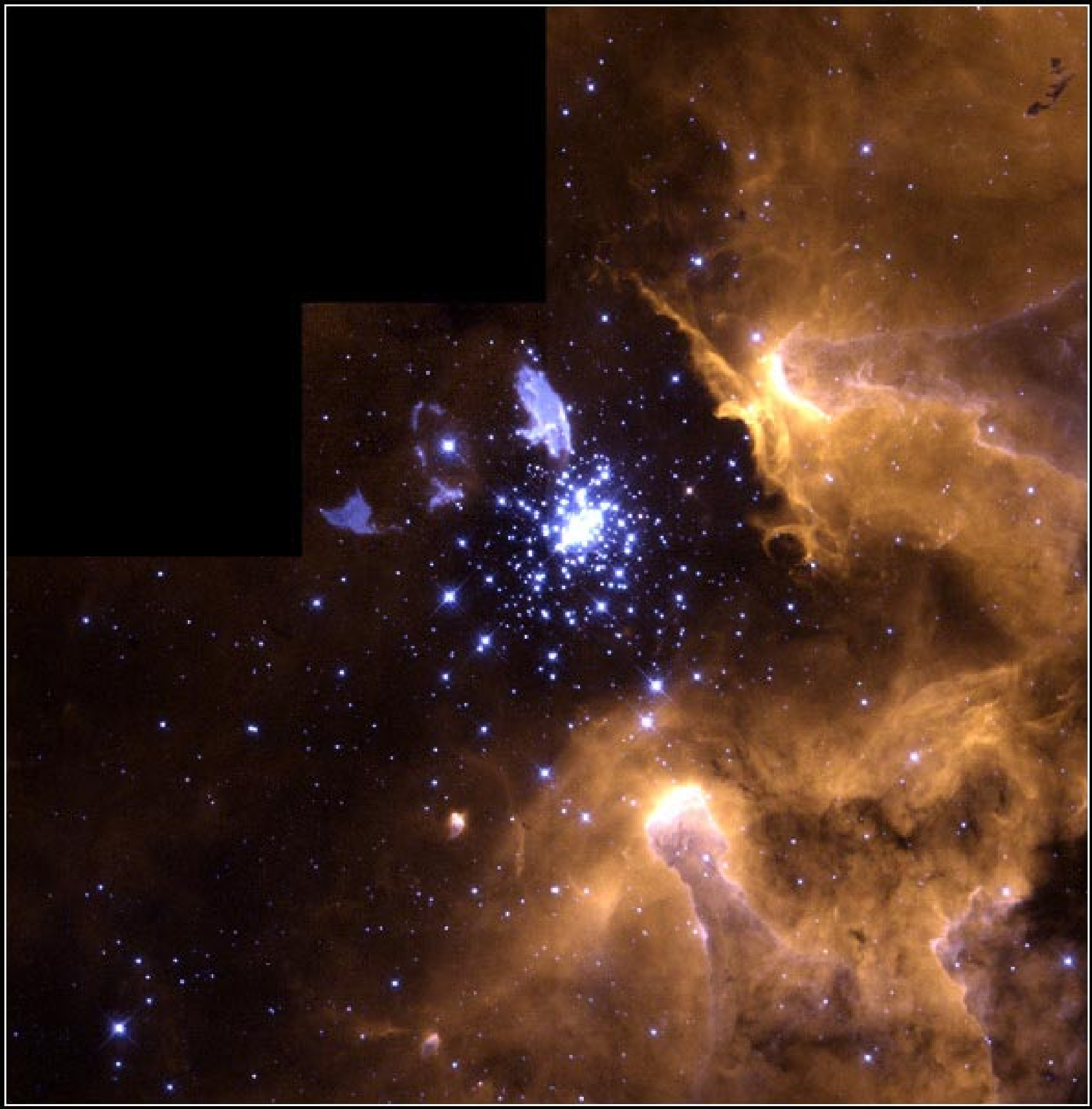
Recycling in the Universe

Alyssa A. Goodman

Department of Astronomy
Harvard University

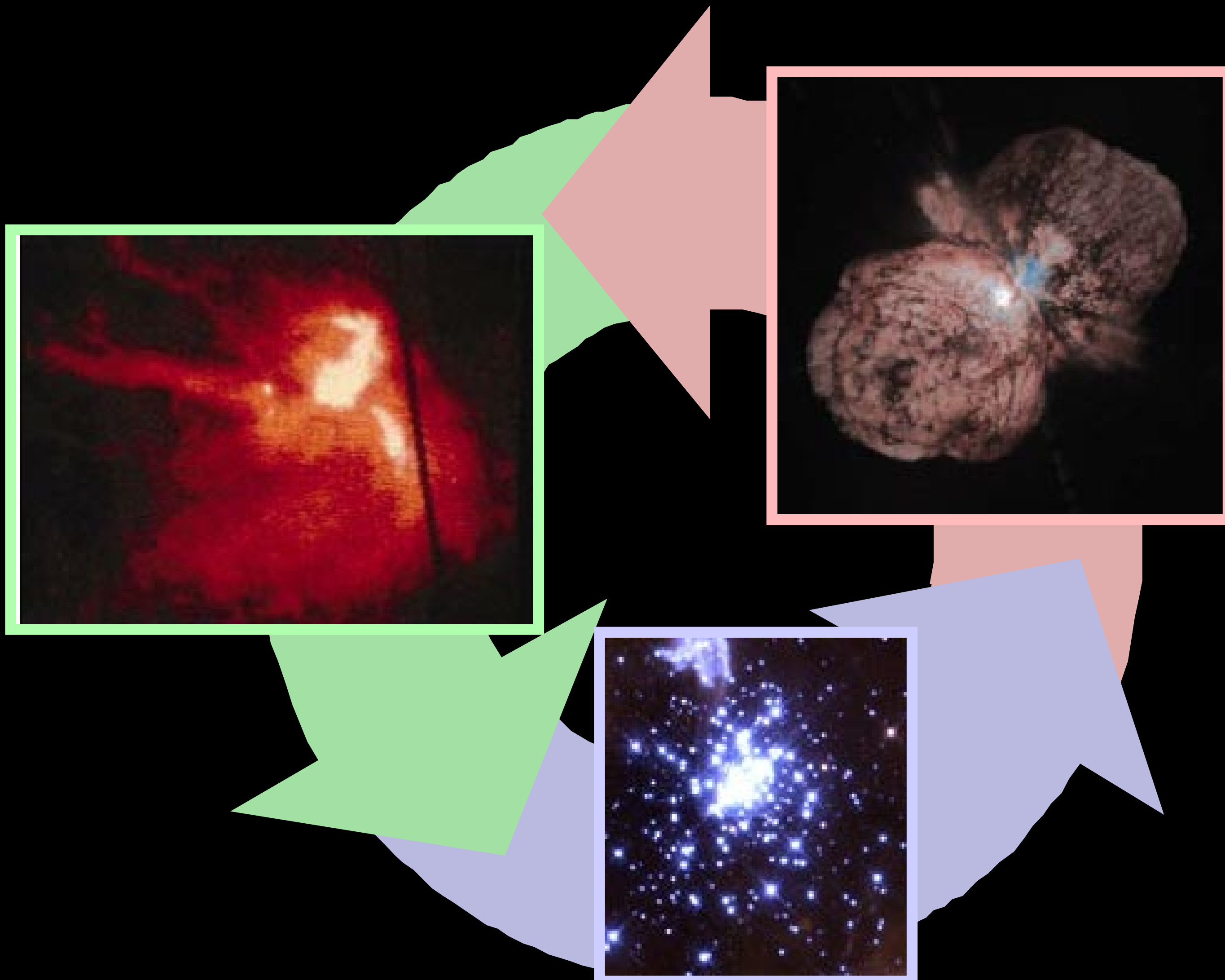


NGC 3603 HST • WFPC2
PRC99-20 • STScI OPO • June 1, 1999
Wolfgang Brandner (JPL/IPAC), Eva K. Grebel (Univ. Washington), You-Hua Chu (Univ. Illinois, Urbana-Champaign) and NASA

Recycling on Earth & In Galaxies

	On Earth	In Galaxies
Storage	Neatly, in a "Recycling" Bin	Not as neatly, in the Interstellar Medium
Collection	Big Trucks	Gravity & Supernova "Snowplows"
Processing	Recycling Plant	Molecular Clouds
Production	Factories	Star-forming Cores in Molecular Clouds
Consumption	Humans	Stars
Discarding	Human Tosses	Stellar Winds
Efficiency of One Cycle	Pretty Low, Maybe 10%	Pretty High, Maybe 90%
Timescale for One Cycle	Weeks to Years	Millions to Billions of Years

