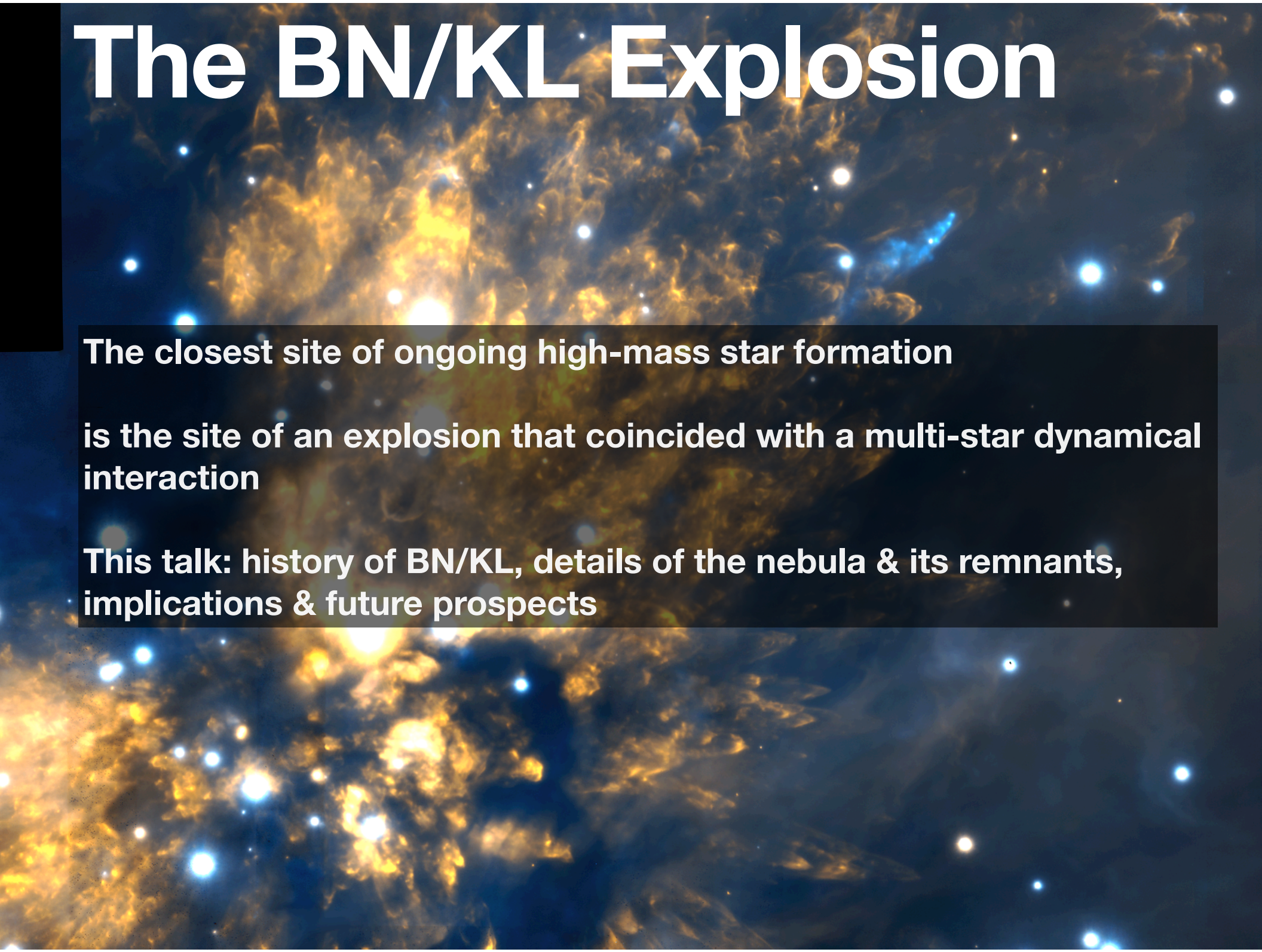
Today's topic: one of John's favorites


The Orion Explosion
Gemini-S
GSAOI + GEMS
(Bally et al. 2015)
2013 Gemini S AO
H_2 at 2.12 μm
[FeII] at 1.64 μm
JOHN BALLY
…he already gave the talk, so we can move on

The BN/KL Explosion

Adam Ginsburg [PhD under Bally]
John Bally [Bally]
Allison Youngblood [Masters under Bally]
Devin Silvia [CU grad I roped into BN/KL]
Nick Moeckel [PhD under Bally]
Mark McCaughrean [gave JWST images]
Cara Battersby [PhD under Bally, escaped Orion]
(I've kept my students away from Orion so far…)

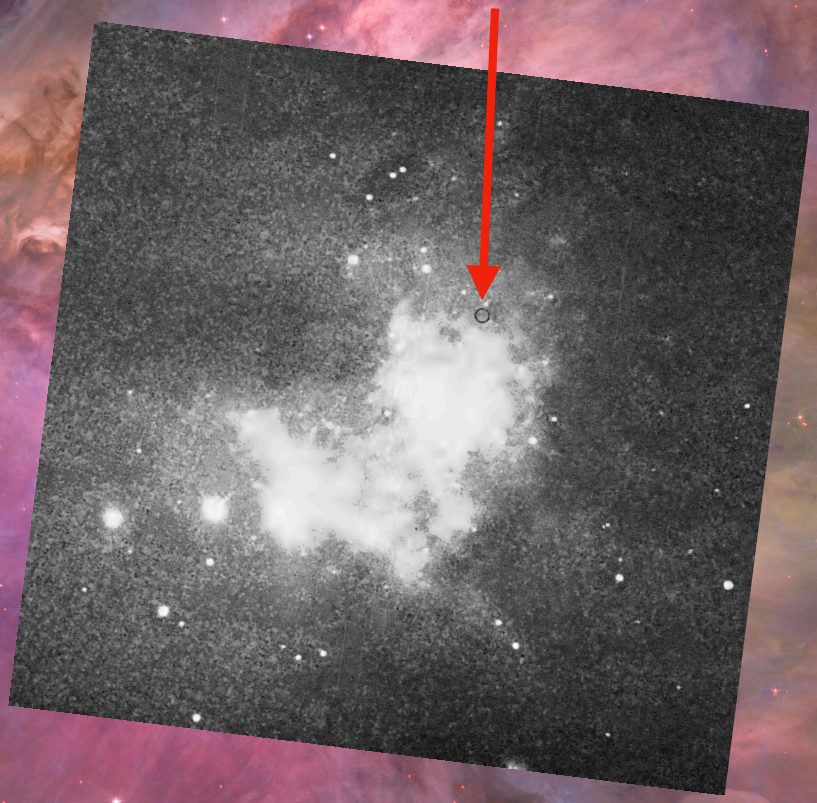
The BN/KL Explosion



The closest site of ongoing high-mass star formation

is the site of an explosion that coincided with a multi-star dynamical interaction

This talk: history of BN/KL, details of the nebula & its remnants, implications & future prospects



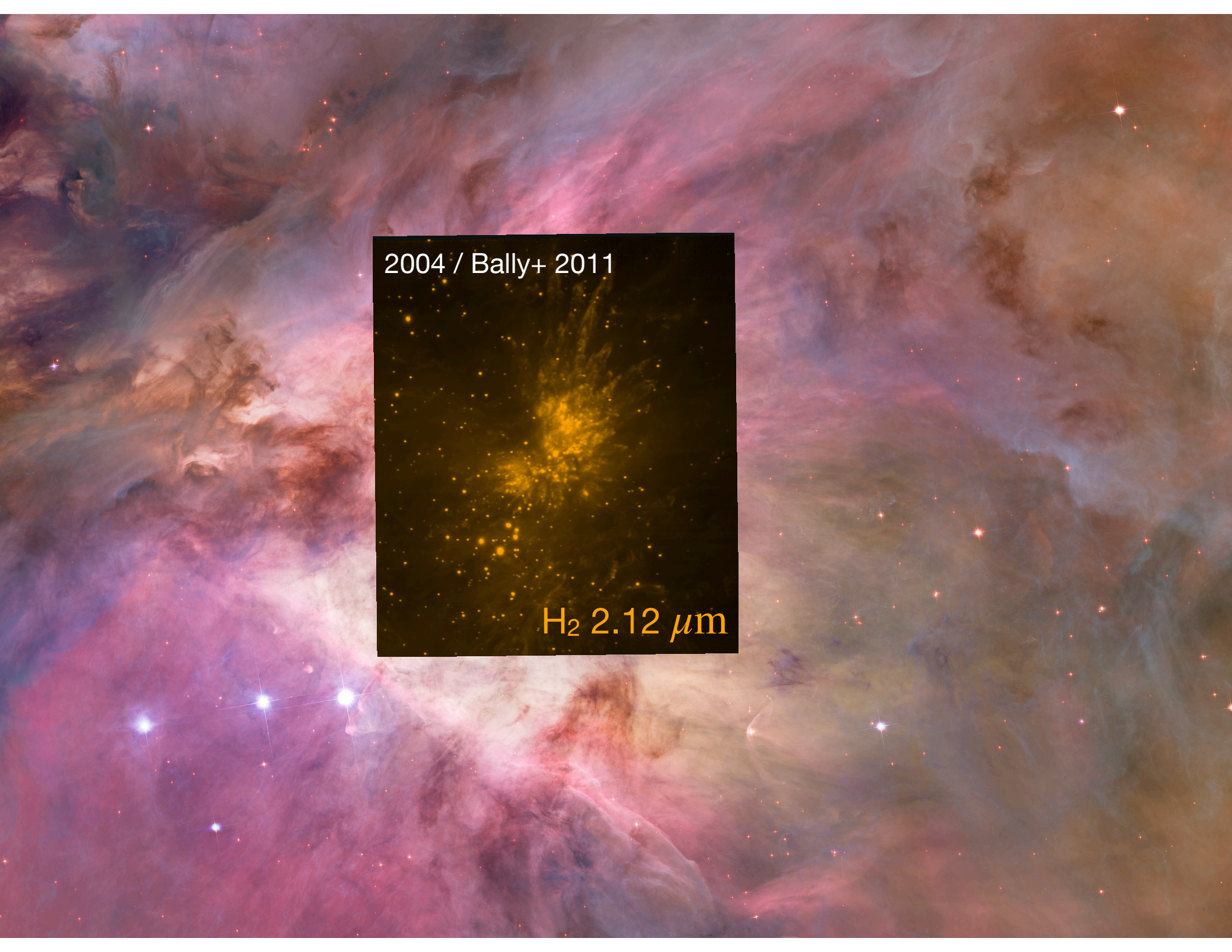
Becklin & Neugebauer 1967

TABLE 1

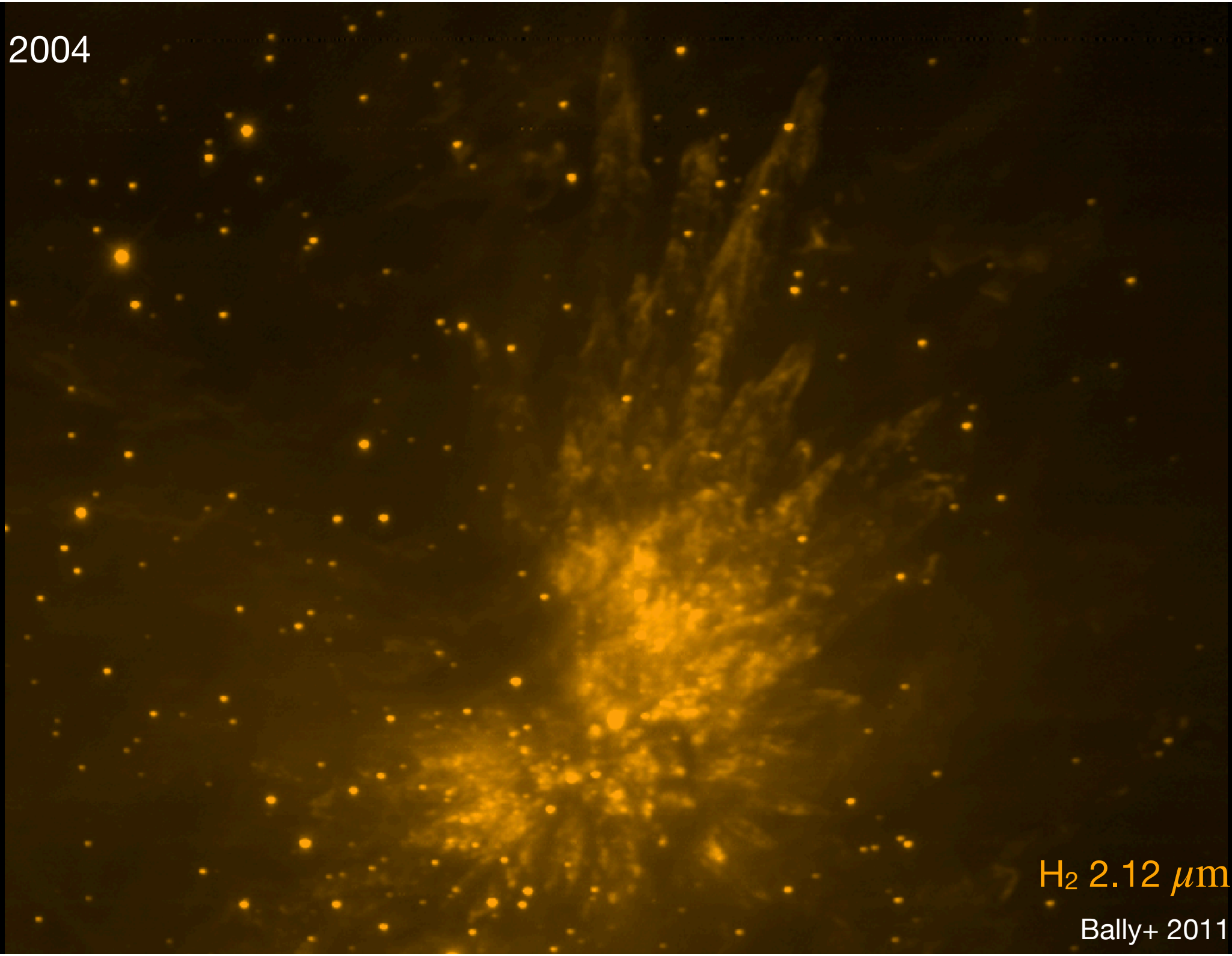
PHOTOMETRIC RESULTS

Effective Wavelength (μ)	Wave-length Pass Band (μ)	Magnitude	Absolute Flux (W cm^{-2} μ^{-1}) $\times 10^{16}$
1 65	0 3	9 8	0 14±0 03
2 2	0 4	5 2	3 4 ± 2
3 4	0 7	2 0	13 2 ± 8
10 0	5 0	−1 2	3 4 ±0 3

Kleinmann & Low 1967
looks about the same


2004 / Bally+ 2011
H_2 2.12 μm

Gemini Observatory Legacy Image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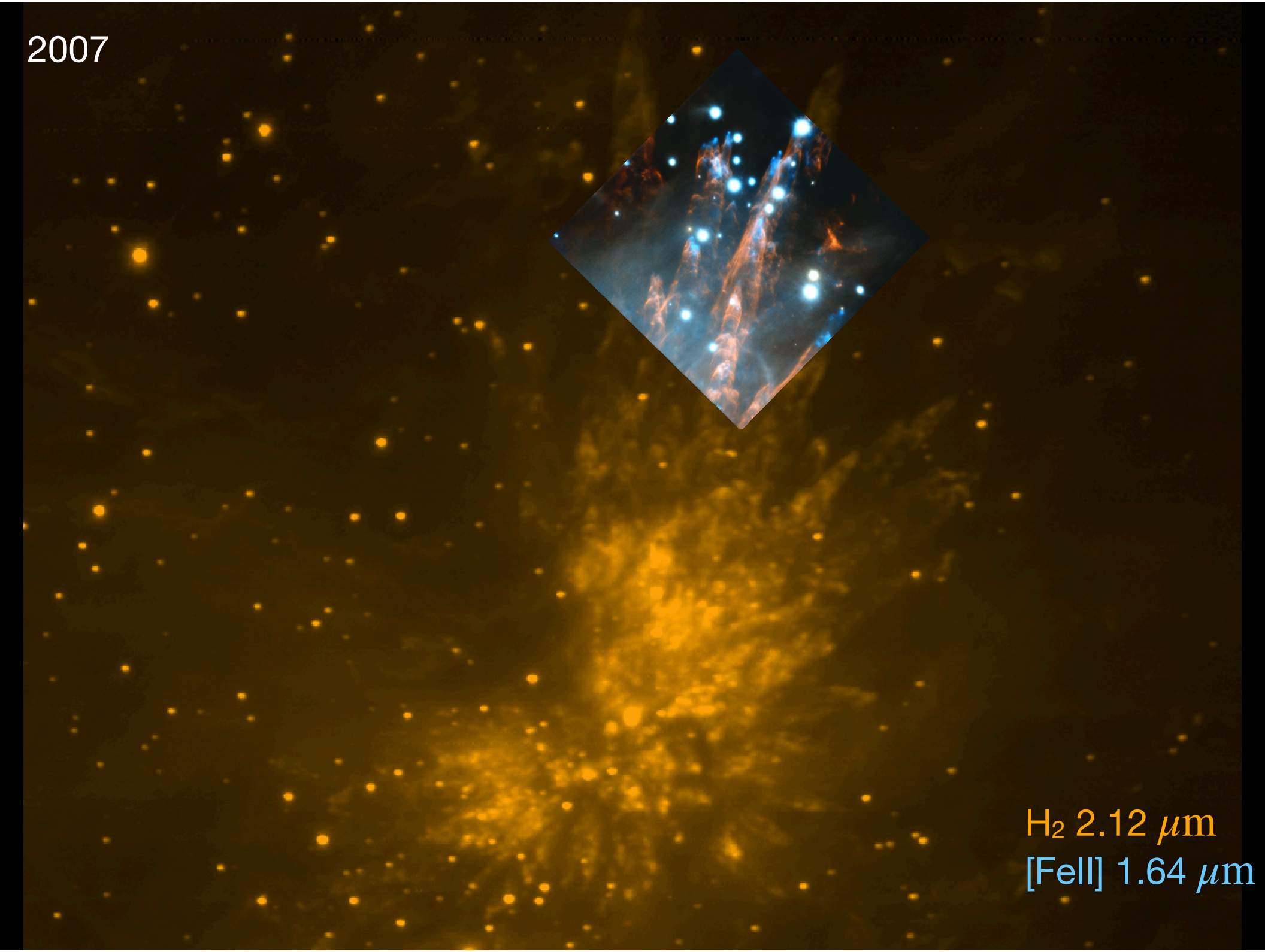
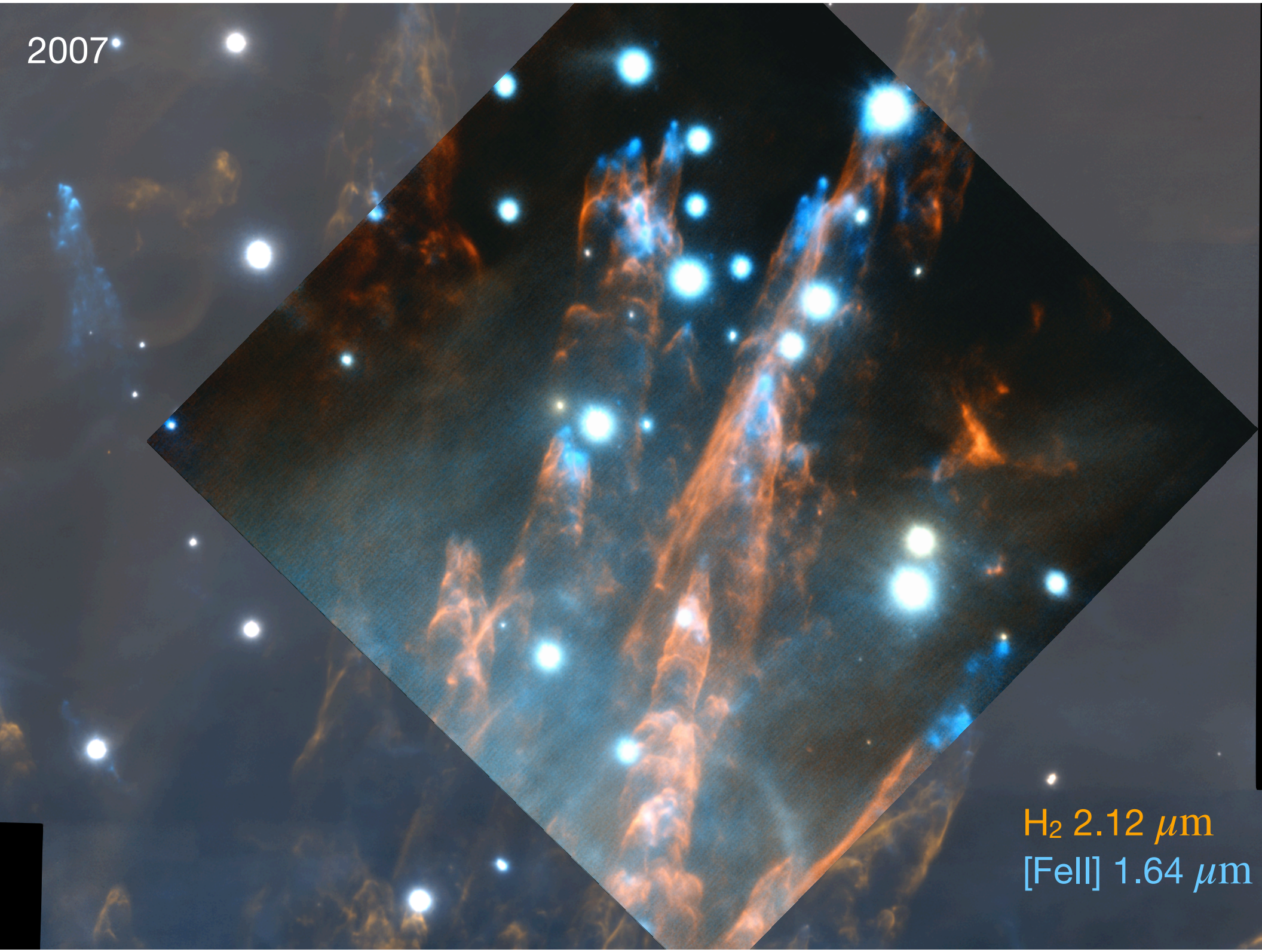

