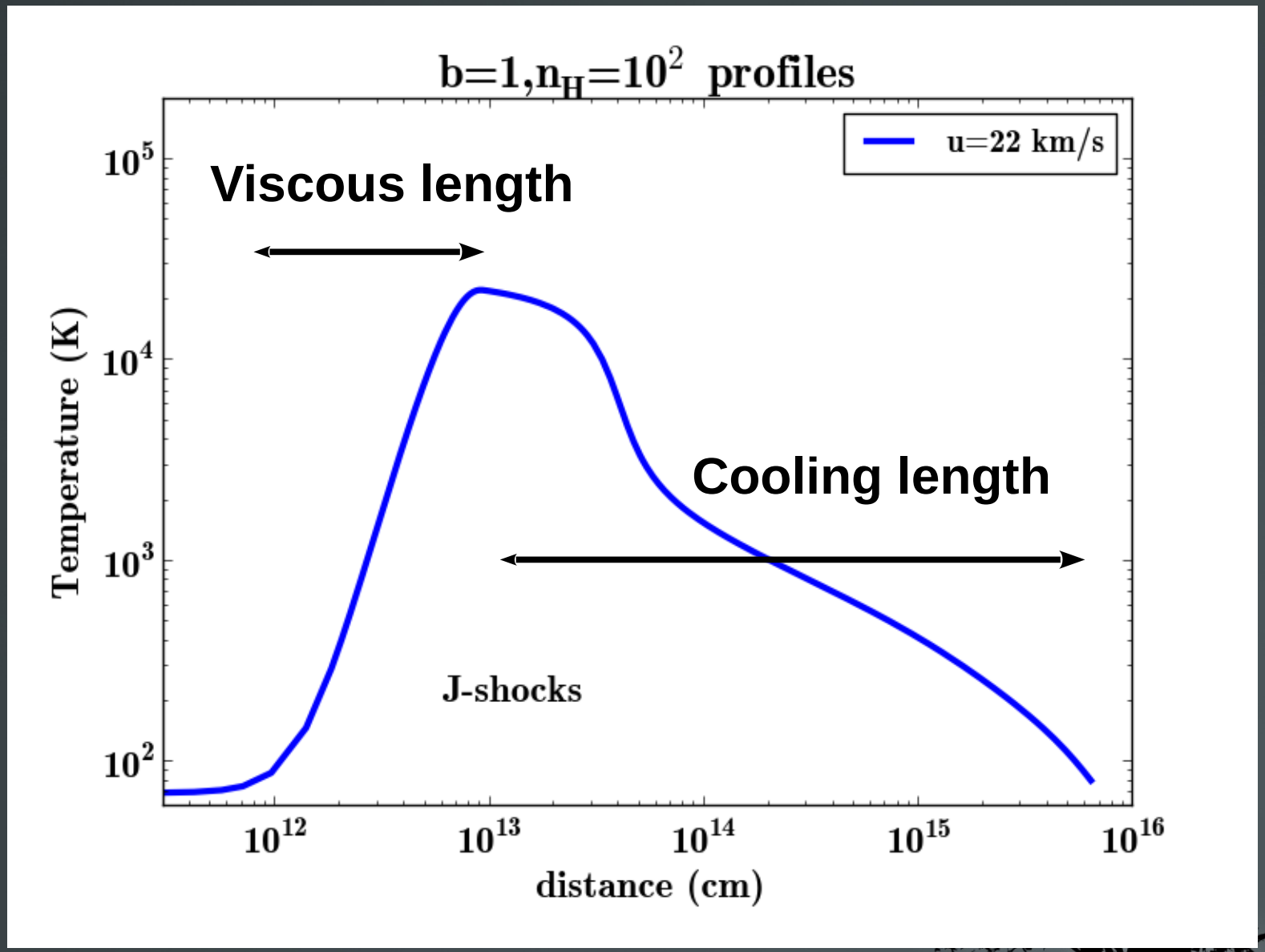
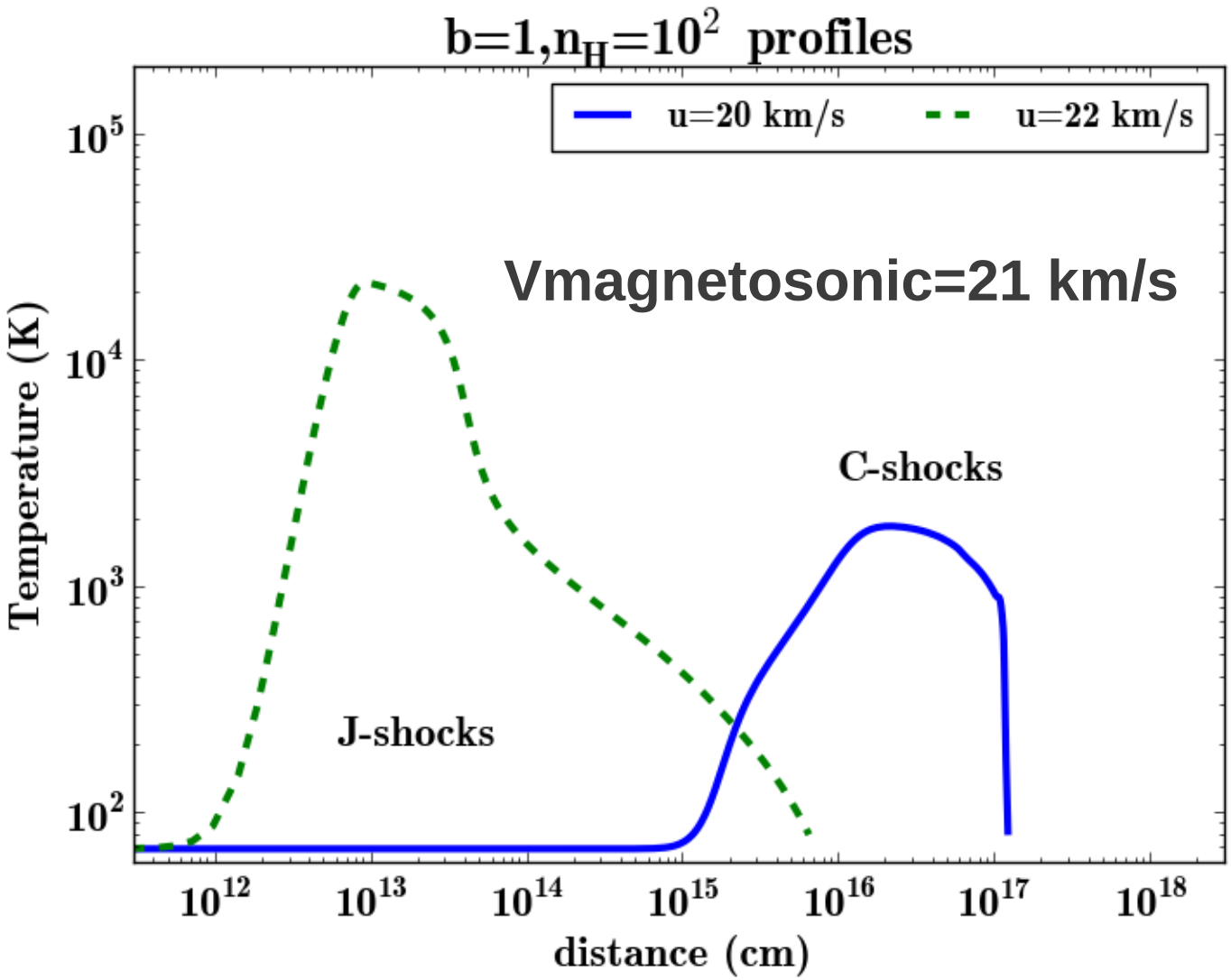


