Galactic Radio Science

Including recent results from NRAO facilities

Claire Chandler, NRAO (with thanks to Cornelia Lang and Crystal Brogan)

Associated Universities, Inc.

Atacama Large Millimeter/submillimeter Array
Karl G. Jansky Very Large Array
Robert C. Byrd Green Bank Telescope
Very Long Baseline Array

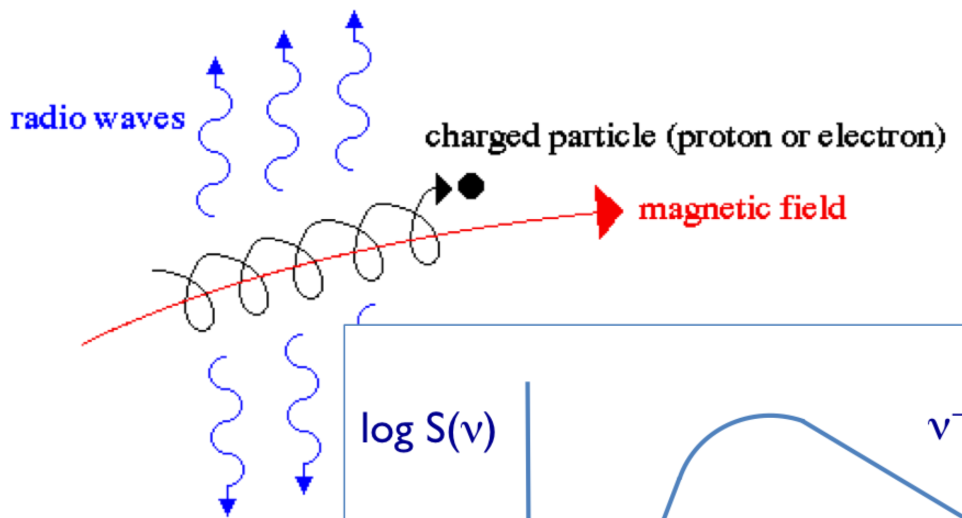
NRAO

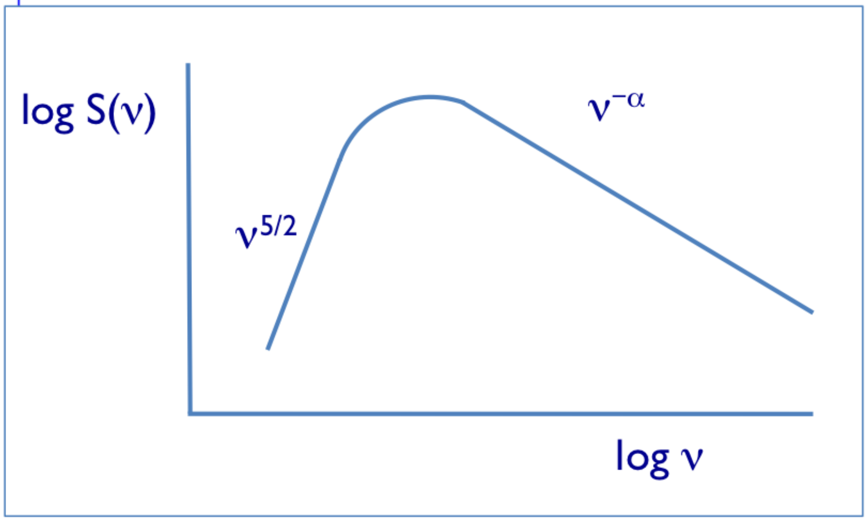
Outline

- What can we learn from radio emission – radio emission mechanisms with examples
  - Thermal and non-thermal continuum emission
  - Thermal and non-thermal spectral line emission
  - Considerations for observing galactic sources
- A tour of selected galactic radio sources
  - Stellar birth
  - Stars
  - Stellar death
  - The interstellar medium

Radio emission mechanisms

- Synchrotron radiation
  - Non-thermal continuum process, arises from energetic charged particles spiraling (accelerating) along magnetic field lines
  - Emission spectral index → energy distribution of electrons
  - Equipartition → magnetic field strength
  - Polarization → direction of magnetic field



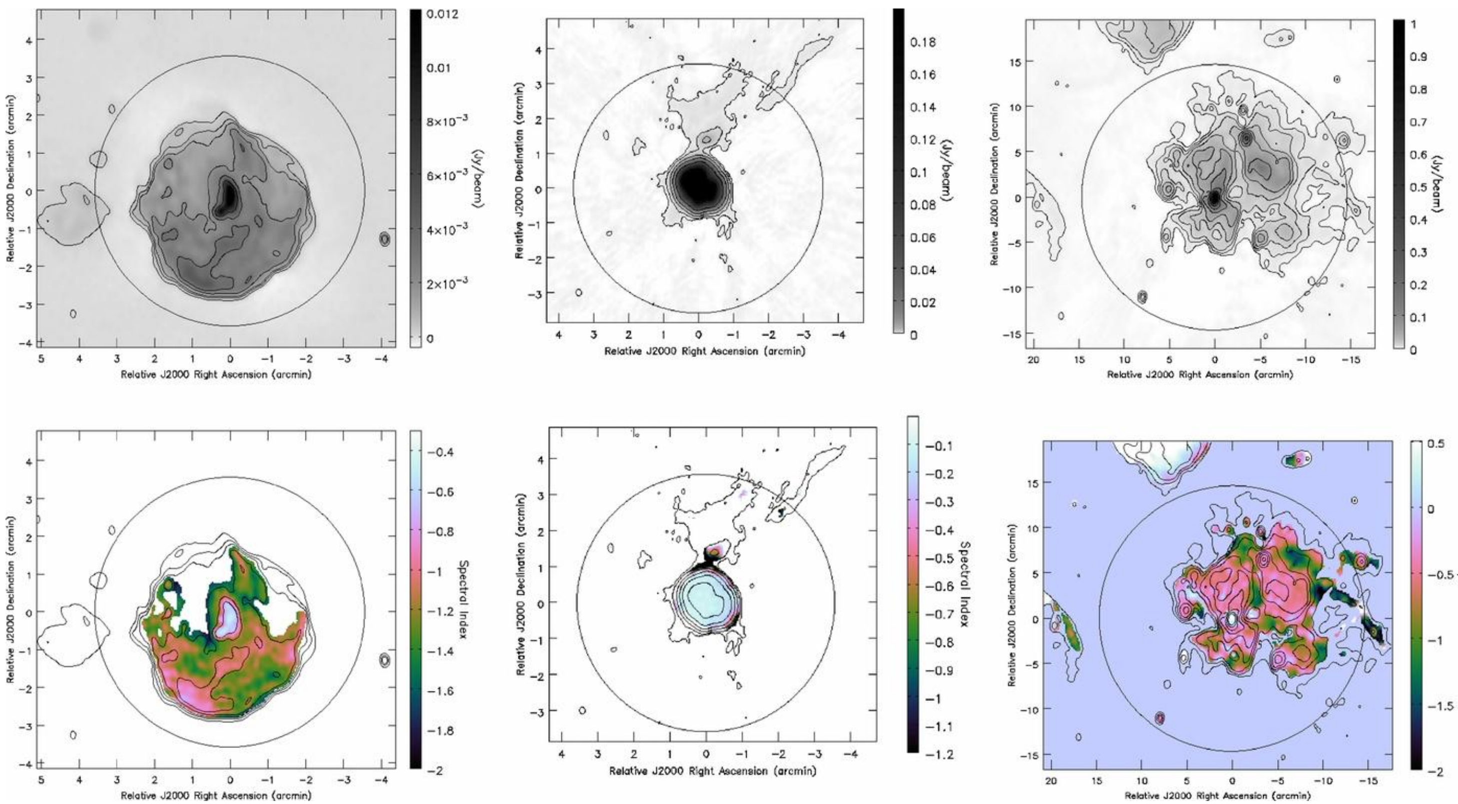


Synchrotron emission: SNRs

- EVLA imaging of supernova remnants (Bhatnagar et al. 2011)

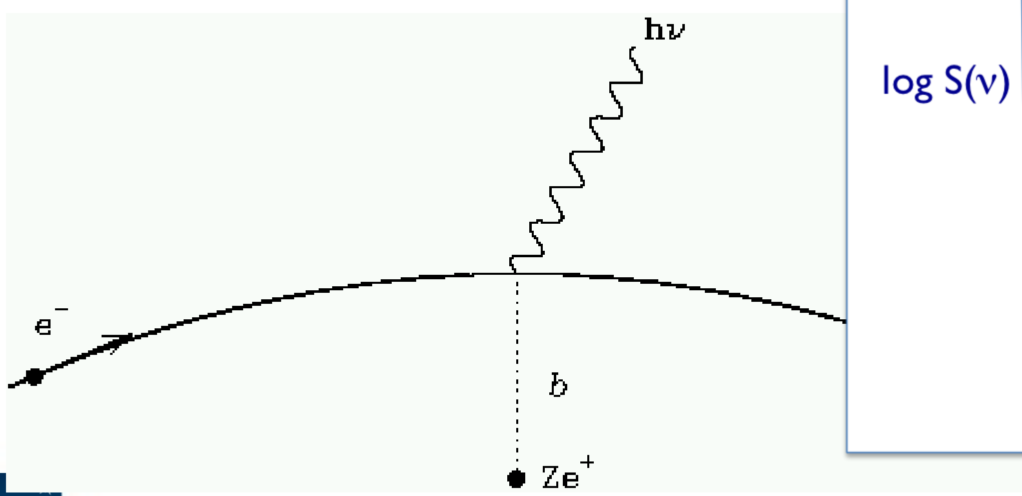
Stokes I

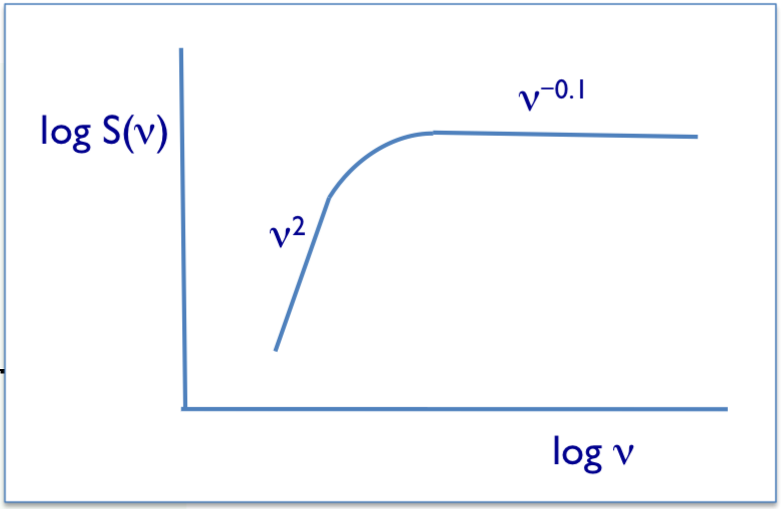
Spectral index, α



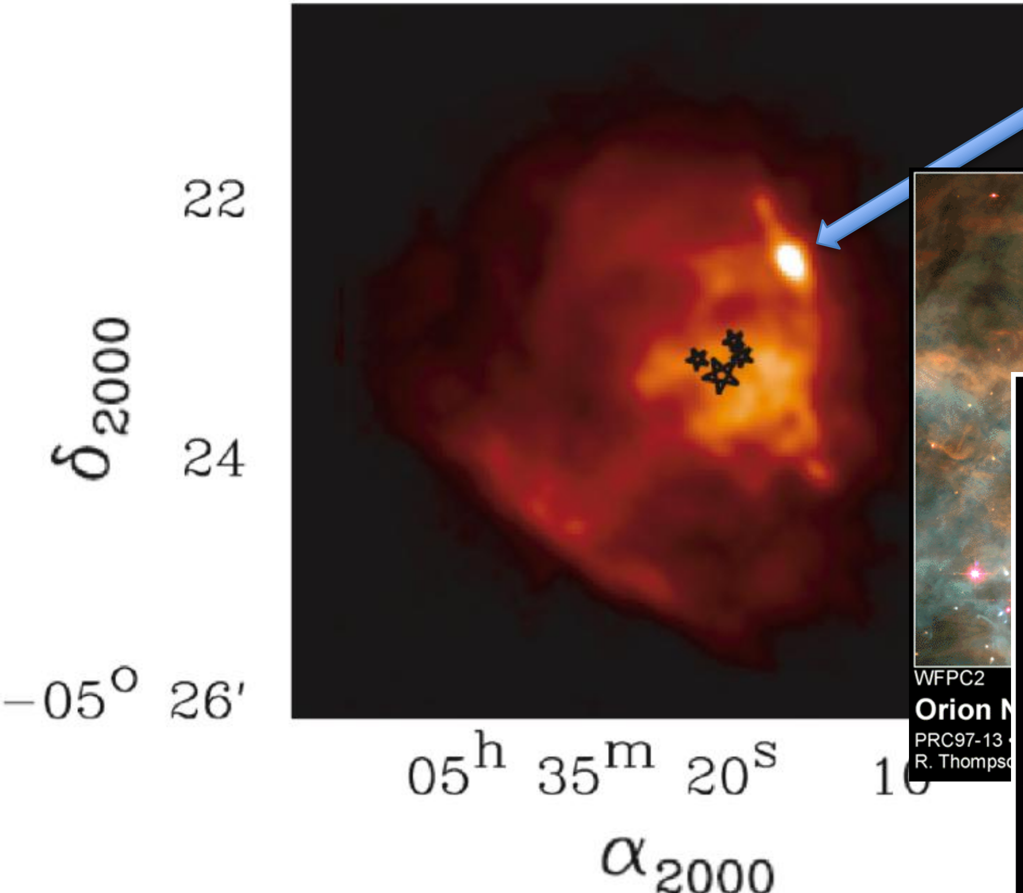
Radio emission mechanisms

- Bremsstrahlung (free-free) emission
  - Thermal continuum process, arises from electrons being accelerated by ions in a plasma
  - Mass of ionized gas
  - Optical depth
  - Density of electrons in the plasma
  - Rate of ionizing photons

