A SOFIA/GREAT view on the Cepheus E outflow from an intermediate-mass protostar

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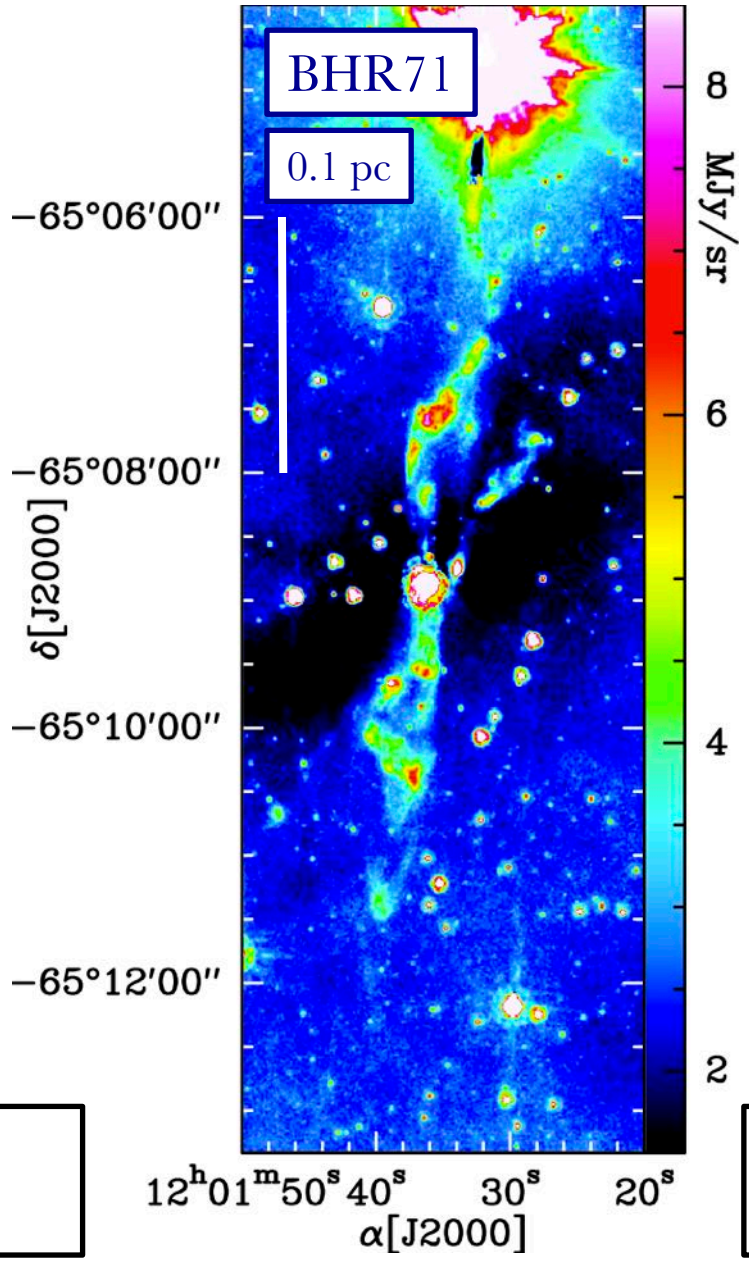
Outline

- Motivations
- Previous studies of Cepheus E
- The SOFIA/GREAT observations: CO
- The SOFIA/GREAT observations: [OI]
- Shock modelling in Cepheus E
- Perspectives

Motivations

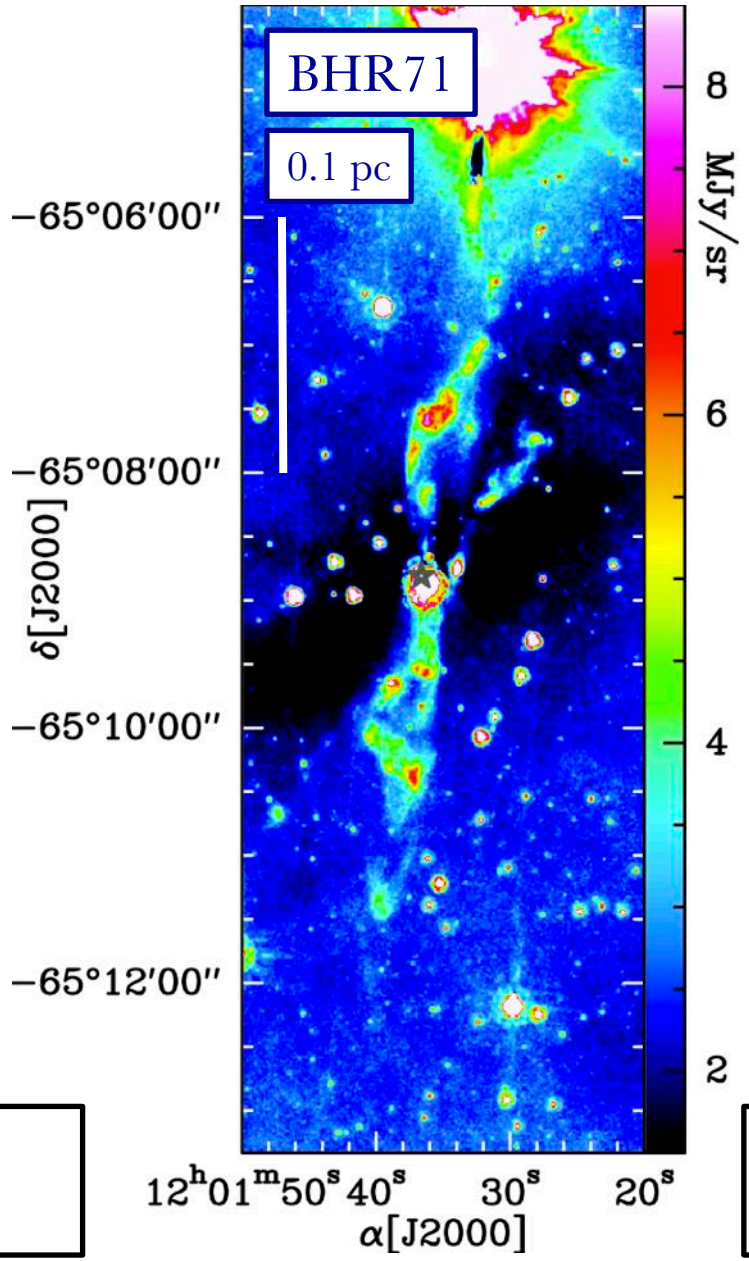
Motivations



archive image
Spitzer/IRAC 8 μm

adapted from
Gusdorf et al. 2015

Motivations



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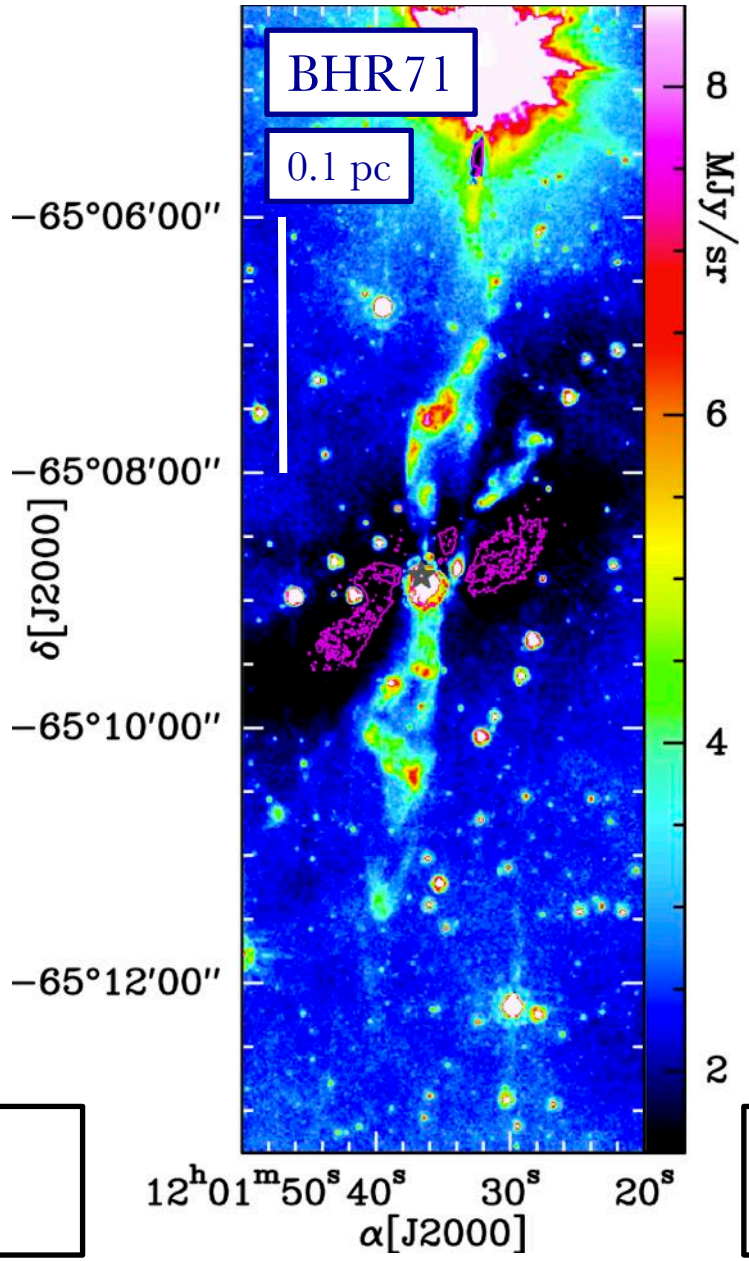

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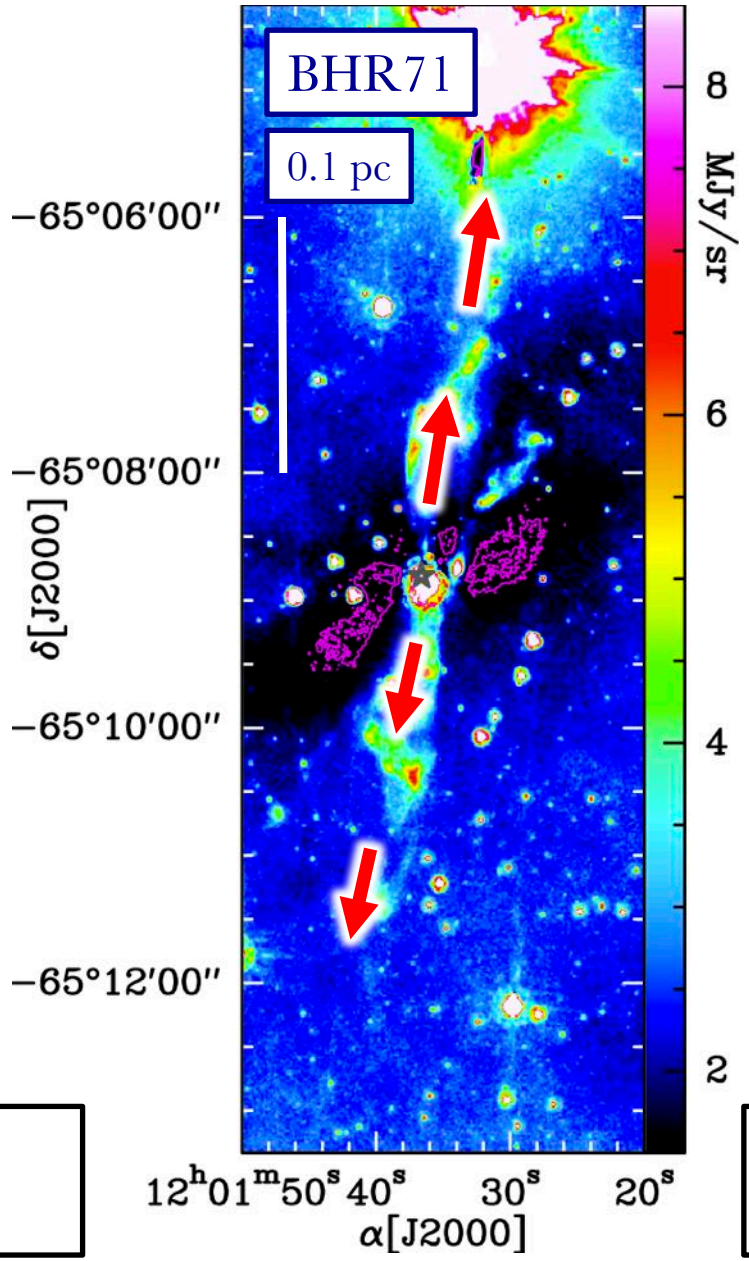

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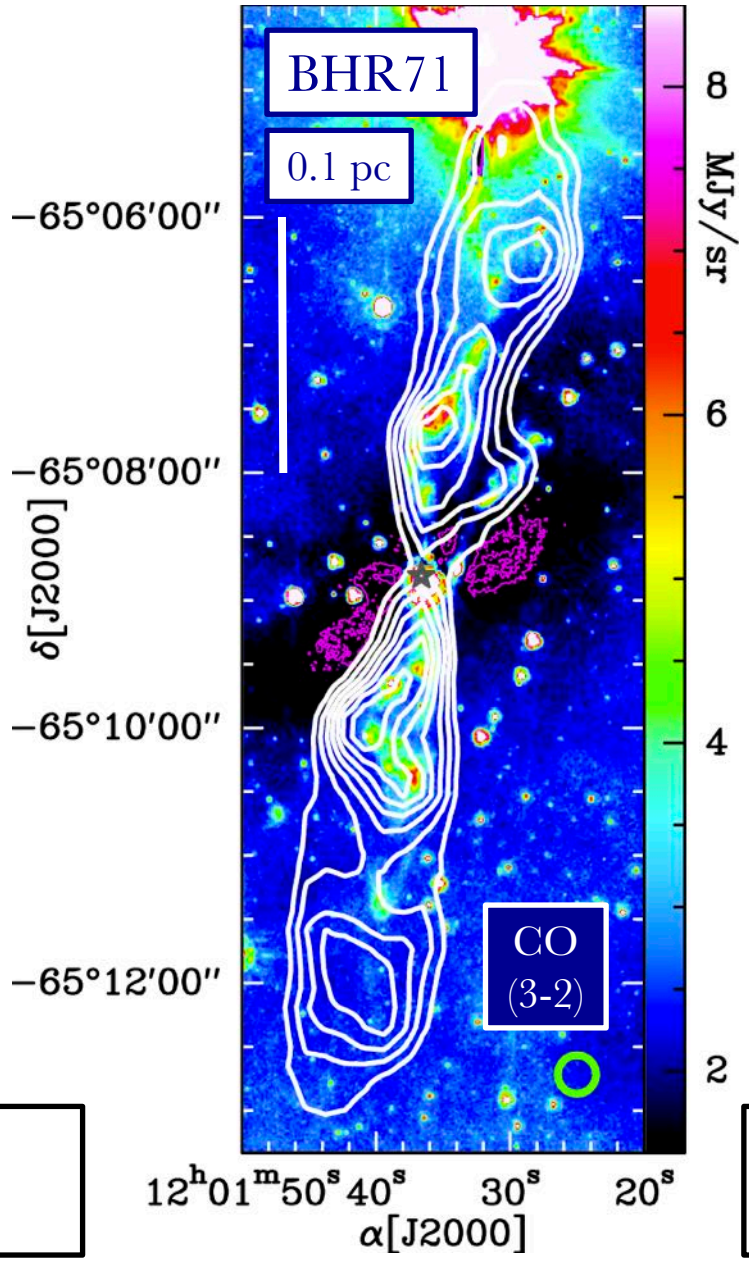


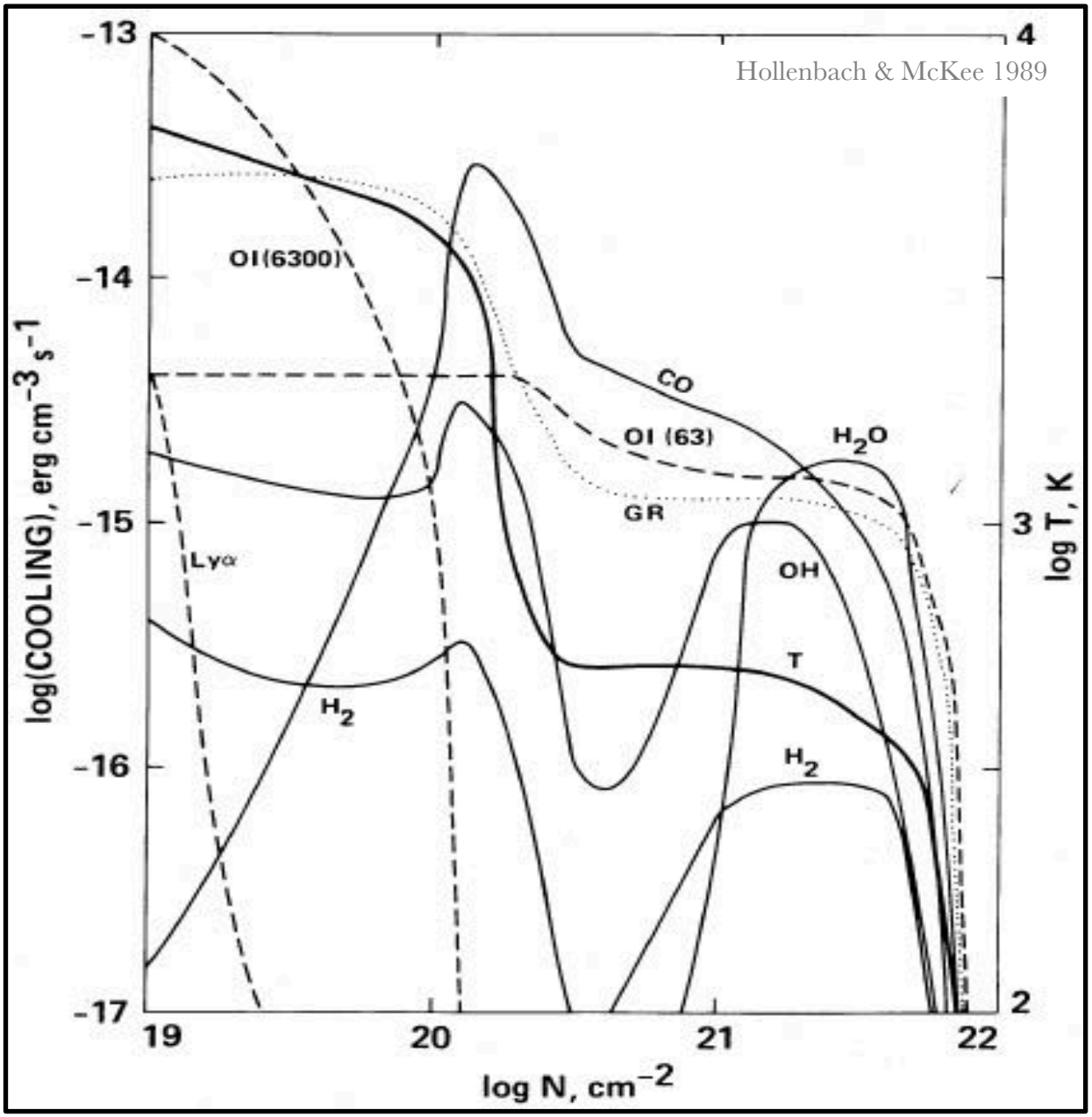
archive image
Spitzer/IRAC 8 μm

adapted from
Gusdorf et al. 2015

Motivations

Physical mechanisms, nature of shocks:

- parametric molecular
Jimenez-Serra et al. 2008
- molecular
Neufeld & Kaufman 1996
Flower & Pineau des Forêts 2015
- radiative precursor
Hollenbach & McKee 1989
- irradiated (=FUV-illuminated)
Lesaffre et al. 2013,
Melnick & Kaufman 2015



Motivations

Physical mechanisms, nature of shocks

Astrochemistry:

- SiO

Caselli et al. 1997, Schilke et al. 1997, Gusdorf et al. 2008a,b, 2011, Guillet et al. 2009, Jimenez-Serra et al. 2009, Nguyen Luong et al. 2011, Anderl et al. 2013, Leurini et al. 2014,…