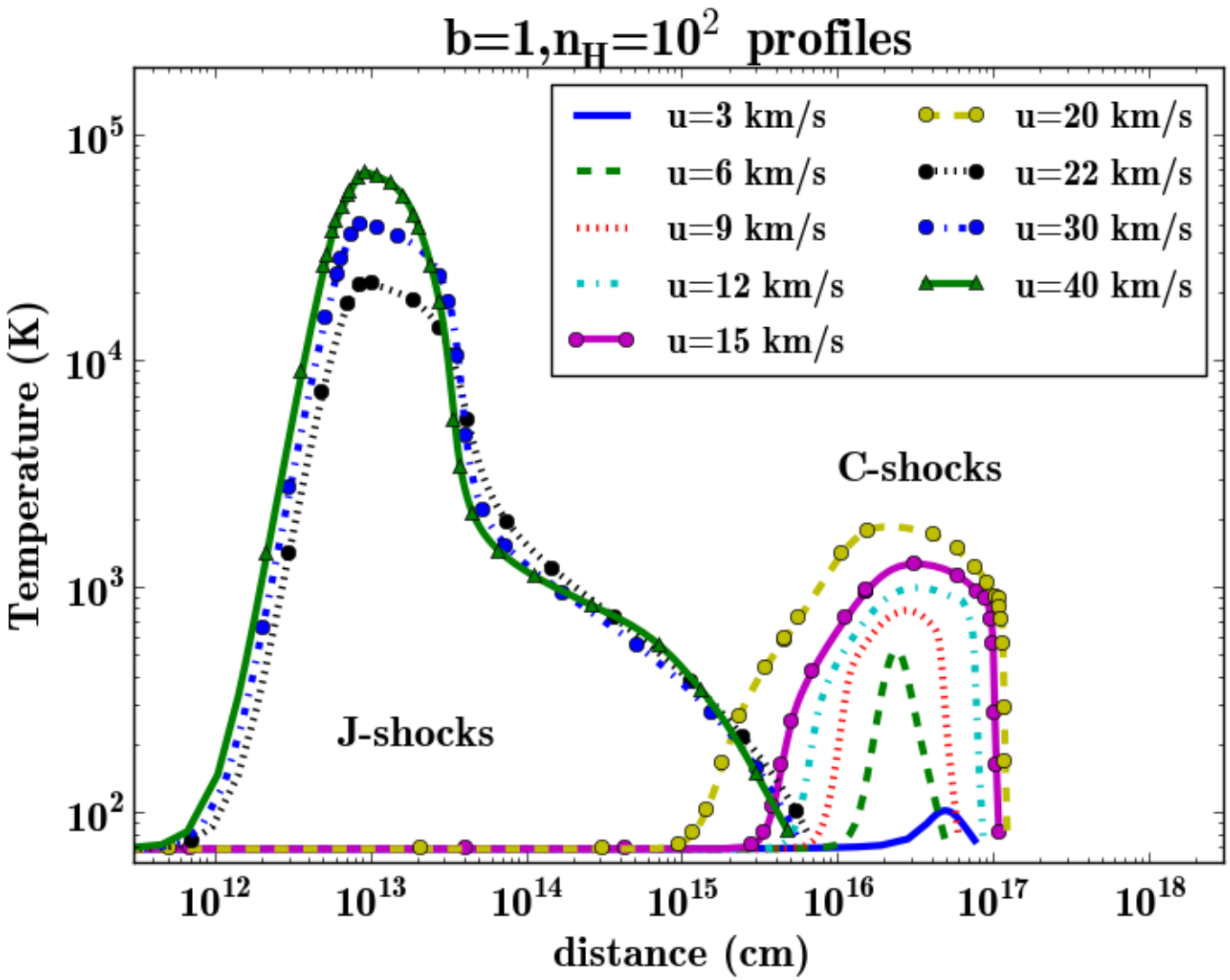
Dissipation in shocks



