# IN-SITU ENERGETIC PARTICLES* ACCELERATION IN YOUNG STELLAR OBJECTS

Alexandre Marcowith (Laboratoire Univers Particules Montpellier, France)

collaboration:

A. Araudo (Astronomical Institute, Czech Republic), M.Padovani (Arcetri observatory, Italy), K.Ferrière (I.R.A.P., France), P.Hennebelle (AIM-CEA, France)

based on:

Padovani et al 2015, A&A, 582, L13

Padovani et al 2016, A&A, 590, A8.

Araudo et al, in prep., MNRAS.

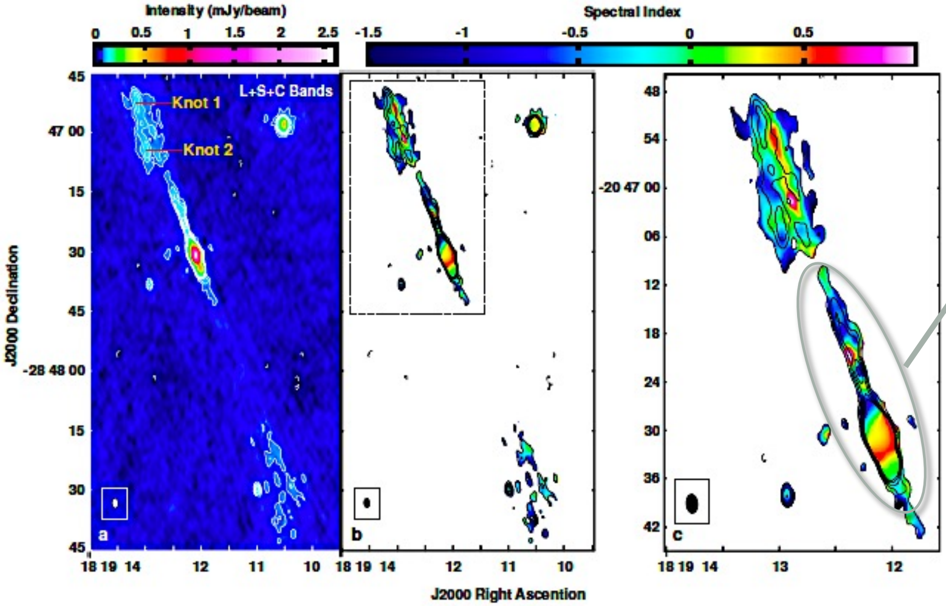
* possibly Cosmic Rays, but for our purpose not necessarily …

# Non-thermal emission in YSO

- Radio emission with negative indices (synchrotron radiation, at cm wavelength):
  - **NGC 6334I-CM2** [Brogan +2016]. , $\alpha$=-0.5
  - **W3($H_2$O)-W3(OH)** [Wilner +1999, Reid +1995], $\alpha$=-0.6
  - **HH80-81** [Marti +1993, Rodriguez-Kamenetzky +2017], $\alpha$=-0.5(+/-0.4) or smaller.
  - **IRAS 16547-4247** [Garay +1996, Rodriguez +2005]. , $\alpha$=-0.6 (+/-0.2)
  - **Serpens** [Rodriguez-Kamenetzky +2016], $\alpha$=-0.35(+/-0.02)
  - **OMC2-FIR3** [Osorio +2017]. $\alpha$=-0.59 (+/-0.2), $\alpha$=-1.07 (+/-0.07), $\alpha$=-1.3 (+/-0.4)
  - **L778-VL6** [Girart +2002]. , $\alpha$=-0.82(+/-0.04)
  - **DGTau** [Ainsworth +2014], $\alpha$=-0.89 (+/-0.07) and in the Taurus molecular cloud region [Ainsworth + 2016].
  - 13 more southern sources [Purser +2017] with $<\alpha>=-0.55$
  - Several sources in the Perseus molecular cloud [Tychionec +2018].

  - Usually a low polarization (<10%) but linearly polarized emission in HH80-81 [Carrasco-Gonzalez + 2010].
- Hard non-thermal (?) X-rays (E> 2keV):
  - HH80-81 [Lopez-Santiago +2013]

# HH80-81/IRAS18162-2048 non-thermal emission details

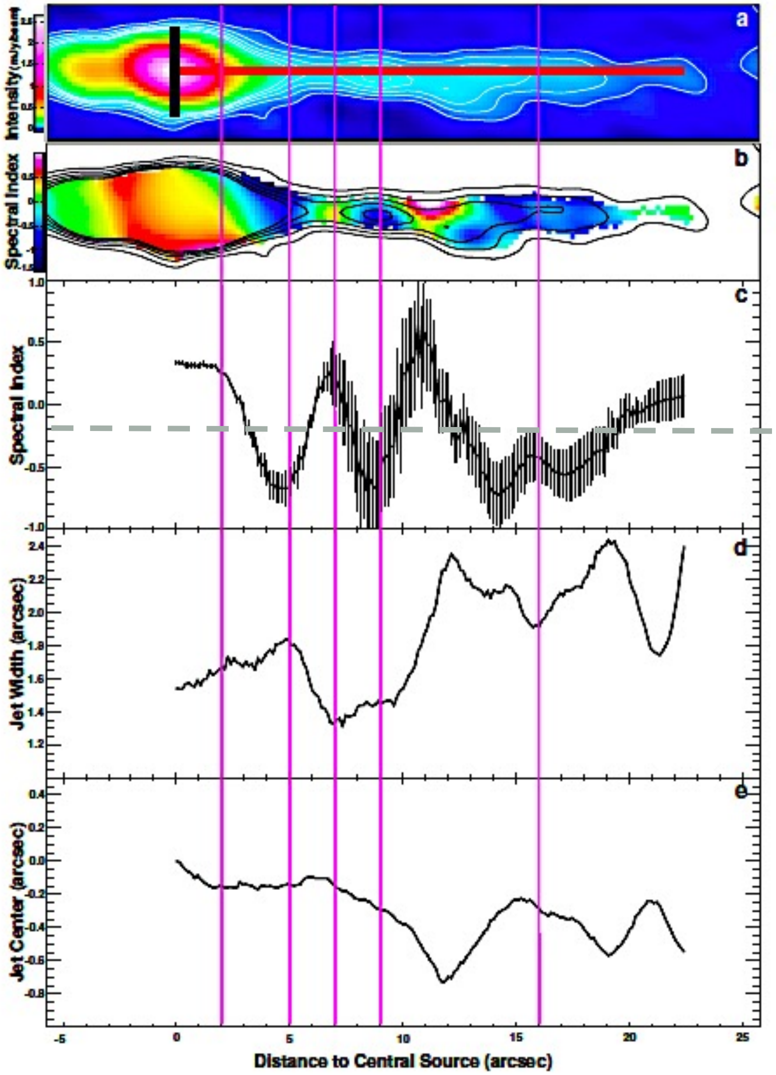


Intensity and index map of the collimated jet region (JVLA, 4-6 GHz).

positive index ⇔ narrow jet regions
negative index ⇔ the jet widens

may be interpreted as recollimation shocks in the jet pattern.

