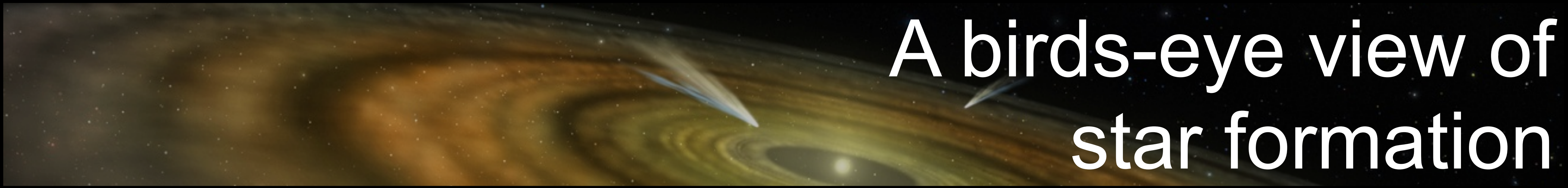
School of Physics and Astronomy
FACULTY OF ENGINEERING AND PHYSICAL SCIENCES

DARA Unit 1
Star and Planet Formation

Dr Catherine Walsh
c.walsh1@leeds.ac.uk

Section 1
Star Formation

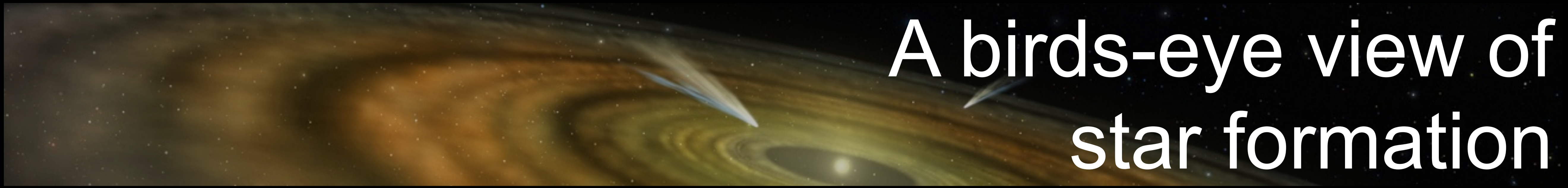


A birds-eye view of star formation

NGC 602
(SMC)

X-rays
Infrared
Optical

Images: X-ray: NASA/CXC/Univ.Potsdam/L.Oskinova et al; Optical: NASA/STScI; Infrared: NASA/JPL-Caltech

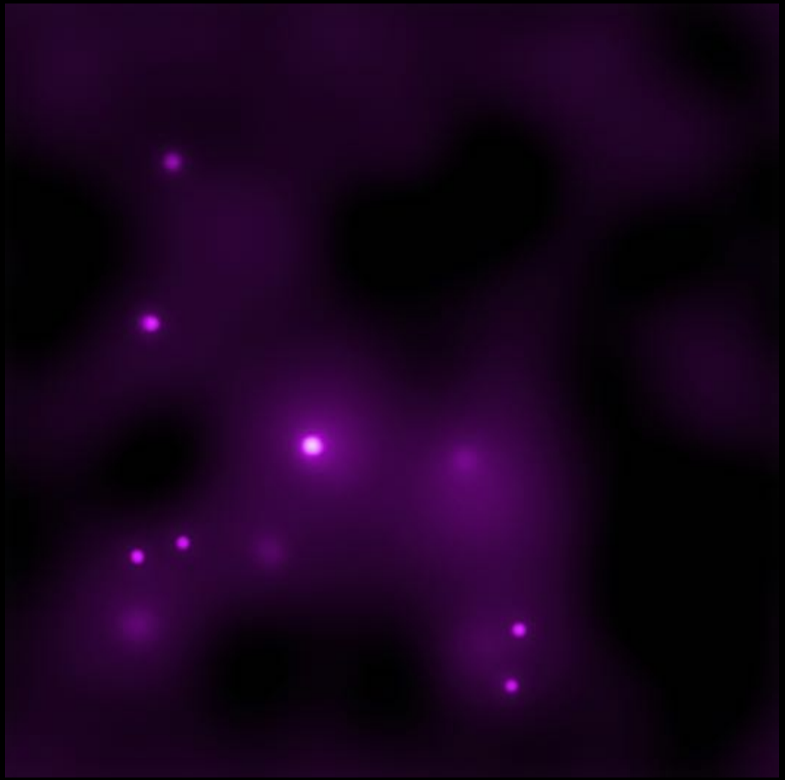


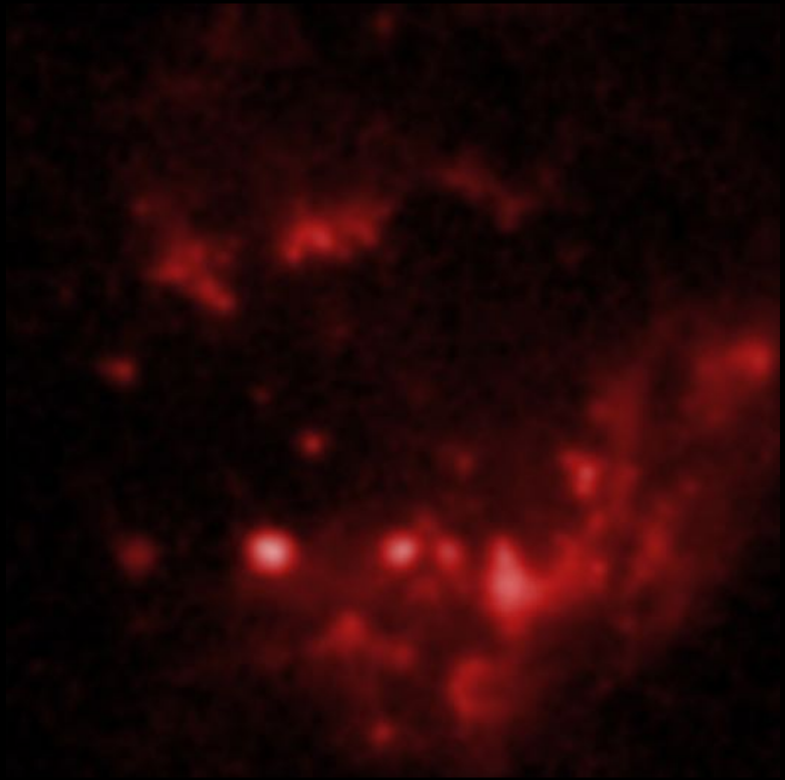
A birds-eye view of star formation

NGC 602
(SMC)

Optical
Hubble

X-rays
Chandra





Infrared
Spitzer

Images: X-ray: NASA/CXC/Univ.Potsdam/L.Oskinova et al; Optical: NASA/STScI; Infrared: NASA/JPL-Caltech

Molecular clouds

Barnard 68

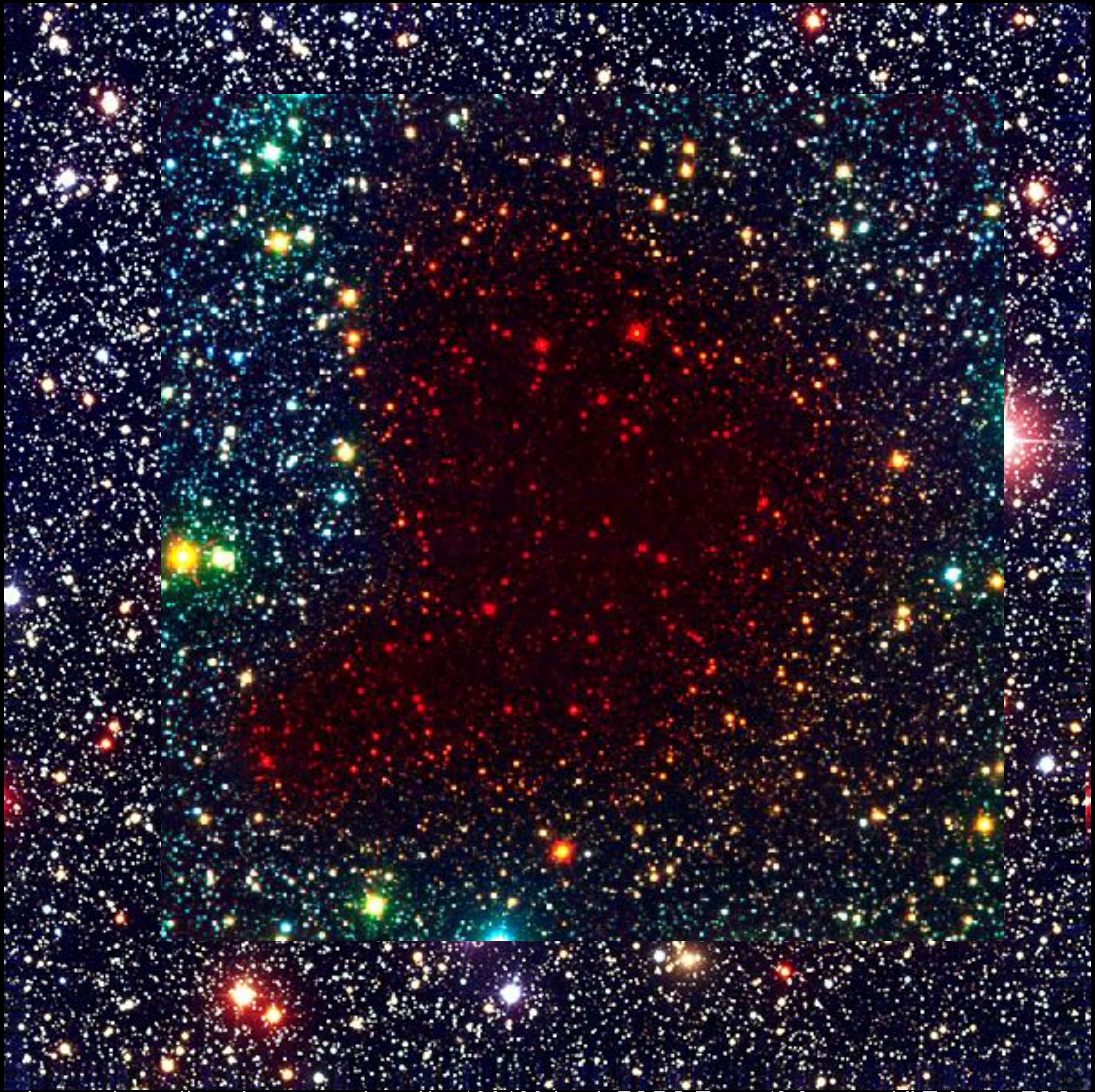
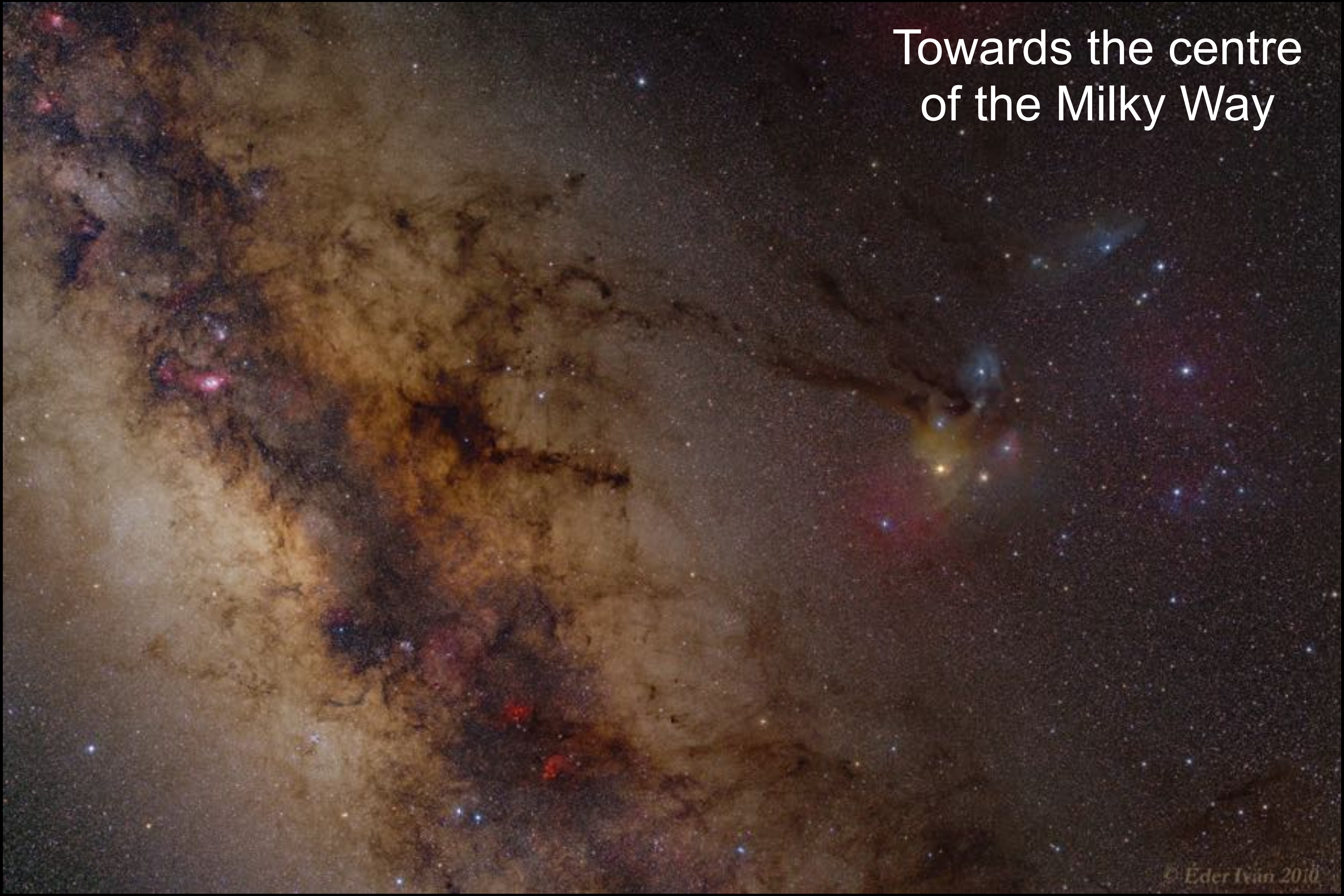


