Laboratoire d'Études du Rayonnement et de la Matière en Astrophysique et Atmosphères

Towards irradiated shocks

Antoine Gusdorf, LERMA, Paris, France

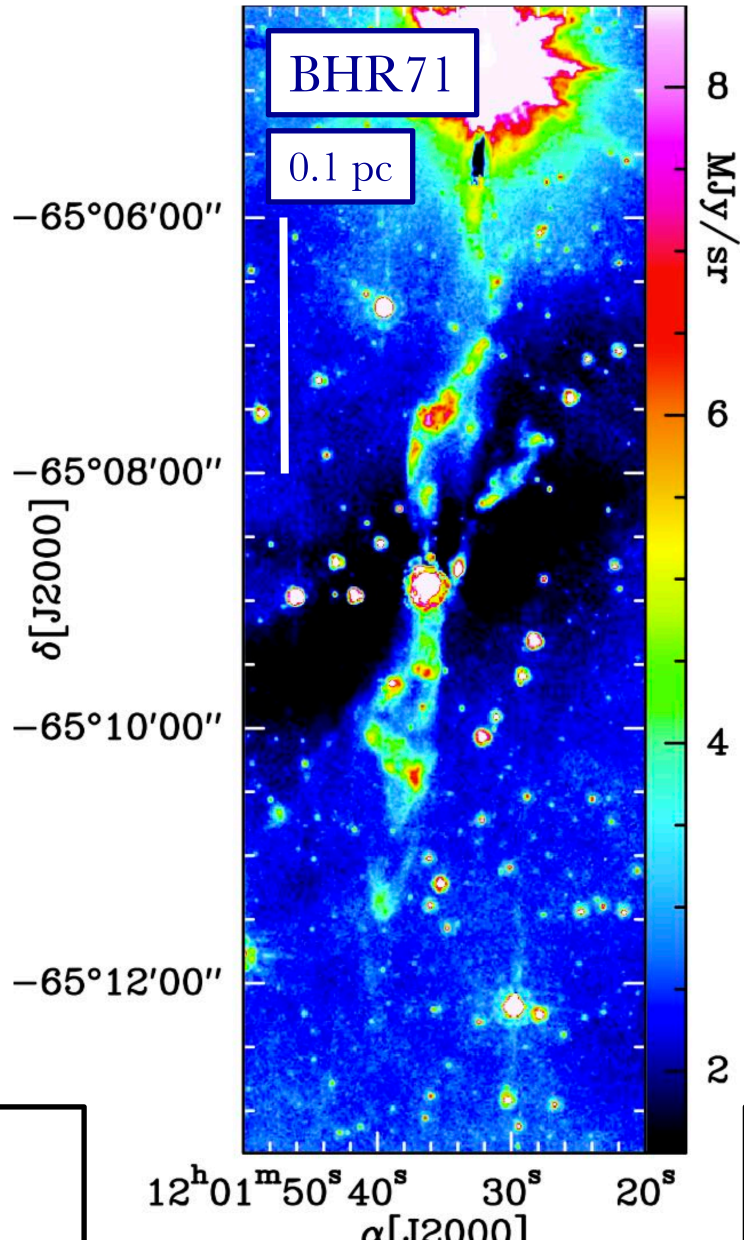
Claudio Codella, INAF, Firenze, Italy • Maryvonne Gerin, LERMA, Paris, France • **Benjamin Godard**, LERMA, Paris, France • Rolf Güsten, MPIfR, Bonn, Germany • Bertrand Lefloch, IPAG, Grenoble, France • **Pierre Lesaffre**, LERMA, Paris, France • Silvia Leurini, INAF, Cagliari, Italy • Frédérique Motte, IPAG, Grenoble, France • **Guillaume Pineau des Forêts**, LERMA, Paris, France

Outline

- The importance of shocks in the interstellar medium of galaxies
- Shock modelling: from 'simple' models…
- The need for irradiated shock models
- Irradiated shock models
- Perspectives

The importance of shocks in the interstellar medium of galaxies

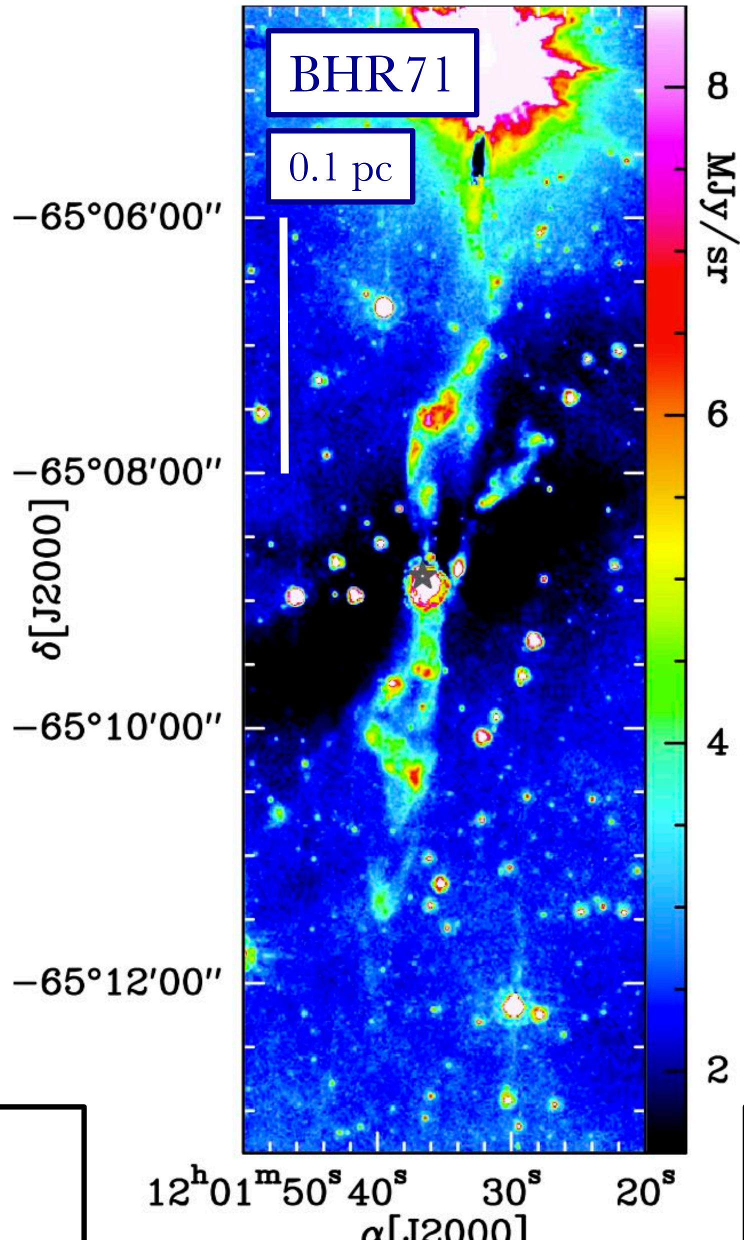
The importance of shocks in the ISM of galaxies



archive image
Spitzer/IRAC 8 μm

adapted from
Gusdorf et al. 2015

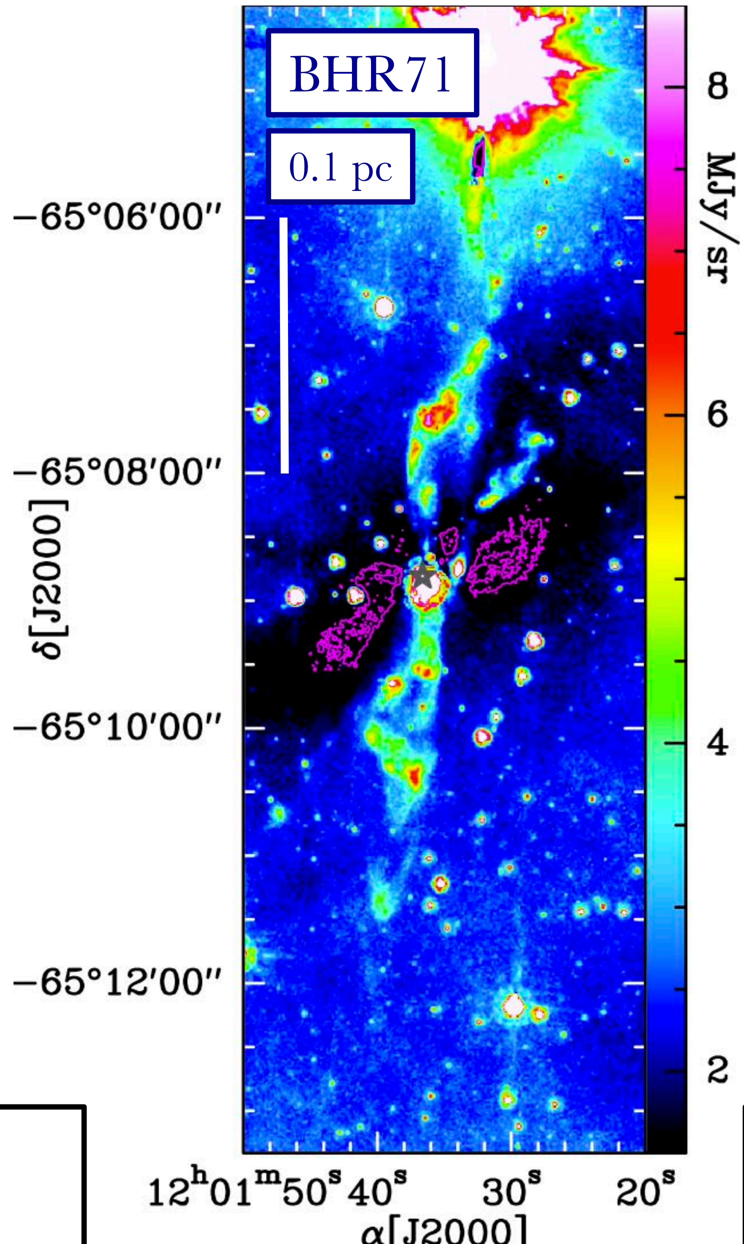
The importance of shocks in the ISM of galaxies



archive image
Spitzer/IRAC 8 μm

adapted from
Gusdorf et al. 2015

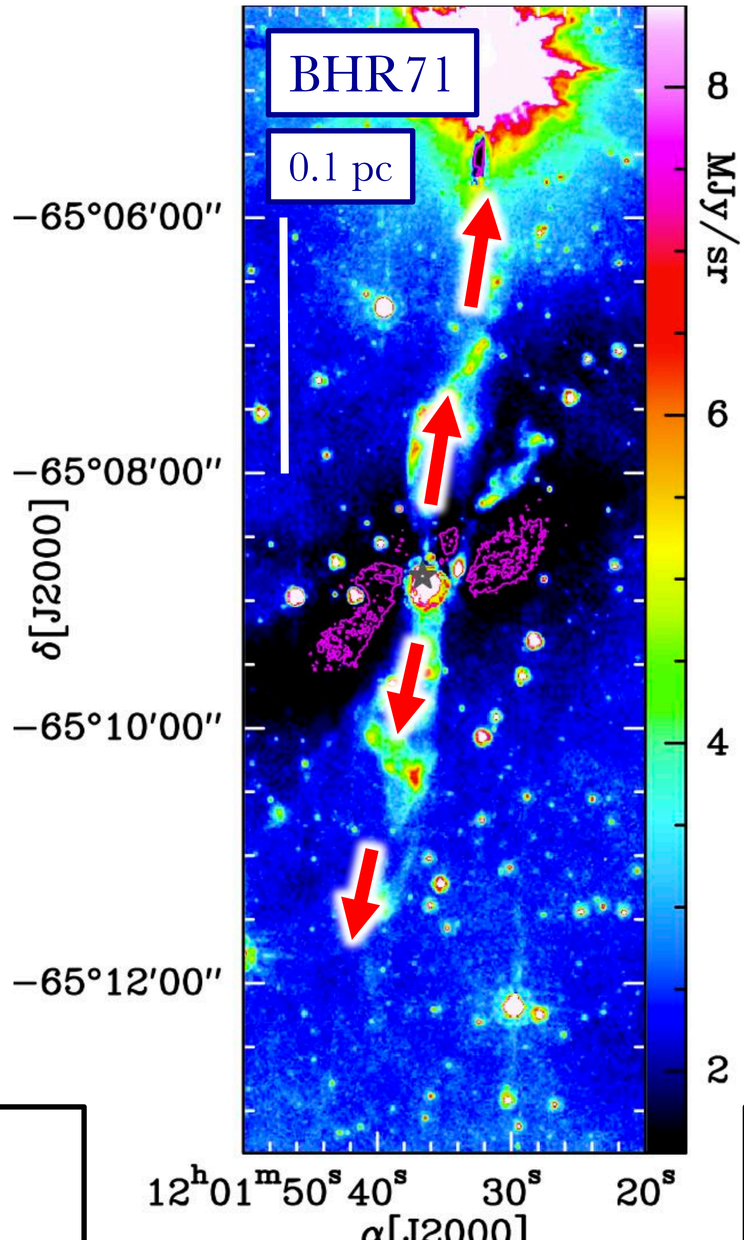
The importance of shocks in the ISM of galaxies



archive image
Spitzer/IRAC 8 μm

adapted from
Gusdorf et al. 2015

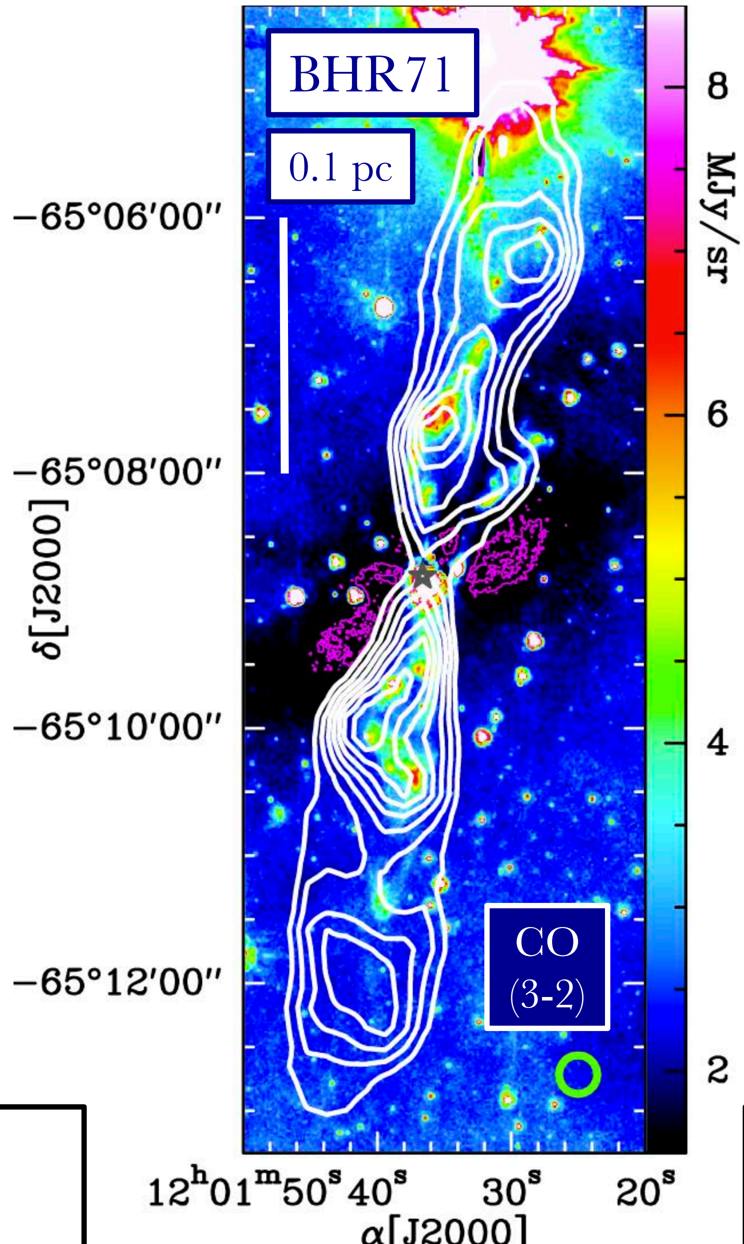
The importance of shocks in the ISM of galaxies



archive image
Spitzer/IRAC 8 μm

adapted from
Gusdorf et al. 2015

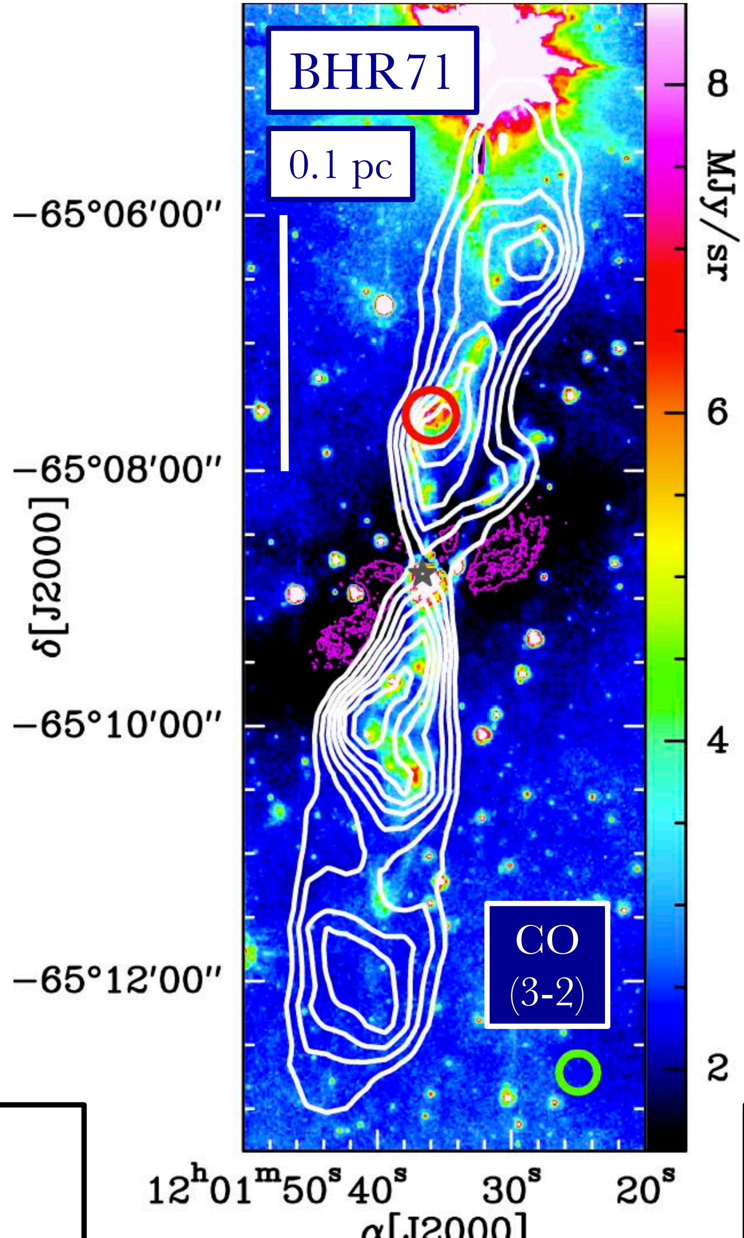
The importance of shocks in the ISM of galaxies



