Neutrino astronomy

- Sun


- Core-collapse supernova

One event so far (SN 1987A)
The Sun: How bright is it?

- Neutrino luminosity:
  - $L_\nu \sim 10^{25}$ W

- Solar luminosity (in light)
  - $L_\gamma \sim 4 \times 10^{26}$ W

Neutrinos carry away a small fraction of total energy created
Supernova: How bright is it?

- Massive stars (more than 8 $M_{\text{sun}}$) form iron core at their center
- When the core collapses, copious number of neutrinos are produced, leaving a neutron star (or a black hole) behind
- Gravitational binding energy released:

$$E_B = \frac{G M_{\text{NS}}^2}{R_{\text{NS}}} \approx 3 \times 10^{53} \text{ erg}$$

<table>
<thead>
<tr>
<th>Percentage</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>99%</td>
<td>MeV neutrinos</td>
</tr>
<tr>
<td>1%</td>
<td>Shock waves</td>
</tr>
<tr>
<td>0.01%</td>
<td>Photons</td>
</tr>
</tbody>
</table>
The Universe: How bright is it?
The Universe: How bright is it?  

... in photons

**Gilmore et al. (2012)**

![Graph](image-url)
The Universe: How bright is it?

... in photons

- Energy density of infrared background photons:
  \((2–3) \times 10^{-14} \text{ erg/cm}^3\)
The Universe: How bright is it — in neutrinos?
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- Each supernova releases $3 \times 10^{53}$ erg by neutrinos
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Energy/SN  Global SN rate
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$$
How bright is the Universe?: Summary

- Universe is filled with radiation ($\gamma$ and $\nu$)

<table>
<thead>
<tr>
<th></th>
<th>Energy density</th>
</tr>
</thead>
<tbody>
<tr>
<td>CMB</td>
<td>$4 \times 10^{-13}$ erg cm$^{-3}$</td>
</tr>
<tr>
<td>CIB/EBL</td>
<td>$(2-3) \times 10^{-14}$ erg cm$^{-3}$</td>
</tr>
<tr>
<td>CXB</td>
<td>$10^{-16}$ erg cm$^{-3}$</td>
</tr>
<tr>
<td>CGB</td>
<td>$10^{-17}$ erg cm$^{-3}$</td>
</tr>
<tr>
<td>CSN$\nu$B</td>
<td>$3 \times 10^{-14}$ erg cm$^{-3}$</td>
</tr>
<tr>
<td>TeV$\nu$B</td>
<td>$&lt; 10^{-19}$ erg cm$^{-3}$</td>
</tr>
</tbody>
</table>
Outline

• Thermal neutrinos from SNe
  • Diffuse SN $\nu$ background (DSNB) and SN rate estimates
  • SN mini bursts in nearby galaxies

• High-energy neutrinos
  • GRB–SN association
  • Joint detection of GW and HE$\nu$

IR/optical/UV

X/$\gamma$/GW
Diffuse supernova neutrino background (DSNB)

- DSNB flux depends on two inputs:
  1. $\nu$ spectrum from each SN
     
     Only $\nu$ telescopes and/or simulations can tell us

  2. SN rate in the past

$$\frac{dF_\nu}{dE_\nu} = c \int_0^{z_{\text{max}}} R_{\text{SN}}(z) \frac{dN_\nu(E'_\nu)}{dE'_\nu} (1 + z) \frac{dt}{dz} dz$$
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SN rate estimates


- **Counting SNe**
  - Less statistics but more direct
  - Hard to correct for dim SNe (e.g., Horiuchi et al. 2011)

- **Conversion from cosmic star formation rate (SFR)**
  - FIR/Hα/UV luminosity: how many massive stars are formed
  - Less direct but more statistics
  - These are complementary and match well, leaving factor of < 2 uncertainty
How rapidly has this business progressed?


Event rate of DSNB in Super-K


- Solar, reactor, atmospheric neutrinos and invisible muons
- Energy window of >18 MeV (pure water) and >10 MeV (Gadolinium-enhanced detectors)
Upper limits by Super-K

![Diagram showing upper limits for different models and neutrino energies.]

