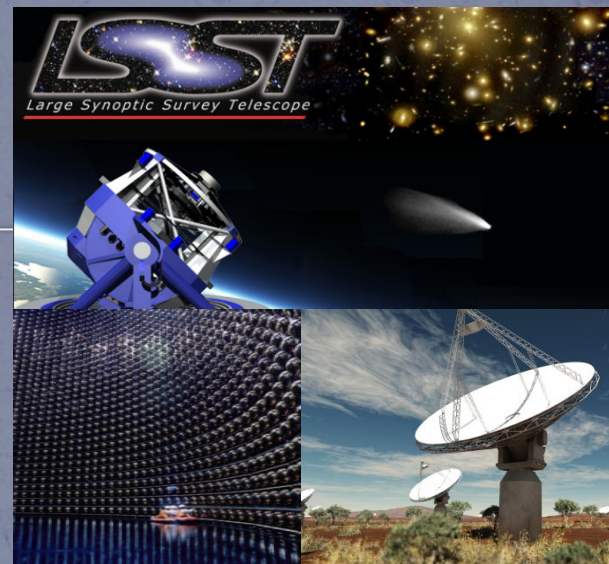
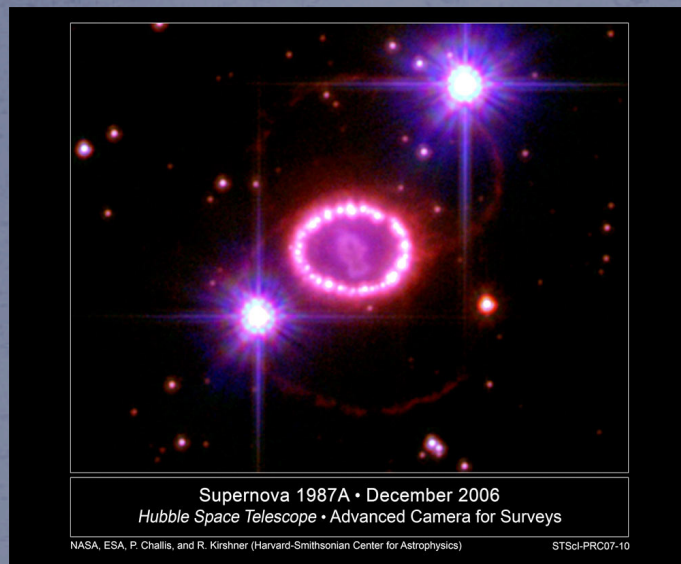


Revealing Optically Invisible Core-Collapse Supernovae in the Great Survey Era

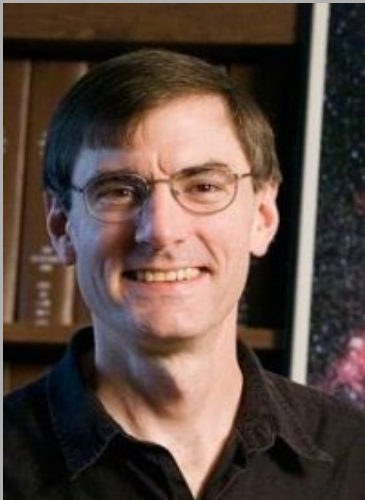


Amy Lien (連雅琳)

University of Illinois at Urbana-Champaign

Goddard Seminar, 2011/07/06

Special Thanks to



Brian Fields
(U of Illinois)



John Beacom
(Ohio State U)



Nachiketa Chakraborty
(U of Illinois)



Athol Kembball
(U of Illinois)