archive image
Spitzer/IRAC 8 μm

adapted from
Gusdorf et al. 2015

The importance of shocks in the ISM of galaxies

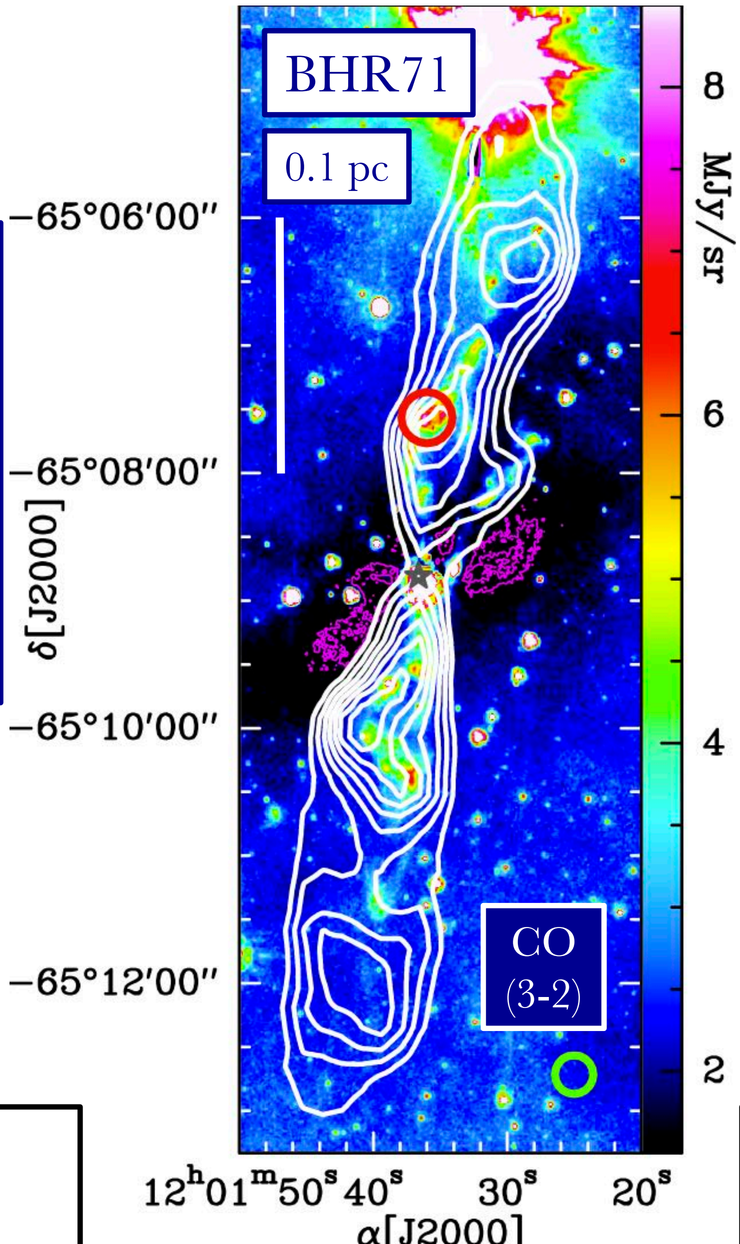


archive image
Spitzer/IRAC 8 μm

adapted from
Gusdorf et al. 2015

The importance of shocks in the ISM of galaxies

- physical processes (B, jet/outflow)
- chemical enrichment (H2O, SiO,…)

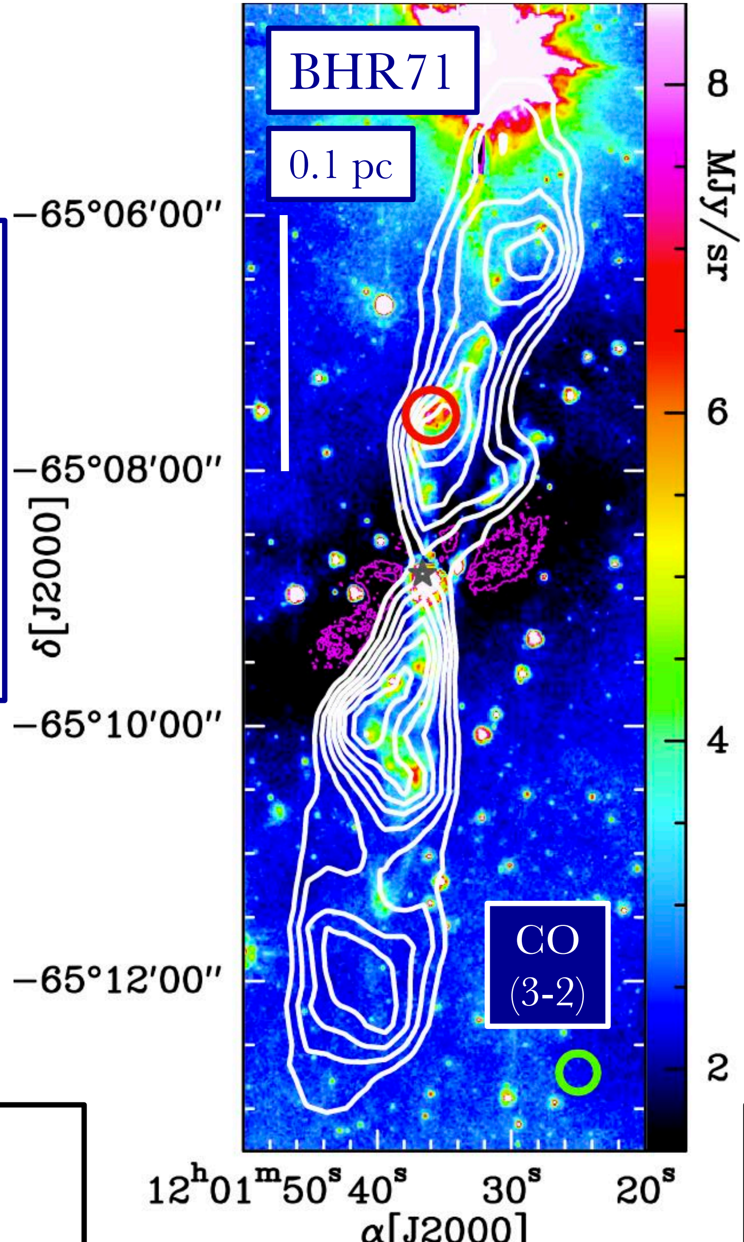


archive image
Spitzer/IRAC 8 μm

adapted from
Gusdorf et al. 2015

The importance of shocks in the ISM of galaxies

- physical processes (B, jet/outflow)
- chemical enrichment (H2O, SiO,…)



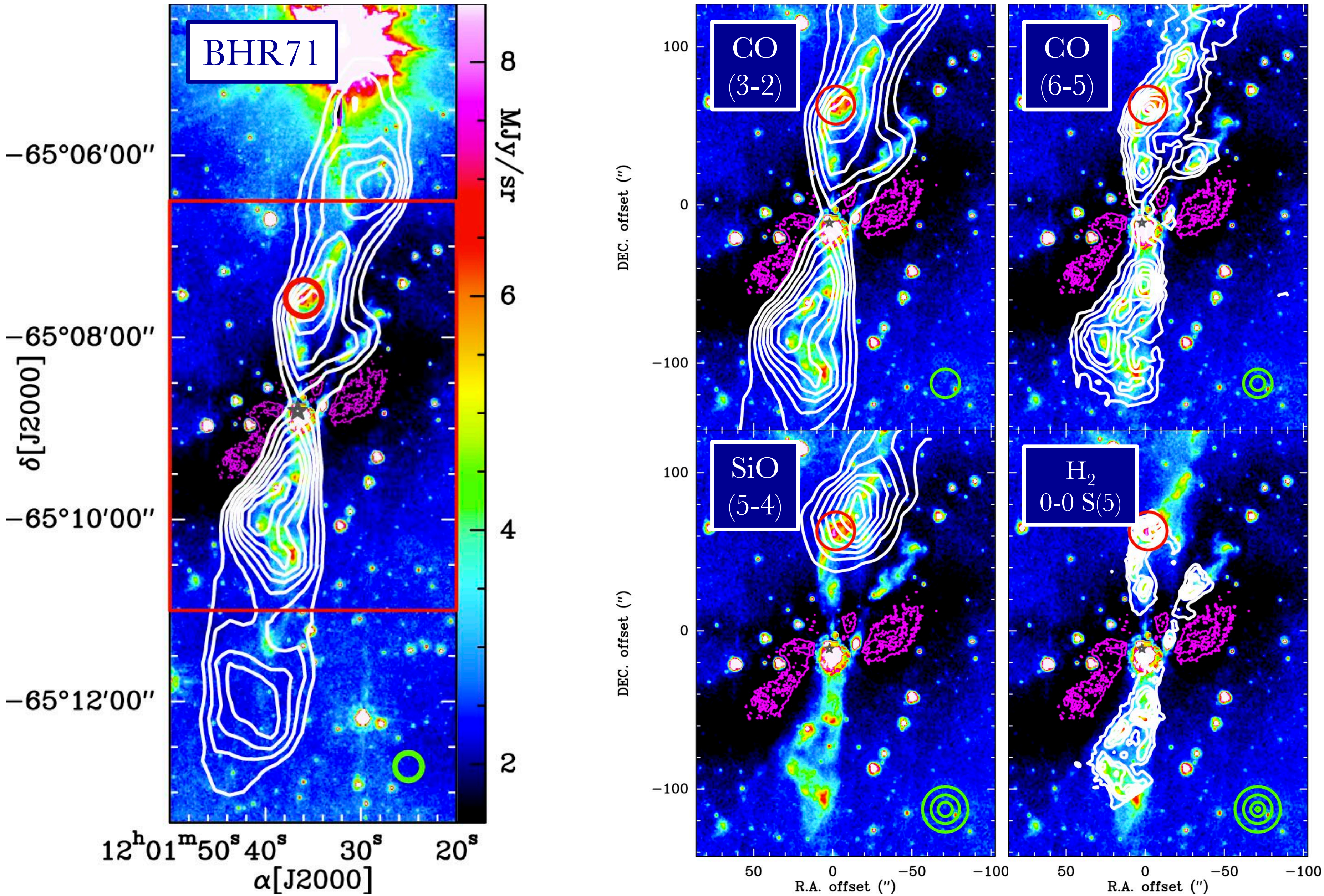
- energetic impacts
- star formation:
  - scenarios
  - triggered
- cosmic rays