Image: https://apod.nasa.gov/apod/ap120129.html; FORS Team (8.2-meter VLT Antu); ESO

Molecular clouds are found throughout galaxies



Towards the centre of the Milky Way

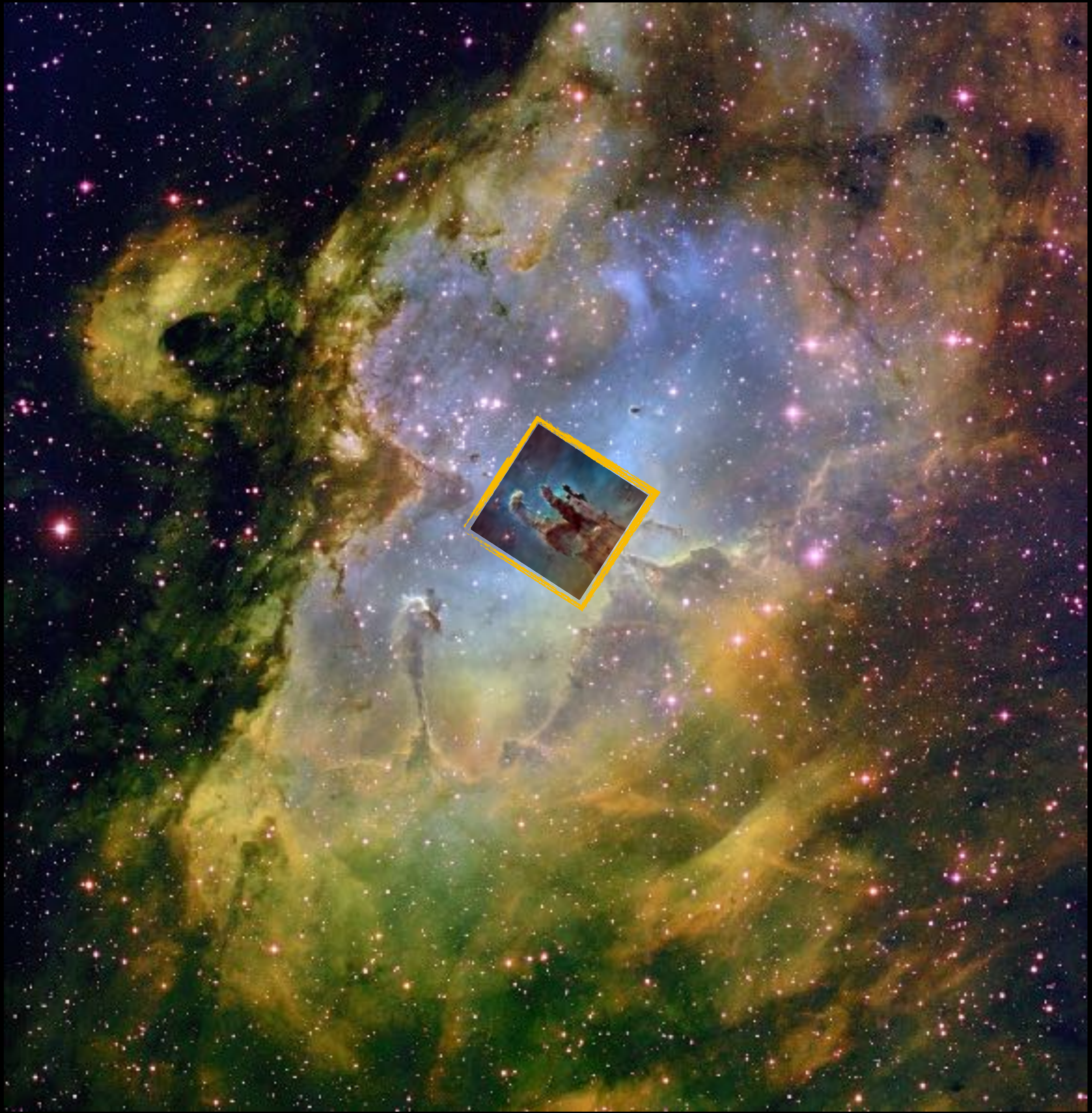
Image: https://apod.nasa.gov/apod/ap120106.html; I. Eder

Molecular clouds are found throughout galaxies

Thackeray's globules
in IC 2944

Image: NASA/ESA and The Hubble Heritage Team (STScI/AURA)

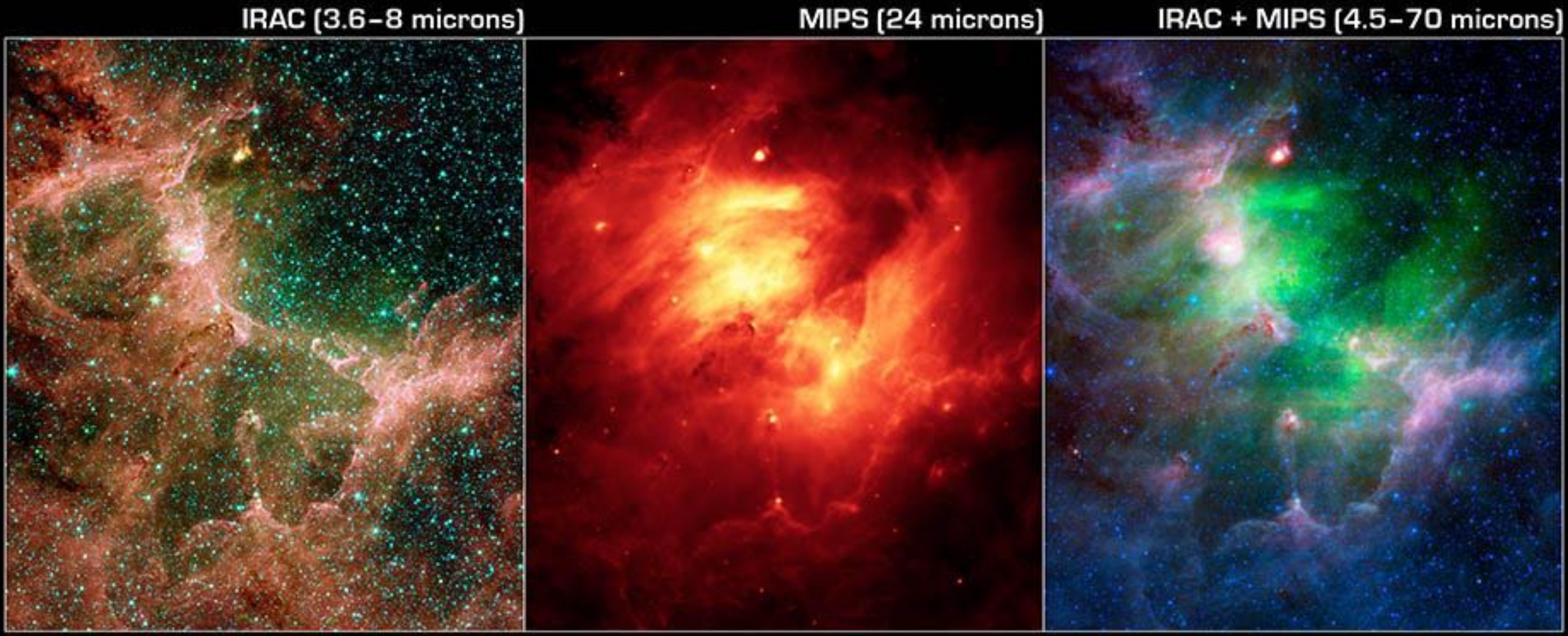
Molecular clouds are found throughout galaxies



Pillars of Creation in
the Eagle Nebula
(M16)

Images: T. A. Rector & B. A. Wolpa (NOAO/AURA); NASA, ESA and the Hubble Heritage Team (STScI/AURA)

Molecular clouds at different wavelengths



IRAC (3.6–8 microns)

MIPS (24 microns)