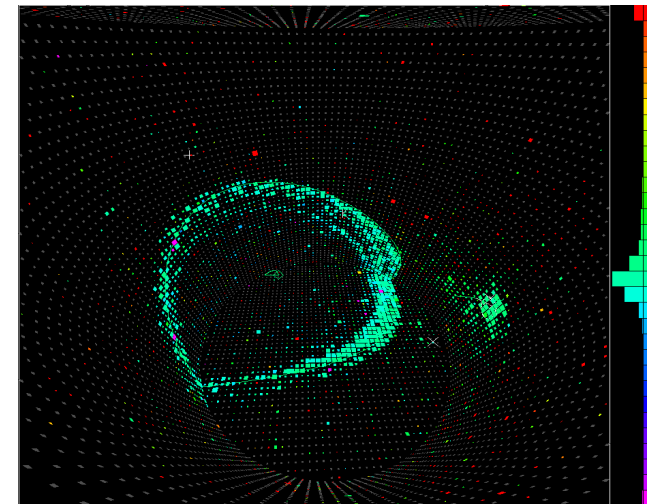
Outline

- 0 Core-collapse supernovae (CC SNe)
- 0 The Great Survey Era
 - 0 LSST
- 0 Probing optically invisible supernovae
 - 0 LSST & Neutrinos
 - 0 LSST & Radio Surveys
- 0 Conclusions

Core-Collapse Supernovae

- Observational Point of View

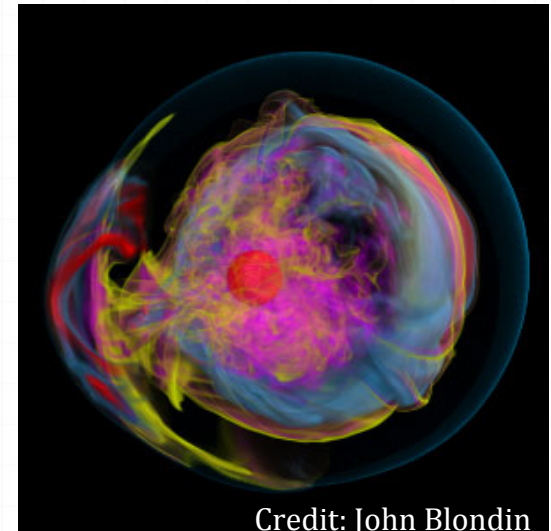
- 0 Explosions of massive stars
 - 0 Type Ib, Ic, and Type II
- 0 CC SN rate traces star formation rate
 - 0 CC SN rate $\propto$ star formation rate
- 0 99% of energy released in neutrinos
 - 0 1987A:
 - Only extrasolar/extragalactic detection



Core-Collapse Supernovae

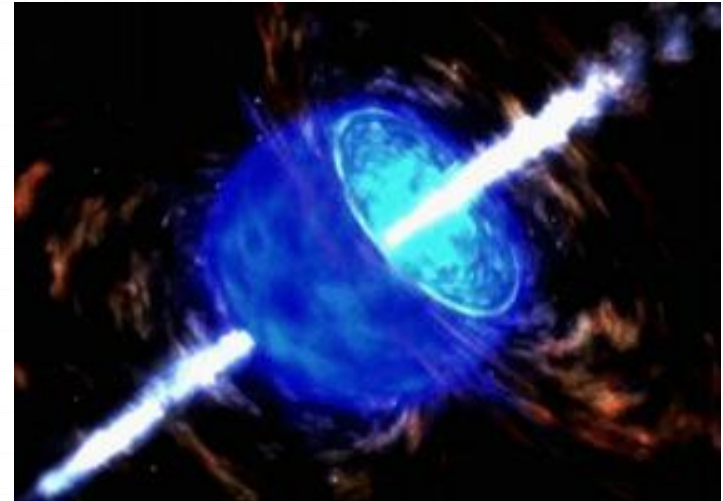
- Theoretical Point of View

- 0 Theoretical challenge
 - Hard to make them explode
- 0 Failed Supernovae/Collapsars? (Woosley et al.)
 - 0 Generally:
 - Black hole forming supernovae with dim or no optical signals
 - 0 In this talk:
 - Supernovae that collapse directly into black holes without optical outbursts

