A personal summary of the meeting (Stockholm, May 28 – June 1, 2018)

Shocking Supernovae: surrounding interactions and unusual events

By Noam Soker

1st day summary

Norbert Langer: mentioned 7 process for pre-explosion mass loss.

(1) LBV. **My comment:** major LBV eruptions require a binary companion.

(2) RSG pulsations. **(3)** RSG ionization-confined shells. (4) Pulsation pair instability. **(5)** Wave driven mass loss.

My comment: What about **magnetic activity in the core**? (Soker & Gilkis 2017).

(6) Late Roche-lobe overflow.

(7) Chemically homogeneous evolution.

My comment: This seems to require a binary companion, but the companion will have more pronounced effects than just mixing.

My general comment: Binary companions play a major role in most (or all) enhanced mass loss rate cases (see below). This includes RSG mass loss and LBV (two groups discussed by **Francesco Taddia**.)

Selma de Mink: An interesting talk that points to the major role of binaries (in about 75% of cases). **My comment:** binaries play major roles in more than 75% of core collapse supernovae (CCSNe), as many low mass stars, 1-3Mo, that are hard to detect must play a role as well.
She mentioned that it is hard to remove helium with binaries in a large fraction of stars. **My comment:** Jets that are launched by a companion that accretes mass can help removing the envelope, like in the grazing envelope evolution (GEE) model for SN IIb (Soker 2017).

Manos Zapartas: Binaries can explain the diversity of CCSNe II.

My comment: I completely agree with that. We suspected this since the binary model for SN 1987A 30 years ago.

Nathan Smith: Gave a nice overview on circumstellar matter (CSM). Many cases suggest disk like mass loss geometry. There can be two photospheres: one of the ejecta one of the CSM. He ends by mentioning departure from axi-symmetry.

My comment: In Planetary Nebulae, we already discussed all these, and more, processes. He adopted many of his listed processes from the planetary nebula community, directly, or via works of others (See my poster).

More comments: (1) His model for the torus in Eta Carinae **does not work** (Kashi, A., & Soker, N. 2018, ApJ, 858, 117).

(2) He mentioned that before explosion the star expands and causes binary interaction for pre-explosion outbursts, like my model for SN 2010mc (posted February 2013), but cited Smith & Arnett (2014; posted 5 months later).

Charlie Kilpatrick, Erkki Kankare, Jacob Jencson: Very important talks that convinced me that many CCSNe are obscured in the visible, including those with masses above about 20Mo.

Several posters suggest that stars with initial mass of >20Mo do explode, e.g., **Raya Dastidar**.

My comment: This is a problem to the neutrino-driven mechanism, but not to the jittering-jets explosion mechanism.

Maayane Soumagnac, Ofer Yaron: CSM is important in many cases and very likely not spherical. Some posters suggest that as well, e.g., **Jonathan Quirola**, **Sebastian Gomez**, **Emir Karamehmetoglu**, **Petr Kurfürst**, **Samaporn Tinyanont**, **Patrick John Vallely**

Evan O'Connor: No explosion from the neutrino-driven mechanism.
However, the pre-collapse perturbations that seed turbulence cause very large shear and stochastic angular momentum accretion. ➔These are crucial for the launching of jets!

My comment: jets explode all core collapse supernovae. Many by stochastic jets, in what is termed the **jittering jets explosion mechanism**. Several posters suggest the importance of jets, e.g., **David Alexander Kann**, (as well as ears seen in supernova remnants, e.g., W44, see poster by **Sara Loru, Elise Egron**).

Main points of 1st day

➔ Without saying it explicitly in talks and posters, we adopt asymmetrical geometry of the CSM from hundreds of planetary nebulae. (see my poster; poster by **Aleksander Cikota**).

➔We should adopt jet feedback mechanism for core collapse supernova explosions from active galactic nuclei feedback in galaxy formation (see my review from 2016).