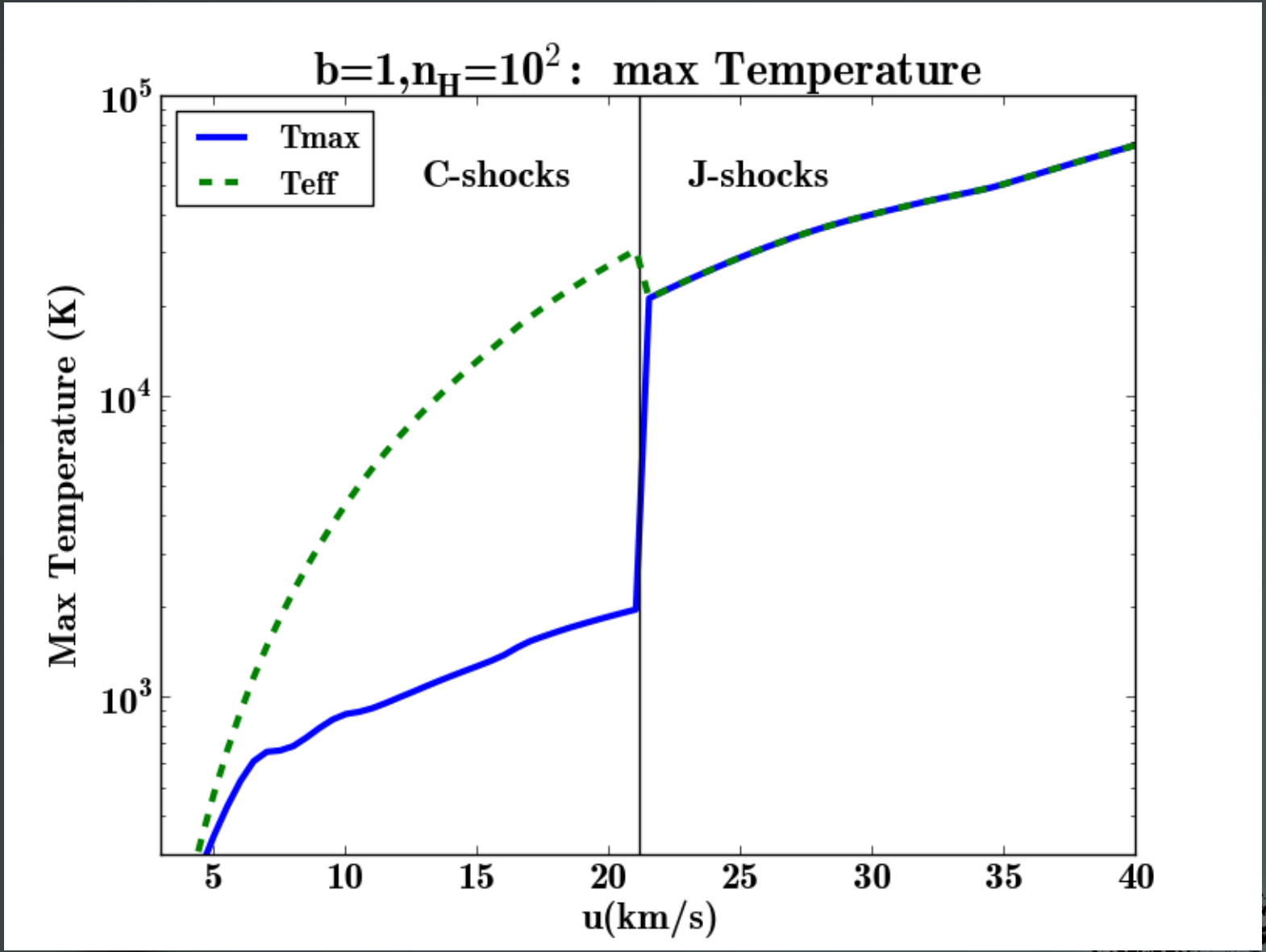
J- and C-type shocks



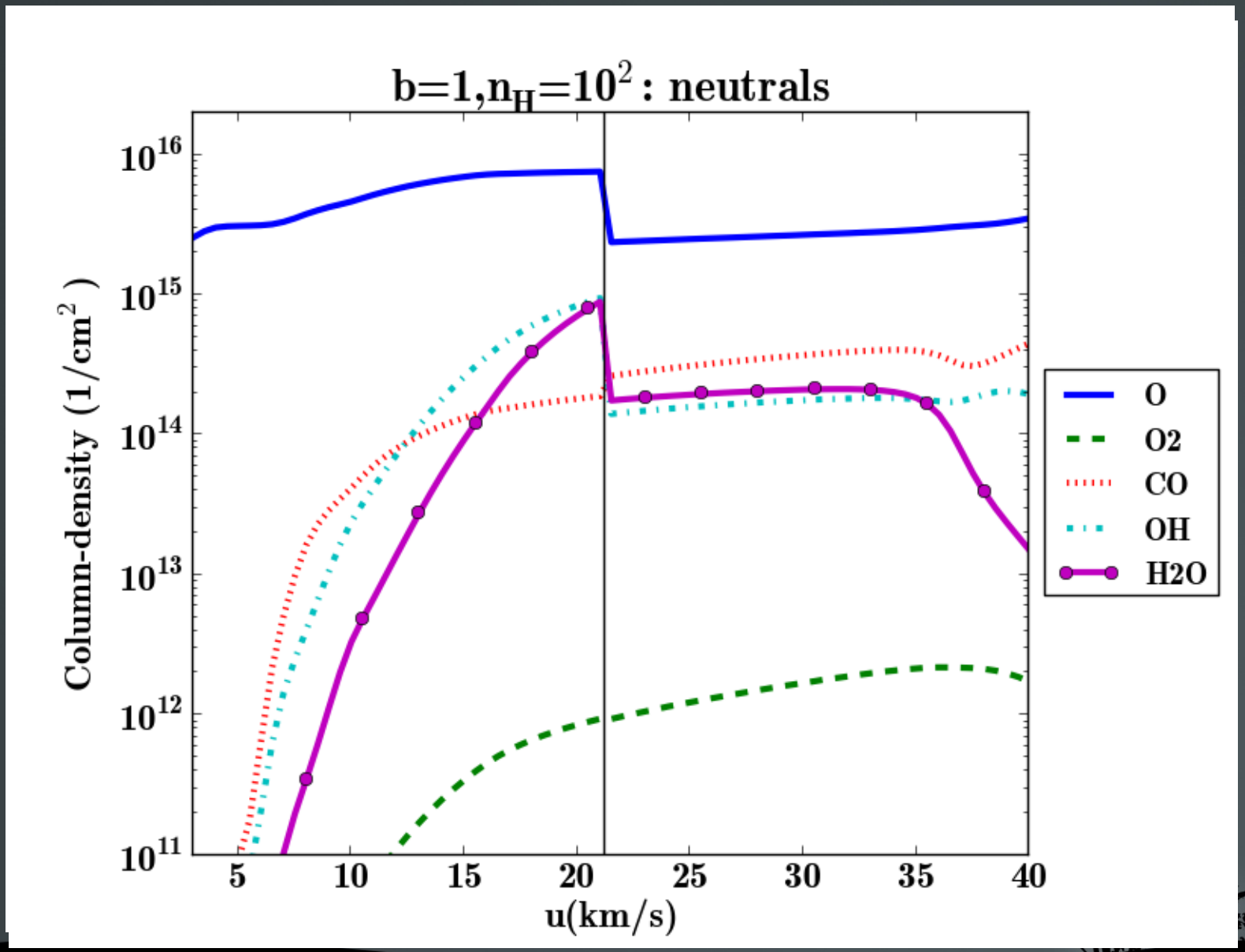
