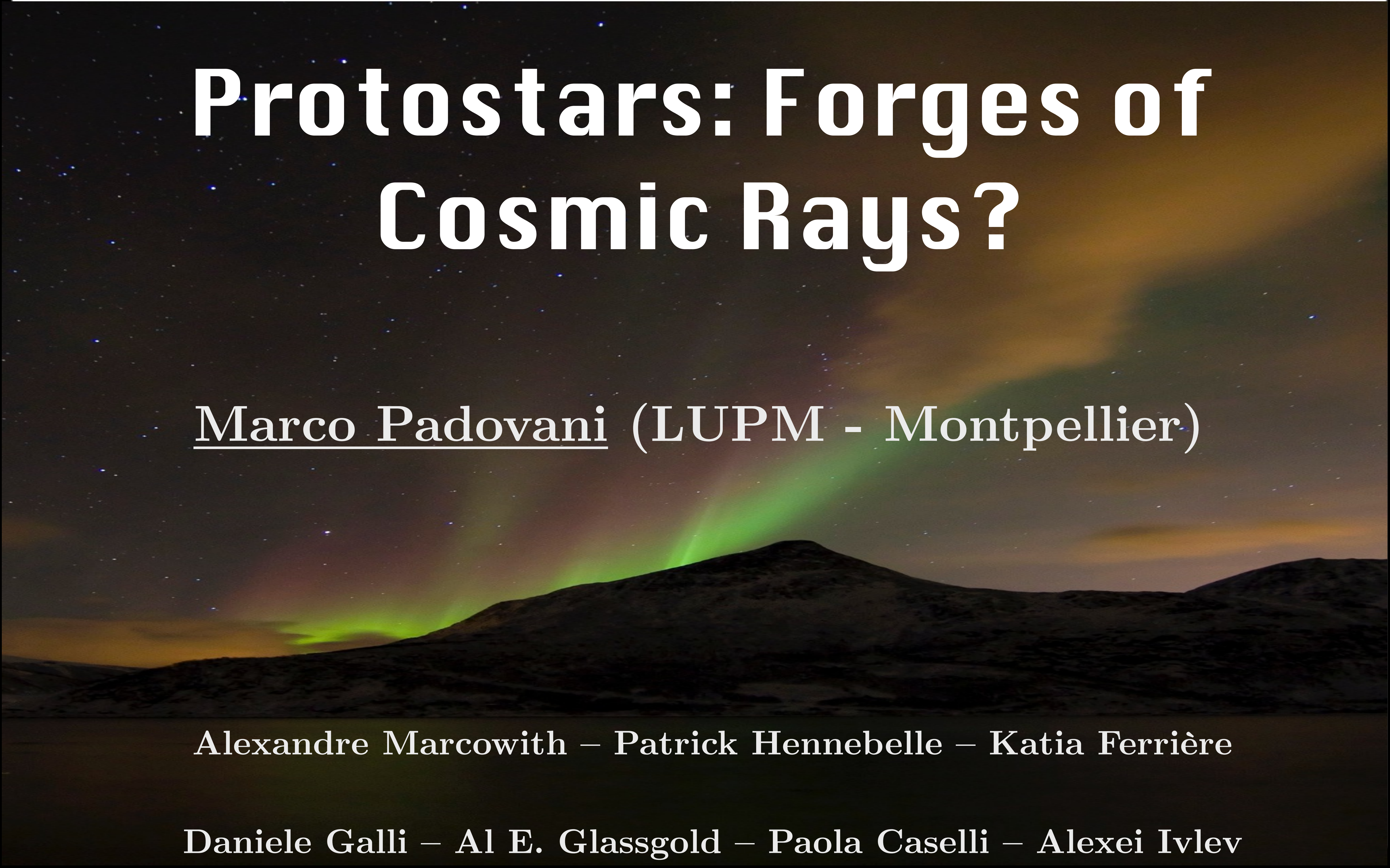
OCEVU-WG Astro Workshop

IRAP - Toulouse, *Mar 22th 2016*



Protostars: Forges of Cosmic Rays?

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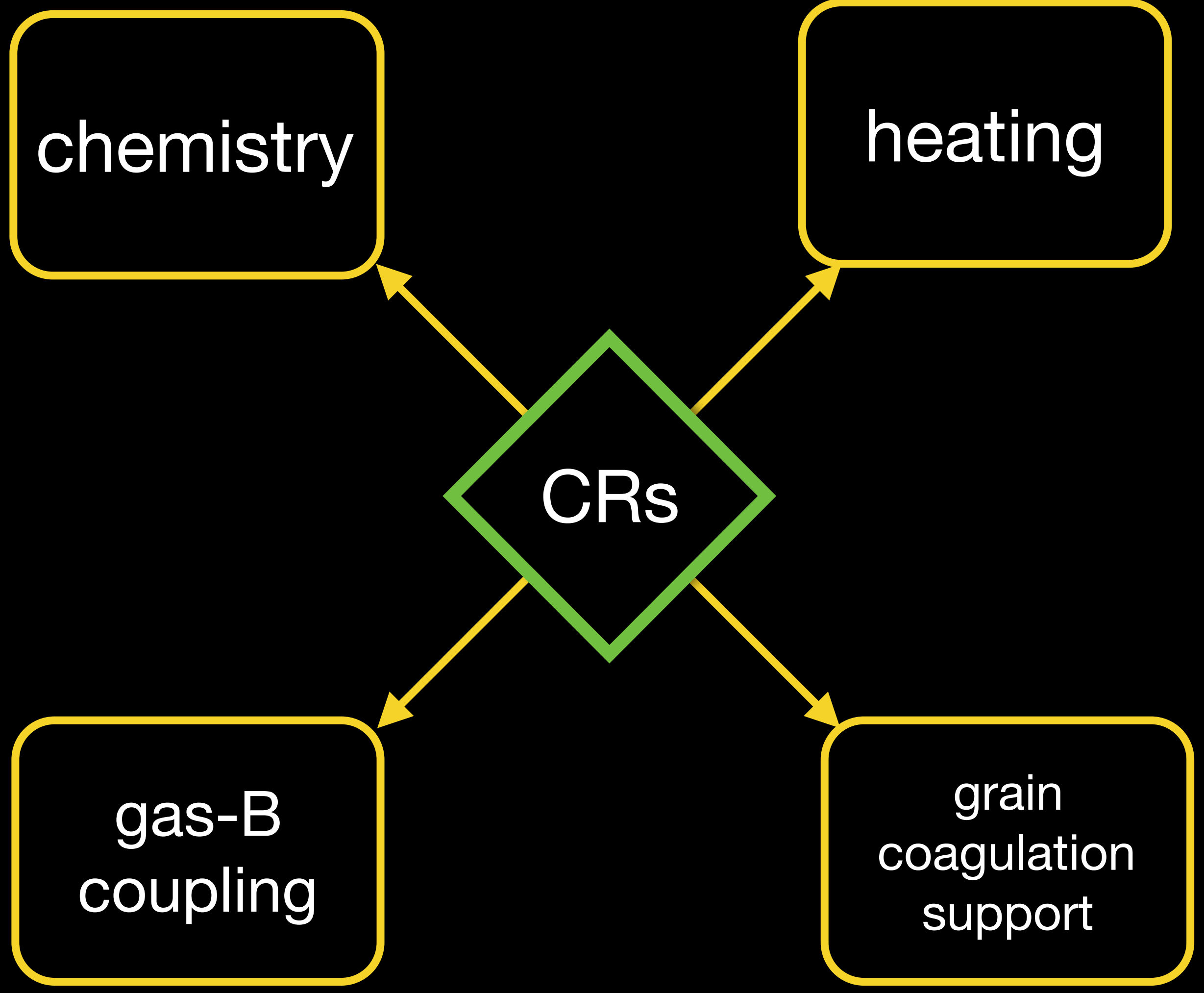
Alexandre Marcowith – Patrick Hennebelle – Katia Ferrière

Daniele Galli – Al E. Glassgold – Paola Caselli – Alexei Ivlev

Cosmic rays and interstellar medium in one slide



see e.g. Caselli & Ceccarelli (2012) for a recent review

Glassgold & Langer (1973)
Cravens & Dalgarno (1978)
Dalgarno+ (1999)
Glassgold+ (2012)
Galli & Padovani (2015)

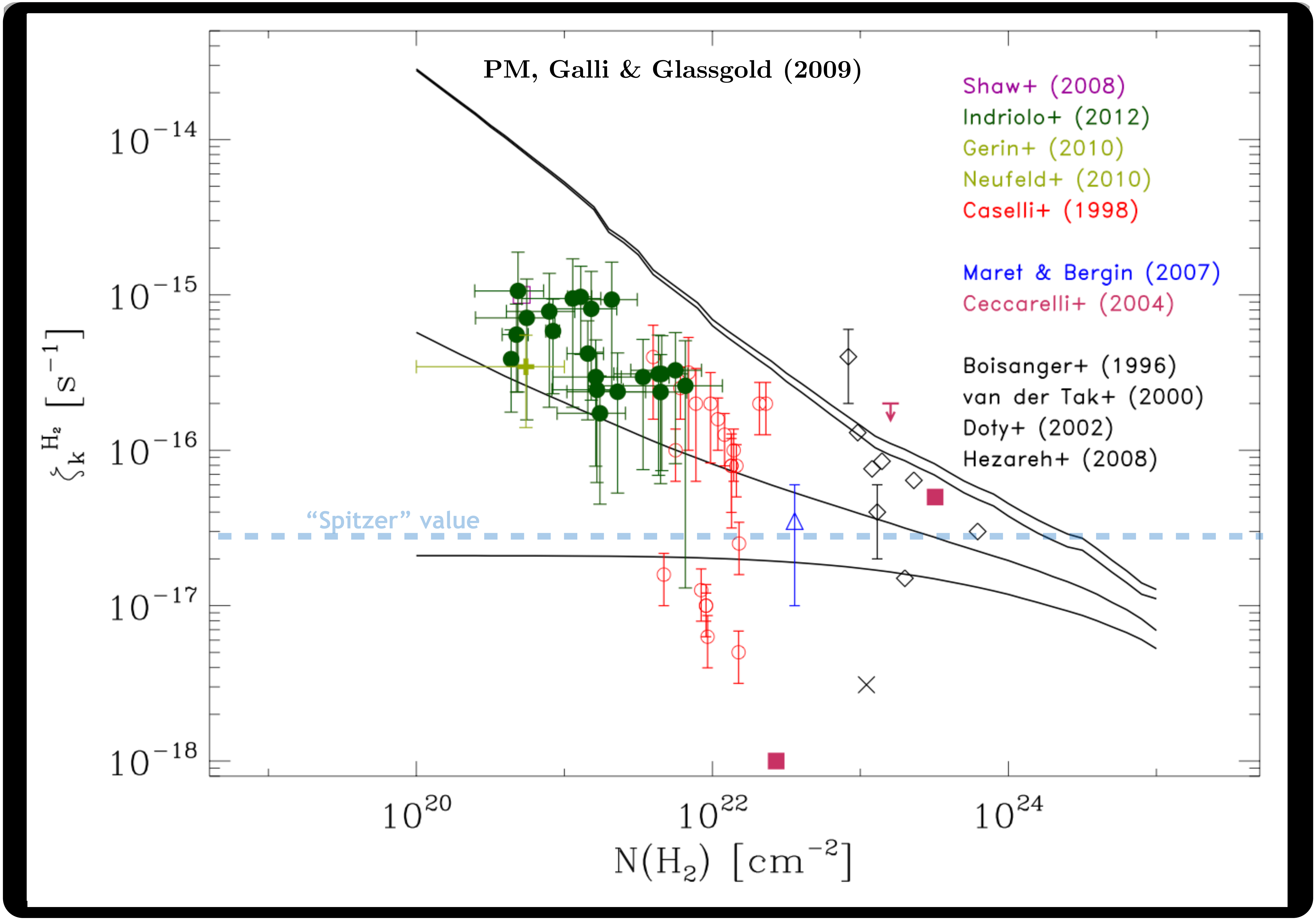
Nakano+ (2002)
Padovani+ (2013,2014)

