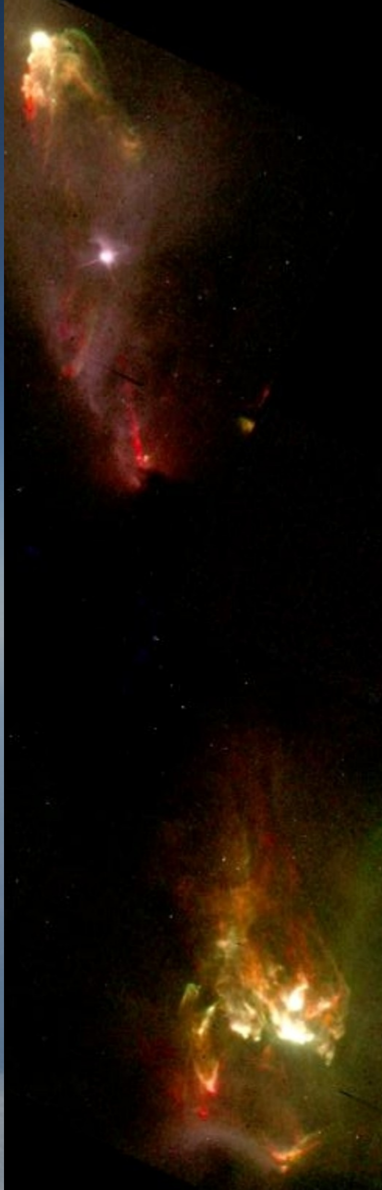
Atomic gas in Protostellar outflows

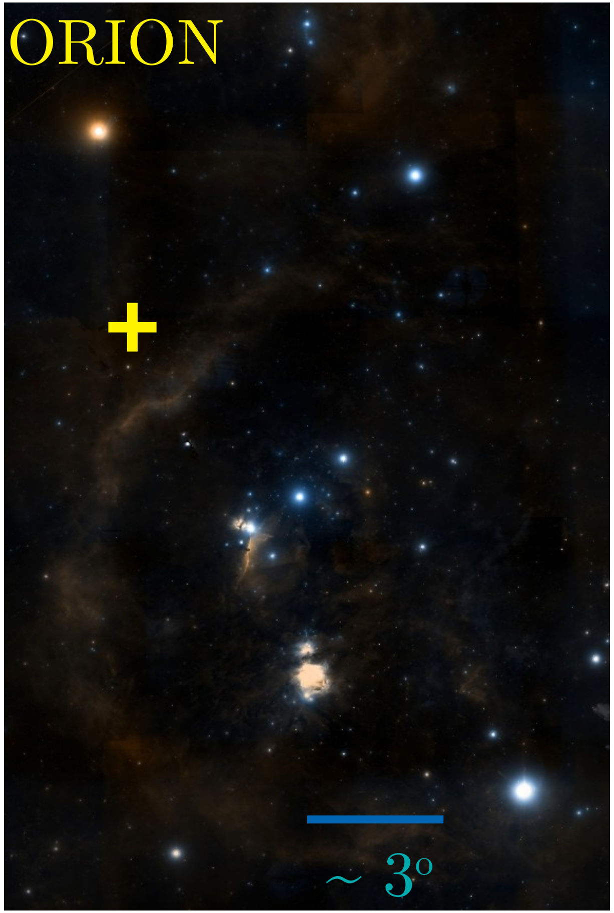
SOFIA Tele-Talk
August 04, 2021

Thomas Sperling
Thüringer Landessternwarte

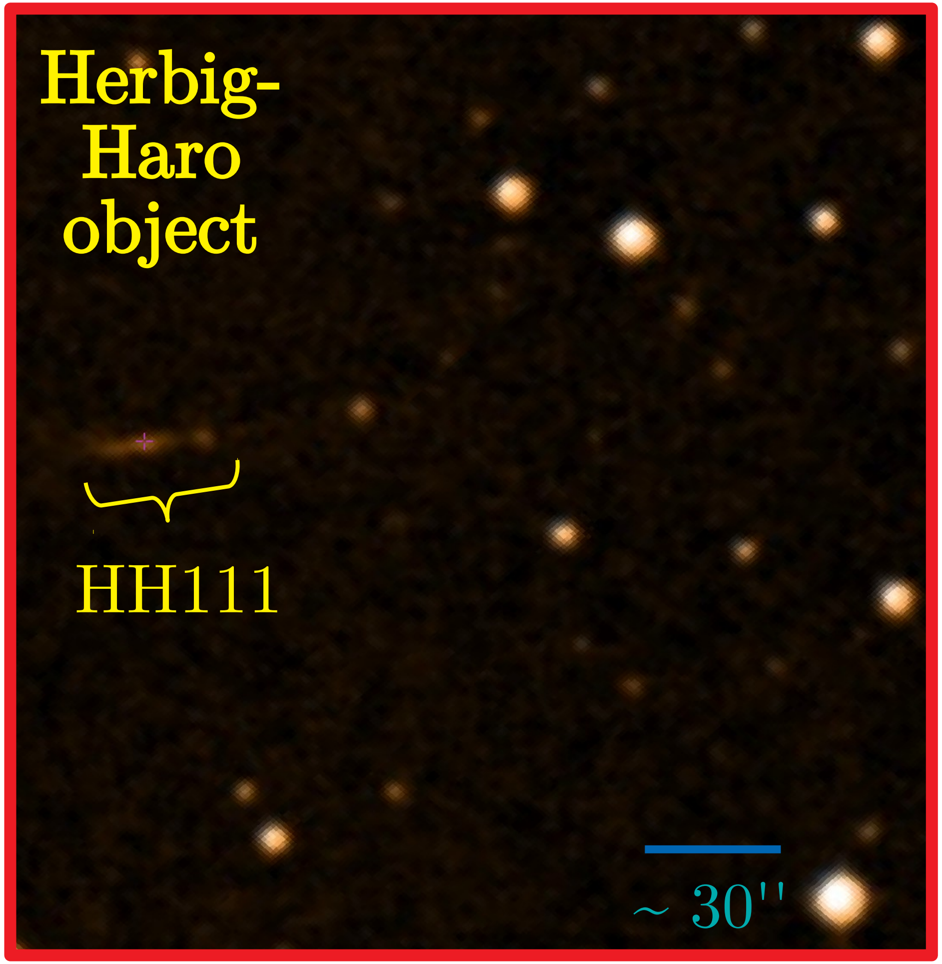


Collaborators: J. Eislöffel, B. Nisini, T. Giannini, C. Fischer, A. Krabbe

A mysterious object in Orion



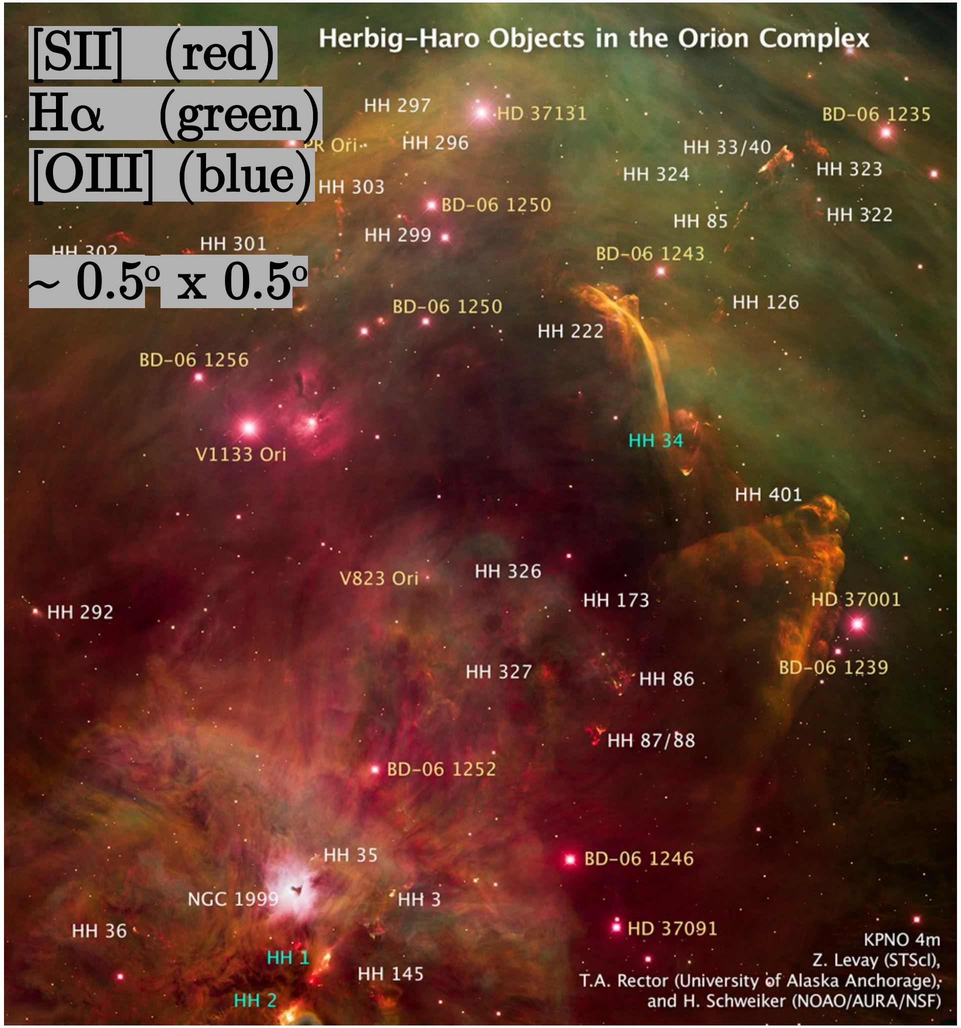
zoom in



Herbig 1951
Haro 1952

DSS colored

Herbig-Haro objects



- powered by an **outflow** from a **forming star**

Schwartz 1975,1978

- detected in various **emission lines**
  - ✓ **optical:** [SII], [NII], [OI], Hα
  - ✓ **near-IR:** [FeII], H_2
  - ✓ **sub-mm/mm:** CO, SiO