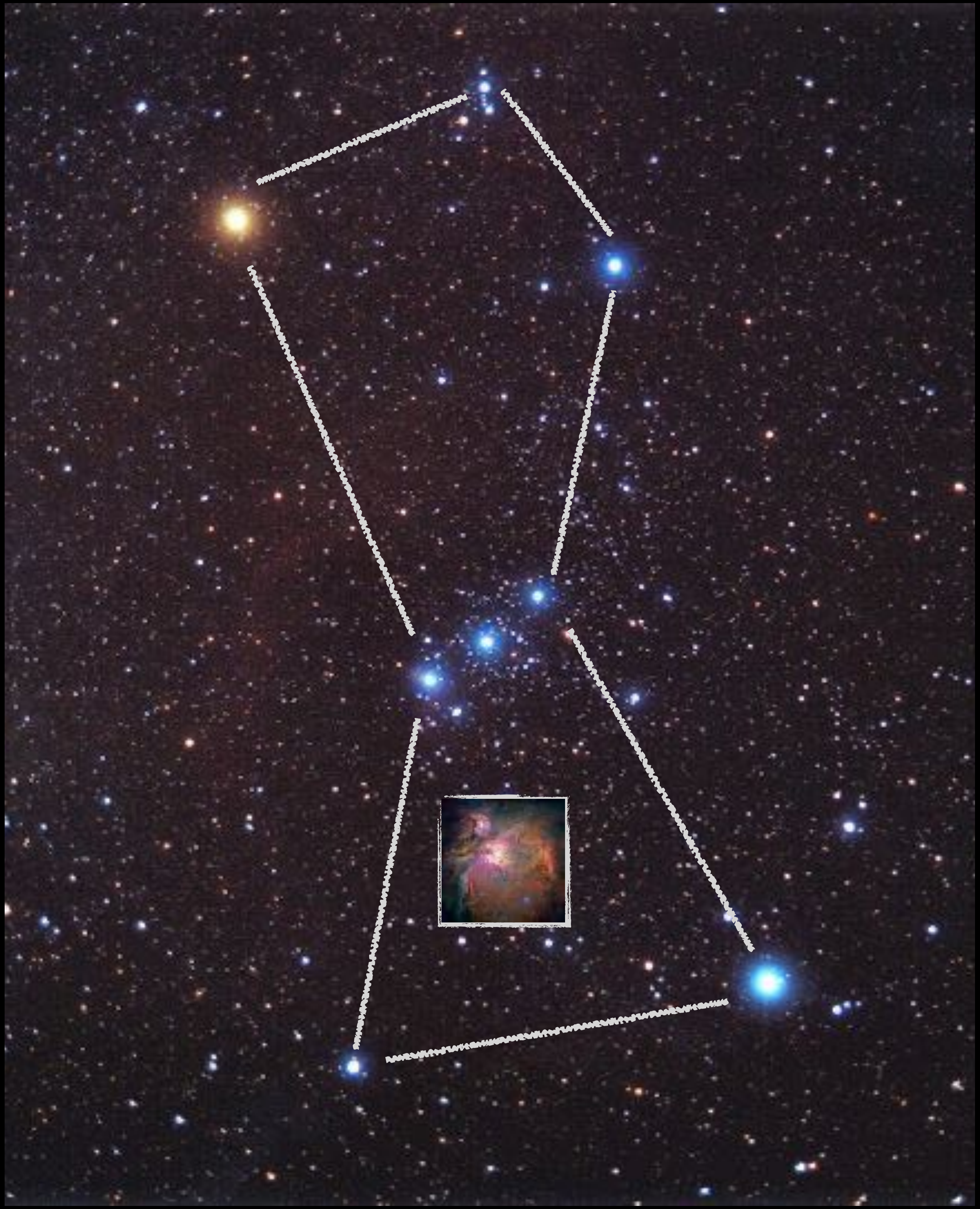
IRAC + MIPS (4.5–70 microns)

Many Colors of the Eagle Nebula (M16) **Spitzer Space Telescope • IRAC • MIPS**

NASA / JPL-Caltech / N. Flagey (SSC/Caltech) & the MIPSGAL Science Team ssc2007-01c

Massive-star forming regions

The Orion Nebula (M42)



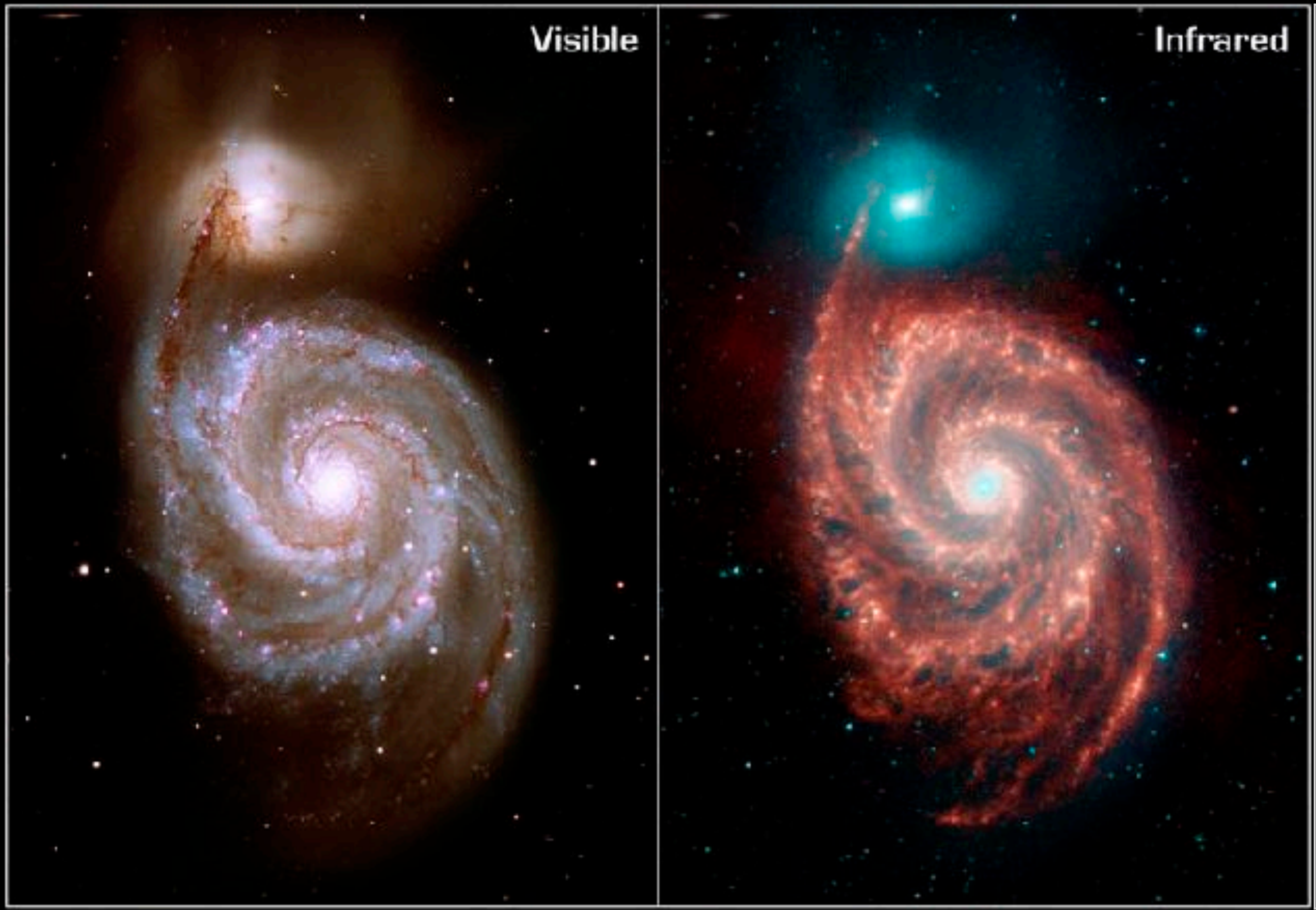
Images: NASA, ESA, M. Robberto (STScI/ESA) and the HST Orion Treasury Project Team; https://apod.nasa.gov/apod/ap030207.html; M. Spinelli

Star formation in other galaxies

The Whirlpool Galaxy
(M51)

Image: NASA, ESA, S. Beckwith (STScI) and the Hubble Heritage Team (STScI/AURA)

Star formation in other galaxies

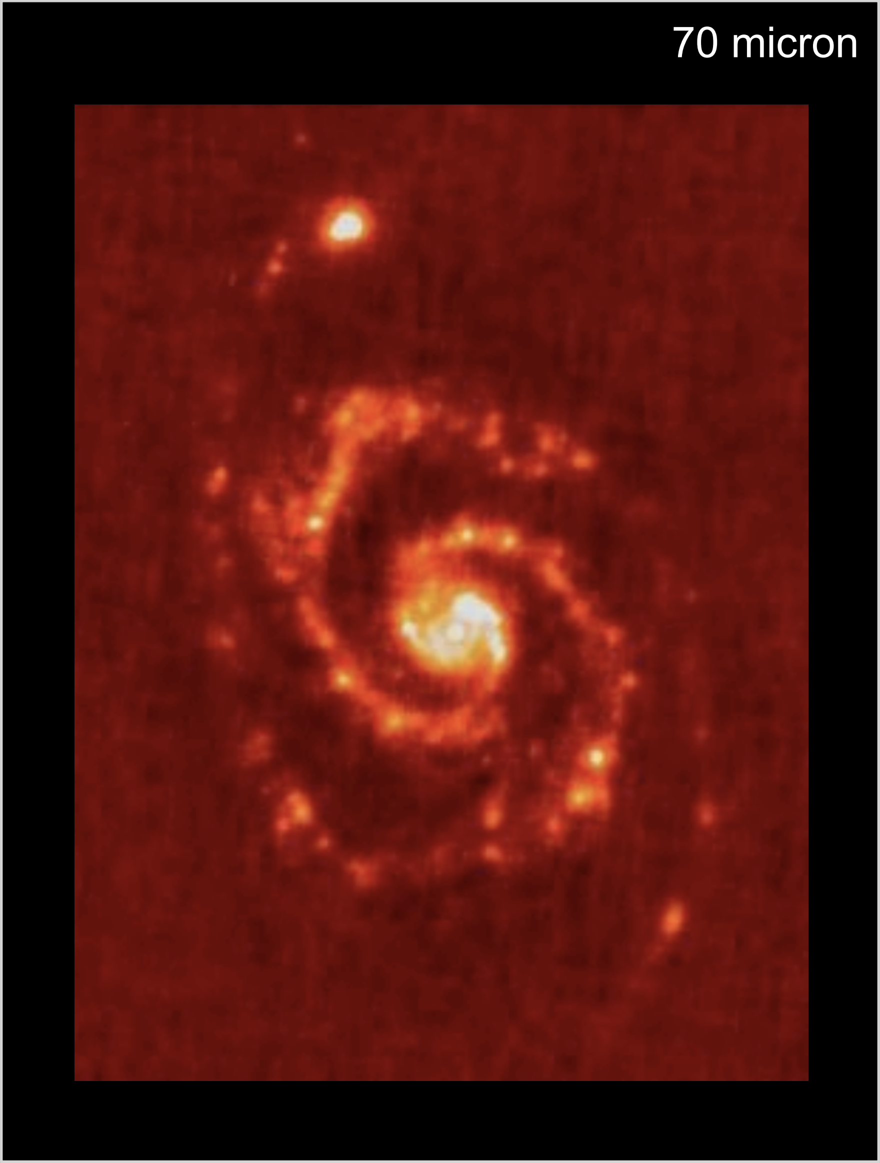


Spiral Galaxy M51 ("Whirlpool Galaxy")