2007
H2 2.12 μm
[FeII] 1.64 μm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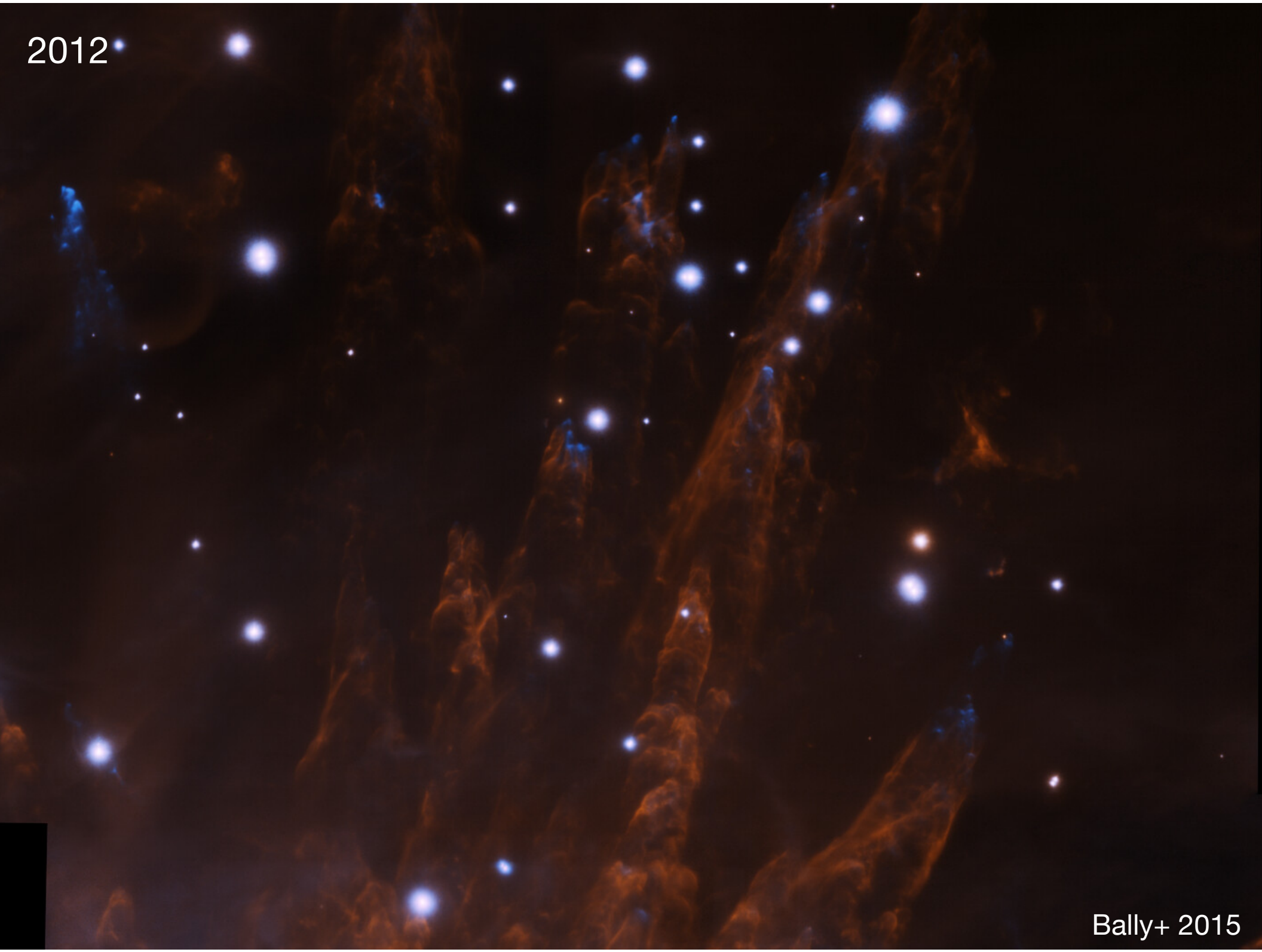
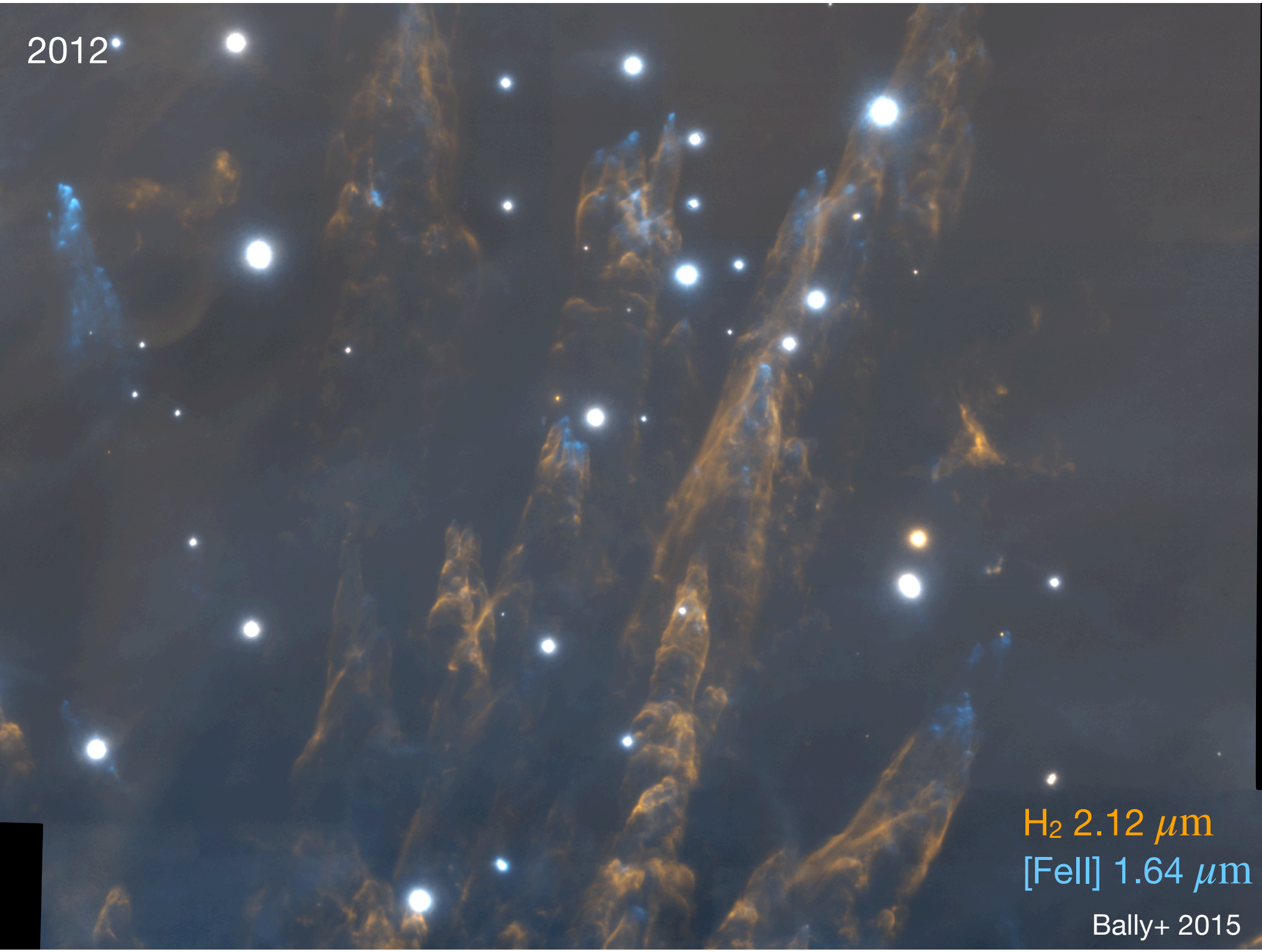

2012
Bally+ 2015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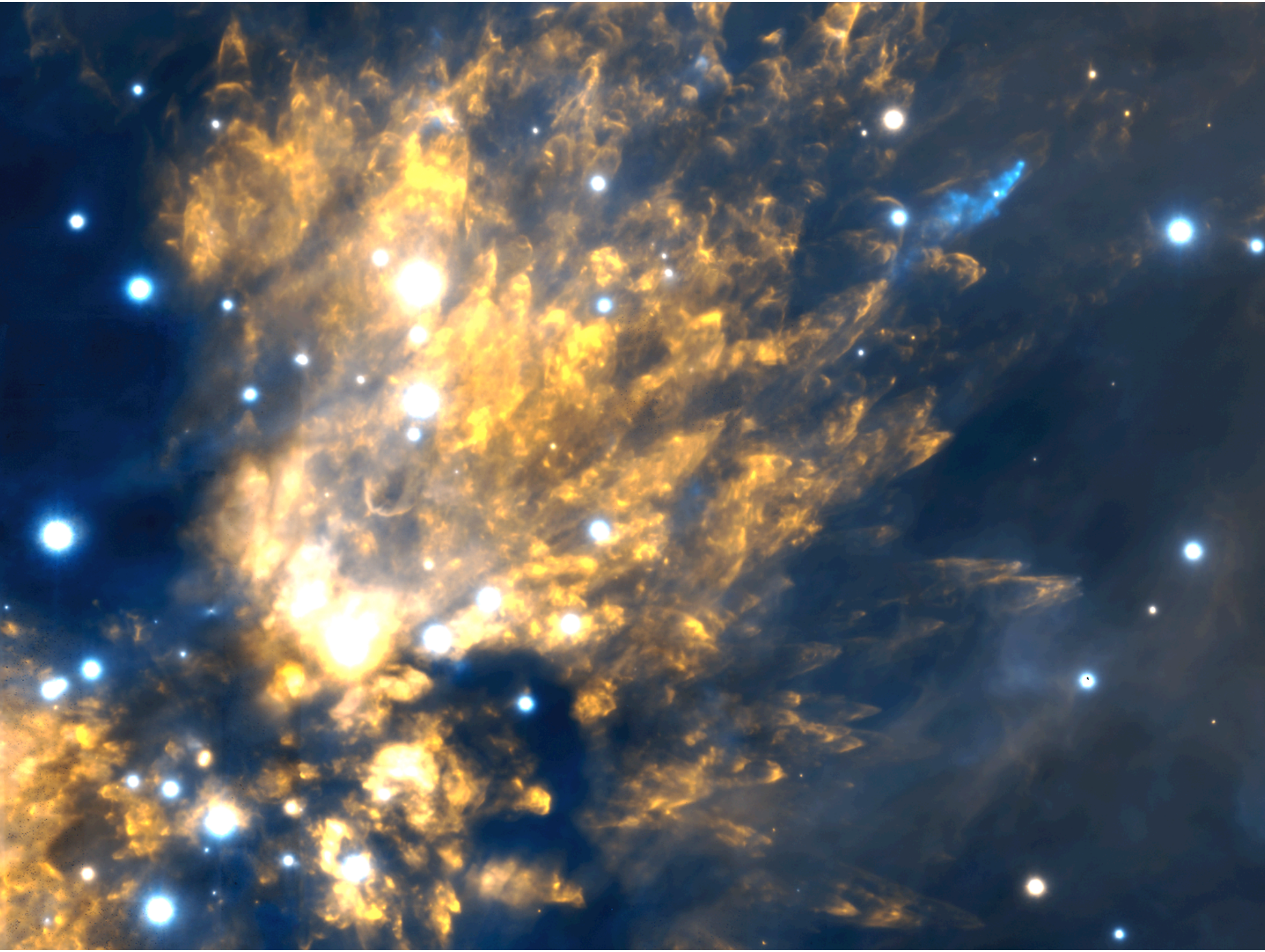

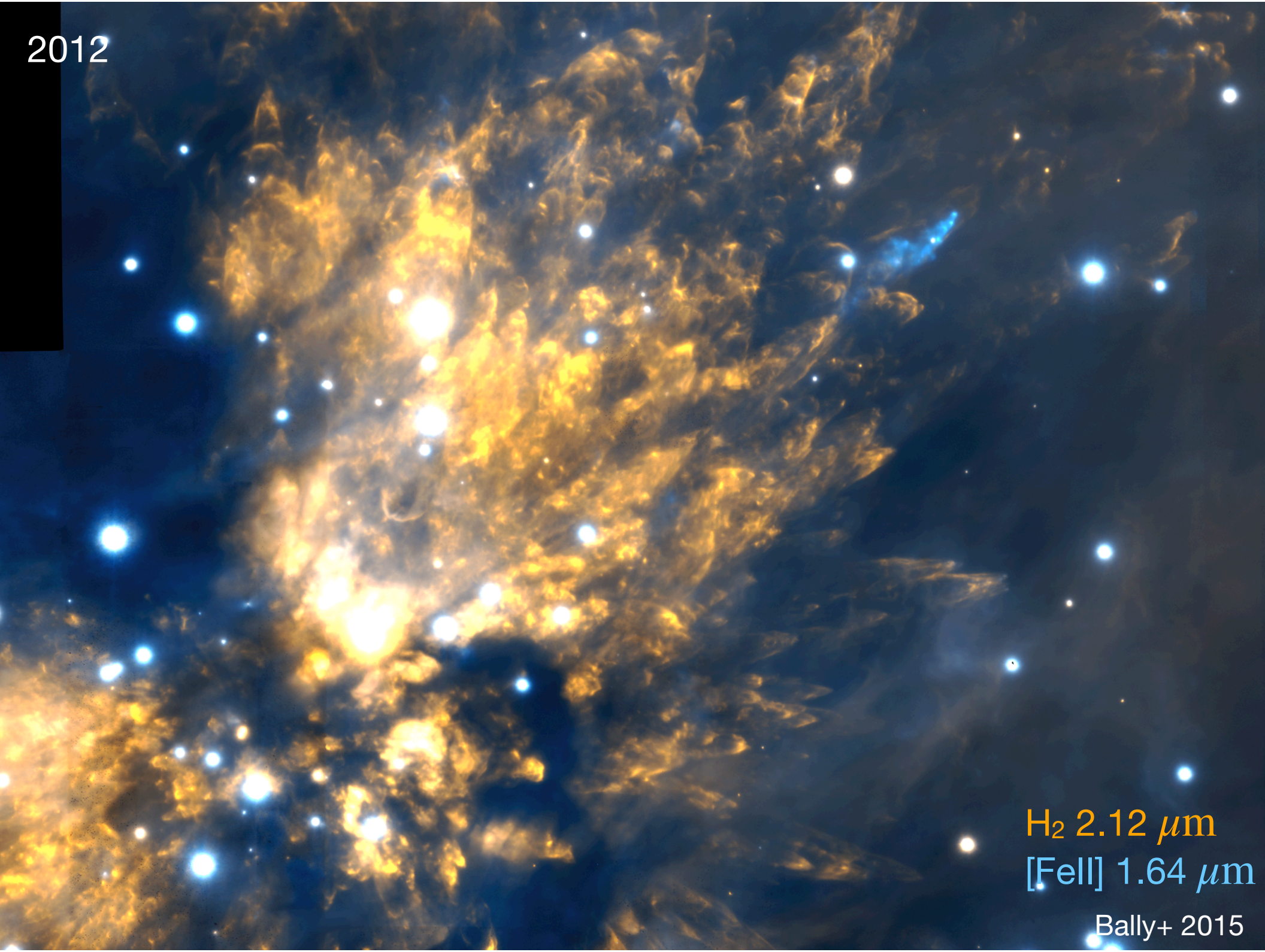
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2023
H2 2.12 μm
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McCaughrean & Pearson 2023


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H_2 2.12 μm
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McCaughrean & Pearson 2023