Rodriguez-Kamenetzky + 2017



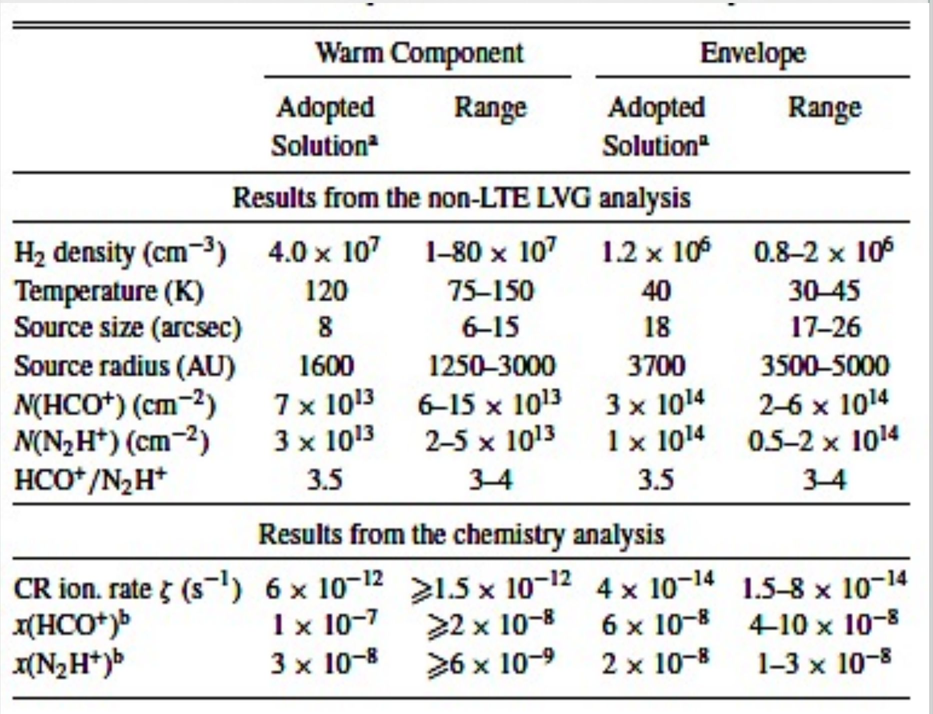
# Ionization rates “anomalies”

- High ionization rates measurements (see also Favre + 2017)

OMC2-FIR4 : Ceccarelli + 2014

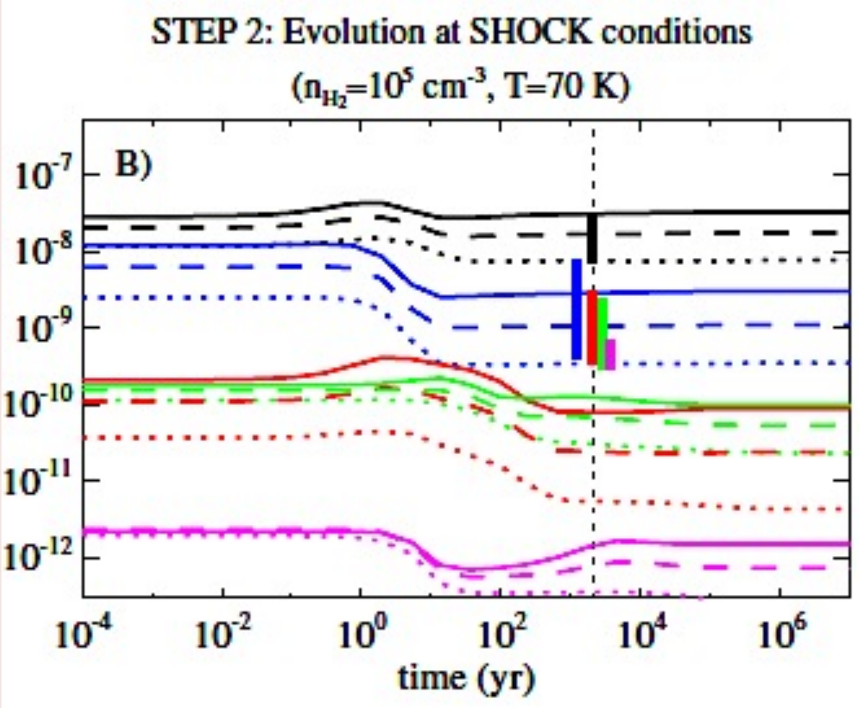
L1157-B1 : Podio + 2014

Herschel observations of HCO$^+$, N$_2$H$^+$ ion species



| | Warm Component | | Envelope | |
|---|---|---|---|---|
| | Adopted Solution$^a$ | Range | Adopted Solution$^a$ | Range |
| Results from the non-LTE LVG analysis | | | | |
| $H_2$ density (cm$^{-3}$) | $4.0 \times 10^7$ | $1–80 \times 10^7$ | $1.2 \times 10^6$ | $0.8–2 \times 10^6$ |
| Temperature (K) | 120 | 75–150 | 40 | 30–45 |
| Source size (arcsec) | 8 | 6–15 | 18 | 17–26 |
| Source radius (AU) | 1600 | 1250–3000 | 3700 | 3500–5000 |
| $N(HCO^+)$ (cm$^{-2}$) | $7 \times 10^{13}$ | $6–15 \times 10^{13}$ | $3 \times 10^{14}$ | $2–6 \times 10^{14}$ |
| $N(N_2H^+)$ (cm$^{-2}$) | $3 \times 10^{13}$ | $2–5 \times 10^{13}$ | $1 \times 10^{14}$ | $0.5–2 \times 10^{14}$ |
| $HCO^+/N_2H^+$ | 3.5 | 3–4 | 3.5 | 3–4 |
| Results from the chemistry analysis | | | | |
| CR ion. rate $\zeta$ (s$^{-1}$) | $6 \times 10^{-12}$ | $\geqslant 1.5 \times 10^{-12}$ | $4 \times 10^{-14}$ | $1.5–8 \times 10^{-14}$ |
| $x(HCO^+)^b$ | $1 \times 10^{-7}$ | $\geqslant 2 \times 10^{-8}$ | $6 \times 10^{-8}$ | $4–10 \times 10^{-8}$ |
| $x(N_2H^+)^b$ | $3 \times 10^{-8}$ | $\geqslant 6 \times 10^{-9}$ | $2 \times 10^{-8}$ | $1–3 \times 10^{-8}$ |

Herschel observations of HCO$^+$, N$_2$H$^+$ ion species show abundances explain by $\zeta$~3 $10^{-16}$ s$^{-1}$ (continuous line below)


STEP 2: Evolution at SHOCK conditions ($n_{H_2}=10^5$ cm$^{-3}$, T=70 K)

# Needs for in-situ acceleration

- Simple energetic arguments (see Padovani +2016)
  - Gravitational luminosity of accretion shocks impinging the stellar surface:

$$L_{grav} = \frac{G\dot{M}M}{R_{sh}} \sim 3\times 10^{34}\,\mathrm{erg/s}$$

Class 0 low mass protostar

  - Background (ISM) Cosmic Ray luminosity impinging the core of a molecular cloud:

$$L_{CR} \sim R_{core}^2 V_a e_{CR} \sim 1.2\times 10^{29}\,\mathrm{erg/s}$$

$e_{CR}$ CR energy density

  - The CR luminosity close to the star is even smaller due to strong ionization losses, hence: **a small fraction of $L_{grav}$ is needed in in-situ energetic particles to dominate $L_{CR}$.**
  - These EP are necessary explain high ionization fractions (and non-thermal radiation).

