Diversity of CSM: Interacting SNe and SN Impostors

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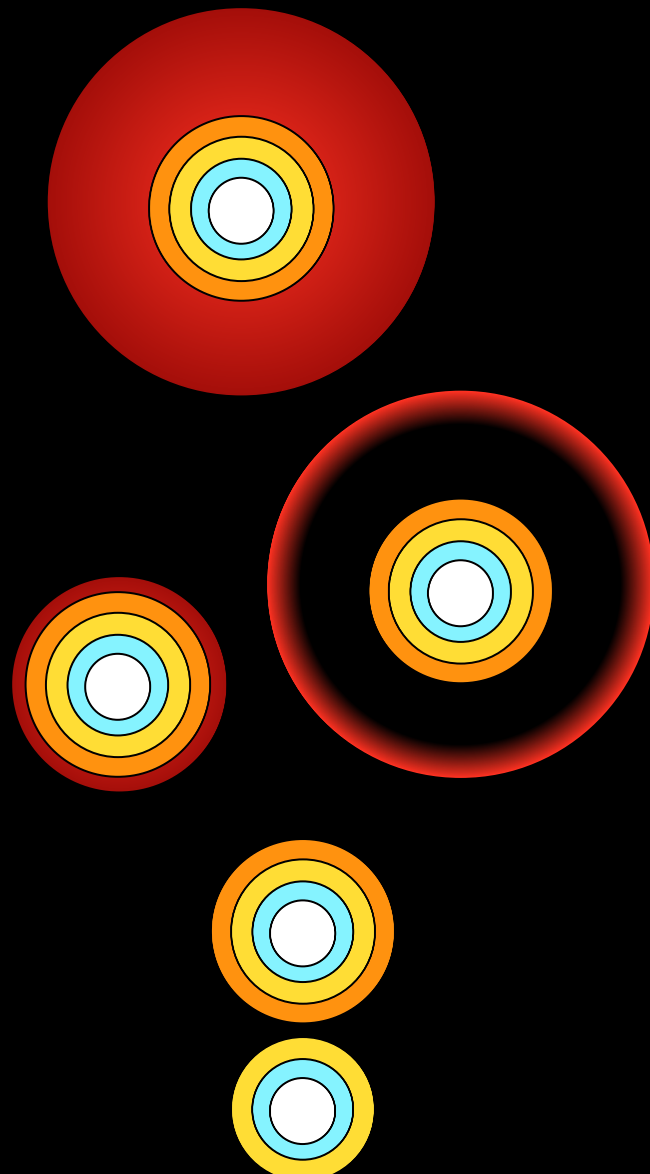
A central issue in Massive Star Evolution:
SHEDDING THE HYDROGEN ENVELOPE

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 IIn, Ibn, IIb, II-pec,

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.

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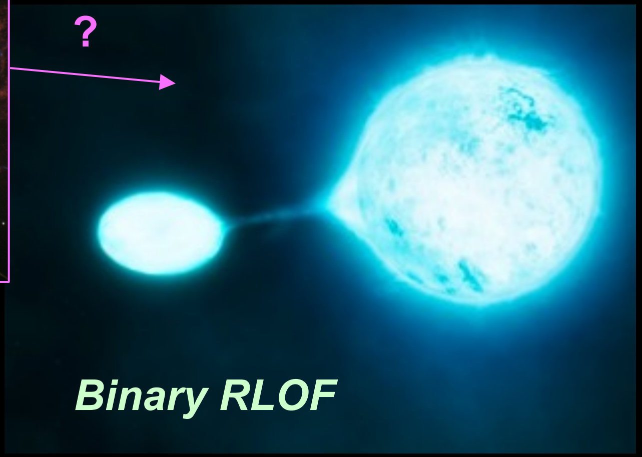
ERUPTIONS
what the heck are they?



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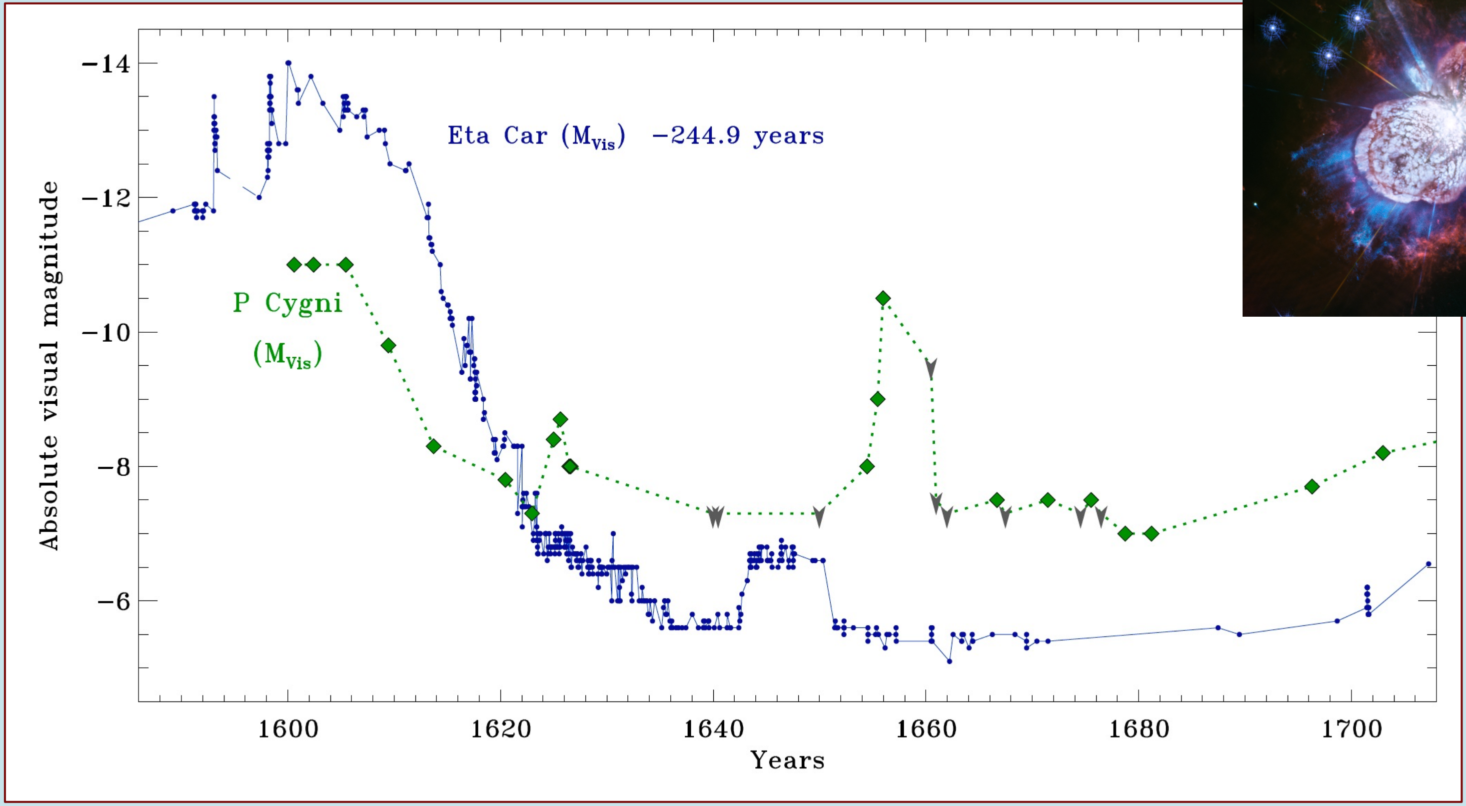
LBV Eruptions



Luminous Blue Variables (LBVs): Diverse observed phenomena. Irregular brightening events associated with eruptive mass loss of massive stars (20-200 $M_{\odot}$). Timescales of 10 d to 20 yr, and brightening of 0.1 mag to 7 mag. Some are minor and caused by temperature changes with little increase in wind mass loss, while some show major increase in L_{Bol} and lots of mass loss and explosive outflows. Bulk outflow speeds of 100-1000 km/s typically, but some faster material too.

For recent LBV review, see Smith 2025 chapter in the Encyclopedia of Astrophysics (out soon).

LBV Eruptions

PHYSICAL MECHANISM

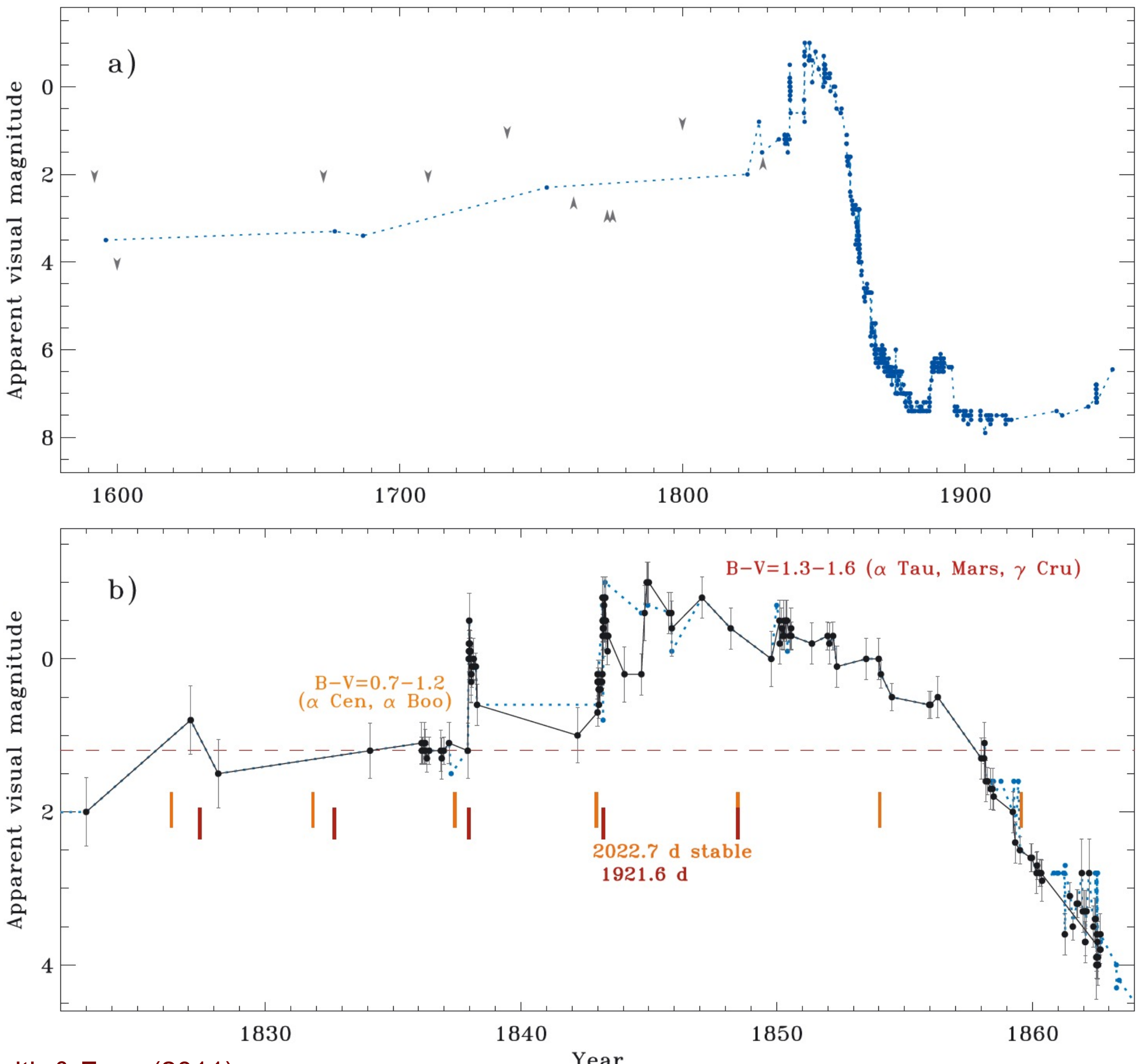
We still don't know what triggers LBV eruptions.
Something must provide 10^{48}-10^{50} ergs of extra energy.
Usually people discuss 2 main scenarios:

1. **Super-Eddington outbursts (a.k.a. "single-star outburst").** This is the more traditional view. Can drive mass loss in principle if you exceed L_{Edd}, obviously, but **why does L increase in a single star in the first place**? *There has never been a model for this*. Even if we ignore that, SE winds fail to account for many of the detailed observations (especially explosive high velocities and high KE/E_{rad} ratio, spectral evolution, etc.).