Prasad & Tarafdar (1983)
Cecchi-Pestellini & Aiello (1992)
Shen+ (2004)
Ivlev+ (2015)

$$\zeta\ [\mathrm{s}^{-1}] \longrightarrow$$

key-brick parameter:

— observed molecular abundances;
— chemical models;
— non-ideal MHD simulations.


PM, Galli & Glassgold (2009)
Shaw+ (2008)
Indriolo+ (2012)
Gerin+ (2010)
Neufeld+ (2010)
Caselli+ (1998)
Maret & Bergin (2007)
Ceccarelli+ (2004)
Boisanger+ (1996)
van der Tak+ (2000)
Doty+ (2002)
Hezareh+ (2008)
“Spitzer” value
$\zeta_k^{H_2}$ [s^{-1}]
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{20}
10^{22}
10^{24}
$N(H_2)$ [cm^{-2}]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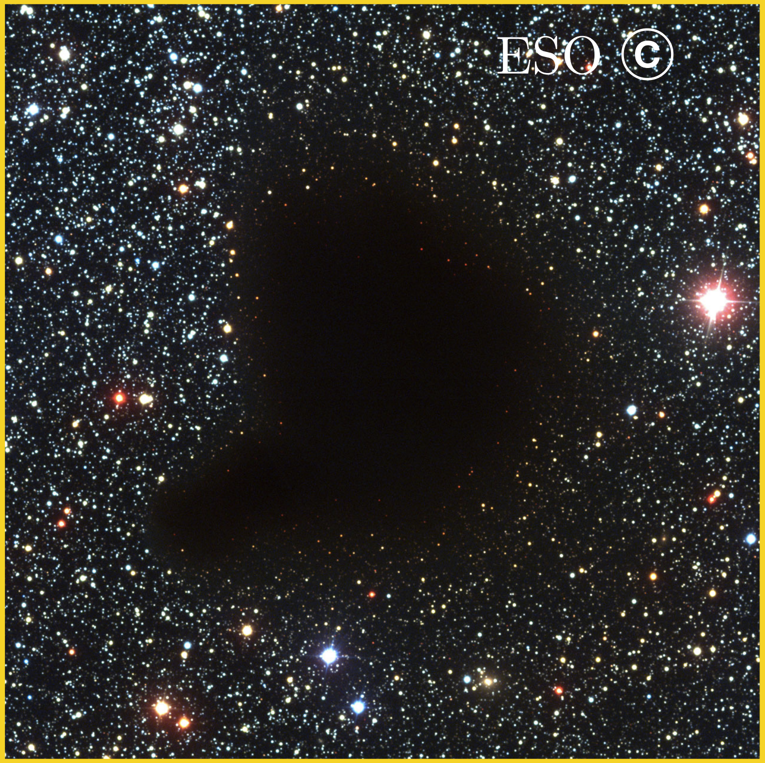
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$\approx 10^{-19}$ 10^{-17} 10^{-15}

10^{-22} 10^{-18} 10^{-16}

$\zeta\ [\mathrm{s}^{-1}]$

protostar

set by decay of short- and
long-lived radionuclei
Cleeves+ 2013; 2015

dense

$\mathbf{HCO^+, DCO^+}$

Guélin+ 1977
Caselli+ 1998
Maret & Bergin 2007

diffuse

$\mathbf{H_3^+, OH^+, H_2O^+}$

McCall+ 1993; Geballe+ 1999;
McCall+ 2003; Indriolo+ 2009,2012,2015
Gerin+ 2010; Neufeld+ 2010

New results from IRAM-30m, Herschel & GMRT

Recent studies suggest unexpected high ionisation rates in Class 0/I protostars

- **$\zeta \sim 3\times10^{-16}$ s^{-1} in L1157-B1**
(Podio, Lefloch, Ceccarelli, Codella & Bachiller 2014);

- **$\zeta \sim 4\times10^{-14}$ s^{-1} and 8×10^{-12} s^{-1} in OMC-2 FIR 4**
(Ceccarelli, Dominik, López-Sepulcre, Kama, Padovani, Caux & Caselli 2014);

and tentative evidence for synchrotron emission

- **$S_\nu \propto \nu^{-0.89\pm0.07}$ in the bow shock of DG Tau;**
(Ainsworth, Scaife, Ray, Taylor, Green & Buckle 2014);

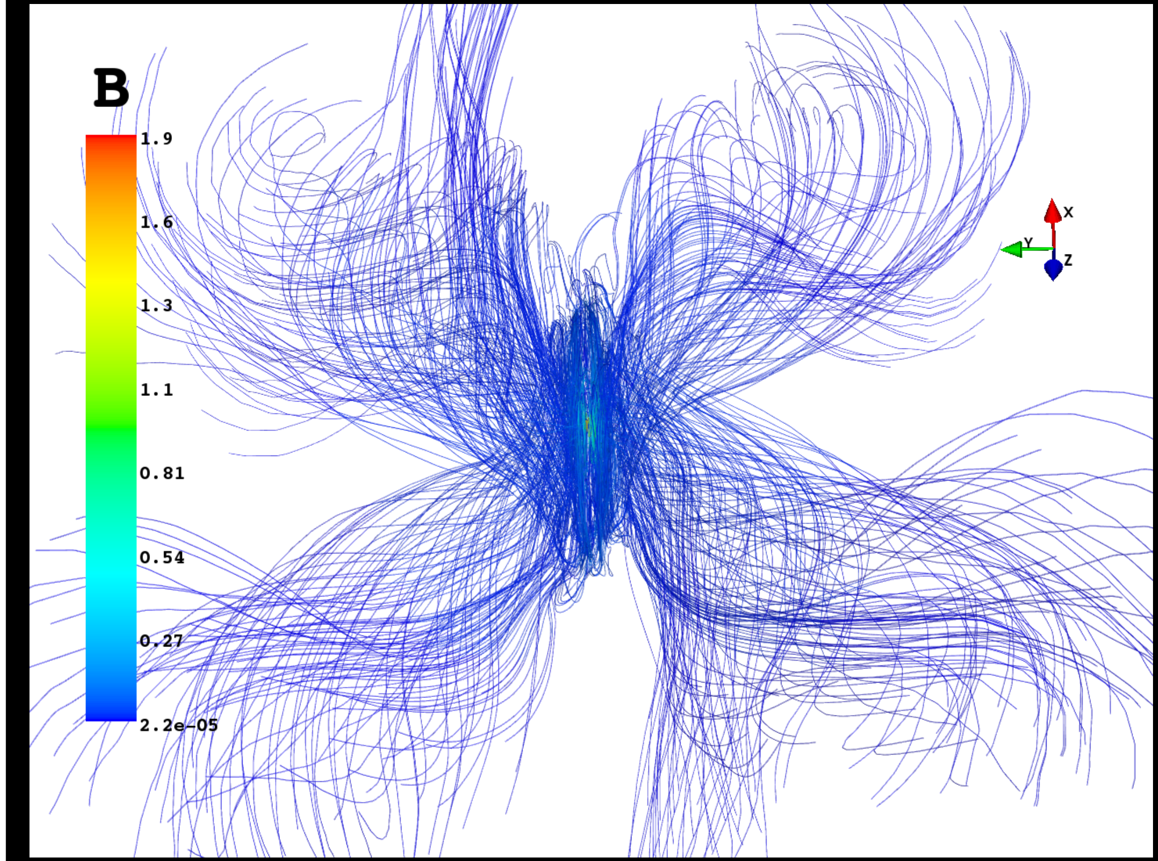
What are the possible sources of energetic particles?

