Pleasantness Review*

Department of Physics, Technion, Israel

The role of jets in exploding supernovae and shaping their remnants

Crete 2016

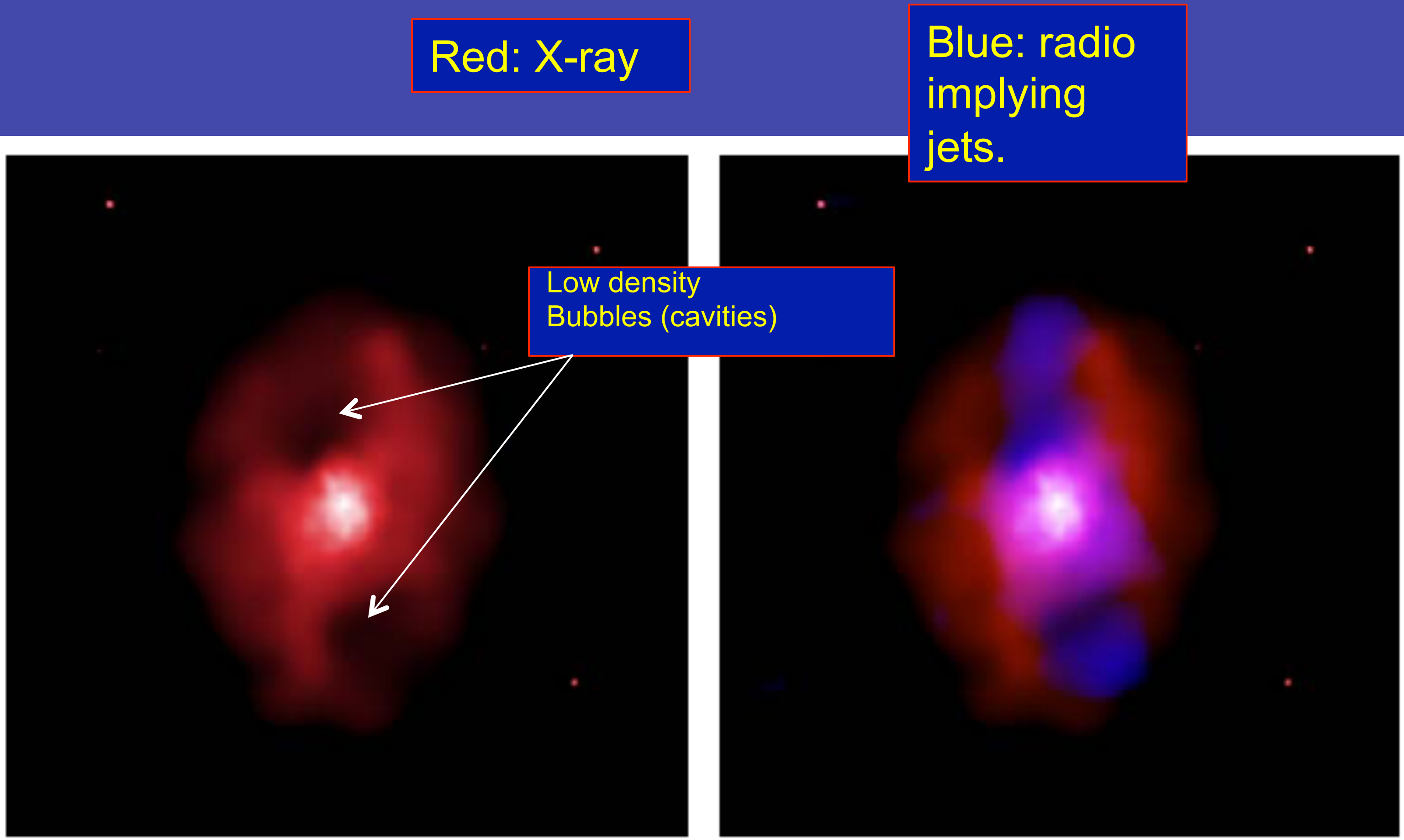
Noam Soker

•**Dictionary translation of my name from Hebrew to English (real!):**
Noam = Pleasantness
Soker = Review

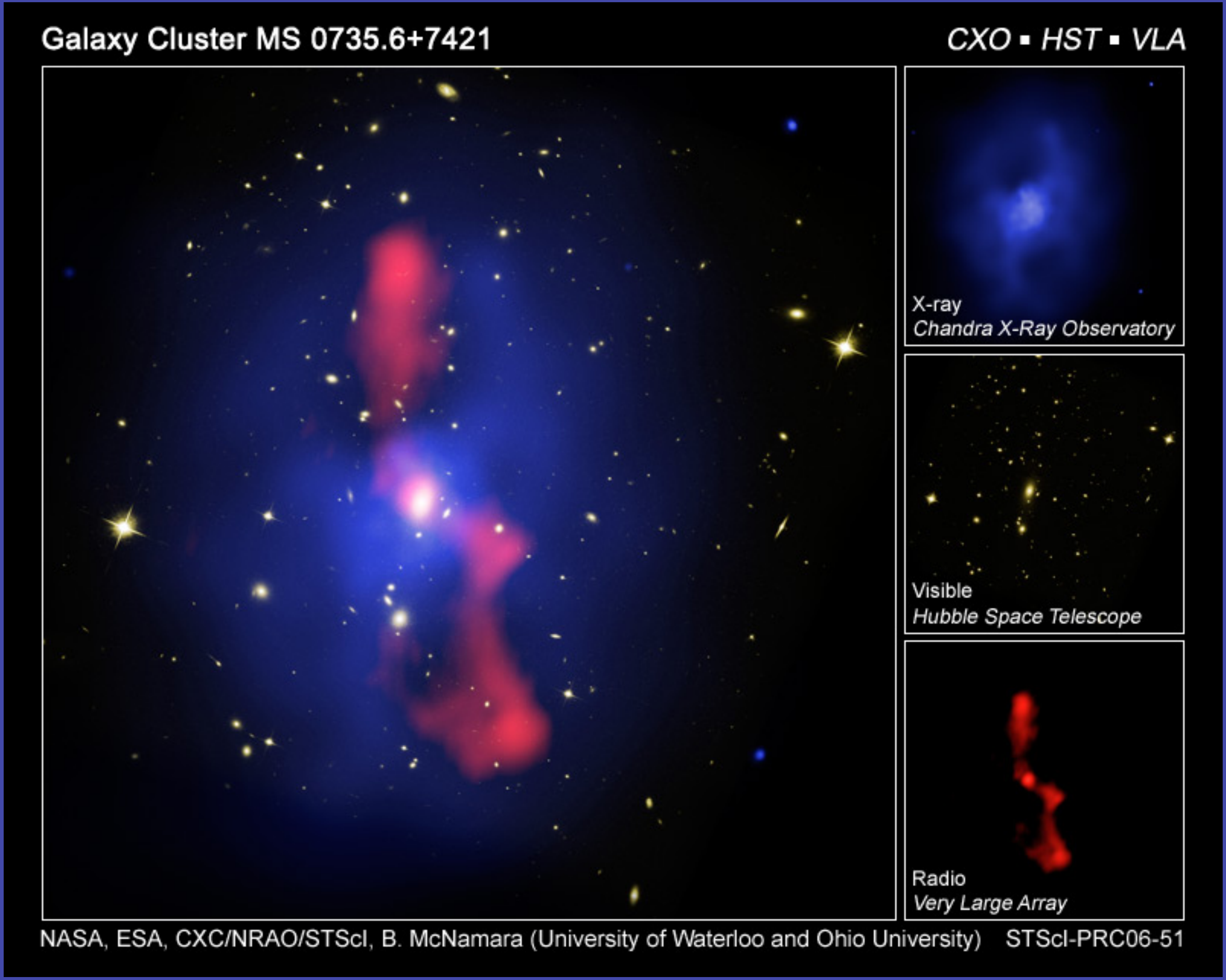
A short summary

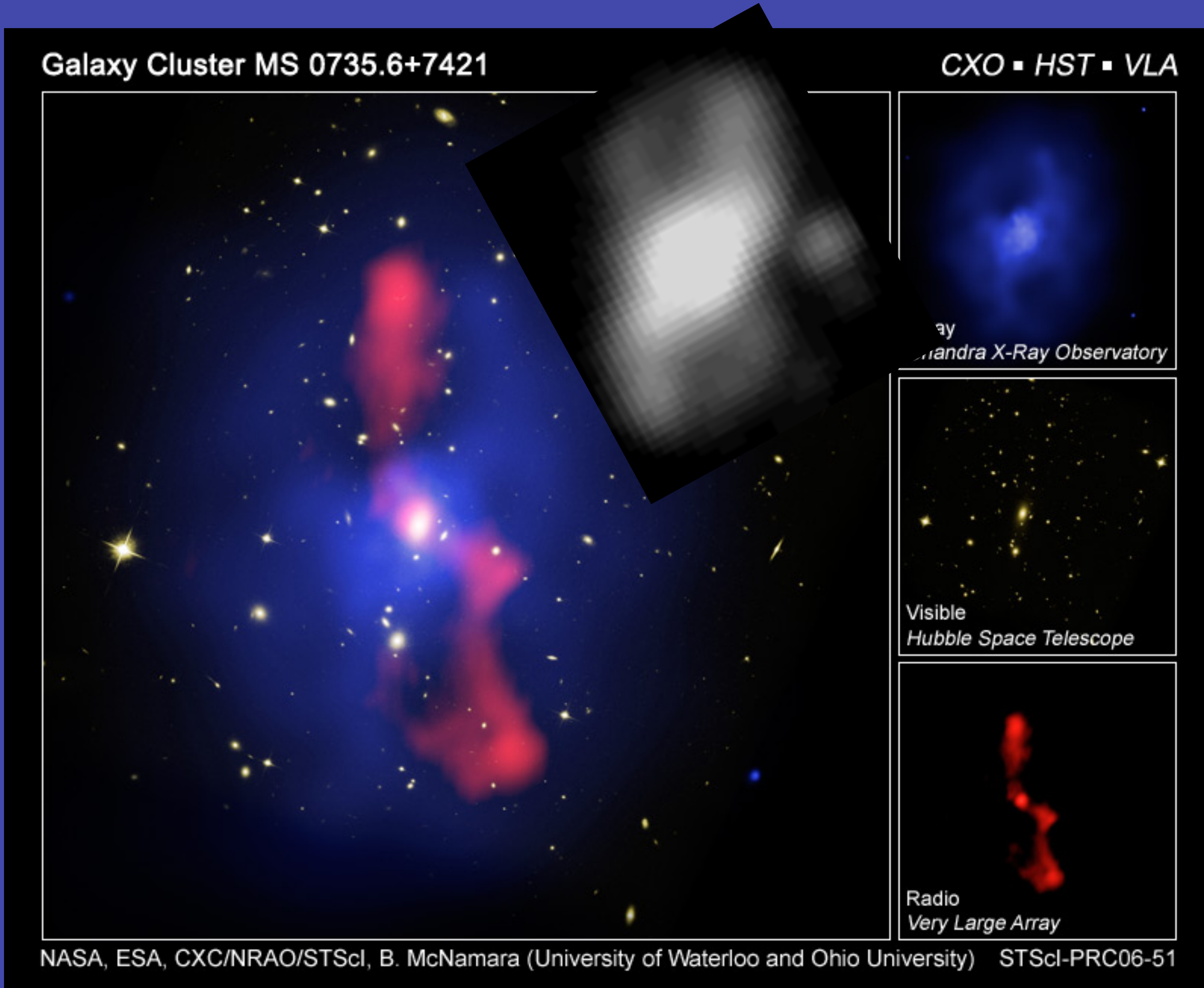
JETS

See review posted to astro-ph in May 2016:
Soker, N., 2016, arXiv: 160502672



The galaxy cluster MS 0735.6+7421: An X-ray image (red), and the radio image (blue) added in the right panel (From Brian McNamara and collaborators). The edge-to-edge linear scale is about one million light year.


Galaxy Cluster MS 0735.6+7421
CXO ▪ HST ▪ VLA
X-ray
Chandra X-Ray Observatory
Visible
Hubble Space Telescope
Radio
Very Large Array
NASA, ESA, CXC/NRAO/STScI, B. McNamara (University of Waterloo and Ohio University)
STScI-PRC06-51



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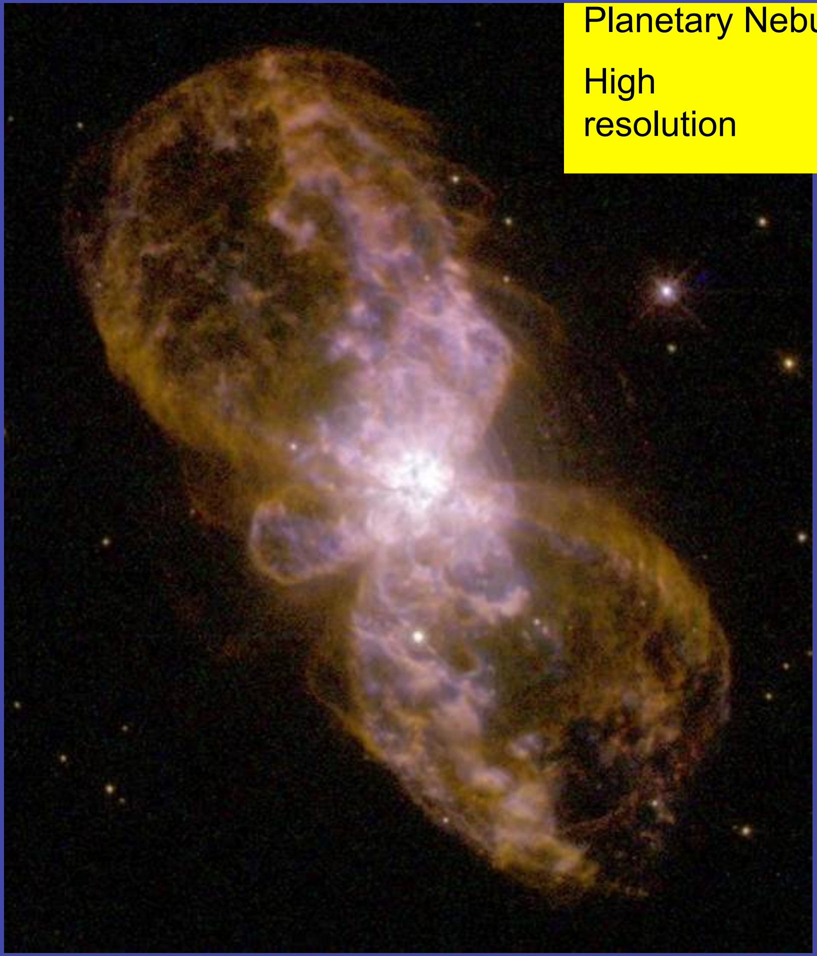
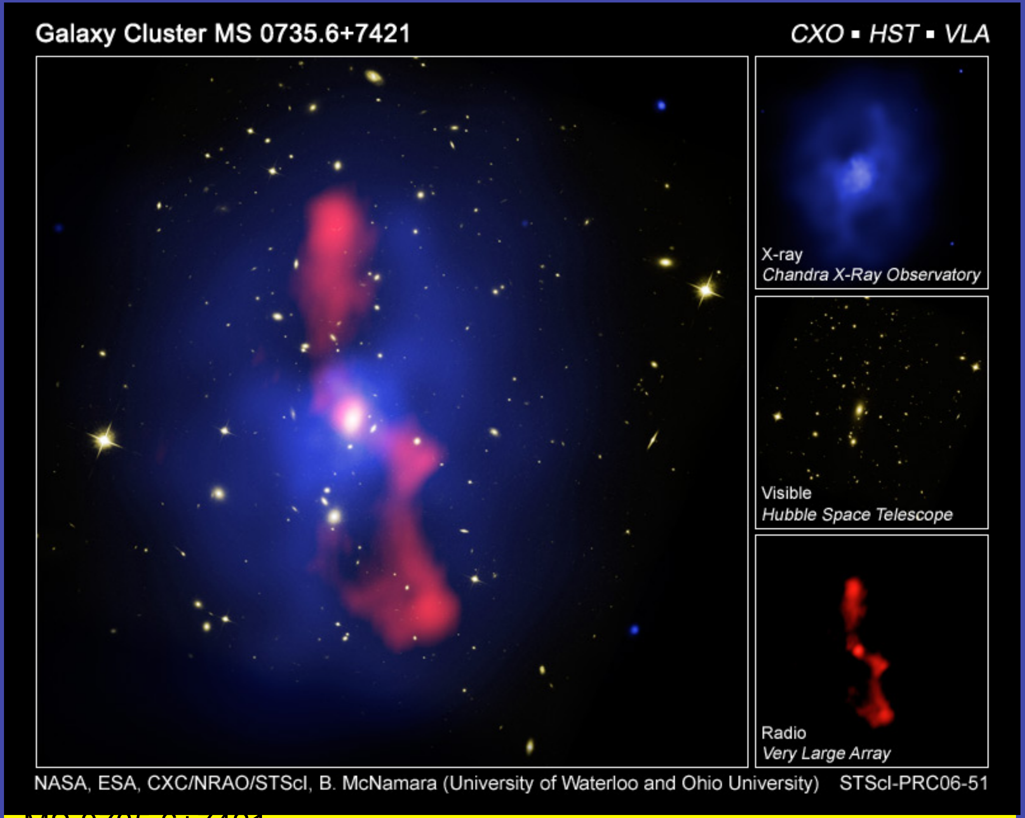