2^{nd} day summary

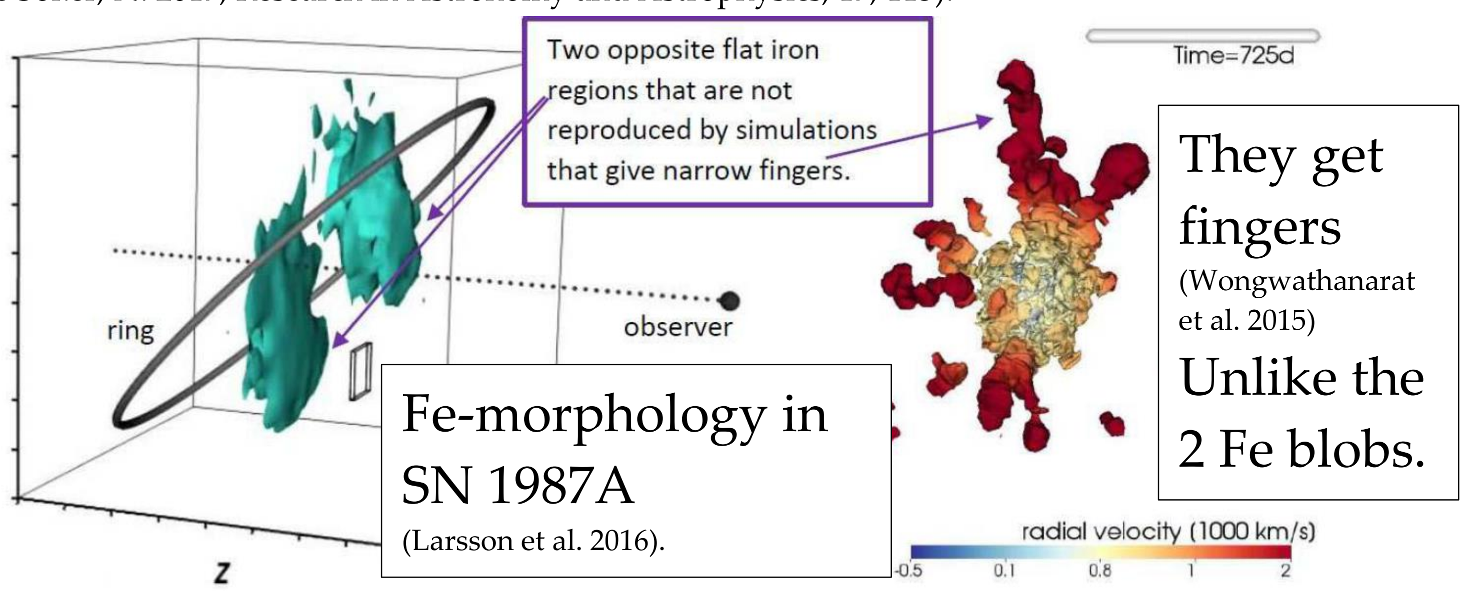
<u>Hans-Thomas Janka:</u> A very informative and interesting talk about 3D modeling of neutrino-driven explosion and attempts to explosion. They can explode low mass stars, but not stars > 10Mo. Even with favorable conditions, they need several seconds to explode. Material accreted from large radii in the core will also help jets formation (PhD of Avishai Gilkis).

My comment 1: Rotation and B-fields are crucial; will lead to jets.

My comment 2: He did not mention any of the **generic problems** of the neutrino-driven mechanism, like that they cannot get explosion energy > 2e51 erg.

Michael Gabler (+Janka): Presented the distribution of metals in supernova remnants (SNRs) according to their simulations.

My comment: They **<u>do not</u>** fit all aspects of neither Cassiopeia A (all their instability fingers are Ni-rich, while the jet in Cas A is Si/Mg-rich), nor do they fit all features of SN 1987A
(see Soker, N. 2017, Research in Astronomy and Astrophysics, 17, 113).