NASA / JPL-Caltech / R. Kennicutt (Univ. of Arizona)

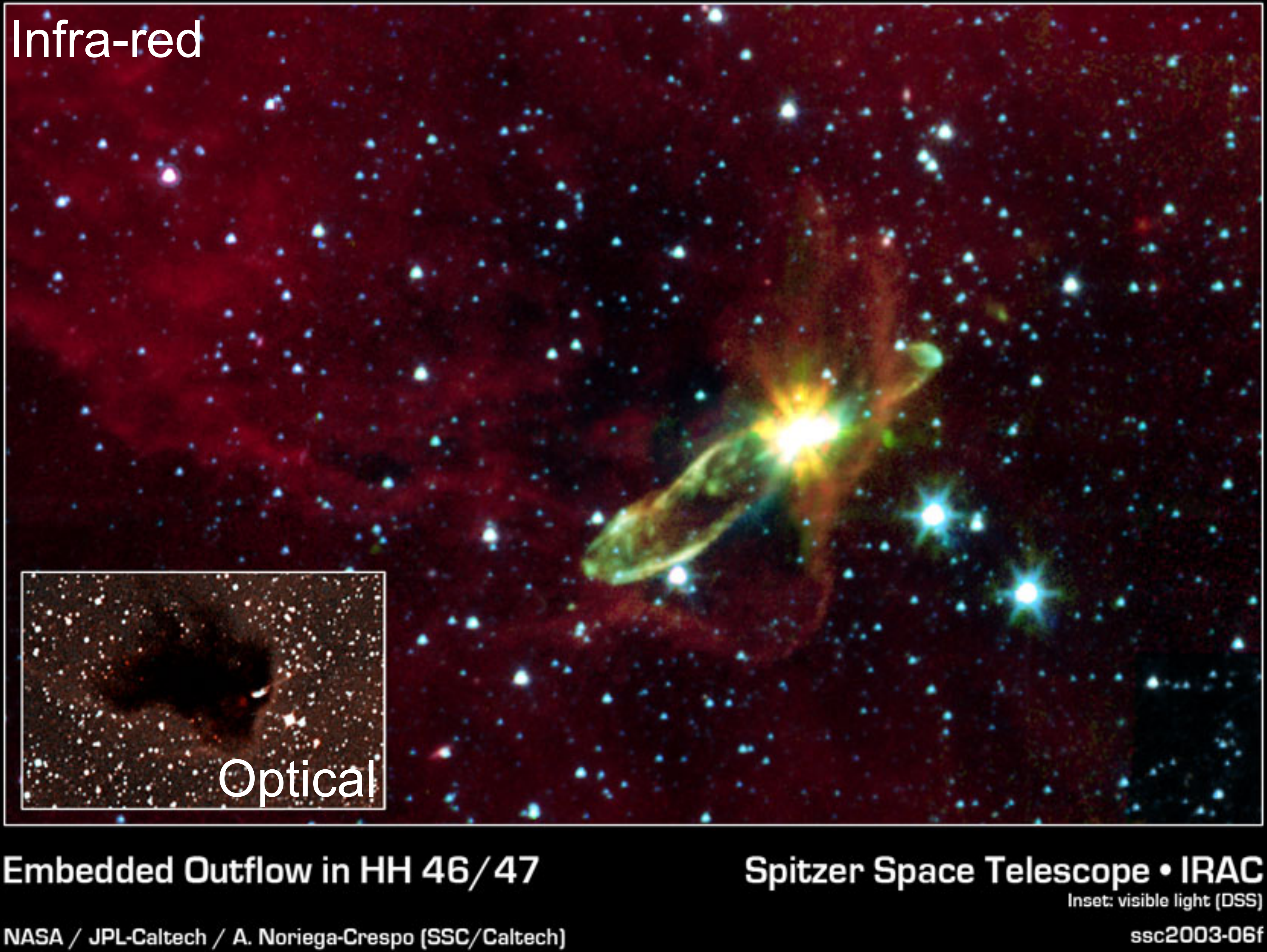
Spitzer Space Telescope • IRAC

ssc2004-19a



Herschel Space Observatory - PACS
ESA & the PACS Consortium

Embedded forming stars



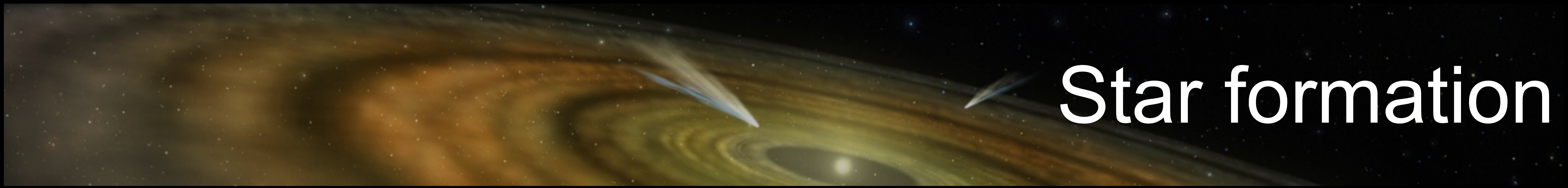
Embedded Outflow in HH 46/47

Spitzer Space Telescope • IRAC

Inset: visible light (DSS)

NASA / JPL-Caltech / A. Noriega-Crespo (SSC/Caltech)

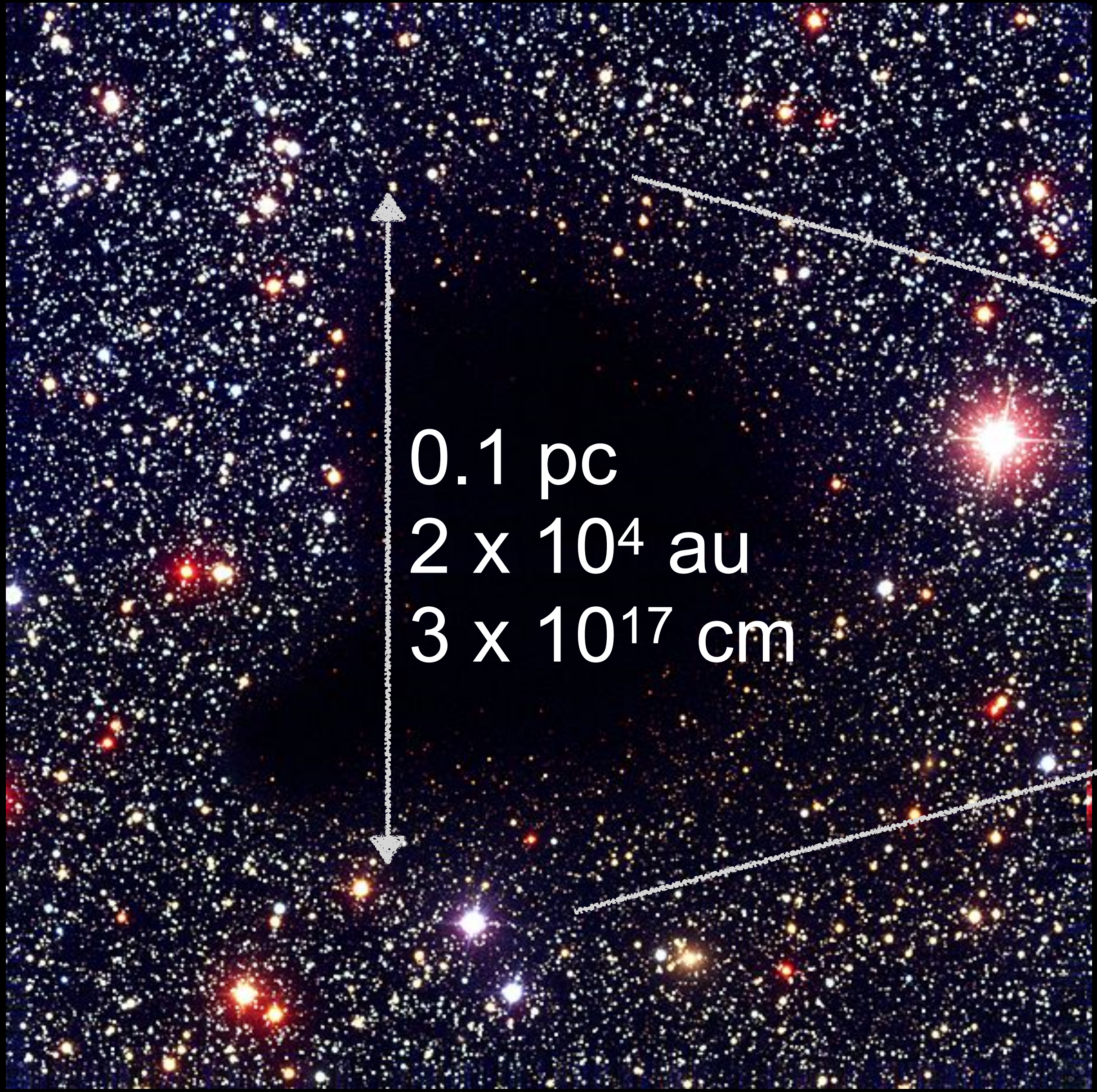
ssc2003-06f



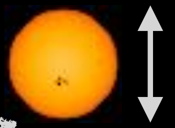
Star formation

Barnard 68

Sun

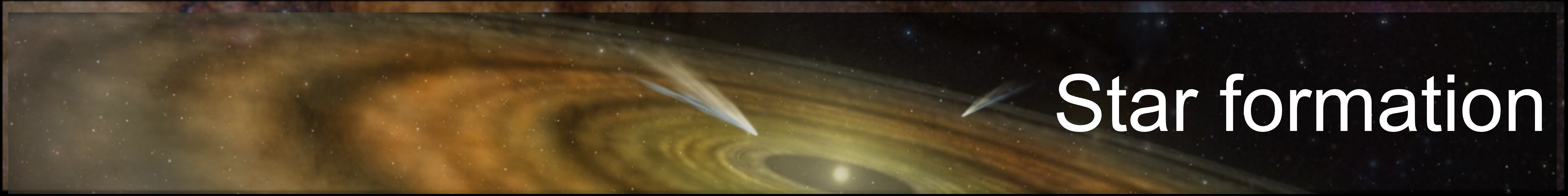


When stars form, collapse from ~ 20,000 au to ~ 1/200 au occurs: 6-7 orders of magnitude



The density increases from ~ 10^4 cm^{-3} to ~ 10^{26} cm^{-3} => 22 orders of magnitude

Images: Image: https://apod.nasa.gov/apod/ap120129.html; FORS Team (8.2-meter VLT Antu); ESO; NASA/SDO

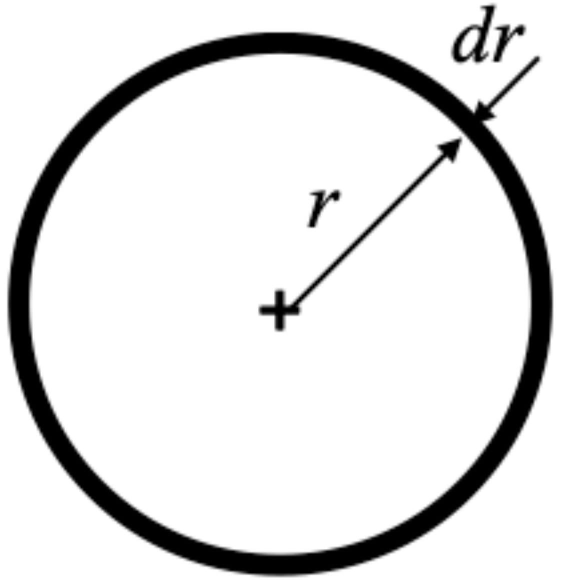


Star formation

Consider a cloud that maintains equilibrium through the forces of self-gravity and thermal pressure only.