Planetary Nebula Hb 5:

High resolution

Low resolution

Shaping by jets



MS 0735.6+7421

A cluster of galaxies

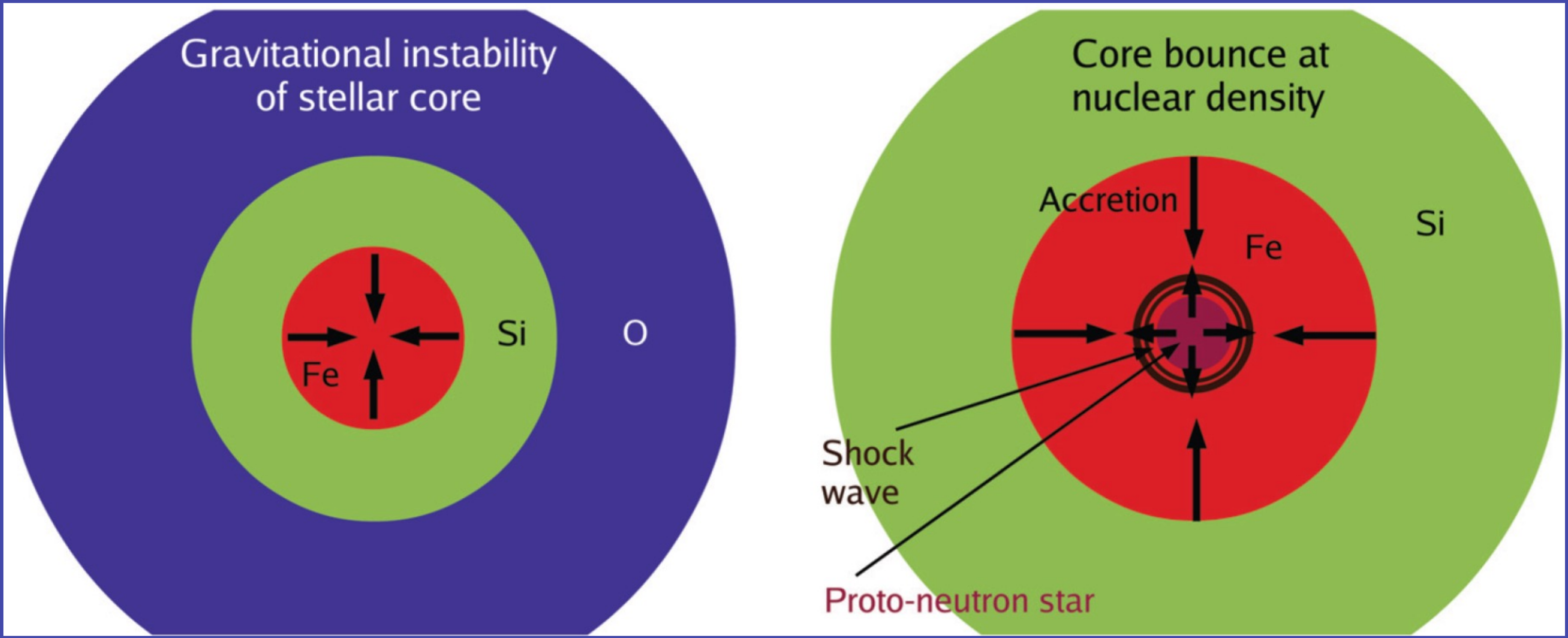
The popular model in the literature (but not among massive stars) for explosion is the delayed neutrino mechanism.

Task for next two days:

Find me one paper where the delayed neutrino mechanism has achieved 1foe=1B=1e51erg !

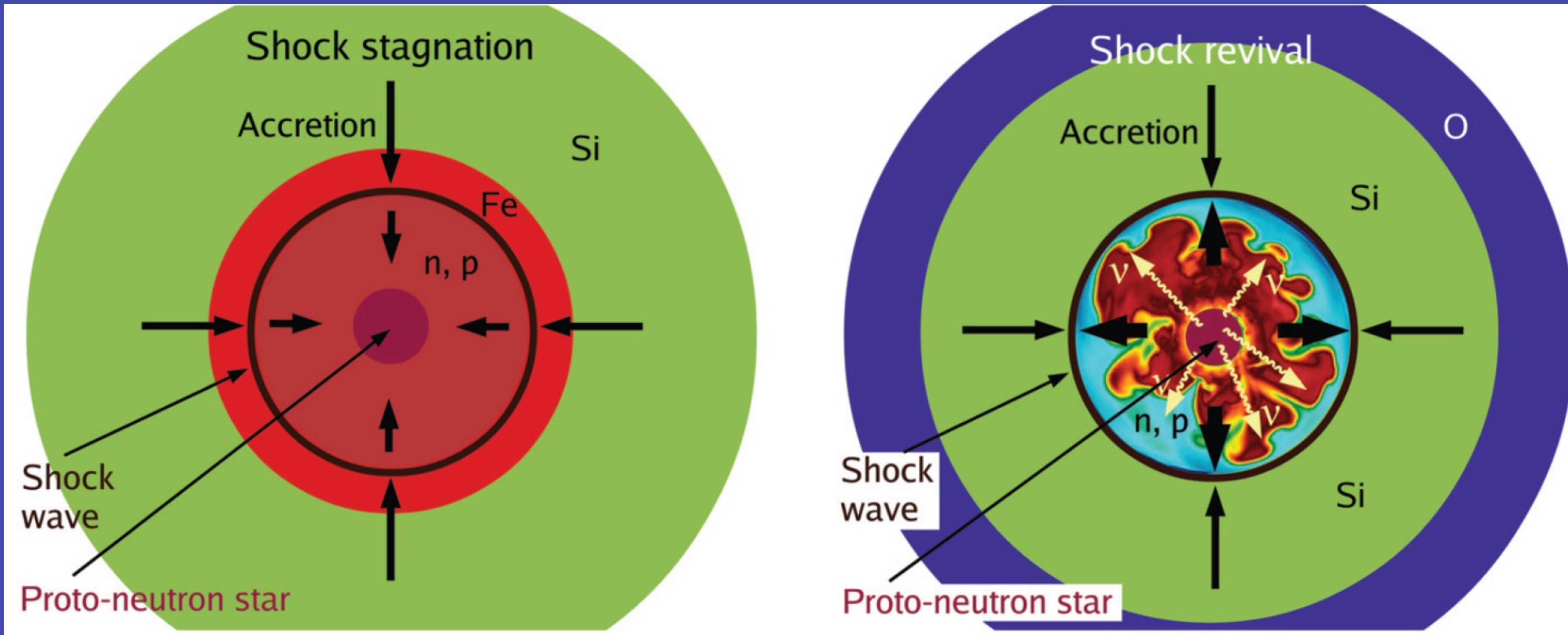
One paper is enough!!

The collapse: A proto-neutron star (NS)



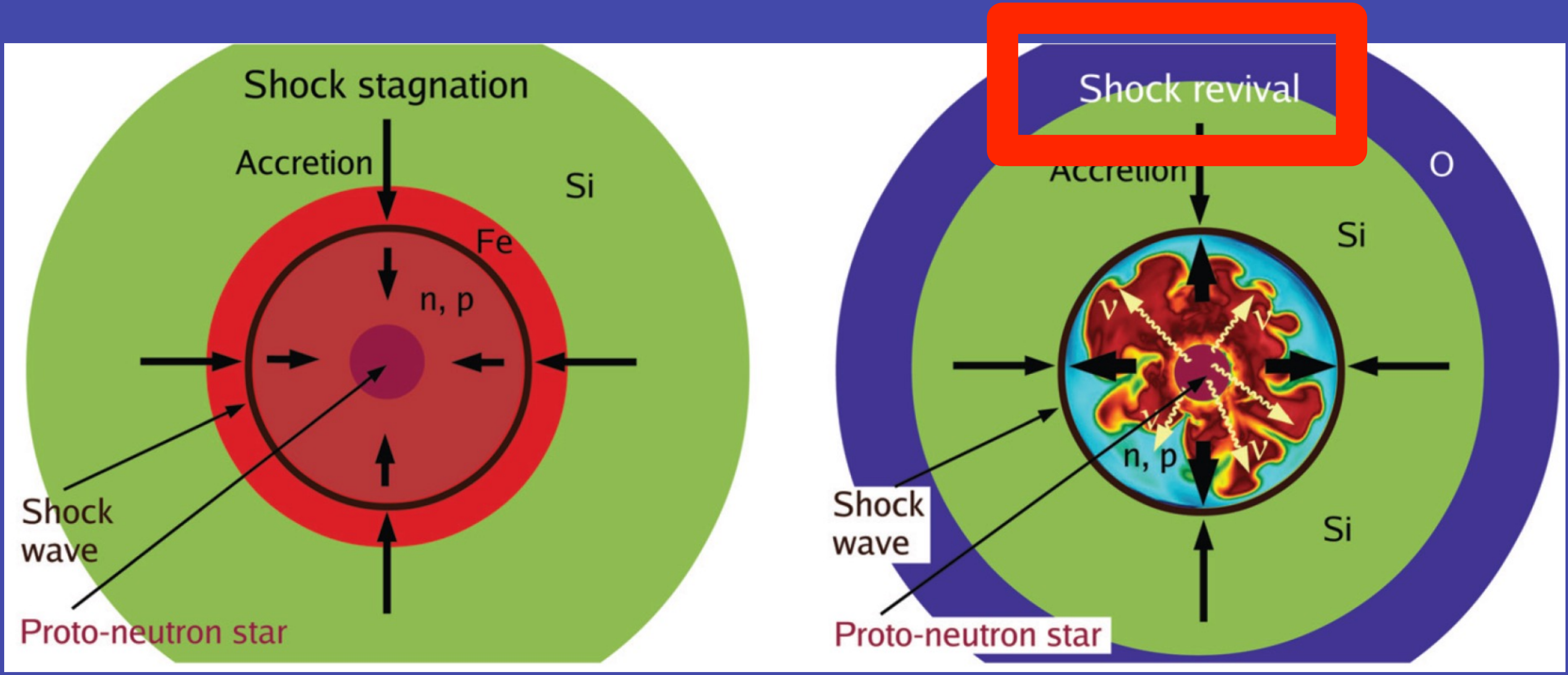
(from Janka et al. 2012)

The collapse



(from Janka et al. 2012)

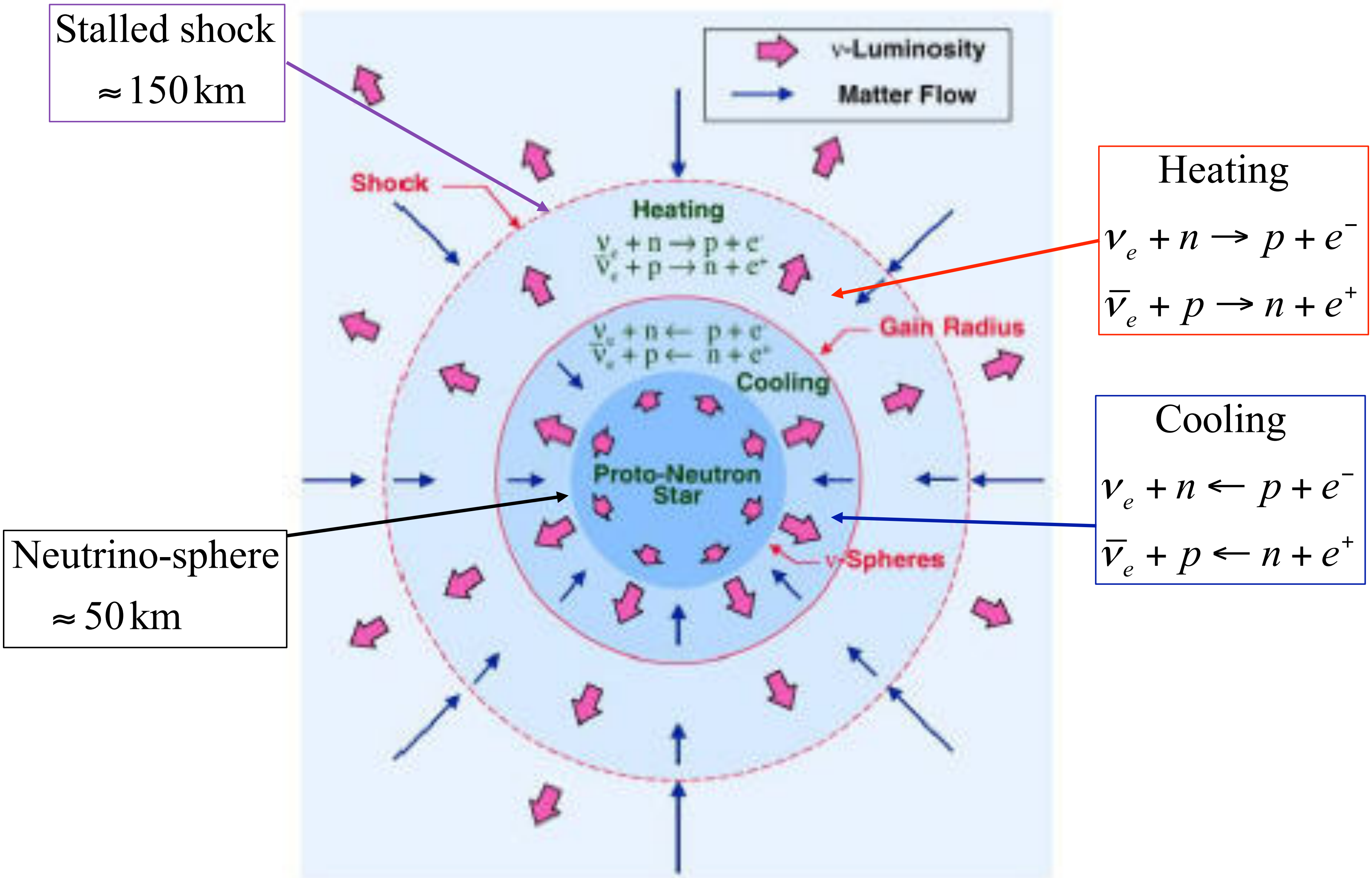
The collapse: The stalled shock



Shock revival is a challenge in the delayed-neutrino mechanism

The failure of the delayed-neutrino mechanism

Figure 9: SNe structure (from astronomyonline.org)



The failure of the delayed-neutrino mechanism

The delayed neutrino mechanism has 3 problems:

(1) To revive the stalled shock.
(2) To achieve the common energy of 1foe=1B
(3) It cannot account for energy of more than 2Bethe.
So even if the mechanism works, we need another energy source.

$$1\mathrm{B} = 10^{51}\,\mathrm{erg}$$

The failure of the delayed-neutrino mechanism

Problem 2 (Papish, Nordhaus, Soker 2015):

The neutrino-sphere is at $r \approx 50\text{km}$.

