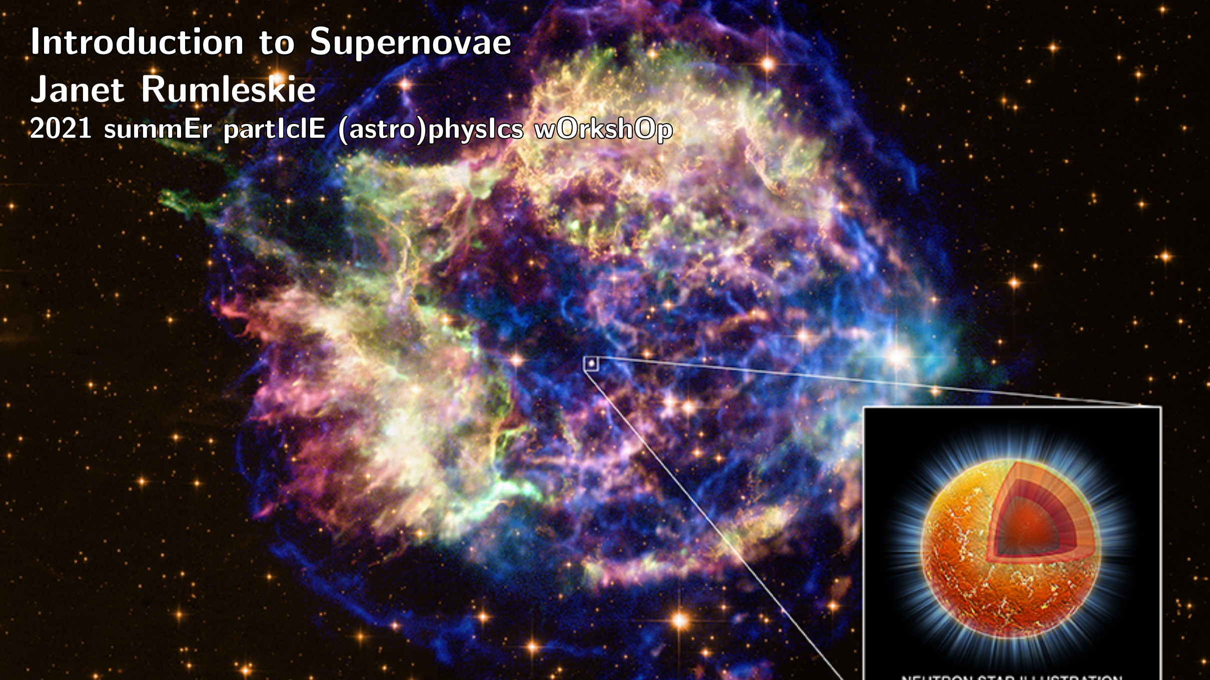
Introduction to Supernovae

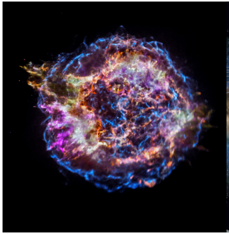
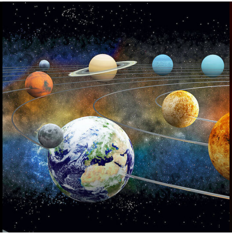
Janet Rumleskie

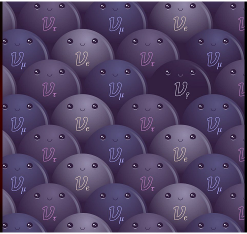
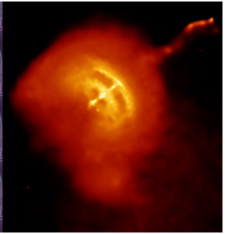
2021 summEr partIclE (astro)physIcs wOrkshOp



Why should we care about exploding stars (supernovae)?

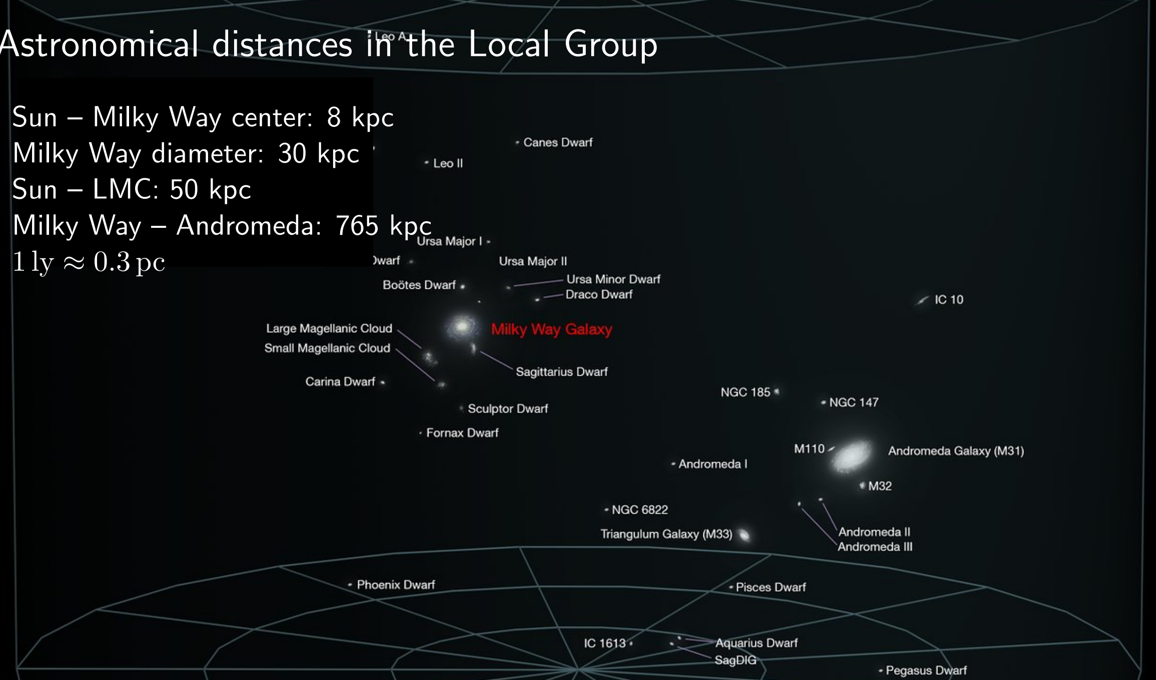
- Where do we come from? Solar system + heavy elements created by a supernova (SN)
- Open questions:
  - How does the SN explode? For what kinds of stars? Which ones make neutron stars? Black holes? ...and many more
  - Do sterile neutrinos exist? What is the neutrino's magnetic moment? What neutrino oscillations are possible? ...and many more
- Neutrinos (ν) can answer many of these questions! Can also be used as alerts for other detectors searching for supernovae