# Particle acceleration mechanims

- Magnetic reconnection (stellar flares, coronal process).
- Stochastic (re)acceleration (turbulent accretion disk).
- Diffusive shock acceleration (this talk).

See E.Amato’s talk (this meeting).

# Diffusive shock acceleration (DSA) in YSO

- YSO jets are particular places for DSA
- Shock speeds:
  - 50-150 km/s in Low Mass (LM)-YSO and 100-1000 km/s in High Mass (HM)-YSO (Araudo + 2017, Bosch-Ramon + 2010).

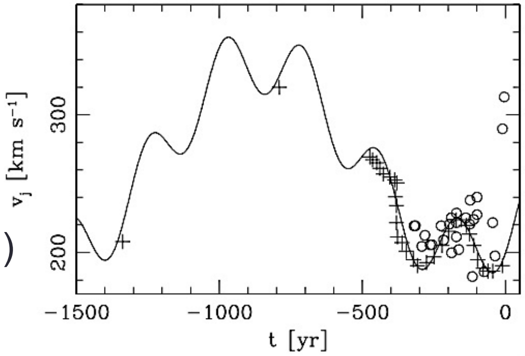
1. Foreshock properties poorly known:
   - Temperature T ~$10^4$-$10^5$ K => shock Mach numbers.
   - Magnetic field B , background density n => shock Alfvénic Mach numbers, radiative losses can be become important.
   - Partially ionized media => strong wave damping through ion-neutral collisions (pepper side of the problem).
2. Geometry matters:
   - EP can escape transversally (contrary to supernova remnants).

- Shocks at the stellar surface are possible sites for DSA.

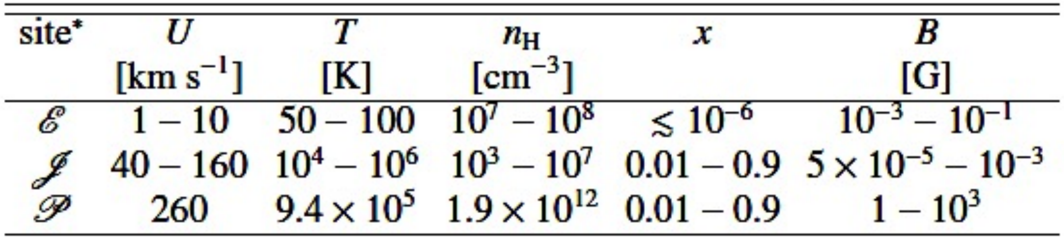
# Modelling in-situ acceleration in (class 0 & I) YSO

Acceleration sites: (Padovani + 2016)

- Accretion enveloppe
- Accretion shocks
- Shock in jet (travelling or recollimation)
- Termination shock

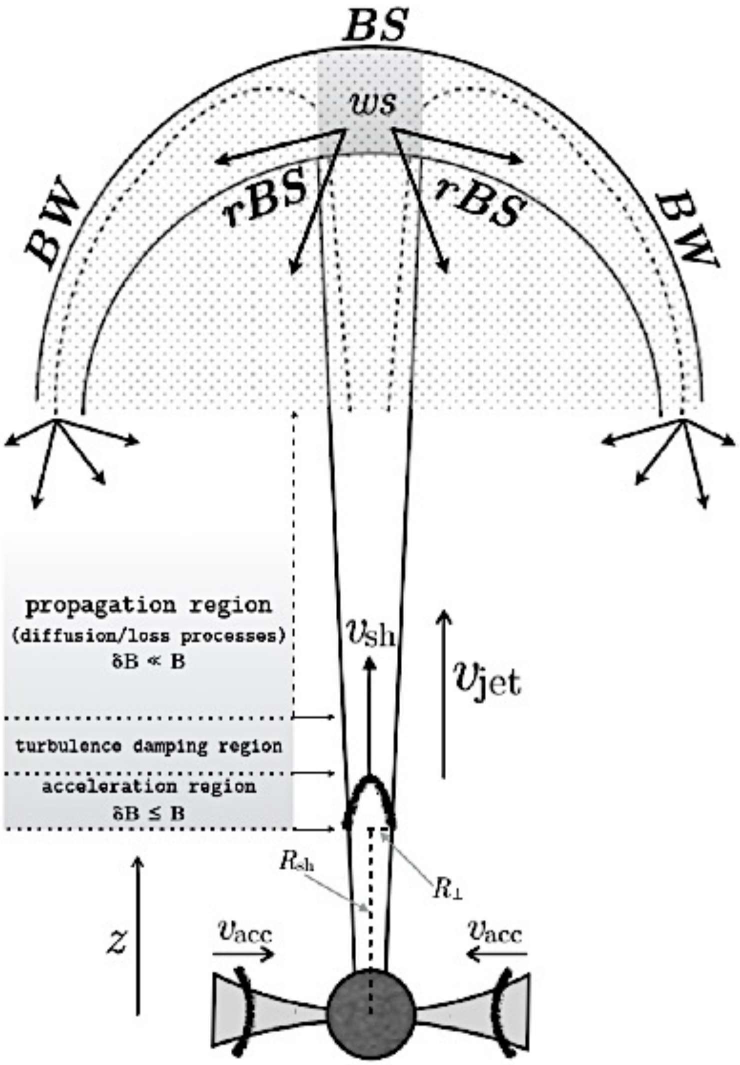


example of non steady ejection (HH34, Raga +2002)



| site* | $U$ [km s$^{-1}$] | $T$ [K] | $n_H$ [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 | $5 \times 10^{-5} - 10^{-3}$ |
| $\mathscr{P}$ | 260 | $9.4 \times 10^5$ | $1.9 \times 10^{12}$ | 0.01 – 0.9 | $1 - 10^3$ |

E= enveloppe
J= jet
P= protostar surface



# Conditions for DSA

1) Supersonic and super-Alfvénic shocks: $V_{sh}>Max(c_s,V_A)$
2) Ionization/Coulomb losses: $t_{acc} < t_{loss}$
3) Condition in partially ionized media (Drury + 1996).

