ALMA Observations of Irradiated Protoplanetary Disks

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YSOs near massive stars: UV photo-ablation of disks
irradiated jets

d253-535 in M43

Outline

- **Most stars and planets form in clusters / OB associations: (Lada & Lada 03)**
  - **UV: External (OB stars) + Self-irradiation**
    - **=> Disk photo-ablation => mass loss: EUV, FUV**
      - **Review Orion's proplyds**
    - **=> Metal depletion in wind / enrichment of disk**
    - **=> UV-triggered planetesimal formation**
    - **= Jets => active accretion => disks**
  - **Carina**
  - **The Bolocam 1.1 mm survey of the Galactic plane**

- **What will ALMA Contribute?: [5 to 50 mas resolution!]**
  - **Surveys of HII regions & clusters (Orion, Carina, …)**
  - **Best done as community-led Legacy surveys**
    - **=> Clusters of sources: disk radii, masses, I-front radii**
    - **=> Resolve ionized flows, disks features, protoplanets**
      - **f-f, recombination lines, entrained hot dust**
    - **=> Neutral flow composition, velocity, structure**
      - **CI, CO, dust, photo-chemistry products**
    - **=> Disk B (Zeeman & dust), composition, structure, gaps**
      - **the organic forest**

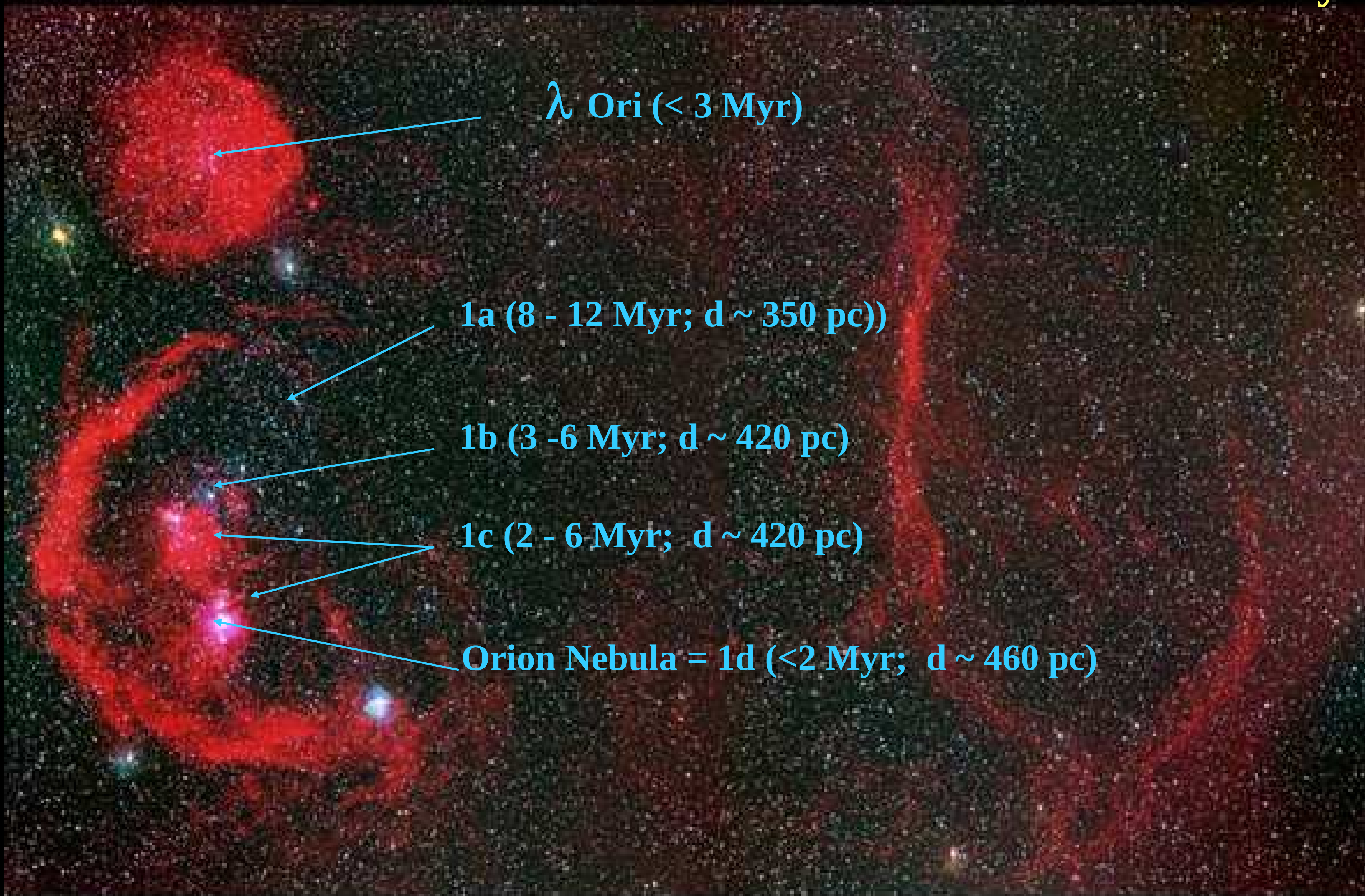
ALMA & irradiated disks

10 μJy sensitivity & 10 mas resolution

	3 mm	1.3 mm	850 μm	450 μm	350 μm
Band	3	6	7	9	10
Resolution (B = 14 km)	0.04" AU	0.019" AU	0.013" AU	0.007" AU	0.005" AU
Sco-Cen (150 pc)	6	3	2	1	0.7
Orion (430 pc)	17	8	6	3	2
Carina (2,200)	90	42	29	15	11

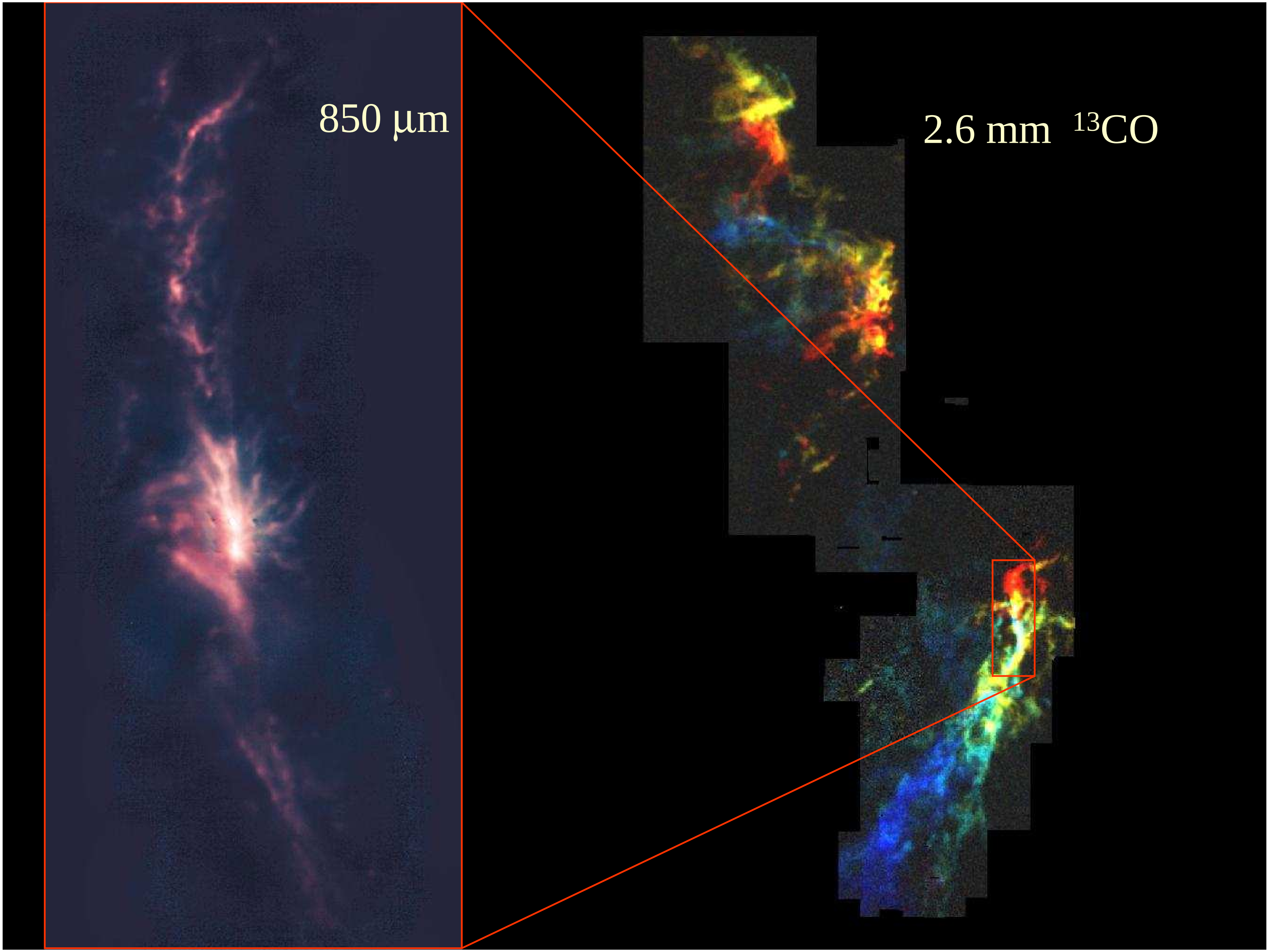
The Orion/Eridanus Bubble ($H\alpha$): d=180 to 500pc; l > 300 pc

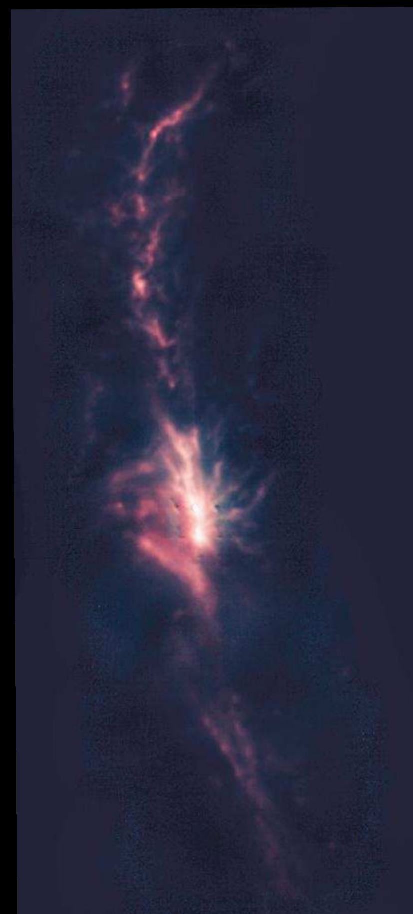
Orion OB1 Association: ~ 40 > 8 M stars: ~ 20 SN in 10 Myr

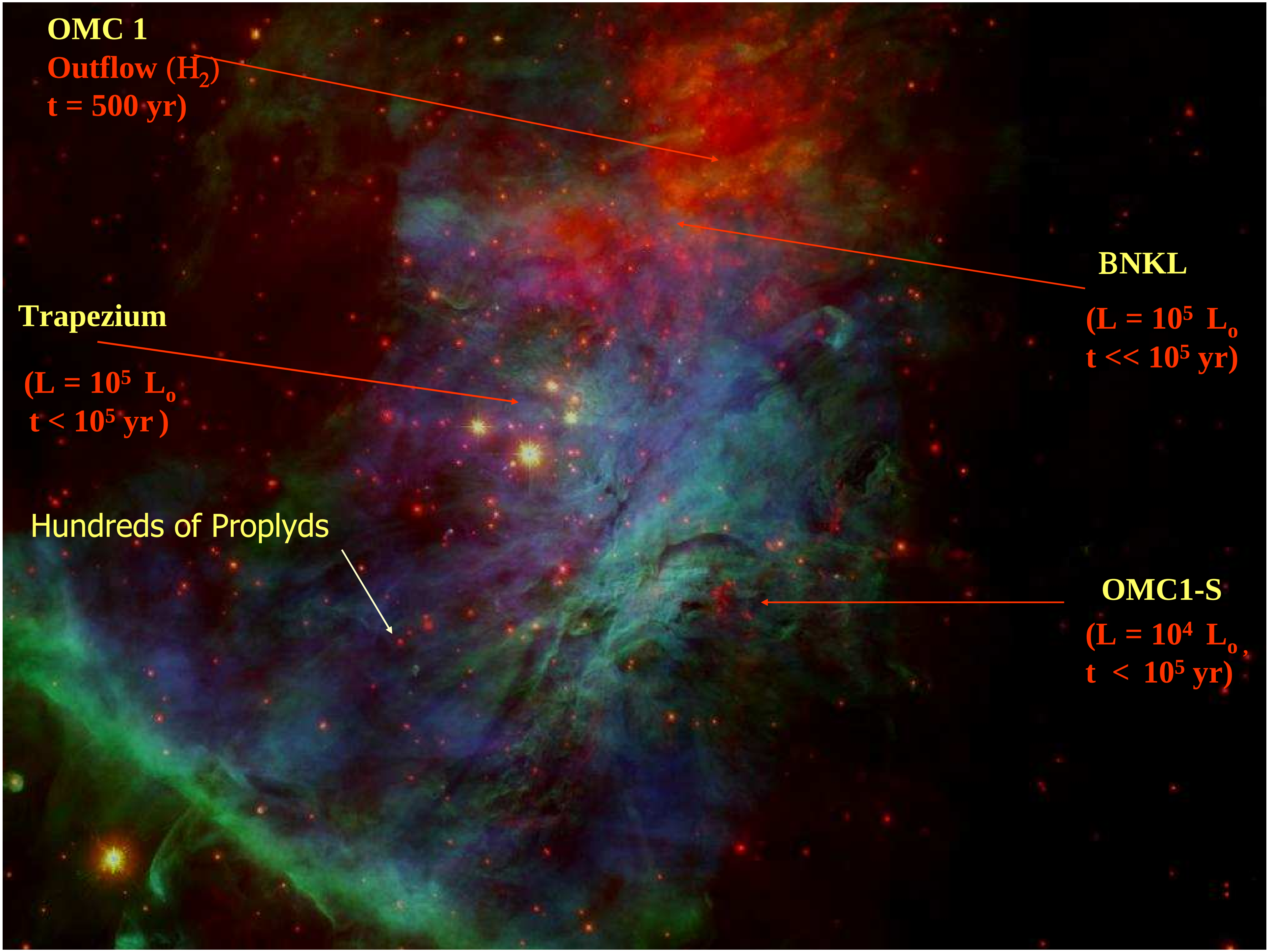


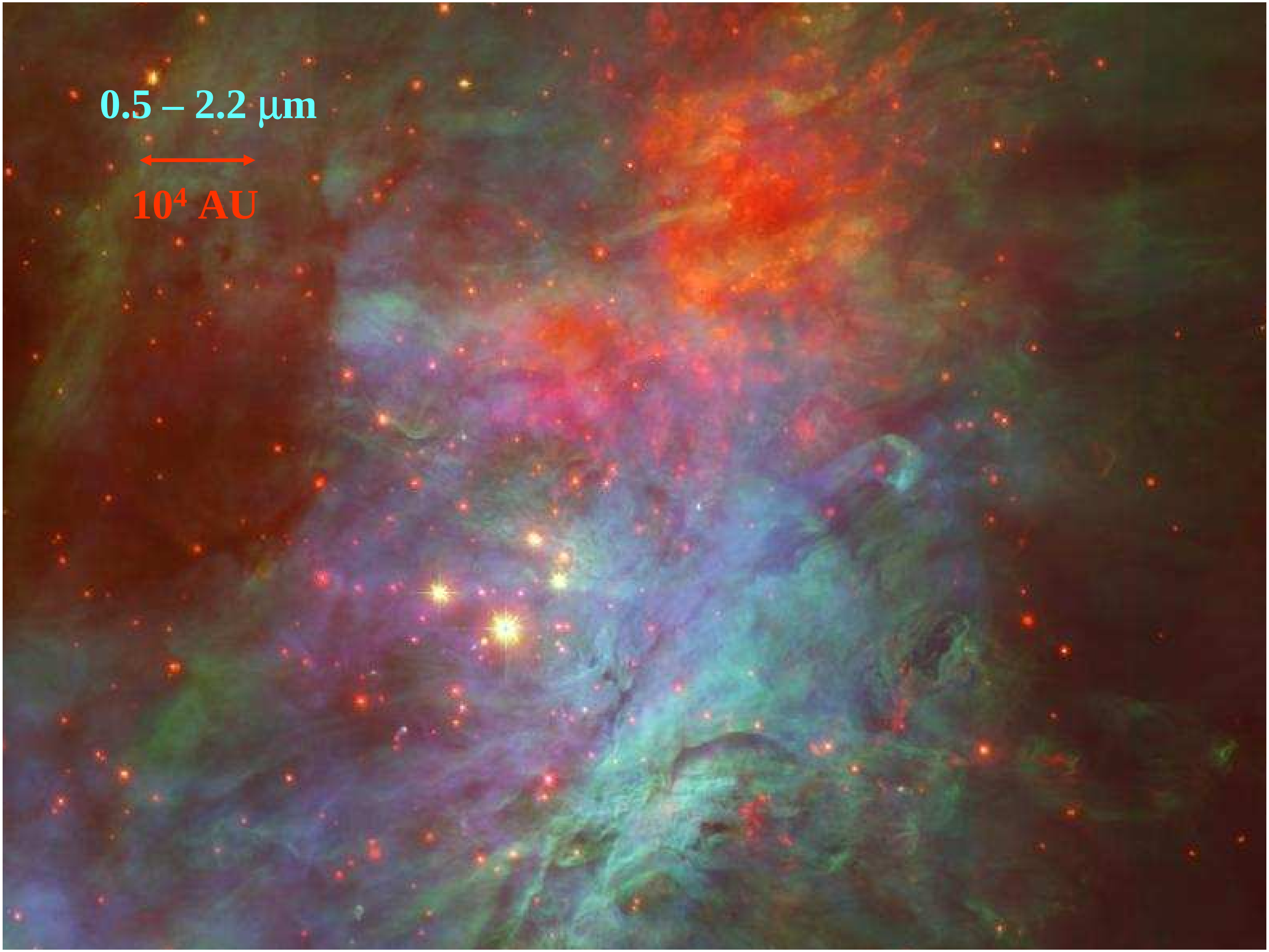
Barnards's Loop

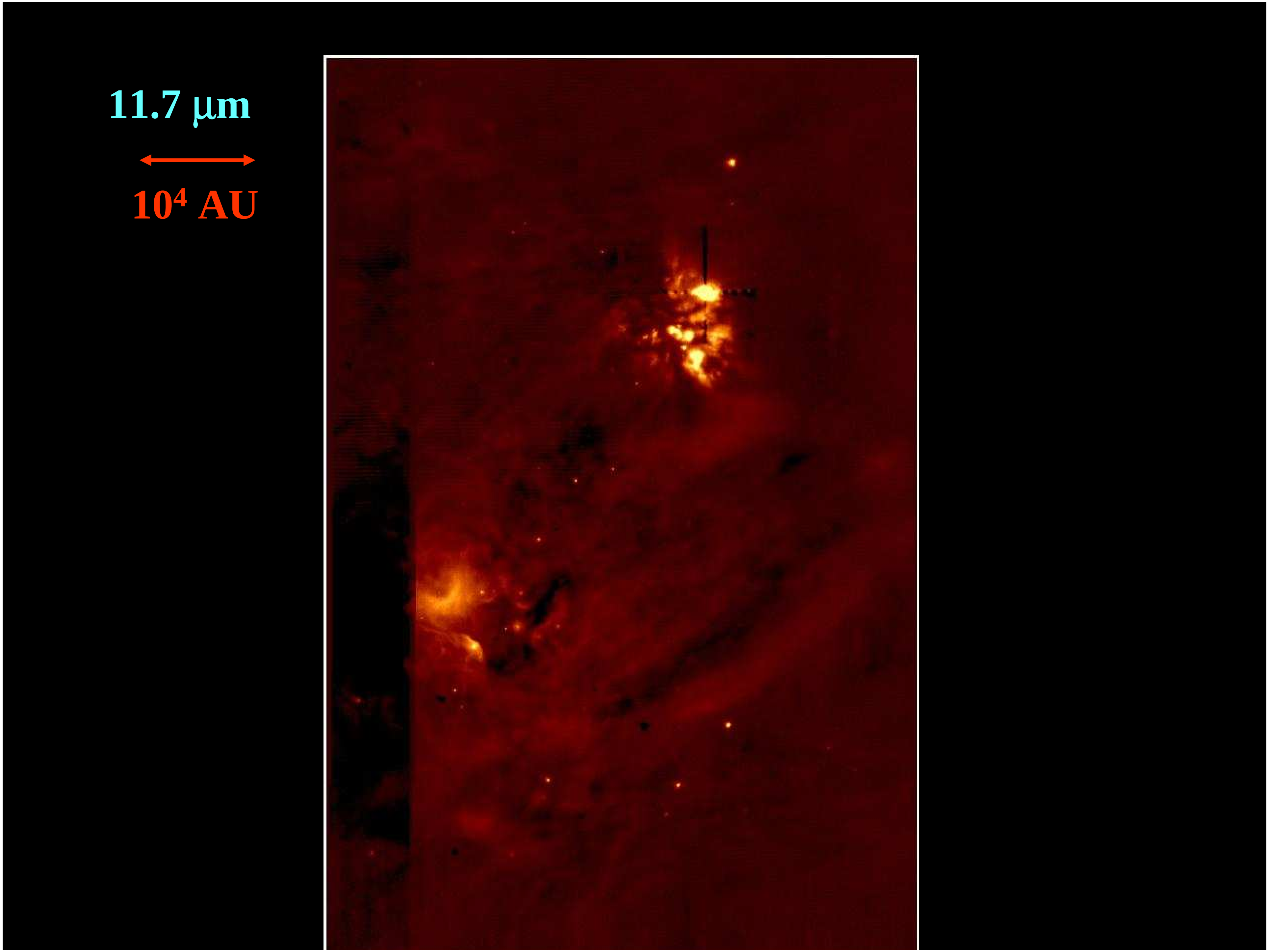
Eridanus Loop


850 μm
2.6 mm ^{13}CO

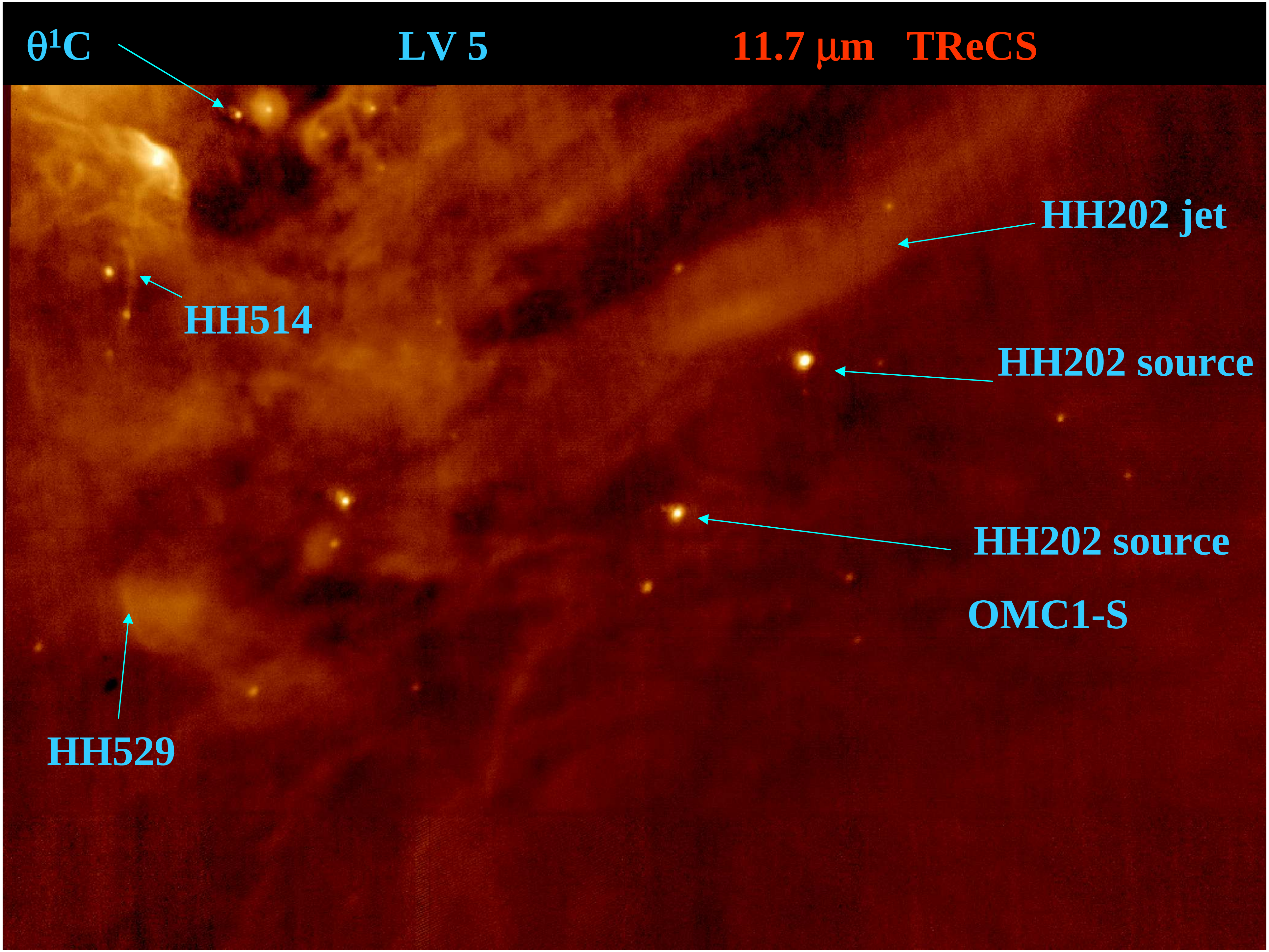



OMC 1
Outflow (H_2)
t = 500 yr)
BNKL
(L = 10^5 L_o
t << 10^5 yr)
Trapezium
(L = 10^5 L_o
t < 10^5 yr)
Hundreds of Proplyds
OMC1-S
(L = 10^4 L_o,
t < 10^5 yr)