2. **Binary interaction events, mergers, accretion, etc.** *Merger event easily provides the necessary energy*. Combination of inspiral, outburst, and CSM interaction can potentially account for most LBV-like transients (including LBVs, SN impostors, LRNe, ILOTs, etc.), and their diversity.

   Prototype: Eta Car was a merger in a triple (Smith et al. 2018)

LBV Eruptions



Smith & Frew (2011)

Light Echoes: Eta Car's eruption happened before the invention of the astronomical spectrograph. But we can get spectra using light echoes!

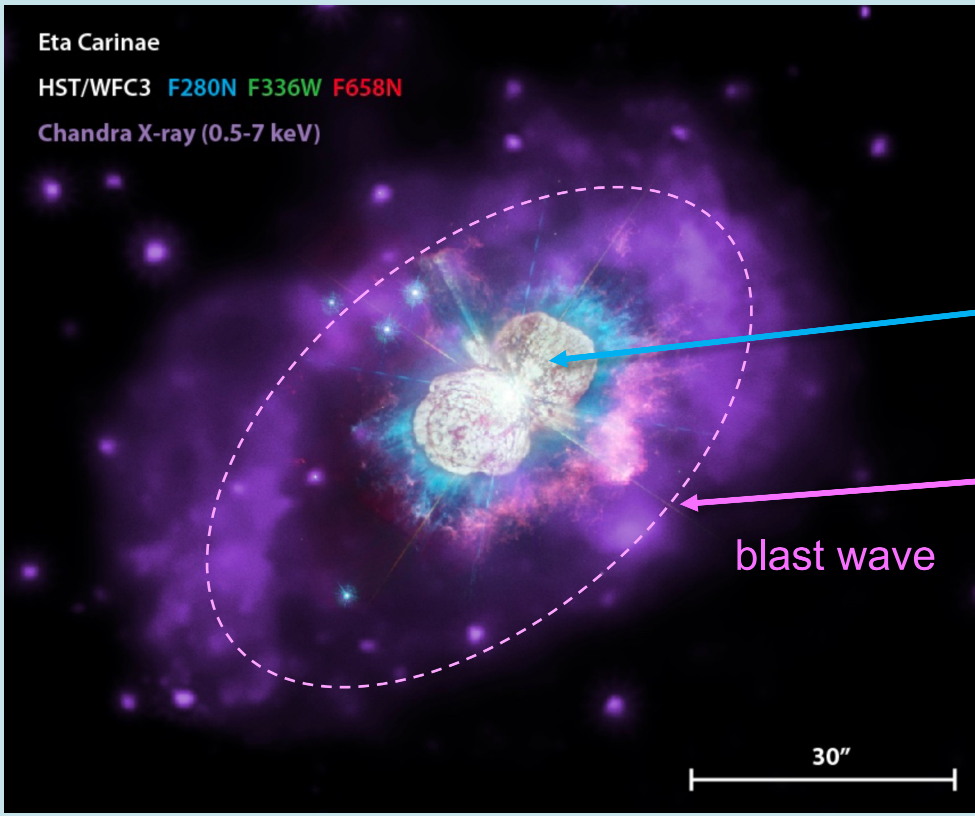
Me, Armin Rest, Fed Bianco, Jen Andrews, Jose Prieto, Jacob Jencson, et al.

Eta Carinae: Historical visual observations of 19th century "Great Eruption". Transitioned from yellow to very red over >2 decades.

Exceptionally fast ejecta seen in light echoes of Eta Carinae's Great Eruption

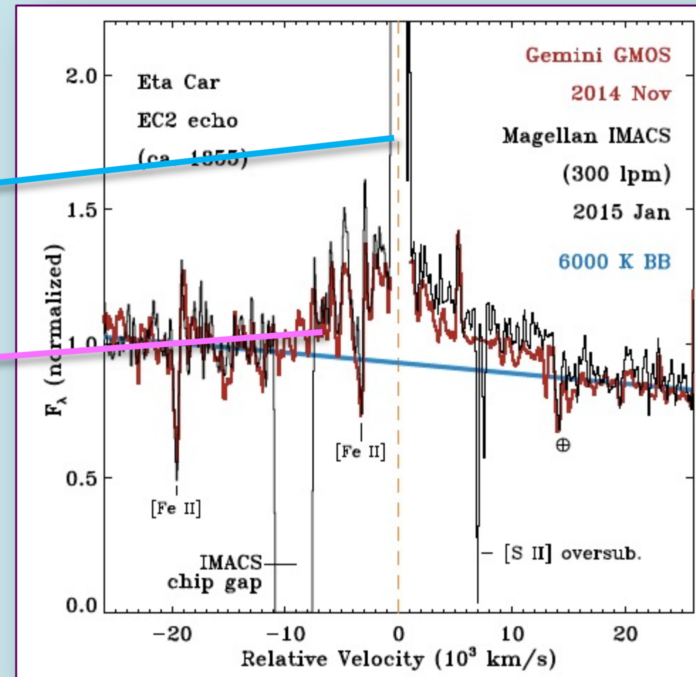
MNRAS, 480, 1457

Nathan Smith,[1★] Armin Rest,[2,3] Jennifer E. Andrews,[1] Tom Matheson,[4] Federica B. Bianco,[5,6] Jose L. Prieto,[7,8] David J. James,[9] R. Chris Smith,[10] Giovanni Maria Strampelli[2,11] and A. Zenteno[10]



650 km/s

10,000 km/s



Light echoes from the plateau in Eta Carinae's Great Eruption reveal a two-stage shock-powered event

MNRAS, 480, 1466

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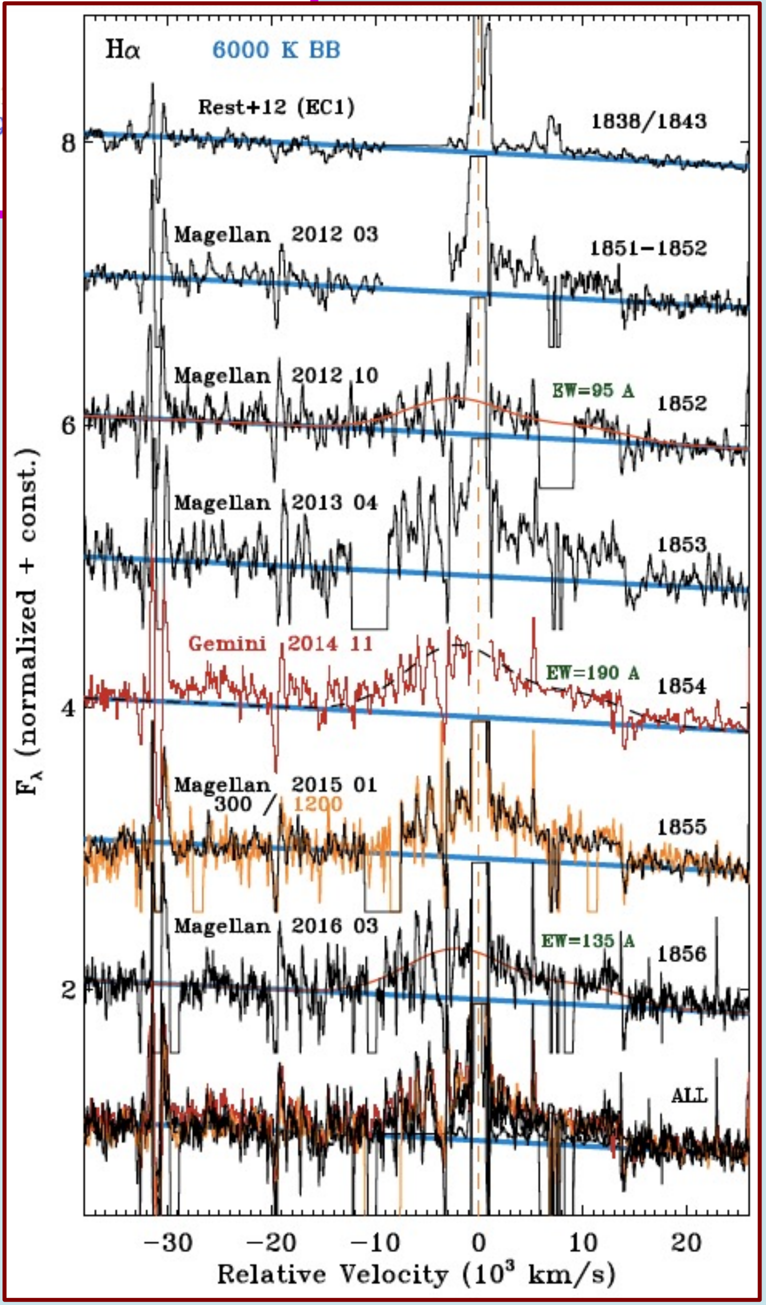

Evolution of light echo spectra over several years during plateau shows a major transition.

Stage I: Early peaks, early plateau.

- **Slow outflow (150-200 km/s), cool temp, absorption lines, weak narrow emission lines (Rest +12, Prieto +14).**

Stage II: Late 1840s/1850s plateau.