- Region E does not pass this constraint (R < 1)

Two important energies

ion-neutral coupling energy $E_{coup}$

i. $E > E_{coup}$ EP are in resonance with MHD (Alfvén) waves in the coupled ion-neutral regime ⇔ weakly damped
ii. $E < E_{coup}$ EP are in resonance with Alfvén waves in the decoupled ion-neutral regime ⇔ strongly damped.

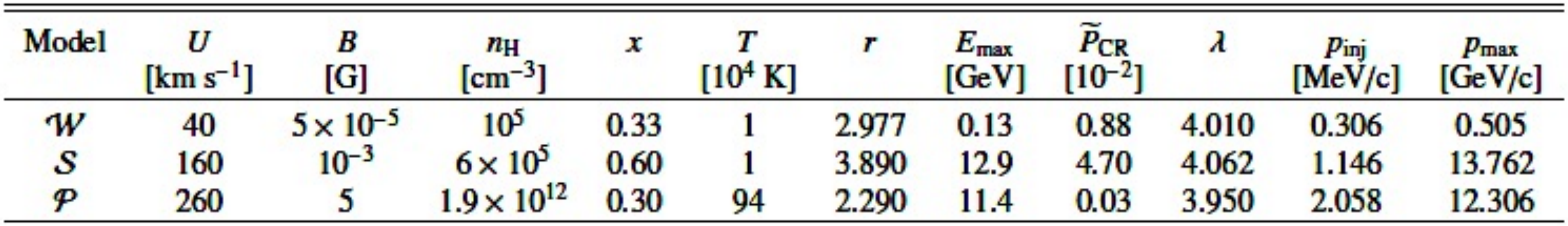
Flux-limited energy $E_{damp}$

set by balancing EP flux downstream and escaping EP upstream due to ion-neutral damping.

$R = E_{damp} / E_{coup}$ ; acceleration can proceed if R > 1, if $E_{damp}$ is in the weakly damped regime.

# Models

- Model P: protostar accretion shock
- Jet model S (strong) of fast shock
- Jet model W (weak) of slower shock solutions.



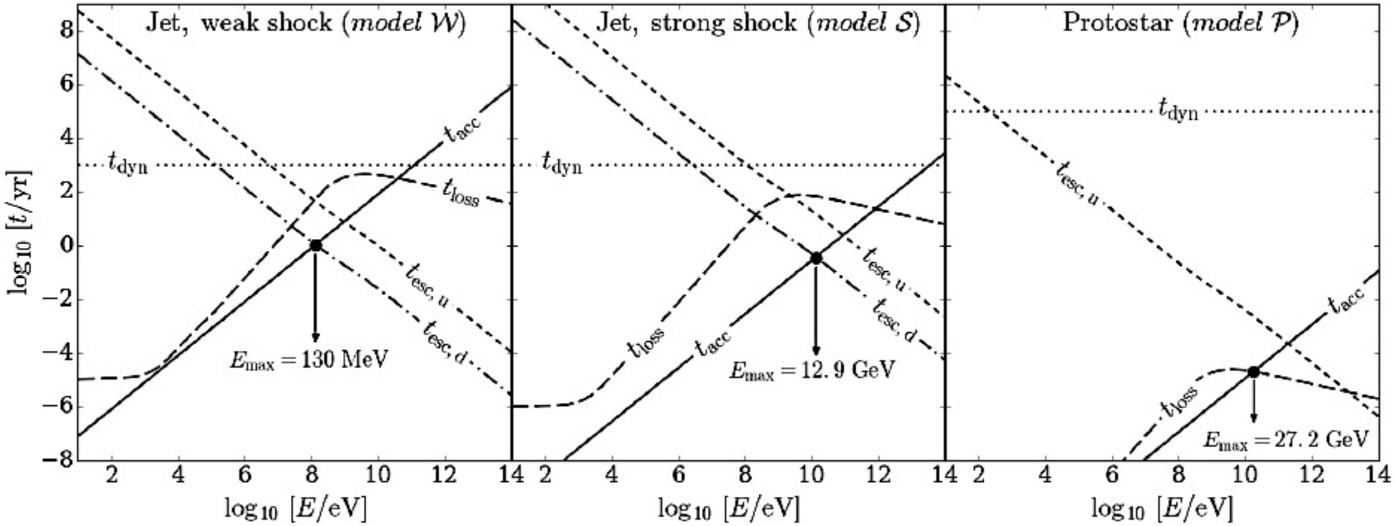
| Model | $U$ [km s$^{-1}$] | $B$ [G] | $n_H$ [cm$^{-3}$] | $x$ | $T$ [$10^4$ K] | $r$ | $E_{max}$ [GeV] | $\widetilde{P}_{CR}$ [$10^{-2}$] | $\lambda$ | $p_{inj}$ [MeV/c] | $p_{max}$ [GeV/c] |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $\mathcal{W}$ | 40 | $5 \times 10^{-5}$ | $10^5$ | 0.33 | 1 | 2.977 | 0.13 | 0.88 | 4.010 | 0.306 | 0.505 |
| $\mathcal{S}$ | 160 | $10^{-3}$ | $6 \times 10^5$ | 0.60 | 1 | 3.890 | 12.9 | 4.70 | 4.062 | 1.146 | 13.762 |
| $\mathcal{P}$ | 260 | 5 | $1.9 \times 10^{12}$ | 0.30 | 94 | 2.290 | 11.4 | 0.03 | 3.950 | 2.058 | 12.306 |

* all models have low acceleration efficiency $\eta = 10^{-5}$, so EP pressure is << 10% than shock ram pressure.

# Maximum energy

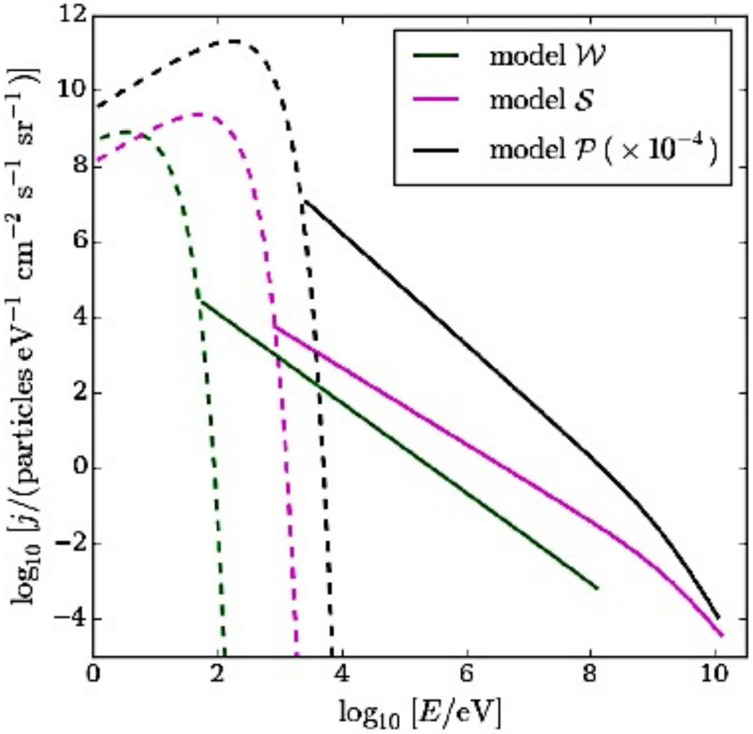
- Conditions to set $E_{max}$
  1) Age limit: $t_{acc}=t_{age}$ => $E_{age}$
  2) Geometrical limit :
     - i. Upstream $D/V_{sh}= \varepsilon R_{sh}$ => $E_{esc,u}$
     - ii. Downstream $t_{acc}= t_{res}=R_t^2/D$ => $E_{esc,d}$
  3) Loss limit: $t_{acc}=t_{loss}$ => $E_{loss}$
  4) Limit imposed by ion-neutral collisions (see previous slide) => $E_{damp}$