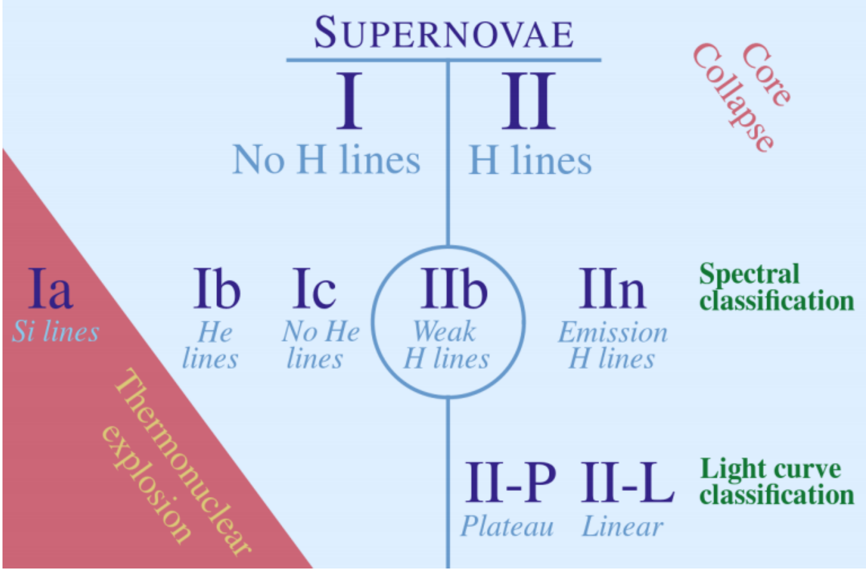



Astronomical distances in the Local Group

Sun – Milky Way center: 8 kpc
Milky Way diameter: 30 kpc
Sun – LMC: 50 kpc
Milky Way – Andromeda: 765 kpc
$1\,\mathrm{ly} \approx 0.3\,\mathrm{pc}$



Supernova Classification



10 SN/1 s in visible Universe

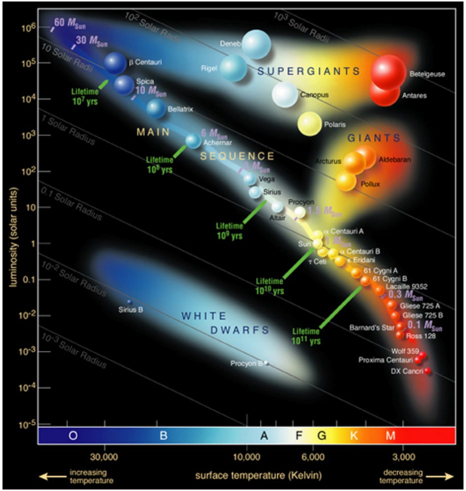
1–3 /100 yr in Milky Way

Outshine host galaxy

ν signature from CC and thermonuclear SN are different!

Crash course in stellar evolution

- Dust in the interstellar medium clumps under gravity
- Eventually forms a proto-star, commences hydrogen burning
- Becomes a Zero Age Main Sequence (ZAMS) star once hydrogen fusion supports it against gravity
- Once hydrogen burning in the core stops, things get interesting
- Stars with mass $M_{\mathrm{ZAMS}} < 8\,\mathrm{M}_{\odot}$ eventually swell to become a giant, shed outer layers, then become white dwarves. White dwarves are the source of Type Ia SN!
- Stars with mass $M_{\mathrm{ZAMS}} \geq 8\,\mathrm{M}_{\odot}$ swell to supergiants, eventually undergo a core collapse SN!
- Some uncertainty for stars $M_{\mathrm{ZAMS}} \geq 60\,\mathrm{M}_{\odot}$



Nuclear fusion inside a star

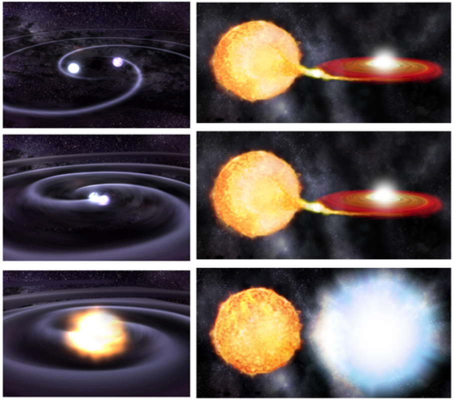
C. Giunti and C. W. Kim Fundamentals of Neutrino Physics and Astrophysics