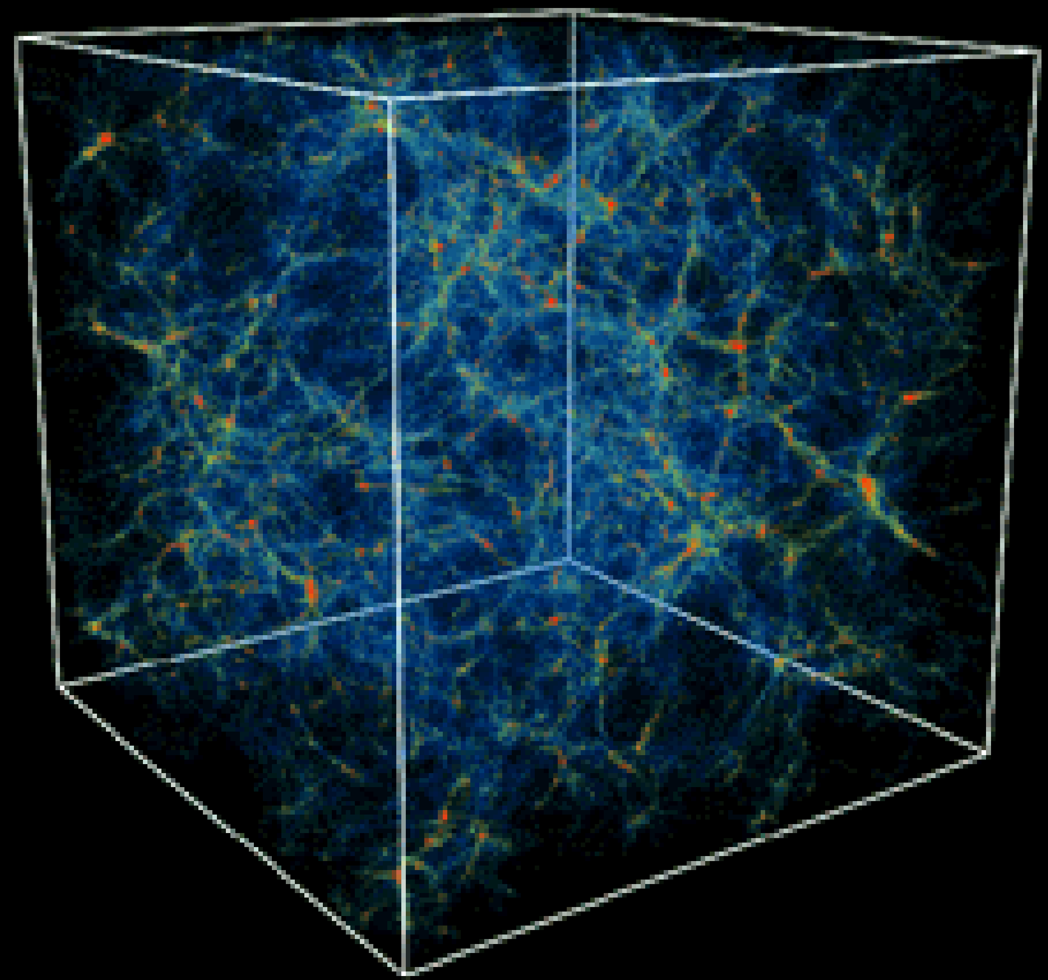
Recycling in the Universe



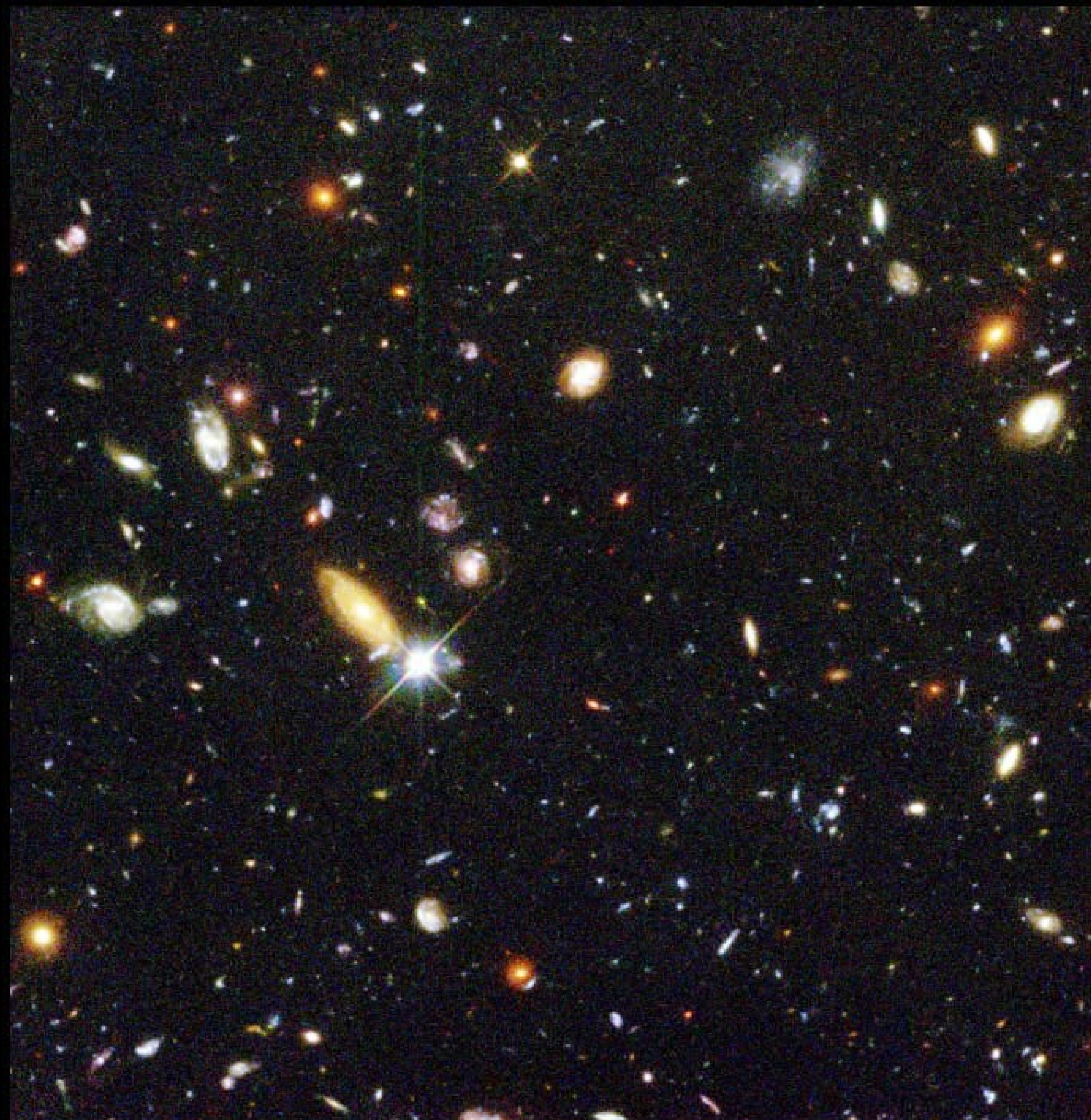
Making the First Recyclables...

Fluctuations about 300,000 years after the Big Bang lead to "Structure Formation."

Gravitational collapse of some of these "structures" produces the first stars and galaxies.



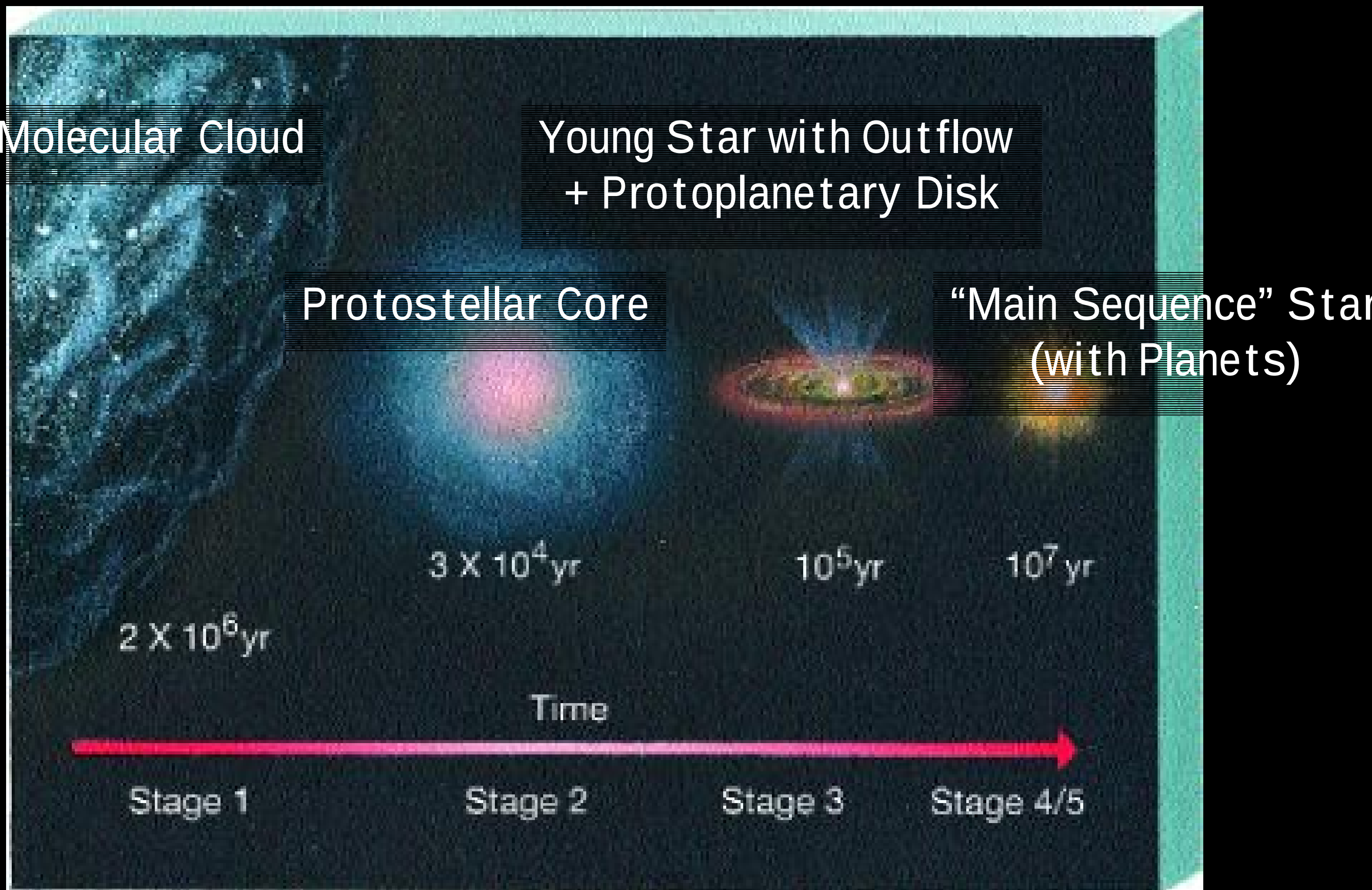
Pretty young galaxies



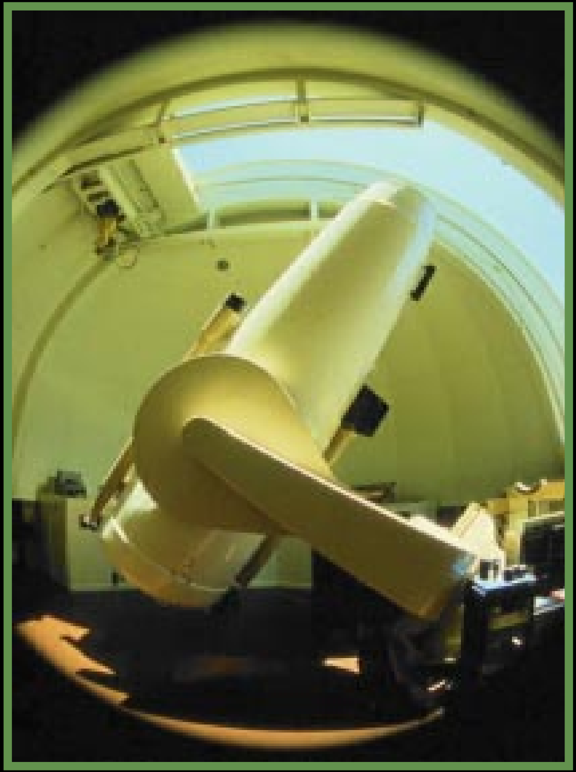
Hubble Deep Field HST · WFPC2

PRC96-01a · ST ScI OPO · January 15, 1996 · R. Williams (ST ScI), NASA

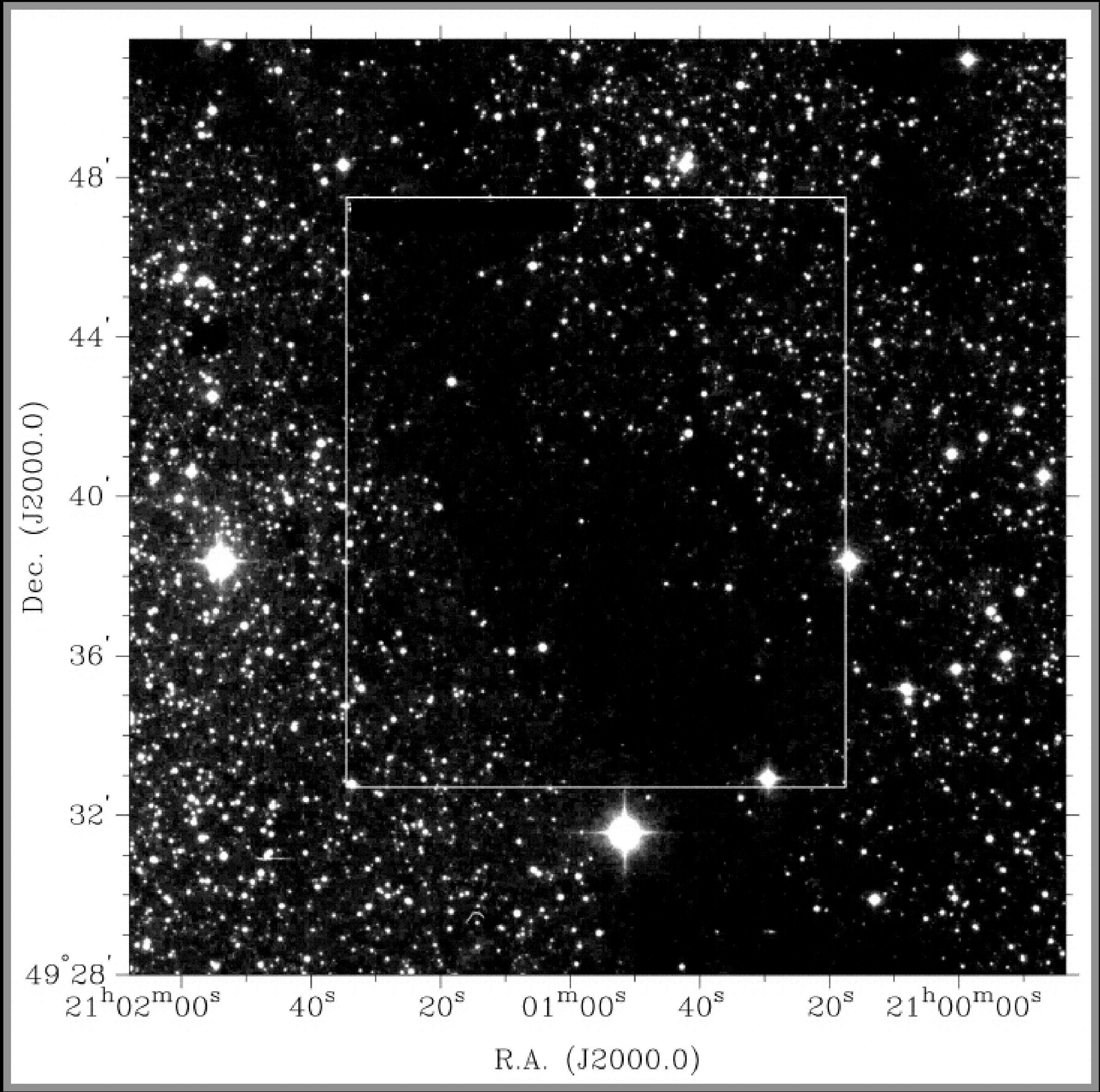
"Star Formation 101"