Frank+2014
Bally 2016
Lee 2020
Ray & Ferreira 2020

- **shock-excited**

Schwartz 1977
Hartigan+1995

The evolution of low-mass protostars

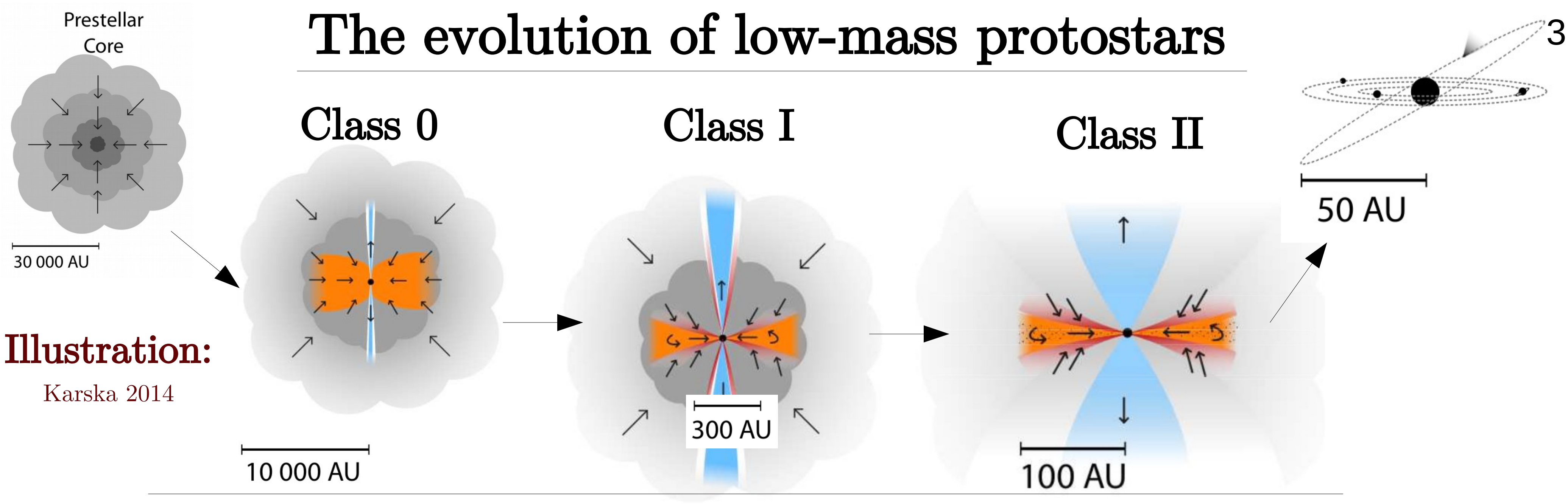


Illustration:

Karska 2014

Examples:

The evolution of low-mass protostars

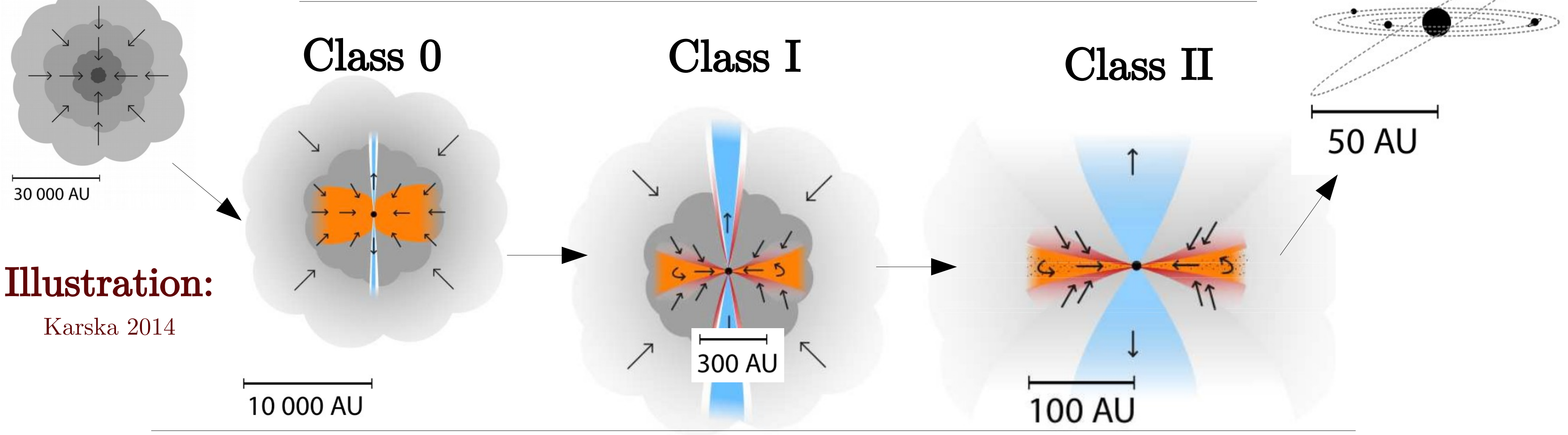


Illustration:

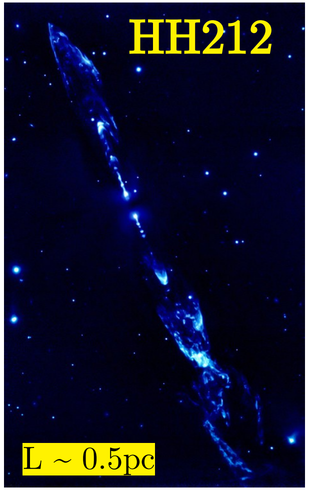
Karska 2014

Examples:

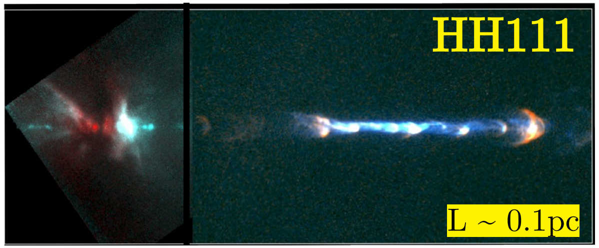
Reipurth+1999

McCaughrean+2002

NASA, Watson+2008



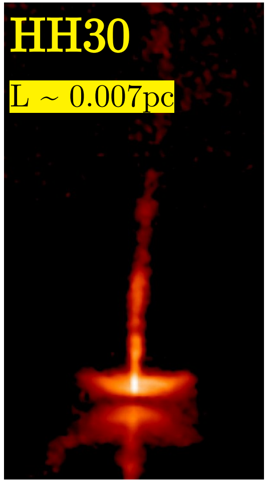
near-IR H_2



[FeII] turquoise, H_2 red

[SII] blue, Hα orange

coexisting gas components

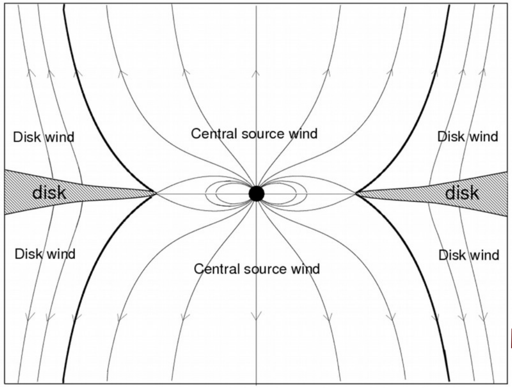


Optical R Band

L ... length of the shown outflow

Three challenges

Accretion/ejection mechanism?



Tsinganos 2010

- efficiency:

$$f = \frac{\dot{M}_{\rm out}}{\dot{M}_{\rm acc}}$$

- X-wind vs. disk wind

Shu+2000 Ferreira+1997

Outflow evolution?

- Class 0:

mainly molecular

- Class I:

?

- Class II:

mainly atomic/ionic

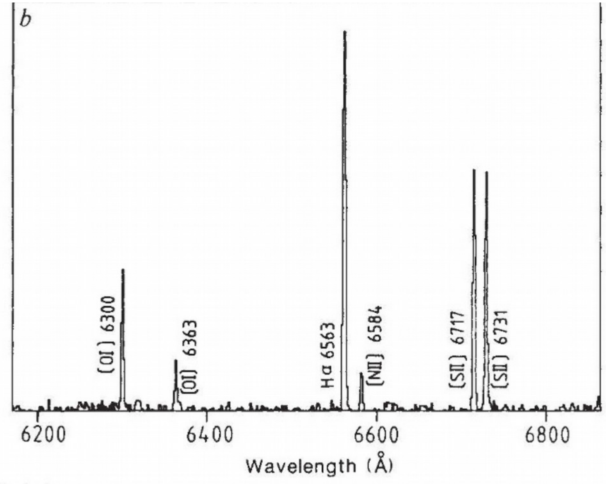
TIME

Ellerbroek+2013, Watson+2016

Importance of FIR [OI]?

$$\left\{ \begin{array}{l} [\mathrm{O\,I}]_{63\mu\mathrm{m}} \\ [\mathrm{O\,I}]_{145\mu\mathrm{m}} \end{array} \right\}$$