For a shell of mass $dM(r)$ at radius r,

$$4\pi r^2\, dP(r) = -\frac{GM(r)\, dM(r)}{r^2}$$



A thin spherical shell at a radius, r, and width, dr

The sphere has a volume, $V(r) = \frac{4}{3}\pi r^3$

Substitution gives,

$$3V(r)\, dP(r) = -\frac{GM(r)\, dM(r)}{r}$$

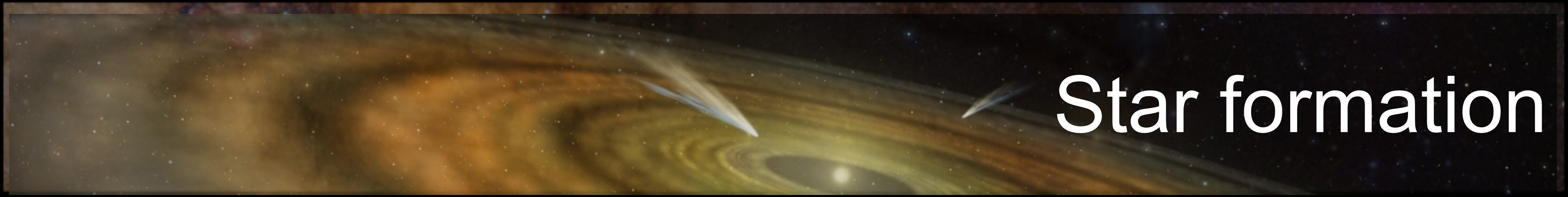
Star formation

Integrating over both sides results in the following expression:

$$\boxed{3V_C P_S = 2U + \Omega}$$

Here, V_C is the cloud volume, P_S is the external pressure, U is the total kinetic energy of the cloud, and Ω is the total gravitational potential energy of the cloud.

This expression only takes into consideration gravity and internal pressure; however, other forces can be included, e.g., magnetic fields.



Star formation

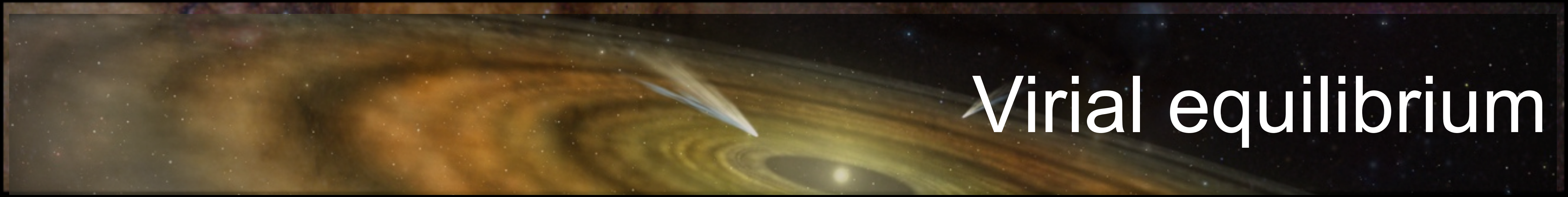
Now, to simplify the collapse criterion, consider a cloud with

- a constant density, ρ_C
- a constant pressure, P_C, up to R_C
- and zero external (surface) pressure, $P_S = 0$

Then, we have,

$$\boxed{2U + \Omega = 0}$$

This is the VIRIAL EQUATION.

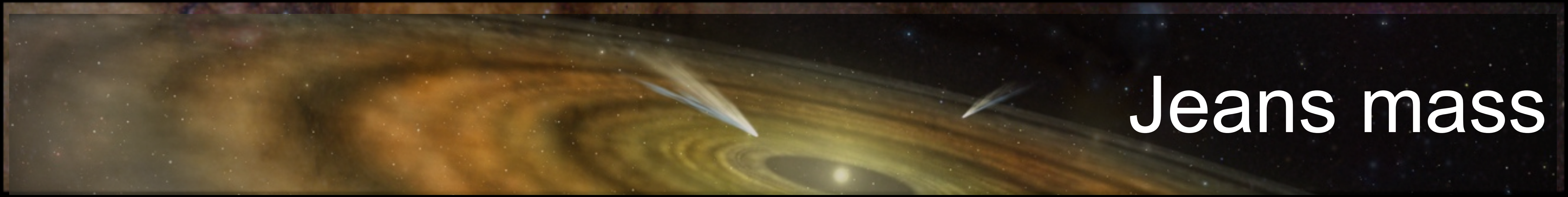


Virial equilibrium

Significance of the Virial criterion/equation for cloud stability:

$$\boxed{2U + \Omega = 0}$$

- if $2U = -\Omega$ → stable
- if $2U > -\Omega$ → pressure wins: dispersion of cloud
- if $2U < -\Omega$ → gravity wins: contraction of cloud



Jeans mass

By substituting back in the physical values, we can derive a criterion for collapse:

$$\boxed{M_C > M_J \simeq \left(\frac{5kT}{G\mu m_H}\right)^{\frac{3}{2}} \left(\frac{3}{4\pi\rho_C}\right)^{\frac{1}{2}}}$$

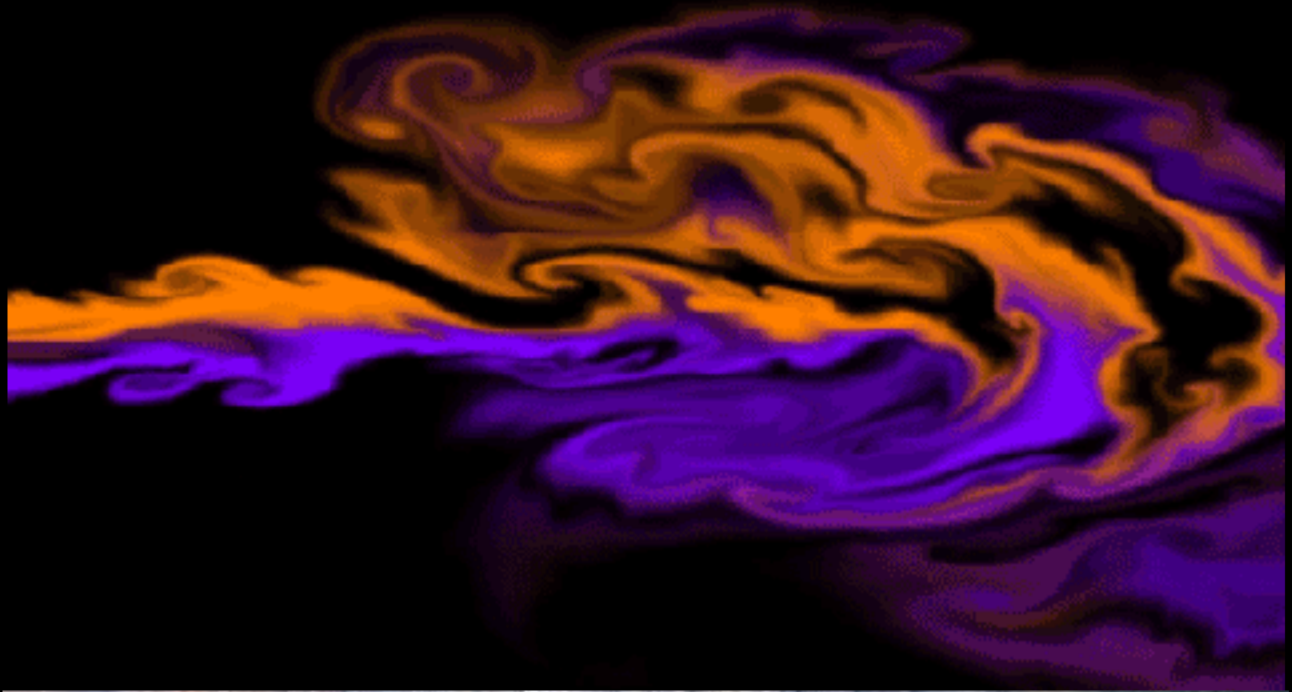
This critical mass, M_J, is known as the JEANS MASS.

We will work out a value for the Jeans mass for a typical molecular cloud in the workshop. We will also consider how the Jeans mass varies with density and temperature.

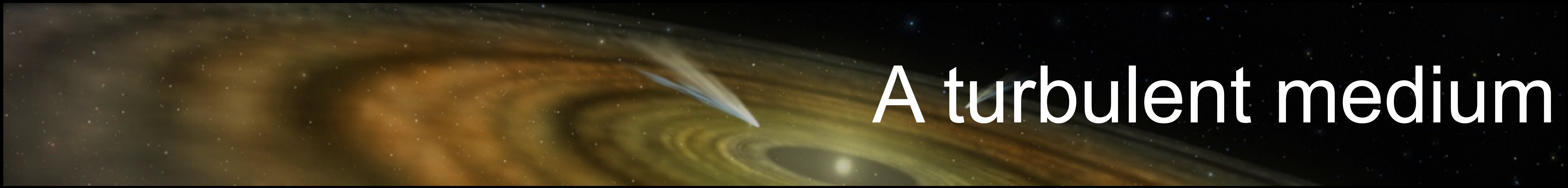
Large scale star formation

Video: http://www.astro.ex.ac.uk/people/mbate/Cluster/cluster3d.html; Bate, M. R. 2009, MNRAS, 392, 590

Storm in a teacup



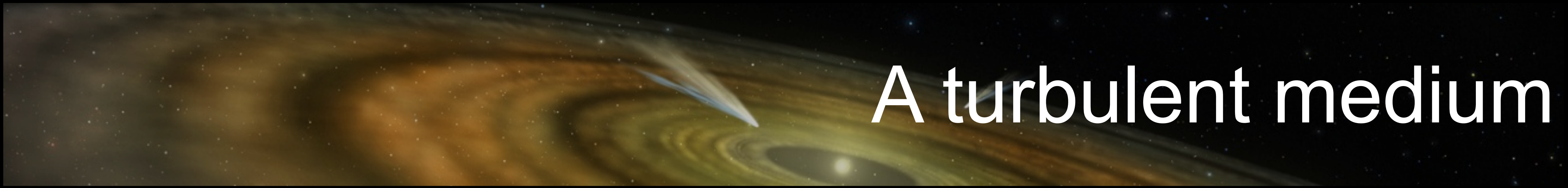
Images: NASA/JPL-Caltech/SwRI/MSSS/G. Eichstäd/S. Doran; http://www.algorizk.com/;