Molecular Clouds: The Stuff of New Stars



The Oschin telescope,
48-inch aperture wide-field
Schmidt camera at Palomar

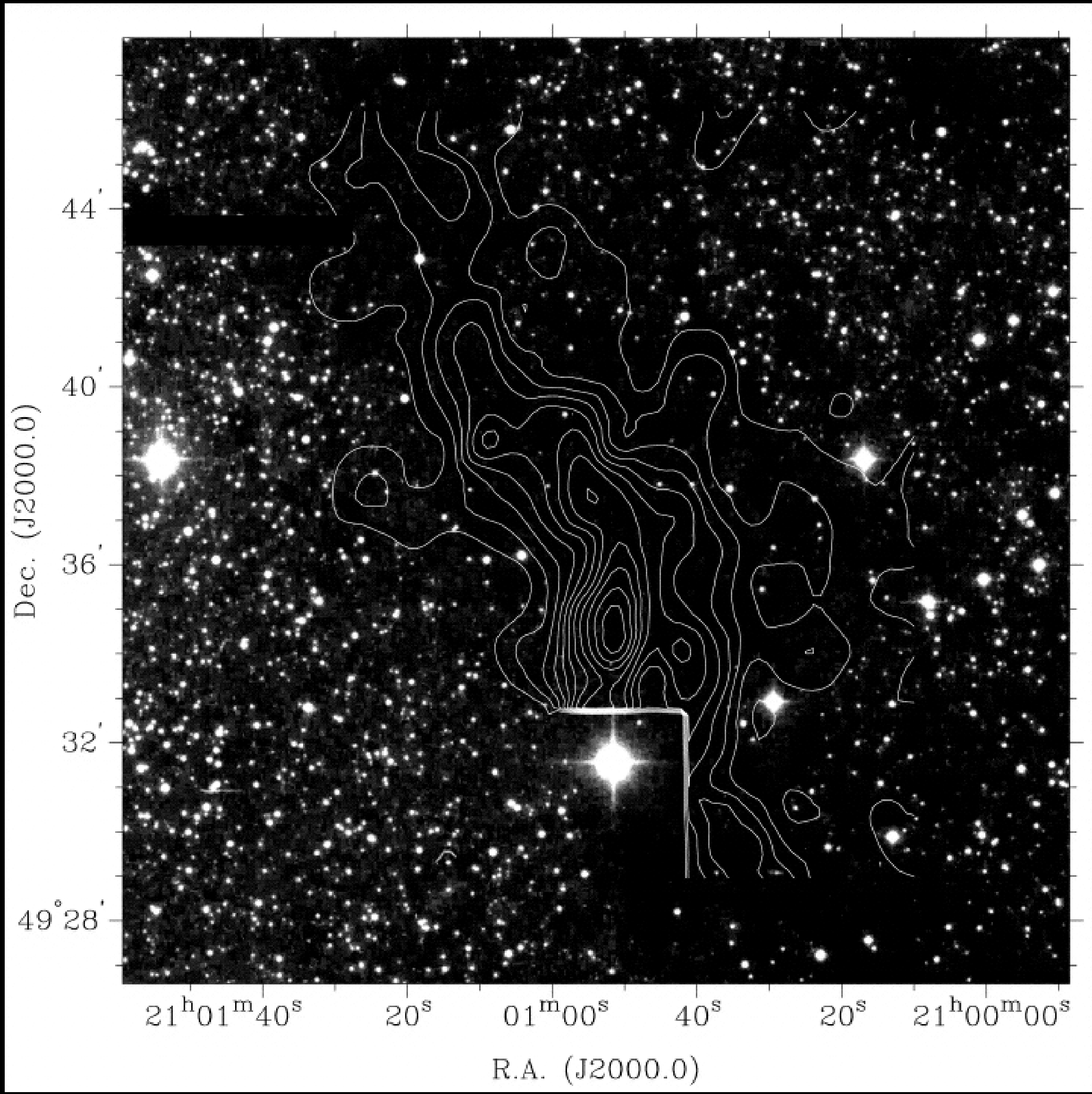


Red Plate, Digitized Palomar Observatory Sky Survey

How much stuff is there?

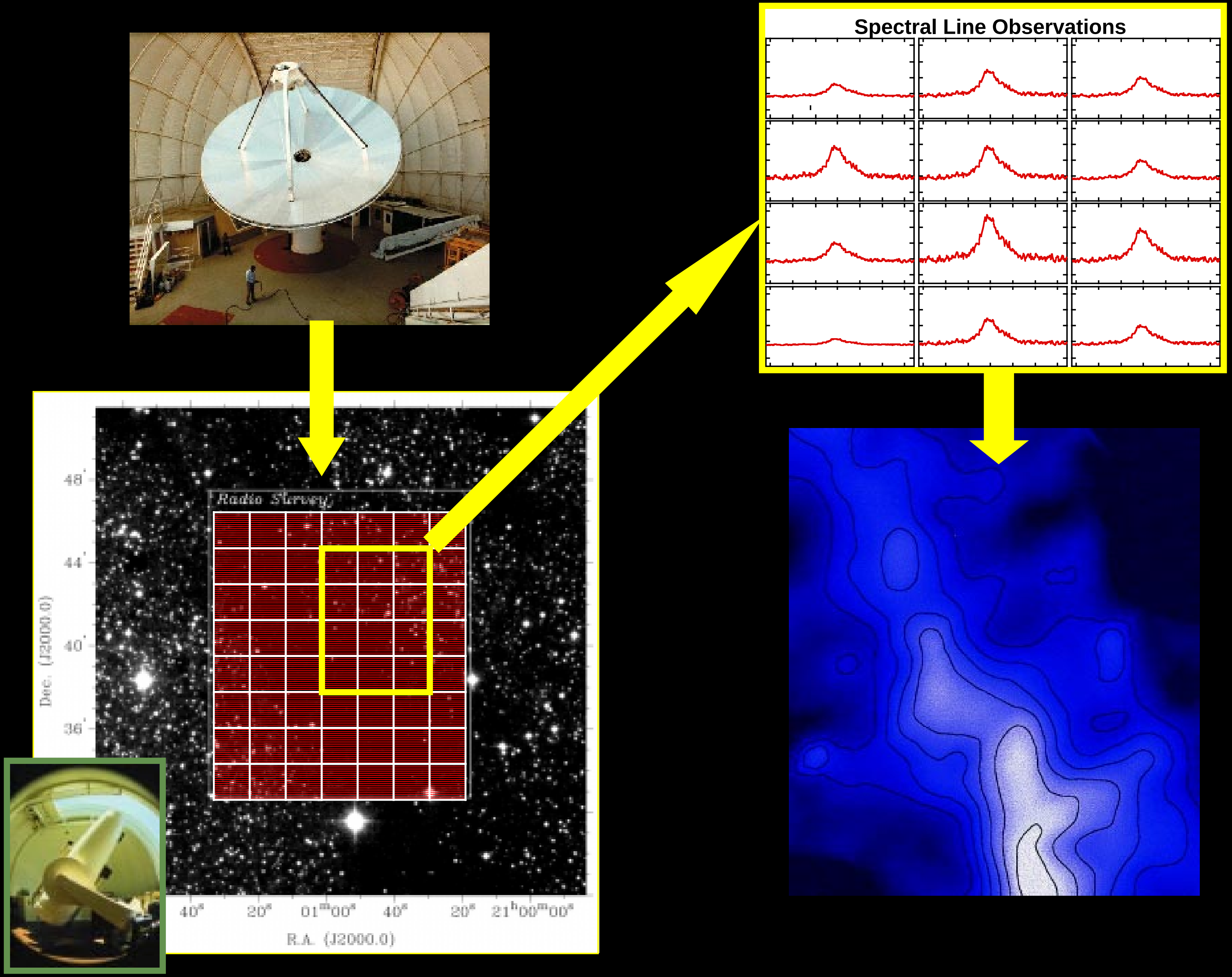
“Star-counting”

Counts of stars per unit area measure how much material must be producing obscuration.