Full grid of models: http://cemag.ens.fr



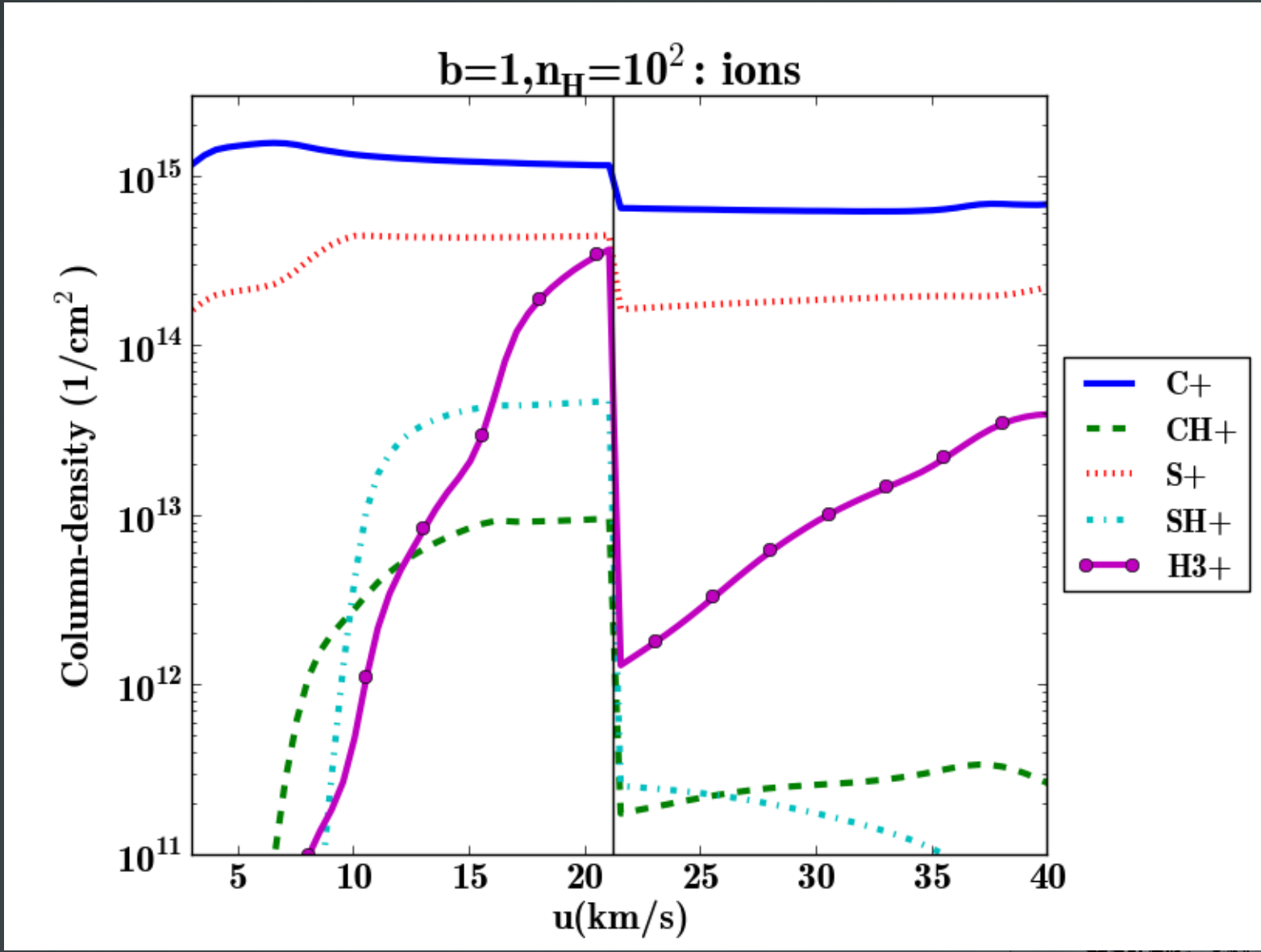
Maximum temperature in shocks