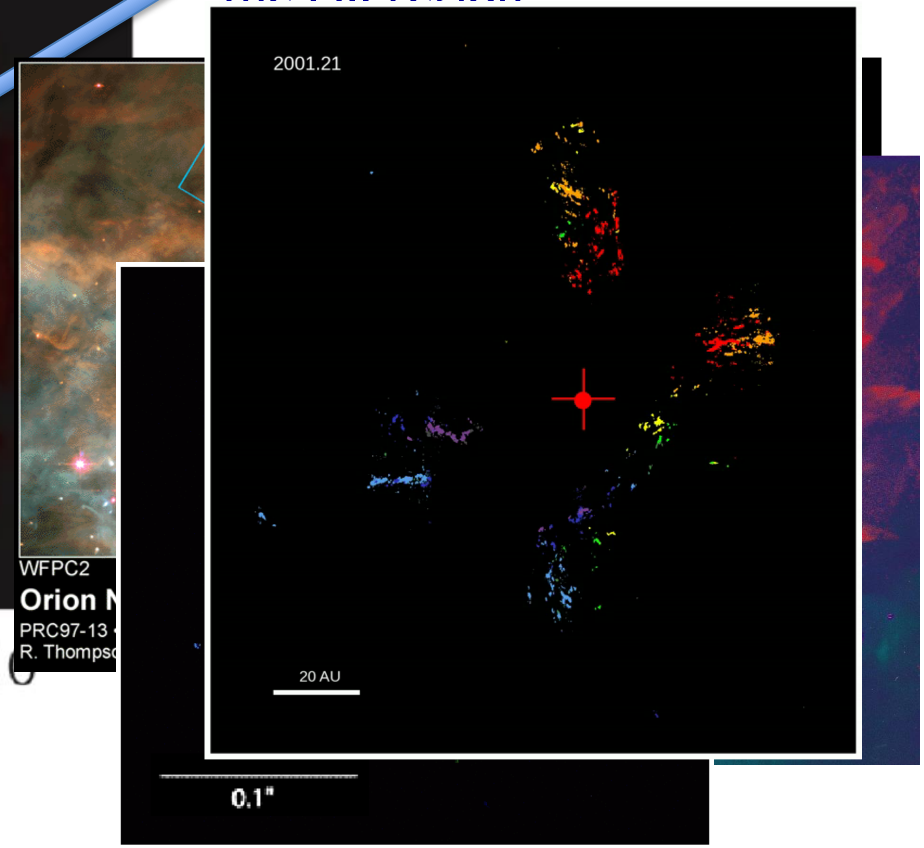




Bremsstrahlung emission: Orion nebula



Dust cloud located *behind* the HII region

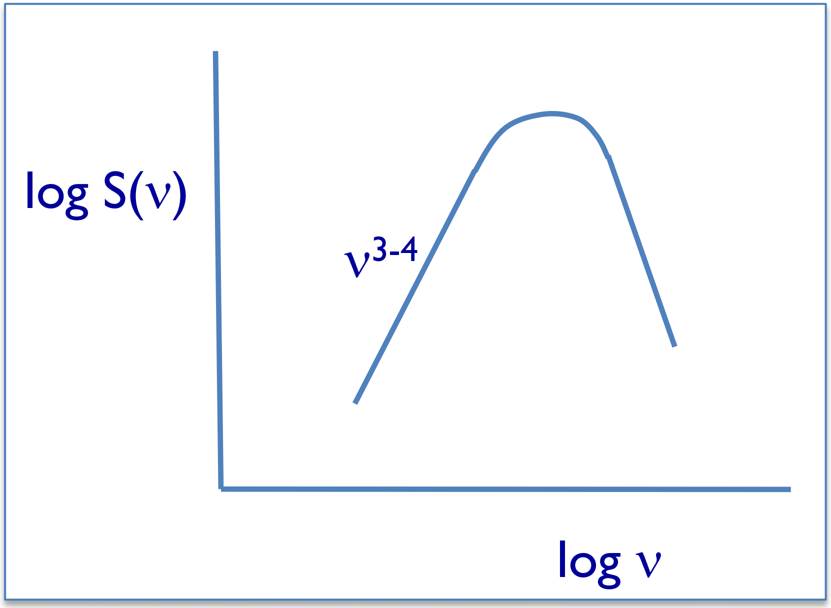


Orion nebula observed with 90 GHz camera on GBT (Dicker et al. 2009)

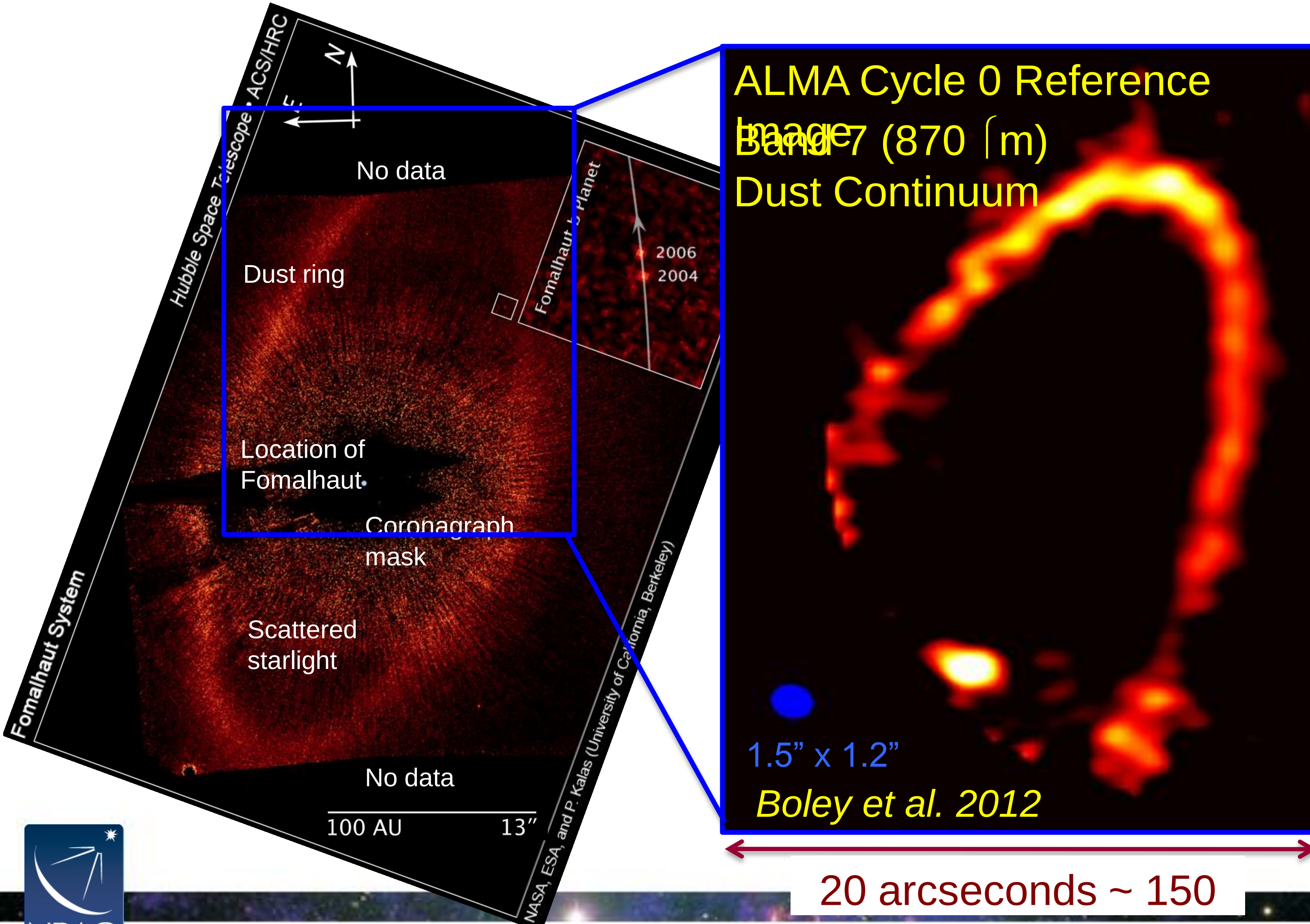
Source I: Reid et al. (2007), Matthews et al. (2010)

Radio emission mechanisms

- Dust emission
  - Thermal continuum process, modified black-body emission from dust grains ~10 to ~ few 100 K
  - Spectrum of dust emissivity/opacity → dust properties (grain size)
  - Dust temperature
  - Dust mass (assume a gas-to-dust ratio → total gas mass)



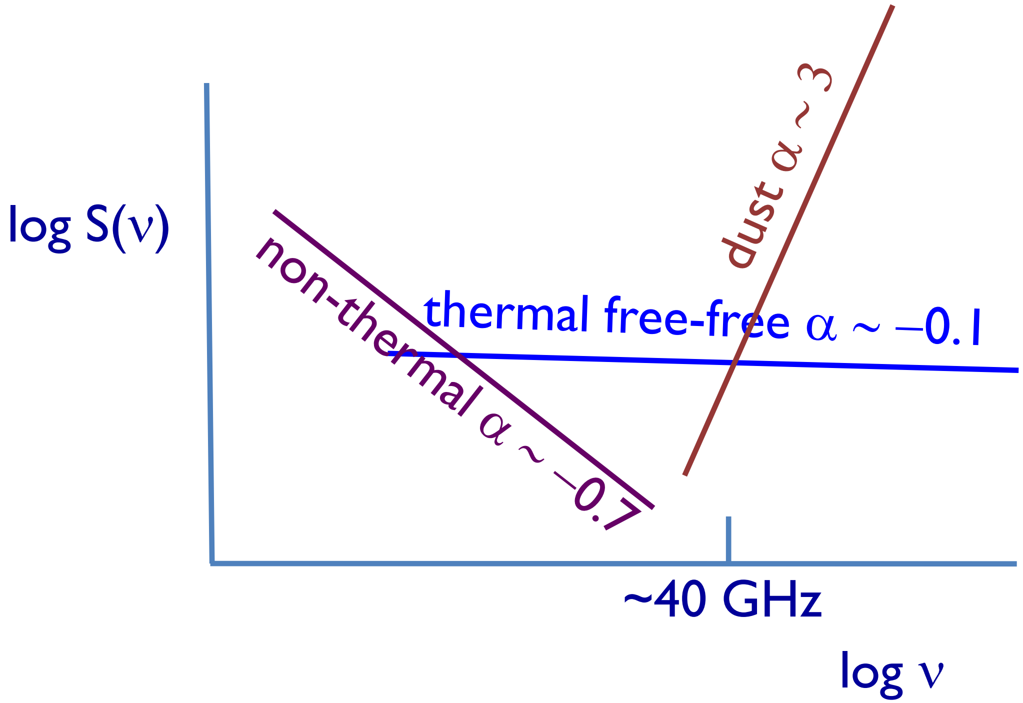
Dust emission: Fomalhaut



20 arcseconds ~ 150 AU

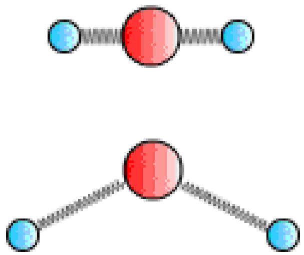
Continuum spectral index

- $S(\nu) \propto \nu^{\alpha}$
- Measurement of spectral index, α, is key to interpreting the origin of the radio emission, and translating $S(\nu)$ into physical properties of the source