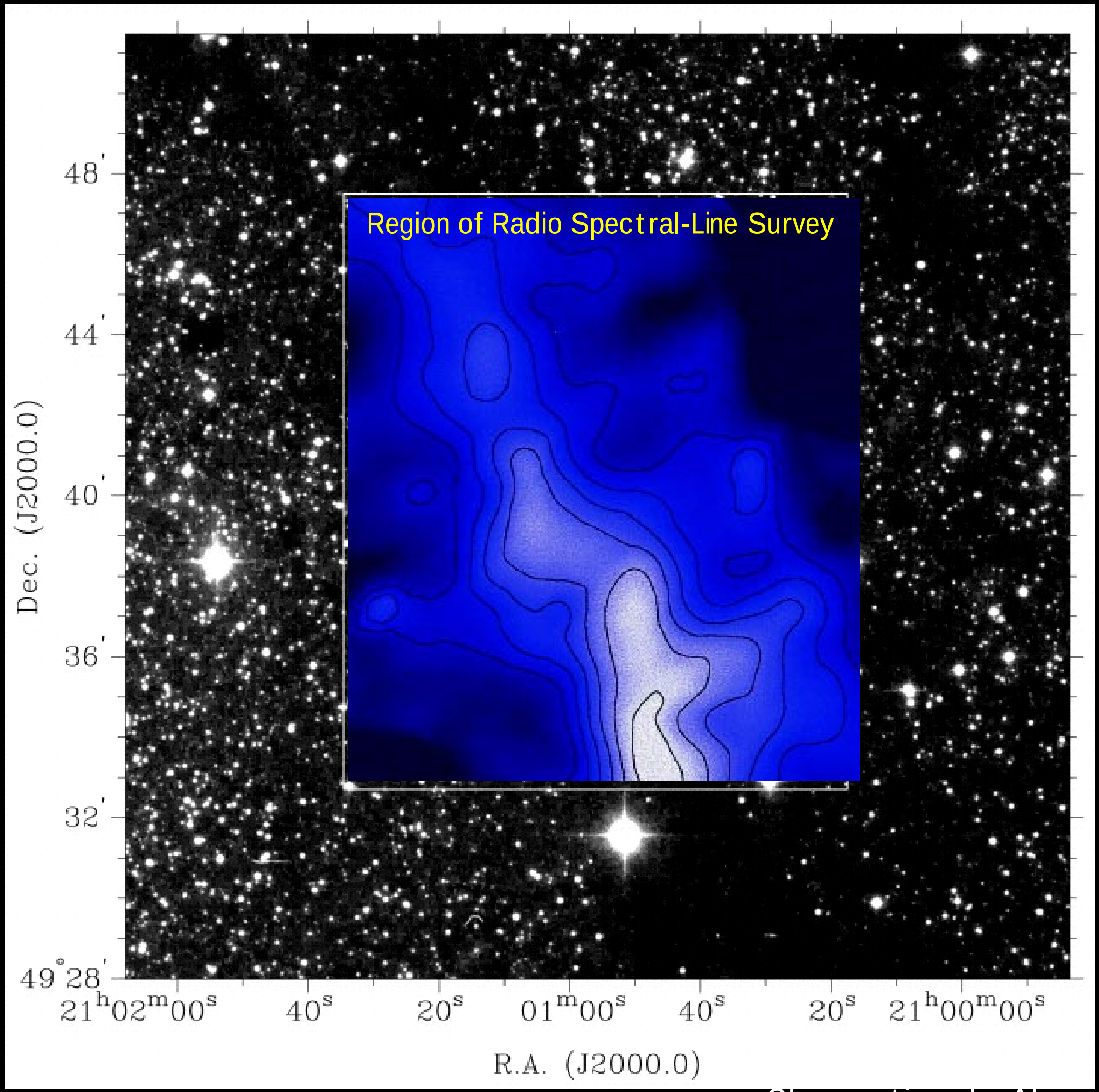


Observations by Alves, Lada & Lada 1999

Radio Spectral-line Observations of Molecular Clouds

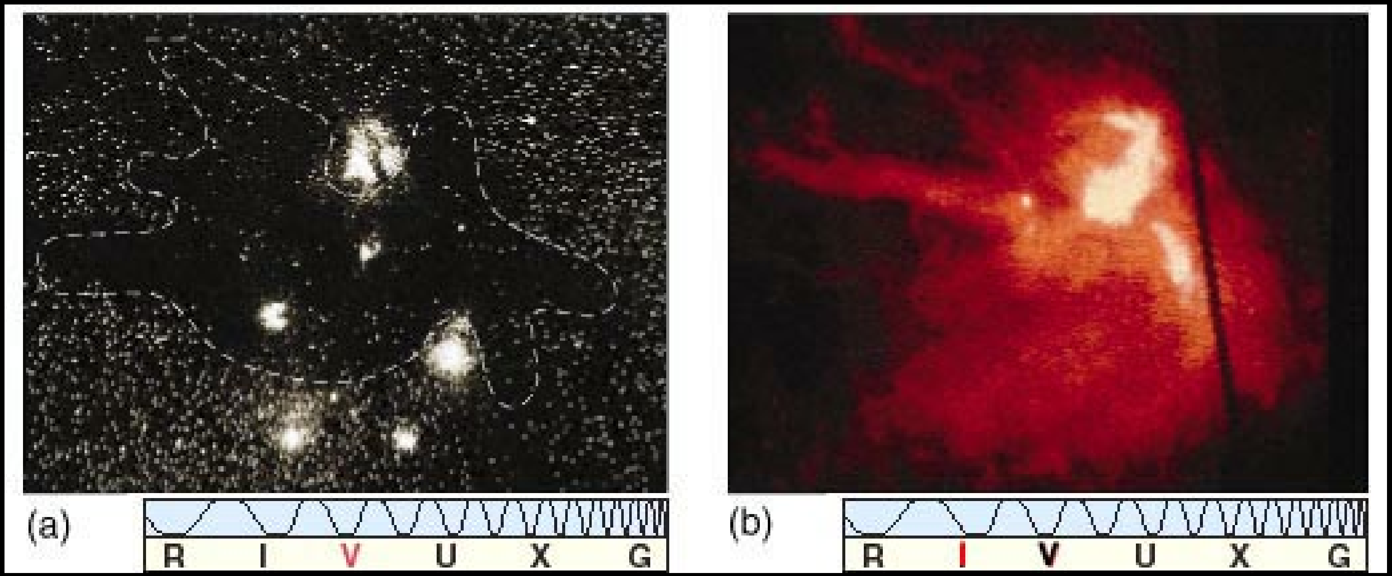


How do Optical & Radio Views Compare?



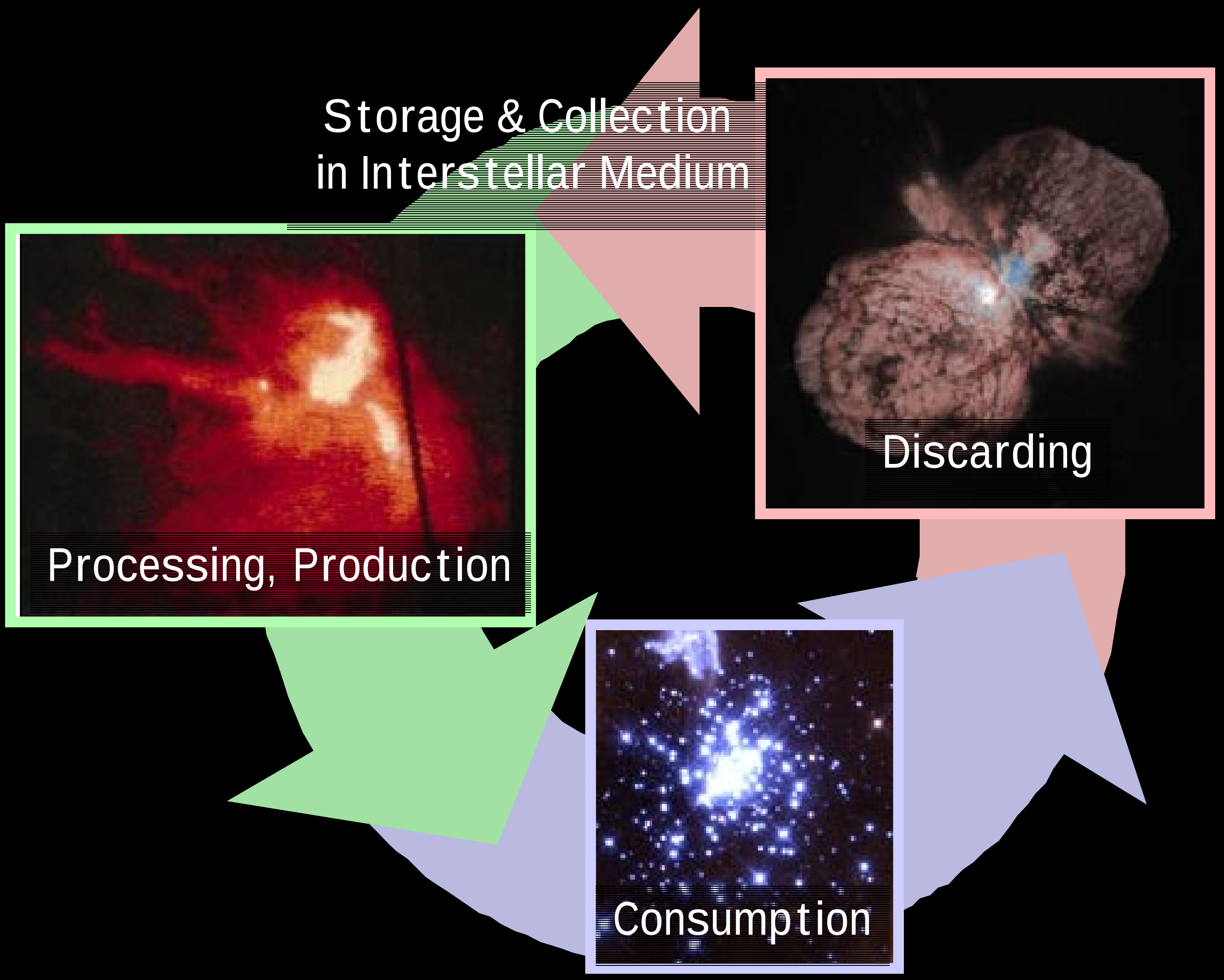
Observations by Alves, Lada & Lada 1999

Cold, Dark & Dusty



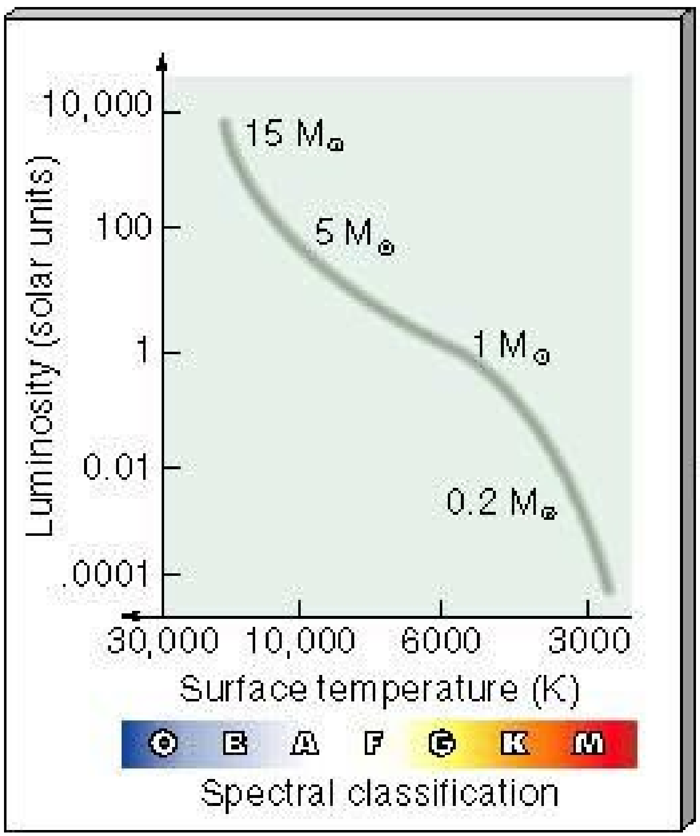
- Gas and Dust are Very Cold in Molecular Clouds, T~10=100 Kelvin
- Dust at 10 K “Glows” in the Far-Infrared

Recycling in the Universe

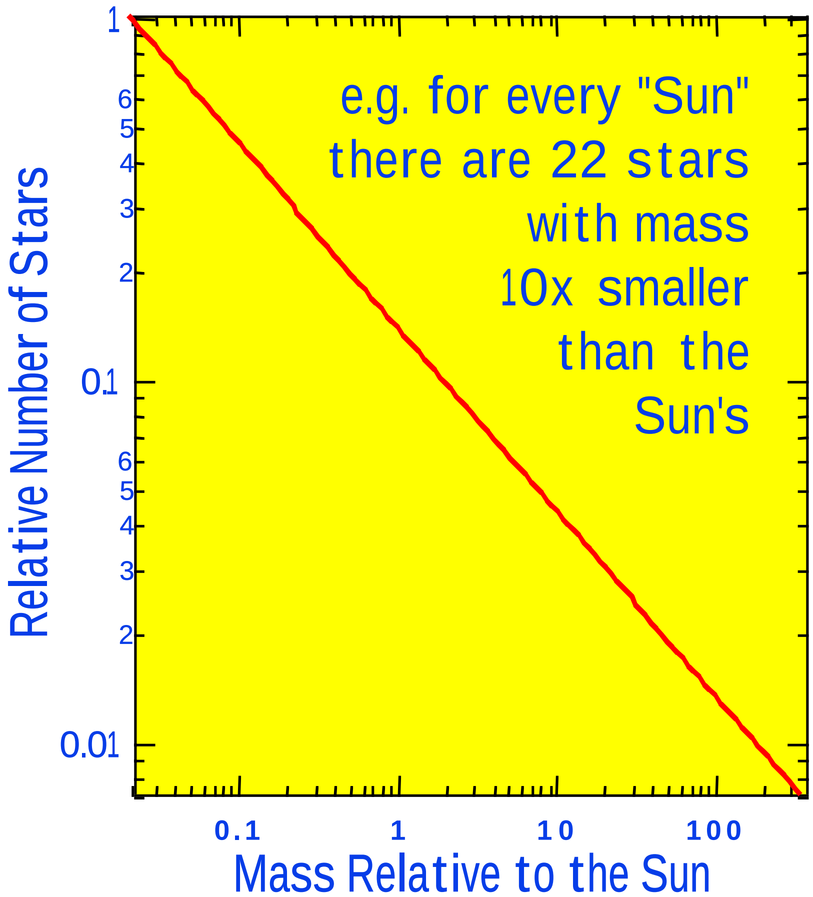


Consumption of Recyclables

The Hertzprung-Russell Diagram

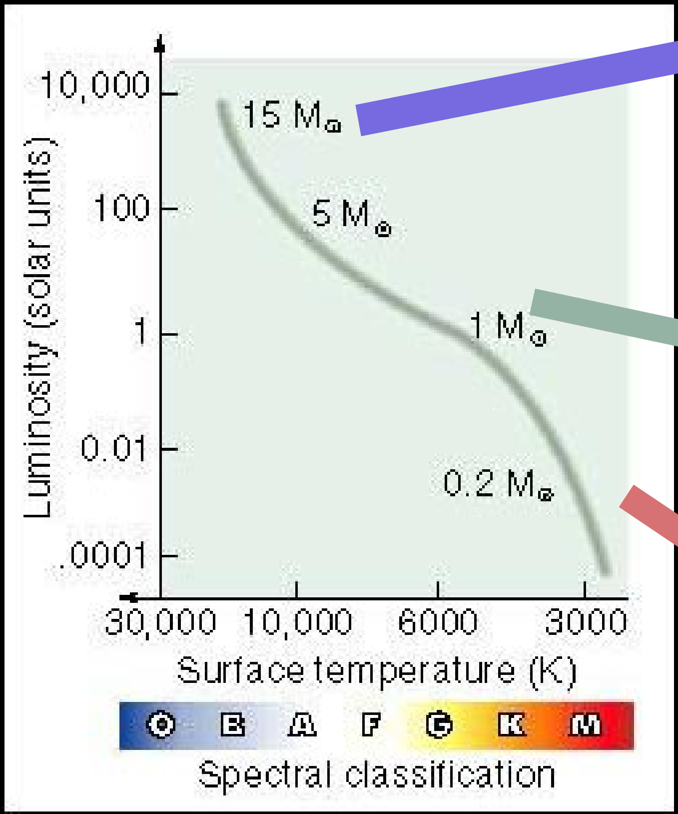


The "Initial Mass Function" (IMF)



Stellar Recyclables

The Hertzprung-Russell Diagram



Supernova, then neutron star/pulsar or black hole

Spectacular contribution, and collection. Explosion injects, and "sweeps up" interstellar material.