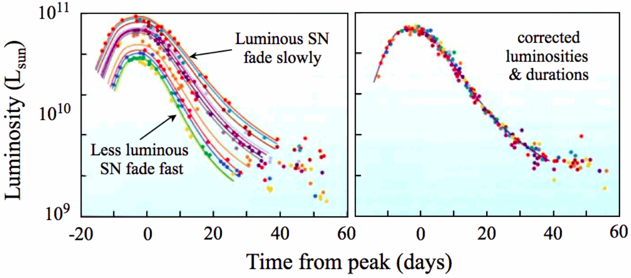
Reaction	T_c [K]	ρ_c [g cm^{-3}]	Δt [yr]	Termination point
$H \to {}^4He$	3.53×10^7	5.81	1.11×10^7	
${}^4He \to {}^{12}C,\ {}^{16}O$	1.78×10^8	1.39×10^3	1.97×10^6	$M_{\mathrm{ZAMS}} < 8\,\mathrm{M}_\odot$
${}^{12}C \to {}^{16}O,\ {}^{20}Ne, {}^{24}Mg$	8.34×10^8	2.39×10^5	2.03×10^3	$M_{\mathrm{ZAMS}} < 10\,\mathrm{M}_\odot$
${}^{20}Ne \to {}^{16}O,\ {}^{24}Mg$	1.63×10^9	7.24×10^6	0.732	
${}^{16}O \to {}^{28}Si,\ {}^{32}S$	1.94×10^9	6.66×10^6	2.58	
${}^{28}Si \to Fe$	3.34×10^9	4.26×10^7	5.01×10^{-2}	

Overview of core burning stages for a massive, $M_{\mathrm{ZAMS}} = 15\,\mathrm{M}_\odot$ star. The last reaction of other stars is also indicated.

Type Ia supernova

- White dwarf accumulates too much matter, undergoes a thermonuclear explosion
- Star is completely unbound, no compact remnant (e.g. neutron star) left behind
- Very similar light curves, important "standard candles" for measurements of the universe
- ν signal: over in 1 – 3 seconds, is 4-5 orders of magnitude less luminous than a CCSN!





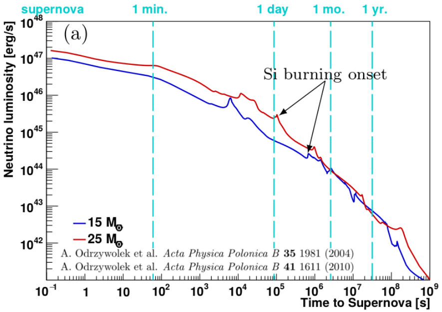
Pair instability supernova?

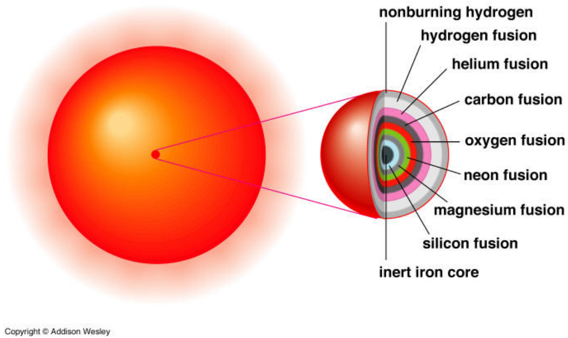
$\gamma \leftrightarrow e^+ + e^- \rightarrow \nu_e + \bar{\nu}_e$ processes is highly temperature dependent
Once carbon burning reached, unbinds stars that are too massive
Possible for stars $140\ \mathrm{M}_\odot \lesssim M_{\mathrm{ZAMS}} \lesssim 260\ \mathrm{M}_\odot$
Thermonuclear explosion, star completely unbinds
ν emission:

- Duration $\sim$30 seconds, spectrum does not change rapidly
- $\sim$2 orders of magnitude more than type Ia from white dwarf accretion
- $\sim$3 orders of magnitude lower than CCSN

Late-stage evolution of massive stars ($8\ M_\odot \lesssim M_{\rm ZAMS} \lesssim 40\ M_\odot$)

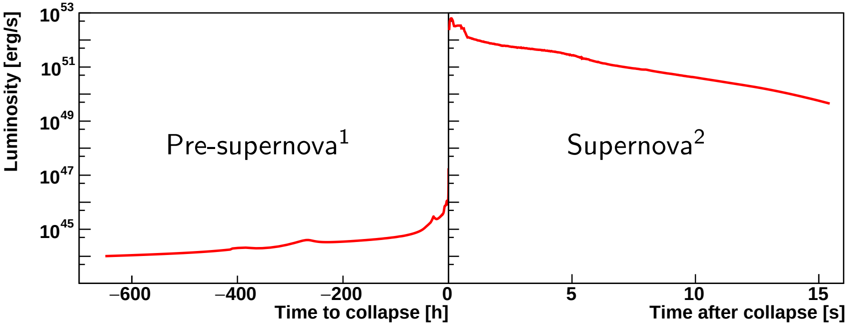
- Star develops an onion-like structure. Ends up with an Fe core (or ONeMg)
- After central carbon burning begins, the star emits more energy as neutrinos than as light
- Emission of neutrinos is temperature dependent and increases as the star ages
- Neutrinos in the last ∼days before SN can be detected if close enough!





