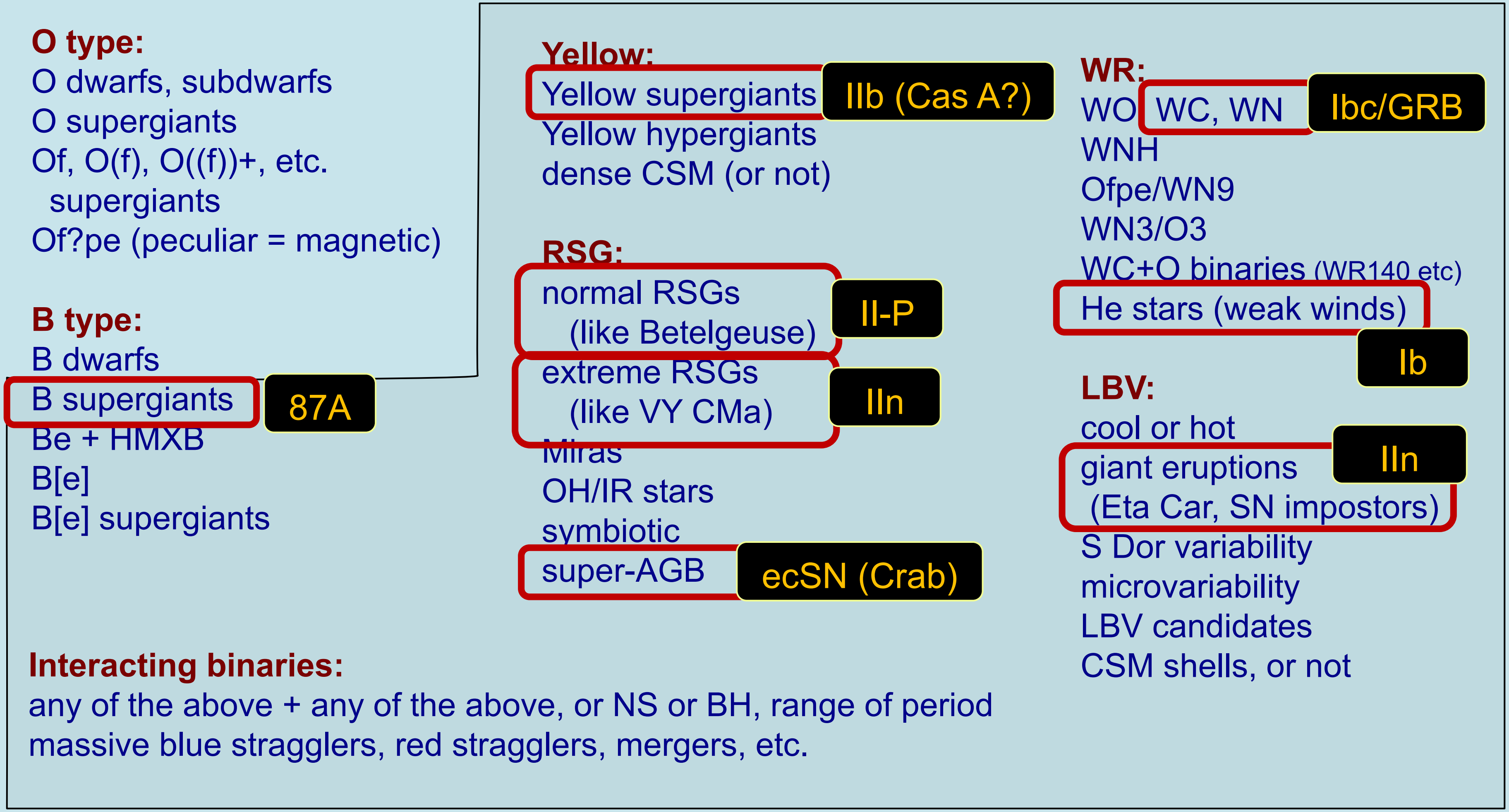
# Massive Star Progenitors of SNe & SNRs with CSM Interaction

**Nathan Smith**
*University of Arizona/Steward Observatory, USA*

# *Observed Massive Star Diversity*



**O type:**
O dwarfs, subdwarfs
O supergiants
Of, O(f), O((f))+, etc.
supergiants
Of?pe (peculiar = magnetic)

**B type:**
B dwarfs
B supergiants 87A
Be + HMXB
B[e]
B[e] supergiants

**Yellow:**
Yellow supergiants IIb (Cas A?)
Yellow hypergiants
dense CSM (or not)

**RSG:**
normal RSGs
(like Betelgeuse) II-P
extreme RSGs
(like VY CMa) IIn
Miras
OH/IR stars
symbiotic
super-AGB ecSN (Crab)

**WR:**
WO WC, WN Ibc/GRB
WNH
Ofpe/WN9
WN3/O3
WC+O binaries (WR140 etc)
He stars (weak winds)
Ib

**LBV:**
cool or hot
giant eruptions IIn
(Eta Car, SN impostors)
S Dor variability
microvariability
LBV candidates
CSM shells, or not

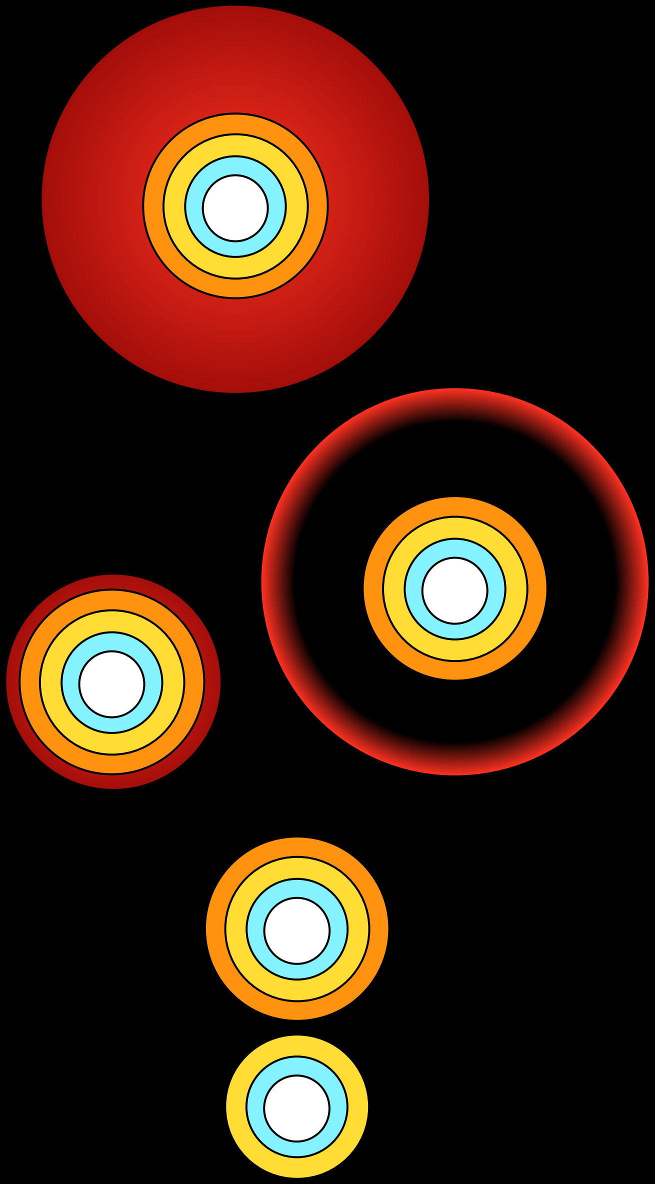
**Interacting binaries:**
any of the above + any of the above, or NS or BH, range of period
massive blue stragglers, red stragglers, mergers, etc.

# *Observed core-collapse SN Diversity*

Types Ib, Ic, Ic BL, IIb (IIb-e vs IIb-c), Ibn, Ibn/IIn, Icn, GRB, SLSN Ic
Types II-P, II-L, IIn-P, IIn (huge variety), SLSN IIn, SLSN II

# A central issue in Massive Star Evolution:
# *SHEDDING THE HYDROGEN ENVELOPE*

Massive stars are born as H-rich O-type stars on the main sequence, and they die as:



**H-rich RSGs**
**---**
**Type II-P/II-L SNe**

**(weird things in between)**
**YSG, BSG, LBV, other**
**---**
**Type IIb, II-pec, IIn, Ibn**

**H-free Wolf-Rayet or**
**lower-mass He stars**
**---**
**Type Ib/Ic SNe, GRBs**

# A central issue in Massive Star Evolution:
# *SHEDDING THE HYDROGEN ENVELOPE*

## 2 competing stories for how we make WR stars and stripped envelope SNe

Requires high luminosity (high $M_{ZAMS}$)

Stronger at higher Z (line-driven or dust)

Observed classes are a monotonic time sequence of progressive mass loss:

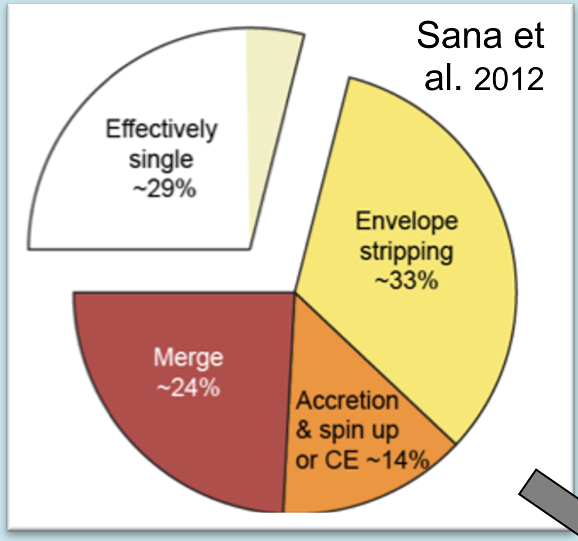
O star ➔ LBV or RSG ➔ WR ➔ SN Ibc

Works across all $M_{ZAMS}$

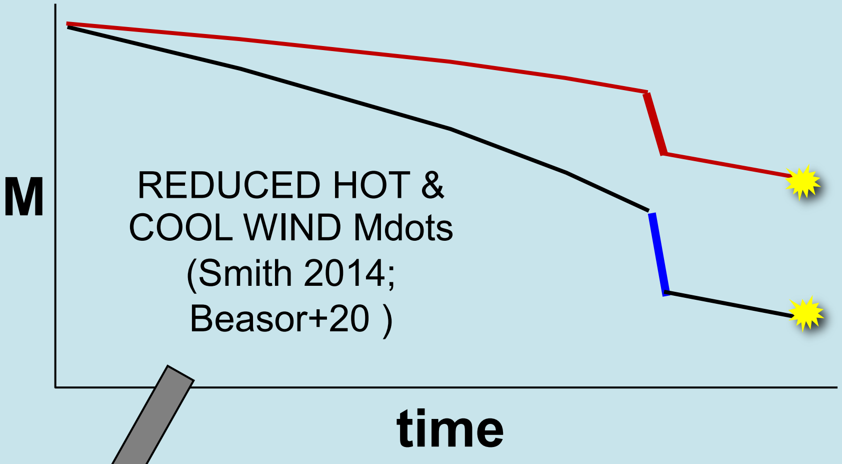
Can work at low Z too

Observed classes are a result of different evolutionary paths:

**Mass donor, mass gainer, common env., merger, etc.**

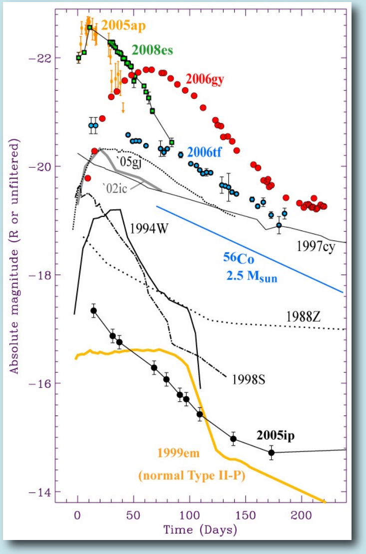


LOTS OF BINARIES
(and triples)

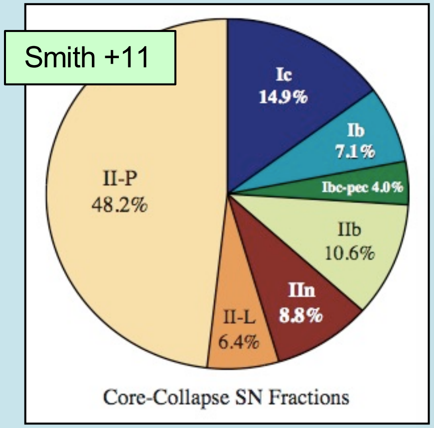


REDUCED HOT &
COOL WIND Mdots
(Smith 2014;
Beasor+20 )

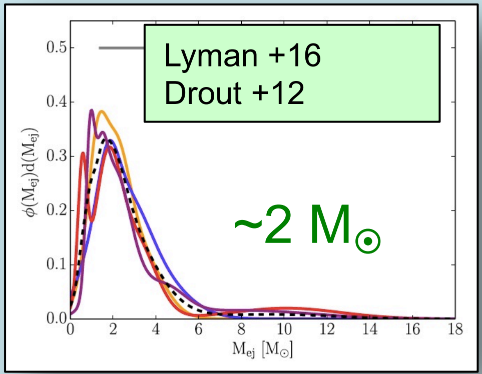
BINARY INTERACTION
DOMINATES THE MASS LOSS
OF MASSIVE STARS AND THE
DIVERSITY OF THEIR SNe
(not Z-dependent steady winds)

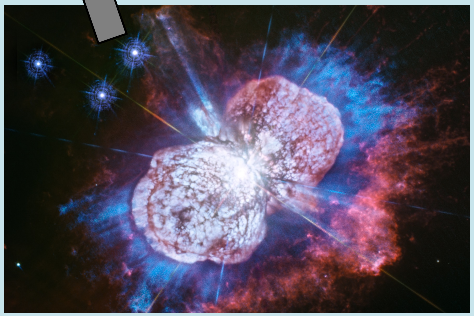


WEIRD SNe, CSM
INTERACTION, ETC



TOO MANY seSNe and
LOW EJECTA MASS





LBVs: these are all binary products.
Mergers & mass gainers (ask me later).

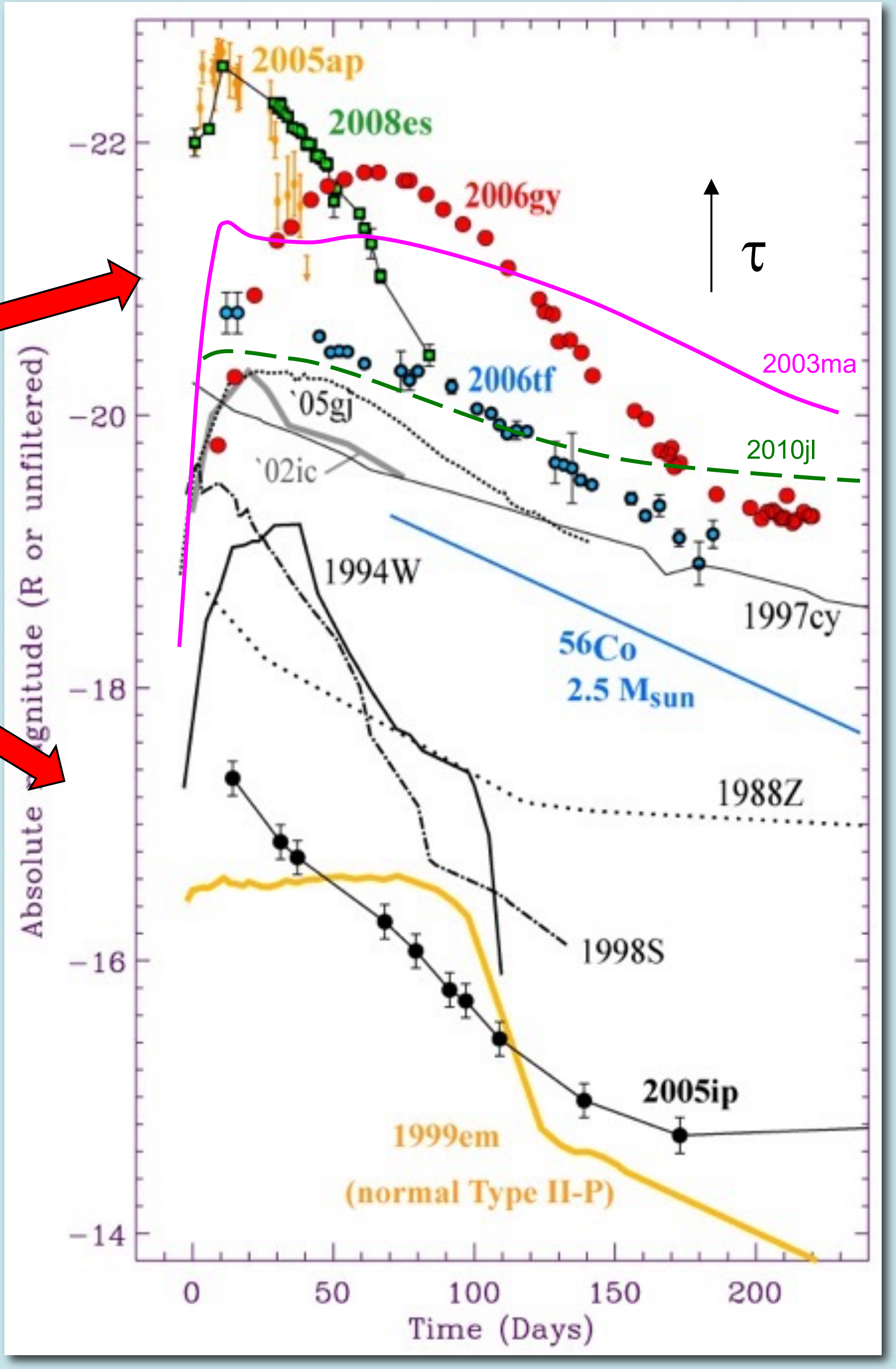
# CSM INTERACTION DIVERSITY

## Observations

## SNe IIn lightcurves – diversity in L and duration

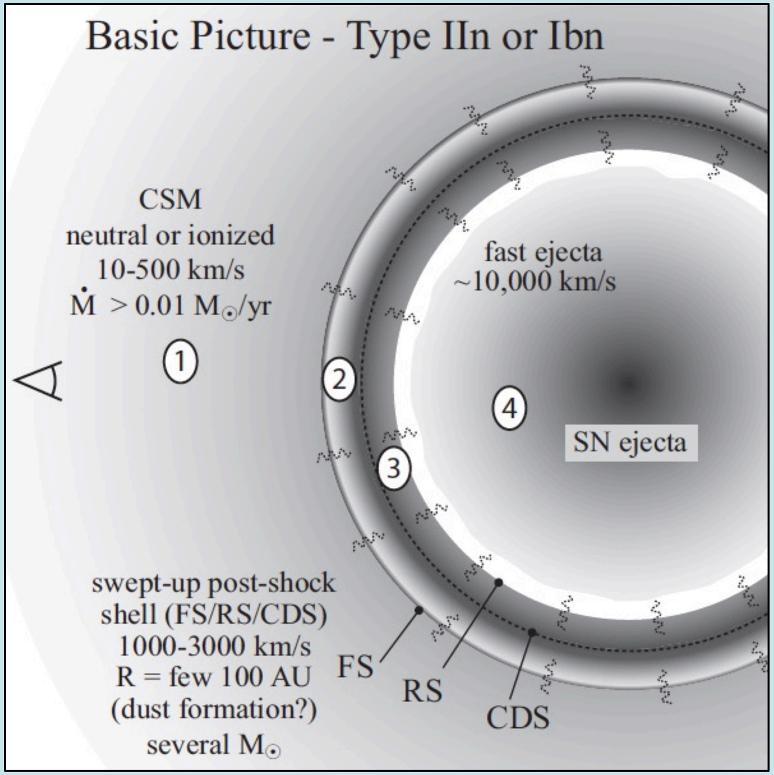
Huge range of CSM interaction ***luminosity***, from SLSNe IIn where CSM interaction completely dominates, down to cases where there is almost no CSM interaction or it makes a minor addition to L.

Also, huge range of total radiated energy: $10^{49}$ erg < $E_{rad}$ < few x $10^{51}$ erg



**Diversity of CSM interaction for SNe IIn results from a range of CSM mass and its radial distribution**
(several talks already on CSM interaction in session 2; Chandra, Chiotellis, etc.)