- H_2O/OH/OI

WISH/WADI *Herschel* KP, Recent SOFIA works

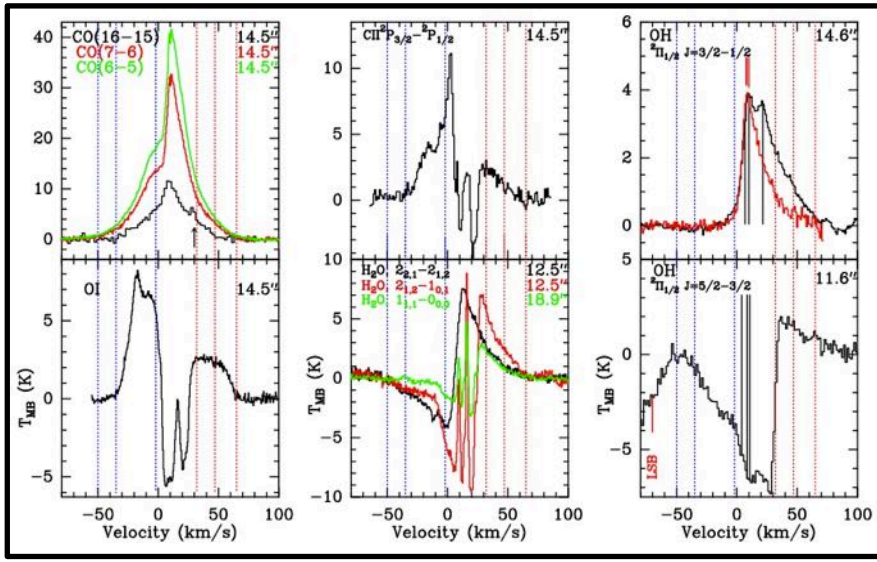
- ionized species

Podio et al. 2014 & ref. therein

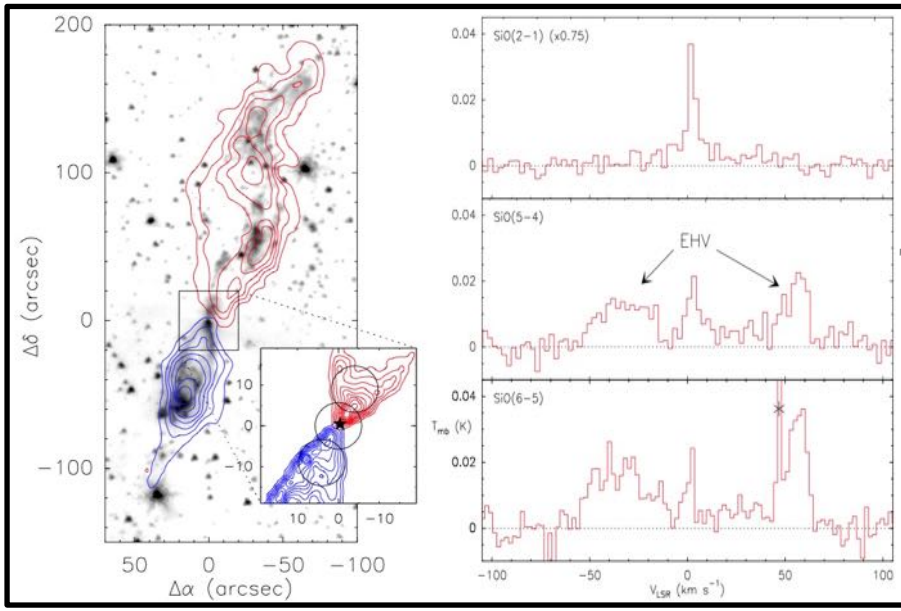
- COMs

Codella et al. 2015 & ref. therein

Also see L. Podio's talk



Leurini et al. 2015
G5.89-0.39



Tafalla et al. 2015
L1157

Motivations

Physical mechanisms, nature of shocks

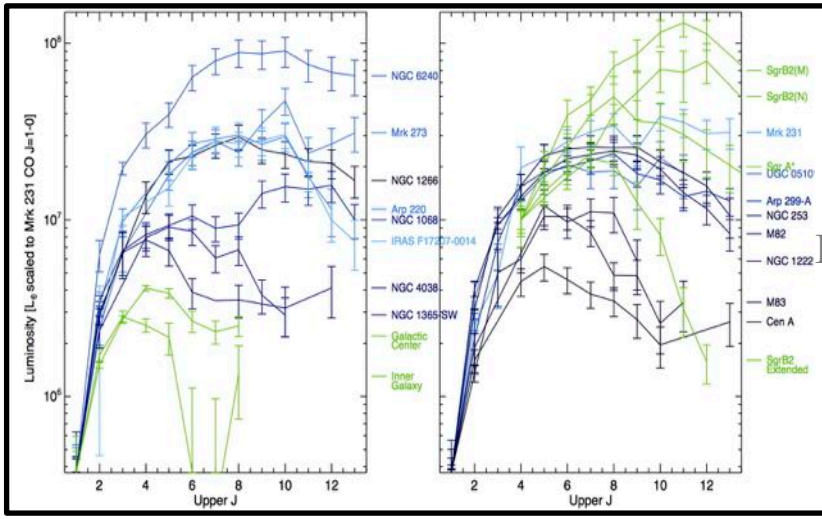
Astrochemistry

Energetic impacts and contribution to energetic balance of galaxies:
- Galactic studies

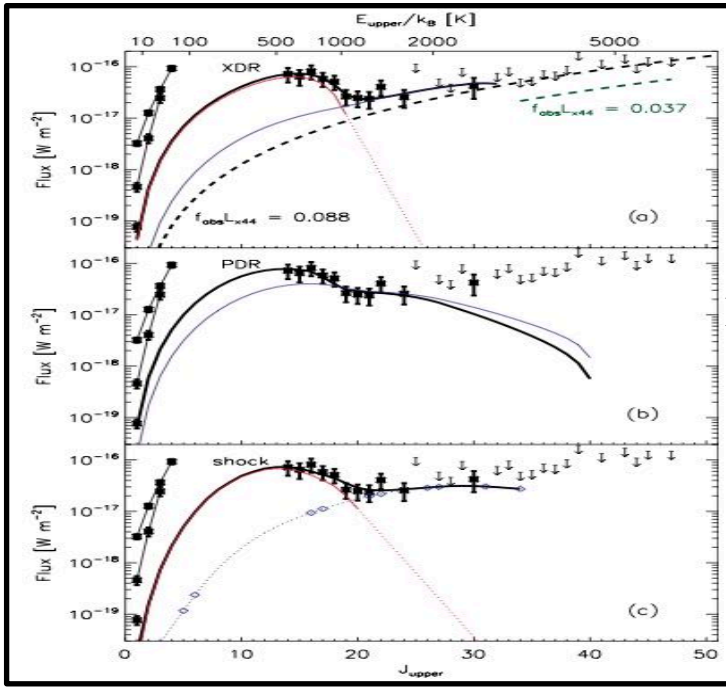
Cabrit & Berthout 1990,
Bontemps et al. 1996,
Beuther et al. 2002,
Zhang et al. 2005,
Lopez-Sepulcre et al. 2009,
Visser et al. 2014 & ref. therein

- extragalactic studies

Hailey-Dunsheath et al. 2012,
Meijerink et al. 2013,
Kamenetzky et al. 2014
& ref. therein



Kamenetzky et al. 2014
CO ladders



Hailey-Dunsheath et al. 2012
CO ladders in NGC1068

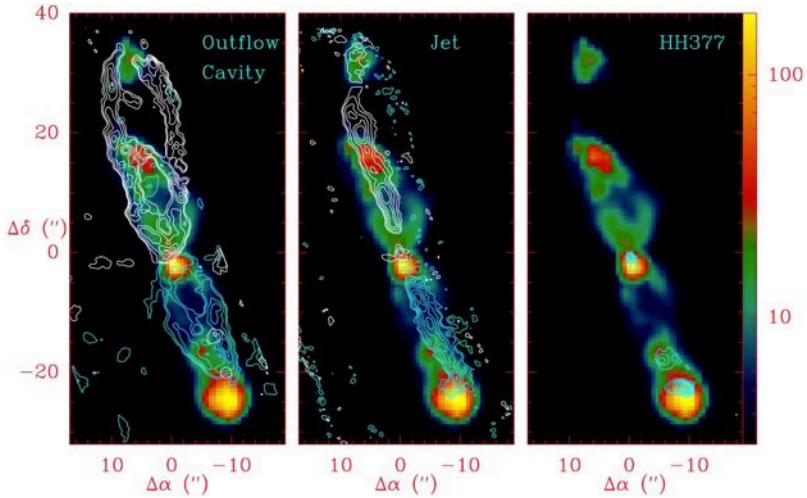
Motivations

Physical mechanisms, nature of shocks

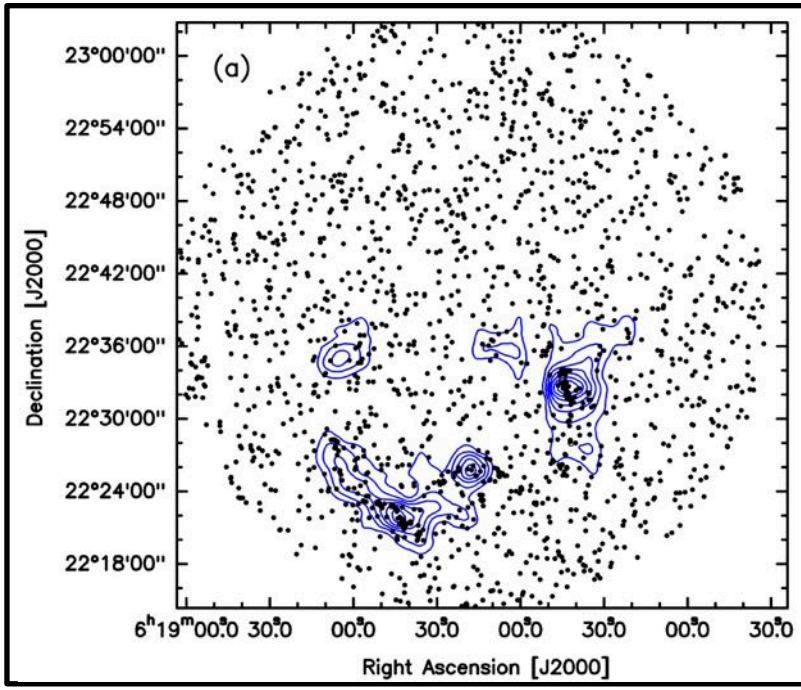
Astrochemistry

Energetic impacts and contribution to energetic balance of galaxies

Star formation scenarios through the mass-ladder:
- inducing
low-mass to high-mass
Codella et al. 2012,
CALYPSO program,
Lefloch et al 2015,
Hunter et al. 2008
- induced
Xu et al. 2011



Lefloch et al. 2015
CO in Cep E



Xu et al. 2011
SF induced by SNR shock in IC443 ?

Motivations

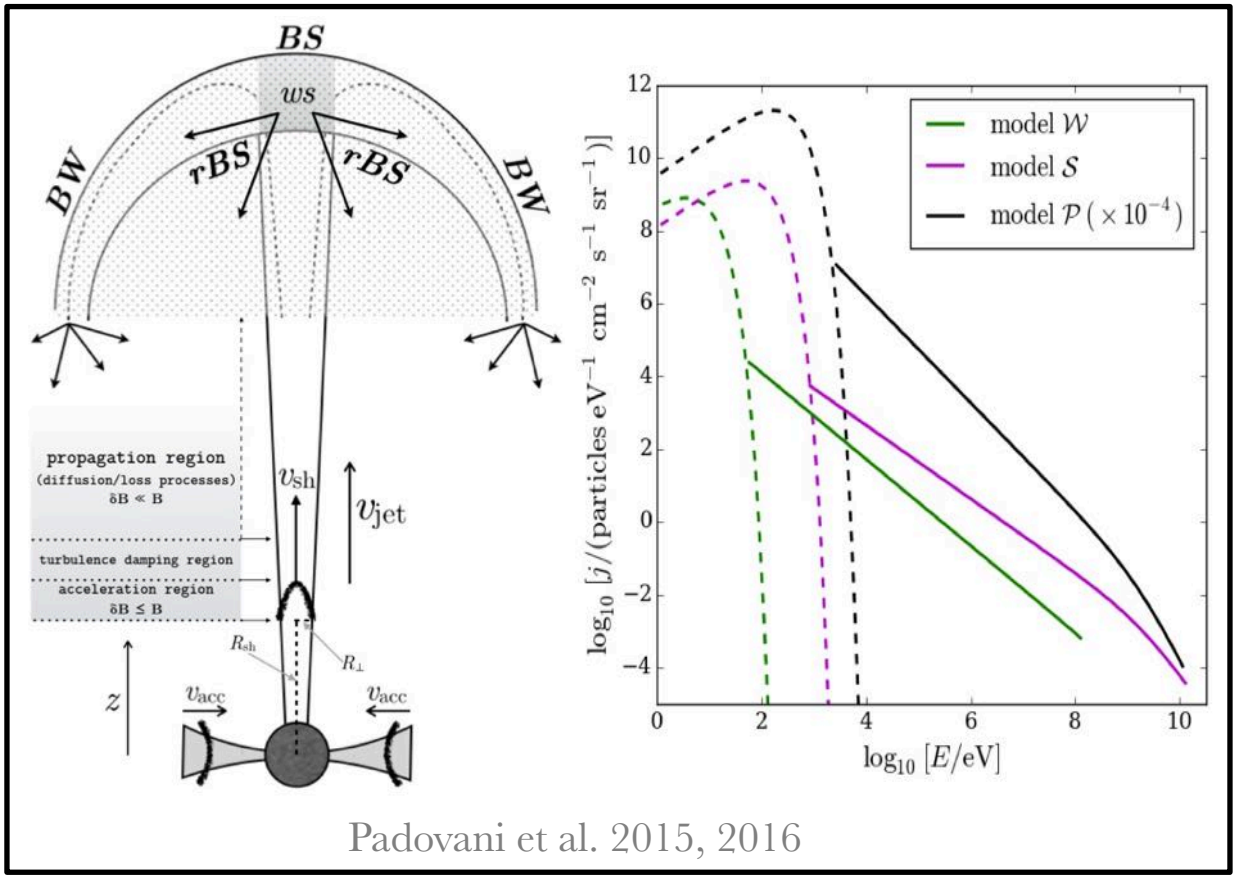
Physical mechanisms, nature of shocks

Astrochemistry

Energetic impacts and contribution to energetic balance of galaxies

Star formation scenarios through the mass-ladder (induced or inducing shocks)

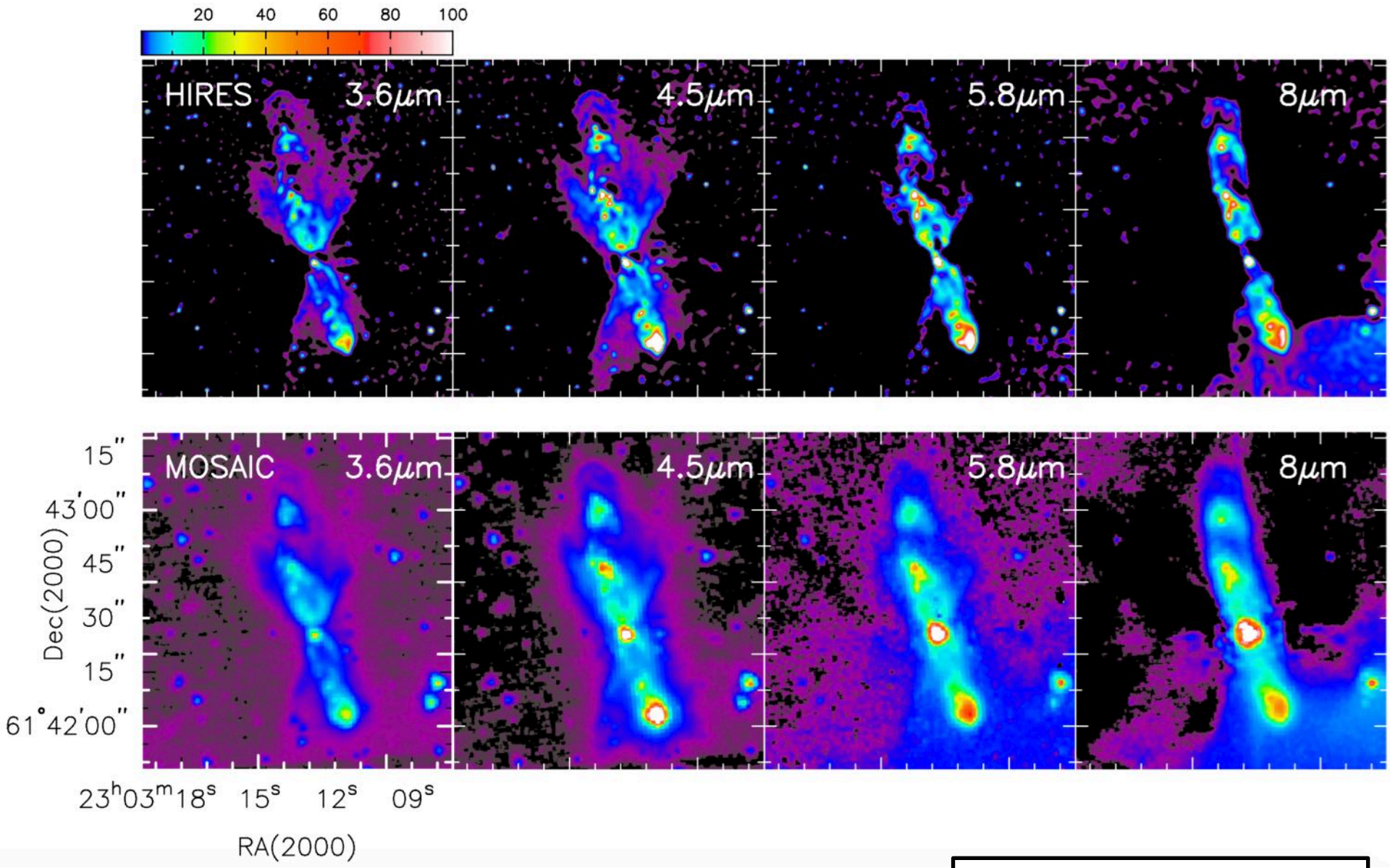
CR-related questions: acceleration, composition, propagation:
Araudo et al. 2007,
Bosch-Ramon et al. 2010,
Munar-Adrover et al. 2011,
Padovani et al. 2015, 2016



