Neutrino Oscillation Workshop
Otranto, Lecce, Italy
September 14, 2012

Multimessenger astronomy and neutrinos

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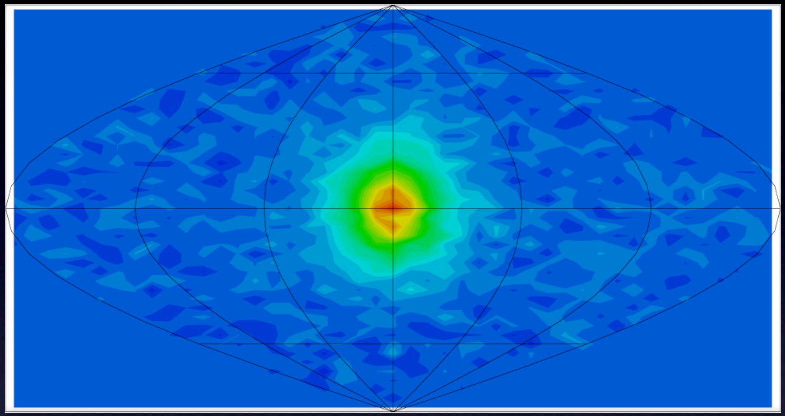
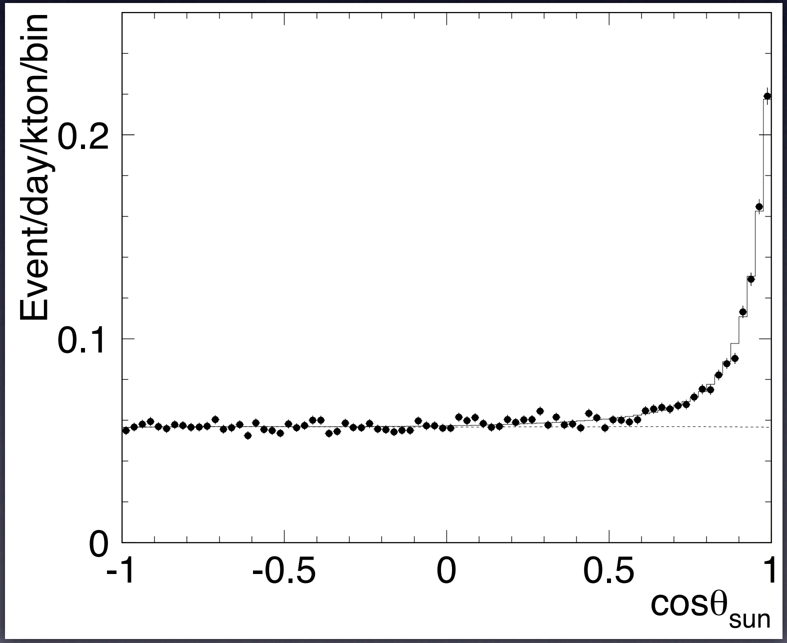
Neutrino astronomy

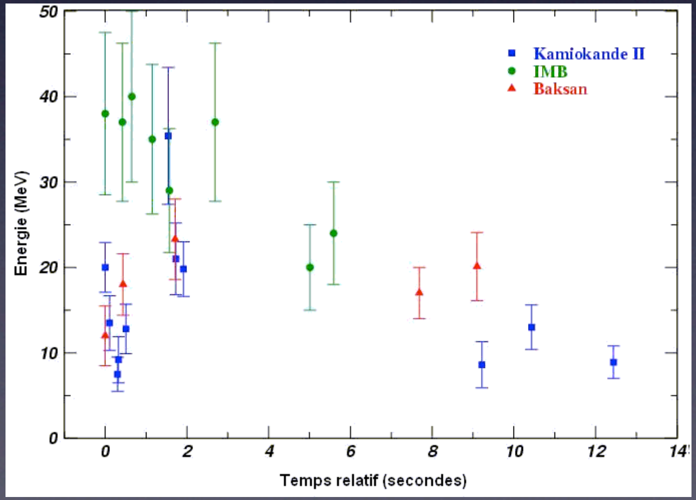
- Sun





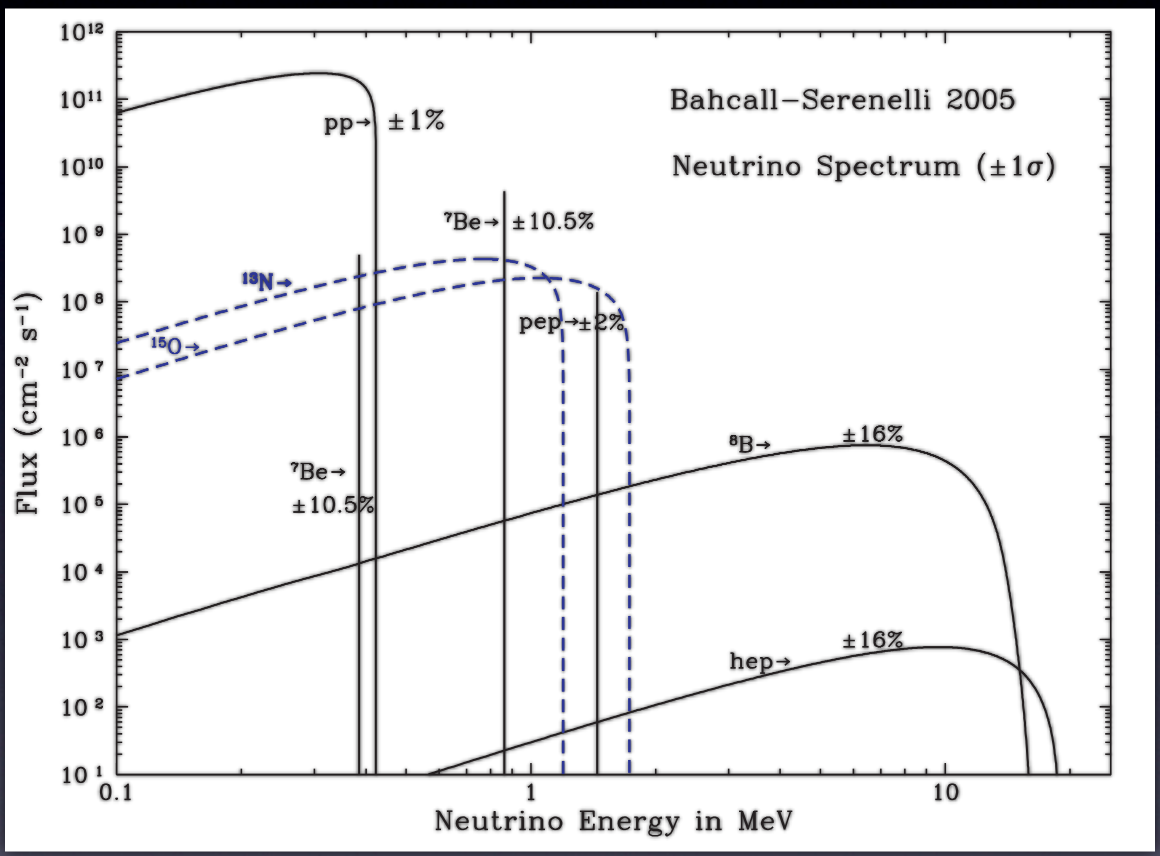
Super-K, *Phys. Rev. D* **83**, 052010 (2011)

- Core-collapse supernova



One event so far (SN 1987A)

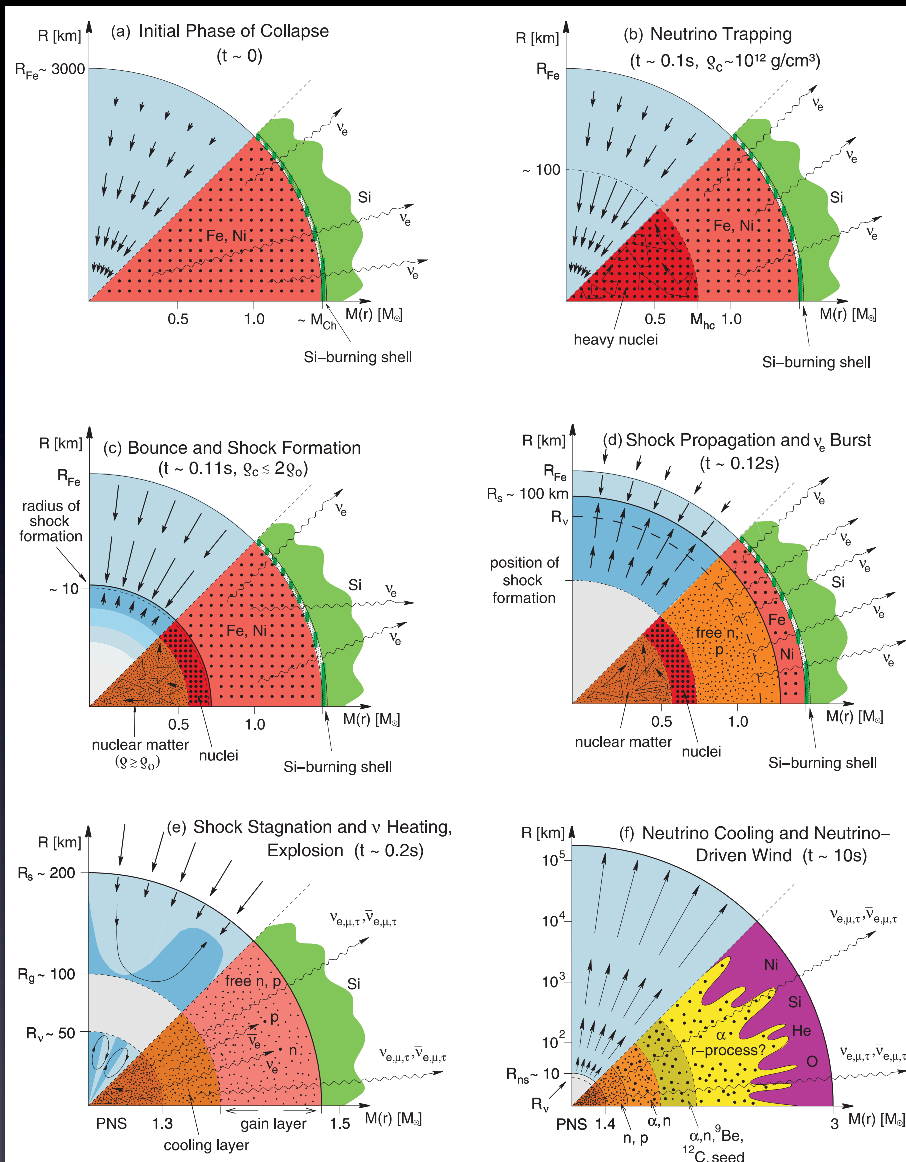
The Sun: How bright is it?



- 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?



Janka et al. *Phys. Rep.* **442**, 38 (2007)

- Massive stars (more than 8 M_{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:

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

99%	MeV neutrinos
1%	Shock waves
0.01%	Photons

The Universe: How bright is it?

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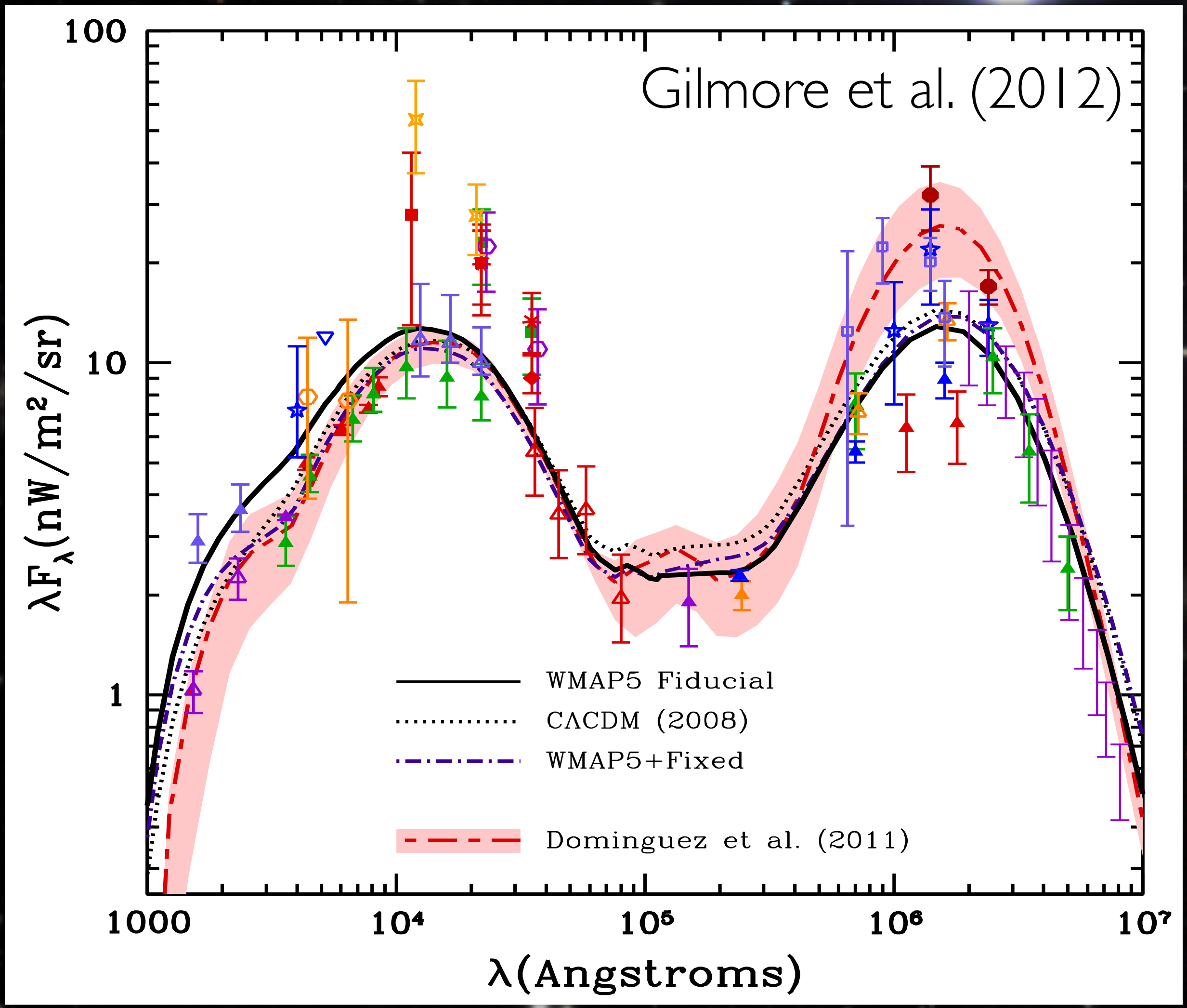
... in photons