Nisini+2015



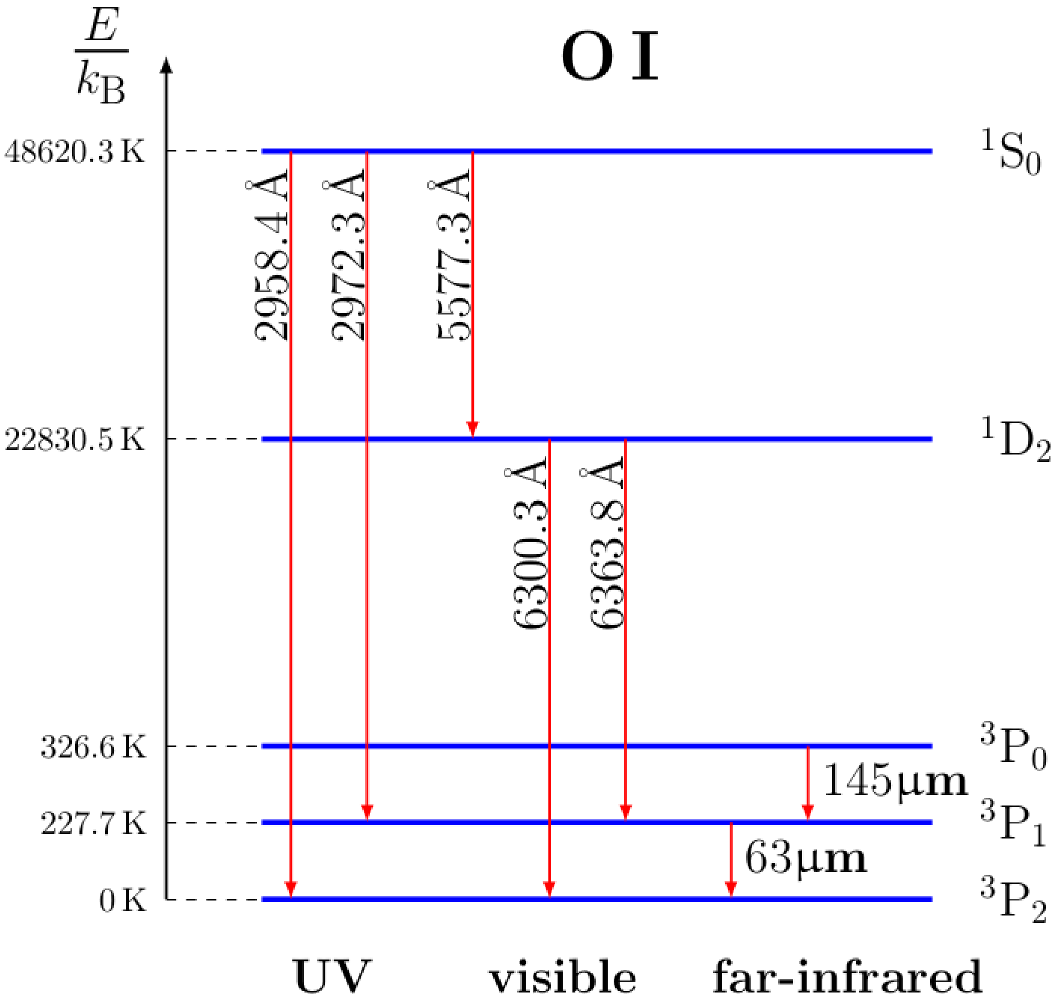
Reipurth 1989a

Optical spectrum of HH111

The far-infrared [OI] lines

Osterbrock & Ferland 2006

Draine 2011



- **Collisional excitation**

$$O(^3P_j) + p \xrightarrow{\text{collision}} O(^3P_{j'}) + p, \qquad j > j'$$

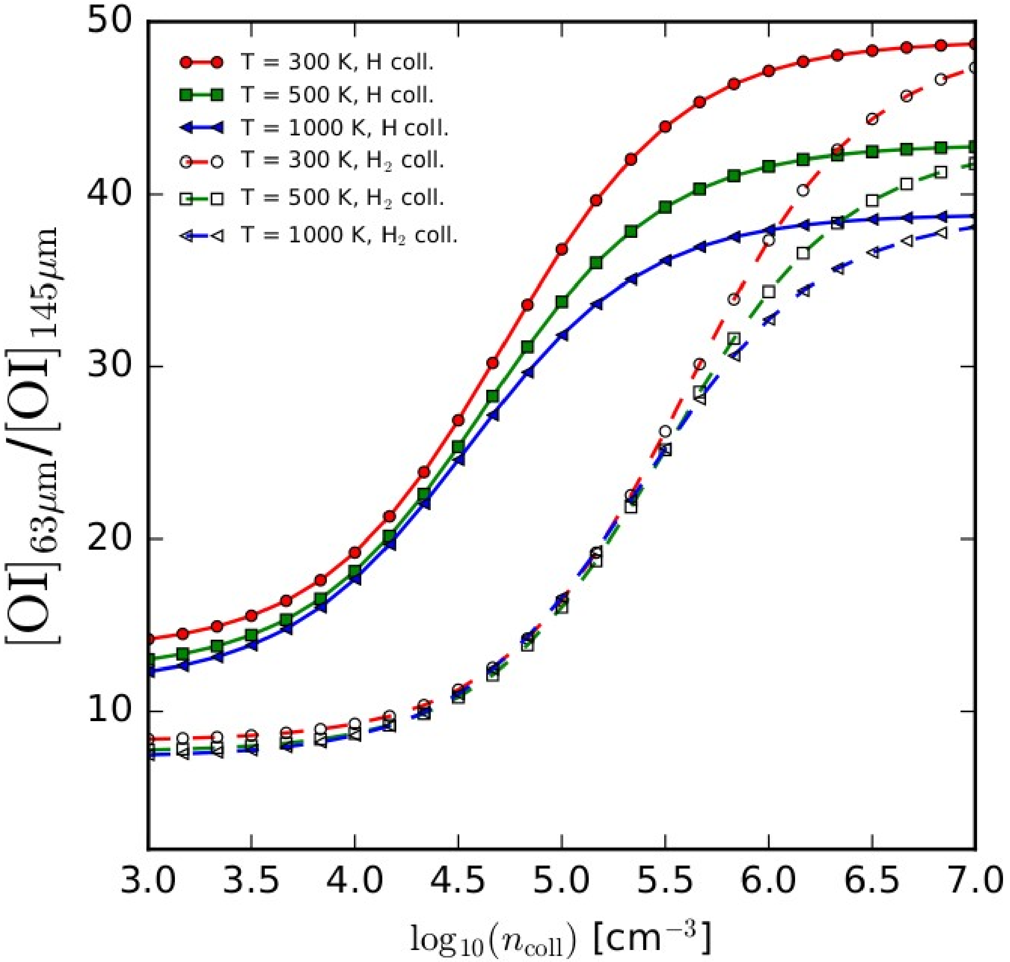
- **Radiative decay**

$$O(^3P_1) \xrightarrow{\text{time}} O(^3P_2) + h\nu_{63\mu m}$$

- **Extinction negligible**

The OI line ratio is density sensitive

OI line ratio ↑



→ DENSITY

Nisini+2015

[OI]63µm is not observable from the ground!

ESA (image by AOES Medialab); background image: ESA/NASA/HST

Mostly Class 0 outflows have been mapped in [OI]!

Nisini+2015, Dionatos+2018, Dionatos & Güdel 2017

It became clear, that...

- bulk [OI] emission ⟶ **shocks**
- [OI] traces **warm, atomic gas**

Hollenbach & McKee 1989

Watson+2016

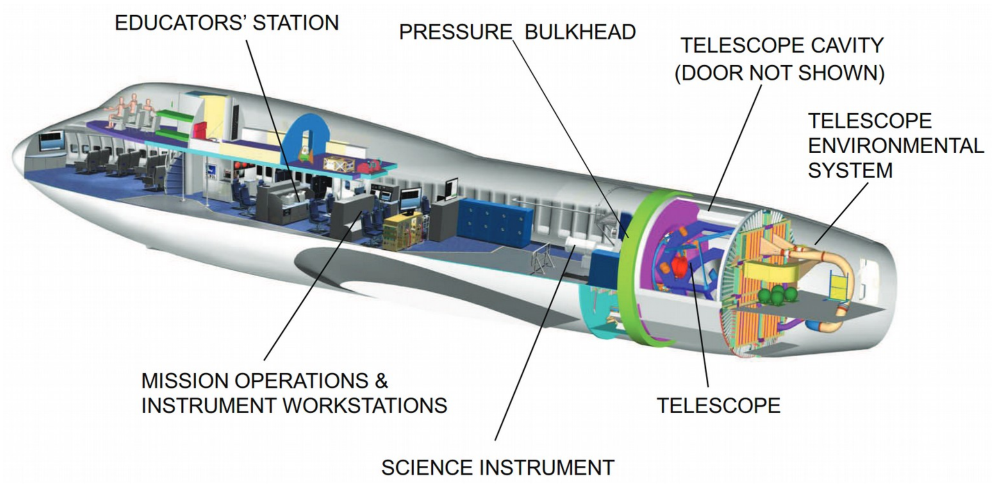
Alonso-Martinez+2017

What about more evolved **Class I** sources?