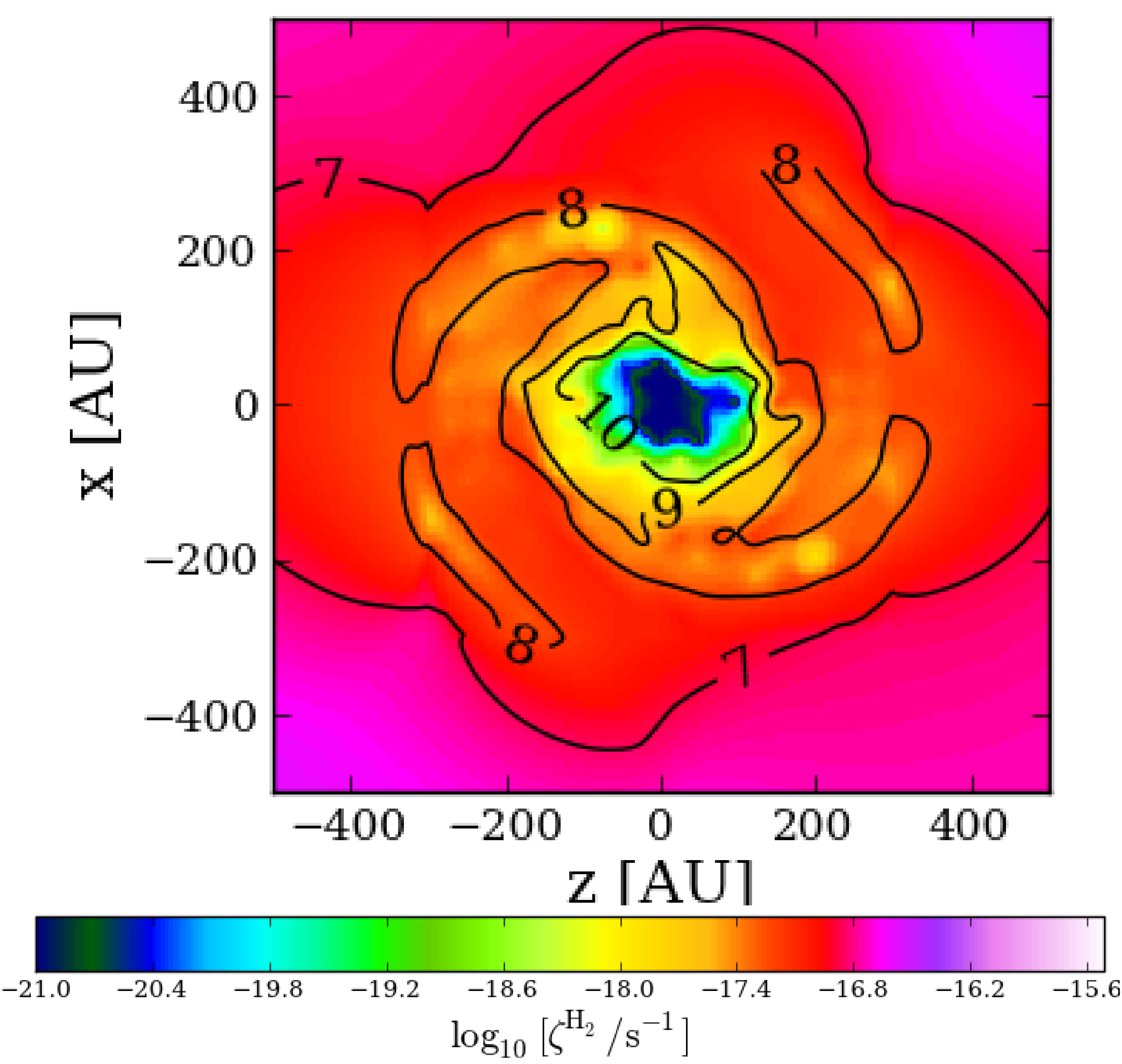
CR propagation in 3D simulations of collapsing rotating core

Intermediate magnetisation λ=5

Perpendicular rotator (**J**,**B**)=π/2

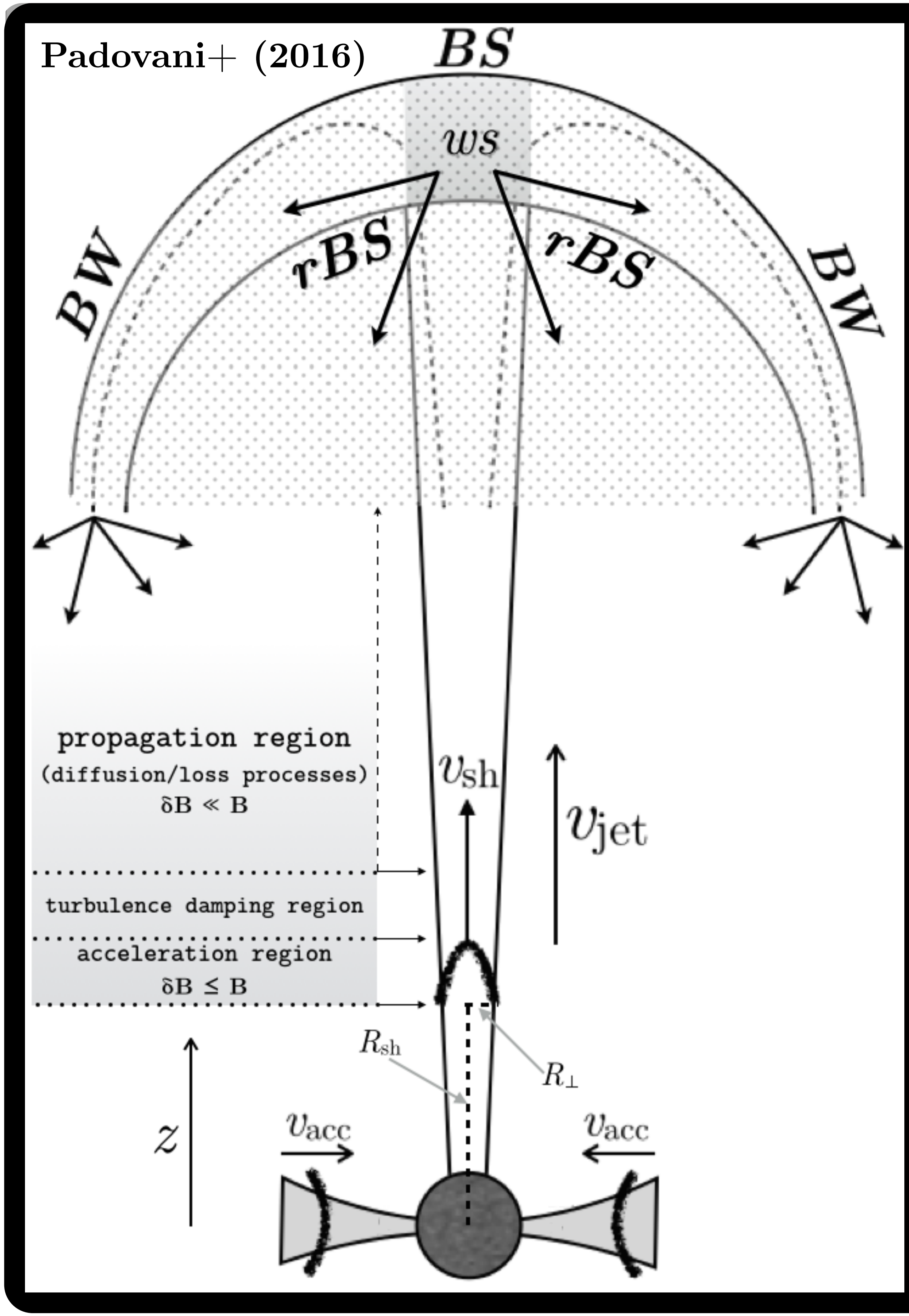
Field lines in the inner 600 AU





PM, Hennebelle & Galli (2013)

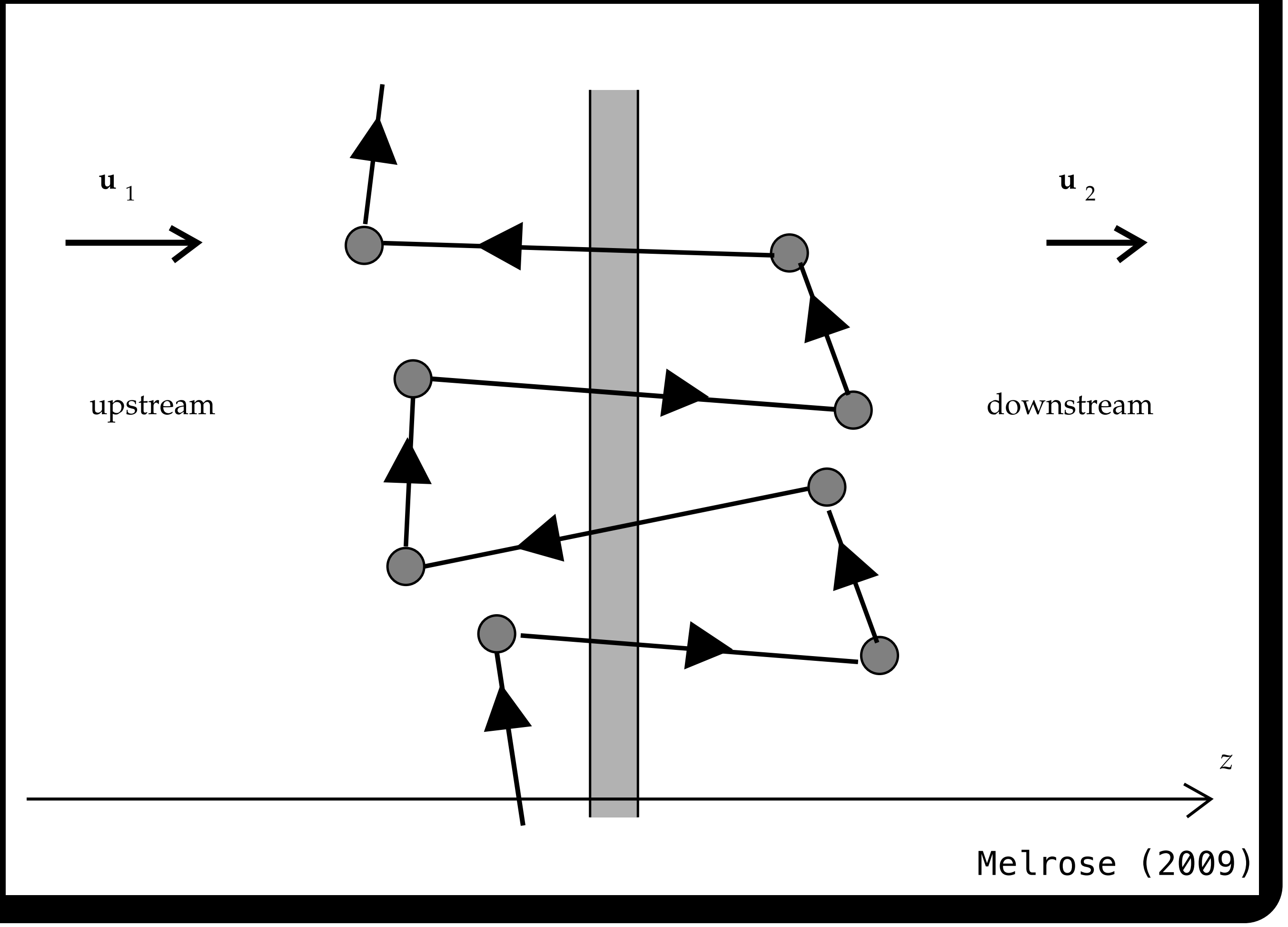
Padovani+ (2016)