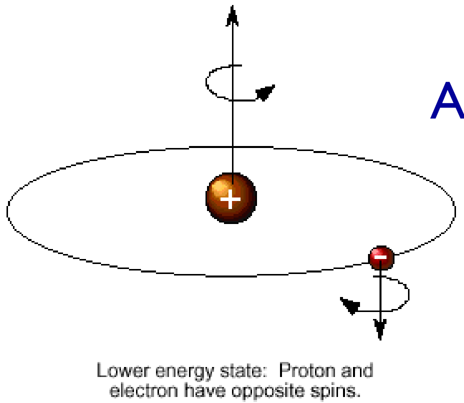


Radio emission mechanisms

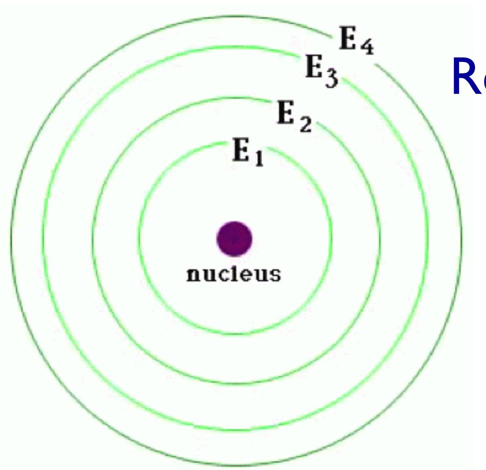
- Spectral line emission: discrete transitions in atoms and molecules
  - Physical and chemical conditions of the gas (density, temperature)
  - Kinematics (Doppler effect)
  - Zeeman effect → B-field
  - Masers



Molecular lines:
CO, CS, H_2O,
SiO, CH_3OH,
NH_3, etc…



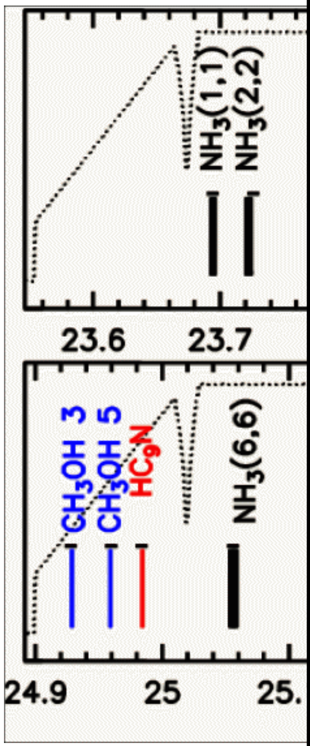
Atomic hydrogen:
21cm "spin-flip" transition

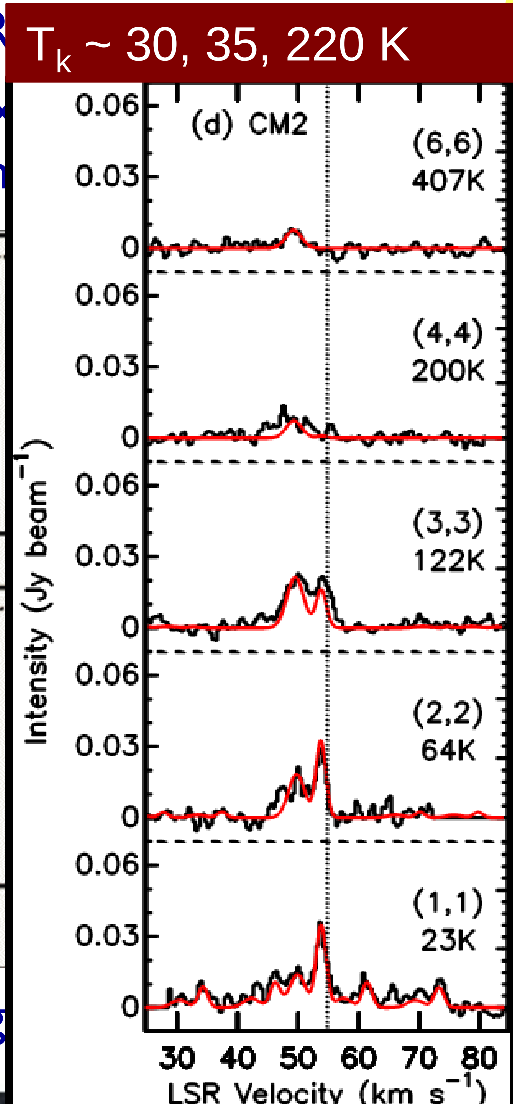


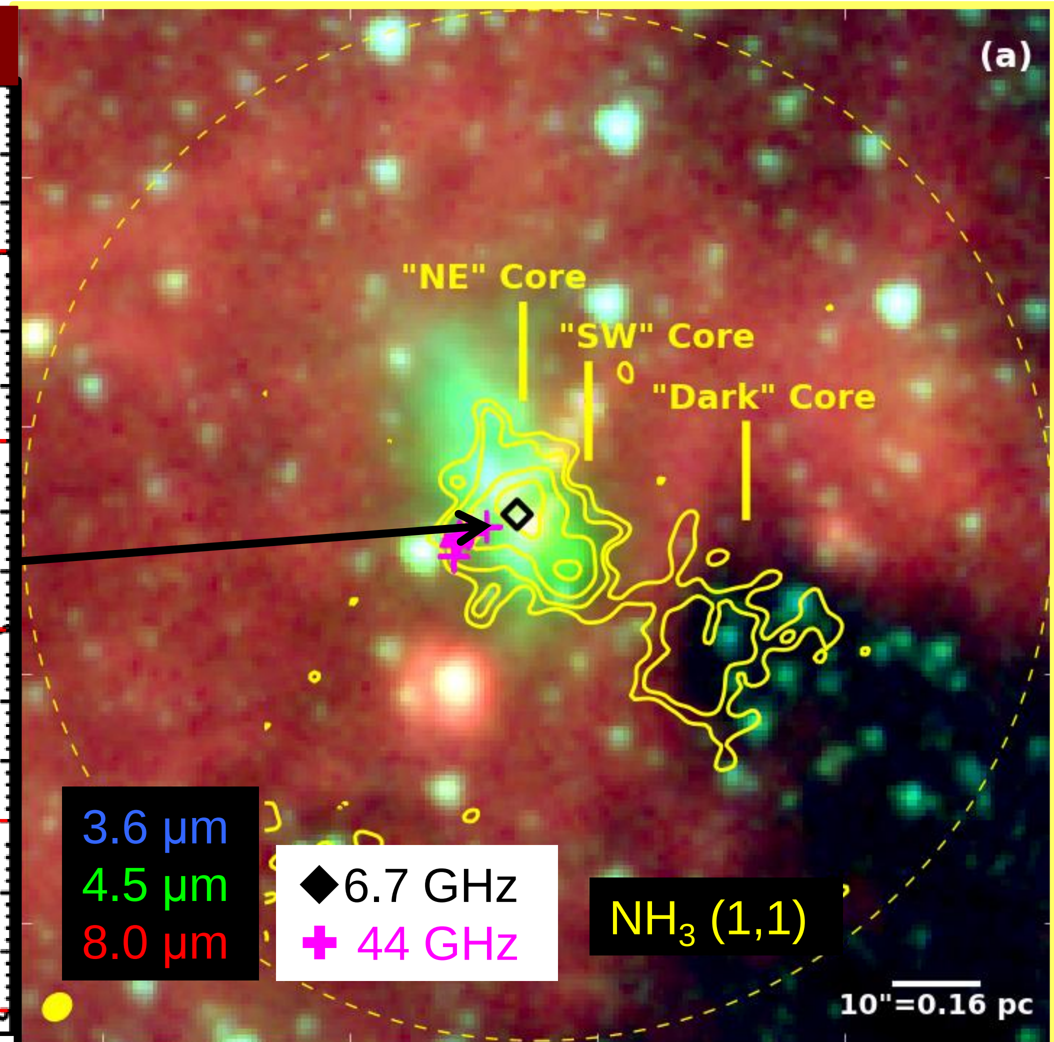
Recombination lines:
outer electronic transitions of H, He, C

Spectral line emission: G35.03+0.35

- WIDAR
  - 16 x
    tran







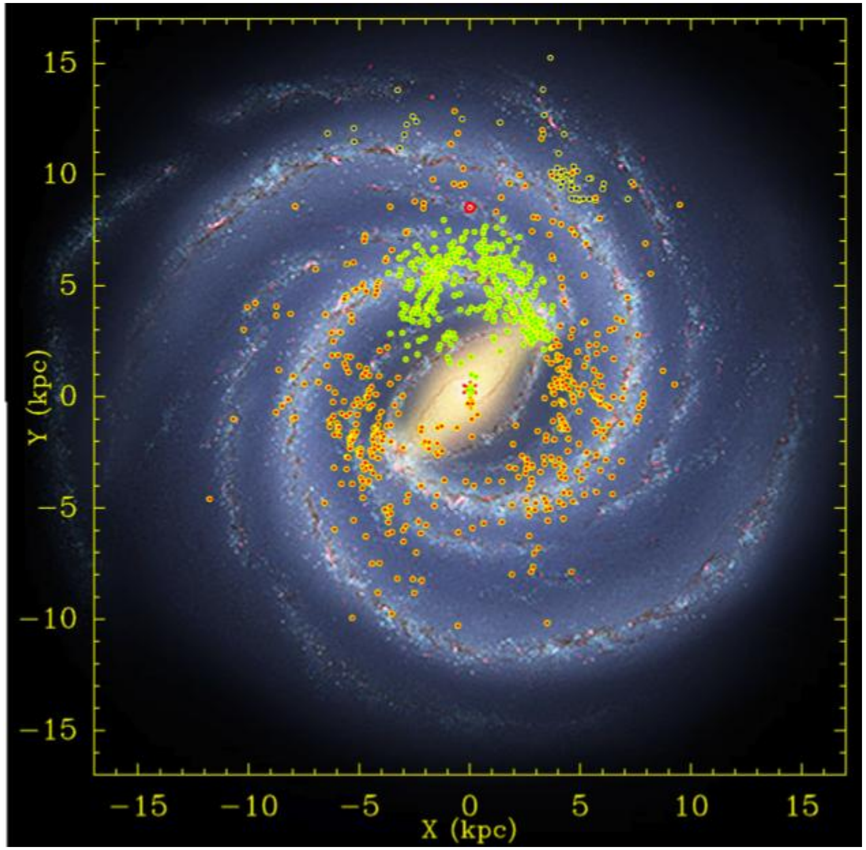
  - Cyg

Considerations for proposing/observing

- Need multi-frequency to determine α
- Instrument sensitivity
- Source structure!
  - Galactic sources range from point-like (stars, masers) to very extended (GMCs, SNRs) – match your science goals to your telescope/configuration
- From the D to A configurations the VLA varies its angular resolution by a factor ~35 (depends on *largest* baseline/telescope separation) at a given frequency, reconfigures every ~4 months
  - The *shortest* baseline sets the largest angular scale measured
  - Compact configurations give less spatial resolution but better surface brightness sensitivity
- ALMA will be continuously re-configuring its antennas
- VLBA/VLBI has the highest spatial resolution of *any* ground-based observatory but requires very high surface brightness $\rightarrow$ mostly non-thermal sources