PACS' twin instrument aboard SOFIA

Stratospheric **O**bservatory **F**or **I**nfrared **A**stronomy

Telescope

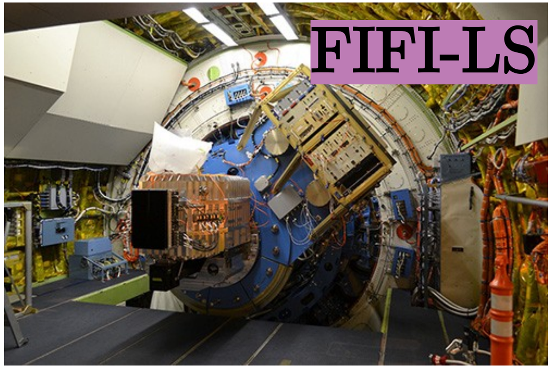


- **Effective aperture**: 2.5m

Young+2012, Krabbe+2013

Instrument

Field **I**maging **F**ar-**I**nfrared **L**ine **S**pectrometer



5x5 Integral Field Unit

Wavelength Range Resolving Power R =λ/Δλ	Field of View Features
51 – 200 μm R = 600 – 2,000	30" x 30" (Blue) 60" x 60" (Red) 2x(16x25) Ge:Ga

Colditz+2018, Fischer+2018

Mitigating the Earth atmosphere

(1) Gaussian emission line

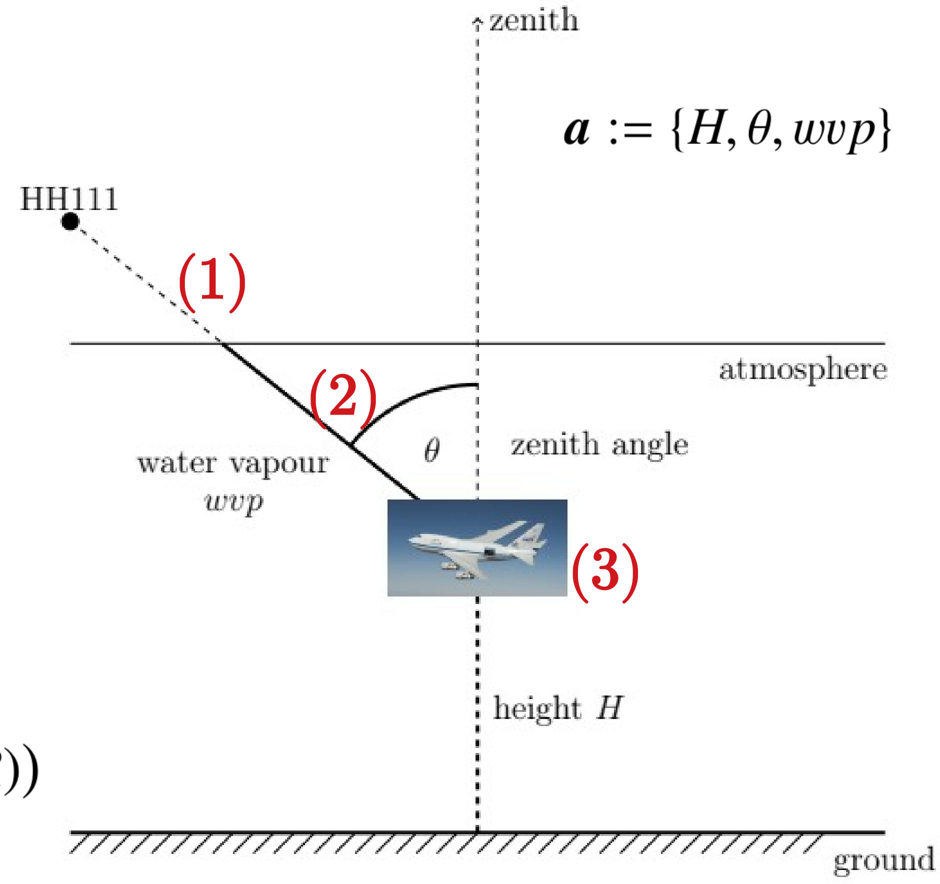
$$\varphi(\lambda; \boldsymbol{b}) = \frac{A}{\sqrt{2\pi}\sigma} \exp\left[-\frac{1}{2}\left(\frac{\lambda-\mu}{\sigma}\right)^2 \right] + B$$

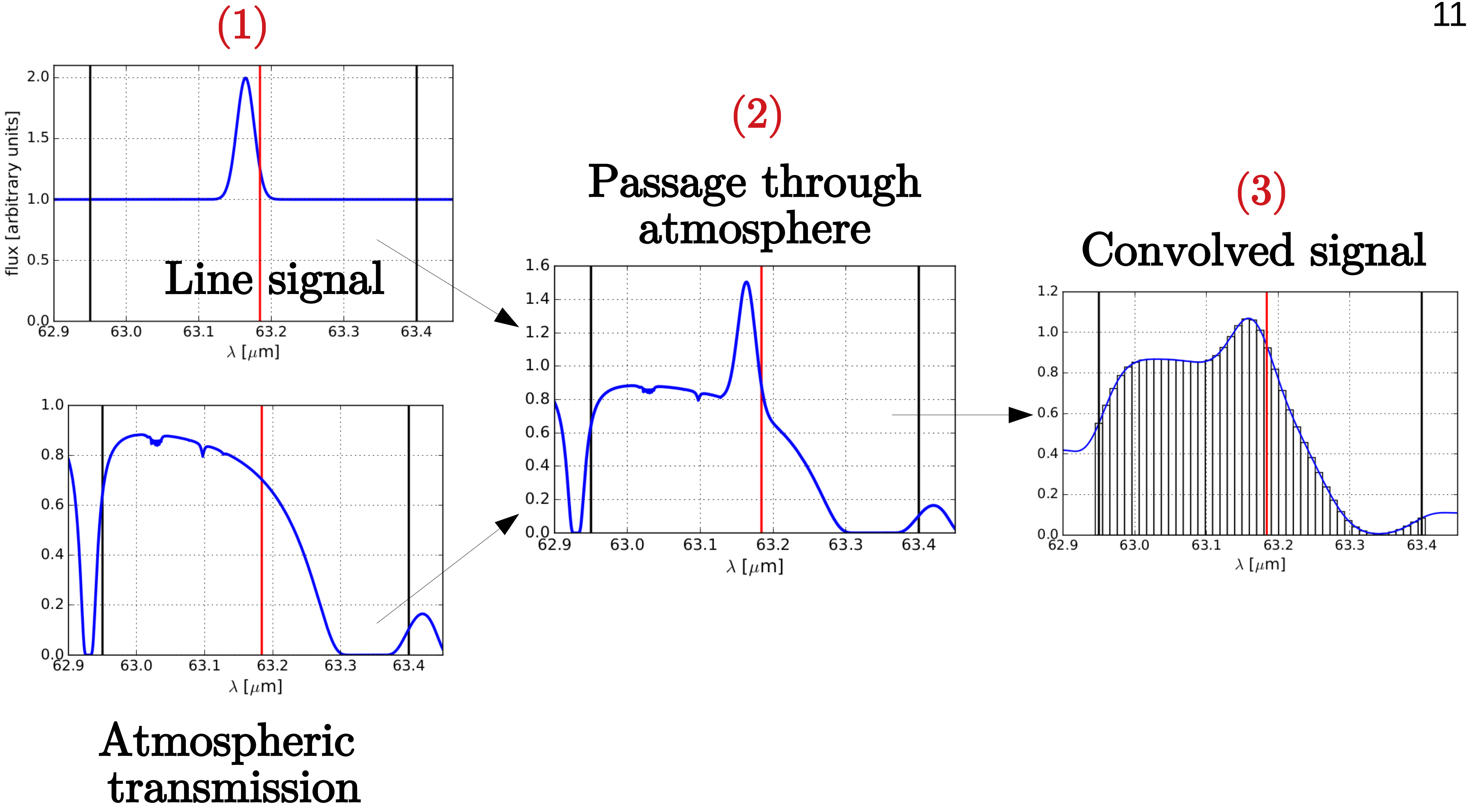
(2) Passage through atmosphere

$$\varphi(\lambda; \boldsymbol{b}) \cdot \tau(\lambda; \boldsymbol{a})$$

(3) Telescope + instrument

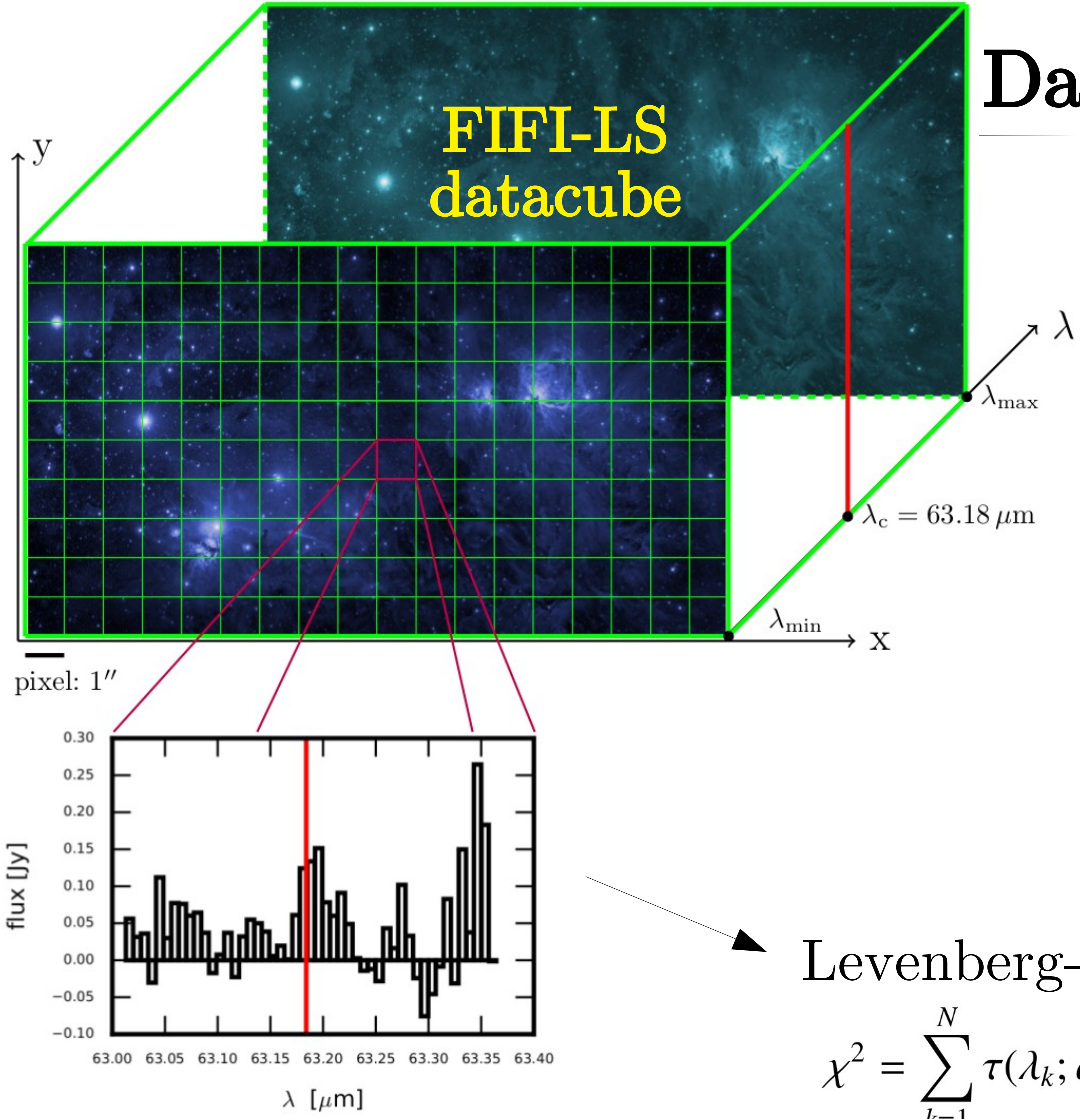
$$y(\lambda_k; \boldsymbol{a}, \boldsymbol{b}, R) = S\left(\left[\varphi(\lambda; \boldsymbol{b}) \cdot \tau(\lambda; \boldsymbol{a})\right] * \mathrm{SIF}(\lambda; R)\right)$$