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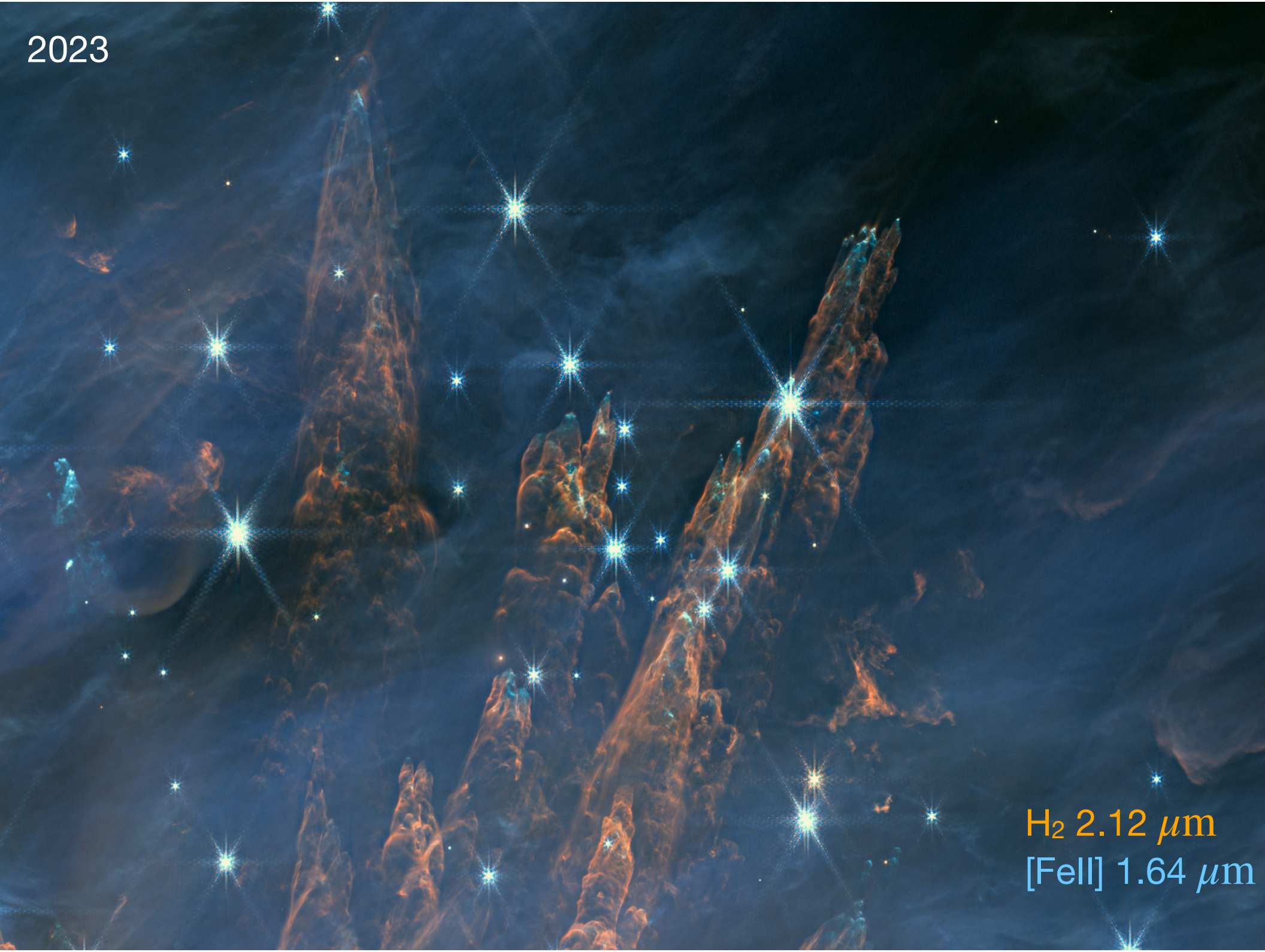
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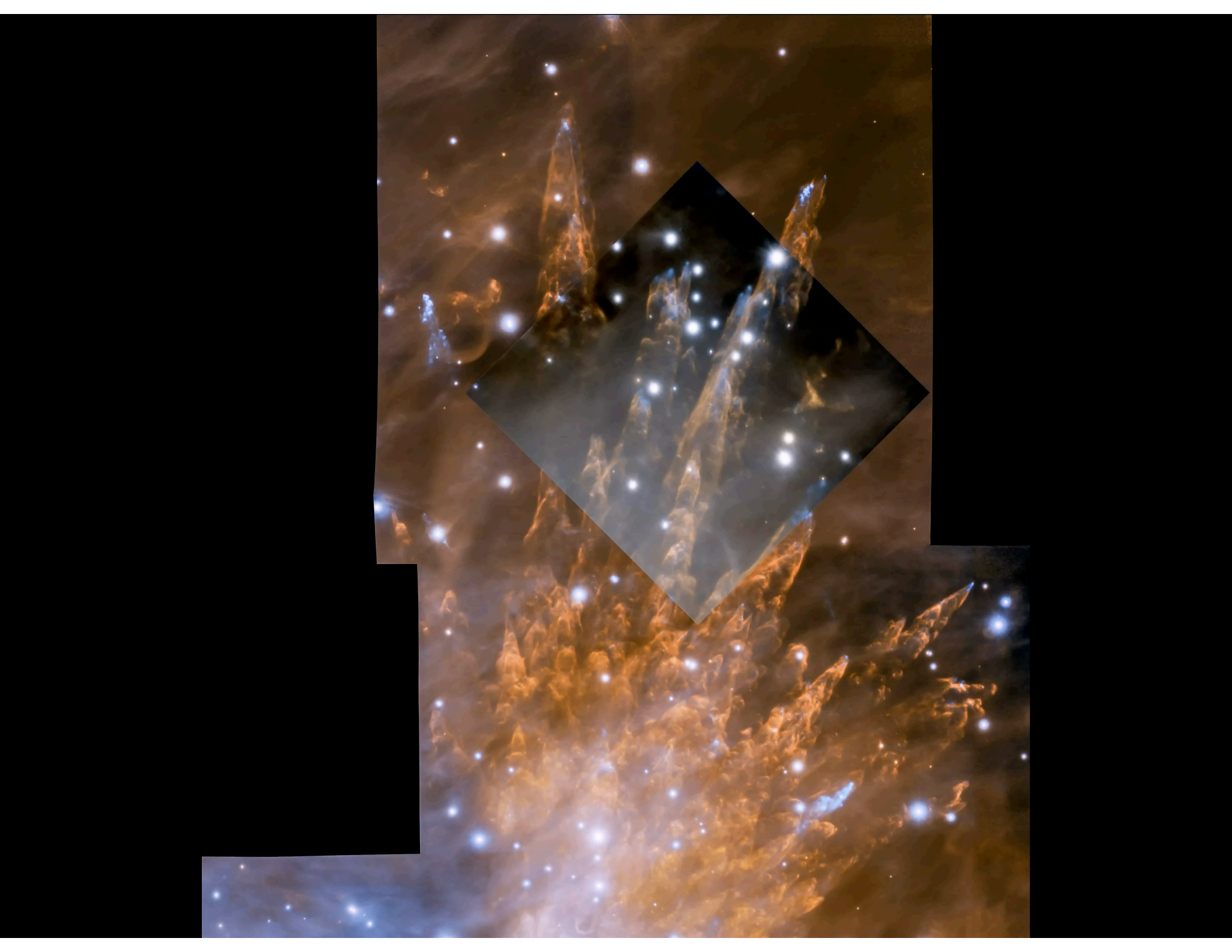
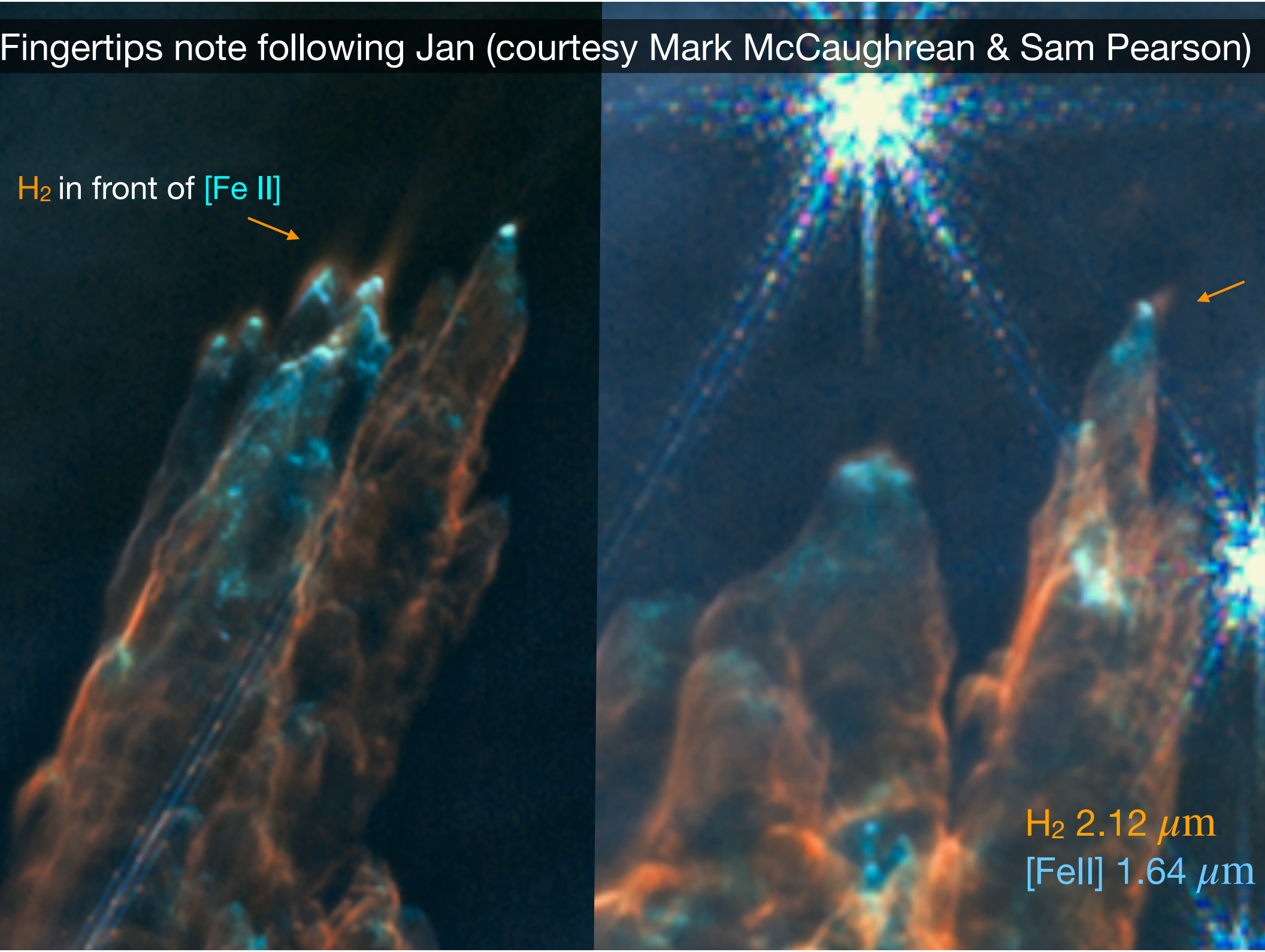
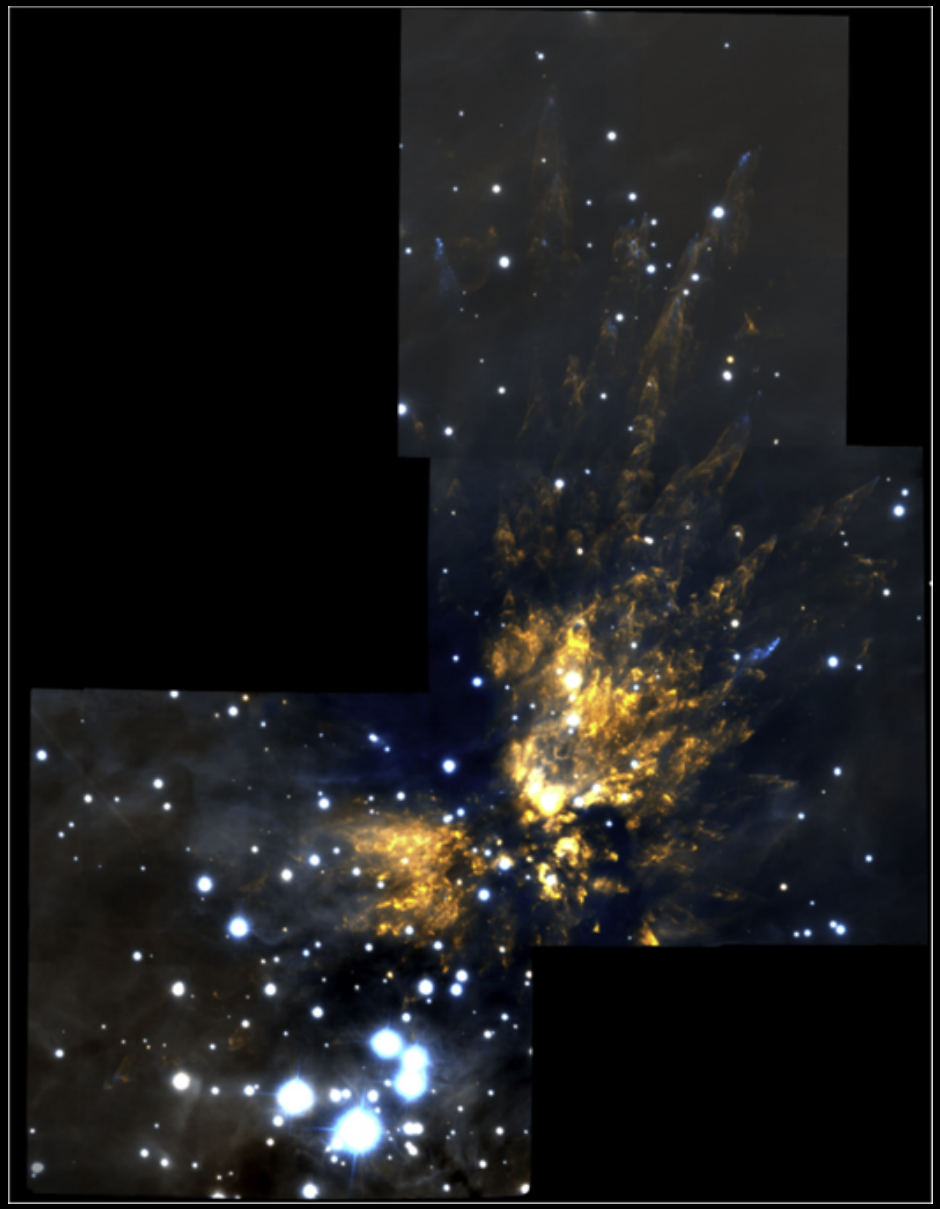
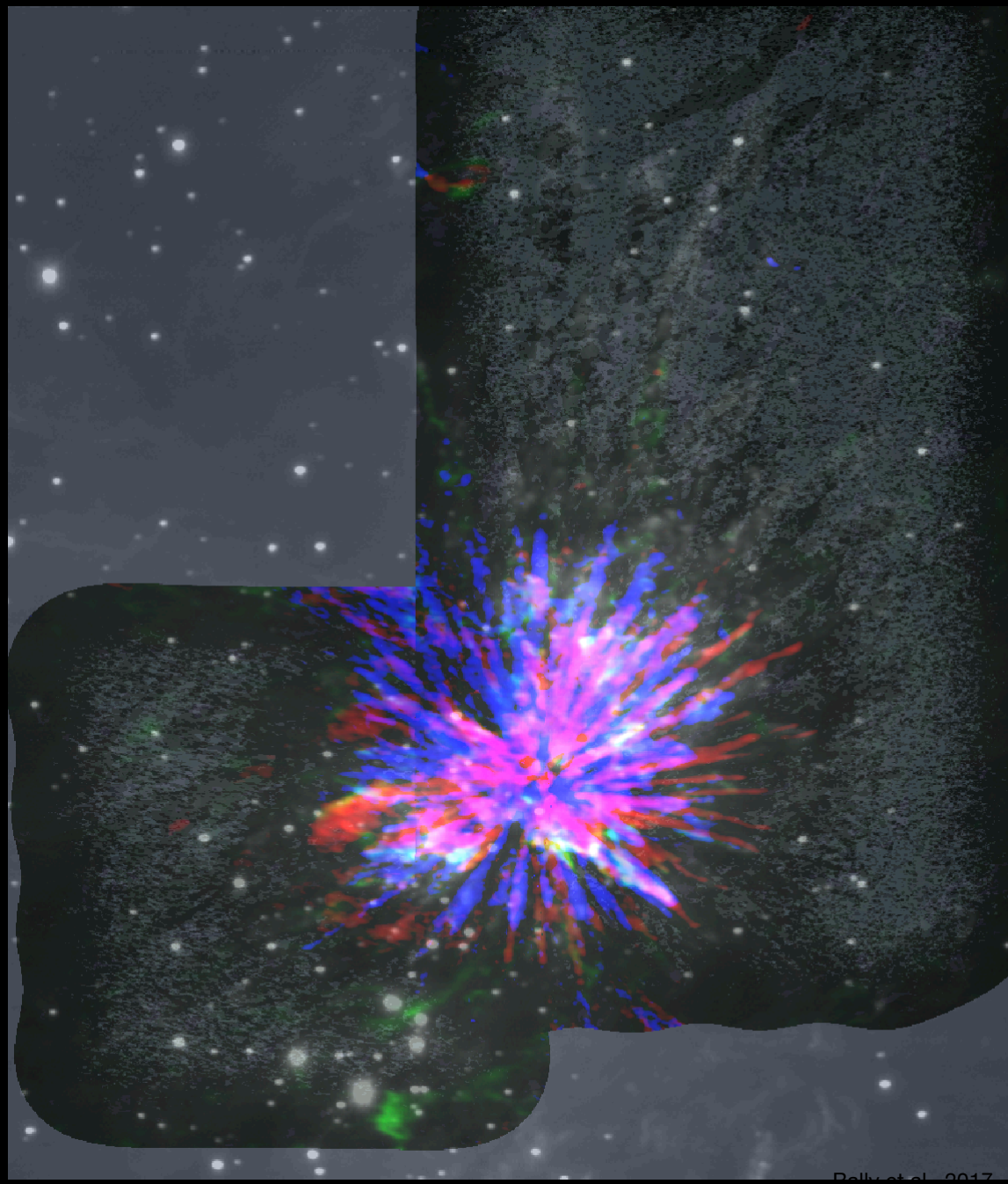


Fingertips note following Jan (courtesy Mark McCaughrean & Sam Pearson)



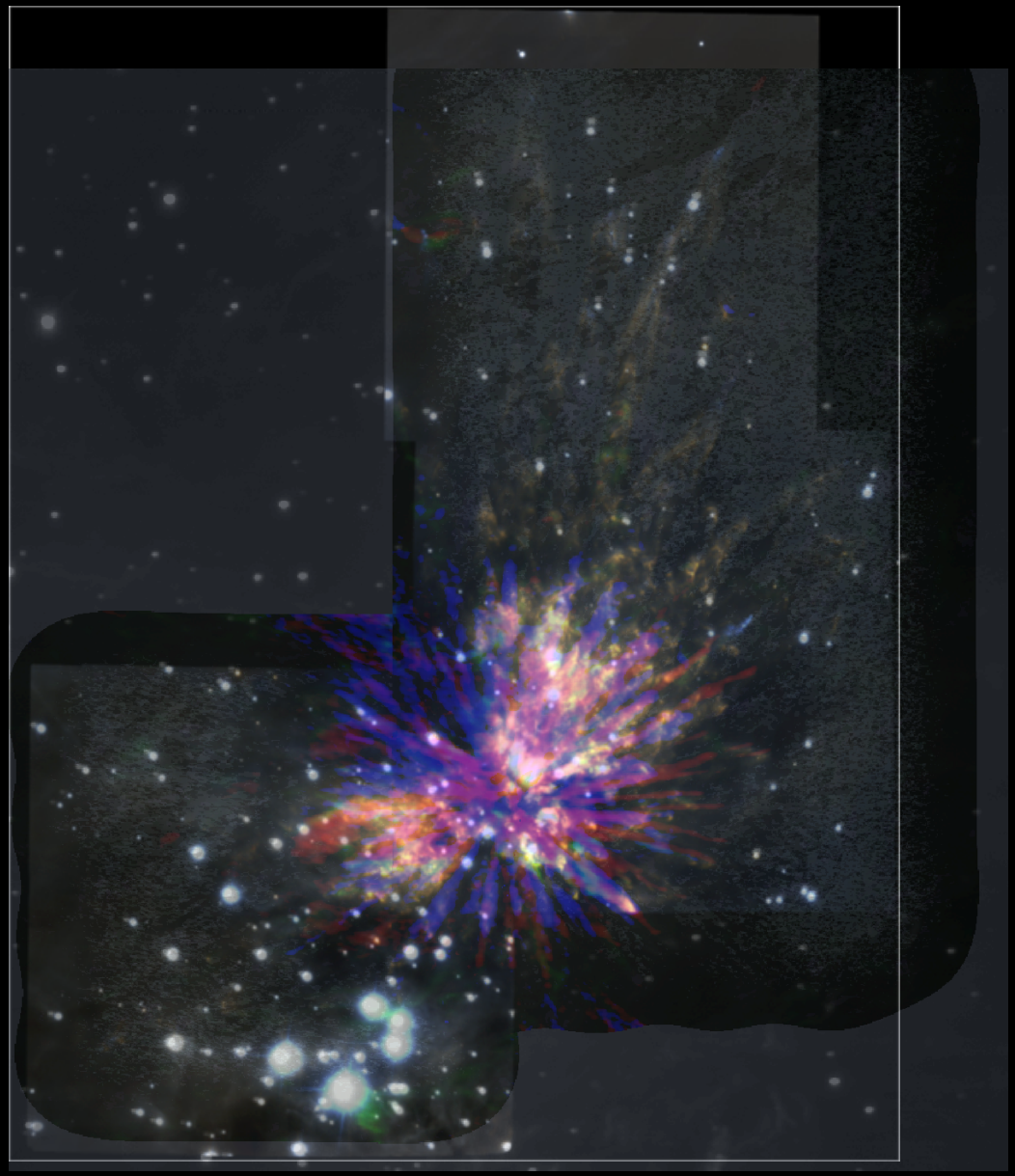
ALMA showed the explosion was closer to isotropic than bipolar





Reilly et al., 2017

ALMA showed the explosion was closer to isotropic than bipolar



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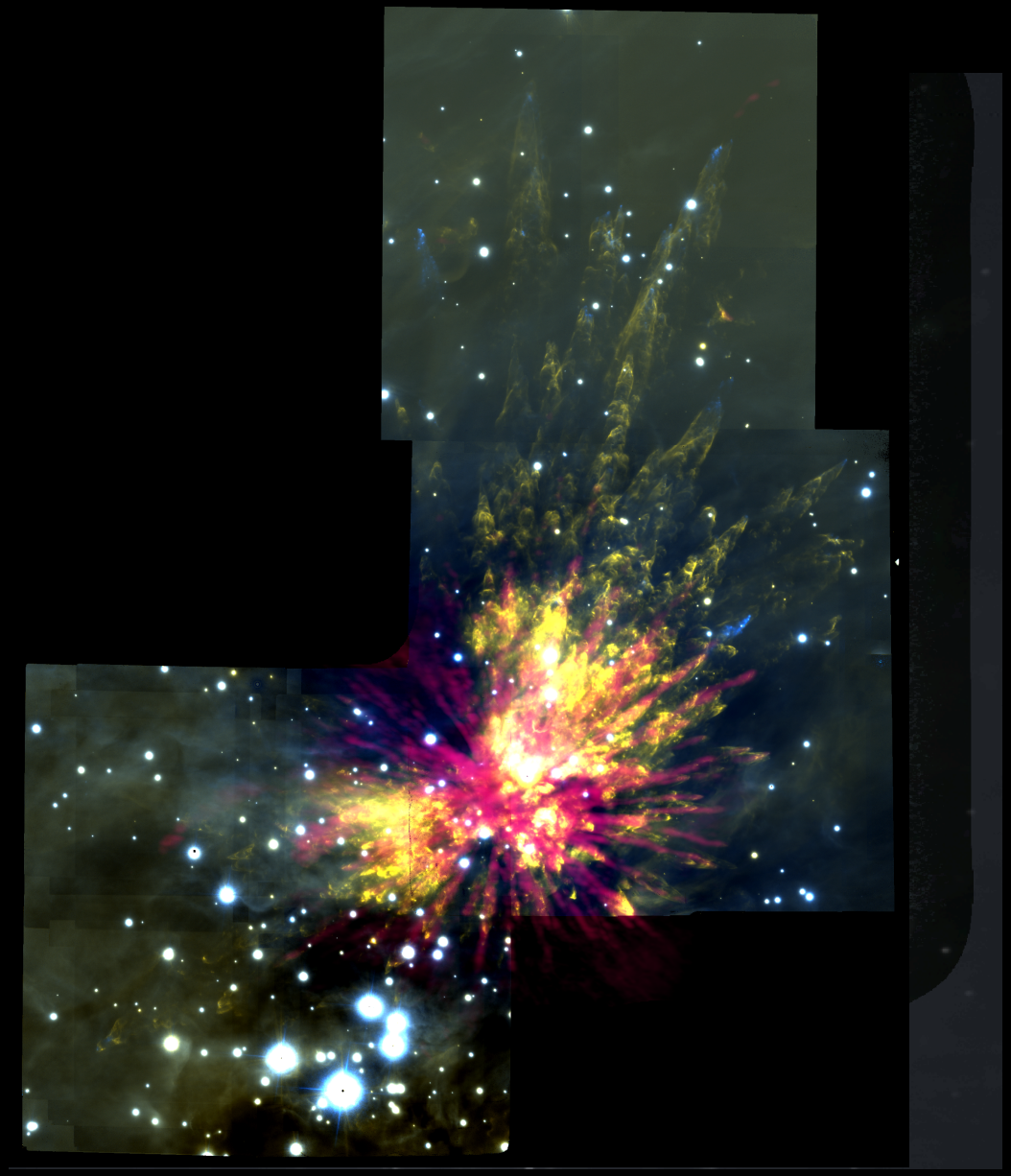
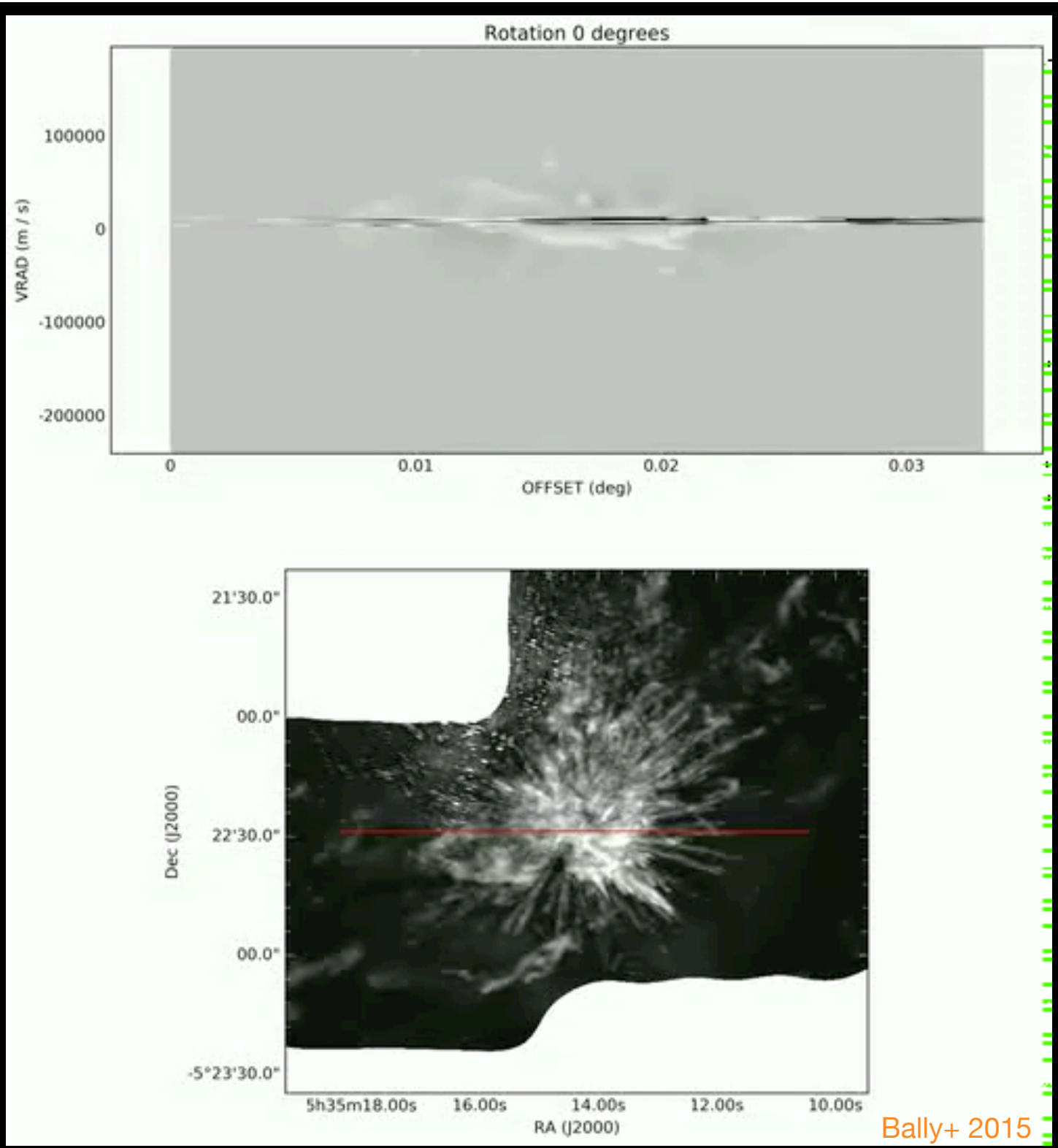




Bally+ 2015

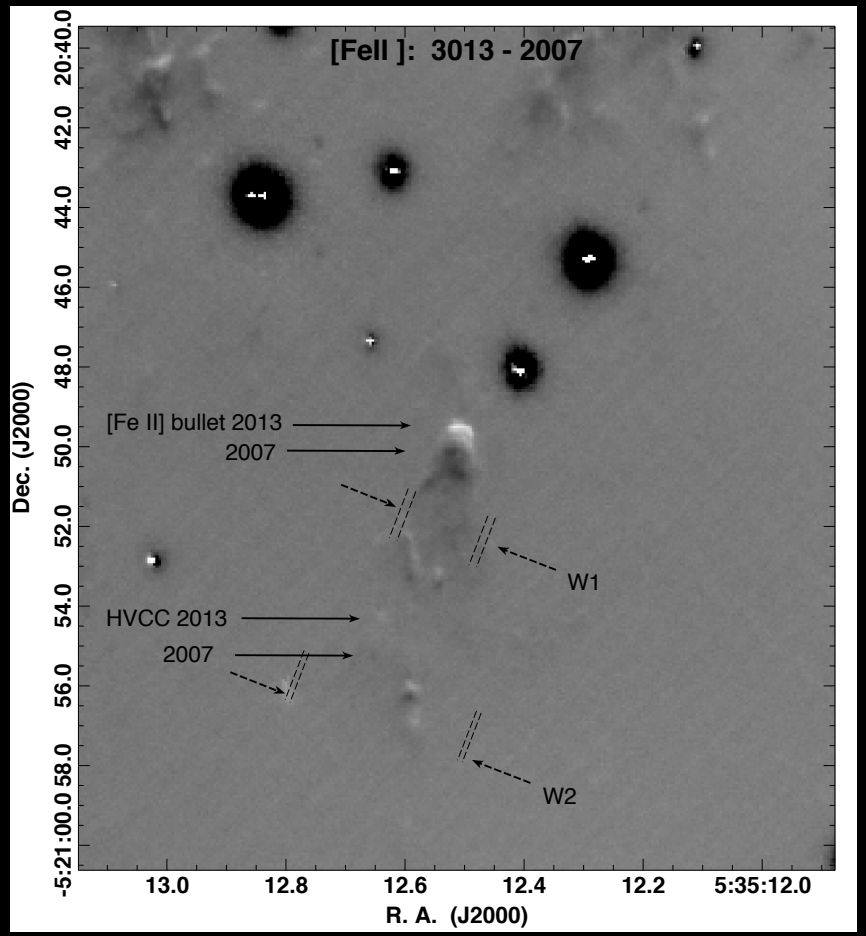
"Hubble Flow"