archive image
Spitzer/IRAC 8 μm

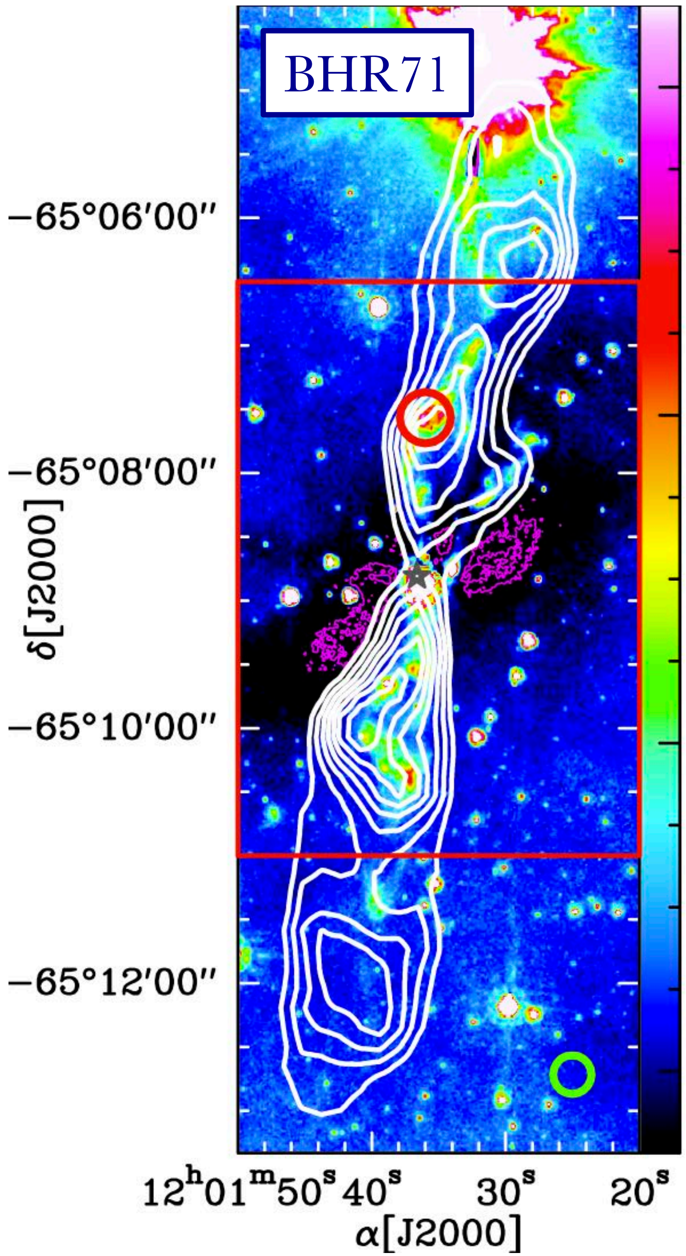
adapted from
Gusdorf et al. 2015

Shock modelling: from 'simple' models…

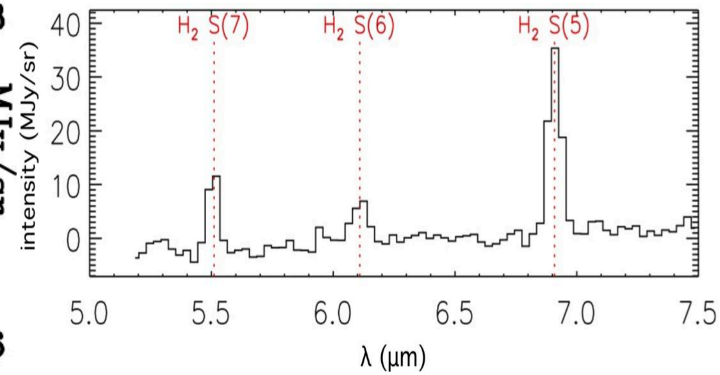
Shock modelling: from 'simple' models…

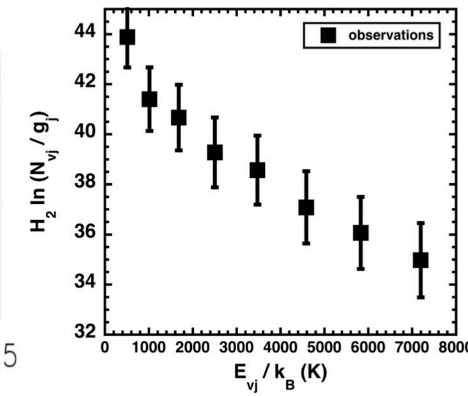


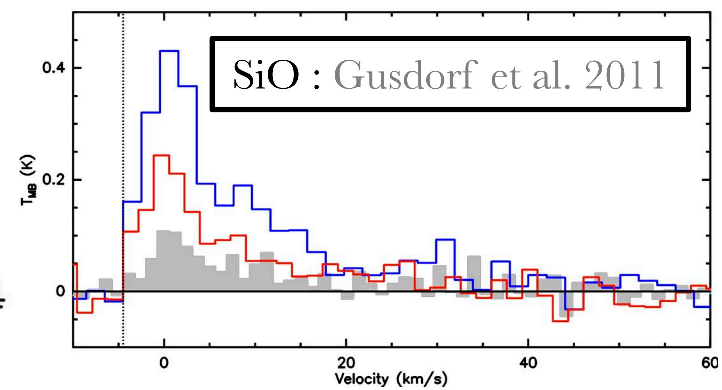
Shock modelling: from ‘simple’ models…

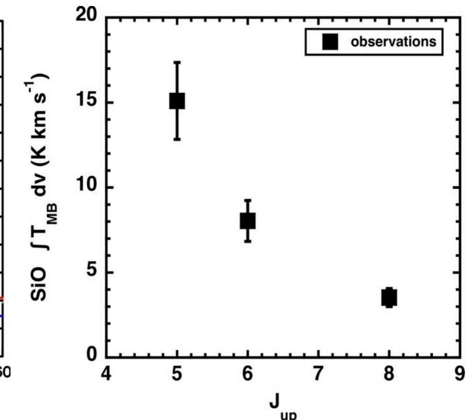


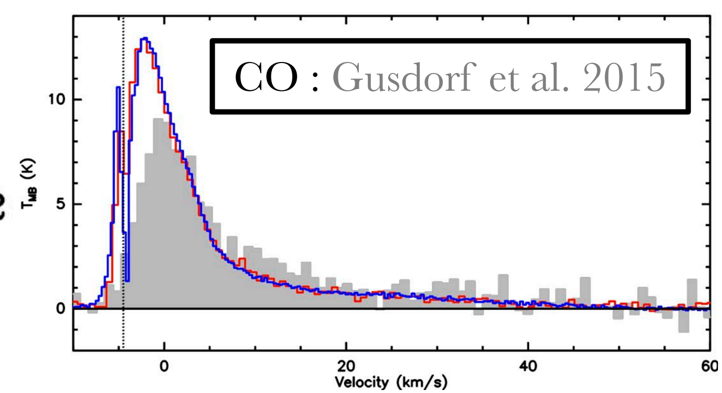
H_2 : Giannini et al. 2010

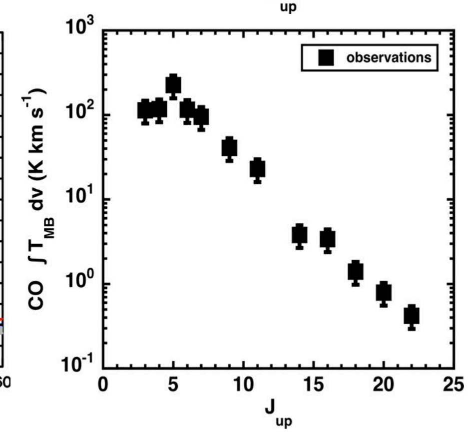












Shock modelling: from 'simple' models…

$n_H = 10^4$ cm^{-3} ; v_s = 30 km/s

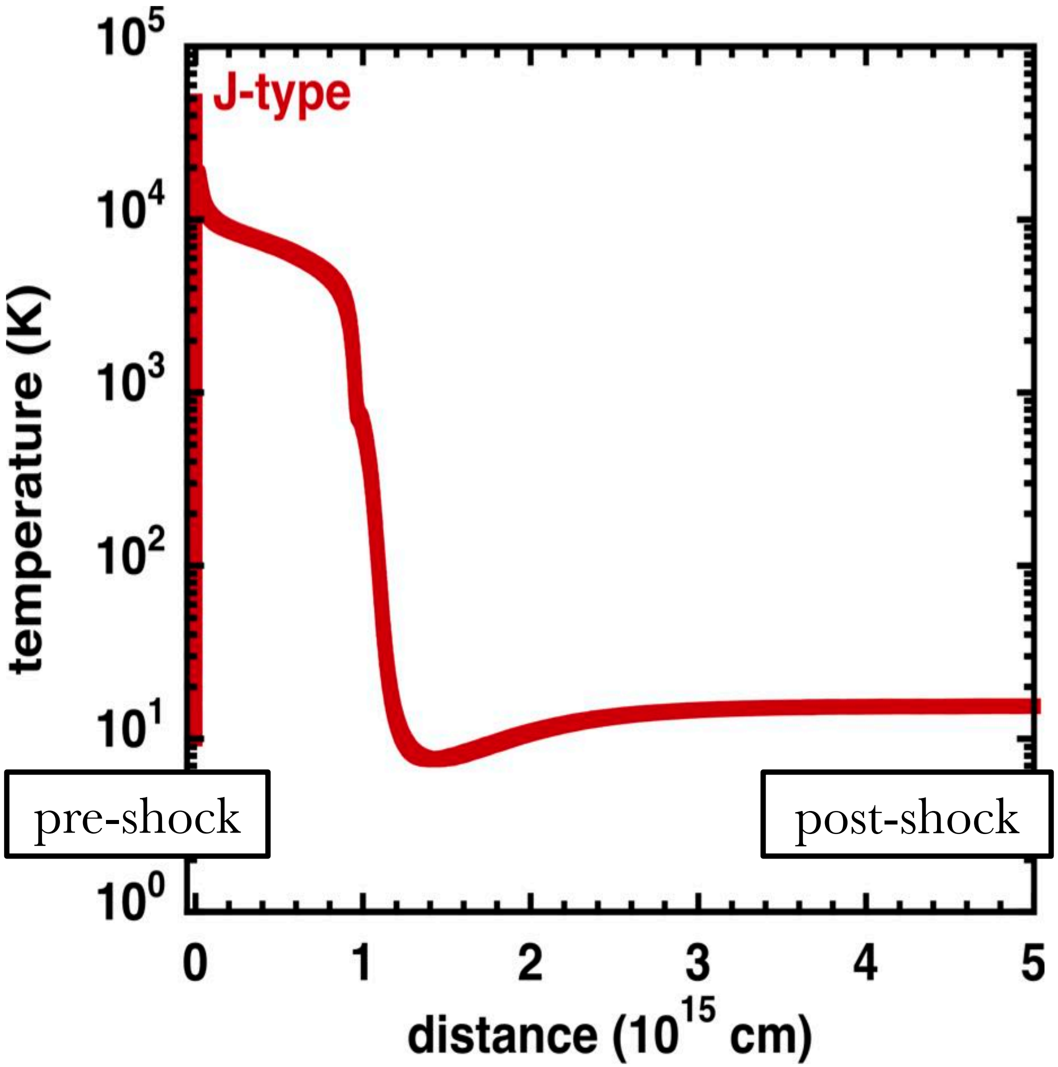
- J shock (Jump) ;

B = 10 μG

$v_s > v_{critical}$

impulse heating ;

single fluid



Shock modelling: from ‘simple’ models…

$n_H = 10^4$ cm^{-3} ; $v_s = 30$ km/s

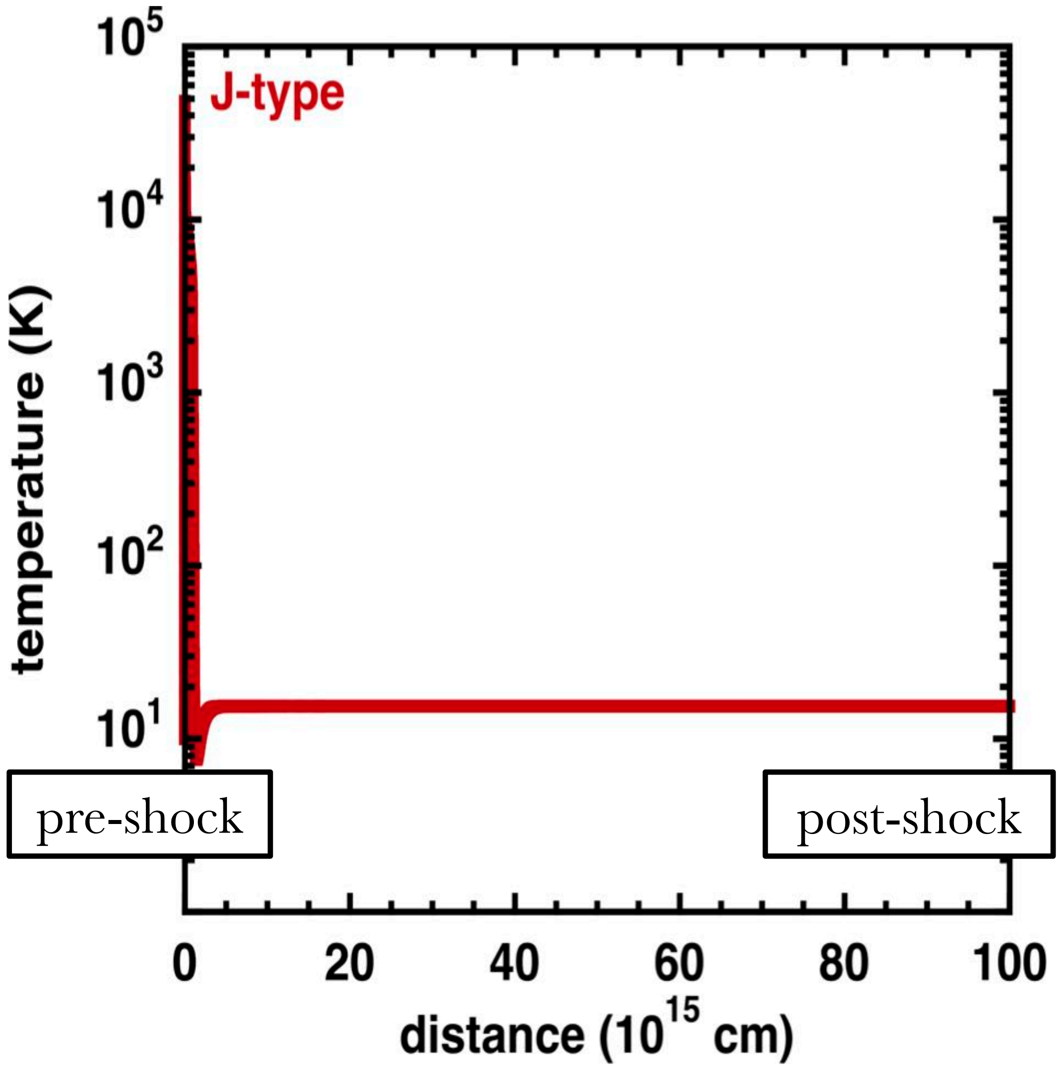
- J shock (Jump) ;

B = 10 μG

$v_s > v_{critical}$

impulse heating ;

single fluid



Shock modelling: from 'simple' models...

$n_H = 10^4\ cm^{-3}$; $v_s = 30$ km/s

- J shock (Jump) ;

B = 10 μG

$v_s > v_{critical}$

impulse heating ;

single fluid

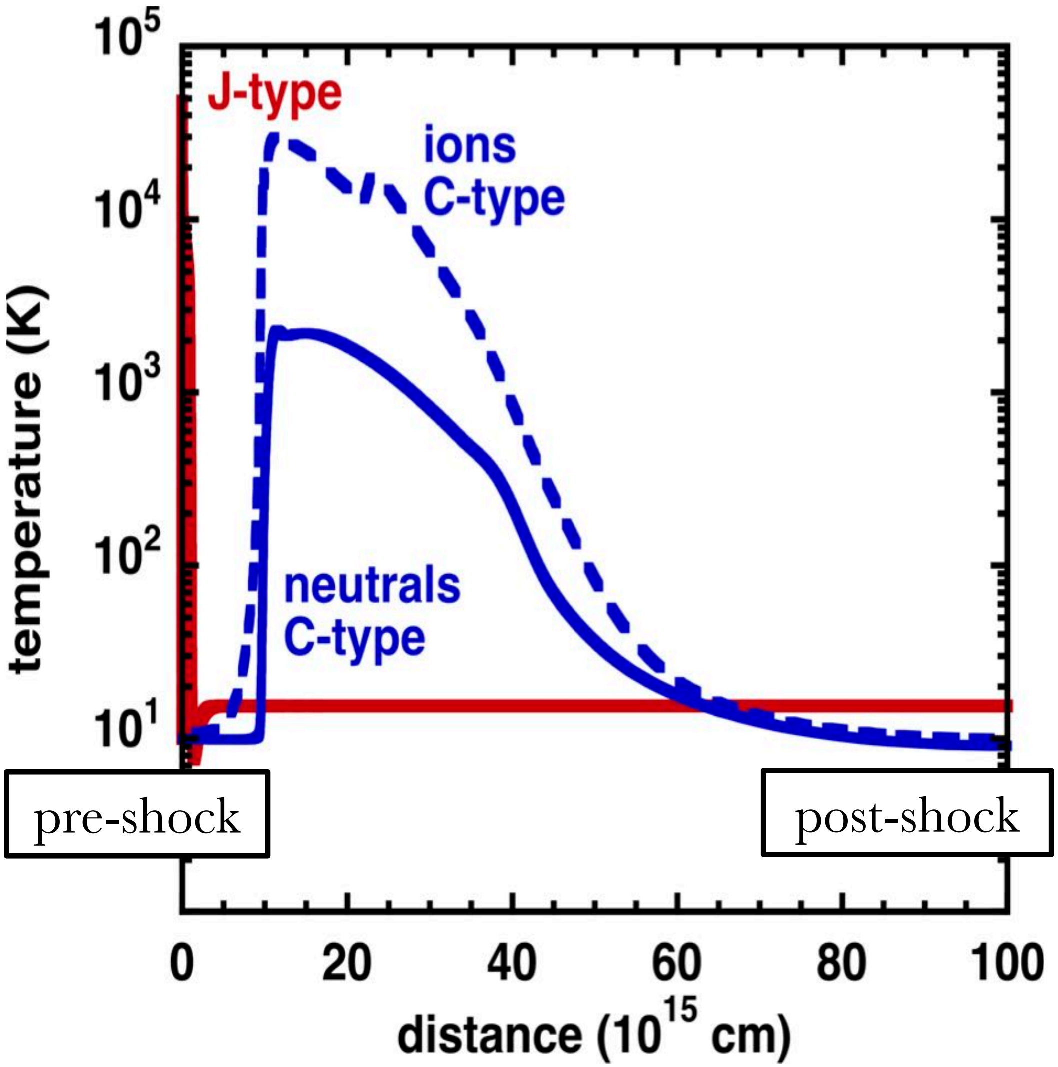
- C shock (Continuous) ;

B = 100 μG

$v_s < v_{critical}$

ion-neutral friction ;

multi-fluid



Shock modelling: from ‘simple’ models…

$n_H = 10^4\ cm^{-3}$; $v_s = 30$ km/s

- J shock (Jump) ;

B = 10 μG

$v_s > v_{critical}$

impulse heating ;

single fluid

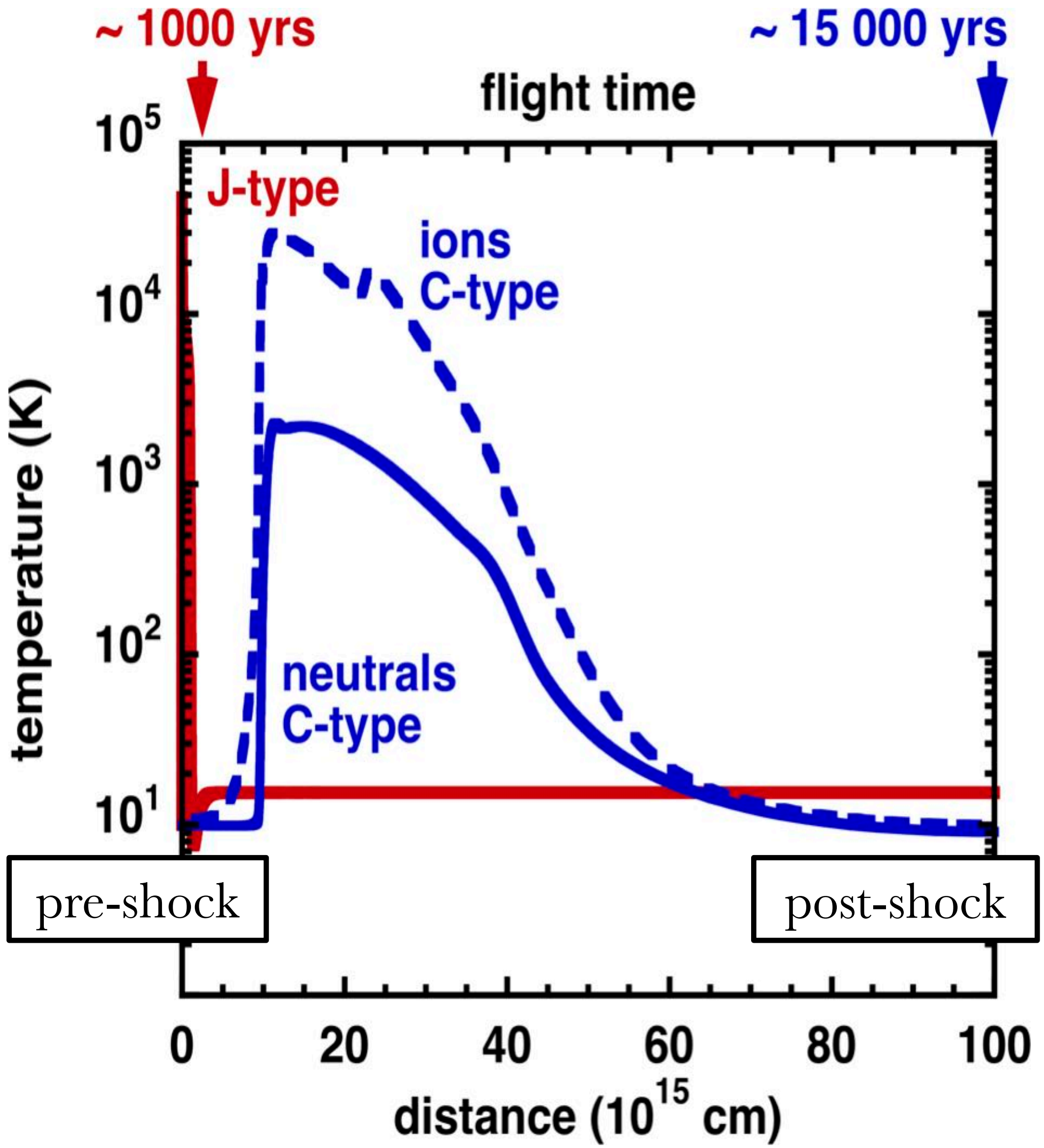
- C shock (Continuous) ;

B = 100 μG

$v_s < v_{critical}$

ion-neutral friction ;