Padovani et al. 2015, 2016

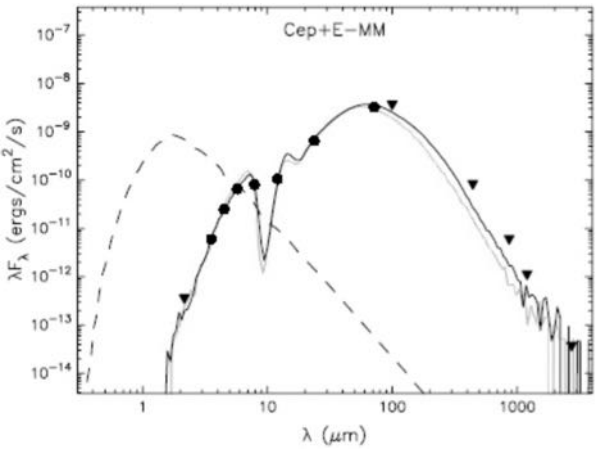
Previous studies of Cepheus E

Previous studies of Cep E

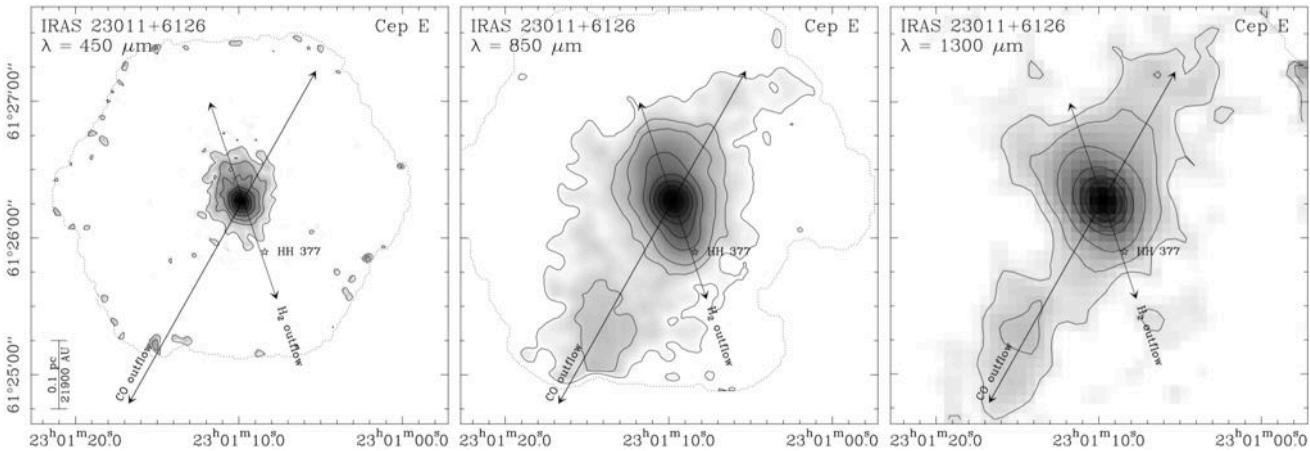


Velusamy et al. 2011

Previous studies of Cep E



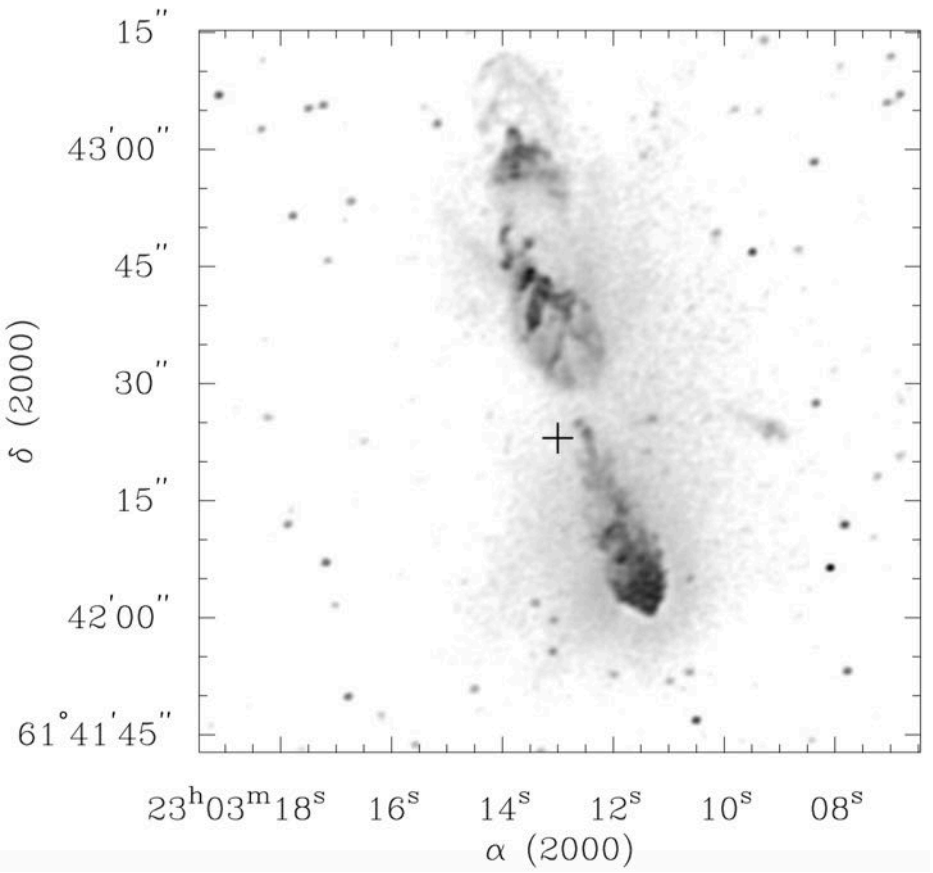
Velusamy et al. 2011



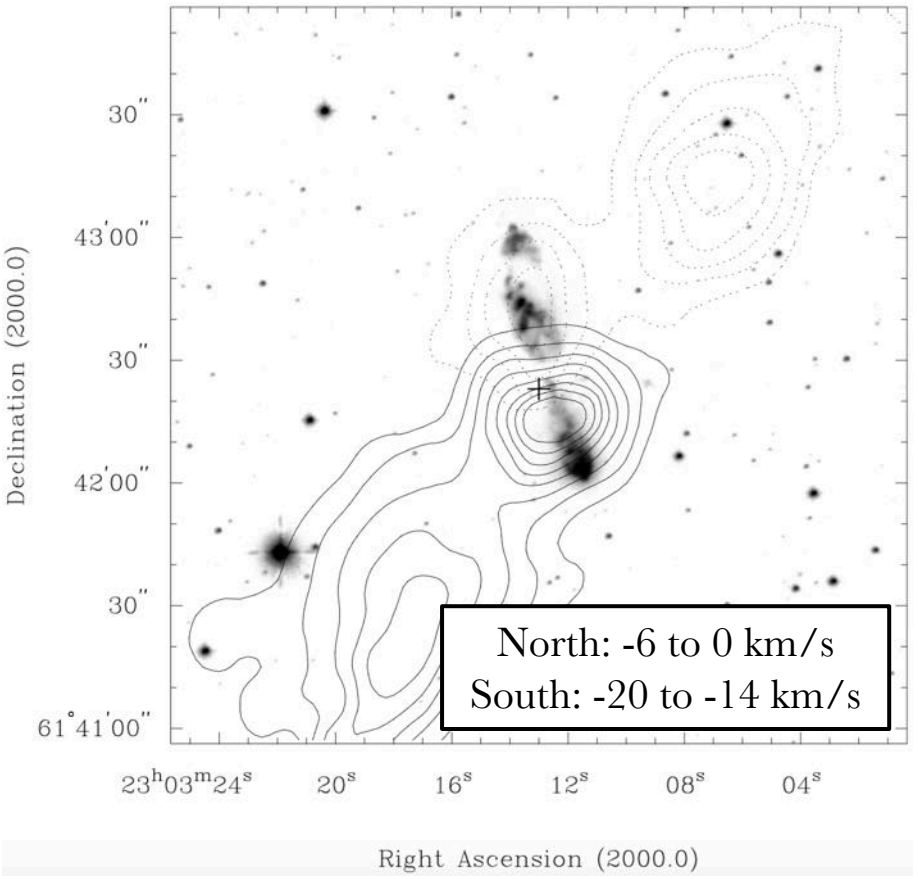
Chini et al. 2001

- Lefloch et al. 1996, Ladd & Hodapp 1997, Chini et al. 2001, Froebrich et al. 2003, Noriega-Crespo et al. 2004, Velusamy et al. 2011:
  - Class 0, few 10 000 yrs
  - $L \sim 100\ L_\odot$; $M \sim 3\ M_\odot$; $L_{smm} \sim 0.017\ L_{bol}$
  - $d = 730$ pc, $v_{lsr} = -11.2$ km/s
  - Compact cloud core: 0.18 pc size, 8 $M_\odot$
  - $M_{disk} \sim 7 \cdot 10^{-3}\ M_\odot$; $M_{disk}' \sim 3 \cdot 10^{-8}\ M_\odot/yr$
  - $M_{env} \sim 7.4\ M_\odot$; $M_{env}' \sim 10^{-4} M_\odot/yr$

Previous studies of Cep E



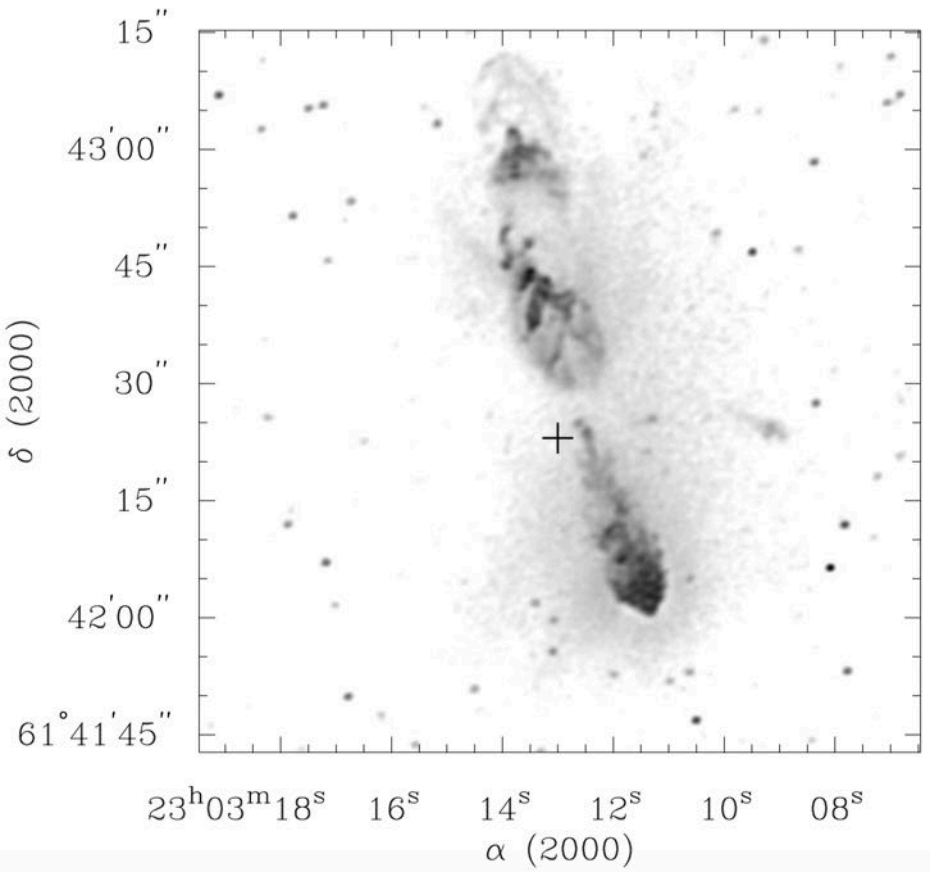
Cep E in H_2 1-0 S(1) at 2.12 μm…



…and CO (2-1)

Ladd & Hodapp 1997

Previous studies of Cep E



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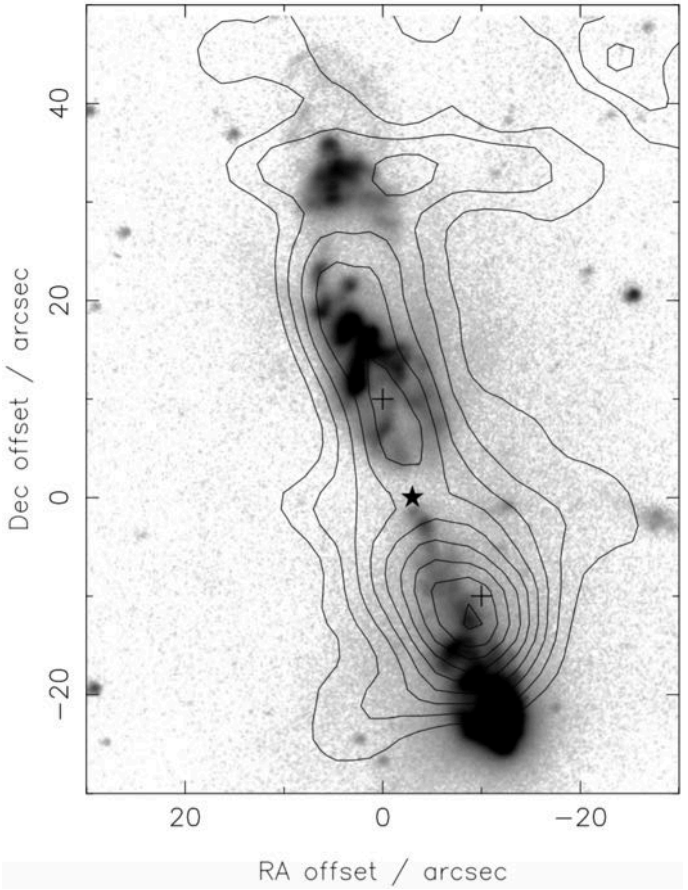


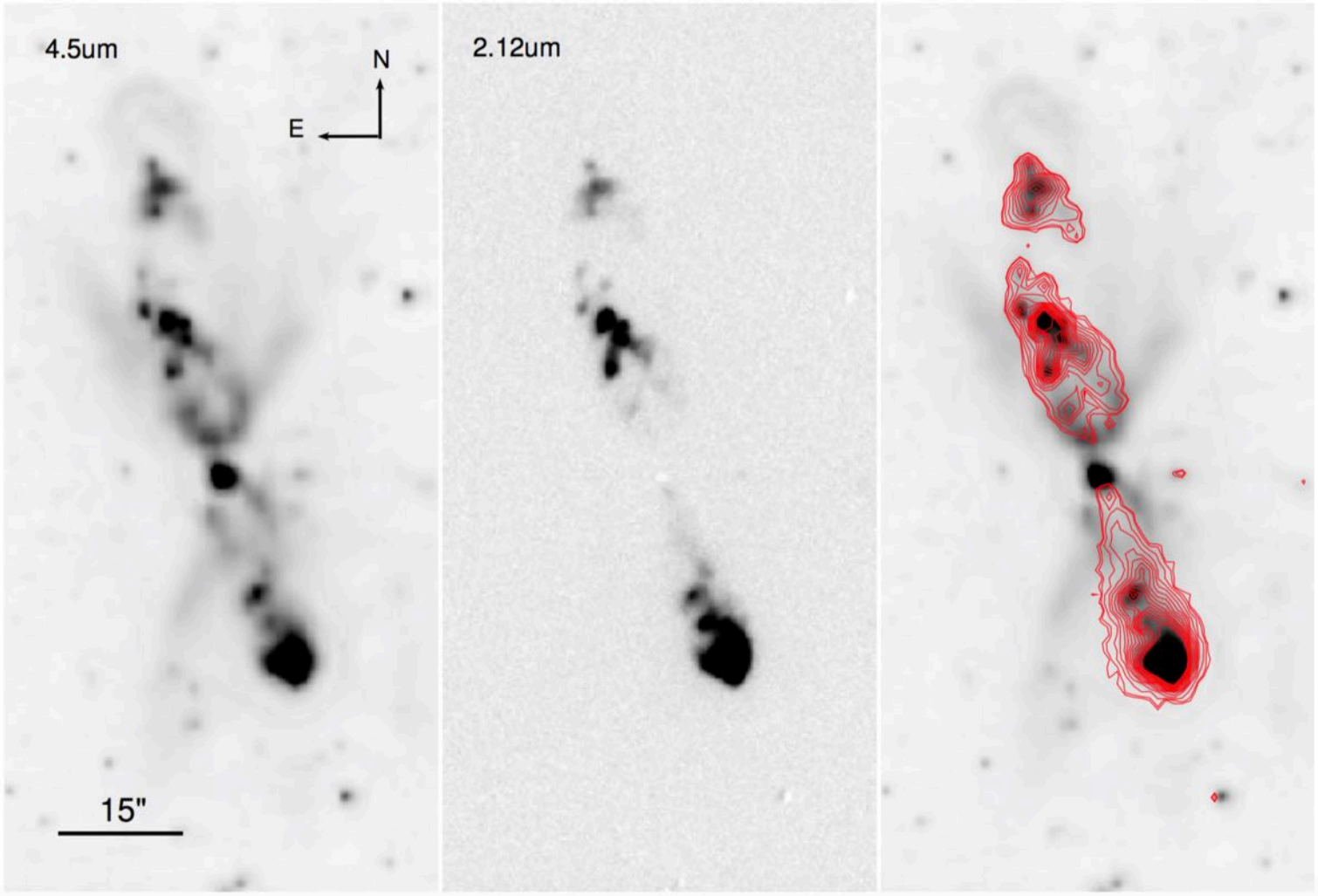
…and CO (4-3)

Ladd & Hodapp 1997, Hatchell et al. 1999

Previous studies of Cep E

- Numerous NIR, MIR and sub-mm observations (ISO, *Spitzer*, IRAM-30m):

Eislöffel et al. 1996, Noriega-Crespo et al. 1998, 2014, Moro-Martin et al. 2001, Smith et al. 2003, Lefloch et al. 2011, …



The SOFIA/GREAT observations: CO

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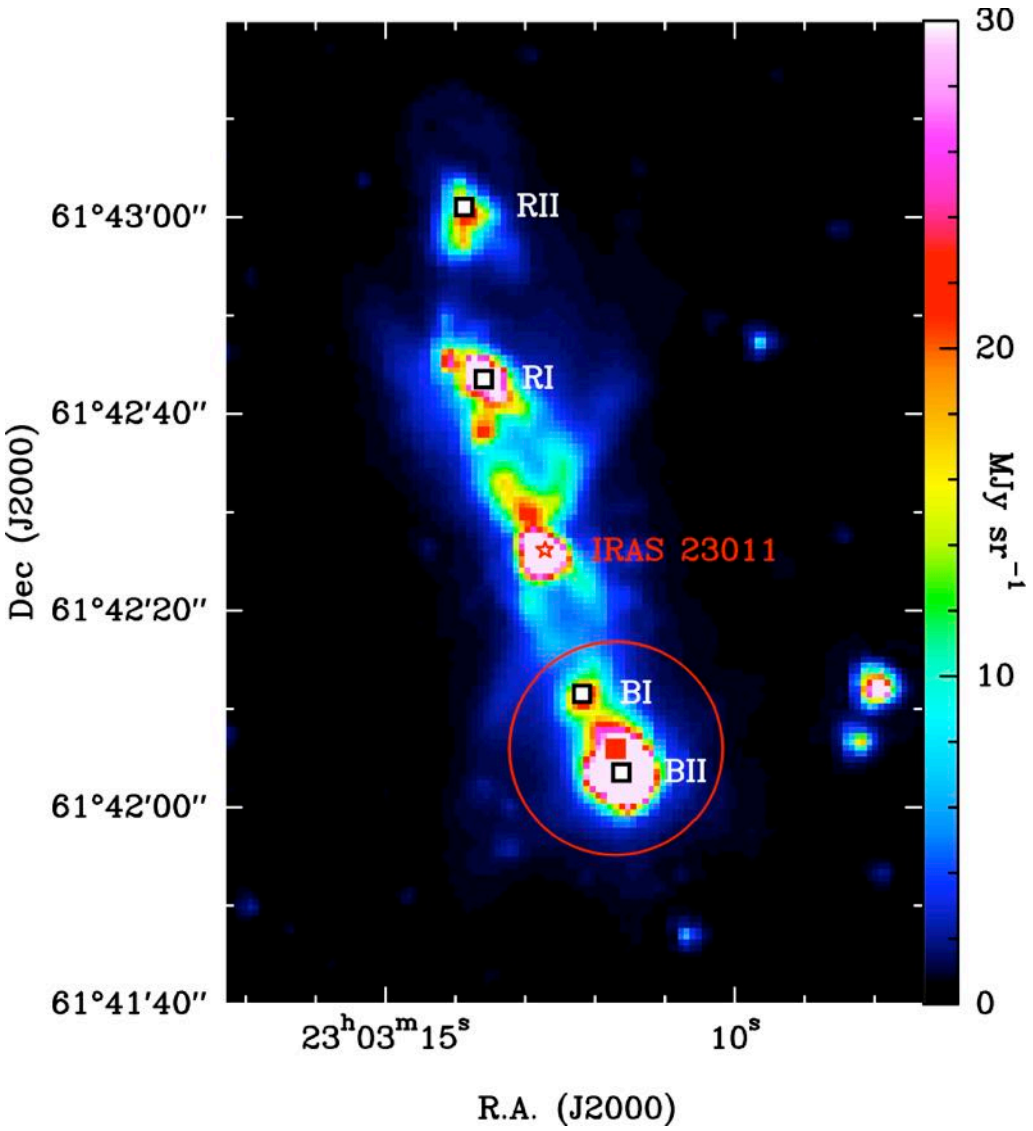
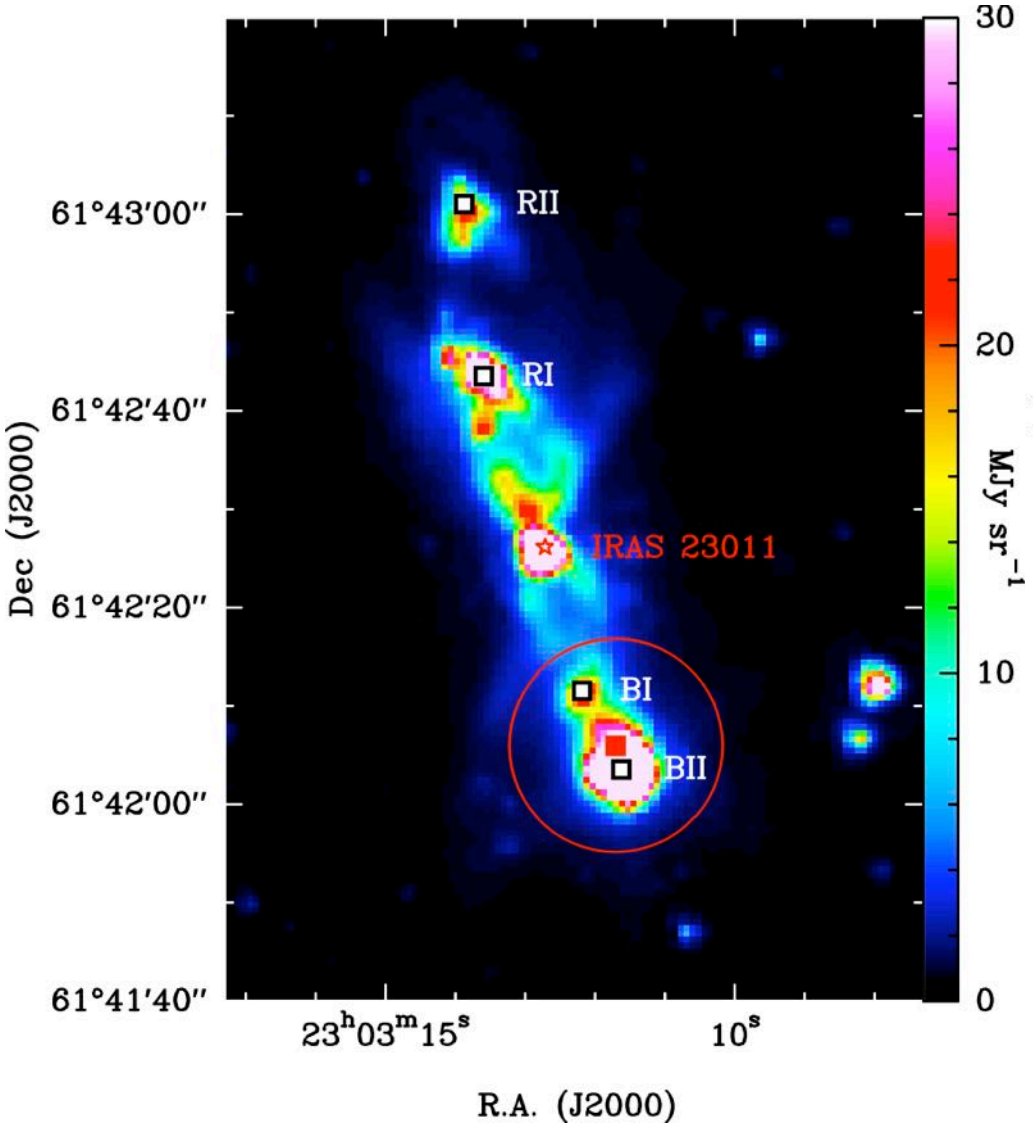
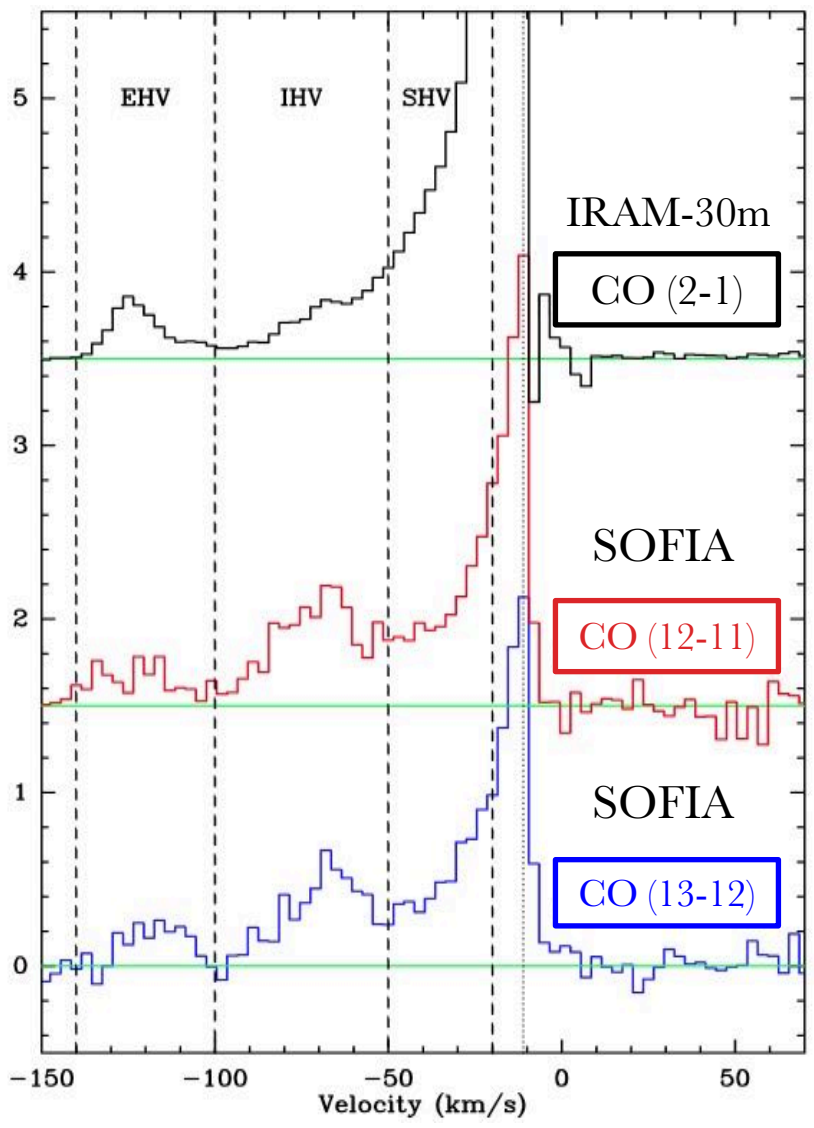