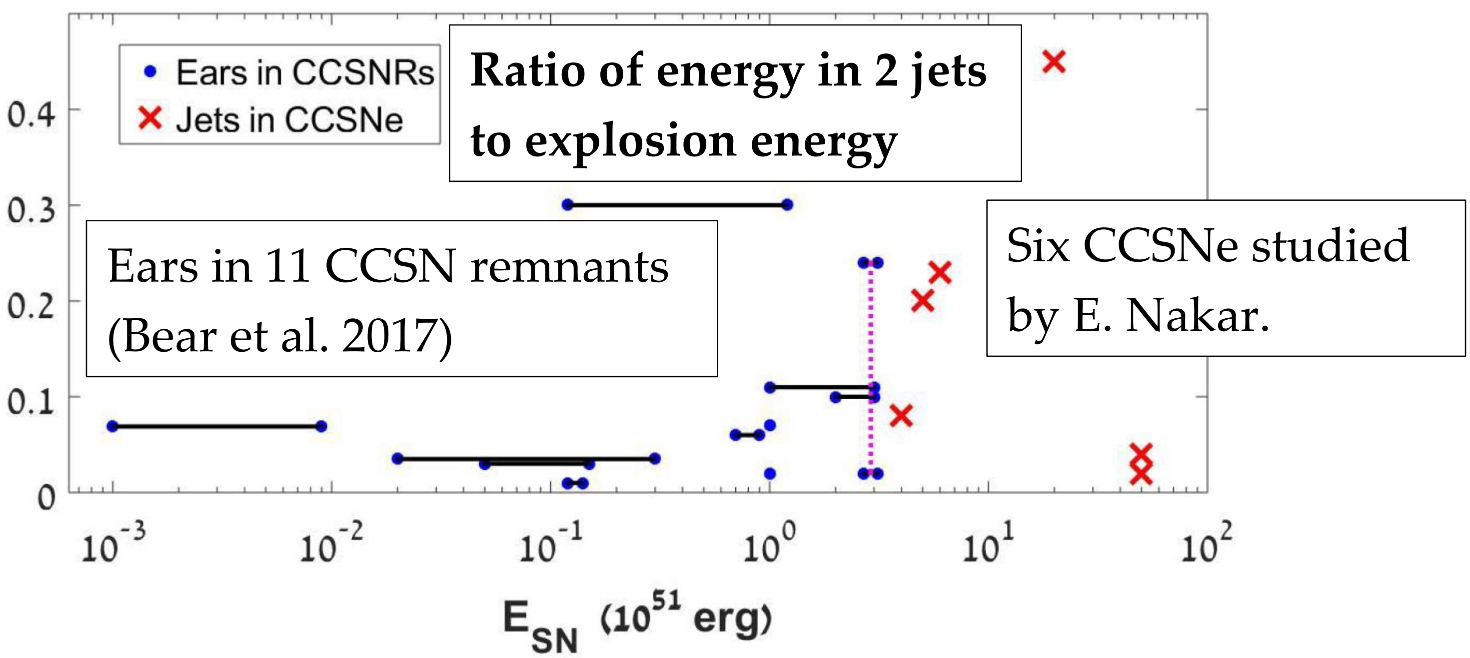


We need jets. Jittering jets in SN 1987A (Bear &Soker 2018 MNRAS)

__**Ehud Nakar:**__ Talked about choked jets, where the shocked gas breaks out. The shocked gas is termed `**cocoon**' (also termed `**bubbles**'). He described 6 core collapse supernovae (CCSNe) where there are 2 peaks in the energy distribution as a function of the velocity.

My comments: (1) the energy of explosion in these 6 CCSNe is Eexp>4e51, hence cannot be achieved by neutrinos. Jets (**by jets I also refer to very wide bipolar outflows, like disk winds**) must drive the explosion. (2) The typical ratio of the jets' energy to explosion energy that they find is similar to what we find for jets' energy as inferred from `ears' in CCSN remnants (Bear, Grichener, Soker 2017).

This ratio of ~1% to few 10% is compatible with the last jets to be launched in the jittering jets explosion mechanism.



(3) There is something universal as jets explode all CCSNe (see my poster).