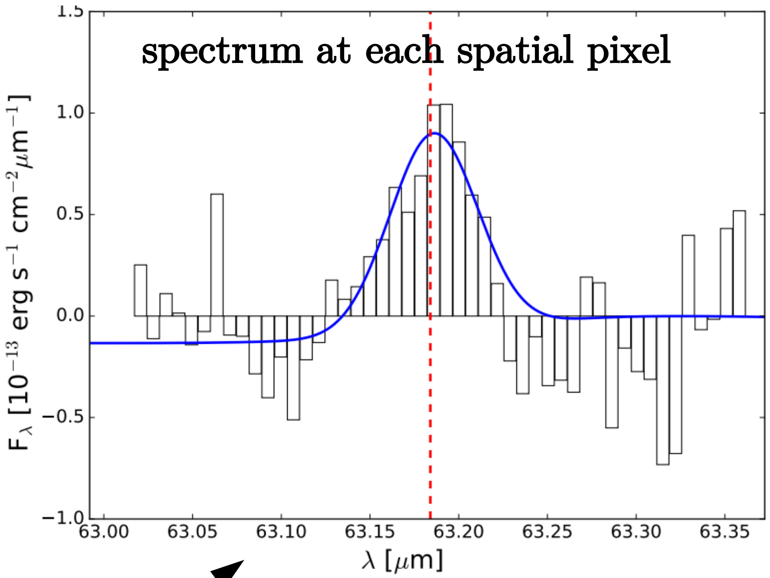



(1)
Line signal
flux [arbitrary units]
0.0
0.5
1.0
1.5
2.0
62.9
63.0
63.1
63.2
63.3
63.4
λ [μm]
Atmospheric transmission
(2)
Passage through atmosphere
(3)
Convolved signal
λ [μm]

Data reduction with JENA.py

Jet EmissioN Analysis





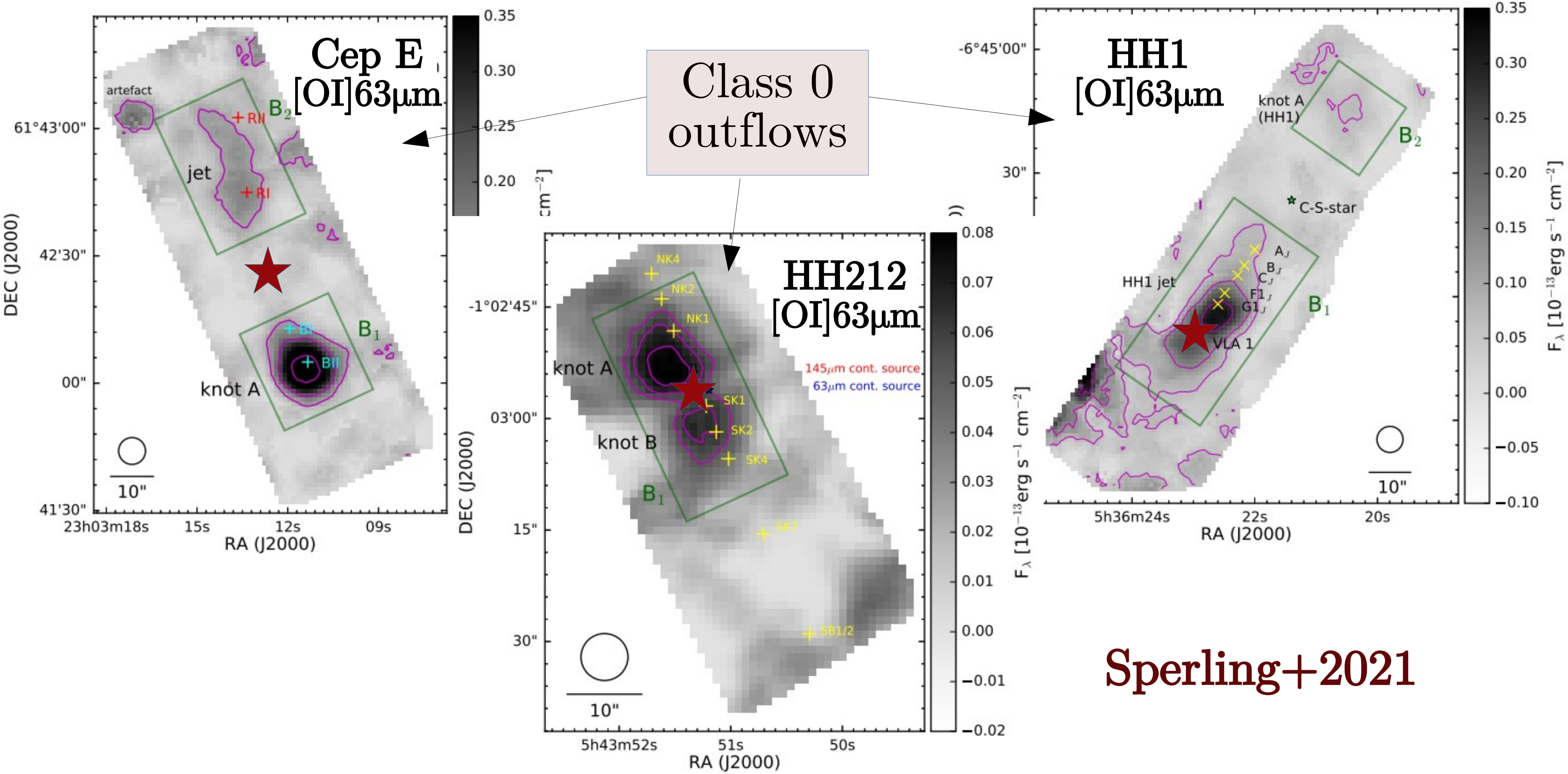
Levenberg-Marquardt algorithm

$$\chi^2 = \sum_{k=1}^{N} \tau(\lambda_k; \boldsymbol{a}) \cdot \left(\frac{\text{data}(\lambda_k) - y(\lambda_k; \boldsymbol{a}, \boldsymbol{b}, R)}{\epsilon(\lambda_k)} \right)^2$$

Sperling+2020

RESULTS

First [OI] mappings of...