- **Narrow emission lines got broader (650 km/s)**
- **Very broad emission wings appeared (10,000-20,000 km/s).**

(Spectra look a lot like the broad + intermediate line profile shapes in SNe IIn)

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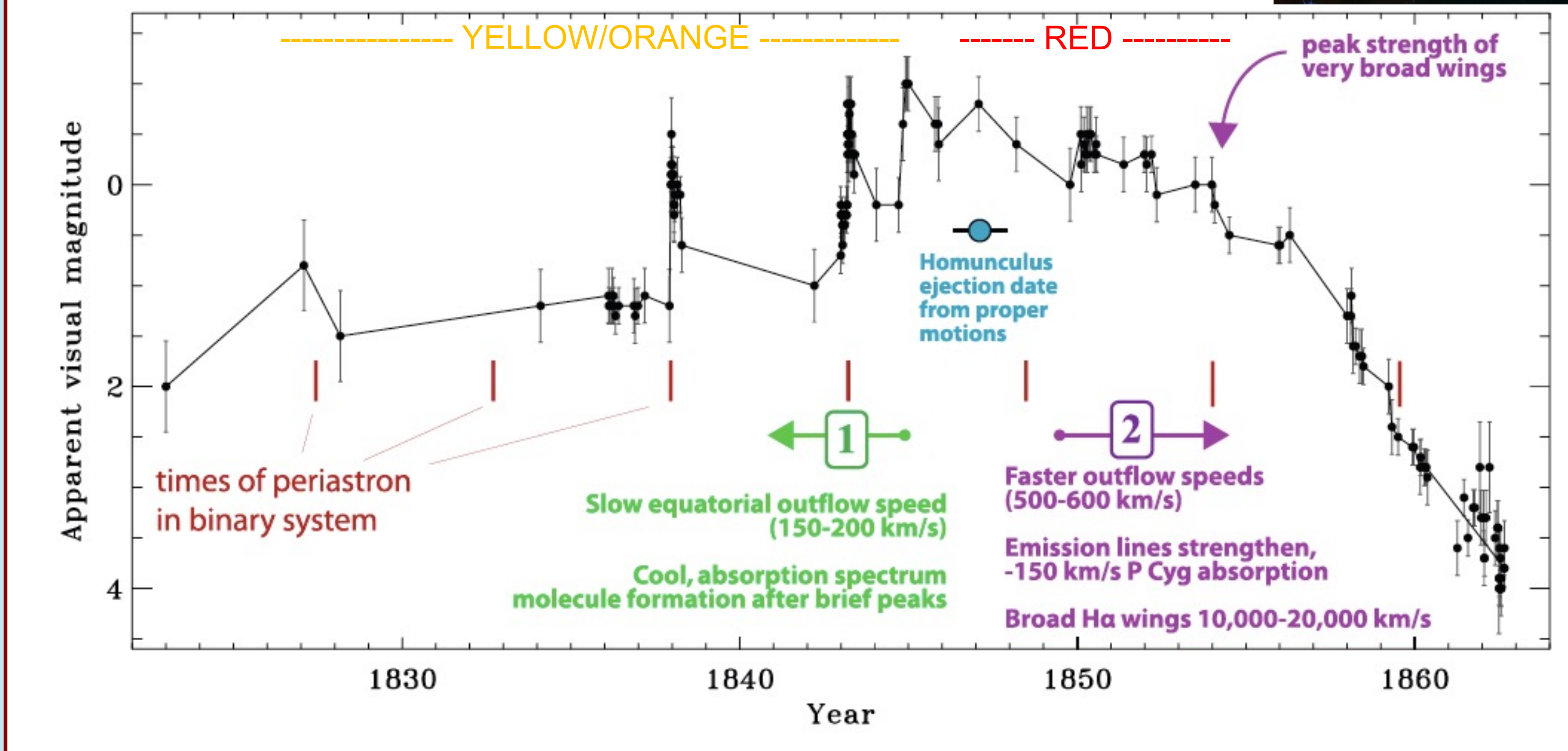

This transition from a slow to fast outflow coincided with ejection date of Homunculus inferred from proper motions with HST.

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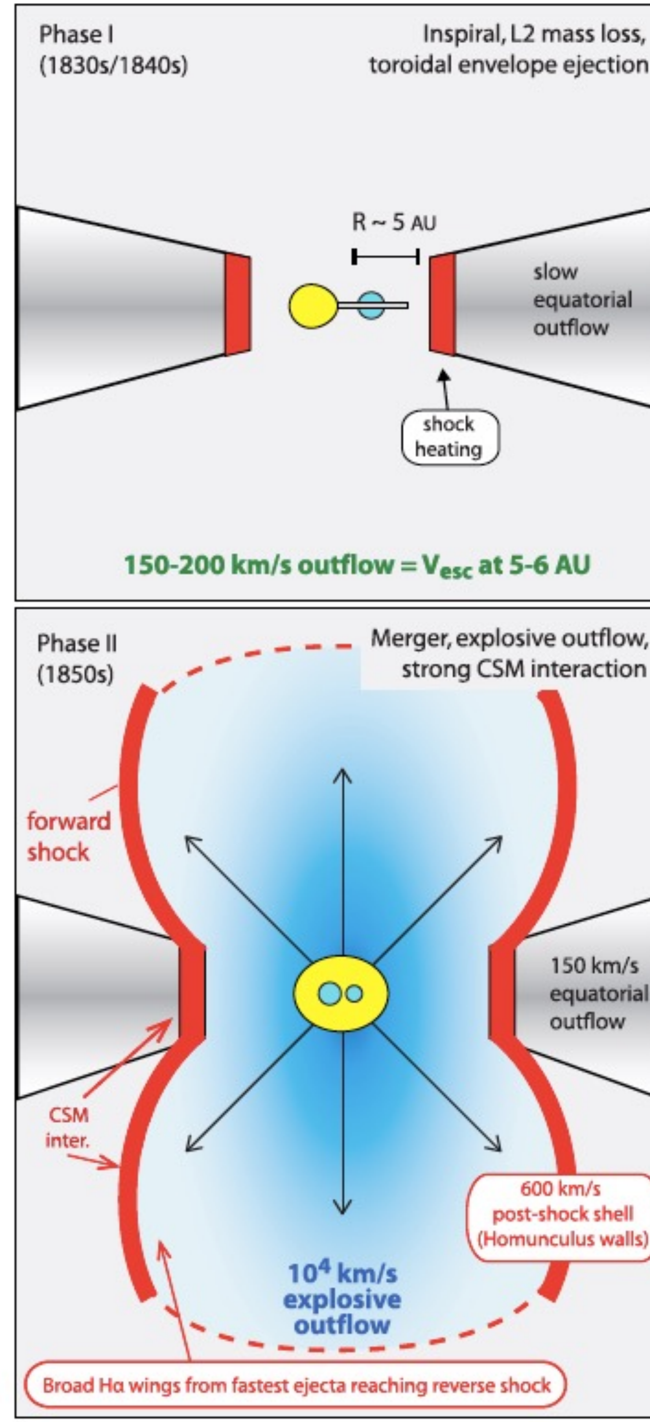
Merger in a triple (Smith +18): Our interpretation of this observed two-stage transition is a slow, dense, 150 km/s outflow (inspiral) followed by a fast explosive outflow (final core merger).

Stage I is the inspiral.

- **L2 mass loss makes a dense and slow100 km/s disk/torus (see Pejcha +16 model V1309 Sco).**
- **Light curve peaks are periastron passes of the 5.5 yr eccentric companion.**

Stage II is the explosion and CSM interaction.
Like a Type IIn SN, but 1e50 ergs.

- **Strengthening/broadening 600 km/s emission lines are post-shock gas getting accelerated.**
- **10,000 km/s wings are explosive ejecta hitting reverse shock. Shock breakout from merger energy deposition inside common envelope.**

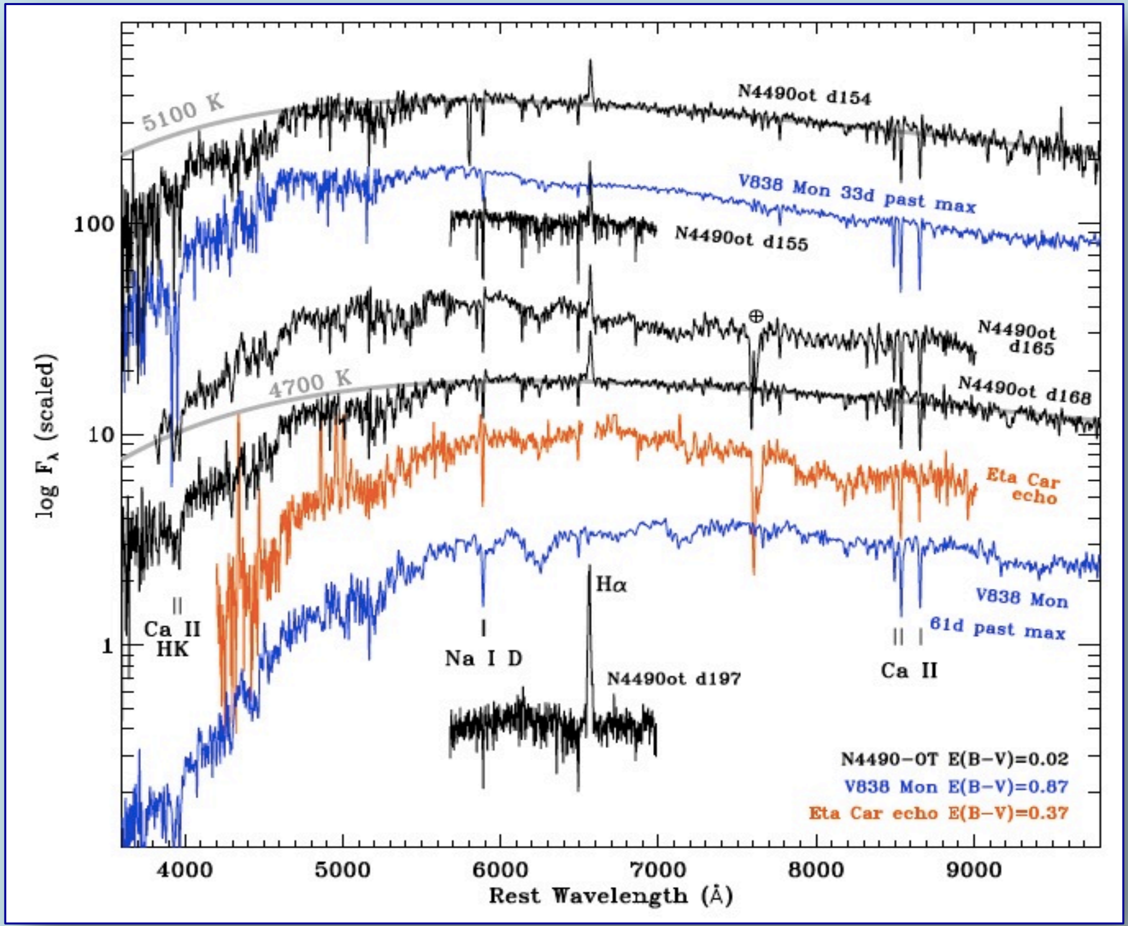


Many (most?) LBVs/SN impostors may be merger events.

A stellar merger model might help unify a range of non-SN transients: LBVs, SN impostors, ILOTS, Luminous Red Novae, whatever…

Diversity of peak L and duration may arise from range of stellar mass, mass ratio, orbital energy, evolutionary phase, etc.