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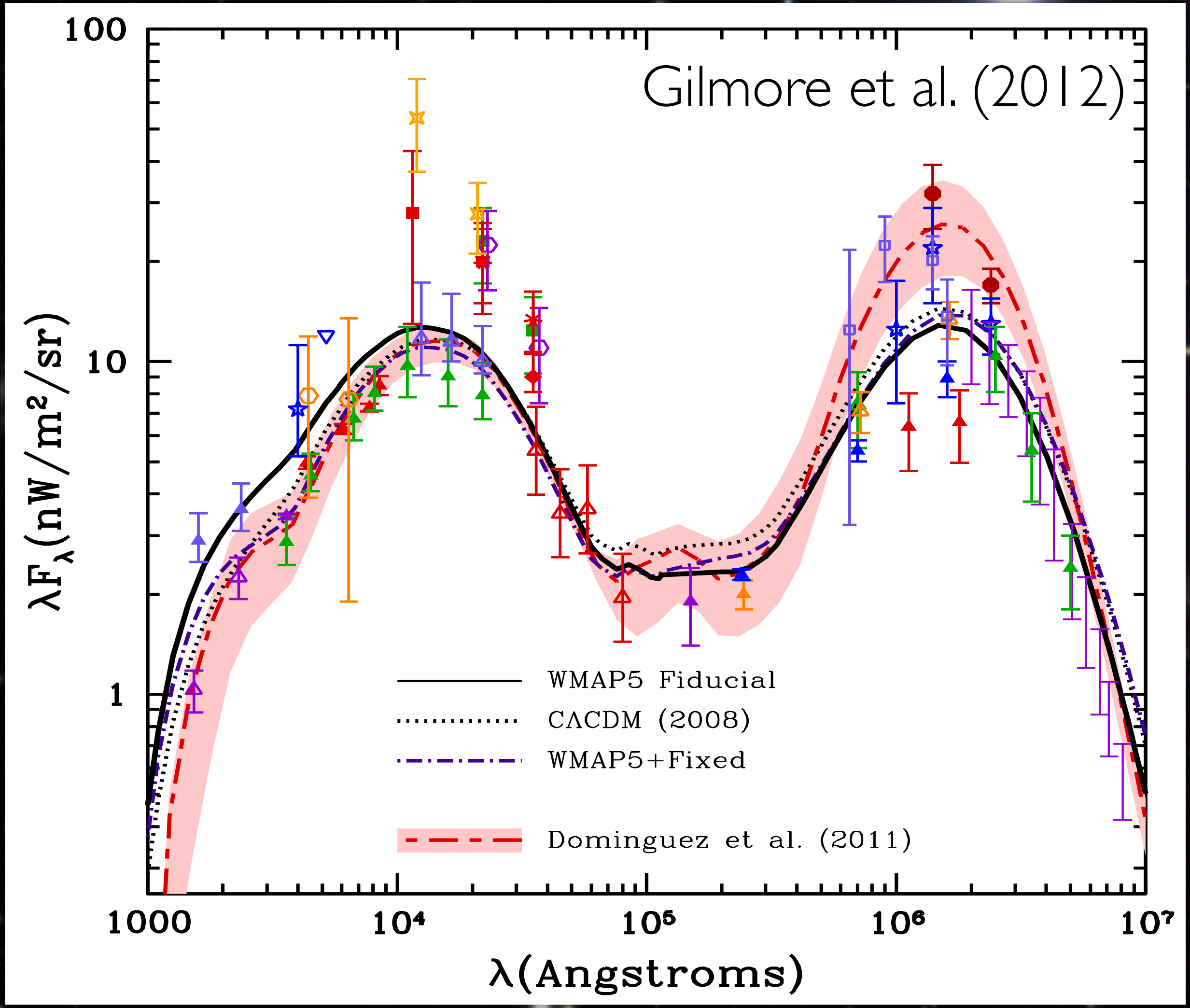

- Energy density of infrared background photons: (2–3) x 10^{-14} erg/cm^3

The Universe: How bright is it — in neutrinos?

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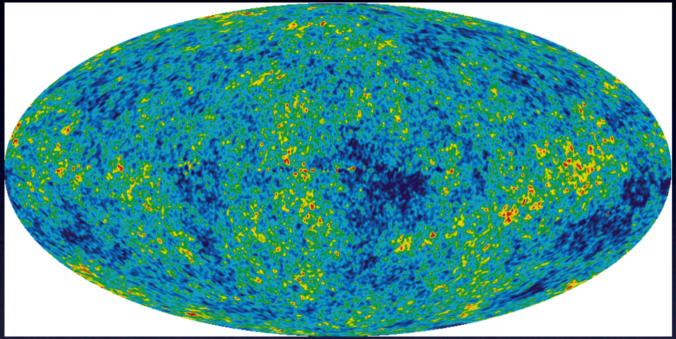
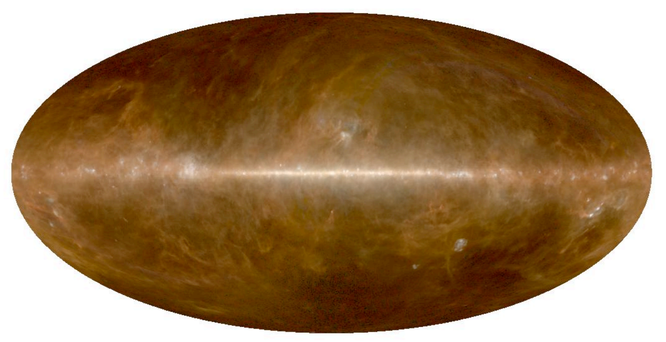
How bright is the Universe?: Summary

- Universe is filled with radiation (γ and ν)

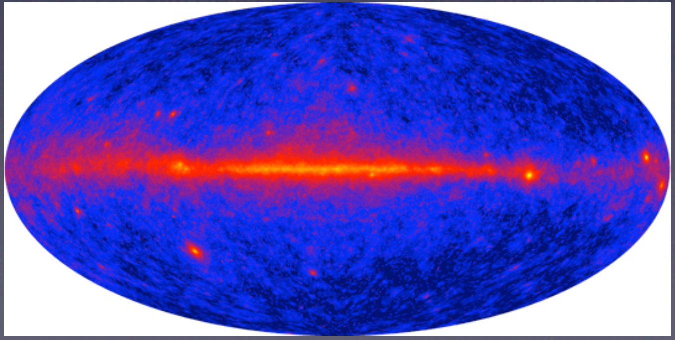
CMB



CIB



CGB



	Energy density
CMB	4×10^{-13} erg cm^{-3}
CIB/EBL	$(2\text{–}3) \times 10^{-14}$ erg cm^{-3}
CXB	10^{-16} erg cm^{-3}
CGB	10^{-17} erg cm^{-3}
CSNνB	3×10^{-14} erg cm^{-3}
TeVνB	$< 10^{-19}$ erg cm^{-3}

Outline

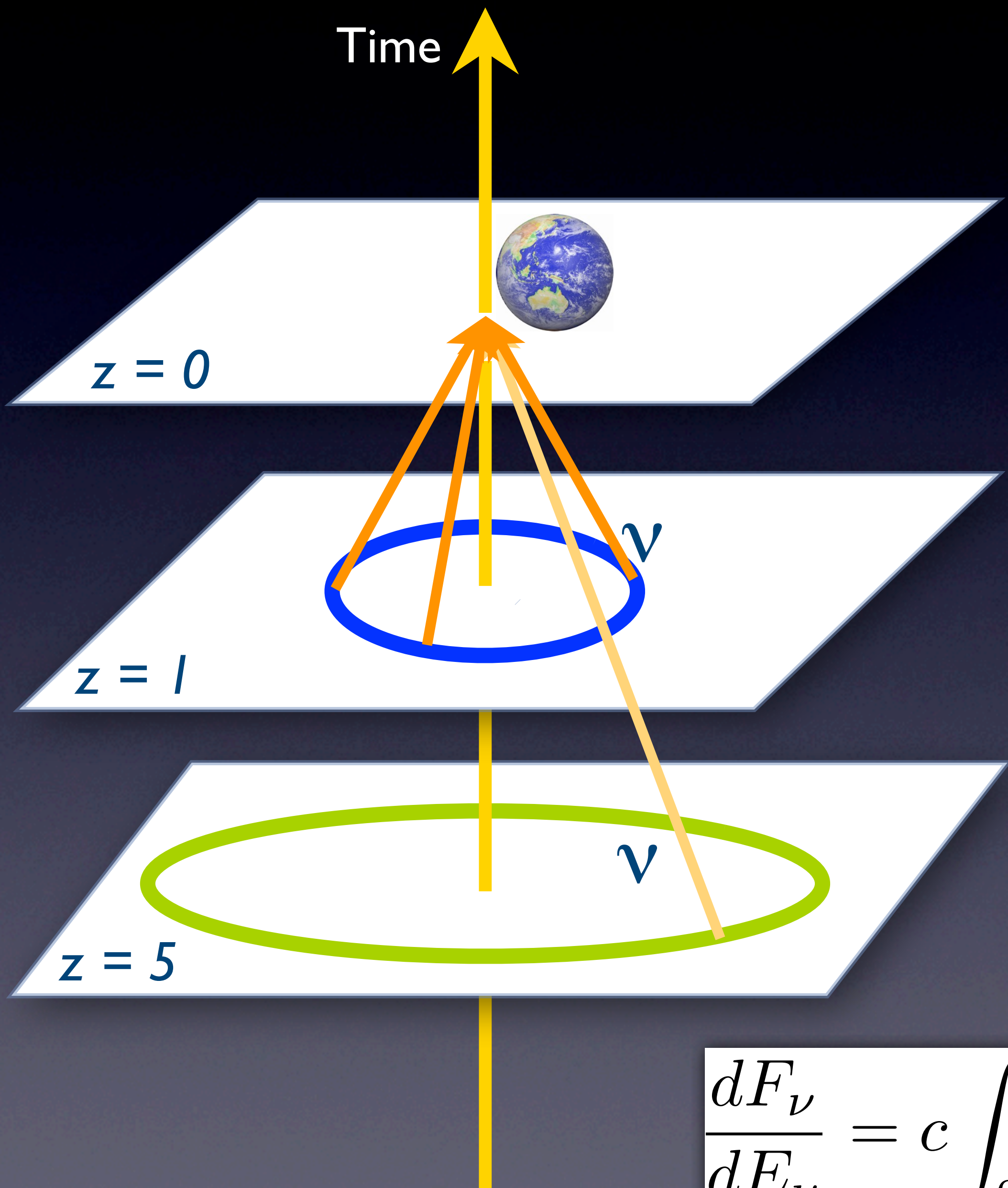
- Thermal neutrinos from SNe
  - Diffuse SN ν background (DSNB) and SN rate estimates
  - SN mini bursts in nearby galaxies

IR/optical/UV

- High-energy neutrinos
  - GRB–SN association
  - Joint detection of GW and HEν

X/γ/GW

Diffuse supernova neutrino background (DSNB)



- DSNB flux depends on two inputs:

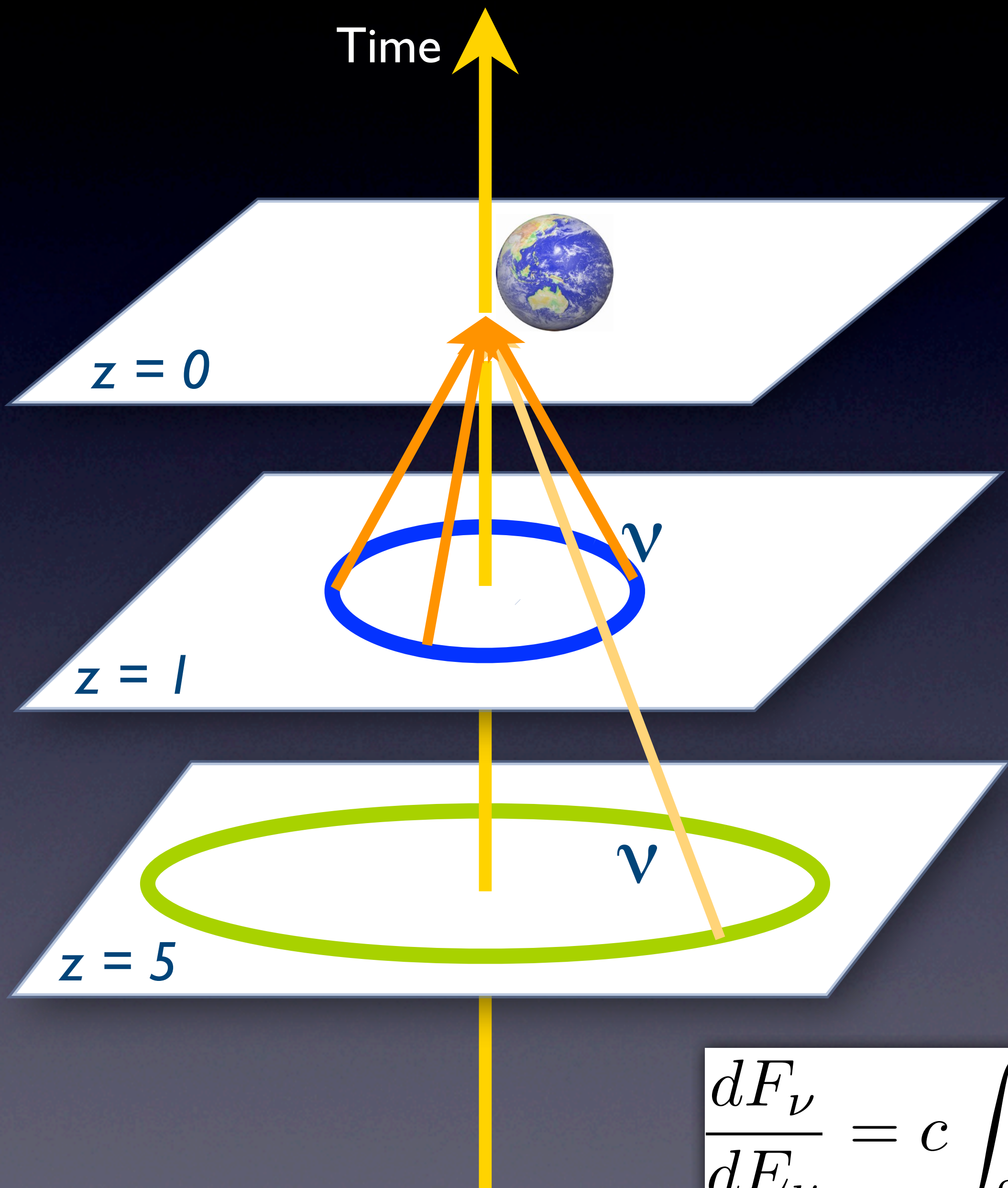
  1. ν spectrum from each SN

     Only ν telescopes and/or simulations can tell us

  2. SN rate in the past

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

Diffuse supernova neutrino background (DSNB)



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     Astronomy!
     IR/optical/UV