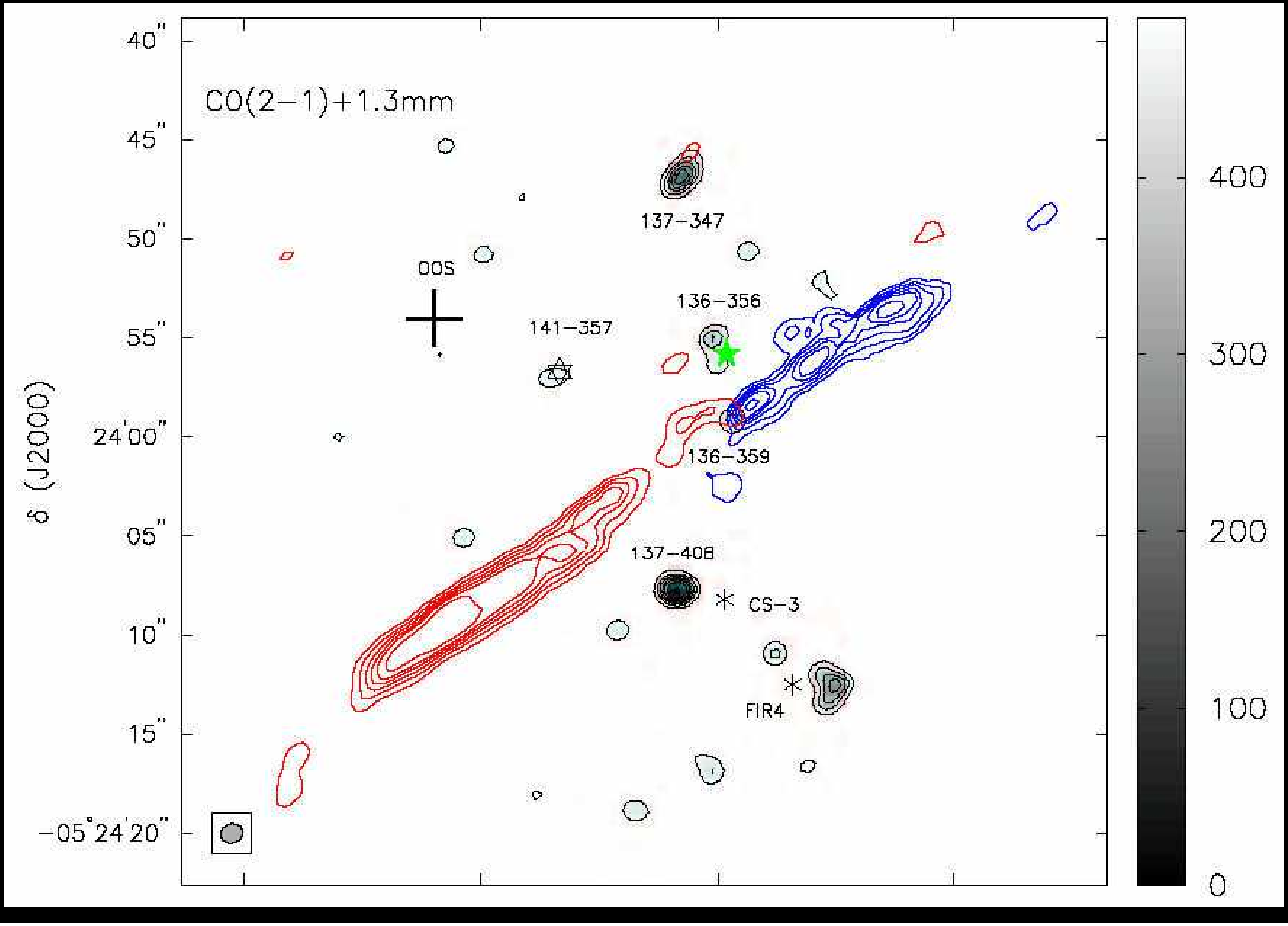

0.5 – 2.2 μm
10^4 AU


11.7 μm
10^4 AU

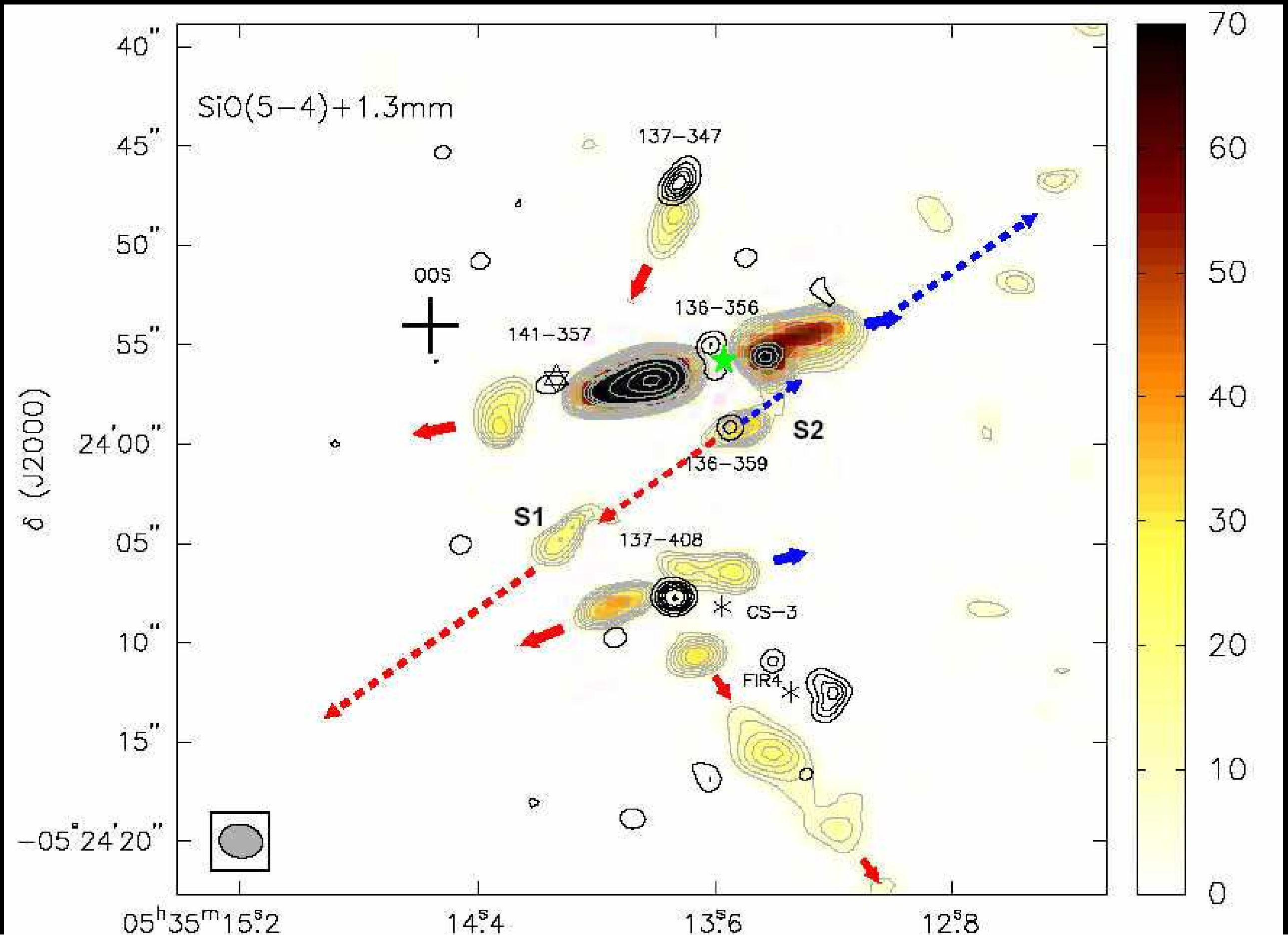

θ1C
LV 5
HH202 jet
HH514
HH202 source
HH202 source
OMC1-S
HH529

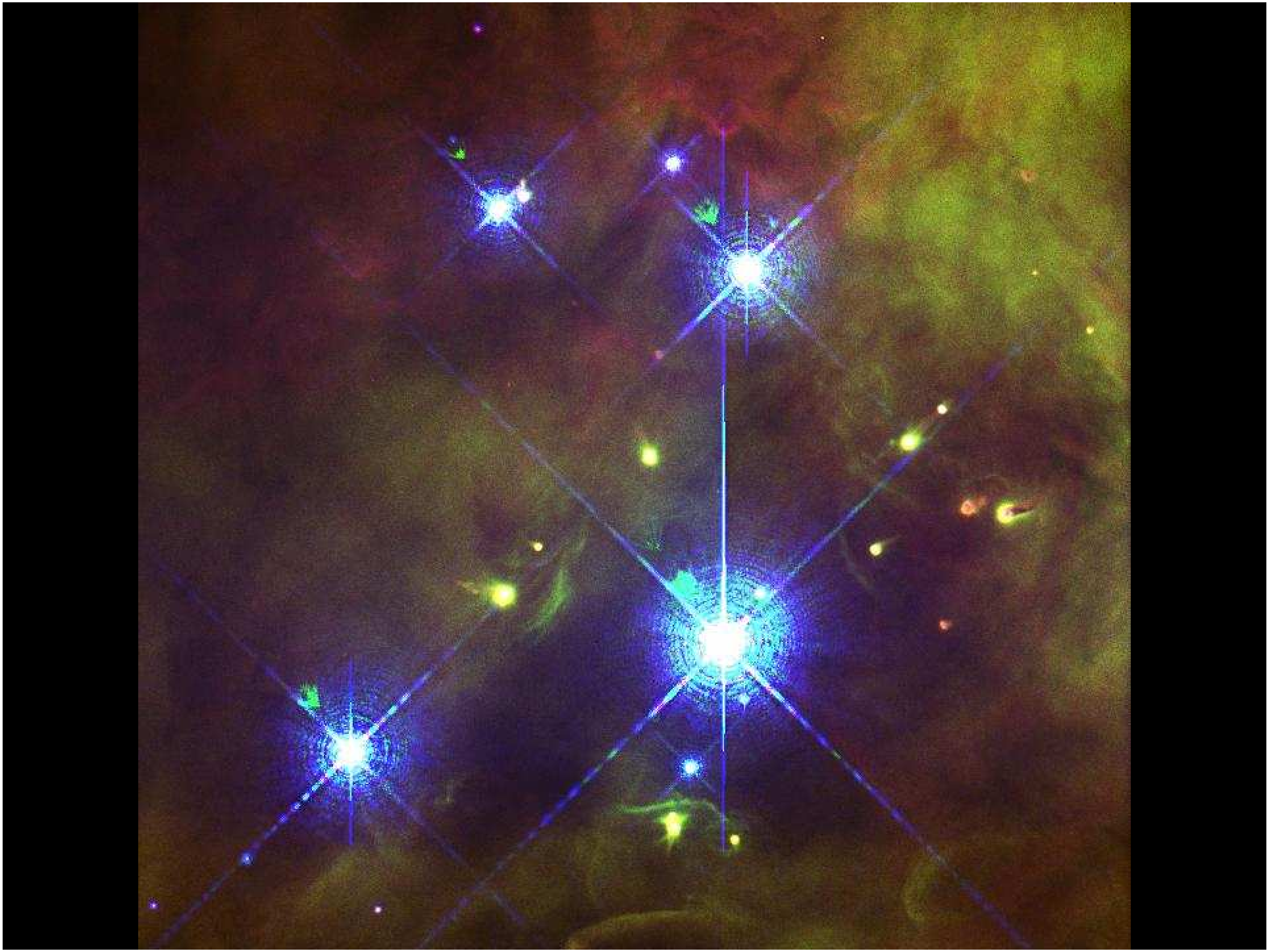

θ1C
LV 5
11.7 µm TReCS
HH202 jet
HH514
HH202 source
HH202 source
OMC1-S
HH529

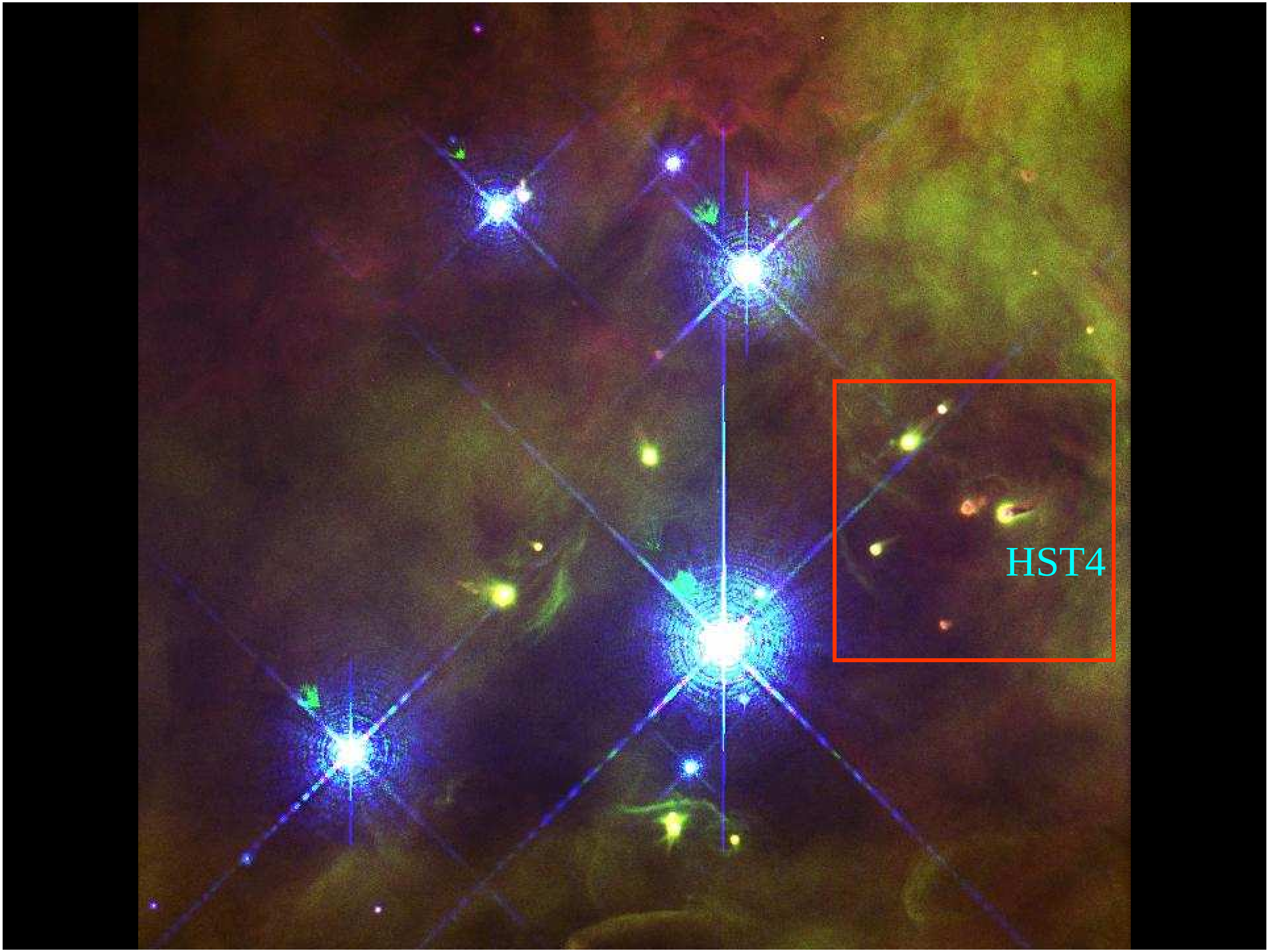
OMC-1S: Zapata et al. (2005)



OMC-1S: Zapata et al. (2005)





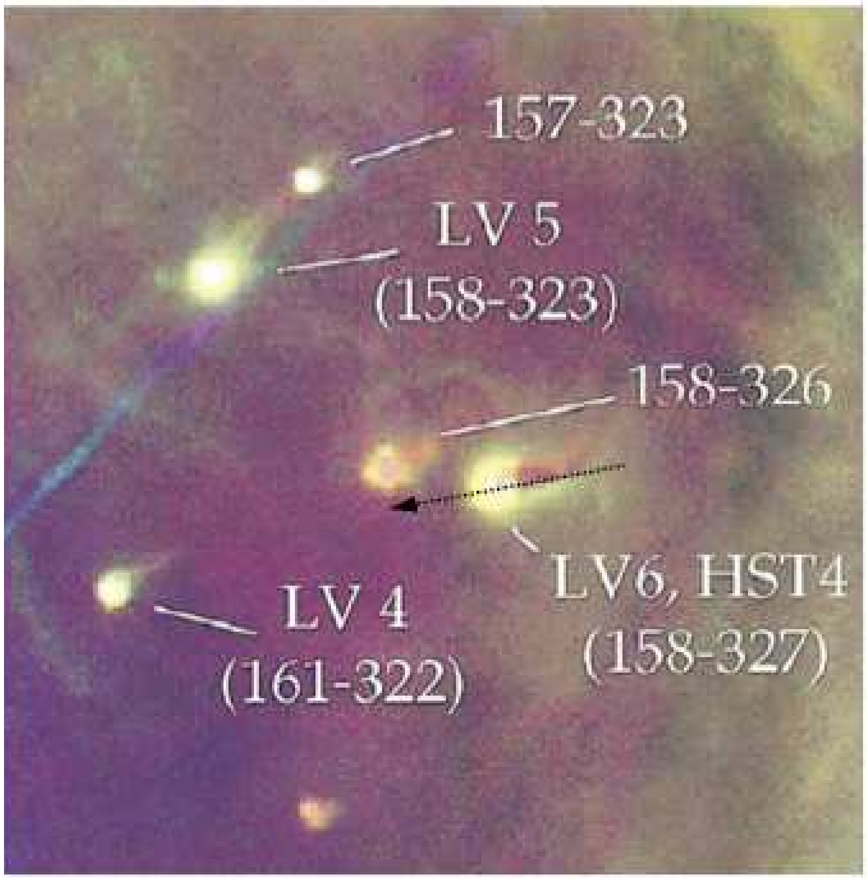

HST4

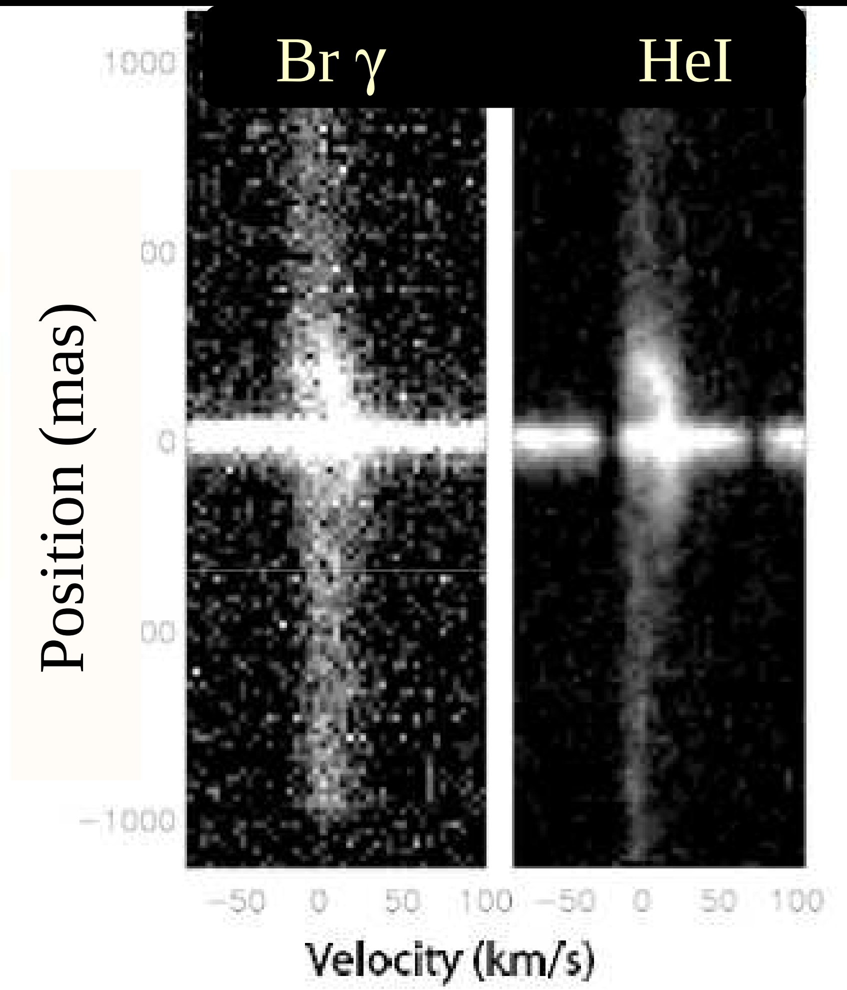
Proplyd photo-ablation flows: $dM/dt \sim 10^{-7}\, M_o\, yr^{-1}$

HST4 (LV 6), LV 1

Keck NIRSPEC + AO

(Shuping et al. 2006)





Disk Photo-ablation

Ionizing EUV: $\lambda < 912$ A (E > 13.6 eV) :

$H \Rightarrow H^+$

T ~ 10,000 K c_{II} ~ 10 km/s

Soft FUV: 912 A < λ < ~2,000 A (~6 eV < E < 13.6 eV)

heating by dust photo-electrons, $2H \Rightarrow H_2$

T ~ 100 to 5,000 K c_I ~ 1 – 5 km/s

Escape at $r > fGM / c^2$ ~ 5 AU for c_{II} (for Solar mass)