Acceleration sites

(1) accretion flows;
(2) protostellar surface;
(3) jet shock;

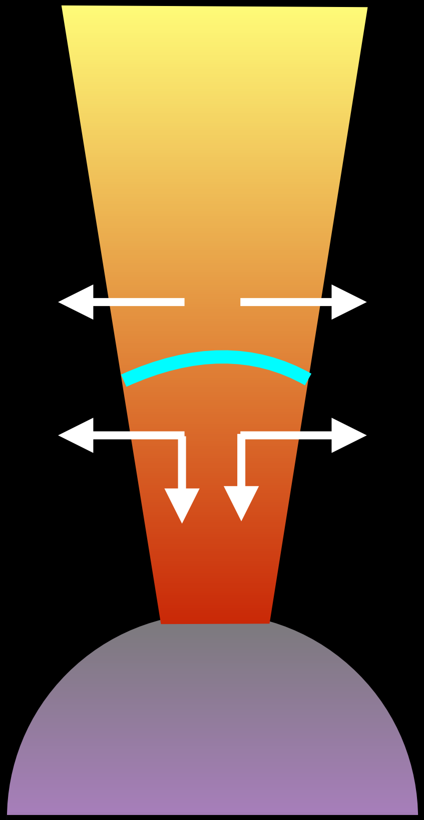
Diffusive Shock Acceleration (DSA) or
First-order Fermi acceleration



Melrose (2009)

Conditions to be fulfilled

Condition on flow velocity: **supersonic** and **super-Alfvénic**.



(1) shock **acceleration rate larger** than **collisional loss rate**;

$$E^{\rm max}_{\rm loss}$$

(2) **acceleration time shorter** than **dynamical time**;

$$E^{\rm max}_{\rm age}$$

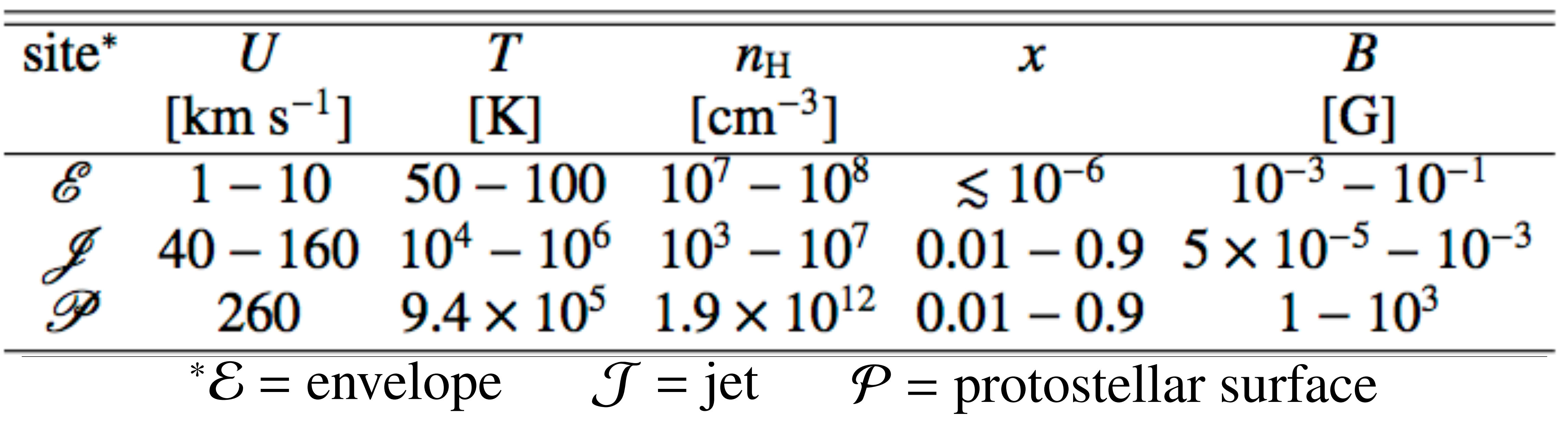
(3) **shock geometry**: particles have to be accelerated before they start to escape by diffusion processes.

$$E^{\rm max}_{\rm esc} = \min[E^{\rm max}_{\rm esc,u}, E^{\rm max}_{\rm esc,d}]$$

Presence of an ***incomplete ionised medium***: neutrals can decrease the effectiveness of the DSA mechanism damping the particle's self-generated Alfvén waves that are responsible of the particle scattering back and forth the shock (Drury+ 1996);

$$E^{\rm max} = \min[E^{\rm max}_{\rm loss}, E^{\rm max}_{\rm age}, E^{\rm max}_{\rm esc}, E^{\rm max}_{\rm damp}]$$

Parameters needed for the model



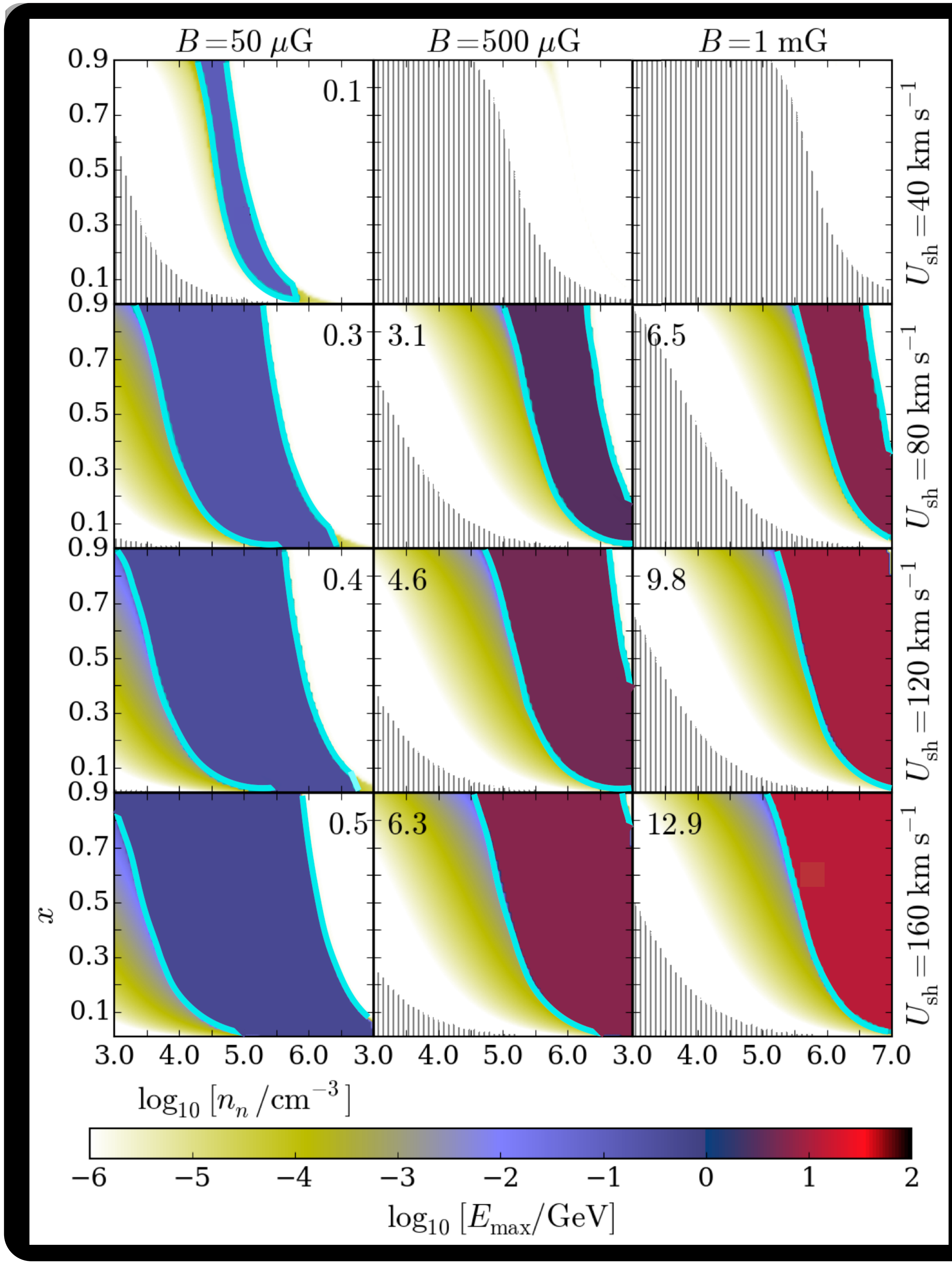
site*	U [km s^{-1}]	T [K]	$n_{\rm H}$ [cm^{-3}]	x	B [G]
$\mathscr{E}$	$1-10$	$50-100$	10^7-10^8	$\lesssim 10^{-6}$	$10^{-3}-10^{-1}$
$\mathscr{J}$	$40-160$	10^4-10^6	10^3-10^7	$0.01-0.9$	$5\times10^{-5}-10^{-3}$
$\mathscr{P}$	260	9.4×10^5	1.9×10^{12}	$0.01-0.9$	$1-10^3$

$^*\mathcal{E}$ = envelope $\mathcal{J}$ = jet $\mathcal{P}$ = protostellar surface

Refs: U_{sh} (Raga+ 2002,2011; Hartigan & Morse 2007; Agra-Amboage+ 2011);
T (Frank+ 2014);
$n_{\rm H}$ (Lefloch+ 2012; Gómez-Ruiz+ 2012);
x (Nisini+ 2005; Podio+ 2006; Antoniucci+ 2008; Garcia López+ 2008; Dionatos+ 2010; Frank+ 2014; Maurri+ 2014);
B (Tesileanu+ 2009, 2012)
For protostellar surface shock, parameters from Masunaga & Inutsuka (2000)

- DSA works *only* for protons (electrons lose energy too fast, $E^{max}(e)<300$ MeV);

- DSA is effective *only* in jet and protostellar surface shocks (in accretion flows, x and U_{sh} are too small, quenching the particle acceleration; B is as large as to produce a sub-Alfvénic shock).