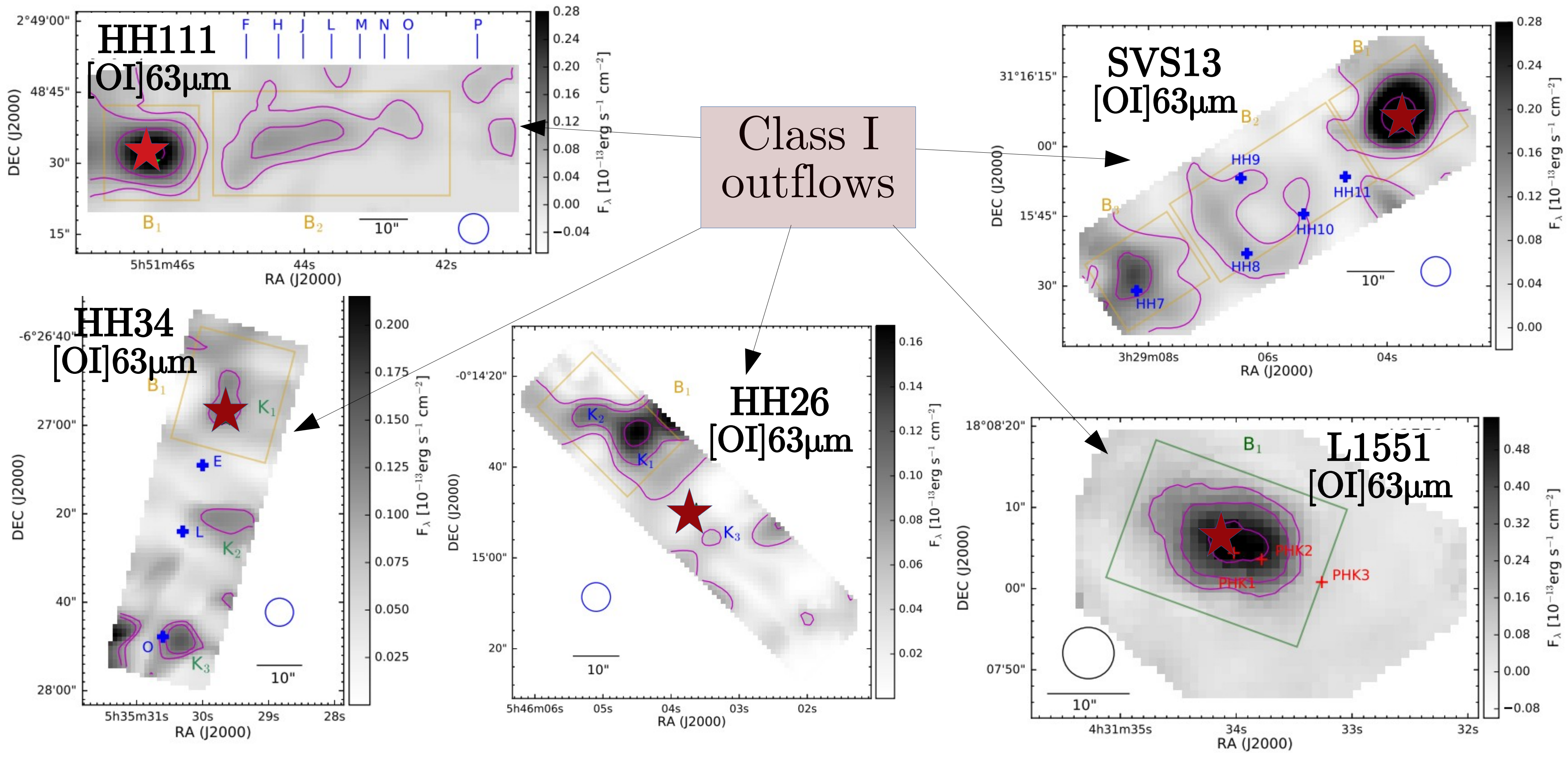


Class 0 outflows

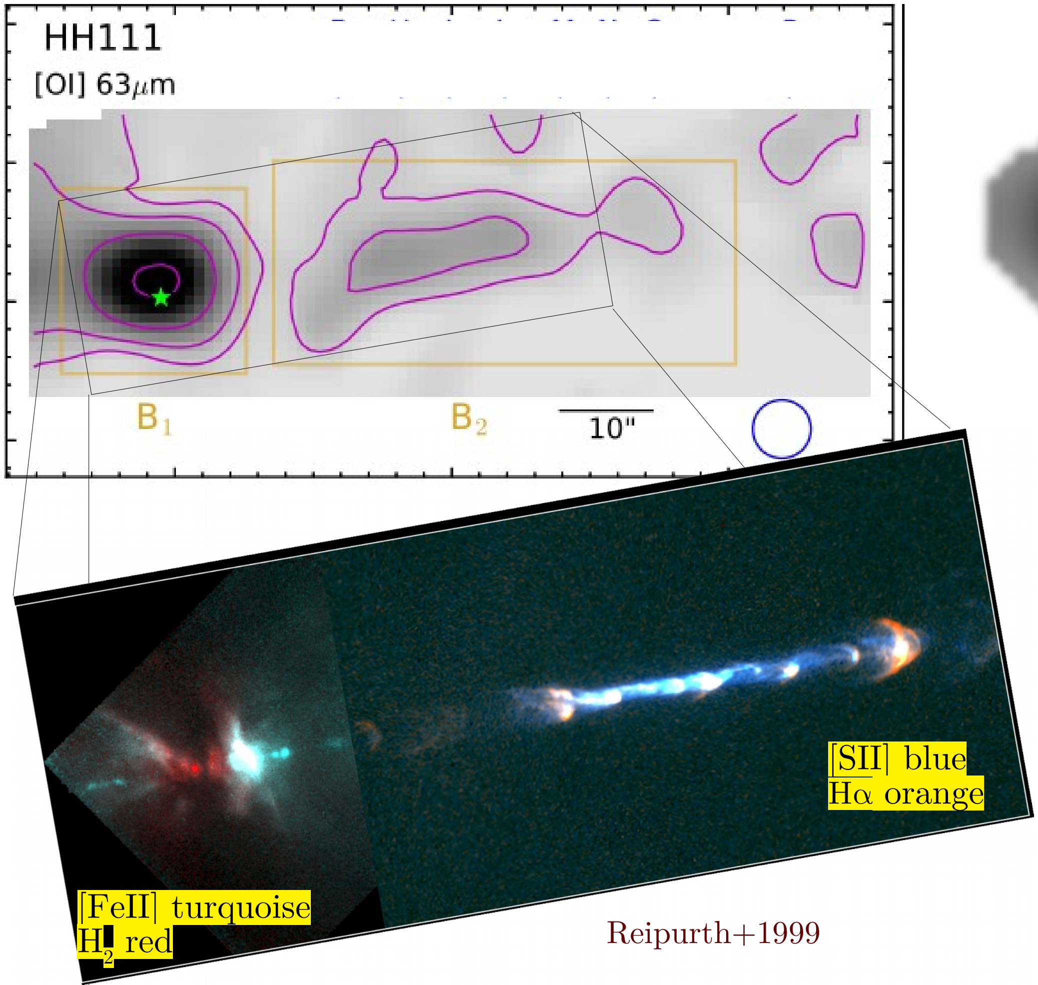
Sperling+2021

First [OI] mappings of...

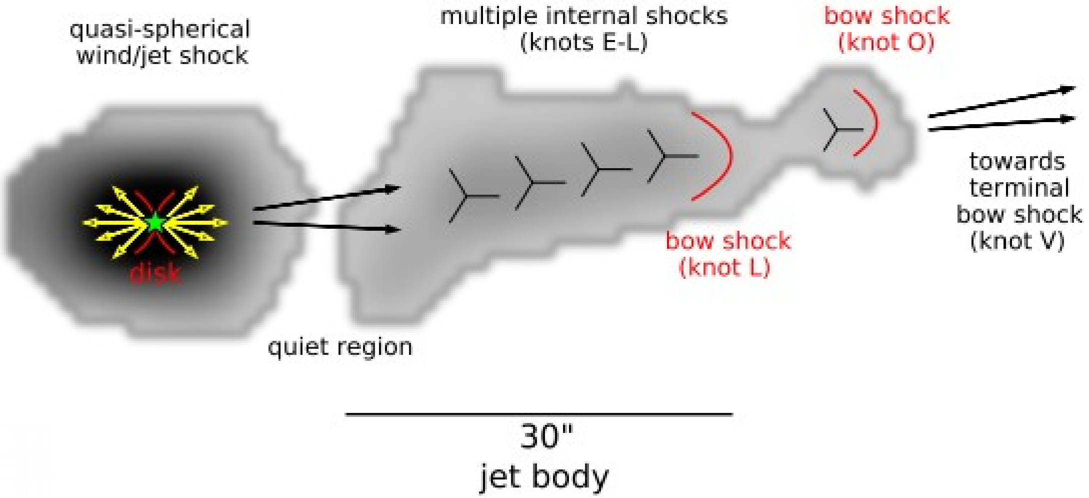
Sperling+2020, 2021



The spectacular HH111 jet



Reipurth+1999



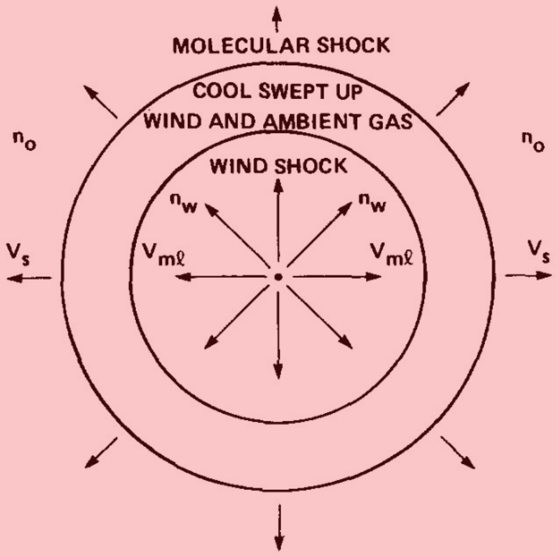
- shock excitation
- luminosity measurements

$$L([\mathrm{O\,I}]_{63}) \xrightarrow{?} \dot{M}_{\mathrm{out}}$$

Mass-loss rates

Shock model (HM89)

Hollenbach 1985,
Hollenbach & McKee 1989



b) $$\left(\frac{\dot{M}_{\rm out}}{M_\odot\,{\rm yr}^{-1}}\right) = 10^{-4}\cdot\left(\frac{L([{\rm O\,I}]_{63})}{L_\odot}\right)$$

In a nutshell...