Anders Jerkstrand: Further discussed the fate of stars with different masses (see summary of 1st day on obscured CCSNe).

Norbert Langer commented that one must include binary interaction to know the fate, like electron capture supernovae.

Alak Ray: Discussed ejecta-CSM interaction. Many posters also refer to the presence of CSM and ejecta-CSM interaction, e.g., **Niloufar Afsari, Kelsie Krafton, A. J. Nayana**

Stuart Ryder: The mass loss from the progenitor of Type IIb SN 2001ig was regulated periodically, Porb=400 days.
My comment: The period is like in low mass stars (1-4 Mo) that are post-AGB stars with a main sequence companion. I suggest that these low mass binary stars and many SN IIb are formed via the **grazing envelope evolution** (Soker, N. 2017, MNRAS, 470, L102).

Anatoly Spitkovsky: Discussed particle acceleration in shocks.
Elad Steinberg: instabilities make acceleration more efficient.

Deanne Coppejans: No direct detection of radio from jets in super-luminous CCSNe (SLSNe). Radio emission is much below GRBs. This is an important study.
My comment: We do not expect the jets to break out.

Vikram Dwarkadas: Type IIn are the brightest in X-ray. IIP are the faintest. A very interesting study of X-ray emission. Their finding of a relatively massive CSM in the SN Ia 2012ca suggests that the most likely progenitor origin is the **core degenerate scenario**.

Ori Fox: (also poster by **Tamas Szalai**)
A very interesting talk that forces us to think `BINARY'!

Dust outside the forward shock, v=100-200 km/sec, and gas mass of ~10Mo. All points to an LBV. Mass loss rate 0.001-0.1Mo/yr.
SN Ia-CSM occupy the same region as SN IIn in the plane of magnitude (in Spitzer) versus time. He argued that the **core-degenerate scenario** best explains this for SN Ia.
Summarized by stating that there are many types of progenitors.
Claimed there are problems with LBVs progenitors.

My comment: It is not the LBV class that is fundamental, but rather it is the **binary interaction that is the common engine**. It is the binary interaction that gives us the many types of interactions, much as in planetary nebulae.

Several poster discuss the importance of binary interaction, e.g., **Shane Moran, Eva Laplace, Teppo Heikkila**.

Antonia Bevan: Discussed dust formation in SN 2005ip. She prefers that the dust form in the ejecta.

Main points of 2nd day

➔ The results of **Janka** (some explosions) and **O'Connor** (no explosion) bring us to the same situations the neutrino-driven community had in 1D and in 2D: some do and some do not get explosion.

➔ The rich variety of types of progenitors comes mainly from the rich variety of **binary interaction** types (Roche lobe overflow; common envelope; grazing envelope evolution; eccentric orbit; jets launched by the companion) and the types of companions, including a neutron star companion, that in some cases might lead to **common envelope jets supernovae** (see poster by Avishai Gilkis).
This is like the situation in **planetary nebulae**, were each planetary nebula is `unique', but all come from binary interaction.

➔The high mass loss rates before explosion come from strong **binary interaction**, and in many CCSNe jets or cocoons break out, implying that **asymmetrical effects are crucial** (see also posters by **Takashi Nagao, Antonio Tutone**), and that important processes (like recombination; **Tamar Faran**) should eventually be studied in complicated geometries of ejecta-CSM interaction.

3rd day summary

The third day had two main subjects. (1) Processes in **ejecta-CSM** interaction (e.g., **A.J. Nayana** on radio emission).
(2) The properties of **SN 1987A**.

Processes in the ejecta-CSM interaction

Roger Chevalier: very nice and accurate analytical calculations of the interaction of the ejecta with the CSM in spherical symmetry. Applied these to SN 2010jl. Lower column density along line of sight suggest non-spherical CSM.