$$\boxed{E_{max} = \mathrm{Min}(E_{age},E_{esc,u},E_{esc,d},E_{loss},E_{damp}).}$$

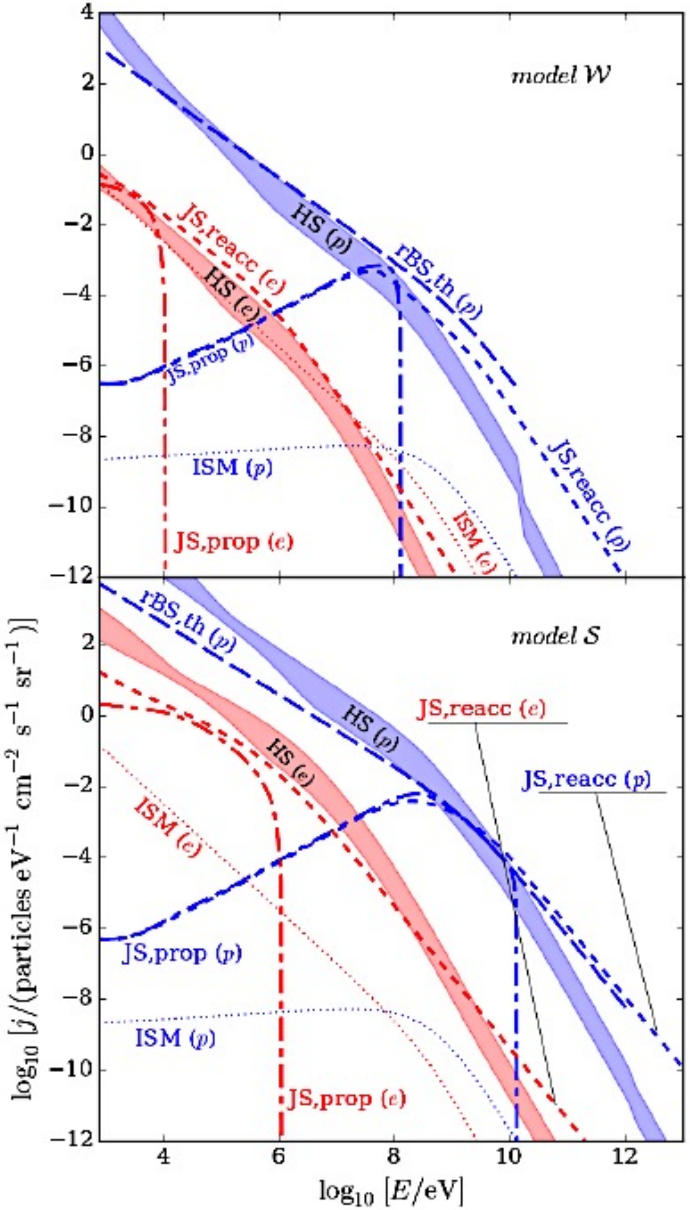


# Spectral energy distribution

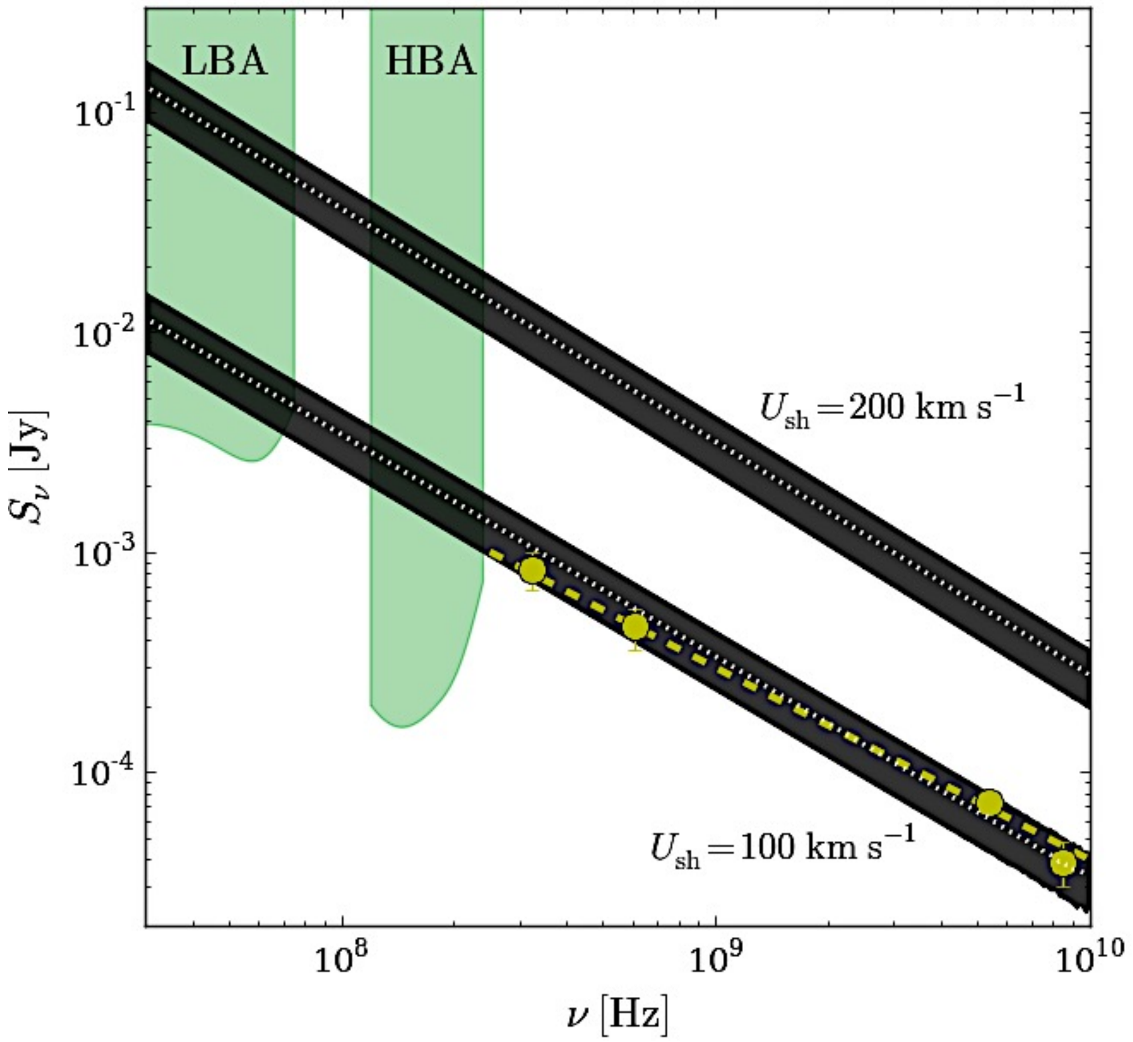
Jet propagated + TS spectrum
(proton: blue, electron: red)