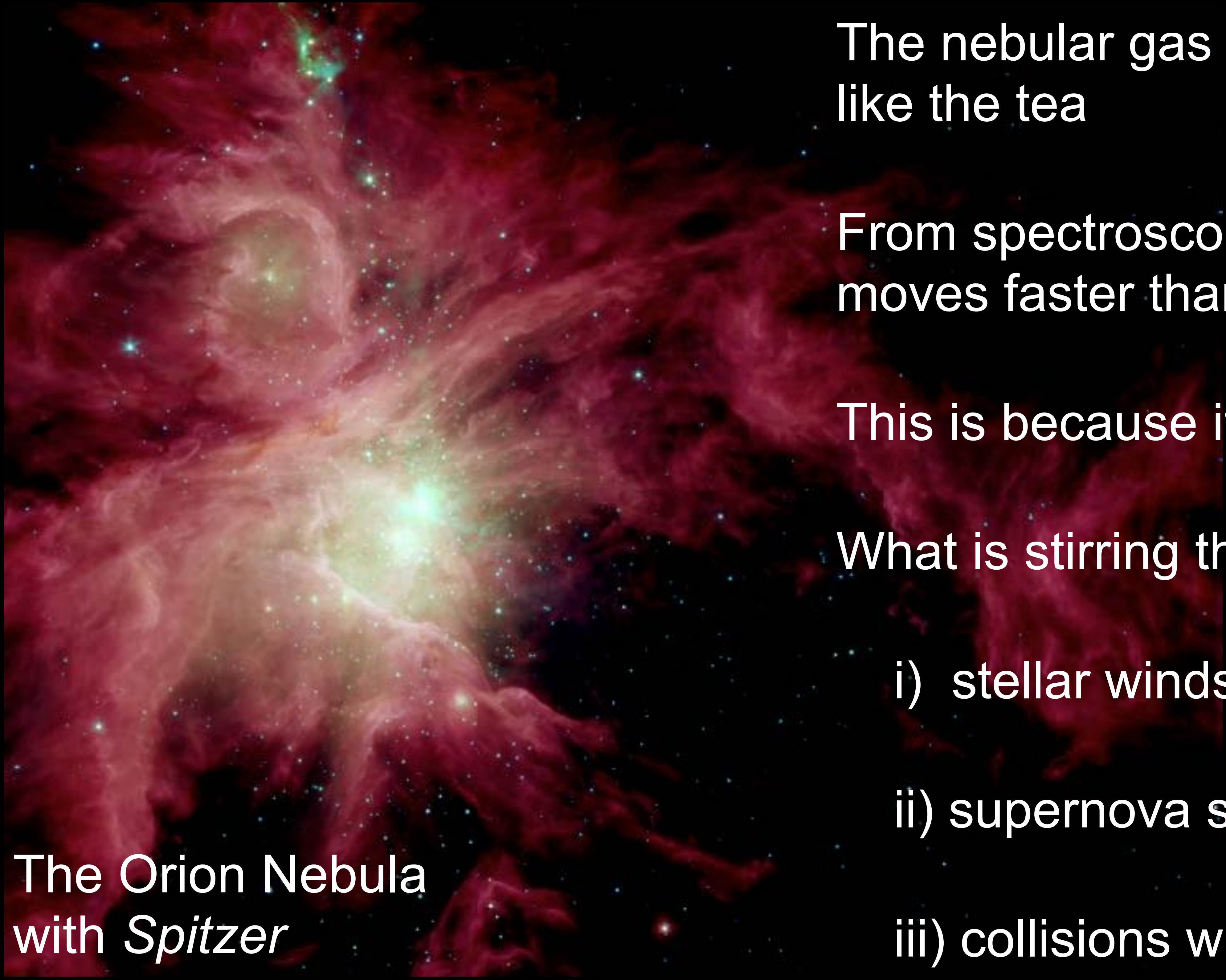
A turbulent medium

The Carina Nebula
with *Hubble*

Image: NASA, ESA, N. Smith (University of California, Berkeley), and the Hubble Heritage Team (STScI/AURA)



A turbulent medium



The Orion Nebula with *Spitzer*

The nebular gas and dust looks like the tea

From spectroscopy, the gas moves faster than it should

This is because it is *turbulent*

What is stirring the gas and dust?

i) stellar winds

ii) supernova shocks

iii) collisions with other clouds

Image: NASA/JPL/SSI

How do we know that the gas is turbulent?

For typical molecular cloud conditions

- $T \sim 10\,\mathrm{K}$
- $\mu \approx 2.4$

$$\Delta v \sim c_s = \sqrt{\frac{kT}{\mu m_{\mathrm{H}}}}$$

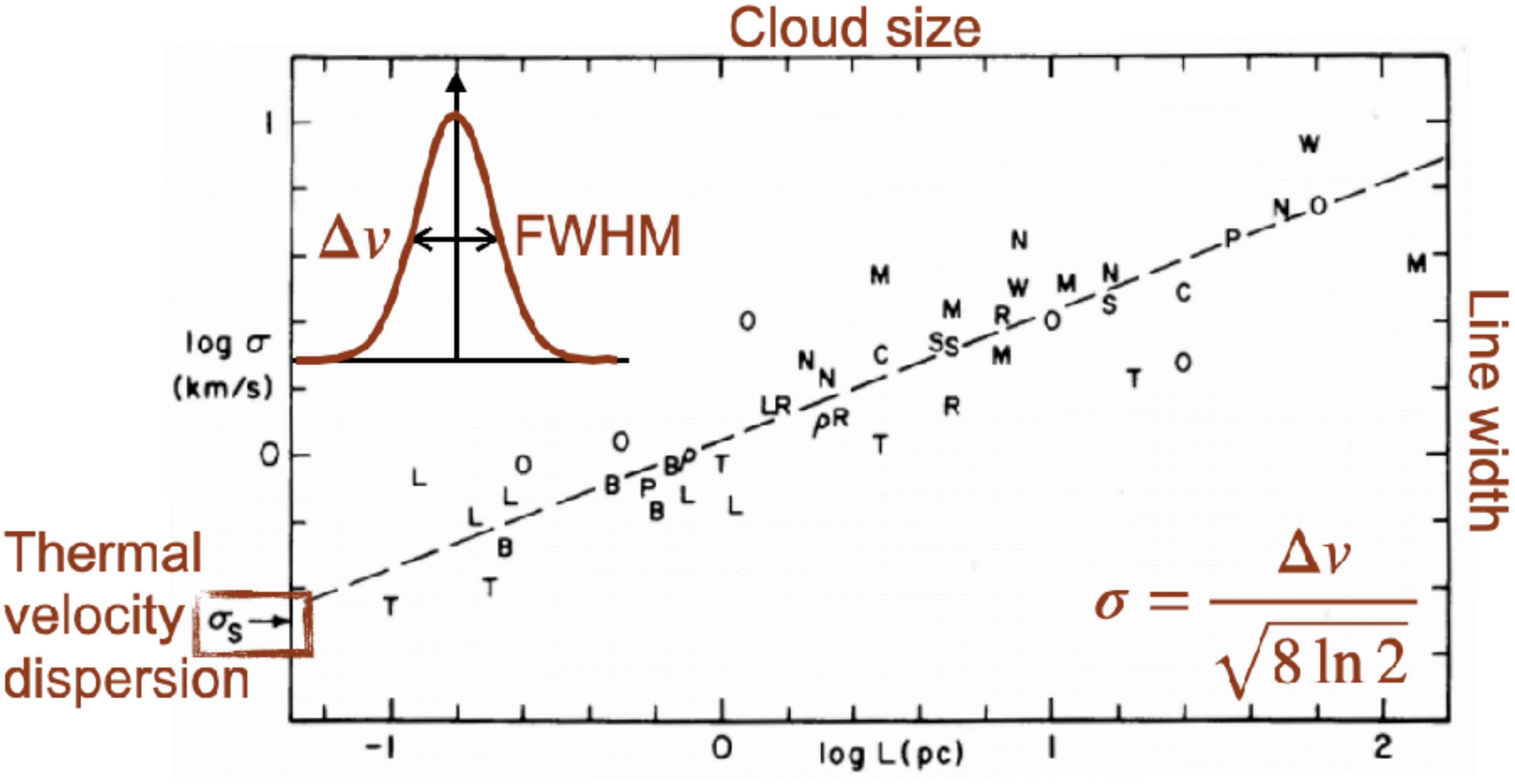
We observe the projected (line of sight) velocities, and due to Doppler shifting, we see emission over a range of velocities.

The emission line is Gaussian shaped, with a dispersion on the order of $0.1\ \mathrm{km\ s^{-1}}$: the full-width half maximum (FWHM) is about 2.3 times the dispersion.

We will work out the typical velocity of molecules in a molecular cloud in the workshop.

How do we know that the gas is turbulent?

In the 1980's, our first real insights into the special nature of molecular clouds was revealed in a seminal study by Larson



$$\sigma = \frac{\Delta v}{\sqrt{8 \ln 2}}$$

Image: Larson, R. B. 1981, MNRAS, 194, 809

How do we know that the gas is turbulent?

Larson compiled a large dataset for a number of clouds at a variety of sizes, distances, scales, and resolutions

The velocity widths in these studies are the total (observed) velocity widths:

$$\Delta v^2 = \Delta v_{\rm th}^2 + \Delta v_{\rm NT}^2$$

Thermal

Non-thermal

Non-thermal velocities are observed to dominate over the thermal component

If we consider successively smaller clouds, the velocity approaches the ambient thermal velocity. We will discuss how turbulence affects star formation in the workshop.