Eran Ofek: Discuss CCSNe where the pre-explosion mass loss rate is inferred to be > 0.001Mo/yr. Some massive CSM, e.g., 10Mo in 2010jl. Ejecta interaction with shells/clumps in the CSM can explain bumps in the SN light curve (also **Anders Nyholm** for iPTF13z). Repeated the need for **non-spherical CSM** in the SN studied by Maayane Soumagnac. Most (>98%) of SN IIn have pre-explosion outbursts within 2 years before explosion.

Kohta Murase: Young SNRs might be the bulk source of cosmic rays up to 1e17ev (the knee). The CSM should be **non-spherical** or clumpy to explain low absorption of radio emission.

Andrea Pastorello: Discussed Type Ibn supernovae. This group is not uniform, but more homogeneous than the group of SN IIn.

My comments: (1) the non-uniformity of SN Ibn progenitors might result from the rich variety of binary interaction parameters.
(2) Non-spherical CSM due to binarity: see **planetary nebulae**.

Supernova 1987A

Marco Miceli: Performs 3D hydrodynamical simulations and obtain synthetic spectra for SN 1987A.

Josefin Larsson: (i) Central object: L<22Lo (no obscuration) or L<138Lo (dust along line of sight). She prefers an isolated neutron star that does not accrete mass.
(ii) Ejecta: Fe+Si blobs powered by 44Ti. Alma observations show molecular CO torus perpendicular to the equatorial plane of the inner ring.
(iii) CSM: First new spot outside the ring (appeared in 2013).

Yvette Cendes: Detected radio emission beyond the ring. Claimed that the half-opening angle of their torus model for the inner ring is 45 degrees (quite large!).

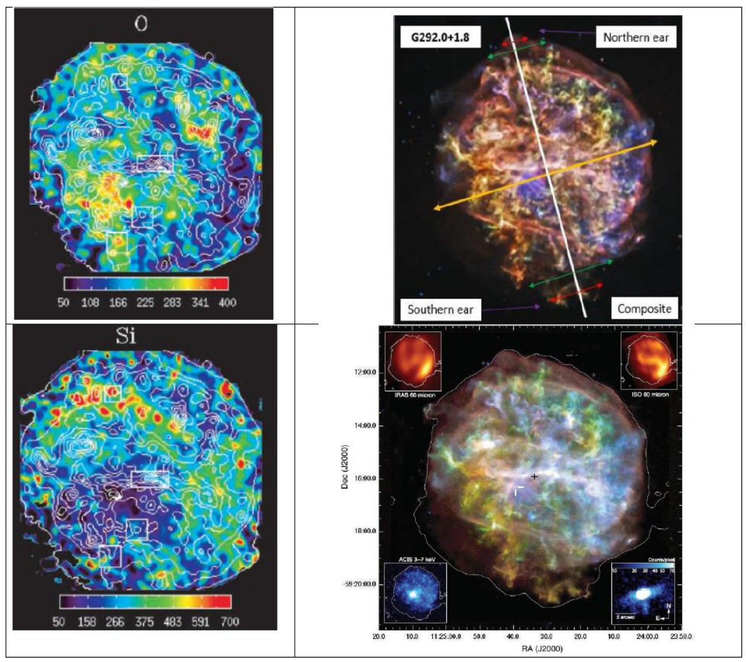
My comment: the CSM of SN 1987A, that now starts to reveal regions beyond the inner ring, is similar to some **planetary nebulae**, including the displacement of the CSM from axisymmetry (the explosion is not at the center of the three rings).

Main points of 3rd day

➔ The properties of the ejecta of SN 1987A is challenging (not fully fit the expectation from neutrino-driven simulations; see 2nd day summary).