Emerging EP (proton) spectrum



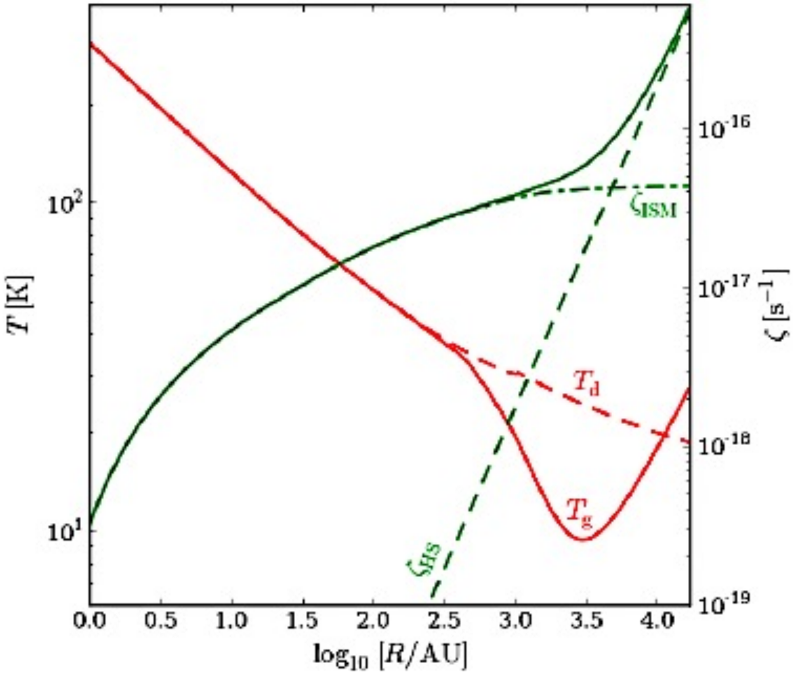
# DG tau bow shock radio spectrum



<u>Data</u>:
Lynch + 2013
Ainsworth + 2014

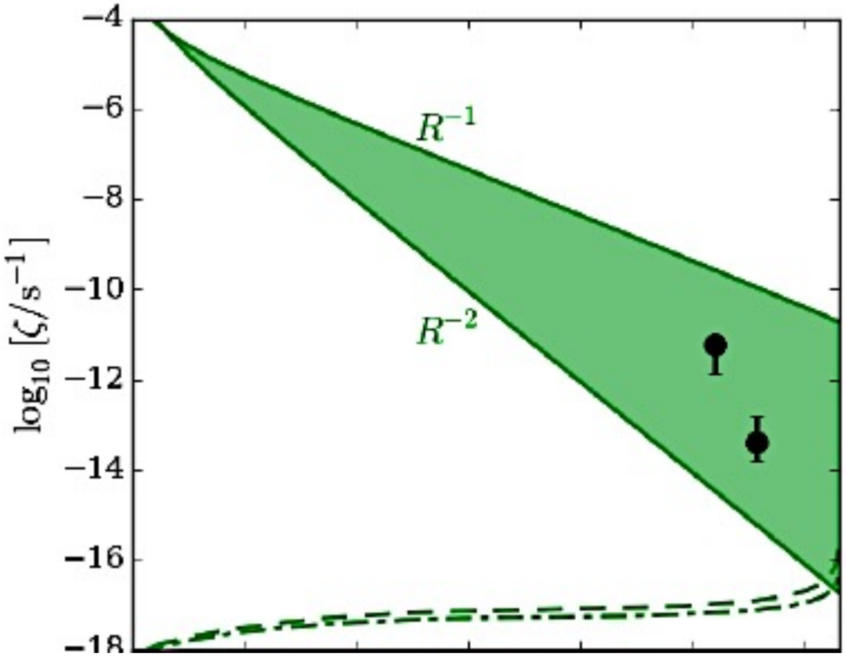
# Ionization fraction calculations

L1157-B1



ionization rate calculated from jet propagated CR background CR can not produce such an ionization rate.

OMC2-FIR4



calculated from model P, with solutions as $R^{-1}$ pure diffusion or $R^{-2}$ free streaming.

But, detailed transport modelling is needed + high angular observations (Rab + 2017, Rodgers-Lee + 2017)

# in summary what is needed to calculate acceleration efficiency ?

1. Jet temperature T.
2. Jet magnetic field strength B.
3. Jet density n.
4. Jet ionization fraction X.
5. Geometry: jet length $L_j$ and width $l_j$.
6. Shock speeds $V_{sh}$.

… by jet I mean, foreshock quantities

- Usually all a loosely known so observers can greatly help modellers by constraining these numbers ! but this is a difficult task.

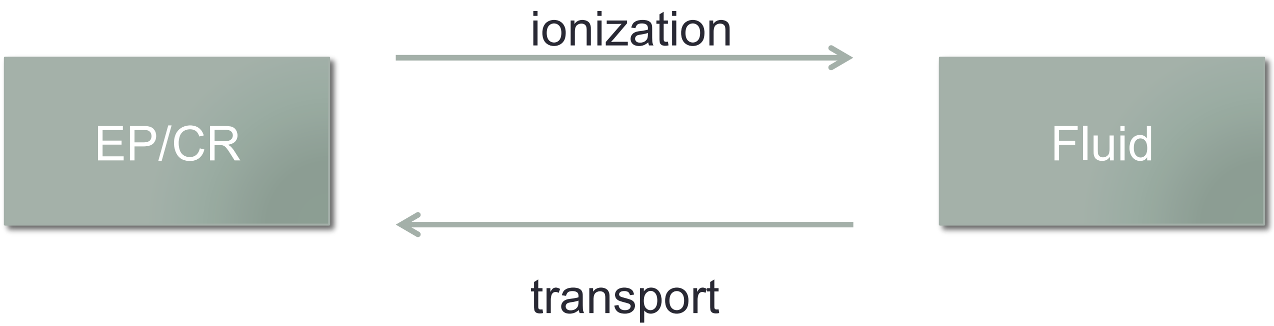
# Perspectives for high-mass YSO

- Shock speeds are higher there, be up to one order of magnitude.
- If jet density is not too large then synchrotron radiation can dominate over thermal free-free emission.
- If typical foreshock quantities are not strongly different as in LM-YSO then one could expect more efficient particle acceleration.
  - ➢ Stronger magnetic field generation at shocks (eg non-resonant streaming instability discussed in the supernova remnant context).
  - ➢ High maximum energies up to TeV (so here a link with high-energy astrophysics in the CTA era, https://www.cta-observatory.org/)
- See A. Araudo’s talk in this meeting.