Galactic structure with the VLBA

- Bar and Spiral Structure Legacy Survey (BeSSeL) project: use methanol and water masers in star-forming regions, along with exquisite astrometry from the VLBA, to map out the spiral structure of the Milky Way using trigonometric parallax
  - Probes obscured regions to far side of Galaxy
- Results so far:
  - Milky Way 2 times more massive than previously thought
  - $R_{\odot}$ = 8.3 kpc (vs. 8.5 kpc)
  - $\Theta_{\odot}$= 239 km/s (vs. 220 km/s)
  - Previous values can yield kinematic distanced in error by a factor of 2



http://www.mpifr-bonn.mpg.de/staff/abrunthaler/BeSSeL

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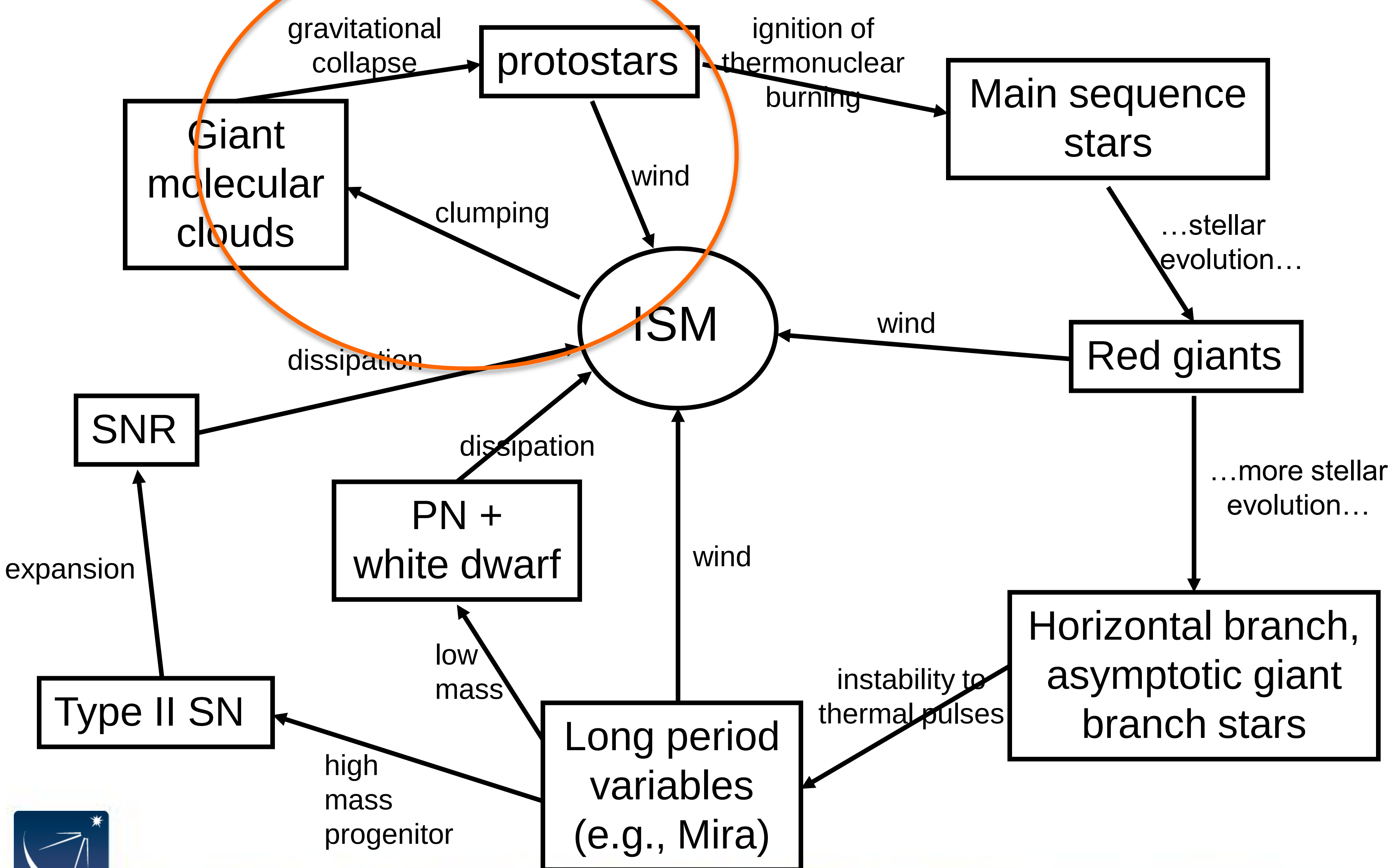
Stellar birth, death, and the ISM

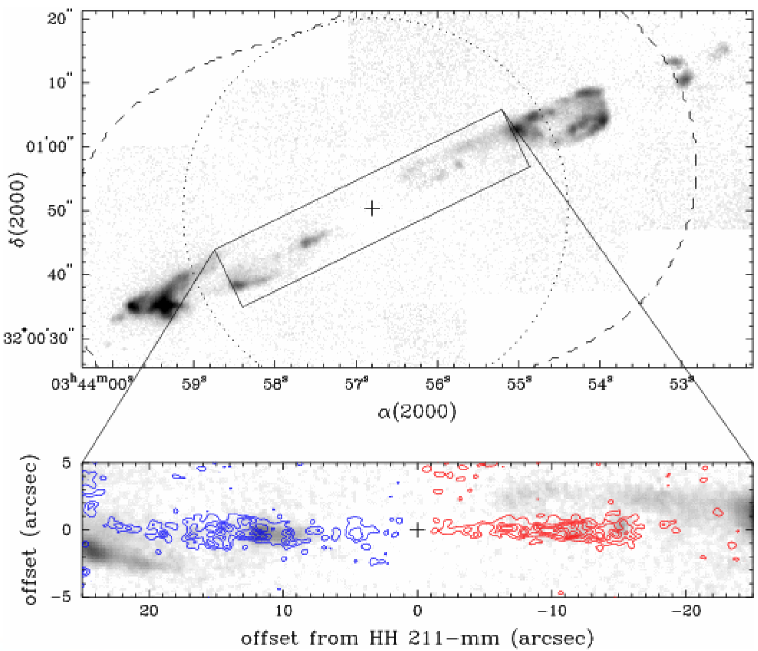


Star formation

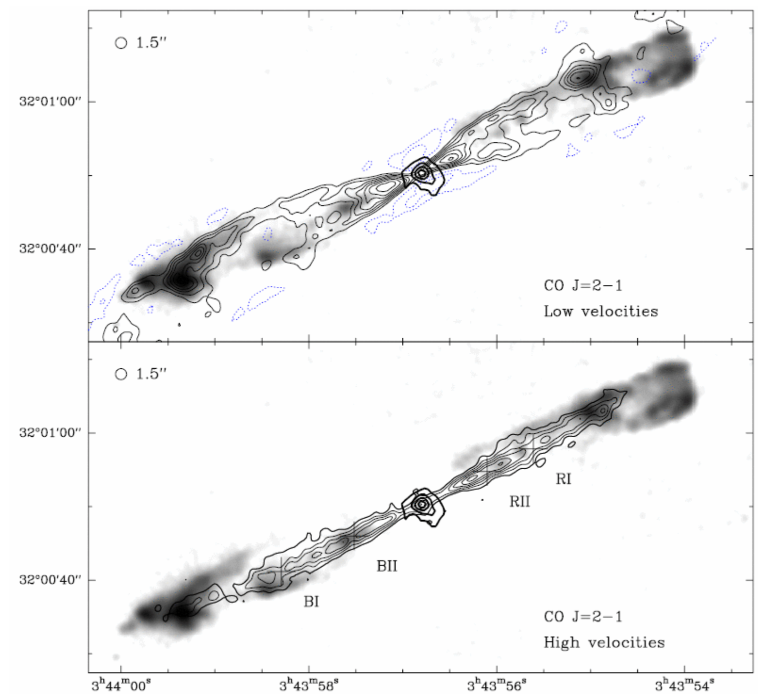
- Formation of massive stars, HII regions (Orion)
- Formation of protoclusters (G35.03)
- Formation of low-mass stars (examples on next slides)
  - Radio techniques vital for penetrating the dust that obscures star formation at optical/IR wavelengths, especially for the very young, deeply embedded sources
  - First showed that protostars have energetic winds and jets $\Rightarrow$ *mass loss*
- Formation of planetary systems (Fomalhaut)

Low-mass star-formation: HH211

- Collimated jet shows shocked H_2 emission (2.2μm) but protostar obsured in infrared, SiO(1–0) emission at 43 GHz traces jet closer to source
- Swept-up molecular gas is traced by CO(2–1) emission at 230 GHz and dense dust disk is detected in continuum emission



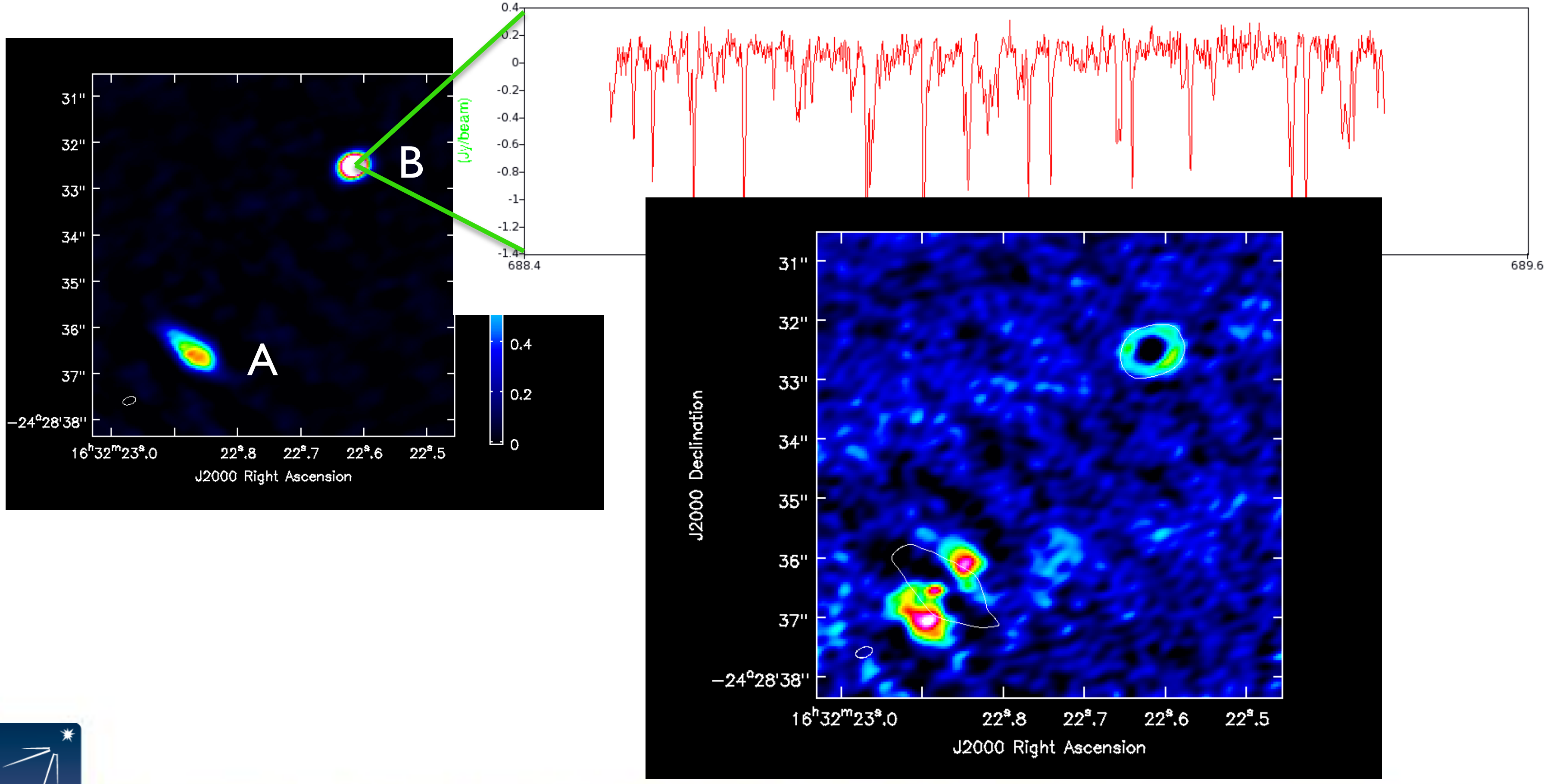
(Chandler & Richer 2001)