<table>
<thead>
<tr>
<th>Model</th>
<th>SK-I</th>
<th>SK-II</th>
<th>SK-III</th>
<th>All</th>
<th>Predicted</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas infall (97)</td>
<td>&lt;2.1</td>
<td>&lt;7.5</td>
<td>&lt;7.8</td>
<td>&lt;2.8</td>
<td>0.3</td>
</tr>
<tr>
<td>Chemical (97)</td>
<td>&lt;2.2</td>
<td>&lt;7.2</td>
<td>&lt;7.8</td>
<td>&lt;2.8</td>
<td>0.6</td>
</tr>
<tr>
<td>Heavy metal (00)</td>
<td>&lt;2.2</td>
<td>&lt;7.4</td>
<td>&lt;7.8</td>
<td>&lt;2.8</td>
<td>&lt;1.8</td>
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<tr>
<td>LMA (03)</td>
<td>&lt;2.5</td>
<td>&lt;7.7</td>
<td>&lt;8.0</td>
<td>&lt;2.9</td>
<td>1.7</td>
</tr>
<tr>
<td>Failed SN (09)</td>
<td>&lt;2.4</td>
<td>&lt;8.0</td>
<td>&lt;8.4</td>
<td>&lt;3.0</td>
<td>0.7</td>
</tr>
<tr>
<td>6 MeV (09)</td>
<td>&lt;2.7</td>
<td>&lt;7.4</td>
<td>&lt;8.7</td>
<td>&lt;3.1</td>
<td>1.5</td>
</tr>
</tbody>
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Future prospects


- Determination of SN-ν parameters with Gd-enhanced Super-K and/or Mton scale detectors
Learning SN model or neutrino parameters

Lunardini, Tamborra, JCAP 07, 012 (2012)

- Dependence on progenitor mass and neutrino mass hierarchy
- Study of neutrino decay (Ando 2004; Fogli et al. 2004), etc...
\[ \gamma \text{-ray luminosity vs SFR} \]

- Fermi-LAT Collaboration (2012)
Intermediate regime?

Super-K

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### Intermediate regime?

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### Intermediate regime?

- **Study of SN neutrino parameters**
- **Reconstruct luminosity evolution**
- **Help look for gravitational waves, etc.**

#### Super-K

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<td></td>
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</table>
SN frequency in local volume


Scaling from B-band luminosity

Direct SN counts

- Only M31 (Andromeda) within $\sim3$ Mpc
- A few starburst galaxies (M82, NGC 253) around 3–4 Mpc; cumulative SN rate of $\sim1$ yr$^{-1}$ within 4 Mpc
How well can Megaton detectors perform?

- Reasonable chance of detecting multiple $\nu$ events per burst at $\sim 3$ Mpc
- Small background

What would happen if we had 5-Mton detector?
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- Reach of burst mode ($\geq 5$ events)
- Scaled by $10^4$ events from a supernova at 10 kpc at 32 kton detector
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What would happen if we had 5-Mton detector?

32 kton
1 Mton
5 Mton

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What would happen if we had 5-Mton detector?

- Reach of burst mode ($\geq 5$ events)
- Scaled by $10^4$ events from a supernova at 10 kpc at 32 kton detector
- 5-Mton detector can take us beyond the “desert”
What could have been done


<table>
<thead>
<tr>
<th>SN</th>
<th>Type</th>
<th>Host</th>
<th>D [Mpc]</th>
<th>( \nu ) events</th>
</tr>
</thead>
<tbody>
<tr>
<td>2002hh</td>
<td>II-P</td>
<td>NGC 6946</td>
<td>5.6</td>
<td>2.4</td>
</tr>
<tr>
<td>2002kg</td>
<td>II/In/LBV</td>
<td>NGC 2403</td>
<td>3.3</td>
<td>6.8</td>
</tr>
<tr>
<td>2004am</td>
<td>II-P</td>
<td>NGC 3034 (M82)</td>
<td>3.53</td>
<td>5.9</td>
</tr>
<tr>
<td>2004dj</td>
<td>II-P</td>
<td>NGC 2403</td>
<td>3.3</td>
<td>6.8</td>
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<td>2.4</td>
</tr>
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<td>2005af</td>
<td>II-P</td>
<td>NGC 4945</td>
<td>3.6</td>
<td>5.7</td>
</tr>
<tr>
<td>2008S</td>
<td>II/In</td>
<td>NGC 6946</td>
<td>5.6</td>
<td>2.4</td>
</tr>
<tr>
<td>2008bk</td>
<td>II-P</td>
<td>NGC 7793</td>
<td>3.91</td>
<td>4.8</td>
</tr>
<tr>
<td>2008iz</td>
<td>II?</td>
<td>NGC 3034 (M82)</td>
<td>3.53</td>
<td>5.9</td>
</tr>
<tr>
<td>NGC 300-T</td>
<td>II?</td>
<td>NGC 300</td>
<td>2.15</td>
<td>16.0</td>
</tr>
</tbody>
</table>
Two projects for multi-Mton detector