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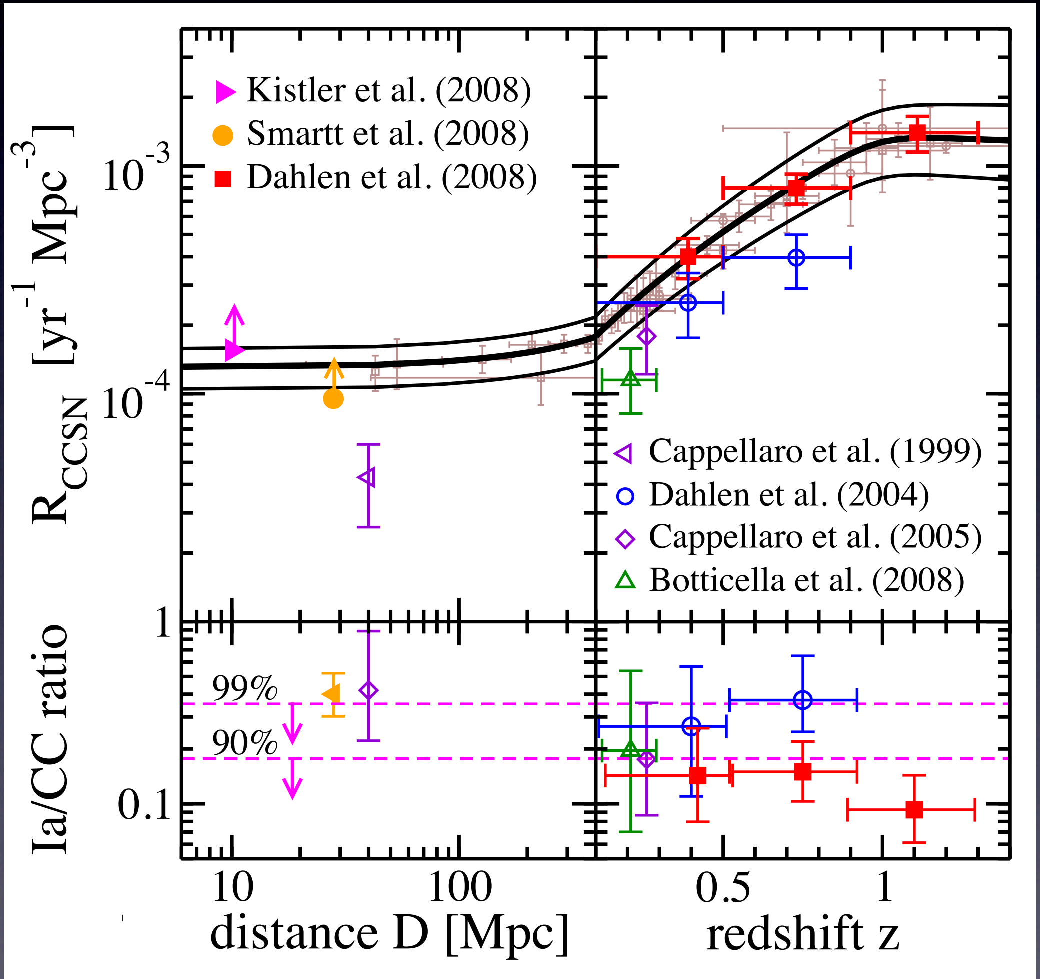
SN rate estimates

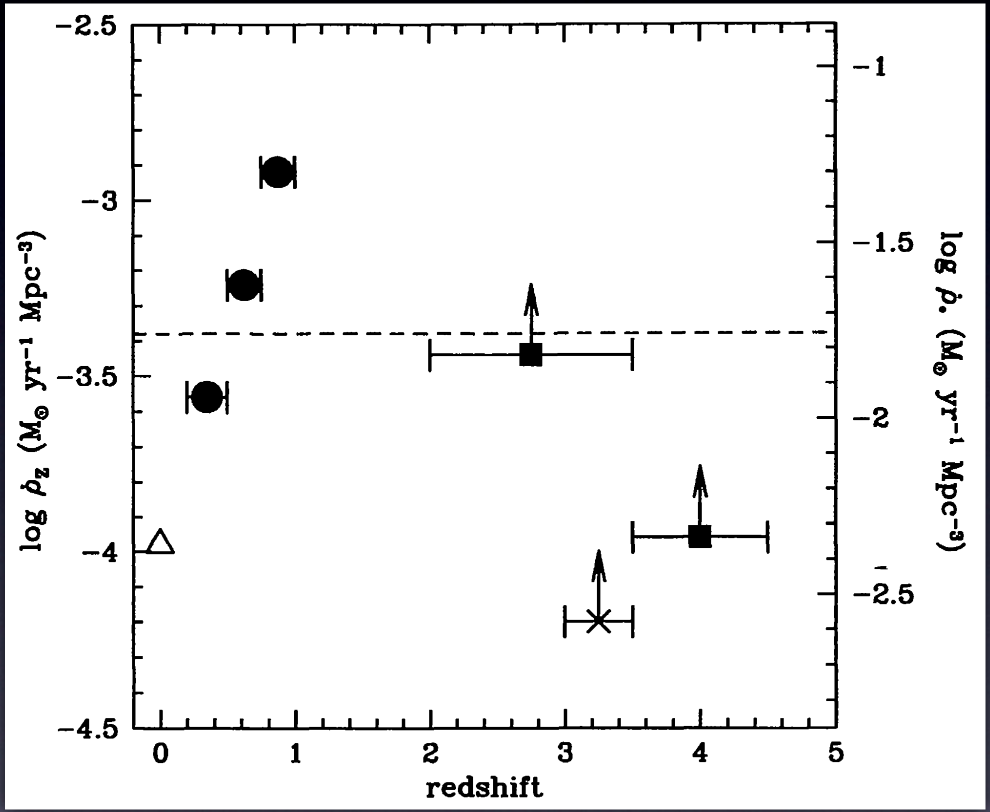
Horiuchi et al., *Phys. Rev. D* **79**, 083013 (2009)

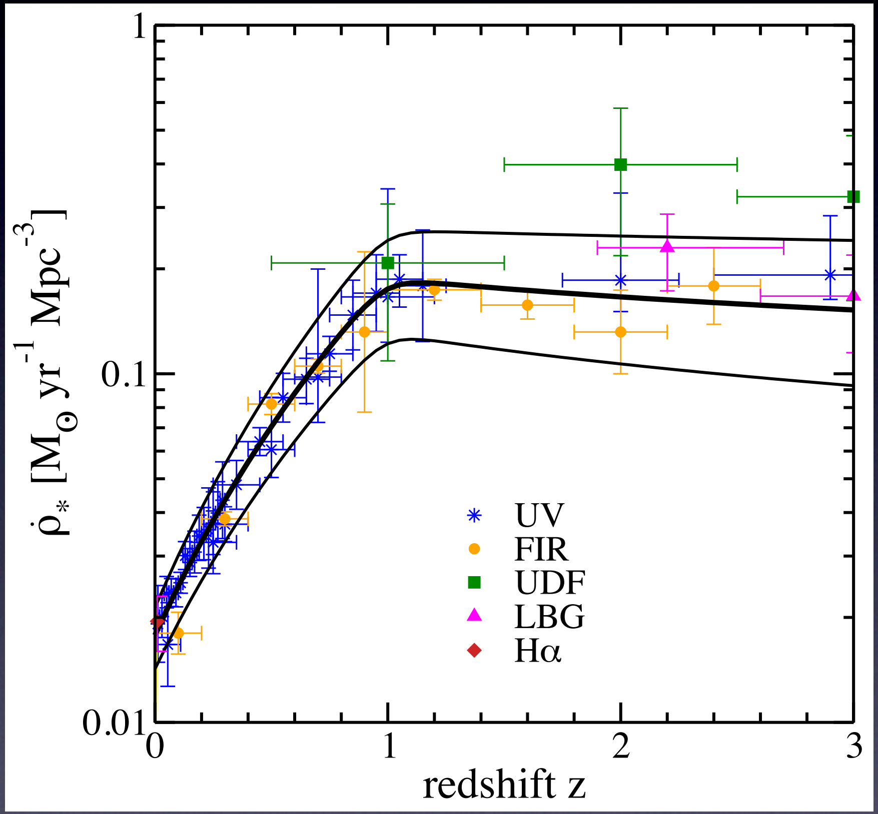


- **Counting SNe**
  - Less statistics but more direct
  - Hard to correct for dim SNe (e.g., Horiuchi et al. 2011)
- **Conversion from cosmic star formation rate (SFR)**
  - FIR/Hα/UV luminosity: how many massive stars are formed
  - Less direct but more statistics
- These are complementary and match well, leaving factor of < 2 uncertainty

How rapidly has this business progressed?

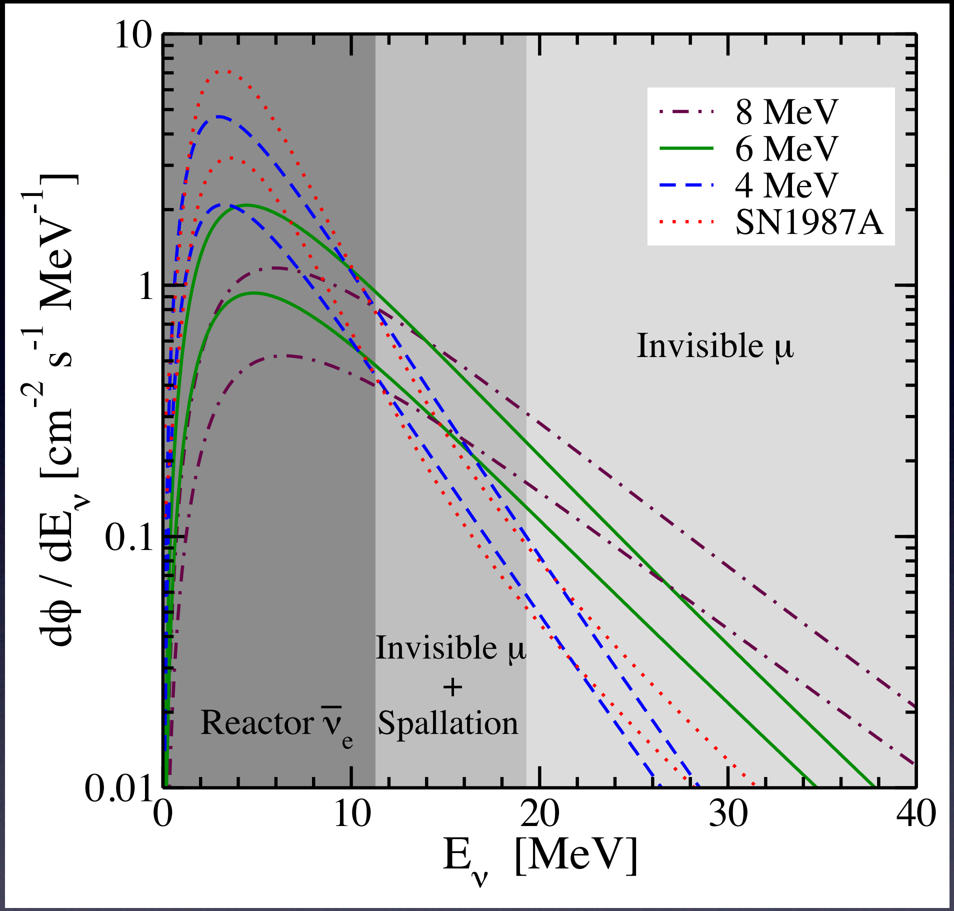
Horiuchi et al., *Phys. Rev. D* **79**, 083013 (2009)

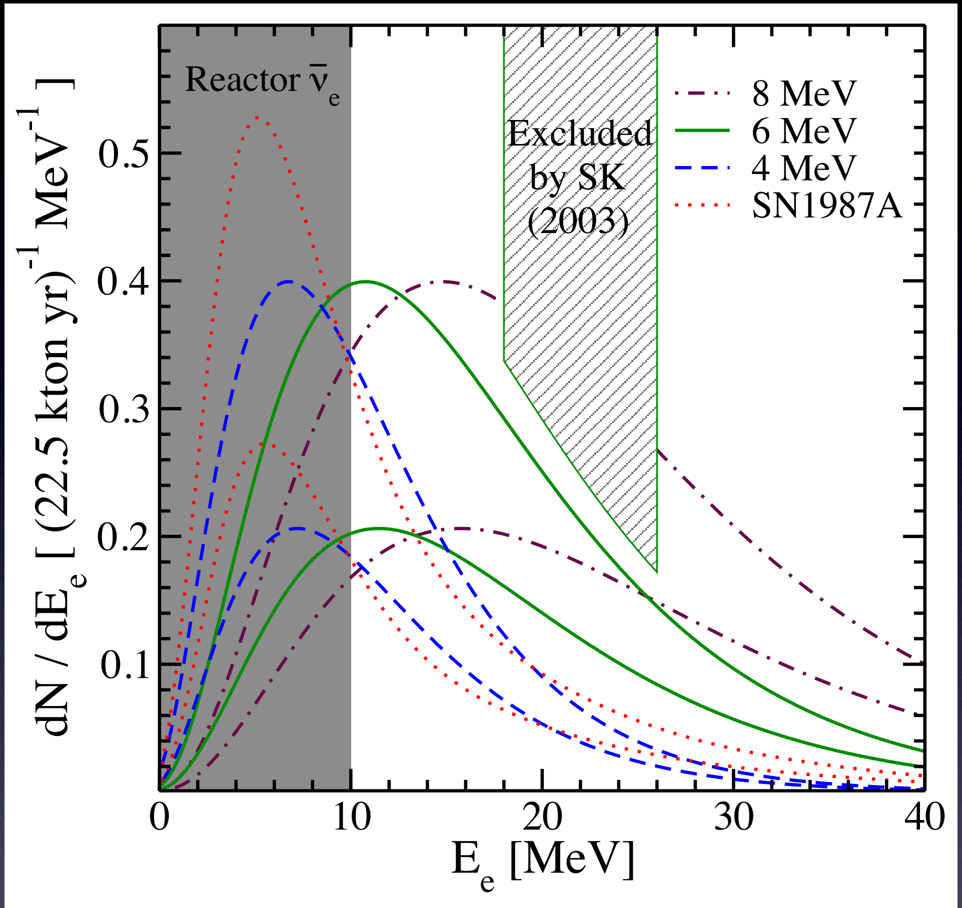




Madau et al., *Mon. Not. R. Astron. Soc.* **283**, 1388 (1996)

Event rate of DSNB in Super-K

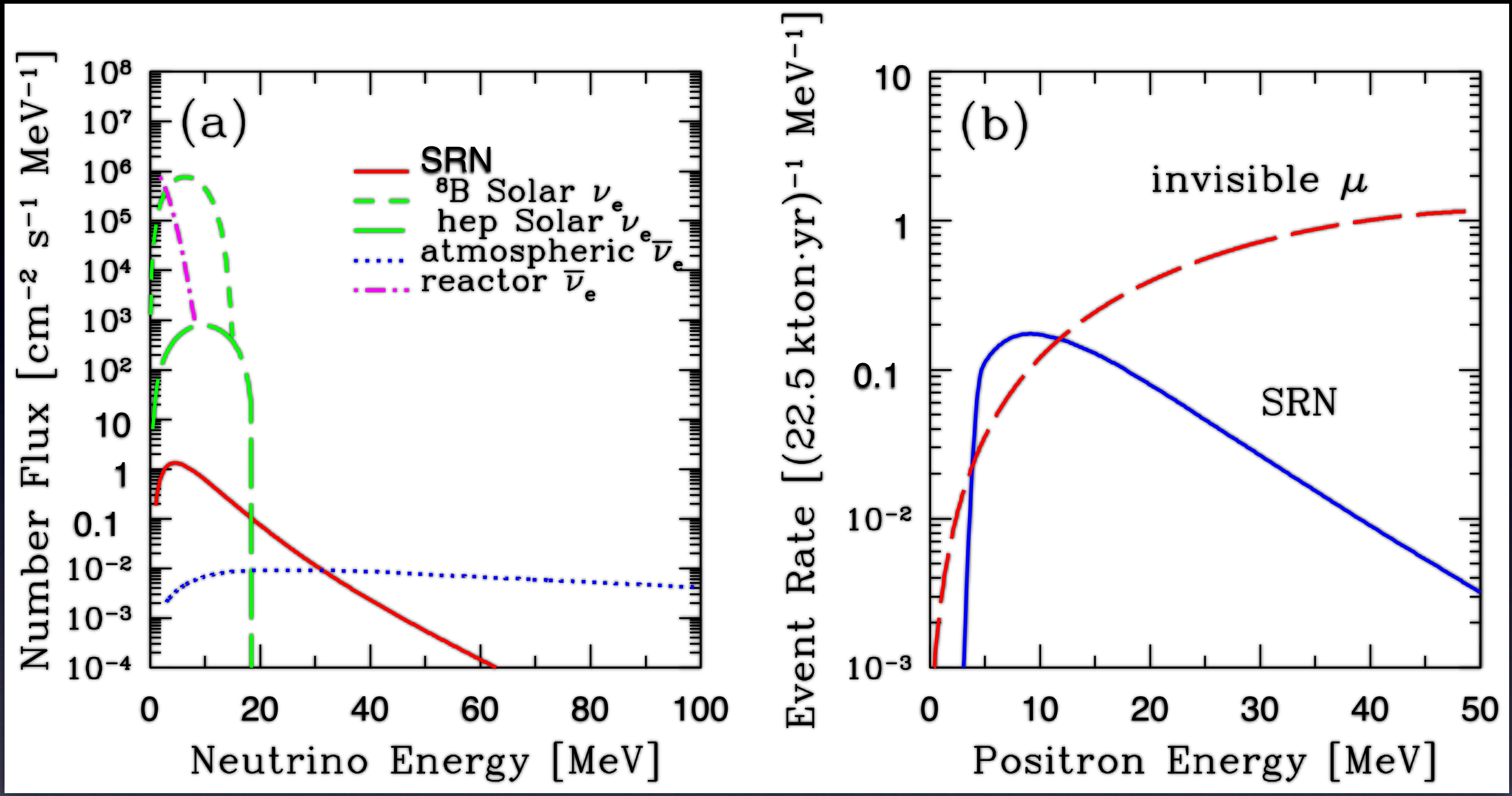




Horiuchi et al., *Phys. Rev. D* **79**, 083013 (2009)