# CSM INTERACTION DIVERSITY
## Observations



## SNe IIn spectra

1. narrow (< 1000 km/s) pre-shock CSM

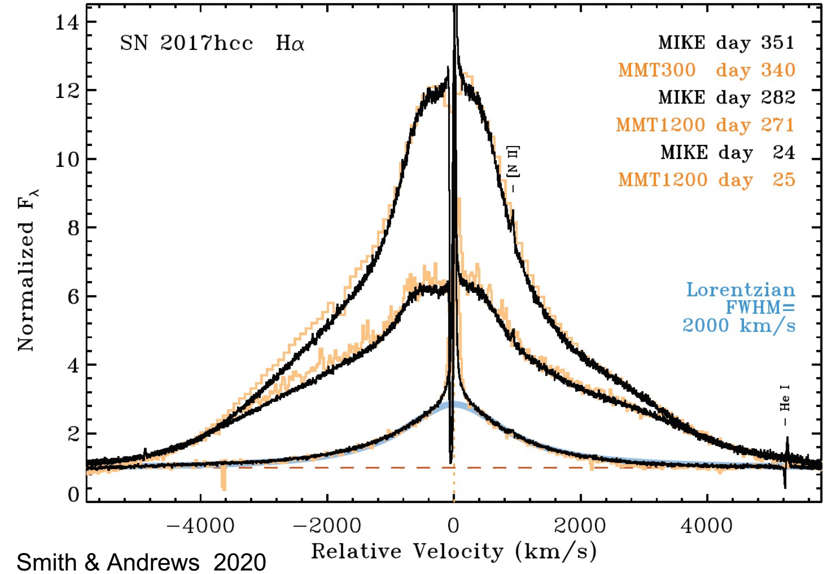
2. intermediate-width (1000-3000 km/s) from shocked CSM (or e- scattering at early times).

3. Broad (~3,000-15,000 km/s) components at some phases (especially late) from reverse shock or SN ejecta. Broad Hα = ***H-rich SN ejecta***.

Inferred CSM mass and progenitor Mdot values are HUGE.

$$L = \frac{1}{2} w V_{SN}^3 = \frac{1}{2}\dot{M}\frac{V_{SN}^3}{V_w}$$

**Generally, if CSM is detectable at visual wavelengths, required mass-loss rates are higher than any normal winds.**



Smith & Andrews 2020

# CSM INTERACTION DIVERSITY
## Observations

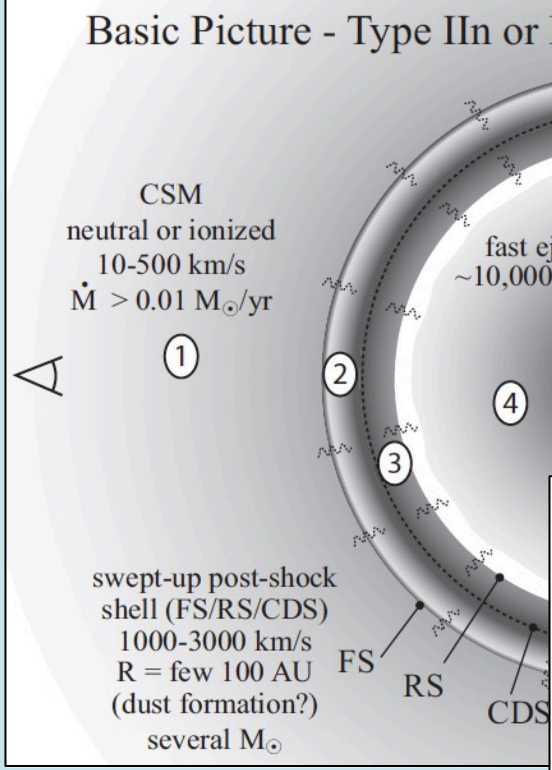
## DUST

High density CSM leads to radiative cooling of post-shock layer.  It forms a cold dense shell (CDS).

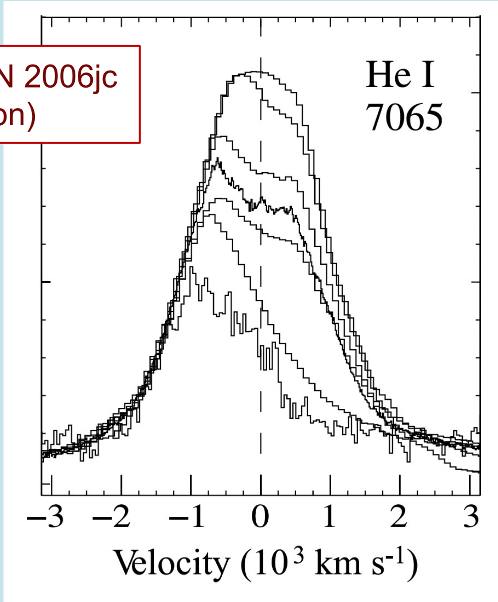
This appears to trigger **rapid dust formation** in the post-shock gas.

Blueshifted line profiles (dust blocks far side) and IR excess seen in many SNe IIn – especially SLSNe IIn.

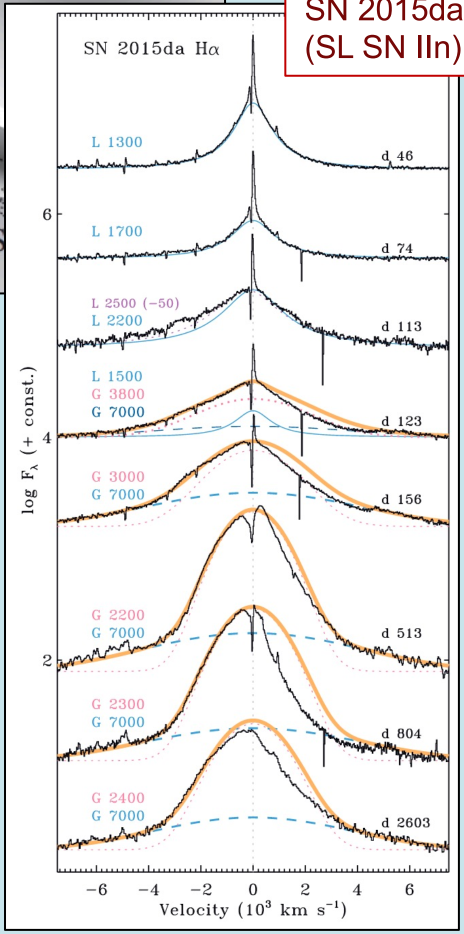
** We will hear more about dust in Session 6 on Thursday.



SN 2006jc (Ibn)



SN 2015da (SL SN IIn)



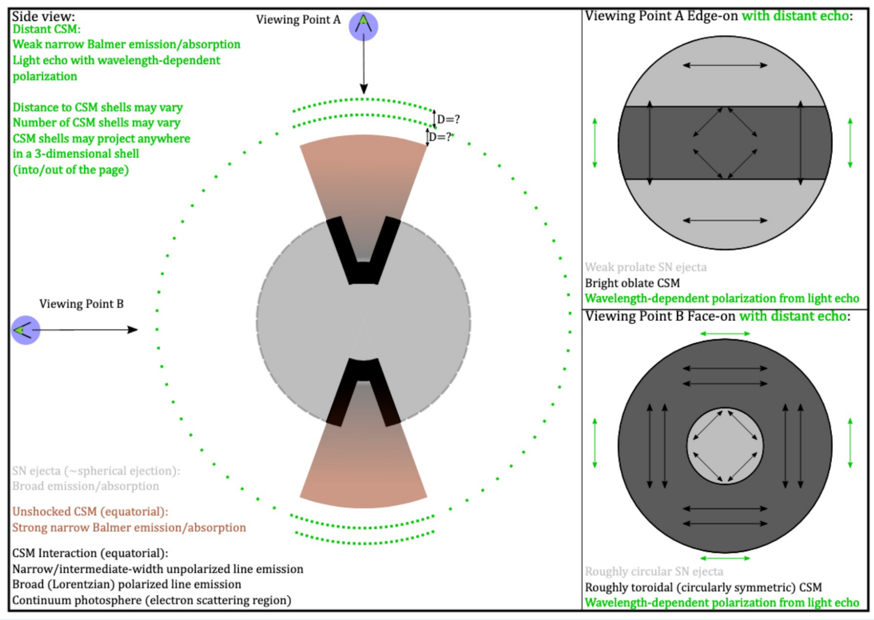
# CSM INTERACTION DIVERSITY

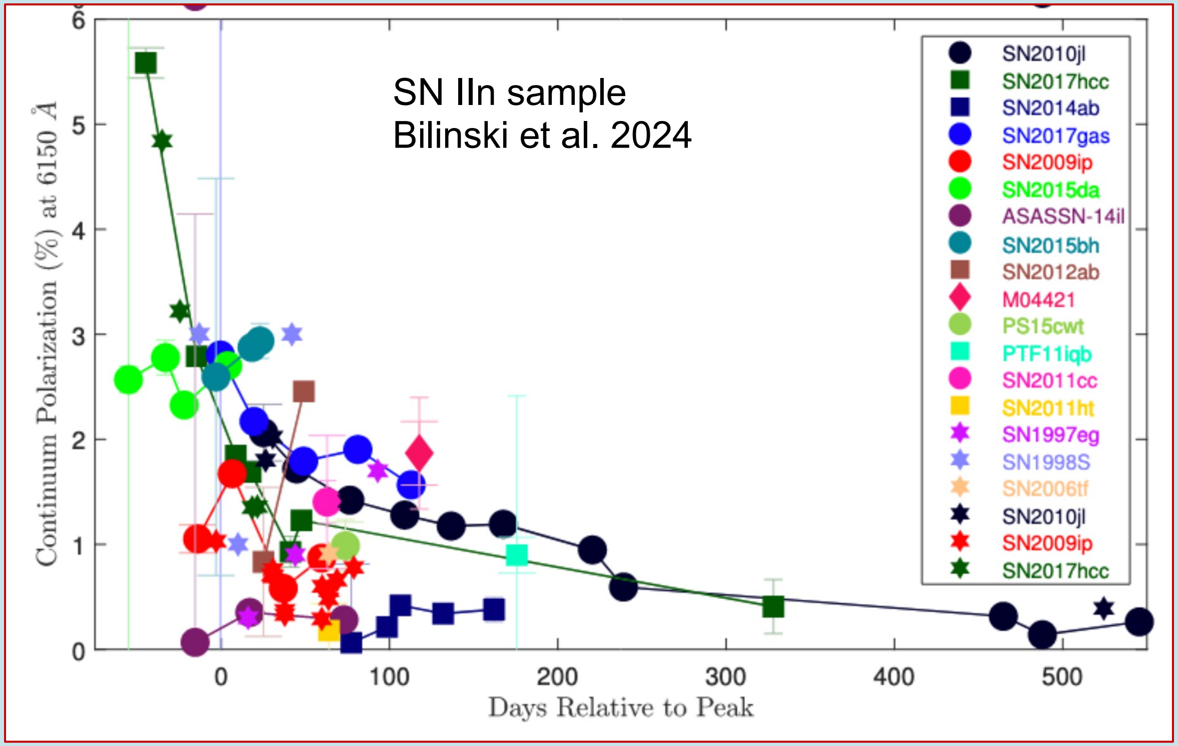
## Observations

**CSM Asymmetry:** from specpol…

Chris Bilinski PhD thesis **(2024, MNRAS, 529, 1104)**

- In sample of SNe IIn, typical polarization during main peak is ~2% (that's high).
- Only about 30% of SNe IIn have low/undetectable polarization below 1%.