**Deep-TITAND**

- IceCube "lab" has been completed – significant (positive) experience with deployment & operation
- Very clear, pure & stable detection medium
- Cost-effective operation for Megaton instrumented volume with 10 MeV threshold

**PINGU**

Special simulation:
- 61 strings
- 300 m long strings
- 23000 HQE-PMTs
- \( \nu \)-events: \( N_{\text{hits}} \geq 5 \)
Outline

- Thermal neutrinos from SNe
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- SN mini bursts in nearby galaxies
- High-energy neutrinos
  - GRB–SN association
  - Joint detection of GW and HEν

IR/optical/UV

X/γ/GW
Long GRB-supernova association

- Supernova/hypernova is likely a source of long GRBs
- What’s the underlying relation between them?

<table>
<thead>
<tr>
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<th>GRB</th>
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<tbody>
<tr>
<td>Energy</td>
<td>$10^{51}$ erg</td>
<td>$10^{51}$ erg</td>
</tr>
<tr>
<td>Rate</td>
<td>$\sim 1$ cen$^{-1}$ gal$^{-1}$</td>
<td>$\sim 1$ Myr$^{-1}$ gal$^{-1}$</td>
</tr>
<tr>
<td>$\Gamma$</td>
<td>$\sim 1$</td>
<td>$\sim 100–10^3$</td>
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</table>

Are there sources in between?

Hjorth et al. 2003; Stanek et al. 2003
Are there “dark” GRBs?

- If $\Gamma < 100$, photons don’t escape from the source $\rightarrow$ no GRB-like signal
- This doesn’t mean these sources don’t exist
  - They might be even more frequent

$$M_{ej} = \frac{E_K}{\Gamma c^2} \approx 10^{-5} M_{\odot} \left( \frac{E_K}{10^{51} \text{ erg}} \right) \left( \frac{\Gamma}{100} \right)^{-1}$$

- Tension of low-baryon issue is loosened for $\Gamma \sim 3$ burst

More baryons $\rightarrow$ more neutrino production
Could be strong GW sources
Unknown rate but could be large
Unrevealed supernova-GRB connection?

<table>
<thead>
<tr>
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<th>“Failed” GRB</th>
<th>GRB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
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</tr>
<tr>
<td>Rate/gal</td>
<td>$\sim 10^{-2}$ yr$^{-1}$</td>
<td>$10^{-5} - 10^{-2}$ yr$^{-1}$</td>
<td>$\sim 10^{-5}$ yr$^{-1}$</td>
</tr>
<tr>
<td>$\Gamma$</td>
<td>$\sim 1$</td>
<td>$\sim 3 - 100$</td>
<td>$\sim 100 - 10^3$</td>
</tr>
</tbody>
</table>

- Barion rich
- Nonrelativistic
- Frequent

- Baryon poor
- Relativistic jets
- Rare

Similar kinetic energy

- Evidence of mildly relativistic jets:
Events at km$^3$ detectors


- $E = 3 \times 10^{51}$ erg; $\Gamma = 3$

- Expected events above 100 GeV:
  - $\sim 30$ @ 10 Mpc
  - $\sim 3$ @ 30 Mpc

- These events cluster within 10–100 s time and 3° angular bins

- Extremely low background
No significant excess of multiple $\nu$ events

Upper limits on jet energy and source density

No optical SNe associated
Joint search for HEν and GW

IceCube-22 +
Initial LIGO-Virgo

IceCube-86 +
Advanced LIGO-Virgo

Summary

- The Universe is bright both in photons and neutrinos, at the comparable level
- IR/opt/UV astronomy helps us estimate cosmic supernova rate, hence DSNB flux
- DSNB is within reach for Super-K (and larger) enhanced with Gd
- SN mini-bursts can be detectable at multi-Mton detectors from galaxies around 3 Mpc (each year)
- GRB-like SN jets may be a good emitter of high-energy neutrinos and GW