$v \sim r$

If everything is launched at once, the most distant stuff is fastest

(the wakes show that there's still gas expanding in the bullet's wake)

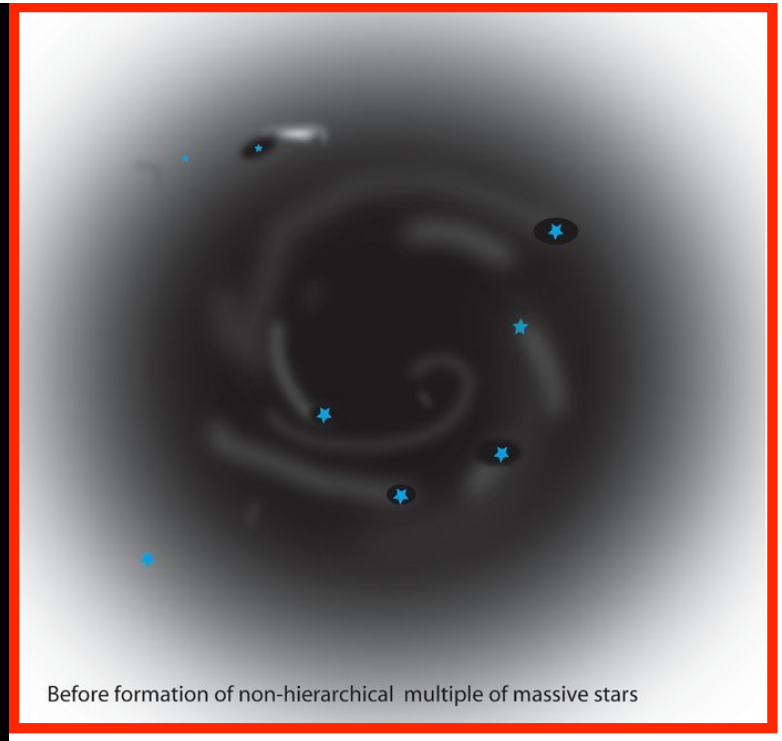
John measured
vectors for ~100 shocks,
proper motion measurements
for ~dozens



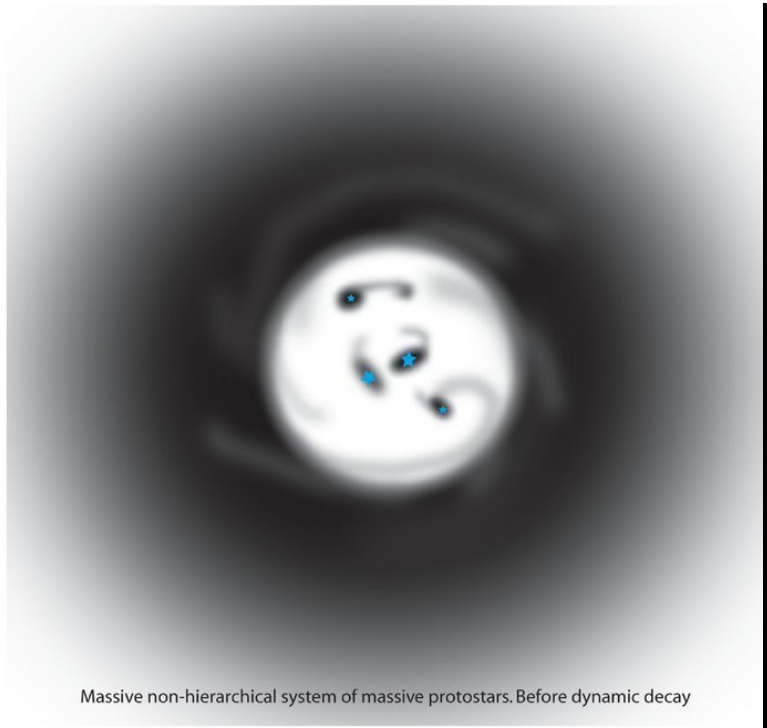
The model:

1. **Stars form in a dense cloud**
2. (massive) stars migrate to the center
3. Non-hierarchical multiple system forms… then disrupts

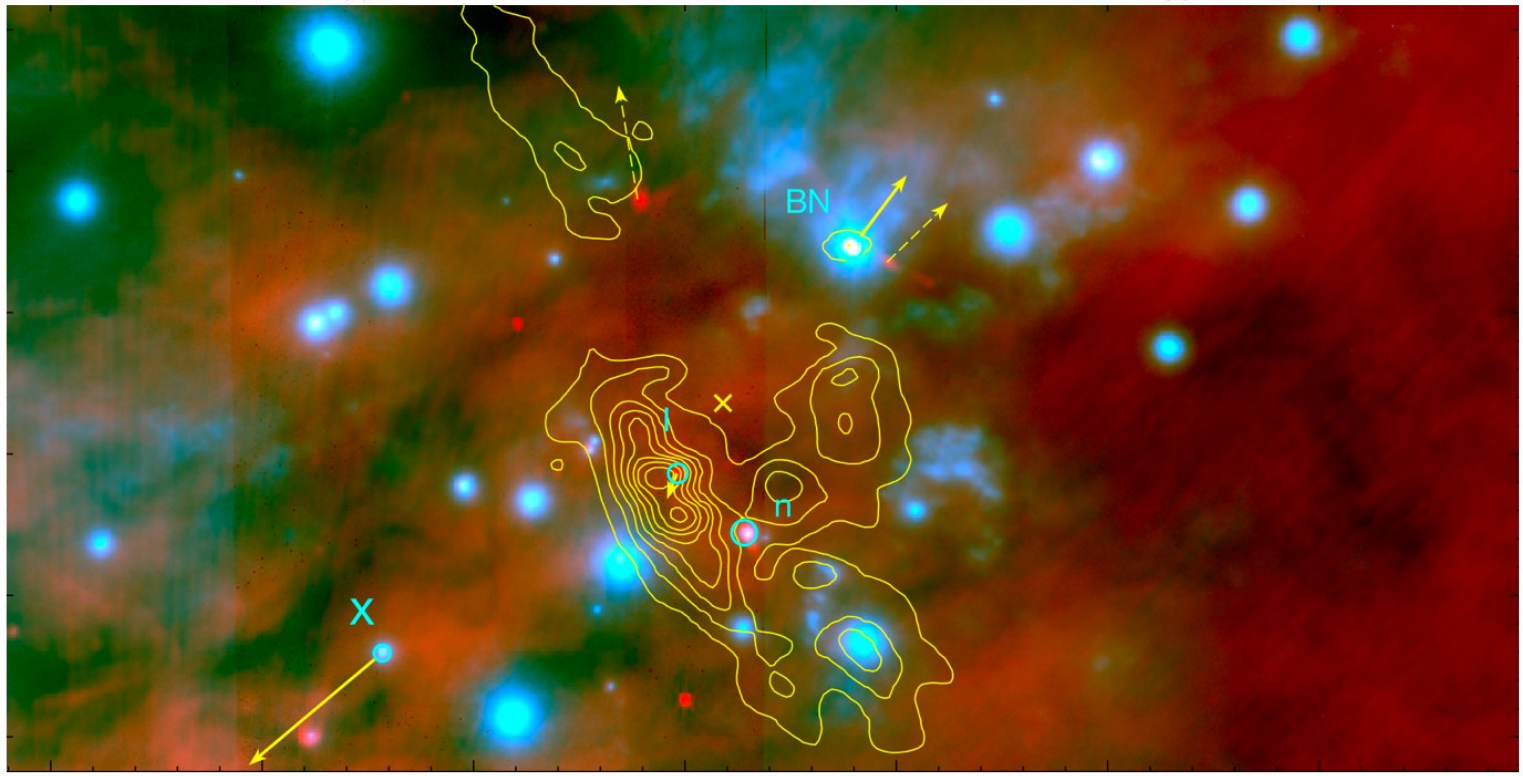
Bally+ 2011, 2020



(a)



(b)

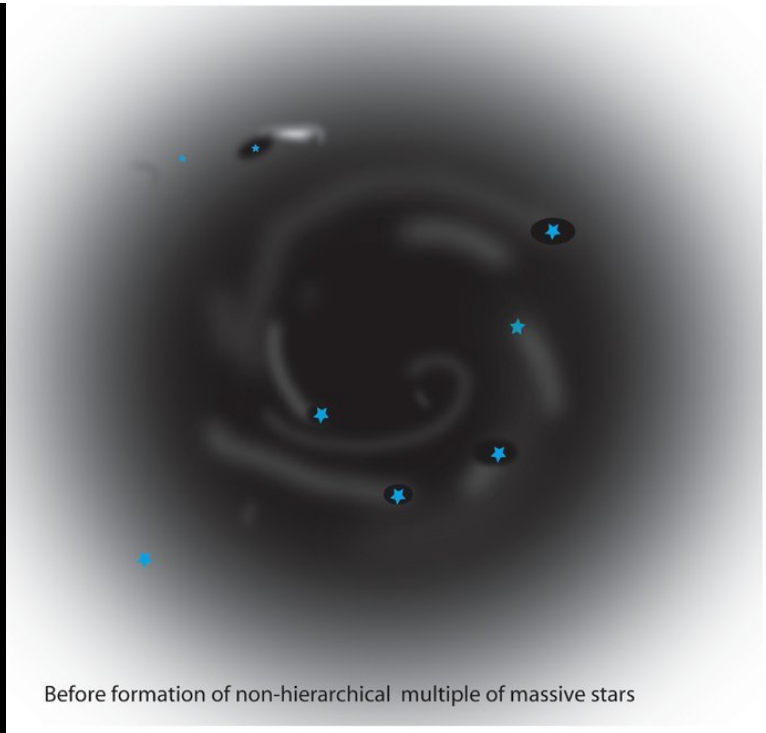


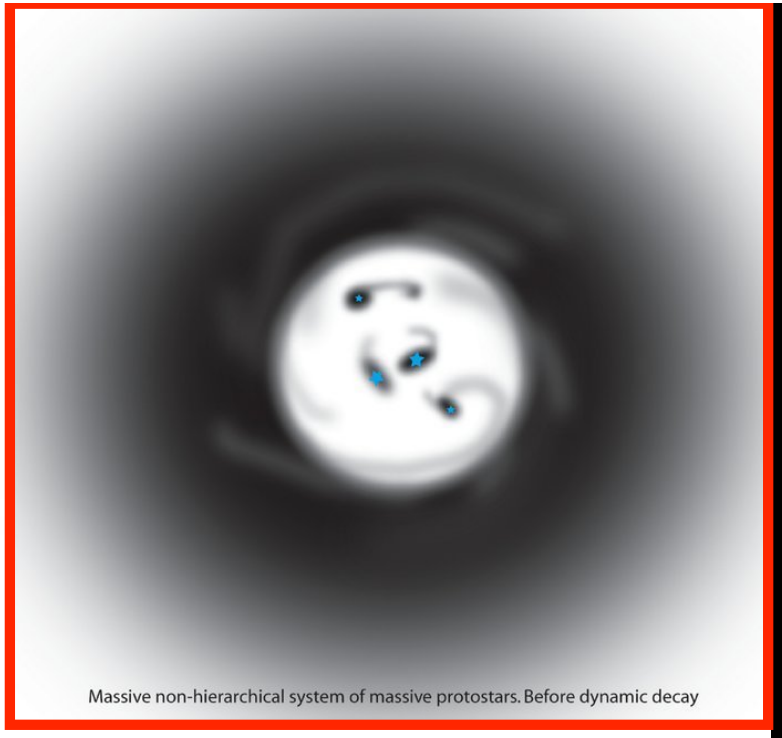
(c)

The model:

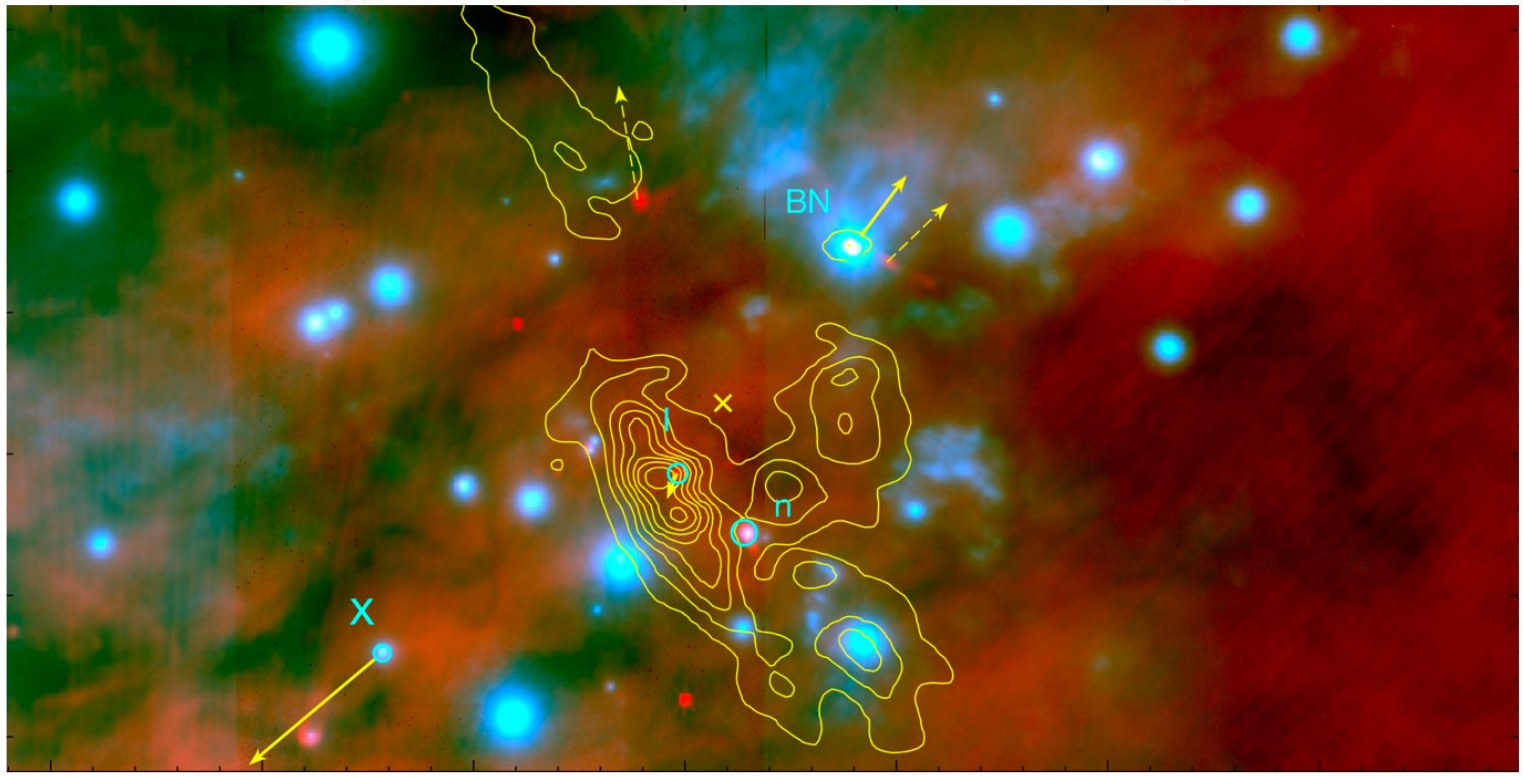
1. Stars form in a dense cloud
2. **(massive) stars migrate to the center**
3. Non-hierarchical multiple system forms… then disrupts

Bally+ 2011, 2020





(a) (b)



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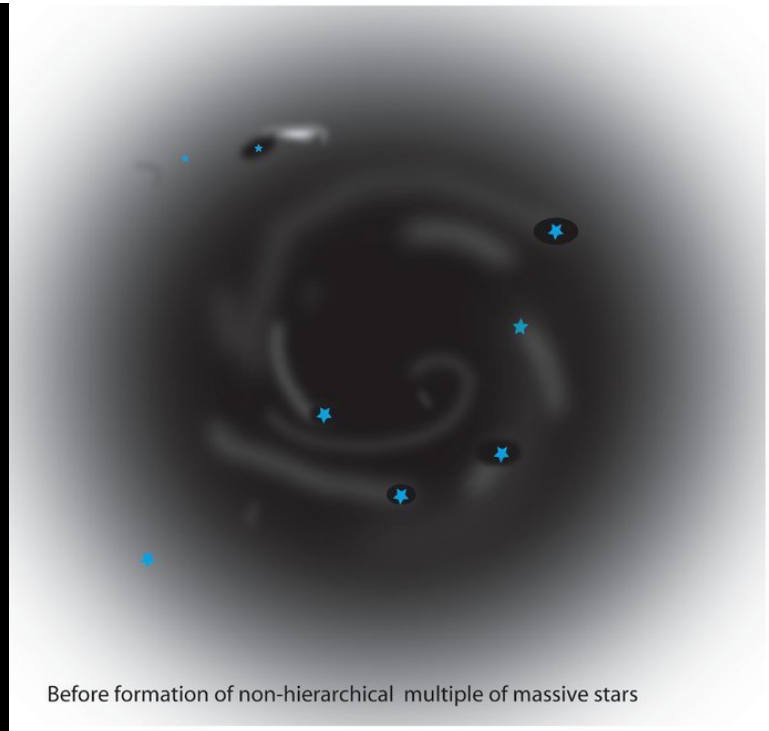
The model:

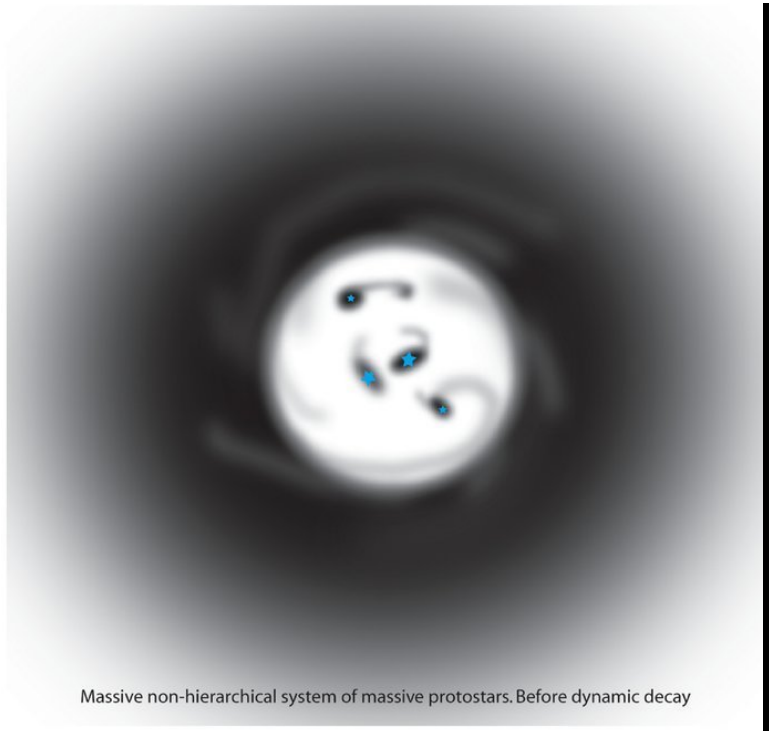
1. Stars form in a dense cloud

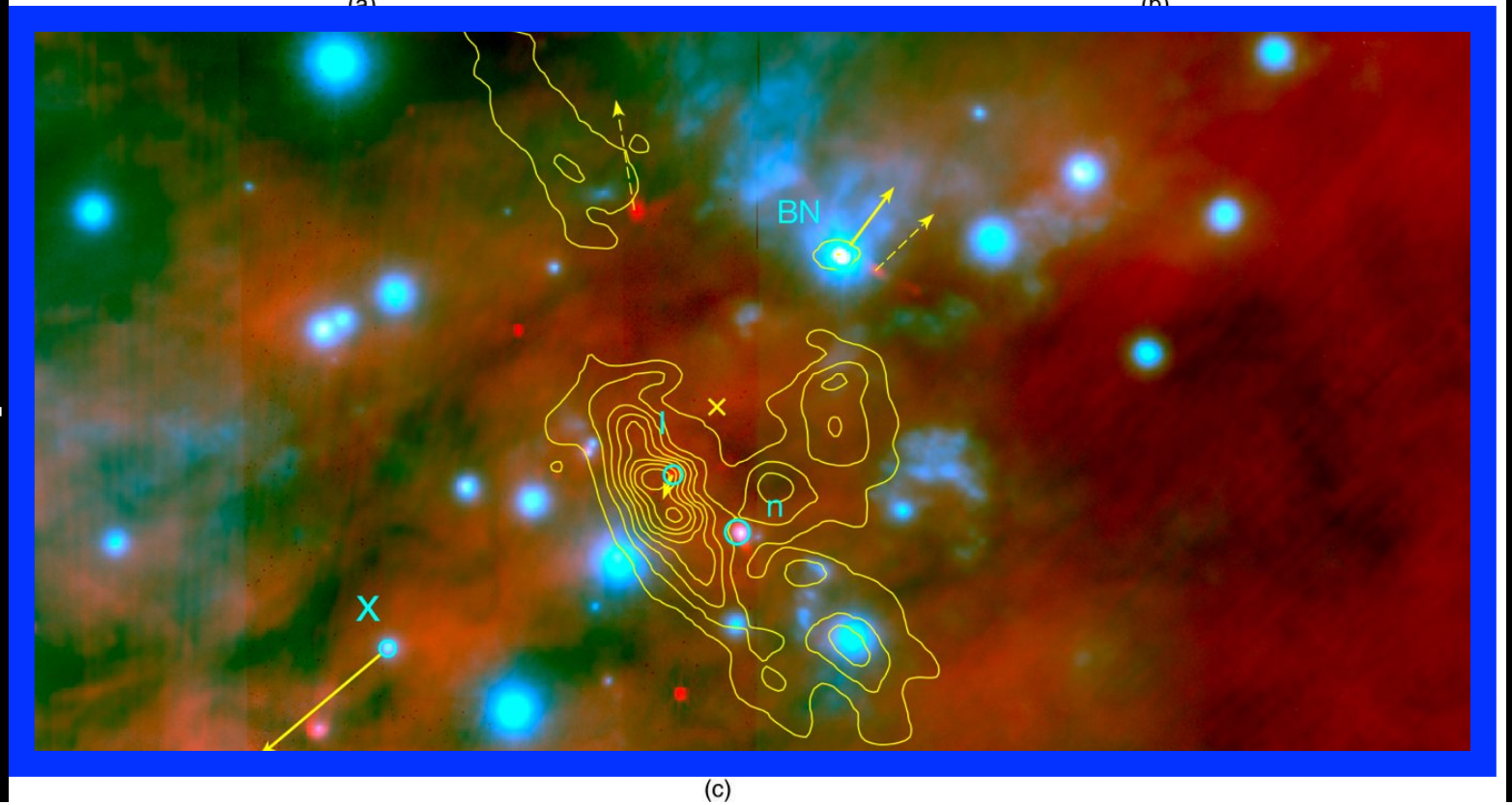
2. (massive) stars migrate to the center