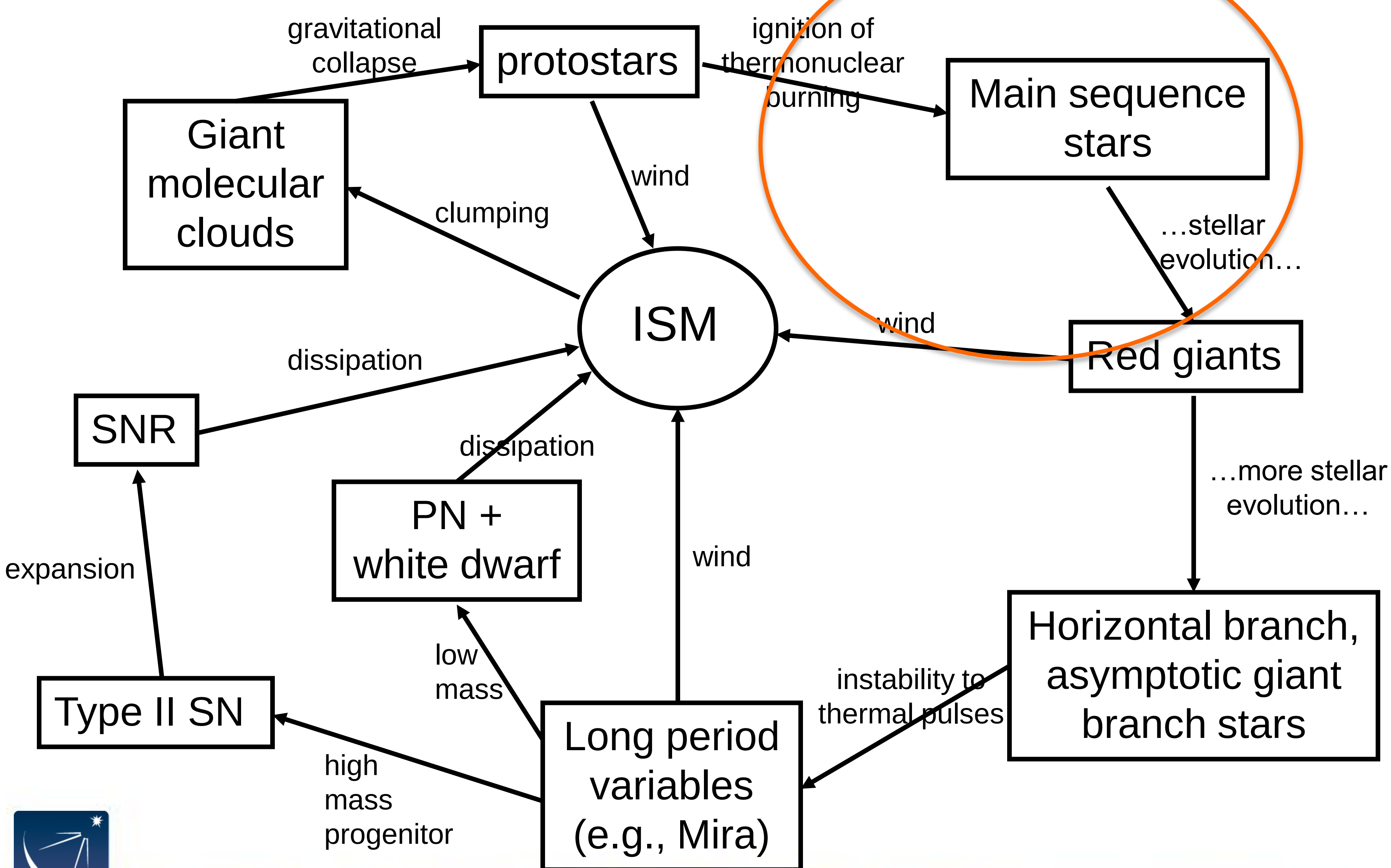
(Gueth & Guilloteau 1999)

Low-mass star-formation: IRAS16293-2422

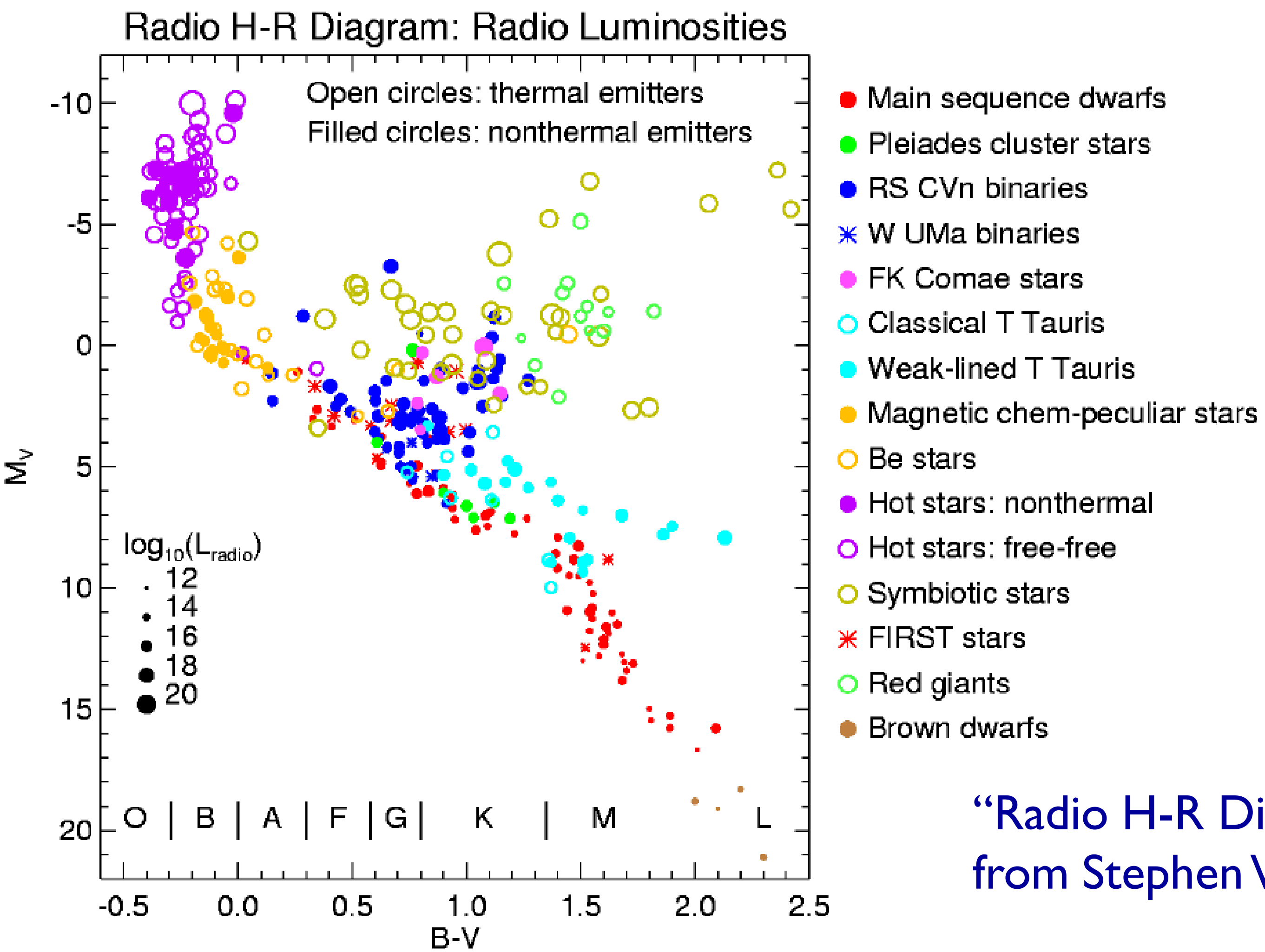
- Band 9 (690 GHz) SV data from ALMA shows optically-thick dust continuum emission from source B, T_B~150 K