Red giant then white dwarf

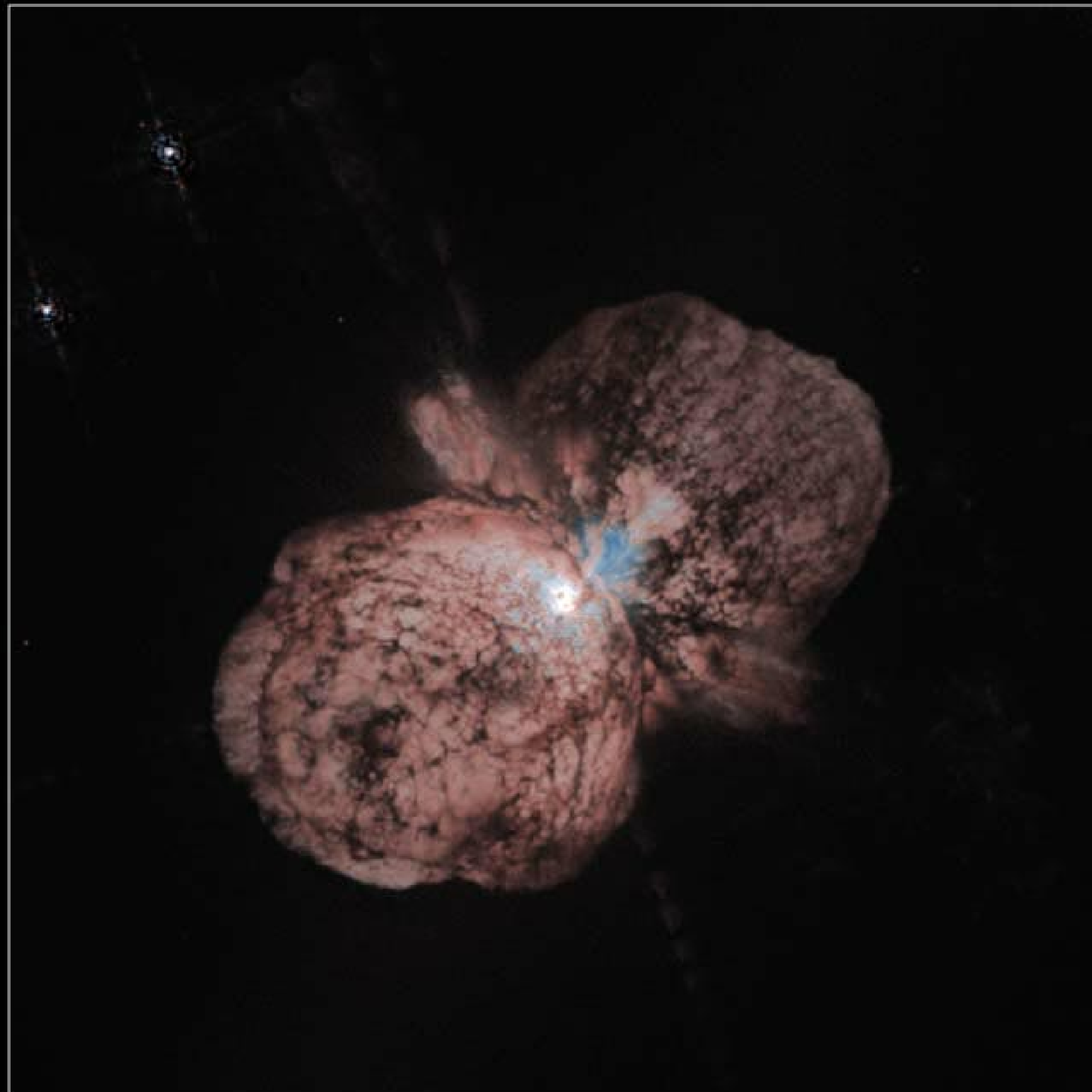
Good recyclables. Red-giant wind main dust injection in ISM.

Long-lived brown dwarfs

"Styrofoam"

Stellar Winds: Discarding the Recyclables

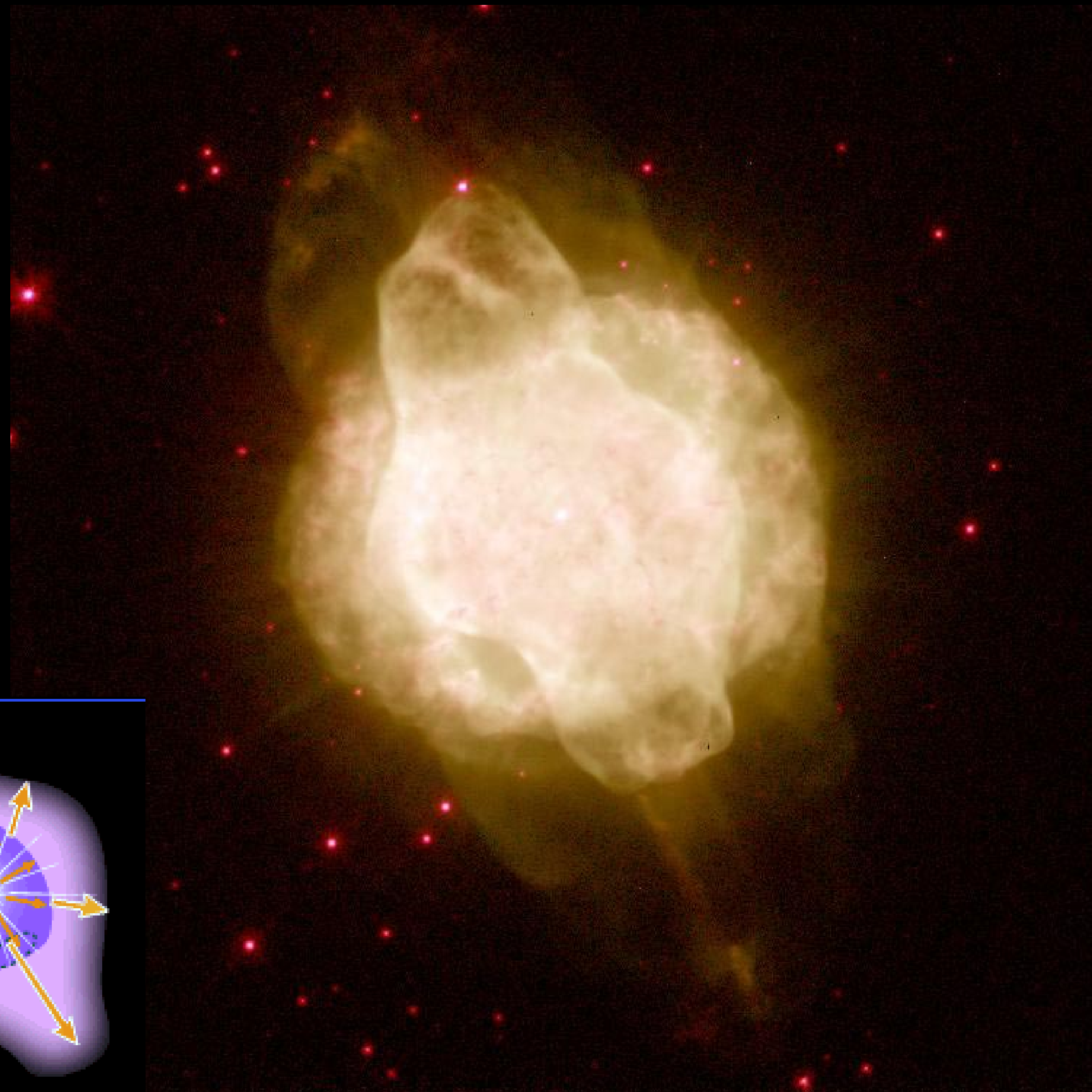
Mass=100 x Sun

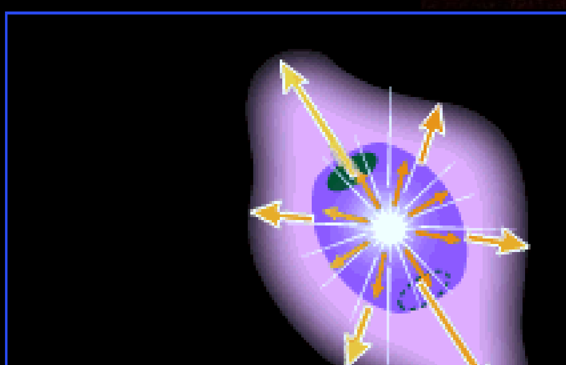


Eta Carinae HST • WFPC2
PRC96-23a • ST ScI OPO • June 10, 1996
J. Morse (U. CO), K. Davidson, (U. MN), NASA

"Excess Gas?"

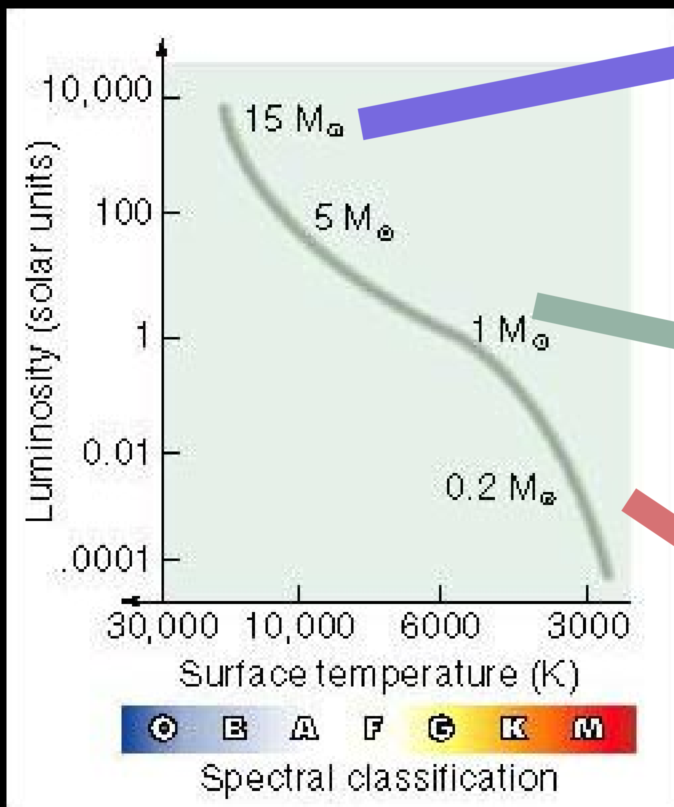
(Post-red-giant planetary nebula)