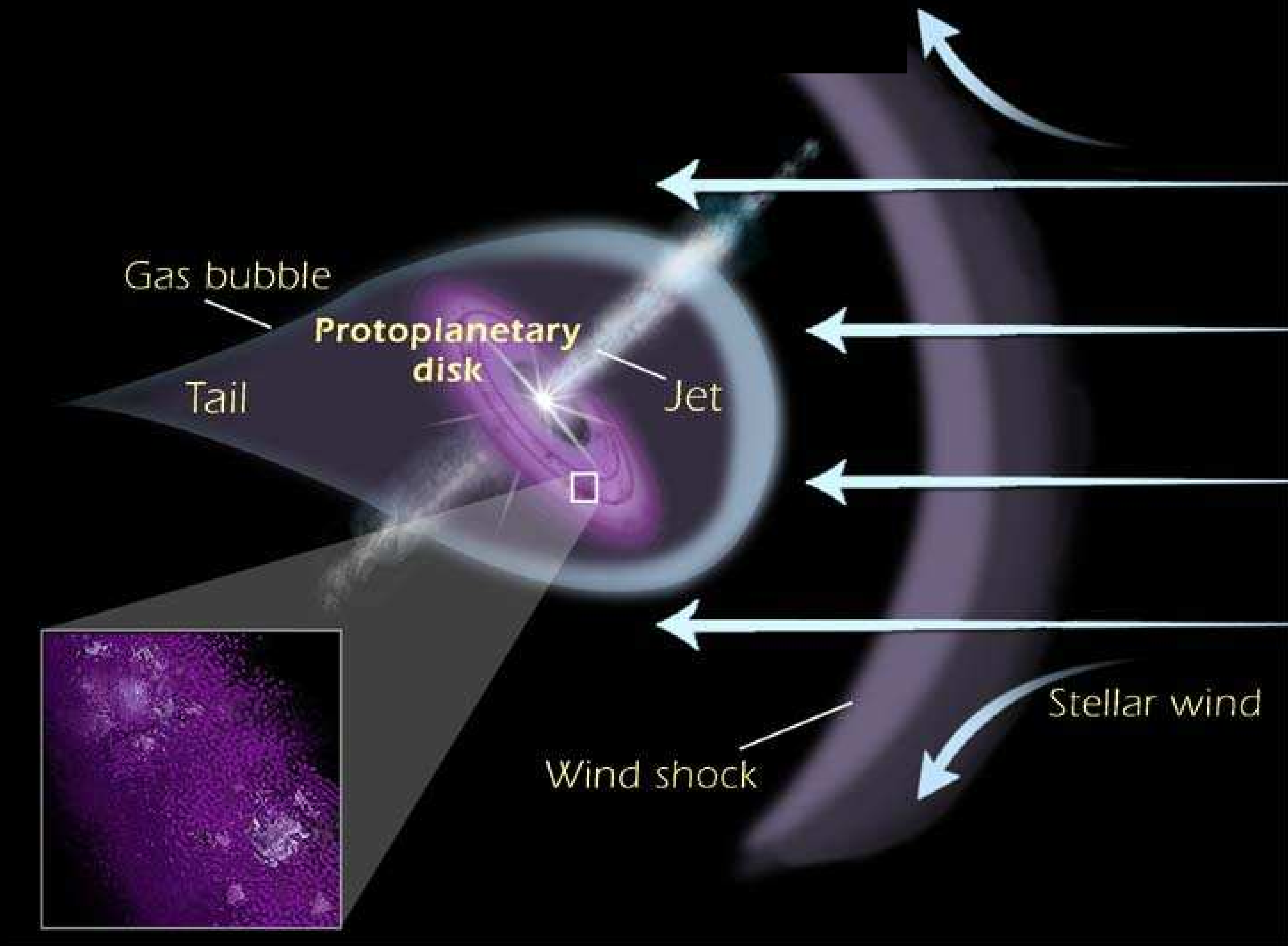
~ 40 AU for c_I

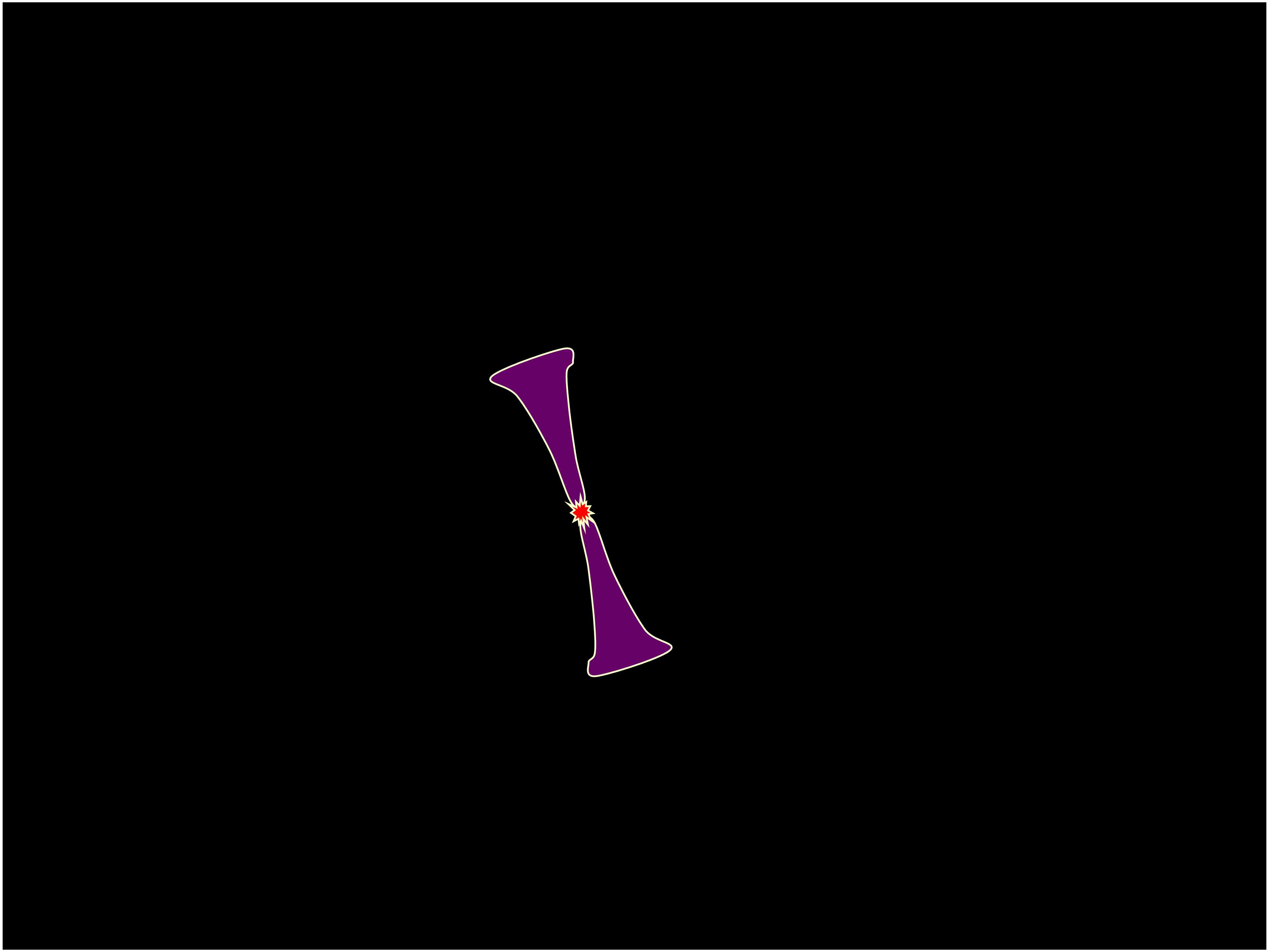
Self-irradiation vs. External irradiation:

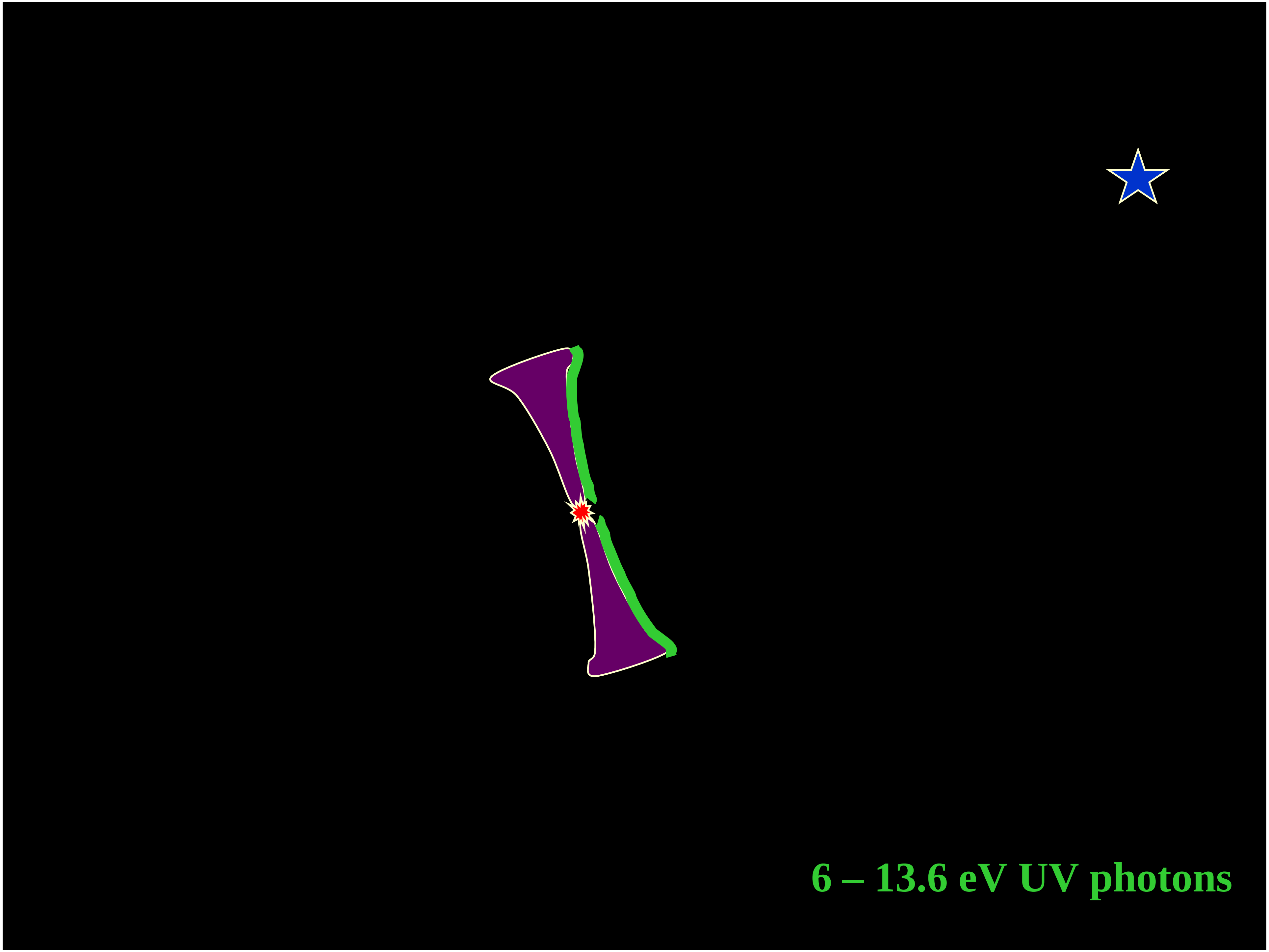
$$L_{self}(UV) / 4 \pi d_*^2 = L_{external}(UV) / 4 \pi d_{OB}^2$$

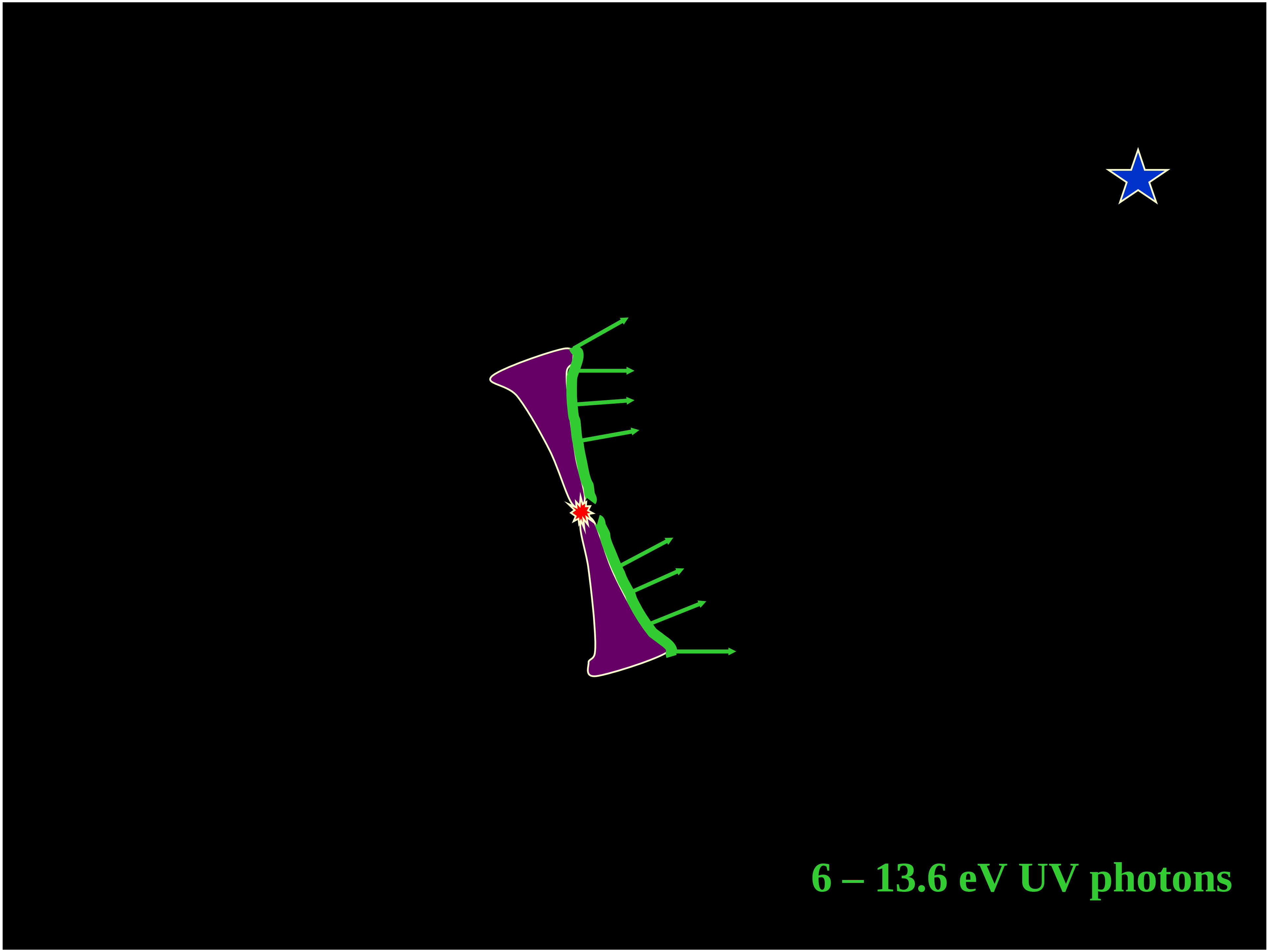
External irradiation: $L_{external}(UV) \sim 10^{49}$ photons / sec
Self - irradiation: $L_{self}(UV) \sim 10^{40} - 10^{43}$ photons / sec

Anatomy of a proplyd






6 – 13.6 eV UV photons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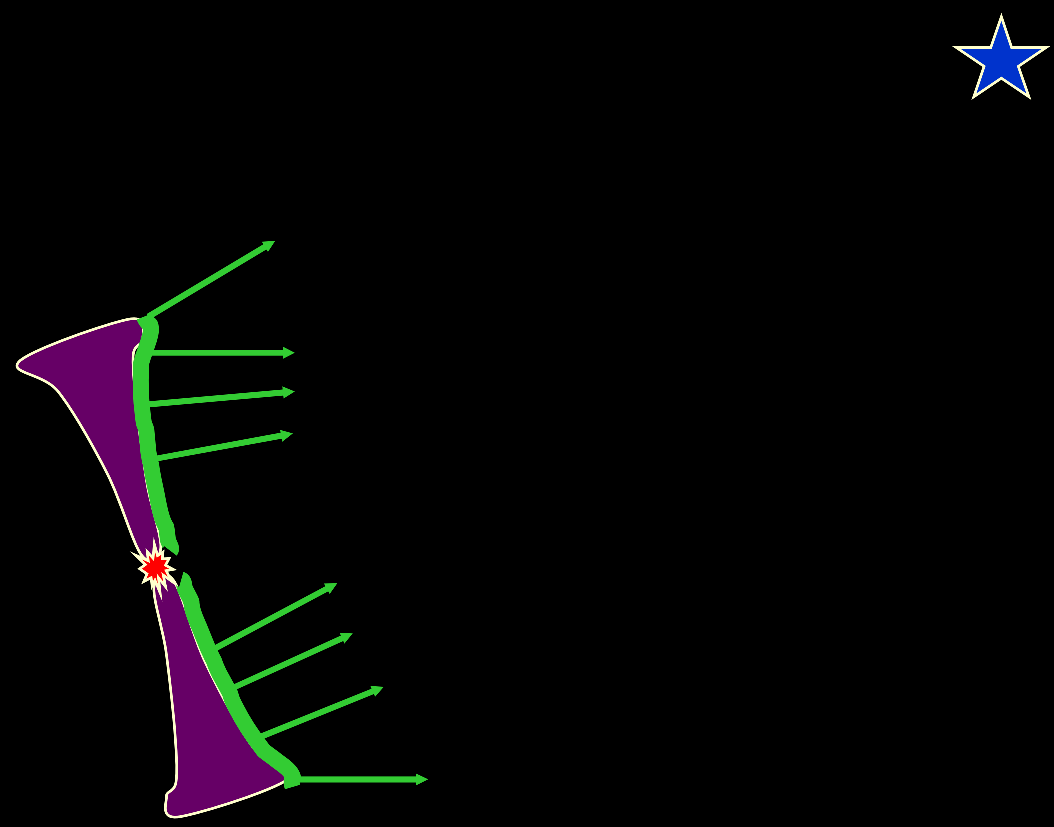
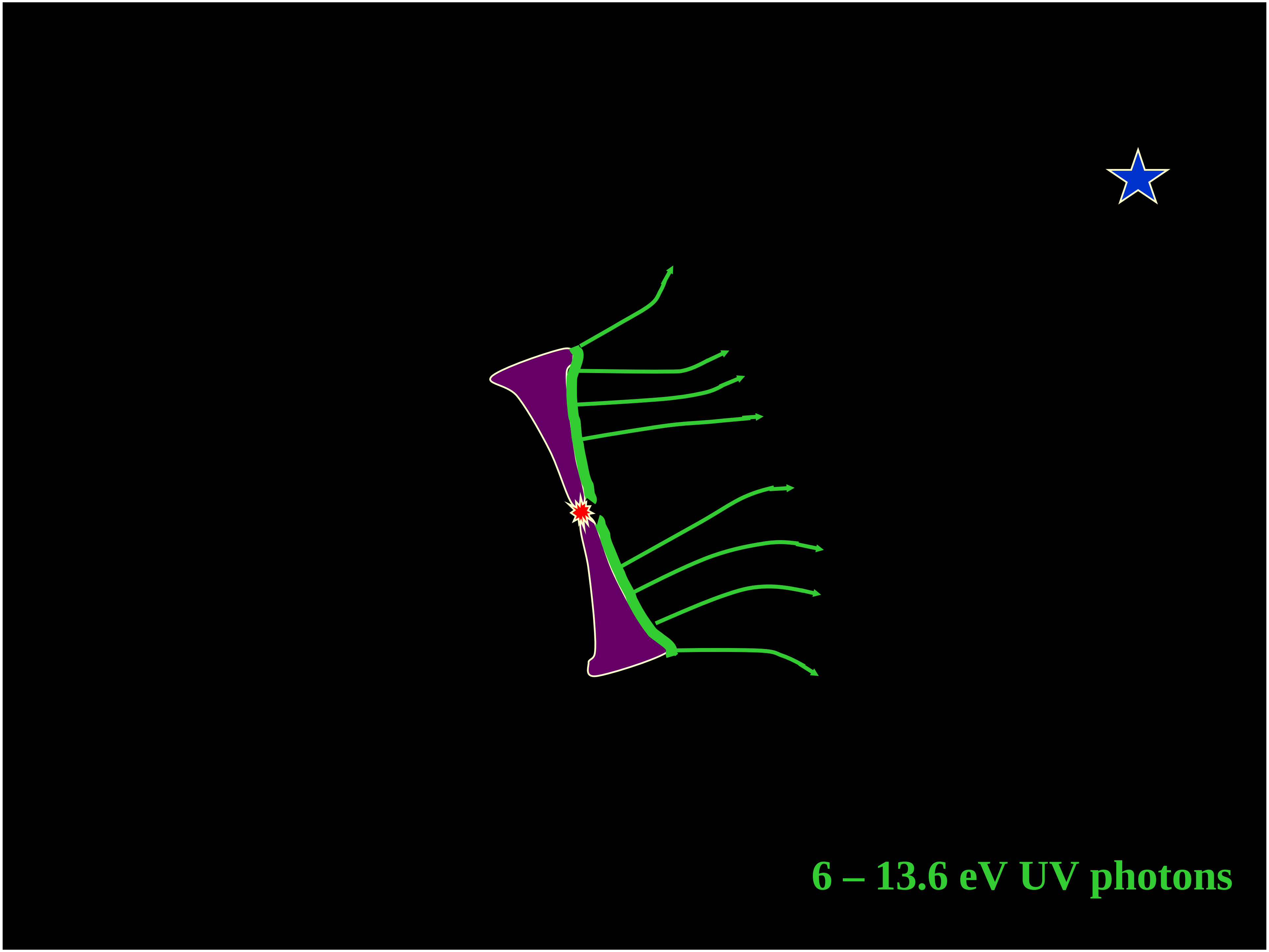
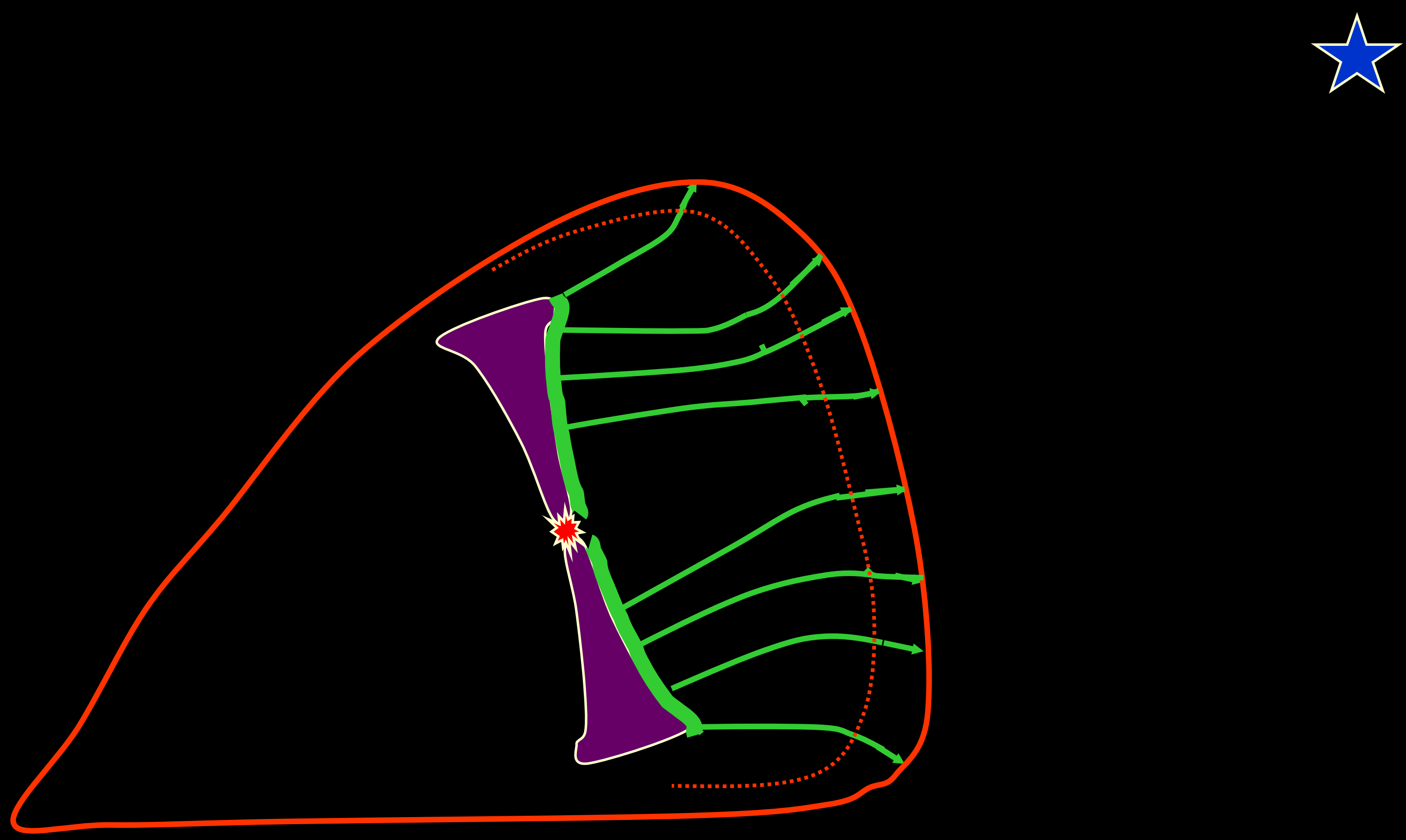