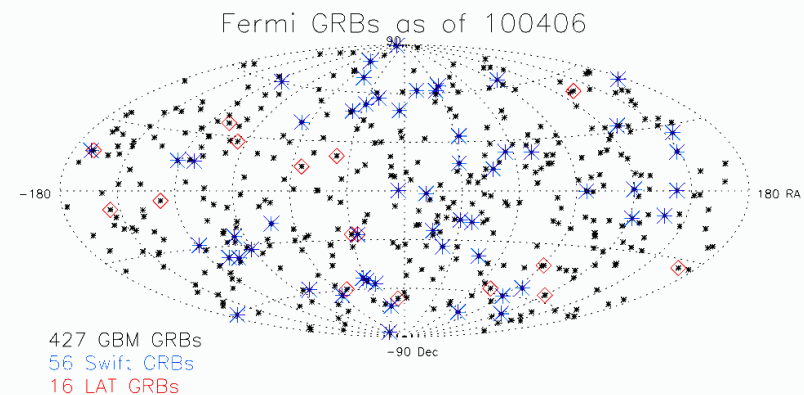


Failed Supernovae and GRBs

- 0 Failed supernovae:
Possible origins for the long
Gamma-Ray Bursts (GRBs)
- 0 Type Ibc supernovae
- 0 GRBs without visible
supernovae?
 - 0 GRB060505 (Ofek et al. 2007)
 - 0 GRB060614 (Gehrels et al. 2006)

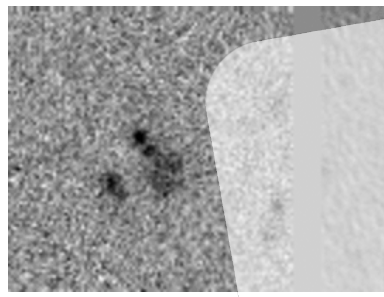


Credits: NASA/Dana Berry



G...g

- 0 Scanning sky (e.g. SDSS, DE... Factory, ...
- 0 Happening r... Transient



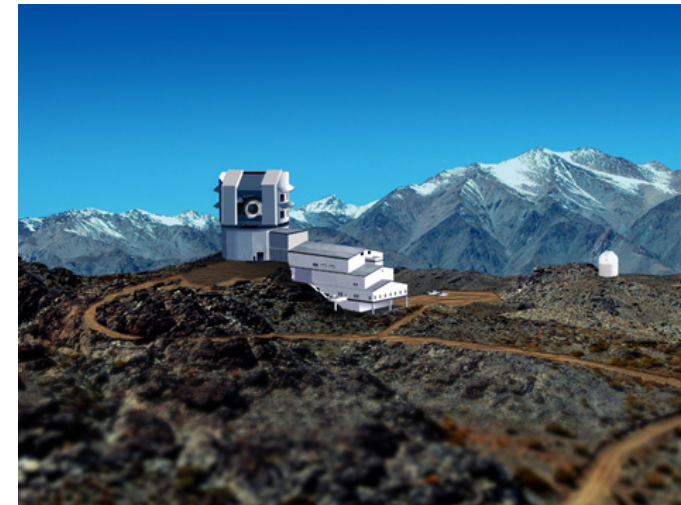
LSST
1st Ground-Based Survey
Starting in 2018!