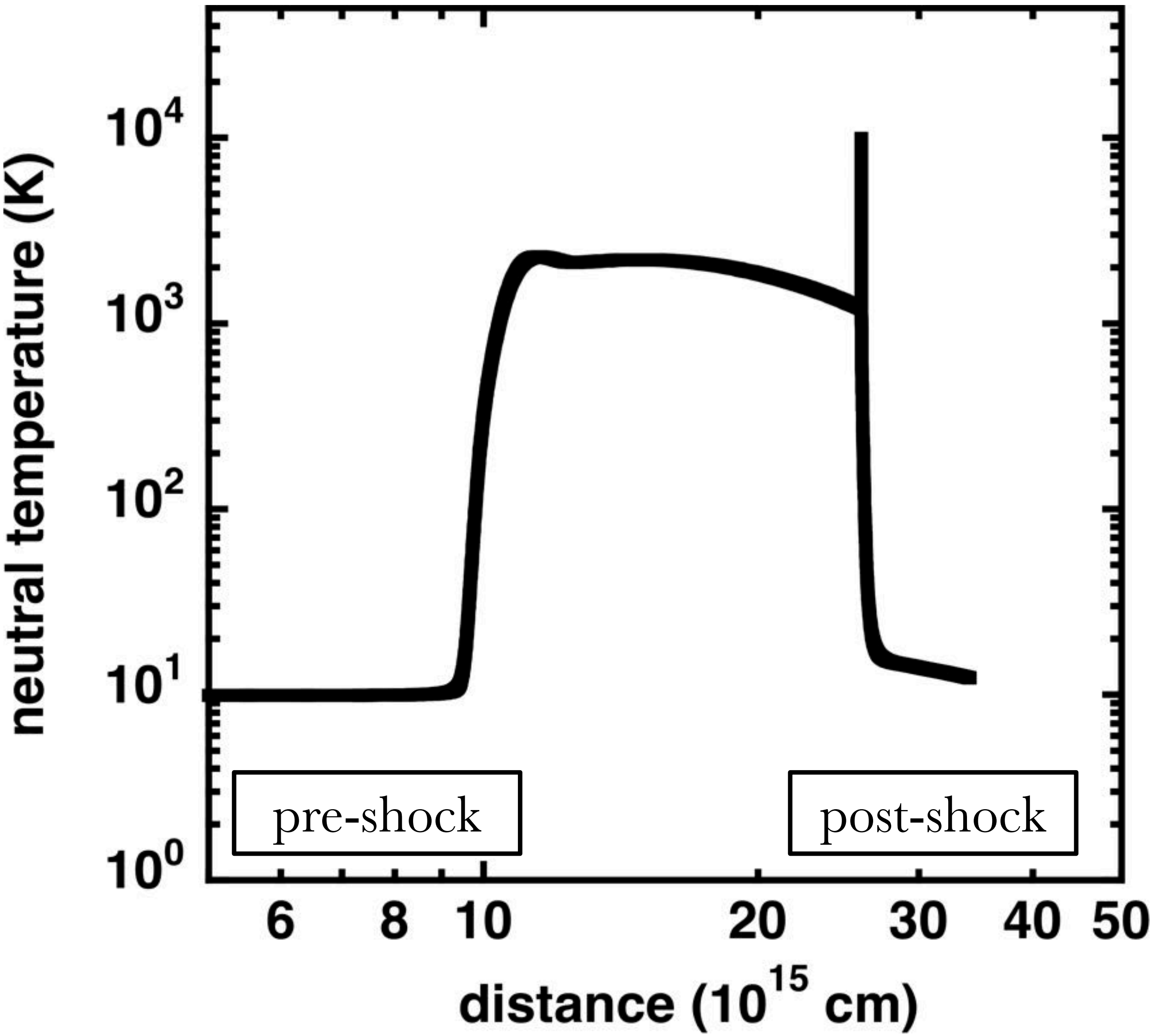
multi-fluid



Shock modelling: from 'simple' models…

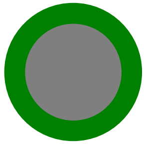
$n_H = 10^4\ cm^{-3}$
$v_s = 30\ km/s$
age 2000 yrs

CJ shock



Shock modelling: from ‘simple’ models…

pre-shock medium:



Si^{**} ∈ cores

SiO^{*} ∈ mantles

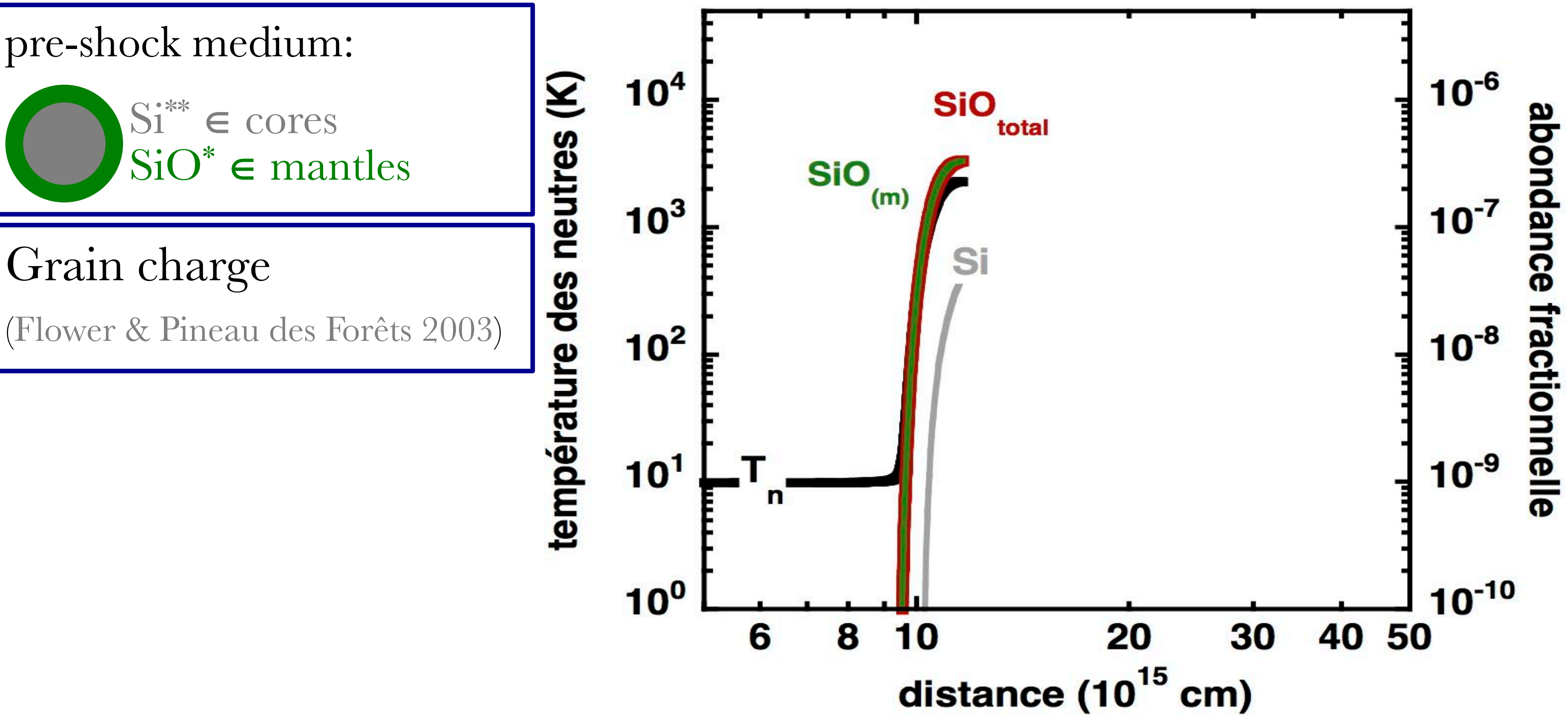
Shock modelling: from 'simple' models…

pre-shock medium:

Si** ∈ cores
SiO* ∈ mantles

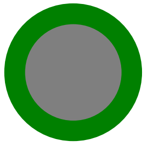
Grain charge

(Flower & Pineau des Forêts 2003)



Shock modelling: from ‘simple’ models…

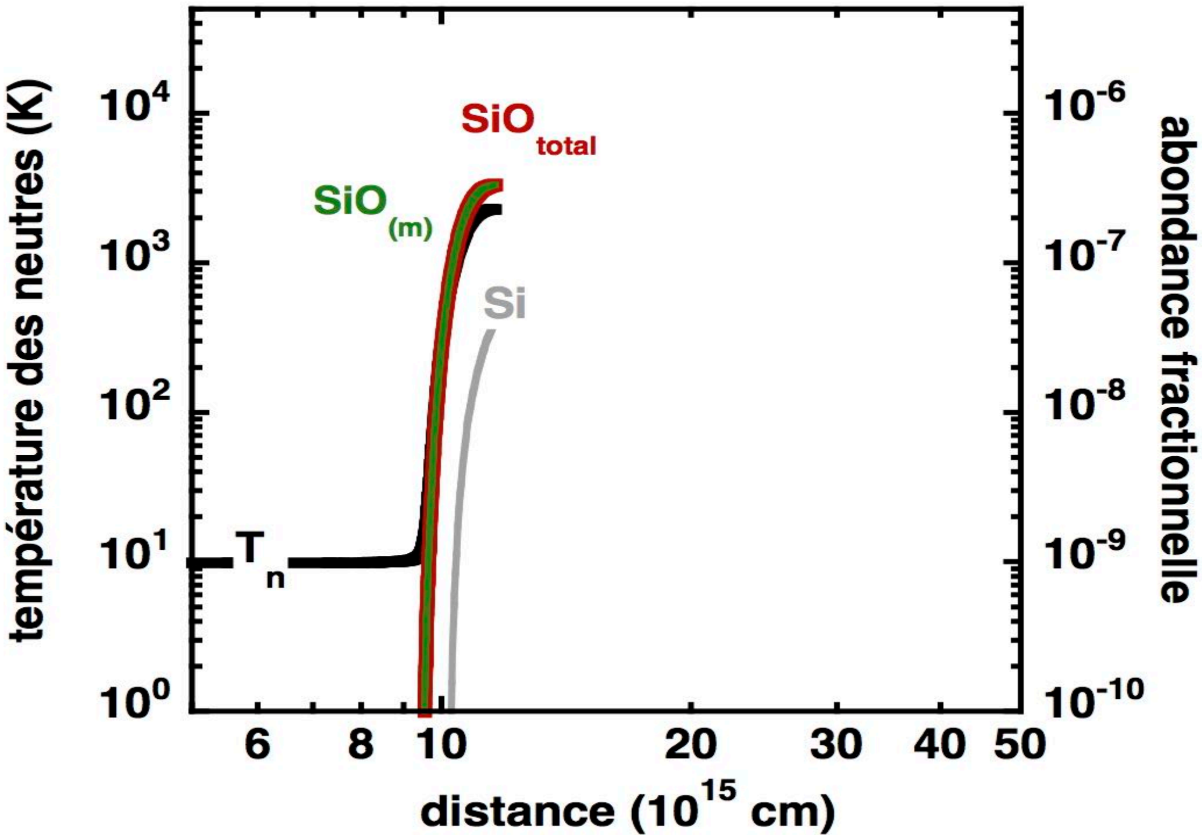
pre-shock medium:



Si^{**} ∊ cores
SiO^{*} ∊ mantles

Grain charge

(Flower & Pineau des Forêts 2003)



mantle sputtering (Flower & Pineau des Forêts 1994, semi-classical prescriptions) :

SiO^{*} + (H, He, H_2) → SiO + (H, He, H_2)

core erosion (May et al. 2000, Monte-Carlo simulations) :

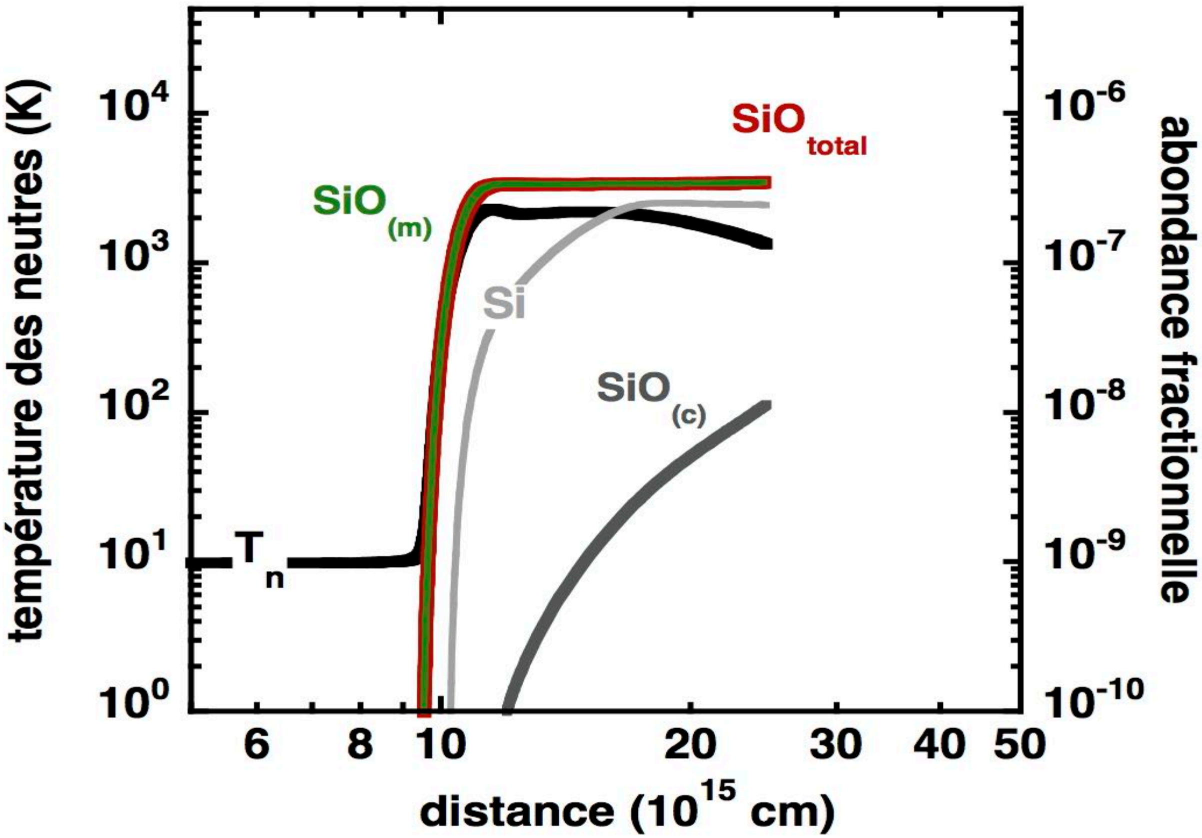
Si^{**} + (He, C, N, O, H_2O, N_2, CO, O_2) → Si + (He, C, N, O, H_2O, N_2, CO, O_2)

Shock modelling: from ‘simple’ models…

pre-shock medium:

Si^{**} ∊ cores
SiO^{*} ∊ mantles

grain charge
core erosion
mantles sputtering



SiO formation in the gas phase, from grain-core silicium:

$Si + O_2 \rightarrow SiO + O$

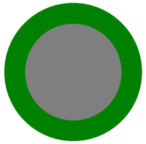
(Le Picard et al. 2001, CRESU experiment)

$Si + OH \rightarrow SiO + H$

(Rivero-Santamaria, Dayou et al. 2014, quantum calculations)

Shock modelling: from 'simple' models…

pre-shock medium:



Si^{**} ∈ cores

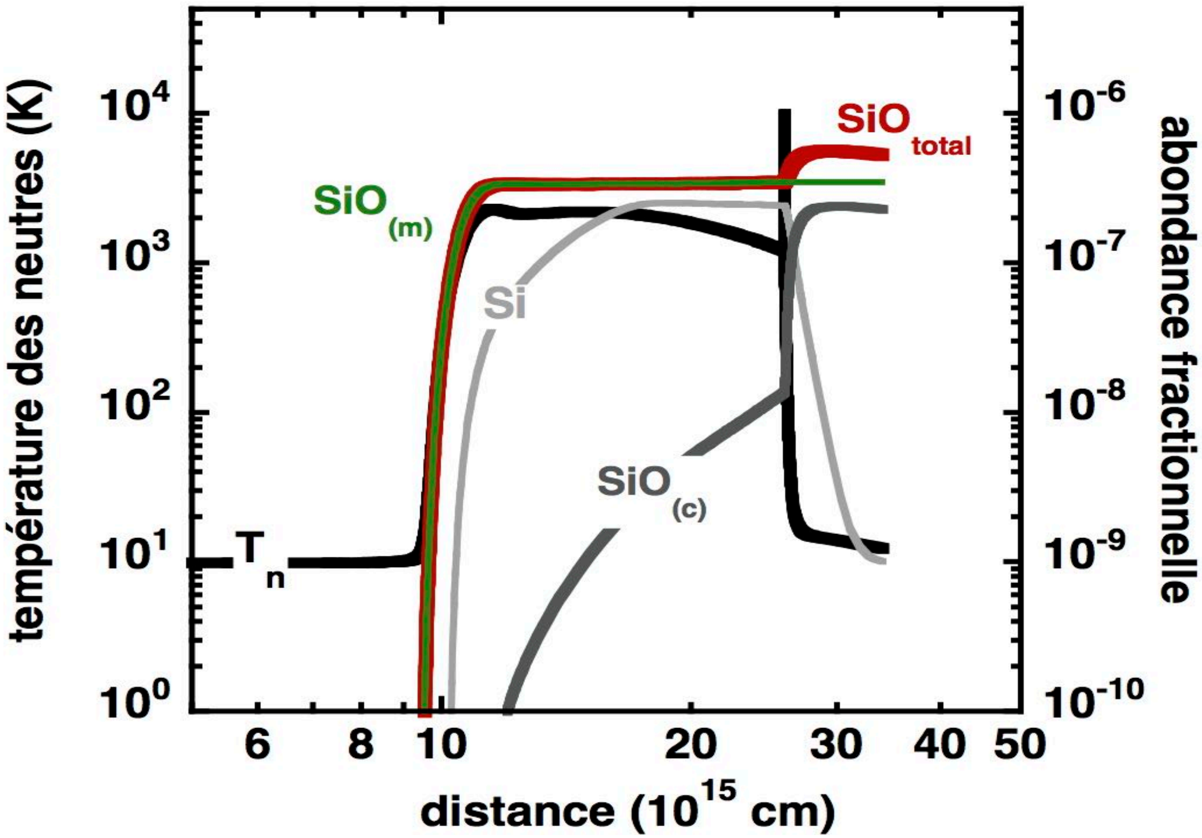
SiO^* ∈ mantles

grain charge

core erosion

mantles sputtering

gas phase formation



gas phase, chemical destruction of SiO:

$SiO + OH \rightarrow SiO_2 + H$

(prescription E. Herbst)

adsorption (freeze-out) on to grains :