3. **Non-hierarchical multiple system forms… then disrupts**

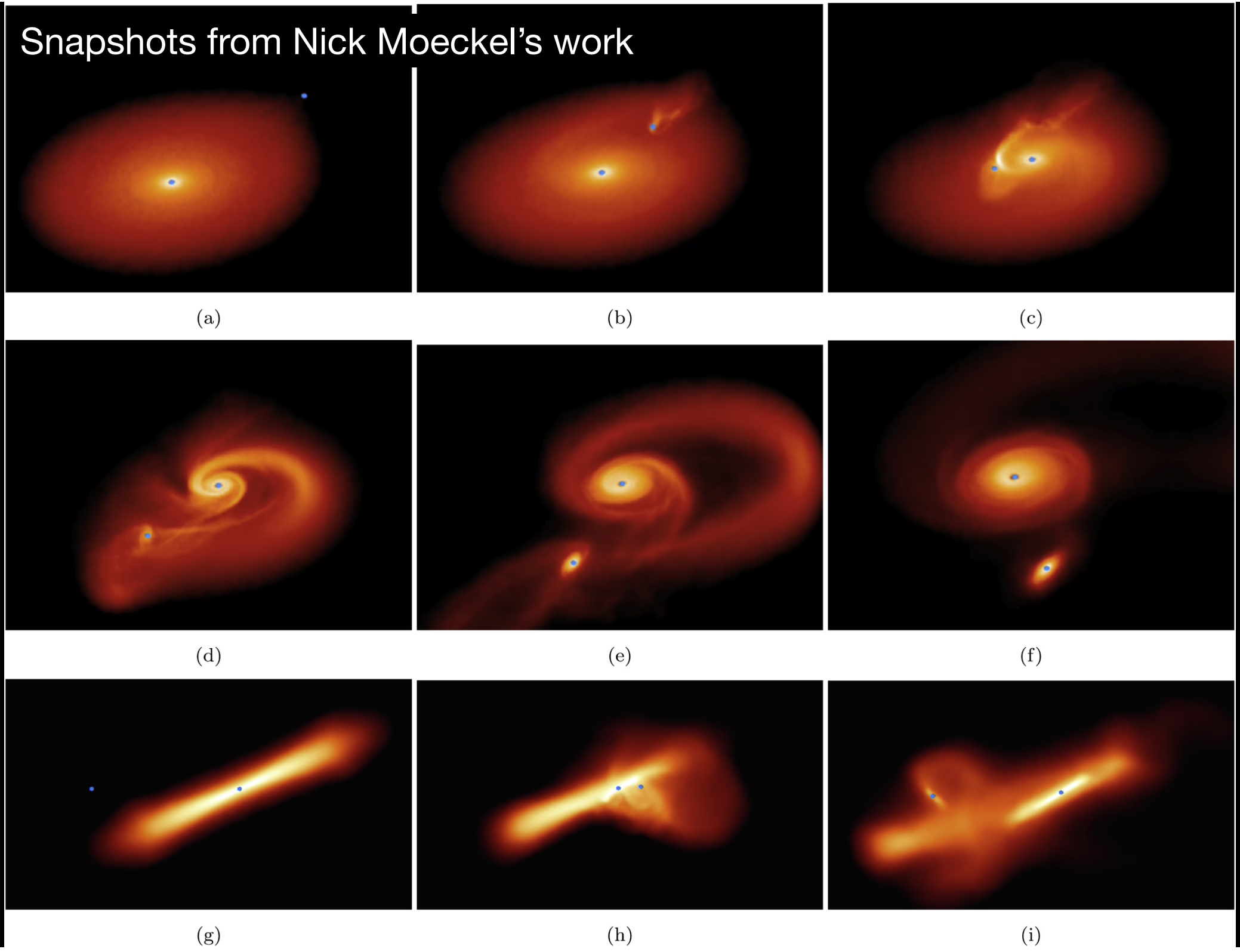
Bally+ 2011, 2020

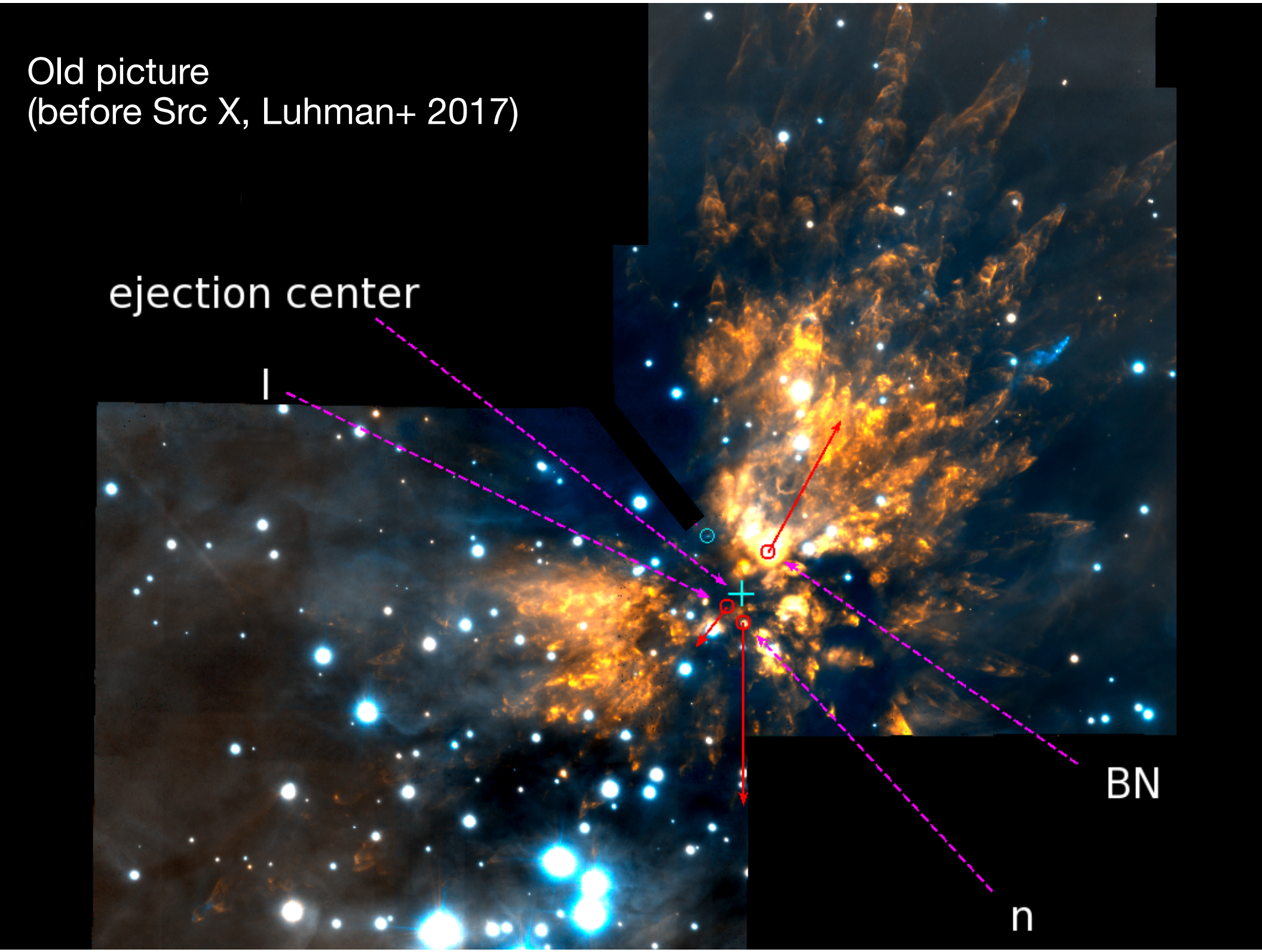


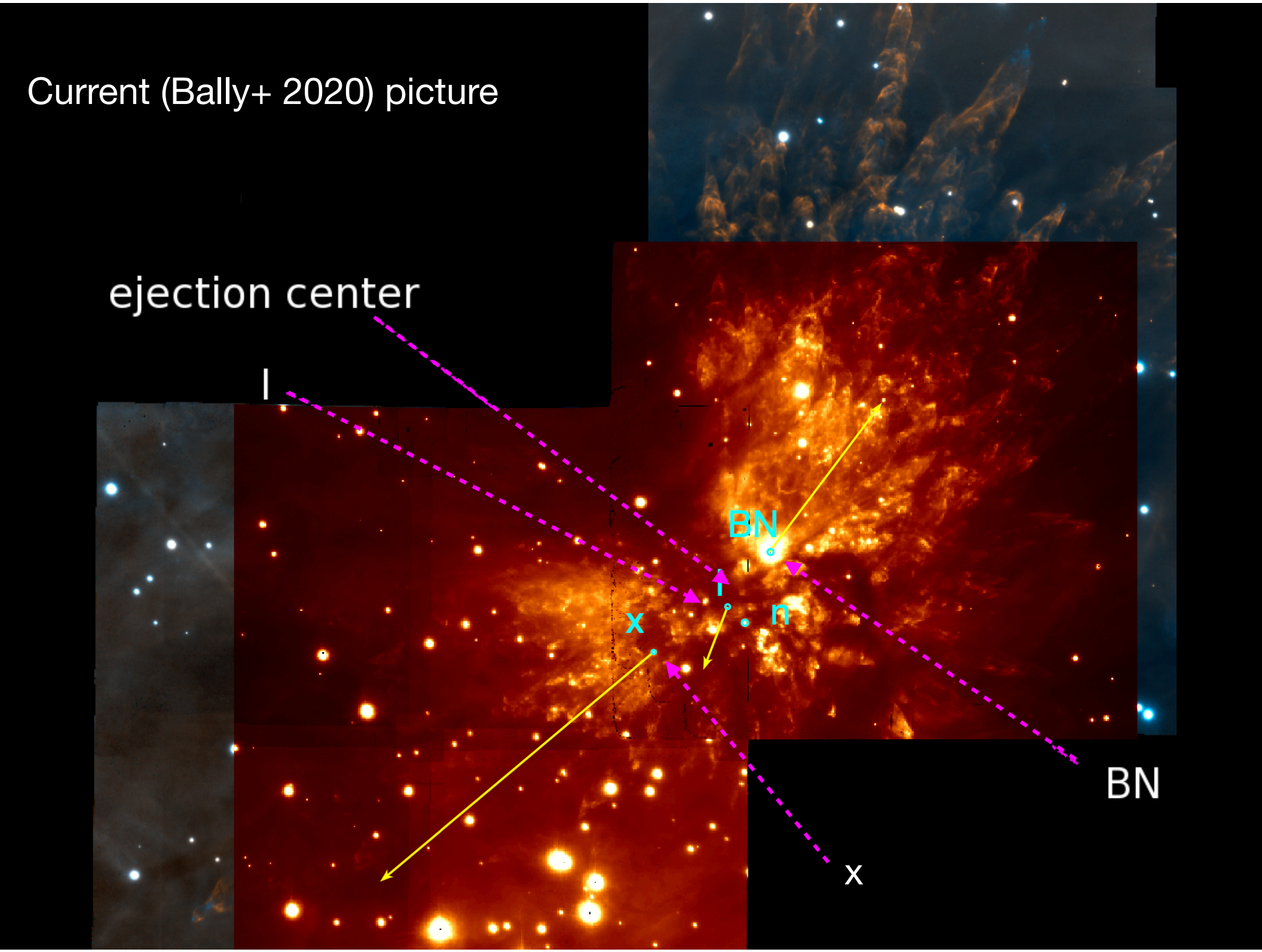




Snapshots from Nick Moeckel's work




Old picture
(before Src X, Luhman+ 2017)
ejection center
I
BN
n


Current (Bally+ 2020) picture
ejection center
I
BN
I
n
x
BN
x

Orion Source I

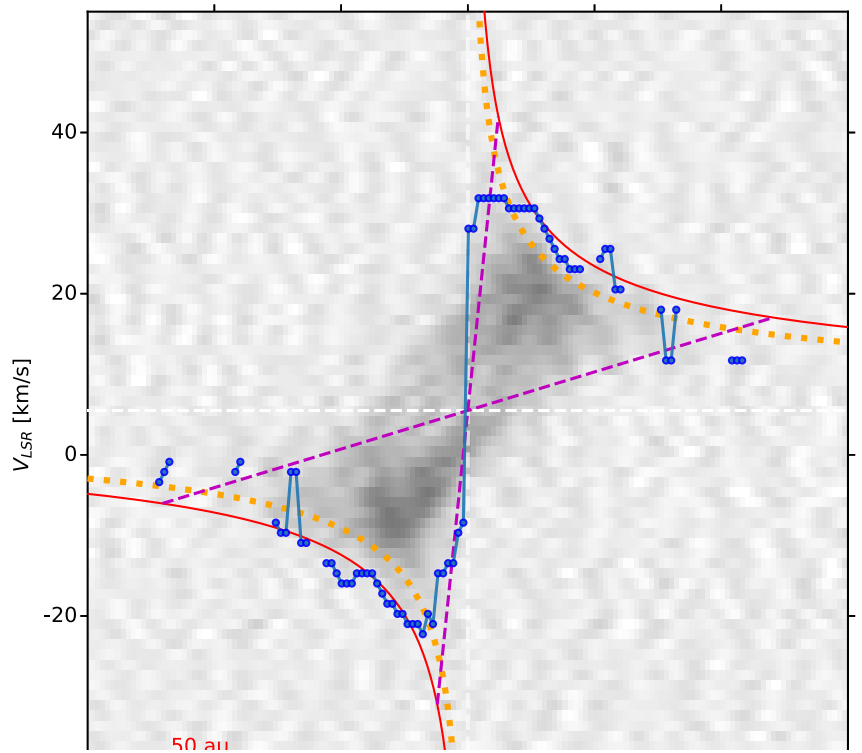
$M_\star = 15 \pm 2\ M_\odot$

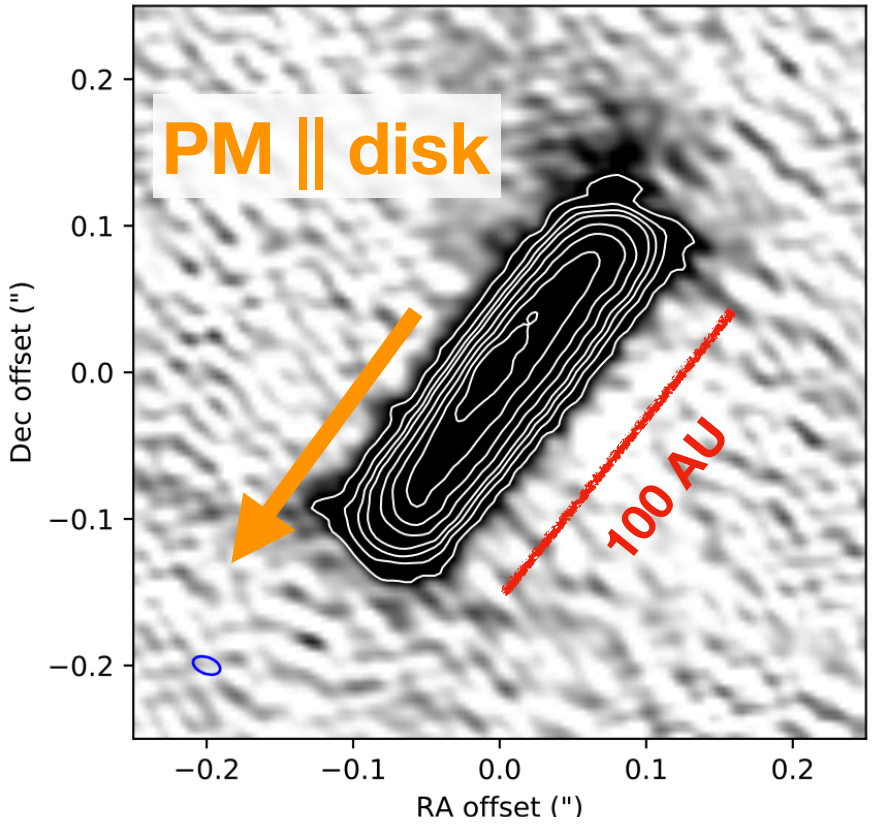
$M_D < 1\ M_\odot \therefore M_{now} \approx M_{final}$

Plambeck+ 2016,
Ginsburg+ 2018, 2019,
Wright+ 202{0,2,3,4}
Hirota+ 201{2,4,5,6,7,8}, 2020

A disk got dragged along

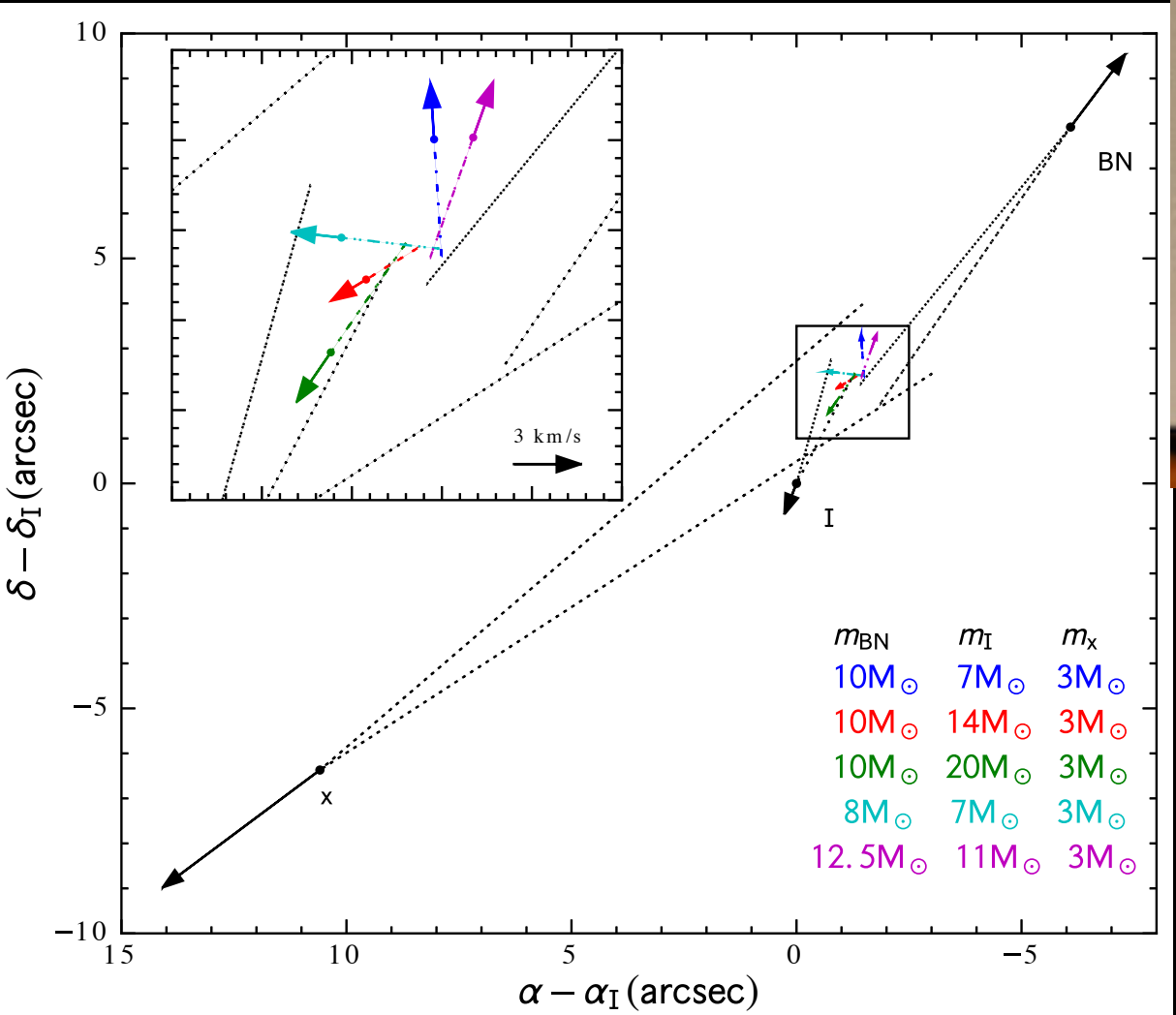
$v_{esc}(200\ \mathrm{au}) \approx 11.5\ \mathrm{km\ s^{-1}}$

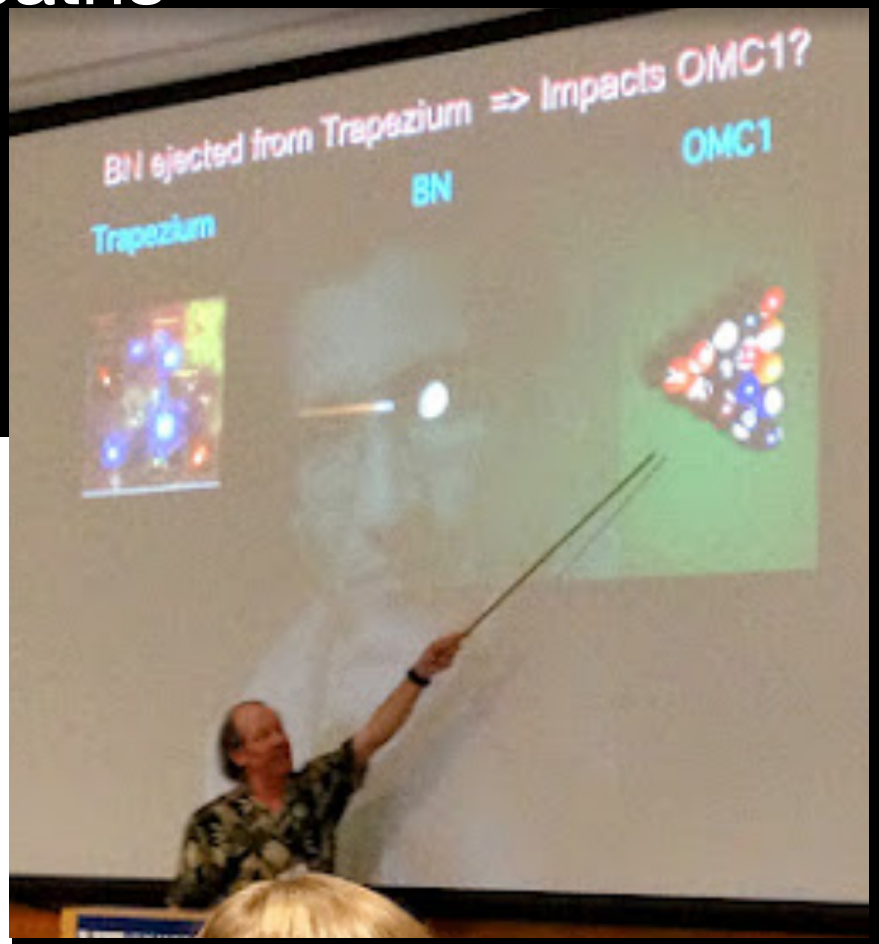




Competing Theories and their deaths

Multiple outflows from different sources (Beuther+ 2008), ended with ALMA isotropy observations
[this situation remains very common in other HMSFRs]