$\bar{\nu}_e$ spectrum	events $[(22.5\ \text{kton yr})^{-1}]$	
	$10 < E_e/\text{MeV} < 26$	$18 < E_e/\text{MeV} < 26$
8 MeV	4.2 ± 1.4	2.0 ± 0.7
6 MeV	3.5 ± 1.1	1.3 ± 0.4
4 MeV	1.8 ± 0.5	0.4 ± 0.1
SN 1987A	1.7 ± 0.5	0.5 ± 0.1

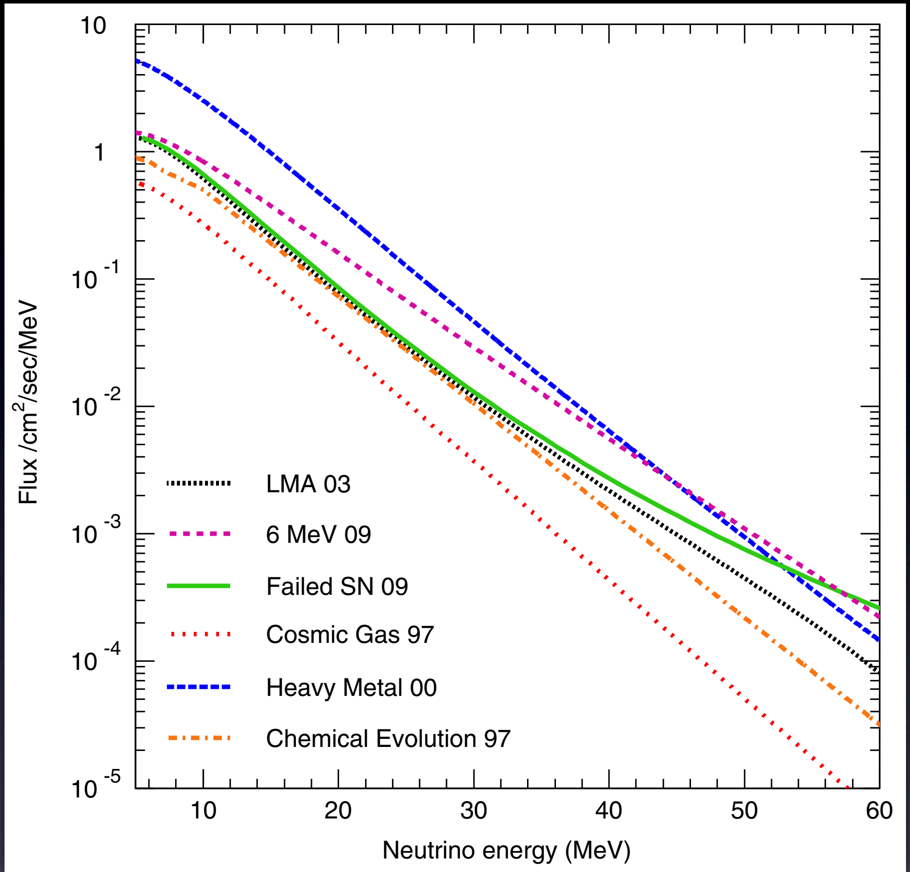
Background against detection

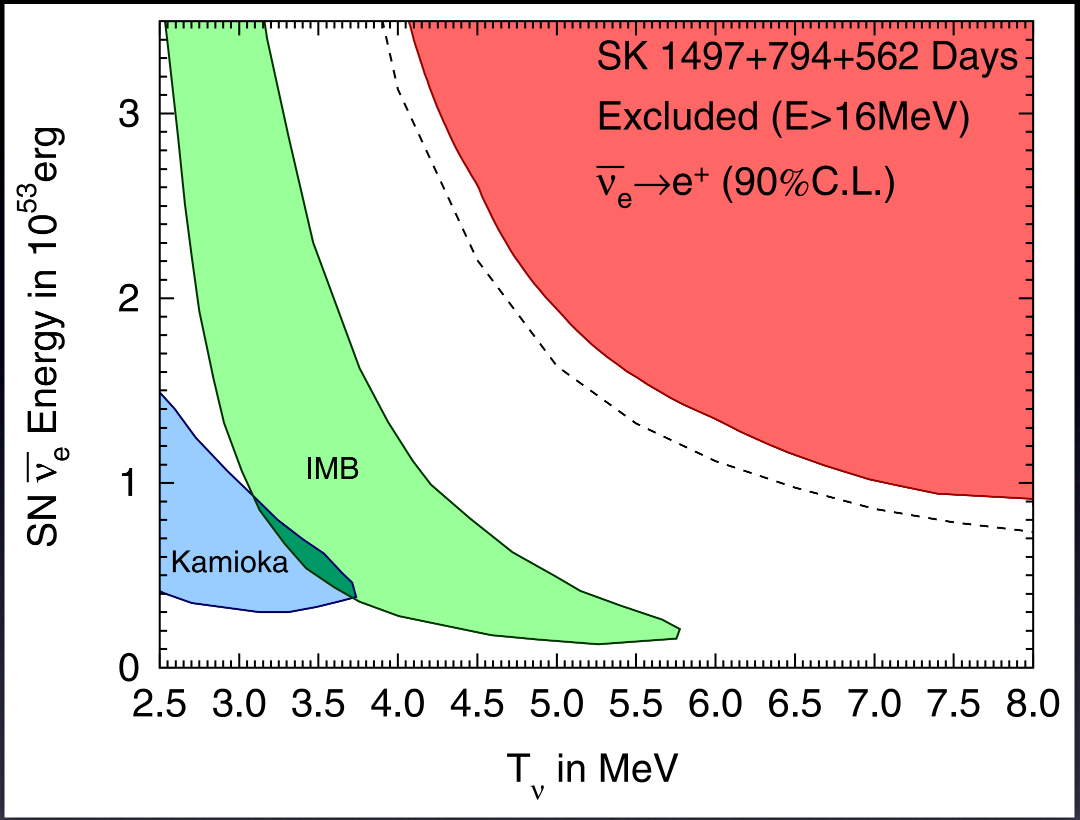


Ando, Sato, *New J. Phys.* **6**, 170 (2004)

- 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

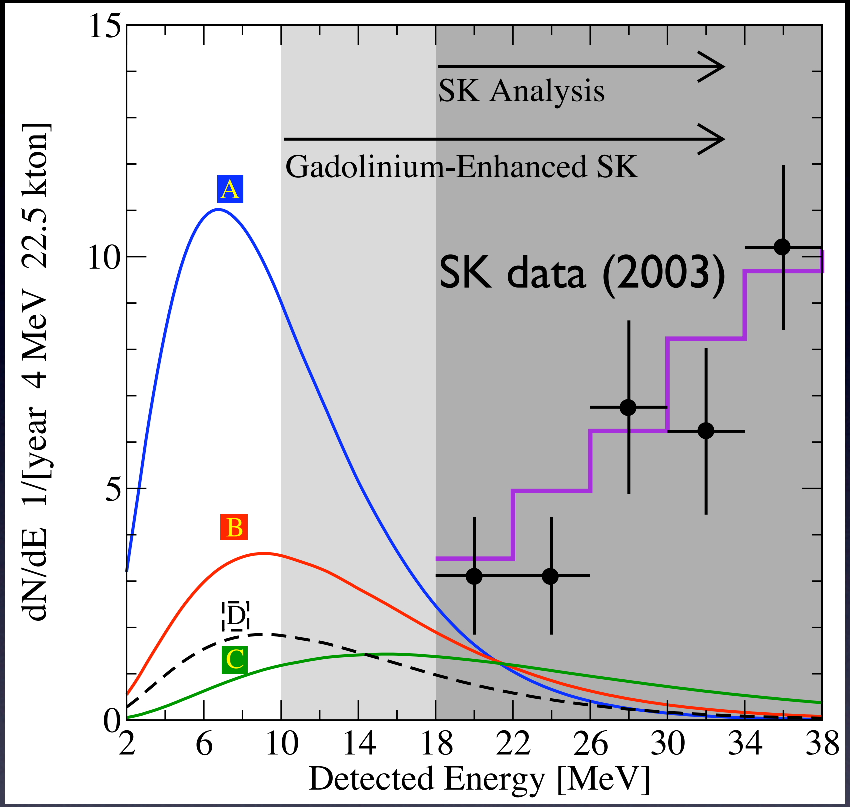


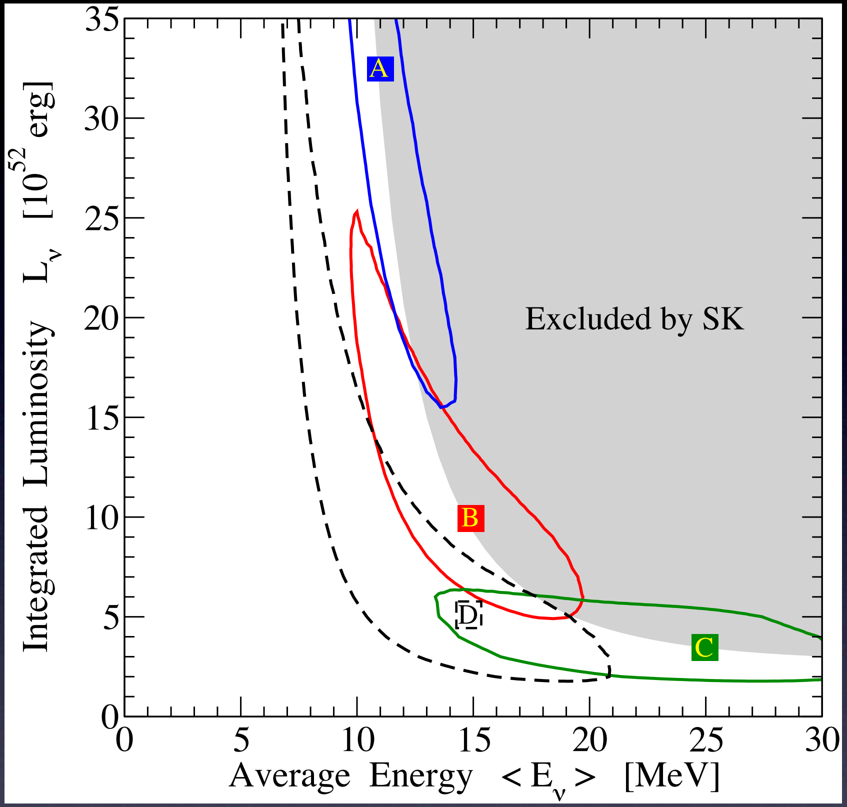


Model	SK-I	SK-II	SK-III	All	Predicted
Gas infall (97)	<2.1	<7.5	<7.8	<2.8	0.3
Chemical (97)	<2.2	<7.2	<7.8	<2.8	0.6
Heavy metal (00)	<2.2	<7.4	<7.8	<2.8	<1.8
LMA (03)	<2.5	<7.7	<8.0	<2.9	1.7
Failed SN (09)	<2.4	<8.0	<8.4	<3.0	0.7
6 MeV (09)	<2.7	<7.4	<8.7	<3.1	1.5

Super-K, *Phys. Rev. D* **85**, 052007 (2012)

Future prospects



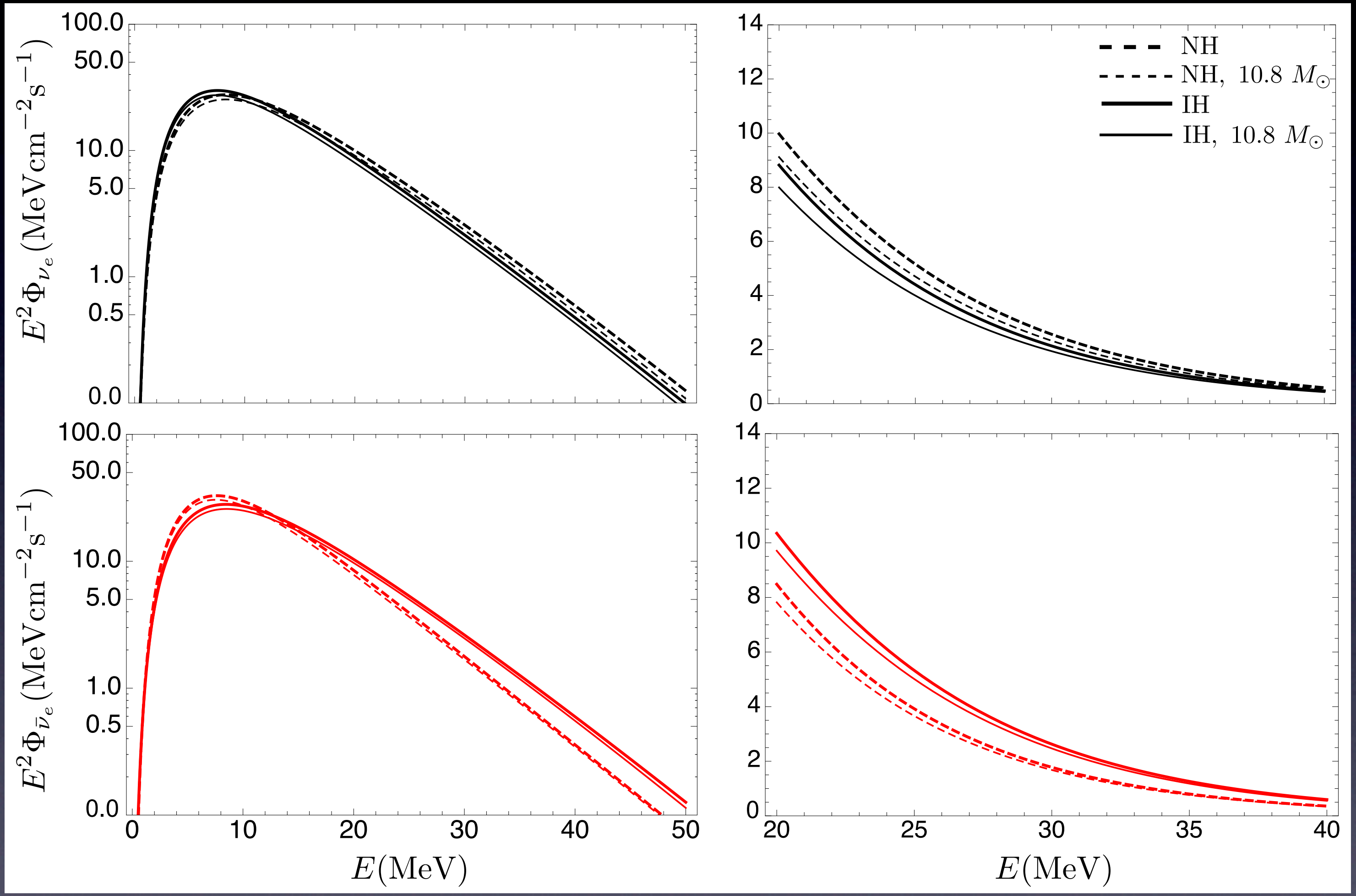


Yuksel, Ando, Beacom, *Phys. Rev. C* **74**, 015803 (2006)