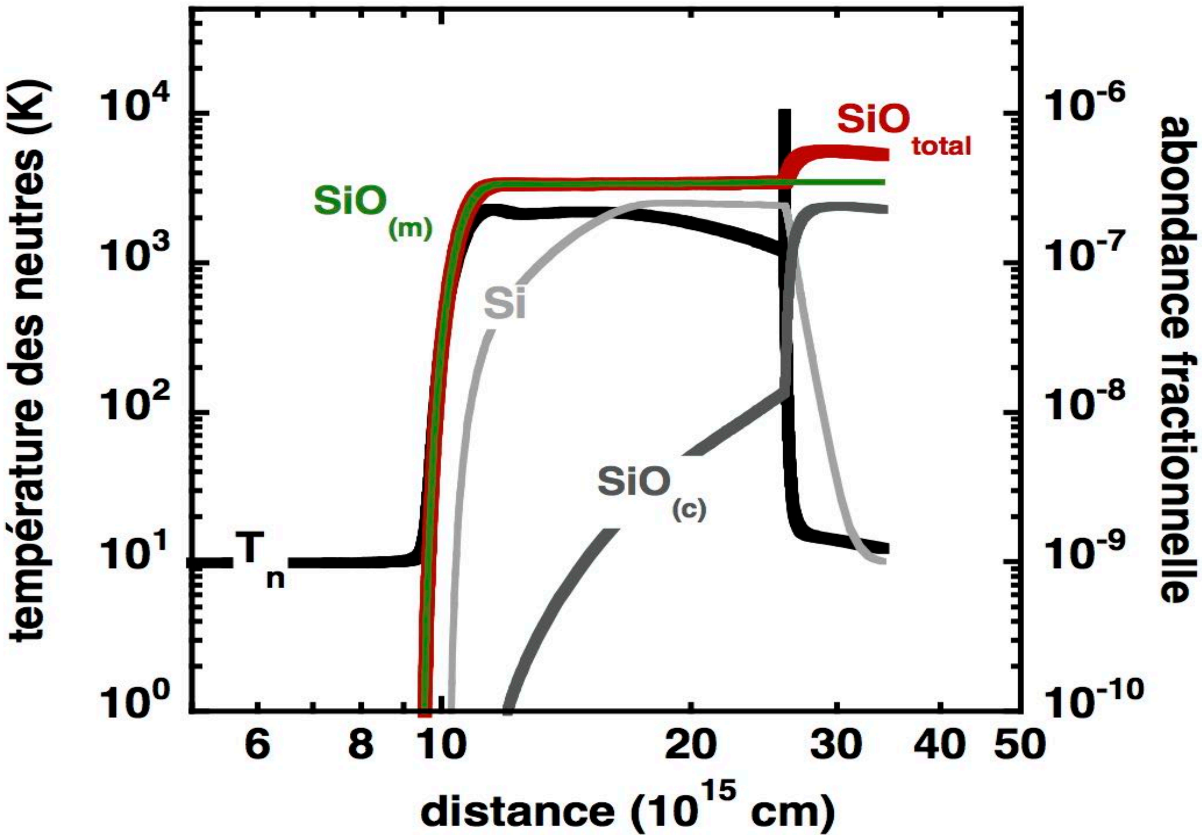
$SiO + grain \rightarrow SiO^* + grain$

Shock modelling: from 'simple' models…

pre-shock medium:

Si** ∈ cores
SiO* ∈ mantles

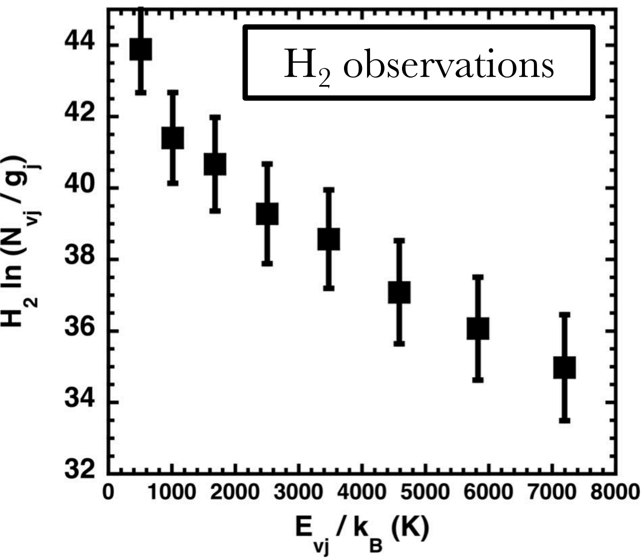
grain charge
core erosion
mantles sputtering
gas phase formation
gas phase destruction
adsorption

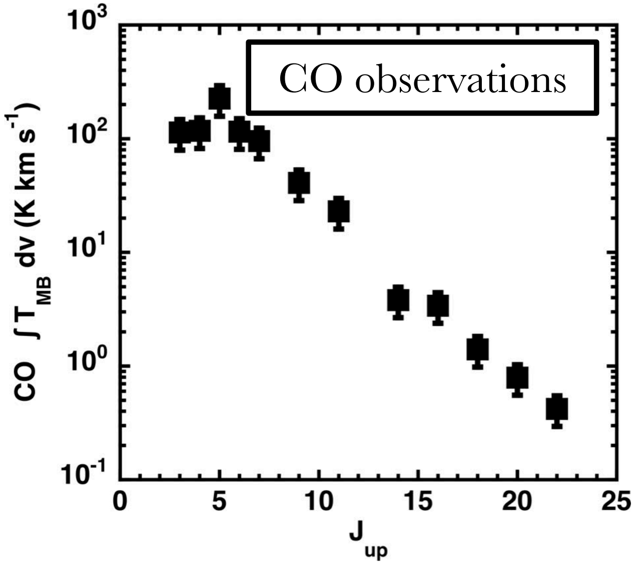


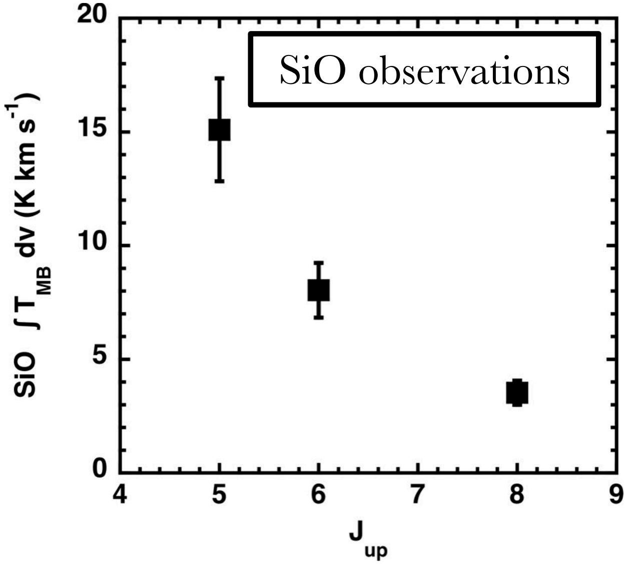
- level populations and transition emissivities calculations:
  - statistical equilibrium equations
  - 'Large Velocity Gradient' (LVG) assumption
  - collisional excitation rate coefficients of SiO by H_2, H, He

(calculated by Dayou & Balança 2006)

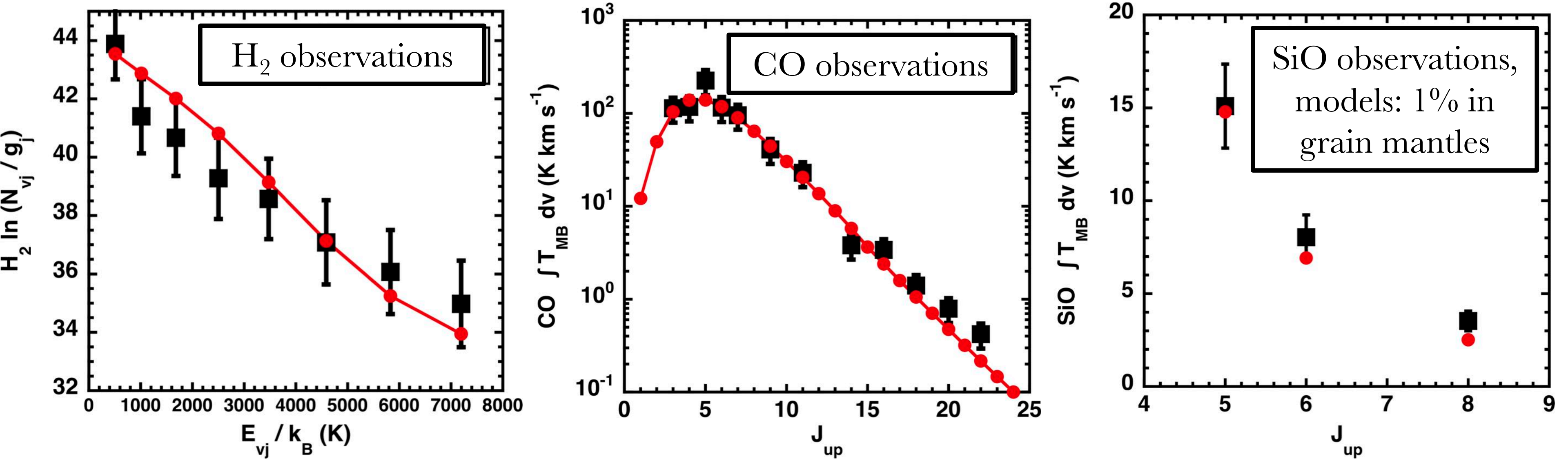
Shock modelling: from 'simple' models…



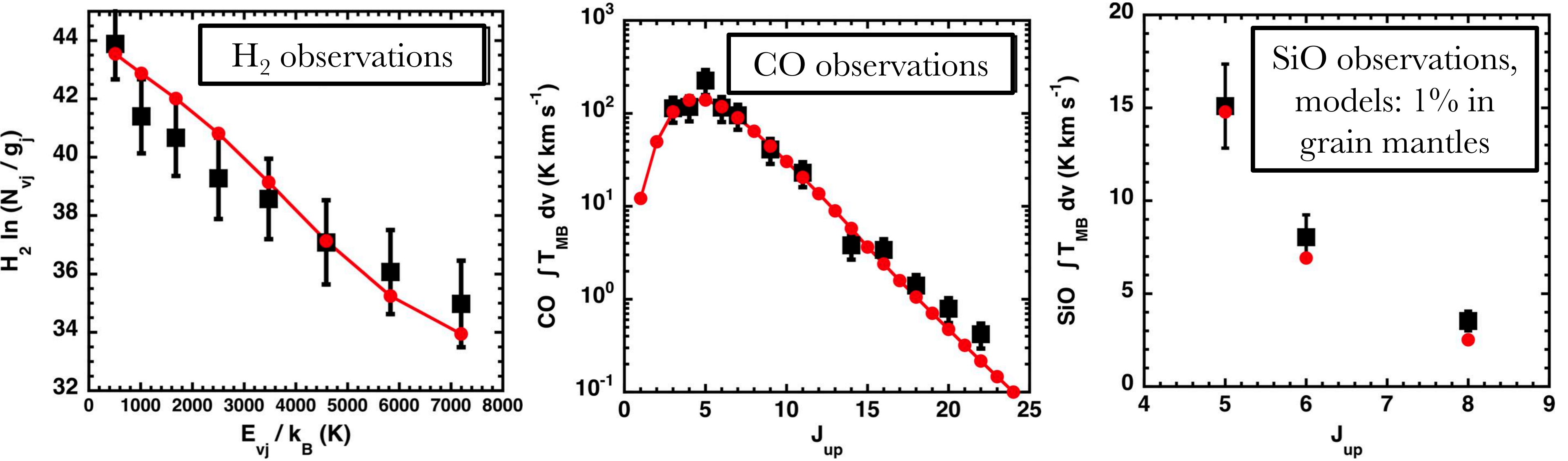




Shock modelling: from 'simple' models…



Shock modelling: from 'simple' models…



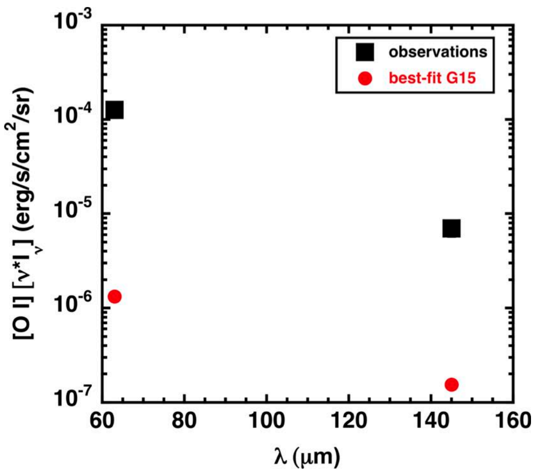
- CJ model, $n_H = 10^4$ cm^{-3}, v_s = 22 km/s, B = 150 μG ; 1% of Si ∊ SiO* (pre-shock)

  - physical conditions are constrained (shock age, magnetic field strength)
  - silicon chemistry constrained (initial distribution, processes)
  - ejection rate (precise) measure: $7 \cdot 10^{-6}$ $M_\odot$/an
  - pure shock diagnosis

Gusdorf et al. 2015

The need for irradiated shock models

The need for irradiated shock models

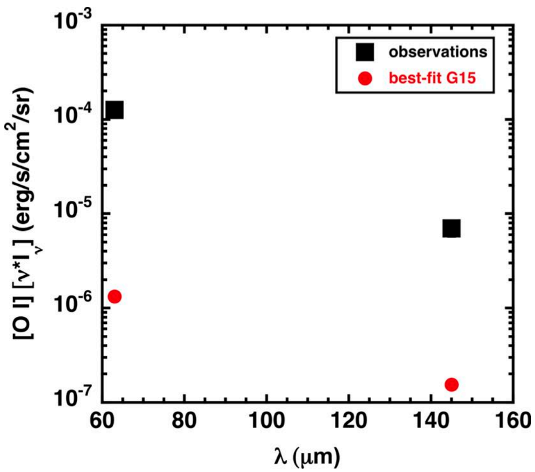


- OI is underproduced by models by 2 orders of magnitude !

same for OH, but not for H_2O (Benedettini et al., 2017)

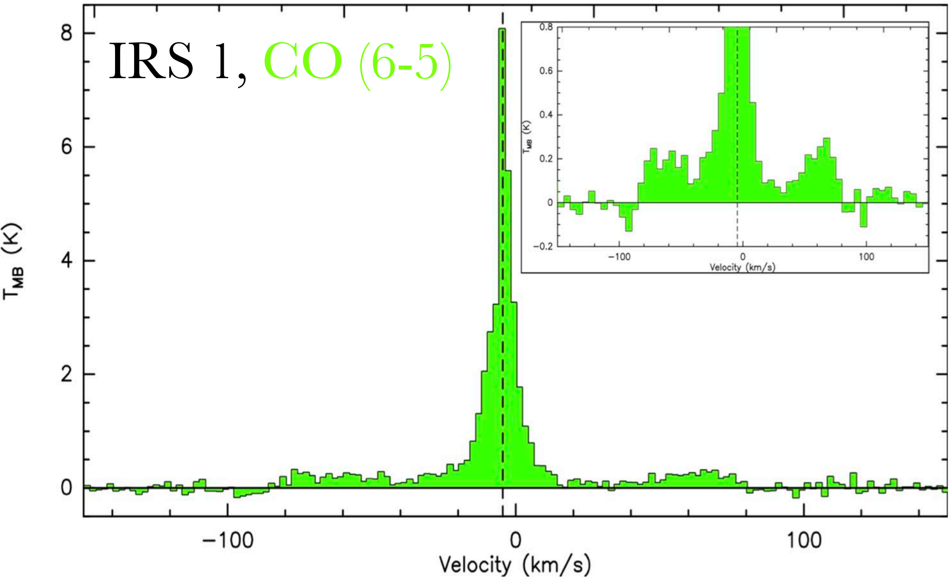
=> presence of a jet ? Fast shocks

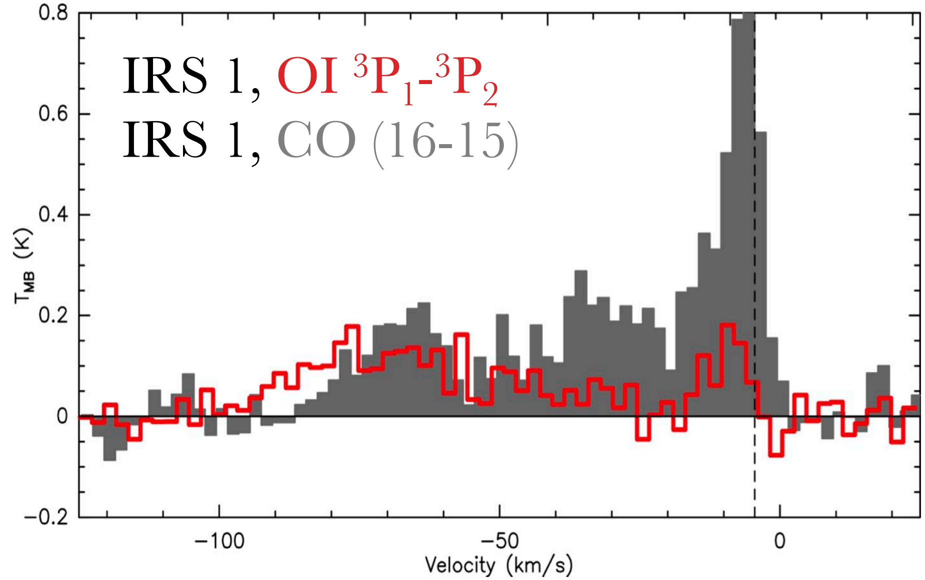
The need for irradiated shock models



- OI is underproduced by models by 2 orders of magnitude ! same for OH, but not for H_2O (Benedettini et al., 2017)