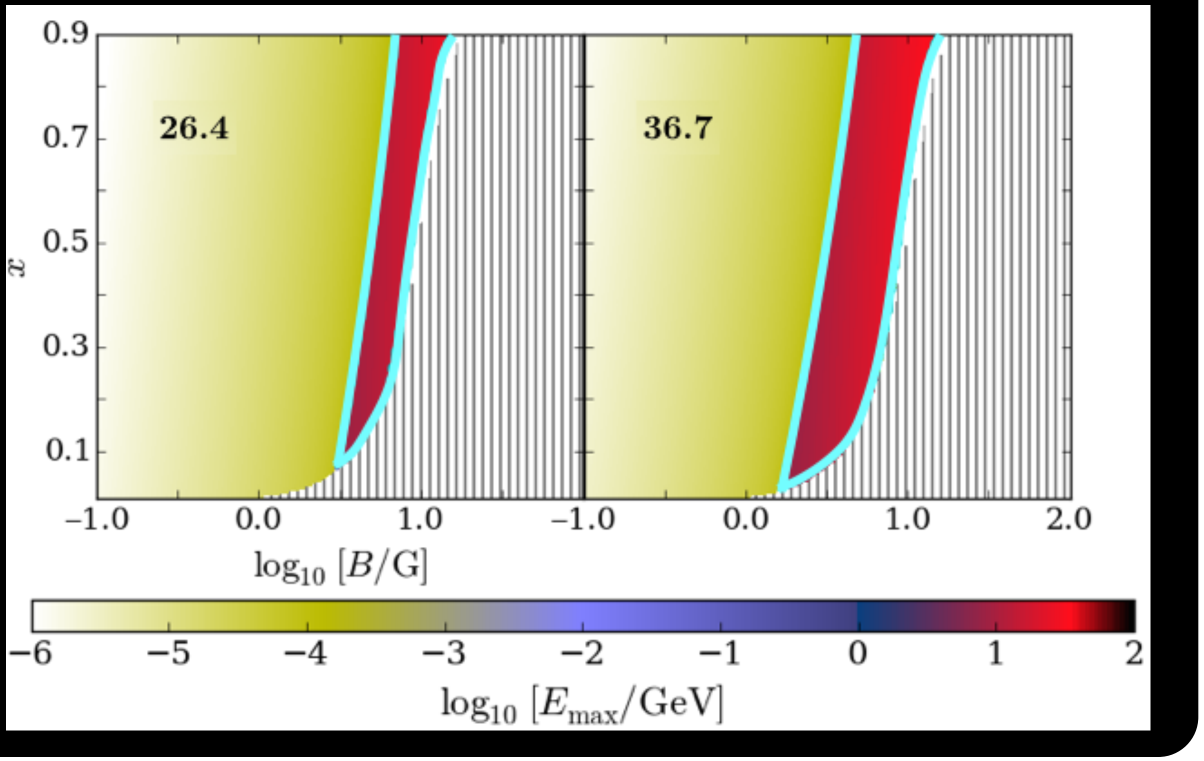
PM, Hennebelle, Marcowith & Ferrière (2015)

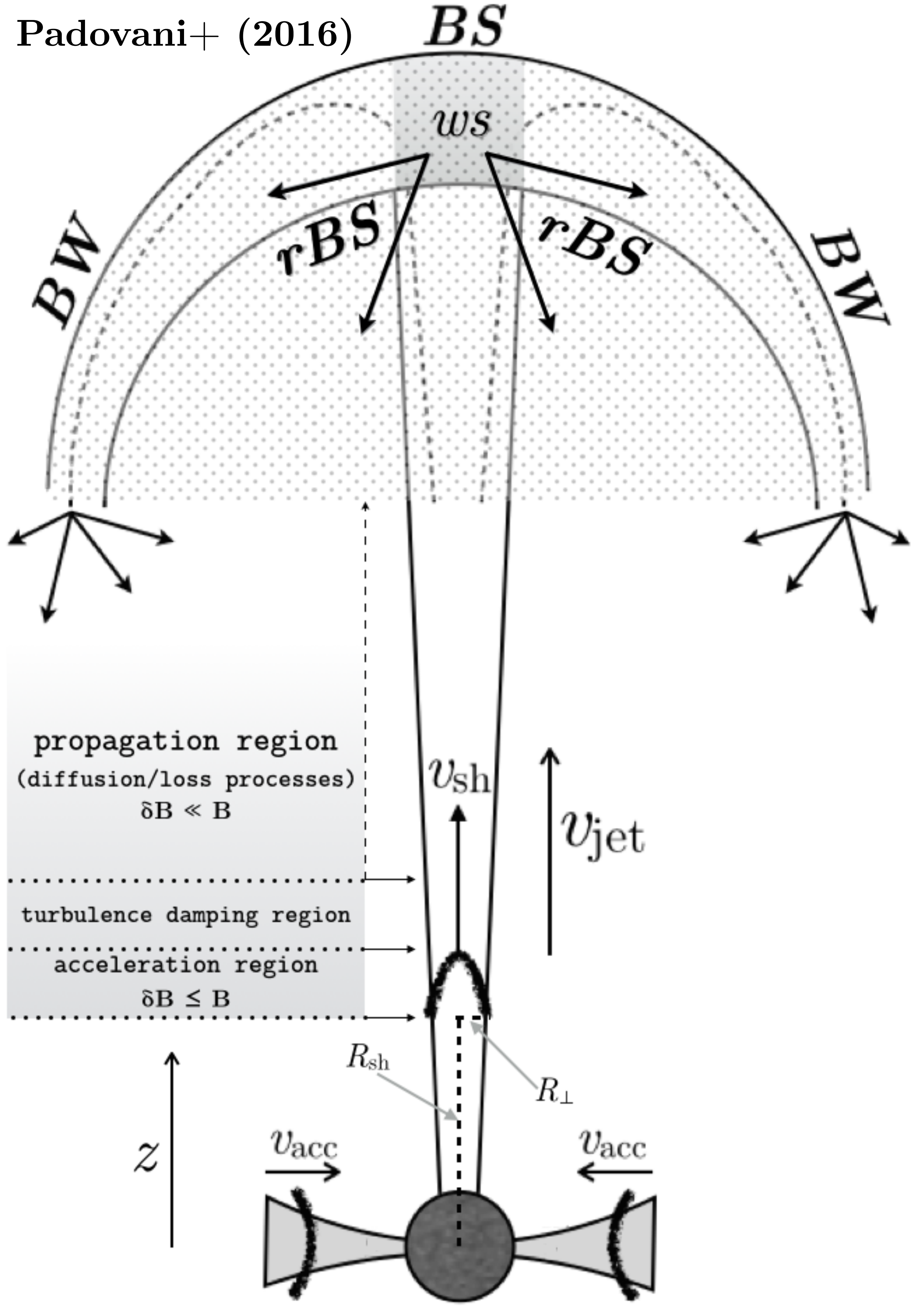
Shock along the jet

Shock on protostellar surface

parallel shock

perpendicular shock




Padovani+ (2016)

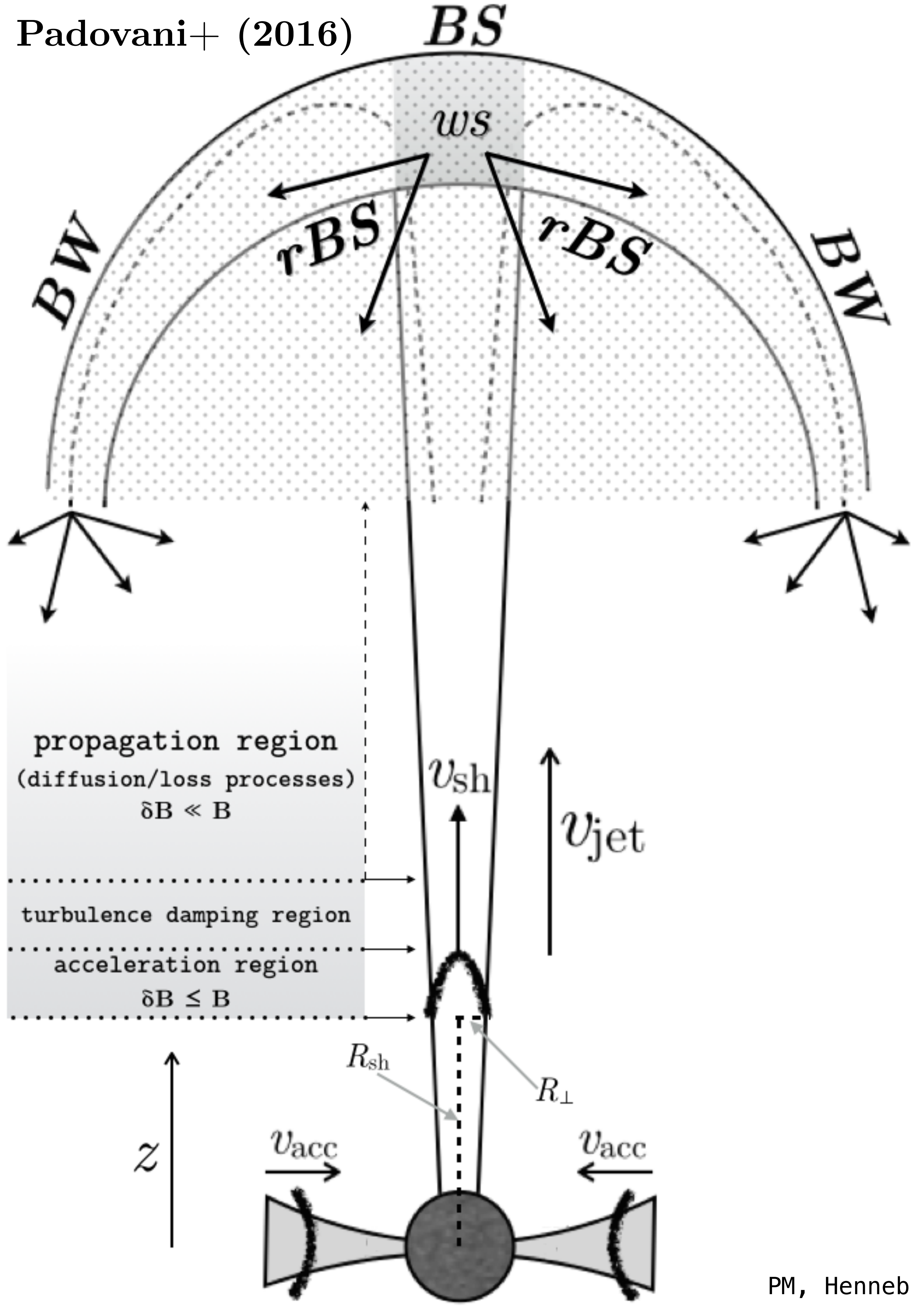
The jet morphology is far from being universally defined.

