The death throes of massive stars

SOFIA WALLSTRÖM

Collaborators: S. Muller, J. H. Black, E. Lagadec, C. Biscaro, A. Tielens, I. Cherchneff, J. Rho, R. Oudmaijer, H. Olofsson, A. Zijlstra, and others

Seminar, EAO, May 23rd 2017

Massive stars

- Massive stars have a huge impact on their environment
  - Radiative
  - Mechanical
  - Chemical
- Generally explode as supernovae
  - As much energy as the Sun will produce over its lifetime

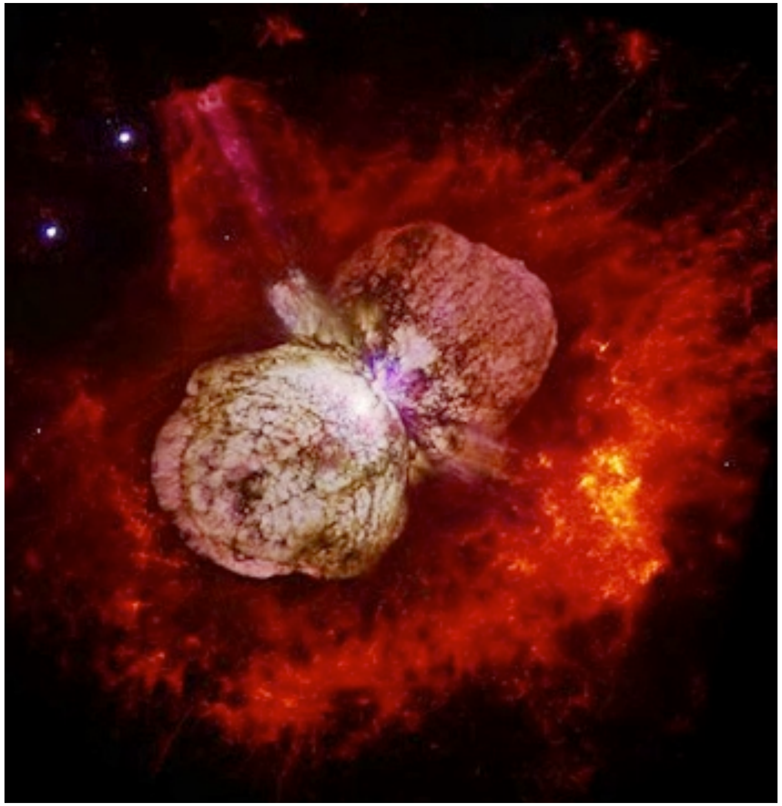
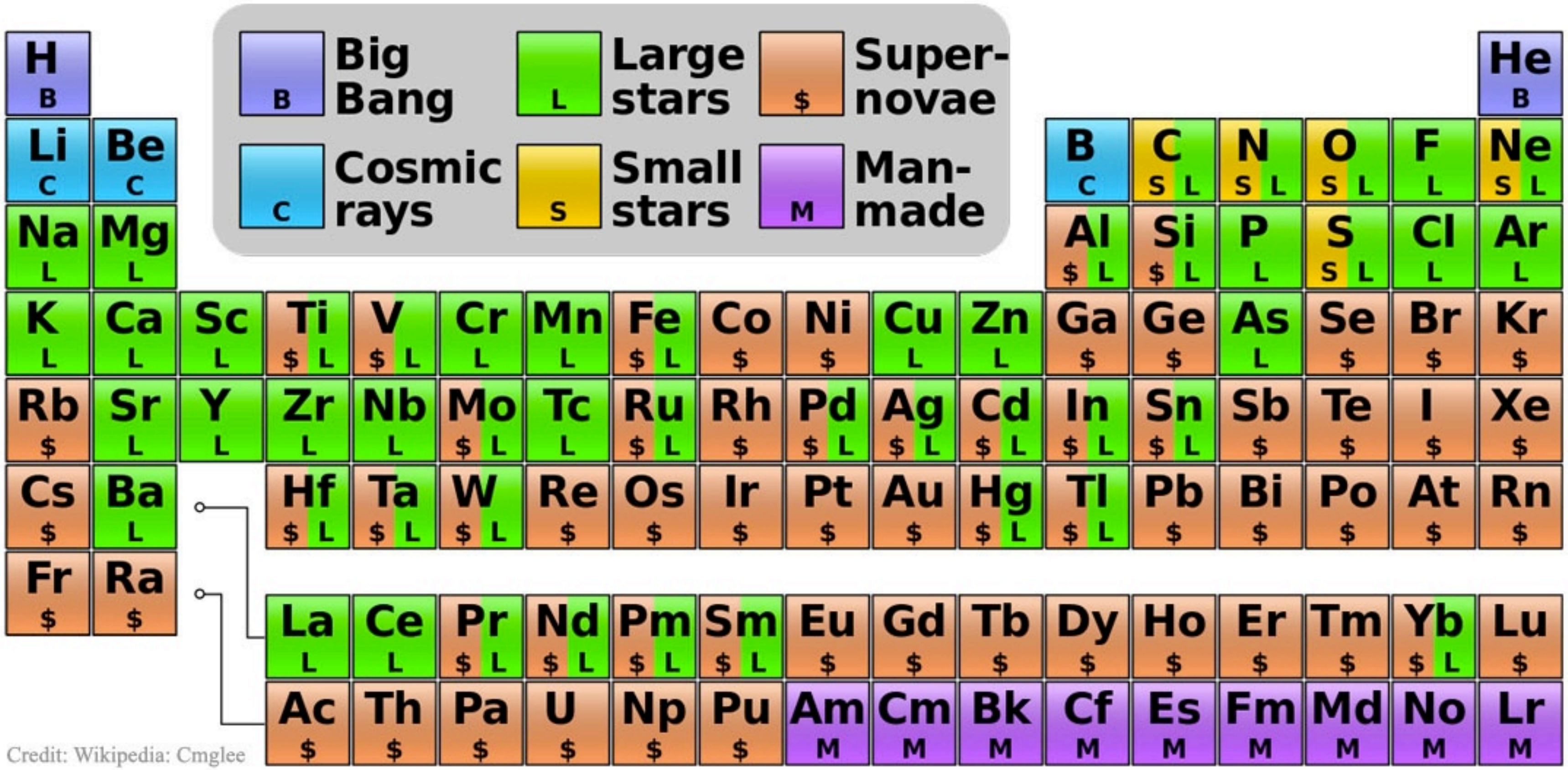


Image credit: NASA/HST/Nathan Smith

Nucleosynthesis



Credit: Wikipedia: Cmglee

Stellar evolution

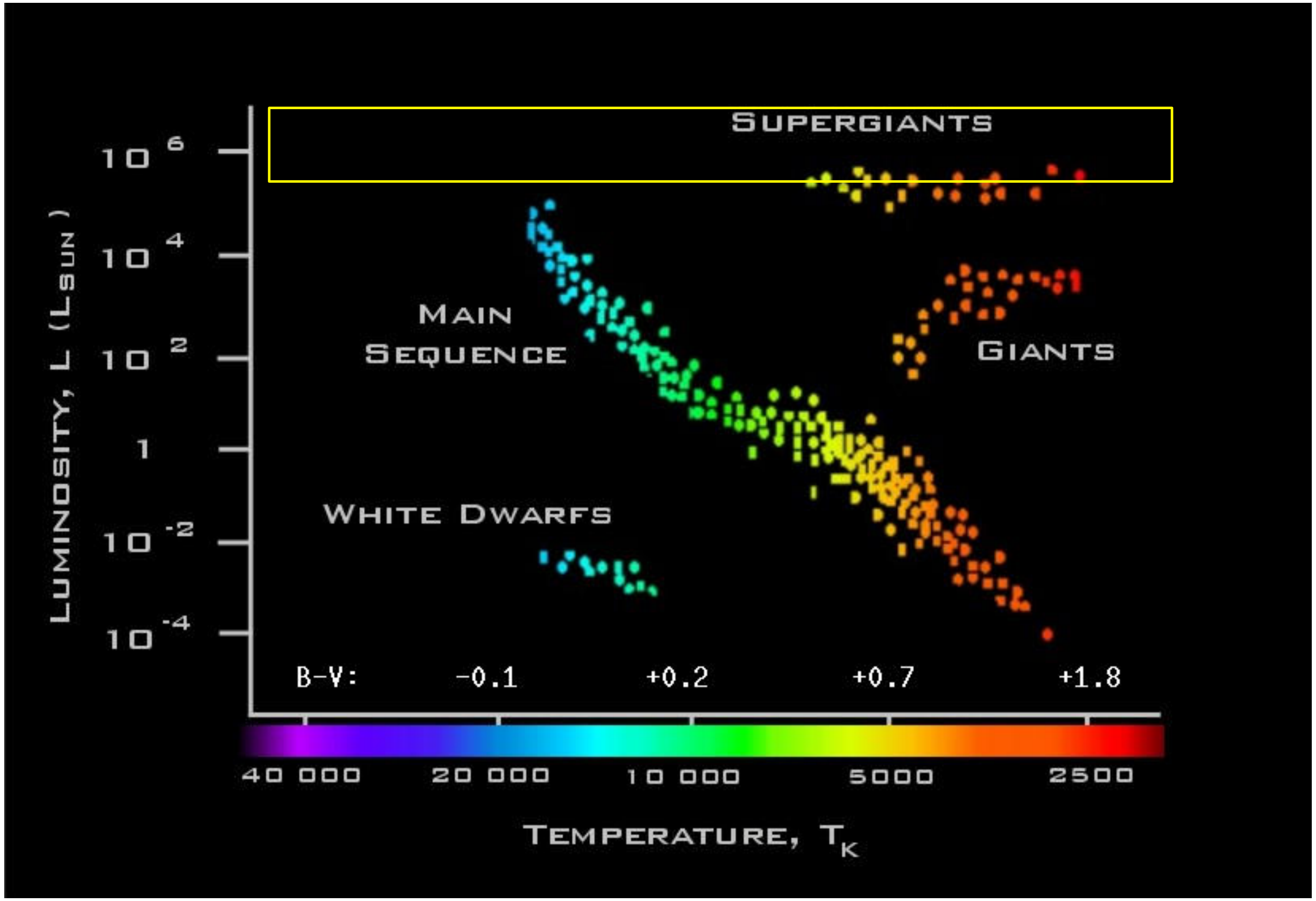


Image credit: University of Oregon

Yellow hypergiants

- M_{init} = 20-40 $M_{\odot}$
- Evolutionary stage linking Red Supergiants and Luminous Blue Variables
  - Timescale 10^{2-3} years
- High luminosity, large periodic mass-loss