Image: Larson, R. B. 1981, MNRAS, 194, 809

Jets and outflows

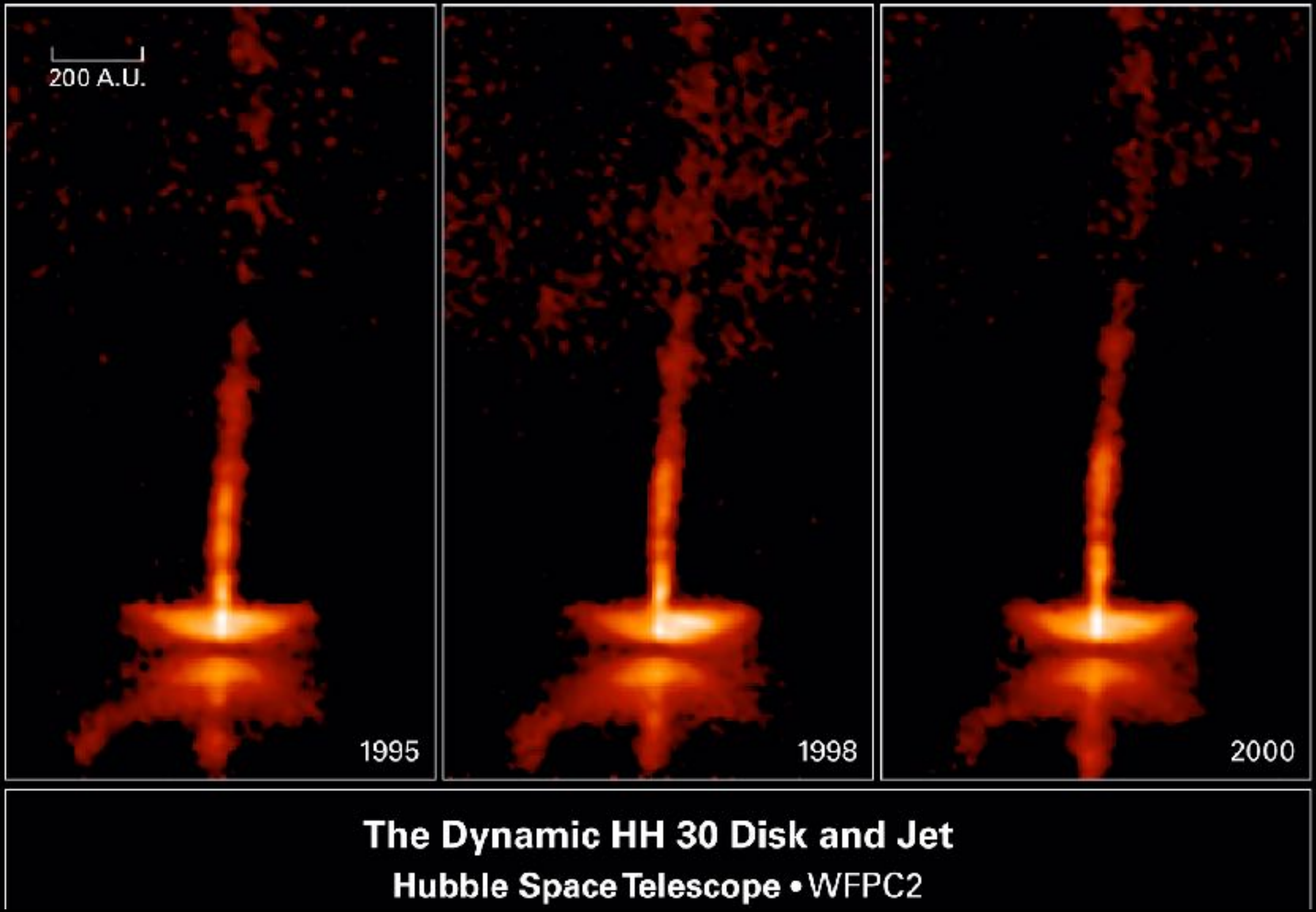
Image: ESO/Bo Reipurth/NTT

Jets and outflows

Image: ALMA (ESO/NAOJ/NRAO)/ESO/H. Arce. Acknowledgements: Bo Reipurth

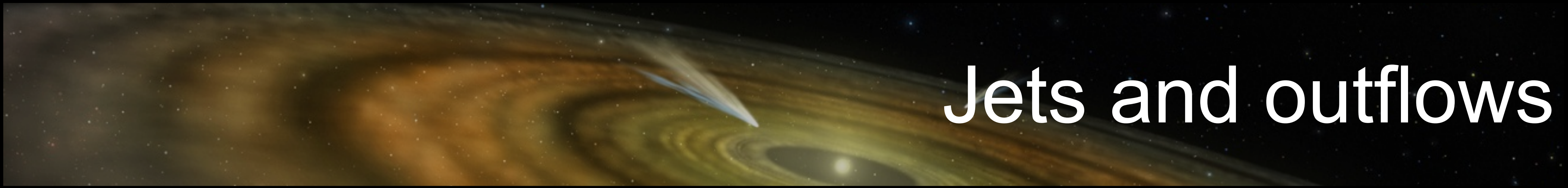
Jets and outflows

Jets and outflows



The Dynamic HH 30 Disk and Jet
Hubble Space Telescope • WFPC2

Image: NASA (A Watson)



Jets and outflows

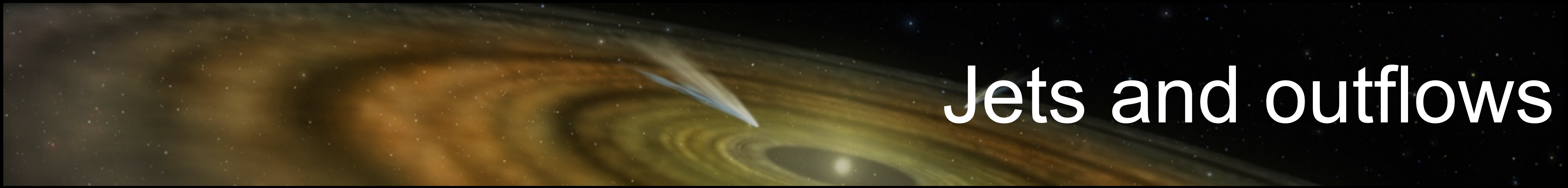
Properties of optical jets:

- ✳ Shocked ionised gas (H-α, [SII])
- ✳ Low ionisation fraction (~ 10%)
- ✳ Highly collimated (~ 100:1)
- ✳ Dense (~ 10^9 cm^{-3})
- ✳ Fast (~ 300 km/s)
- ✳ Knots along the jet
- ✳ Some evidence of precession

$$v_{\mathrm{esc}} = \sqrt{\frac{2GM}{R}}$$

We will calculate the typical launch radius of a jet in the workshop.

Image: NASA (A Watson)



Jets and outflows

- Low-density molecular gas seen at high velocities (10-50 km/s)
- Mainly CO J=1-0 line (2.6 mm), collisionally excited
- Red and blue lobes, spatially separated -> bipolar outflow
- Usually poorly collimated (~ 2-1)
- Extent is ~ arcmin (~1-3 pc)
- Masses ~ 0.1 - 100 $M_\odot$

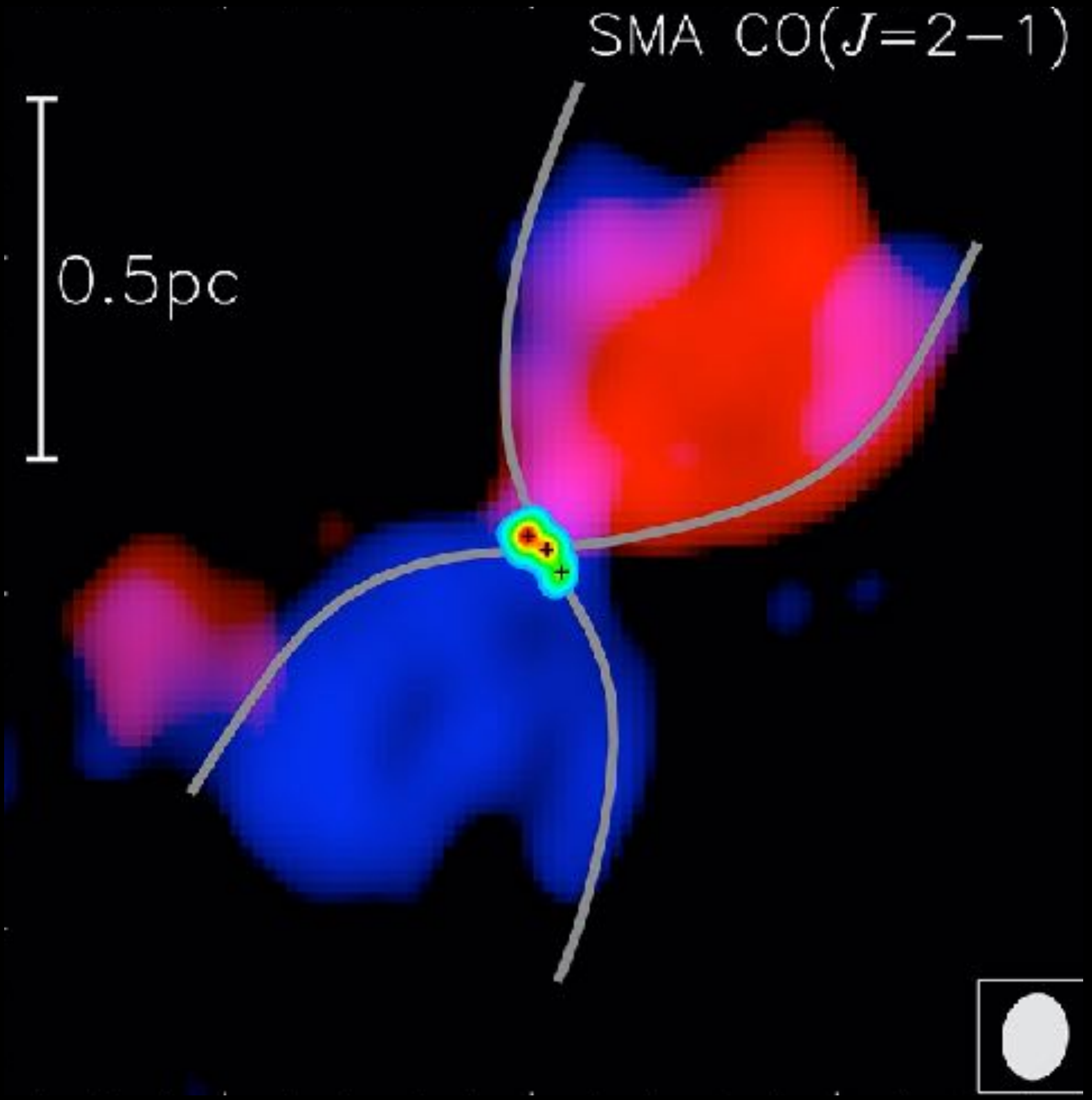
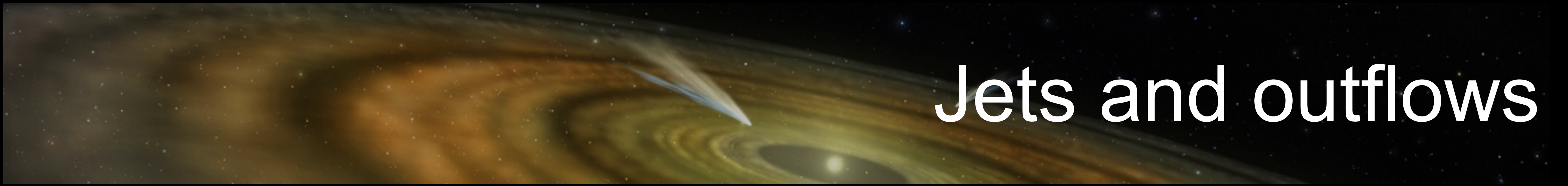
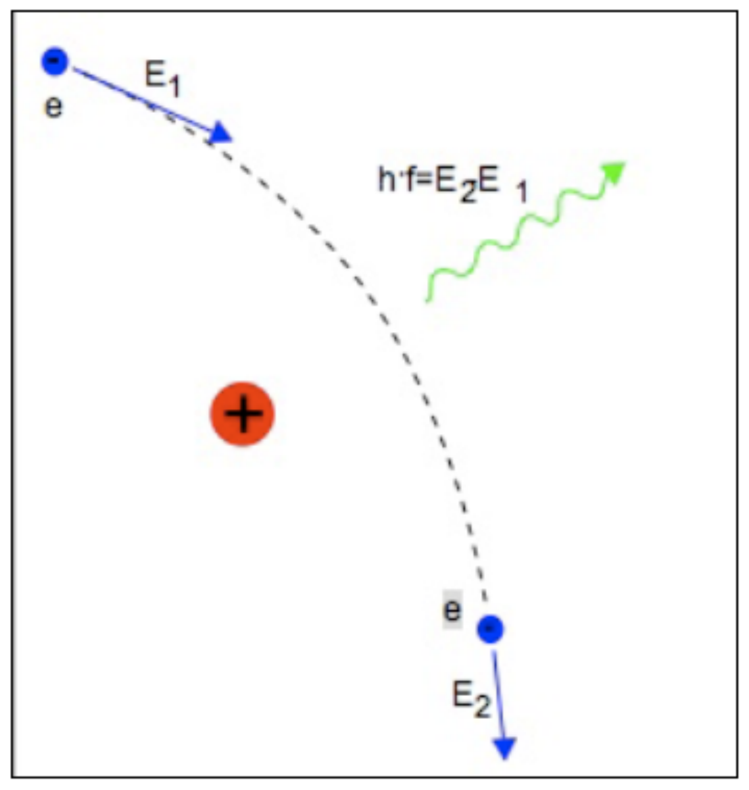