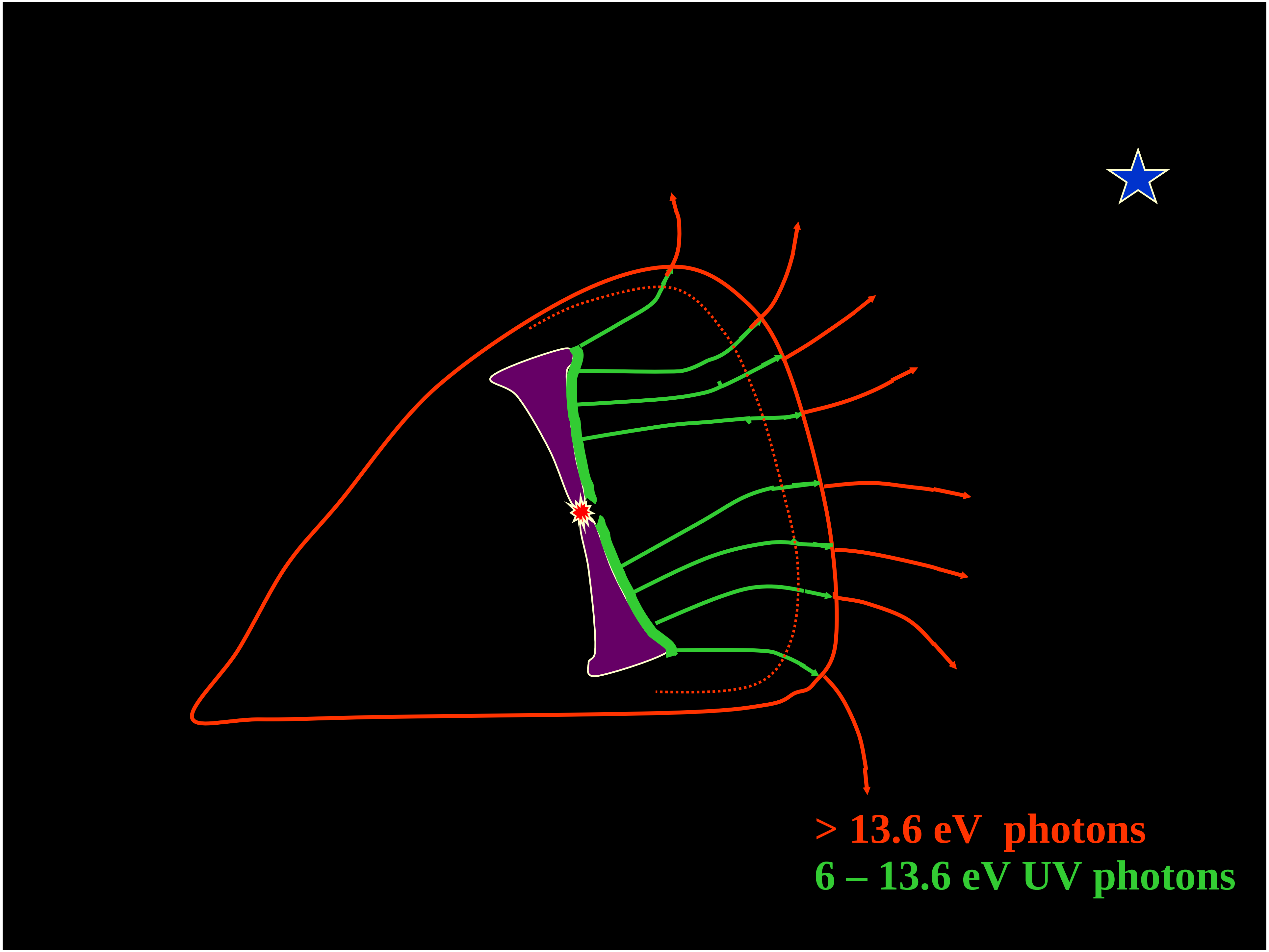
6 – 13.6 eV UV photons


6 – 13.6 eV UV photons

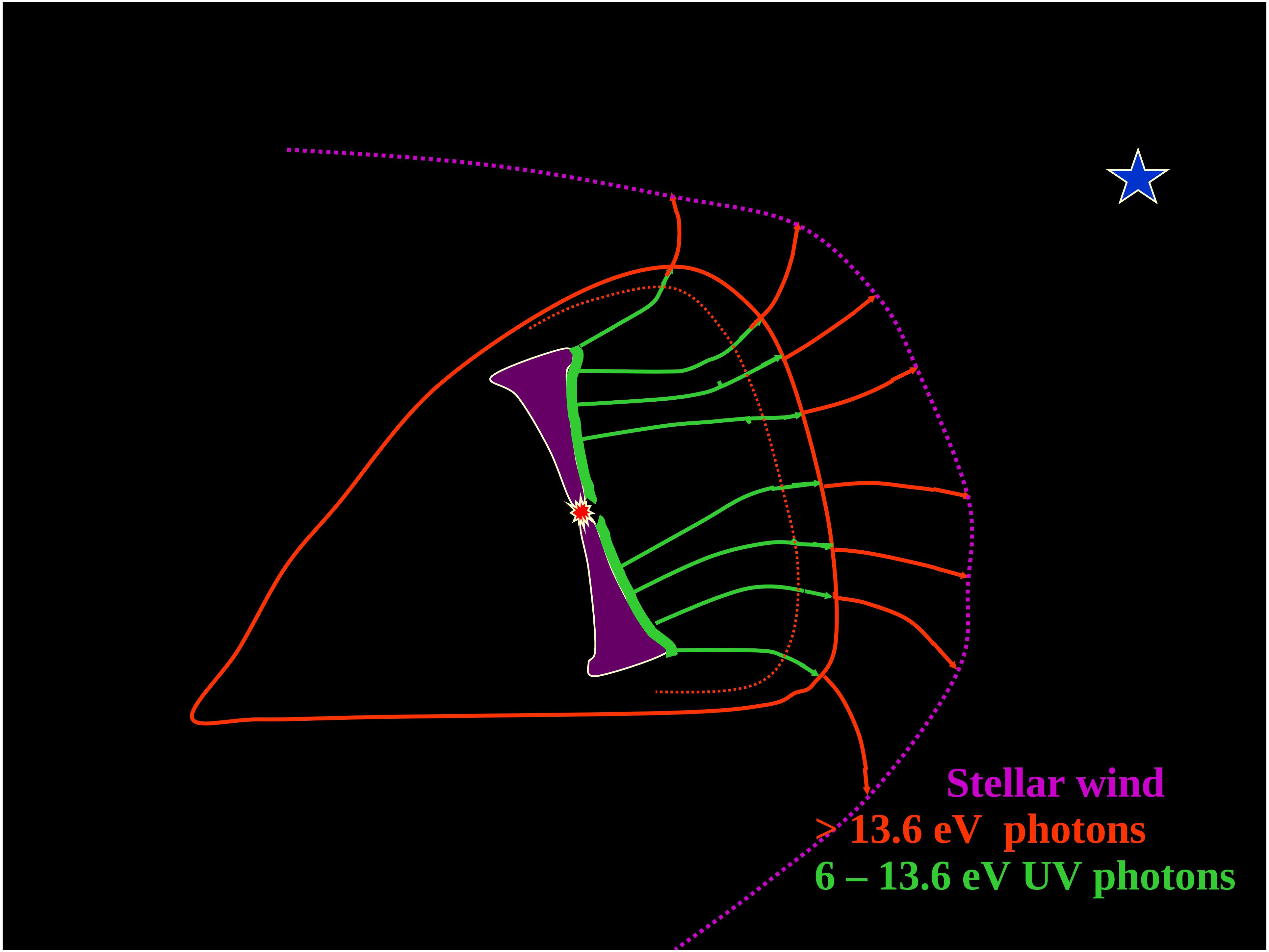


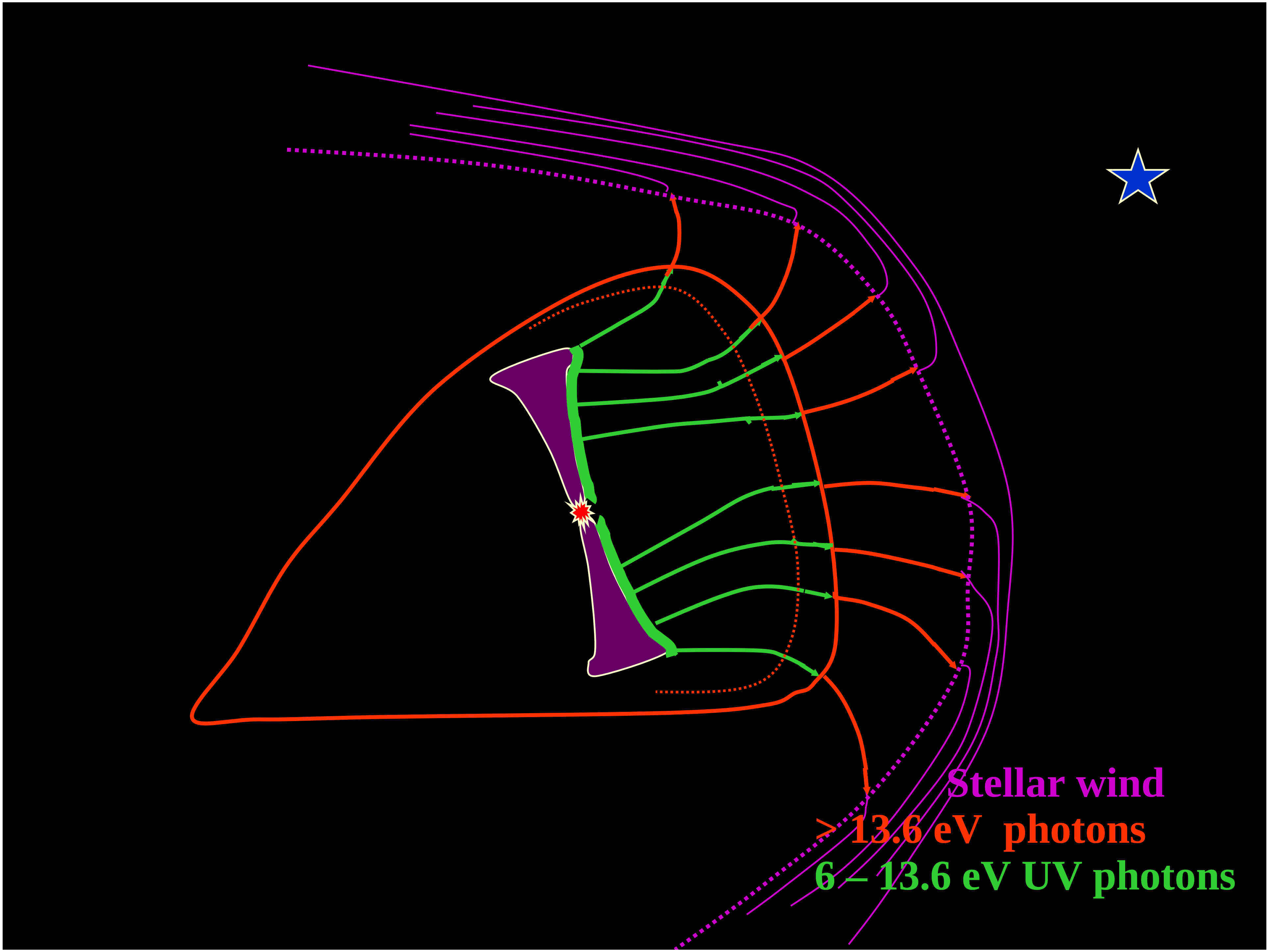
> 13.6 eV photons

6 – 13.6 eV UV photons



> 13.6 eV photons
6 – 13.6 eV UV photons


Stellar wind
> 13.6 eV photons
6 – 13.6 eV UV photons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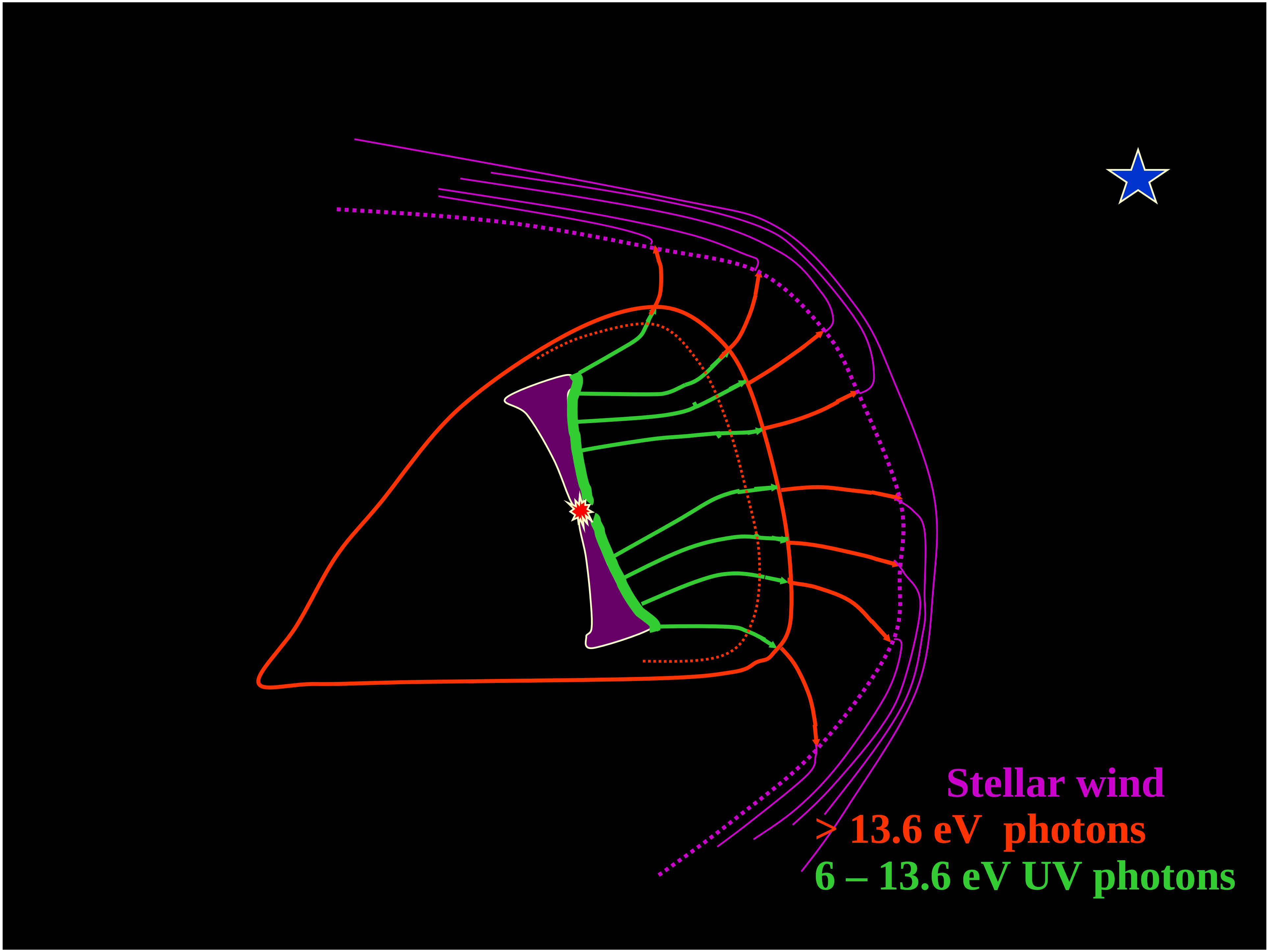
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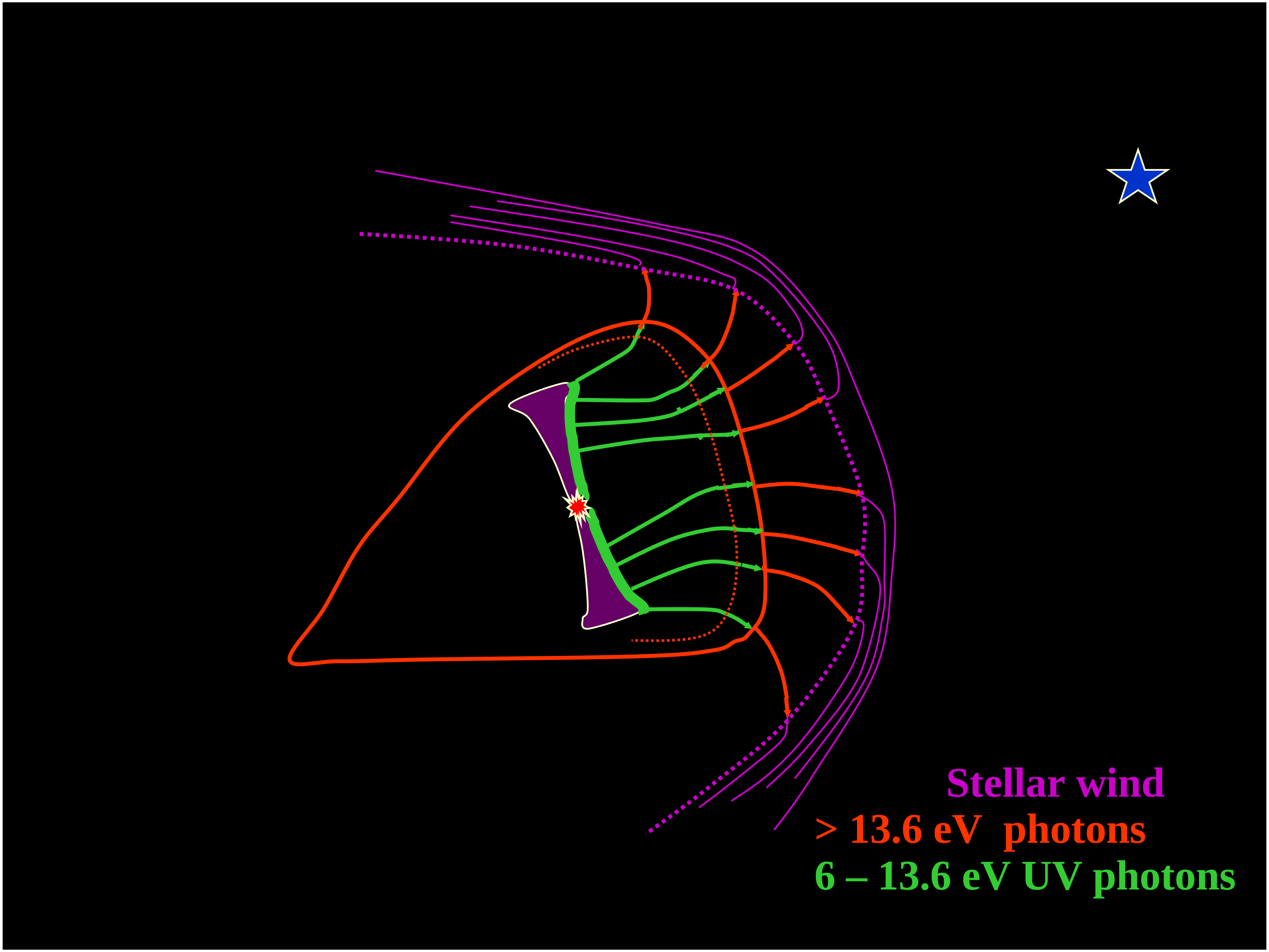
Stellar wind
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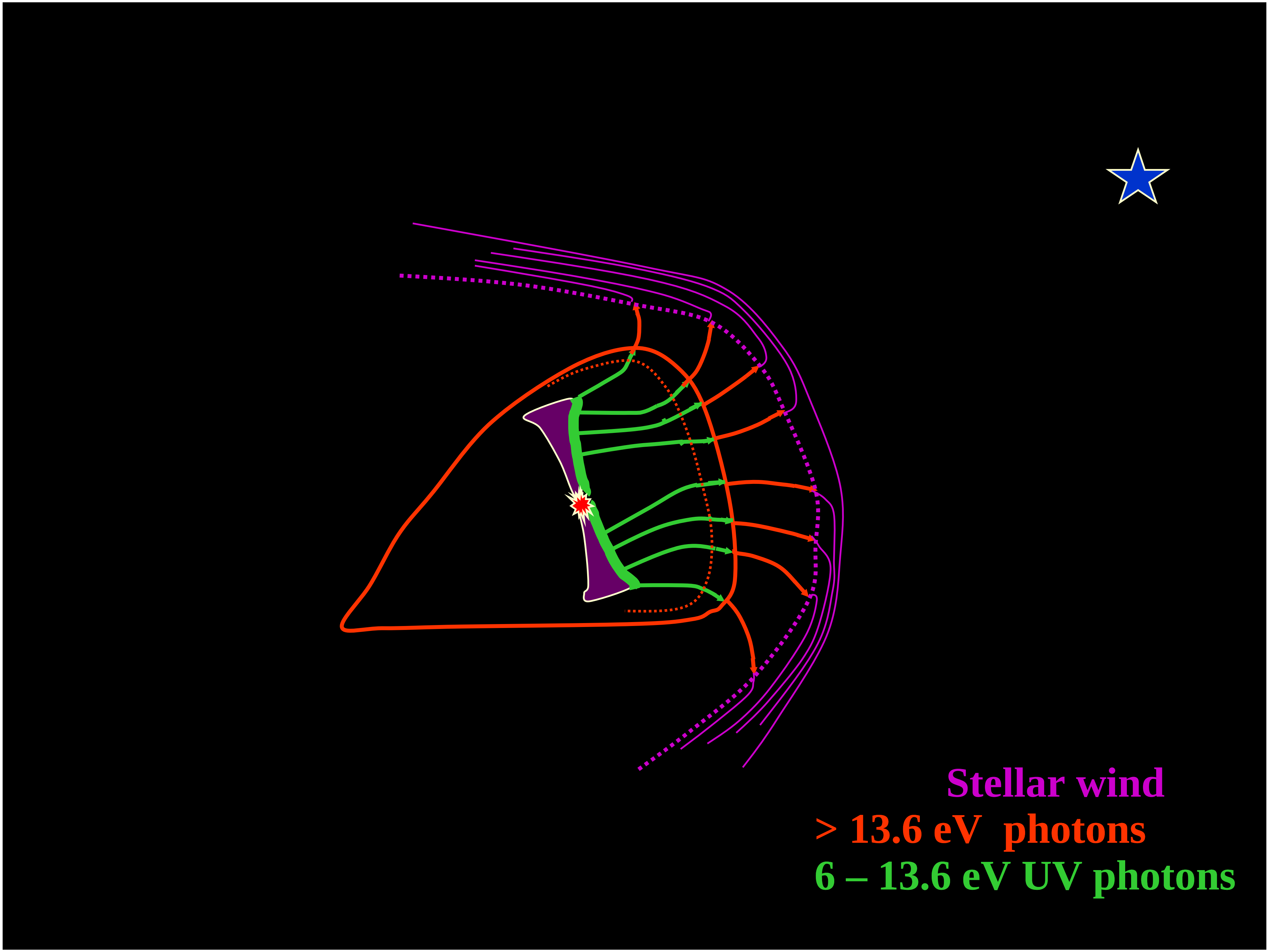
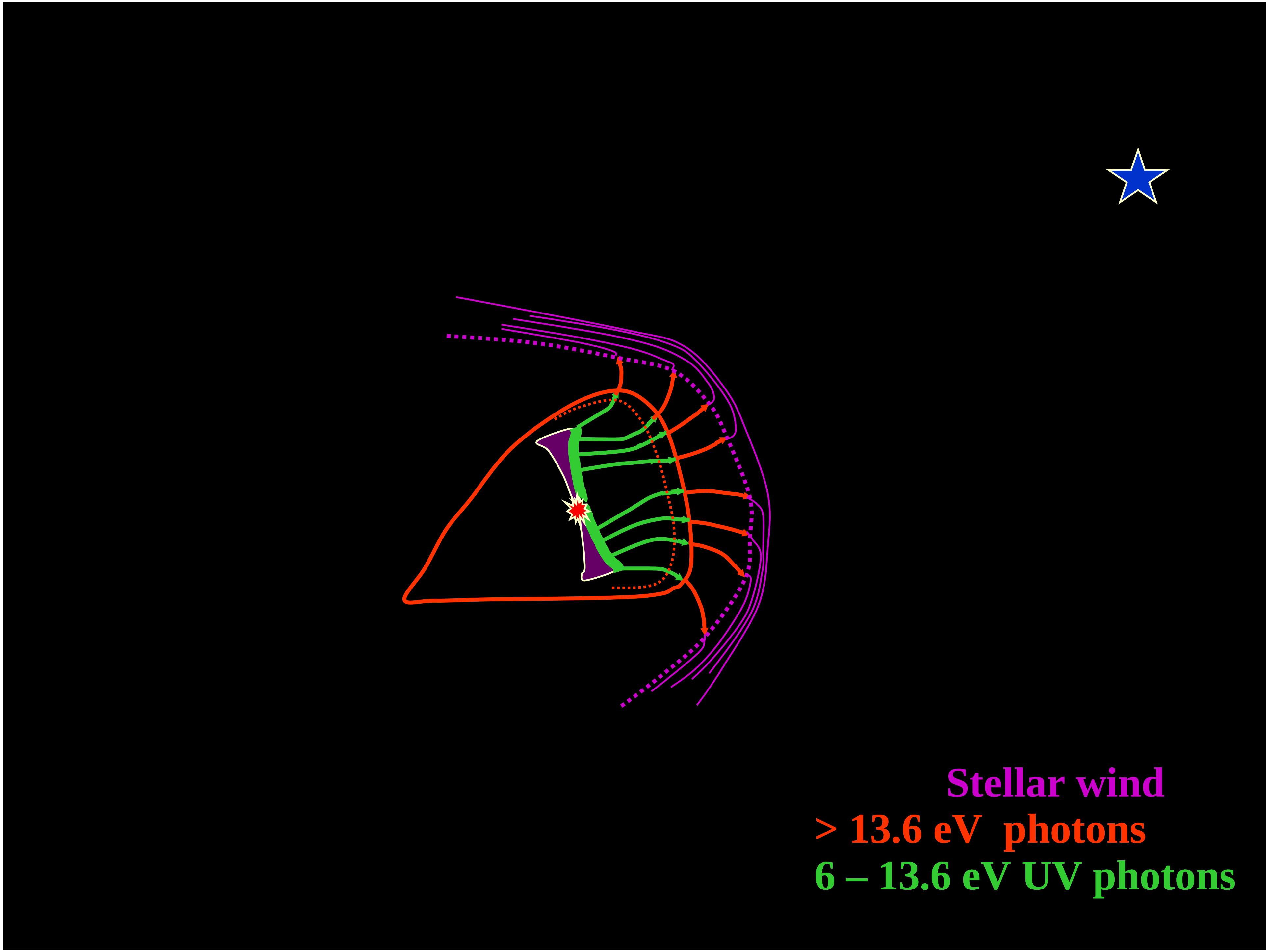

Stellar wind
> 13.6 eV photons
6 – 13.6 eV UV photons

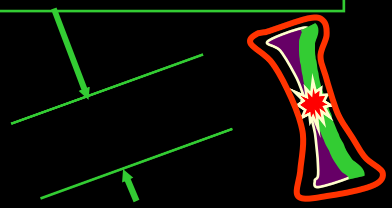

Stellar wind
> 13.6 eV photons
6 – 13.6 eV UV photons

$t \sim f \; M_{disk} \; N_{21}^{-1} \; r_{disk}^{-1} \; C_I^{-1}$ (years)