Also, environments require that LBVS are massive blue stragglers, not massive single stars (Smith & Tombleson 2015)



Smith et al. 2016

Repeating LBV eruptions / SN impostors

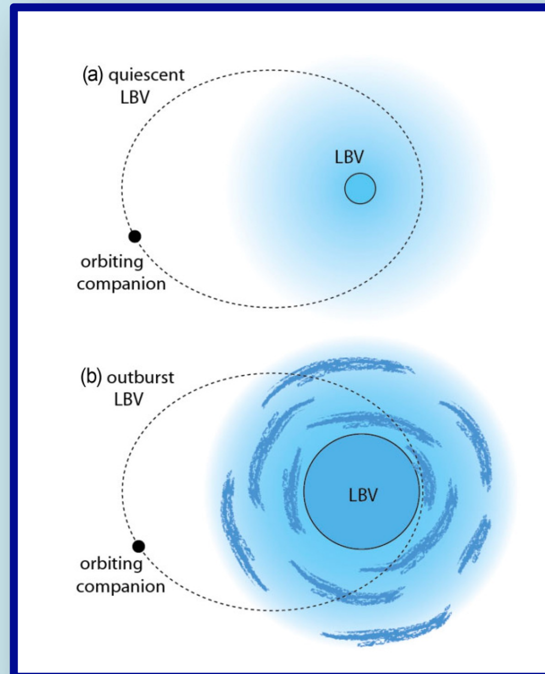
Non-SN transients with repeating quasi-periodic eruptions. Peak M_V ~ -13 to -15 mag.

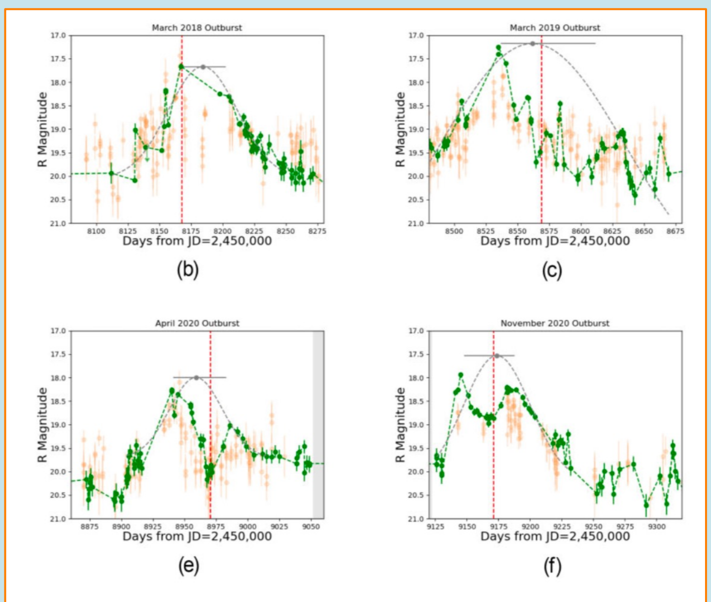
SN 2000ch (~60 $M_\odot$)
erupts with 201 d period
(Aghakhanloo +23a, Pastorello et al. 2010)

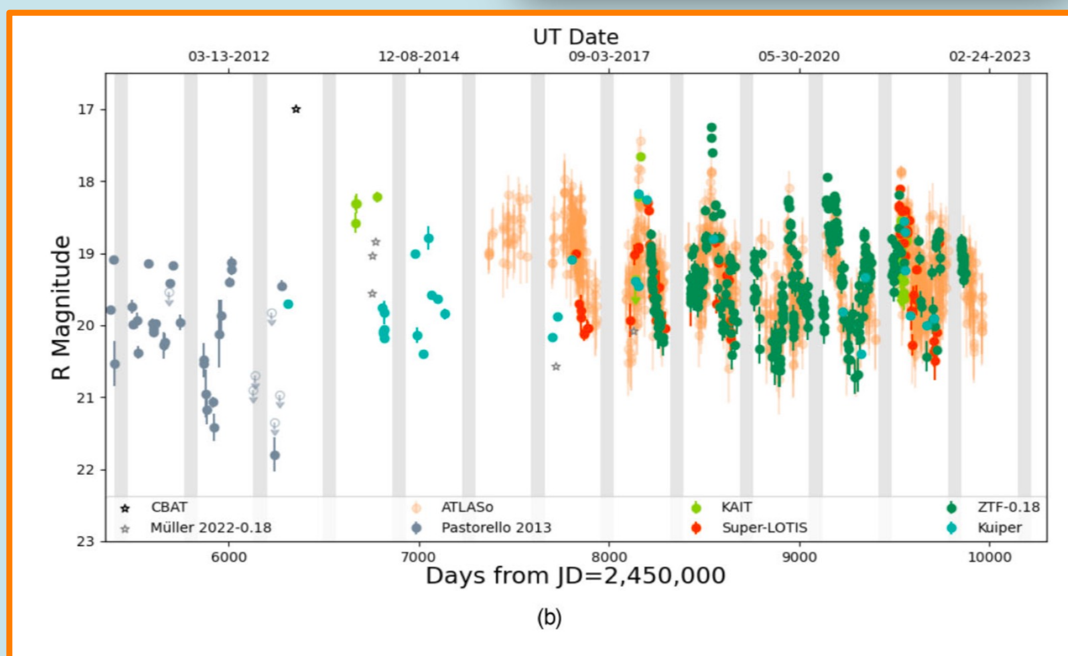
AT2016blu (>33 $M_\odot$)
erupts with 113 d quasi-period
(Aghakhanloo +23b)

Companion could be star or compact object.

See Aghakhanloo_23a, and several papers by Soker & Kashi (accretion models)







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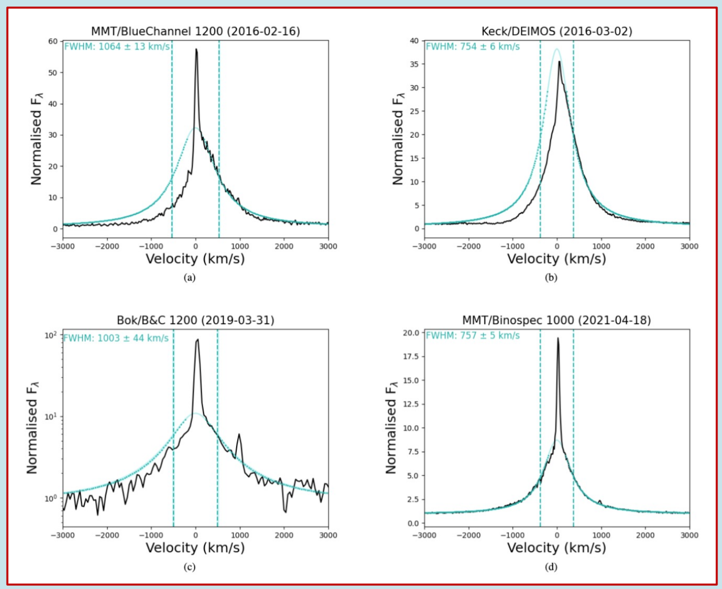
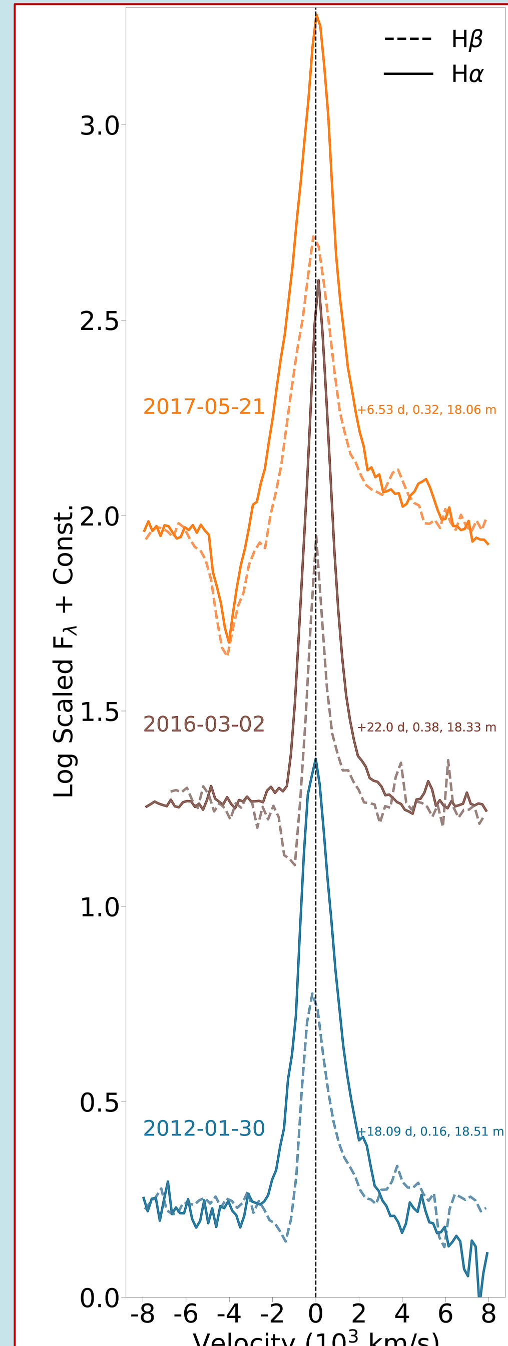
(Aghakhanloo +23b)

Strong broad H Balmer lines and He I lines with P Cygni absorption that comes and goes, and changes velocity.

Spectra of AT 2016blu from Aghakhanloo (2025)