- jet lengths spread over orders of magnitudes;
- usually there is not a single final bow shock, but innermost knots are resolved into bow shocks (time-variable jet emitting dense-gas bullets, McCaughrean+ 2002);
- jet angle variations due to precession (Devine+ 1997) or orbital motions (Noriega-Crespo+ 2011);

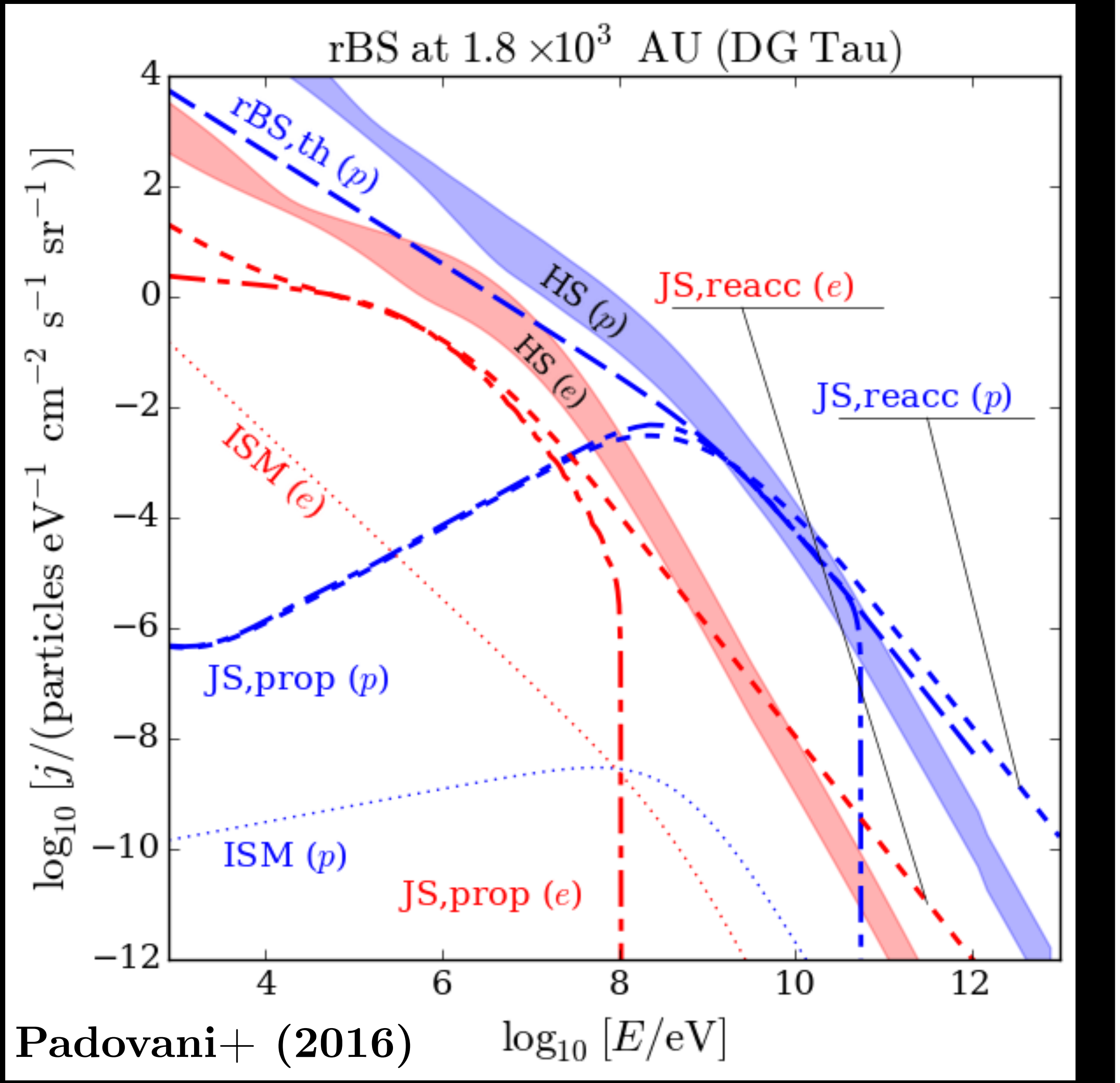
For the sake of clarity we consider

- a single shock at R_{sh}=100 AU from the protostar;
- follow the propagation up to the rBS and the HS.

energy losses (Padovani, Galli & Glassgold 2009)
magnetic effects (Padovani & Galli 2011,2013;
Padovani, Hennebelle & Galli 2013)

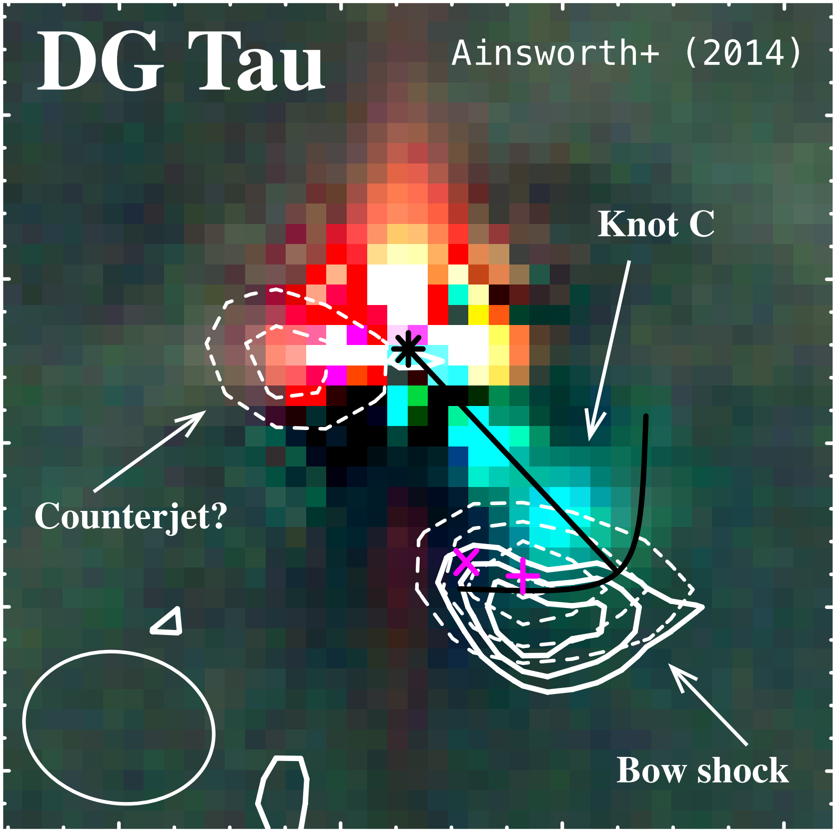


- Thermal *p* acceleration in an inner shock;
- propagation up to the rBS also accounting for the generation of secondary *e*;
- rBS: acceleration of new component of thermal *p* PLUS re-acceleration of previously accelerated *p*/*e*;
- propagation in the hot-spot region.



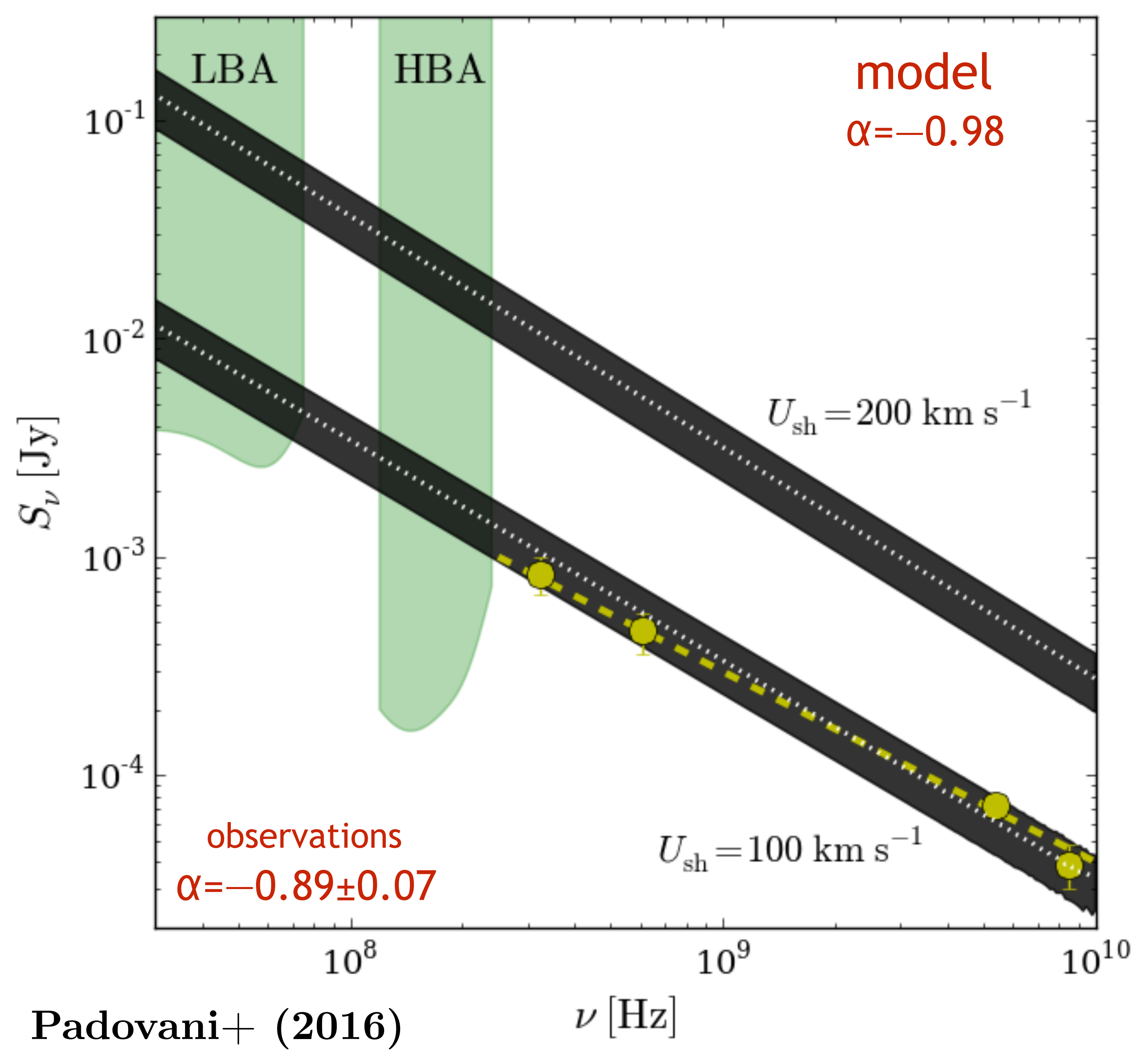
Application of the modelling: comparison with available observations

Ainsworth+ (2014) detected synchrotron emission (GMRT) towards the bow shock (knot C) of DG Tau, speculating that this could be due to relativistic electrons accelerated in the interaction between the jet and the ambient medium.