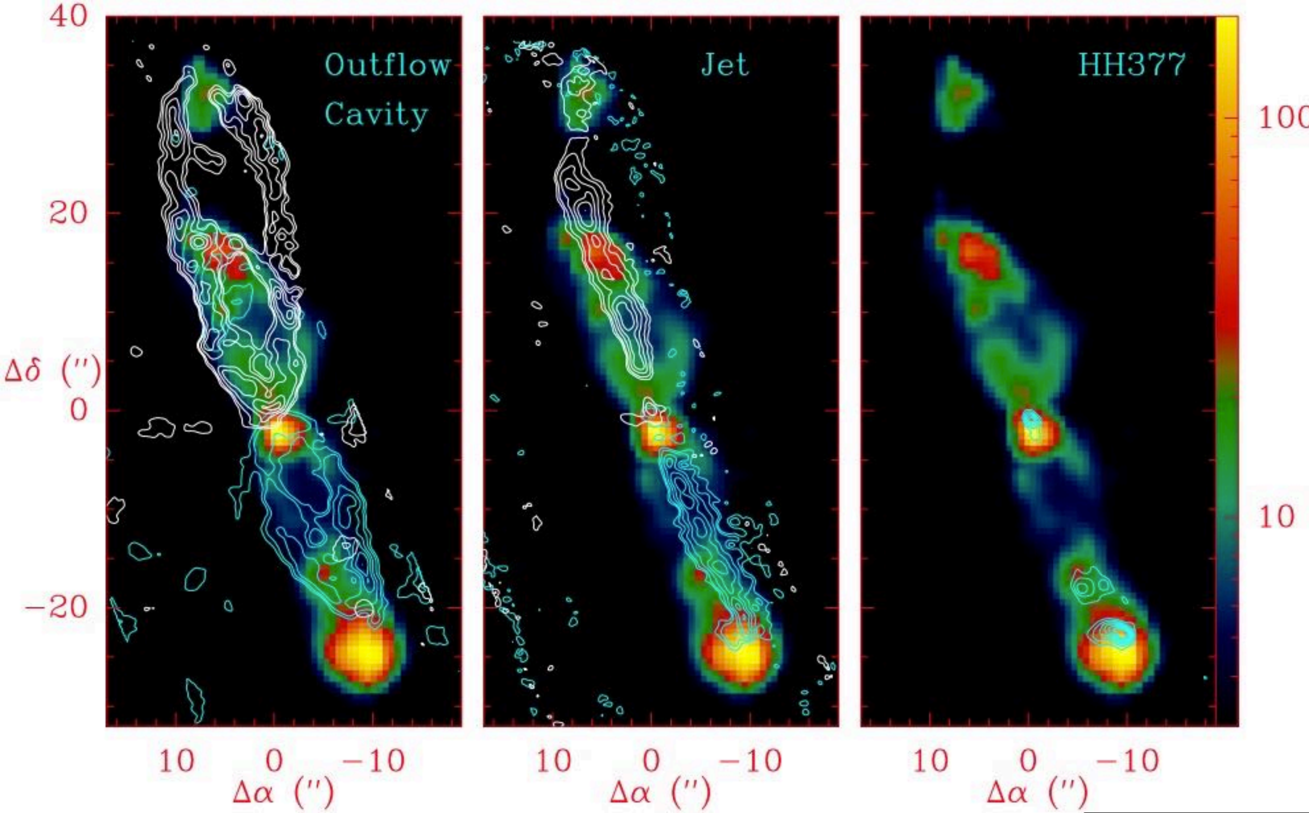
=> presence of a jet ? Fast shocks

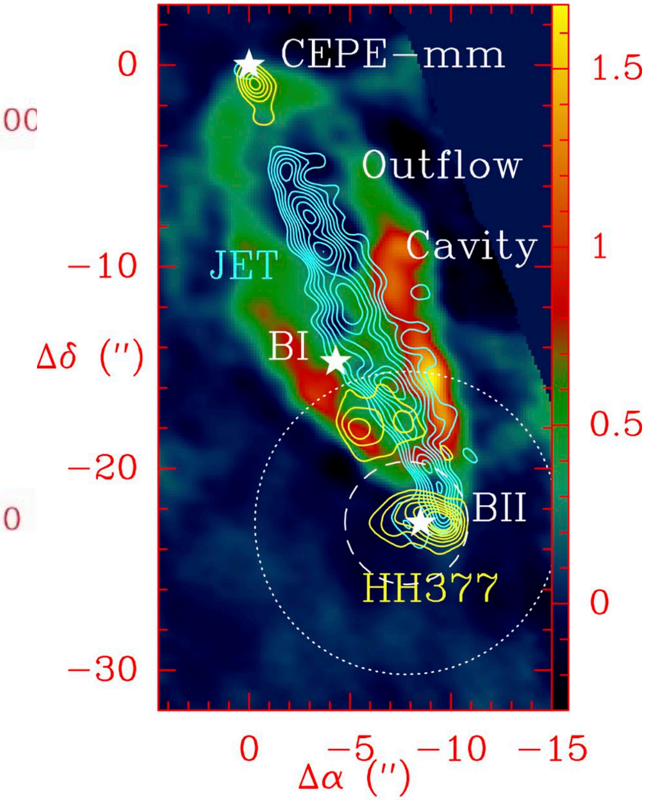




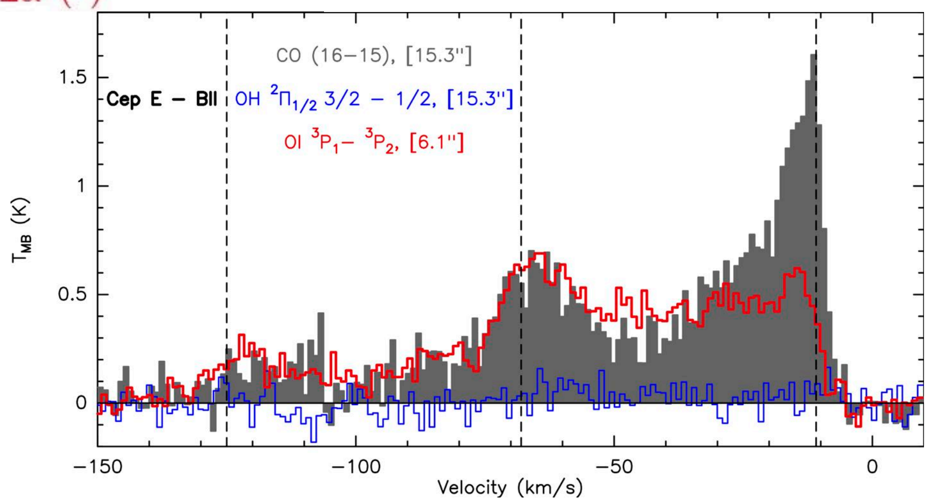
Gusdorf et al., in prep.

The need for irradiated shock models

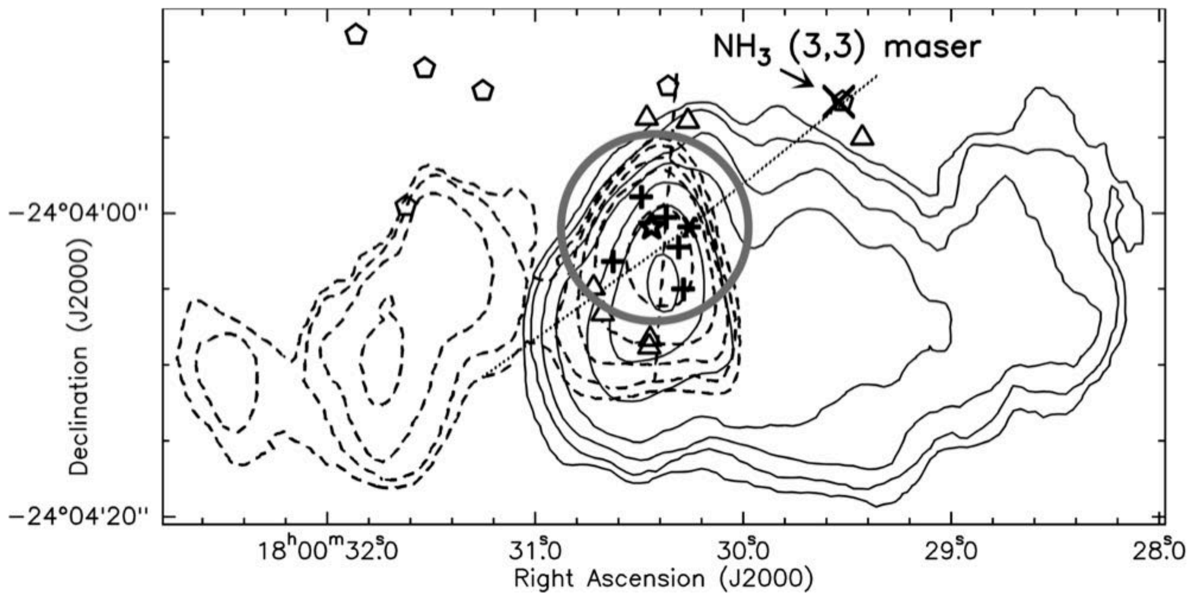




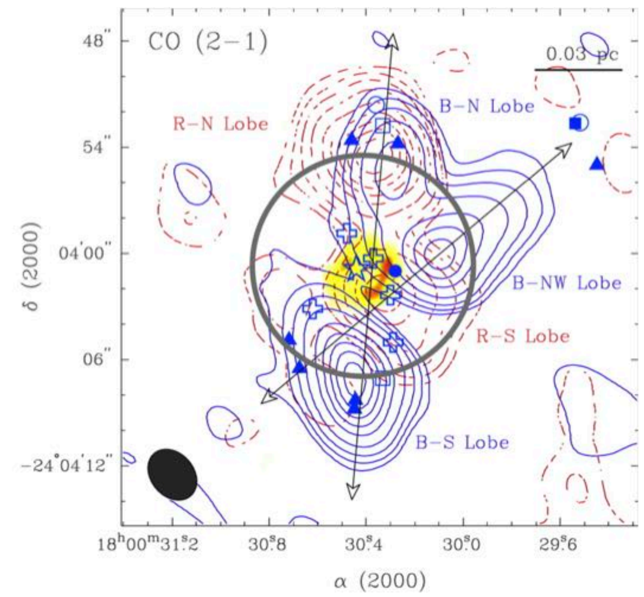
See also SOFIA observations of Cep E:
Gomez-Ruiz et al. 2012, Lefloch et al. 2015, Gusdorf et al. 2017



The need for irradiated shock models



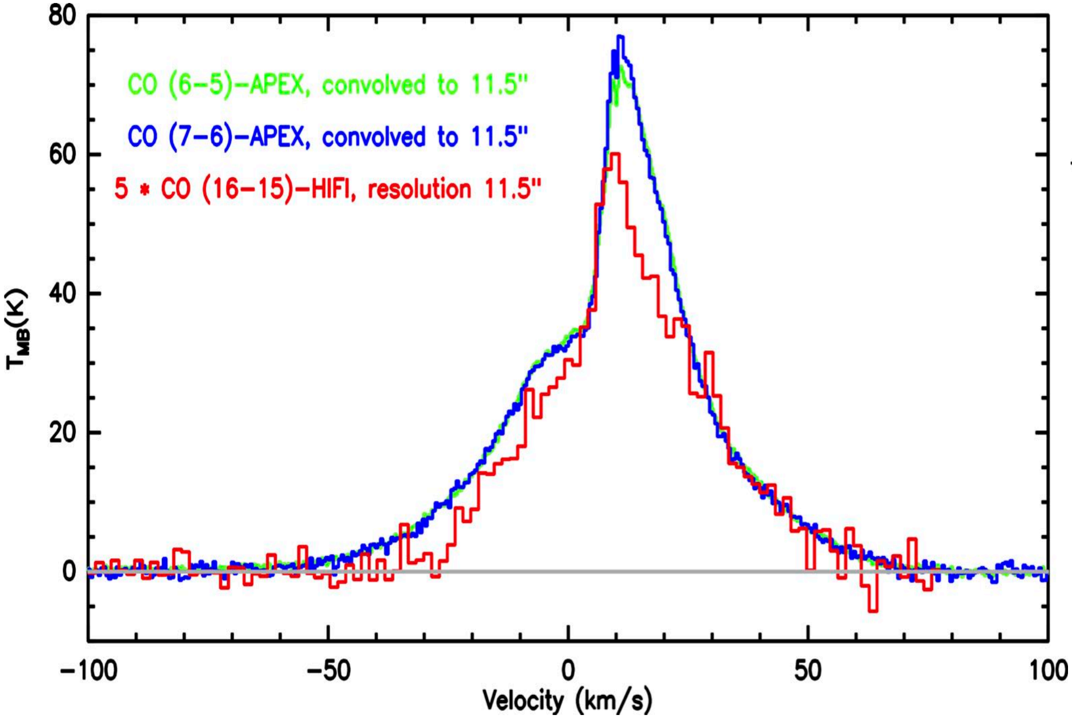
Hunter et al. 2008

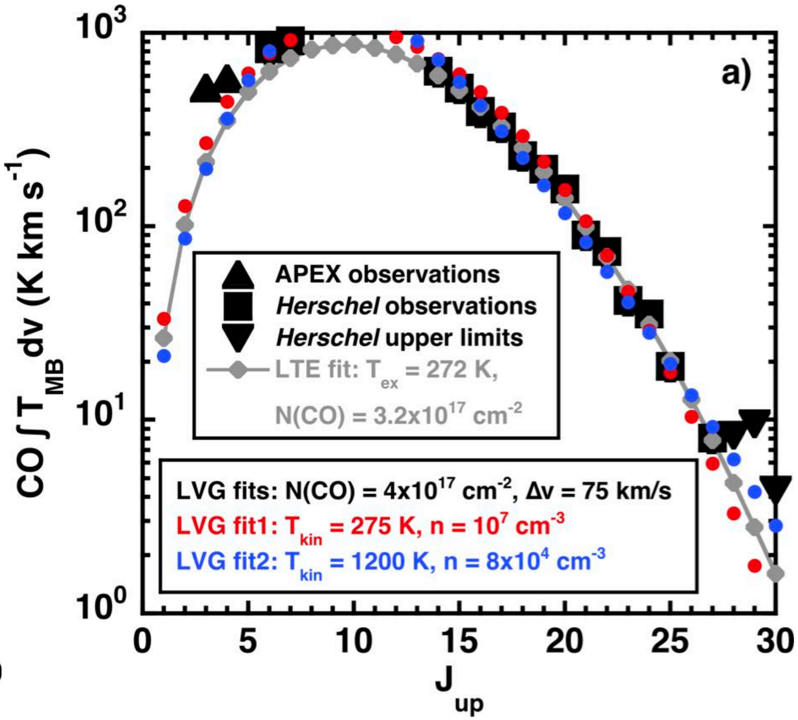


Su et al. 2012

- "The Harvey & Forveille 1988 outflow":
  - one massive O-type (imaged) star (Feld's star);
  - one UC HII region surrounded by a PDR-like cocoon, 5 continuum sources;
  - one Brγ outflow, 3 molecular outflows (seen in H_2, CO, SiO and HCO^+);
  - a collection of OH, H_2O, CH_3OH, and NH_3 maser spots

The need for irradiated shock models





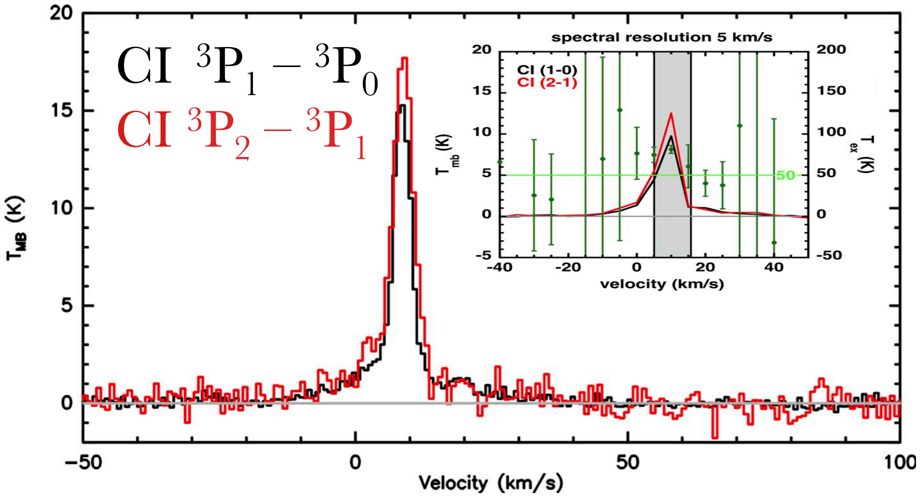
- APEX and *Herschel* (HIFI and PACS) observations of ^{12}CO and ^{13}CO

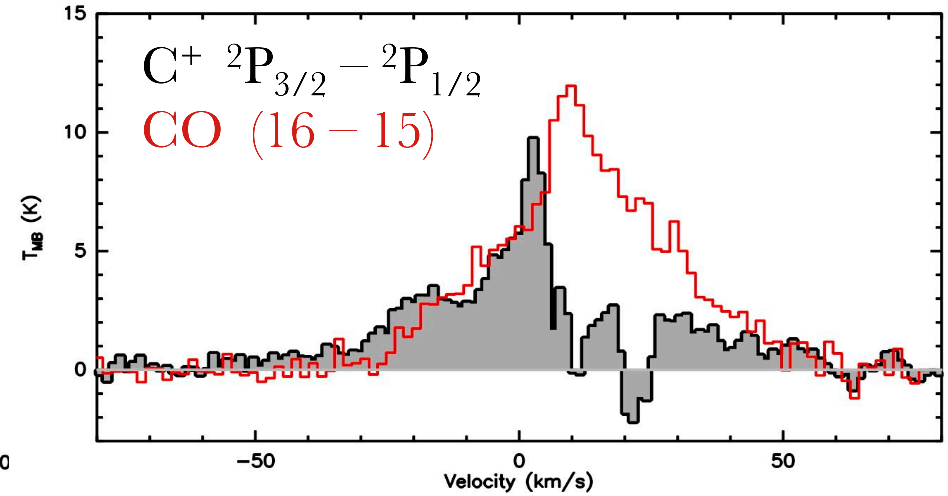
- Analysis of CO emission:
    - warm component (275 K, 10^7 cm^{-3}) or (1200 K, 10^5 cm^{-3}); N~$3 \cdot 10^{17}$ cm^{-2}
    - colder component thanks to APEX observations of ^{13}CO (3-2), (6-5):

(75 K, $6 \cdot 10^{18}$ cm^{-2})

Gusdorf et al., submitted to A&A

The need for irradiated shock models





- CI optically thin and in LTE conditions
- T_{ex} ~ 70 +/- 20 K,

N_{blue} ~ N_{red} ~ $3{\cdot}10^{17}$ cm^{-2}

=> associated to CO cold component

- CII LTE assumption
- similarity of profile with CO (16-15)