SN IIn sample
Bilinski et al. 2024

Diversity in viewing angle?

IF all SNe IIn have CSM in a disk/torus… then with random viewing angles, about 30% will be viewed from 45° to the pole (face on, low %P).

This suggests that highly asymmetric CSM is the norm.

# SNe probe recent temporary mass loss phases before SN

## Range of timescales before core collapse.

| **Expansion timescales at $V_{SN}=10^4$ km/s:** | **Pre-SN timescales at $V_W=10^2$ km/s:** |
|---|---|
| 1 day = 5 AU | 100 days |
| 2 days = 10 AU | 200 days |
| 10 days = 50 AU | ~3 yr |
| 100 days = 500 AU | ~30 yr |
| 1 yr = 2000 AU | 100 yr |
| 10 yr = 0.1 pc | 1000-$10^4$ yr |
| 100 yr = 1 pc | few x $10^4$ yr |

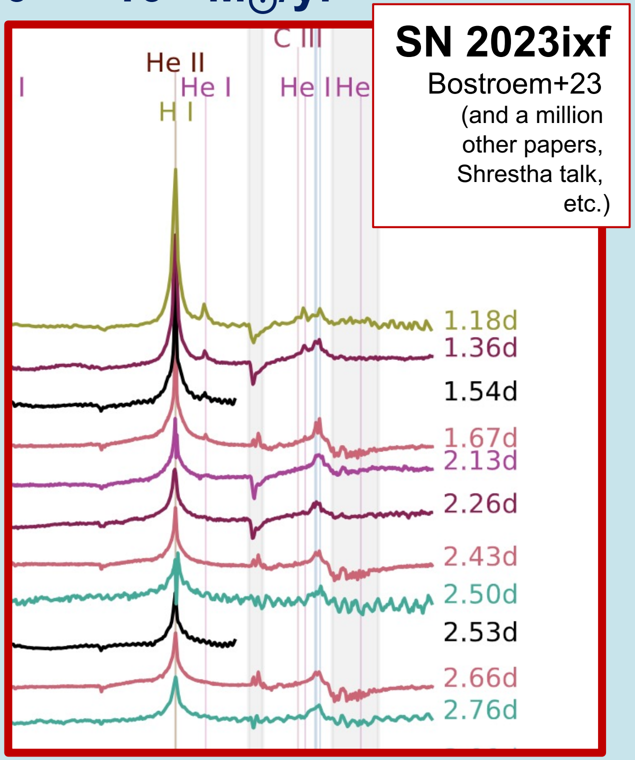
## Close-in CSM, disks, cocoons. Limited to small radii.

- **Enhanced pre-SN winds.** Just a few years before SN.
- **Keplerian disks / Magnetically confined disks.** Rapid rotators (Be stars), binary RLOF/L2, magnetic stars.
- **Immediate pre-SN common envelope or binary interaction.** Probably disk-like shape, radii = 10s AU

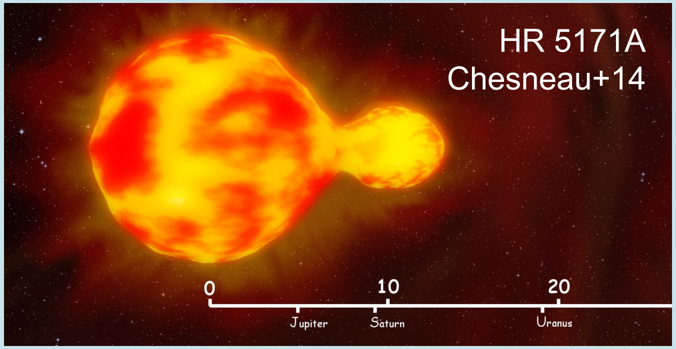
Interaction signatures fade after a few days

| **Expansion timescales at $V_{SN}=10^4$ km/s:** | **Pre-SN timescales at $V_W=10^2$ km/s:** | **Observed Examples:** |
|---|---|---|
| 1 day = 5 AU | 100 days | Flash Spec/<br>Early bumps |
| 2 days = 10 AU | 200 days | |
| 10 days = 50 AU | ~3 yr | Fleeting IIn (98S) |
| 100 days = 500 AU | ~30 yr | SNe IIn/SLSNe |
| 1 yr = 2000 AU | 100 yr | Late interaction |
| 10 yr = 0.1 pc | 1000-$10^4$ yr | 87A, 88Z, 05ip |
| 100 yr = 1 pc | few x $10^4$ yr | SNRs (Cas A) |

$10^{-3} – 10^{-2}$ $M_\odot$/yr



**SN 2023ixf**
Bostroem+23
(and a million other papers, Shrestha talk, etc.)



HR 5171A
Chesneau+14

# Cocoons, young bipolar nebulae, massive disks, strong winds

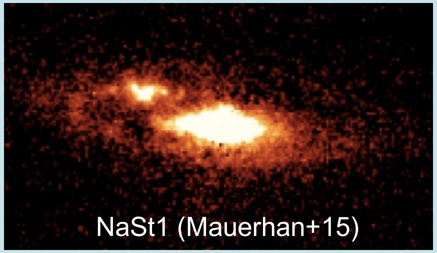
- **B[e] disk/torus.** Rapid rotation or binary RLOF
- **Sustained dense winds.** Extreme RSGs/YHGs with strong winds.
- **Recent LBV eruption or common envelope.** Massive shell. Probably bipolar shape (pinched waist = early, lobes = late).

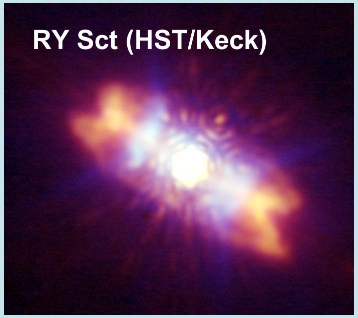
Strong interaction in main peak (Type IIn) and late times.

| Expansion timescales at $V_{SN}=10^4$ km/s: | Pre-SN timescales at $V_W=10^2$ km/s: | Observed Examples: |
|---|---|---|
| 1 day = 5 AU | 100 days | |
| 2 days = 10 AU | 200 days | Flash Spec/<br>Early bumps |
| 10 days = 50 AU | ~3 yr | Fleeting IIn (98S) |
| 100 days = 500 AU | ~30 yr | SNe IIn/SLSNe |
| 1 yr = 2000 AU | 100 yr | Late interaction |
| 10 yr = 0.1 pc | 1000-$10^4$ yr | 87A, 88Z, 05ip |
| 100 yr = 1 pc | few x $10^4$ yr | SNRs (Cas A) |

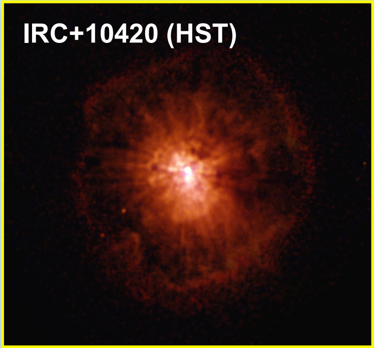
Candidates for SNIbn-like CSM are rare. One possibility is NaSt1 (WR122)

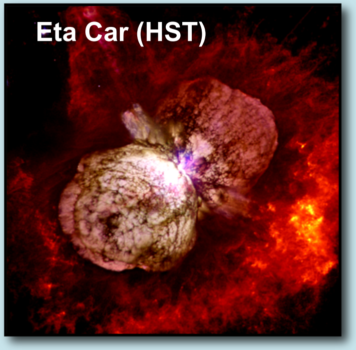
↓


NaSt1 (Mauerhan+15)


RY Sct (HST/Keck)


VY CMa (HST)


IRC+10420 (HST)


Eta Car (HST)

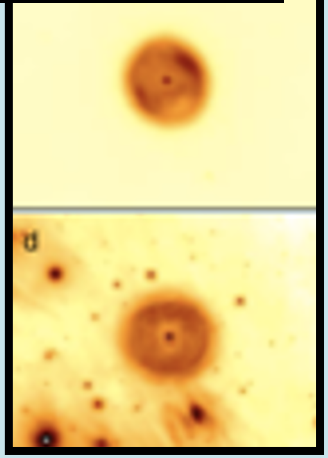
# Distant CSM: bubbles, shells, bipolar, strong winds

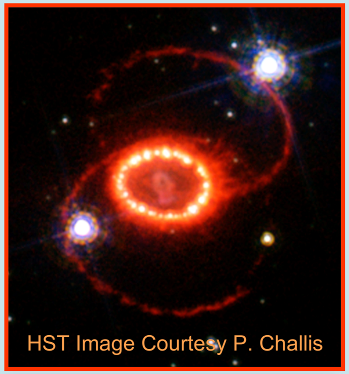
- **Fast wind sweeps into slow wind.** As for previous slide, but smaller (slower winds, more recent transition). Asymmetry in slow wind.
- **Sustained mass loss.** Extreme RSGs with strong, dense winds.
- **Past eruption or common envelope.** Coasting massive shell.

Onset of interaction (or sustained) at late times. IR echoes.

| Expansion timescales at $V_{SN}=10^4$ km/s: | Pre-SN timescales at $V_W=10^2$ km/s: | Observed Examples: |
|---|---|---|
| 1 day = 5 AU | 100 days | Flash Spec/ Early bumps |
| 2 days = 10 AU | 200 days | |
| 10 days = 50 AU | ~3 yr | Fleeting IIn (98S) |
| 100 days = 500 AU | ~30 yr | SNe IIn/SLSNe |
| 1 yr = 2000 AU | 100 yr | Late interaction |
| 10 yr = 0.1 pc | 1000-$10^4$ yr | 87A, 88Z, 05ip |
| 100 yr = 1 pc | few x $10^4$ yr | SNRs (Cas A) |

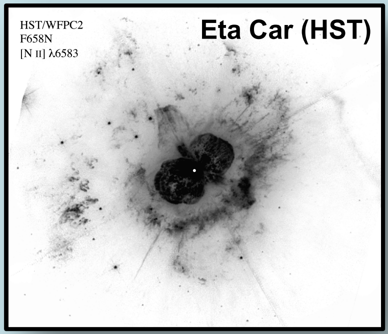
MIPS nebulae:
Gvaramadze et al.
Wachter et al.




