The day before Betelgeuse dies: identifying a near-earth pre-supernova star from its neutrinos

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Credits: A plume of gas nearly the size of our solar system erupts from Betelgeuse’s surface in this artist's illustration of real observations gathered by astronomers using the Very Large Telescope in Chile. European Southern Observatory, L. Calçada
Based on:


Work supported by: National Science Foundation (NSF)

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Si Burning

early warning, SN direction, progenitor physics

Mantle Contraction Cooling

equation of state, energy loss rates, PNS radius, diffusion time, BSM physics

Core Cooling

v-Sphere Recession

NS vs. BH formation, transparency time, integrated losses, BSM physics

Accretion

flavor mixing, neutronization, SN distance, multi-D effects

Fallback

Credits: Frank Timmes

Following Li, Roberts & Beacom, 2020
Si Burning
early warning, SN direction, progenitor physics

Pre-SN

Main Signal

Late Time

Accretion

Mantle Contraction Cooling

Core Cooling

equation of state, energy loss rates, PNS radius, diffusion time, BSM physics

Spherical Expansion

NS vs. BH formation, transparency time, integrated losses, BSM physics

Si Burning
early warning, SN direction, progenitor physics

SN Neutrinos
(Already well-known)

Luminosity $\bar{\nu}_e$ (erg s$^{-1}$)

$10^{53}$

$10^{52}$

$10^{51}$

$10^{50}$

$10^{49}$

$10^{48}$

$10^{47}$

$10^{-2}$

0

Time (s)

post-bounce

$10^{-1}$

$10^{0}$

$10^{1}$

$10^{2}$

$10^{3}$

Credits: Frank Timmes

Following Li, Roberts & Beacom, 2020

Months, weeks, days, hours…before collapse

SN Neutrinos (Already well-known)
Presupernova Neutrinos

- What?

Neutrinos of energy $0.1 - 5$ MeV

Low energy neutrinos

Presupernova Neutrinos

- When?

Last stages of nuclear burning of a massive star

Presupernova Neutrinos

- How?
  I) Thermal processes
    - Pair production
  II) Weak reactions
    Beta processes mainly $e^-/e^+$ captures and nuclear decays

Is this talk about the details of presupernova neutrinos?

No.... → Where to look?

Patton et.al. (2017 a,b) and References
References:


B) Kutschera, Odrzywolek, Misiaszek, 2009, Acta Physics Polonica B, 40, 3063


F) Guo, Qian, Heger 2019, Phys. Lett., B796, 126
Is this talk about the details of presupernova neutrinos?

No... → Where to look?

Patton et al. (2017 a,b) and References → Then what?

Try to use this signature to locate the progenitor in the sky and serve as an early warning system (this talk....)

Also see: Li, Li, Wen and Zhou 2020, arXiv 2003.03982
Motivations

Early alert of collapse:

Observe a star before and during collapse to test stellar evolution.

$\sim 100$ IBD events for nearby (0.2 kpc) star like Betelgeuse in a detector like JUNO
Motivations

Early alert of collapse:

Observe a star before and during collapse to test stellar evolution.

Aligns with SN neutrino burst warning which is already considered an early warning.
Motivations

Very early alert of SN explosion (or BH formation):

1. Precedes the neutrino burst by hours (or even days): useful for decision making

2. Can be the only useful alert for fast-exploding stars (< 1 hours from collapse to explosion)
Motivations

Prepare GW detectors: multi-messenger observations

Plenary talk by Prof. Barry Barish
Motivations

Prepare GW detectors: multi-messenger observations

Prepare to observe exotic physics during collapse: point axion detectors

Detectors

- Fiducial detector mass: 17 kt
- Efficiency: 1
- Liquid Scintillator: LAB (Linear Alkylbenzene)

JUNO (Jiangmen Underground Neutrino Observatory)
Detectors

Hypothetical setup with Li dissolved in liquid scintillator for enhanced angular sensitivity

Tanaka & Watanabe 2014, Scientific Reports, 4, 4708
Inverse Beta Decay (IBD)

\[ \bar{\nu}_e + p \rightarrow n + e^+ \]

Why?

- Low energy threshold (1.8 MeV)
- Timing
- Energy resolution
- Background discrimination performance
Inverse Beta Decay (IBD)
Some details....