Stellar birth, death, and the ISM



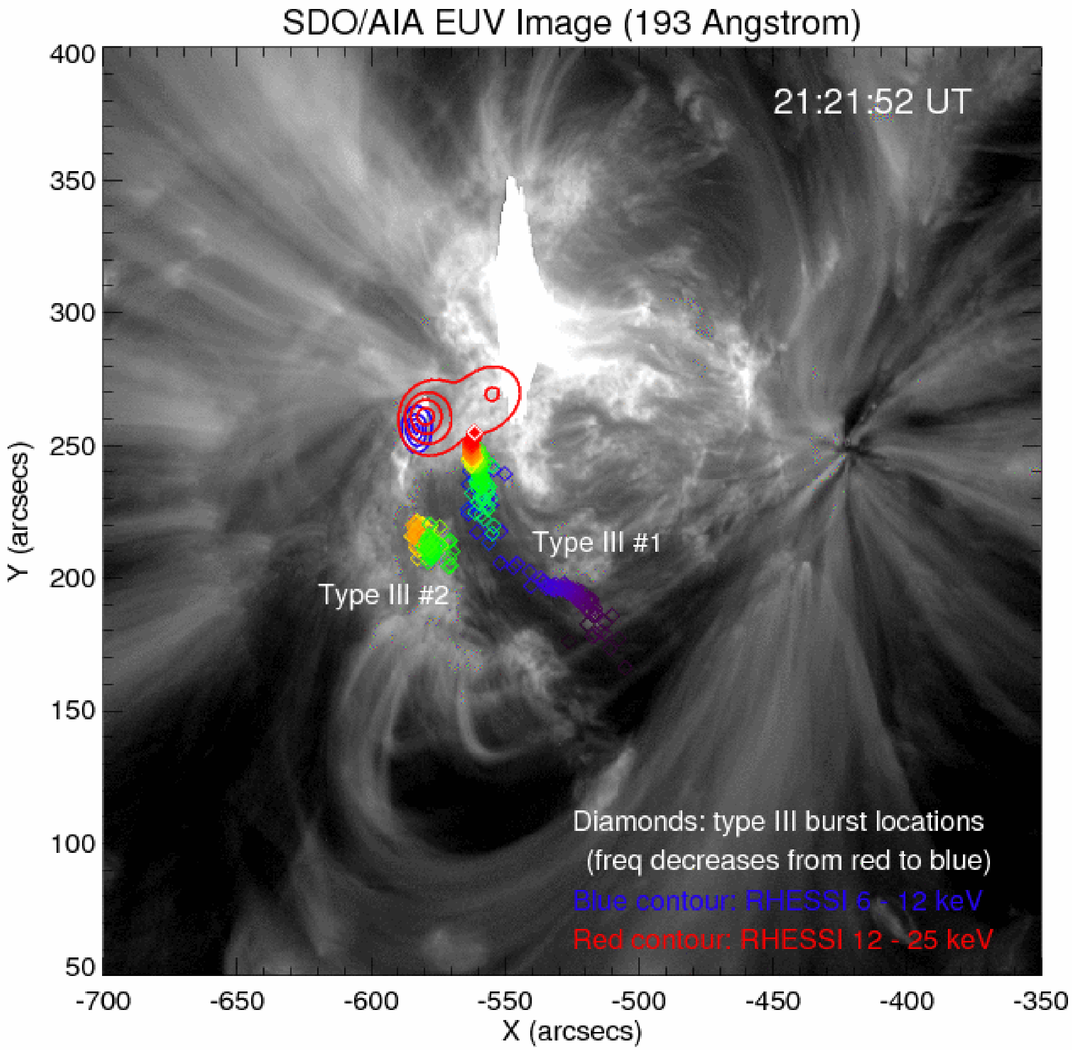
Radio emission from stars



"Radio H-R Diagram" from Stephen White

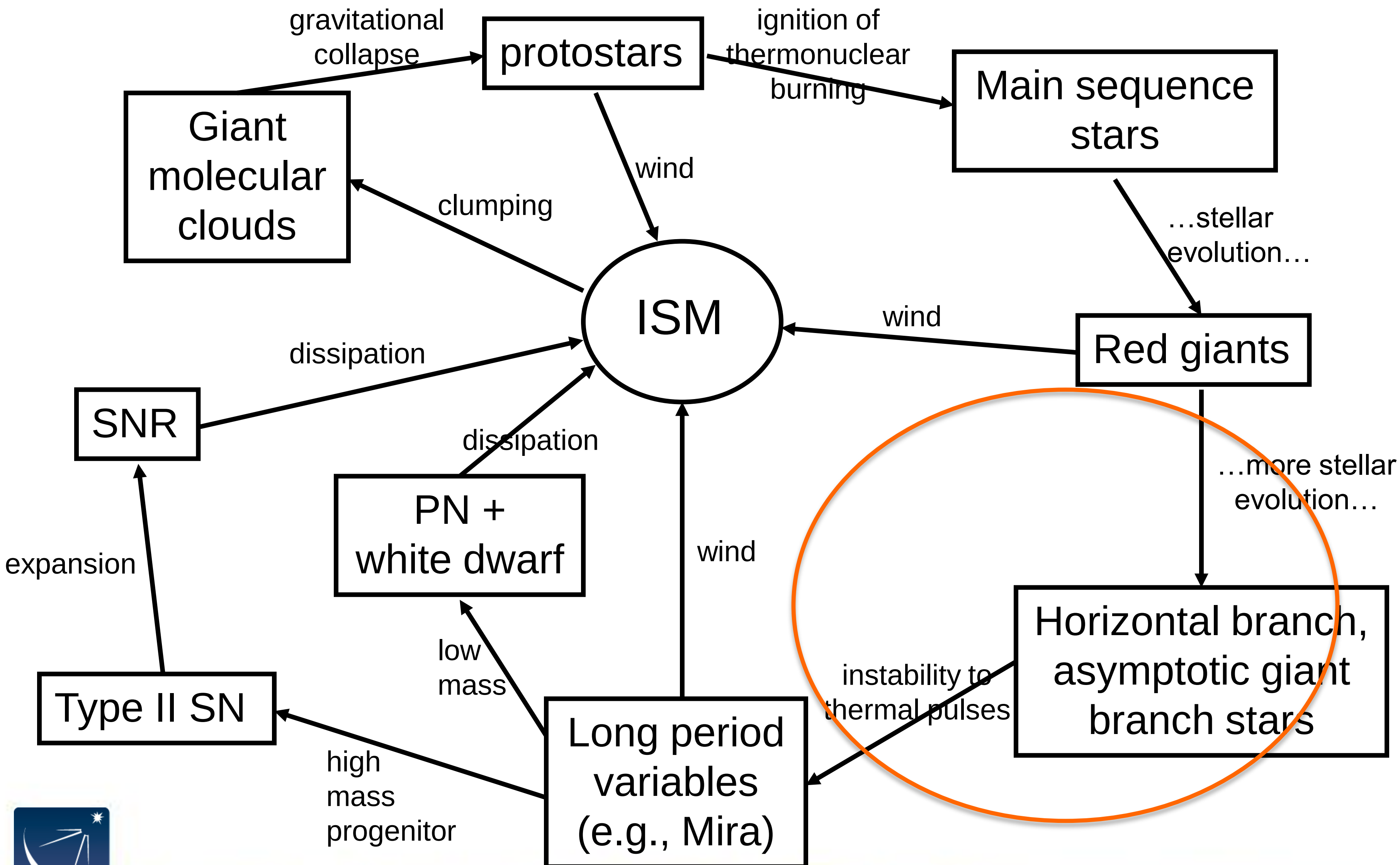
The Sun

- Strongest radio source in the sky, at ν > 100 MHz!
- 5 Nov 2011, Type III burst
  - Electrons accelerated via magnetic reconnection, emit at plasma frequency, $\nu \propto n_e^{1/2}$
  - Burst lasts < 100 ms
  - Location of peak emission from 1.5 to 1.0 GHz traces density gradient, reveals topology of B-field
- Big flares can be associated with 10s-100s of bursts



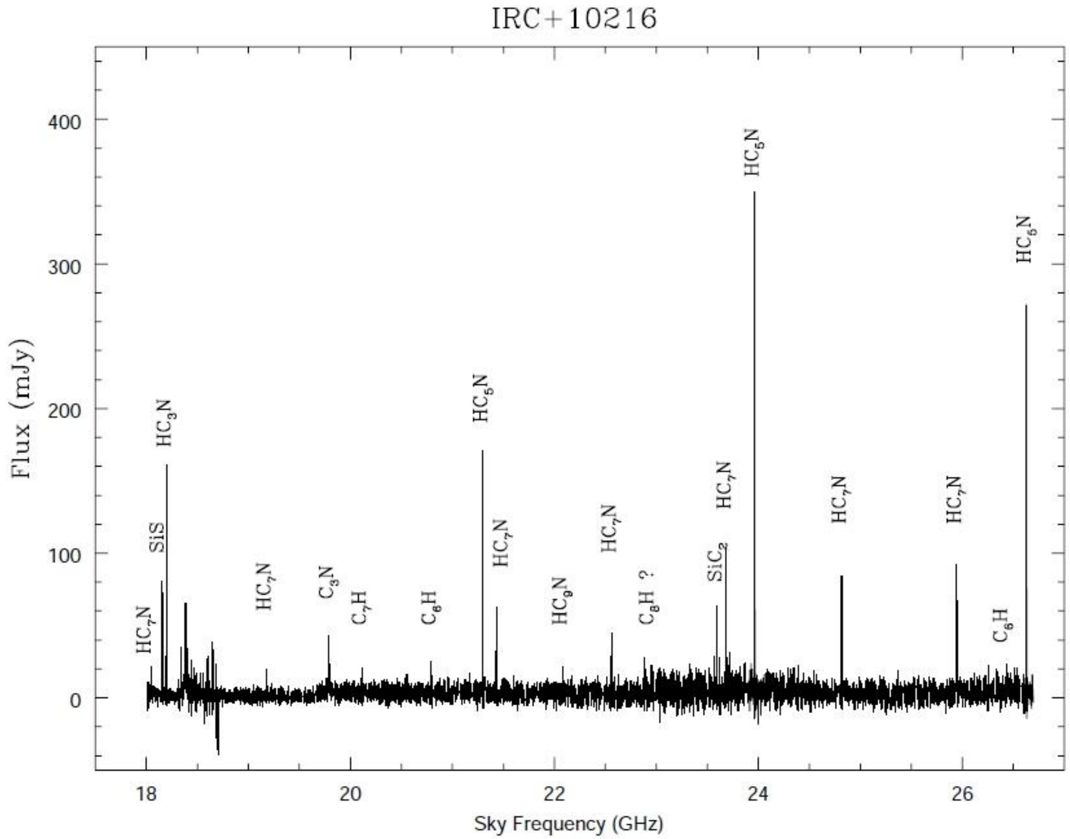
Chen et al. (in prep)

Stellar birth, death, and the ISM



The carbon-rich AGB star IRC+10216

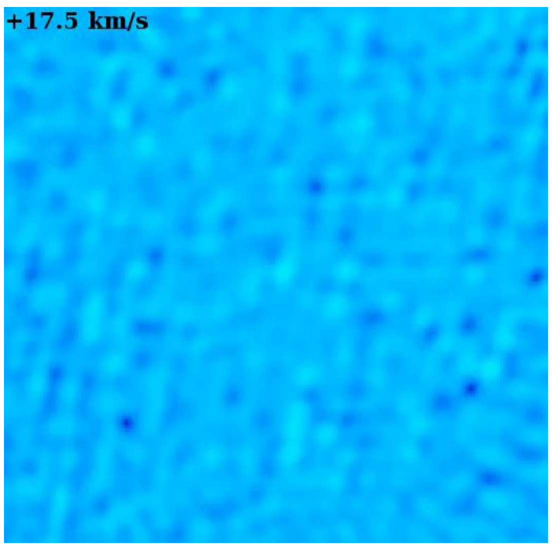
- Spectroscopy and imaging at 1.3cm (K-band)



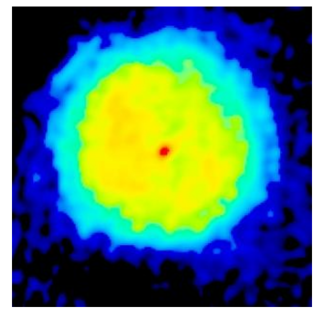
- https://science.nrao.edu/facilities/evla/early-science/demoscience

Spectral movie of IRC+10216

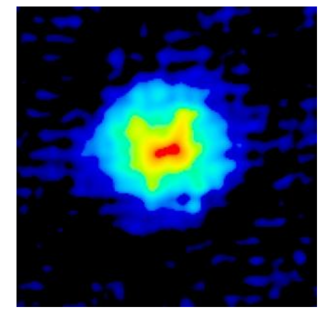
- HC_3N(4–3) emission at 36.4 GHz traces the expanding shell
- Similar movies for HC_5N(9–8), HC_7N(22–21), SiS(2–1), reveal chemical structure of the envelope