The Cep E outflow at 4.5 μm by *Spitzer*/IRAC

Gomez-Ruiz et al. 2012

The SOFIA/GREAT observations: CO





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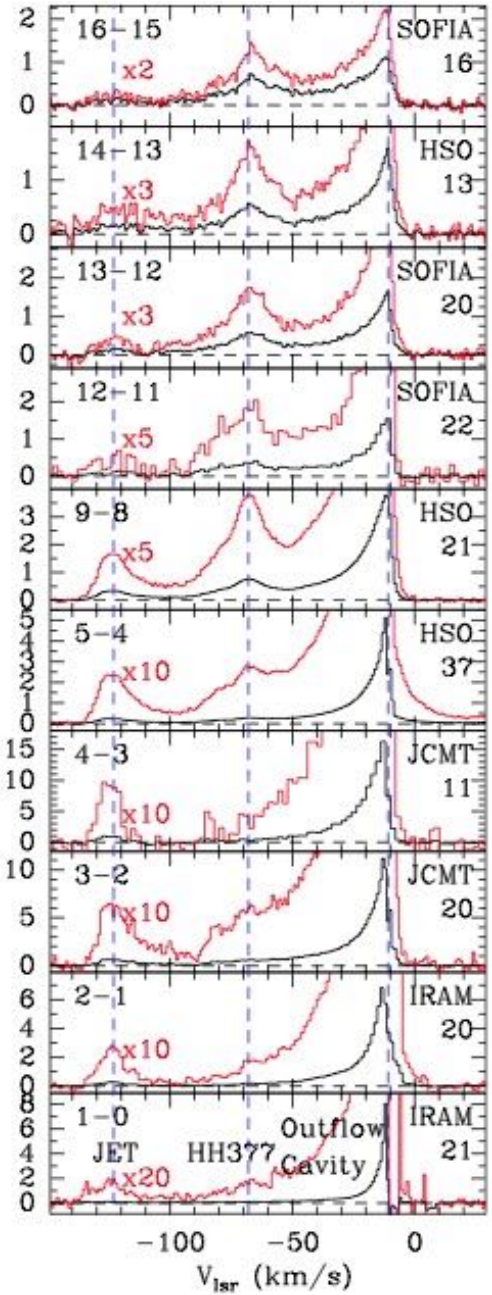
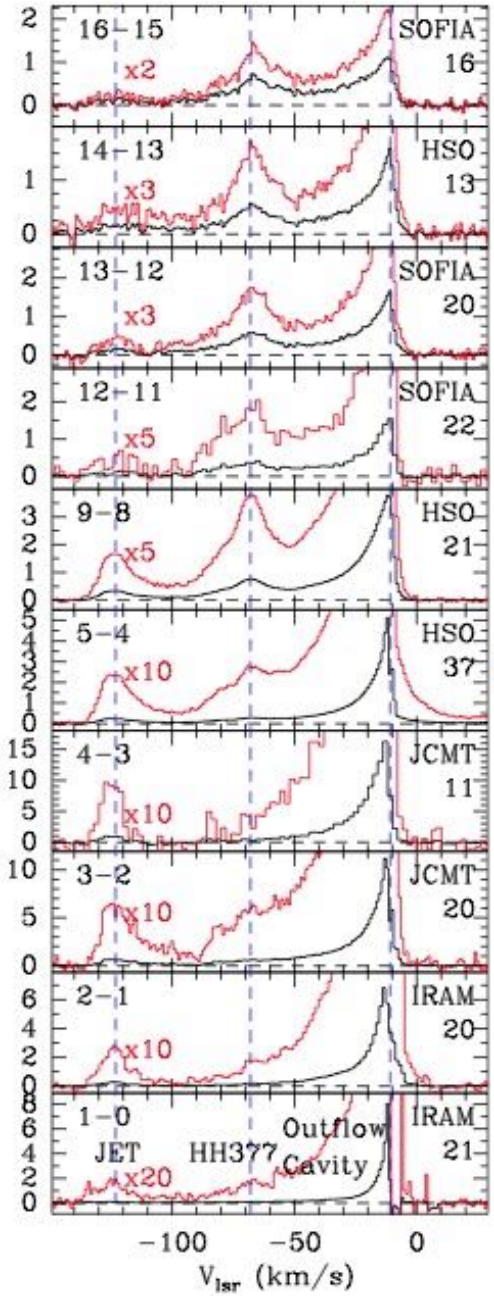


CO spectra: IRAM-30m, JCMT, *Herschel*, SOFIA

Also: ^{13}CO (2-1) by IRAM-30m and ^{13}CO (5-4) by *Herschel*

The SOFIA/GREAT observations: CO



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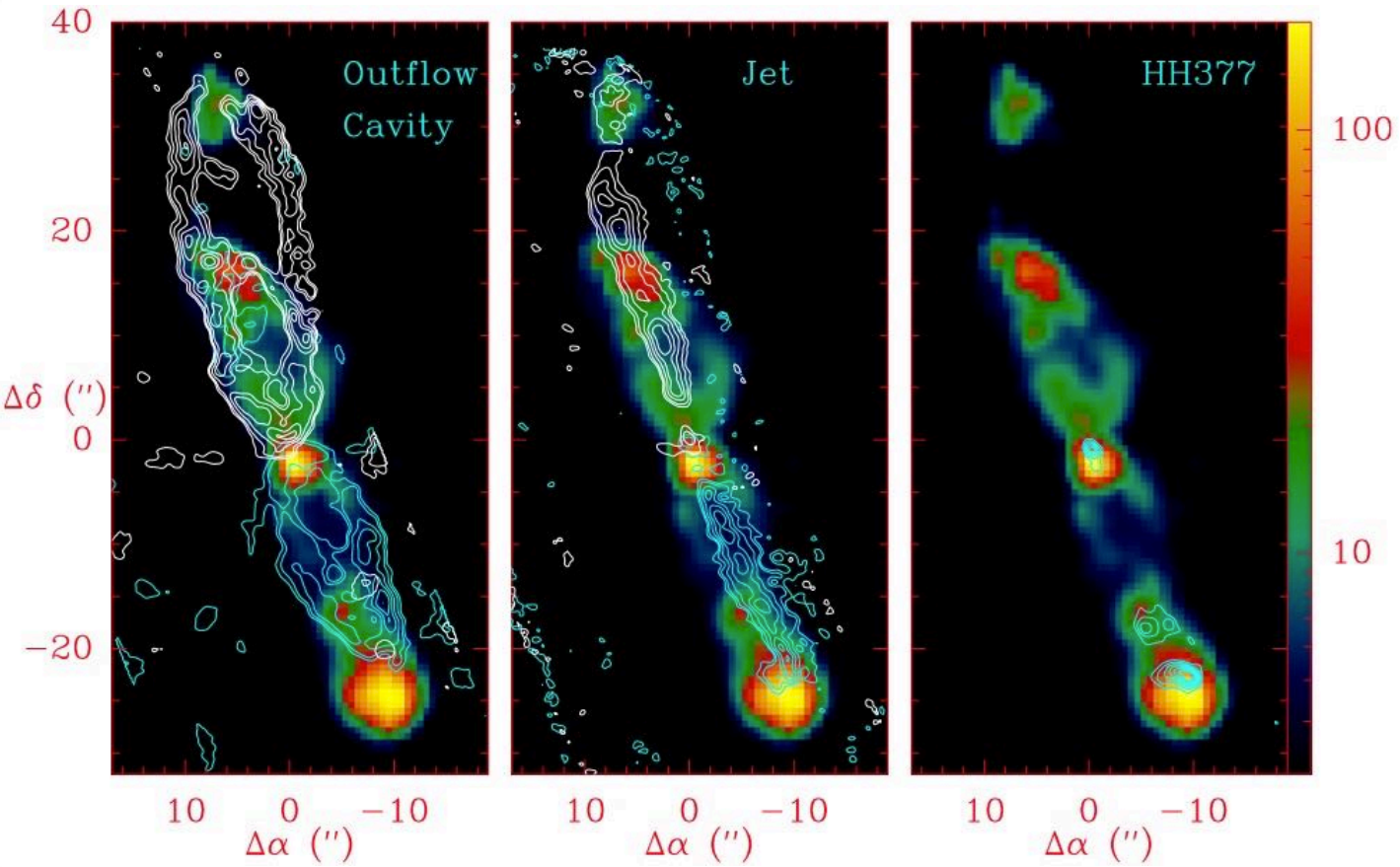
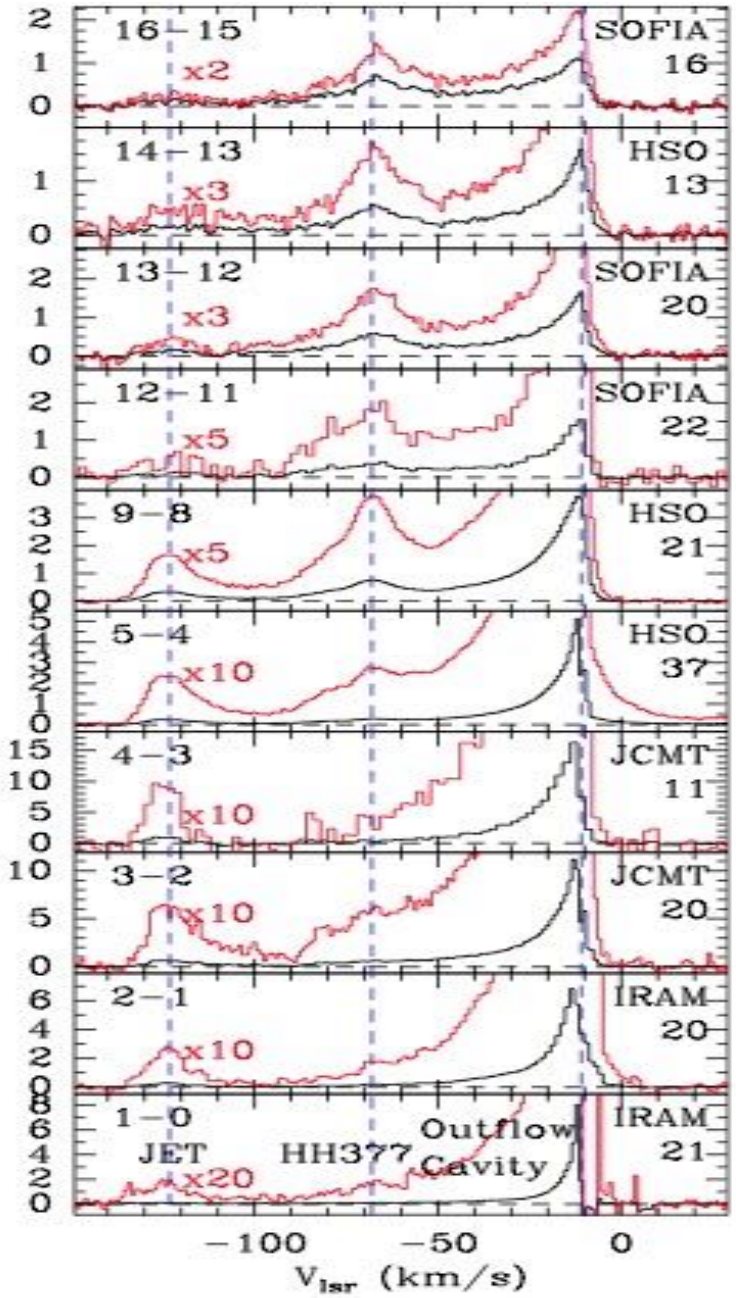
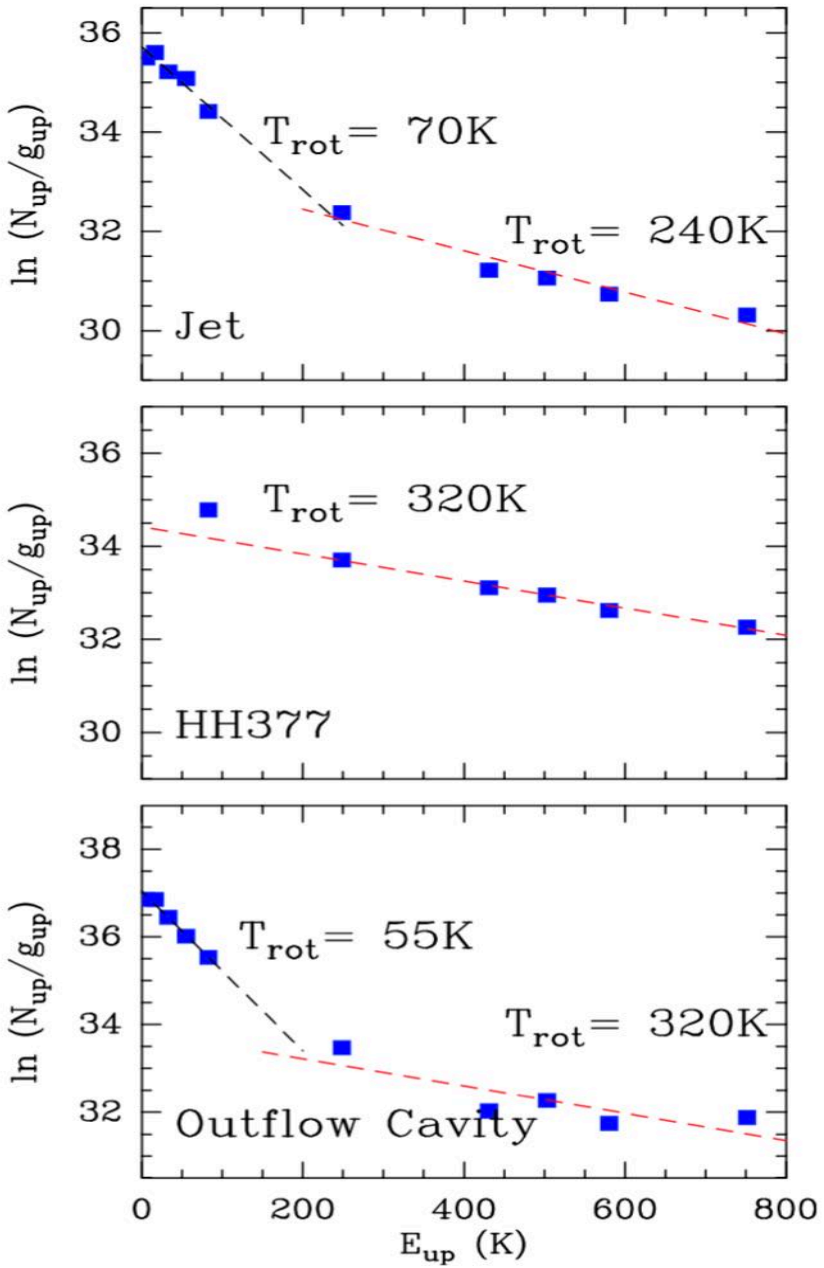


The Cep E outflow in CO (2-1) by the PdBI, Lefloch et al. 2015

The SOFIA/GREAT observations: CO





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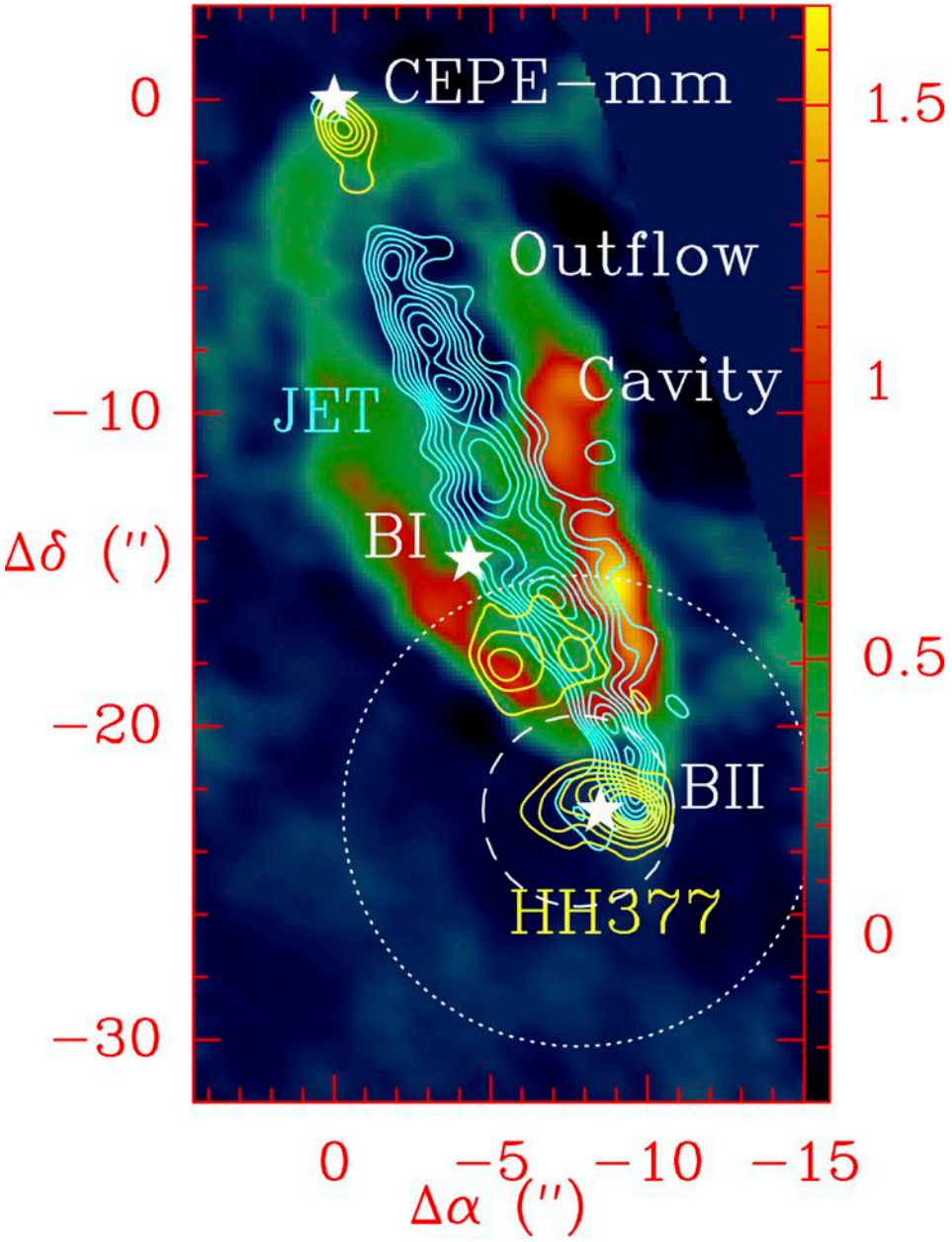