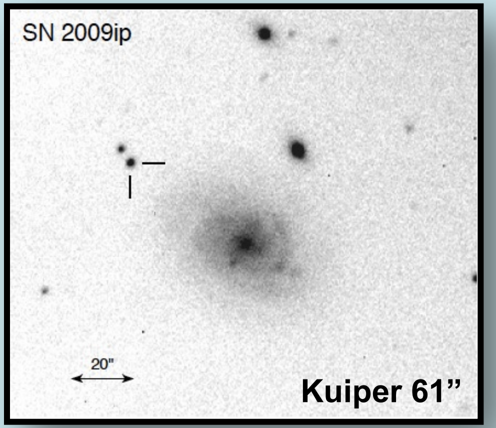


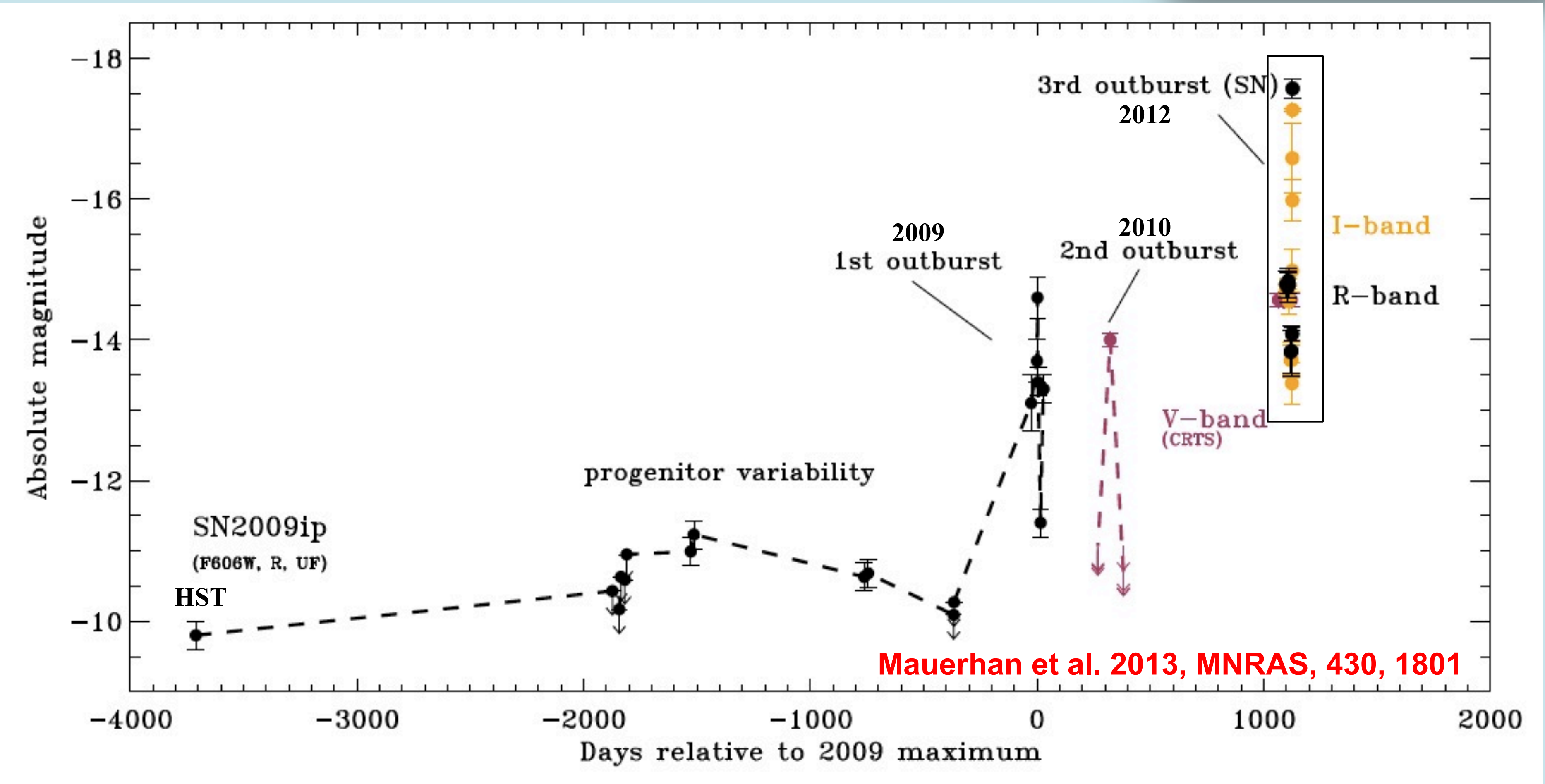
These periodic LBV-like eruptions are VERY similar to the progenitor outbursts of SN2009ip.

SN 2009ip:a non-SN in 2009, exploded as a SN in 2012)

2009 transient was an eruption of a massive star, not a SN (Smith et al. 2010). But then it exploded as a SN in 2012 while we were watching!

Repeating progenitor LBV-like eruptions were very fast/brief and had spectra like SN 2000ch (Smith+10, Mauerhan+13, Pastorello+13)



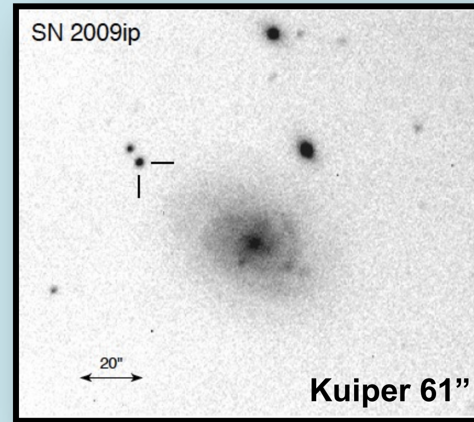


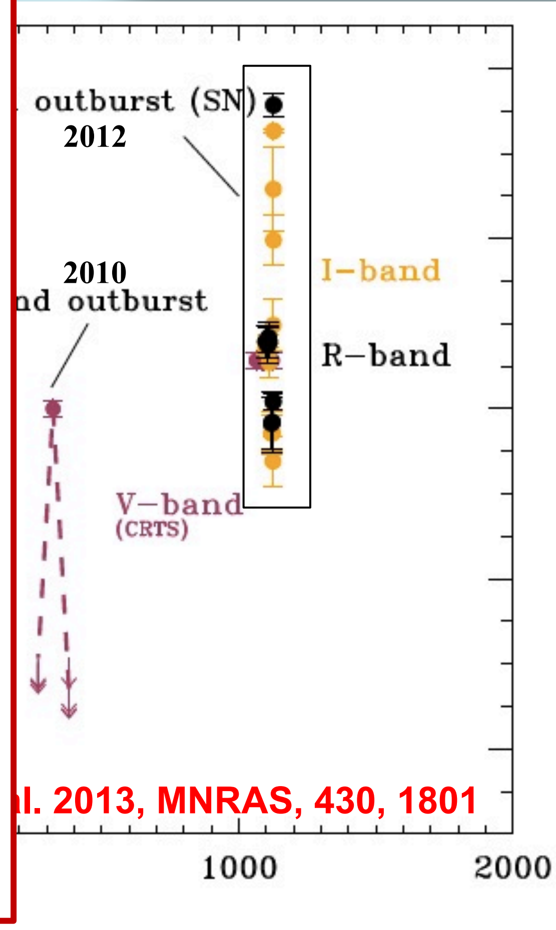
SN 2009ip:a non-SN in 2009, exploded as a SN in 2012)

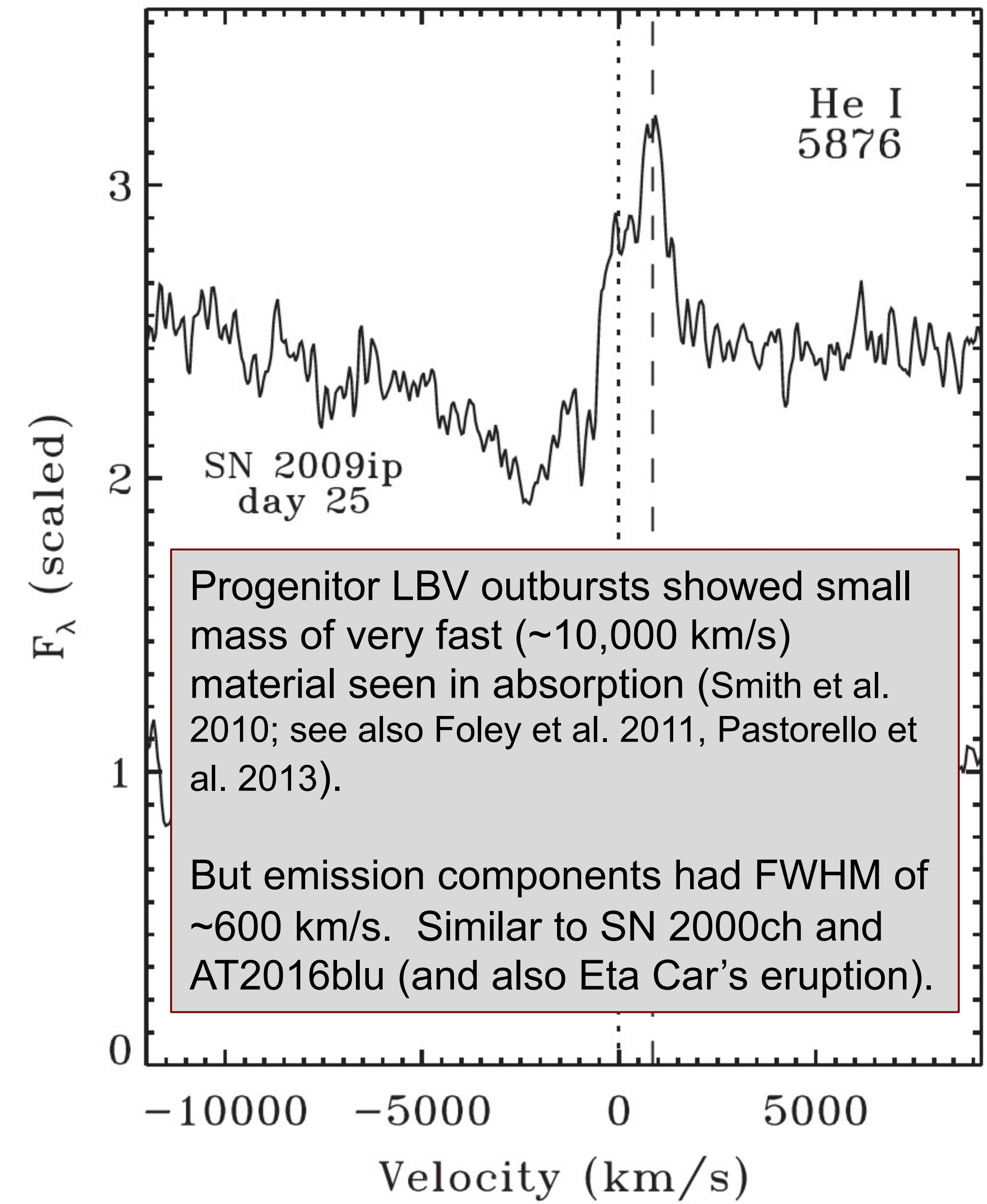
Discovered
Was an eru

But then it

Brief proge







Progenitor LBV outbursts showed small mass of very fast (~10,000 km/s) material seen in absorption (Smith et al. 2010; see also Foley et al. 2011, Pastorello et al. 2013).

But emission components had FWHM of ~600 km/s. Similar to SN 2000ch and AT2016blu (and also Eta Car's eruption).