$\sim 10^5 - 10^6$ years

$r_{GI} = GM/c_I^2 \sim 40$ AU

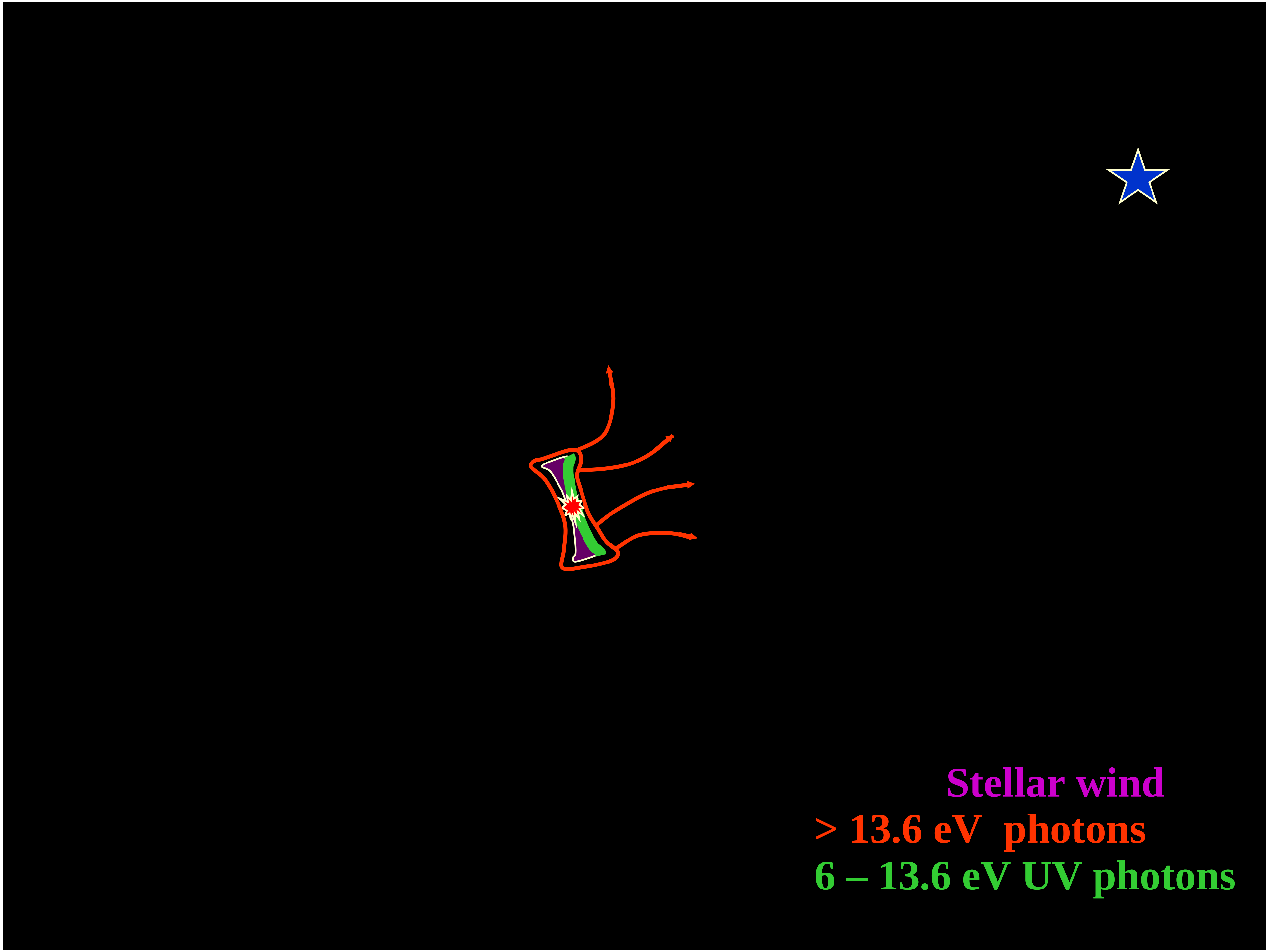
$c_I \sim 3$ km/s



Stellar wind

> 13.6 eV photons

6 – 13.6 eV UV photons


Stellar wind
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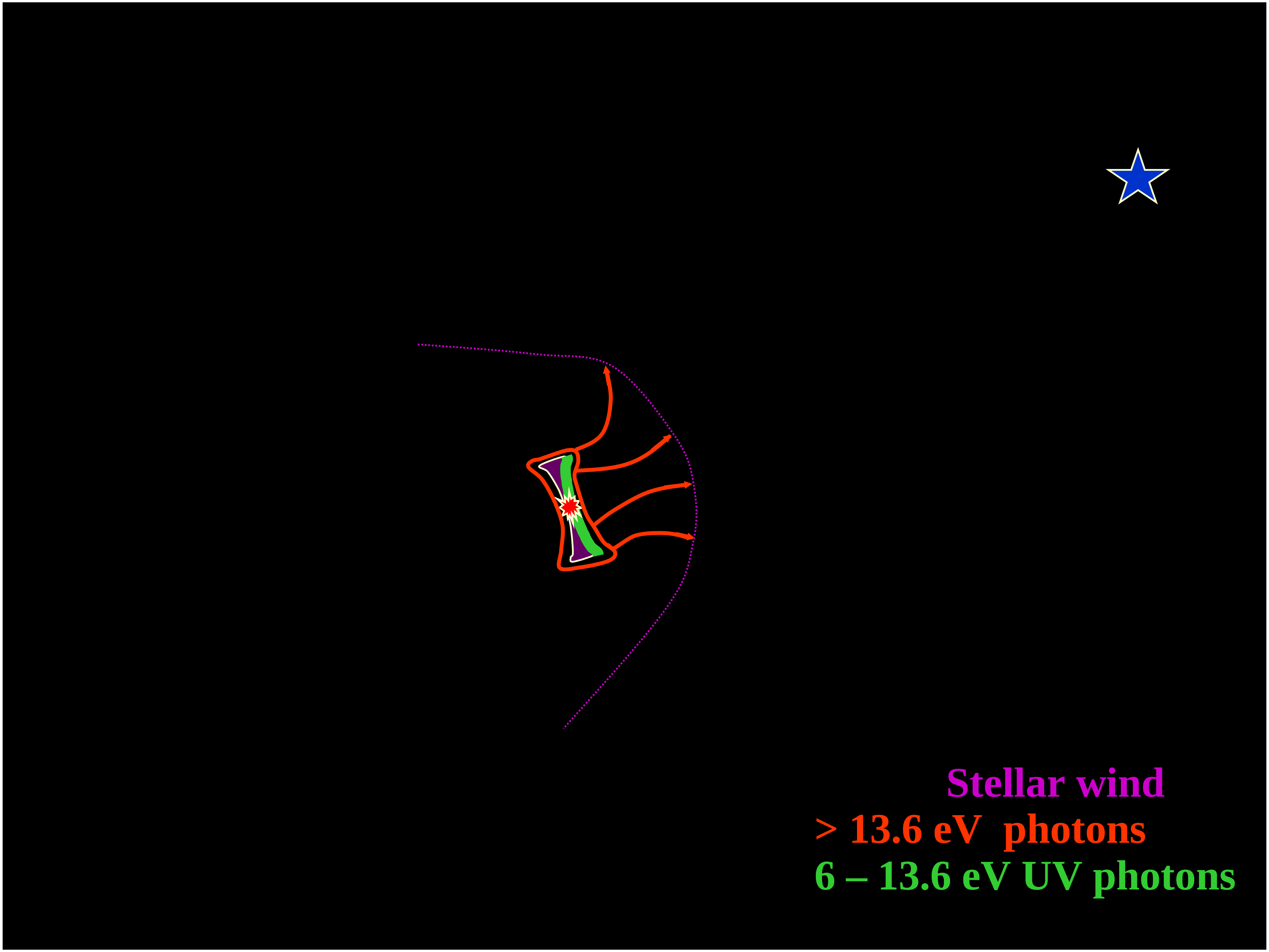

Stellar wind
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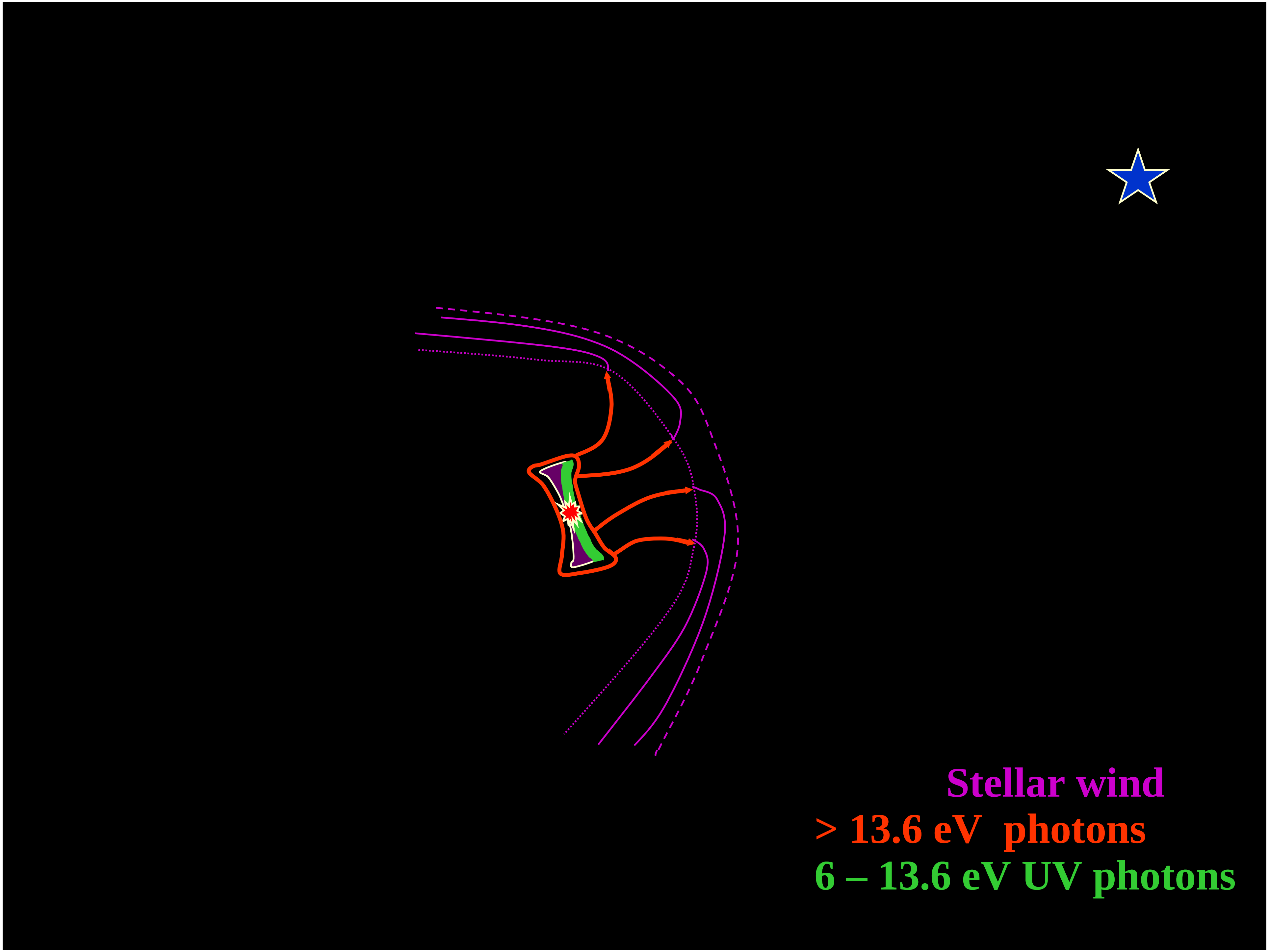
Stellar wind
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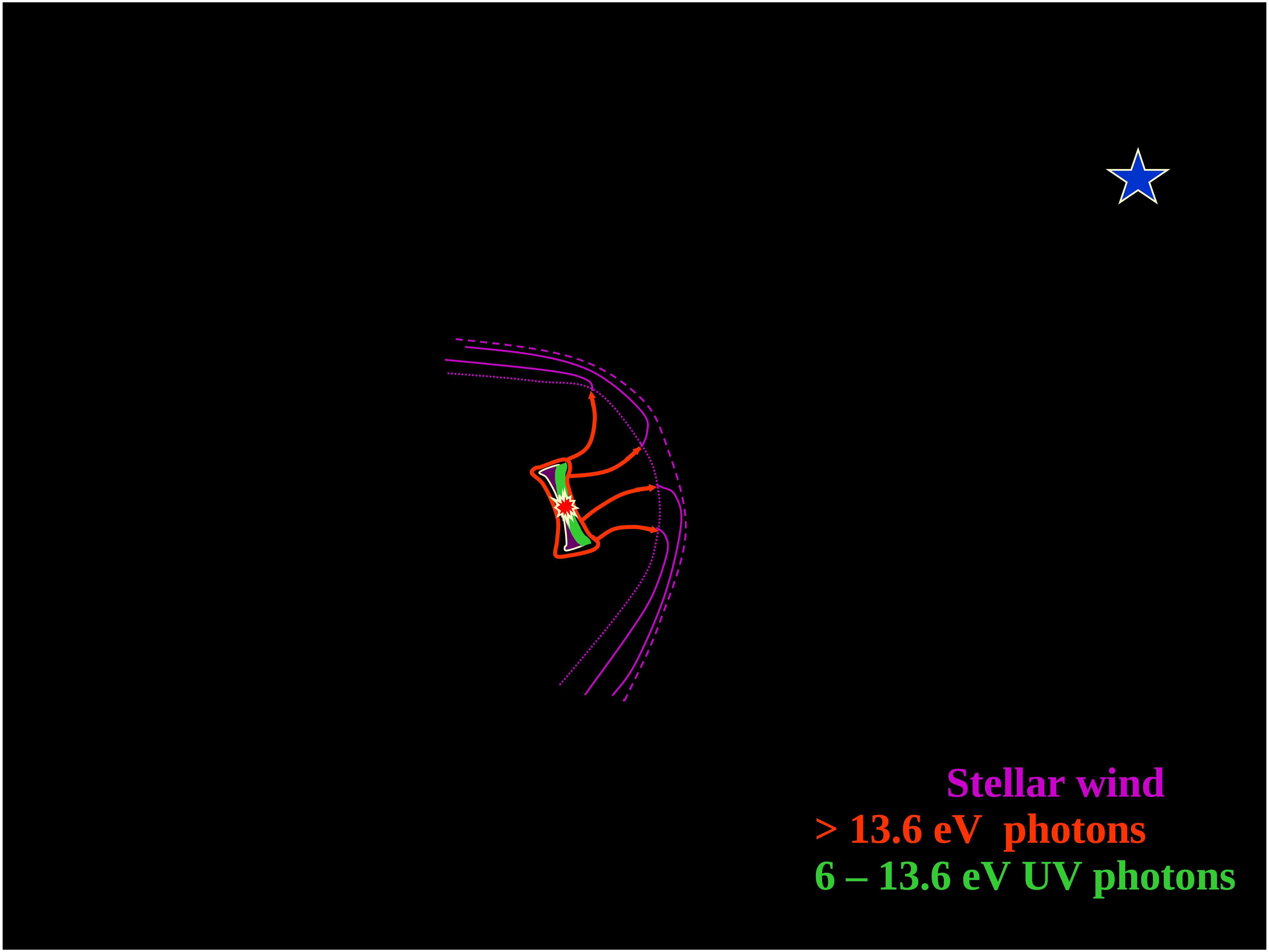
Stellar wind
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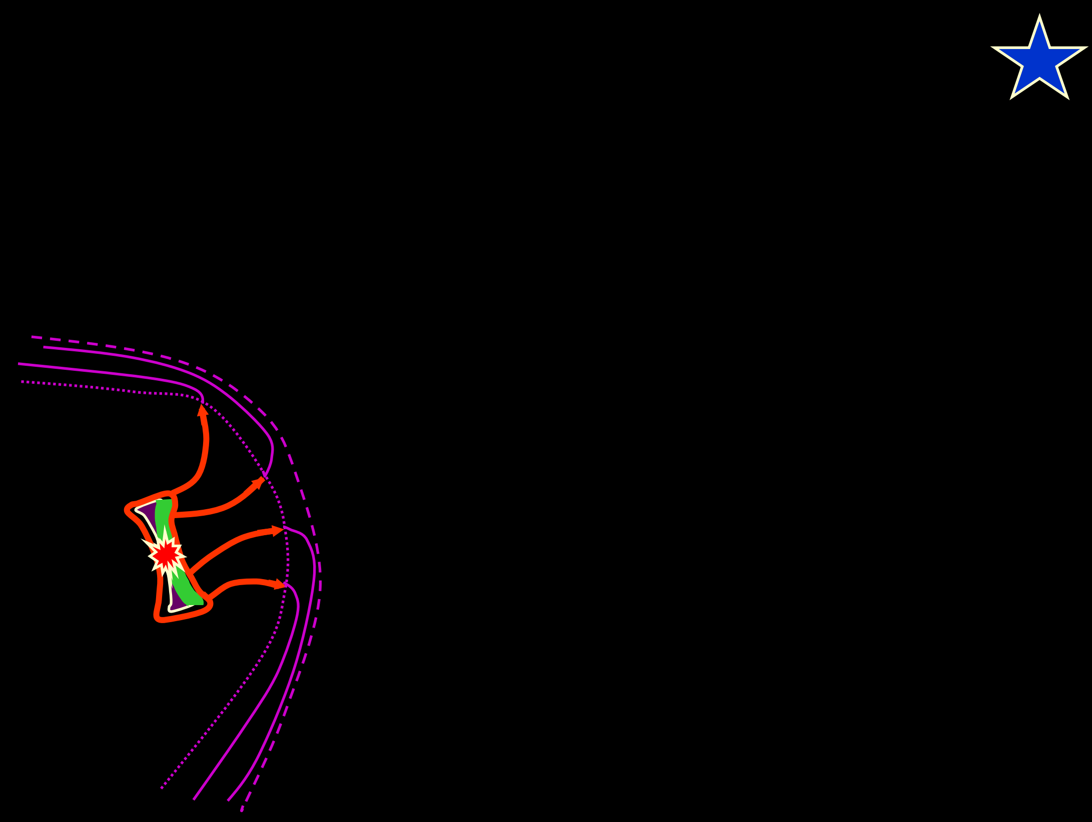
6 – 13.6 eV UV photons



Stellar wind
> 13.6 eV photons
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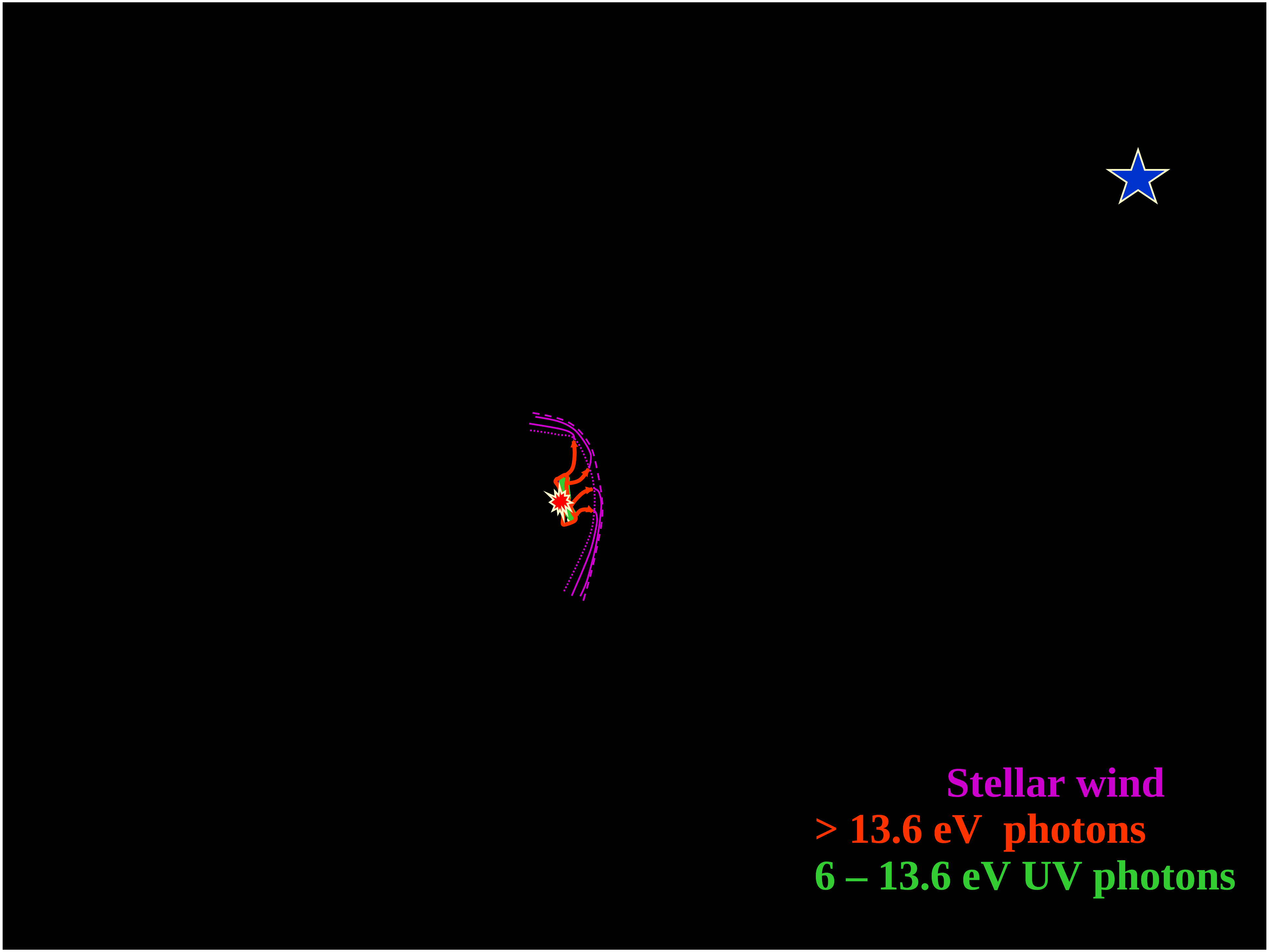
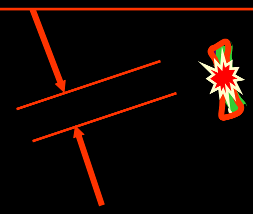

Stellar wind
> 13.6 eV photons
6 – 13.6 eV UV photons

$t \sim 9 \times 10^6\ Q_{49}^{-1/2}\ cII_{10}^{-1}\ d_{1pc}^{-1}\ M_o\ r_{10AU}^{-3/2}$ years