- Jet, cavity, HH 377: CO

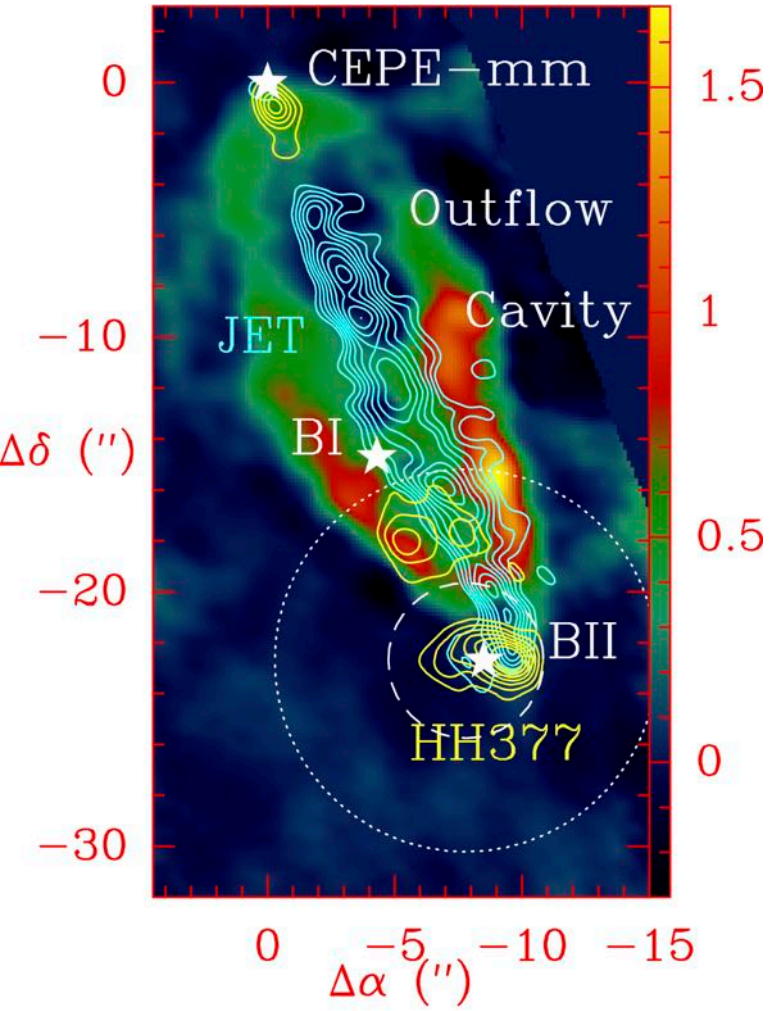
LVG analysis => (N, T_{kin}) estimates

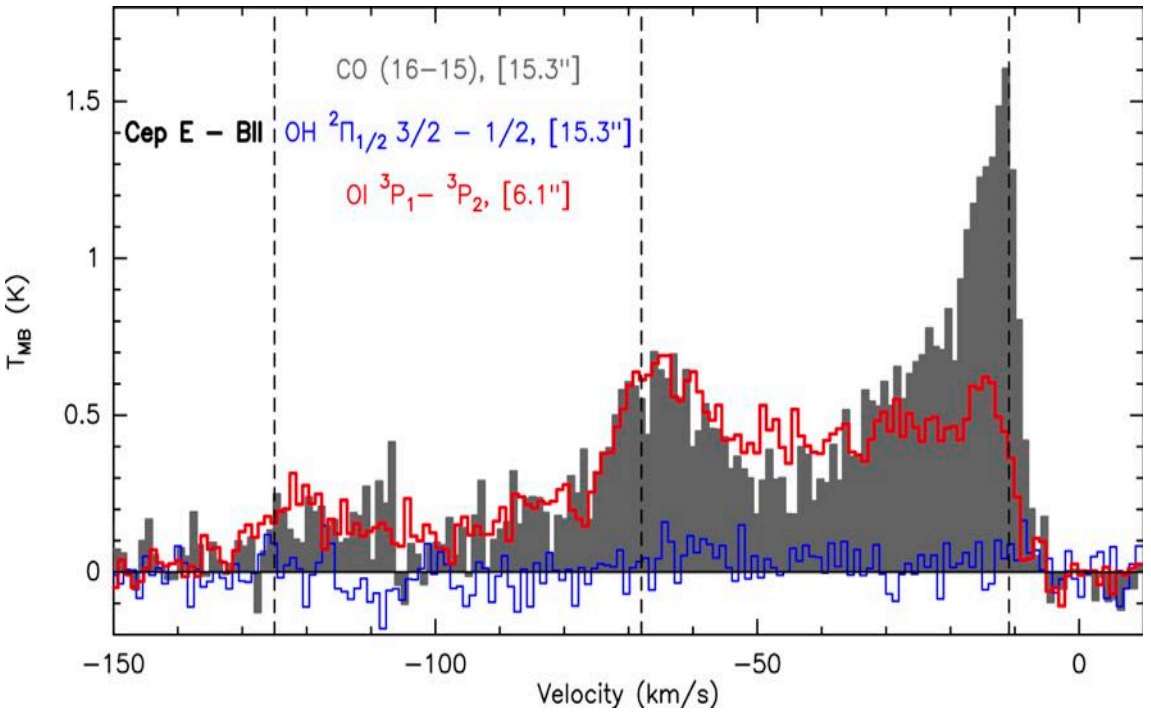
- Southern lobe:
  - jet mass: 0.02 $M_\odot$, 1.7 $M_\odot$km/s
  - outflow cavity mass: 0.32 $M_\odot$, 2.8 $M_\odot$km/s

$\Rightarrow$ molecular jet driven bowshock

The SOFIA/GREAT observations: [OI]

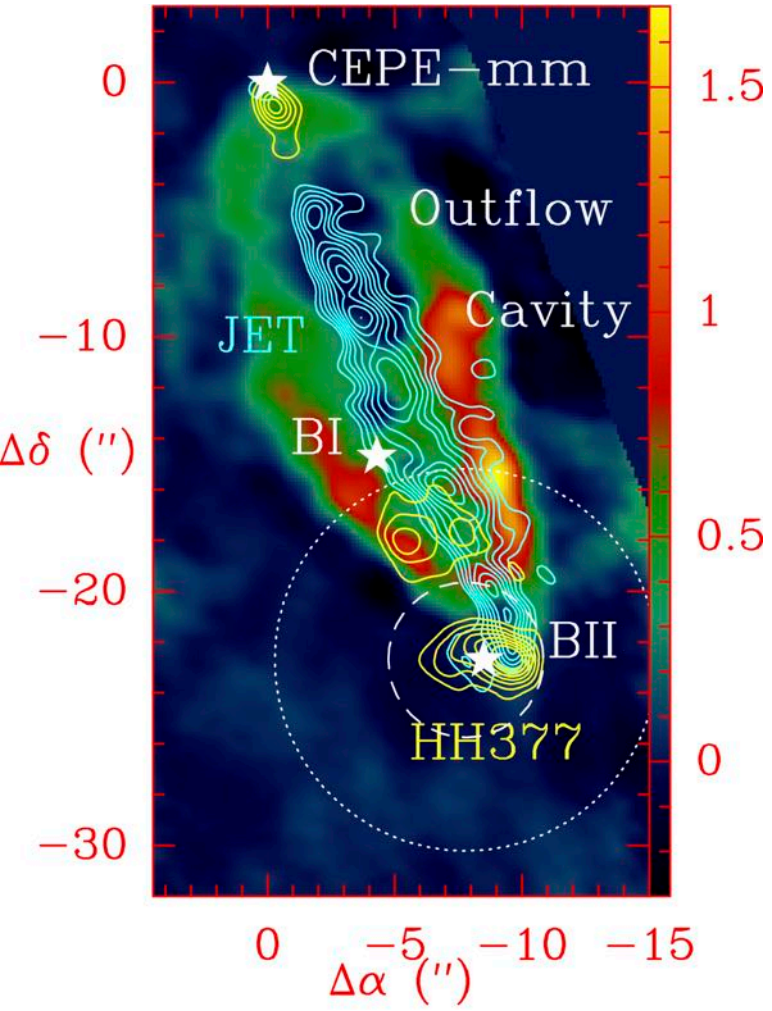
The SOFIA/GREAT observations: [OI]

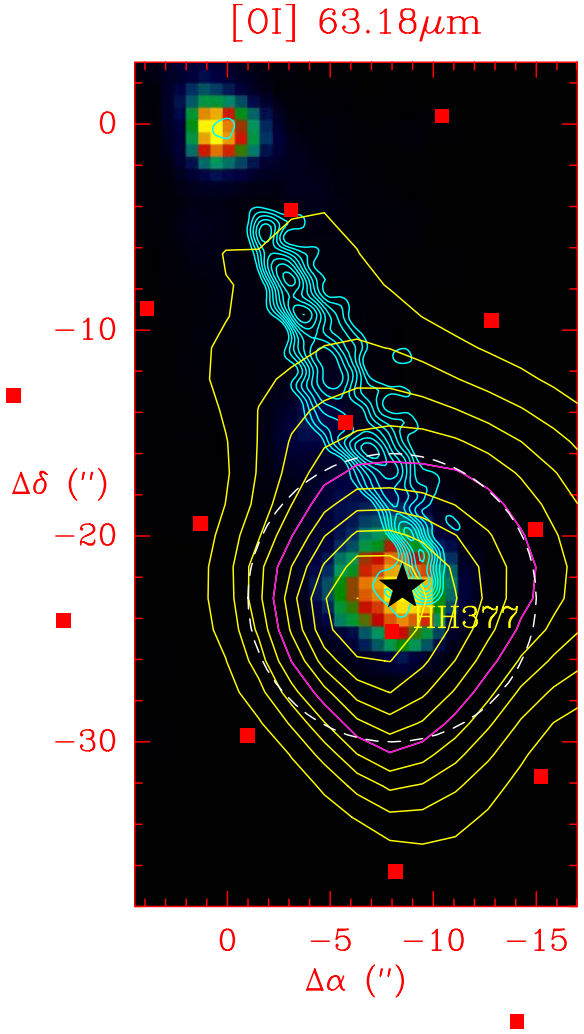




Gusdorf et al., 2017

The SOFIA/GREAT observations: [OI]

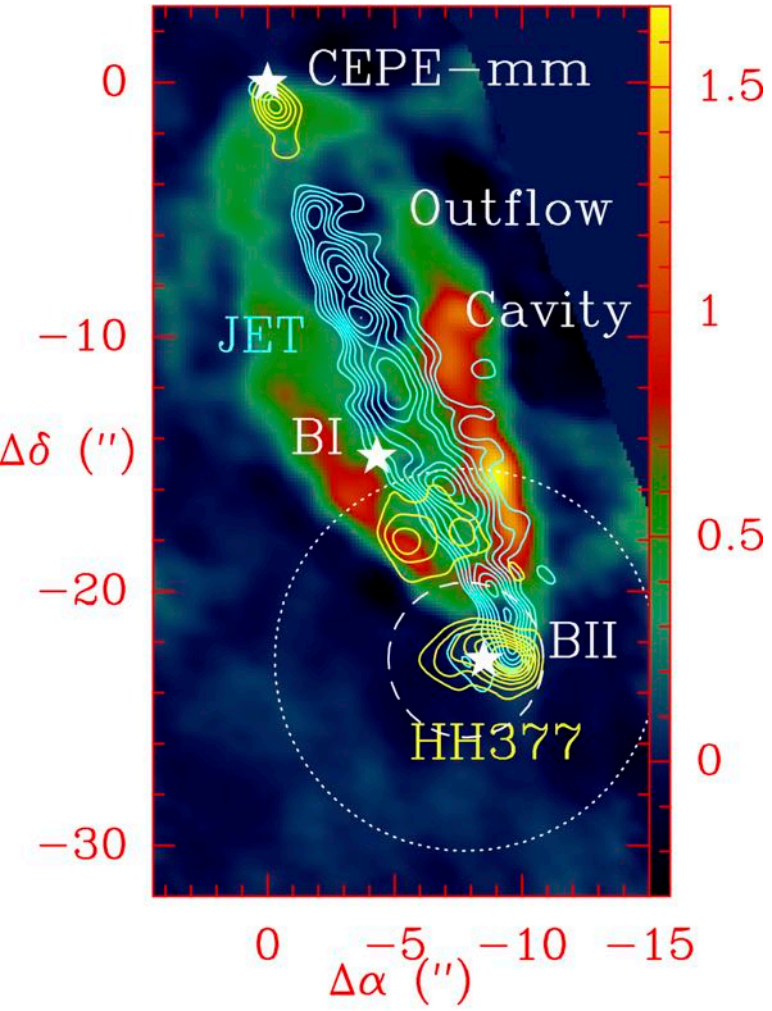


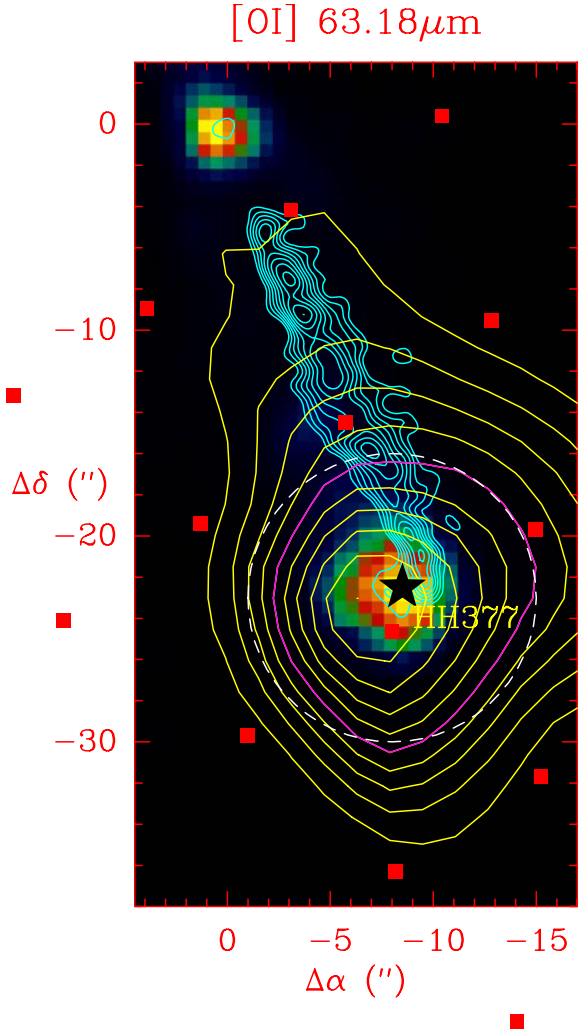


Spitzer/IRAC 3.6 μm
PdBI CO (2-1) jet
Herschel/PACS $[OI]_{63\ \mu m}$

Gusdorf et al., 2017

The SOFIA/GREAT observations: [OI]



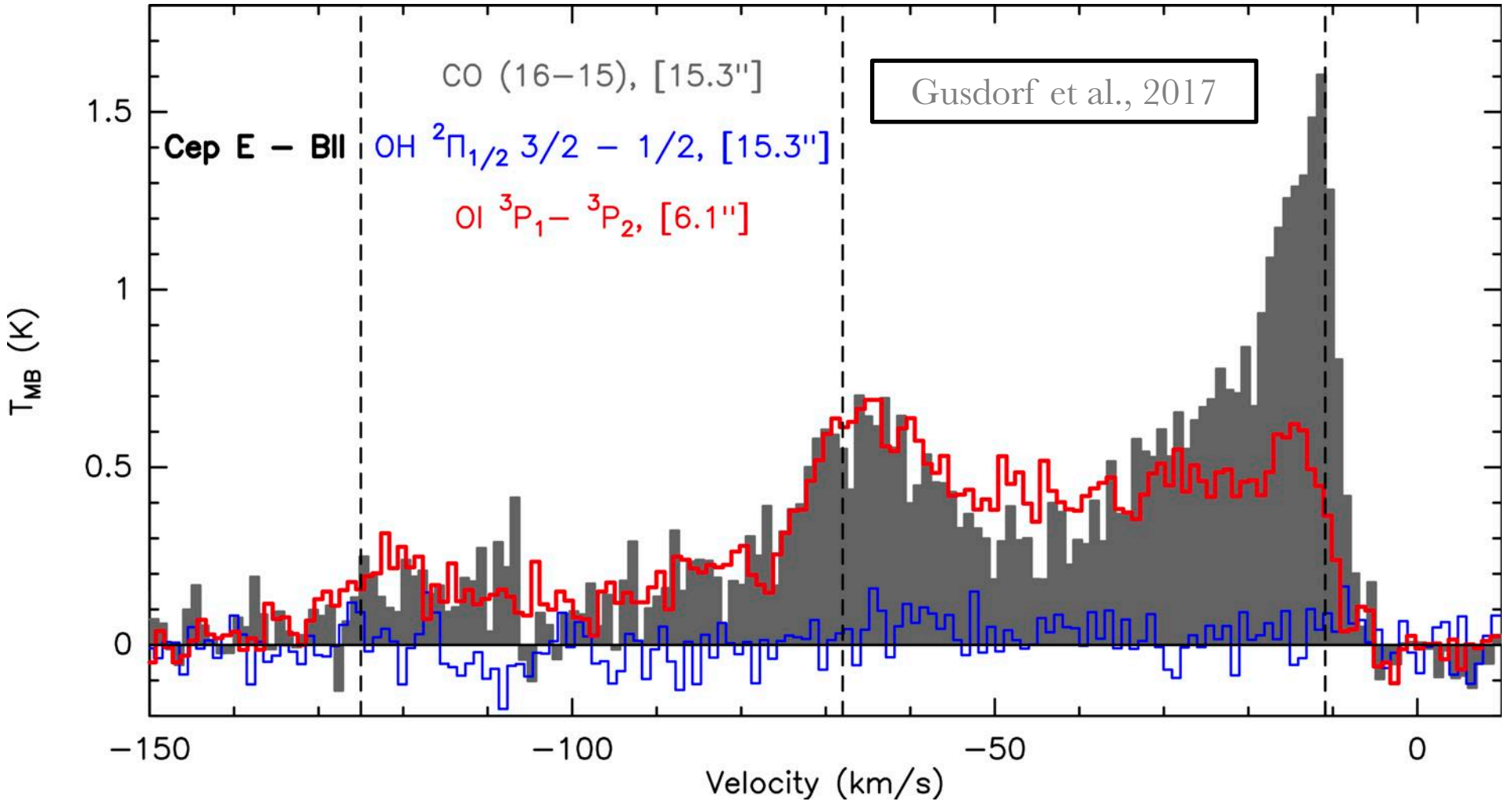


Spitzer/IRAC 3.6 μm
PdBI CO (2-1) jet
Herschel/PACS $[OI]_{63\ \mu m}$

Gusdorf et al., 2017

Component	Jet	Bow-shock	Outflow cavity
Filling factor OI $^3P_1 \rightarrow {}^3P_2$	0.25 ± 0.05	0.55 ± 0.15	<1
Filling factor CO (16–15)	0.09	0.06	0.15

The SOFIA/GREAT observations: [OI]