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

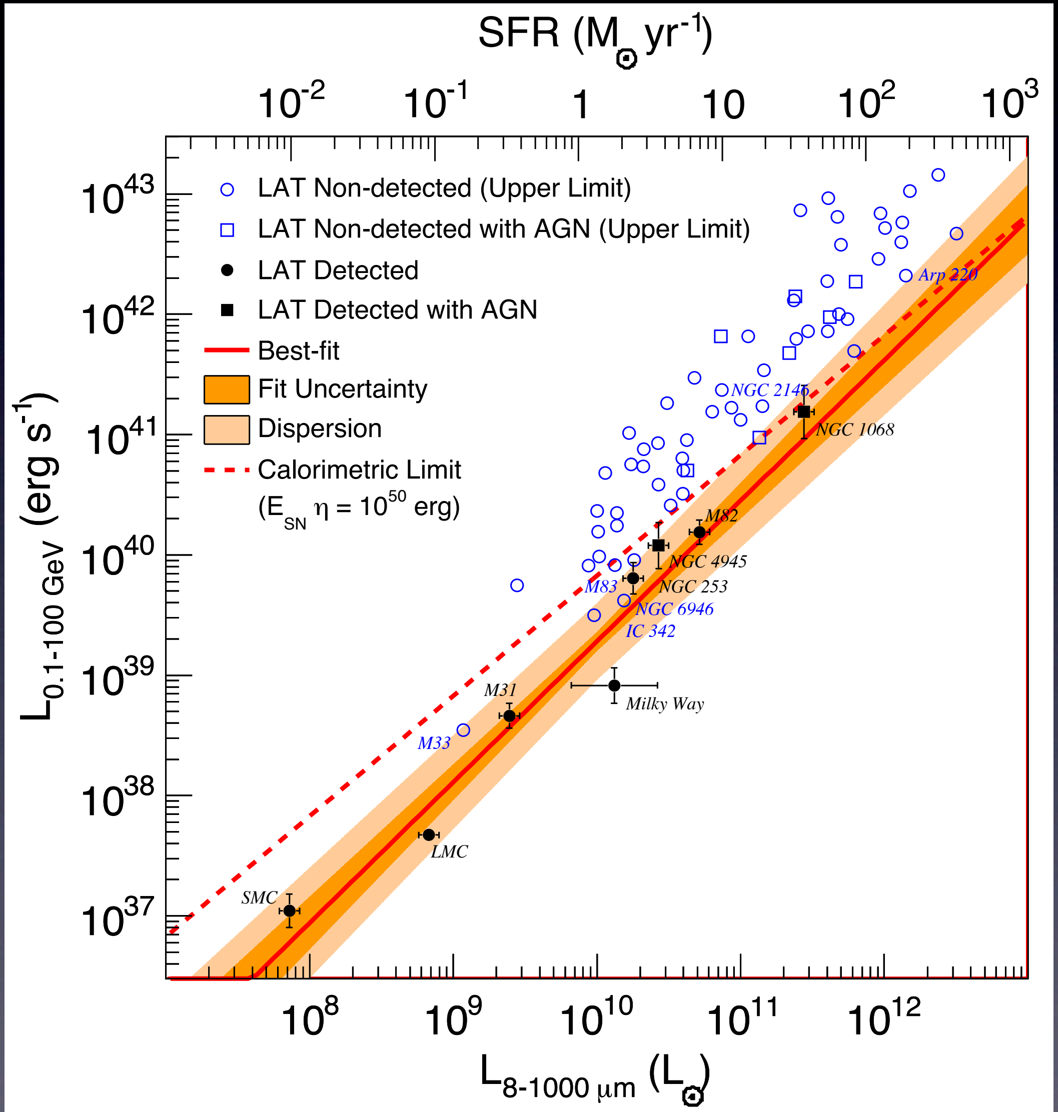
Learning SN model or neutrino parameters

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...

γ-ray luminosity vs SFR



Fermi-LAT, *Astrophys. J.* **755**, 164 (2012)

Intermediate regime?

Super-K

	N_{det}
Galactic SN	$\sim 10^4$ Clear "burst" detection
Beyond	$<< 1$ contribute to DSNB

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Megaton

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Galactic SN	$\sim 10^5$ Clear "burst" detection
Galaxies around 1–3 Mpc	1–10
Beyond	<< 1 contribute to DSNB

Intermediate regime?

Super-K

	N_{det}
Galactic SN	~10^4 Clear “burst” detection
Beyond	<< 1 contribute to DSNB

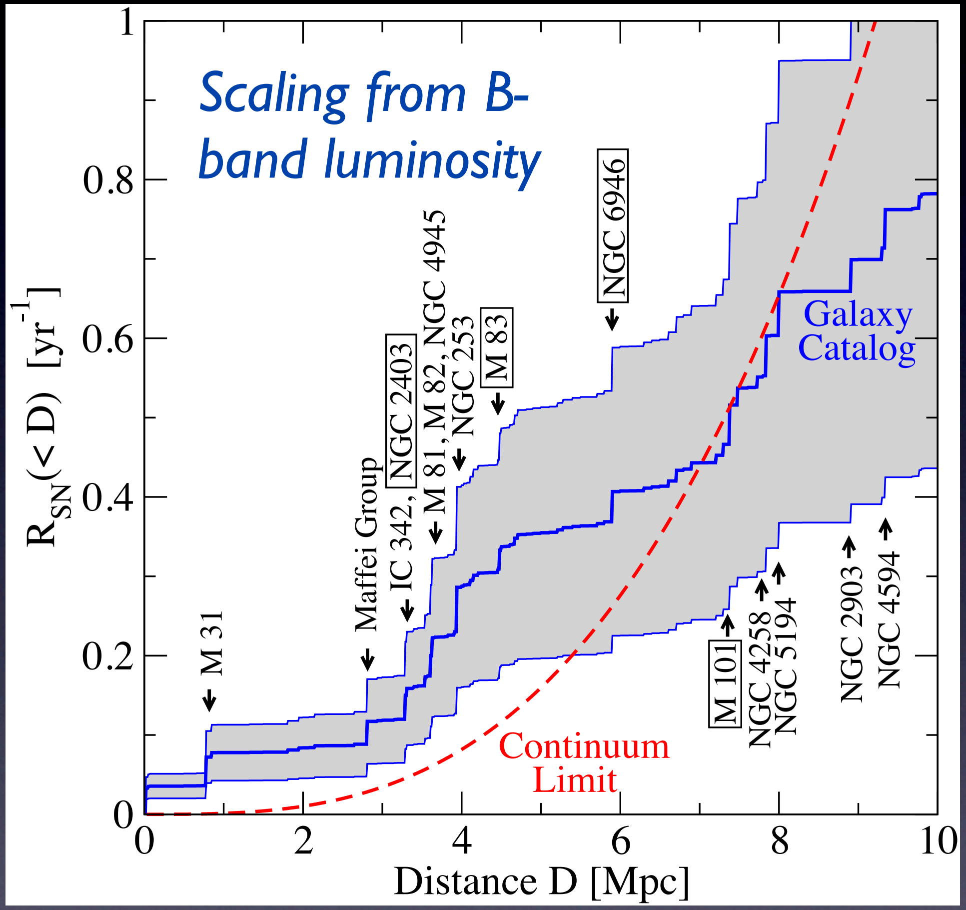
Megaton

	N_{det}
Galactic SN	~10^5 Clear “burst” detection
Galaxies around 1–3 Mpc	1–10
Beyond	<< 1 contribute to DSNB

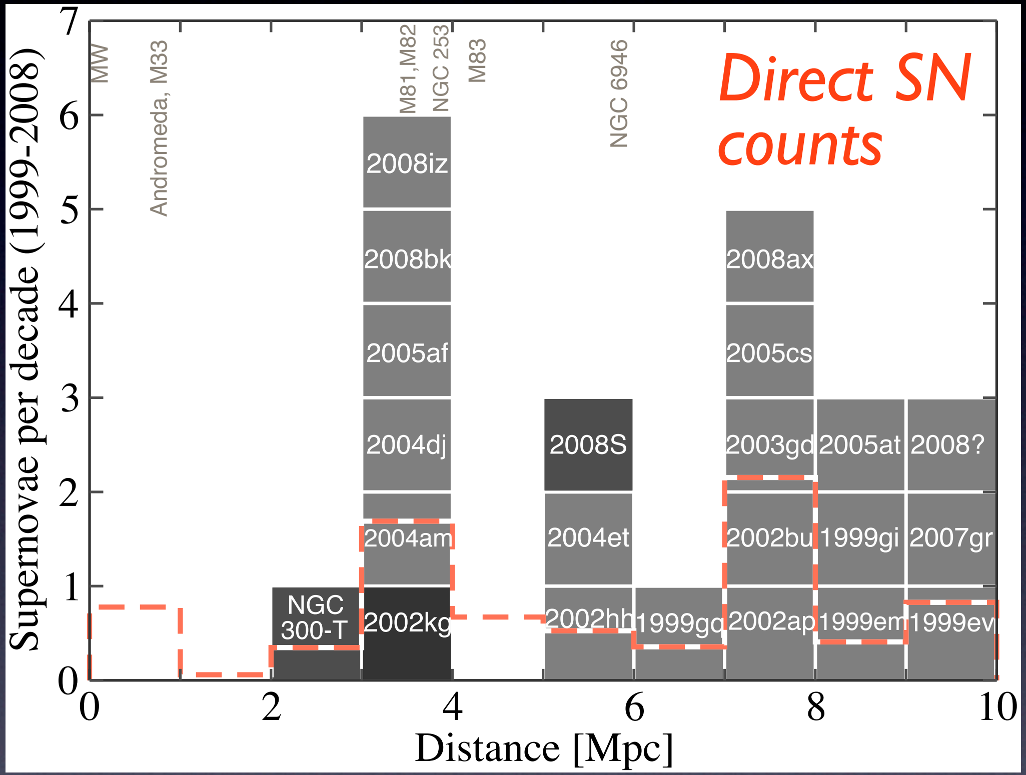
- Study of SN neutrino parameters
- Reconstruct luminosity evolution
- Help look for gravitational waves, etc.

SN frequency in local volume

Ando, Beacom, Yuksel, *Phys. Rev. Lett.* **95**, 171101 (2005)

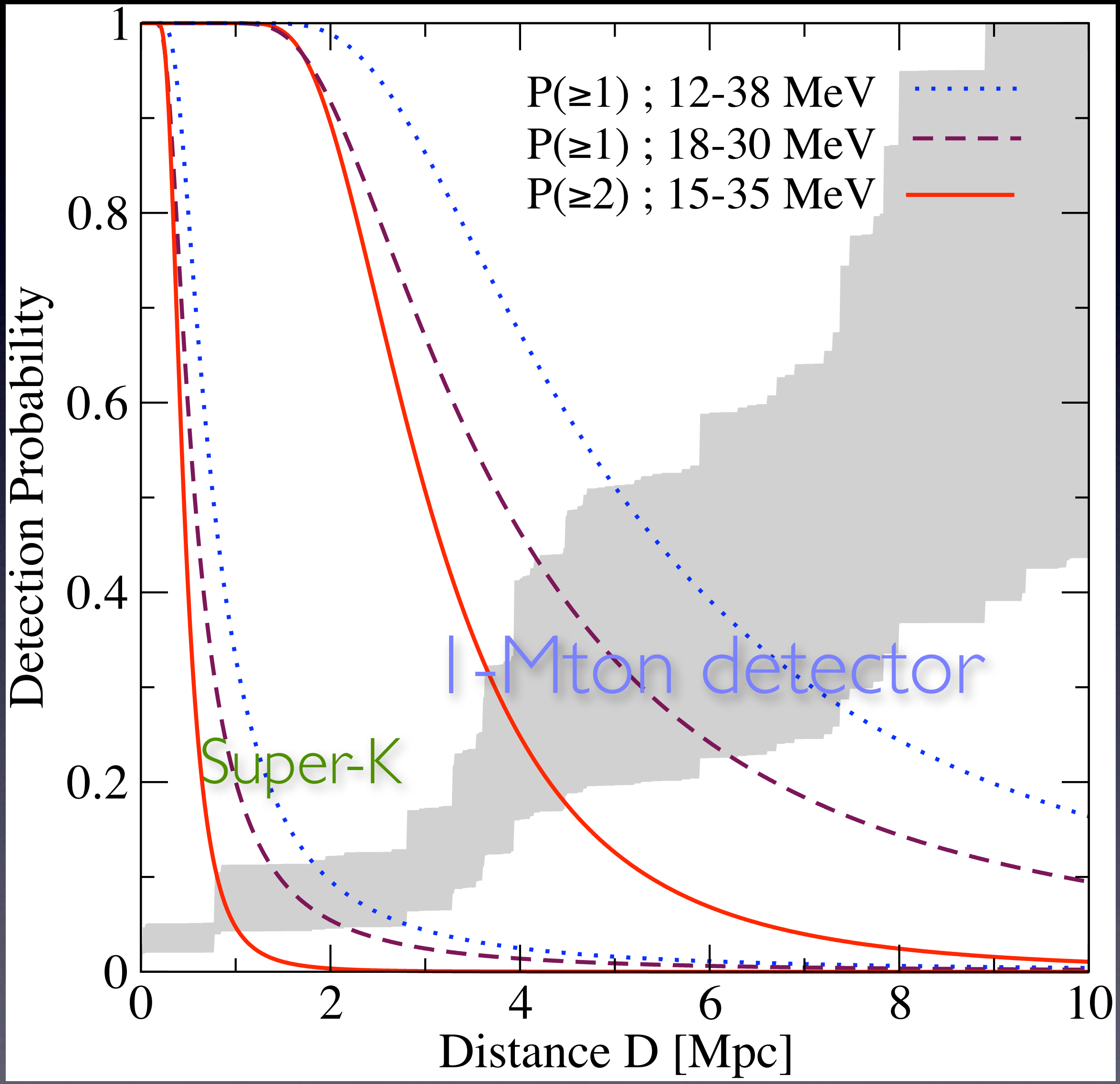


Kistler, Yuksel, Ando, Beacom, Suzuki, *Phys. Rev. D* **83**, 123008 (2011)