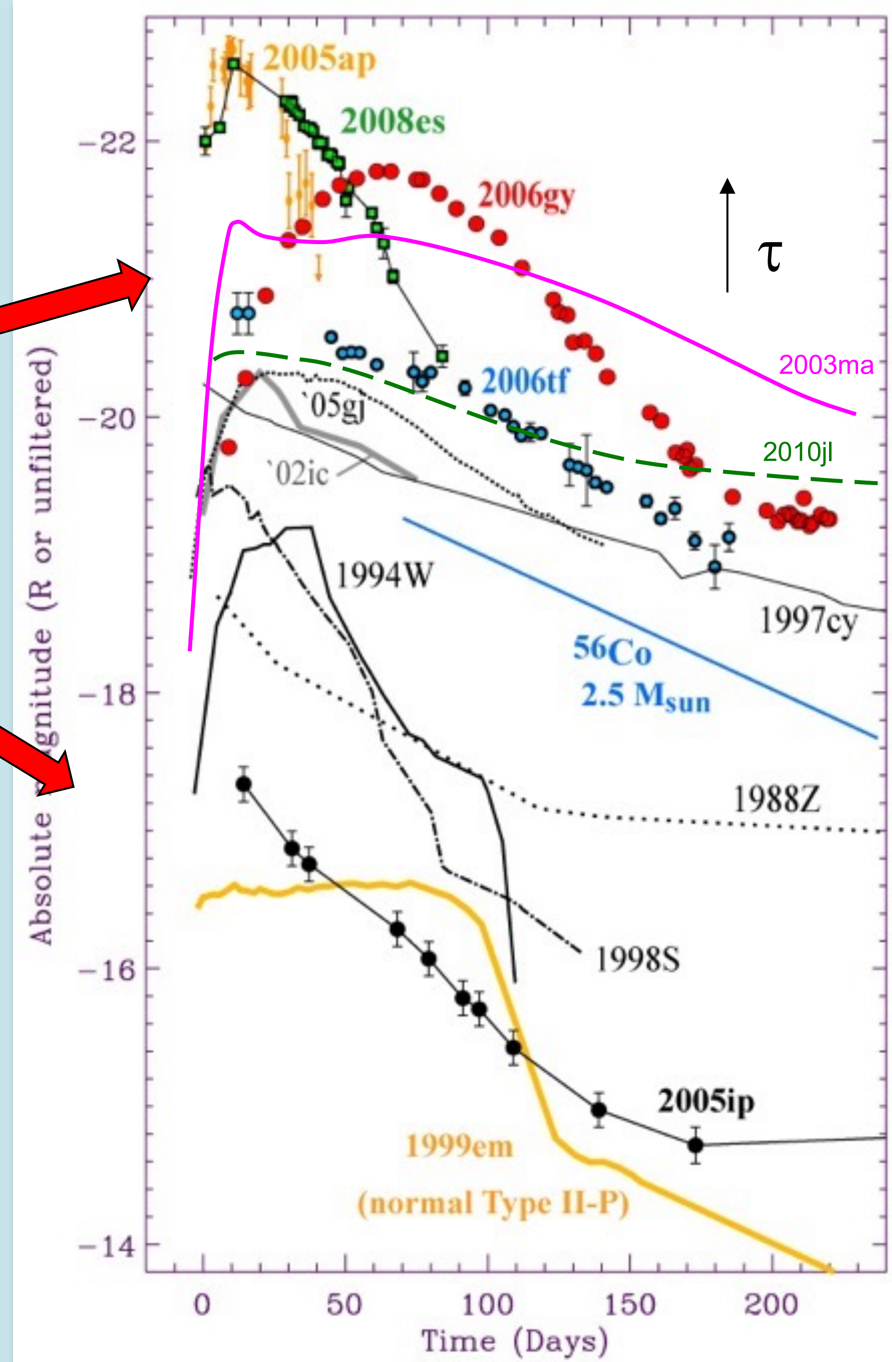
CSM INTERACTION DIVERSITY
Observations

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, or just narrow lines as in Flash SNe.

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. Important question is how that CSM is ejected.



CSM INTERACTION DIVERSITY
Observations

SNe IIn spectra

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

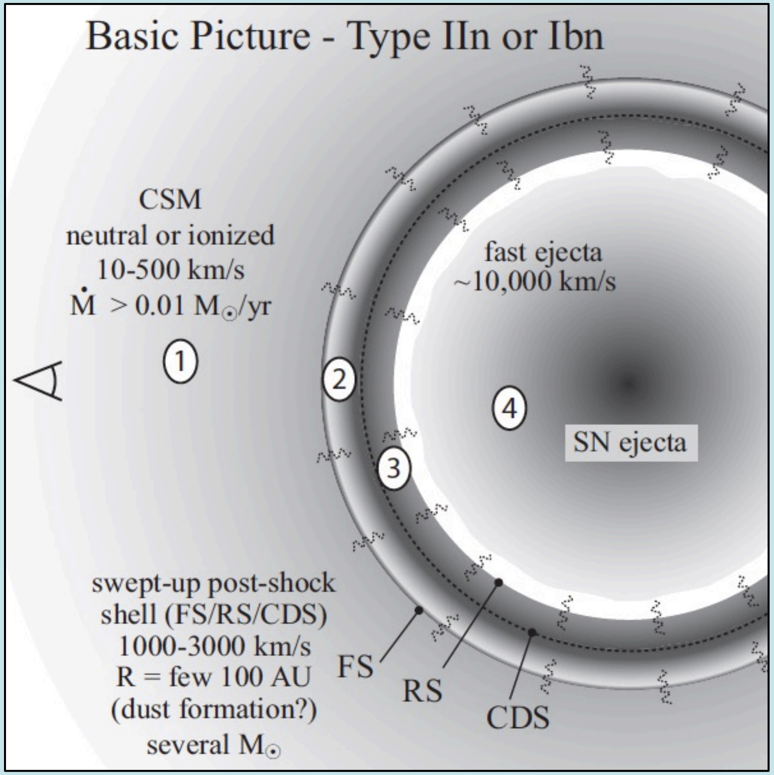
2. intermediate-width (1000-3000 km/s) from shocked CSM (or e- scattering at early times).

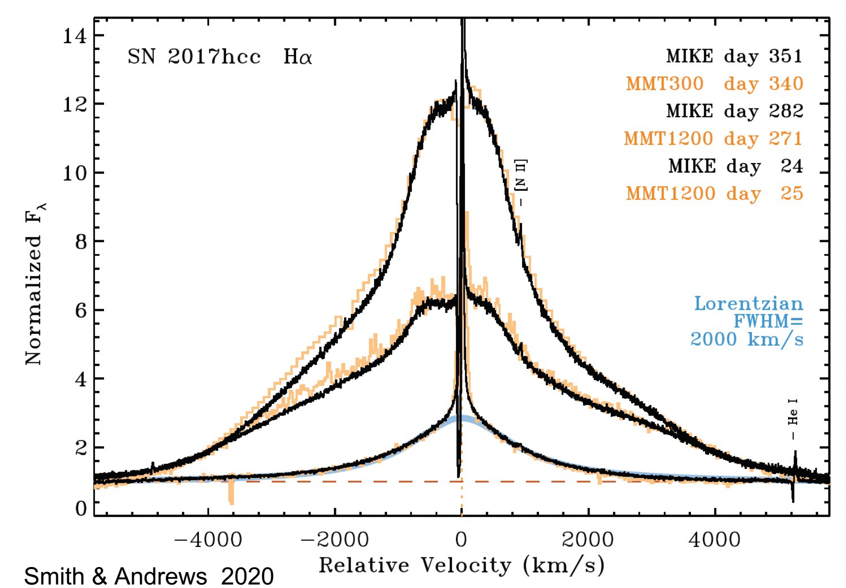
3. Broad (~3,000-15,000 km/s) components at some phases (especially late) from reverse shock or SN ejecta. Broad Hα = ***H-rich SN ejecta***.

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.



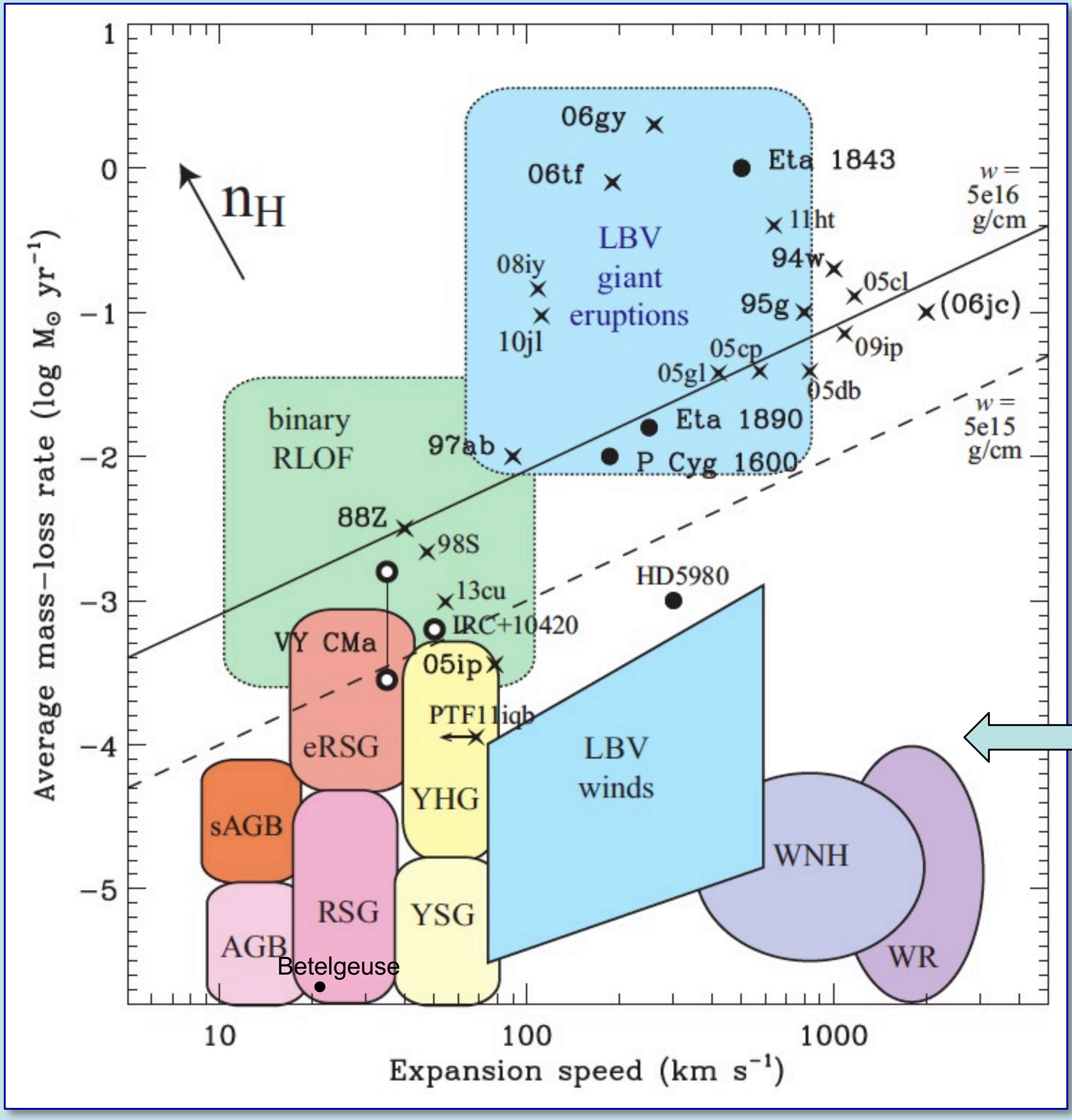


Smith & Andrews 2020

CSM INTERACTION DIVERSITY
Observations

COMPARE:

Mdot and V_W inferred for interacting SNe to those of various types of stars (from Smith 2014 review).



What we really measure is required wind density parameter (***w***), and then infer Mdot from adopted speed.

Down here we get bright radio and X-ray emission.