$1\ \text{foe} = 10^{44}\ \text{J} = 10^{51}\ \text{erg}$

Core collapse supernovae



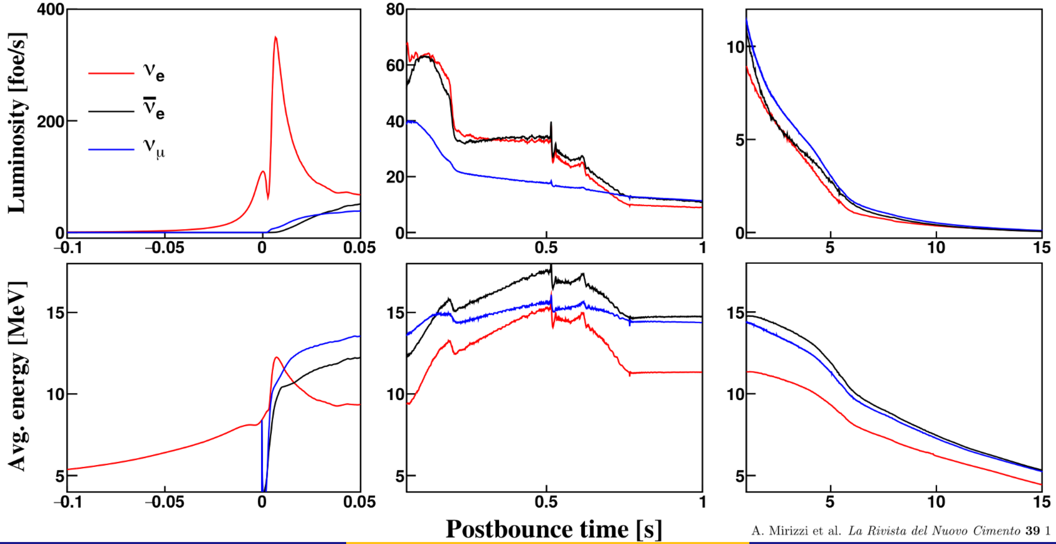
Neutrino luminosity before and during a core-collapse supernova.
Note the axes!

[1] $25\mathrm{M}_\odot$ model from A. Odrzywolek et al. *Acta Physica Polonica B* **35** 1981 (2004), A. Odrzywolek et al. *Acta Physica Polonica B* **41** 1611 (2010)

[2] LS220-s27.0co model from A. Mirizzi et al. *La Rivista del Nuovo Cimento* **39** 1 (2016)

Core collapse supernova timeline

Onset ν_e Burst Accretion Shock Revival, Explosion Cooling



A. Mirizzi et al. *La Rivista del Nuovo Cimento* **39** 1 (2016)

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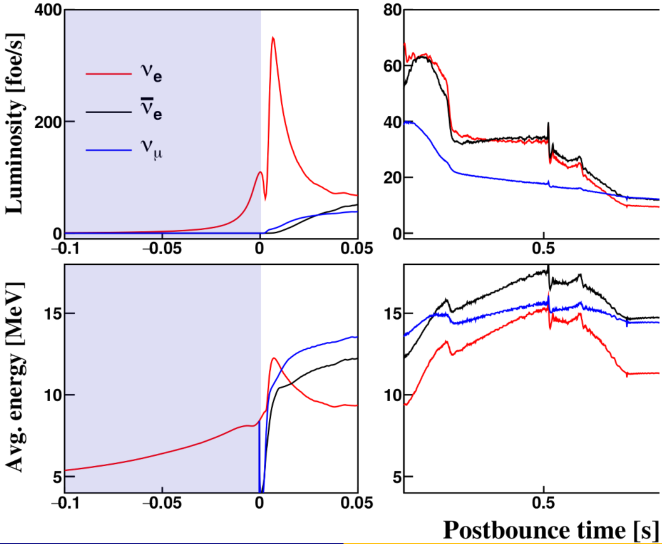

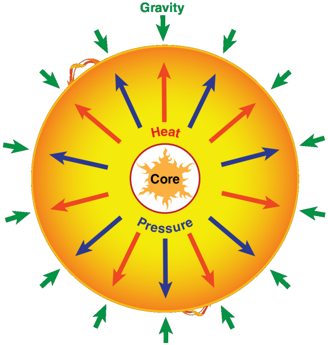

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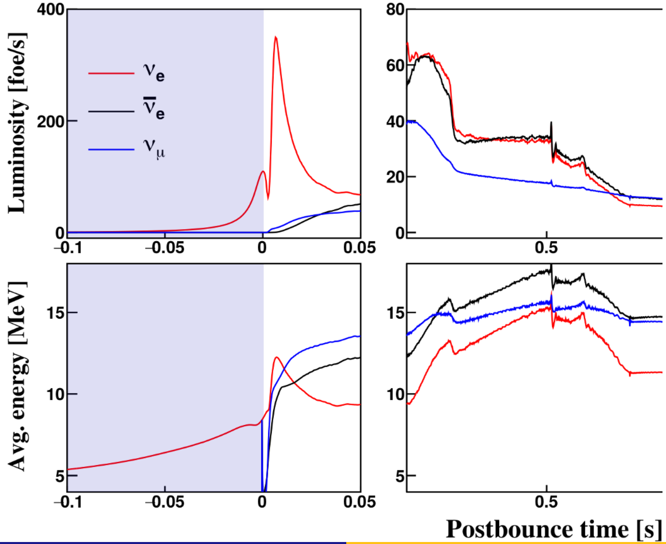
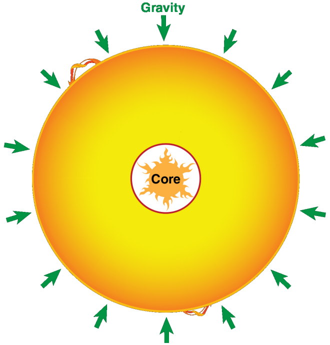


