Core-Collapse Supernovae in the Great Survey Era: Impact on Particle Astrophysics and Cosmology

Amy Lien (連雅琳)
University of Illinois at Urbana-Champaign

Brian Fields (U. of Illinois), John Beacom (Ohio State U.)

The CCAPP Symposium, Ohio State University, 2011/04/05
Outline

- Core-collapse supernovae (CC SNe)
- The Great Survey Era
- Particle astrophysics in the Great Survey Era
  - LSST & Neutrinos
    - Diffuse supernova neutrino background (DSNB)
    - SN neutrino physics
    - Invisible supernovae?
- Conclusions/Discussions
Core–Collapse Supernovae

- Explosions of massive stars
  - Types Ib/c, and II
- Core–collapse rate \( \propto \) star formation rate
- 99% of energy released in neutrinos
- Failed supernovae?
  - Collapse \( \rightarrow \) Black hole
  - No optical explosion
  - Neutrino emission same or enhanced!

(MacFadyen & Woosley 1999, Nakazato et al. 2008)
Why Now – Great Expectations

- Scanning sky surveys (e.g. SDSS, DES, Pan-STARRS 1, SNLS, Palomar Transient Factory, LSST)
  - Happening now or next decade.

2010 Decadal Survey

LSST
1st Ground-Based Survey Starting in 2018!
The Large Synoptic Survey Telescope (LSST)

- Location: Cerro Pachón, Chile
- Synoptic: repeated-scan
- Survey depth (flux sensitivity): $\sim 24^{\text{mag}}$
- Large field of view: $9.6 \text{ deg}^2 (\sim 20 \text{ full moons})$
- Large Sky Coverage:
  $\sim 20,000 \text{ deg}^2 (\text{entire night sky})$ every $\sim 3$ nights
- Observe unchanging sky to great depth (co-add images)
- Unbiased and complete search for transients to great depth
Supernova Surveys and Neutrinos

0 Main upcoming CC SN survey:
   - LSST
     0 Ideal rate: 10/sec in the whole univ.
     0 Detection rate: ~ $10^5$/year to $z \sim 1$

0 Main neutrino detector: Super-Kamiokande (Super-K)
   0 Detection energy range: 18-26 MeV
   0 Possible future detection energy range: 10-26 MeV

0 Neutrino detection peak at similar redshift range of SN surveys
0 76% of 10-26 MeV DSNB comes from SN with $z < 1$
Neutrino flux from all cosmic supernovae
- Energy range $\sim 10 - 26$ MeV

Neutrino observatories
- Expect first detection of background SN neutrinos in next $\sim 10$ yrs

Forecast: Surveys + Neutrinos
- Imagine: SN rate known to $z \sim 1$
- Dust effects and SN luminosity distribution understood
- Assume 5% precision

Example: Probing different SN neutrino models
Failed Supernovae?

- Massive stars which collapse directly into black holes without optical explosions.
- Current theories suggest:
  - $8 \text{ M}_\odot < M_{\text{star}} < 25 \text{ M}_\odot$: explode (81%)
  - $M_{\text{star}} > 40 \text{ M}_\odot$: failed (9%)
  - $25 \text{ M}_\odot < M_{\text{star}} < 40 \text{ M}_\odot$: ??? (10%)
- Most of the failed supernovae create neutrinos with higher energies
- Neutrinos as a tool to probe the fraction of failed supernovae
- Horuichi et al. (2011) suggests a larger fraction of optically dim supernovae
Failed SN
- Collapse → Black hole
- No optical explosion
- Neutrino emission same or enhanced!

Missed in optical SN surveys
Detected by neutrino observatories

Revealing Failed Supernovae

How far away from zero can it be?
Failed SN
- Collapse → Black hole
- No optical explosion
- Neutrino emission same or enhanced!

Missed in optical SN surveys
Detected by neutrino observatories
Failed SN
  ◦ Collapse → Black hole
  ◦ No optical explosion
  ◦ Neutrino emission same or enhanced!
Missed in optical SN surveys
Detected by neutrino observatories
Failed SN
- Collapse → Black hole
- No optical explosion
- Neutrino emission same or enhanced!

Missed in optical SN surveys
Detected by neutrino observatories

Revealing Failed Supernovae
Revealing Failed Supernovae

- Failed SN
  - Collapse → Black hole
  - No optical explosion
  - Neutrino emission same or enhanced!
- Missed in optical SN surveys
- Detected by neutrino observatories
Failed SN
- Collapse \(\rightarrow\) Black hole
- No optical explosion
- Neutrino emission: same or enhanced!
- Missed in optical SN surveys
- Detected by neutrino observatories
Conclusions

**LSST SNe**
- Measure cosmic SN rate to \( z < 1 \) via direct counting
- Star-formation rate to high precision out to \( z < 1 \)
- Remove astro uncertainty in DSNB

**LSST SNe + Neutrinos**
- Distinguish different supernova neutrino models.
- Probe failed supernovae.
  - DSNB flux should be at least 10% higher than flux from observed supernovae.

**LSST SNe + Neutrinos + ?**
Back-up Slides
How Many is 1 Million Supernovae?

Historical Supernovae

Year

SN Number

1000 1100 1200 1300 1400 1500 1600 1700 1800 1900 2000

Historical Supernovae

Year

SN Number

1 2 4 6 7 19 15 122 186 160 229 940 3557

Forecasts for Synoptic Surveys

- $>10^5$ CC SNe per year to $z \sim 1$.
- SN rate by direct counting!
- <10% statistical precision for the CC SNe rate in one year of detection (current uncertainty > 40%).
- LSST plot:
  - Scan area: 20000 deg$^2$
  - Proposed limiting magnitude for SNe: 23$^{\text{mag}}$
  - Bin size: $\Delta z=0.1$
Failed SN
- Collapse → Black hole
- No optical explosion
- Neutrino emission same or enhanced!

Missed in optical surveys
Detected by neutrino observatories
What is the likely failed supernova rate?

Lien et al. (2010)
What is the likely failed supernova rate?

Lien et al. (2010)
What is the likely failed supernova rate?

Lien et al. (2010)
What is the likely failed supernova rate?

Lien et al. (2010)
What is the likely failed supernova rate?

Lien et al. (2010)
What is the likely failed supernova rate?

![Graph showing the relationship between visible and invisible supernova rates](Image)

- Observed CSFR and Uncertainty
- DSNB Limit (4 MeV, 7.5 MeV)
- DSNB Limit (6 MeV, 7.5 MeV)
- Sensitivity to Stellar Disappearance

Lien et al. (2010)
What is the likely failed supernova rate?

Lien et al. (2010)
What is the likely failed supernova rate?

Lien et al. (2010)