Figure from Smith (2017) in Handbook of Supernovae

CSM INTERACTION DIVERSITY
Observations

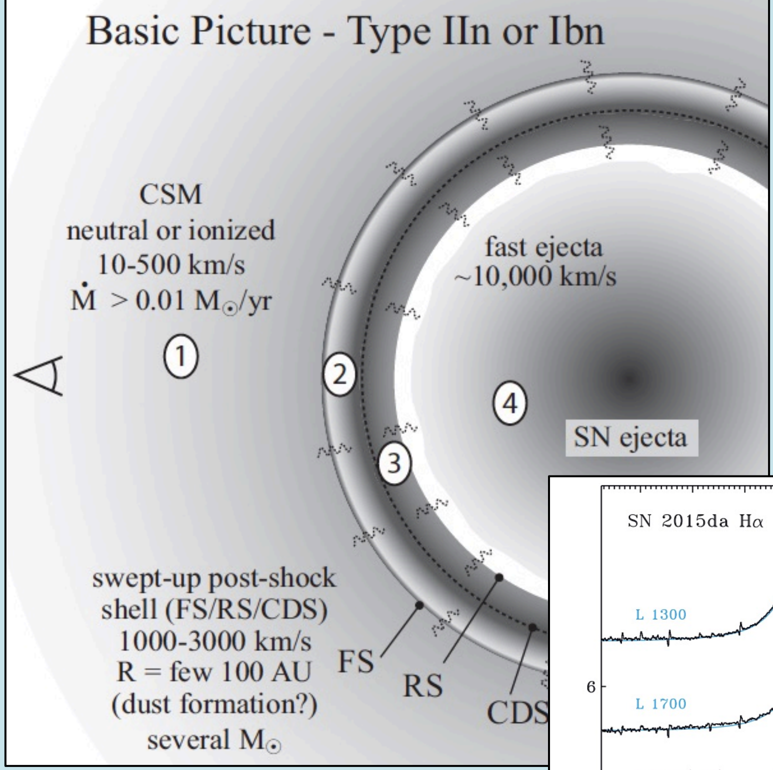
DUST

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

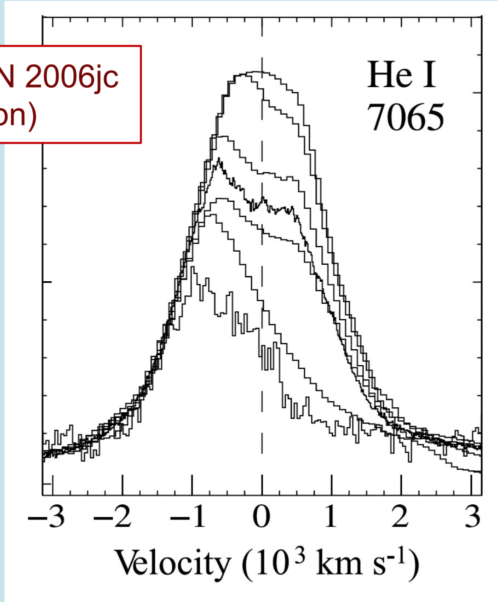
This appears to trigger **rapid dust formation** in the post-shock gas.

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

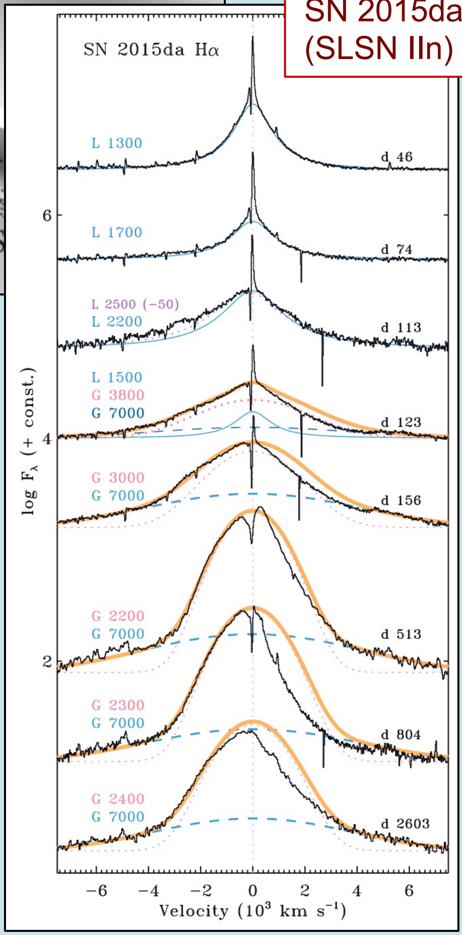
plus lots of new results from dust formation in SNe IIn coming from JWST (Melissa Shabande's talk… *oops, talk was cancelled.*)



SN 2006jc (Ibn)



SN 2015da (SLSN IIn)

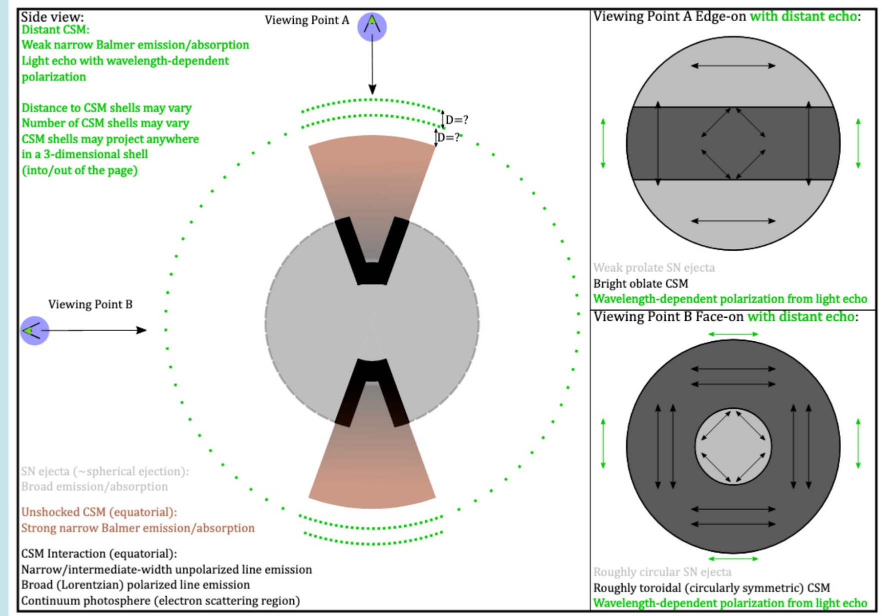


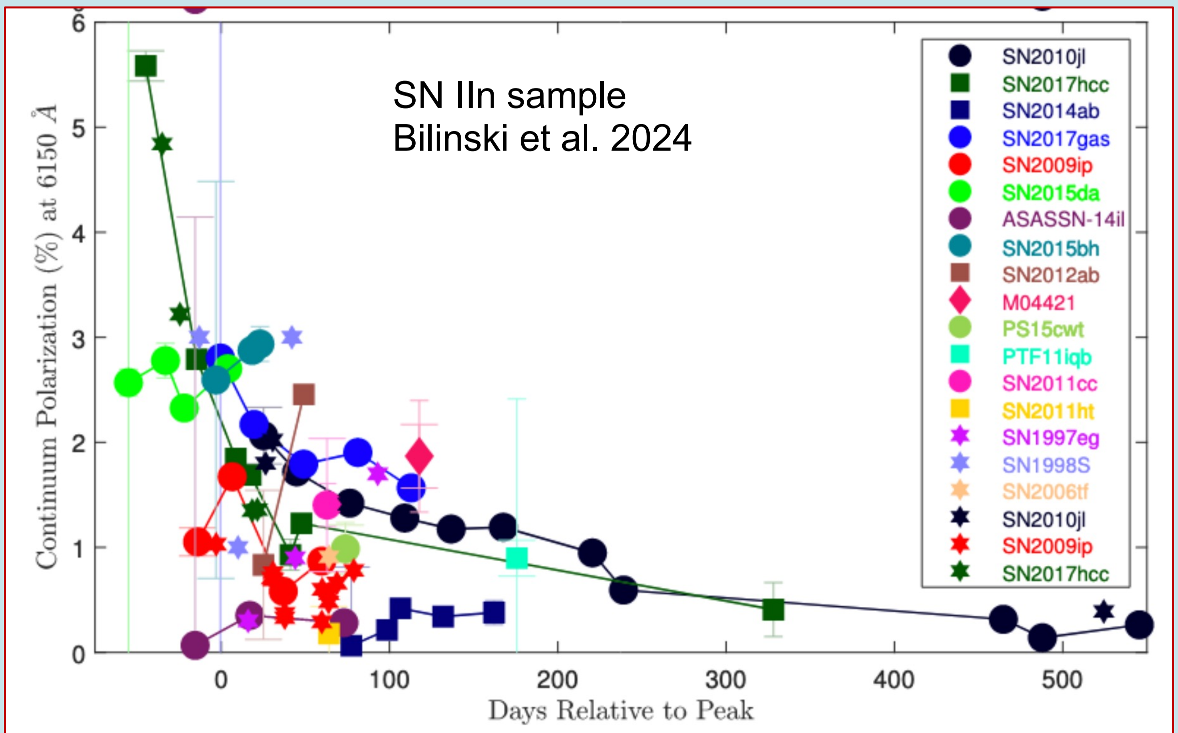
CSM INTERACTION DIVERSITY
Observations

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%.





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.

CSM INTERACTION DIVERSITY
Eruption/Explosion mechanisms

Potential mechanisms to produce the outbursts and/or CSM. How well do they match SN IIn properties and diversity?

Pulsational Pair Instability: way too rare; almost none match expectations
(Woosley 2017; Heger & Woosley 02; Renzo+20; Renzo & Smith 2025)

8-11 $M_\odot$ (ecSNe, degenerate flashes, etc.): limited to low-mass, low-E explosions. Crab maybe; can't explain majority of interacting SNe.
(Woosley & Heger 2015; Nomoto 84,97; Arnett 1979)

Wave driving: Limited to 1 yr before CC. Very weak mass loss if it works. Cannot explain CSM in vast majority of interacting SNe IIn (>1 yr).
(Quataert & Shiode12, SQ14, Fuller17, Wu&F21,22)

Other late burning instabilities: most known instabilities are also during O burning (same problem as wave driving = 1yr). 3D - needs more study.
(Smith & Arnett 2014; Arnett & Meakin 2011)

no global asymmetry expected

Pre-SN Binary Interaction: works in principle – asymmetry, velocities, wide range of stellar and CSM mass, massive stars are mostly in binaries. May be triggered by late inflation of star or merger with compact object.
(Smith & Arnett 2014; Smith+24; Chevalier 2012, Schroder+20)

Short version: None of these actually work to explain SNe IIn, except maybe pre-SN binary interaction.

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Eruption/Explosion mechanisms

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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?