$< 2 - 5 \times 10^6$ years

$r_{GII} = GM/c_{II}^2 \sim 5$ AU

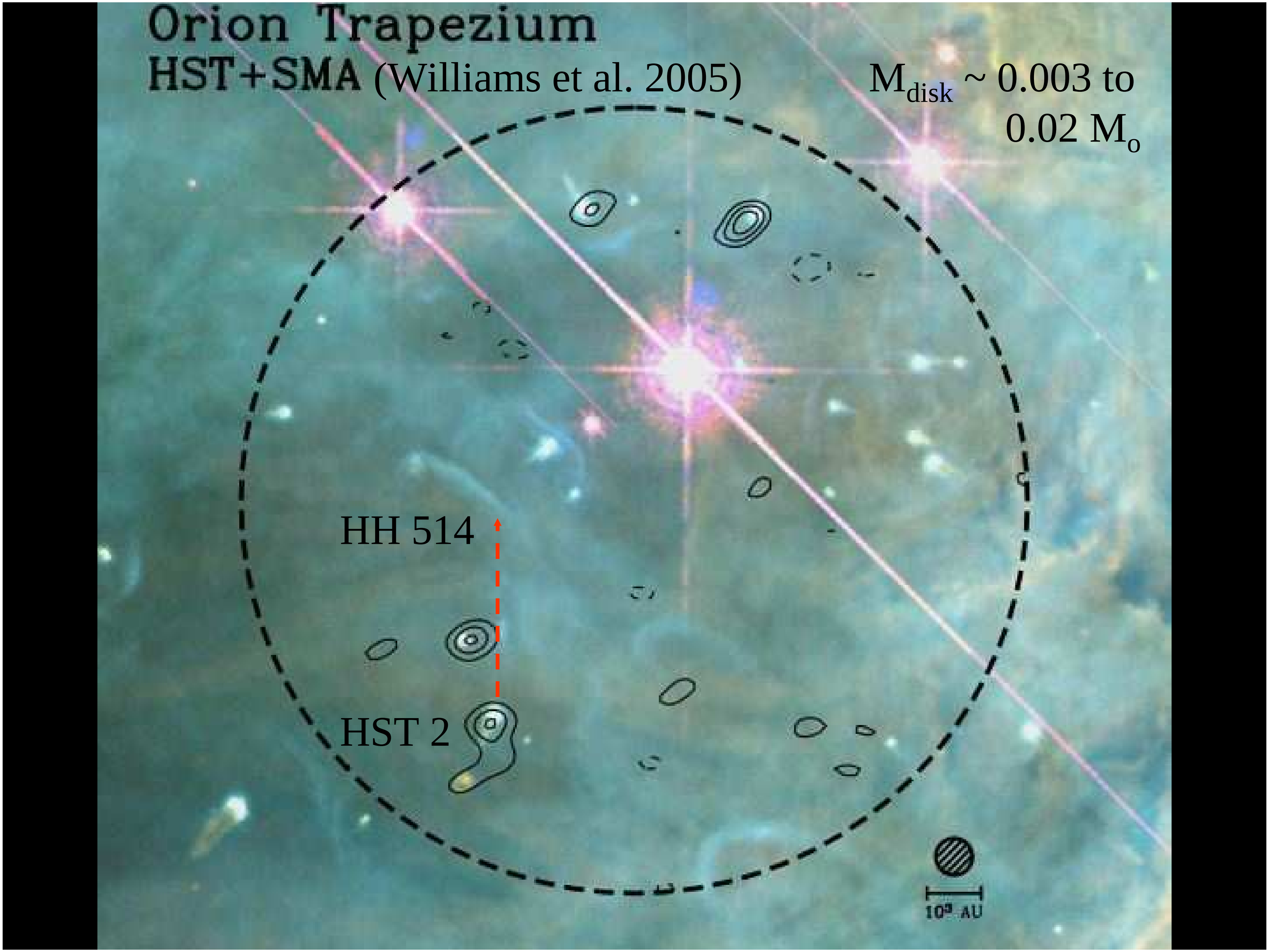
$c_{II} \sim 10$ km/s



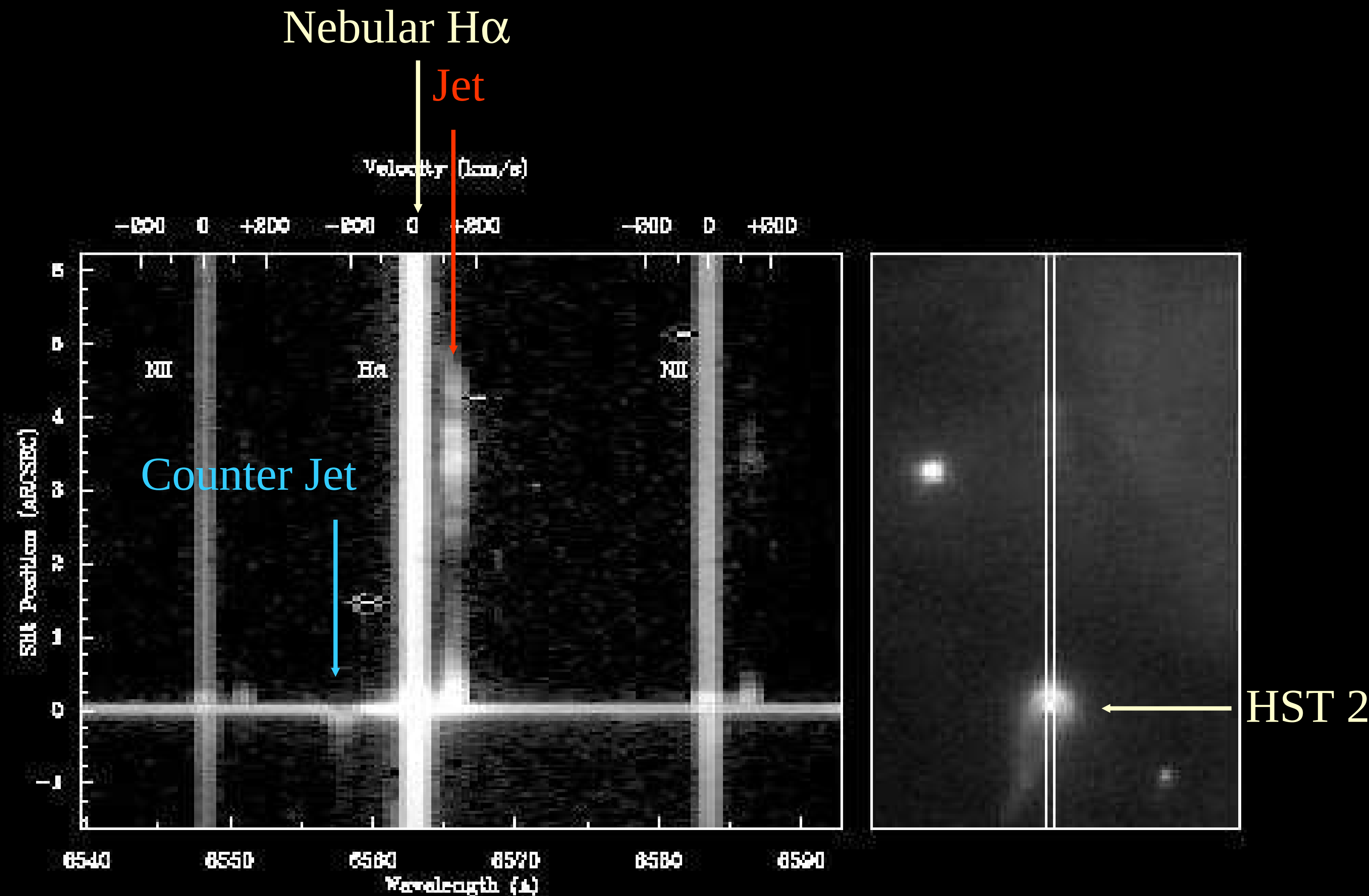
Stellar wind

> 13.6 eV photons

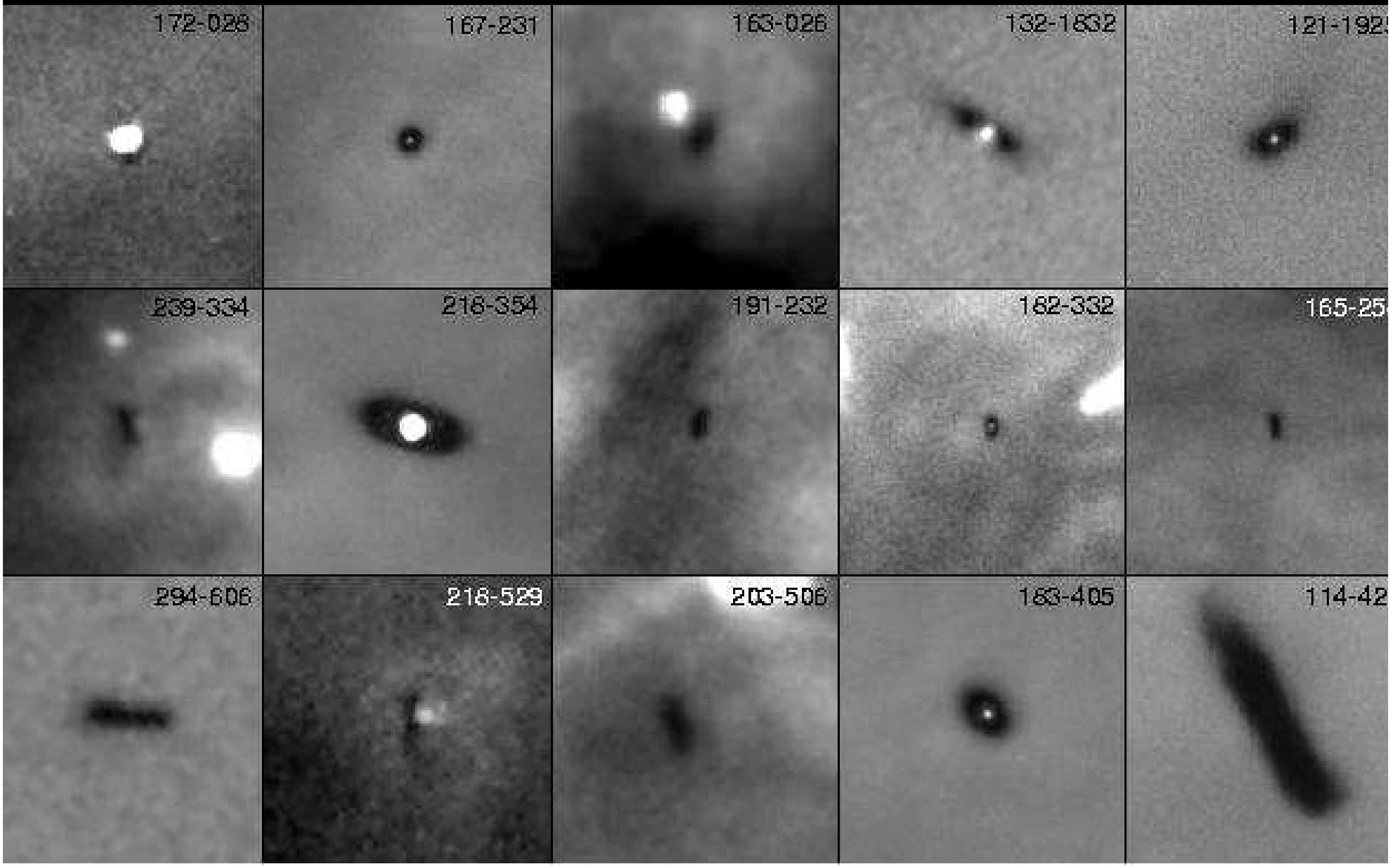
6 – 13.6 eV UV photons

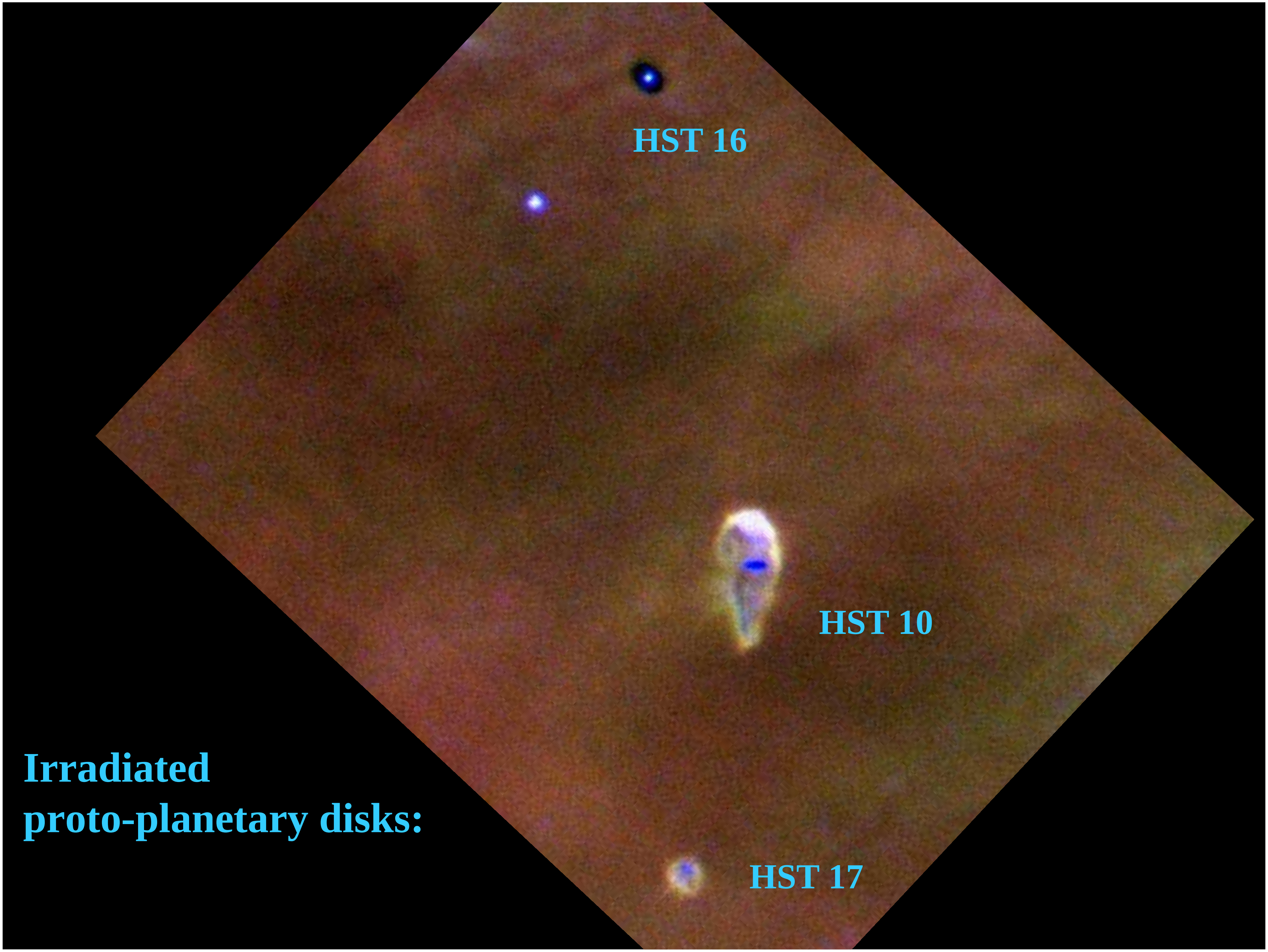

Orion Trapezium
HST+SMA (Williams et al. 2005)
M_disk ~ 0.003 to 0.02 M_o
HH 514
HST 2
10^3 AU

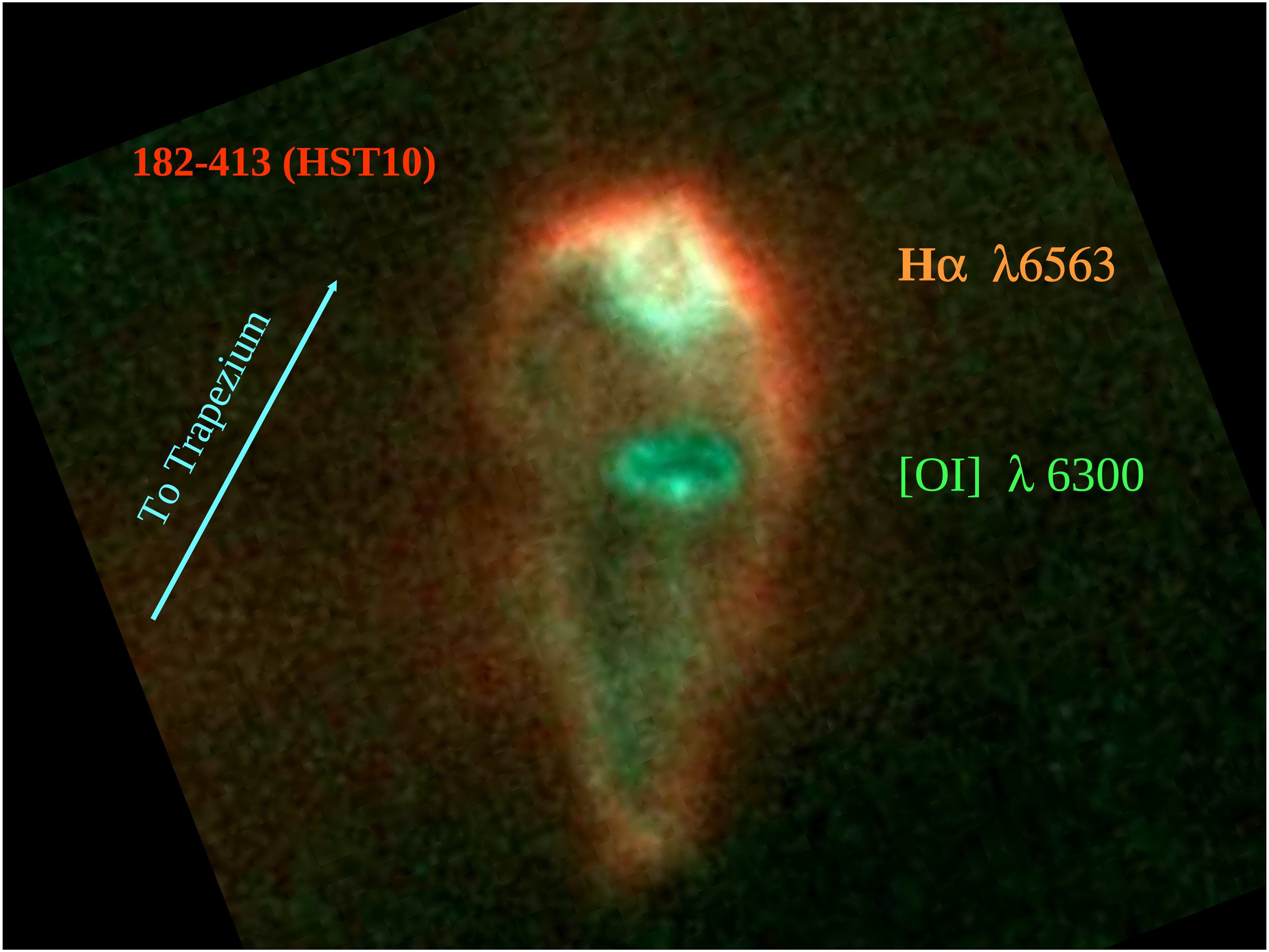
HH 514 micro-jet in Orion: Hα, [HII] (HST/STIS)



Orion Nebula: > 50 disks seen in silhouette

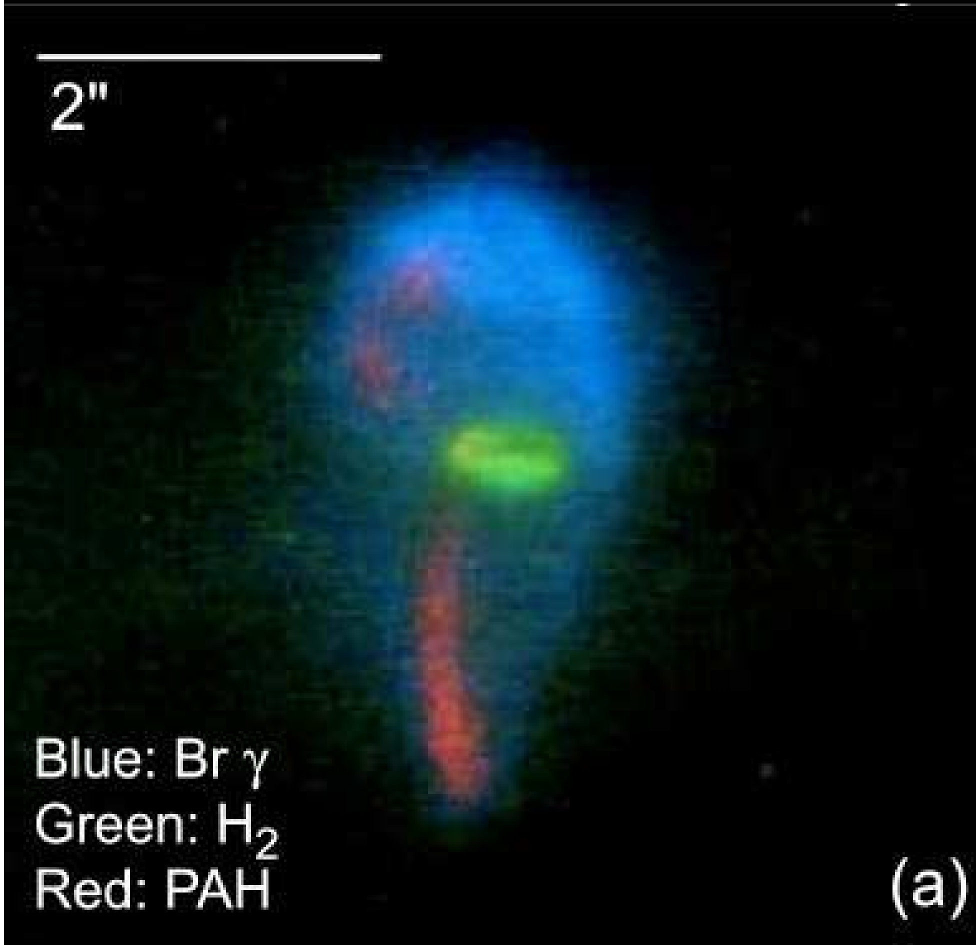



HST 16
HST 10
Irradiated
proto-planetary disks:
HST 17


182-413 (HST10)
To Trapezium
Hα λ6563
[OI] λ 6300

Keck AO IR

HST Hα



2.12 μm H_2

0.6563 μm Hα

=> Soft UV photo-heating of disk surface

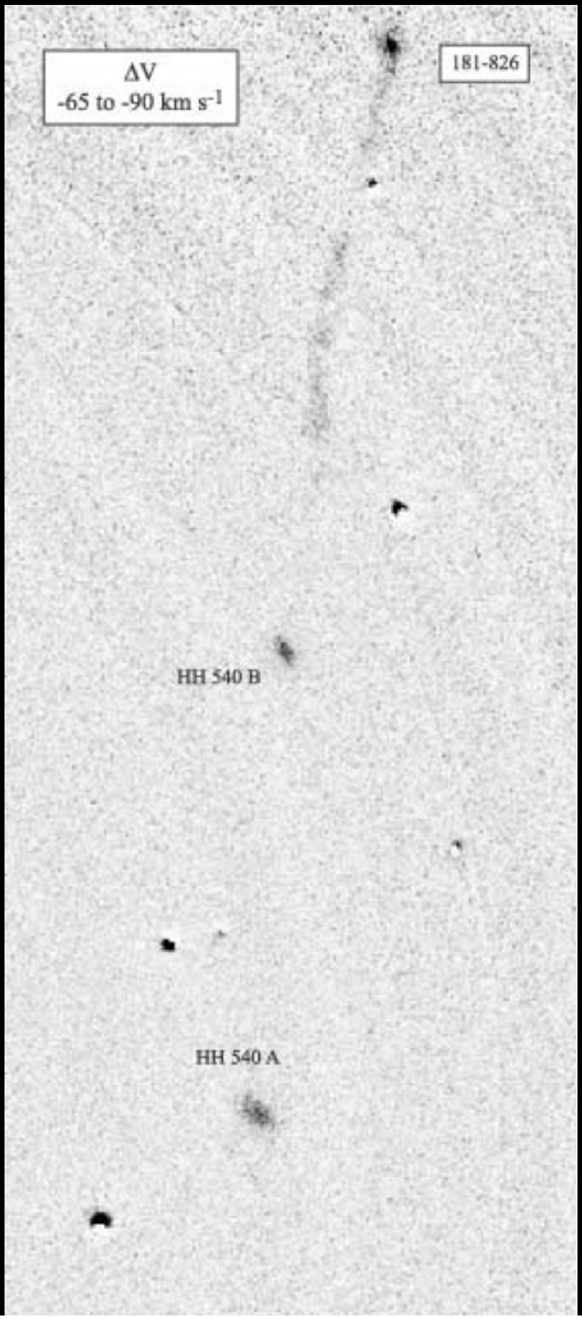
(Kassis et al. 2007, in preparation)

Evidence for Sedimentation:

Proplyd winds are dust depleted

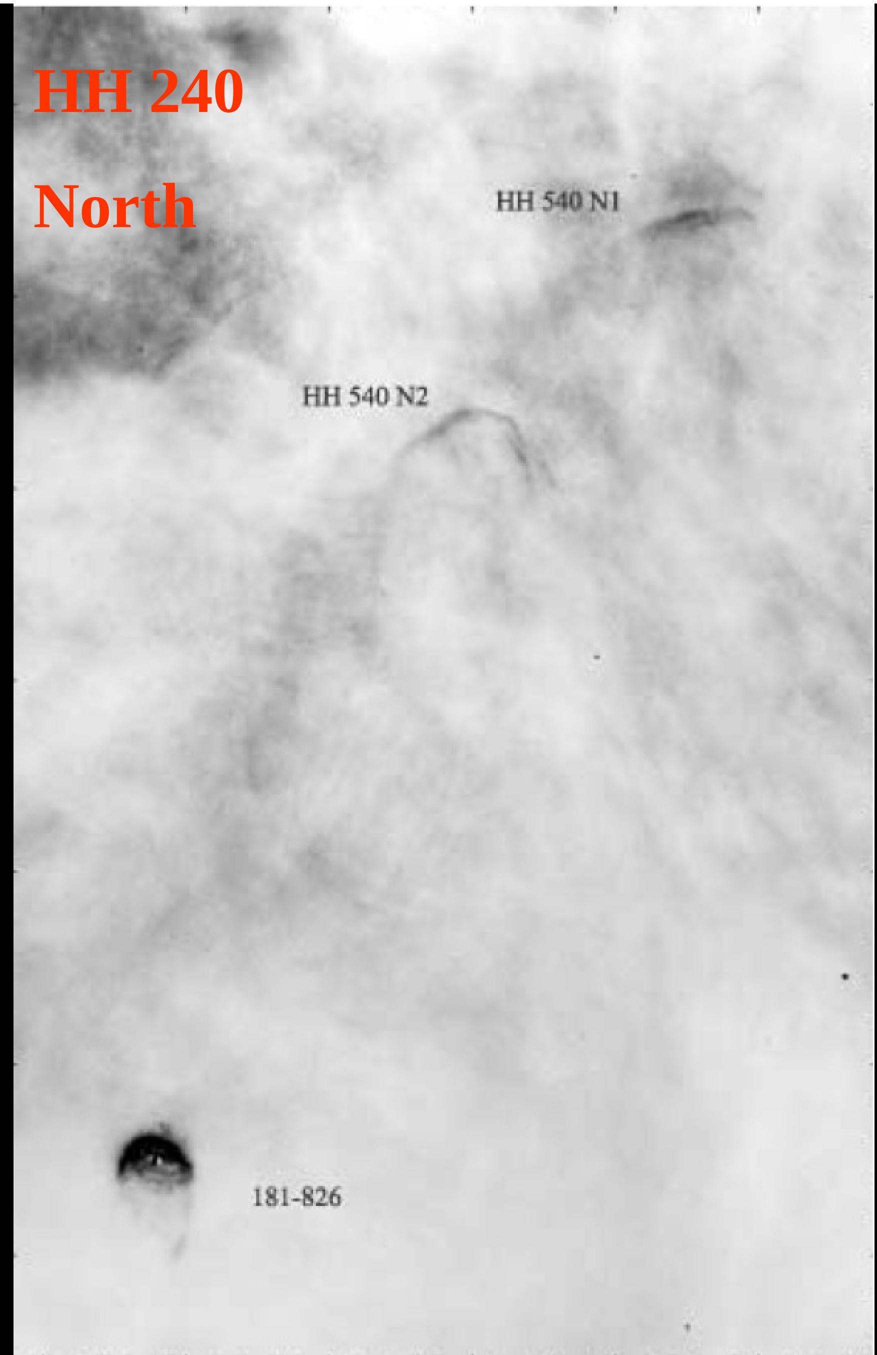
- **Near-UV penetration:**
  - UV penetration depth, N(H) ~ 2 to 4 x 10^{21} (cm^{-2})
    => gas /dust > 3 x ISM
  - R_V ~ 5 => grains are larger than ISM
    => grey
- **Chandra X-ray attenuation at 0.3 – 1 KeV**
  - Ionization front (flux & radius)
    => n_e = n(H), dM/dt ~ f n(H) c_{II}
  - Wind model => N(H)
  - Chandra => N(metals)
  - N(H) / N(metals) > 3 – 5 x ISM