HC_3N

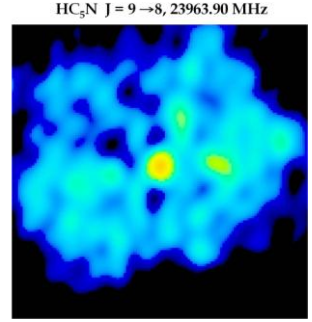


SiS



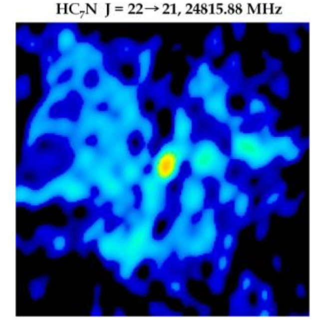
HC_5N

HC_5N J = 9 → 8, 23963.90 MHz

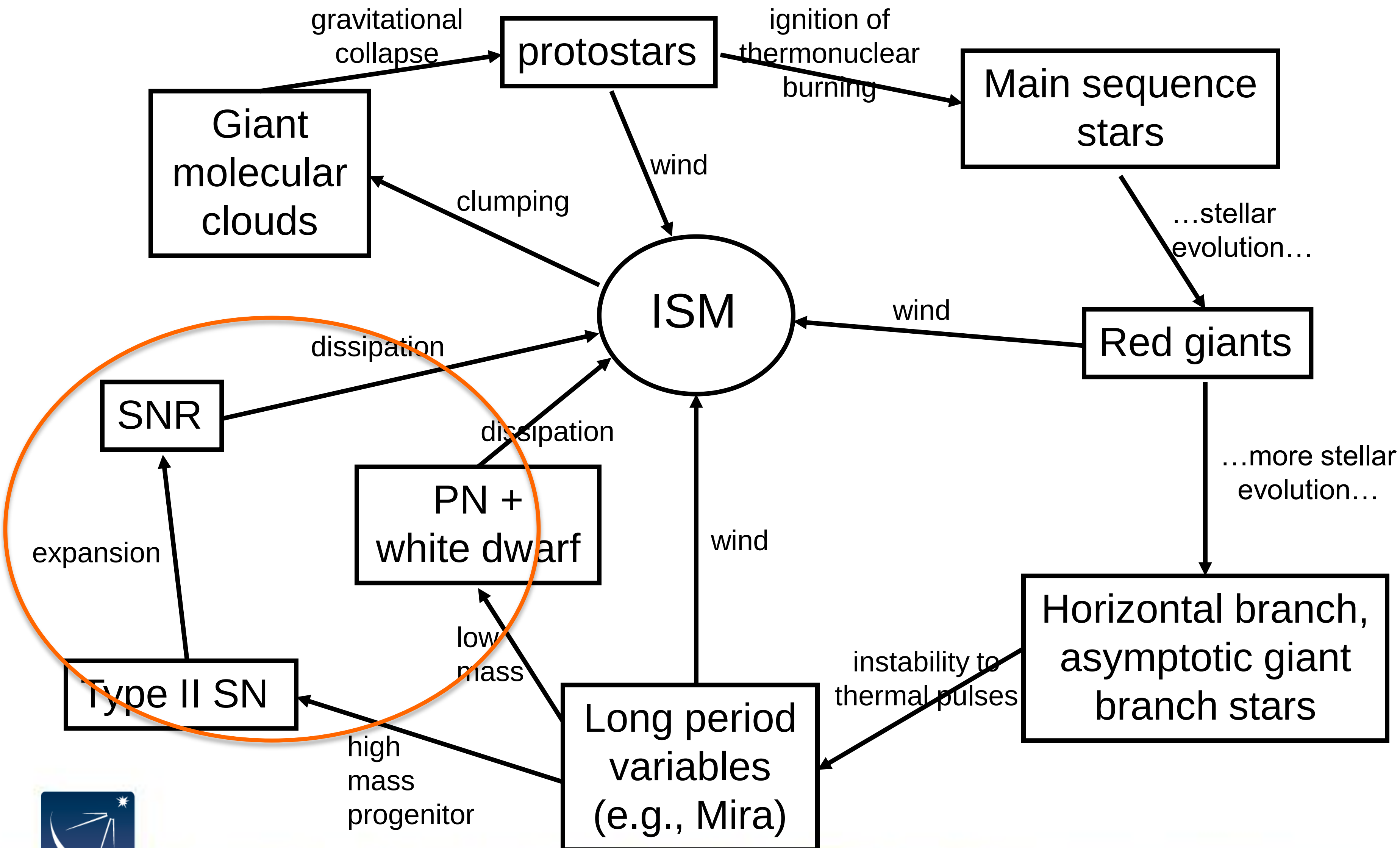


HC_7N

HC_7N J = 22 → 21, 24815.88 MHz

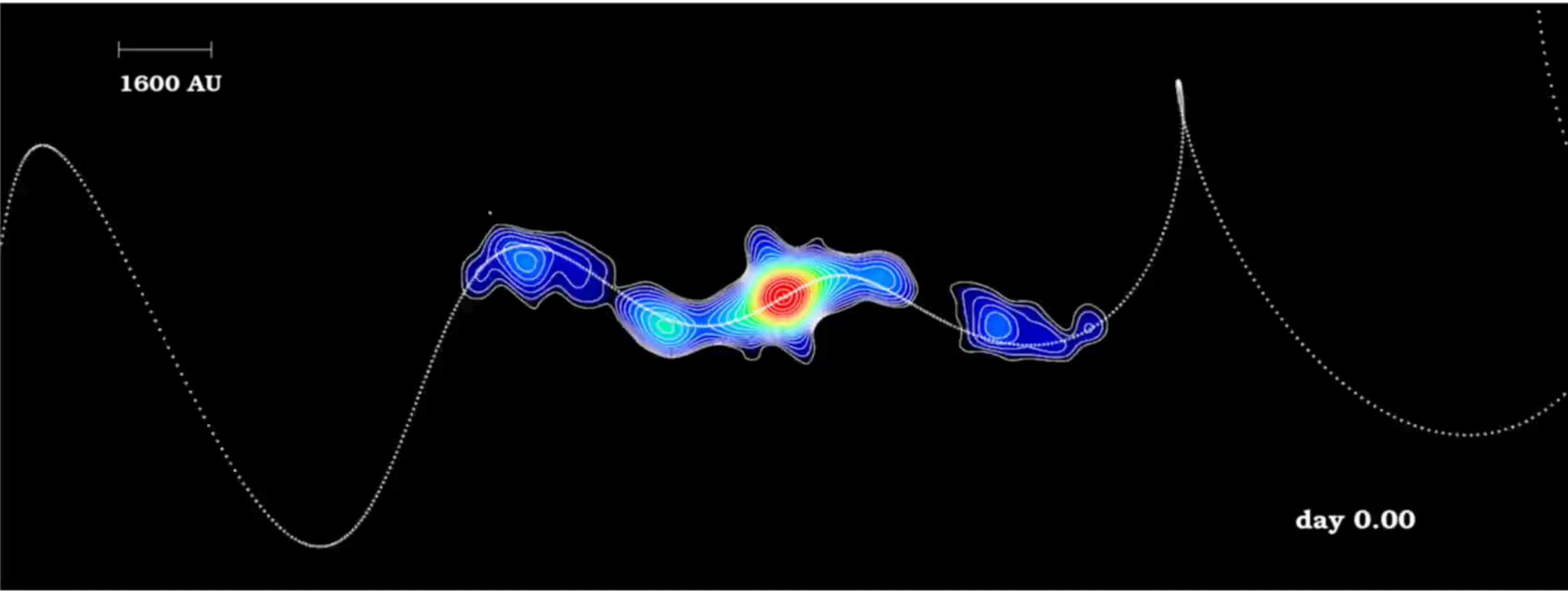


Stellar birth, death, and the ISM

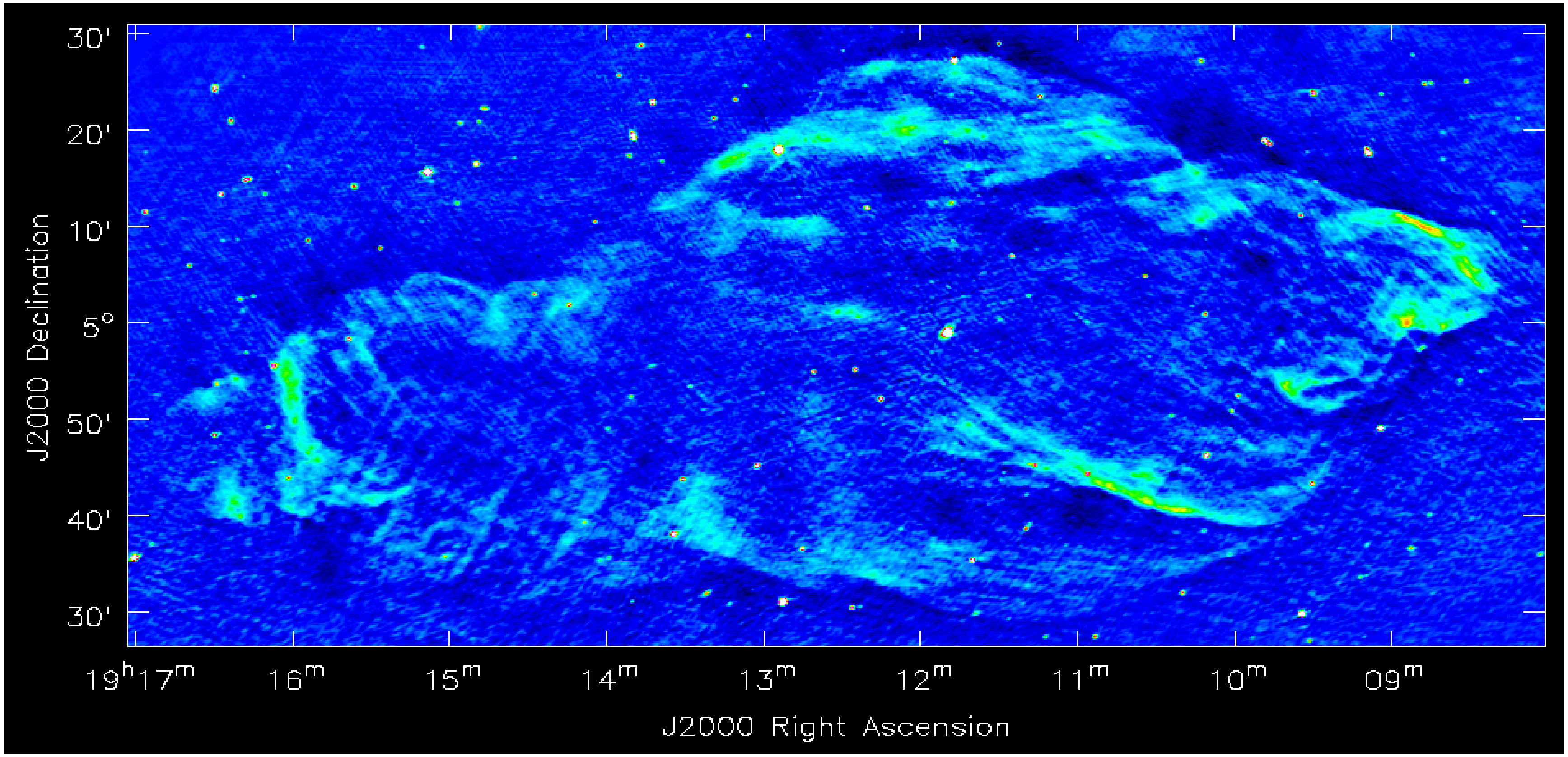


SS433 and the W50 nebula

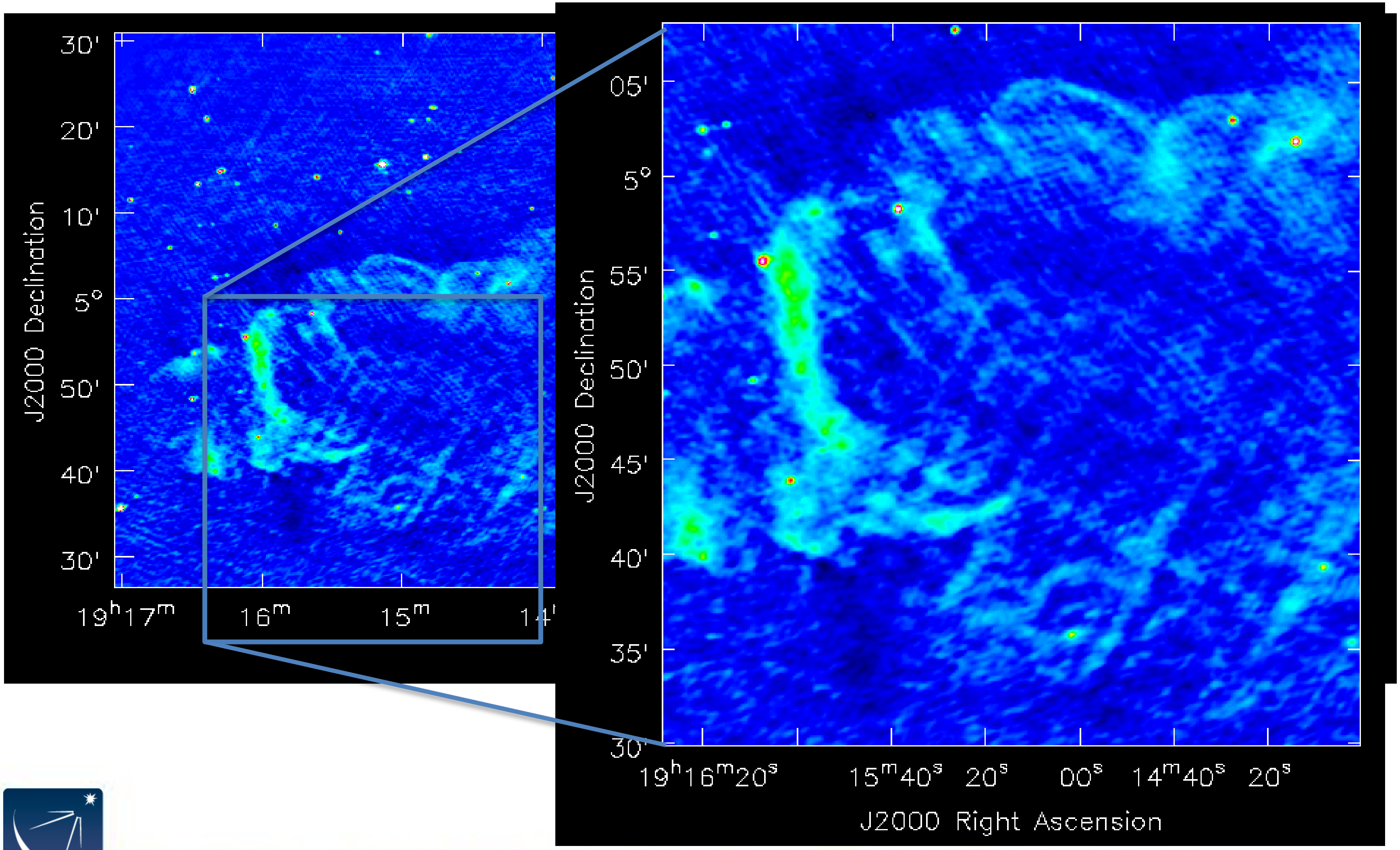
- 26 GHz emission from SS433, 0.095” (520 AU) resolution