The optical depth above the neutrino-sphere is

$$\tau_\nu \simeq 0.1(\text{r}/100\,\text{km})^{-3}$$

The acceleration time of the shell is about the dynamical time

$$\text{t}_d \simeq 20(\text{r}/100\,\text{km})^{3/2}\ \text{ms}$$

The energy the accelerated gas can acquire from neutrinos

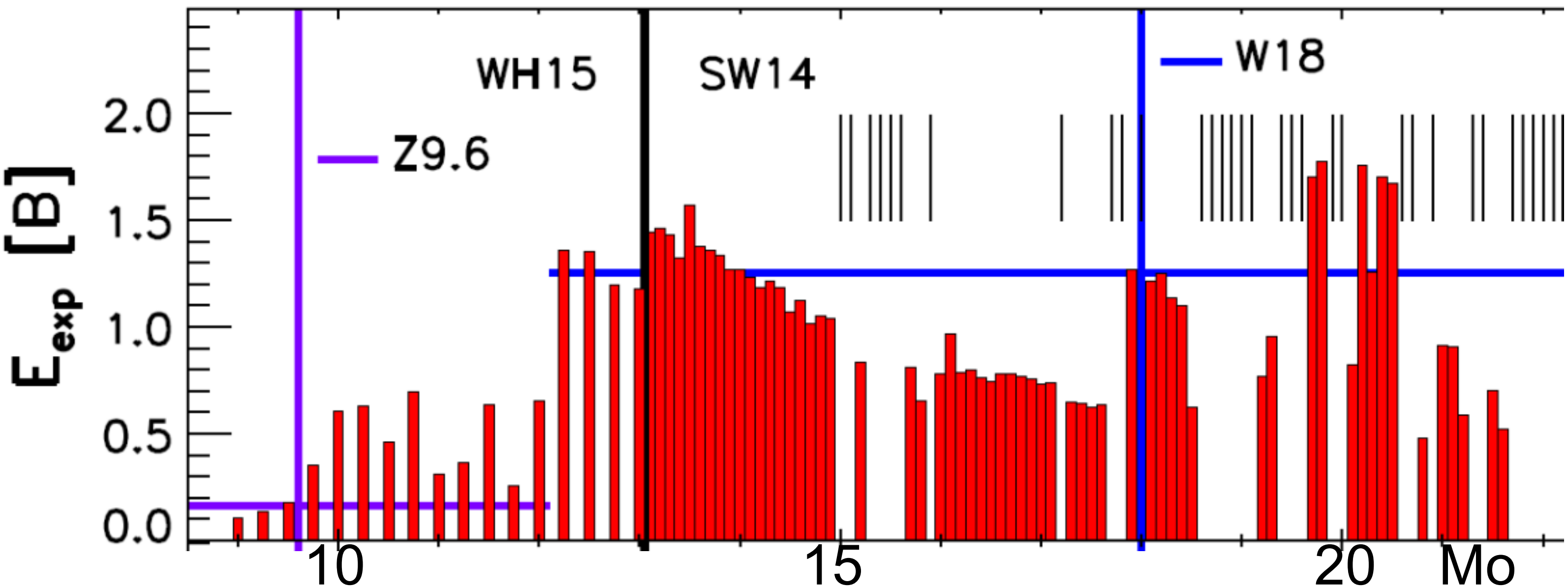
$$E_{\text{shell}} \approx t_d \tau_\nu L_\nu \simeq 0.1 \left(\frac{L_\nu}{5\times10^{52}\text{erg s}^{-1}} \right) \left(\frac{r_{\text{acceleration}}}{100\,\text{km}} \right)^{-3/2} \text{B}$$

This is about 0.1 times the typical energy of supernovae

The failure of the delayed-neutrino mechanism

Problem 3:

Explosion energy in 1B=1Bethe=10^{51} erg



Explosion model calibrated to give the observed energy for SN 1987A and the Crab supernova using a 9.6 Mo progenitor

(from Sukhbold et al. 2016)

That the explosion energy is few times the binding energy suggests a negative feedback mechanism.

I think it is the

Jet Feedback Mechanism (JFM)

See:

Soker, N. 2016

(accepted by astro-ph; arXiv:1605.02672)

"The jet feedback mechanism (jfm) in stars, galaxies and clusters (a review)"

The Jet Feedback Mechanism (JFM)

We are only starting.
If the 30-years old delayed neutrino mechanism is a BMW driven by Hans-Thomas Janka, we are on a scooter.

The Jet Feedback Mechanism (JFM)

However, the core-collapse supernova community is in a traffic jam.

We suggest that core collapse supernovae are exploded by jets launched from the newly born neutron star (or black hole).

This is the **jet feedback mechanism.**

With low angular momentum it is termed the jittering-jets model.

The goal is to reach an energy of B

$$1\text{B} = 10^{51}\text{erg}$$

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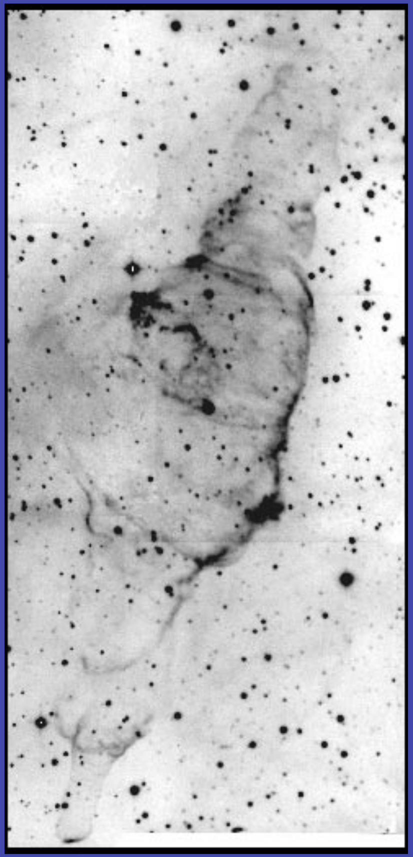
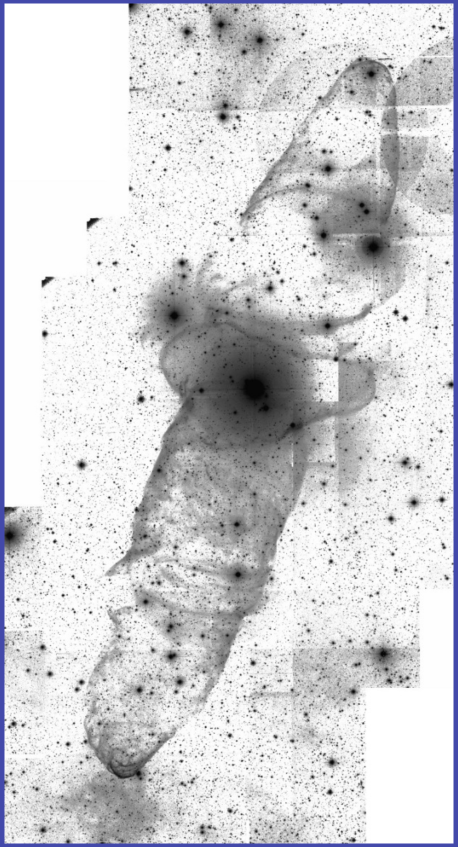
Two jets or not to B

Jets are not exotic!

We see jets in AGN, Young stars, Binary stars, Planetary nebulae, GRBs



KjPn8
(planetary nebula)
(Lopez et al. 2000)



Ou4
(young star)
(Romano Corradi)

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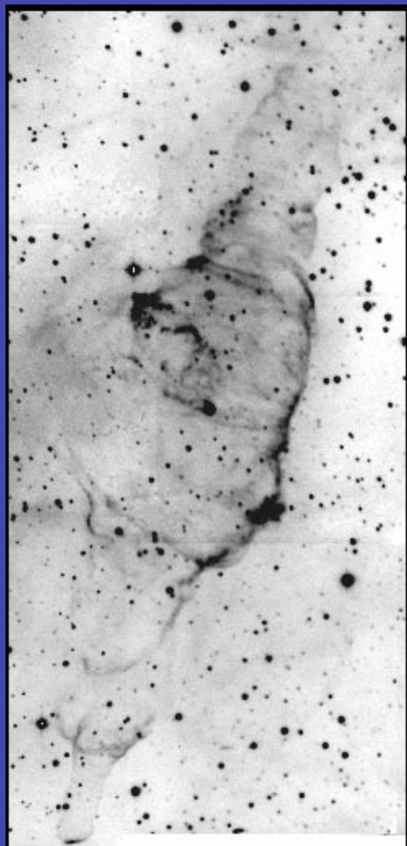

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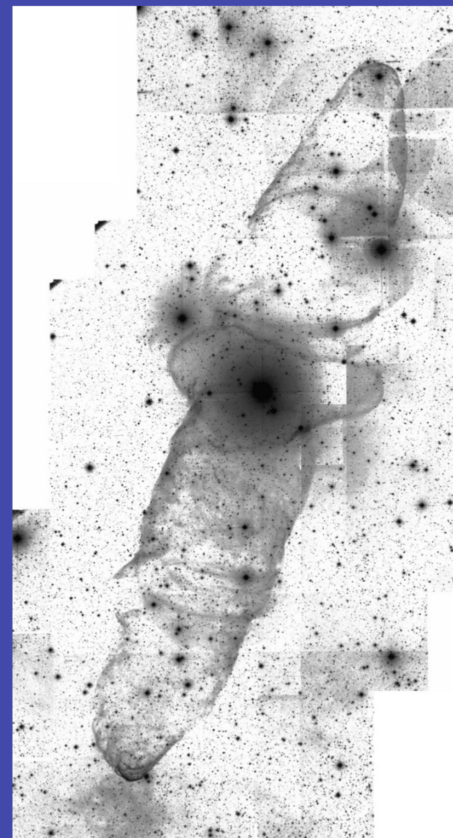


Ou4
(young star)
(Romano Corradi)

A mechanism based on using just 1% of the neutrino energy is exotic.

Jet-driven explosions of CCSNe have been simulated for a long time, but mainly in cases where the pre-collapsing core has both rapid rotation and strong magnetic fields.

(e.g., LeBlanc & Wilson 1970; Meier et al.1976, Bisnovatyi et al. 1976; Khokhlov et al. 1999; MacFadyen et al. 2001, Hoflich et al. 2001; Woosley & Janka 2005; Burrows et al. 2007; Couch et al. 2009; Couch et al. 2011; Takiwaki & Kotake 2011; Lazzati et al. 2012; Bromberg & Tchekhovskoy 2016)

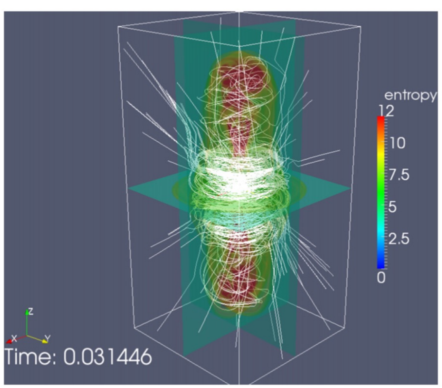
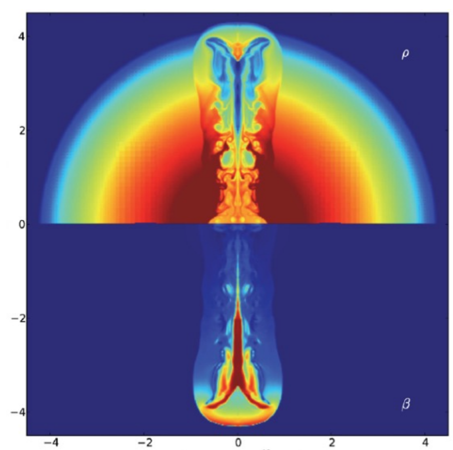


Figure 1. 3D entropy contours spanning the coordinates planes with magnetic field lines (white lines) of the MHD-CCSN simulation ~31 ms after bounce. The 3D domain size is 700 × 700 × 1400 km.



1748 *O. Bromberg and A. Tchekhovskoy*

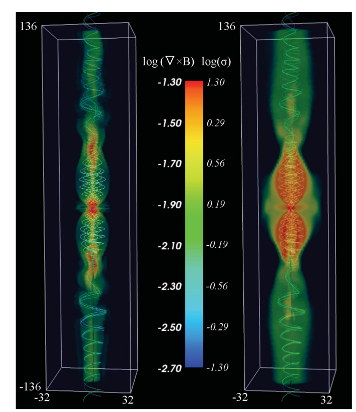
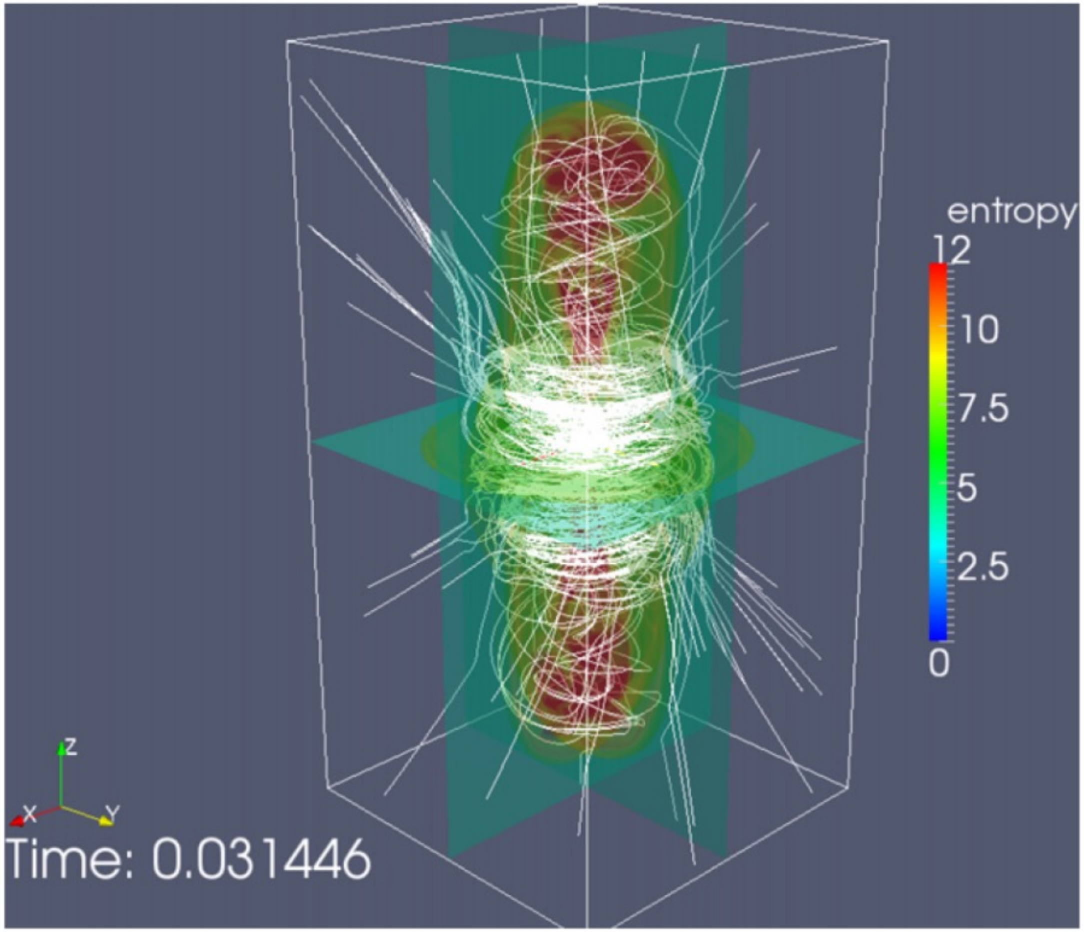


Figure 8. A snapshot of the central region in our fiducial 3D model M3 at $t = 4400 R_L/c \sim 1.5$ s, when the jet head is at $z = 800 R_L \sim 8 \times 10^9$ cm, or about 10 per cent of the stellar radius. The colour scheme in the left-hand panel shows the $\log_{10}(\nabla \times \boldsymbol{B})$, which is a tracer of conduction currents, and the right-hand panel shows the $\log_{10}(\sigma)$, which is a tracer of magnetization.