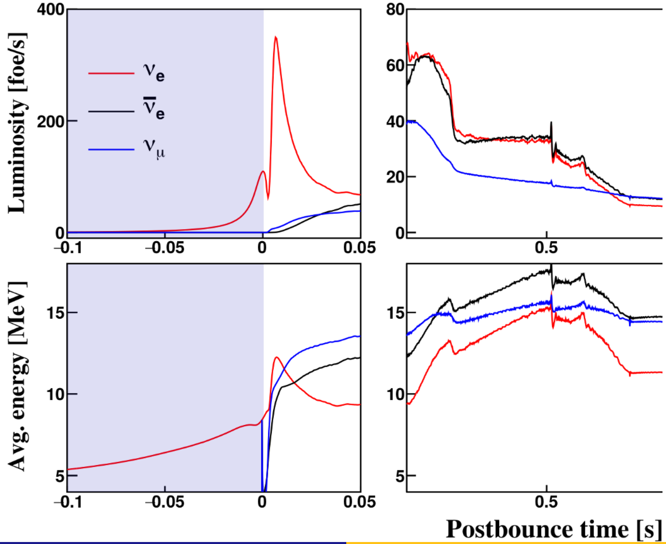
Core begins to collapse under gravity



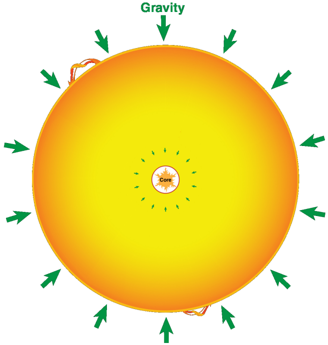
A. Mirizzi et al. *La Rivista del Nuovo Cimento* **39** 1 (2016)

Core collapse supernova timeline

Onset | ν_e Burst | Accretion | Shock Revival, Explosion | Cooling



$$\gamma + {}^{56}\mathrm{Fe} \to 13\alpha + 4n$$
$$e + p \to n + \nu_e$$



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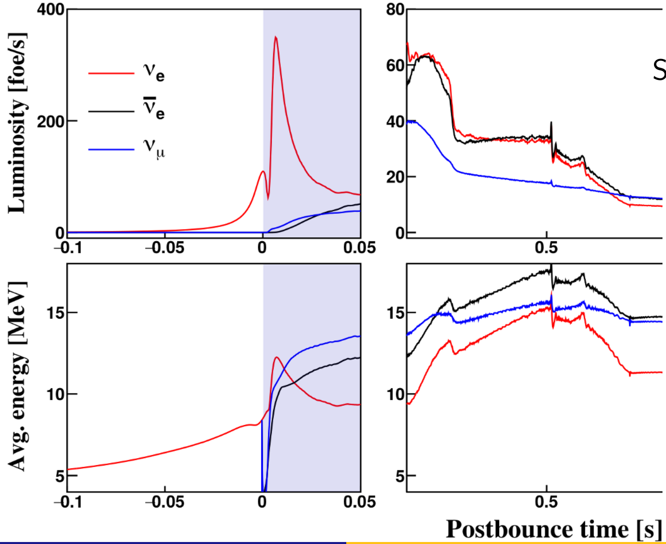
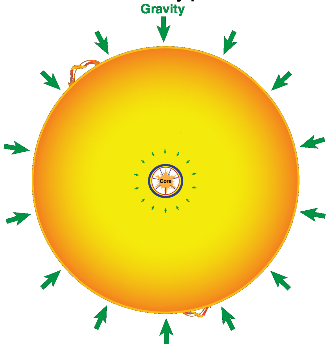
Core collapse supernova timeline

Onset ν_e Burst Accretion Shock Revival, Explosion Cooling



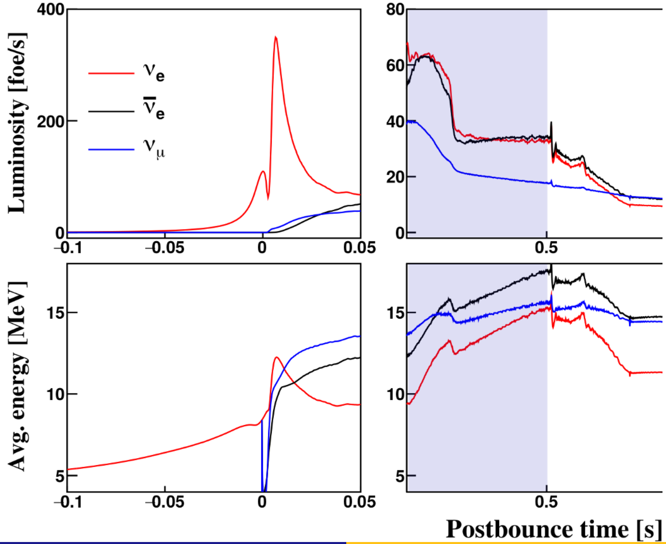
Strong force kicks in, core rebounds
Shock wave forms, propagates outward
Neutrinos of all types now made



A. Mirizzi et al. *La Rivista del Nuovo Cimento* **39** 1 (2016)

Core collapse supernova timeline

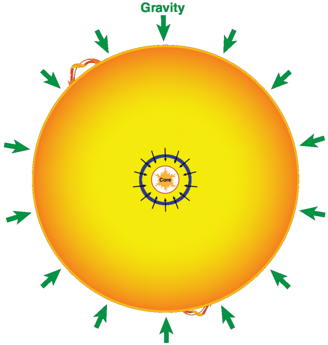
Onset ν_e Burst **Accretion** Shock Revival, Explosion Cooling



Shock is stalled by energy release

Matter continues to accrete on PNS

BH could form and SN fails!