HST Image Courtesy P. Challis


VY CMa (HST)


HD 168625 (Spitzer)

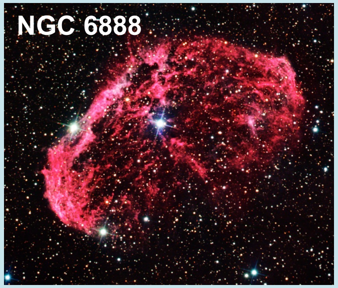

Eta Car (HST)

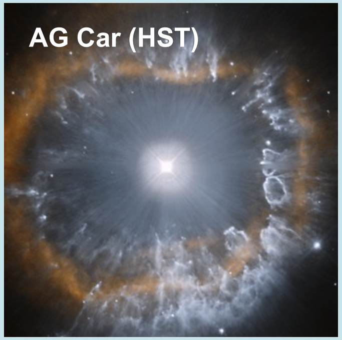
## Large bubbles and shells

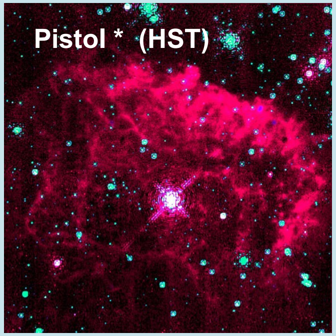
- **Fast wind sweeps into slow wind.** LBV➔WR, LBV eruption➔LBV, RSG➔BSG, blue loops, etc. Cool wind gets swept into a thin, dense shell at large radius. Cavity (fast wind) inside bubble.
- **Stalled wind from external pressure or bow shock.** Slow cool RSG wind stalls at terminal shock due to external pressure; H II region, earlier hot wind, external photoionization. see Mackey +14,16

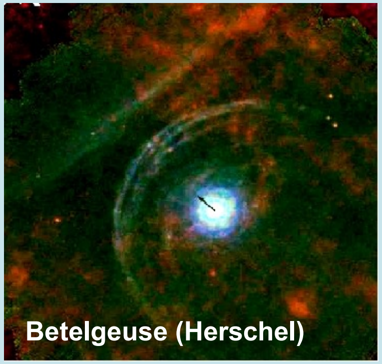
Normal SN (not Type IIn), but with interaction at very late times.

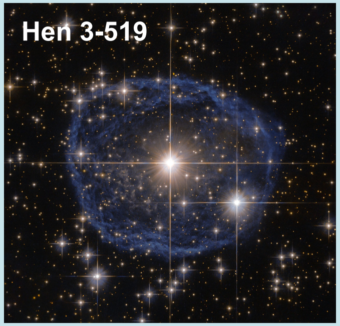
| Expansion timescales at $V_{SN}=10^4$ km/s: | Pre-SN timescales at $V_W=10^2$ km/s: | Observed Examples: |
|---|---|---|
| 1 day = 5 AU | 100 days | |
| 2 days = 10 AU | 200 days | Flash Spec/ Early bumps |
| 10 days = 50 AU | ~3 yr | Fleeting IIn (98S) |
| 100 days = 500 AU | ~30 yr | SNe IIn/SLSNe |
| 1 yr = 2000 AU | 100 yr | Late interaction |
| 10 yr = 0.1 pc | 1000-$10^4$ yr | 87A, 88Z, 05ip |
| 100 yr = 1 pc | few x $10^4$ yr | SNRs (Cas A) |


NGC 6888


AG Car (HST)


Pistol * (HST)


Betelgeuse (Herschel)

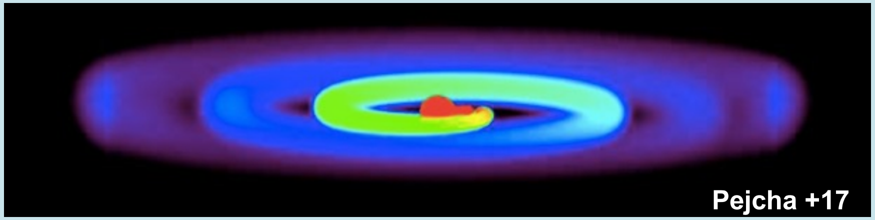

Hen 3-519

# ASYMMETRIC CSM (Part I): DISKS, RINGS, BIPOLAR

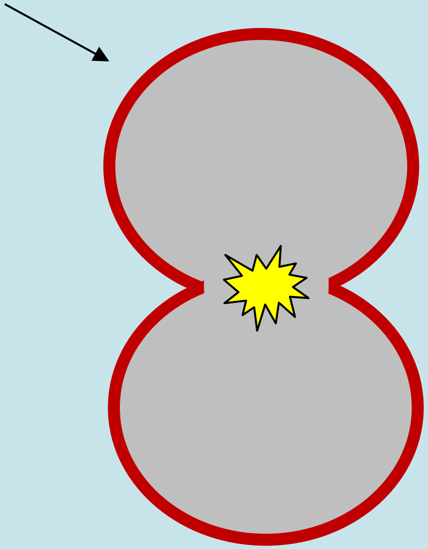
Large (old) CSM shells are often spherical, but small (young) ones are always asymmetric. Asymmetry gets washed out with age.

If it isn't spherical, then a disk is a good first approximation.

- Rapid rotators
- Magnetic stars
- Binary RLOF
- Mergers

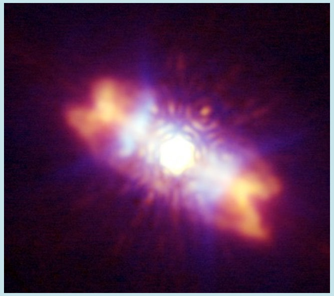
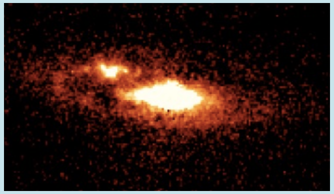
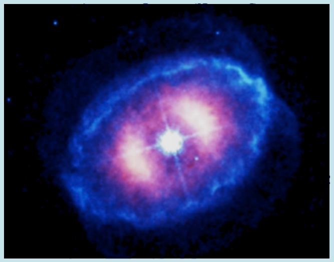

Pejcha +17

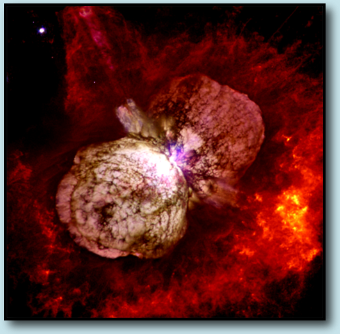
Even bipolar lobes are "disk like" when CSM interaction begins, because of the pinched waist.



Asymmetry impacts our interpretation of the SN observations.

- Energy budget (solid angle)
- Polarization / line profiles
- Multiple optical depths (X-rays escape out poles)
- Two different photospheres seen simultaneously: normal SN ejecta photosphere + shocked CSM
- Added diversity due to viewing angle
- If disk has small R, CSM interaction can be hidden

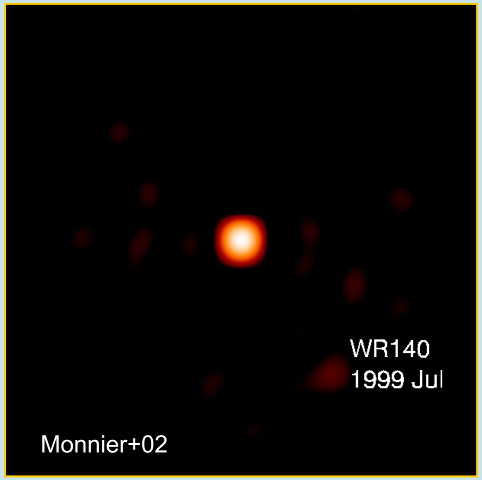


# ASYMMETRIC CSM (Part II): LOPSIDED CSM

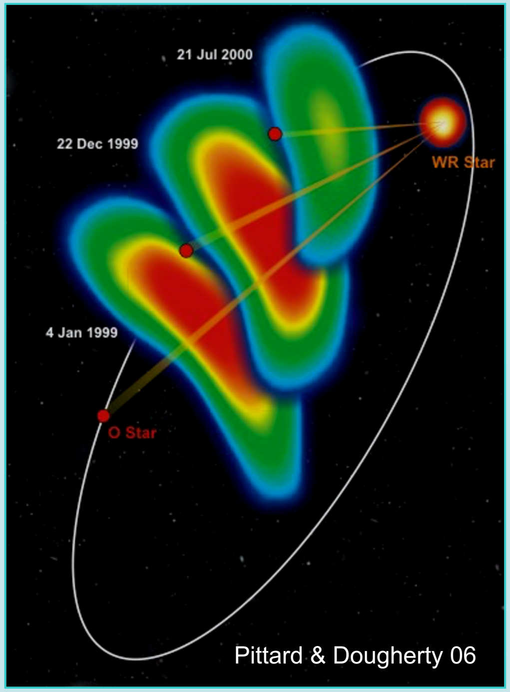
Rapid rotators and close binaries with circular orbits should make primarily ***axisymmetric*** CSM.

Sometimes CSM is non-axisymmetric or even one-sided.

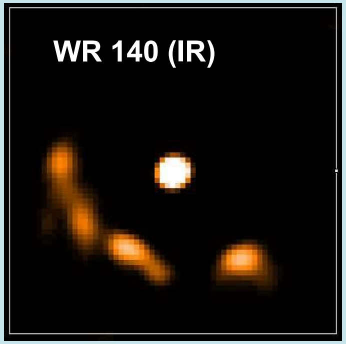
- Eccentric binaries, grazing collisions, colliding winds
- Close binaries with episodic mass loss
- Triple systems
- Runaway stars (bow shocks; large)



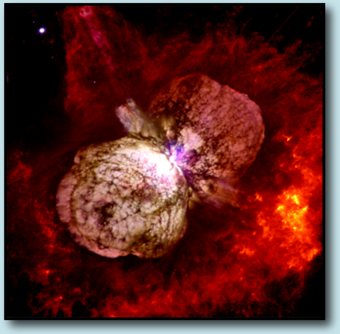
Monnier+02



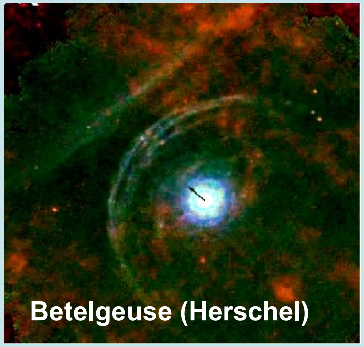
Pittard & Dougherty 06



WR 140 (IR)