The Beehive proplyd; HH 240 irradiated jet

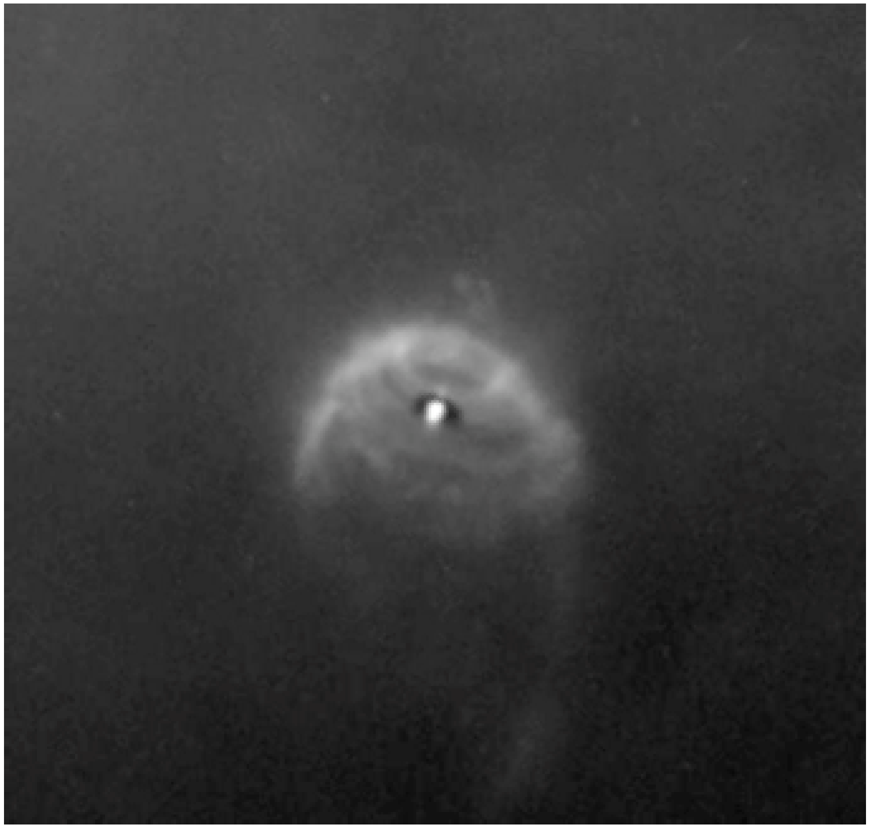


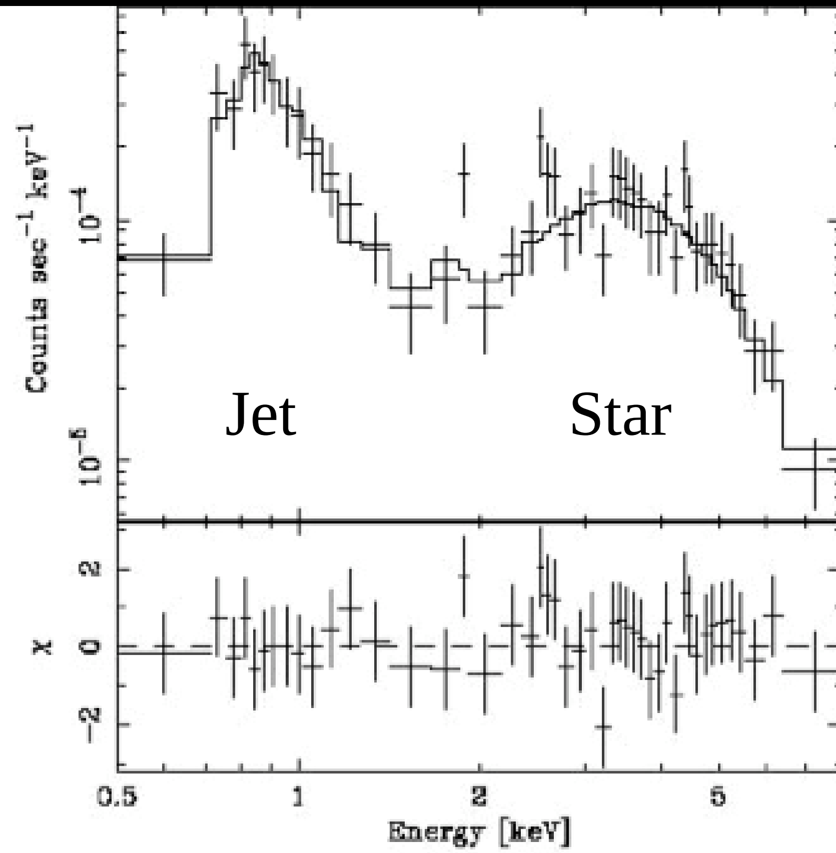
Bally et al. 2005


181-826
HH 540 B
HH 561
HH 540 A
HH 540 C
HH 240
South


HH 240
North
HH 540 N1
HH 540 N2
181-826

d181-825 “Beehive” proplyd Chandra COUP





1280 AU

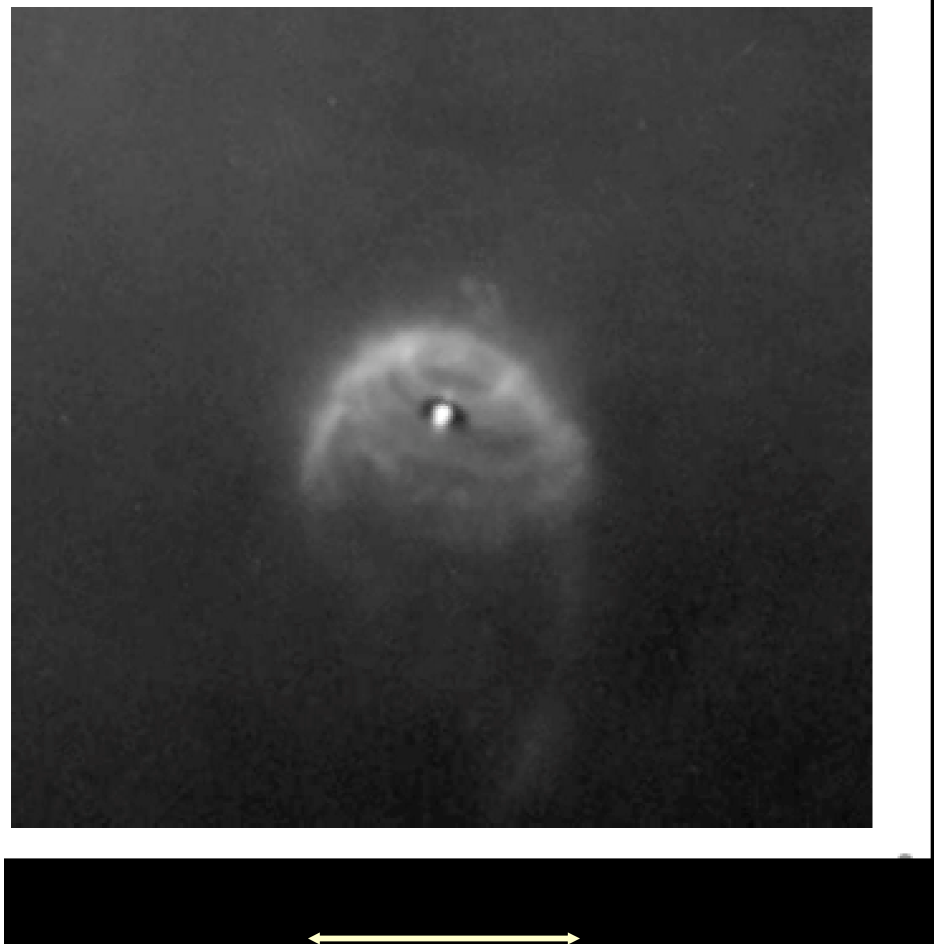
kT ~ 0.57 keV & 3.55 keV

N_H ~ 8 x 10^{20} cm^{-2} (soft)

N_H ~ 6 x 10^{22} cm^{-2} (hard)

(Kastner et al. 2005, ApJS, 160, 511)

d181-825 “Beehive” proplyd



X-ray absorption:

$N_H \sim 8 \times 10^{20}$ cm^{-2}
But, foreground $A_V \sim 1$ mag !

H-alpha:

$n_e(r_I) = 2.6 \times 10^4$ cm^{-3}
$dM/dt = 2.8 \times 10^{-7} M_o$ yr^{-1}

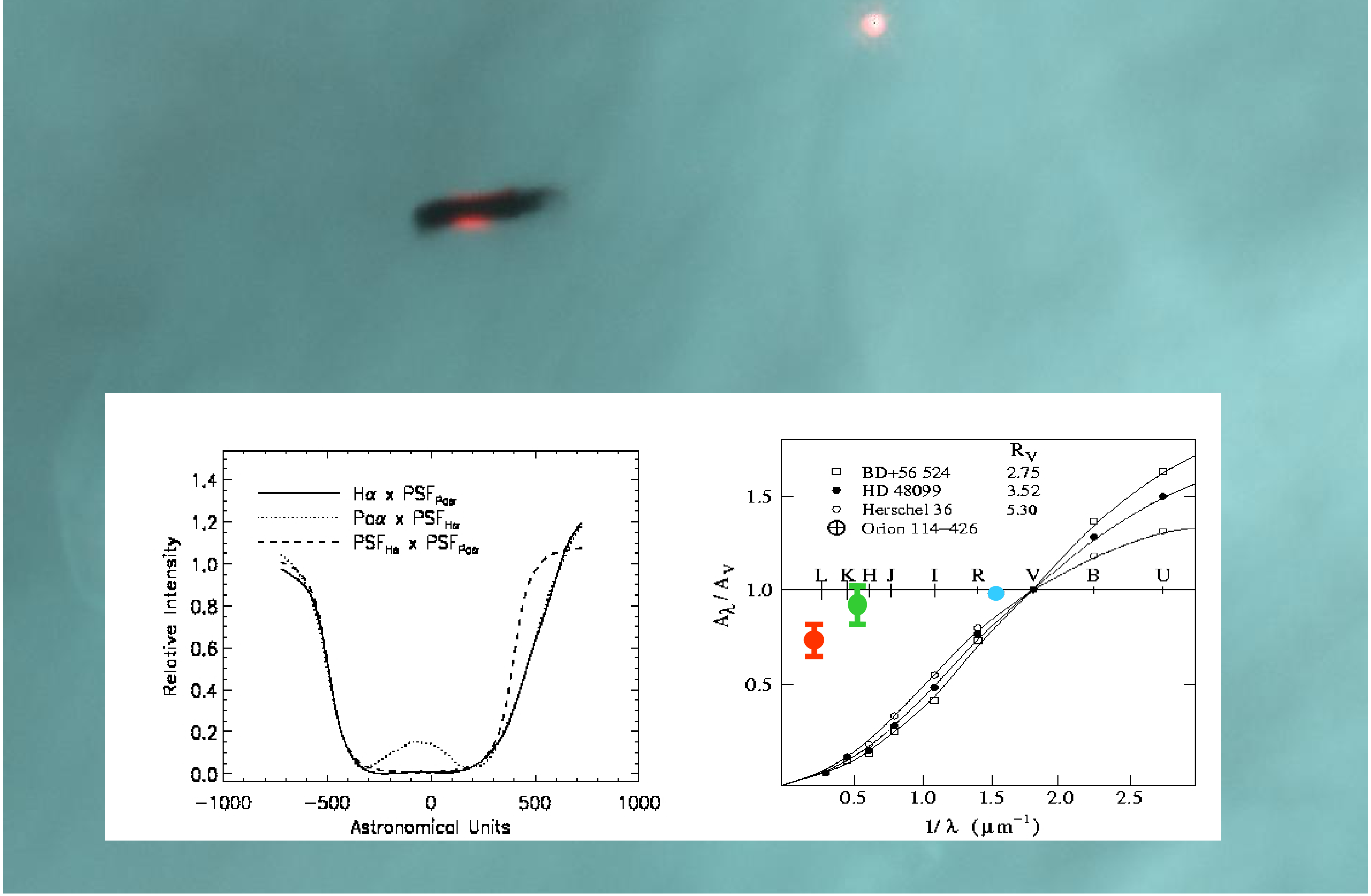
Neutral Column:
(from 50 AU, V = 3 km/s)

$N_H(R_I) = 2.2 \times 10^{21} V_3^{-1} r_{50}^{-1}$

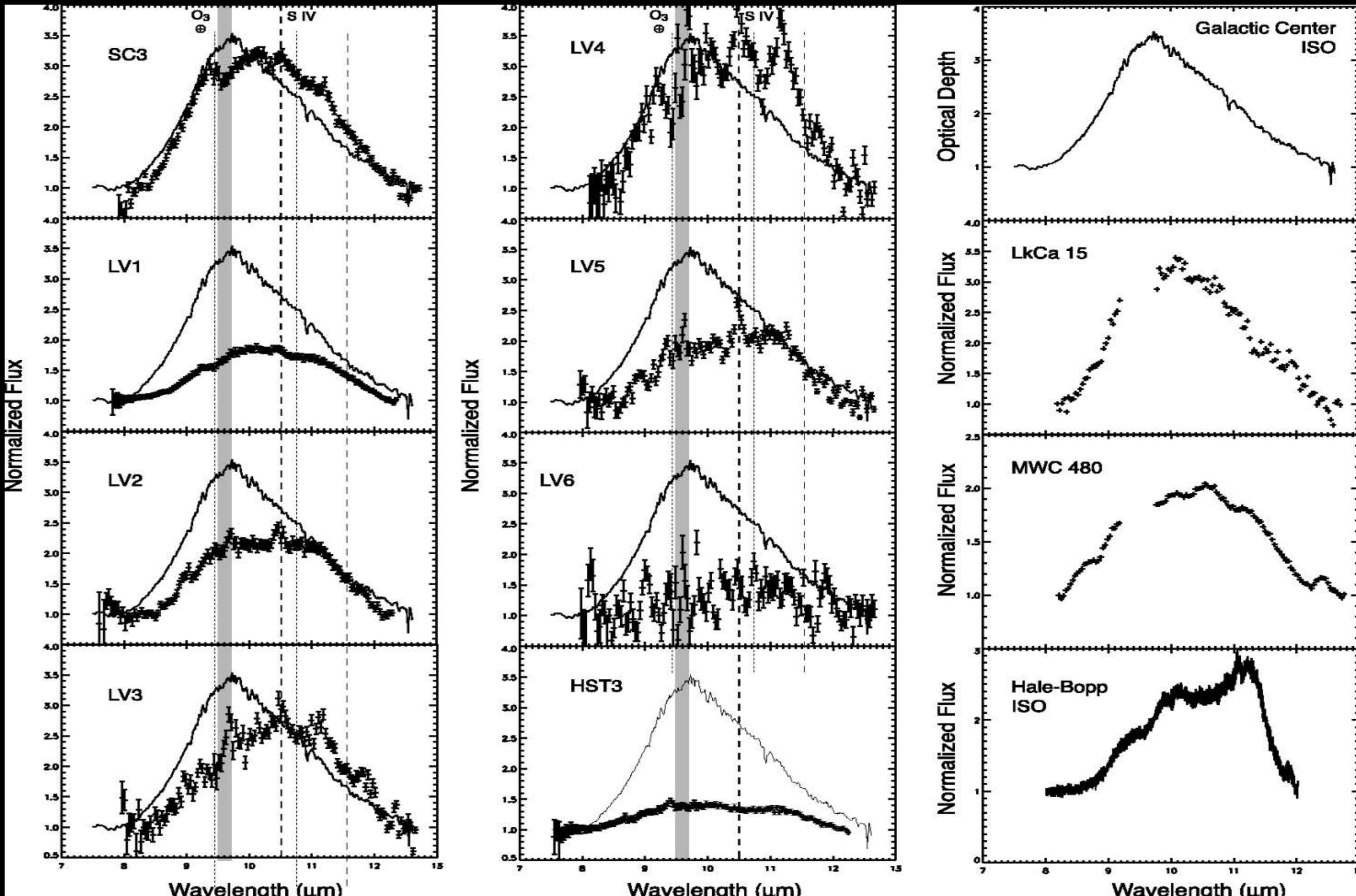
⇒Photo-ablation flow
metal depleted!

(Kastner et al. 2005, ApJS, 160, 511)

Evidence for growing grains: Orion 114-426 (Throop et al. 2001)



Growing grains: Si 10 μm feature (Shuping et al. 2006)



UV-Induced Planetesimal formation:

- **Problem: How do grains grow from**

  d < 100 cm (gravity un-important)

  to

  d ~ 1 - 100 km (gravity dominated)

  c.f. Weidenschilling, S. J., & Cuzzi, J. N. 1993, PP3

  - **Grains not “sticky”**
  - **Collisions tend to fragment & bounce**
  - **Head-wind => radial drift of solids**

    => fast growth

- **Grain growth + sedimentation + UV-photoablation**

⇒ Mass-loss from disk is metal depleted

⇒ Retained disk becomes metal-enriched

Gravitational instability => planetesimals

Youdin, A. N., & Shu, F. H. 2002, ApJ, 580, 494

Throop, H. B. & Bally, J, 2005, ApJ, 623, L149

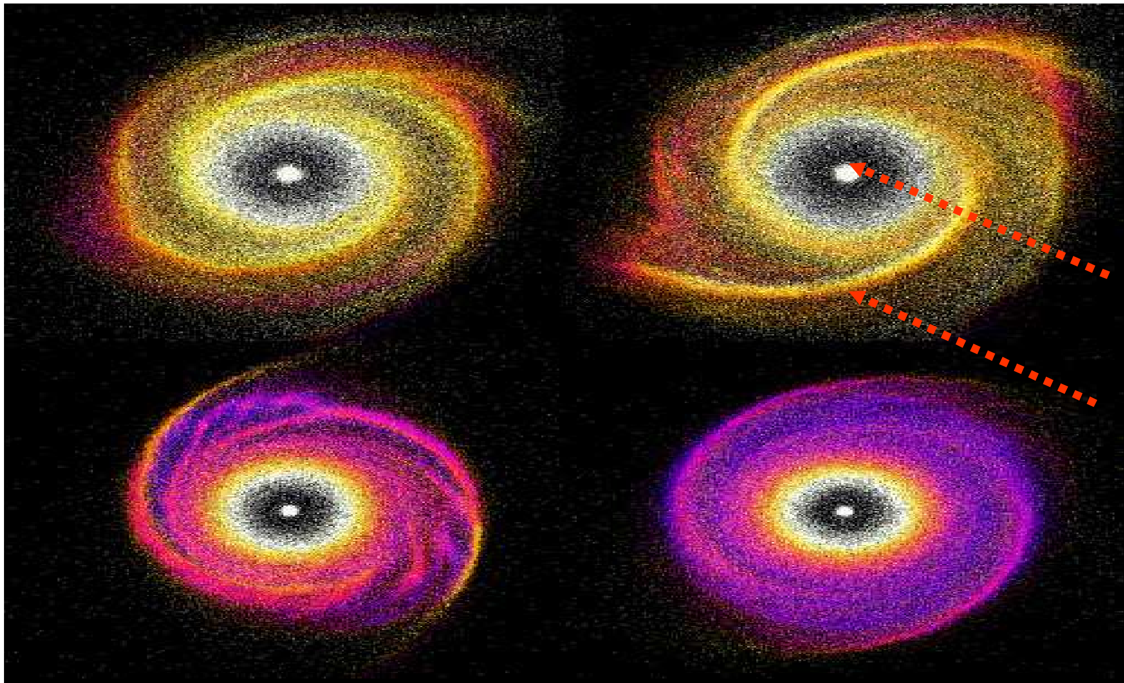
UV => Fast Growth of Planetesimals:

Grain growth => Solids settle to mid-plane
UV => Remove dust depleted gas
=> High metallicity in mid-plane
Gravity => Instability
=> 1 - 100 km planetesimals

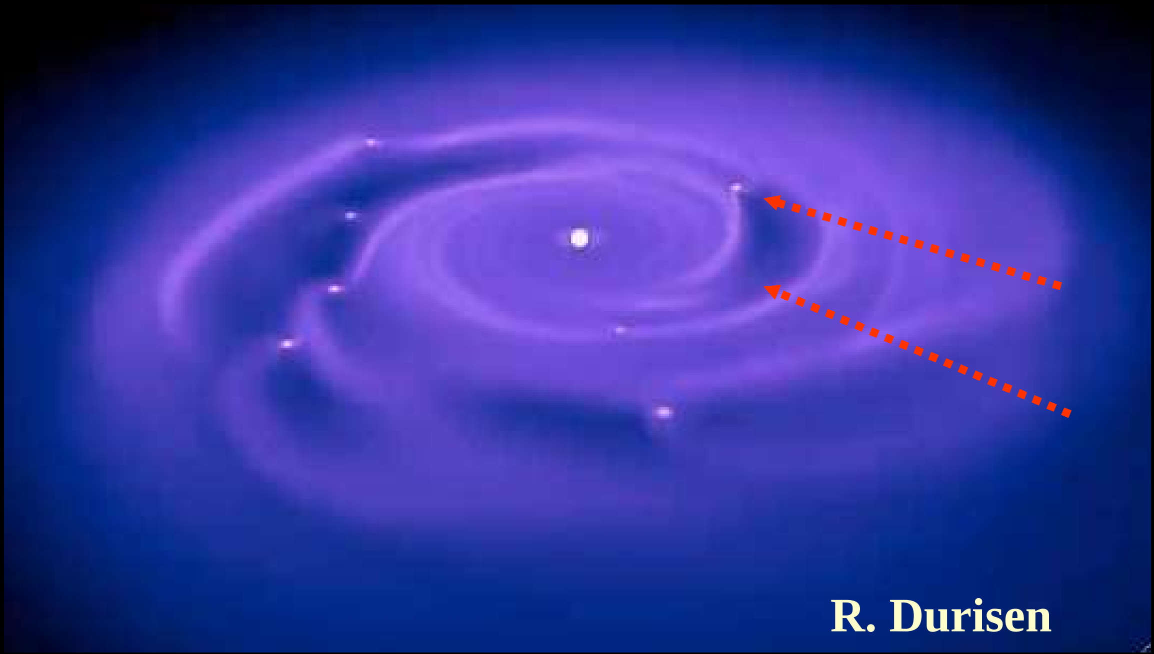
- Fast Formation of 1 to 100 km planetesimals

Throop & Bally et al. 05

What will ALMA see?



NASA / NAI



R. Durisen

Magnetospheric gaps?

Spiral structure?

Composition gradients?

Heavy organics?

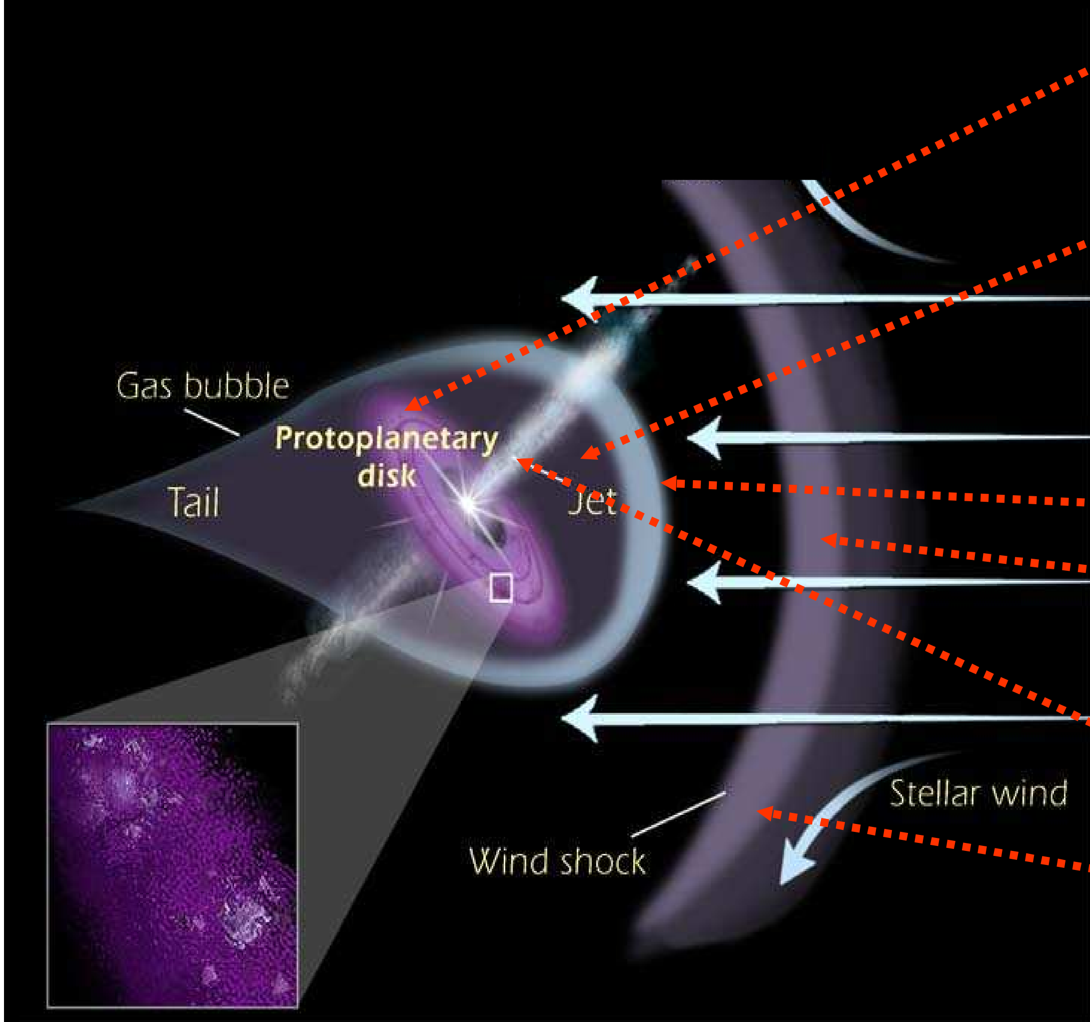
Ice lines?