- Only M31 (Andromeda) within ~3 Mpc
- A few starburst galaxies (M82, NGC 253) around 3–4 Mpc; cumulative SN rate of ~1 yr^{-1} within 4 Mpc

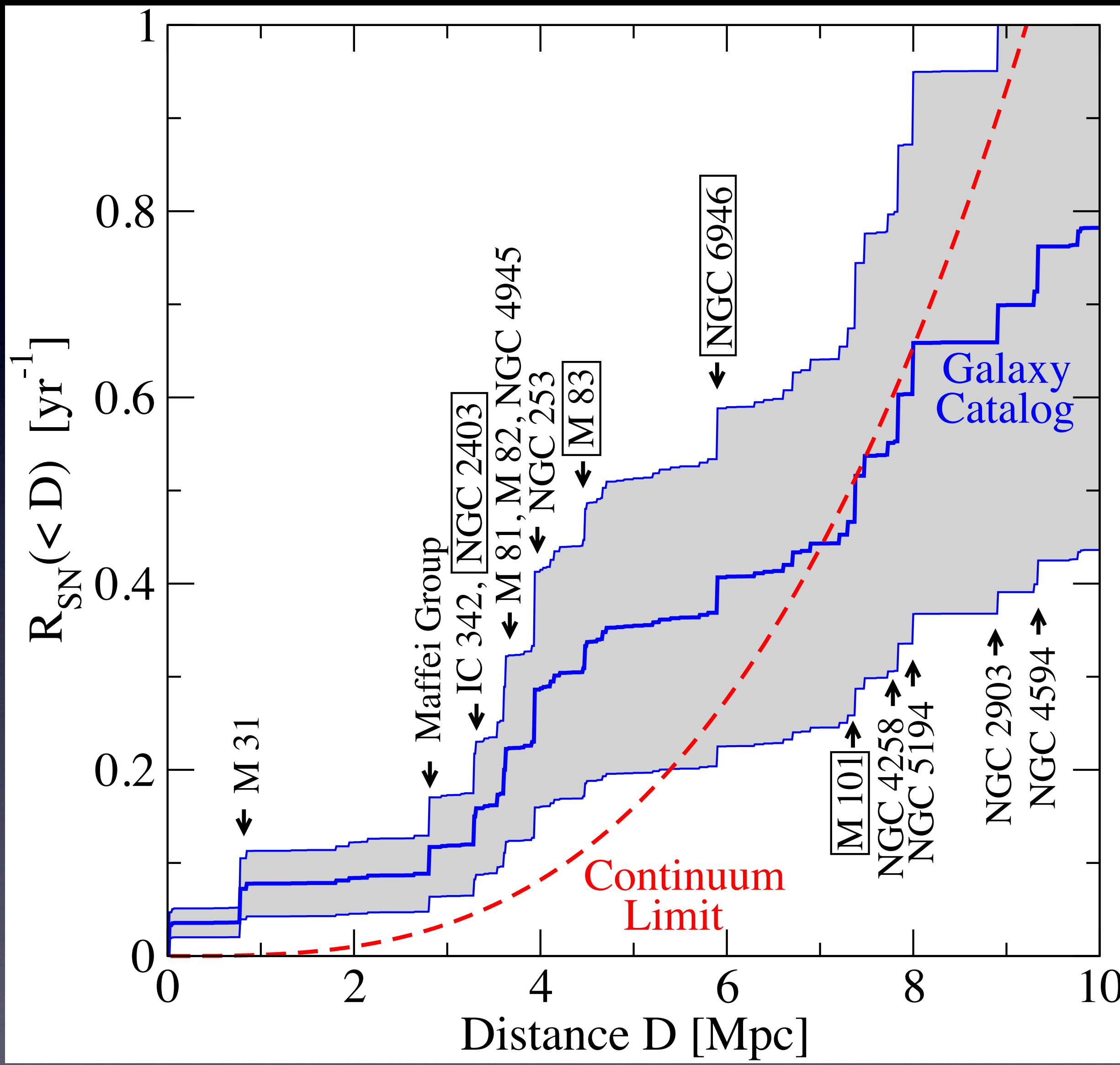
How well can Megaton detectors perform?



Ando, Beacom, Yuksel, *Phys. Rev. Lett.* **95**, 171101 (2005)

- Reasonable chance of detecting multiple ν events per burst at ~3 Mpc
- Small background

What would happen if we had 5-Mton detector?



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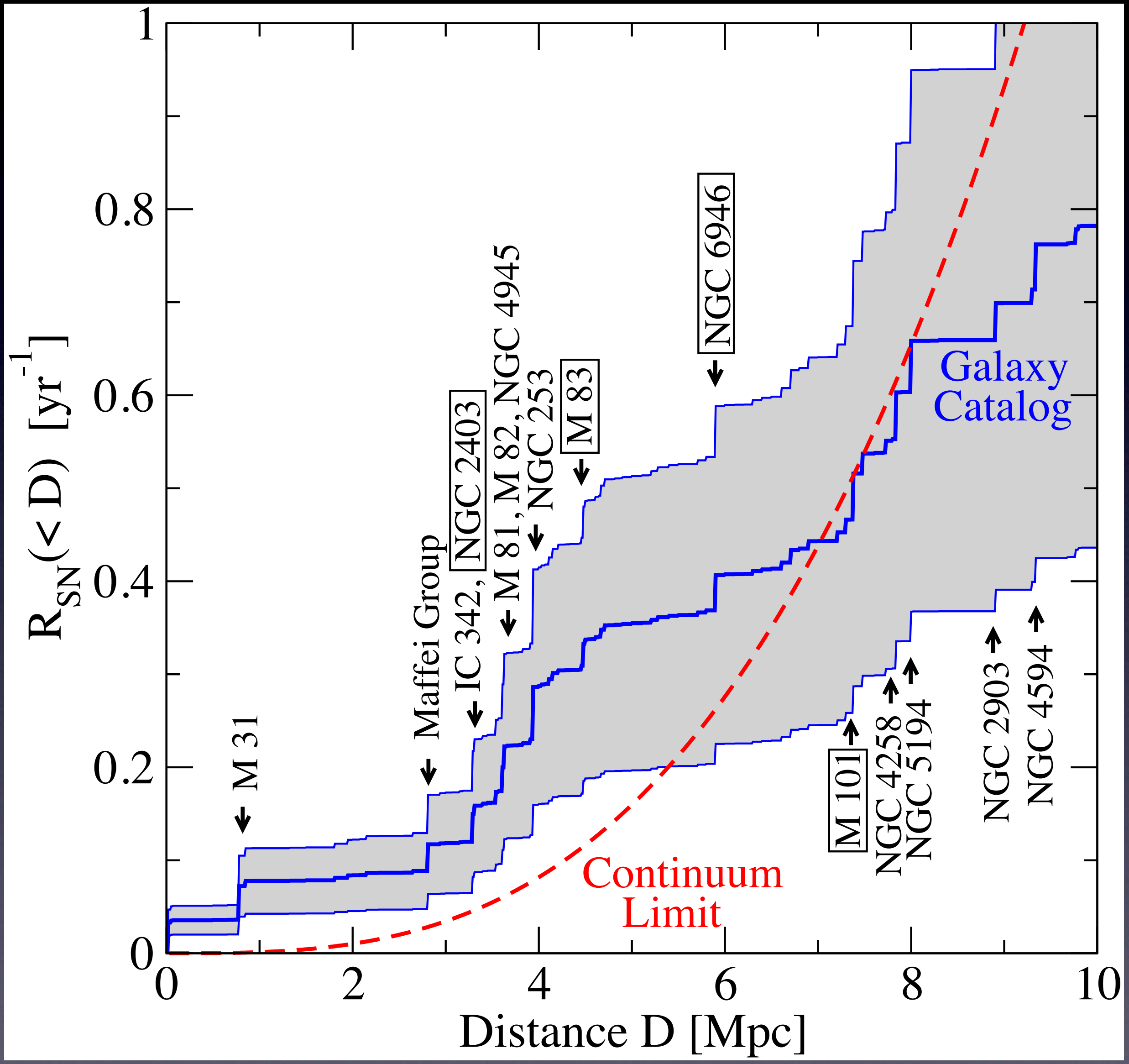

- Reach of *burst mode* (≥ 5 events)
- Scaled by 10^4 events from a supernova at 10 kpc at 32 kton detector

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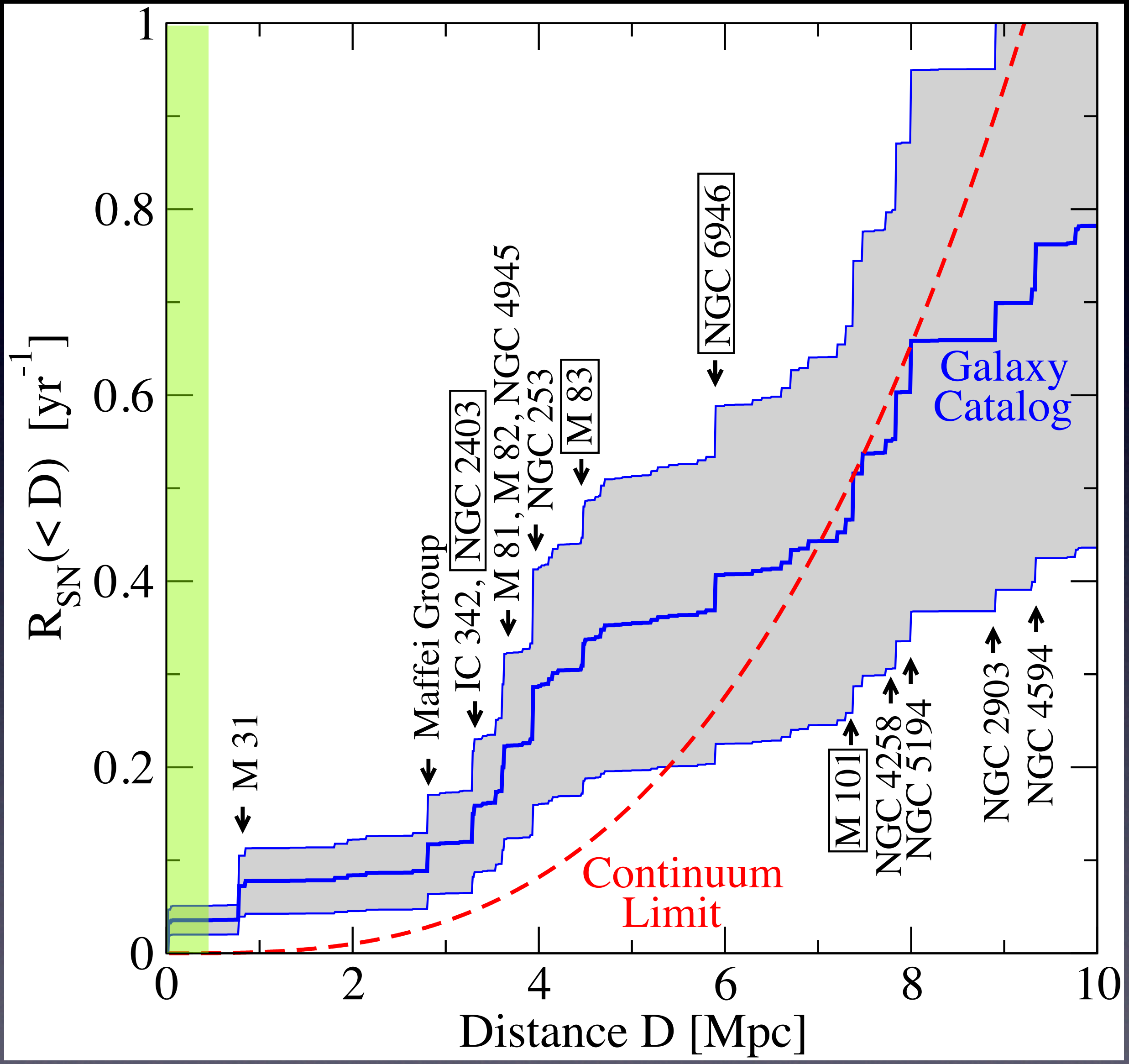

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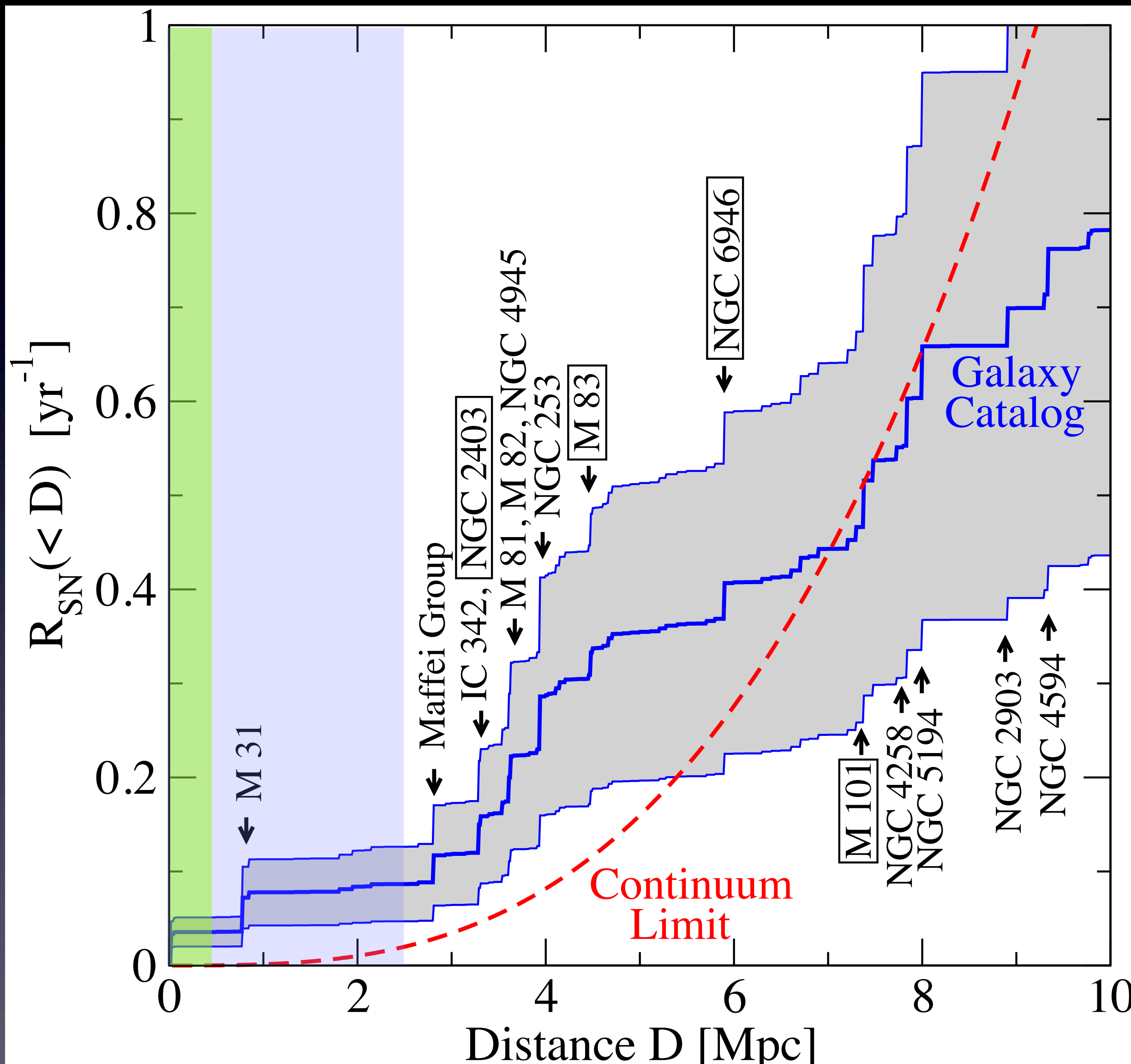