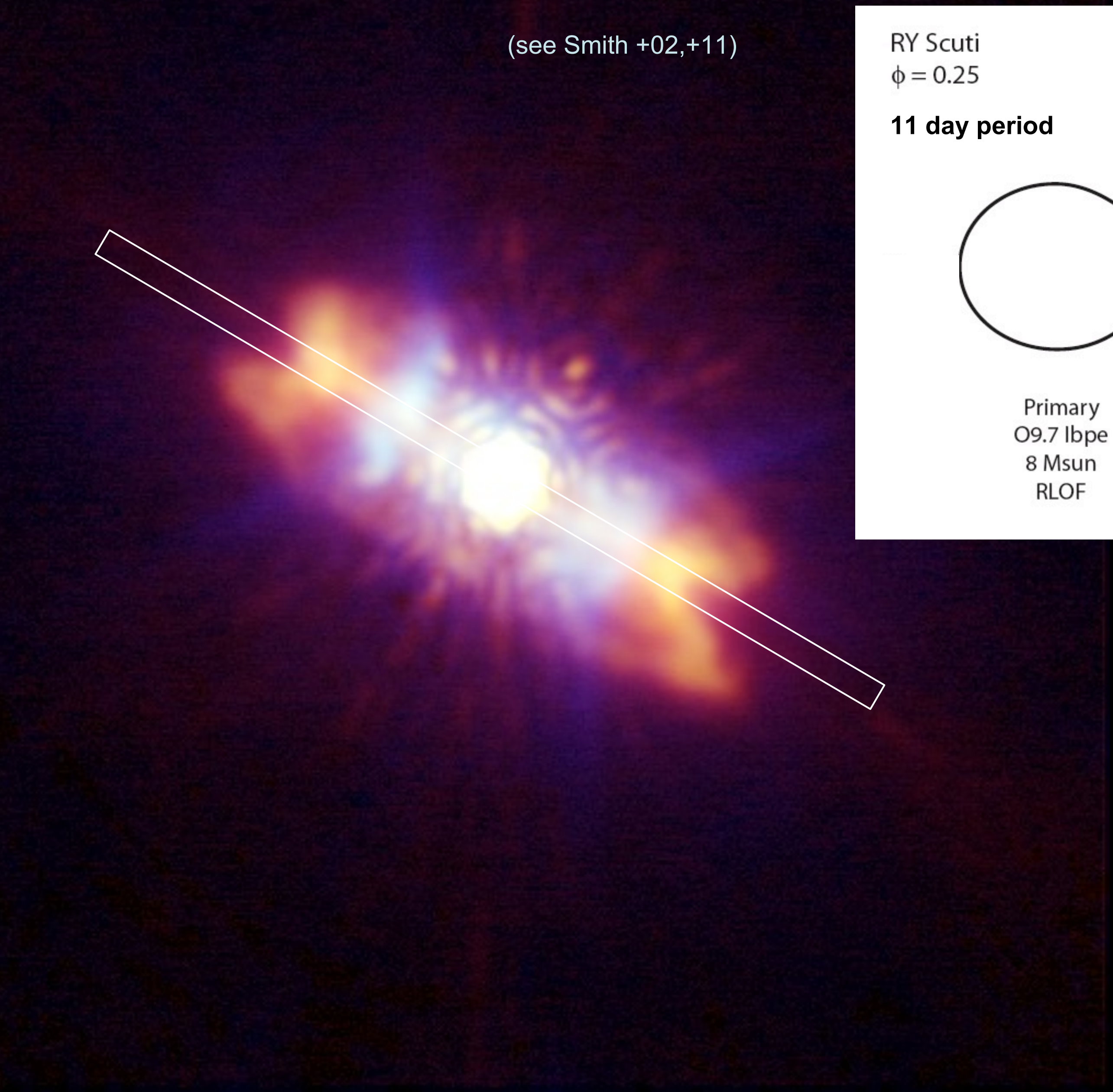
zeta Oph (Spitzer)

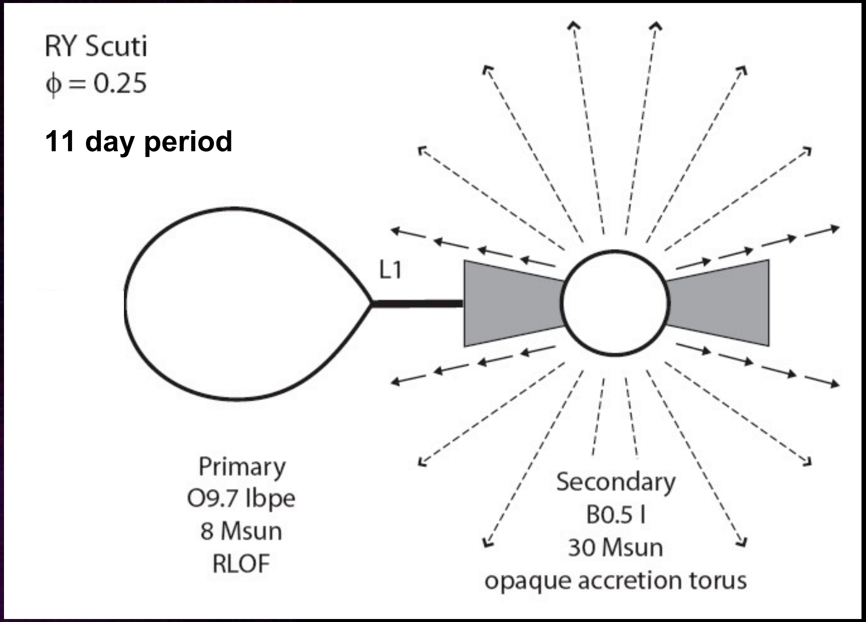


Betelgeuse (Herschel)

# RY Scuti: eclipsing massive binary system in transition to WR+O via RLOF.

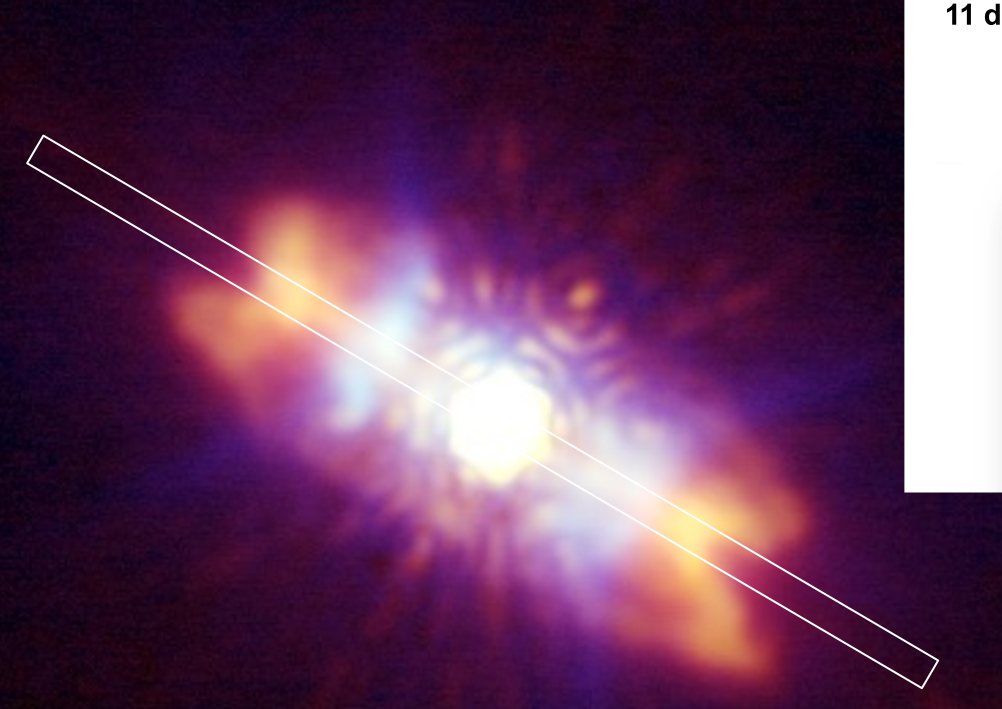
(see Smith +02,+11)

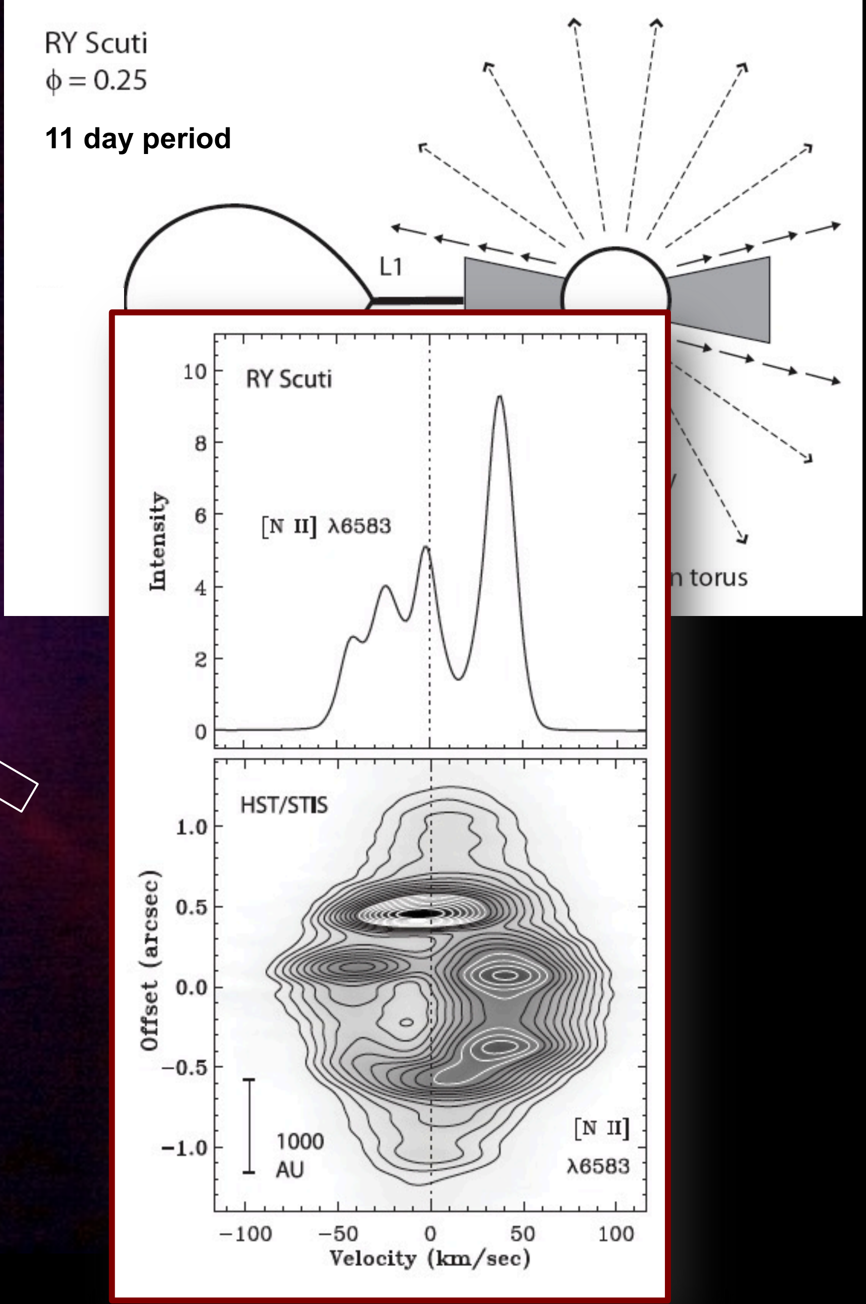




# RY Scuti: eclipsing massive binary system in transition to WR+O via RLOF.

(see Smith +02,+11)