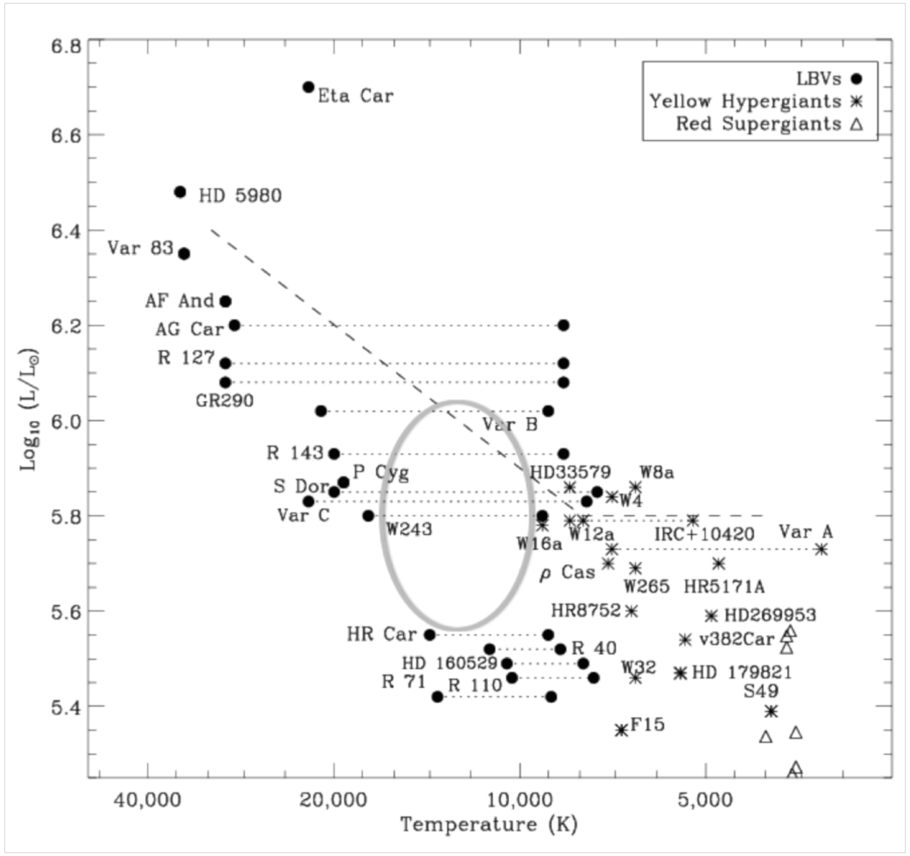


Image from Oudmaijer et al. 2009

References: de Jager 1998; Oudmaijer et al. 2009

The Yellow Void

- The yellow void
  - Unstable photosphere, g_{eff} close to zero
  - Star "bounces" off
  - Periodic mass-loss
- Few YHGs have extended circumstellar envelopes
  - IRC+10420
  - $\dot{M} > 10^{-4}\ M_{\odot}/yr$

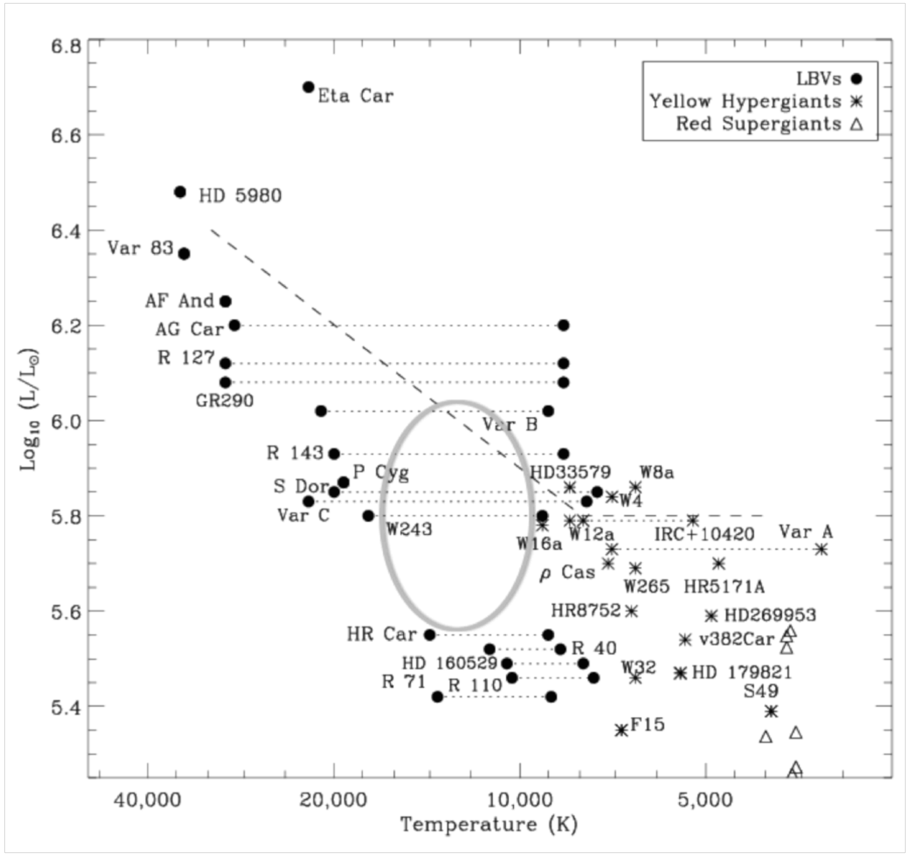
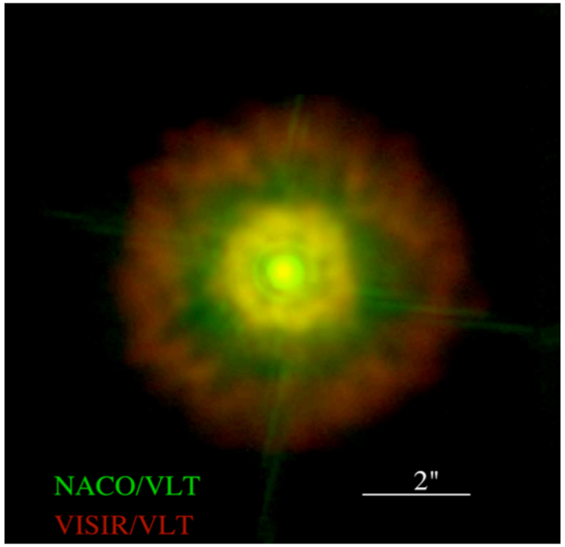


Image from Oudmaijer et al. 2009

References: de Jager 1998; Oudmaijer et al. 2009

The Fried Egg nebula

- IRAS 17163-3907
  - Distance 4 kpc
    - K I absorption lines in optical spectrum
  - Luminosity $5x10^5$ $L_\odot$
- Large dust masses
  - 0.04 $M_\odot$ of warm dust in shells within 5’’
  - 0.17 $M_\odot$ in 50’’ ring