Winteler et al. (2012):

MAGNETOROTATIONALLY DRIVEN SUPERNOVAE AS THE ORIGIN OF EARLY GALAXY r-PROCESS ELEMENTS?



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Lazzati et al. (2012):
UNIFYING THE ZOO OF JET-DRIVEN STELLAR EXPLOSIONS

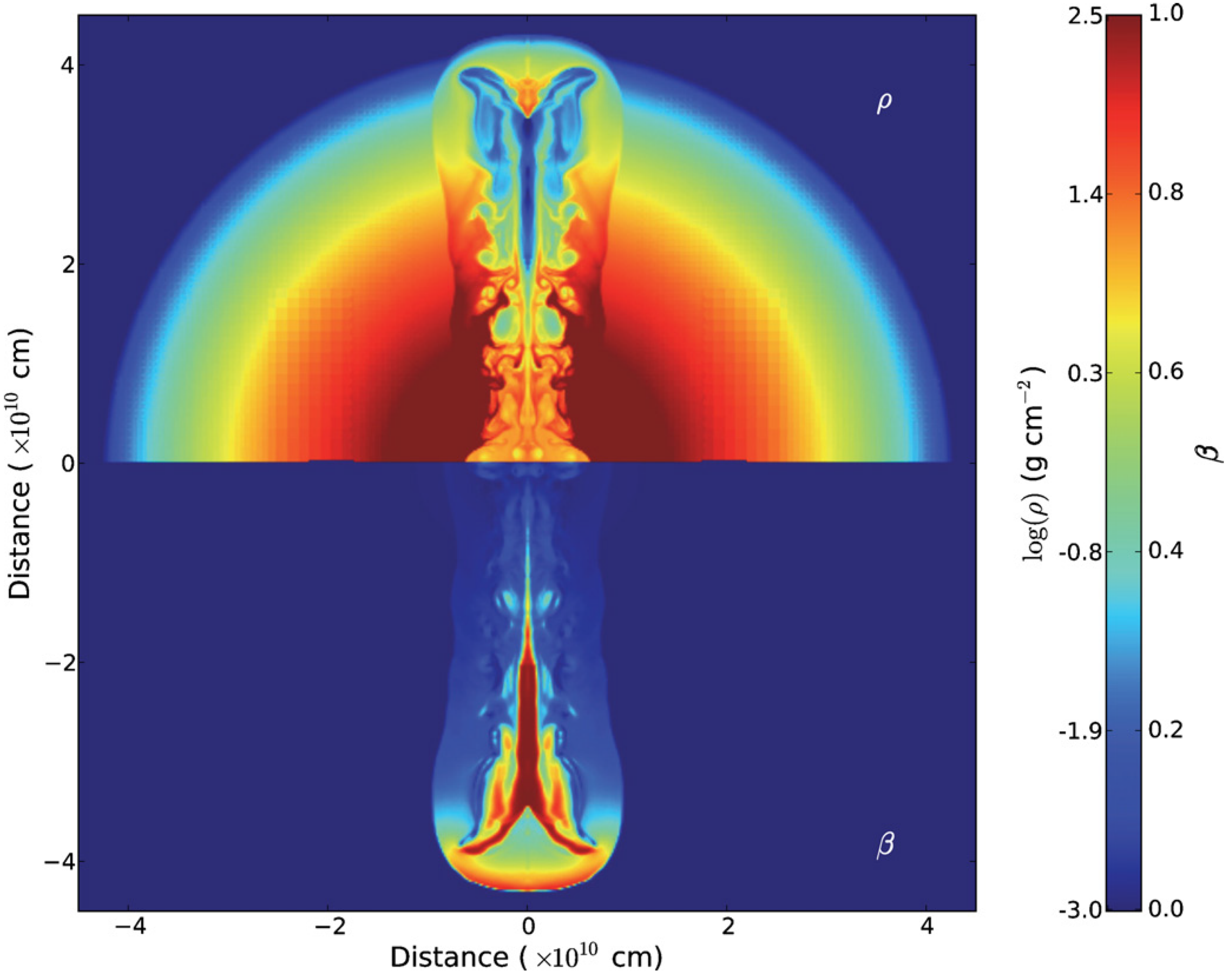
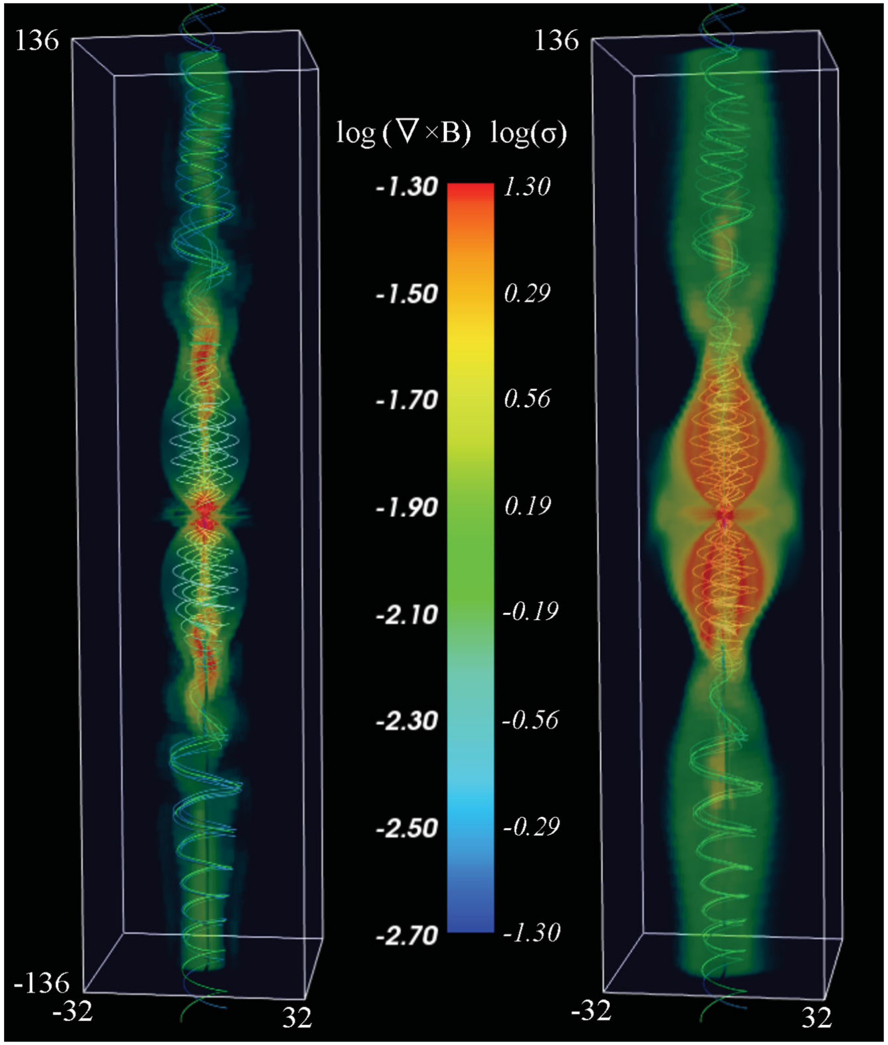


Figure 2. Density and velocity maps for the $t_{\rm eng} = 7.5$ s simulation at breakout ($t = 8.13$ s). The top panel shows a false-color rendering of the logarithm of the density, while the bottom panel shows velocity in units of the speed of light (see color scales on the right).



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The Jet Feedback Mechanism (JFM)

Motivation to consider jets:

(1) People deduce the existence of jets in long gamma ray bursts.

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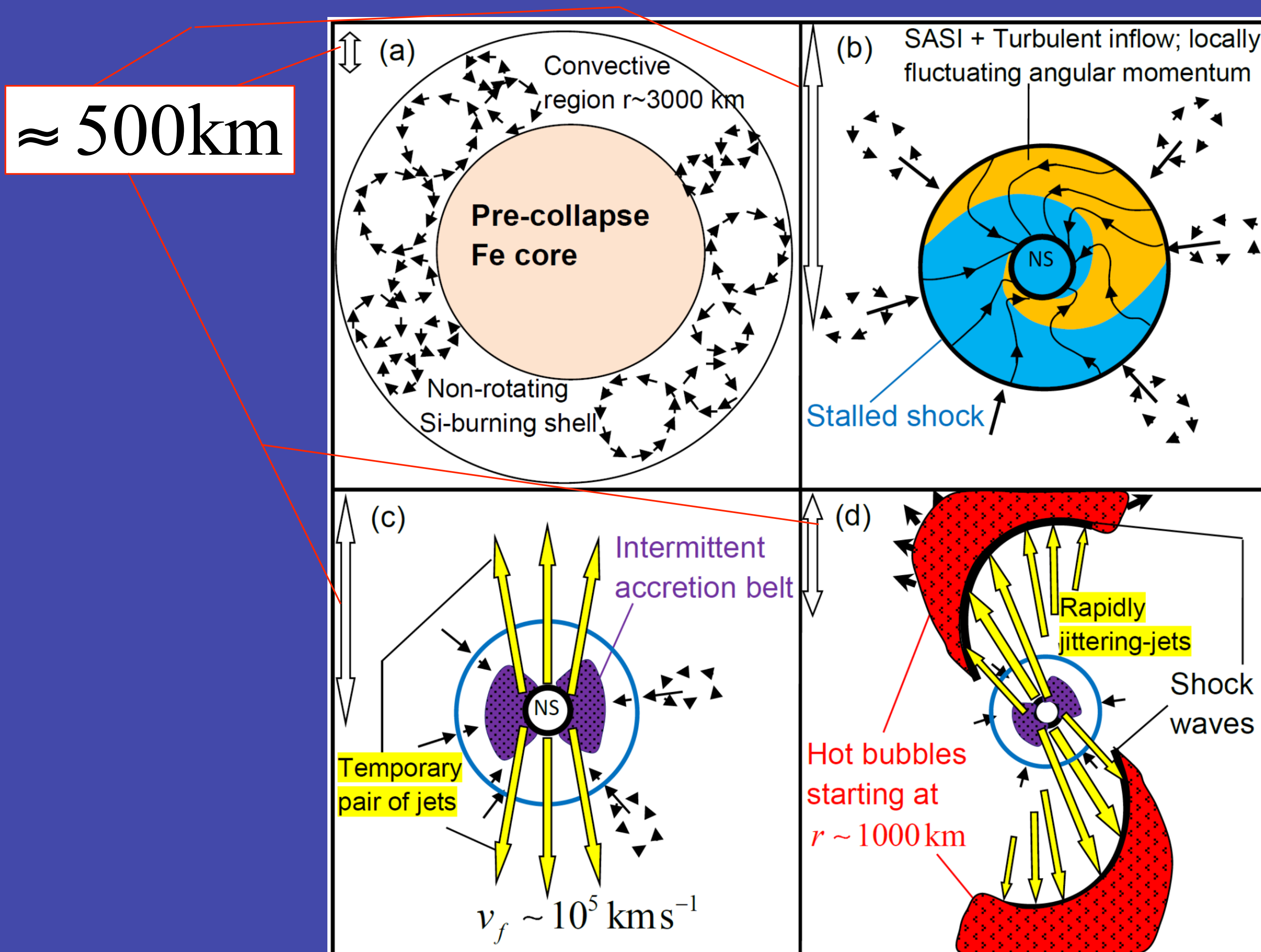
The Jet Feedback Mechanism (JFM)

Motivation to consider jets:

(1) People deduce the existence of jets in long gamma ray bursts.
(2) The explosion energy is several times the binding energy of the core. This hints on a negative feedback mechanism.
(3) Models to achieve energetic explosions seem to require large amount of angular momentum in the pre-collapse core, like the *magnetar* model.

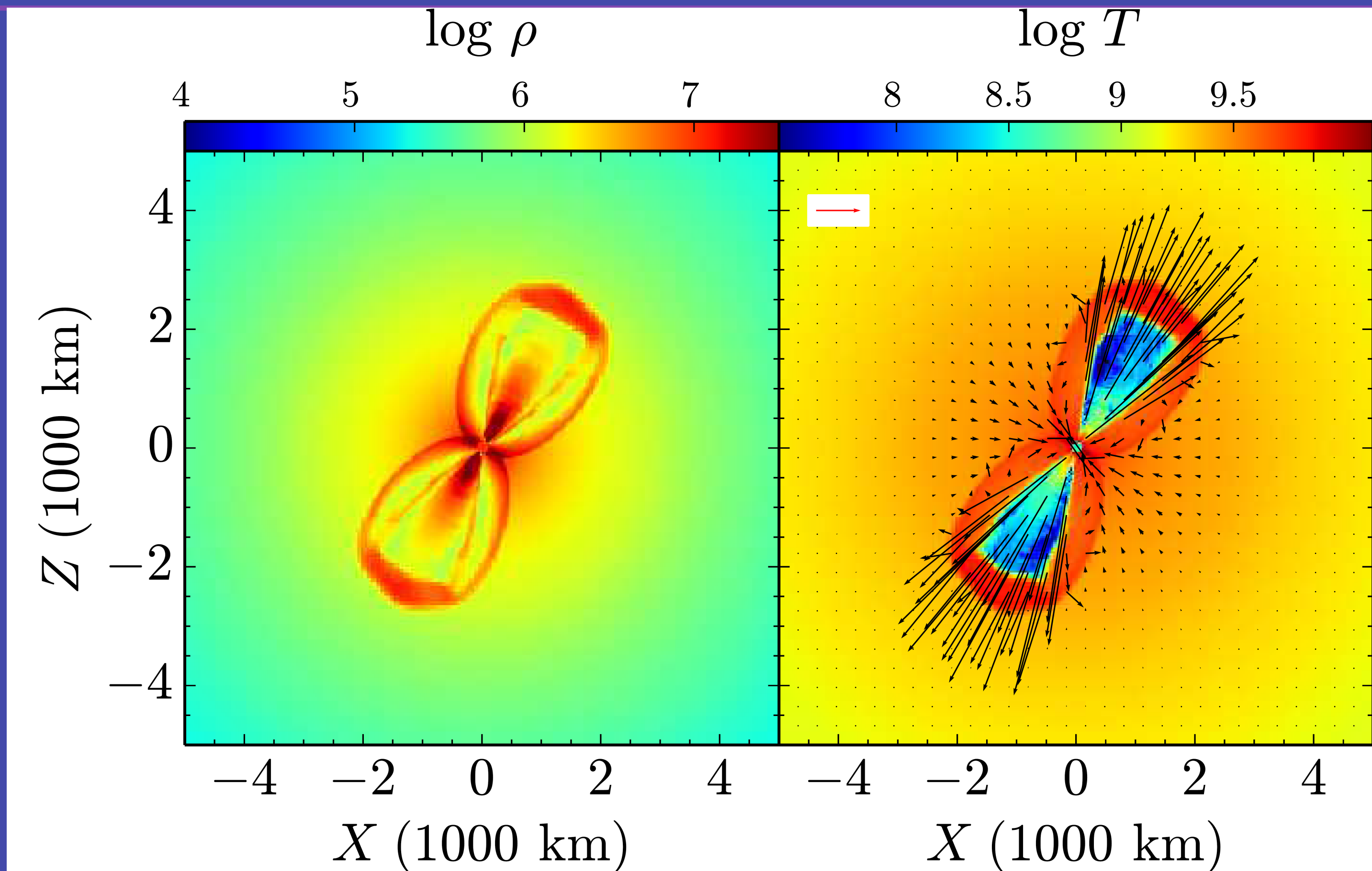
A schematic presentation of the jittering jets mechanism in a non-rotating (or slowly rotating) core, spanning an evolution time of several seconds.