# Conclusions

- Observations:
  - Growing number of YSO radio observations showing negative indices ⬄ synchrotron radiation and particle acceleration in jets (SKA era should provide more quality data)
  - In two objects high ionization fraction levels.
- Modelling:
  - high ionization levels: can not be explained by background CR flux because of strong losses ⬄ in-situ acceleration
  - Main mechanisms: reconnection or shocks (DSA) can be used to explain ionization anomalies.
  - DSA is adapted to explain electron acceleration and radio synchrotron features.
  - High-mass YSO have faster jets and could be sites of TeV particles ⬄ link with gamma-ray astronomy (CTA era should provide interesting constraints)
- Prospects:
  - Modellers need help from observers : constraining relevant parameters for shock models.
  - Need also to include CR in accretion/ejection simulations and MRI studies.

# Conclusions: dynamics



ionization

EP/CR

Fluid

transport

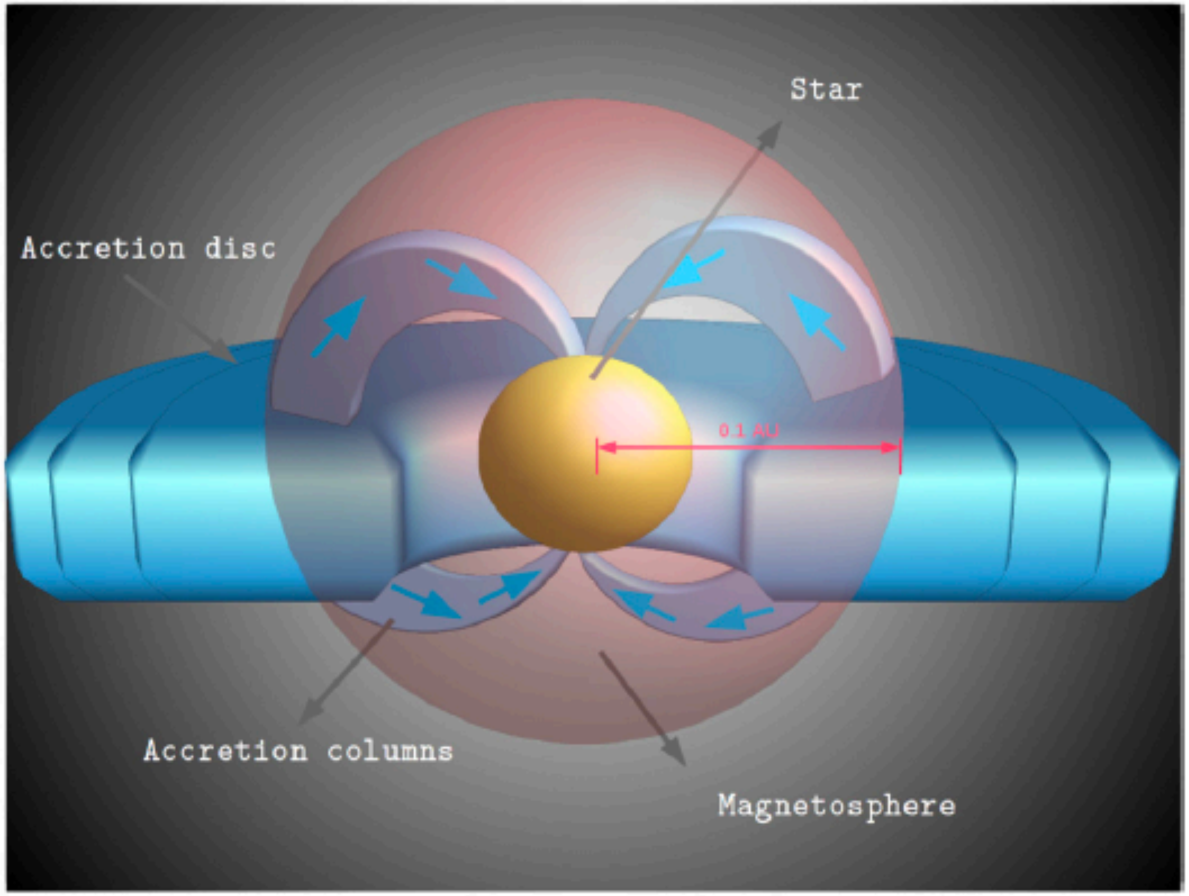
accretion/ejection is a time dependent process !

- A parallel effort is needed to include EP in HD/MHD (multi fluids) simulations.
  - Simulations of jet launching including ionization profiles.
  - How MRI develops accounting the presence of CRs ?

Thanks for your attention and to the organizers for this nice meeting

# Back-up

# Magnetic reconnection

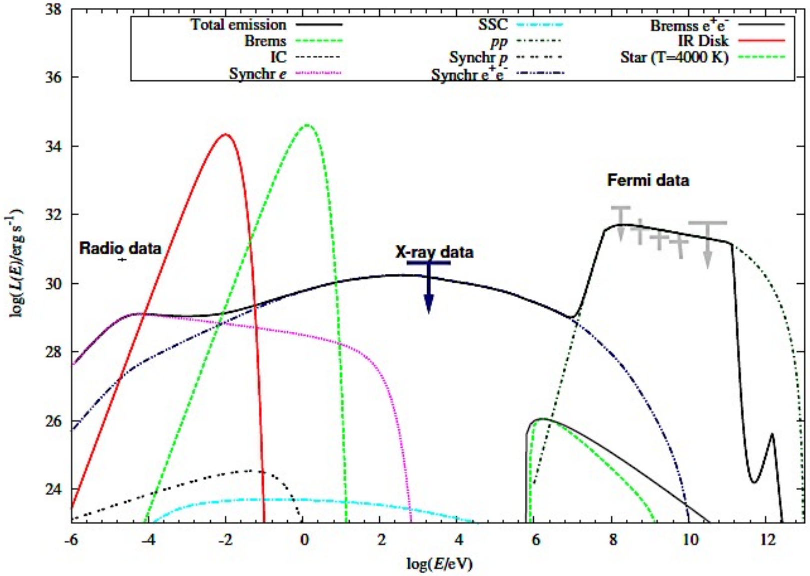


sketch of YSO magnetosphere/inner disk region
del Valle + 2011, Feigelson & Montmerle 1999

# Magnetic reconnection

- YSO are strong X-ray emitters (Feigelson & Montmerle 1999) => upscaling Sun performaces, GeV particles can be accelerated through flares => source of strong ionization in the proto-stellar disk (Rodgers-Lee + 2017, focussed on Class II, Rab + 2017).