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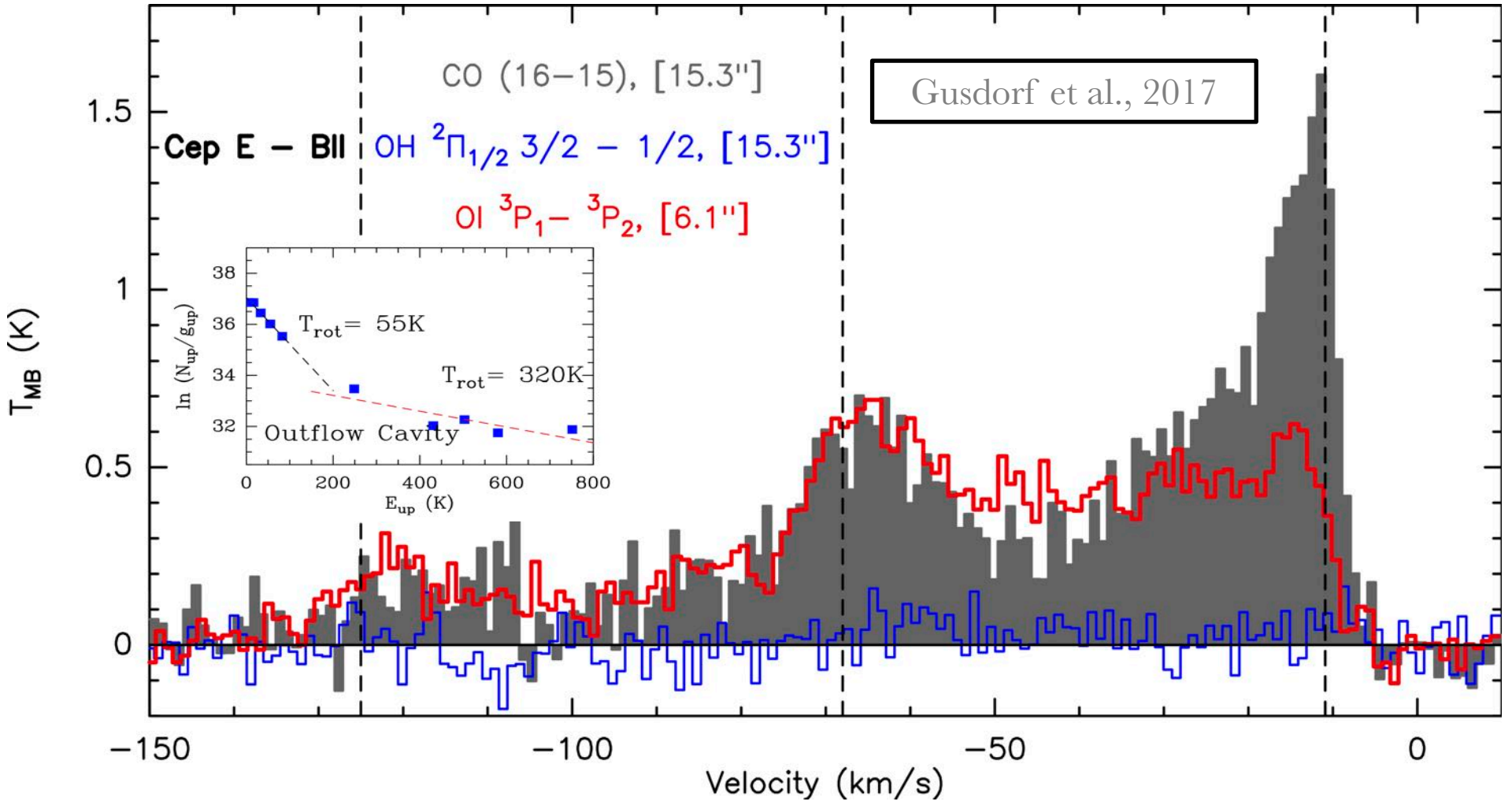

The SOFIA/GREAT observations: [OI]

	Component	Jet	Bow-shock	outflow cavity
Low-excitation assumption	N(CO) (10^{16} cm^{-2})	9.0	–	70.0
	T_{kin} (K)	80–100	–	55–85
	n (cm^{-3})	(0.5–1) × 10^5	–	(1–8) × 10^5
	N(O I) (10^{16} cm^{-2})	24.6 ± 8.5	–	>24.8
	N(O I)/N(CO)	2.7 ± 0.9	–	>0.4
High-excitation assumption	N(CO) (10^{16} cm^{-2})	1.5	10.0	6.0
	T_{kin} (K)	400–750	400–500	500–1500
	n (cm^{-3})	(0.5–1) × 10^6	(1.0–2.0) × 10^6	(1–5) × 10^6
	N(O I) (10^{16} cm^{-2})	4.0 ± 1.0	2.1 ± 0.6	>4.9
	N(O I)/N(CO)	2.7 ± 0.6	0.2 ± 0.1	>0.8

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High-excitation assumption	N(CO) (10^{16} cm^{-2})	1.5	10.0	6.0
	T_{kin} (K)	400–750	400–500	500–1500
	n (cm^{-3})	(0.5–1) × 10^6	(1.0–2.0) × 10^6	(1–5) × 10^6
	N(O I) (10^{16} cm^{-2})	4.0 ± 1.0	2.1 ± 0.6	>4.9
	N(O I)/N(CO)	2.7 ± 0.6	0.2 ± 0.1	>0.8

Shock modelling in Cepheus E

Shock modelling in Cepheus E

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

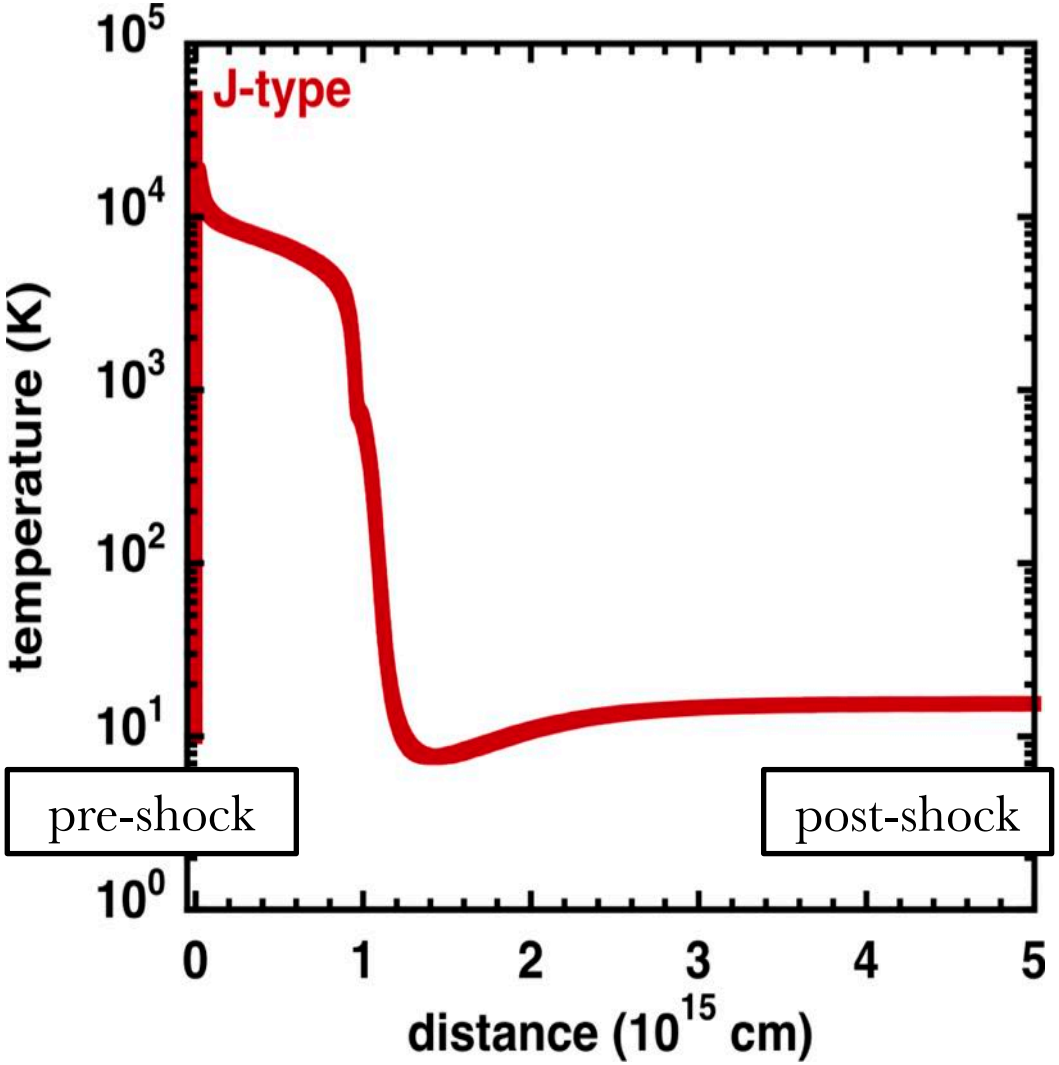
- J shock (Jump) ;

B = 10 μG

$v_s > v_{critical}$

impulse heating ;

single fluid



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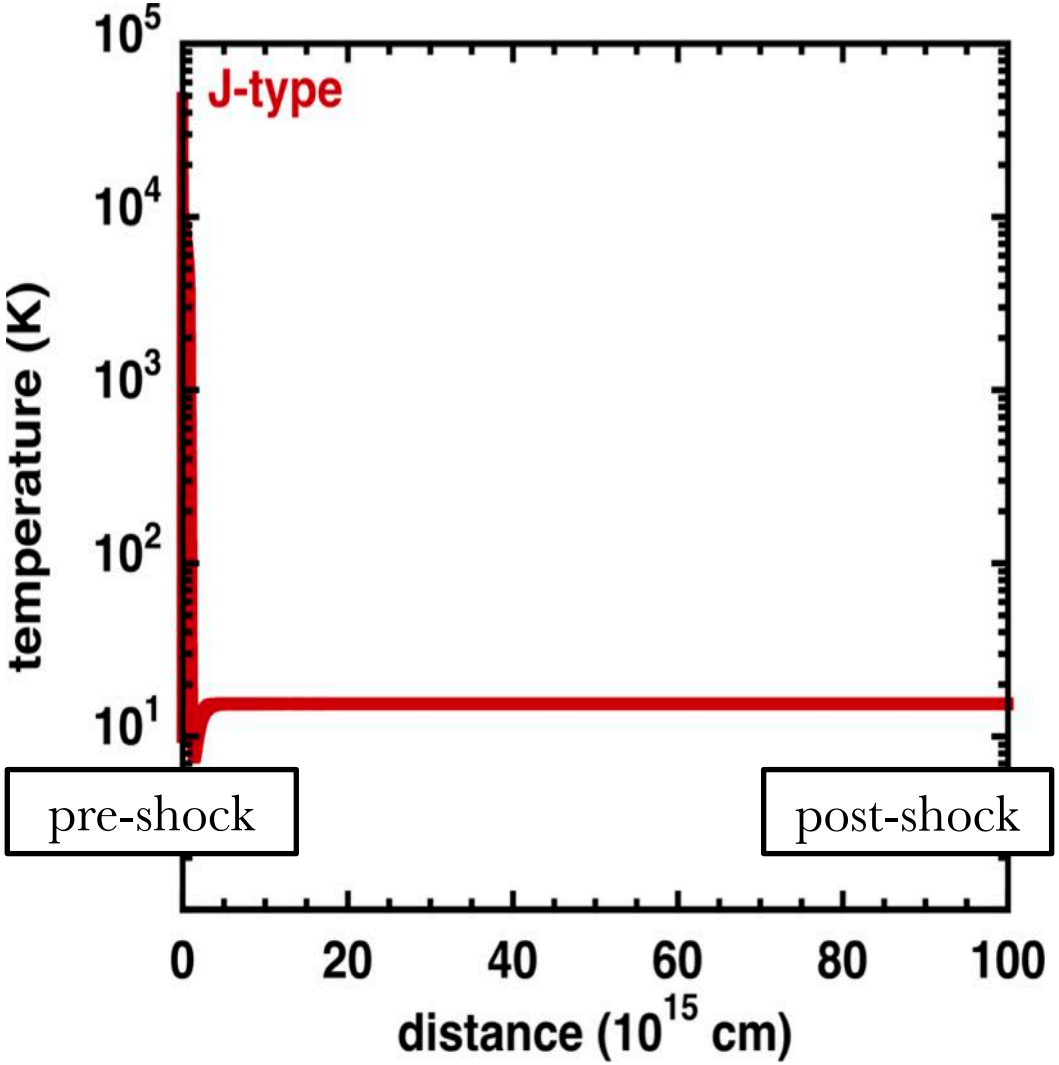


Shock modelling in Cepheus E

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

- J shock (Jump) ;

B = 10 μG

$v_s > v_{critical}$

impulse heating ;

single fluid

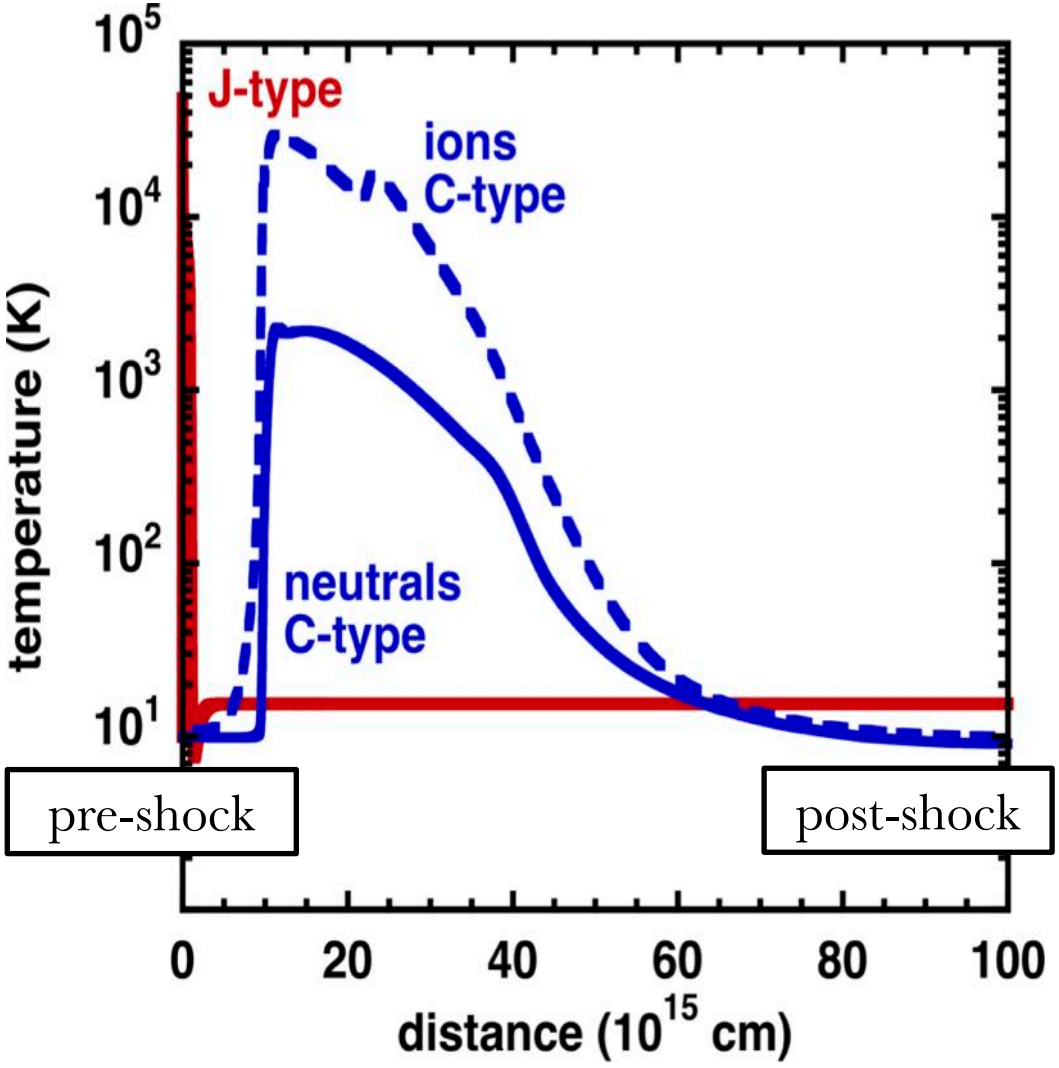
- C shock (Continuous) ;

B = 100 μG

$v_s < v_{critical}$

ion-neutral friction ;

multi-fluid



Shock modelling in Cepheus E

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

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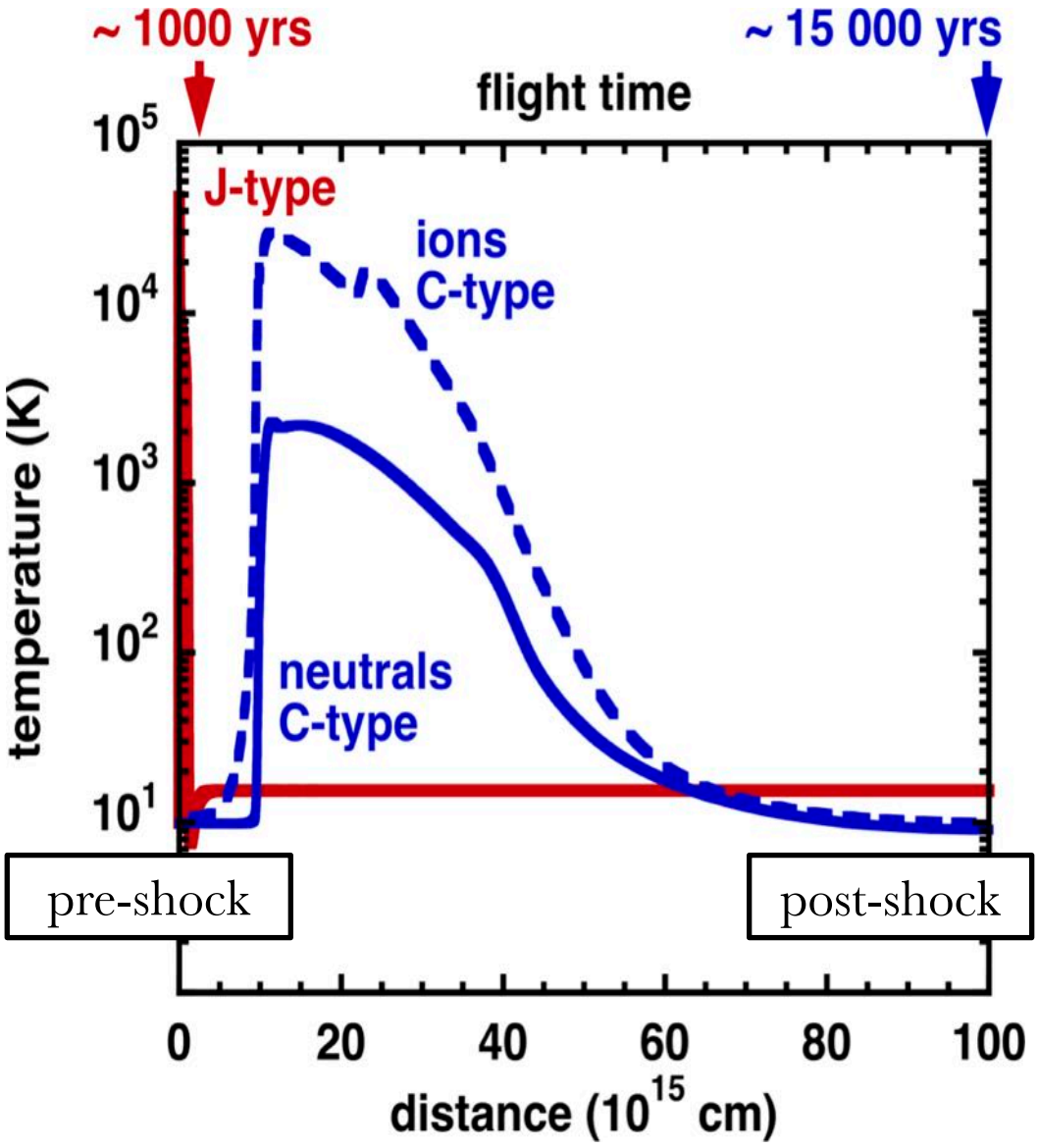