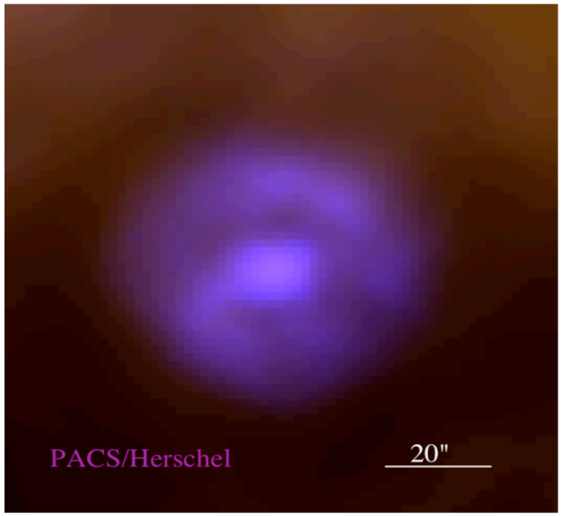
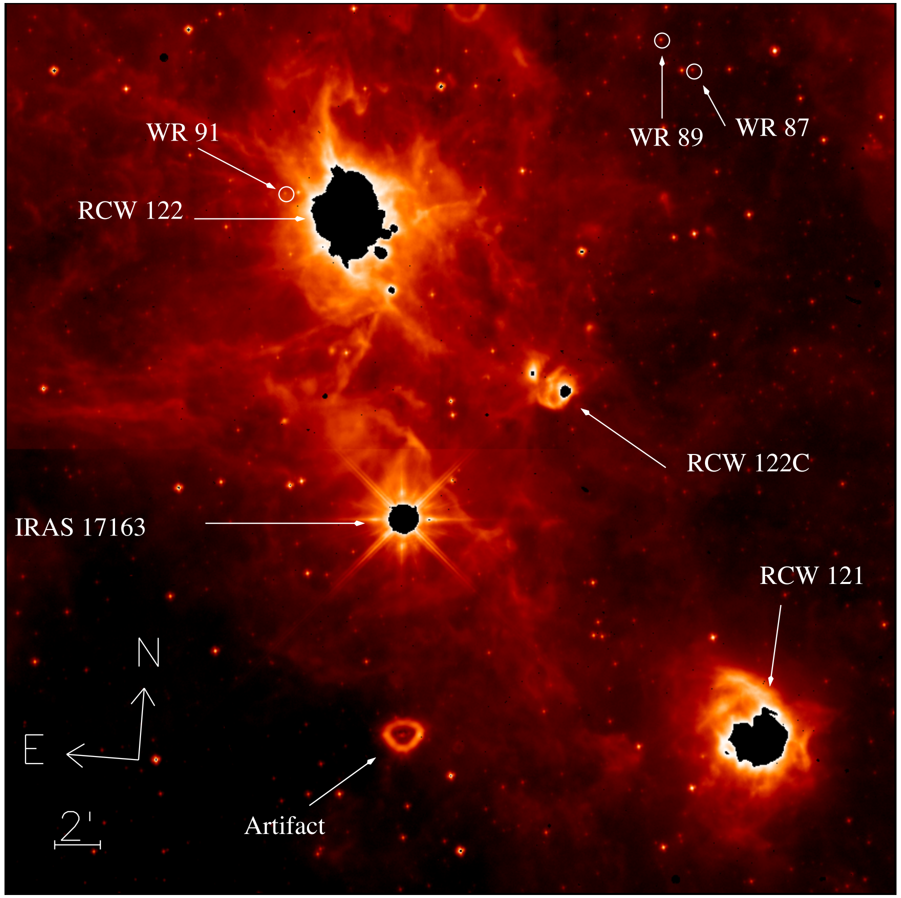


Image credit: Lagadec et al. 2011; Hutsemekers et al. 2013

References: Lagadec et al. 2011; Hutsemekers et al. 2013

APEX observations

- APEX observations
- CO 2-1 and 3-2
  - Beam 27'' and 18''



Reference: Wallström et al. 2015

APEX observations

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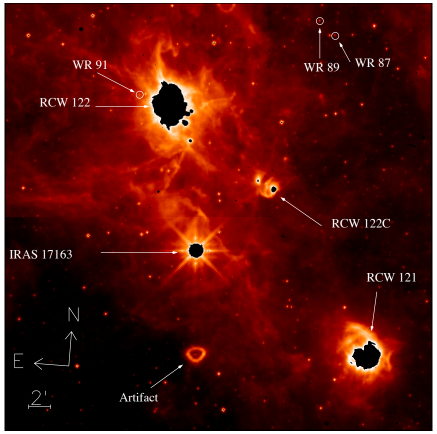
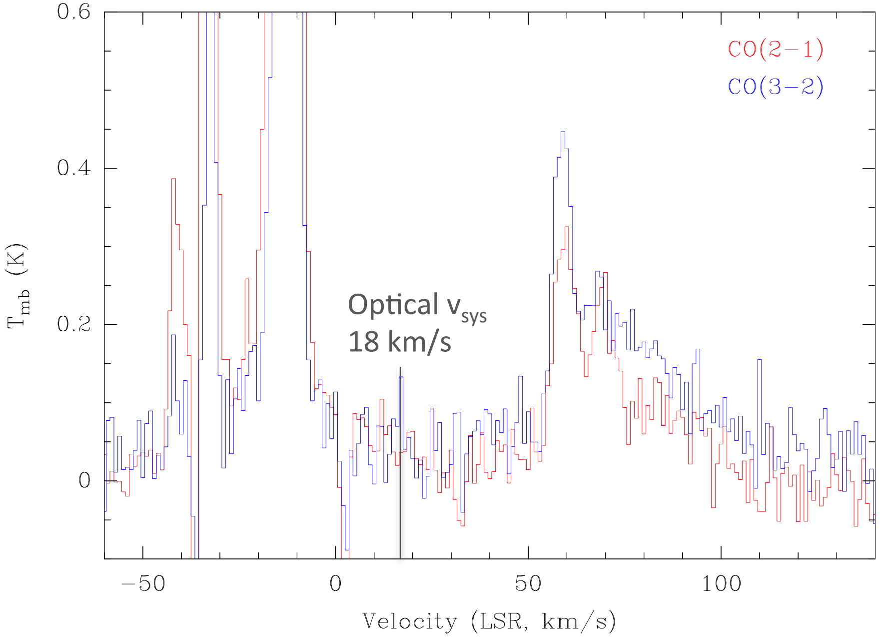
- CO 2-1 and 3-2
  - Beam 27'' and 18''
- Complex asymmetric line shape
- Offset between CO and optical systemic velocity of ~50 km/s

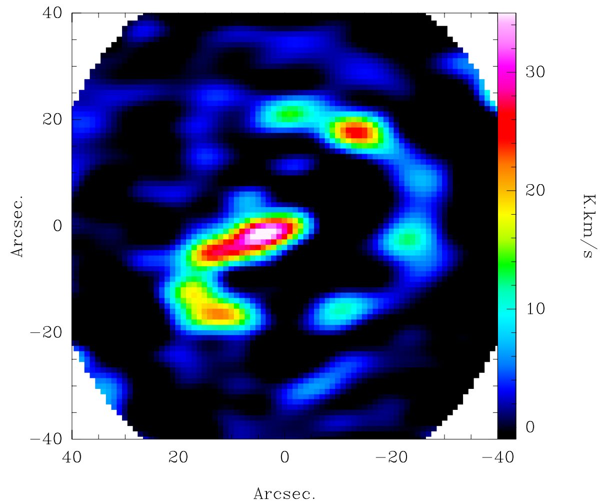


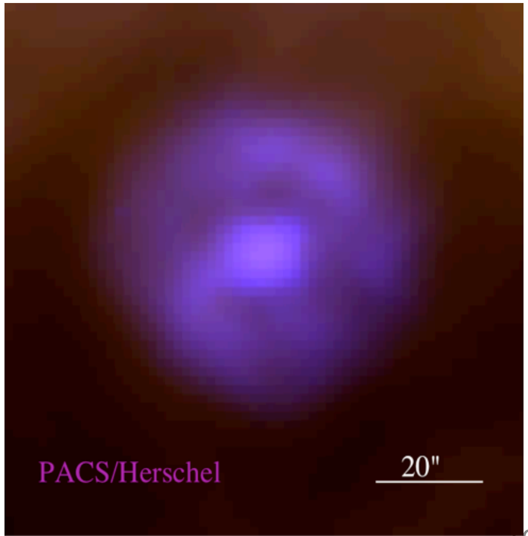


Reference: Wallström et al. 2015

ALMA ACA observations

- ALMA ACA CO 2-1
  - Beam 8'' x 4''
- Asymmetric circumstellar structures
  - In contrast with symmetric dust observations at large (*Herschel* 50'' ring) and small (VISIR 2'' and 5'' shells) scales
  - Bright spur corresponding to APEX emission