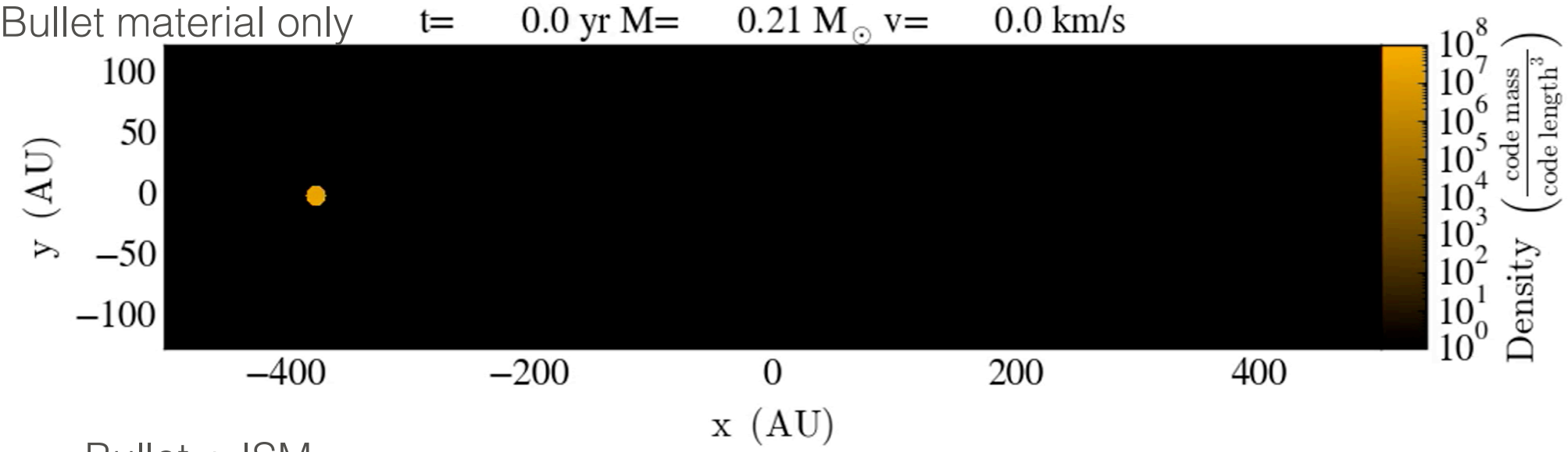
BN was ejected from the Trapezium and flew through the “Orion Hot Core”. (Tan+)

Luhman+2018, Farias+2018 observations & models of source x favor the multiple system decay model

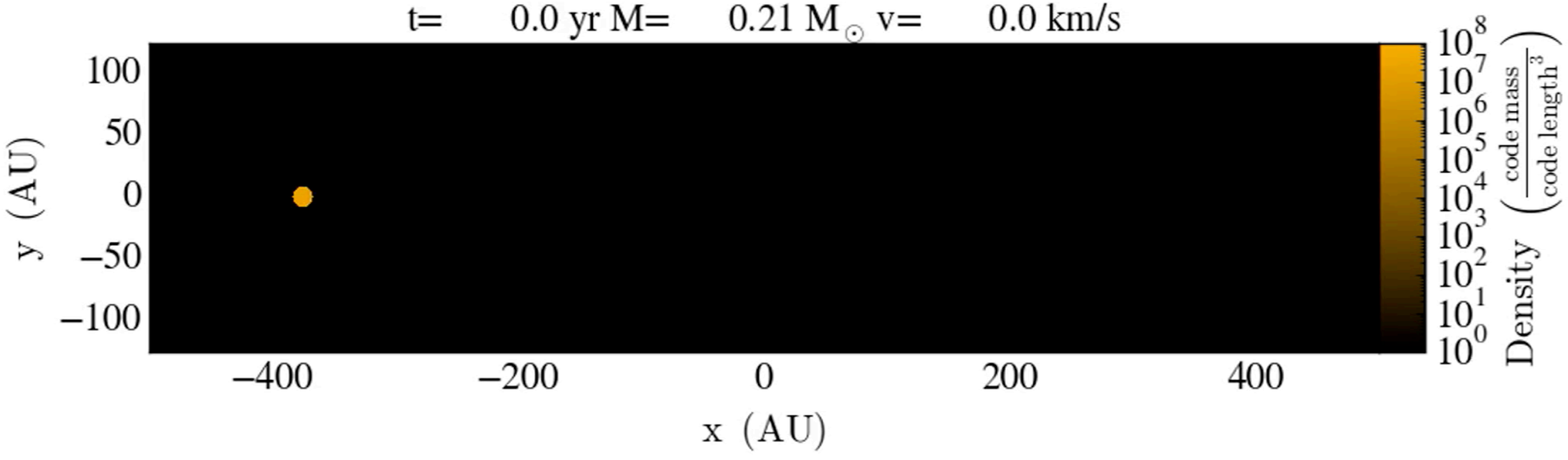
Physical processes in the outflow

"Bullets" match classic cloud-crushing simulations
(gas blob traveling at speed through a medium)

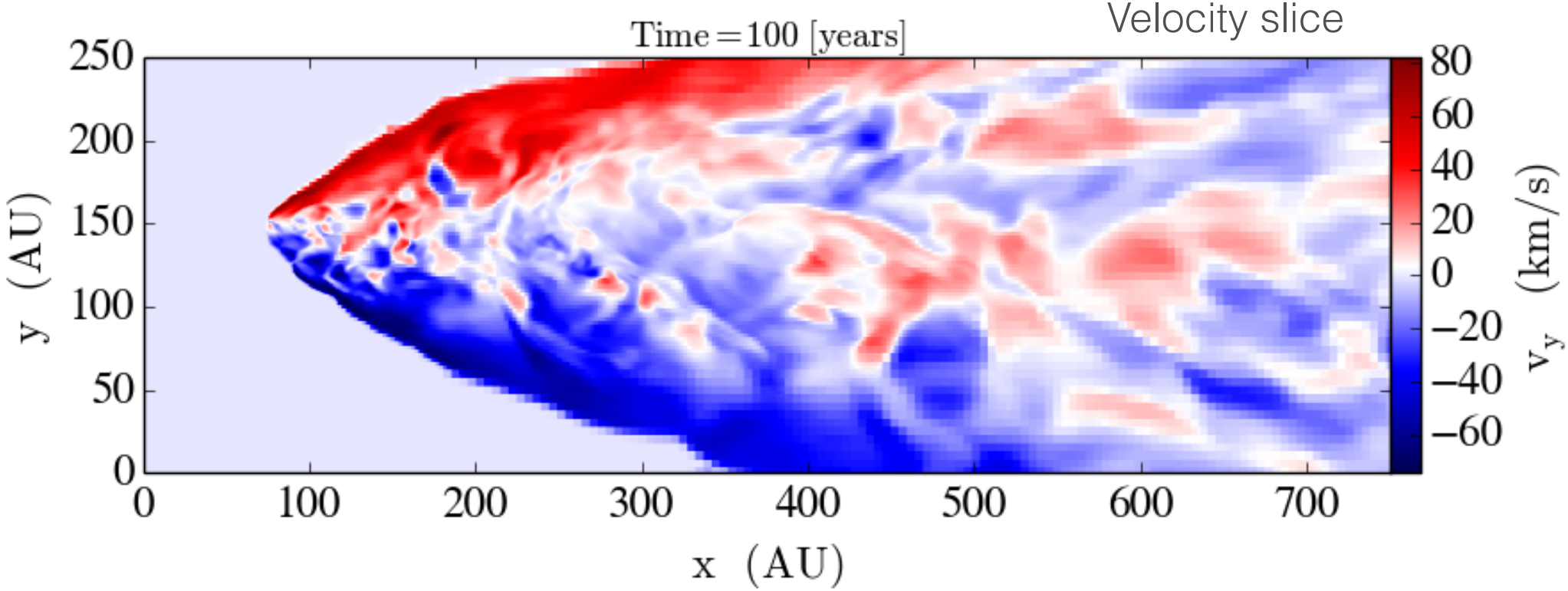
Bullet material only



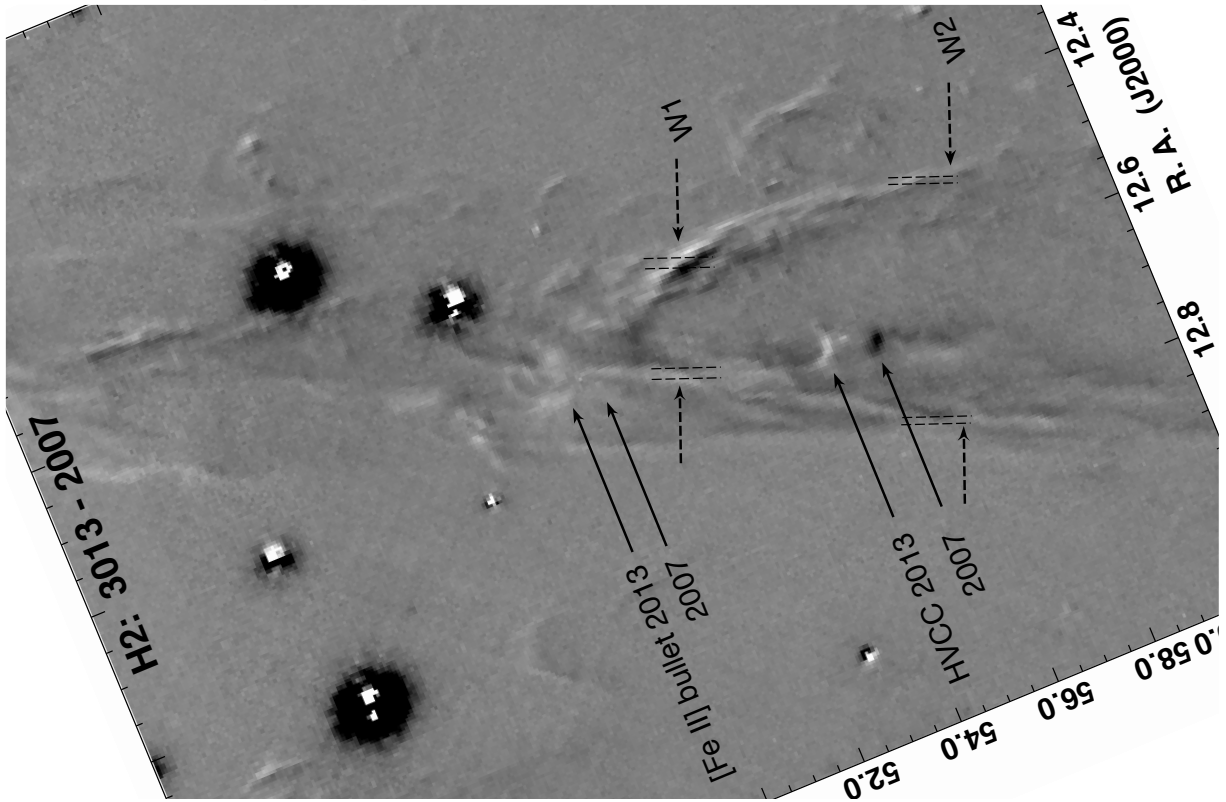
Bullet + ISM

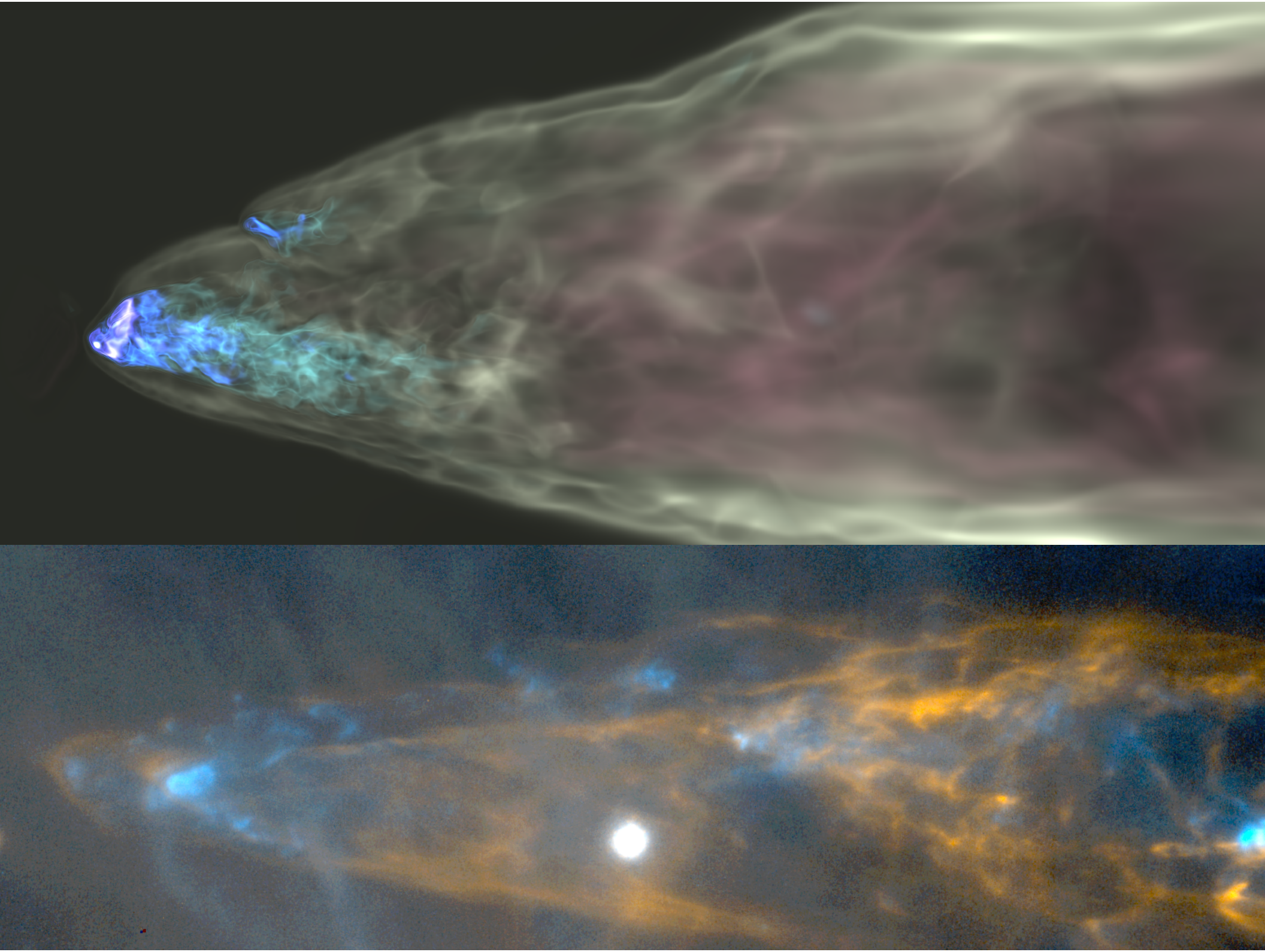


Velocity slice



Simulated wake expansion matches the observed expansion (~40-80 km/s)





What caused the explosion?

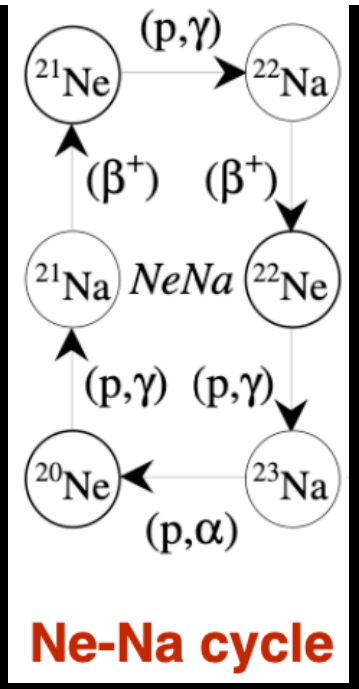
Energetically, it works out. But what *actually* happened?

What caused the explosion?

Energetically, it works out. But what *actually* happened?

- "Simply" a loss of gravitational potential as the stars flew out?
  - $v_{max} \approx 200 - 400 \ \mathrm{km \ s^{-1}}$, requires at least some material to have come from $< 1 \ \mathrm{au}$
- "Magnetic Bomb"? [I never really understood this model]
- Star-through-Disk flyby
- Stellar Merger
  - Lots of circumstantial arguments for this
  - Can we prove it? Can we infer the original components?

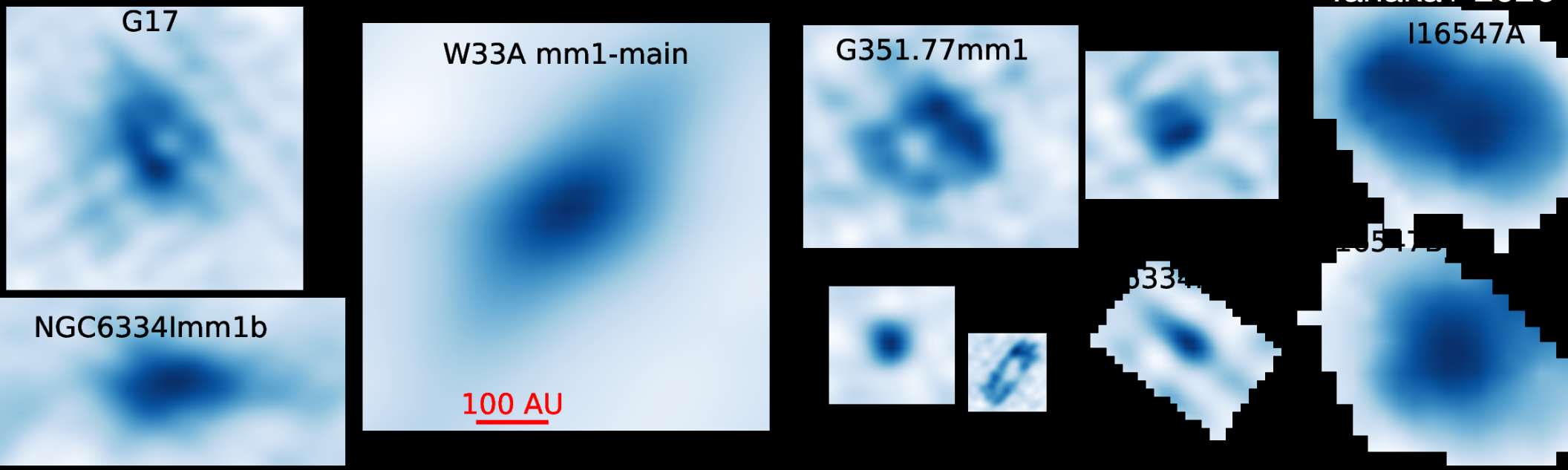
Merger hypothesis:
Are nuclear burning products mixed into the ejecta and disk?



How common are these Explosions?

- If salts are limited to similar events, then not rare, but not common
- Quantitative work TBD

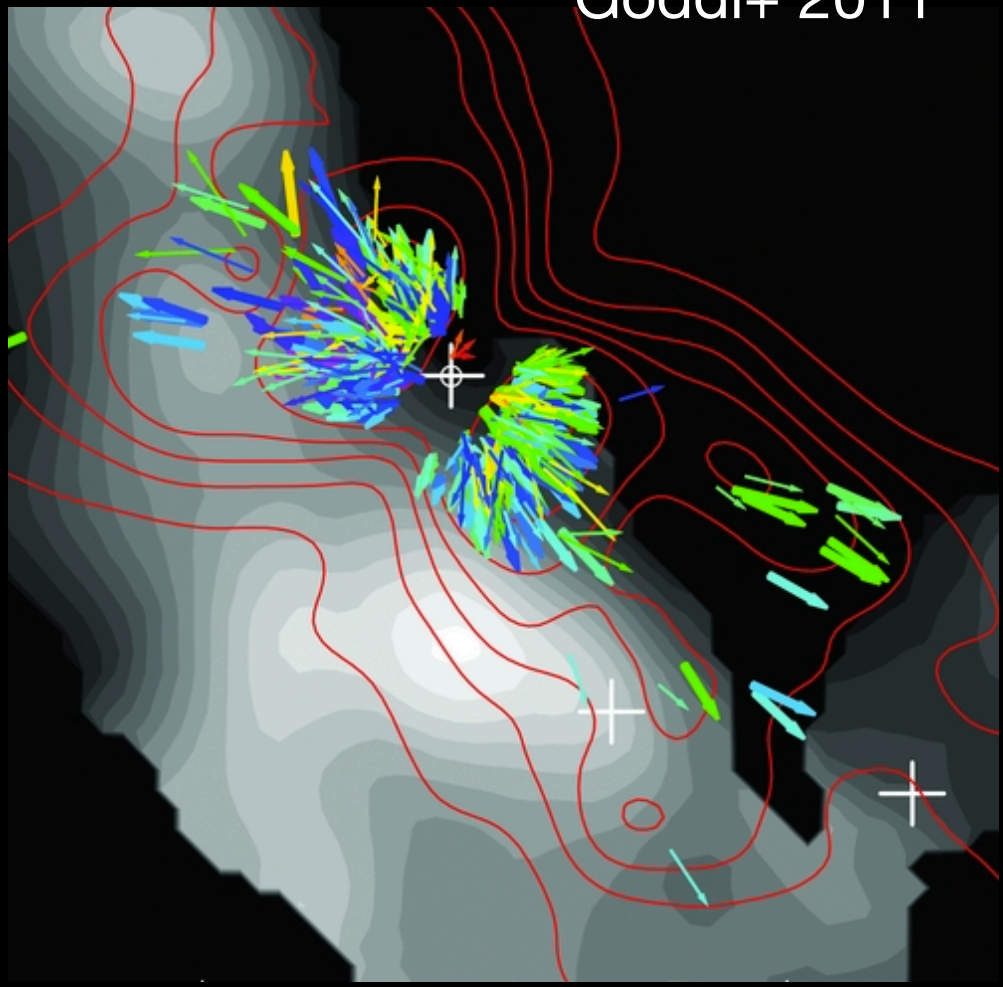
Ginsburg+ 2023
Tanaka+ 2020



How common are these Explosions?

- SrcI's outflow is one of <10 in the Galaxy with SiO masers
- (How closely) is this connected to the Explosion? How much is an orientation effect ($i \approx 85°$)?
- Were there other bright masers ~500 yr ago?