325 MHz (solid contours);
610 MHz (dashed contours).

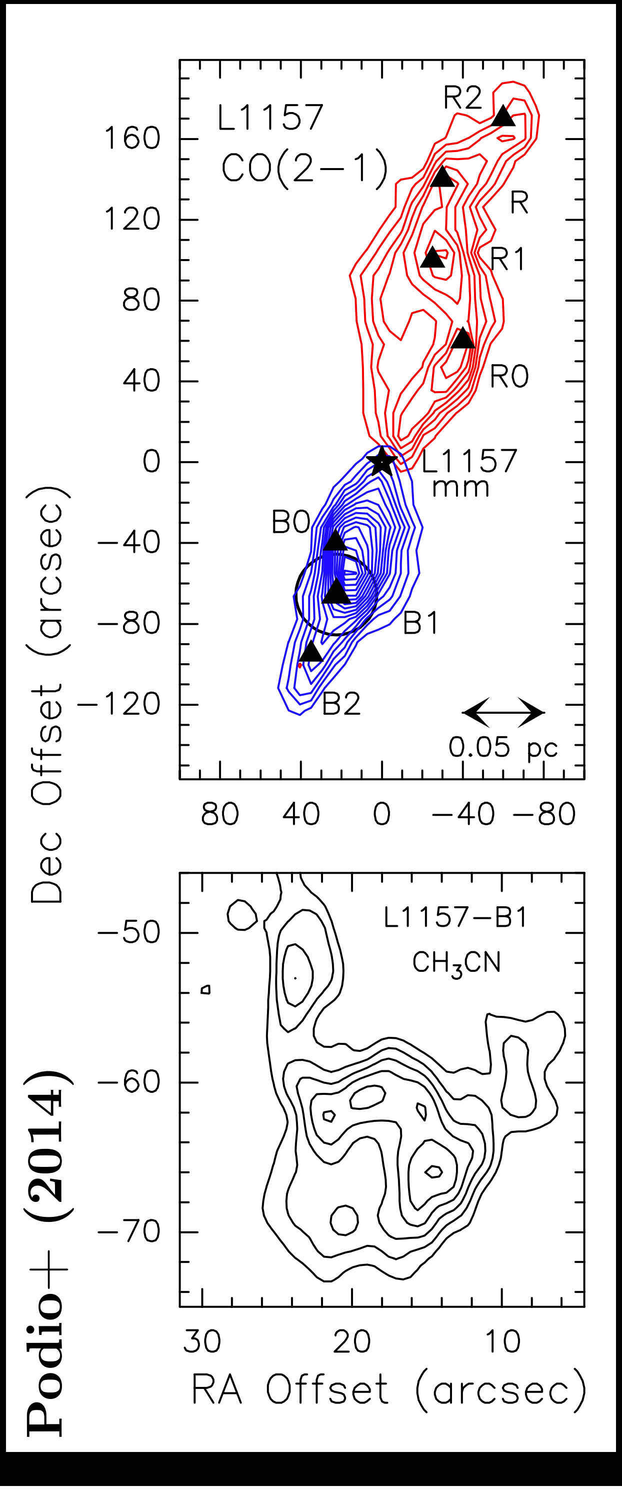
Using results by Lynch+ (2013), EVLA obs.



Padovani+ (2016)

Application of the modelling: comparison with available observations

Podio+ (2014): $\zeta=3\times10^{-16}$ s^{-1} in the bow shock B1 in L1157 (HCO^+, N_2H^+).



Podio+ (2014)

- Youngest knot B0 at 1.2×10^3 AU; B1 at 1.7×10^4 AU with an hot-spot cavity radius of 1.2×10^3 AU (Lefloch+ 2012);
- source distance: 250 pc (Looney+ 2007);
- $v_{\rm flow}\approx100$ km s^{-1}, $v_{\rm jet}=20$-40 km s^{-1} (Bachiller+ 2001; Tafalla+ 2015);
- $n_H=10^5$-10^6 cm^{-3} (Gómez-Ruiz+ 2015);
- embedded source, T=60-200 K (Podio+ 2014), but hints of $T=10^3$ K (Busquet+ 2014) to explain water lines.

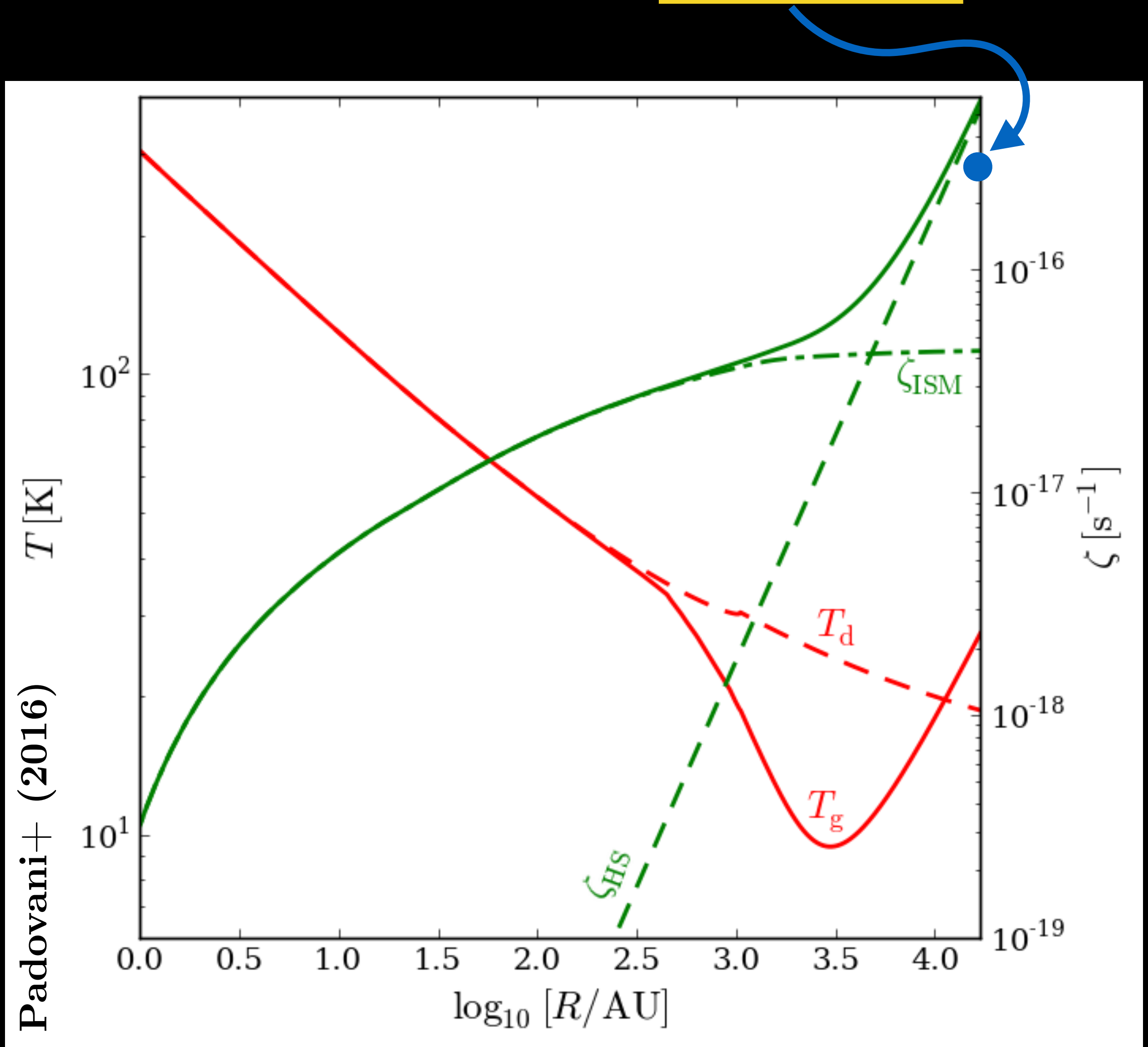
Our modelling: $\zeta=6.1\times10^{-16}$ s^{-1}

The values of *all parameters* can vary along the shock surfaces B0 and B1, this is why our result has to be interpreted as a proof of concept.

Need of polarimetric observations (ALMA) to constrain B configuration

Application of the modelling: comparison with available observations

Podio+ (2014): $\zeta=3\times10^{-16}\ \mathrm{s}^{-1}$ in the bow shock B1 in L1157 (HCO^+, N_2H^+).



- IS CRs, for a Voyager-like spectrum cannot explain the ionisation rate observed;
- the contribution of the hot spot CR flux become negligible at $R<5\times10^3$ AU (geometric dilution factor).

Check on gas temperature, accounting only for the heating due to IS and locally generated CRs (neglecting UV from ISRF).

$$\frac{T_d(R)}{\mathrm{K}} = 300\left(\frac{R}{\mathrm{AU}}\right)^{-0.41}$$ (Chiang+10,12)

- R<300 AU: gas-dust coupling;
- 300 AU<R<3000 AU: T_g ↓ (IS CR heating weak);
- R>3000 AU: T_g ↑ (hot spot CR heating).