Image: Qui et al. 2009, ApJ, 696, 66



Jets and outflows

- Dense ionised gas at the base of the jet seen at radio wavelengths
- Free-free continuum emission
- Usually less than ~ 1 arcsec long and aligned with the outflow axis



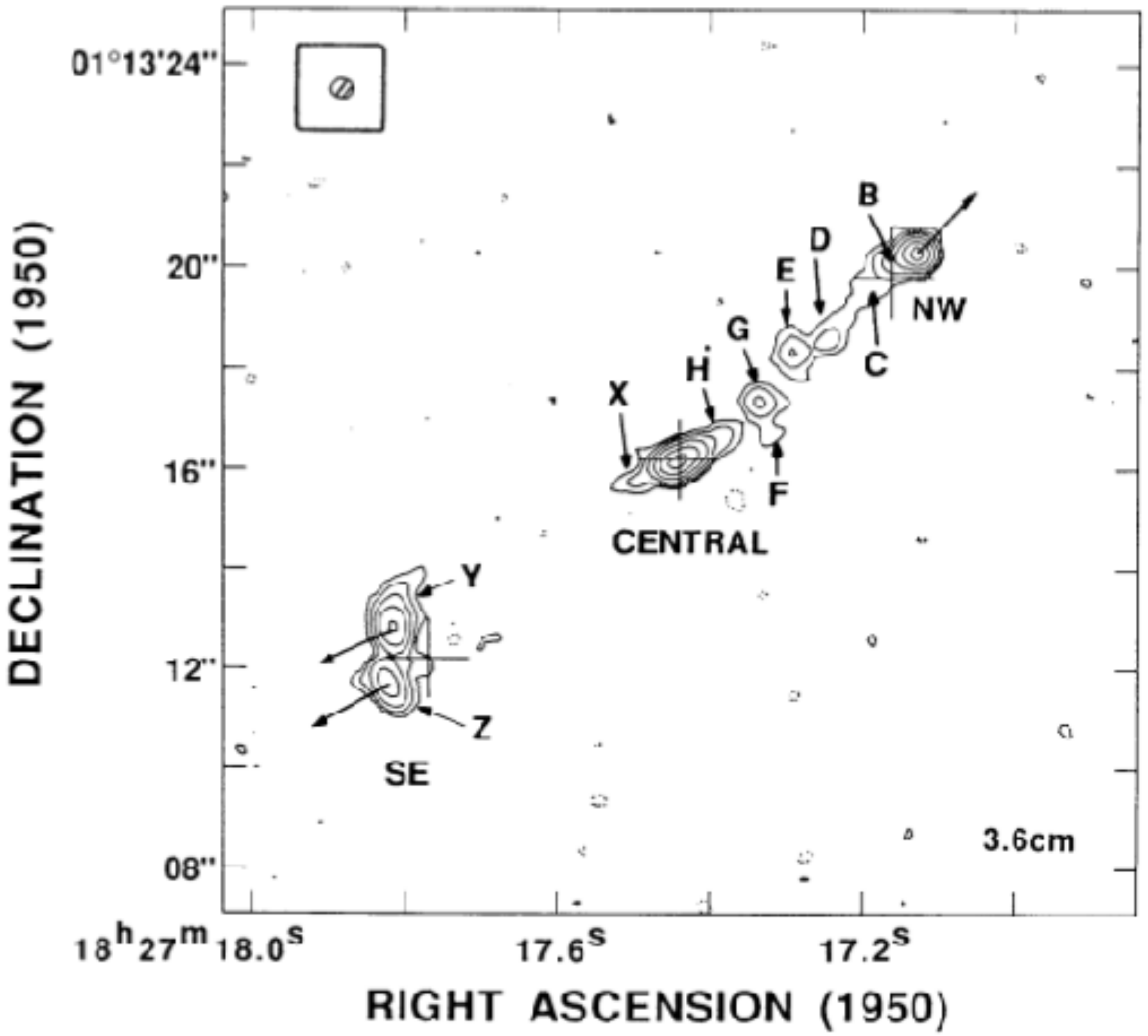
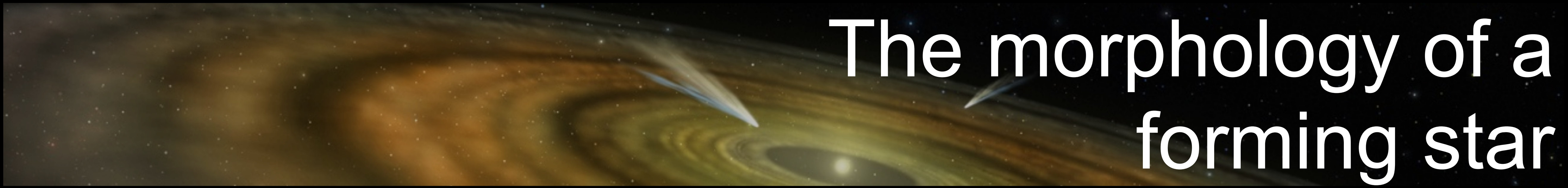
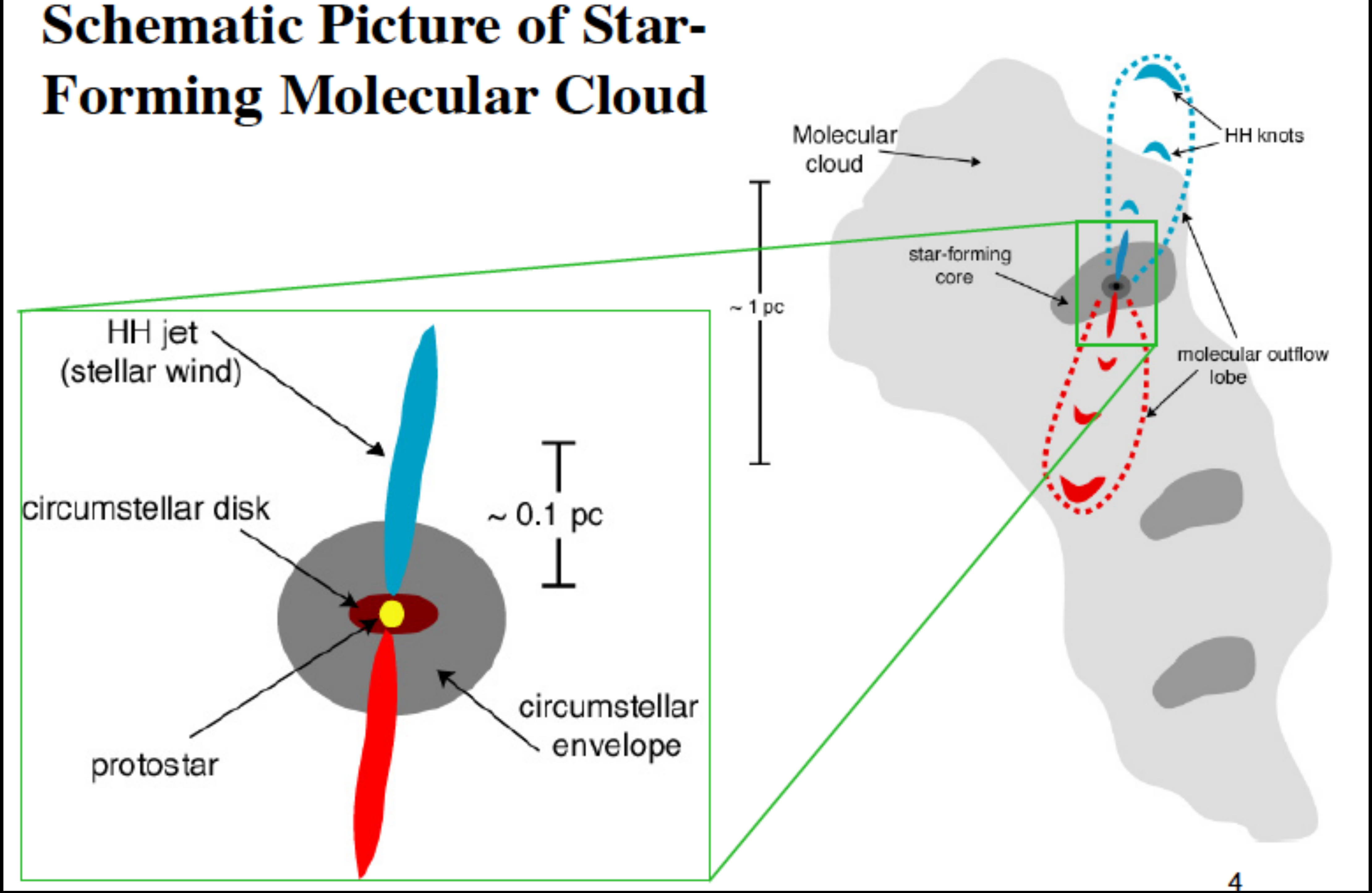


FIG. 2.—The 3.6 cm wavelength map of the Serpens radio jet from Fig. 1. The three main components as well as several knots are identified. The arrows show the projected 15 yr shifts due to the proper motions of the outer NW and SE components. The crosses mark the position of the peak emission at 6 cm of the three main components in the 1984 epoch. At a distance of 300 pc, 1″ corresponds to 300 AU.

Image: Curiel et al. 1993, ApJ, 415, 191

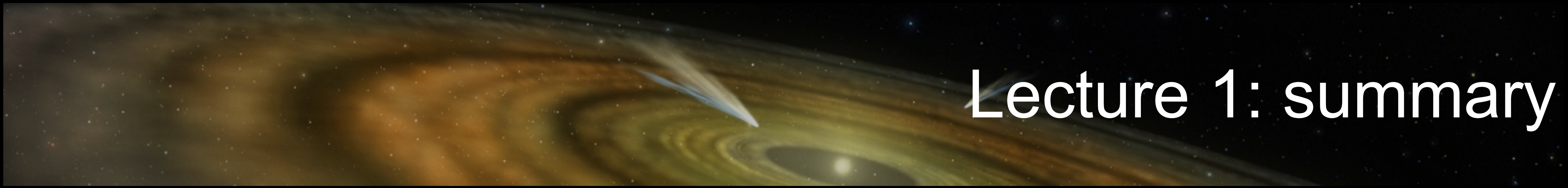


The morphology of a forming star



Schematic Picture of Star-Forming Molecular Cloud

Outflows interact with the cloud at different distances from the source



Lecture 1: summary

In this lecture we discussed the following aspects of star formation:

- Multi-wavelength observations reveal the presence of young stars and star-forming regions in the interstellar medium
- Stars form from the gravitational collapse of molecular clouds
- The viral equation and Jeans mass: these set the stability criteria of molecular clouds
- The interstellar medium is turbulent
- When clouds collapse to form stars, they naturally form a flattened rotating structure through angular momentum conservation
- Young stars also generate jets and outflows that inject energy into the surroundings

In the next lecture we will discuss how planets form around young stars.

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Dr Catherine Walsh
c.walsh1@leeds.ac.uk

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