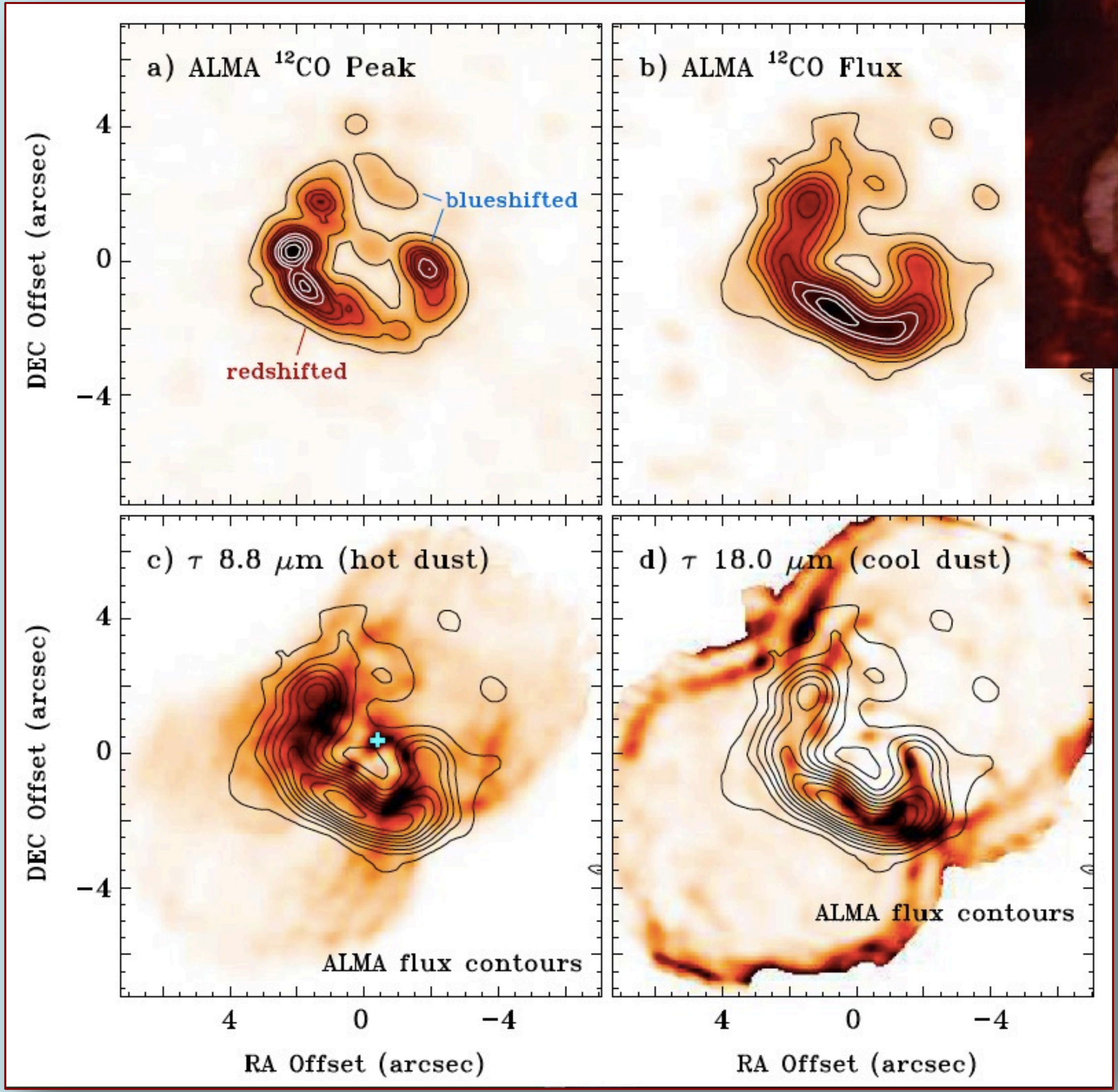


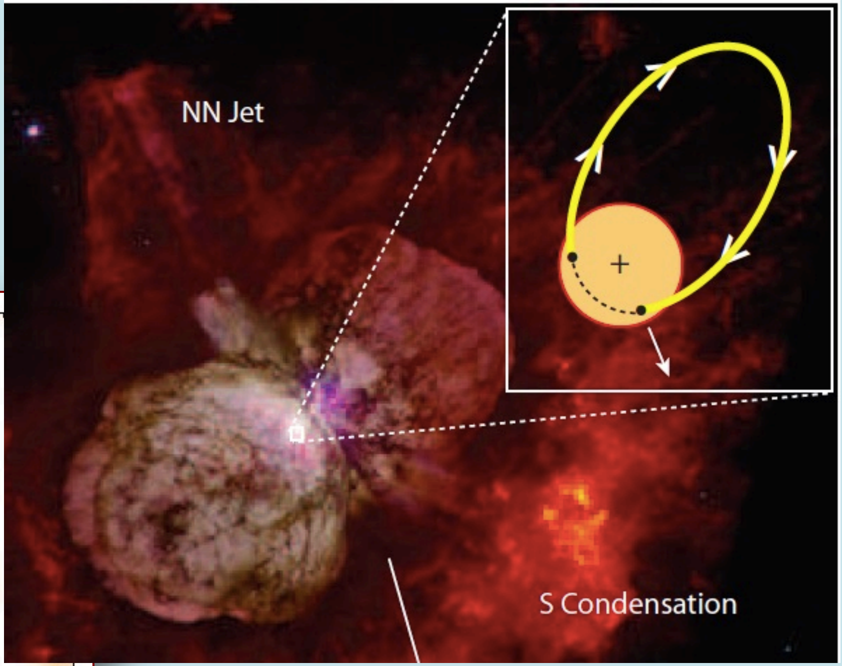
**Azimuthal density distribution around ring is lopsided. Most of the mass on redshifted side, with a C-shape... gap on near side.**

**Seems hard to do in circularized eclipsing binary. Short duration bursts of mass loss?**

# The disrupted torus around Eta Car

## ALMA observations of $^{12}$CO 2-1 230.5 GHz





Although the bipolar nebula appears axisymmetric, the mass distribution in the equatorial ring is very lopsided. Most of the mass is on far side.

NW side of torus is the direction of apastron in the e=0.9 binary orbit (Madura+12) and the opening of the colliding wind shock cone.

Smith, Ginsburg, Bally 2018.

# What happens if a star like this explodes as a supernova?

Raymond: talked about an object in M31, maybe what the remnant of Eta might look like in 2000 yr (?).

But let's talk about its SN explosion and evolution to SNR over 100-200 yr.

HST/WFC3
Smith & Morse (2019)

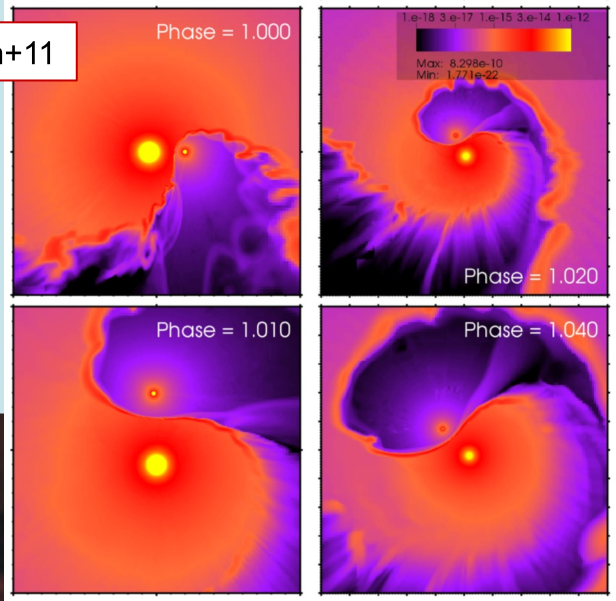
**The fast SN ejecta will crash into this slower circumstellar material (CSM)**

- This "CSM interaction" can make the SN even more luminous (KE → light)
- Shock radiation lights up slow CSM, making narrow lines in the spectrum (Type IIn)

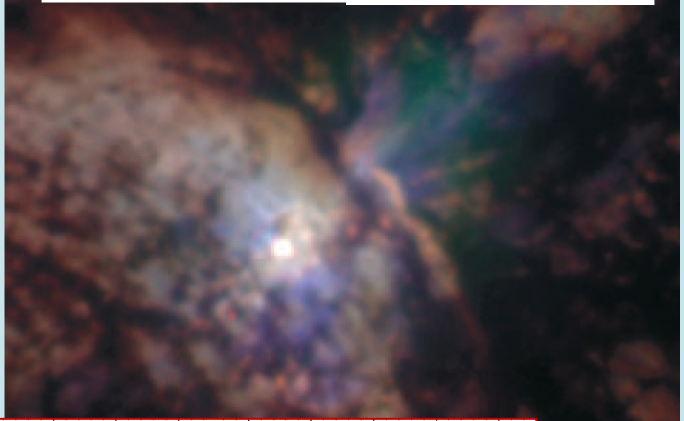
# If Eta Car exploded… what would we see?

- **Slow rising SN.** As a blue supergiant, it might initially be faint (like 87A).
- **Flash features.** Would immediately have CSM interaction with wind (1e-3 Msun/yr) and clumps near star.
- **Normal Type IIn.** For several months to a year, it would interact with dense equatorial clumpy CSM.