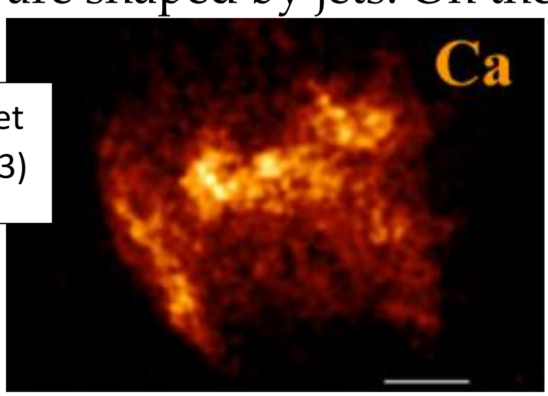
My comment (based on **Bear & Soker** 2018, MNRAS):

Step 1: Compare SN 1987A to CCSN remnants that have clumpy ejecta and show signature of jets (e.g., Cassiopeia A, Vela, W49B). Here is **G292:0+1:8.** **Clumpy distribution of Si and O, scattered around the line connecting the two ears that we suggest are shaped by jets** (images based on Park et al. 2002,7).

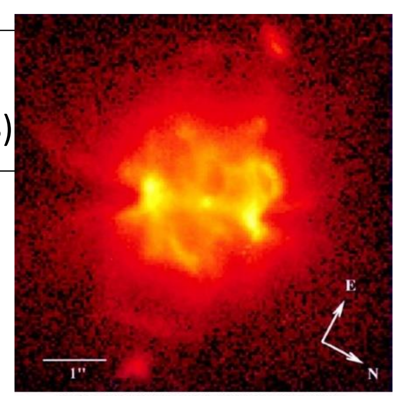


Step 2: Compare these CCSN remnants to planetary nebulae that likely are shaped by jets. On the left is Ca distribution in SNR W49B.

Lopez et al. 2013)

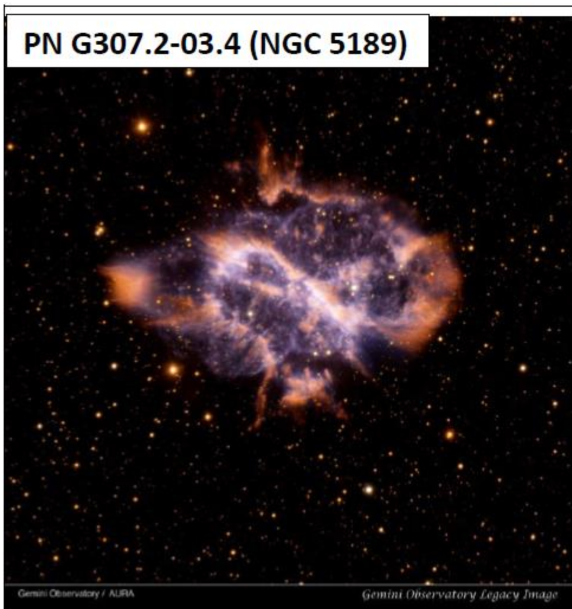


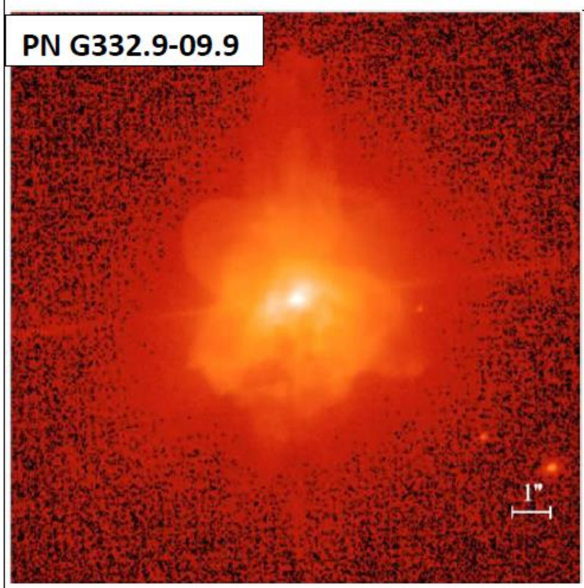
Planetary nebula (Sahai & Trauger 1998)



K 3-66 G167.4-09.1 04 36 37.24 +33 39 29.9, R:G:B = Halpha
HST/WFPC2/PC1 N is NOT up. HST archives, GO 6353
credit: R. Sahai & J. Trauger 1998 AJ, 116 1357

Step 3: Take `messy' planetary nebulae that are shaped by jets





Two planetary nebulae that are thought to be shaped by jets but lack any kind of symmetry. These can hint on the outcome of the **jittering jets explosion mechanism** in some CCSNe.