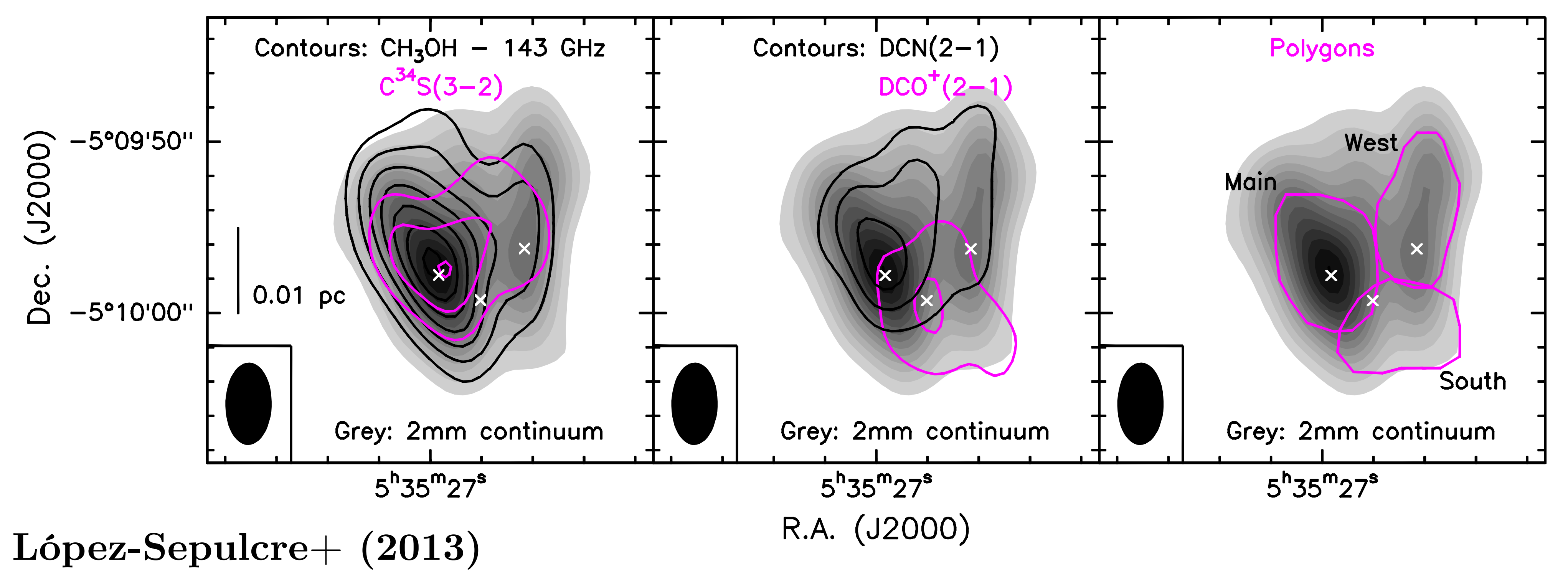
Application of the modelling: comparison with available observations

Ceccarelli+ (2014): $\left\{ \begin{array}{l} \zeta=1.5\times10^{-12}\ \mathrm{s^{-1}}\ \text{at 1600 AU} \\ \zeta=4\times10^{-14}\ \mathrm{s^{-1}}\ \text{at 3700 AU} \end{array} \right\}$ in OMC-2 FIR 4 (HCO^+, N_2H^+).

Caveats (for the application of our modelling):

- it contains a cluster of a few embedded intermediate- and low-mass protostars (Shimajiri+ 2008; López-Sepulcre+ 2013);
- no jet activity detected so far;

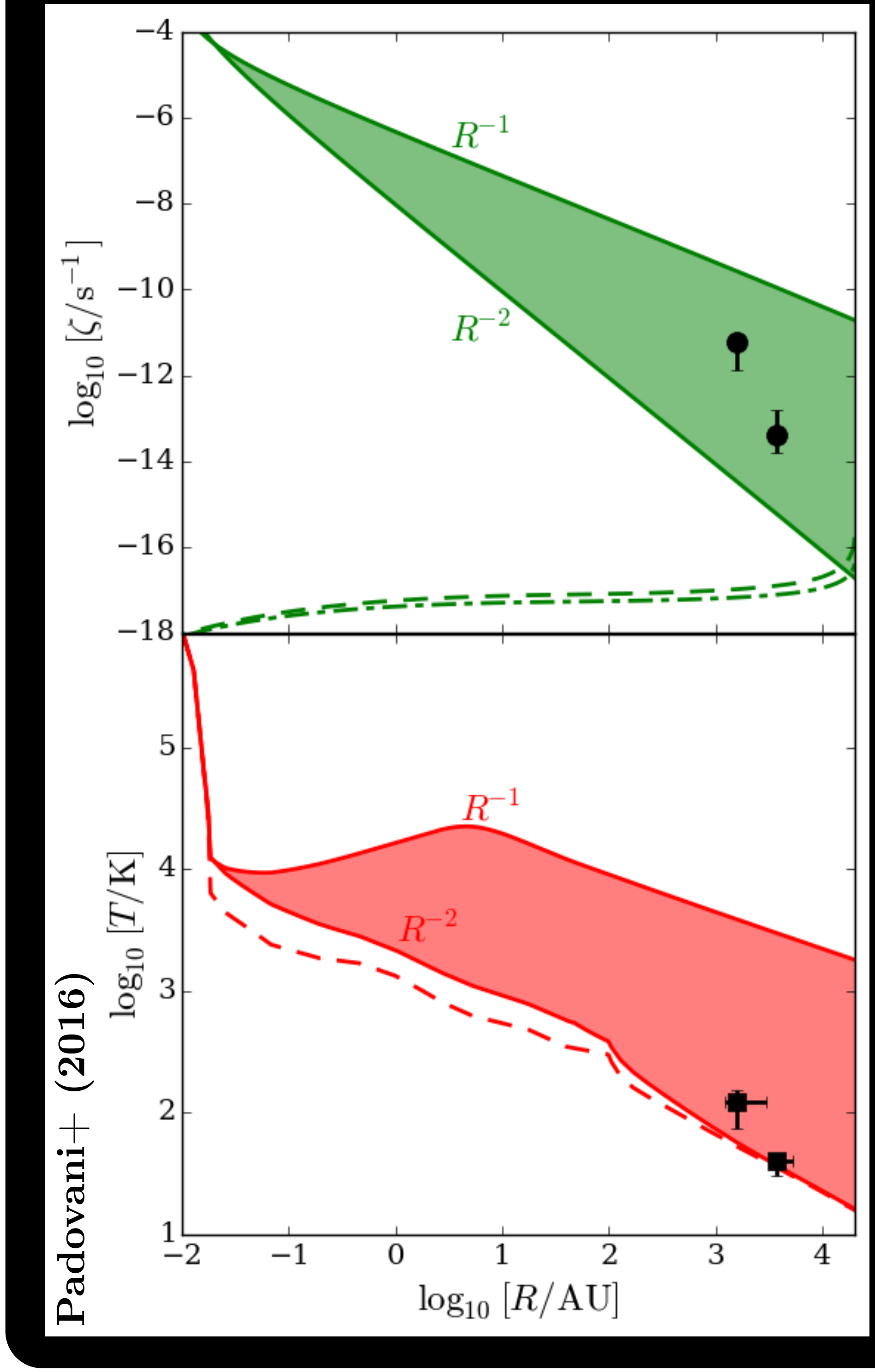
Protostellar surface acceleration model (parameters from Masunaga & Inutsuka 2000).



López-Sepulcre+ (2013)

Application of the modelling: comparison with available observations

Ceccarelli+ (2014): $\left\{ \begin{array}{l} \zeta = 1.5\times10^{-12}\ \mathrm{s}^{-1} \text{ at } 1600\ \mathrm{AU} \\ \zeta = 4\times10^{-14}\ \mathrm{s}^{-1} \text{ at } 3700\ \mathrm{AU} \end{array} \right\}$ in OMC-2 FIR 4 (HCO^+, N_2H^+).



Padovani+ (2016)

- Geometrical dilution factor:
  - free-streaming case → R^{-2}
  - diffusion with $R_{\mathrm{diff}} \gg R$ → R^{-1} (Aharonian 2004)

Check on gas temperature: the case R^{-1} gives too large values of T_g with respect to those computed by a LVG analysis (Ceccarelli+ 2014).

→ The propagation mechanism is probably neither purely diffusive nor free streaming.

Application of the modelling: comparison with available observations

Local CRs could be responsible for the formation of short-lived radionuclei (^{10}Be) contained in calcium-aluminium-inclusions of carbonaceous meteorites.

$[^{10}\mathrm{Be}]_{\mathrm{meteorites}} \gg [^{10}\mathrm{Be}]_{\mathrm{ISM}}$.

Hypothesis: *spallation reactions* during the earliest phases of the protosolar nebula.

Fluence per unit time: $\mathcal{F}_t(E_{\min}) = 2\pi \int_{E_{\min}}^{E_{\max}} j(E)\mathrm{d}E$

$E_{\min} \simeq$ 50 MeV: energy threshold for $p + ^{16}\mathrm{O} \rightarrow ^{10}\mathrm{Be} + \ldots$

$\mathcal{F}_t = 2 \times 10^{17}$ protons cm^{-2} yr^{-1} (purely diffusive case)

$\mathcal{F}_t = 8 \times 10^{18}$ protons cm^{-2} yr^{-1} (free-streaming case)

An irradiation of few tens of years can explain the values of the fluence derived by Gounelle+ (2013) equal to 10^{19}-10^{20} protons cm^{-2}.

Conclusions

★ Set of conditions to be fulfilled highly non-linear: small variations in one or more parameters (B, x, n_H, T, U_{sh}, η, k_u) can make the acceleration process inefficient. Since a protostar is a highly dynamic system, particle acceleration can be a very intermittent process.

E.g.: a local increase of ζ corresponds to a local variation of x, varying the efficiency of the acceleration mechanism.

★ High-resolution observations (e.g. with ALMA and NOEMA) will help to have better constraints, with a special consideration for the magnetic field configuration. Besides (B, x, n_H, T, U_{sh}, η, k_u) are not constant all along the shock surface ⇒ modelling improvements.

★ A number of observations can be explained by our modelling: synchrotron emission in DG Tau, ionisation rate in L1157-B1 and OMC-2 FIR 4.

★ The most limiting condition on E_{max} is the geometry of the jet, in particular $R_\perp$. Far from the source, $R_\perp$ increases and less and less particles are lost in the perpendicular directions. Particles can be accelerated up to 1–10 TeV (CTA targets ?).

★ Comparison with possible competing effects (X-ray ionisation).

★ Role of turbulence (Does the dilution factor goes with R^{-2} or R^{-1} ?)

★ We need more observations (statistics).