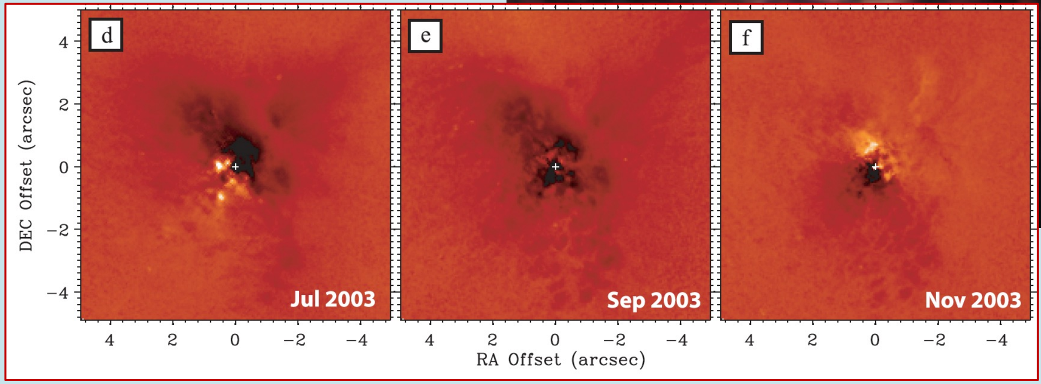
| **Expansion timescales at $V_{SN}=10^4$ km/s:** | **Pre-SN timescales at $V_W=10^2$ km/s:** |
|---|---|
| 1 day = 5 AU | 100 days |
| 2 days = 10 AU | 200 days |
| 10 days = 50 AU | ~3 yr |
| 100 days = 500 AU | ~30 yr |
| 1 yr = 2000 AU | 100 yr |
| 10 yr = 0.1 pc | 1000-$10^4$ yr |
| 100 yr = 1 pc | few x $10^4$ yr |



Parkin+11



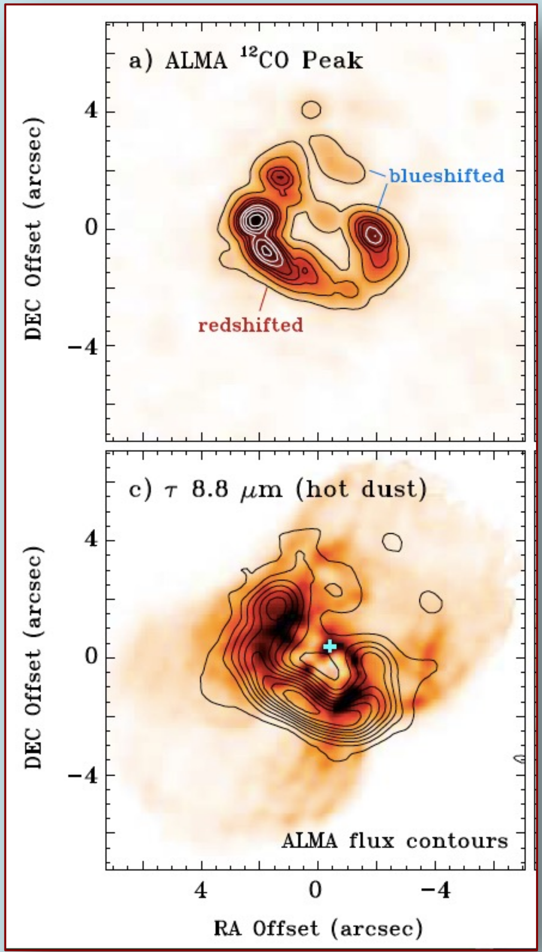
HST/ACS
Smith +04

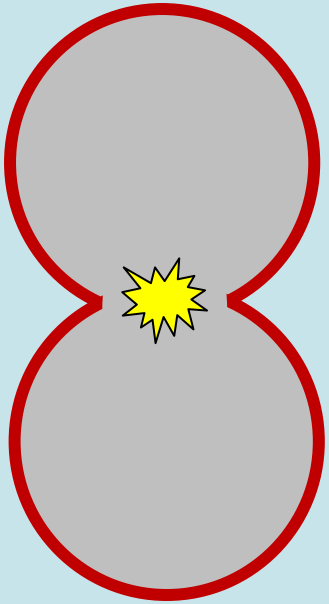


# If Eta Car exploded… what would we see?

- **Main Event.** After delay of 0.5-1 yr, forward shock crashes into waist of bipolar nebula… then walls… then poles.
- **SLSN IIn.** Slowly evolving SLSN IIn for about a decade. Like SN 2015da. 20 $M_\odot$ of CSM. ***(Bright as the full moon.)***
- **Cold Dense Shell**. ~50 $M_\odot$ of post-shock gas cools, collapses, forms molecules and **dust,** coasting outward at 1500 km/s.

| **Expansion timescales at $V_{SN}=10^4$ km/s:** | **Pre-SN timescales at $V_W=10^2$ km/s:** |
|---|---|
| 1 day = 5 AU | 100 days |
| 2 days = 10 AU | 200 days |
| 10 days = 50 AU | ~3 yr |
| 100 days = 500 AU | ~30 yr |
| 1 yr = 2000 AU | 100 yr |
| 10 yr = 0.1 pc | 1000-$10^4$ yr |
| 100 yr = 1 pc | few x $10^4$ yr |





talk this morning by Alexandros. Chiotellis

# If Eta Car exploded… what would we see?

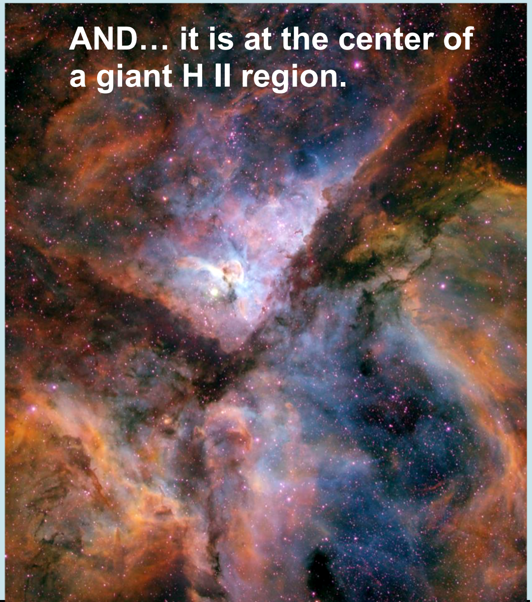
- **Evolution to SN Remnant.** Forward shock breaks through the bipolar nebula, into surrounding medium.
- **Complex structure.** Fast ejecta would squirt through holes, looking like jets. Blast wave would wrap around dense slow knots, leaving them behind.
- **Outer ejecta.** Shock would run through dense N-rich knots for next few centuries. QSFs?

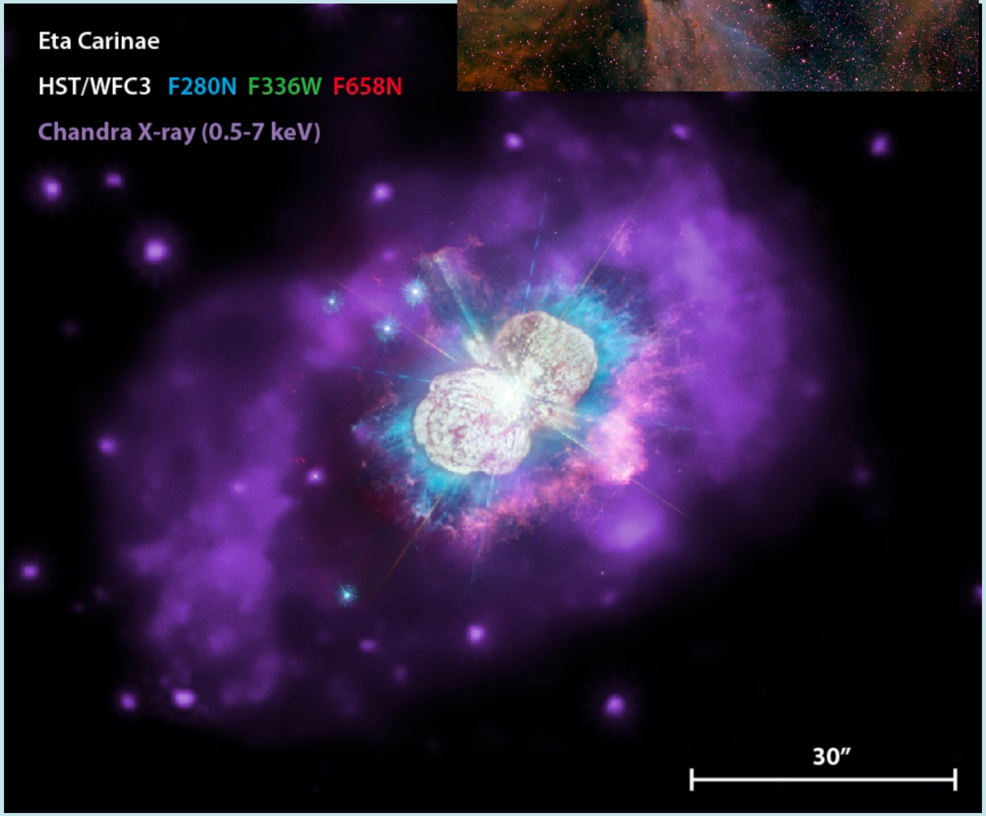
| **Expansion timescales at $V_{SN}=10^4$ km/s:** | **Pre-SN timescales at $V_W=10^2$ km/s:** |
|---|---|
| 1 day = 5 AU | 100 days |
| 2 days = 10 AU | 200 days |
| 10 days = 50 AU | ~3 yr |
| 100 days = 500 AU | ~30 yr |
| 1 yr = 2000 AU | 100 yr |
| 10 yr = 0.1 pc | 1000-$10^4$ yr |
| 100 yr = 1 pc | few x $10^4$ yr |

# If Eta Car exploded… what would we see?

- **Absurdly complex.** Asymmetric, multi-component, mixed, bullets/shrapnel, “jets” (not really), blowouts, etc.
- **Even more confusing.** Eta Car ***already*** looks like a SNR now. Blast wave from 19th century merger. Fast (5000 km/s) N-rich ejecta inside X-ray shell.
- **Binary.** Which star explodes first? Future SNR will have either a super-luminous LBV or an extreme WR star at the center. HMXB.

| **Expansion timescales at $V_{SN}=10^4$ km/s:** | **Pre-SN timescales at $V_W=10^2$ km/s:** |
|---|---|
| 1 day = 5 AU | 100 days |
| 2 days = 10 AU | 200 days |
| 10 days = 50 AU | ~3 yr |
| 100 days = 500 AU | ~30 yr |
| 1 yr = 2000 AU | 100 yr |
| 10 yr = 0.1 pc | 1000-$10^4$ yr |
| 100 yr = 1 pc | few x $10^4$ yr |


AND… it is at the center of a giant H II region.



# CSM INTERACTION DIVERSITY

## Eruption/Explosion mechanisms

**Some potential mechanisms to produce the CSM in interacting SNe.**
**How well do they match SN IIn properties and diversity?**

**Pulsational Pair Instability:** way too rare; almost none match expectations

**8-11 $M_{\odot}$ (ecSNe, degenerate flashes, etc.):** limited to low-mass, low-E explosions. Crab maybe; not most interacting SNe.

**Wave driving:** Limited to 1 yr before CC. Very weak mass loss if it works. Cannot explain CSM in vast majority of interacting SNe (>1 yr).

**Other late burning instabilities:** most known instabilities are during O burning (same problem as wave driving = 1yr). 3D - needs more study.

**Pre-SN Binary Interaction:** works in principle – asymmetry, wide range of mass, massive stars are in binaries. But why synchronIzed with CC?