=> associated to CO warm component

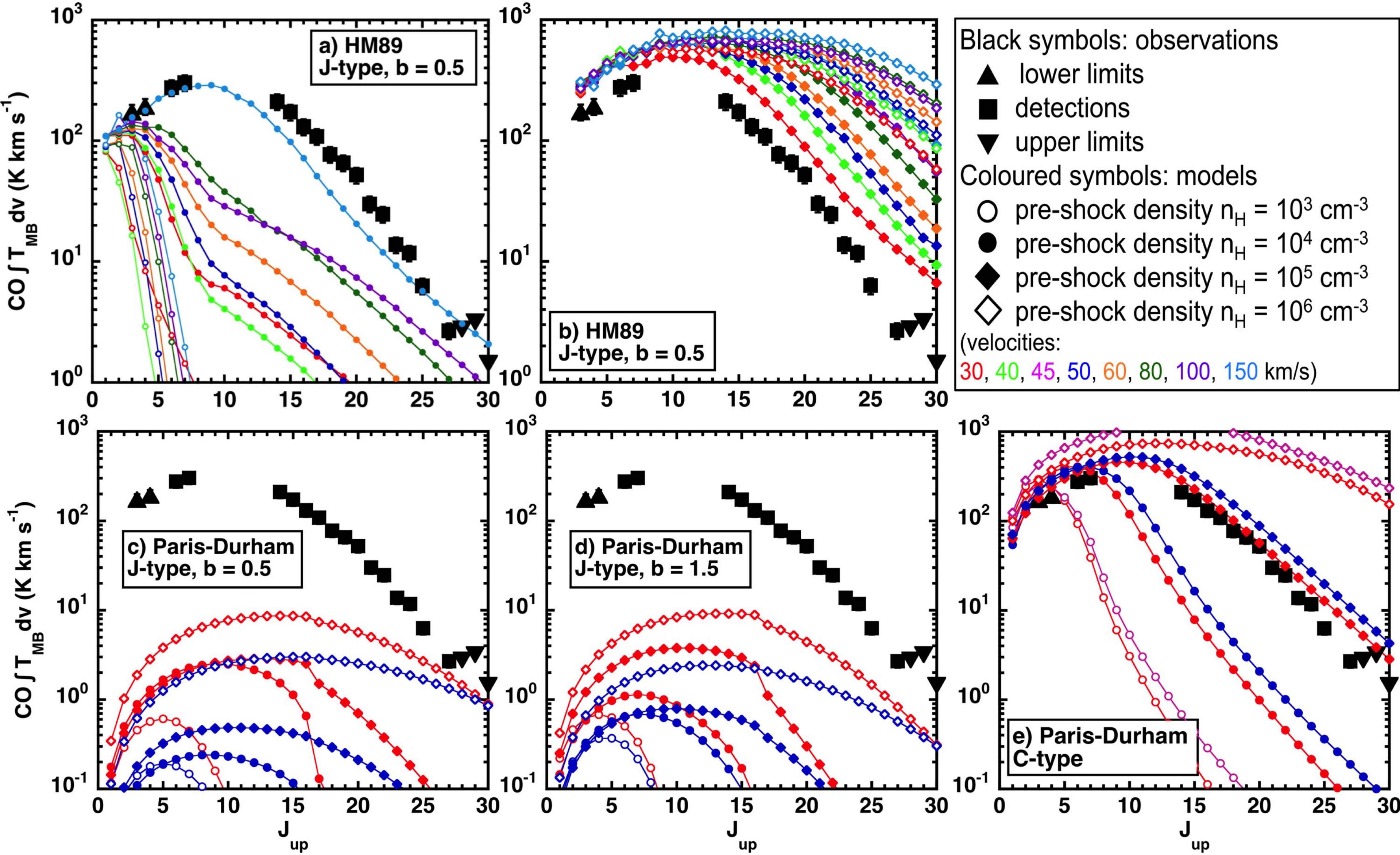
T_{ex} ~ 250 K,

N_{blue} ~ $5{\cdot}10^{17}$ cm^{-2} > N (CO)

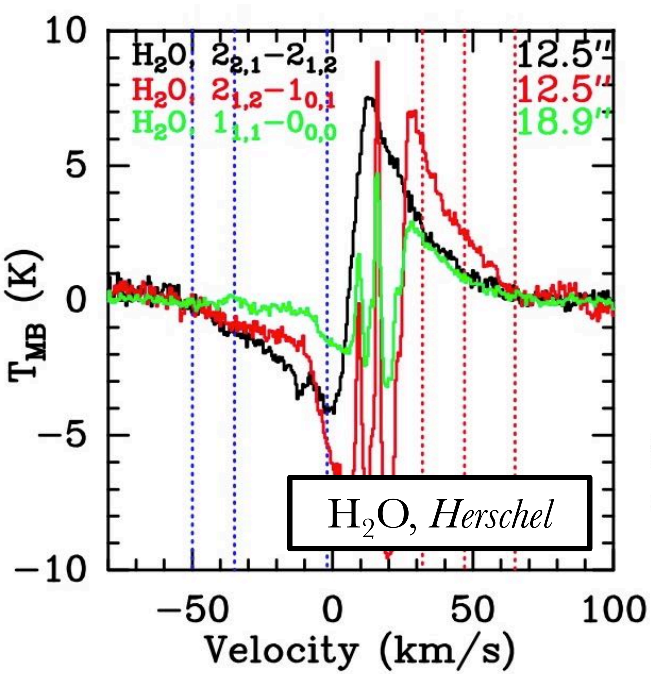
Also observed: SiO, CH^+…

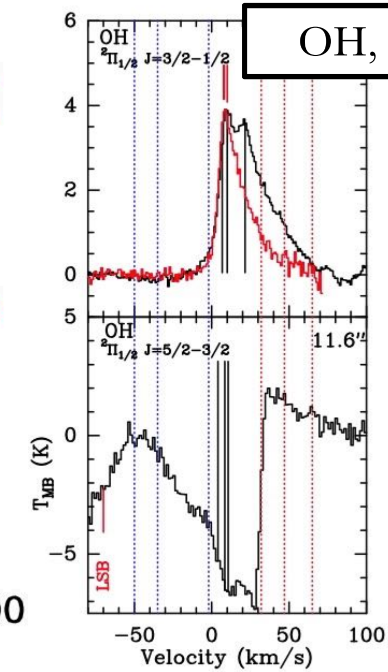
Gusdorf et al., submitted to A&A

The need for irradiated shock models

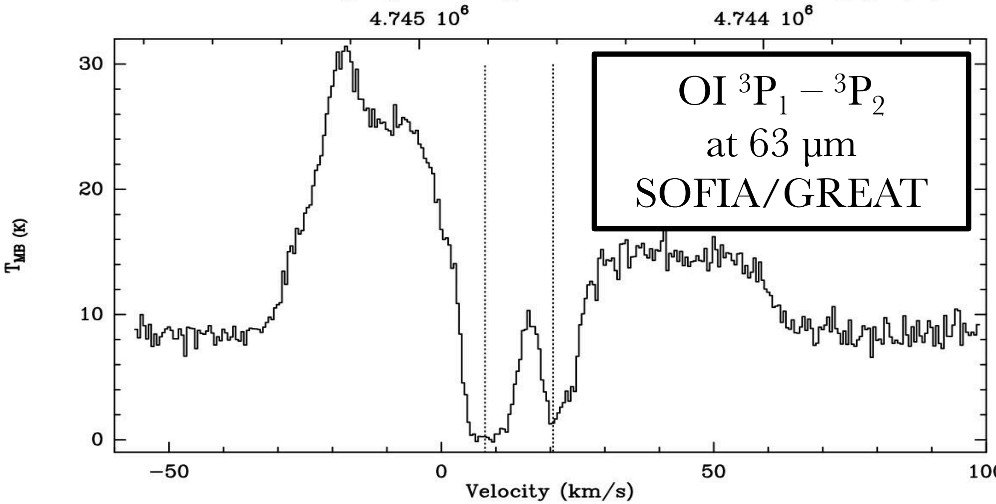


The need for irradiated shock models





	Blue-shifted wing (Δv = [−50, −2] km s^{-1})		
Species	$N_{X_{Tex}}$ (cm^{-2})	$X = \frac{N_{X_{Tex}}}{N_{CO}}$	T$_{ex}$ (K)
HF	$(2.7 \pm 0.5) \times 10^{14}$	2×10^{-3}	14
CO[a]	$(1.3 \pm 0.4) \times 10^{17}$		202
CII	$(3.6 \pm 0.8) \times 10^{18}$	28	200
OH	$(3.5 \pm 0.1) \times 10^{14}$	3×10^{-3}	10
o-H_2O (1661 GHz)	$(3.0 \pm 0.1) \times 10^{16}$	2×10^{-1}	30
o-H_2O (1669 GHz)	$(5 \pm 0.3) \times 10^{15}$	4×10^{-2}	10
	Red-shifted wing (Δv = [+32, +70] km s^{-1})		
CO[a]	$(5 \pm 2) \times 10^{16}$		208
CII	$(1.2 \pm 0.7) \times 10^{18}$	24	200
OH[b]	3×10^{14}	6×10^{-3}	>100
o-H_2O[b]	3×10^{14}	6×10^{-3}	>100
p-H_2O[b]	2×10^{14}	4×10^{-3}	>100

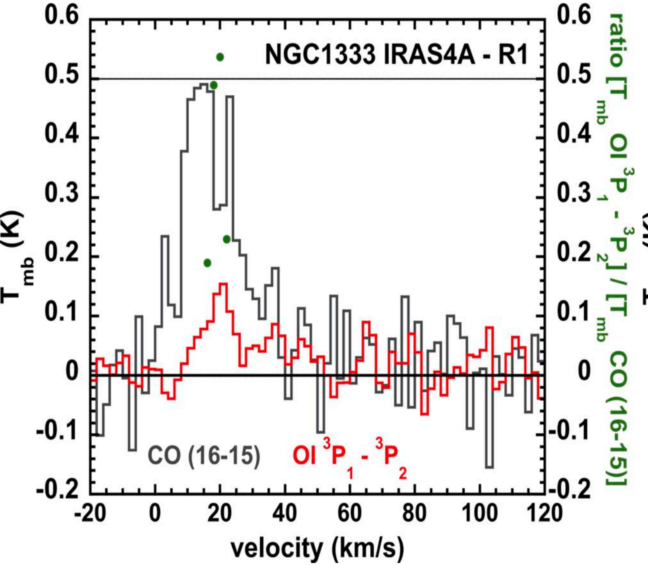


	[OI]$_{63\mu m}$ Blue	[OI]$_{63\mu m}$ Red	CO+[CI]+[CII] Blue	CO+[CI]+[CII] Red
N (10^{21} cm^{-2})	8.3	>7.5	11-22	>(6–11)
M ($M_\odot$)	0.1	>0.1	0.4–0.8	>(0.2–0.4)
Δv_{max} (km s^{-1})	50	58	50	50
t_d (yr)	400	350	760	760
P ($M_\odot$ km s^{-1})	6.1	>6.5	21–41	>(11–21)
F_m (10^{-2} $M_\odot$ km s^{-1} yr^{-1})	2	>2	2.7–5.4	>(1.5–2.7)
E_k (10^{45} erg)	3.1	>3.7	10.3–20.7	>(5.6–10.3)
L_m ($L_\odot$)	63	>89	112–224	>(61–112)

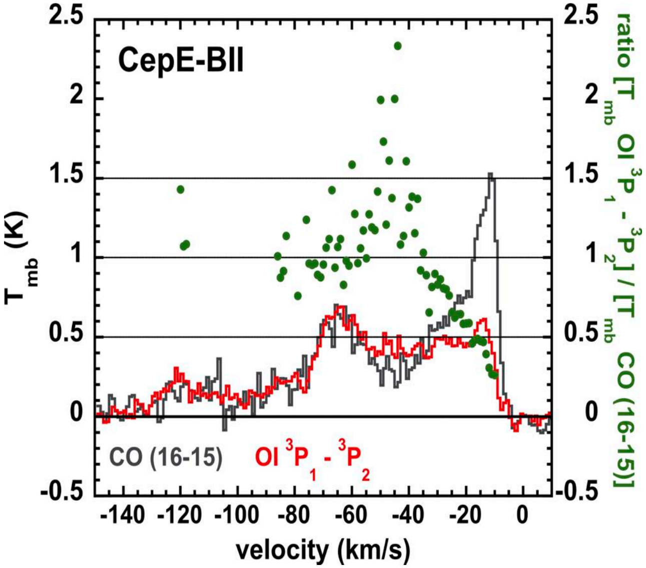
Leurini et al., 2015

The need for irradiated shock models

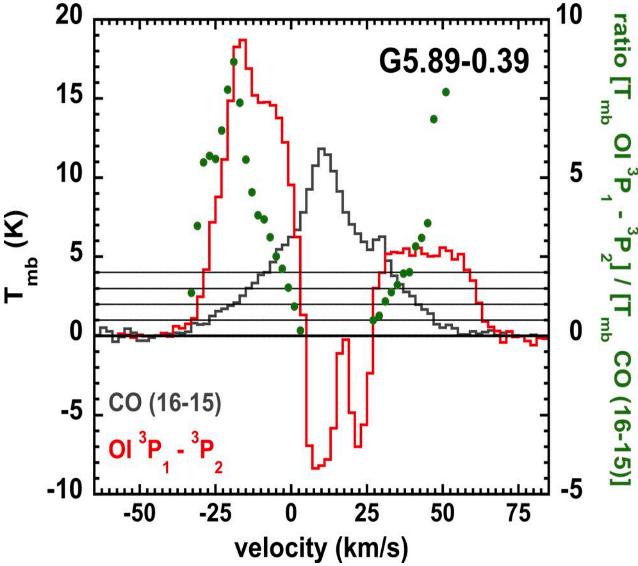
From low-mass… …to high-mass driving proto-stars



Kristensen et al., 2017



Gusdorf et al., 2017



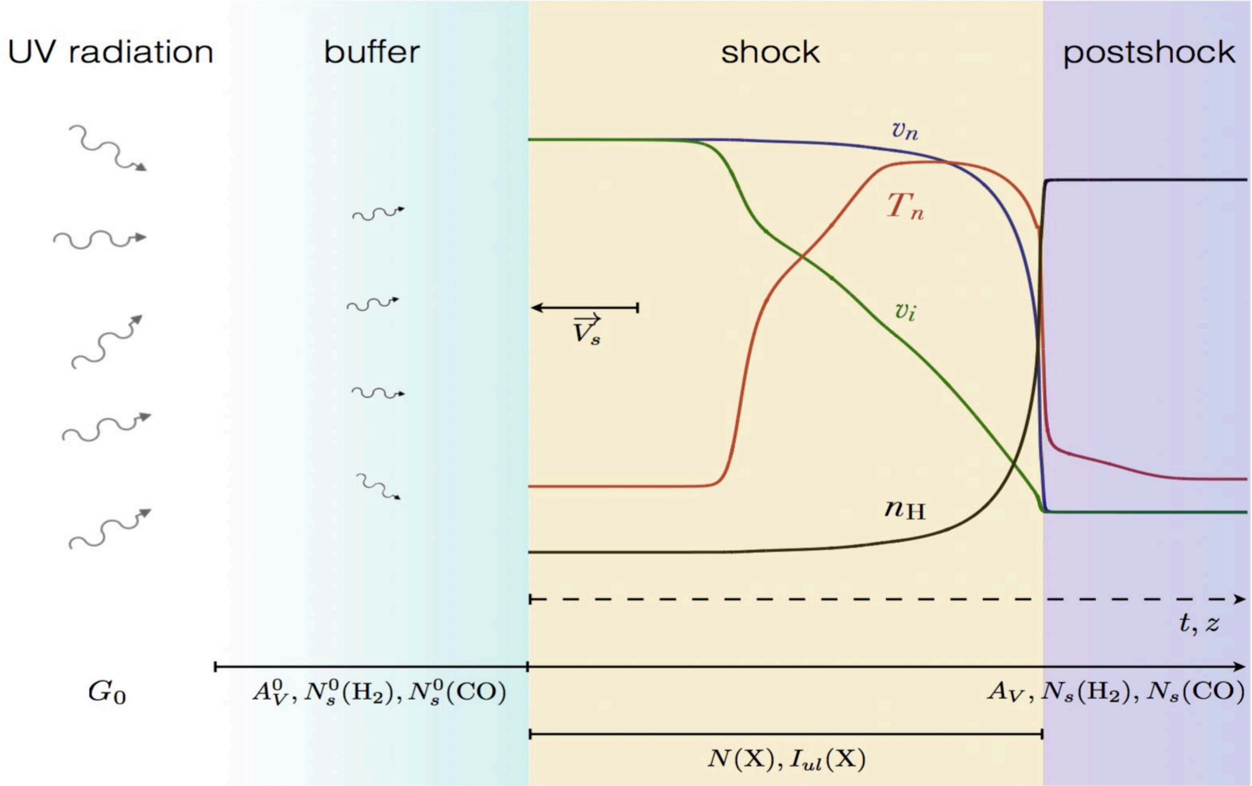
Leurini et al., 2015

Irradiated shock models

(on behalf of Benjamin Godard, Guillaume Pineau des Forêts, & Pierre Lesaffre)

References: Lesaffre et al. 2013, Godard et al., in prep.

Irradiated shocks



name	value	unit	definition
n_H	$10^2 - 10^5$	cm^{-3}	preshock proton density
G_0	$0 - 10^4$	Mathis	impinging UV radiation field
A_V^0	$10^{-6} - 10^2$		preshock visual extinction
u_{turb}	3.5	$km\ s^{-1}$	preshock turbulent velocity
ζ	3×10^{-17}	s^{-1}	H_2 cosmic ray ionization rate
u_s	$2 - 25$	$km\ s^{-1}$	shock velocity
B	$10 - 10^3$	μG	transverse magnetic field

Irradiated shocks: radiative transfer

- Absorption only; no emission/diffusion by dust/gas

- Dust absorption by spherical graphite grains
(Draine & Li 1984, Laor & Draine 1993)

- Gas absorption: only continuum processes (photodissociation and photoionization of atoms and molecules - also see chemistry below). For radiative transfer solving:
  - photodissociation of C_2, C_3, CH, OH, H_2O
  - photoionization of C, S, C_2, CH, OH, H_2O
  - potentially include cross sections available from the Leiden database and recently updated by Heays et al. (2017).

- Radiative transfer equation solved along 20 directions homogeneously spread between 0 and $\pi/2$.