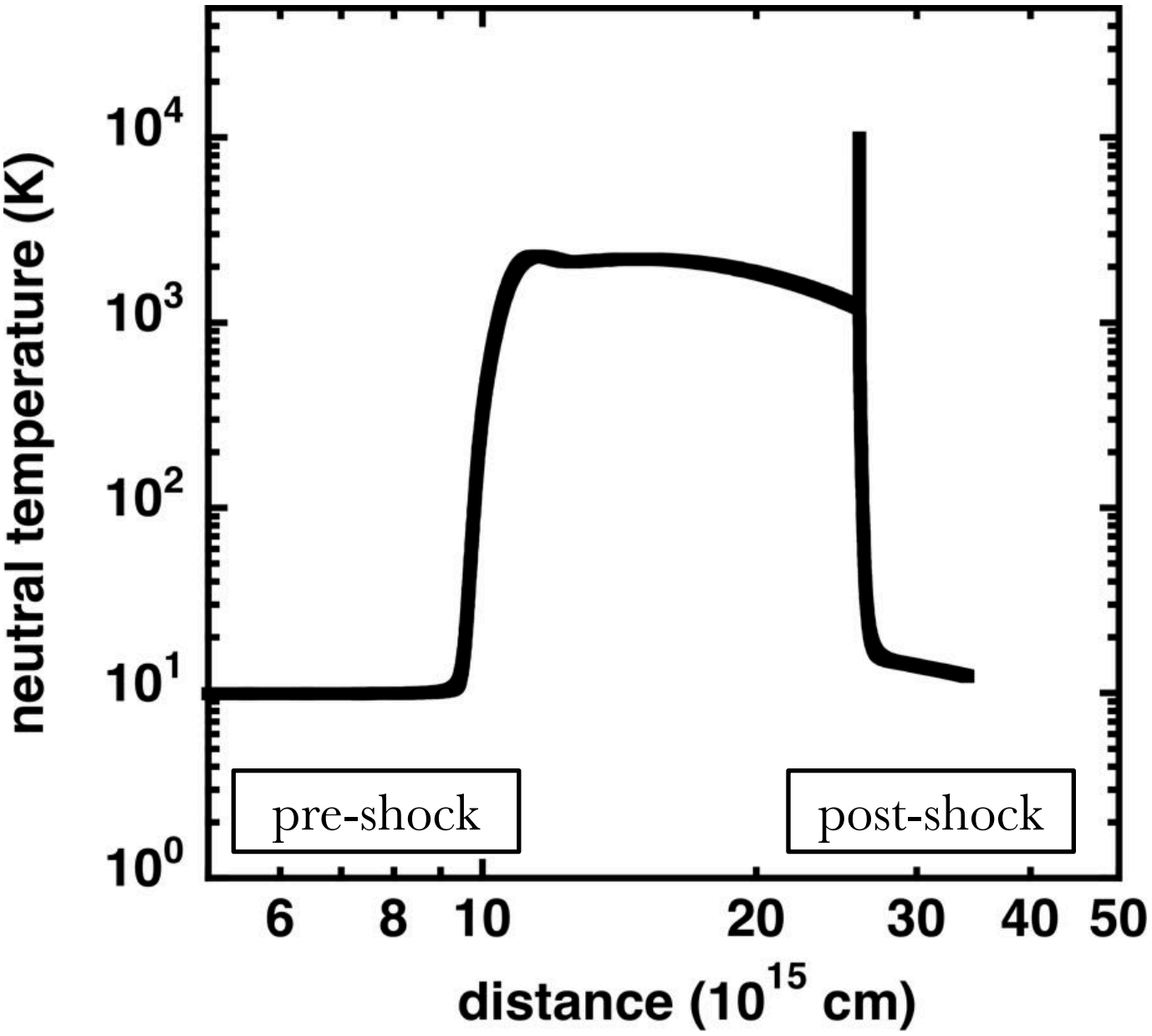
Shock modelling in Cepheus E

$n_H = 10^4$ cm^{-3}

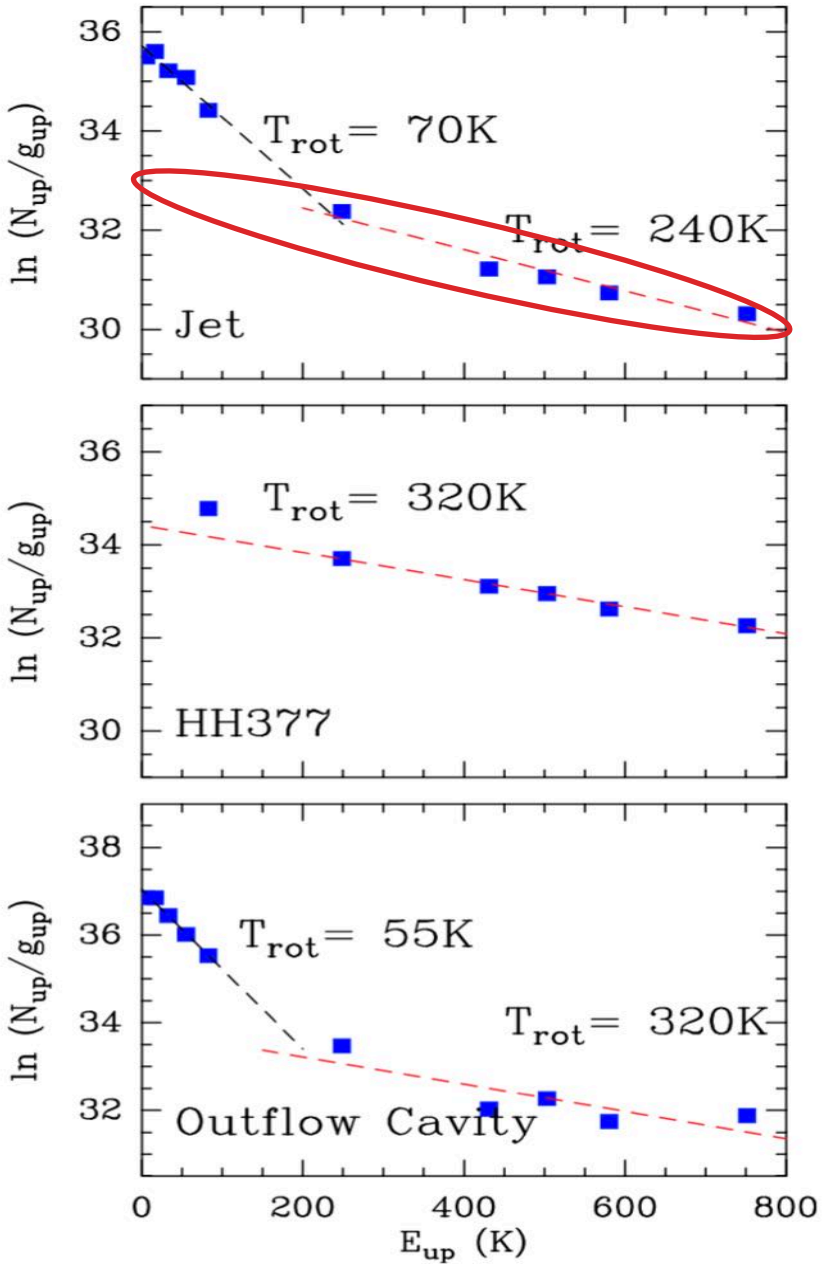
$v_s = 30$ km/s

age 2000 yrs

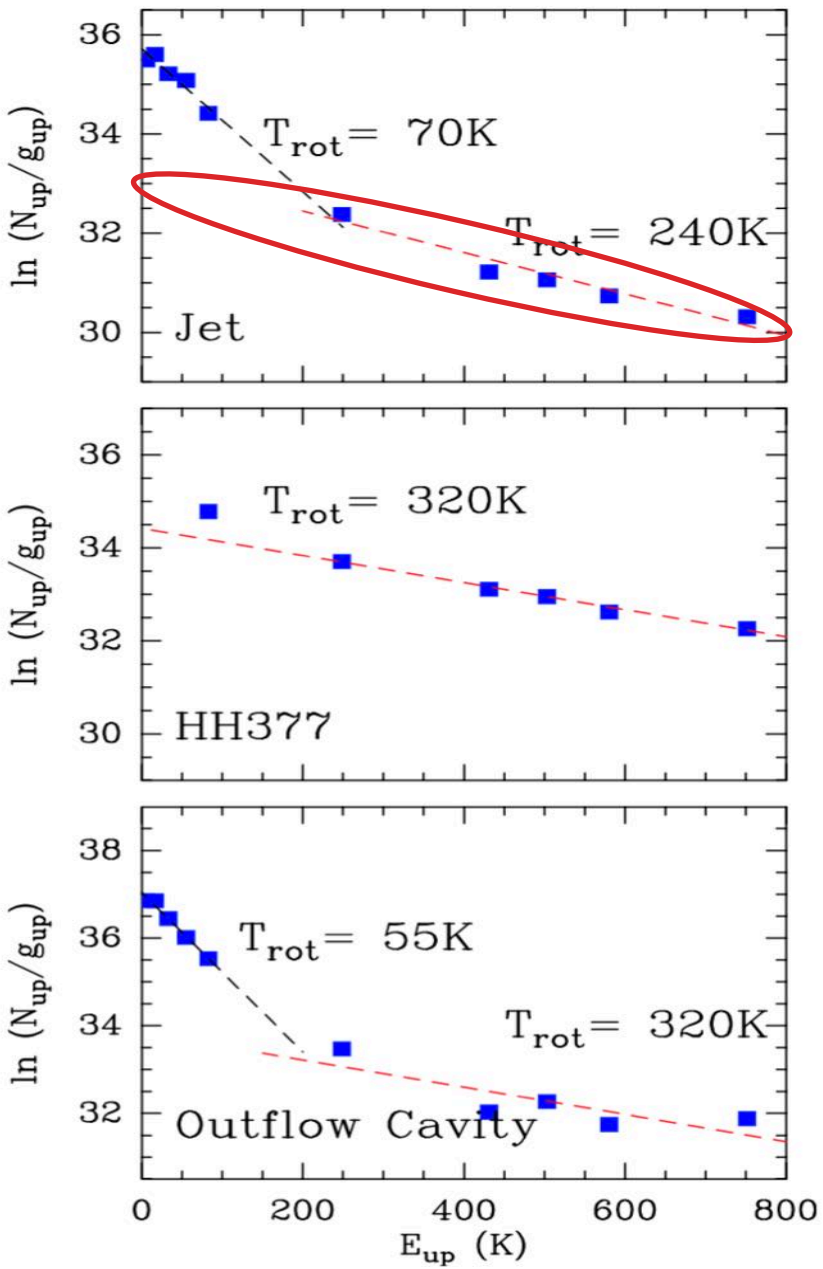
CJ shock

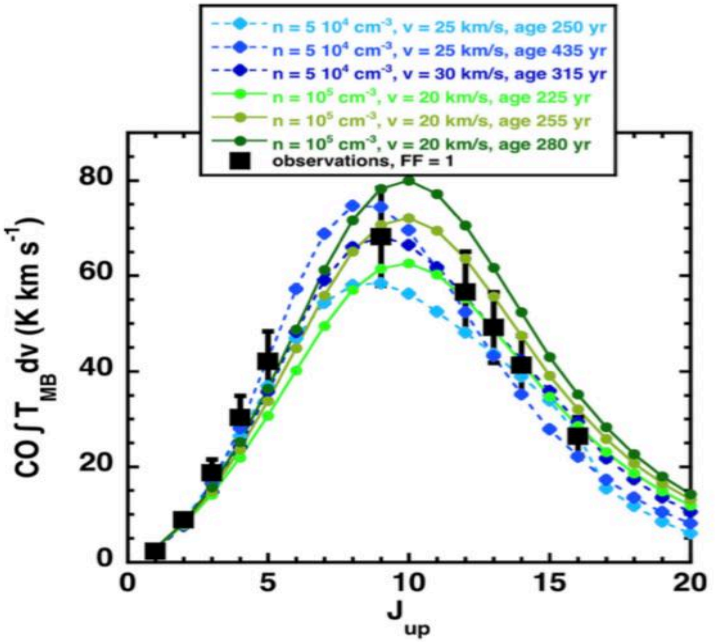


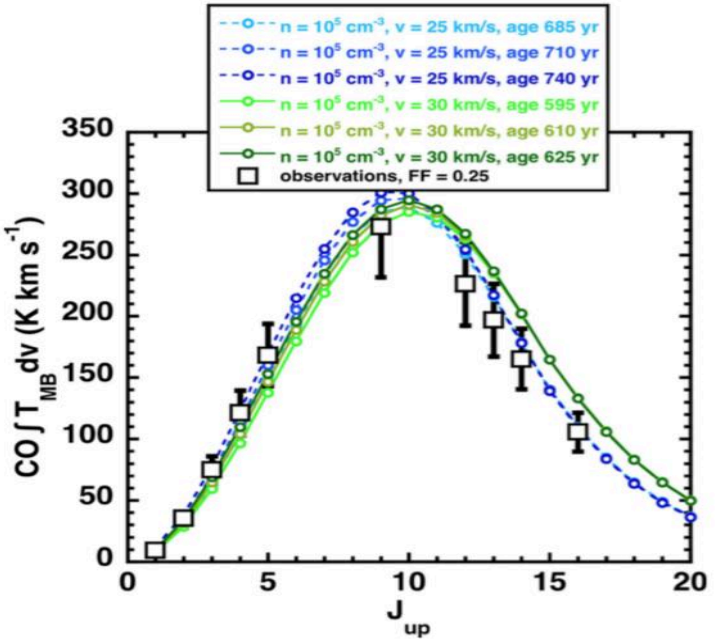
Shock modelling in Cepheus E



Shock modelling in Cepheus E



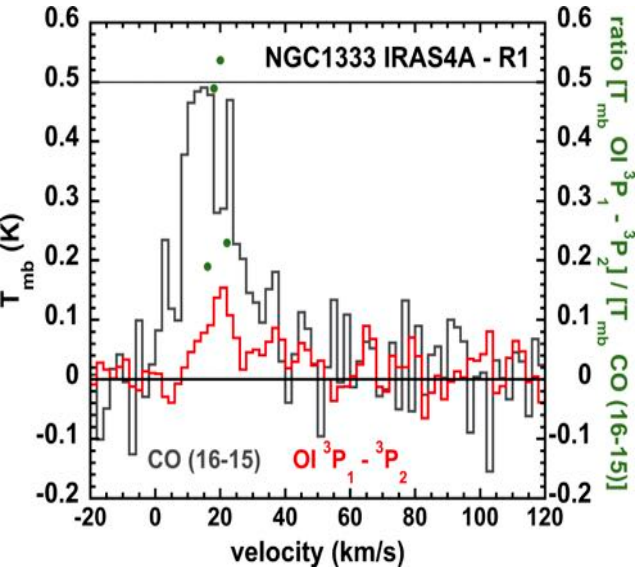




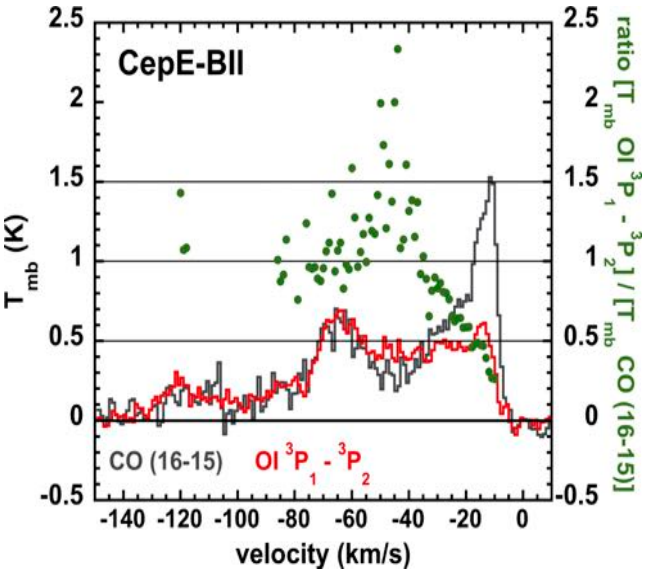
Shock modelling in Cepheus E

From low-mass…

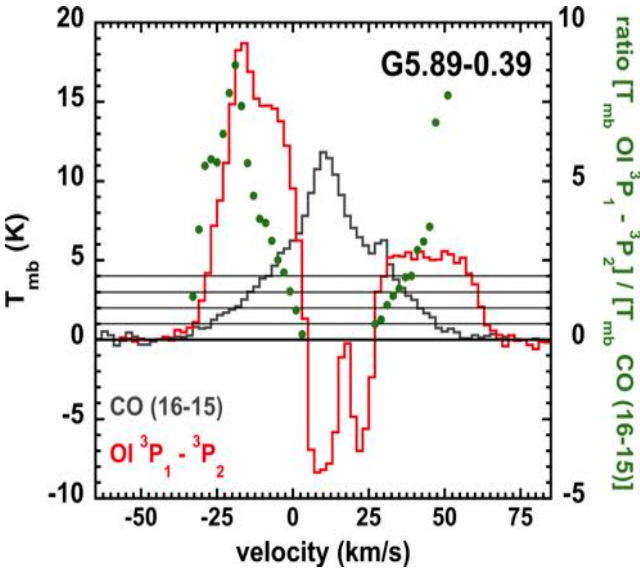
to high-mass driving proto-stars



Kristensen et al., 2017



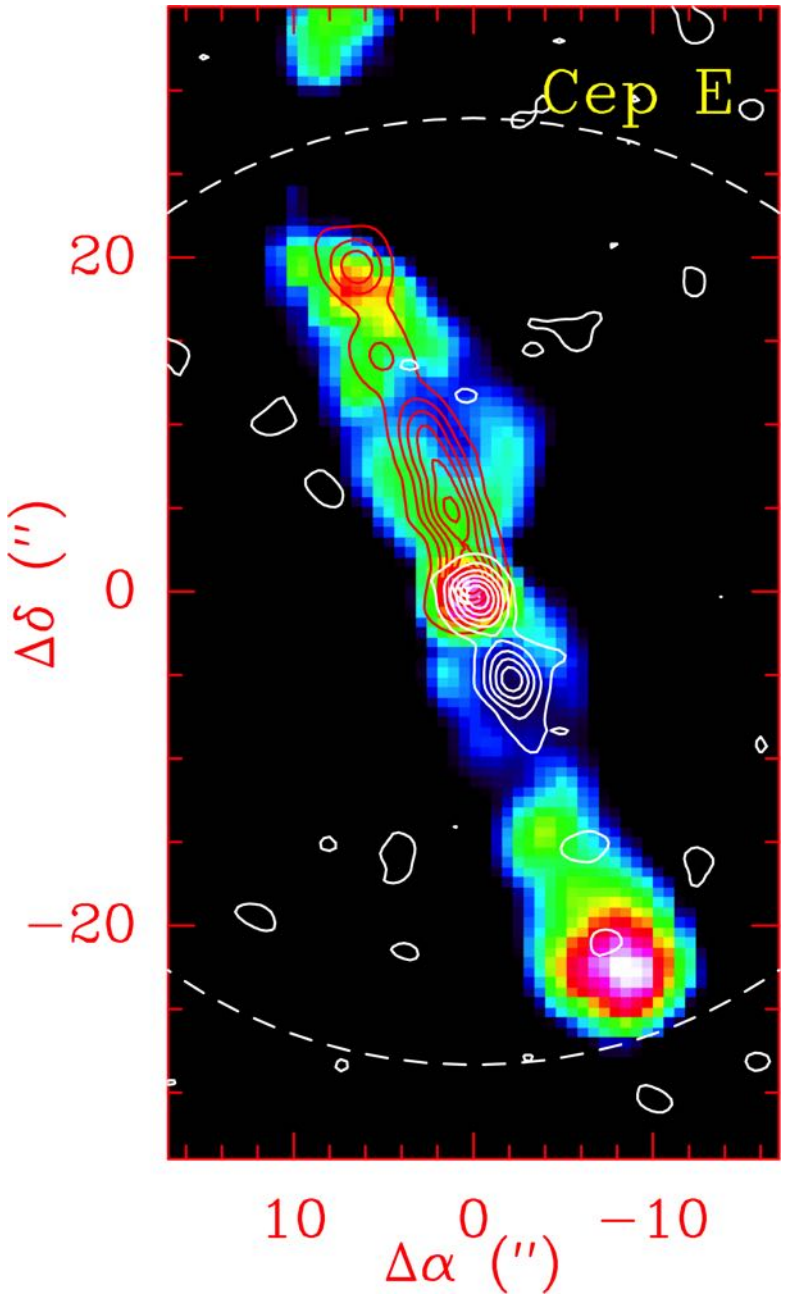
Gusdorf et al., 2017

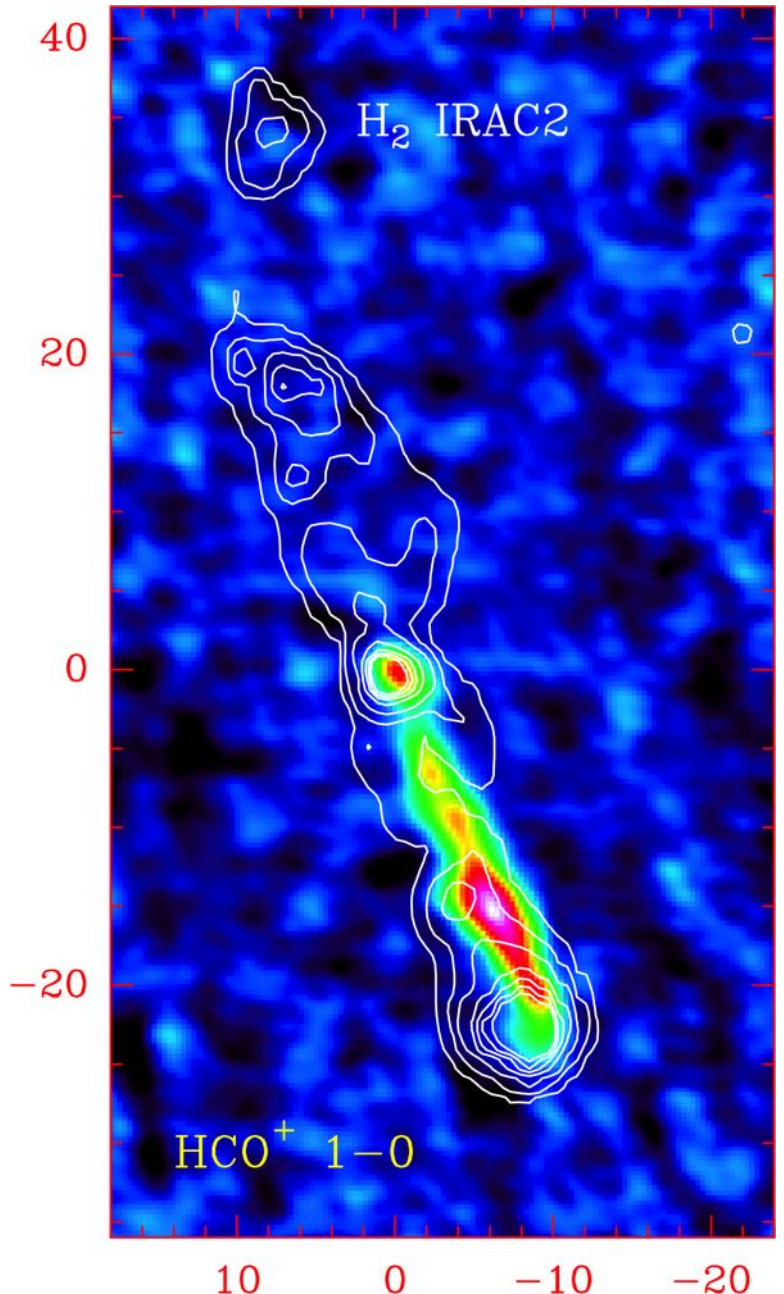


Leurini et al., 2015

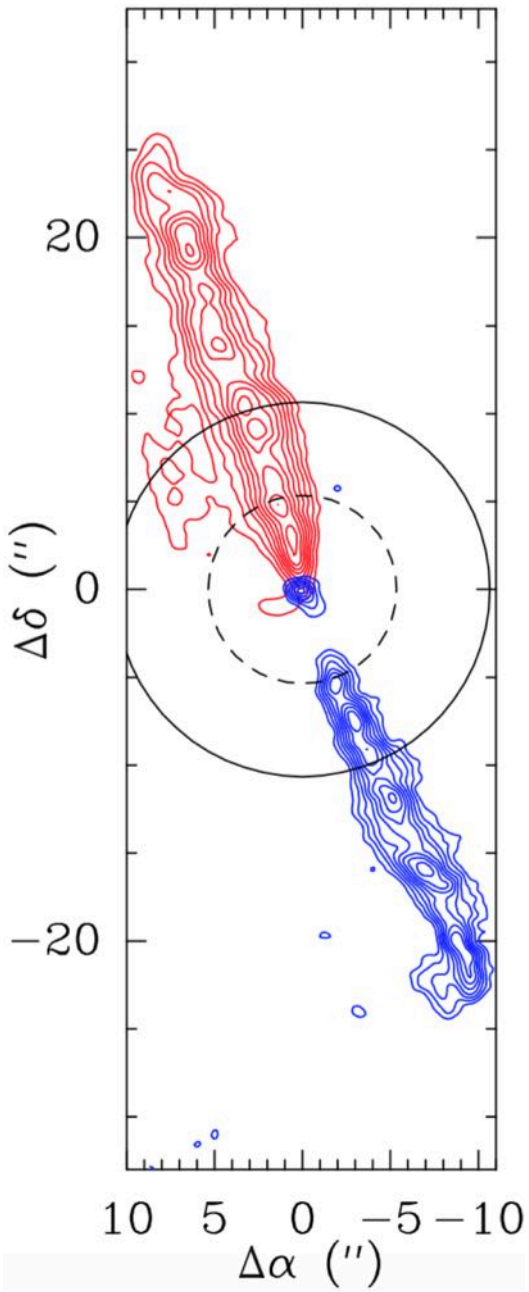
Perspectives

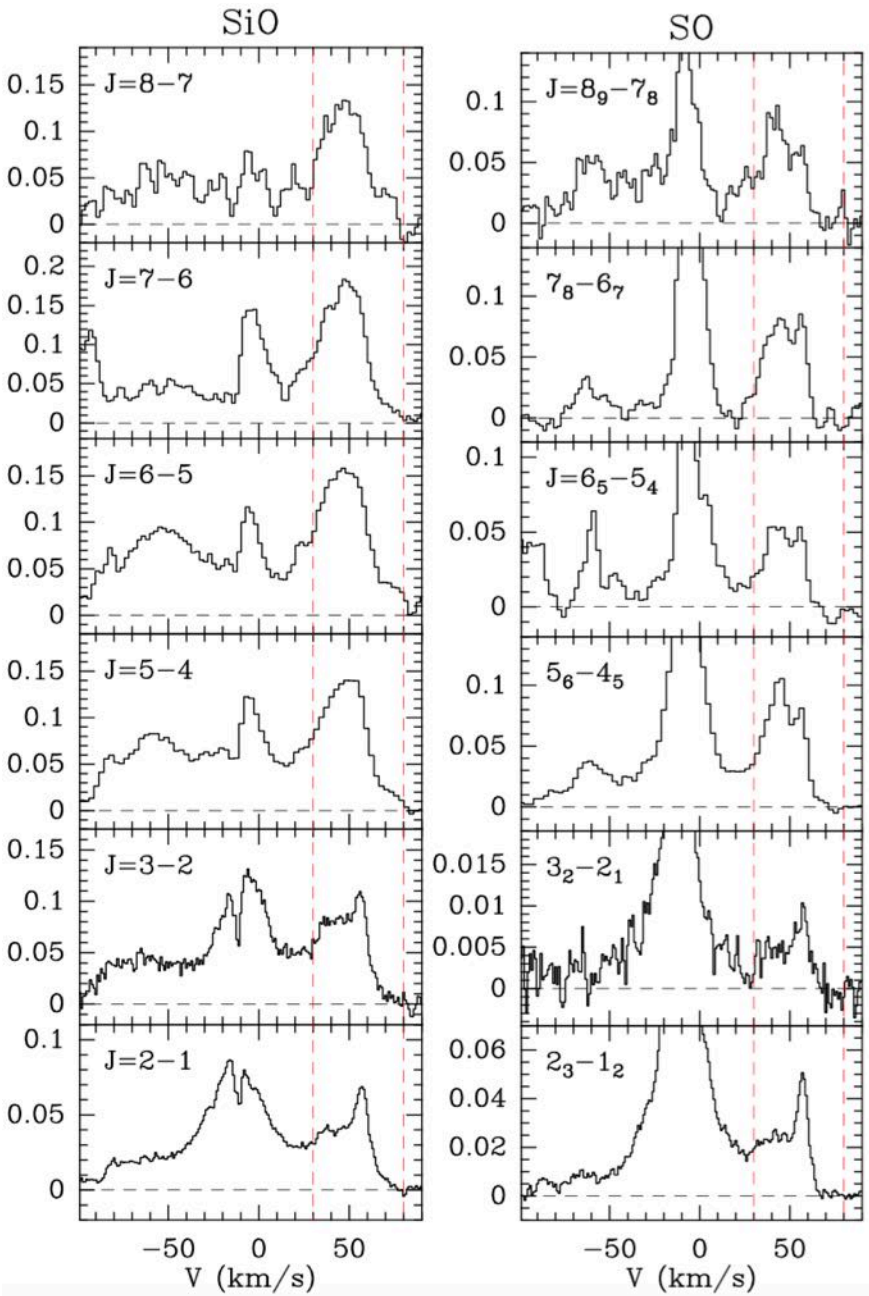
Perspectives (1): astrochemistry (1)

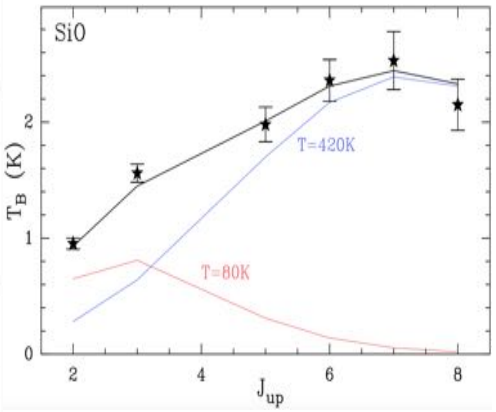


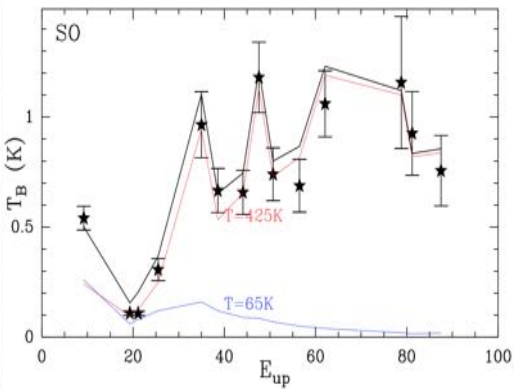