Stellar Recyclables

The Hertzprung-Russell Diagram



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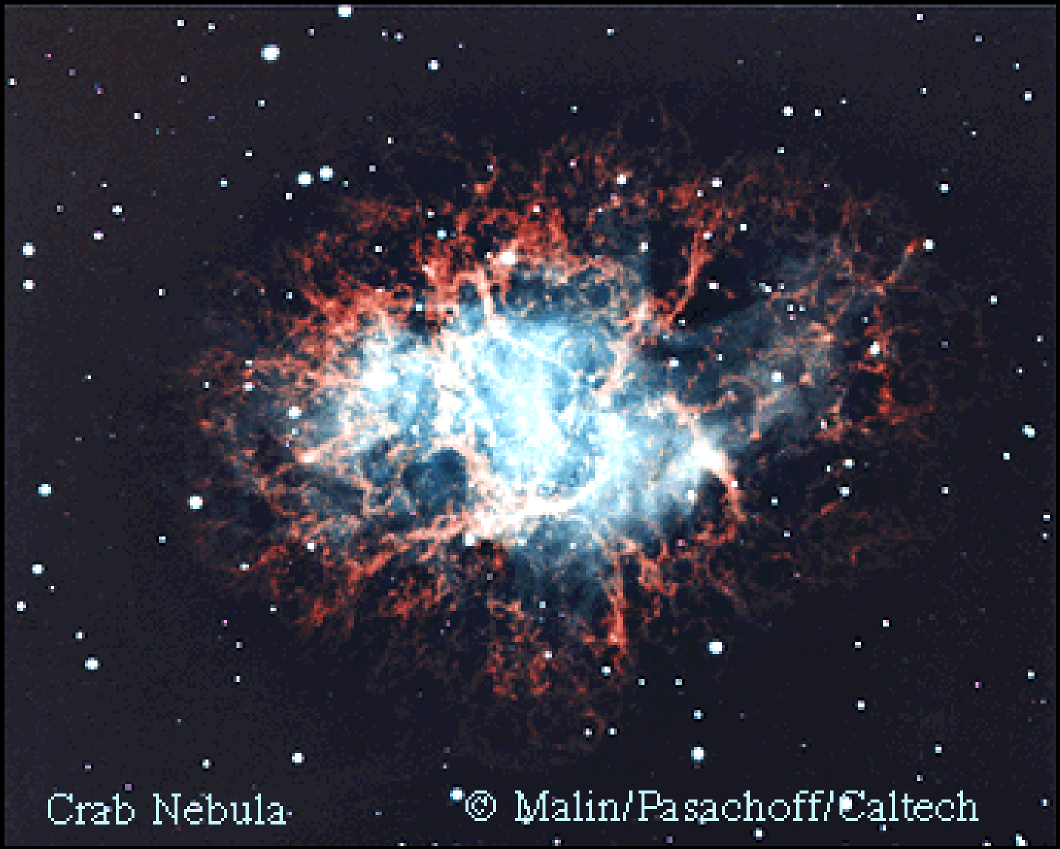
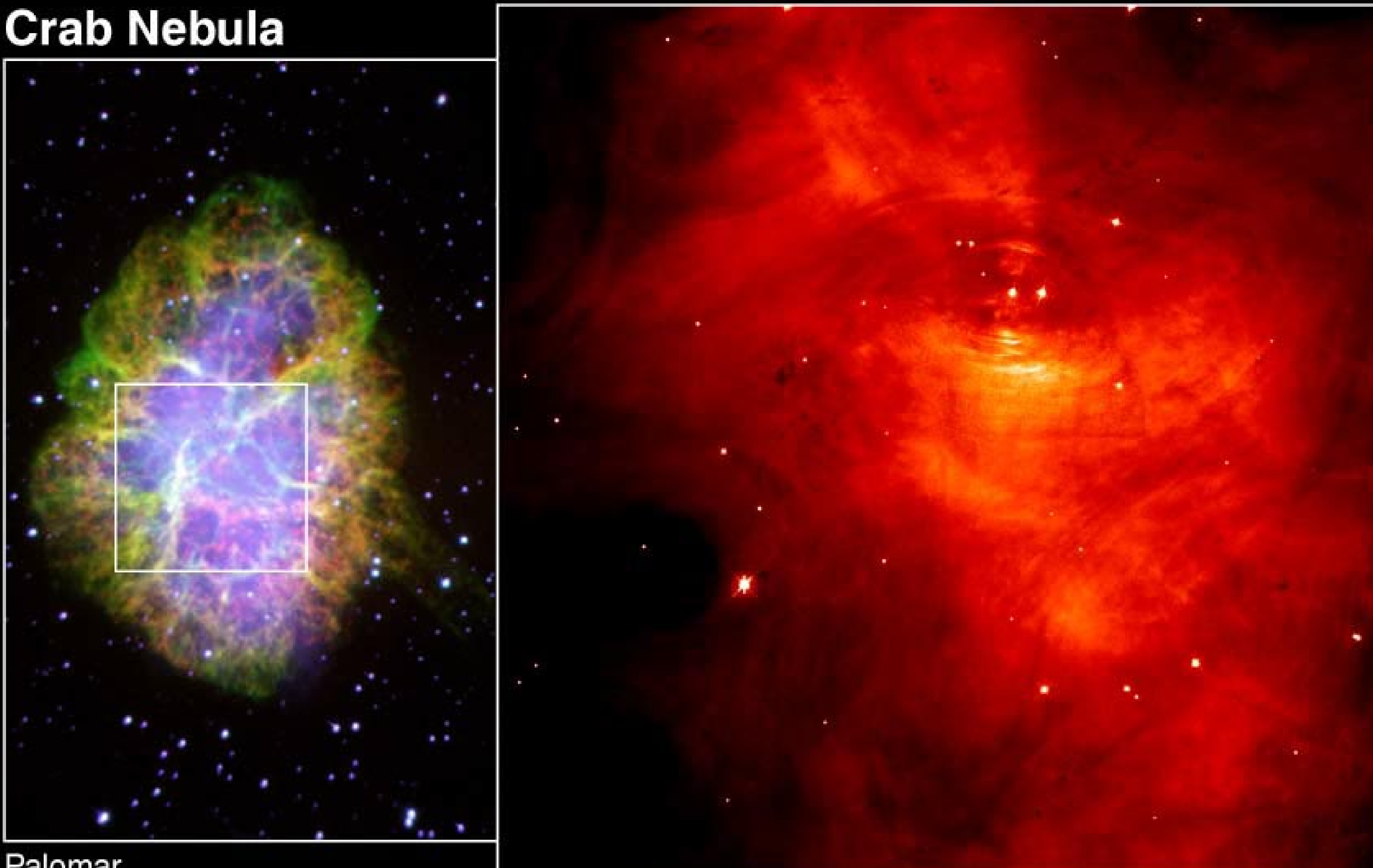
"Styrofoam"

Massive Stars & Supernovae

- Winds from O stars account for 30% of recylcable input to ISM
- Supernovae from O stars throw out much of the remaining mass
- Biggest contribution of (correlated) supernovae is to "collection"



Crab Nebula



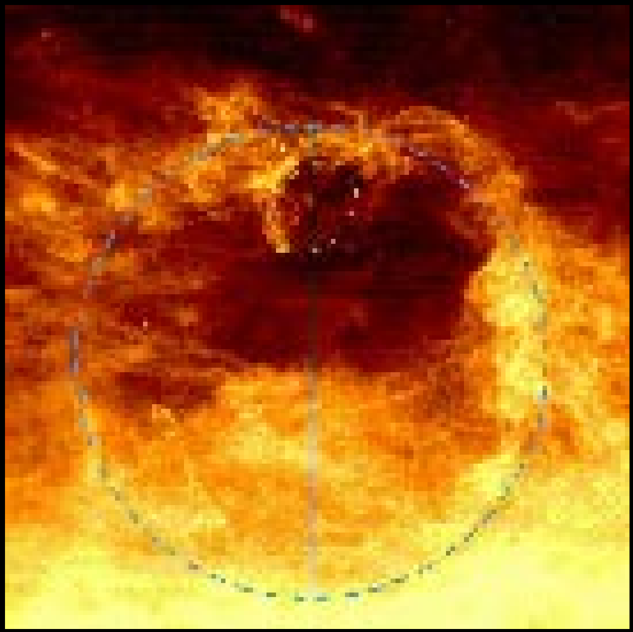
Palomar

HST • WFPC2

PRC96-22a • ST ScI OPO • May 30, 1996

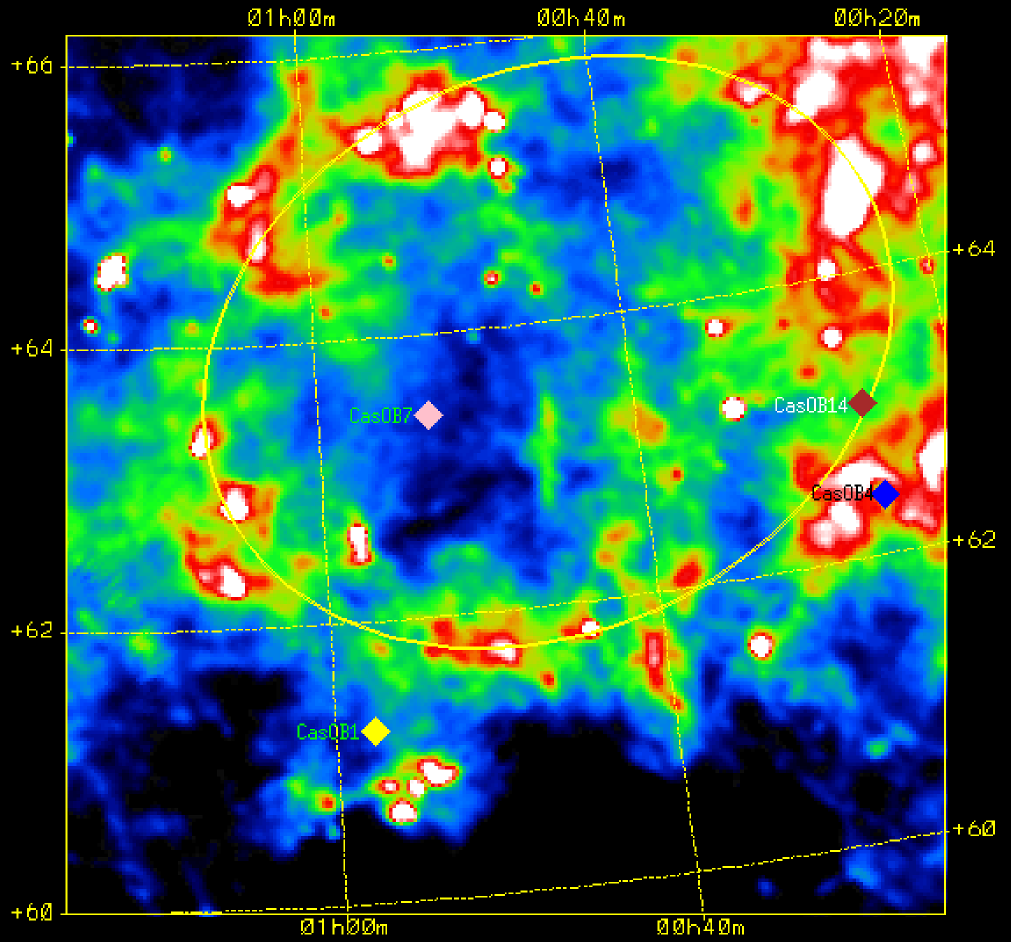
J. Hester and P. Scowen (AZ State Univ.) and NASA

Swept-up Gas:The Next Generation



Far-infrared dust emission
map of North Celestial Pole Loop,

Pound & Goodman 1997



Spectral-line Emission from
Gas In Cassiopeia
Tóth et al. 1995

(At least) How much Gas is Swept-Up?

Warning Globe Readers: Simple Algebra to Follow!