Irradiated shocks: H_2

- Time-dependent calculation of the level populations of H_2

- Inelastic collisions with H, He, H_2, H^+

- Excitation of H_2 subsequent to formation on the grain surface

- Radiative pumping of H_2 electronic lines:chemistry below):
  - absorption of UV photons by the discrete lines of Werner and Lyman bands
  - subsequent cascades in rovibrational levels of the fondamental electronic state
  - line opacities that reduce the radiation field capcable of pumping the electronic states are integrated over H_2 column density using the FGK approximation

Irradiated shocks: chemical reactions

- Photo-destruction processes: absorption of photons:
  - over continuous range of energy;
  - through atomic or molecular lines at given wavelength.

- Continuum absorption processes:
  - photo-destruction cross sections when possible;
  - analytical fits provided by Heays et al. 2017 otherwise.

- Photo-dissociation of H_2 and CO: in lines, including self- and cross-shielding processes (Abgrall et al. 1992, Lee et al. 1996, Le Petit et al. 2002)

Absorption of UV photons by electronic lines of H_2 and CO, and subsequent dissociation probabilities (FGK approximation): all UV lines of Werner/Lyman bands of H_2, and pre-dissociation lines of CO.

- Include secondary photon processes

- Other updates of the gas-phase chemical network: S, N mostly (Neufeld et al. 2015, Le Gall et al. 2014)

Irradiated shocks: grains physics & chemistry

- Role in radiative transfer (see above); adsorption and erosion widths modified

- Update of desorption reactions (already existing: sputtering, CRs and 2ary):
  - thermal desorption added

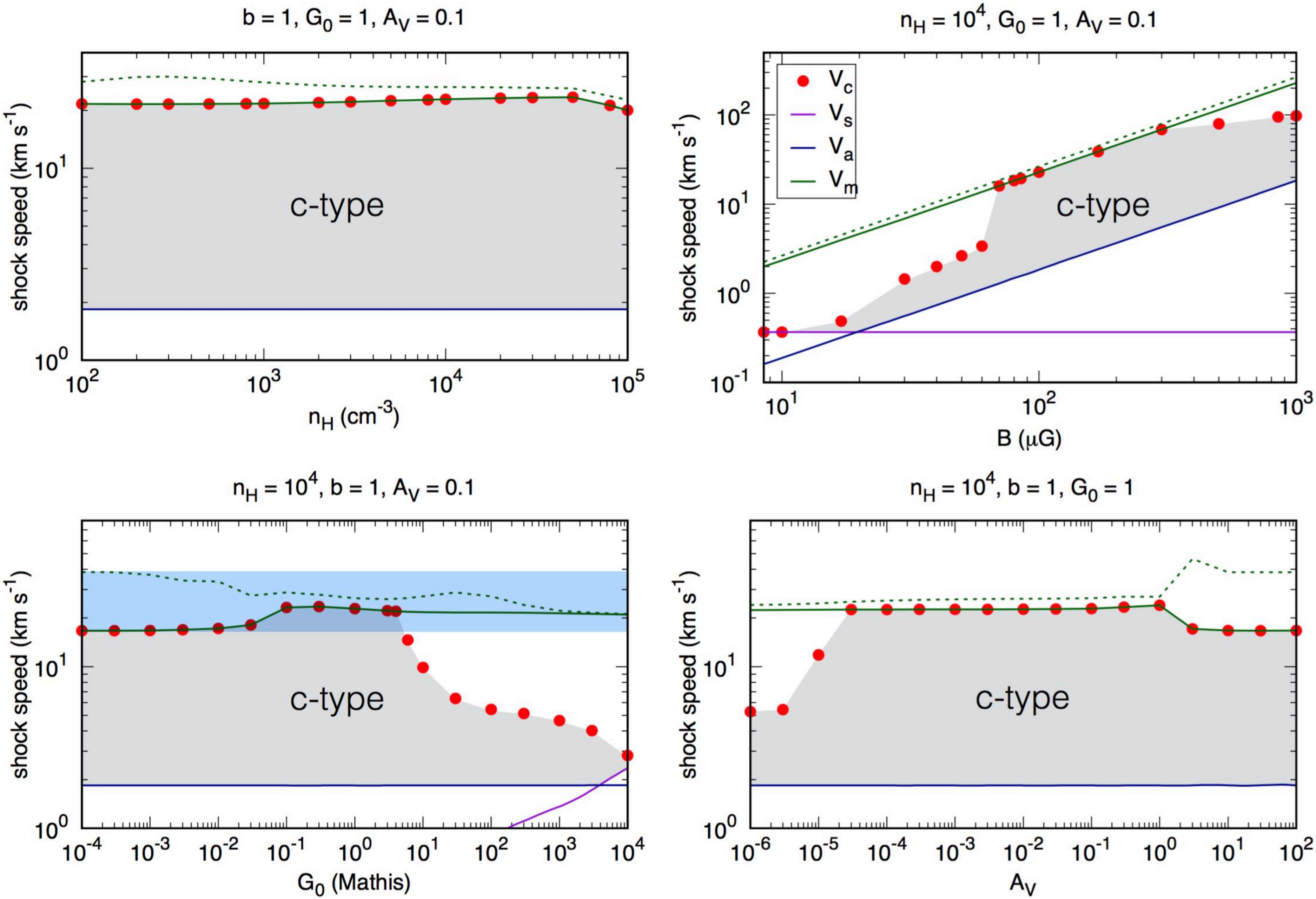
(Hollenbach et al. 2009, Hasegawa & Herbst 1993, Arikawa et al. 1996);
  - photo-desorption added;
  - desorption by secondary photons modified (Flower et al. 2007).

- Update of adsorption reactions

- Photoelectric effect on grains (already in heating, now in chemistry also, together with electron attachment and charge exchanges with ions)

Dust and charge calculation

Irradiated shocks: existence of C-type shocks



Conclusions & Perspectives

Perspectives

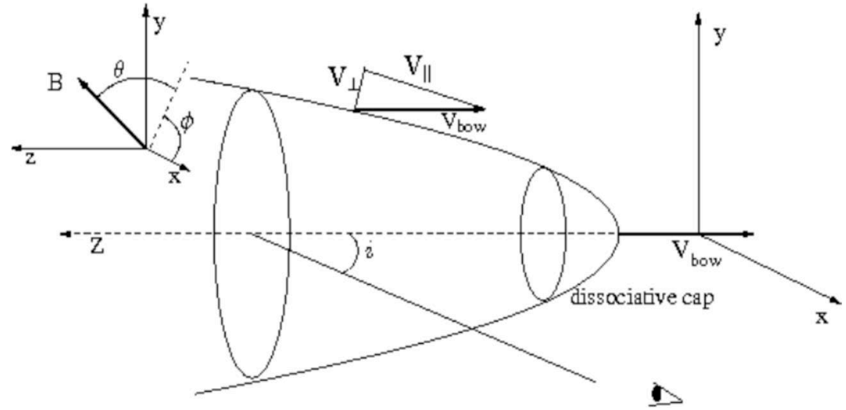
- Observable = map(s) of spectra, result of a combination of:
  - physics (temperature, density)
  - dynamics (velocity)
  - chemistry (abundances)
  - excitation (densities, illumination)
  - geometry (velocity structure, magnetic field structure)

- Our modelling efforts must aim at progressing in all these aspects !
  - grain-grain interactions for fast & dense shocks
  - **better geometrical treatment (better than 1D)**
  - fast shocks (shocks with radiative precursors)
  - crucial need for astrophysical laboratory experiments or calculations (collision and chemical reaction rates)

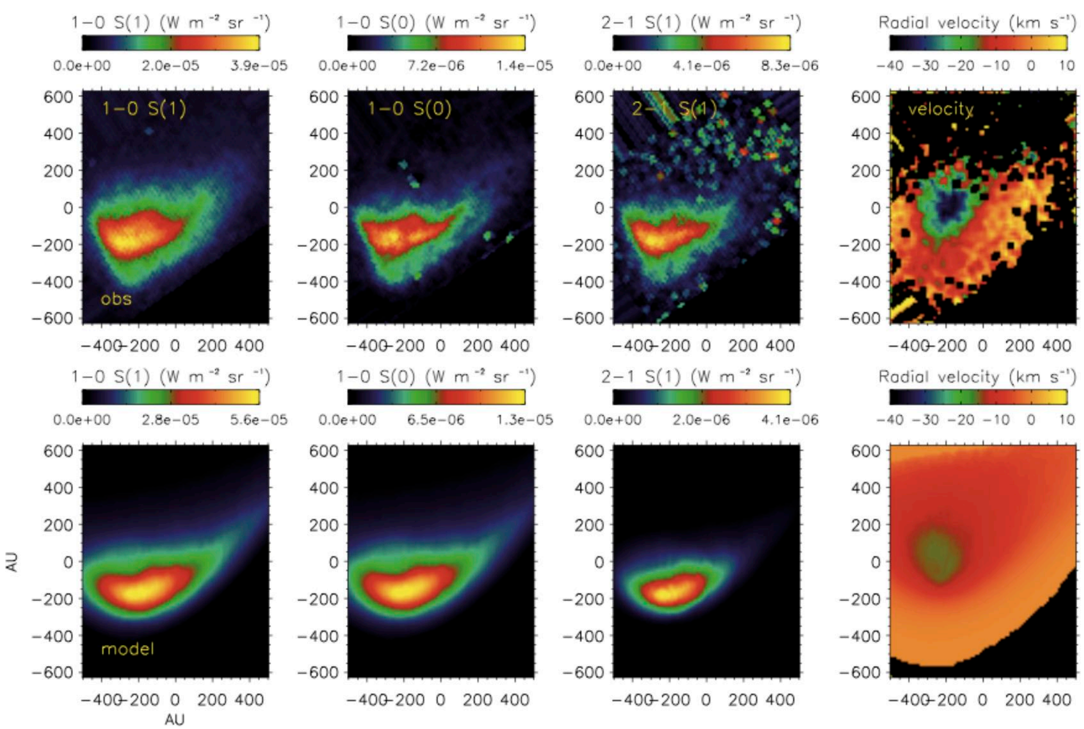
- **Develop databases**

Perspectives (1): pseudo-3D modelling

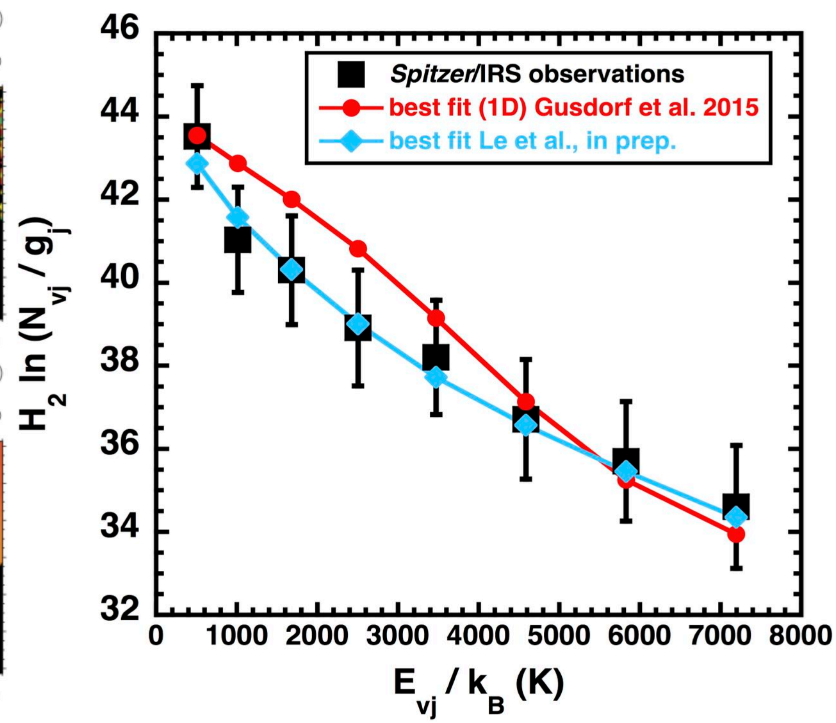
- Kristensen et al. 2008, Gustafsson et al. 2010:
  $n_H = 10^5$ cm^{-3}; v_{bow} = 50 km s^{-1};
  b = 3;
  β = 1.7; r_0 = 610 AU;
  θ = 15°; Φ = 180°; i = 50°



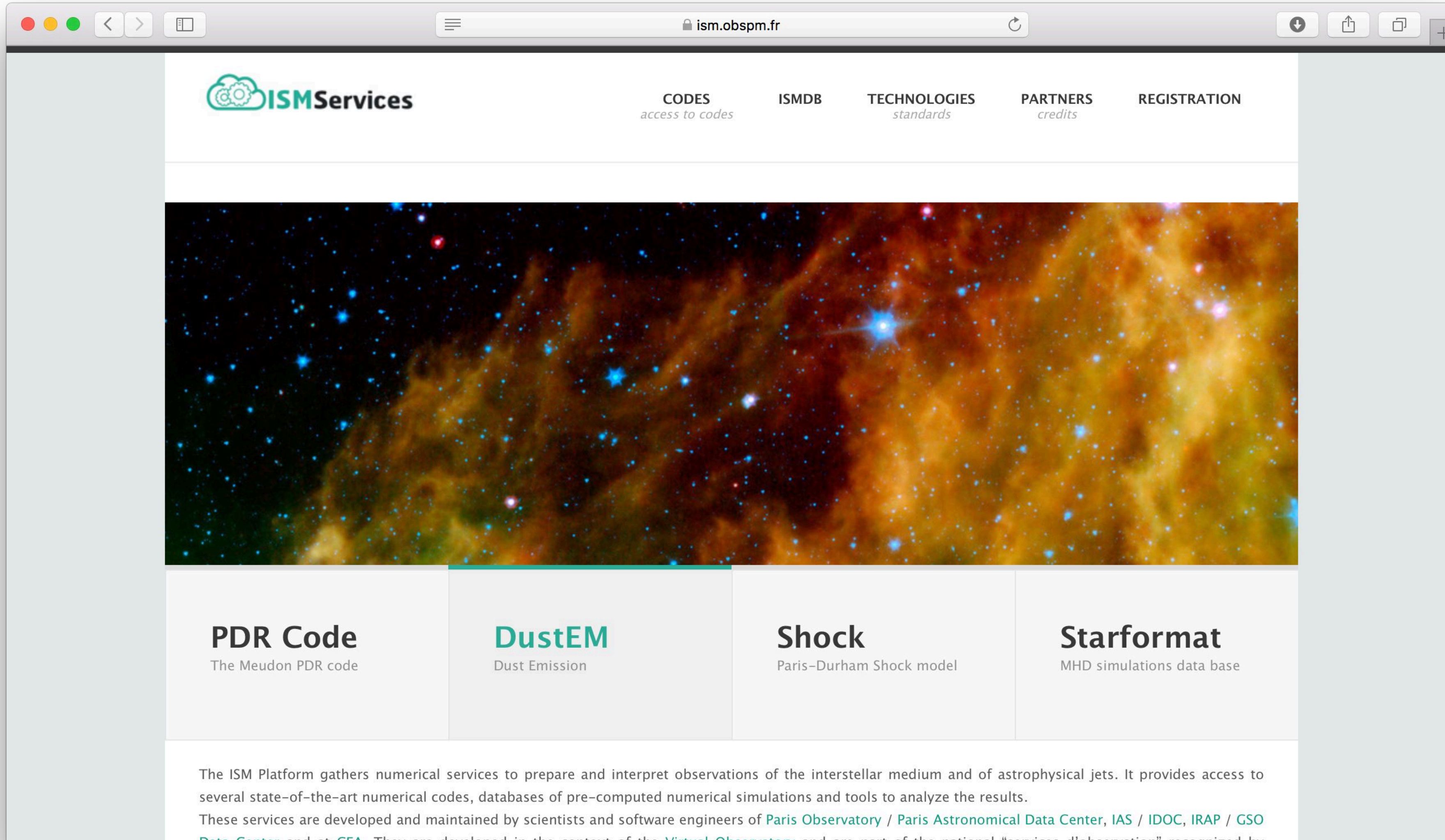
- Applied to H_2 maps of bowshock in OMC1



- Applied to H_2 Excitation diagram in BHR71 (Le et al., in press)



Perspectives (2): databases, search methods



https://ism.obspm.fr

Perspectives (2): databases, search methods

app.ism.obspm.fr

ISMServices CODES ISMDB PARTNERS REGISTRATION

Help Contact

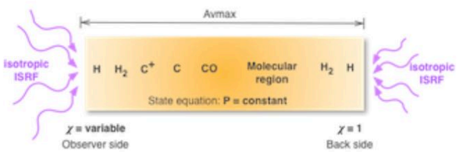
ISM DataBase – Inverse Search service Beta

Grid of isobaric PDR 1.5.2 models *(2016-12-03)*

code: PDR 1.5.2 rev 1714

Parameters

gas_pressure_input: from 1E5 to 1E9 (K cm-3)
avmax: from 1.0 to 40.0 (mag)
radm_ini: from 1.0 to 1E5 (Mathis unit)



Description

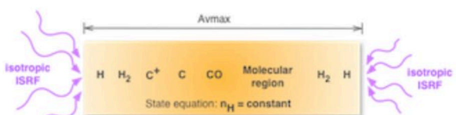
This grid of isobaric PDR 1.5.2 models (revision 1714) covers photo-dominated regions conditions. Explored parameters are thermal pressure, UV field intensity and size of the clouds. The full grid contains 1372 2-side models where the back side of the cloud is submitted to the ISRF.
The chemistry takes into account 222 species, including C and O isotopes, linked by 6243 chemical reaction. No surface reactions are considered excepted for H2. H2 formation model takes into account Eley-Rideal and Langmuir-Hinshelwood mechanisms as described in Le Bourlot et al. (2012).
These models give access to all quantities computed by PDR 1.5.2 (line intensities, column densities, densities, temperature of gas and grains, ...).

Grid of isochoric PDR 1.5.2 models *(2017-02-17)*

code: PDR 1.5.2 rev 1787

Parameters

avmax: from 1.0 to 30.0 (mag)
proton_density_input: from 1E2 to 1E8 (cm-3)



http://ismdb.obspm.fr

Thanks for your attention !