(from Papish, Gilkis, Soker 2015; accepted for publication by astro-ph)

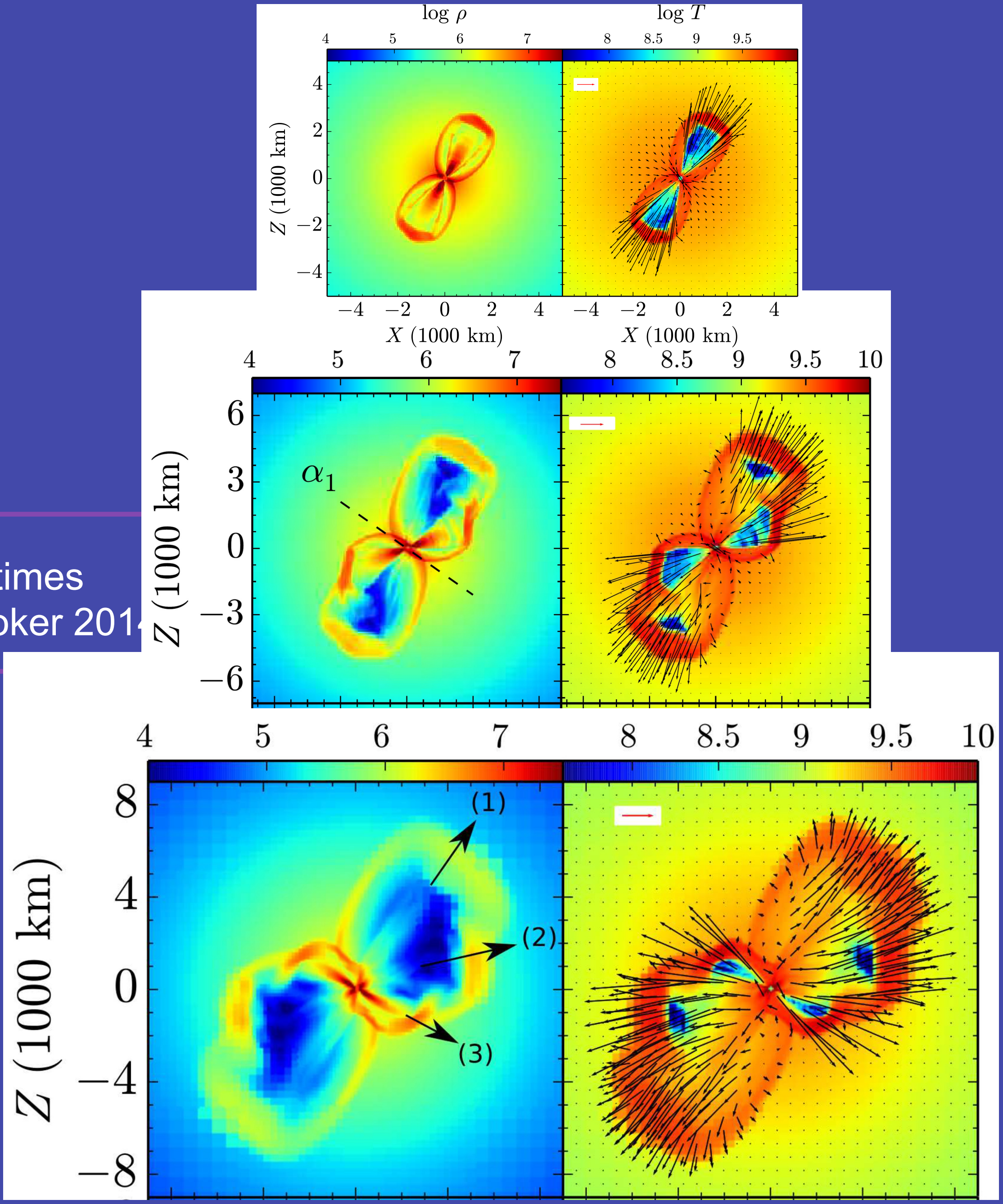


A simulation of 3-pairs of opposite jets launched within 0.15 seconds inside a core of a massive star just after the formation of the new neutron star.

A full 3D simulation. Shown at t=0.05 sec after 1 jet-launching episodes
(Papish & Soker 2014)



Comparing the 3 times
(from Papish & Soker 201



Super-energetic core collapse supernovae: magnetars and jets

- Neutrino-based mechanisms cannon account for explosion energy of >2Bethe.
- Many models assume the formation of a Magnetar (rapidly rotating magnetized neutron star).
- It seems that energetic jets are inevitable during the formation process of a magnetar (Soker 2016, New Astronomy; paper was accepted to New Astronomy in less than it was accepted by astro-ph).

Conclusion: A magnetar can definitely be formed.
But jets are likely to be more energetic than the magnetar.

Main points

- The 31-years old delayed neutrino mechanism has failed (a sophisticated failure) to explode core collapse supernovae with the desired energy.

- There are good reasons to adopt jets: Gamma-ray bursts, the hint for a negative feedback mechanism, and super-energetic supernovae.

- I call for a paradigm shift from neutrino-based explosions to jet-driven explosions for core-collapse supernovae.

Two jets or not to B

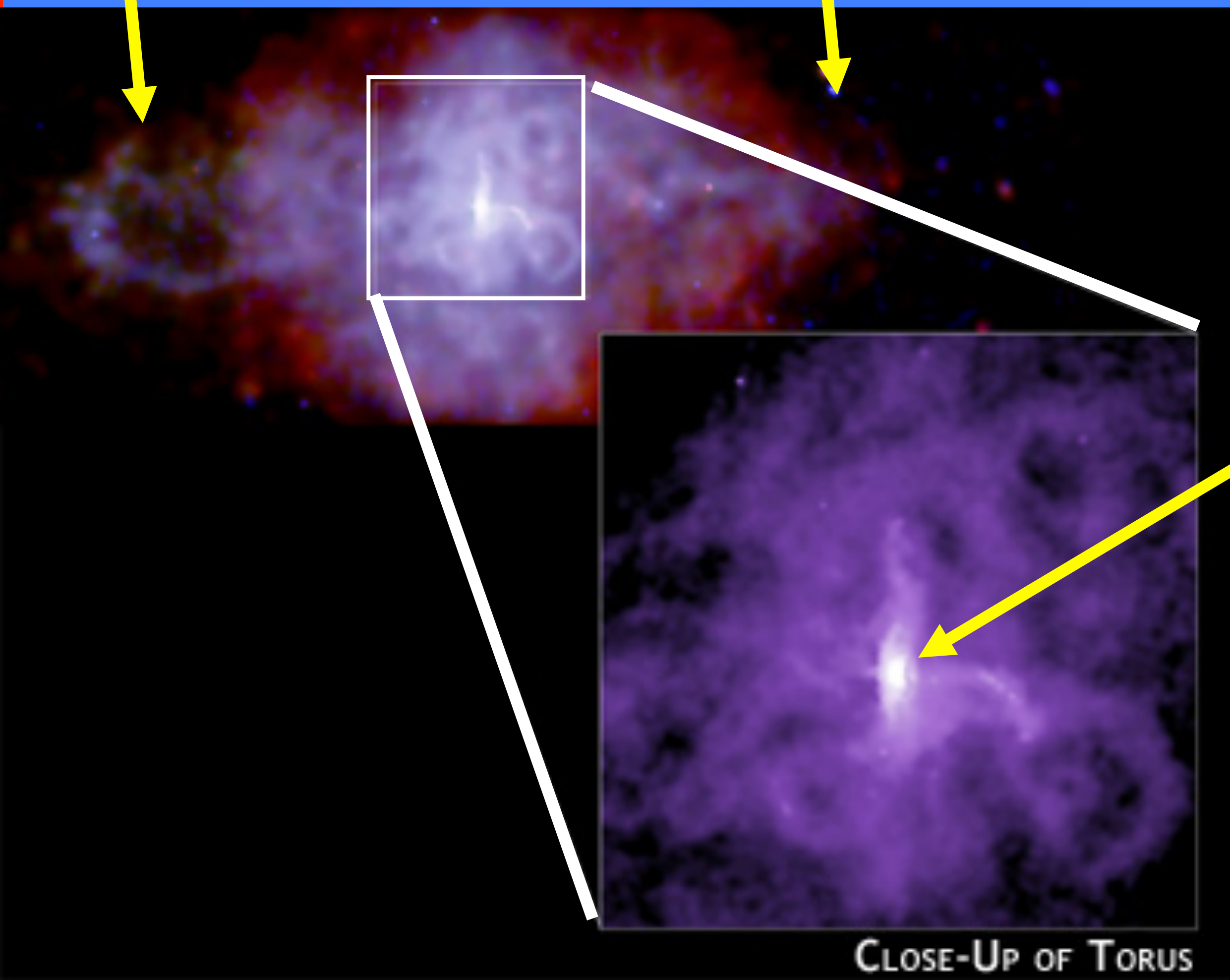
Signatures in SNRs

3C58

Credit: NASA/CXC/SAO/P.Slane et al.