$Radius = R = 20 \text{ pc}$

$Volume = V = \frac{4\pi}{3} R^3$

D [illegible] $Volume = \rho$

$\rho_{ISM} \approx 1 \text{ atom / cc} = 1.67 \times 10^{-24} \text{ g / cc}$

$Mass_{swept-up} = \frac{4\pi}{3} R^3 \rho = 1.5 \times 10^{36} \text{ g} = 800 \text{ Solar Masses}$

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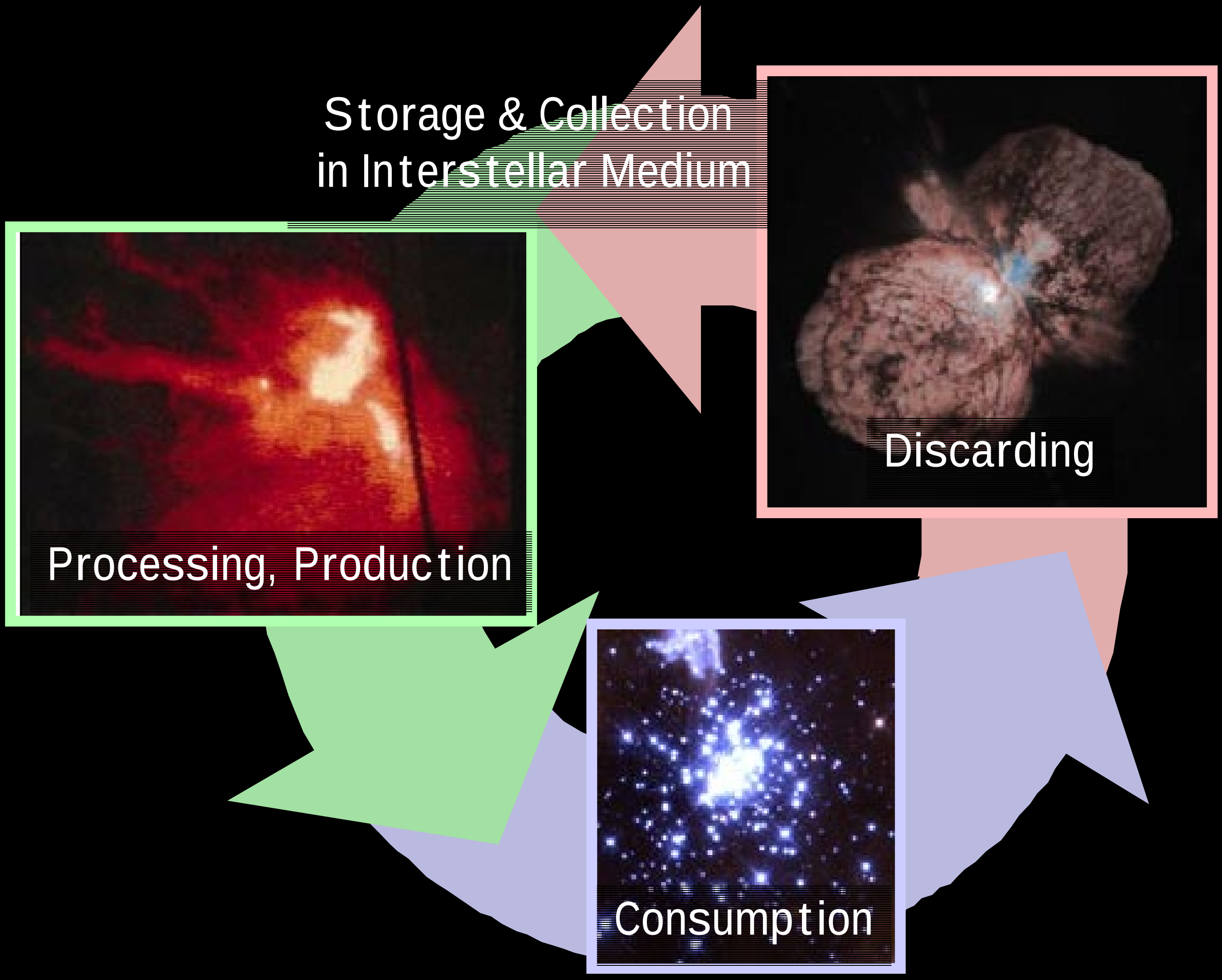
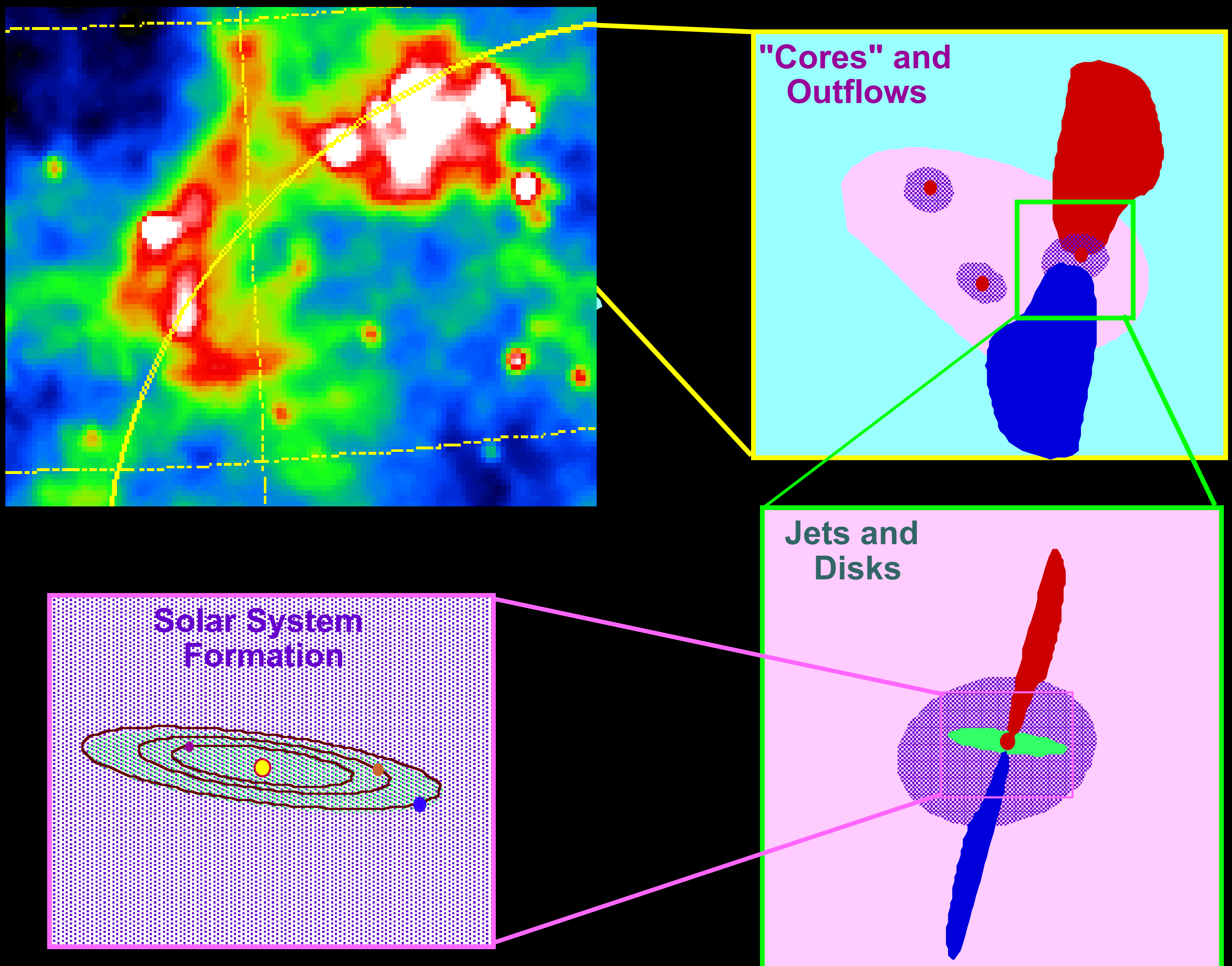
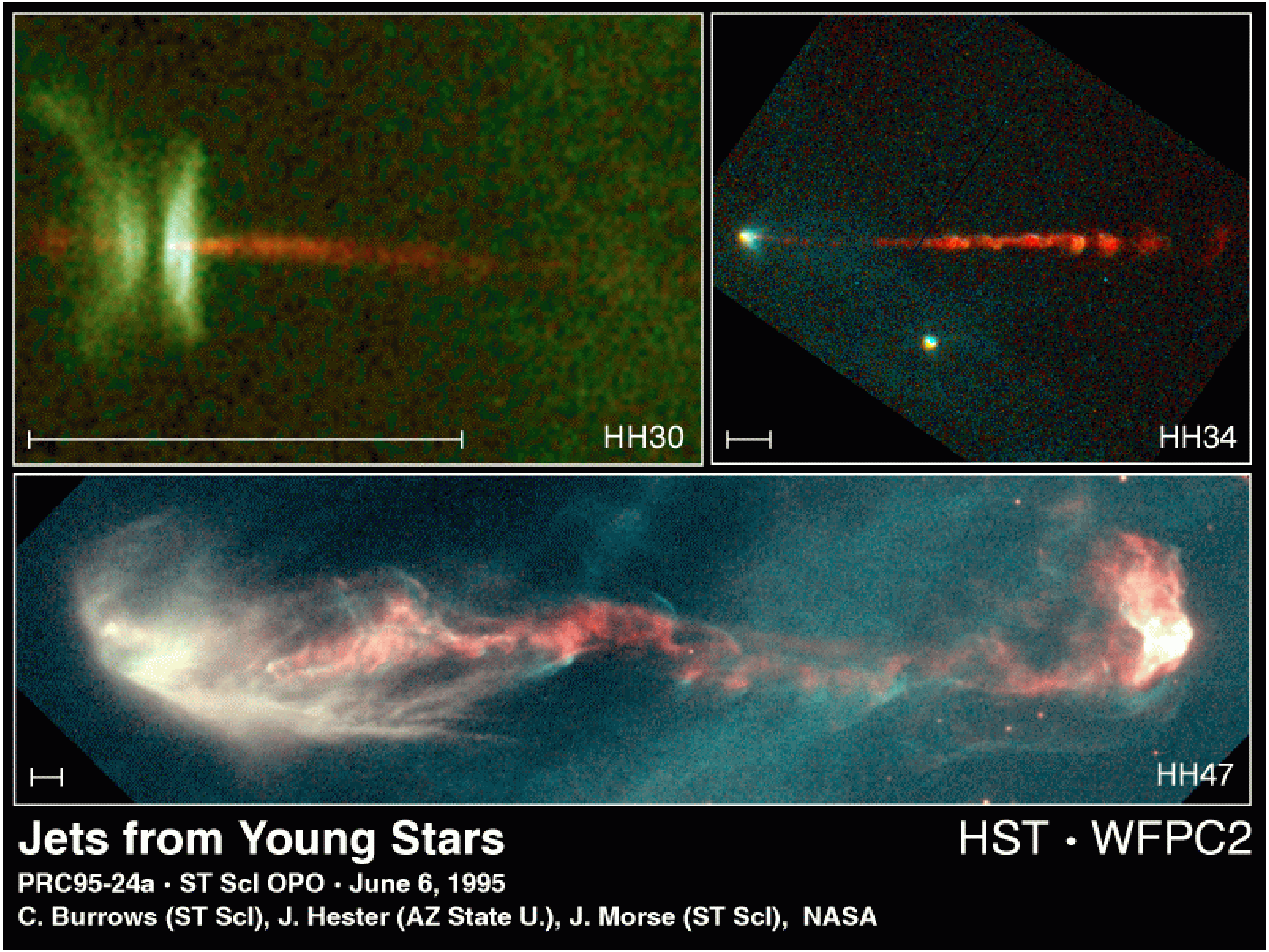
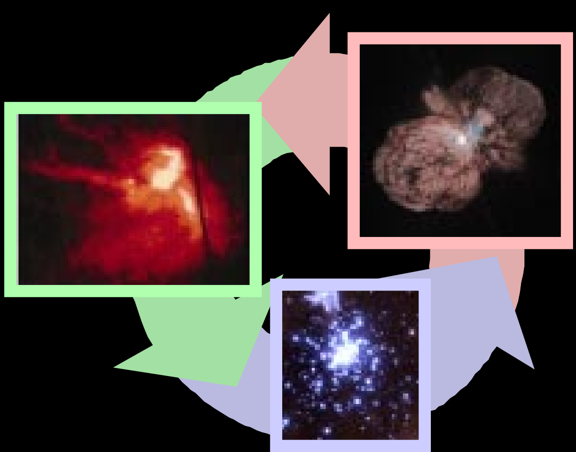