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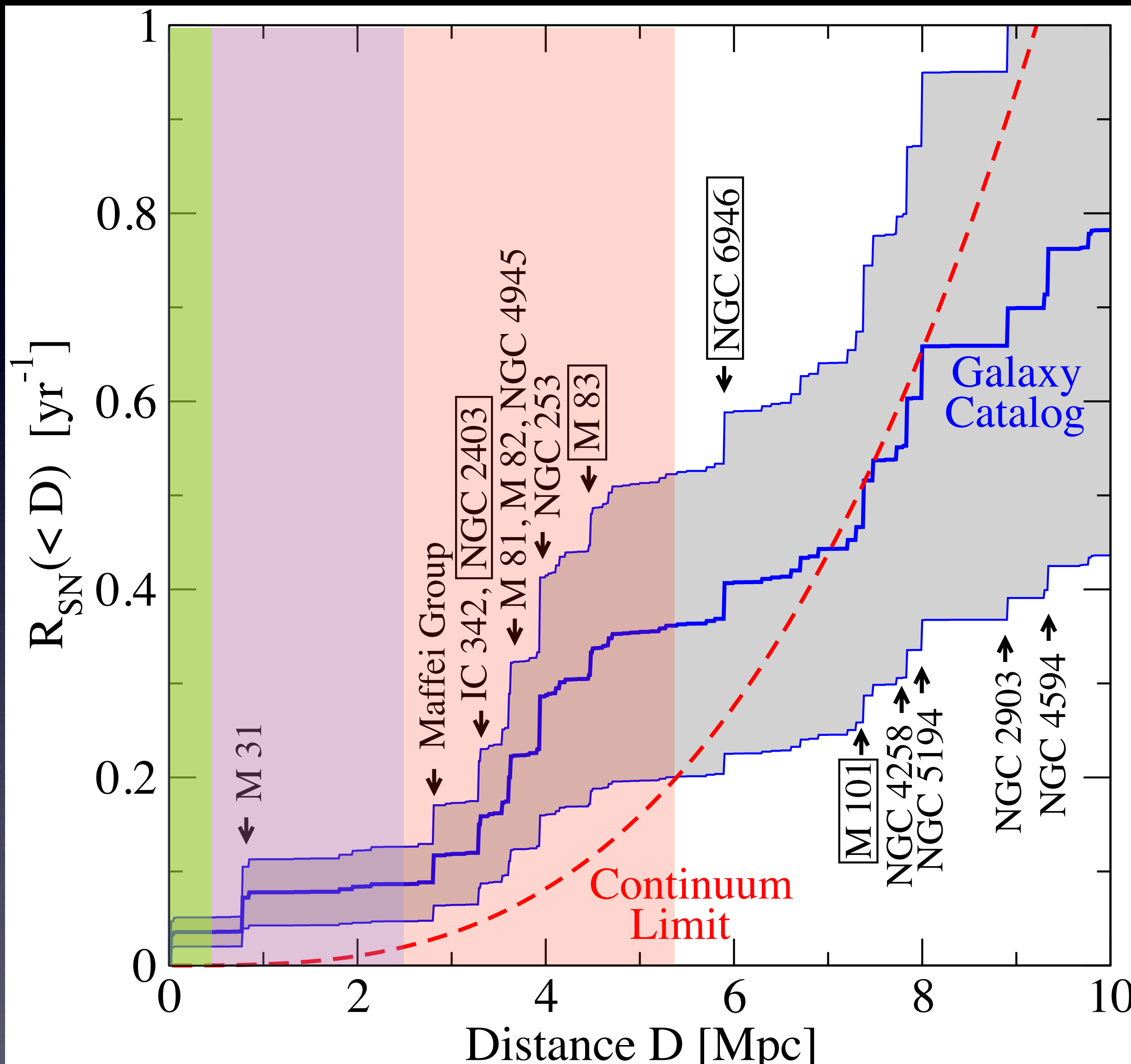

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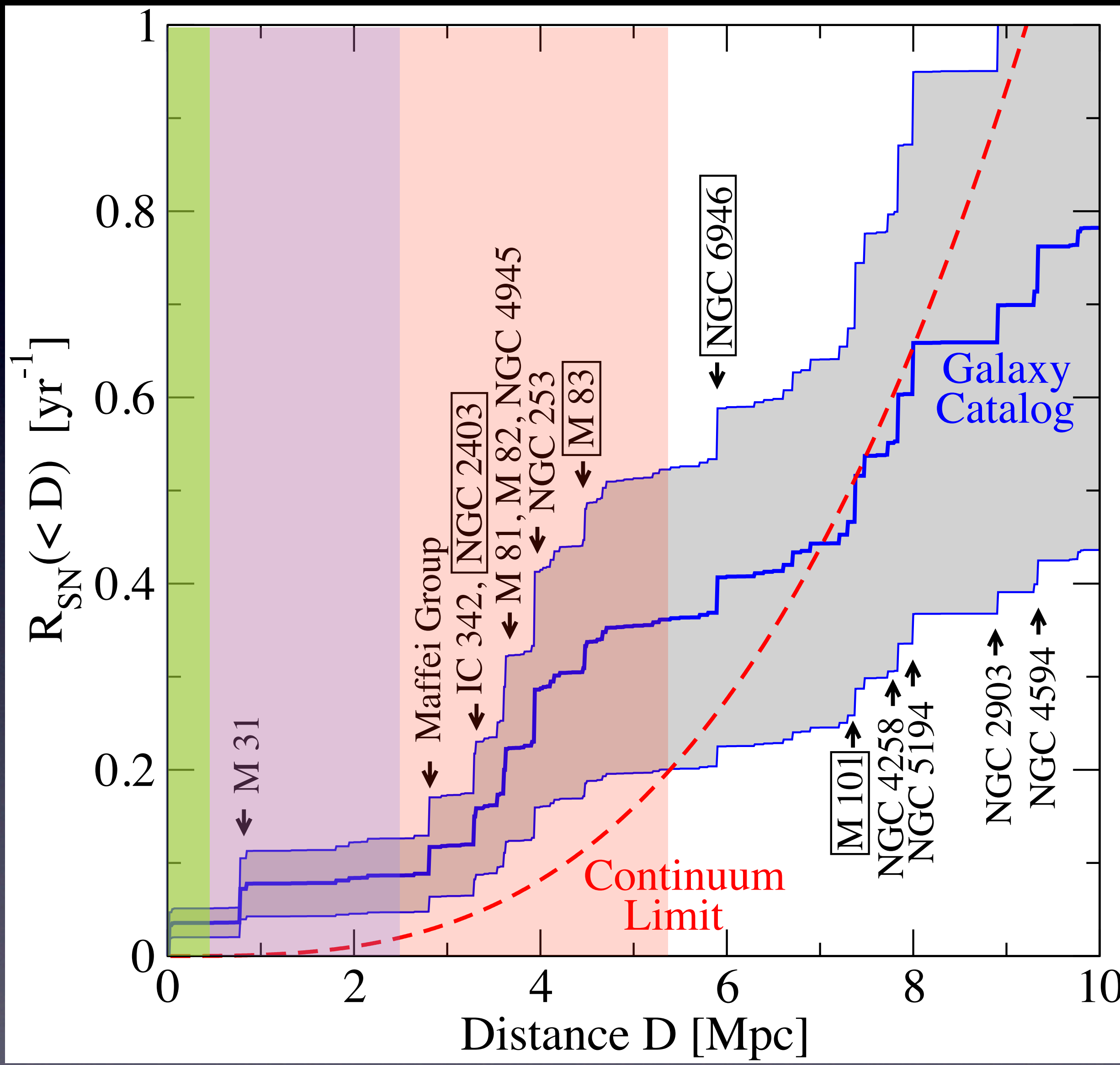


32 kton

1 Mton

5 Mton

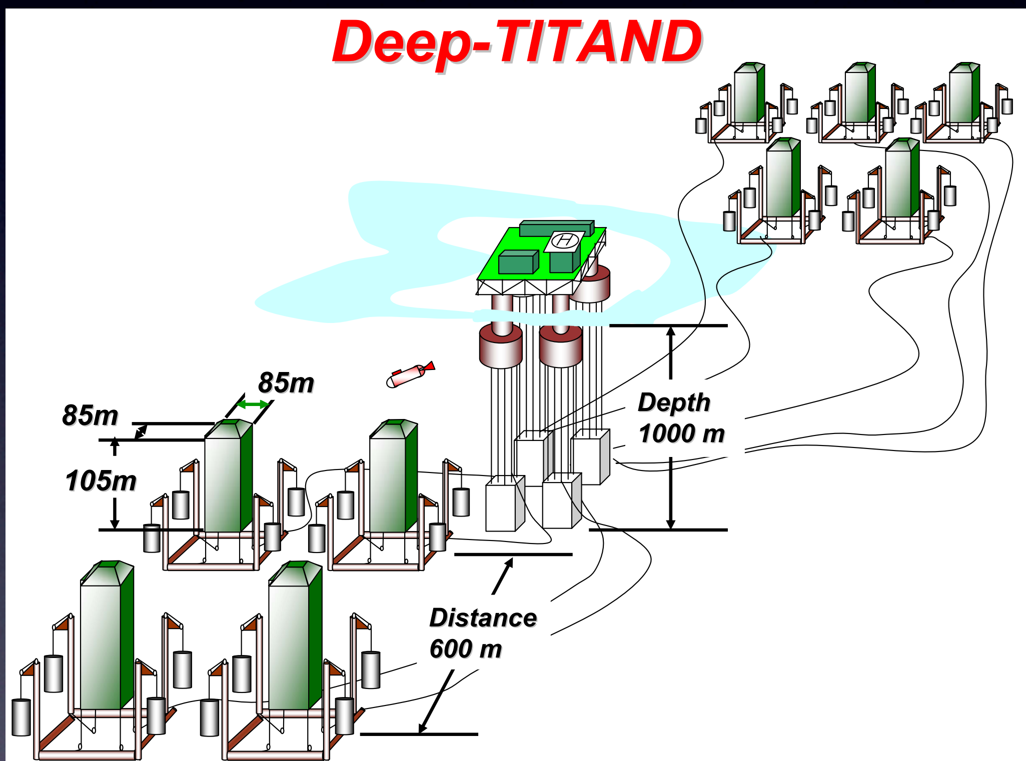
- Reach of *burst mode* (≥ 5 events)
- Scaled by 10^4 events from a supernova at 10 kpc at 32 kton detector
- 5-Mton detector can take us beyond the "desert"

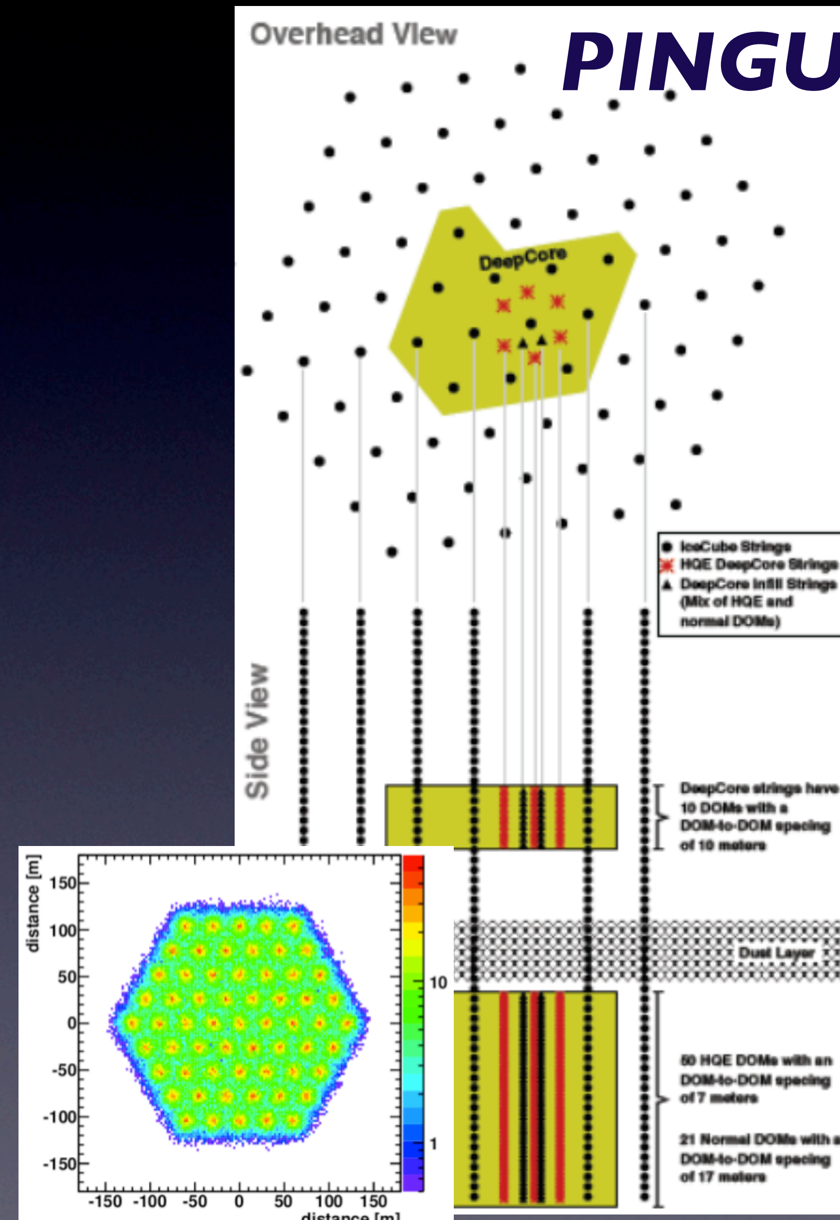
What could have been done

Kistler, Yuksel, Ando, Beacom, Suzuki, *Phys. Rev. D* **83**, 123008 (2011)

SN	Type	Host	D [Mpc]	ν events
2002hh	II-P	NGC 6946	5.6	2.4
2002kg	IIn/LBV	NGC 2403	3.3	6.8
2004am	II-P	NGC 3034 (M82)	3.53	5.9
2004dj	II-P	NGC 2403	3.3	6.8
2004et	II-P	NGC 6946	5.6	2.4
2005af	II-P	NGC 4945	3.6	5.7
2008S	IIn	NGC 6946	5.6	2.4
2008bk	II-P	NGC 7793	3.91	4.8
2008iz	II?	NGC 3034 (M82)	3.53	5.9
NGC 300-T	II?	NGC 300	2.15	16.0