Perspectives (1): astrochemistry (2)



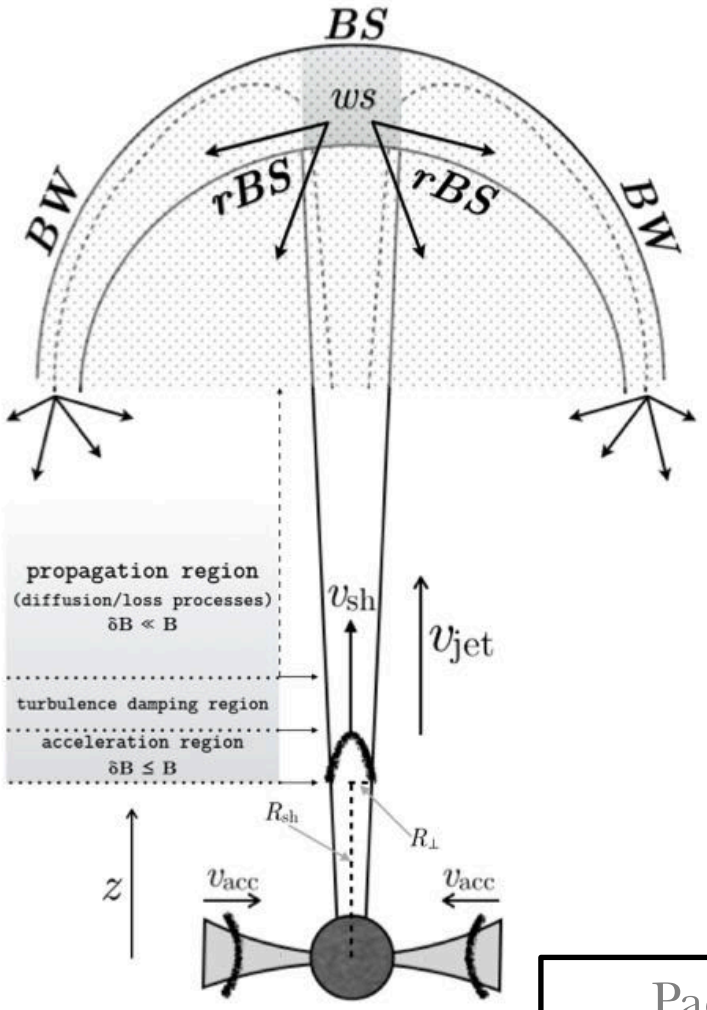


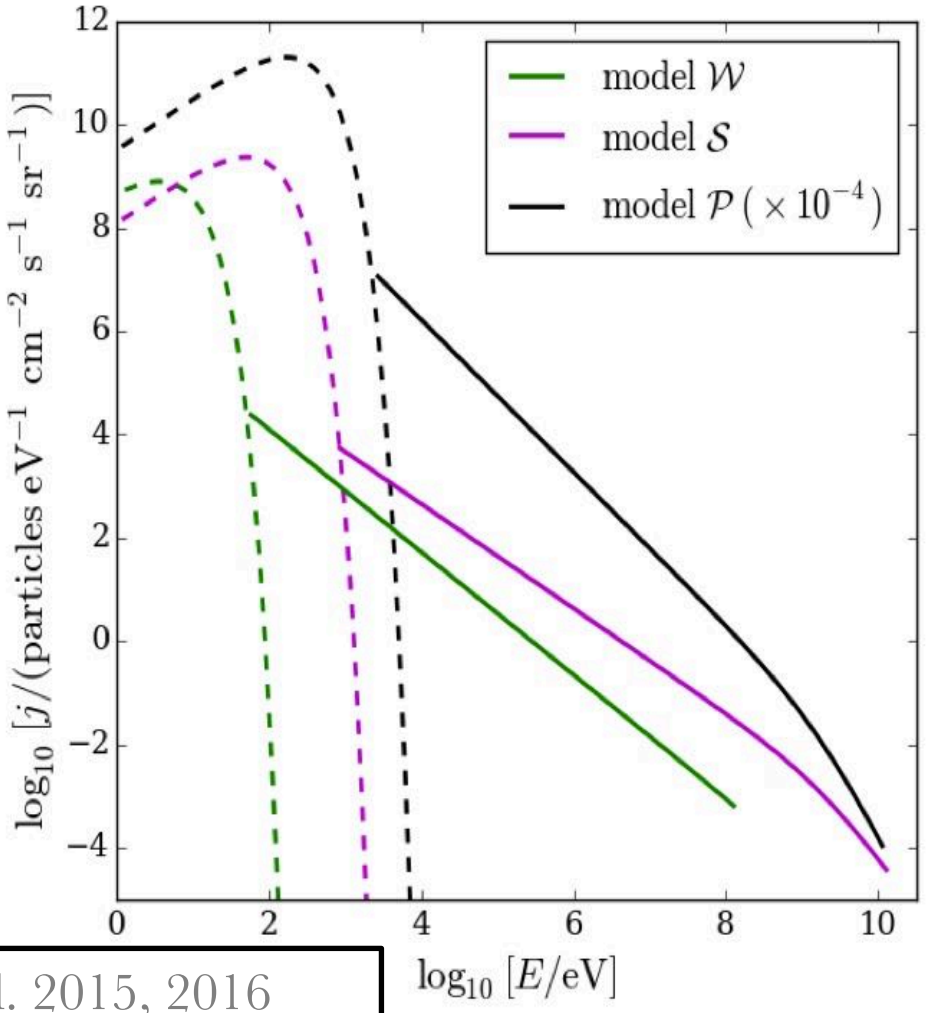




Lefloch et al., in prep.

Perspectives (2): cosmic rays acceleration





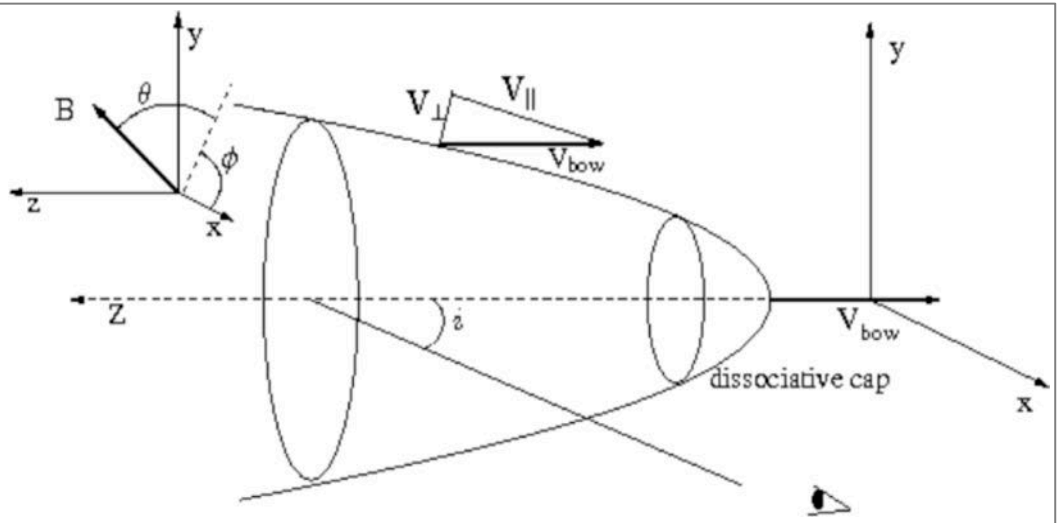
Padovani et al. 2015, 2016

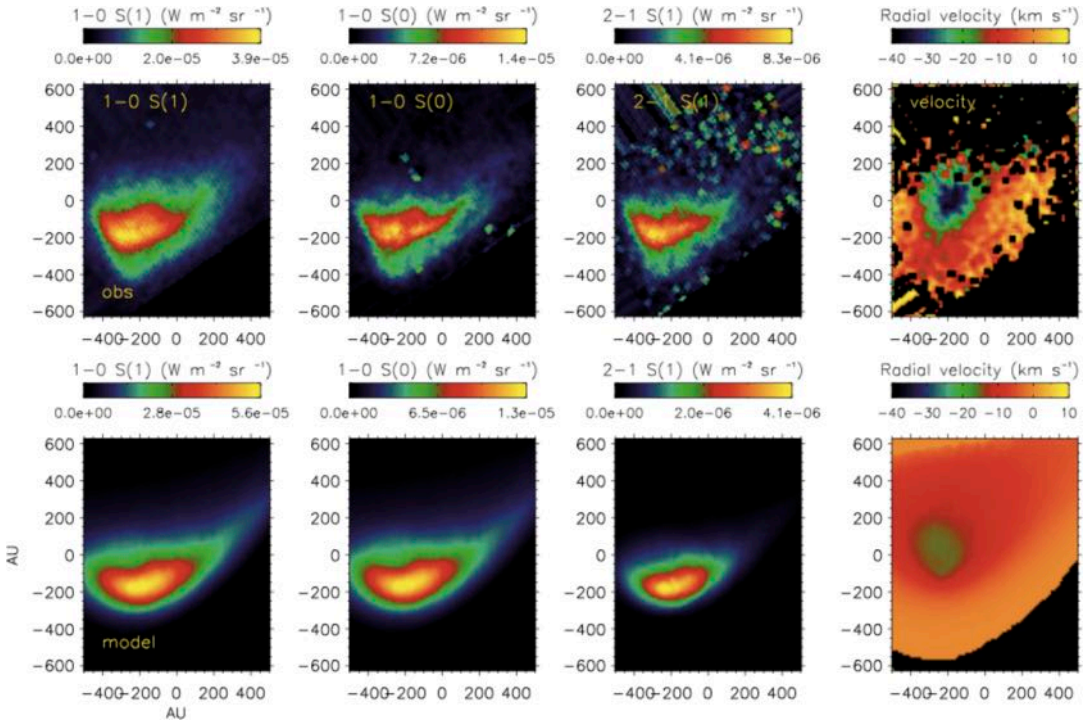
model	U [km s^{-1}]	B [G]	n_H [cm^{-3}]	x	T [10^4 K]	r	E_{max} [GeV]	$\widetilde{P}_{CR}$ [10^{-2}]	λ	p_{inj} [MeV/c]	p_{max} [GeV/c]
$\mathcal{W}$	40	5×10^{-5}	10^5	0.33	1	2.977	0.13	0.88	4.010	0.306	0.505
$\mathcal{S}$	160	10^{-3}	6×10^5	0.60	1	3.890	12.9	4.70	4.062	1.146	13.762
$\mathcal{P}$	260	5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

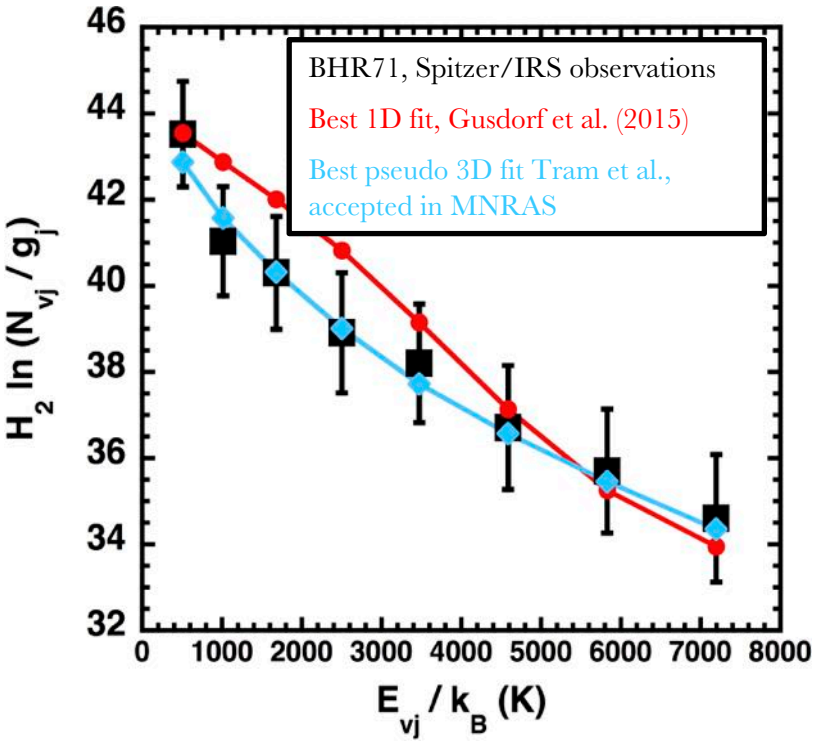
Perspectives (3): shock models

- Kristensent et al. 2008, Gustafsson et al. 2010 Tram et al., accepted in MNRAS:

$n_H = 10^5$ cm^{-3};
$v_{bow} = 50$ km s^{-1};
b = 3;
$\beta = 1.7$; $r_0 = 610$ AU;
$\theta = 15°$; $\Phi = 180°$; i = 50°







Thanks for your attention !