Greenhill+ 2010
Goddi+ 2011

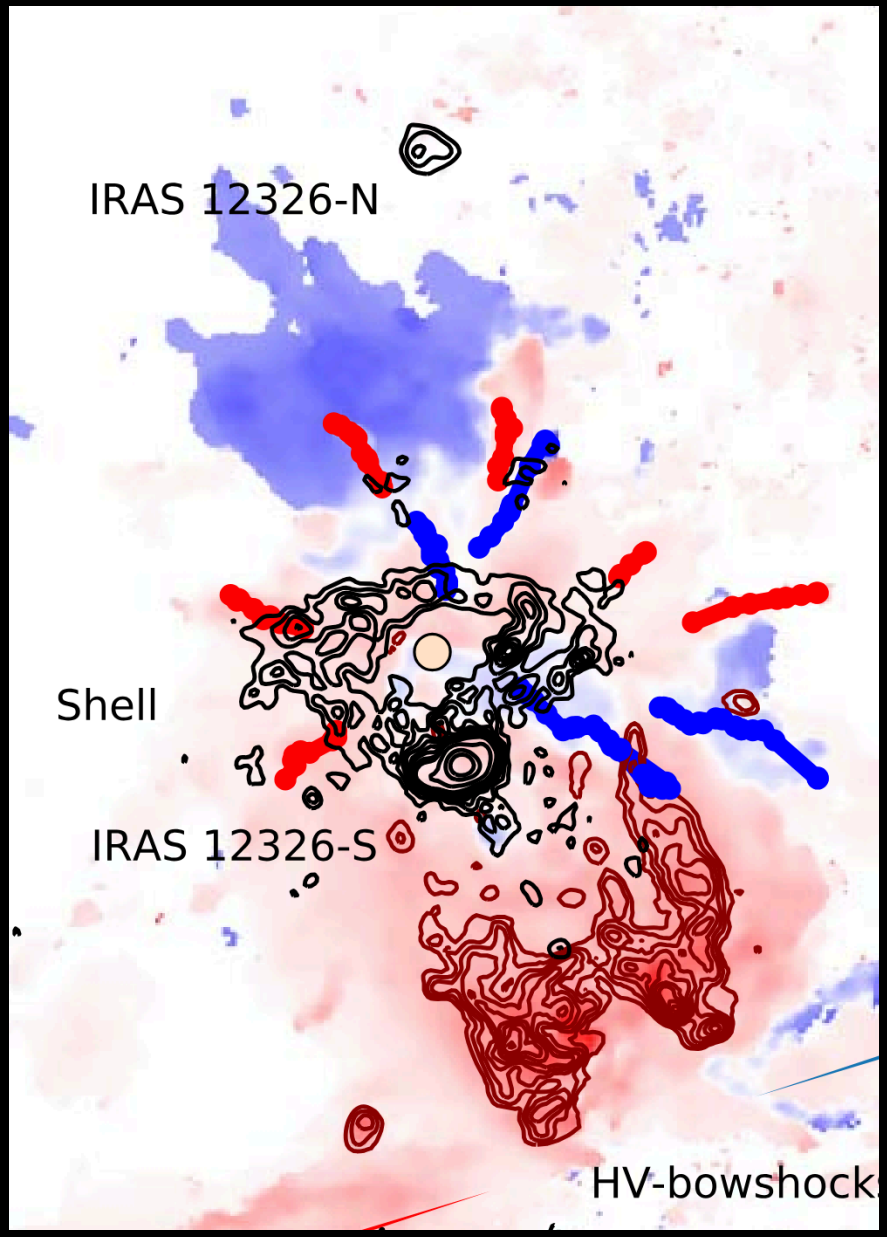


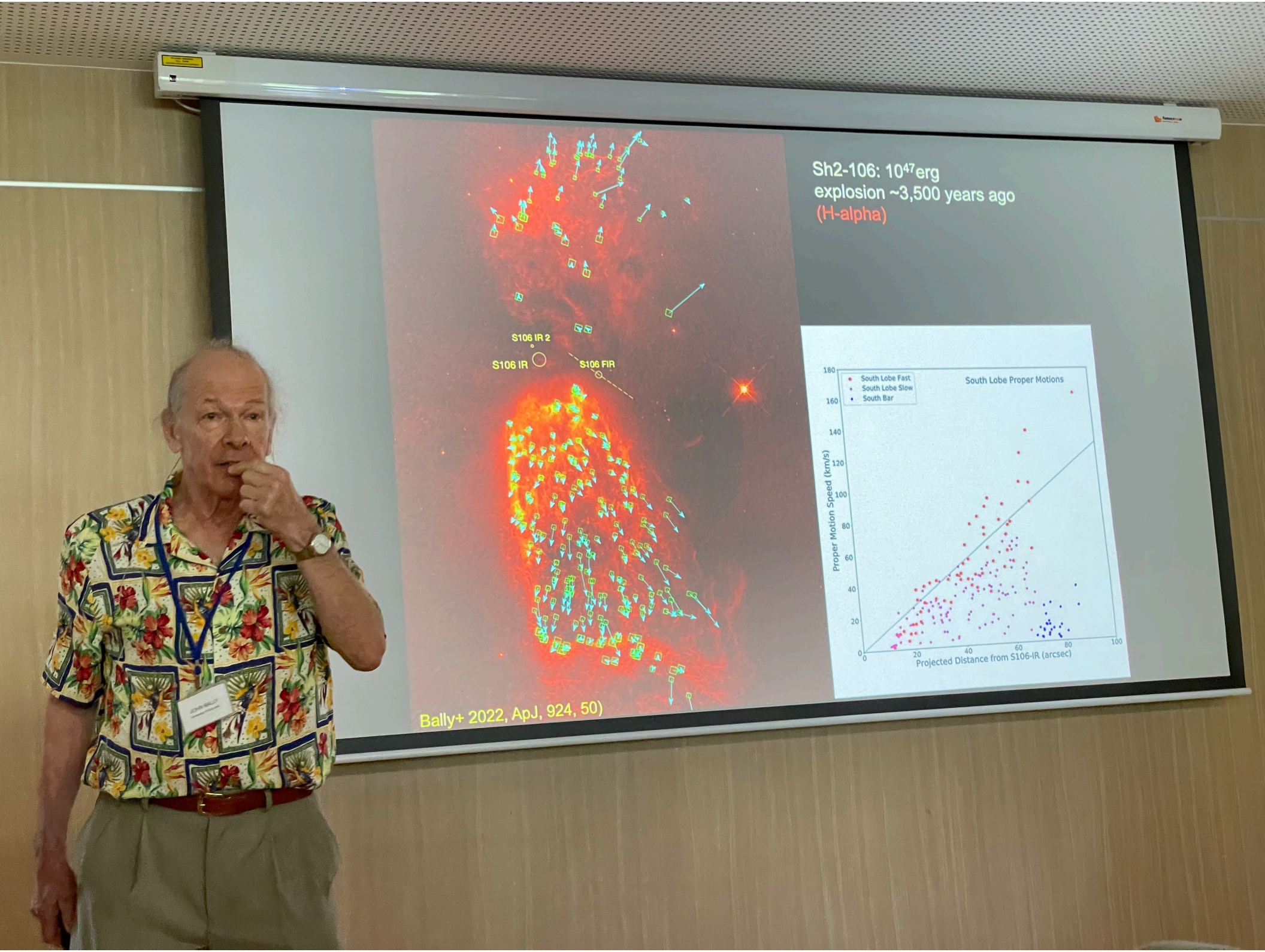
How common are these Explosions?

- There are many other candidates (Zapata, Bally)

- Multi-outflow systems with apparent Hubble flows:
  IRAS 16076-5134 (Guzman-Ccolque+ 2022)
  Rivera-Ortiz + 2021
  IRAS 12326 Zapata+ 2023
  G34.25 Isaac+ 2025

- But many HMSFRs don’t have any! Sgr B2, W51, W43, … seem not to. Late stage?




Sh2-106: 10^47 erg
explosion ~3,500 years ago
(H-alpha)
S106 IR 2
S106 IR
S106 FIR
Bally+ 2022, ApJ, 924, 50)
South Lobe Proper Motions
South Lobe Fast
South Lobe Slow
South Bar
Proper Motion Speed (km/s)
Projected Distance from S106-IR (arcsec)
0
20
40
60
80
100
120
140
160
180

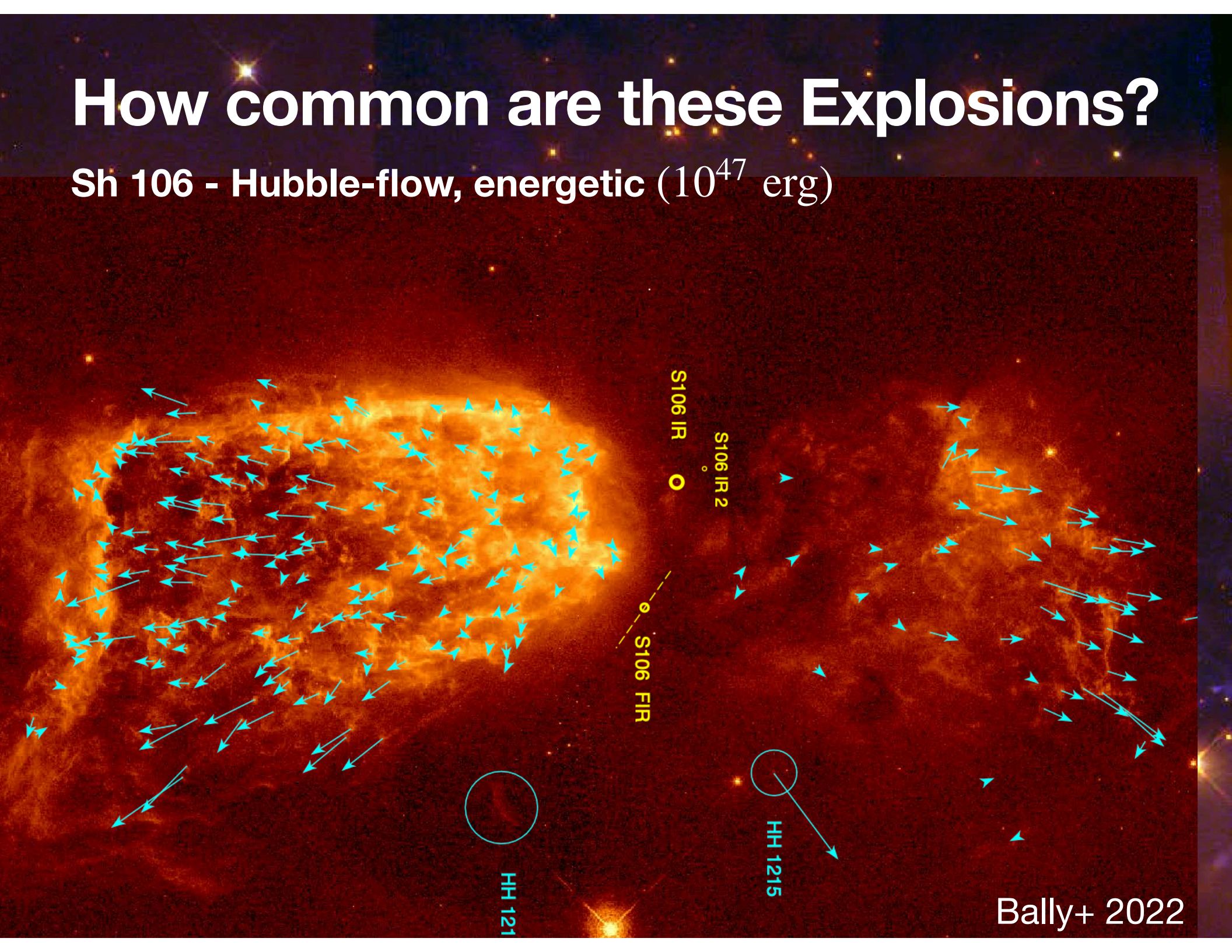
How common are these Explosions?

Sh 106 - Hubble-flow, energetic (10^{47} erg)

Bally+ 2022

How common are these Explosions?

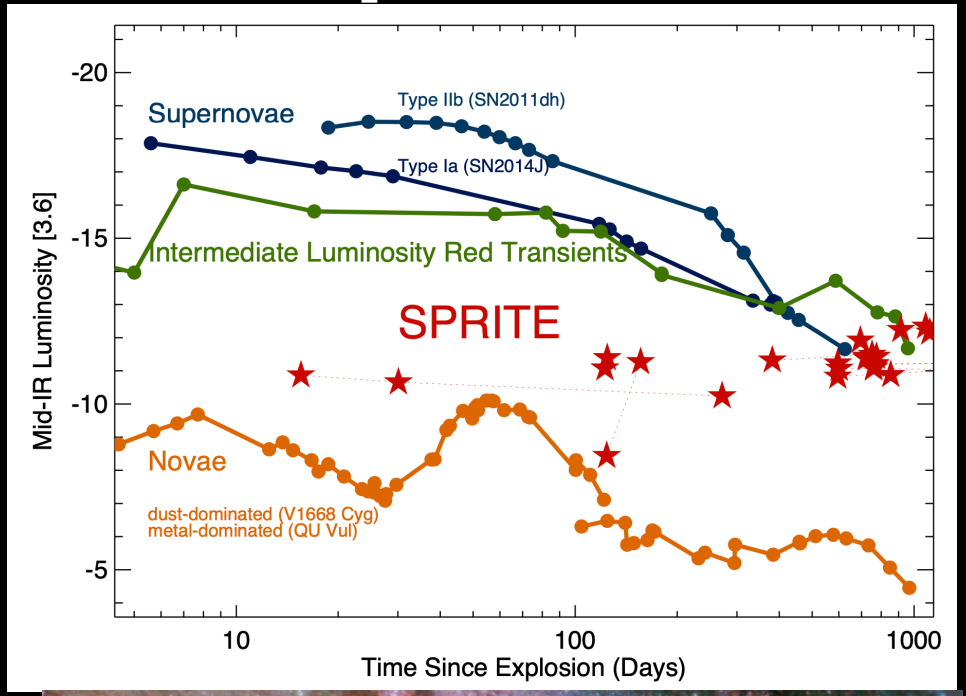
Sh 106 - Hubble-flow, energetic (10^{47} erg)

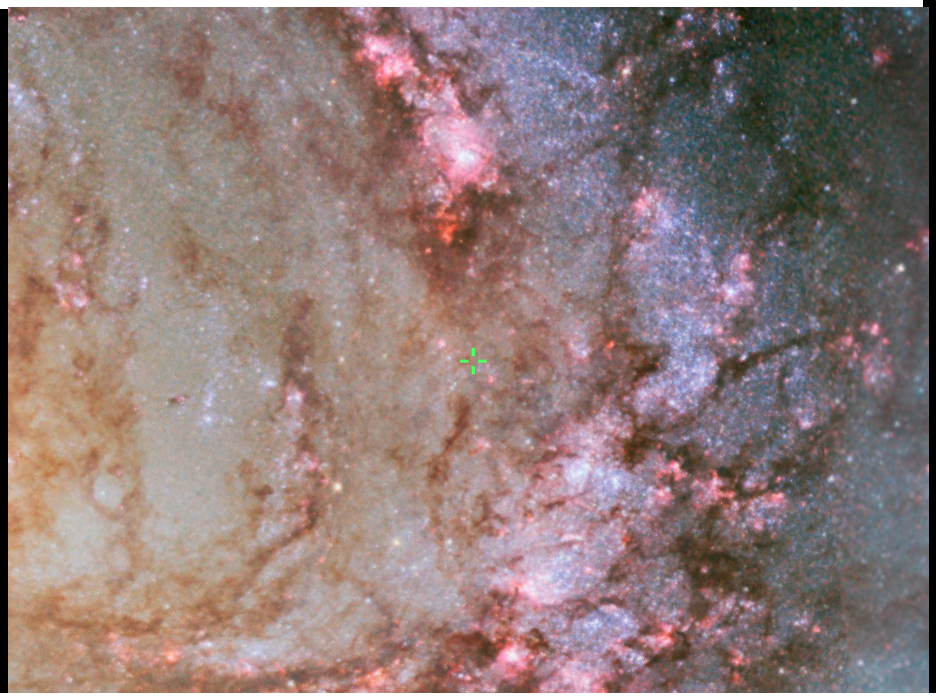


Bally+ 2022

How common are these Explosions?

- They ought to be extragalactically detectable, but they're IR-only
- SPIRITS 14ajc is the first candidate (Kasliwal+ 2017)
- Future:
  JWST revisits
  Roman surveys





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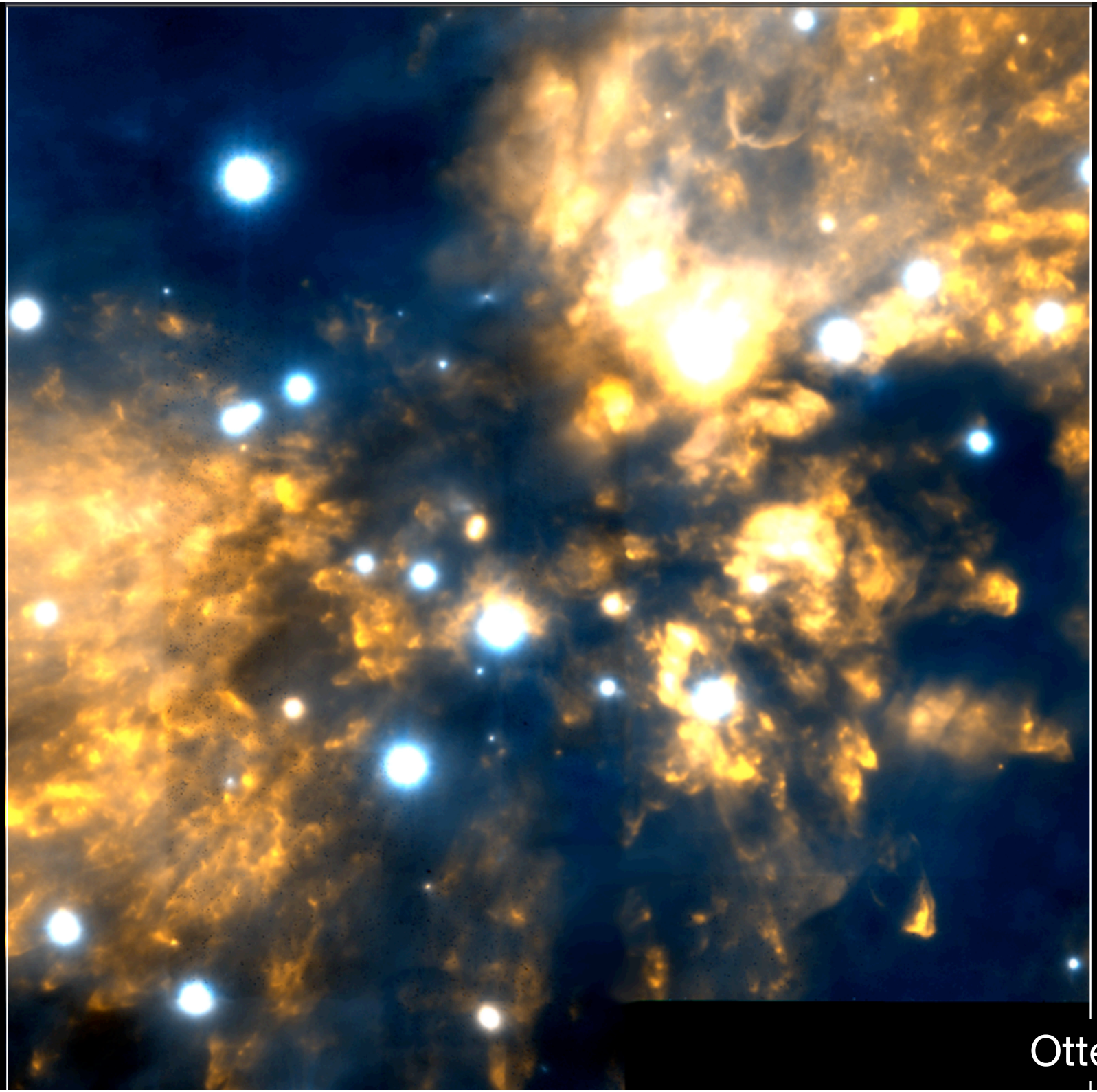
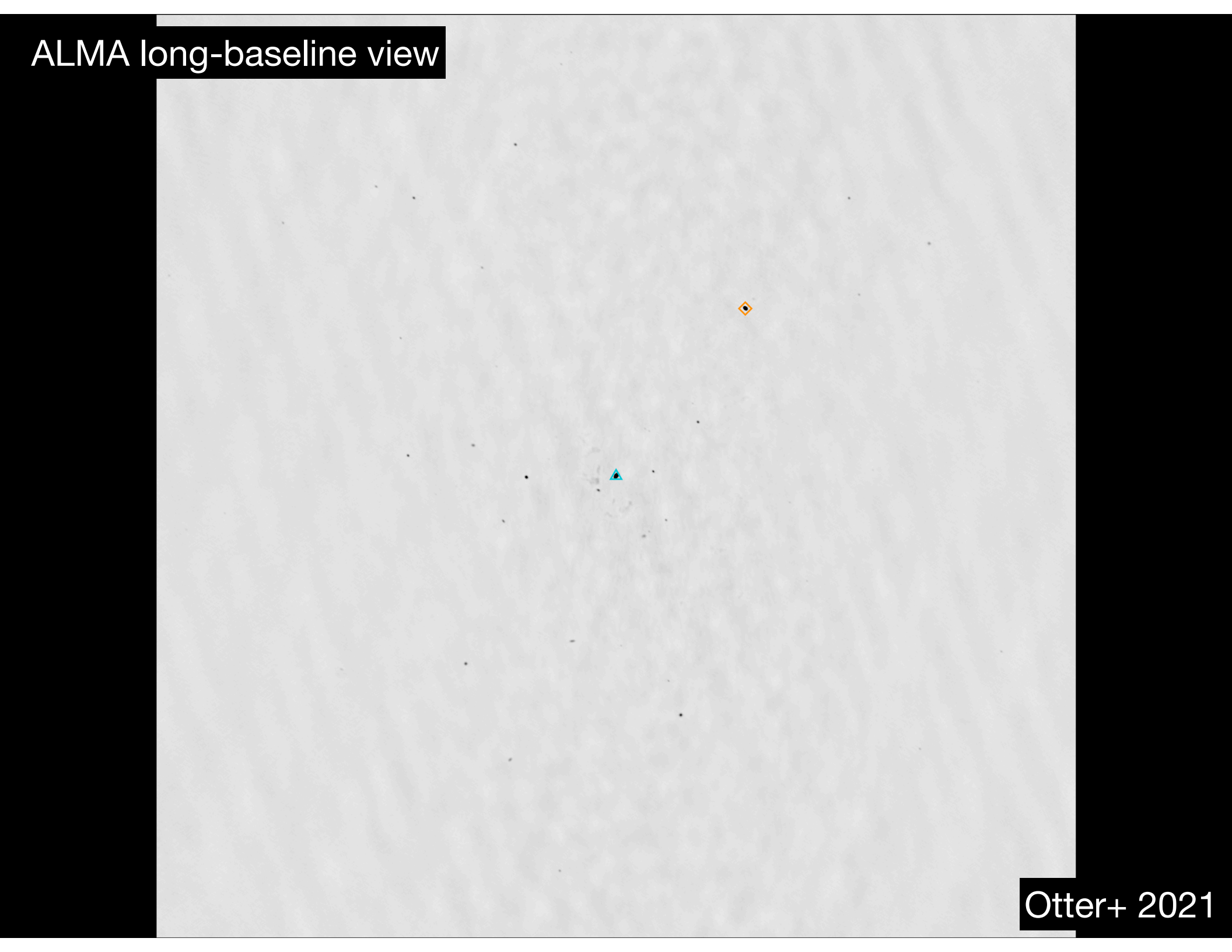
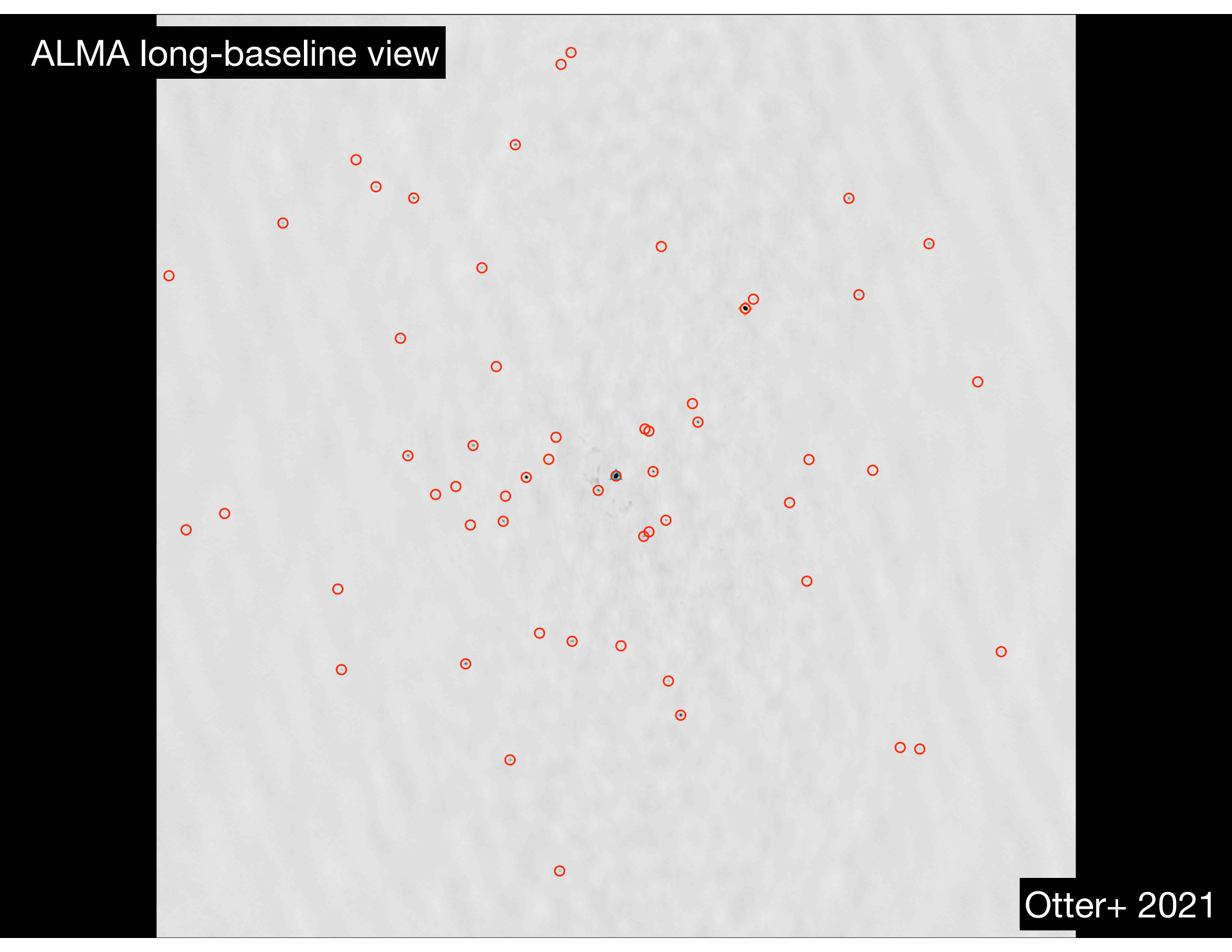