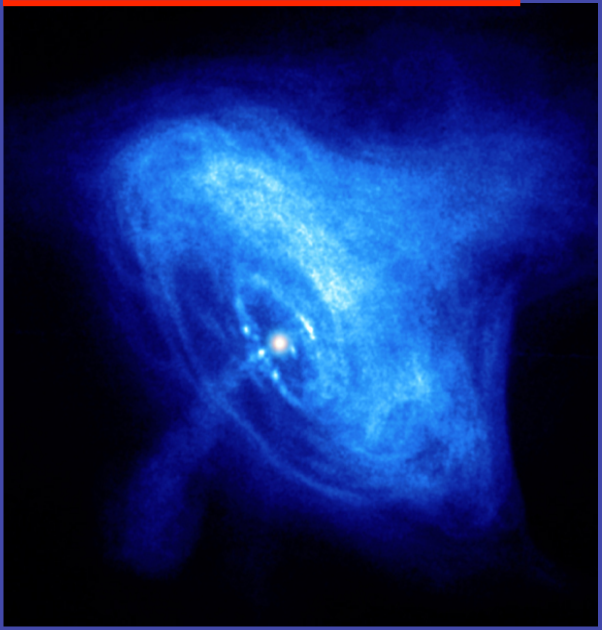
Ears

A neutron star with its jets



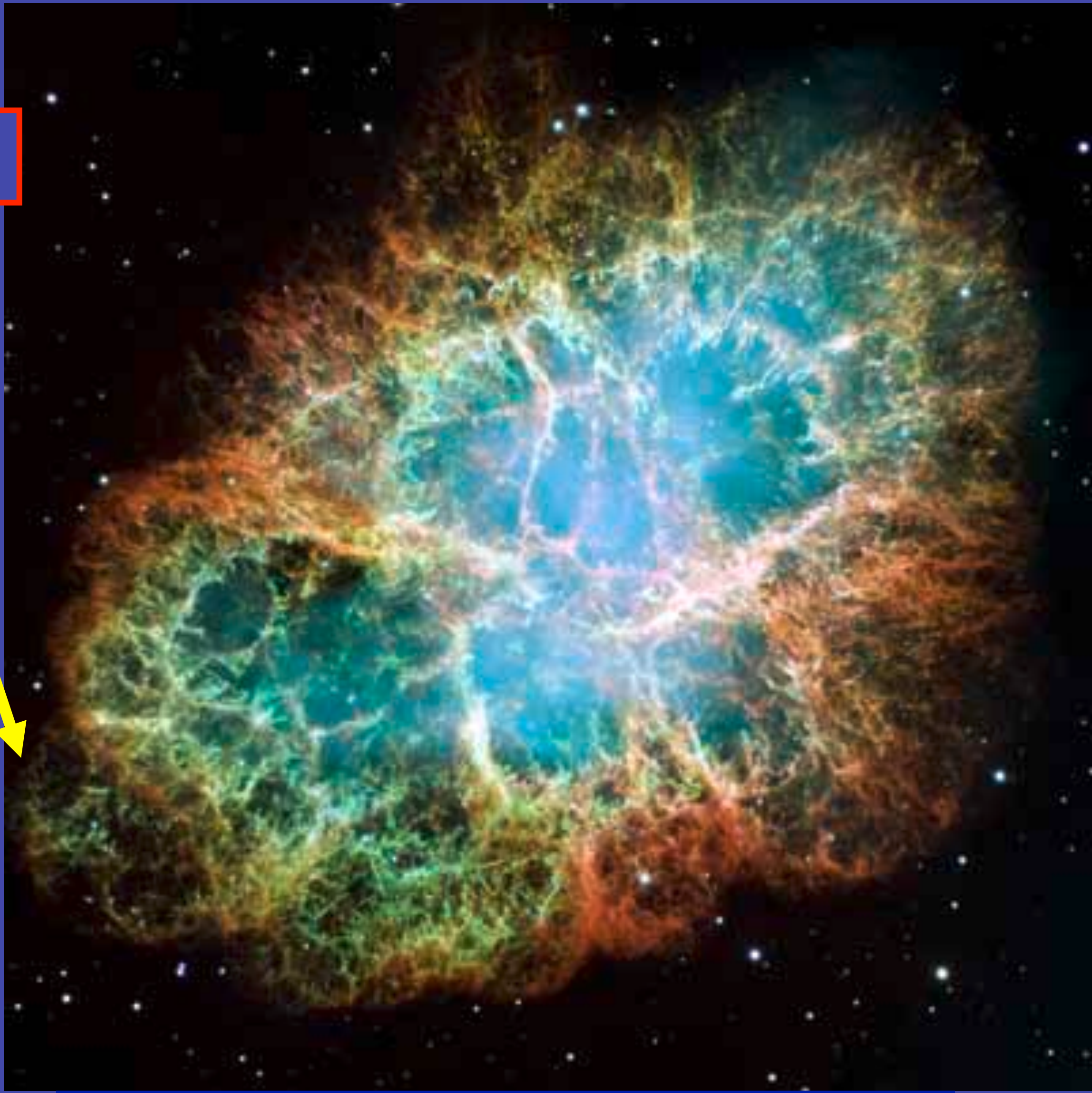
Crab Nebula

A neutron star with its jets



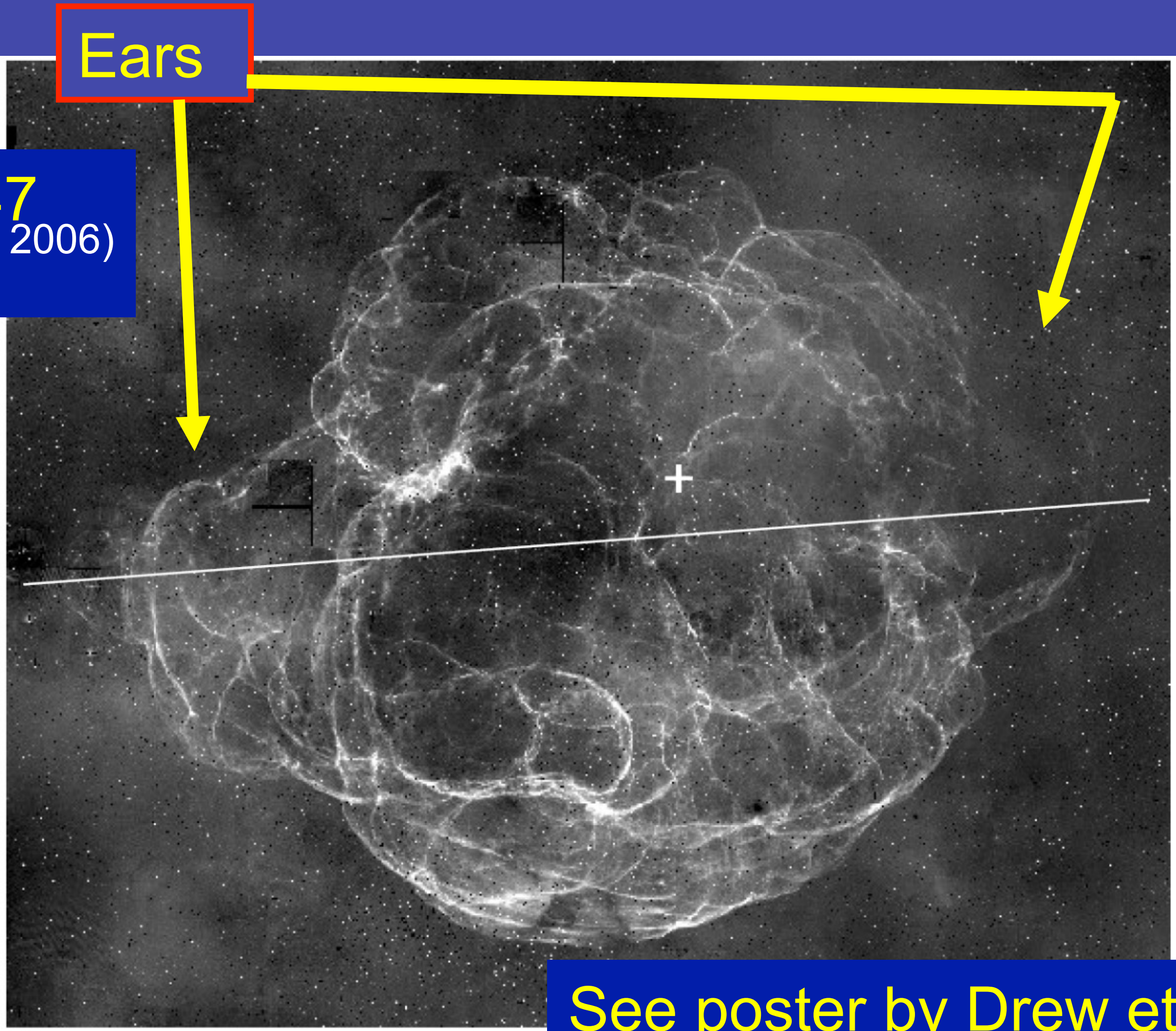
Credit: NASA/CXC/ASU/J.Hester et al

An ear



Credit: NASA, ESA, J. Hester, A. Loll (ASU);
Acknowledgement: Davide De Martin (Skyfactory)

Simeis 147
(V. V. Gvaramadze 2006)



See poster by Drew et al.

Fig. 1. The H_{α} image of the supernova remnant S 147 (Drew et al. 2005; reproduced with permission of the IPHAS collaboration). Position of the pulsar PSR J 0538+2817 is indicated by a cross. The line drawn in the east-west direction shows the bilateral symmetry axis (see text for details). North is up, east at left.

I estimate that the energy required to form the ears is 5-10% of the explosion energy.

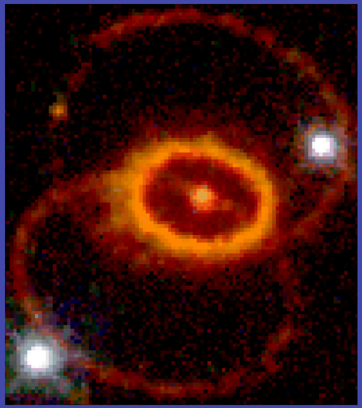
- Area covered by the Ears: A~ 0.05-0.1
- Extra kinetic energy per unit mass due to high velocity e~1
- Extra energy: DE ~ A*e ~ 0.05-0.1

Formation of Ears: I think they are formed by jets

The ears can be formed before the explosion.

This requires a binary companion.

+ A bipolar circumstellar gas is seen in SN 1987A →
+ S147 had a massive binary companion (e.g., Dincel et al. 2015).



The ears can be formed during the explosion.

This might occur in the jet-feedback mechanism. In the last episode jets are launched after the core was exploded. These jets freely expand and form the ears.

+ Expected in the explosion mechanism.
+ Can have 5-10% of the explosion energy.
+ Same angular momentum spins-up the newly born neutron star.

The ears can be formed after the explosion.

+ We observe jets from the pulsar at the center (A note about magnetars).

? Does the pulsar have 5-10% of the explosion energy released in jets? (In 3C58 only ~1e49 erg in the pulsar.)

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I expect jets in the formation process of rapidly rotating neutron stars.

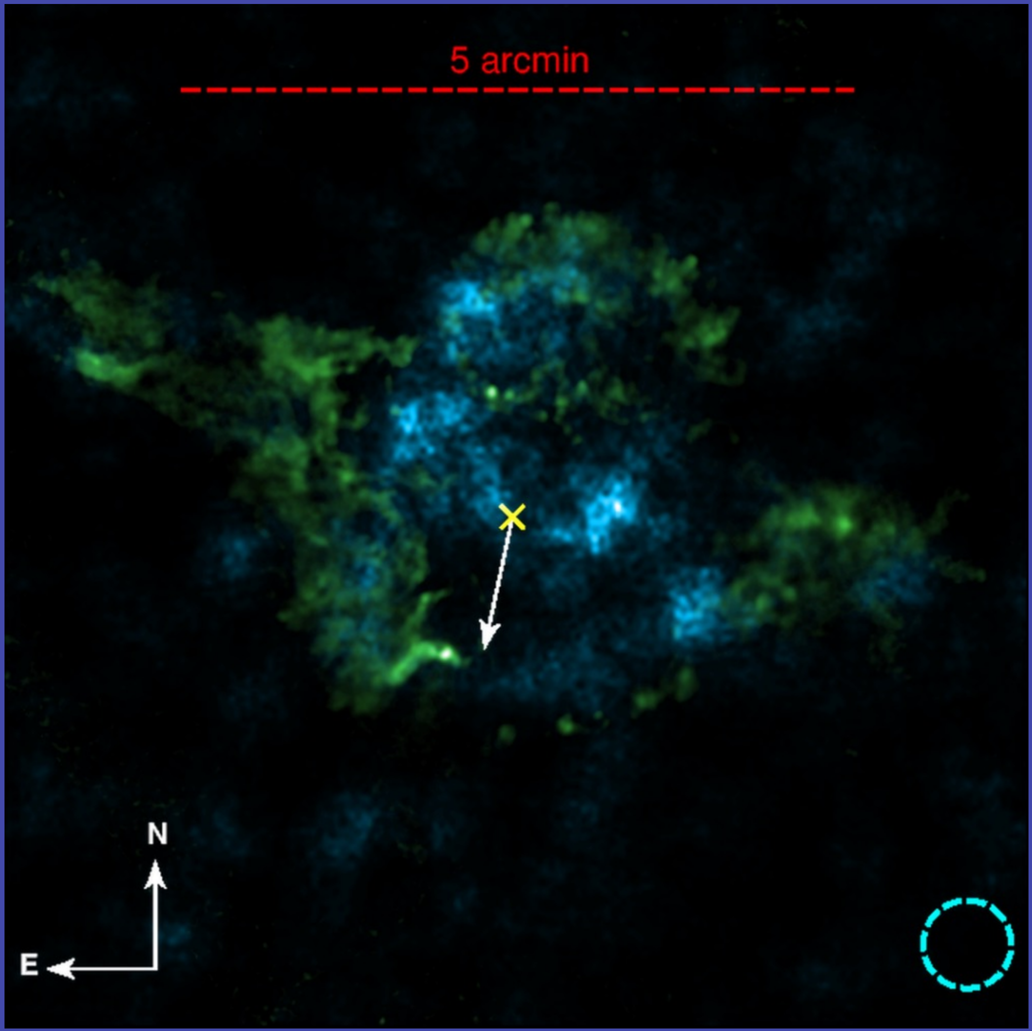
Cassiopeia A

In blue: 44Ti
In Green: Si

A possible explanation in the frame of the jittering jets scenario.

- The 44Ti is formed at early times — first several jets. 44Ti spreads sporadically in inner regions.

- The last jets-launching episode did not collide with dense core gas, hence no 44Ti is formed. These jets expand to large distances.



(Grefenstette et al. 2014)

A religious person is drowning in the flood.

Someone throw him
a rescue wheel.
"No, thanks.
God will help me", he says.

People in a boat suggest help.
"No, thanks. God will help me", he says.

A helicopter with rope ladder comes.
"No, thanks. God will help me", he says.

Eventually he dies in the flood. When he arrives to heaven he asks God:
"Why didn't you rescue me?"
God replies: "I sent you a rescue wheel, a boat and a helicopter; what else did you want me to do?"

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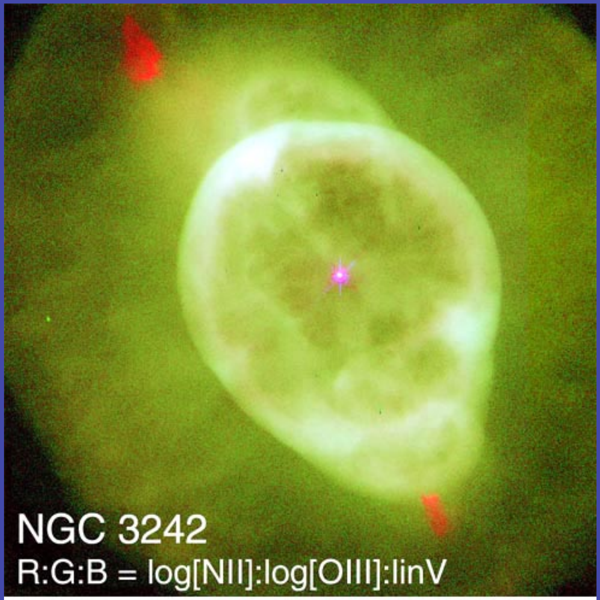
A researcher working on the explosion mechanism of core collapse supernovae gets (at a good age and after using trillions of cpu-hours) to heaven.
He asks God:
"Why didn't you tell us how supernovae explode?"

God replies:
"I failed you for more than 30 years in exploding massive stars with neutrinos, I sent you Gamma Ray Bursts with their jets, I sent you SNR with `Ears' and jets, I exploded super-energetic SNe that you cannot explain with neutrinos; what else did you want me to do?"

Ears in planetary nebulae

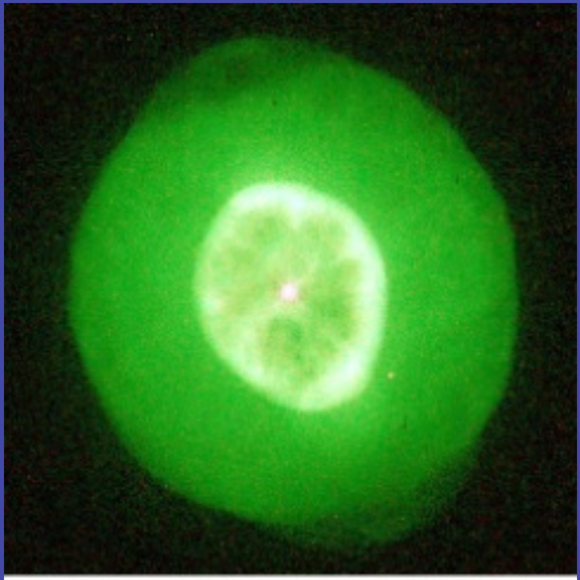


NGC 3242 G261.0+32.0 10 24 46.11 -18 38 32.6, R:G:B = log[NII]: log[OIII]: linear V
HST/WFPC2/PC1 N is NOT up. credit: Hajian et al (unpublished)
HST archives, GO 7501/8390/8773

IC 418 G215.2-24.2 05 27 28.20 -12 41 50.3, R:G:B = [NII], Ha, [OIII]
Hubble Heritage Team, HST/WFPC2/PC?, N is NOT up
ref: hubblesite.org/gallery/album/nebula_collection/pr2000028a/
inset: R:G:B = deep log[NII]:log [NII]:log[OIII] Hajian, HST archives GO7501

NGC 7139 G104.1+07.9 21 46 08.59 +63 47 29.4, R:G:B = unknown
credit: Gert Gottschalk and Sibylle Froehlich/Adam Block/NOAO/AURA/NSF
source: http://www.noao.edu/outreach/aop/observers/n7139.html

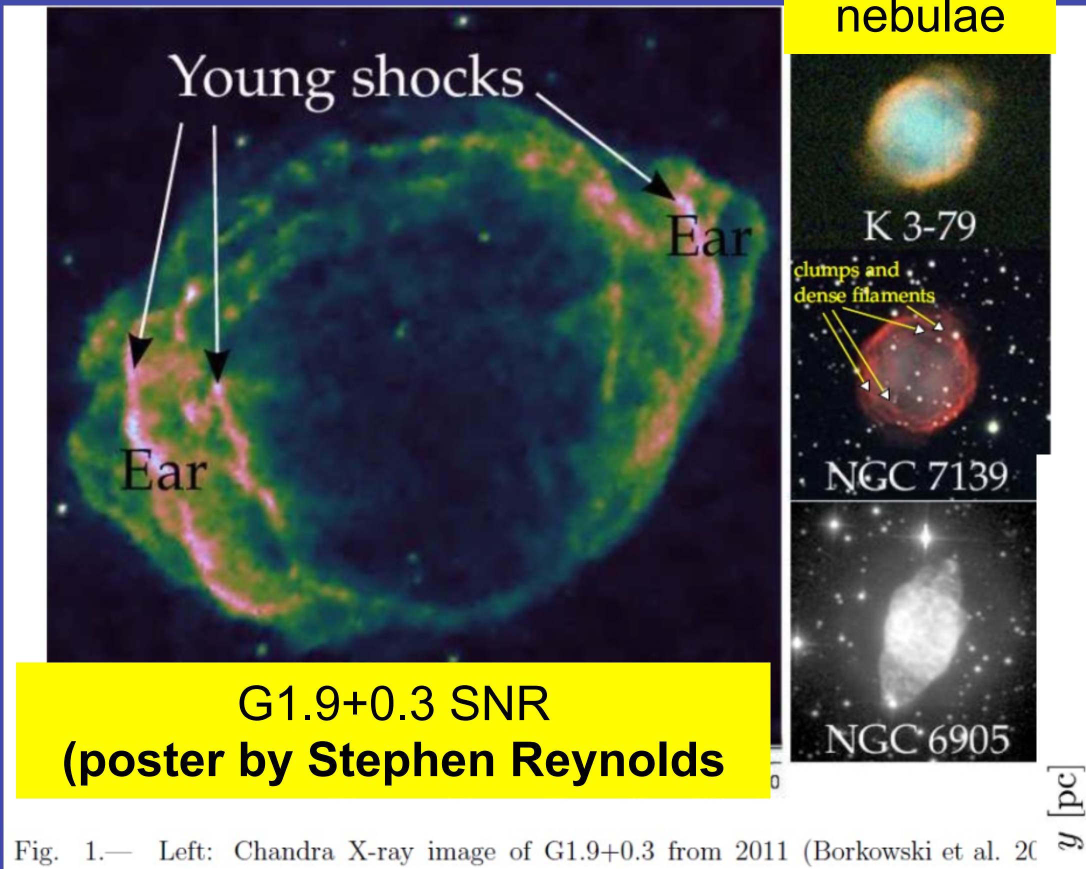
NGC 6563 G358.5-07.3 18 12 02.75 -33 52 07.1, R:G:B=log(Ha+[NII]),both,log[OIII]
ref: Schwarz, H.E., Corradi, R.L.M., Melnick, J 1992 A&A Suppl, 96, 23
image files courtesy R Corradi. N is NOT up. See ref for orientation.