\( N_s \) : No. of IBD signal events in detector

\( N_{Bkg} \) : Background events (Assumption: Isotropic background)

\[ \alpha = \frac{N_s}{N_{Bkg}} \] : Signal to Background ratio
Asymmetry Factor

\[ a_0 = \frac{N_F - N_B}{N_F + N_B} \]

**Backward** 
\[ (\theta > \frac{\pi}{2}) \]
\[ N_{B,S} = \frac{N_S}{2} \left( 1 - \frac{a_0}{2} \right) \]
\[ N_{B,Bkg} = \frac{N_{Bkg}}{2} \]

**Forward** 
\[ (\theta < \frac{\pi}{2}) \]
\[ N_{F,S} = \frac{N_S}{2} \left( 1 + \frac{a_0}{2} \right) \]
\[ N_{F,Bkg} = \frac{N_{Bkg}}{2} \]

\[ a = \frac{(N_{F,S} + N_{F,Bkg}) - (N_{B,S} + N_{B,Bkg})}{2} = \frac{(N_{F,S} + N_{F,Bkg}) + (N_{B,S} + N_{B,Bkg})}{2} \]
Background

Recall...

Main background sources:

- Reactor $\nu$
- Geo $\nu$

\[ 15M_\odot, \bar{\nu}_e, \text{NH, 1kpc} \]
Background

Main background sources:
- Reactor $\nu$
- Geo $\nu$

Assumption: Isotropic

2.6 events/hour in reactor-on phase for JUNO

Yoshida, Takahashi, Umeda, Ishidoshiro 2016, Phys. Rev. D, 93, 123012
Normalized Distribution of $\cos \theta$

\[ f_{LS}(\cos \theta) = 0.2718 + 0.2238 \exp(0.345 \cos \theta) \]

\[ f_{LS-Li}(\cos \theta) = 0.1230 + 0.3041 \exp(1.16 \cos \theta) \]

\[ \alpha = \frac{N_S}{N_{Bkg}} \]

Tanaka & Watanabe 2014, Scientific Reports, 4, 4708

For geo-neutrinos (similar spectrum as pre-SN neutrinos)
Normalized Distribution of $\cos \theta$

$$f(\cos \theta) = \frac{1}{2} \left(1 + a_0 \cos \theta \right)$$

Asymmetry Factor

$$\frac{a_0}{2} = \frac{N_F - N_B}{N_F + N_B}$$
Event Rates

Patton et al. 2017b
Pointing to the progenitor

“We are here

Events

\[ N_{\text{Events}} \]
Pointing to the progenitor

\[ \vec{p} = \frac{1}{N} \sum_{i=1}^{N} \hat{X}^{(i)}_{pn} \]

Events

\[ N_D = 0.2 \text{ kpc} \]

15 M⊙
30 M⊙
30 M⊙

Apollonio, Baldini, Bemporad et. al. 2000, Phys. Rev. D, 61, 012001
Fischer, Chirac, Lasserre et. al. 2015, JCAP, 032
Apollonio, Baldini, Bemporad et al. 2000, Phys. Rev. D, 61, 012001
\[ \beta \text{ as a function of } N \]

**Standard LS**
- Localizes to \( \approx 70^\circ \)
- After 100 events
- \( 68\% \text{ C.L.} \)

**Enhanced LS-Li**
- Localizes to \( \approx 15^\circ \)
- After 100 events
Standard LS localizes to $\approx 70^\circ$ after 100 events

Enhanced LS-Li localizes to $\approx 15^\circ$ after 100 events

68% C.L.
Candidates: Mollweide Projection

Betelgeuse

D ≤ 0.25 kpc
0.25 < D ≤ 0.6 kpc
0.6 < D ≤ 1.0 kpc
Candidates: Mollweide Projection

Why 1 kpc?

\[ \nu \text{ Flux} \sim \frac{1}{r^2} \]

No considerable flux for large distances

\[ \sim 31 \text{ stars in } D < 1 \text{ kpc} \]
Telescopes....
What if it is Betelgeuse?

Distance : $D = 0.222 \, \text{kpc}$

Mass : $M \approx 15 \, M_{\text{Solar}}$
What if we are unlucky: a far away star?

σ Canis Majoris

Distance : $D = 0.513 \ kpc$

Mass : $M \approx 15 \ M_{\text{Solar}}$
We only have considerable signal 2 hours before the collapse....Huge uncertainty even with LS-Li (Only 68% C.L.)
Future prospects

Repeating the analysis for a 100 kt detector like THEIA....

Things to keep in mind:

- ES + IBD events

The sheer size of it can help with the number of events observed in each channel

Low energy threshold

Good directional sensitivity

Picture courtesy: THEIA: an advanced optical neutrino detector - Askins et. al.
Future prospects

Repeating the analysis for a 100 kt detector like THEIA...

Most optimistic
\[ \sim 4^\circ - 6^\circ \text{ error cone} \]

Should significantly help with directional pointing!