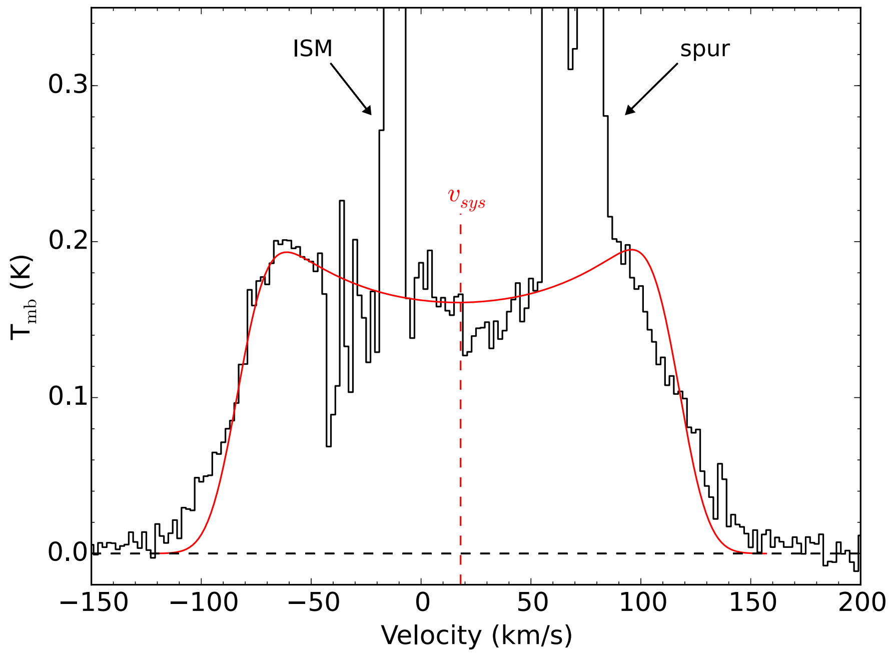




Reference: Wallström et al. 2017

ALMA ACA: central spectrum

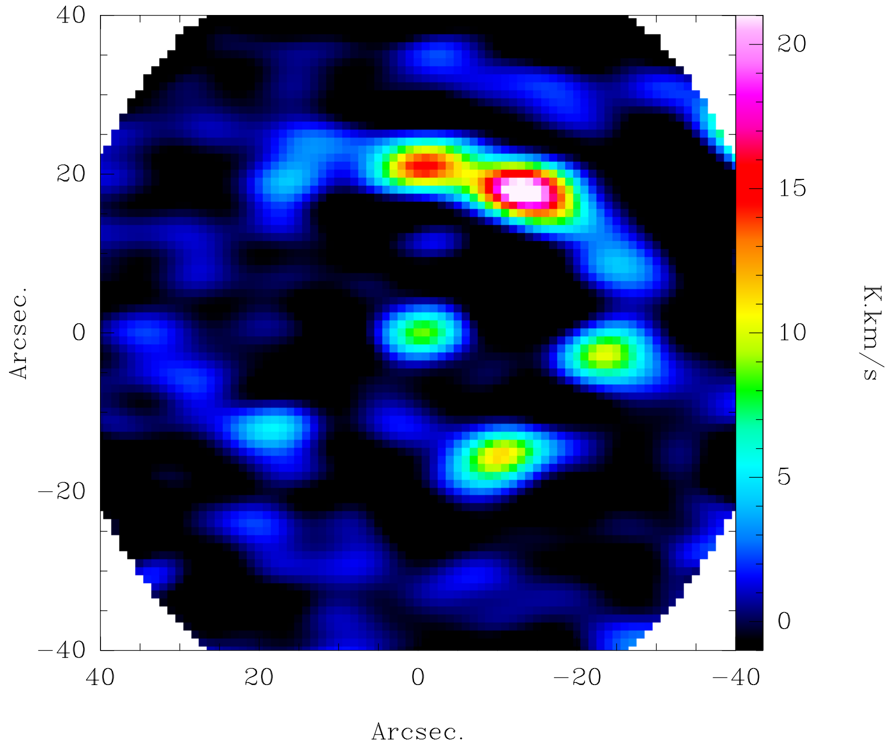
- Spectrum extracted at the star shows ISM, spur and broad plateau
- v_{sys} = 18 km/s
- Isotropic and constant mass-loss model finds:
  - v_{exp} = 100±10 km/s
  - $\dot{M}$ = 8±1.5 x 10^{-5} $M_{\odot}$/yr
  - Timescale ~500 years



Reference: Wallström et al. 2017

Feature: clumpy CO ring

- Integrating around v_{sys} we find a clumpy ring
- Velocity structure like an expanding torus
  - Equatorial ring, not spherically symmetric
- Similar features seen in SN 1987A, some supergiants
  - Possible evidence of a binary companion



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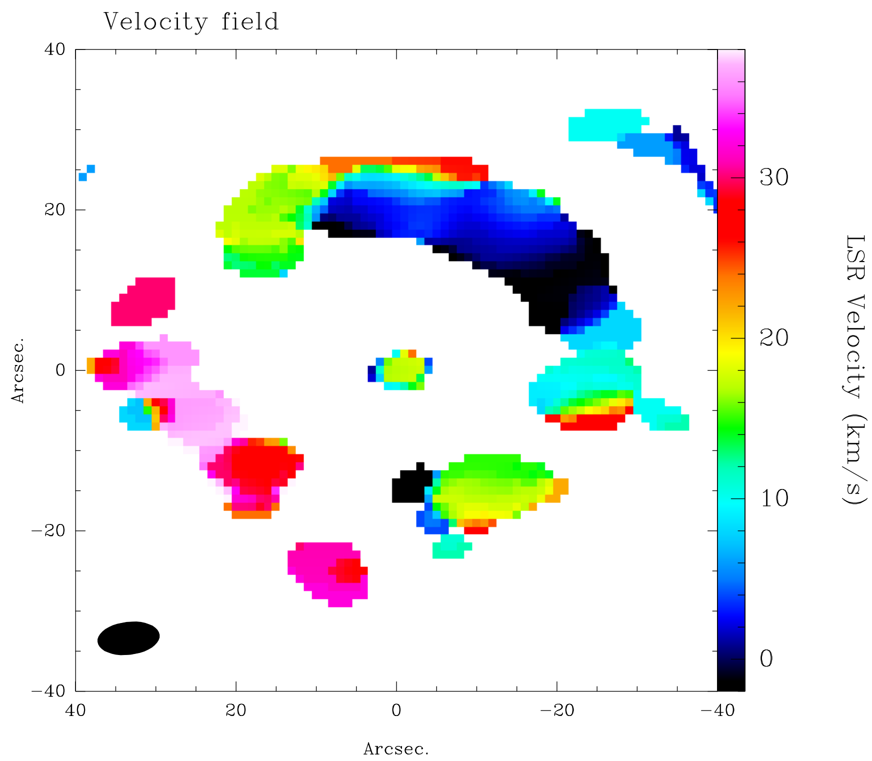
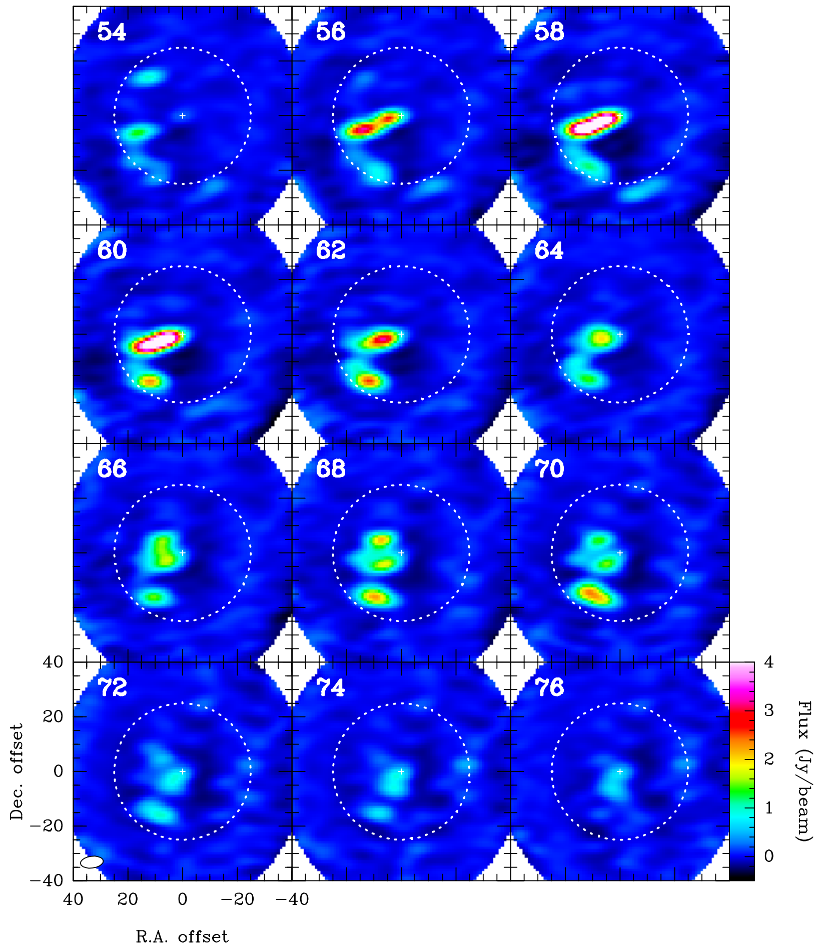