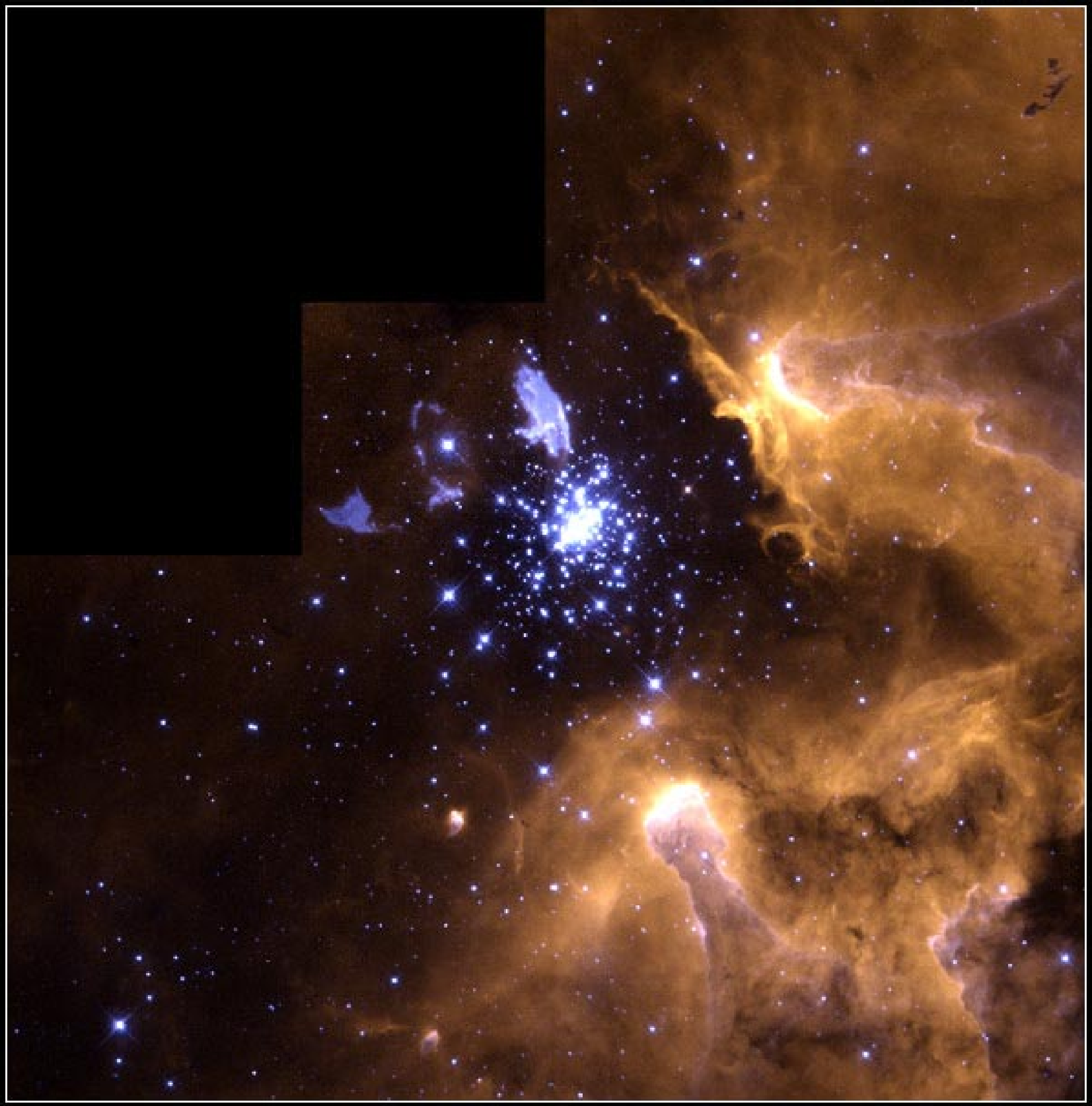
Young Stars do Their Share Too




HH30
HH34
HH47
Jets from Young Stars
HST • WFPC2
PRC95-24a • ST ScI OPO • June 6, 1995
C. Burrows (ST ScI), J. Hester (AZ State U.), J. Morse (ST ScI), NASA

One Picture with the Whole Story





NGC 3603 **HST** • WFPC2

PRC99-20 • STScI OPO • June 1, 1999

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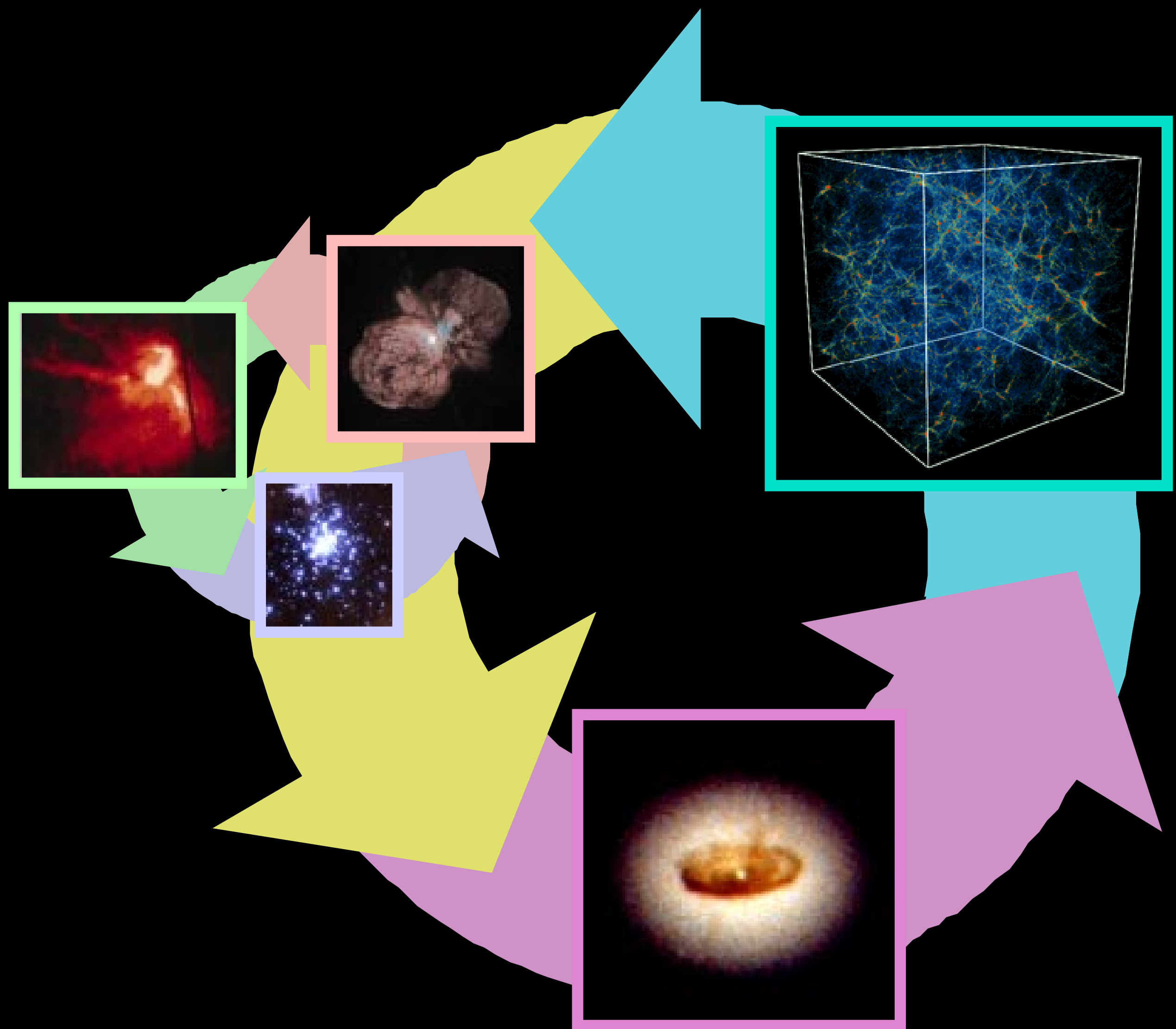
Recycling ~~in~~ the Universe(?)



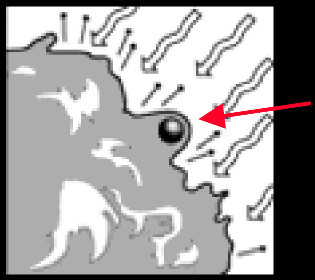
For more information...

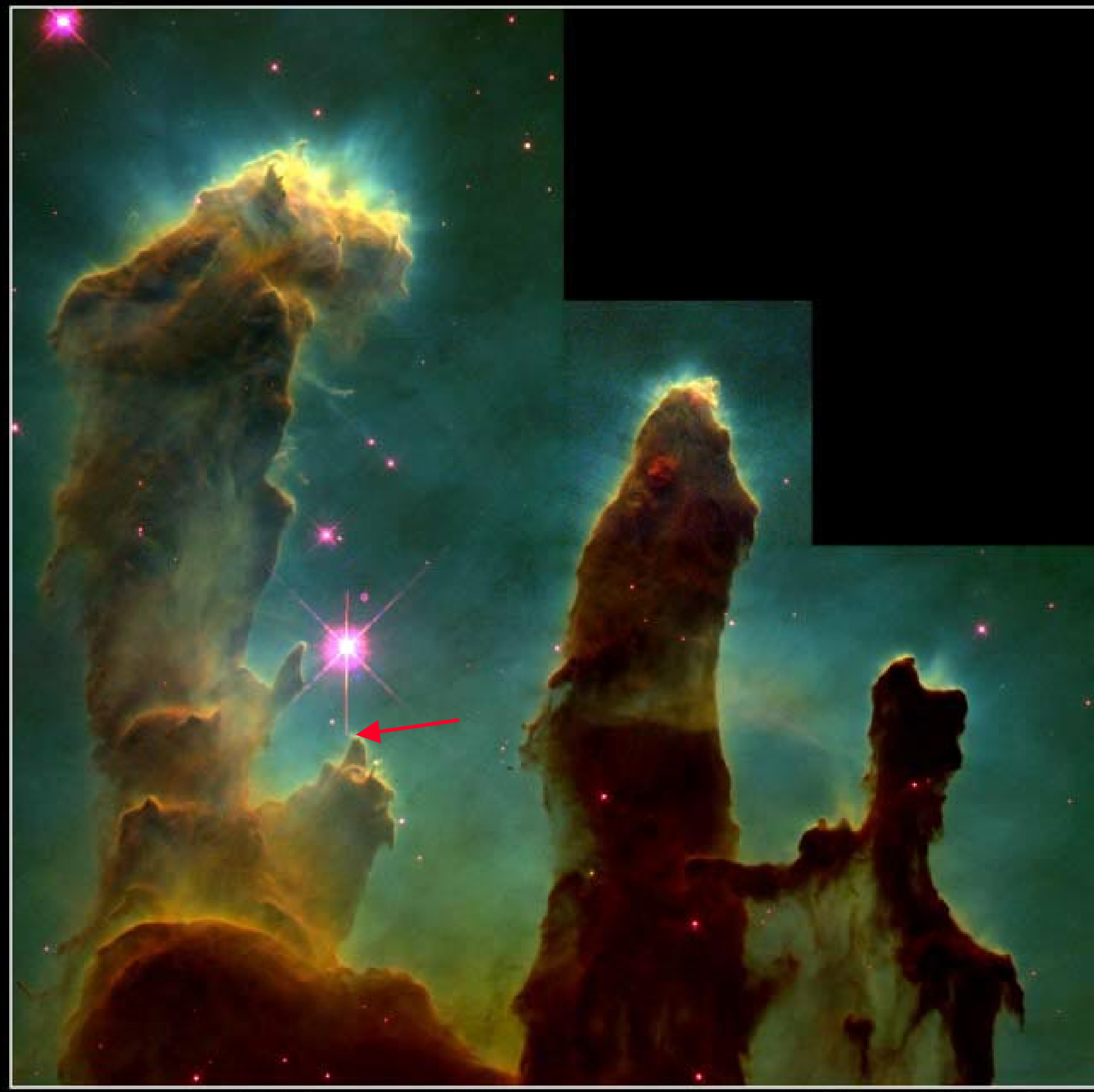
cfa-www.harvard.edu/~agoodman

and

Alyssa Goodman's upcoming article in
Sky & Telescope Magazine

(Unusual?) Stellar Nursery in the Eagle Nebula





Gaseous Pillars · M16 HST · WFPC2

PRC95-44a · ST ScI OPO · November 2, 1995
J. Hester and P. Scowen (AZ State Univ.), NASA

Star Formation Caused by A Galaxy Collision (a.k.a. igniting the trash)