Picture courtesy: THEIA: an advanced optical neutrino detector - Askins et. al.
Summary

→ Pre-SN neutrinos: emitted months, days, hours prior to collapse and are detectable. Even earlier than the known SN neutrino burst

→ Directional sensitivity: Can help with locating the progenitor about to collapse

→ Serves as an early warning system and multi-messenger observations. Useful for GW, neutrino and astronomy community. Can help in testing exotic particle physics — axions....

→ Error cones: \( \sim 70^\circ \) for standard LS detectors, shortlists \( \sim 10 - 12 \) candidates and \( \sim 20^\circ \) for enhanced LS detectors, shortlists \( \sim 4 - 5 \) candidates
Just a Fainting Spell? Or Is Betelgeuse About to Blow?

A familiar star in the constellation Orion has dimmed noticeably since October. Astronomers wonder if its explosive finale is imminent.

Hopefully, we will be able to know at least a few hours (may be even days) in advance through our very early messengers: presupernova neutrinos!

Thank You....
Backup Slides
Core exceeds Chandrasekhar limit, 1.44 M_{\odot}, Core Collapses.

Protons combine electrons and form neutrons. Core shrinks.

Neutrons bounce back infalling matter, due to The Strong Nuclear Force.

Shockwave slows down.

Shockwave accelerated by massive neutrino flow. Star is torn apart. 10^{51} J of energy released. Explosion brighter than entire galaxy. The remnant is a neutron star or a black hole, initially 100 billion degrees K hot.

SN Neutrinos

The figure illustrates the process of supernova (SN) explosions:

1. **Core exceeds Chandrasekhar limit**: 1.44 M$_\odot$;
2. **Core Collapses**;
3. **Protons combine electrons and form neutrons. Core shrinks**;
4. **Neutrons bounce back infalling matter, due to The Strong Nuclear Force**;
5. **Shockwave slows down**;
6. **Shockwave accelerated by massive neutrino flux. Star is torn apart. $10^{45}$ J of energy released. Explosion brighter than entire galaxy. The remnant is a neutron star or a black hole. Initially 100 billion degrees K hot**.

Additionally, the diagram highlights elements like Fe, Si, O, Ne, C, He, and H, indicating the layers and elements involved in the supernova process.
$\beta$ as a function of 'a'
β as a function of 'a'

Motivations on why should we build better neutrino detectors!

\( \beta \) as a function of 'a'

- Improvement!
- LS
- LS-Li
- α = 3
- α = ∞
- 68% C.L.
- 90% C.L.
- 70°
- 18°
- N = 200
Angular Uncertainty $(\beta)$
Angular Uncertainty ($\beta$)

\[
\langle x \rangle = 0 \quad \langle y \rangle = 0 \quad \langle z \rangle = \frac{a}{3} \quad N \to \infty
\]

Mean of $\vec{p}$:

\[
\overrightarrow{p}_m = (0,0,|\vec{p}|) = (0,0,a/3)
\]

\[
\vec{p} = \frac{1}{N} \sum_{i=1}^{N} \hat{X}_{pn}^{(i)}
\]
Angular Uncertainty ($\beta$)

Mean of $\vec{p}$:

$$\vec{p}_m = (0, 0, |\vec{p}|) = (0, 0, a/3)$$

$$f(\cos \theta) = \frac{1}{2} \left( 1 + a \cos \theta \right)$$

Central Limit Theorem

Gaussian Distribution

$$\sigma = \frac{1}{\sqrt{3N}}$$
Angular Uncertainty $(\beta)$

\[ \vec{p} = \frac{1}{N} \sum_{i=1}^{N} \hat{X}_{pn}^{(i)} \]

Probability distribution of $\vec{p}$

\[ P(p_x, p_y, p_z) = \frac{1}{(2\pi\sigma^2)^{3/2}} \exp\left( -\frac{p_x^2 - p_y^2 - (p_z - |\vec{p}|)^2}{2\sigma^2} \right) \]
Angular Uncertainty $(\beta)$

\[ \int P(p_x, p_y, p_z) \, dp_x \, dp_y \, dp_z = I \]

\[ I = 0.68 \quad 68\% \, C.L. \]
\[ I = 0.90 \quad 90\% \, C.L. \]

Black Box (Transform to spherical coordinates....)

(Hush work in progress!)

Nice analytical expression!
What if it is Antares?

Distance: $D = 0.169 \, \text{kpc}$

Mass: $M \approx 15 \, M_{\odot}$
What if it is a huge star?

S Monocerotis A

Distance: \( D = 0.282 \text{ kpc} \)

Mass: \( M \approx 30 M_{\text{Solar}} \)

Huge!
Pointing greatly improves towards the end because of event (flux) distribution (only 68% C.L.)