Reference: Wallström et al. 2017

Feature: spur

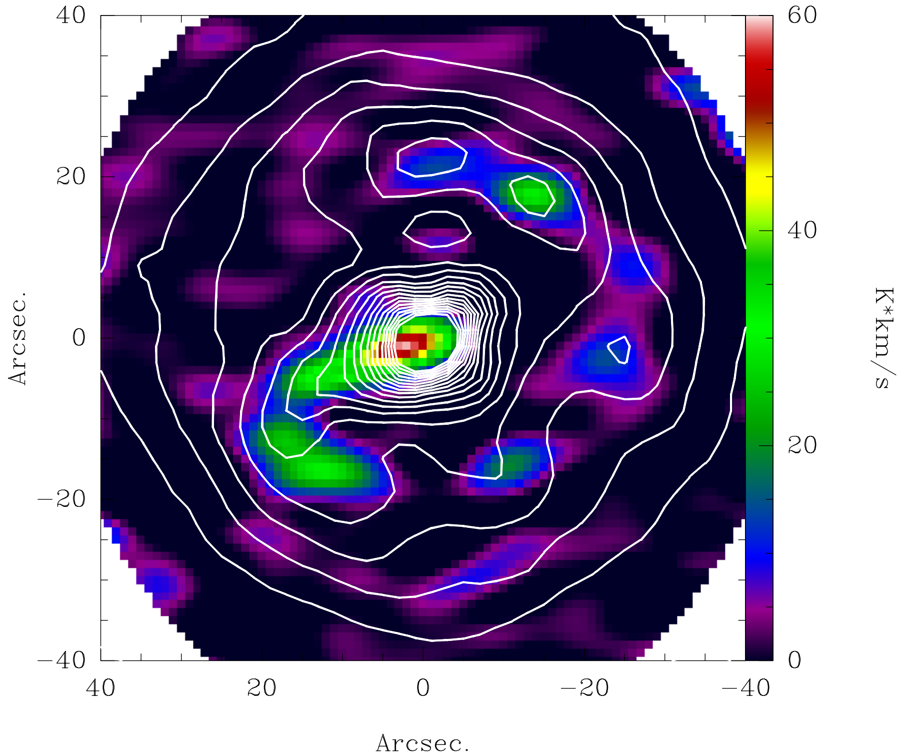
- The brightest feature is a spur around +50-80 km/s
- Unidirectional
  - Timescale > 3700 years
- $^{12}C/^{13}C$ ratio of ~13 points to RSG origin, rather than ISM



Reference: Wallström et al. 2017

Dust and gas

- Clumpy ring and spur match *Herschel* dust contours
  - T ~ 60 K, M_{dust} ~ 0.17 $M_{\odot}$
  - Gas/dust ratio low, ~40
- For inner stellar wind
  - M_{dust} = 0.003 $M_{\odot}$
  - M_{gas} ~ 0.04 $M_{\odot}$
  - Gas mass probably underestimated, given the model assumptions



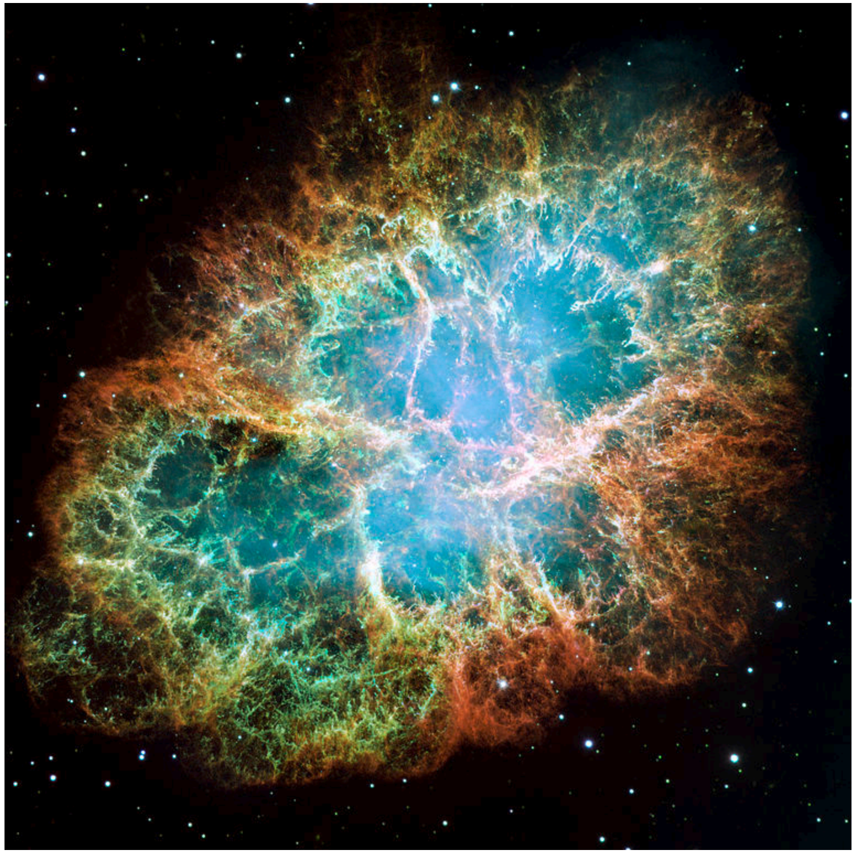
References: Hutsemekers et al. 2013; Wallström et al. 2017

The future of the Fried Egg

- Follow-up with full ALMA array
  - Angular resolution 1.5''
  - Resolve inner ejecta and compare with dust observations
- New VISIR and SPHERE near-IR observations of the central emission

Evolved star ➔ supernova

- Massive stars explode as supernovae after ~10 million years
- Inject local ISM with freshly synthesised elements, kinetic energy… dust?
  - SN dust creation/ destruction still poorly known



Supernovae and dust

- Large dust masses at z>6
  - $10^8\ M_\odot$ in <1 billion years
- Supernovae
  - short timescale
  - refractory elements
  - Need ~0.1-1 $M_\odot$ per SN
  - M_{dust} <$10^{-2}\ M_\odot$ post-explosion, up to 0.7 $M_\odot$ in young SNRs
- How much SN dust survives the reverse shock?

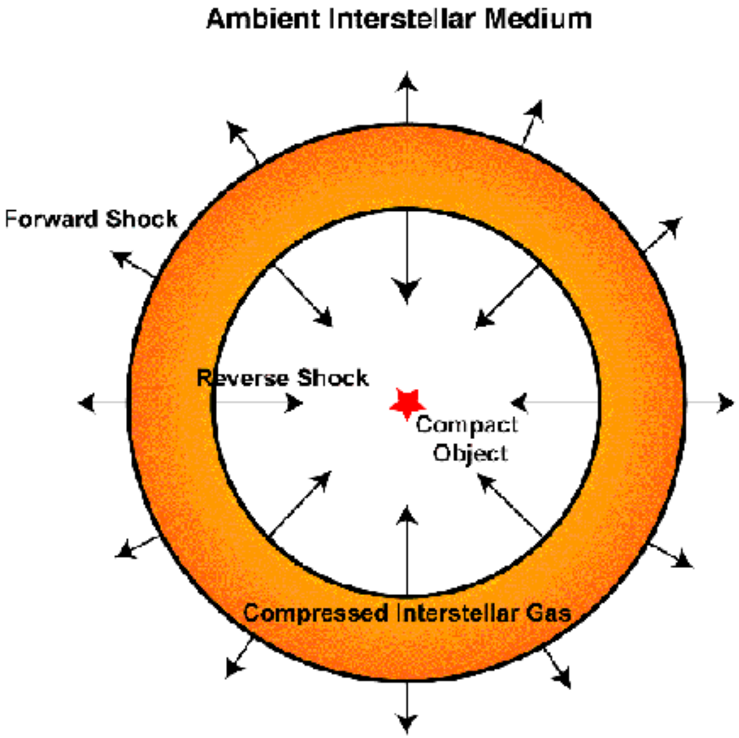


Image credit: South African Astronomical Observatory

References: Bertoldi et al. 2003; Sugerman et al. 2006; Matsuura et al. 2011

SNR Cassiopeia A

- Supernova remnant
  - About 330 years old
  - 3.4 kpc away
- Reverse shock processing the ejecta
- Cool dust: ~0.1 $M_{\odot}$
- Ro-vibrational CO
  - ~20 small (<0.8'') knots