Two projects for multi-Mton detector





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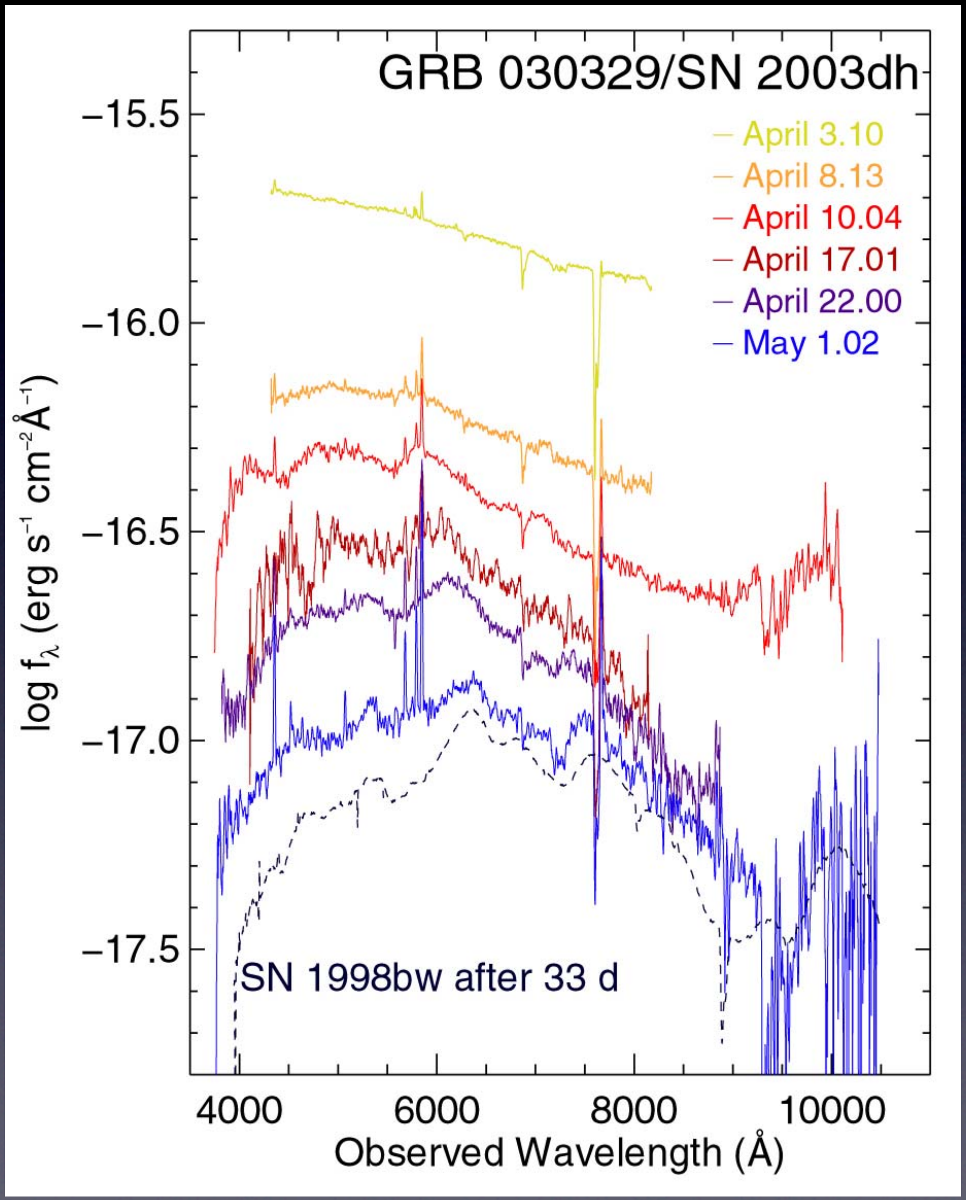
IR/optical/UV

- High-energy neutrinos
  - GRB–SN association
  - Joint detection of GW and HEν

X/γ/GW

Long GRB-supernova association



Hjorth et al. 2003; Stanek et al. 2003

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

	SN	GRB
Energy	10^{51} erg	10^{51} erg
Rate	~1 cen^{-1} gal^{-1}	~1 Myr^{-1} gal^{-1}
Γ	~1	~100–10^3

Are there sources in between?

Are there "dark" GRBs?

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

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

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

More baryons → more neutrino production
Could be strong GW sources
Unknown rate but could be large

Unrevealed supernova-GRB connection?

	SN	"Failed" GRB	GRB
Energy	10^{51} erg	10^{51} erg	10^{51} erg
Rate/gal	$\sim 10^{-2}$ yr^{-1}	10^{-5}–10^{-2} yr^{-1}	$\sim 10^{-5}$ yr^{-1}
Γ	~1	~3–100	~100–10^3

Barion rich
Nonrelativistic
Frequent

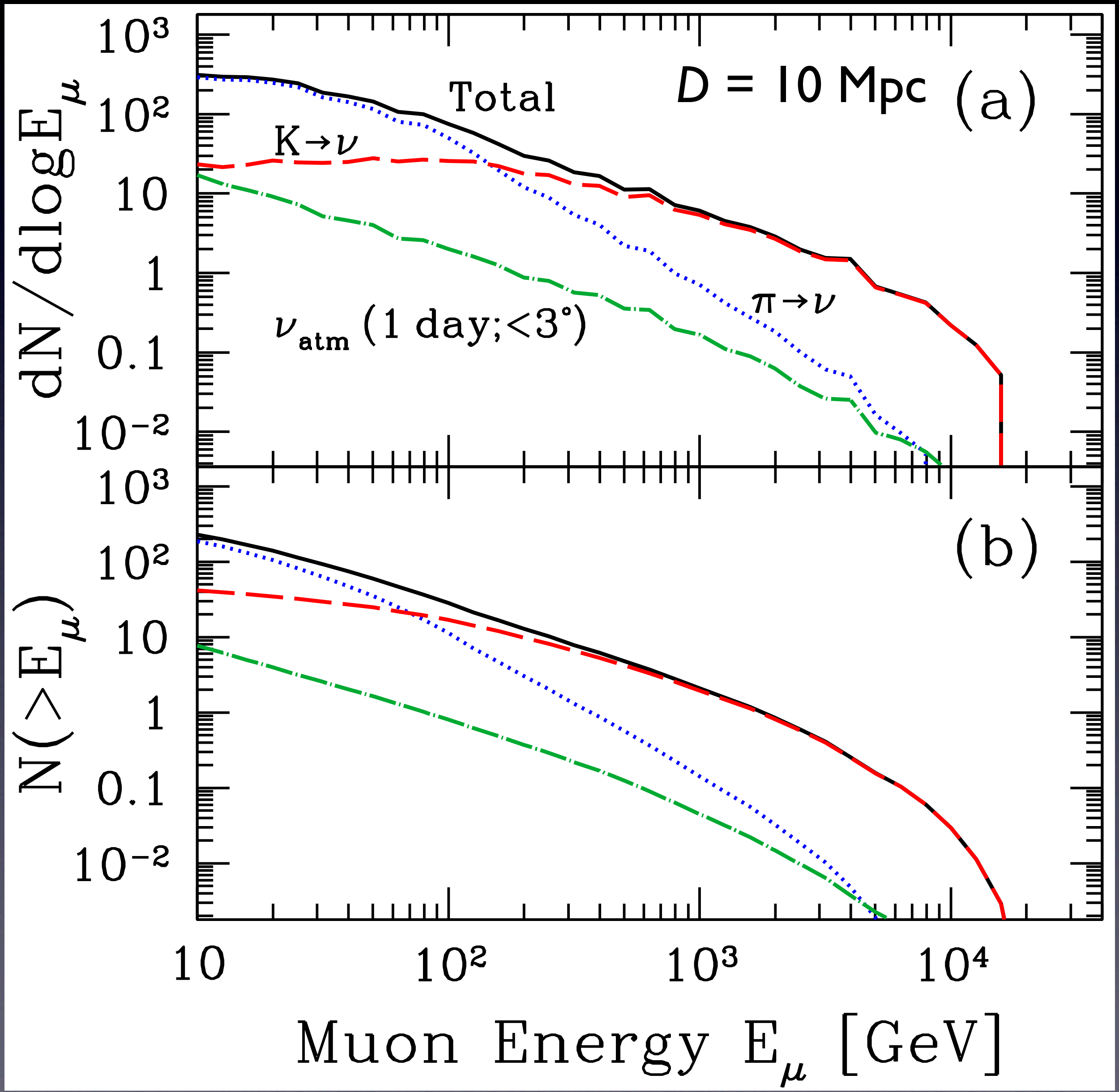
Baryon poor
Relativistic jets
Rare

Similar kinetic energy

- Evidence of mildly relativistic jets:
  Kulkarni et al. 1998; Berger et al. 2003; Totani 2002; Granot & Ramirez-Ruiz 2004; van Putten 2004; Soderberg et al. 2004, 2006, 2008, etc.

Events at km^3 detectors

Ando, Beacom, *Phys. Rev. Lett.* **95**, 061103 (2005)



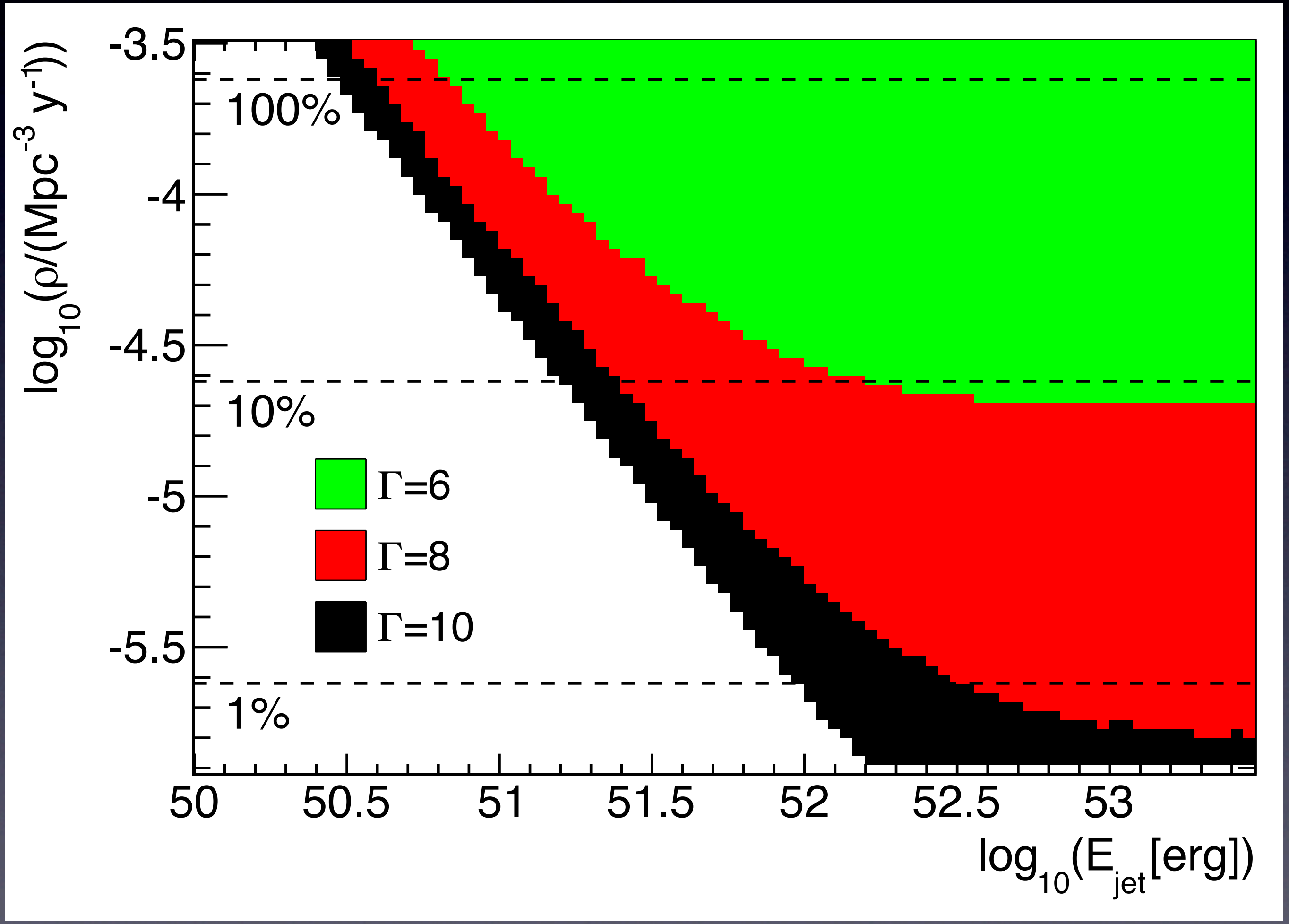
- E = 3 x 10^{51} erg; Γ = 3
- Expected events above 100 GeV:

  ~30 @ 10 Mpc

  ~3 @ 30 Mpc
- These events cluster within 10–100 s time and 3° angular bins
  - Extremely low background

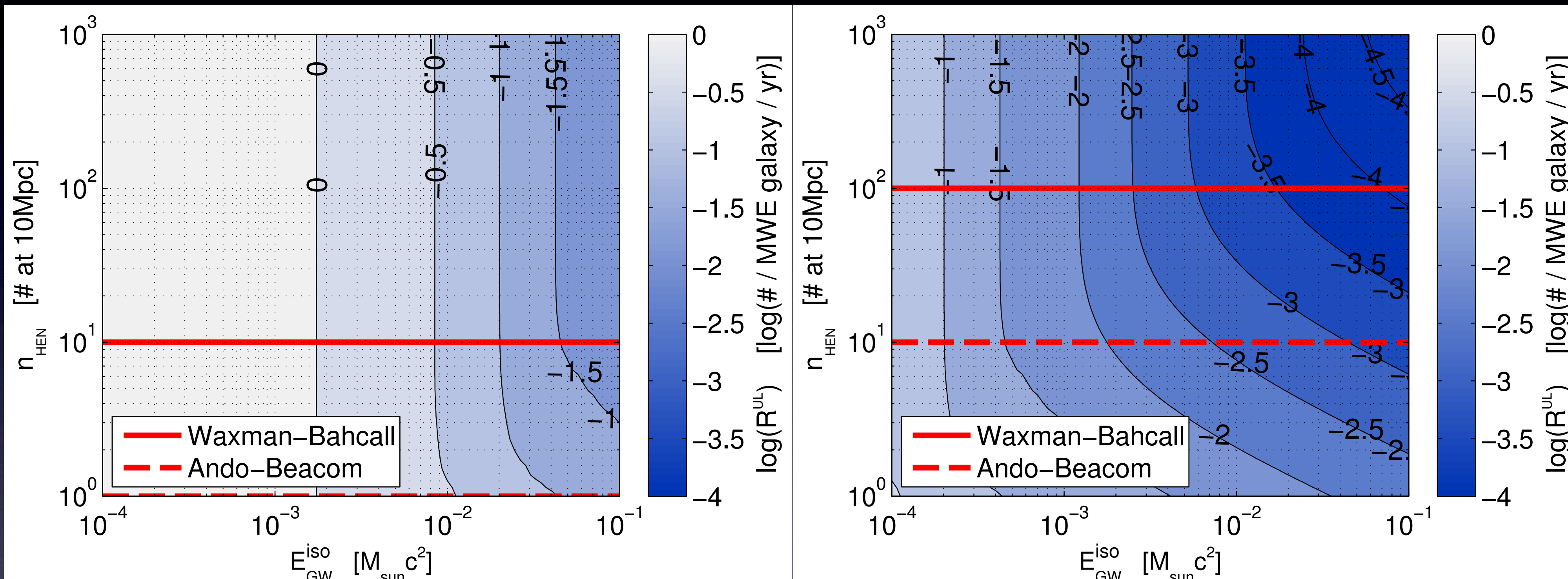
Upper limits by IceCube

Abbasi et al., *Astron. Astrophys.* **539**, A60 (2012)



- No significant excess of multiple ν 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

Bartos et al. *Phys. Rev. Lett.* **107**, 251101 (2011)
Baret et al., *Phys. Rev. D* **85**, 103004 (2012)

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