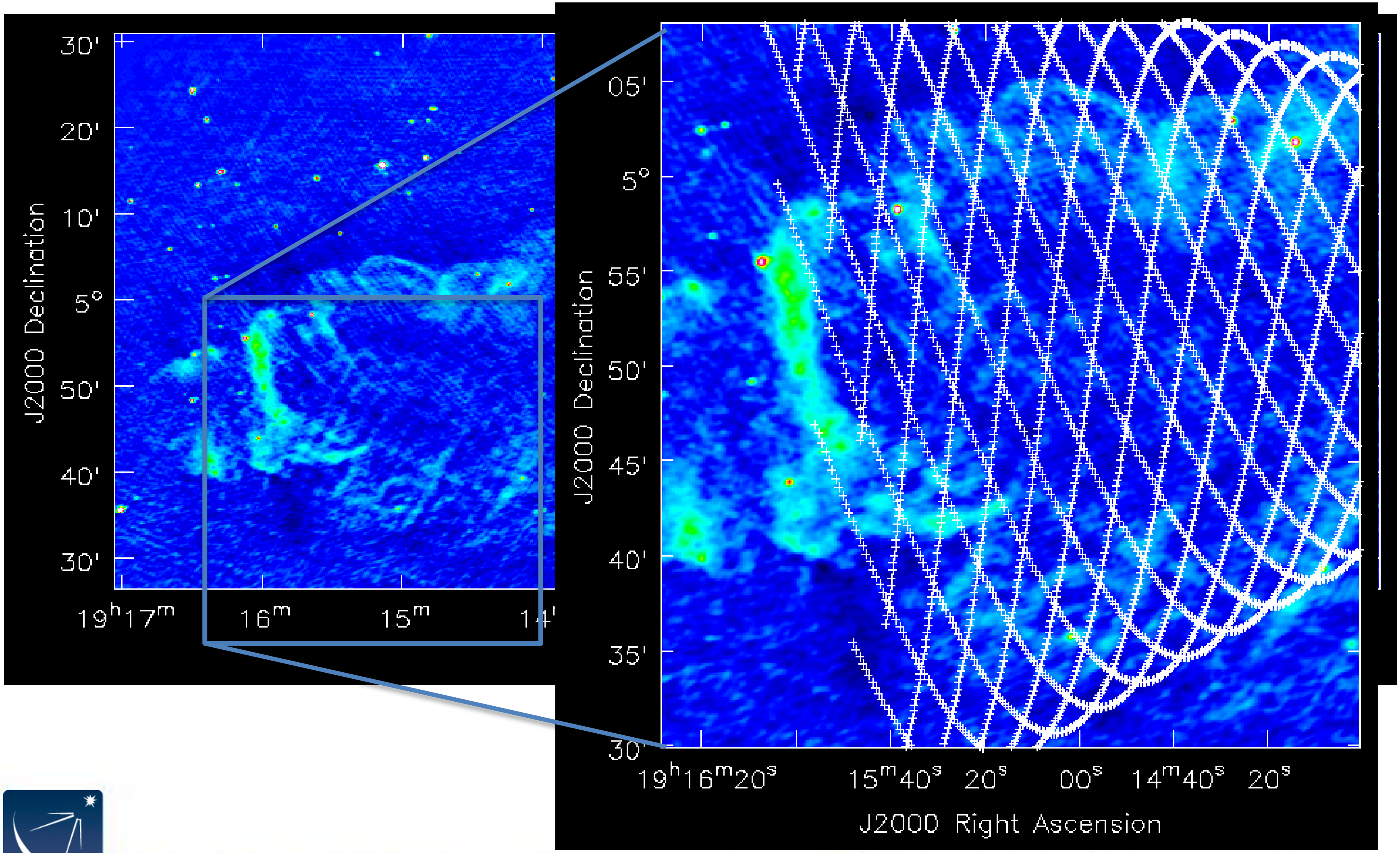
SS433 and the W50 nebula



SS433 and the W50 nebula



SS433 and the W50 nebula



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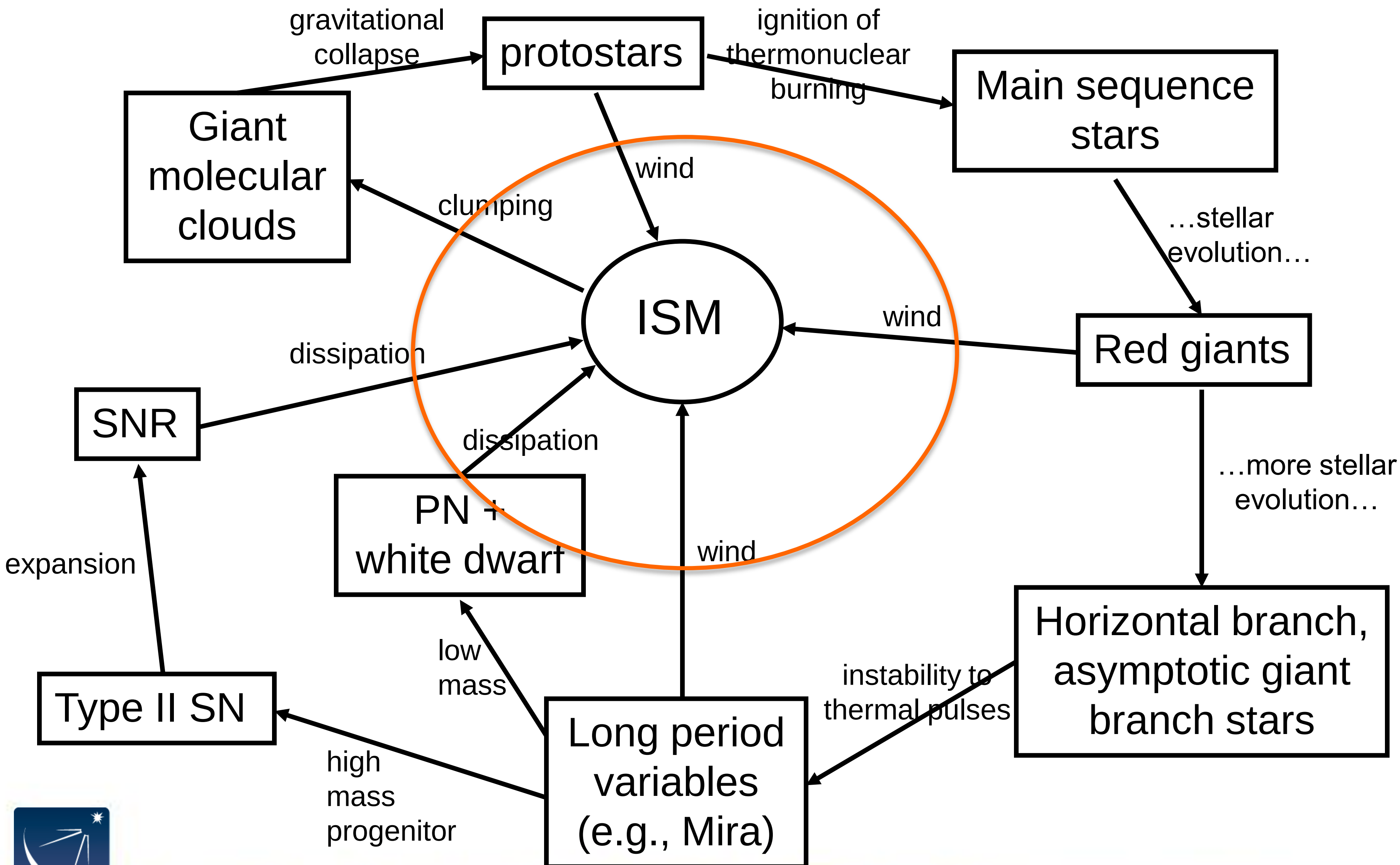
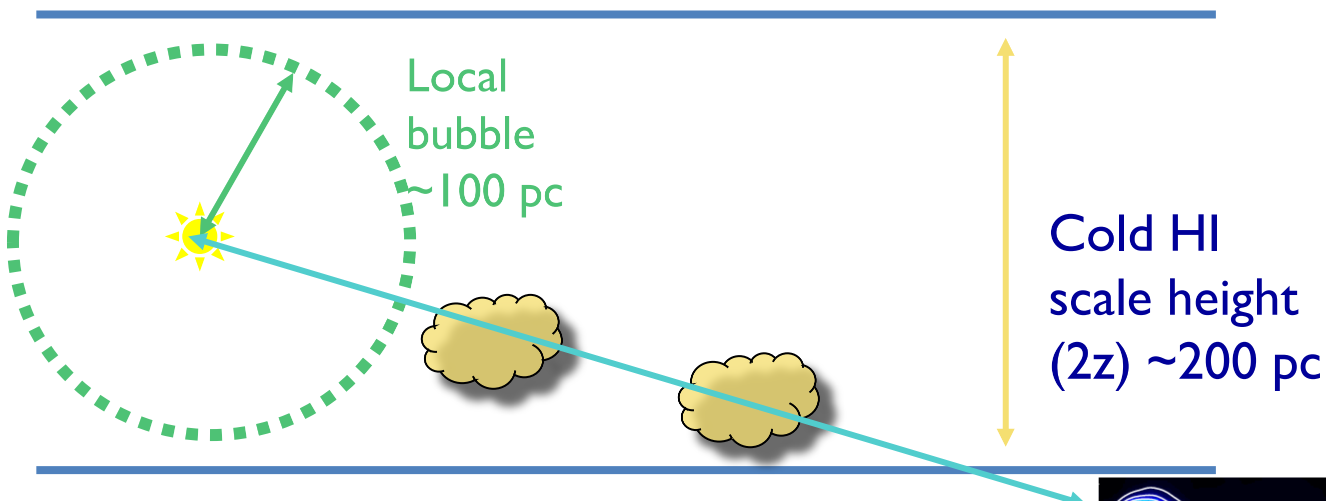
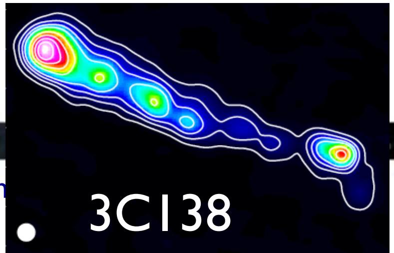


The ISM

- Many applications of radio techniques to the interstellar medium
  - Molecular clouds, chemistry, physics, structure
  - Diffuse clouds (HI)
  - Intercloud medium (HI+HII)
  - Diffuse nebulae (Bremsstrahlung, RRLs)
- Small-scale HI structures detected in absorption against extra-galactic sources: VLBA provides spatial resolution of a few AU!



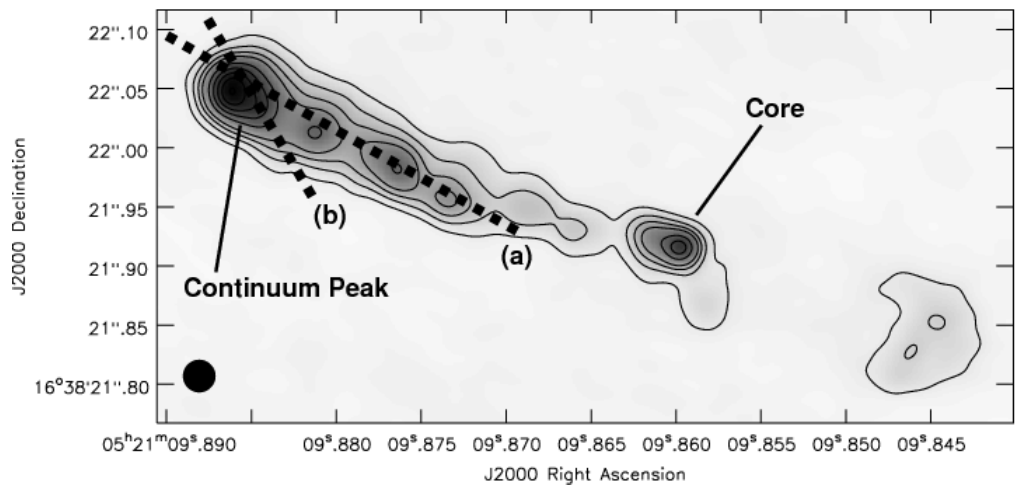
(C. Brogan)

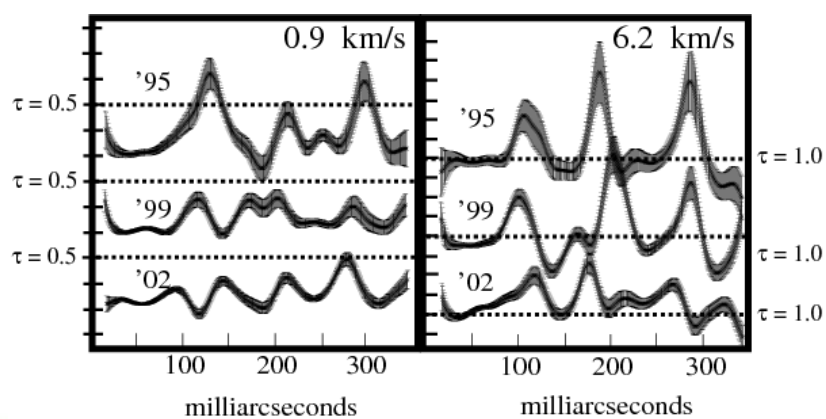


HI absorption toward 3C138

- Multi-epoch VLBA observations, 1995, 1999, 2002
- Resolution 20 mas = 10 AU at 500pc

- Changes in τ indicate changes in density of intervening Galactic atomic gas, size-scale of features ~25AU (Brogan et al. 2005)





Summary

- Radio interferometry is a powerful tool for investigating Galactic sources
  - Especially important in the Galactic Plane, where extinction is a problem at other wavelengths
  - Provides insight into all phases of stellar evolution and the interstellar medium
  - Spatial resolution comparable to (or better than!) other wavelengths $\rightarrow$ enables multi-wavelength approach to solving science problems on matched spatial scales
- New capabilities coming online $\rightarrow$ opportunity for you!