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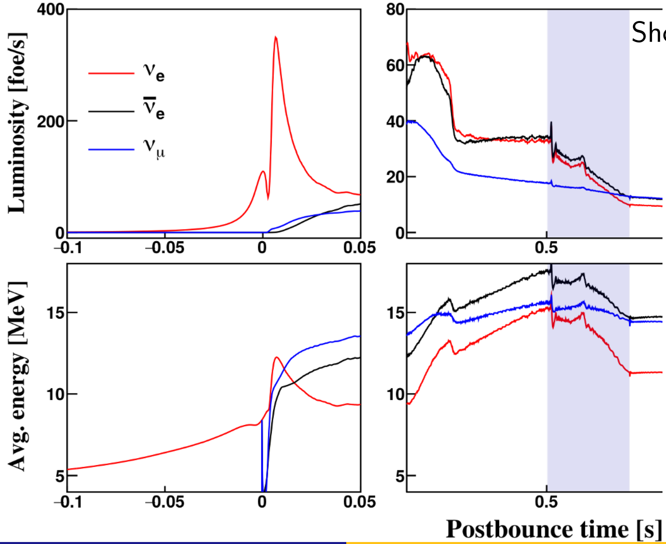
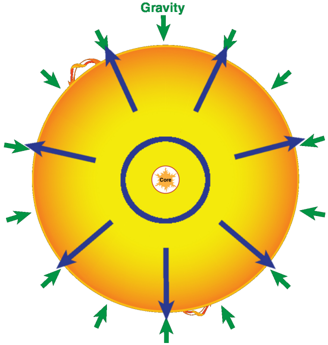
Core collapse supernova timeline

Onset ν_e Burst Accretion **Shock Revival, Explosion** Cooling



Shock is revived: ν heating + convection?

Simulations have difficulty reviving it

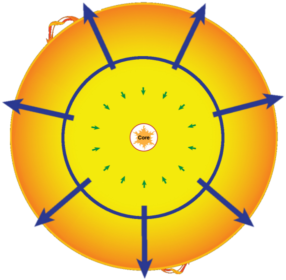


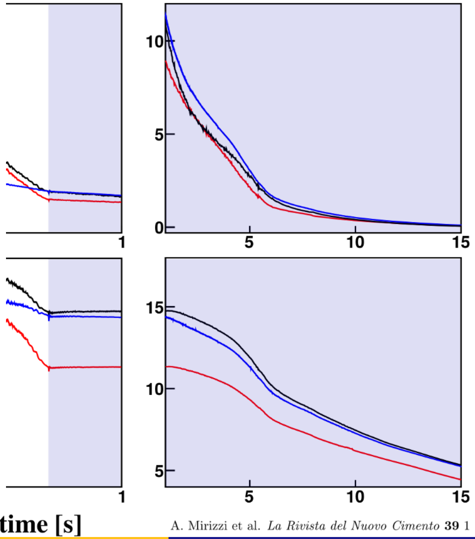
A. Mirizzi et al. *La Rivista del Nuovo Cimento* **39** 1 (2016)

Core collapse supernova timeline

Onset ν_e Burst Accretion Shock Revival, Explosion **Cooling**

Shock sweeps through outer layers of star
BH can still form but SN happens
PNS cools, becomes neutron star





A. Mirizzi et al. *La Rivista del Nuovo Cimento* **39** 1 (2016)

Crab Nebula

SN 1054

SNR spans 10 ly

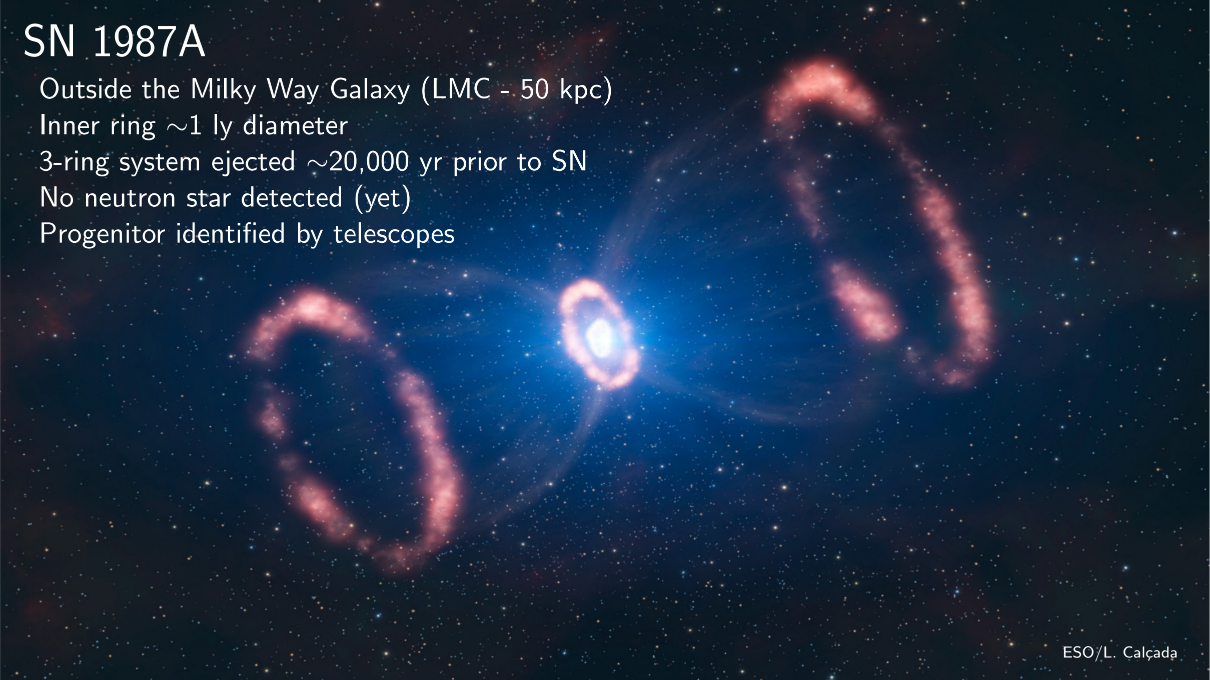
Neutron star:

- radius $\sim$ 10 km
- mass $\sim$ 1.4 $M_\odot$

NASA, ESA, NRAO/AUI/NSF and G. Dubner (University of Buenos Aires)

SN 1987A

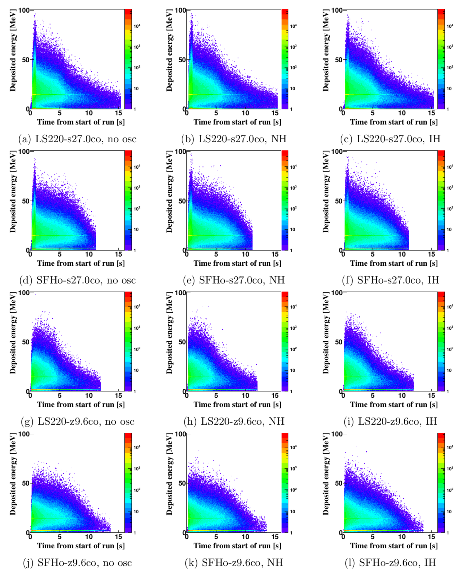
- Outside the Milky Way Galaxy (LMC - 50 kpc)
- Inner ring ∼1 ly diameter
- 3-ring system ejected ∼20,000 yr prior to SN
- No neutron star detected (yet)
- Progenitor identified by telescopes



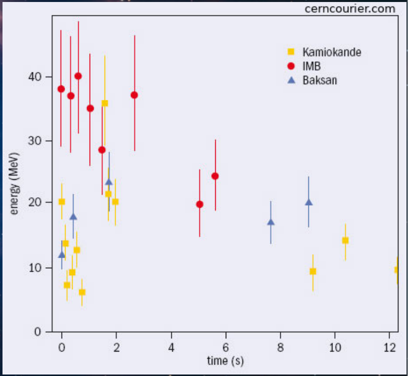
ESO/L. Calçada

SN 1987A

- Outs… kpc)
- Inner
- 3-rin… SN
- No n
- Prog

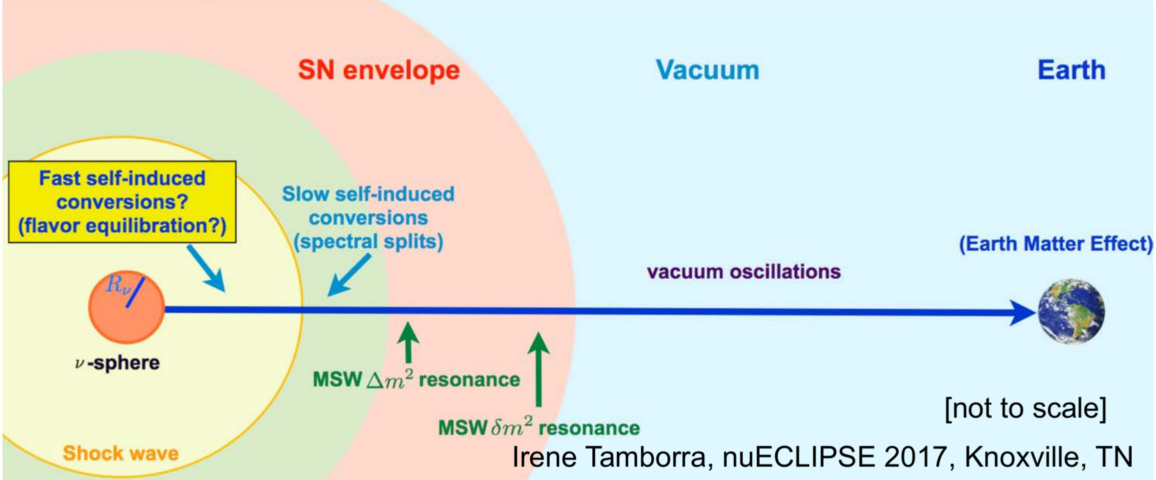


$\stackrel{?}{=}$



ESO/L. Calçada

Neutrino oscillations



Photons vs Neutrinos

Energy budget of a CCSN:

$$\Delta V = \left(\frac{3}{5}\frac{GM^2}{R}\right)_{\text{PNS}} - \left(\frac{3}{5}\frac{GM^2}{R}\right)_{\text{Fe core}} \approx 3 \times 10^{53}\ \text{erg} = 3 \times 10^{46}\ \text{J}$$

Only ∼1 % of this goes to light and kinetic energy. Most to neutrinos ($10^{58}\,\nu$'s)!

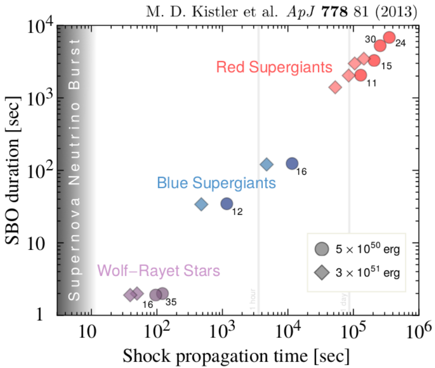
Mean free path l (average distance travelled before interacting):

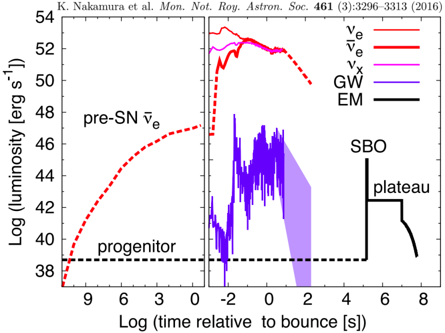
$$l = \frac{1}{\sigma n}$$

Mean free path of photon: 1 mm in the sun
Mean free path of neutrino: 20 light years through lead
Supernova neutrinos probe the core of a supernova!
Observations of photons are still important (progenitor information, distance, nucleosynthesis, SN classification, etc.)