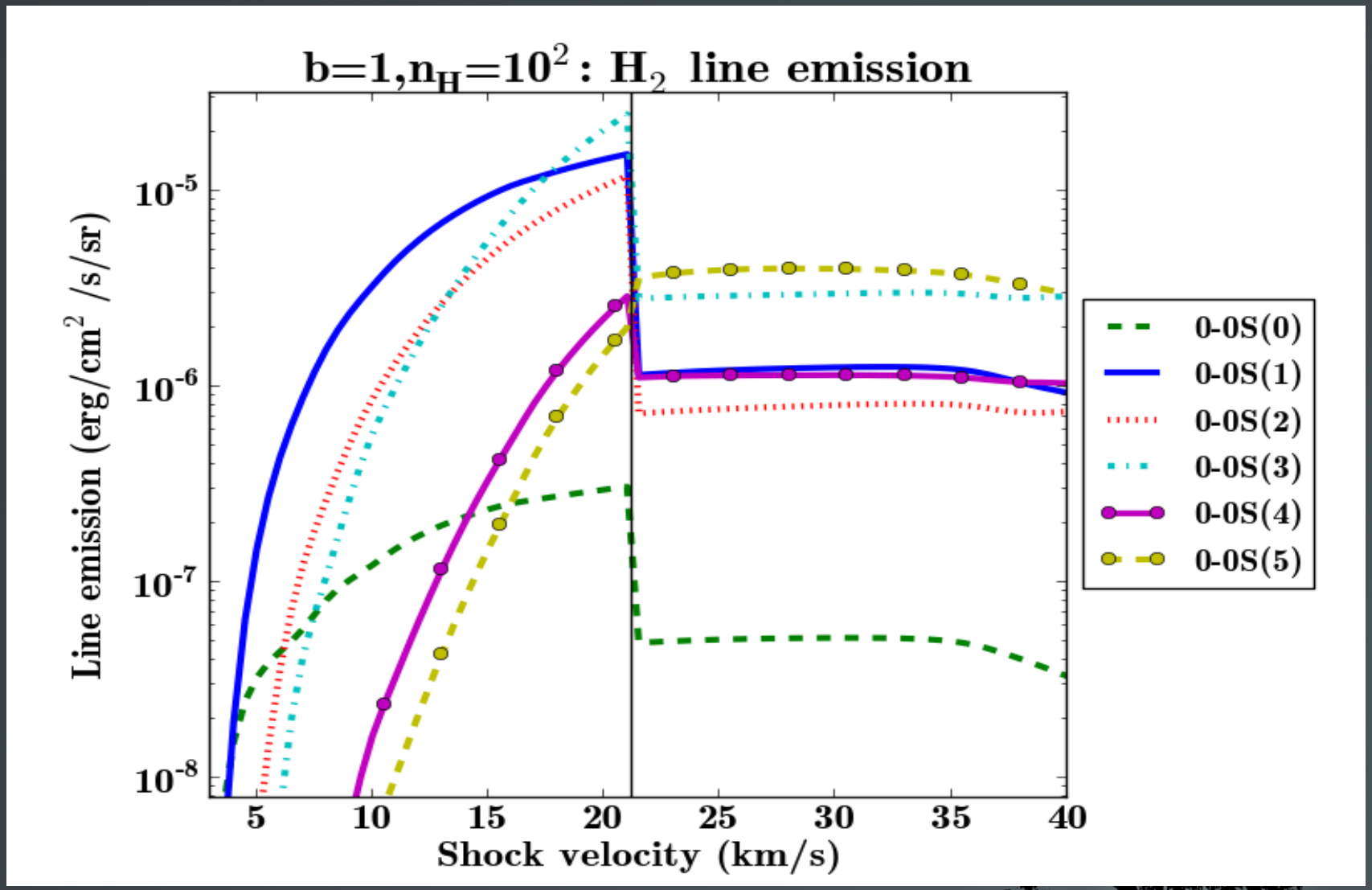
Molecule production in shocks



Molecule production in shocks



Excitation in shocks
H_2 lines



Excitation in shocks atomic emission