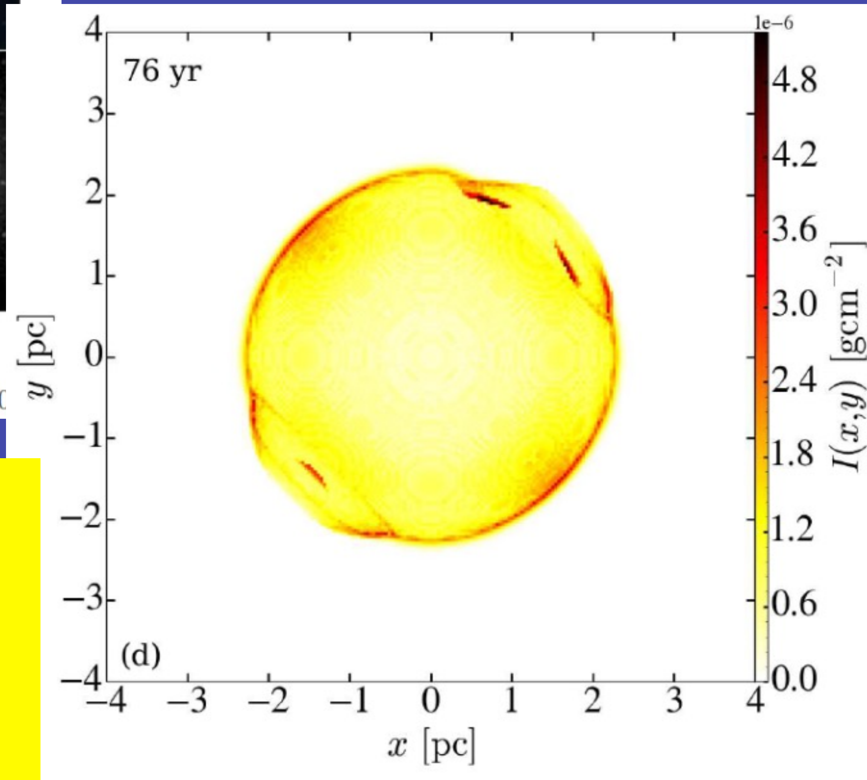
IC 2448 G285.7-14.9 09 07 06.26 -69 56 30.7, R:G:B = log[NII]: log[OIII]: linear V
HST/WFPC2/PC1 N is NOT up. credit: Hajian et al (unpublished)
HST archives, GO 7501/8390/8773

Ears in Type Ia SNRs

Planetary nebulae

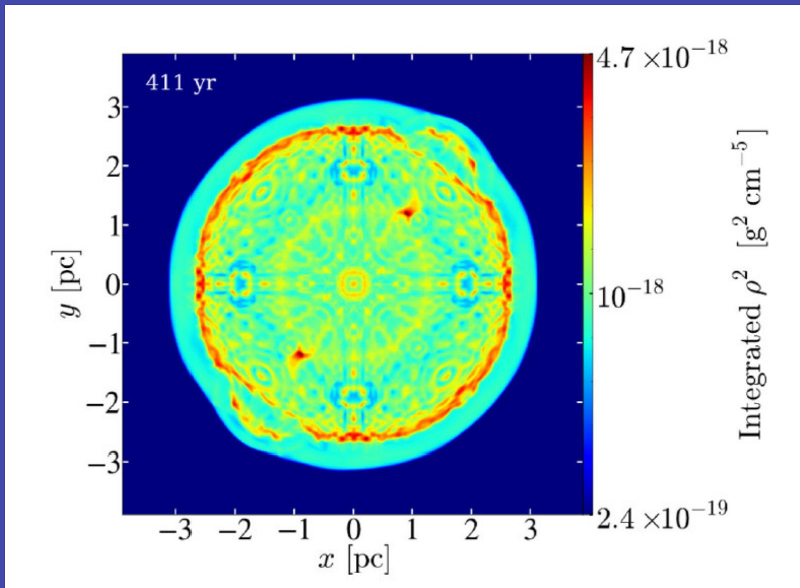


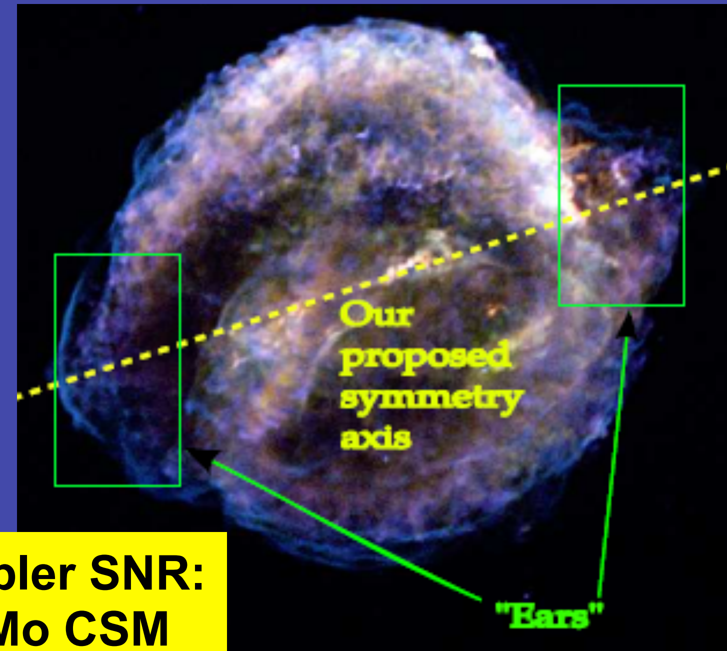
G1.9+0.3 SNR
(poster by Stephen Reynolds



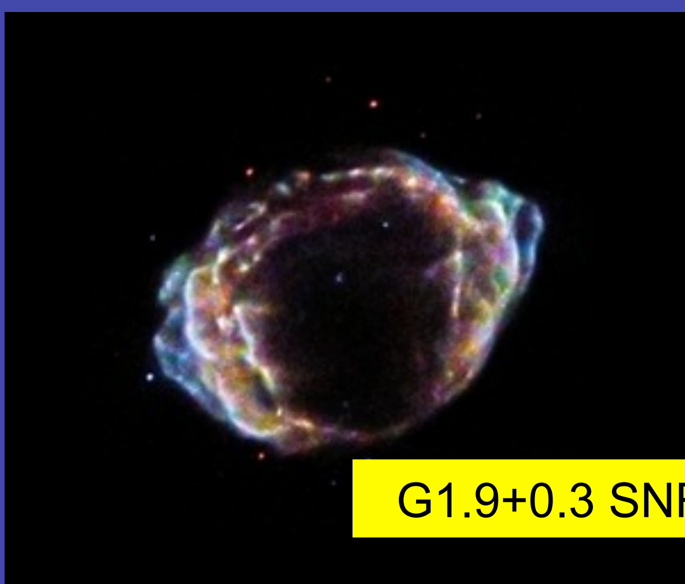
Numerical simulations of a
SN Inside a **P**lanetary nebula
(SNIP)
(from Tsebrenko, D. & Soker, N. 2015)

Ears in Type Ia SNRs

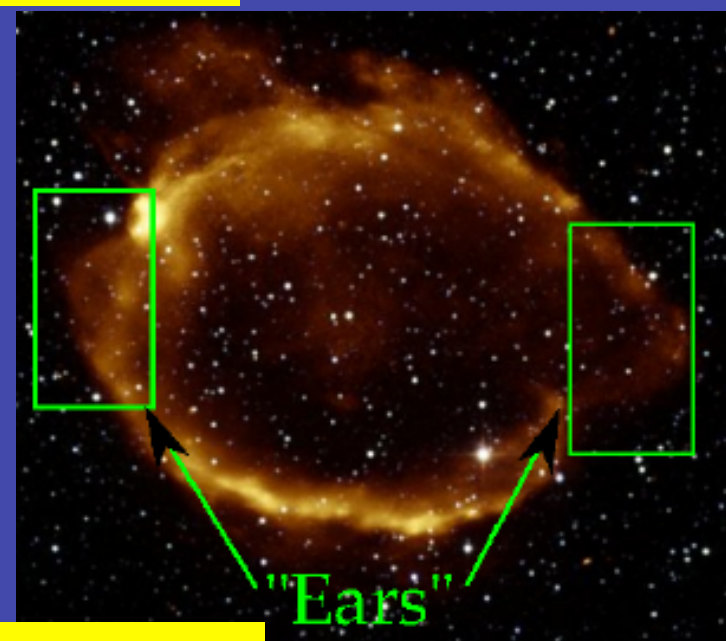




Kepler SNR: ~1Mo CSM

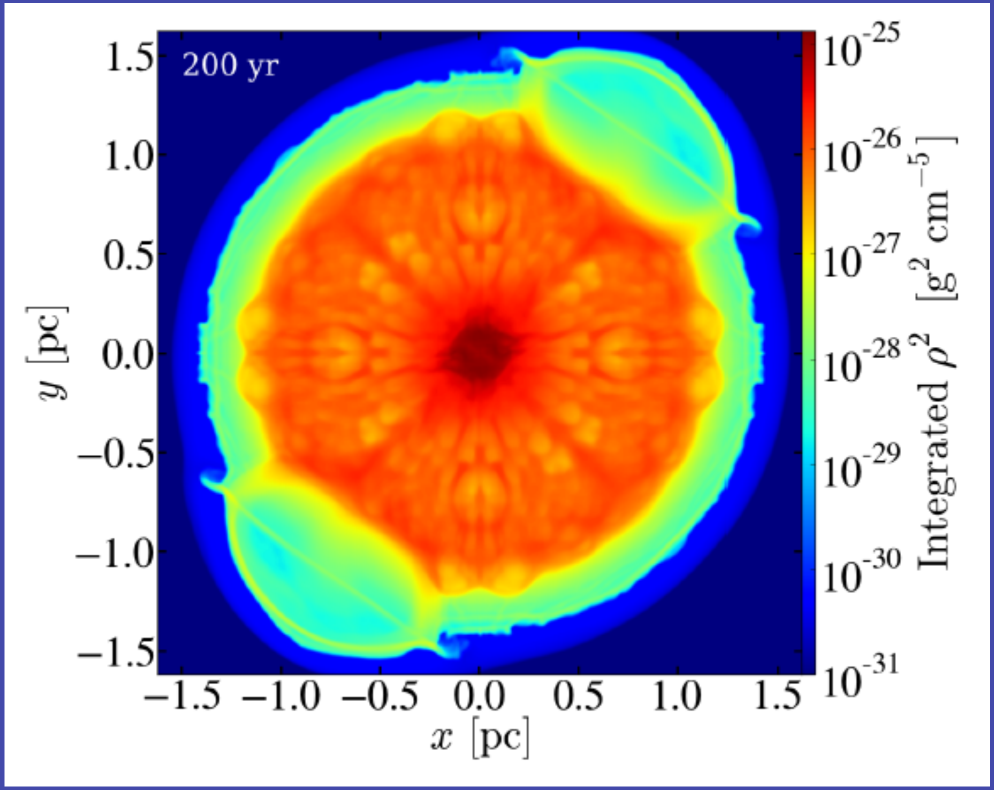


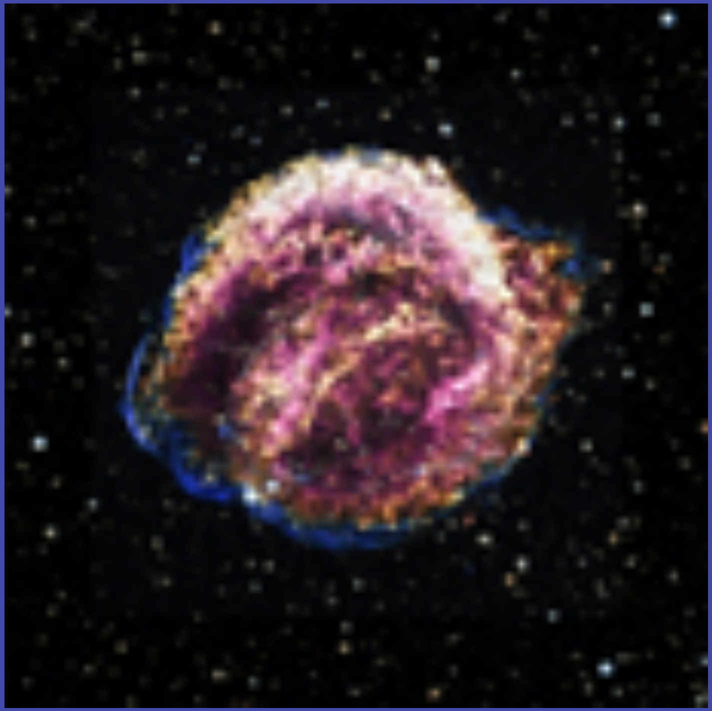
G1.9+0.3 SNR



G299-2.9 SNR

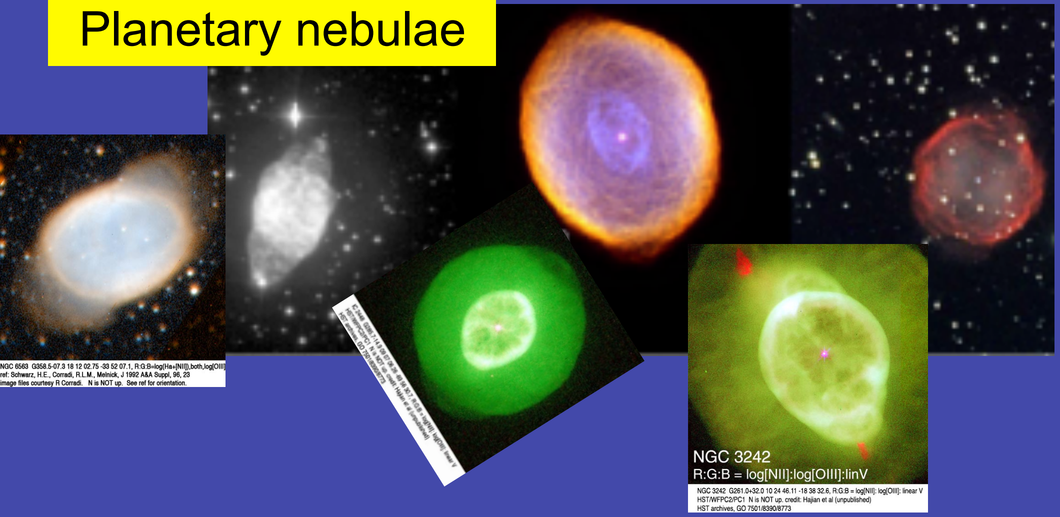
JETS !?