Accreting protoplanets ?

Planetary gaps?

Magnetic fields?

What will ALMA see?



Growing grains &
Proto-planetary gravel?

Photo-dissociation
products? (e.g. CI &
molecular ions)

Shock in neutrals & in
Plasma ?

Jets & disk winds ?

f-f, recombination lines ?

Possible ALMA Projects:

Solicit Legacy programs:

Large, comprehensive surveys

Data to go public immediately

Surveys of Orion, Carina, M8, M16, M17, W40, π Sco…

Disk radii, radial velocity, velocity dispersion, etc.

continuum & line fluxes as functions of location, environment, age

Radial gradients: dust, gas, τ, composition

Surface density: $\Sigma(r) \sim r^{-\alpha}$ What is α ?

Composition:

The organic forest => chemical evolution

Ices => gas transitions (H_2O, NH_3, CH_3OH, …)

Velocity fields => dynamical YSO masses

Structure: Gaps, spirals, accretion-heated protoplanets

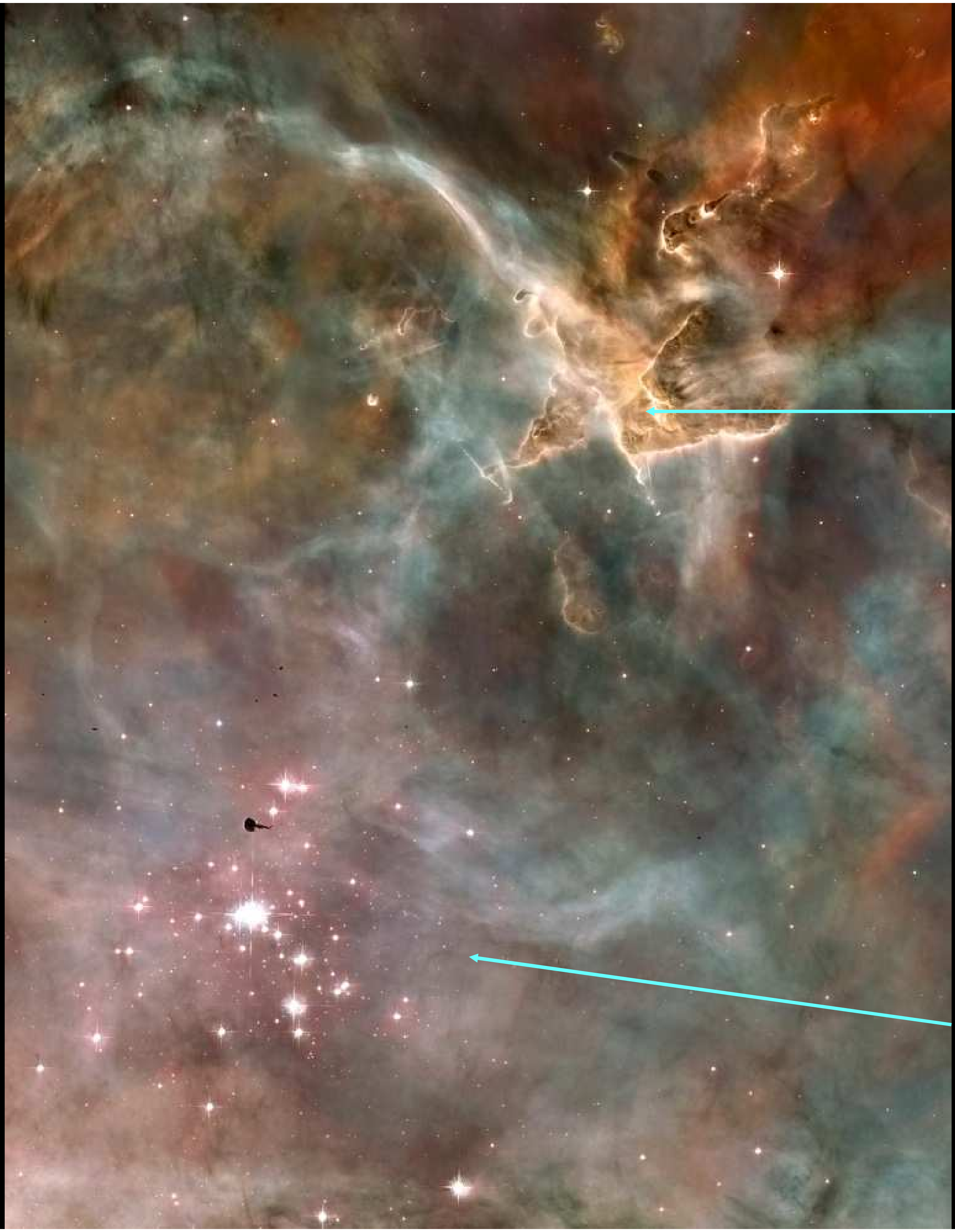
Externally ionized protoplanets & disk features

(late-phase proplyds)

Photo-ablation flows: structure, velocity => mass loss

Magnetic fields: polarized dust, Zeeman in CN, SO, …

η Carinae Nebula: Trumpler 14 region

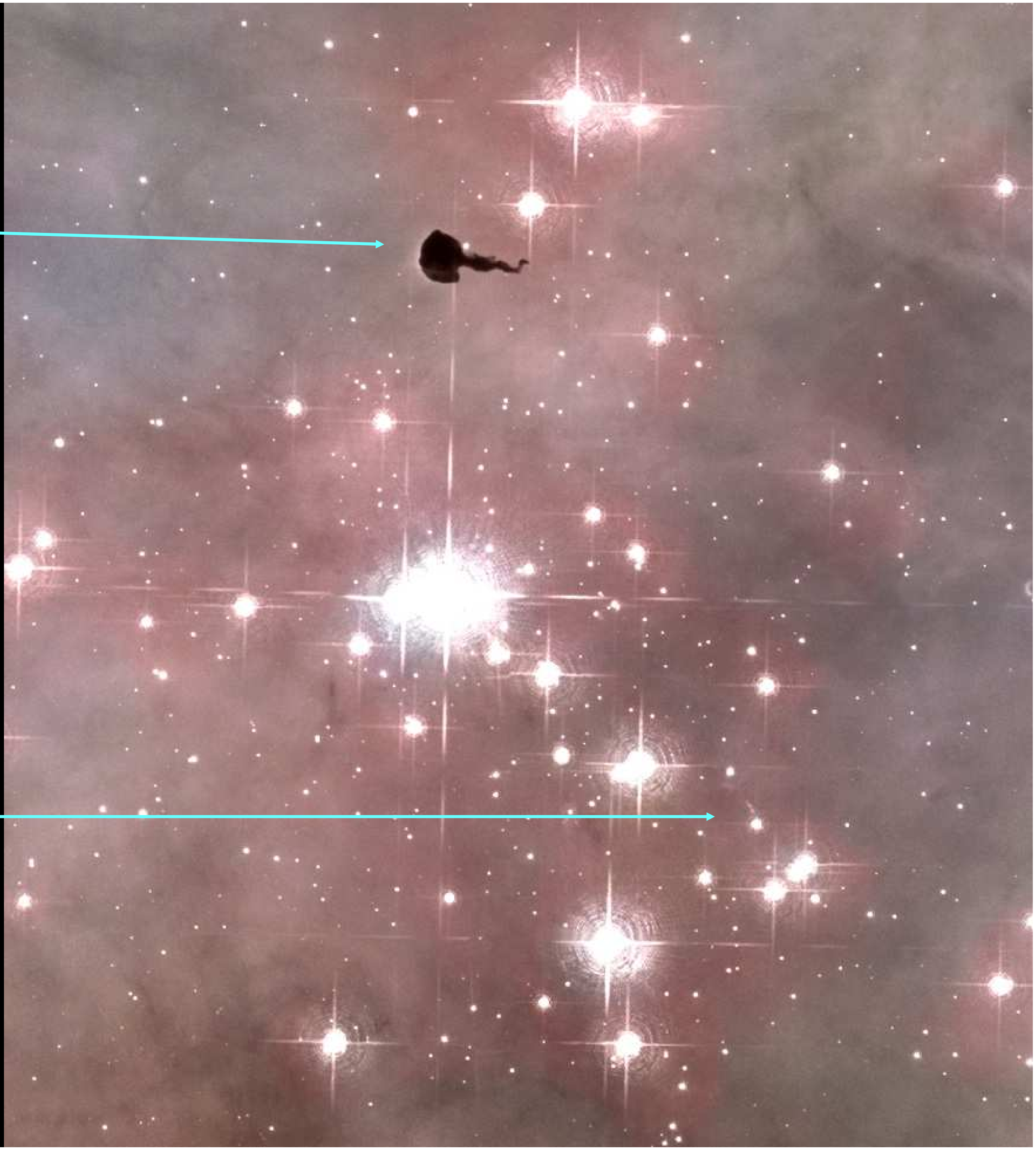


Pillars with jets

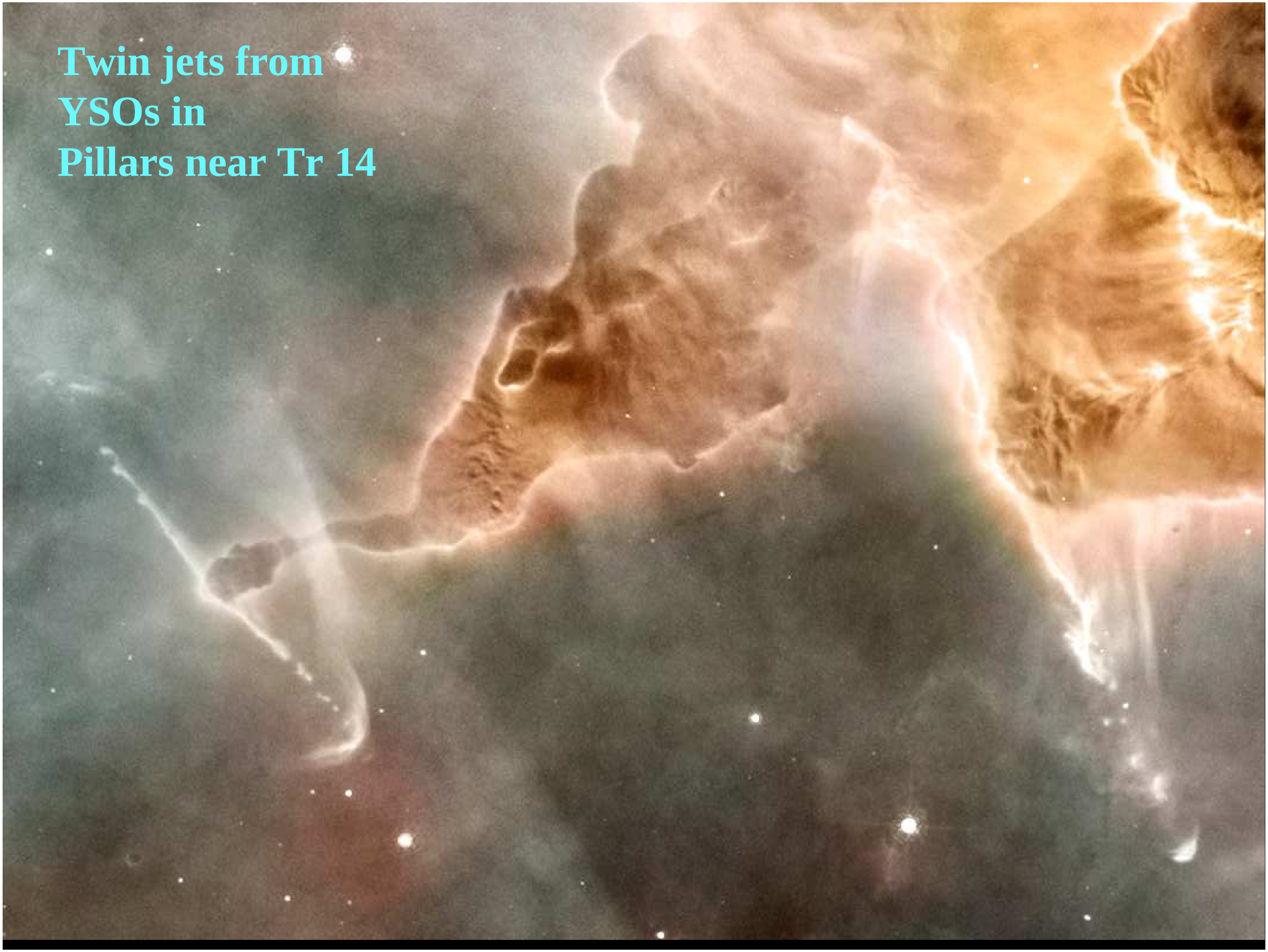
Tr 14 cluster
(< 3 Myr)

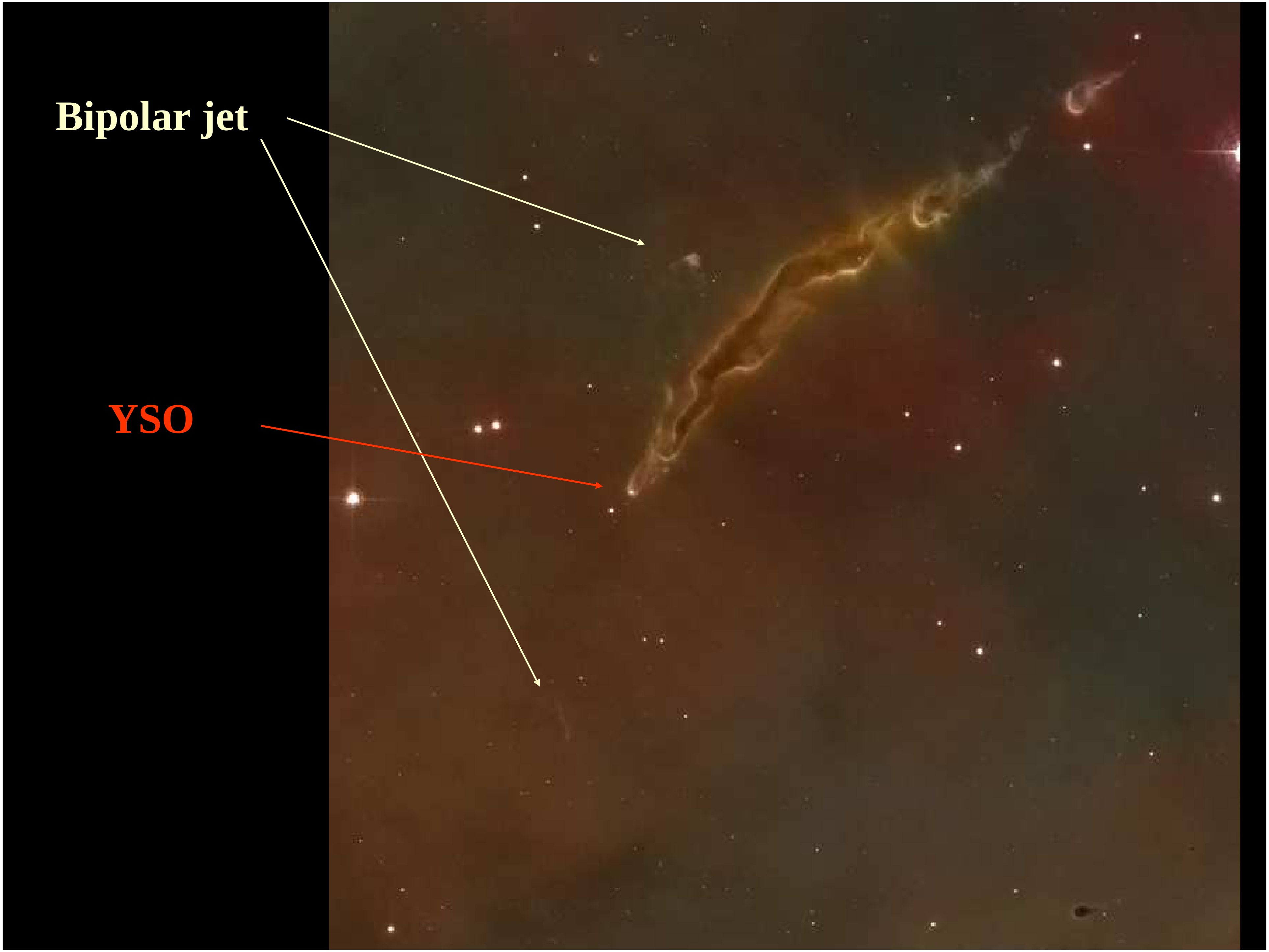
Trumpler 14

Dark globule:
faces η Car



Jet ?

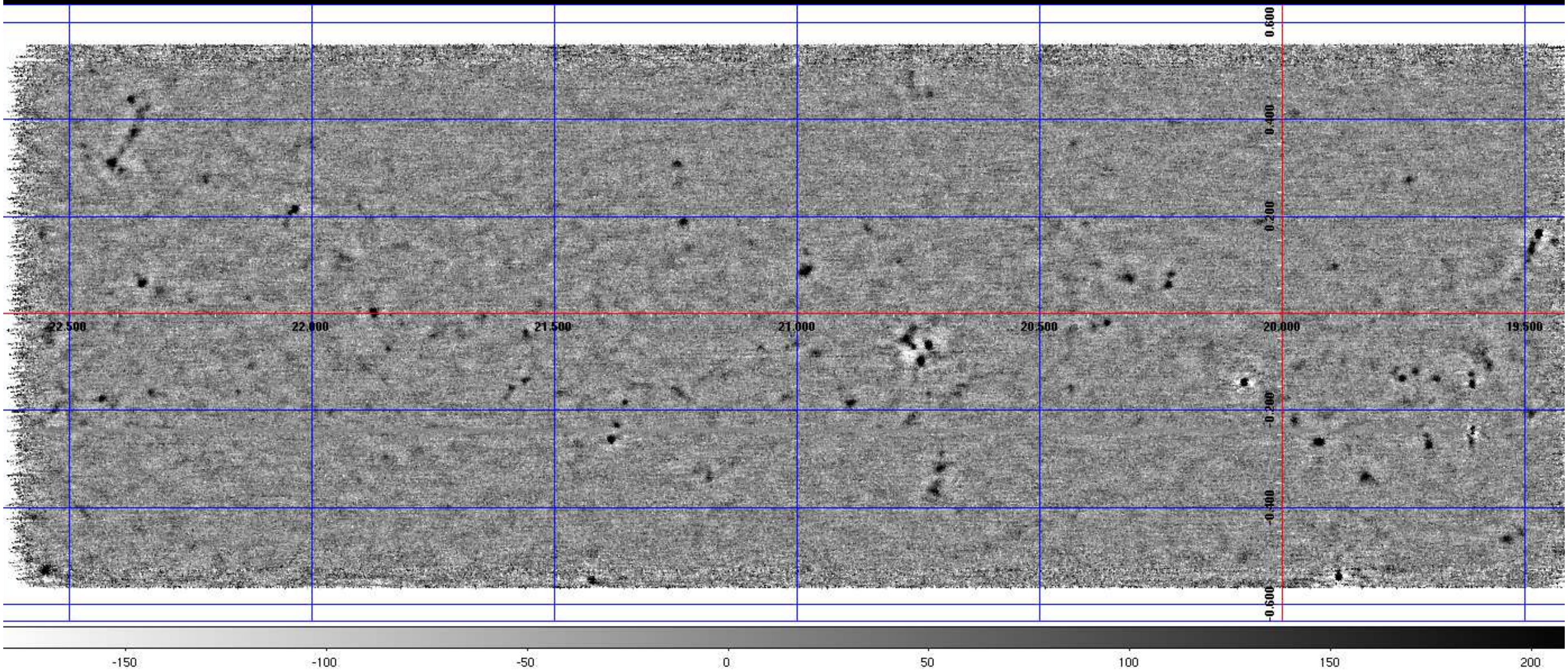

Twin jets from
YSOs in
Pillars near Tr 14

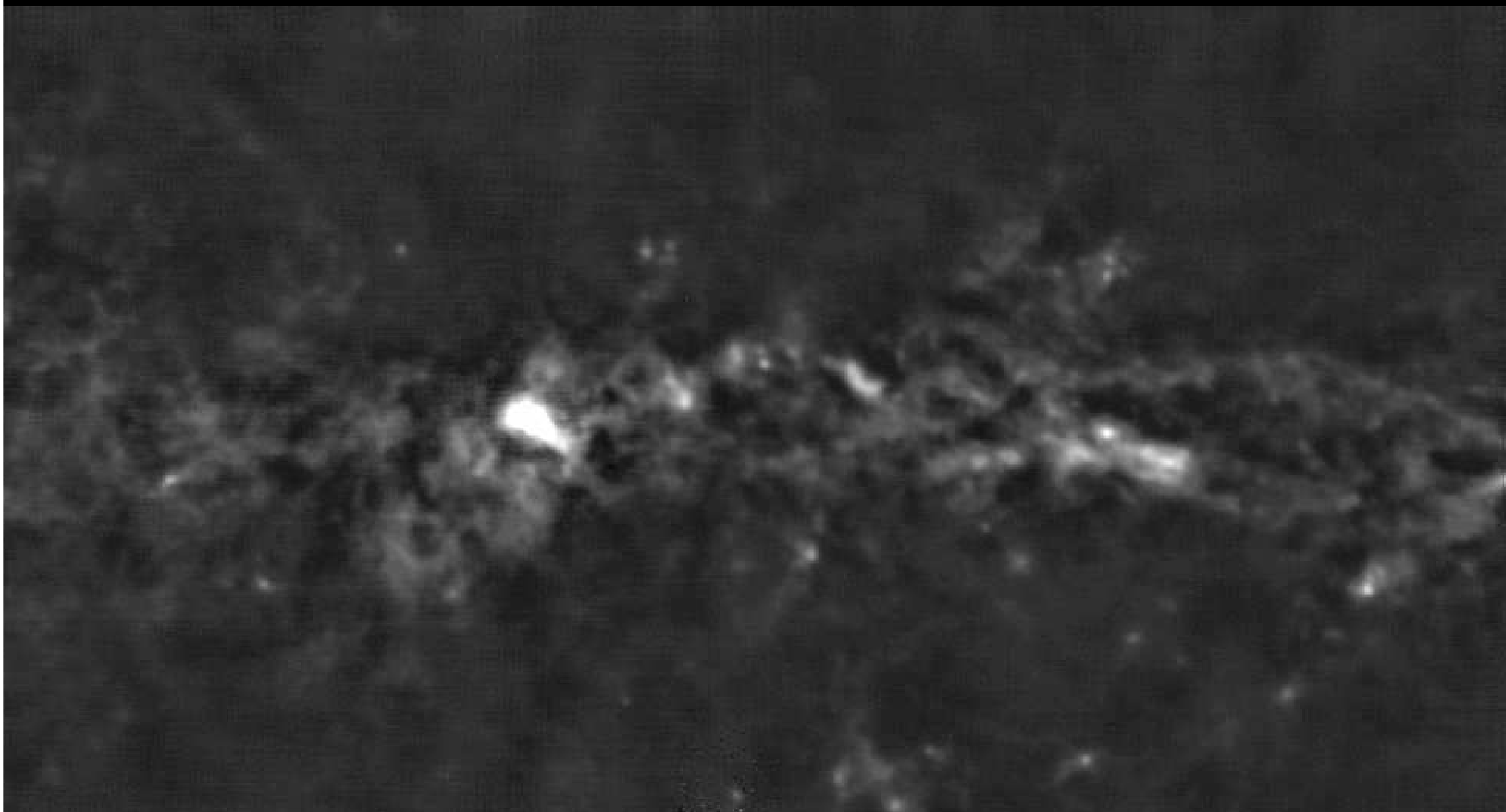

Bipolar jet
YSO

The Bolocam 1.1 mm survey (as of Sept 2006)

- ~ 90 square degrees of the Galactic Plane
- 5,000 dense cloud cores (> 20 mJy / beam)
- Best tracer of massive star-forming cores

Single 45 min scan of 3 x 1 deg field in Plane (100 mJy / beam)





Conclusions

- Most Stars from in dense clusters, near massive stars
  - Most planetary systems likely form in OB associations
- ALMA   Resolution to 0.005” (band 10 @ B = 14 km)
  - Ionized photo-ablation flows, wind, & jets
    - f-f, recombination lines, dust
      - Vradial, n, grain emissivity, mass-loss rates
  - Neutral flow (proplyd body)
    - Dust, CI, CO, HCO+
      - V_{radial}, shocks, flow geometry
  - Disks & Planets: Velocity field, Structure, Composition
    - Dust, molecular lines, Zeeman in CN
      - Velocity field and Structure: radii, spirals, gaps)
    - Grain properties, polarization, ices, ions vs. neutrals
    - Giant protoplanets?
- Emphasize Legacy Surveys rather than GO programs


The End

[redacted]