CSM INTERACTION DIVERSITY
Eruption/Explosion mechanisms

Pulsational Pair Instability (Woosley17, HW02, Renzo+20)

Pros:

- Was actually predicted before SLSNe IIn became a hot topic.
- Can make high-L, long-duration, interaction-powered events with wide diversity in observed properties (Woosley 2017, Renzo+20)
- Gives a good explanation for SN 1961V (Woosley & Smith 2022)

Cons:

- Should be very rare (because of IMF) – not enough for most SNe IIn
- Exclusively high mass - can't match wide progenitor mass range of SNe IIn
- velocities don't match most observed SNe IIn at all
  (too fast for CSM, too slow for ejecta)
- First pulse removes any H envelope, so faster ejecta in 2nd pulse should be H-poor (doesn't match most SNe IIn that show broad Hα)
- First pulse is the most energetic (so if a SN IIn looks like a smaller pre-SN outburst followed by what looks like a ccSN, it aint a p-PISN)
- No reason to expect strongly asymmetric CSM

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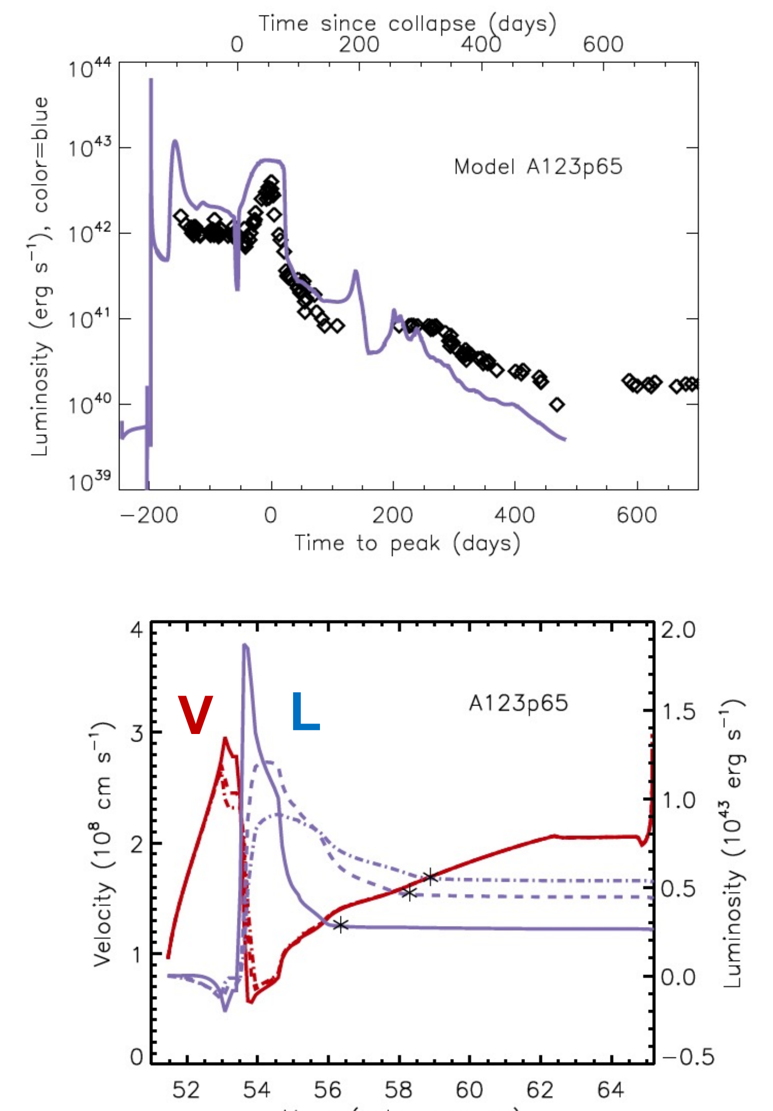


Woosley & Smith 22

CSM INTERACTION DIVERSITY
Eruption/Explosion mechanisms

degenerate flashes 8-11 $M_\odot$ (ecSNe or whatever) (WoosleyHeger15, Nomoto84/87,etc.)

Pros:
- Expect dense H-rich CSM (sAGB wind or ejected by flashes)
- Gives a good explanation for SNe IIn-P or other events (Crab) with low explosion energy, low initial masses, low ^{56}Ni masses, but high L
- Maybe not super-rare because of IMF

Cons:
- Can't explain high-mass CSM, high progenitor masses
- Can't explain high explosion energy needed for many SNe IIn
- Can't explain any of the luminous or super-luminous SNe IIn, or long-lasting events (like 88Z) – CSM mass budget is not high enough
- No reason to expect asymmetric CSM

CSM INTERACTION DIVERSITY
Eruption/Explosion mechanisms

Wave driving (Quataert & Shiode12, SQ14, Fuller17, Wu&F21,22)

Pros:

- Natural outcome of last pre-SN burning phases
- Might give a good explanation for some short-duration events (brief inflation or puff of mass loss right before core collapse)
- Timescale matches some observed pre-SN outbursts (09ip, 06jc…)
- Large diversity of energy injection

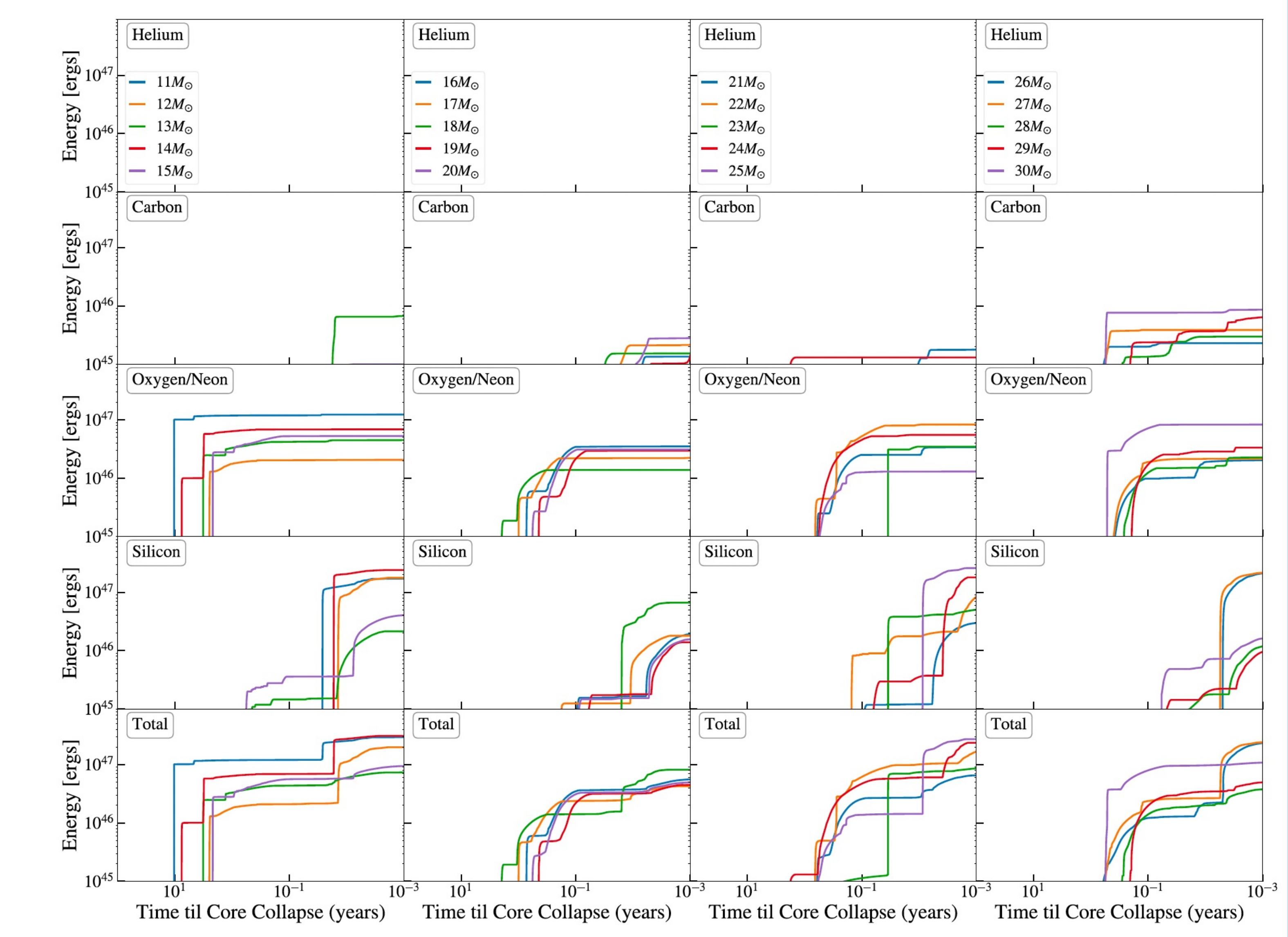
Cons:

- Only works for ~1 yr before core-collapse or less; not viable to explain the vast majority of SNe IIn and SLSNe IIn (where strong mass loss lasts several years/decades/centuries before core collapse).
- Total wave energy = 1e46-1e47 erg (few years before)
  or 1e47-1e48 erg (few days before)

  almost enough E, but too late
- Can it give an explosive ejection of large CSM mass?
- No reason to expect asymmetric CSM

CSM INTERACTION DIVERSITY
Eruption/Explosion mechanisms

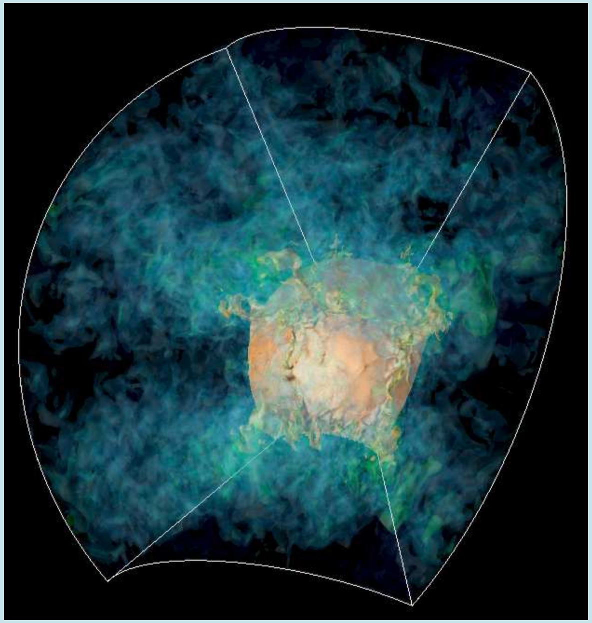
Wave driving (Quataert & Shiode12, SQ14, Fuller17, Wu&F21,22)



Wu & Fuller 21

CSM INTERACTION DIVERSITY

Eruption/Explosion mechanisms



Unsteady late nuclear burning (see Smith & Arnett 2014)

Pros:

- Instabilities in 3D turbulent convection simulations of late burning phases claimed to trigger outbursts (Meakin & Arnett '07, Arnett & Meakin '11a, '11b, Arnett+10,+14)
- Plenty of energy available, in principle, from mixing fresh fuel into deeper layer.
- Large diversity of energy injection

Cons:

- Not enough work done on this phenomenon – what happens to envelope? Predicted observables?
- Like wave driving, probably most likely during Ne, O, Si burning… probably too late for most SNe IIn

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Eruption/Explosion mechanisms

Pre-SN Binary Interaction, RLOF, merger, common envelope (Smith & Arnett 2014)

Pros:

- Majority of massive stars are in binaries or triples or more.
- Expected to happen anyway as all stars swell (some fraction of binaries will be caught interacting with wide companion in 10-10^4 yr before core collapse) and also naturally explains delayed-onset CSM interaction (14C, etc.).
- Might be synchronized with core collapse because any of the previous (esp. wave driving) might inflate the envelope shortly before core collapse to trigger pre-SN mass loss
- Pre-SN merger can drive even the most extreme CSM of SLSNe IIn
- Works across all initial masses, not just high or low
- May also work with compact (NS/BH) companions (Fryer+98,Chevalier12,Schroeder+20)
- Favors Type II because H envelopes are big
- Slow CSM (RLOF during inspiral phase) with diverse properties
- Only mechanism that obviously predicts strong axisymmetry in CSM

Cons:

- it is cheating to invoke them (?).
- need more theoretical work on mergers (esp. NS/BH+star)

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SYNCHRONIZED?

Why would you have a common envelope/merger right before a SN? Three thoughts:

1. Mergers/common envelopes happen over a rage of times (weighted toward end b/c of larger R), and some fraction happen to explode during or soon after common envelope phase. Should be distant shells around many other SNe.
2. Merger triggers an explosion: Maybe a merger with a compact object can do this. Needs more theoretical work.
3. Late nuclear burning instabilities cause star to swell before SN, which causes the merger to happen.