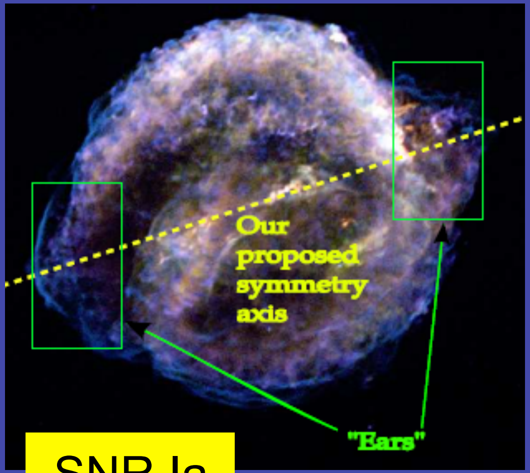




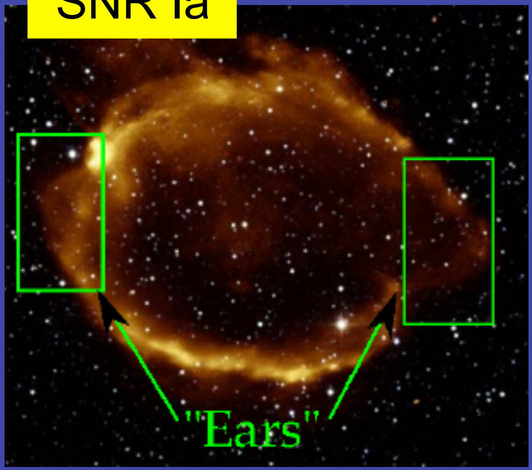
Simulations of jets by Danny Tsebrenko

Planetary nebulae





SNR Ia

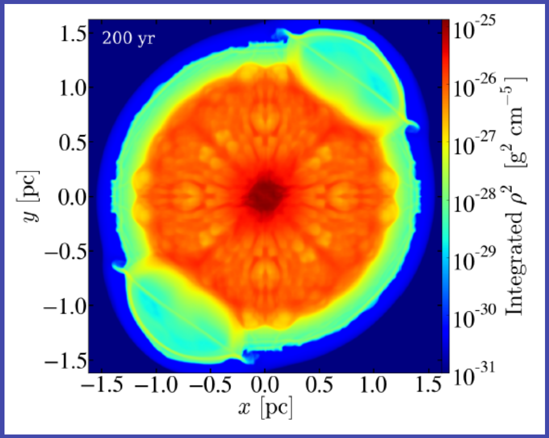


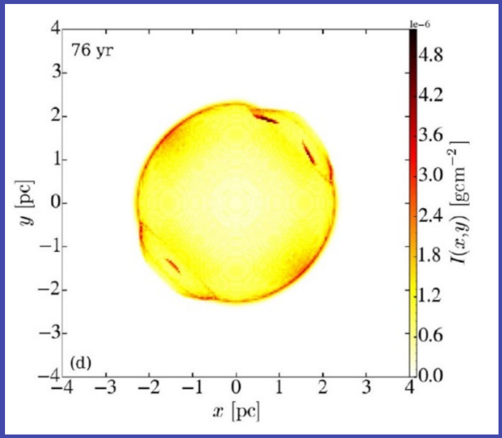
<u>Jets</u> might be common in pre - SN Ia,

(Tsebrenko & Soker 2013, 2015)

SNIP:

Supernovae Inside Planetary nebulae

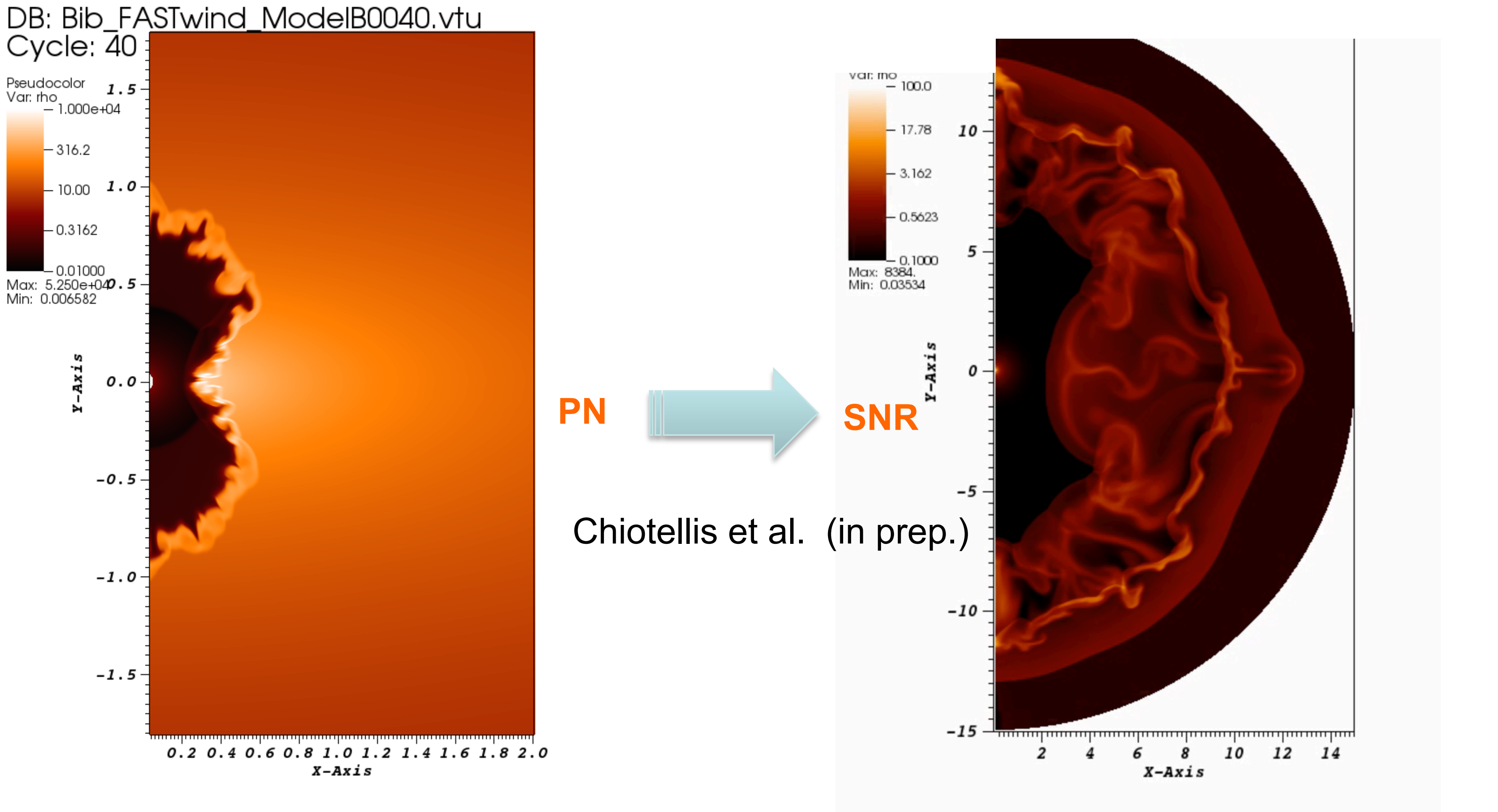




The existence of `Ears'

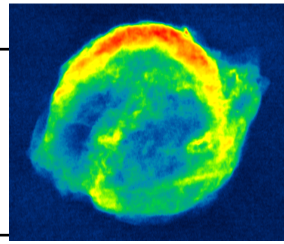
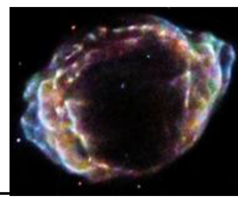
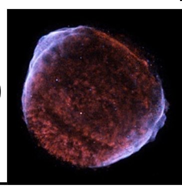
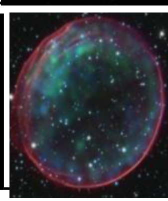
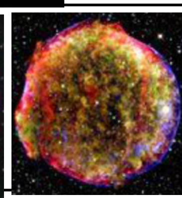
Two jets or not to be

Here is a slide from the talk (Friday) by **Alexandros Chiotellis.** Interaction of a SN Ia with a bipolar PN → 'lobes' (`Ears') in the equatorial plane. We find ears in the poles!! See also Burkey et al. 2013 who also take the equatorial plane to be where we take the symmetry axis (polar directions) in Kepler SNR.



Chiotellis et al. (in prep.)

SNR morphologies and circumstellar-matter (CSM) can be used to examine scenarios of SN Ia (Wolfgang Kerzendorf talk)

Supernovae	Property
PTF11kx Core Degenerate Scenario fits the best	$M_{\rm CSM} \approx 0.8 \left(\frac{\text{CSM size}}{1000\text{AU}} \right)^{3/2} M_{\rm e}$ Soker, N., et al. (2013, MNRAS, 431, 1541)
Kepler SNR 	No giant left ! (Wolfgang Kerzendorf) A SNIP shaped by jets * (Tsebrenko & Soker 2013, MNRAS, 435, 320)
G1.9+0.3 (X-ray) 	A SNIP shaped by jets * (SNIP: Supernova inside Planetary nebula) • In 2015: or by iron bullets (Tsebrenko & Soker 2015)
SN 1006 SNR 0509 SN 1572   	Elliptical remnants
SN 2011fe CD Scenario fits the best Soker, N., Garcia-Berro, E., Althaus, L.G. (2014, MNRAS 437, L66)	• $R_{\rm WD} < 0.02 R_{\rm e}$ • 98% carbon in fastest ejecta • No close CSM • Strong limits on a companion

There are 5 (or even 6) scenarios for SN Ia

When one examines the observations, no scenario is free of problems.

The single-degenerate and the double degenerate scenarios are the oldest.

I think the core-degenerate scenario does the best.

See: Tsebrenko, D. & Soker, N. 2015, MNRAS, 447, 2568

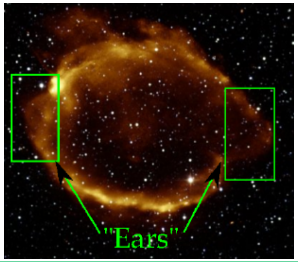
SN Ia scenarios in the literature by alphabetical order (Tsebrenko & Soker 2015)

	Core Degenerate	Double Degenerate	Double Detonation	Single Degenerate	WD-WD collision
Presence of two opposite Ears in some SNR Ia.					
≈ 1M☉ CSM in Keplers SNR + Na lines					
Main Scenario Predictions					
General Strong Characteristics					
General Diffficulties					
Severe Difficulties					
Fraction of SN Ia (TS2015)					
My suggestion					

SN Ia scenarios in the literature by alphabetical order (Tsebrenko & Soker 2015 [TS15])

	Core Degenerate	Double Degenerate	Double Detonation	Single Degenerate	WD-WD collision
Presence of two opposite Ears in some SNR Ia.	Explained by SNIP (Supernovae inside planetary nebulae [PN]) (TS2015).	Low mass Ears if jets during merger (TS2013).	No Ears are expected for He WD companion.	Ears by jets from accreting WD or iron bullets (Tsebrenko & Soker, 15)	No Ears are expected
≈ 1M⊙ CSM in Keplers SNR + Na lines	The massive CSM might be a planetary nebula.	No CSM shell	Any CSM is of a much lower mass	Might be explained by heavy mass loss from an AGB donor.	No CSM shell
Main Scenario Predictions	1. Single WD Exp. 2. Massive CSM in some cases (SNIP)	1. Sufficient WD-WD close binaries 2. DTD ∝ 1/t	1. Asymmetrical explosion 2. $M_{WD} < 1.2 M_\odot$	1. Companion survives 2. $M_{WD} \simeq M_{Ch}$	Asymmetrical explosion
General Strong Characteristics	1. Explains some SN Ia with H-CSM 2. Symmetric Exp.	Explains very well the delay time distribution (DTD)	Ignition achieved	1. Accreting massive WDs exist 2. Many explosions with $\sim M_{Ch}$	1. Ignition easily achieved 2. compact object
General Diffficulties	More work on 1. Ignition process 2. DTD 3. Merge during CE 4. Find massive WDs	1. Ignition process 2. Too much inflated gas around merger product 3. Asymmetrical explosion	Ejected He in some sub-scenarios	1. Cannot account for DTD 2. CSM of PTF 11kx too massive	Cannot reproduce manganese
Severe Difficulties			1. $M_{WD} < 1.2 M_\odot$ 2. Highly asymmetrical Exp.	1. Too few systems 2. No companions 3. No H observed	1. < 1% of SN Ia 2.Highly asymmetrical Exp.
Fraction of SN Ia (TS2015)	> 20%	< 80%	< few × % (Piersanti et al. 2013)	0% (might explain faint and peculiar SN Ia)	< 1% (Soker et al. 2014)
My suggestion	"normal SN Ia" > 85%	Weak SN Ia < 15%	Peculiar transients, **not SN Ia**	Some **Really Strong Novae** (WD survives).	Rare events—if at all

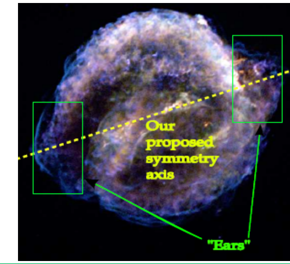
Summary

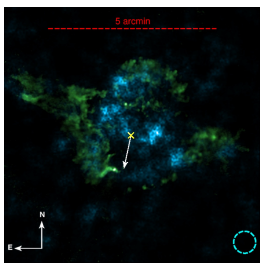


Jets shape some supernova remnants.

Prominent is the existence of `Ears':

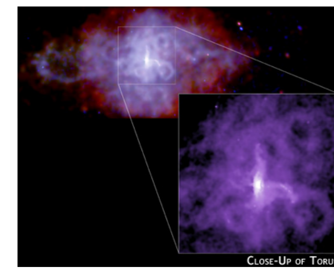
Two jets or not to be

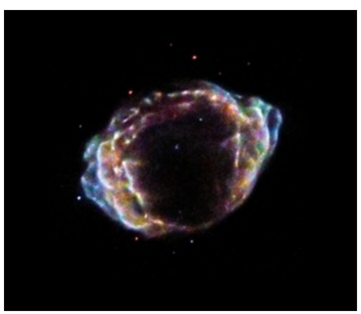




This might support the jet-feedback mechanism for exploding massive stars.

Two jets or not to B





This might support the explosion of some SN Ia inside a Planetary Nebula

SNIP

SNIP is compatible with the Core-Degenerate (CD) Scenario for SN Ia