Observing Supernova Neutrinos to Late Times

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Timescale of a SN

$10^{47}$ $10^{48}$ $10^{49}$ $10^{50}$ $10^{51}$ $10^{52}$ $10^{53}$

$L_{\bar{\nu}_e}$ [erg / s]

pre-SN

Main signal

$t_{\text{post-bounce}}$ [s]

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Timescale of a SN

Figure credit: R.J. Hall

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Timescale of a SN

$L_{\bar{\nu}_e}$ [erg / s]

$t_{\text{post-bounce}}$ [s]

pre-SN | Main signal | Late time

Figure credit: R.J. Hall
Timescale of a SN

Figure credit: R.J. Hall
First input -- simulation

Luke Roberts

Blondin et al., 2003
Late-time neutrinos are interesting & robust!

1/t behavior surprising
Connects SN and NS
Moderate mixing effect

Late-time neutrinos are interesting & robust!

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Late-time neutrinos

Neutrino luminosity and energy

- 1/t behavior surprising
- Connects SN and NS
- Moderate mixing effect

Late-time neutrinos are interesting & robust!

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Supernova neutrino detection

Large cross sections

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

\[ \nu_e + ^{40}\text{Ar} \rightarrow e^- + ^{40}\text{K}^* \]

\[ \nu_x + p \rightarrow \nu_x + p \]

Multi-10 kton

Super-K

DUNE

JUNO

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Supernova neutrino detection

Large cross sections

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

Super-K

\[ \nu_e + ^{40}\text{Ar} \rightarrow e^- + ^{40}\text{K}^* \]

DUNE

\[ \nu_x + p \rightarrow \nu_x + p \]

JUNO

Multi-10 kton

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\( \bar{\nu}_e + p \rightarrow e^+ + n \)

- **Inputs:**
  - 10 kpc SN
  - 22.5 kton
  - 3.5 MeV threshold

Plenty of events in Super-K!

Li, Roberts & Beacom, in prep

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$\bar{\nu}_e$ energy spectrum

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

- $E_{e^+} = E_{\bar{\nu}_e} - 1.3 \text{ MeV}$
- --- known detection threshold

Easily reconstruct neutrino spectrum

Li, Roberts & Beacom, in prep

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Alternative outcome -- BH

Different mechanisms for BH formation

BH may form at late times

Case 1: PNS Cooling
Case 2: Failed SN
Case 3: Metastable PNS

Remnant: BH
Remnant: NS

Neutrino luminosity $L_\nu$ [erg / s]
$t_{\text{post-bounce}}$ [s]

Li, Roberts & Beacom, in prep

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Detecting BH formation

Detection significance of BH formation

We can detect BH formation at late times

Li, Roberts & Beacom, in prep
Conclusions

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Thank you!
Back up
\( \nu_e \) signal rate

\[ \nu_e + ^{40}\text{Ar} \rightarrow e^- + ^{40}\text{K}^* \]

- Inputs:
  - 10 kpc SN
  - 40 kton
  - 5 MeV threshold

Plenty of events to late time in DUNE!

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\( \nu_e + ^{40}\text{Ar} \rightarrow e^- + ^{40}\text{K}^* \)

- \( E_e = E_{\nu_e} - 5.8 \text{ MeV} \)
- **unknown** detection threshold

Detection threshold needs to reach \( \sim 5 \text{ MeV} \)

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Li, Roberts & Beacom, in prep
\( \nu_x \) signal rate

\[ \nu_x + p \rightarrow \nu_x + p \]

Non-negligible events at late time

\( \nu_x \) in JUNO

Event count per bin

\( t_{\text{post-bounce}} \) [s]

Main signal

10s events

\( \nu_x \) in JUNO

Inputs:

- 10 kpc SN
- 22.5 kton
- 0.1, 0.2 MeV threshold

Li, Roberts & Beacom, in prep

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$\nu_x$ energy spectrum

$\nu_x + p \rightarrow \nu_x + p$

- $E_{\text{det}} \ll E_{\nu_x}$
- ___ unknown
detection threshold

Detection threshold is crucial

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