- single dissociative wind **shock of jump (J) type**
- **parameter range**

$$v_{\rm s} = 30 - 150\,{\rm km\,s^{-1}}$$
$$n = 10^3 - 10^6\,{\rm cm^{-3}}$$

- **predictions**

a) $[{\rm O\,I}]_{63\mu{\rm m}}$ is the **dominant cooling line**

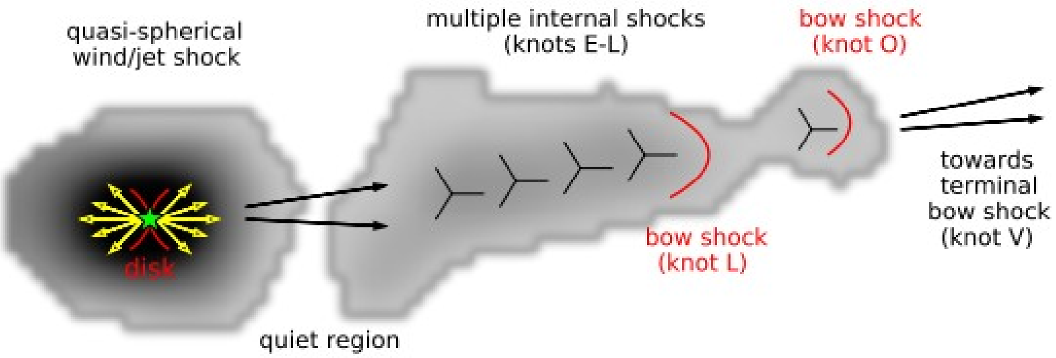
Is the HM89 model applicable?

- **multiple unresolved shocks**

  Dougados+2010, Nisini+2015

- **other emission lines**?

  e.g. [OI]145, [CII]157, [SI]25, [SiII]35, [FeII]26

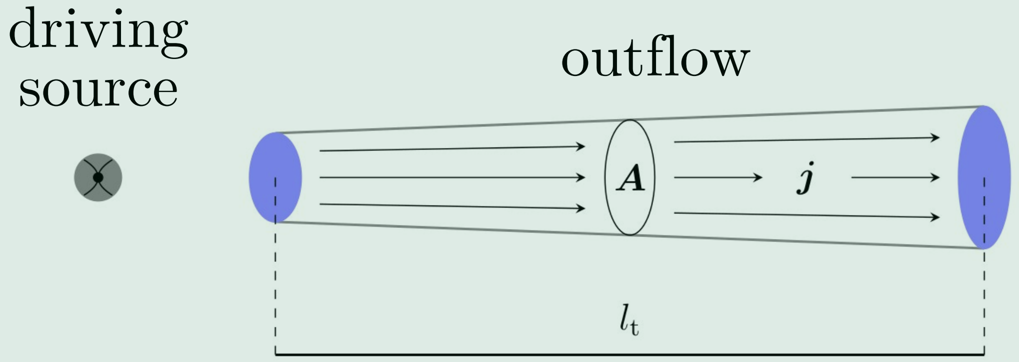


Issues

1. Agreement of specific line ratios with HM89 predictions?
2. J-shock vs. C-shock?
3. [OI]63μm dominant cooling line?
4. Contamination by a Photodissociation region (PDR) or a disk?
5. A 30yr old model (new collisional coefficients, chemical networks...?)

Mass-loss rates – an alternative approach

jet luminosity (Hartigan+1995)



Motivation?

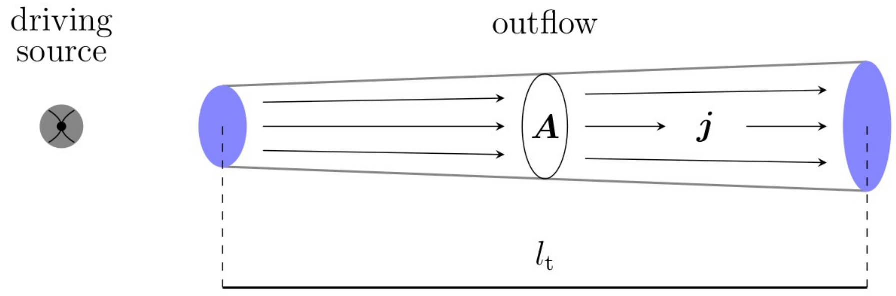
jet geometry

$$\left(\frac{\dot{M}_{\mathrm{out}}}{M_\odot\,\mathrm{yr}^{-1}}\right) = (3.3 - 6.7) \times 10^{-3} \cdot \left(\frac{v_{\mathrm{t}}}{\mathrm{km\,s}^{-1}}\right)\left(\frac{''}{\theta}\right)\left(\frac{\mathrm{pc}}{D}\right)\left(\frac{L([\mathrm{O\,I}]_{63})}{L_\odot}\right)$$

Sperling+2020

Why the range of 3.3-6.7?

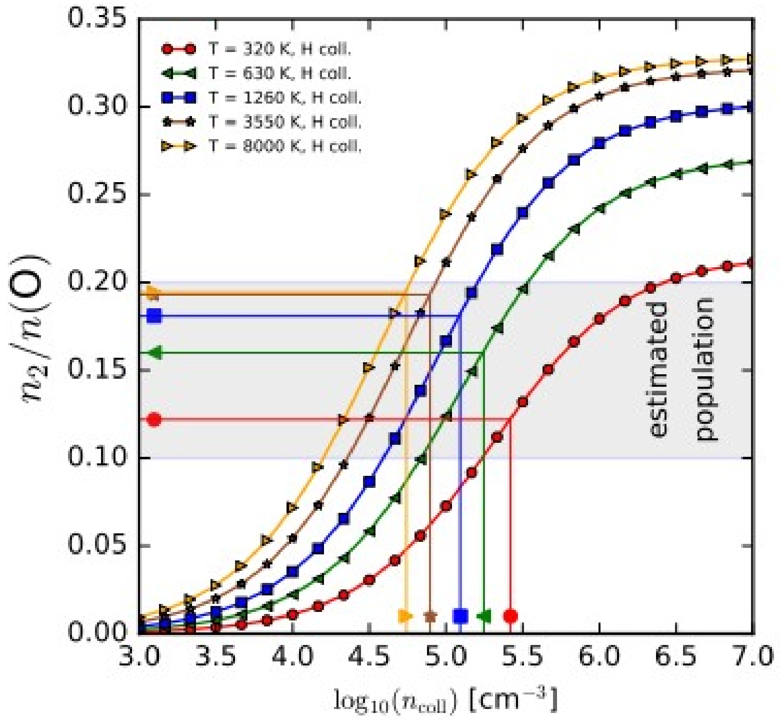
- fluid dynamics
- counting contributing atoms
- solving rate equations of OI



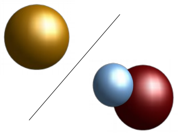
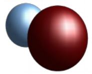
D ... distance to the target
θ ... projected distance
v_t ... component of the velocity on the plane of sky
$L([O\,I]_{63})$ ... [O I]63μm luminosity

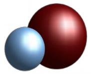
A critical assumption:

- n_{coll} is close to the critical density



The outflow components I

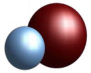
Target	Region	Class	$\dot{M}_{out}([\mathrm{O\,I}])$ $10^{-7}\,M_\odot\,\mathrm{yr}^{-1}$	$\dot{M}_{out}$ & component $10^{-7}\,M_\odot\,\mathrm{yr}^{-1}$	dominant component
HH1	VLA 1 knot A	**0**	$\lesssim 25.9 - 52.6$ $\lesssim 9.5 - 19.4$	~ 6 in [Fe II] ~ 4 in [S II] ~ 0.1 in H_2	
HH212	knot A and B	**0**	$3.9 - 7.9$	~ 10 in CO, SO, SiO $\lesssim 3$ in CO, SiO ~ 1 in H_2	
Cep E	knot A jet	**0**	$\lesssim 22.4 - 45.5$ $\lesssim 7.2 - 14.7$	~ 200 in CO	
L1551	IRS 5	**I**	$5.8 - 11.8$	~ 8.6 in HI ~ 1.7 in [Fe II] ~ 0.4 in H_2	

 = mainly atomic  = mainly molecular

Sperling+2020

The outflow components II

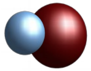
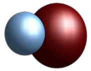
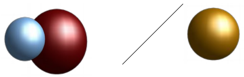
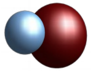
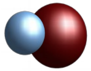
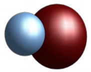
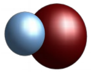
Target	Region	Class	$\dot{M}_{out}$([O I]) $10^{-7}\,M_\odot\,yr^{-1}$	$\dot{M}_{out}$ & component $10^{-7}\,M_\odot\,yr^{-1}$	dominant component
HH111	HH111IRS	I	26 – 53	4 in CO	
	jet (knots F-O)		6 – 12	2 – 6 in [O I]λ6300	
SVS13	SVS13A	I	25 – 51	30 in HI	
	HH8-11		–	8.9 in[Fe II]	
	HH7		–	7.0 in H_2	
HH34	HH34IRS	I	11 – 23	0.7 in [Fe II]	
				0.03 in H_2	
				~ 1.5 in[O I]λ6300	
HH26	HH26A	I	–	0.2 – 0.5 in H_2	

 = mainly atomic  = mainly molecular

Other *fully* mapped outflows

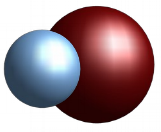
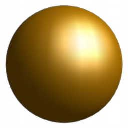
Compilation Sperling+20

Nisini+2015
Dionatos & Güdel 2017
Dionatos+2018
Podio+2020
Lee 2020

Target	Class	$\dot{M}_{out}$([O I]) $10^{-7}\ M_\odot\ yr^{-1}$	$\dot{M}_{out}$ & component $10^{-7}\ M_\odot\ yr^{-1}$	dominant component
L1448	**0**	1 – 2	> 100 in CO	
IRAS4A	**0**	0.3 – 1.0	> 70 in CO	
HH46	**I**	7 – 15	15 – 28 in CO	
BHR 71	**0**	1 – 3	> 180 in CO	
VLA 1623	**0**	0.5 – 1	16 – 160 in CO	
HH211	**0**	2.4 – 4.8	7 – 28 in SiO, CO, SO ~ 20 – 28 in H_2	
IRAS 2A	**0**	0.3 – 0.7	6 in H_2 > 600 in CO	