Multi-messenger signals of a CCSN

Nothing is visible to astronomers until the shock reaches the edges of the star (shock breakout)

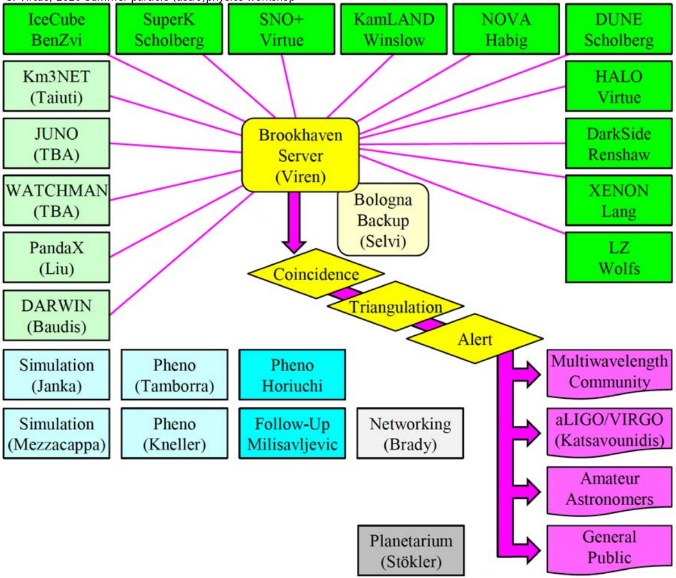




Neutrinos can be used as an advanced alert!

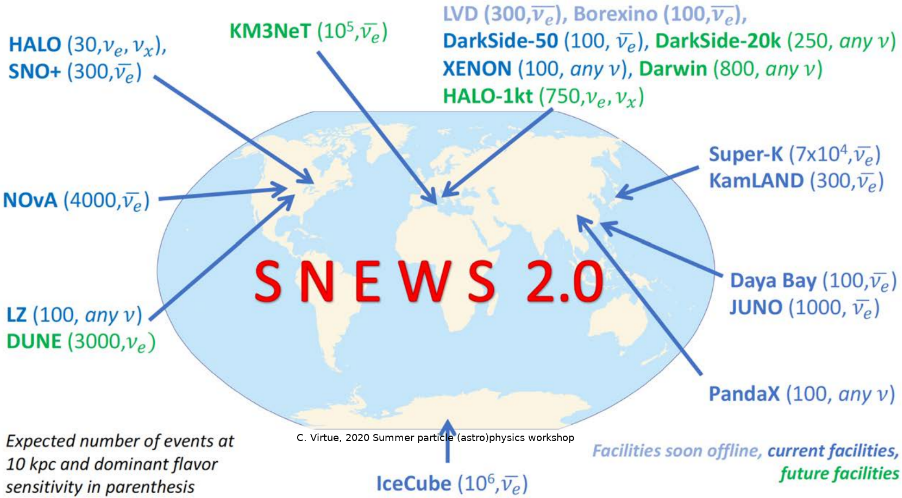
The SuperNova Early Warning System

C. Virtue, 2020 Summer particle (astro)physics workshop



- Takes in alerts from neutrino detectors
- Distribute alert to multi-messenger community
- SNEWS 2.0 updates (soon):
  - Directional information
  - pre-supernova alert
- Amateur astronomers play an important role!

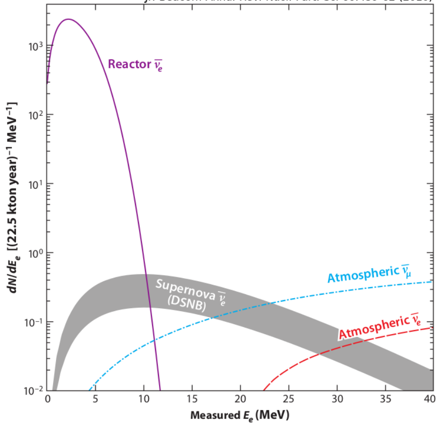
SNEWS 2 Contributing Experiments



The Diffuse Supernova Neutrino Background

- Most detectors are waiting for the next SN: no indication of when this will happen
- So many SN have occurred that the universe should be "full" of ν from SNe
- Measurement of the neutrino background (DSNB) could shed light on:
  - Average SN ν spectrum
  - Total SN rate
  - etc.
- Next-generation experiments may be sensitive enough to detect the DSNB

JF. Beacom Annu. Rev. Nucl. Part. Sci 60:439-62 (2010)



Concluding Remarks

- Core-collapse SN (CCSN) occur for stars $8\ \mathrm{M}_\odot \lesssim M_{\mathrm{ZAMS}} \lesssim 40\ \mathrm{M}_\odot$
- CCSN emit 10^{58} ν's, the most out of all SN
- Pre-SN ν also detectable if nearby
- ν escape a SN before light
- SNEWS: multi-messenger alert using ν
- Many things we don't know about SN, could be uncovered with the next galactic SN
- Next up: A dedicated supernova neutrino detector, HALO