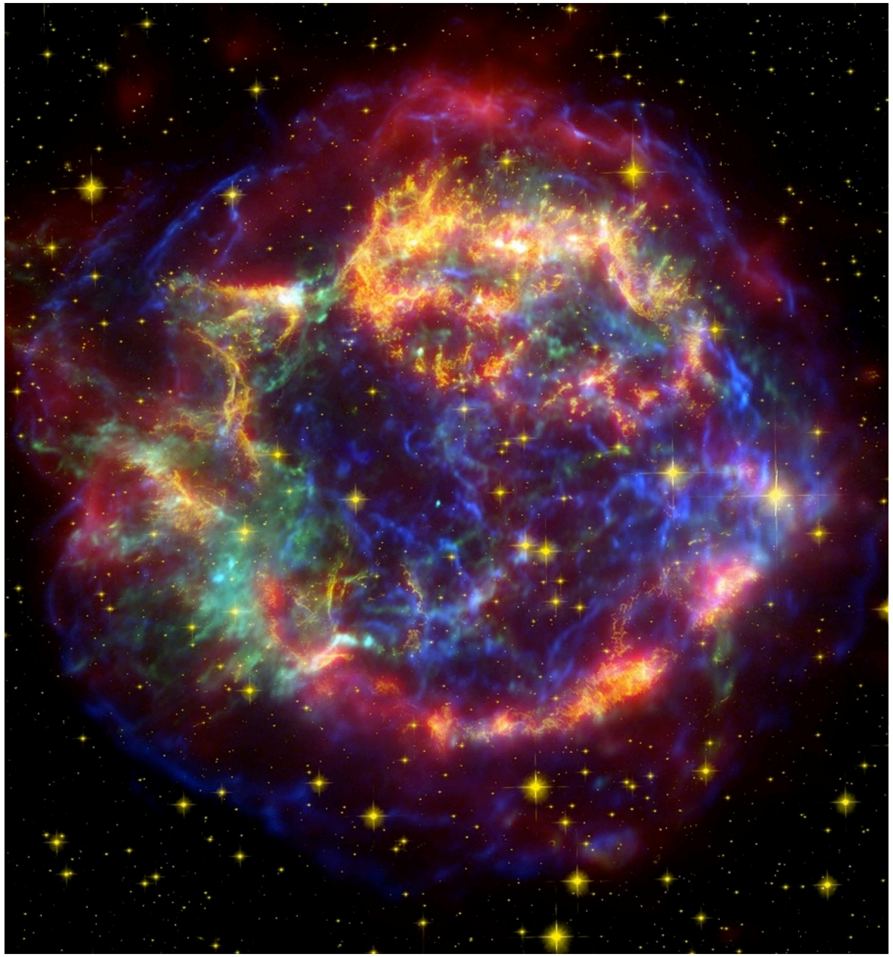
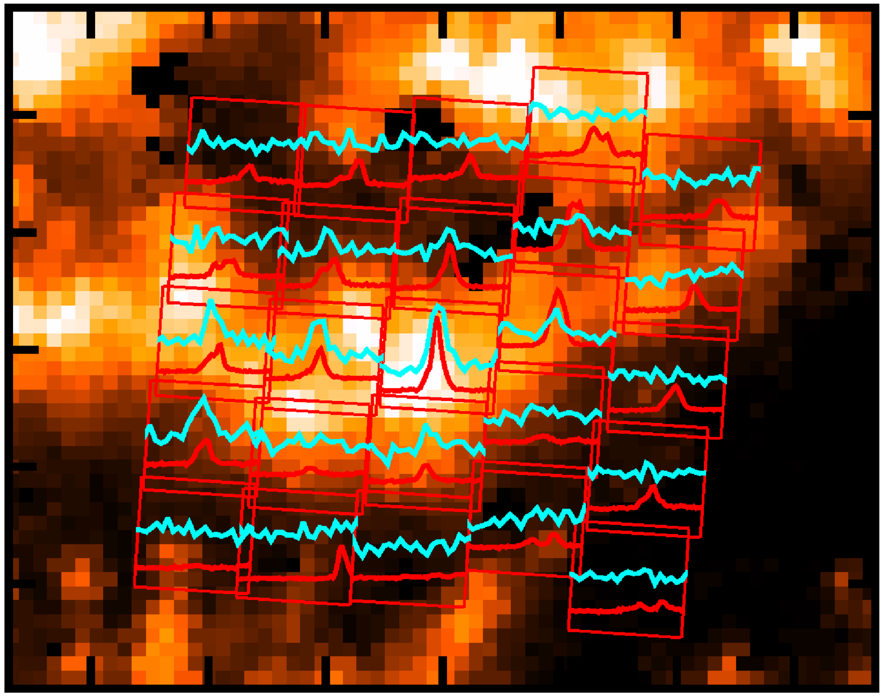


Image courtesy of NASA/JPL-Caltech

References: Rho et al. 2009, 2012

Herschel observations

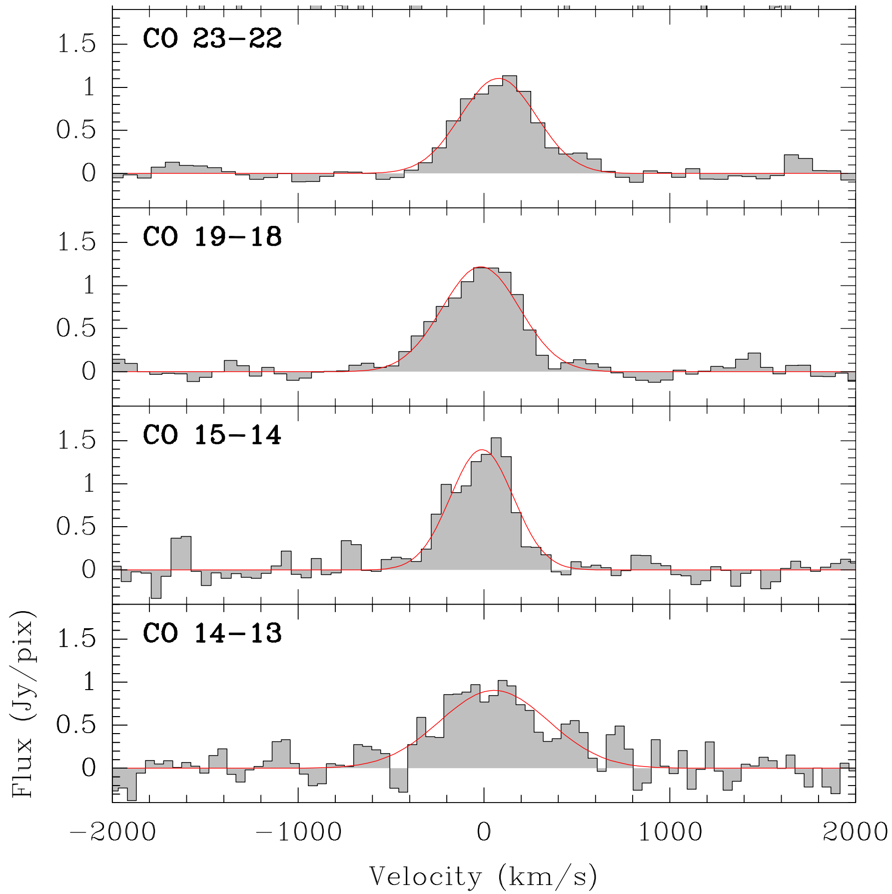
- Herschel PACS
  - Towards the brightest CO knot
- 6 rotational CO lines
- Also detected [O III]
- Excitation diagram + non-LTE modeling to derive physical conditions



Reference: Wallström et al. 2013

Rotational CO results

- $N_{CO} = 5x10^{17}\ cm^{-2}$
- $n_{H2} = 10^{6\text{-}7}\ cm^{-3}$
- T = 400 and 2000 K
- Post reverse shock
  - Broad lines ~400 km/s
- Heating by electron conduction
  - Balanced by evaporation from knot surface, timescale ~2000 years



Reference: Wallström et al. 2013

Supernova dust survival

- Density of the knot will slow the reverse shock
  - cf. Fast Moving Knots (FMK): 2000 km/s shock slowed to 200 km/s in a knot 100x denser than surrounding medium
  - Slowed shock may sputter <50% of SN dust
  - Warm and dense post-shock region conducive to grain growth

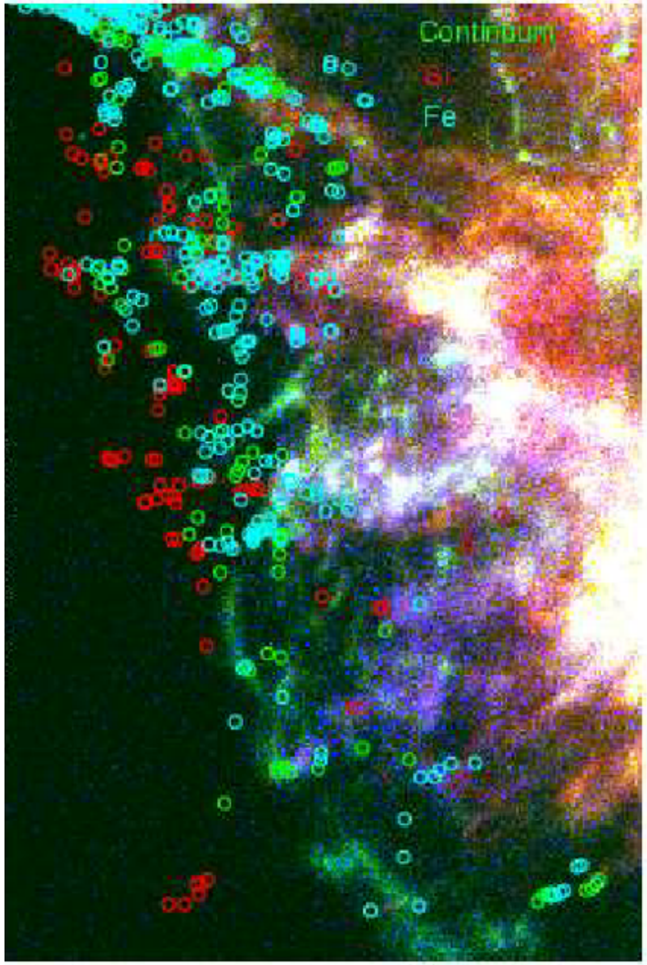
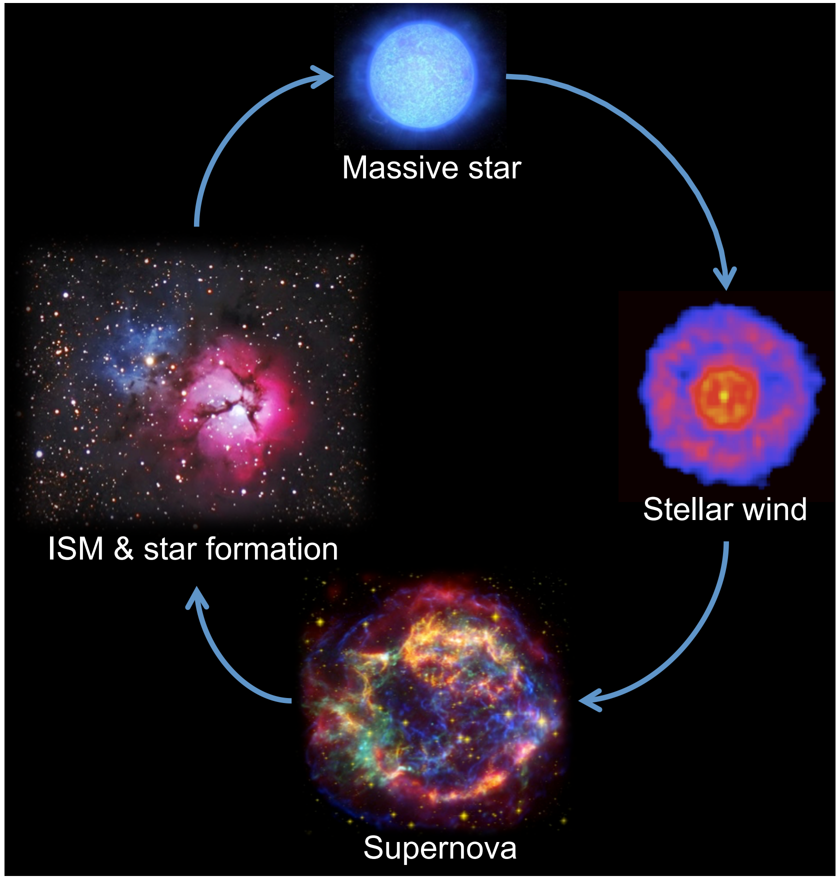