Sperling+2021

RESULTS

Class 0	7 out of 9 
Class I	4 out of 5 

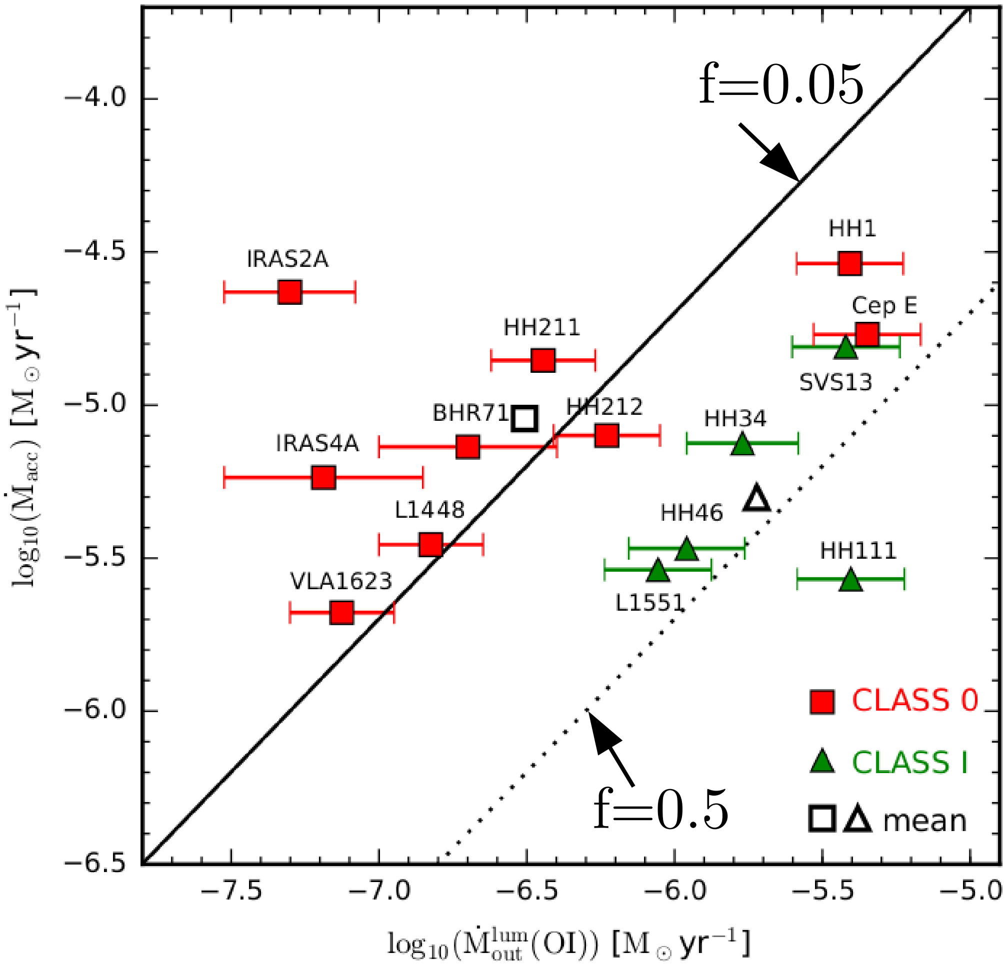
$\dot{M}(\mathrm{OI})$,

...**underestimates** the total mass-loss

...potentially traces the **bulk** mass-loss

Sperling+2021

Outflow efficiencies



- **most outflows:**

  f ~ 0.01-0.5

➔ agreement with

X-wind & disk wind

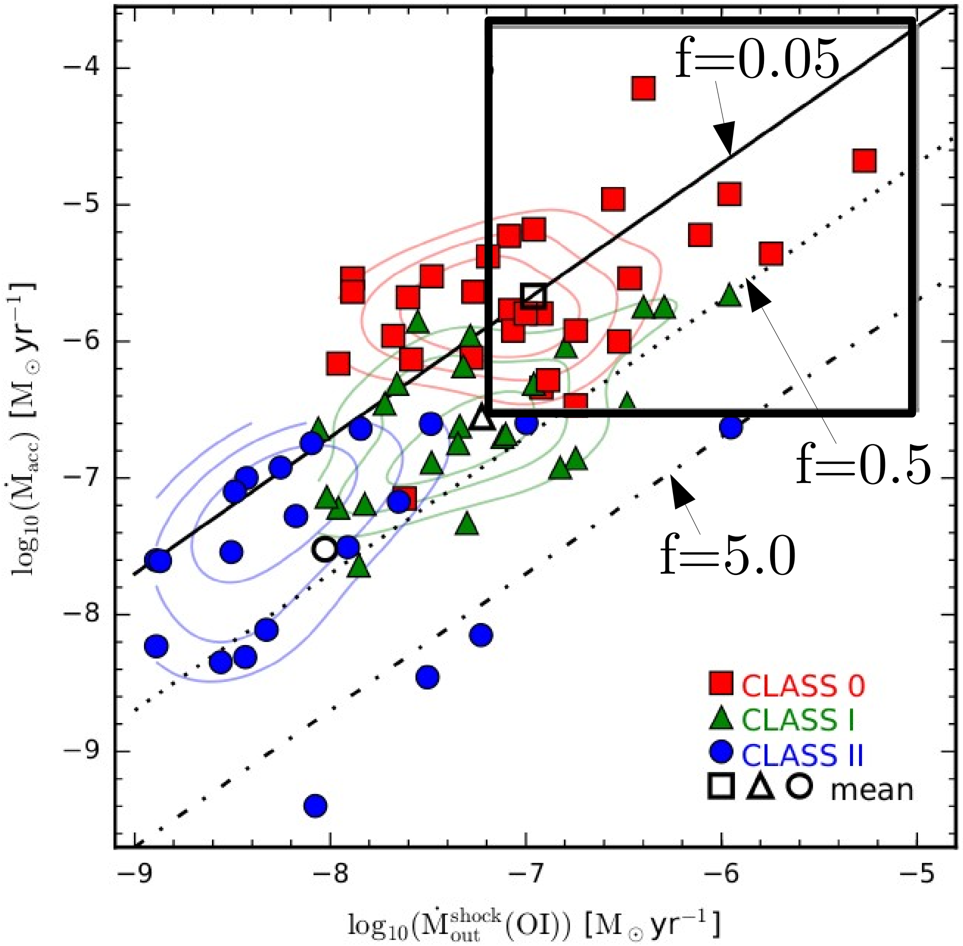
- **many Class 0 outflows**

  f $\lesssim$ 0.05

➔ take into account the molecular component!

Compilation
Sperling+20

Comparing with unresolved outflows



- **WISH+DIGIT+WILL+GASPS** surveys
  - ➔ single Herschel/PACS footprint
  - ➔ only outflows
  - ➔ 28 Class 0, 23 Class I, 21 Class II

Mottram+2017, Alonso-Martinez+2017

Consistent with my findings!

Evolutionary trend apparent!

Main conclusions

- my SOFIA observations support the notion that **protostellar outflows undergo an evolution**
- the bulk **mass-loss from Class 0** outflows resides by tendency in a **molecular** component
- for more evolved **Class I** outflows the **[OI] emission** line tends to trace the **main component**

...but we need more data!

TLS star-formation group

Upgrade of SOFIA instruments? Future prospects?

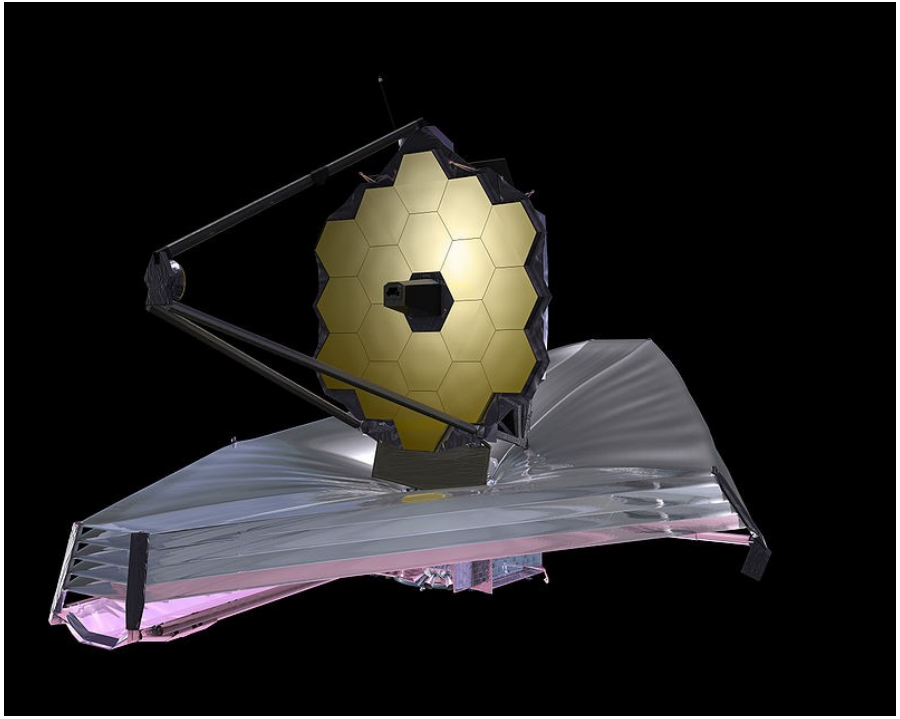
Credit: NASA

SOFIA/FIFI-LS+ → Most likely not sensitive enough!

SOFIA/HIRMES → No extensive mapping possible!

SOFIA/GREAT → No improvement in spatial resolution!

And what about JWST?



Credit: NASA

- **launch:** November 2021?
- D ~ 6.5m
- $\lambda = 0.6\,\mu m - 28\,\mu m$

mid-IR lines

[FeII], [SI], [SiII]...

→ **no observations at FIR [OI] lines**

The End