Otter+ 2021


ALMA long-baseline view
Otter+ 2021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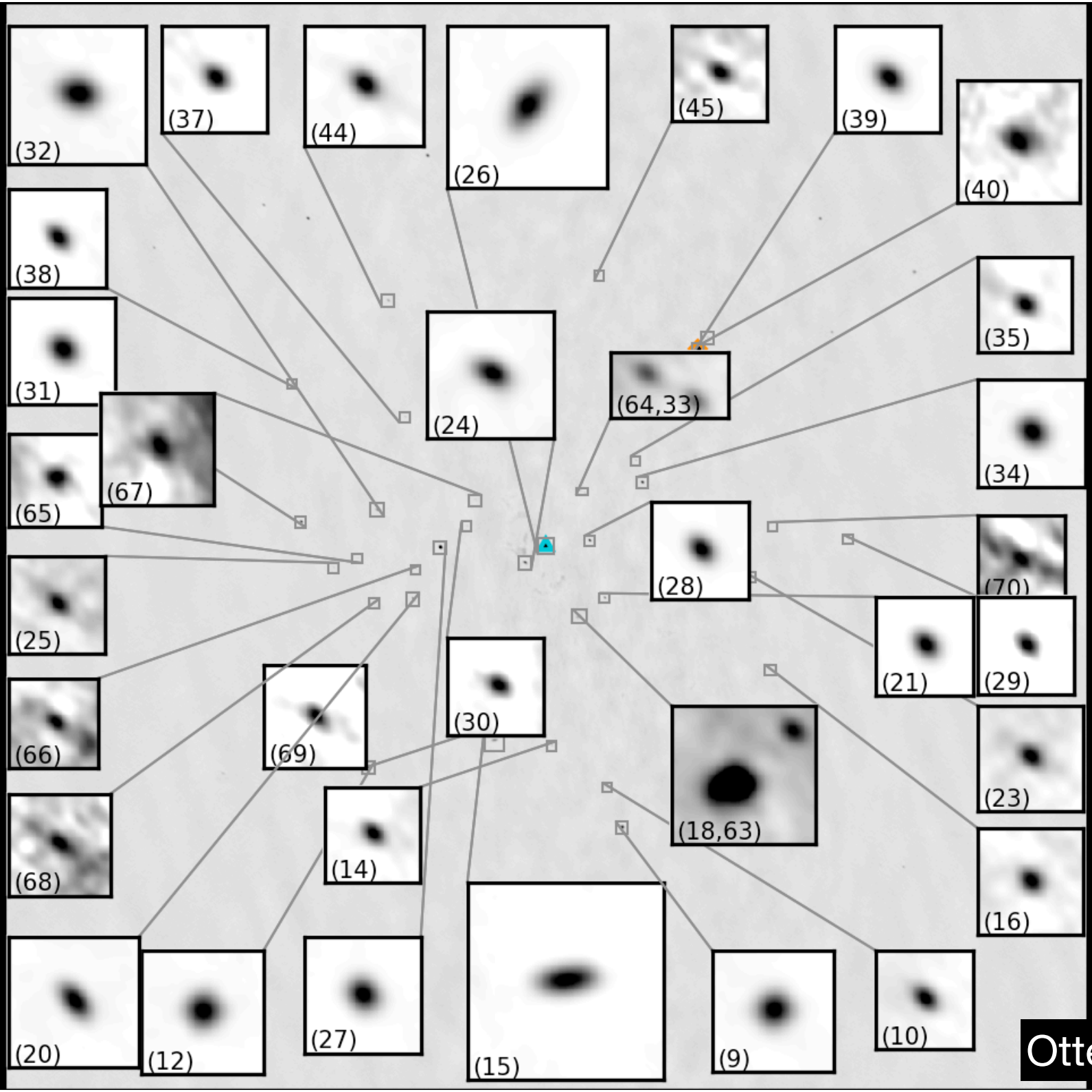
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Otter+ 2021

~50 stars in OMC now

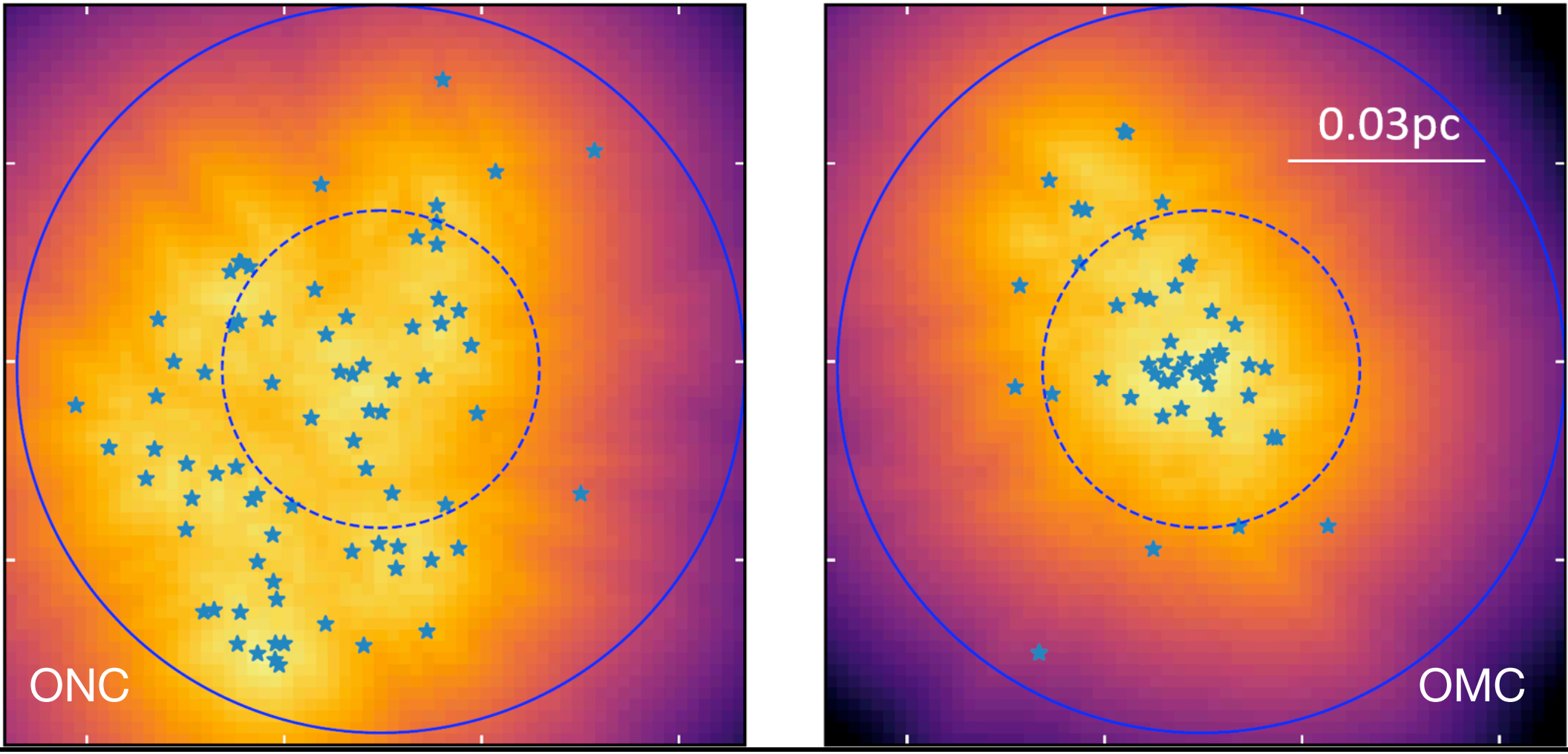
$\bar{M} \approx 0.5$ -> 25 $M_\odot$ in stars

$(M_I + M_{BN} + M_x) \approx 30 M_\odot$

$M_{gas} \lesssim 10\ \mathrm{M}_\odot$

Otter+ 2021

The massive star system that's now running away accounts for most of the binding mass. This "cluster" will dissolve.



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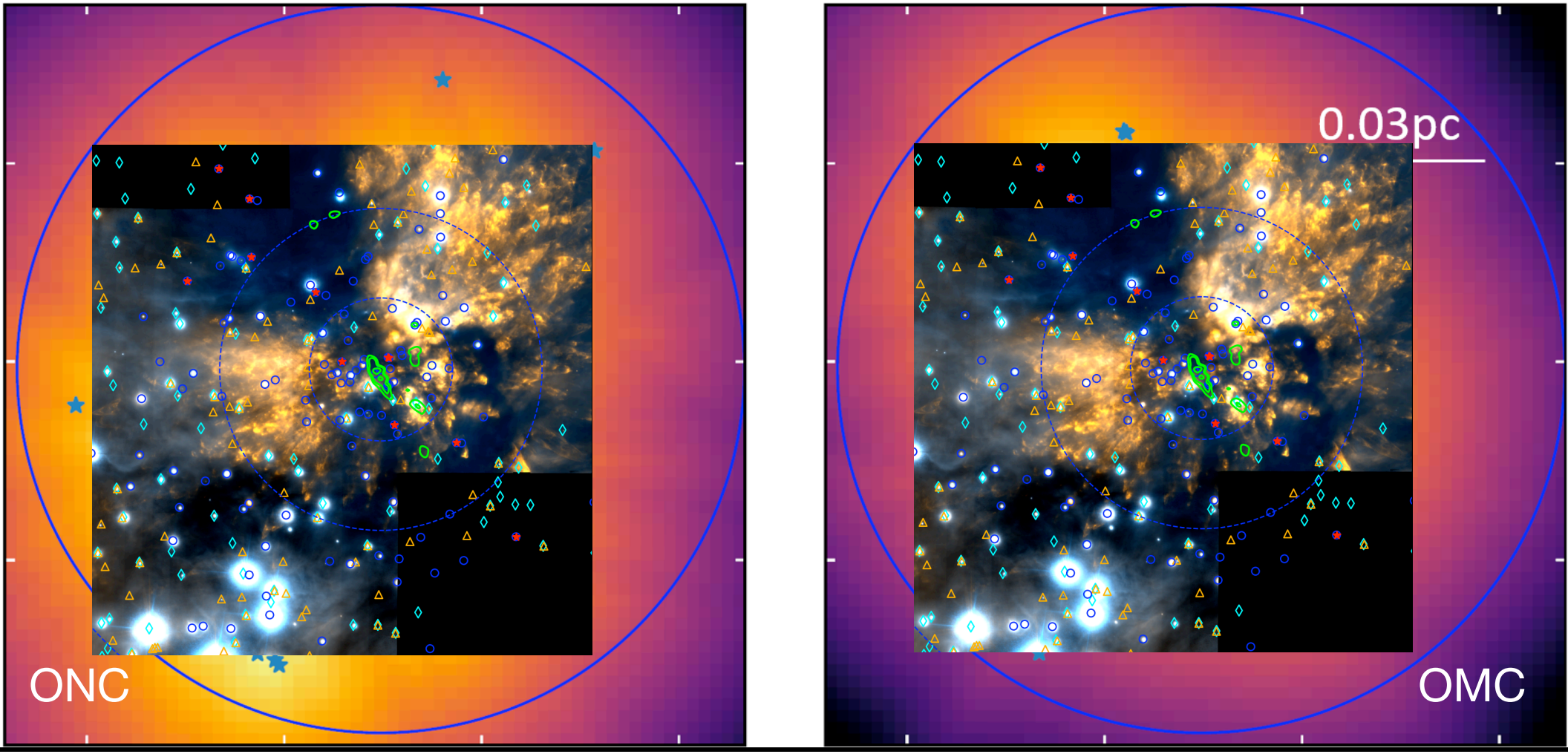

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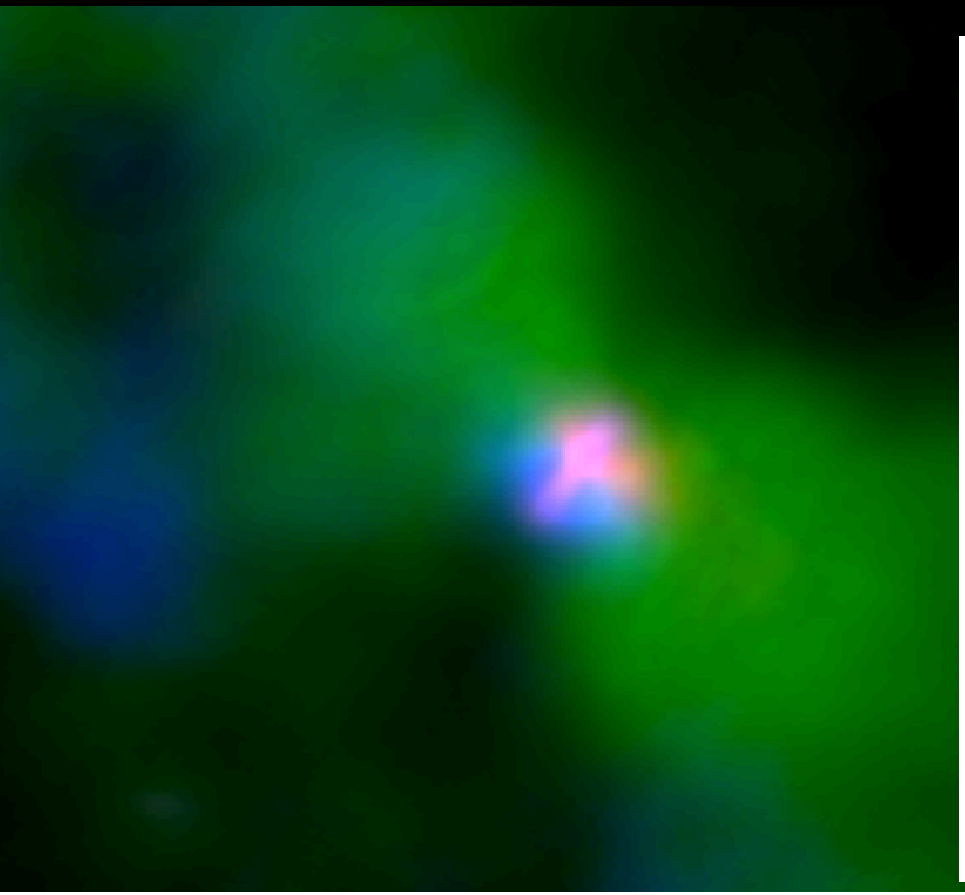
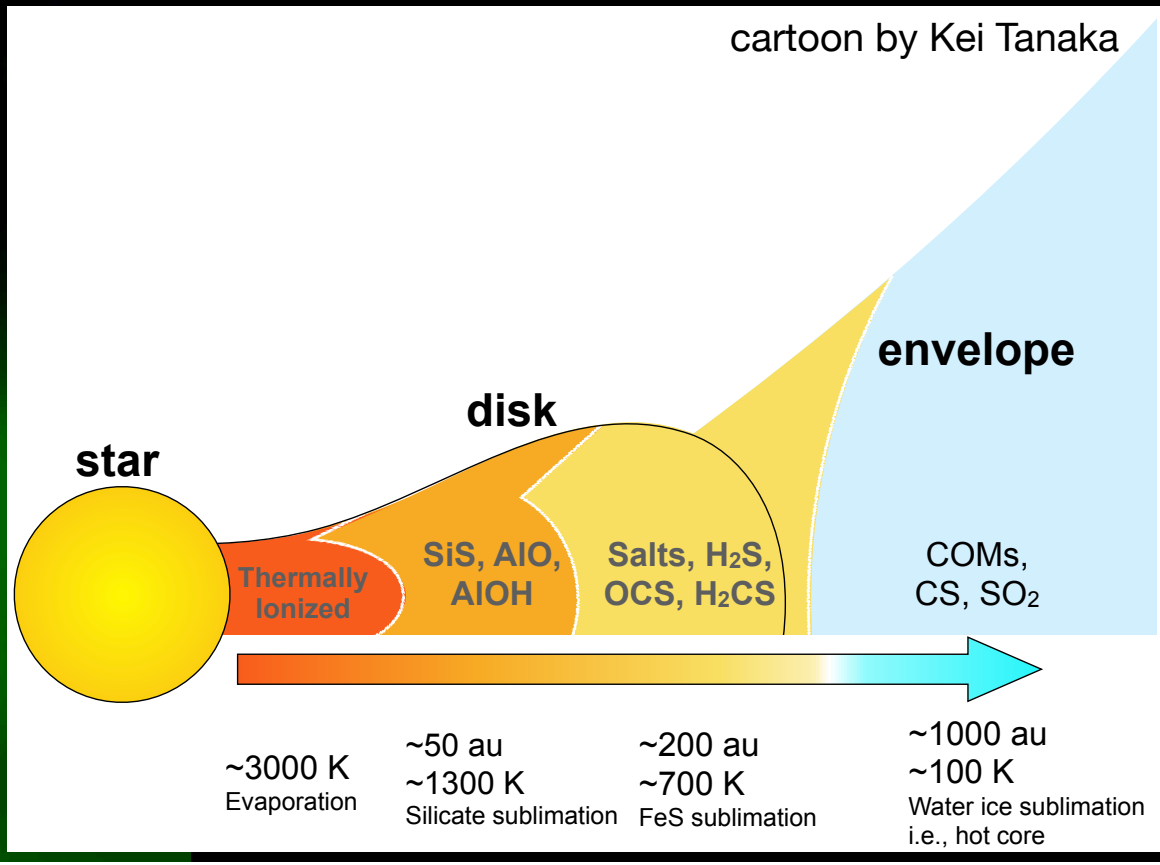
SrcI's disks contains refractories:

NaCl, KCl, AlO, SiS, SO, hot water ….

others to be cataloged?

Do these feed into envelopes (& Oort Clouds / Kuiper Belts) of others? Are these present because of 'normal' chemistry or stellar merger pollution?





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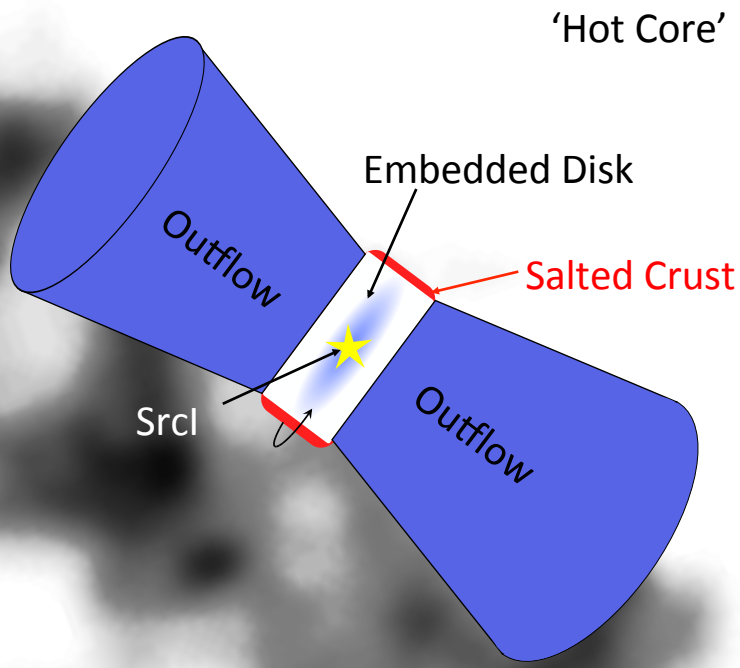
Runaway Src I: The “hot core that is not a hot core” is illuminated by a runaway, not bound to it

Zapata+ 2011



The BN/KL Explosion

The closest site of ongoing high-mass star formation

is the site of an explosion that coincided with a multi-star dynamical interaction

It's a rare class of event, but can't be *that* rare;
there are candidate analogs (but no doppelgangers)

The leftover disk has gas-phase refractory molecules
and the outflow is full of SiO masers

The explosion portends the dissolution of the 'embedded cluster'

Future work needs to better measure the chemistry,
search for Galactic & extragalactic analogs,
and measure the 3D star (and, if possible, gas) kinematics

Final Slide!