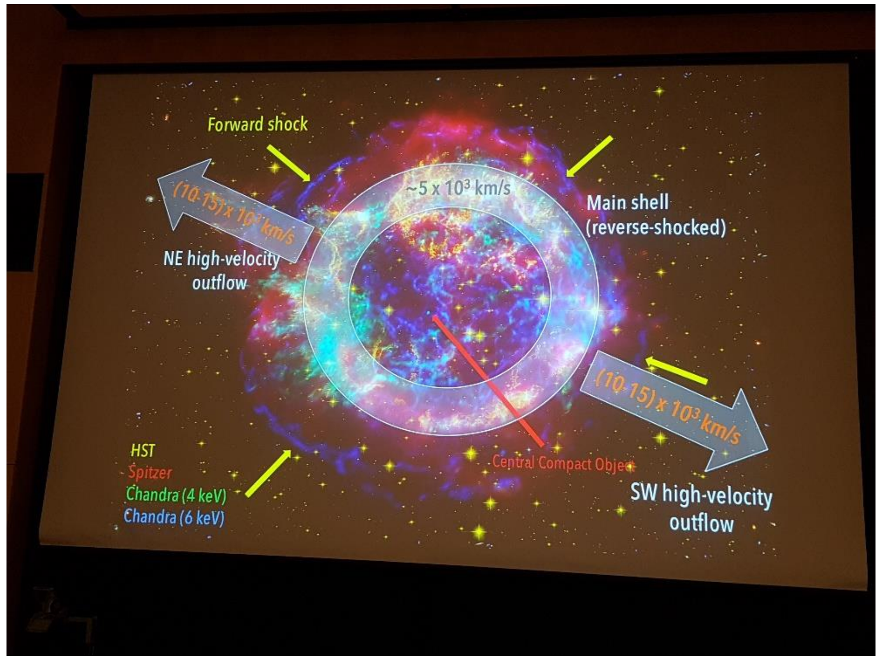
We suggest this **jet-driven** explosion mechanism for SN 1987A

(Bear & Soker 2018, MNRAS, in press, on their site).

PNG 307.2-03.4 (NGC 5189): from Gemini (credit: Gemini Observatory/AURA).

PNG 332.9-09.9 (Hen 3-1333; CPD-568032): from Chesneau et al. (2006).

4th day summary



__Danny Milisavljevic__: A beautiful and thorough study of rings and cavities in Cassiopeia A supernova remnant (SNR; also talk by __Dan Patnaude__).
Two opposite collimated outflows much faster than the rest of the Cassiopeia A supernova remnant (SNR).

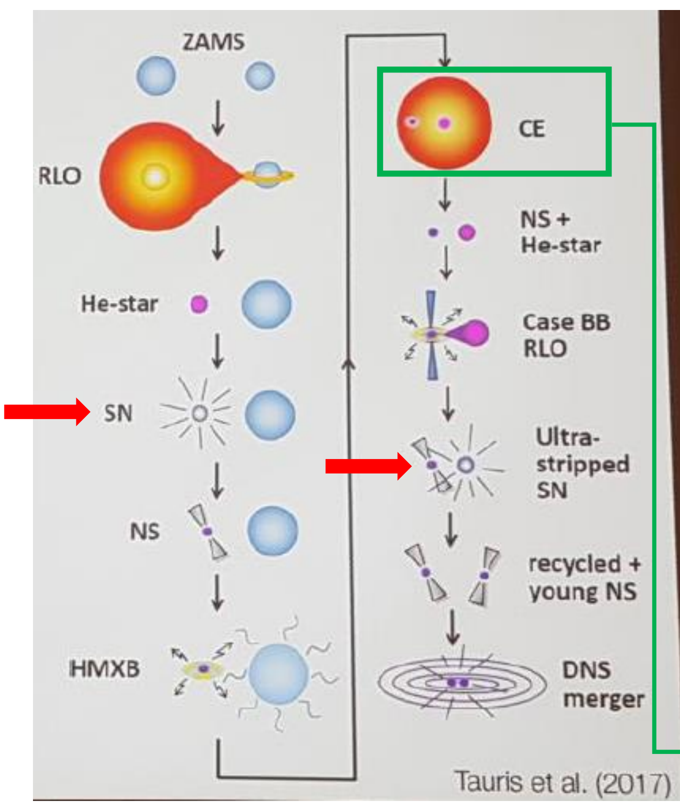
In **galaxies,** such outflows (called <u>jets</u>) expel the ISM.
In **clusters of galaxies** these outflow (called <u>jets</u>) heat the medium.
In **planetary nebulae** these outflows (called <u>jets</u>) shape the nebulae.
I think **jets exploded Cassiopeia A**.