Image credit: Fesen et al. 2008

References: Wallström et al. 2013; Docenko & Sunyaev 2010; Silvia et al. 2012

Galactic chemical evolution

- Stars affect their galaxy
  - Nucleosynthesis products, dust, kinetic energy
- Over time, the metallicity of the galaxy evolves
  - Want to study over the age of the Universe
  - Distant galaxies quickly become too faint to observe in emission



Molecular absorption at high z

- High-z galaxies lensing more distant quasars
  - Molecular absorption, undiluted by distance
  - Study rare isotopologues in distant galaxies
  - Absorption depth proportional to line opacity
    - Direct measurement of isotopic ratios (if lines optically thin)

PKS 1830-211 lensed by MA0.89 at z=0.89

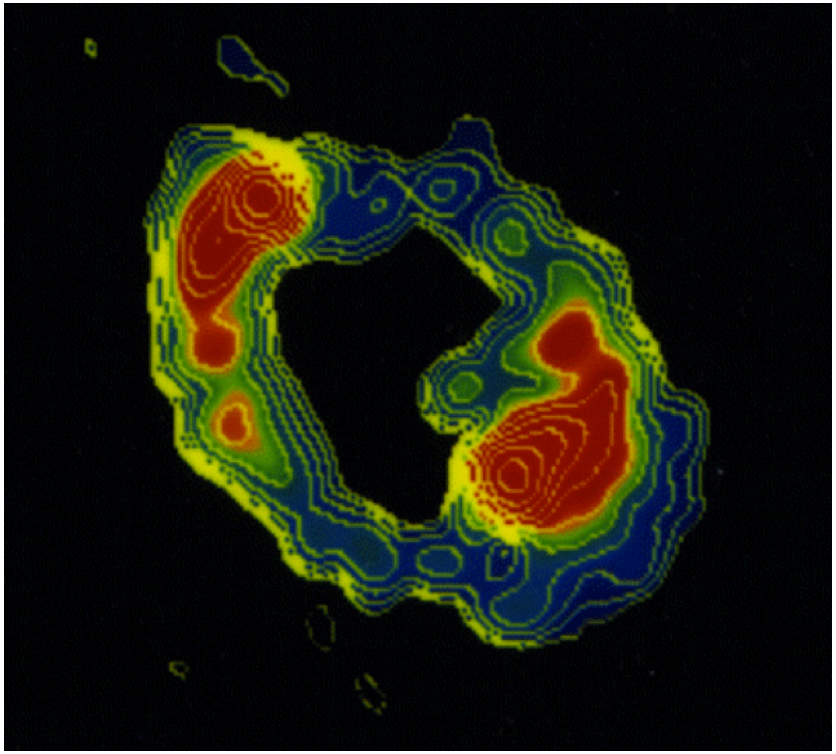


Image credit: Australia Telescope National Facility, CSIRO

Molecular absorber MA0.68

- Absorber at z=0.68, lensing the blazar B0218+357
- Two images 0.3” apart, absorption only for image A
- MA0.68 is nearly face-on spiral galaxy
  - Absorption 2kpc from centre

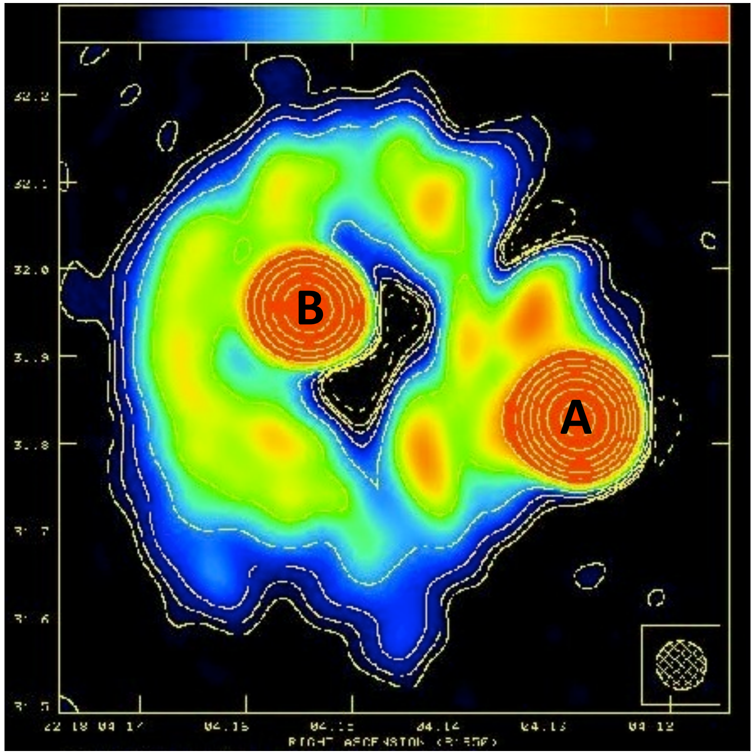
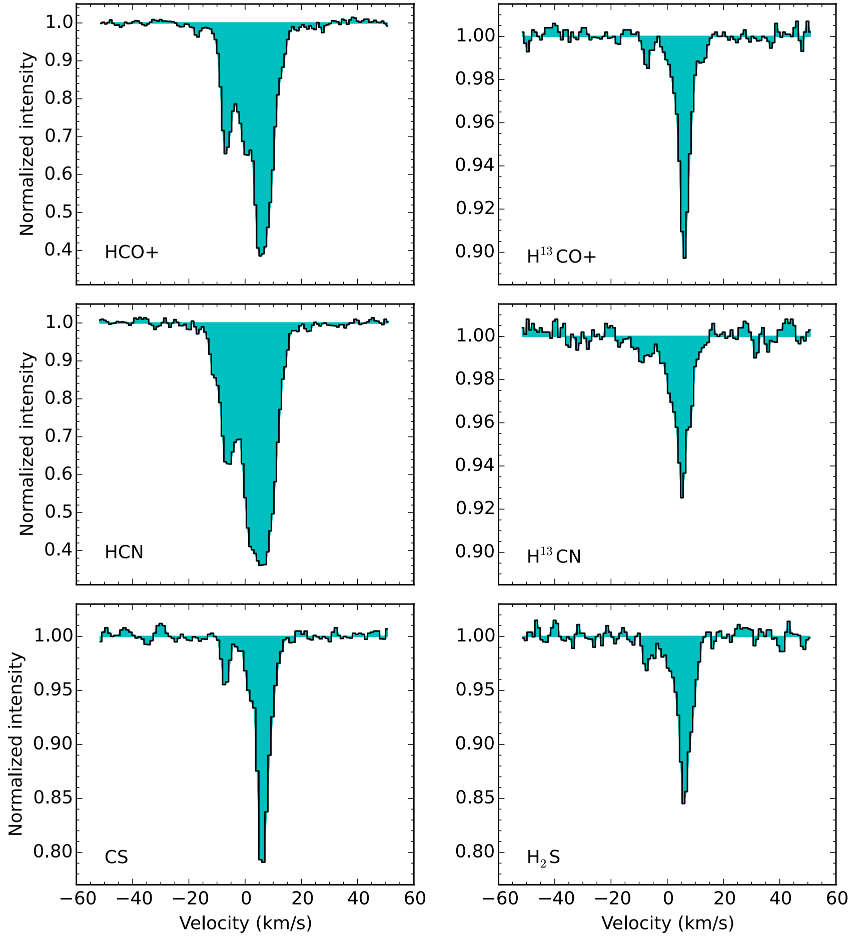