- keV X-ray flares $L_x$ ~$10^{31}$-$10^{33}$ erg/s (Favata +2005) consistent with magnetic power released during intense reconnection events (Gouveia dal Pino + 2010).
- Duration and spatial extend ⇔ stellar corona-inner disk region.
- Magnetic reconnection => local heating, plasma motions and shocks => particle acceleration (del Valle + 2011) up to GeV-TeV range.



del Valle + 2011
SED of a TT star
located at 120 pc

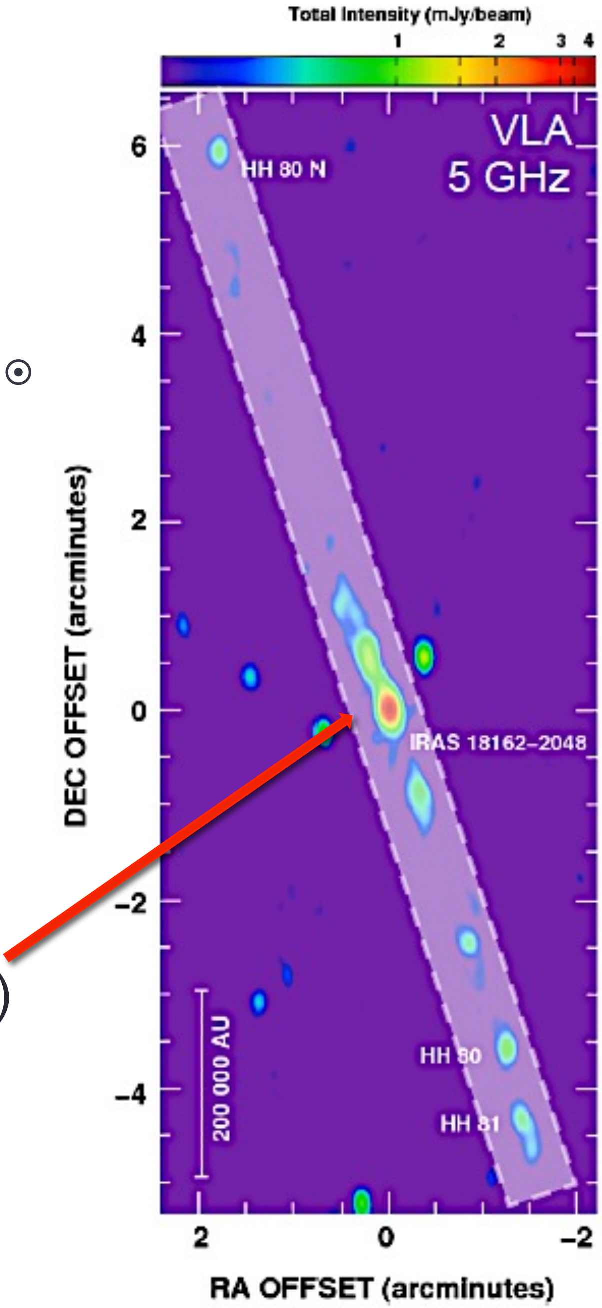
# Non-thermal emission from H80-81 (based on Rodriguez-Kamenetzky +2017, Carrasco-Gonzalez +2010)

Massive YSO IRAS 18162-2048 with M ~10 $M_{\odot}$ at 1.7 kpc

Highly collimated jets (<1$^{o}$ width)

Herbig-Haro objects (Marti + 1993): HH80, HH81, HH80N over ~5.3 pc of extension.

The central source emits thermal radio emission, associated with radiative shocks moving away at high speeds (up to 1000 km/s)



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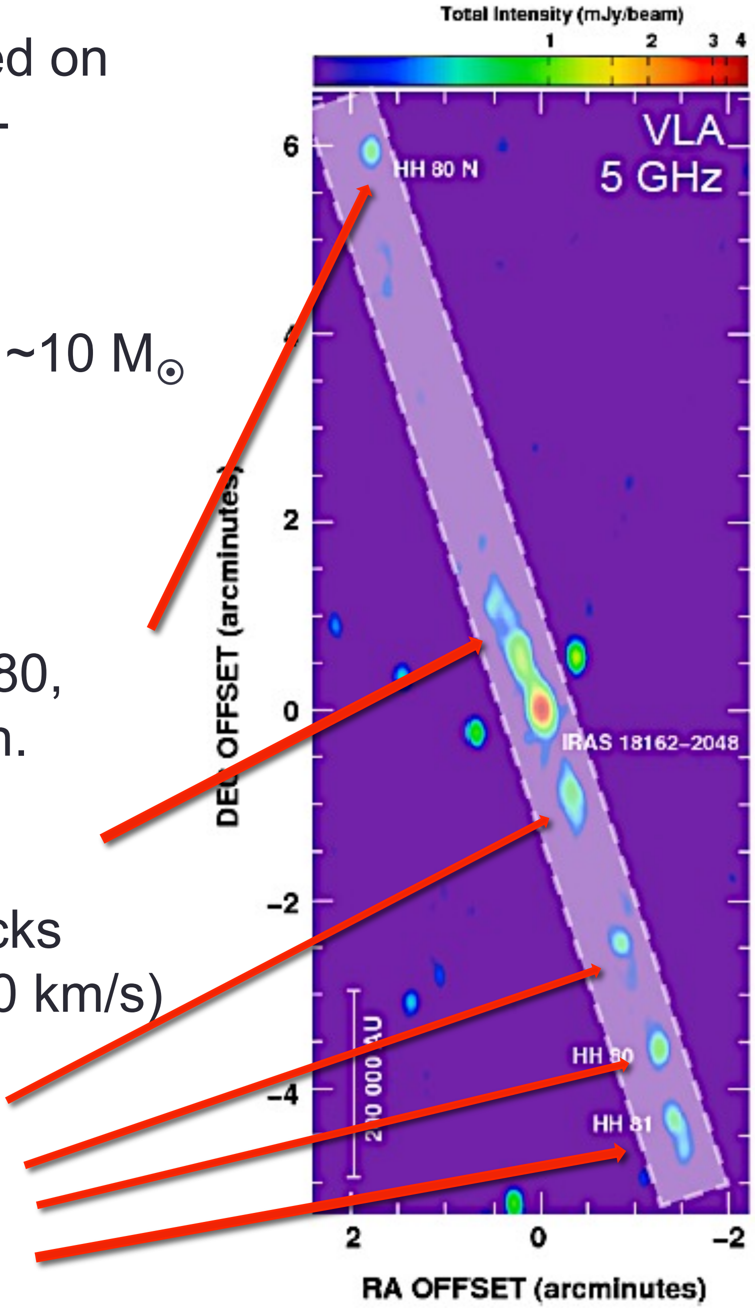

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Several non-thermal knots