__Dan Patnaude__: Constant mass loss rate winds do not explain X-ray of remnants. Variable high mass loss rate 100-10^4 yr pre- explosion.

__Keiichi Maeda__: Four yellow super-giants among five best studied Type IIb. He argued that **binary interaction** explains diversity of SN IIb. **My comment**: I completely agree with that (see my summary from earlier days).
He mentioned Roche lobe overflow to the companion as a model for Type IIb. **My comment:** We should also consider the SN IIb model that is based on the **grazing envelope evolution.**

Toshiki Sato: Beautiful evolving images of Kepler and Cassiopeia A. They find a new center from the expansion of knots in Kepler, but no surviving companion (poster by **Peter Johnson Brown** for other SNe Ia with no companion). They actually kill the single degenerate scenario (again, as it is already dead) for Kepler.
My comment: the **core degenerate scenario** is the best for Kepler. The double degenerate scenario might work if the two WDs merge within a short time by tidal interaction and not gravitational waves.

Mattias Ergon, **Firoza K. Sutaria**, as well as some posters (like **Myoung-Jae Lee**, **Franziska Schmidt, Florian Kirchschlager**), discuss processes in SNe and ejecta-CSM interaction:



Takashi Moriya: Enlightening discussion of **ultra-stripped SN**e. The evolution leads to two core collapse supernovae (arrows), and then to two neutron stars (that later might merge). The second explosion is of only 1e50 erg. Ultra-stripped SNe are 0.1-1% of all SNe.

My comments:

(1) The common envelope with a neutron star (NS) can lead to a **common envelope jets supernova** (rectangle) (see poster by Avishai Gilkis).

(2) Even if the NS is outside the envelope, if the star expands as a result of core activity (see poster by **Ryoma Ouchi**), the inflated envelope might engulf the NS and lead to a bright pre-explosion outburst (Danieli, B. & Soker, N., accepted by astro-ph).

Some talks considered ejecta-CSM interaction.
Hanindyo Kuncarayakti: SN 2017dio is a SN Ic interacting with H-CSM. For Vejecta=10,000 km/sec the CSM peak density is at 1e16cm, and is detached from the star.

Maria Drout: Listed the key questions: (1) How and when the hydrogen was removed? She mentioned **binarity**. (2) What is the final mass loss rates of H-poor stars? (3) What is the behavior of H-poor stars as they evolve towards core collapse?
She mentioned SN 2014c, a SN Ib that turned to SN IIn with a CSM mass of ~1Mo at ~2e16cm.

Esha Kundu: RLOF model for 1993J. There was a change in the mass loss rate about 1e4 years before explosion (deduced from the CSM radius of 4e17cm).

Main points of 4th day

➔Prominent signatures of jets in CCSNe: Cassiopeia A and Kepler.

➔Ejecta-CSM interaction occurs in many types of supernovae.

➔ Binarity can explain the rich variety of CCSN and ejecta-CSM interaction.

[Note that some main points repeat from earlier days].