Image from Biggs et al. 2001

References: Patnaik et al. 1993; Wucknitz et al. 2004

PdBI absorption observations

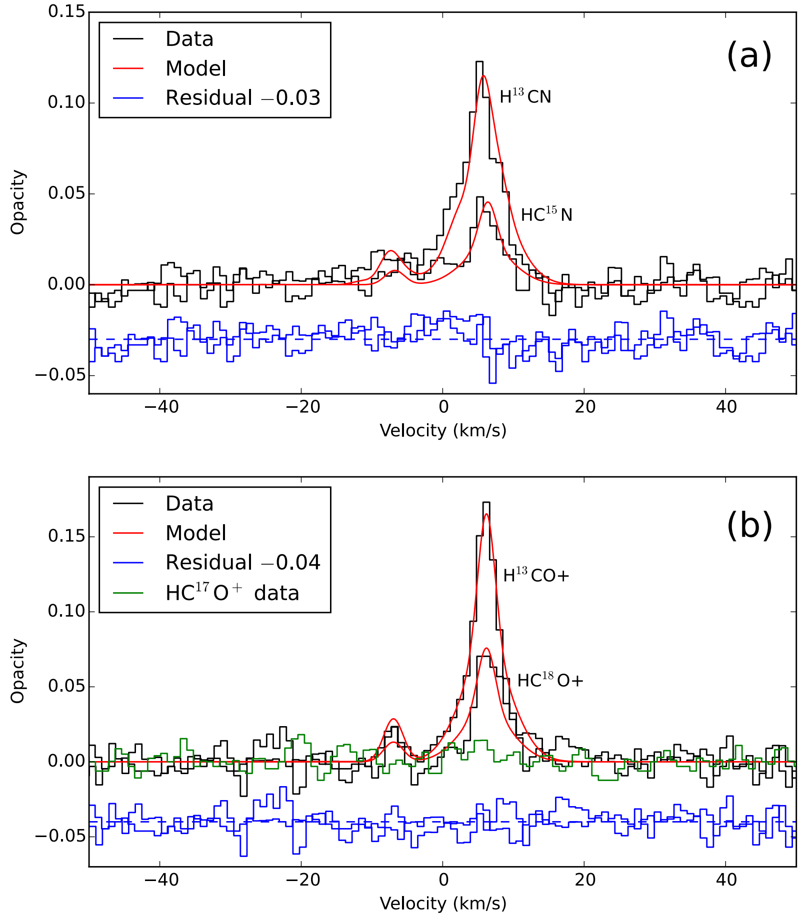
- 3mm band, observed as backup 2005-2008
- Two blazar images not spatially resolved
  - HCO^+ and HCN saturated, but don't reach zero
  - Need to take image flux ratio into account



Reference: Wallström et al. 2016

Fitting line profiles

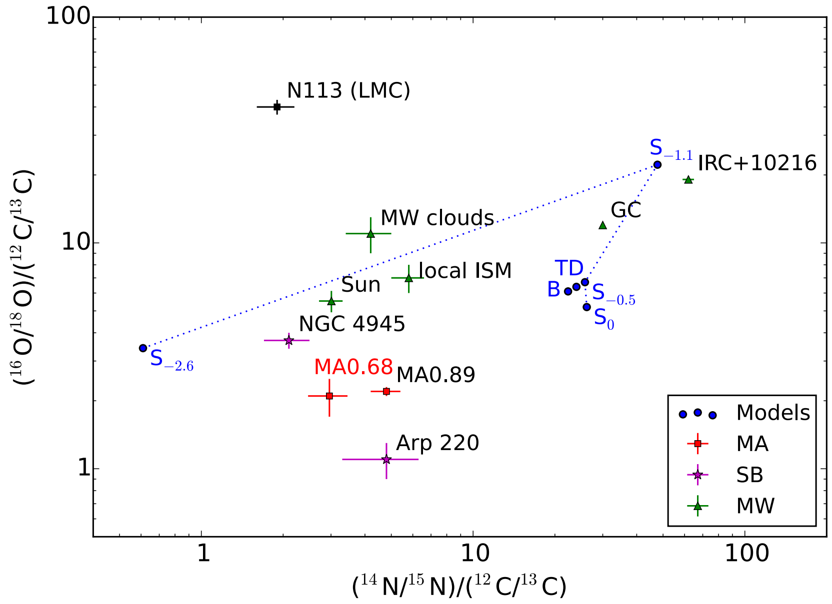
- Fit common 3-gaussian profile to all lines
- Measure isotopic ratios from optically thin lines
  - $^{32}S/^{34}S$, $^{13}C/^{15}N$, $^{13}C/^{18}O$ and upper limit on $^{18}O/^{17}O$
- Estimate $^{12}C/^{13}C$ ratio, and hence $^{14}N/^{15}N$ and $^{16}O/^{18}O$



Reference: Wallström et al. 2016

Isotopic ratios

- All ratios similar to MA0.89, and some starbursts
  - $^{12}C/^{13}C$ and $^{32}S/^{34}S$ similar to Milky Way at 2 kpc
  - All other ratios differ by at least factor of 2
    - MA0.68 enriched in less common isotope
  - Consistent with enrichment mainly by massive stars
    - High ^{18}O and ^{15}N, for example



Reference: Wallström et al. 2016

Chemical evolution models

- Each generation of stars enriches the galaxy
  - Massive stars enrich on shorter timescales, some 10 million years
- Kobayashi et al. 2011
  - Isotopic abundances
  - Star formation rate, star formation history, gas fraction, initial mass function, evolution of different stars…

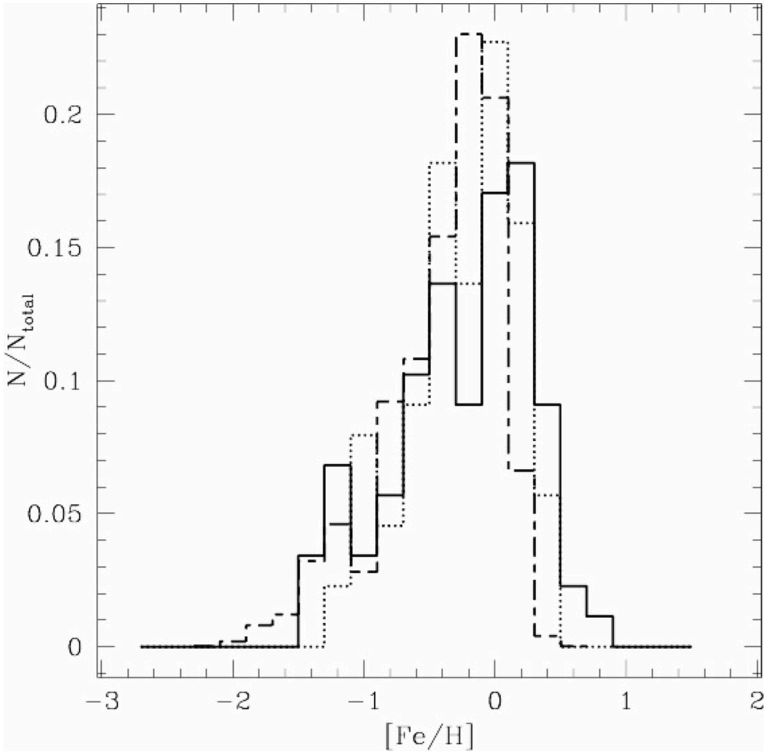


Image from Ballero et al. 2007

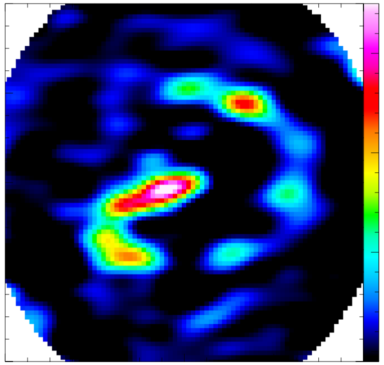
Stellar metallicity distribution in the galactic bulge

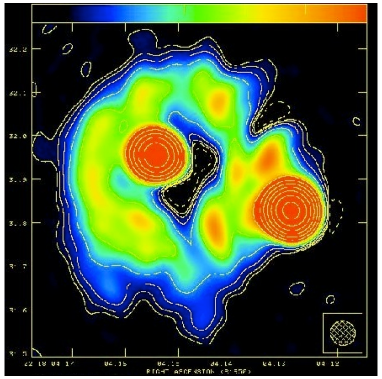
Further study

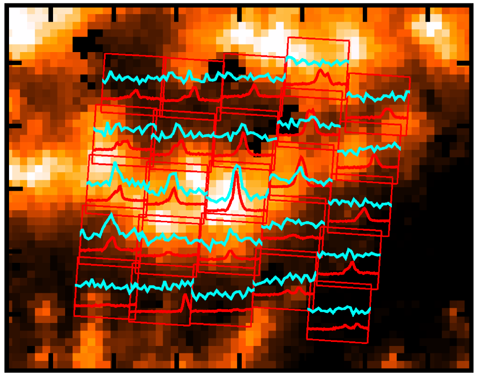
- More data on MA0.68 from ALMA
- ALMA proposal to study C fractionation in MA0.89
- Other sources
  - Only handful of redshifted molecular absorbers
  - Searches for new absorbers at z>1, so far unsuccessful

The death throes of massive stars

- Massive stars impact their surroundings through
  - Complex circumstellar structures
  - (Explode as supernovae)
  - Supernova remnant processing
  - (ISM mixing)
  - Galactic chemical evolution







Thank you !