- 0 2010 Decadal

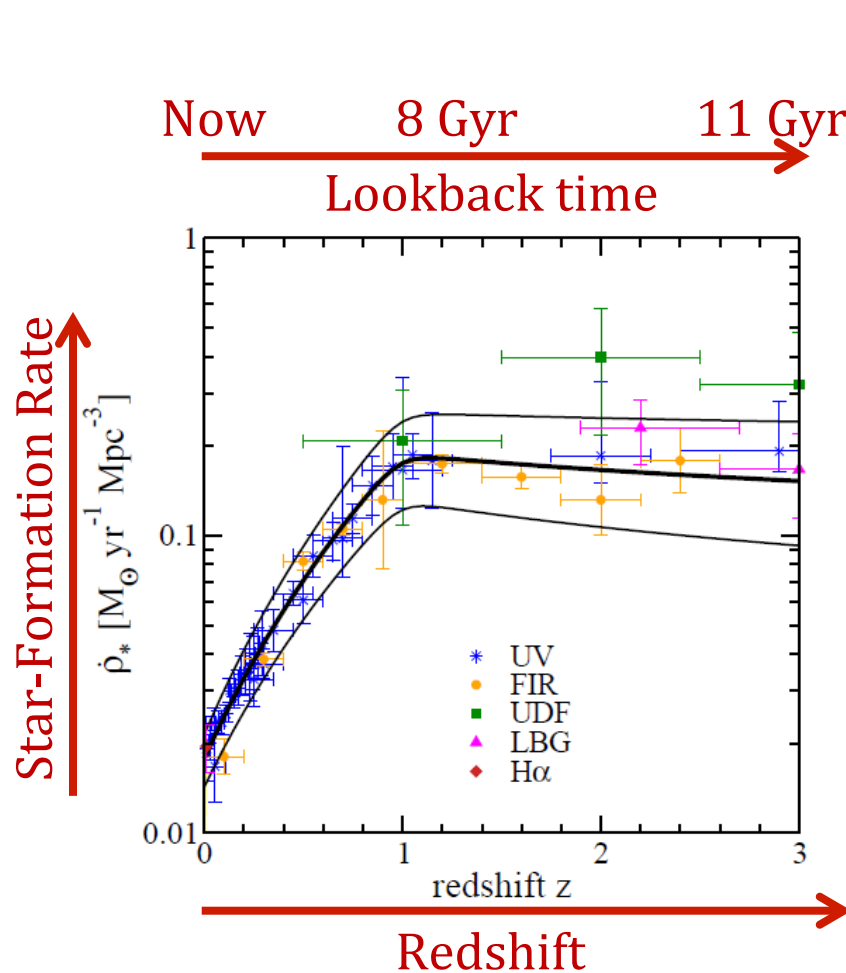


The Large Synoptic Survey Telescope (LSST)

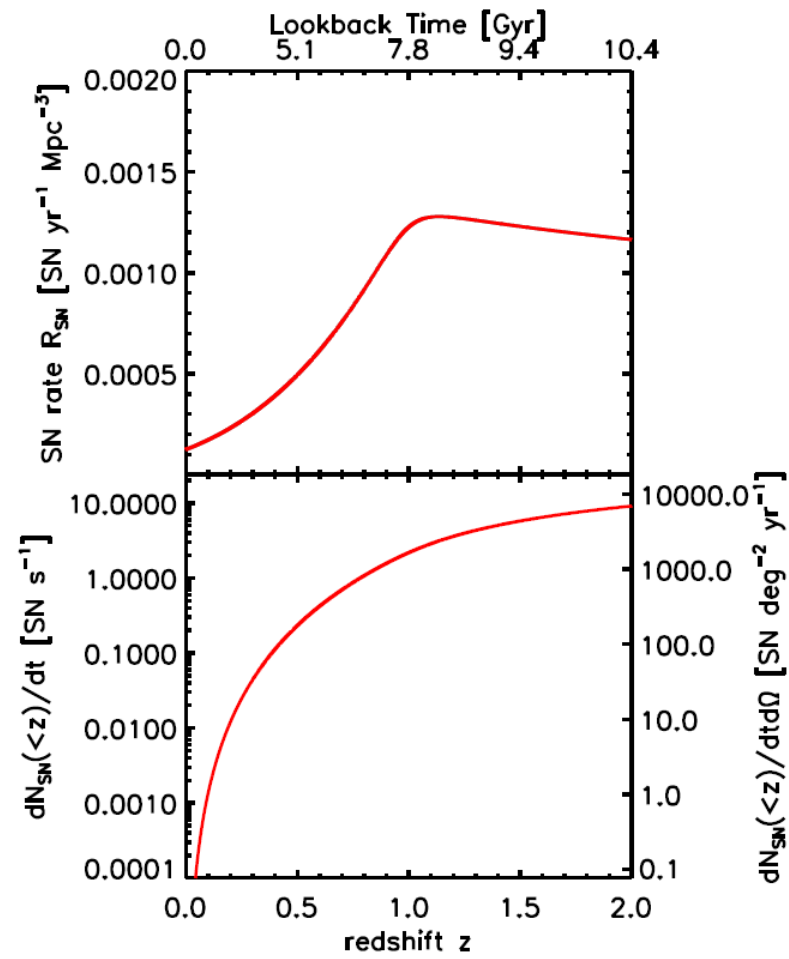
- 0 Synoptic: repeated-scan
- 0 Location: Cerro Pachón, Chile
- 0 Survey depth (flux sensitivity): $\sim 24^{\text{mag}}$
- 0 Large field of view:
9.6 deg² (~ 20 full moons)
- 0 Large Sky Coverage:
 $\sim 20,000$ deg² (entire night sky)
every ~ 3 nights



Cosmic Star-Formation Rate and Supernova Rate



Cosmic Star-Formation Rate
Horiuchi et al. (2009)

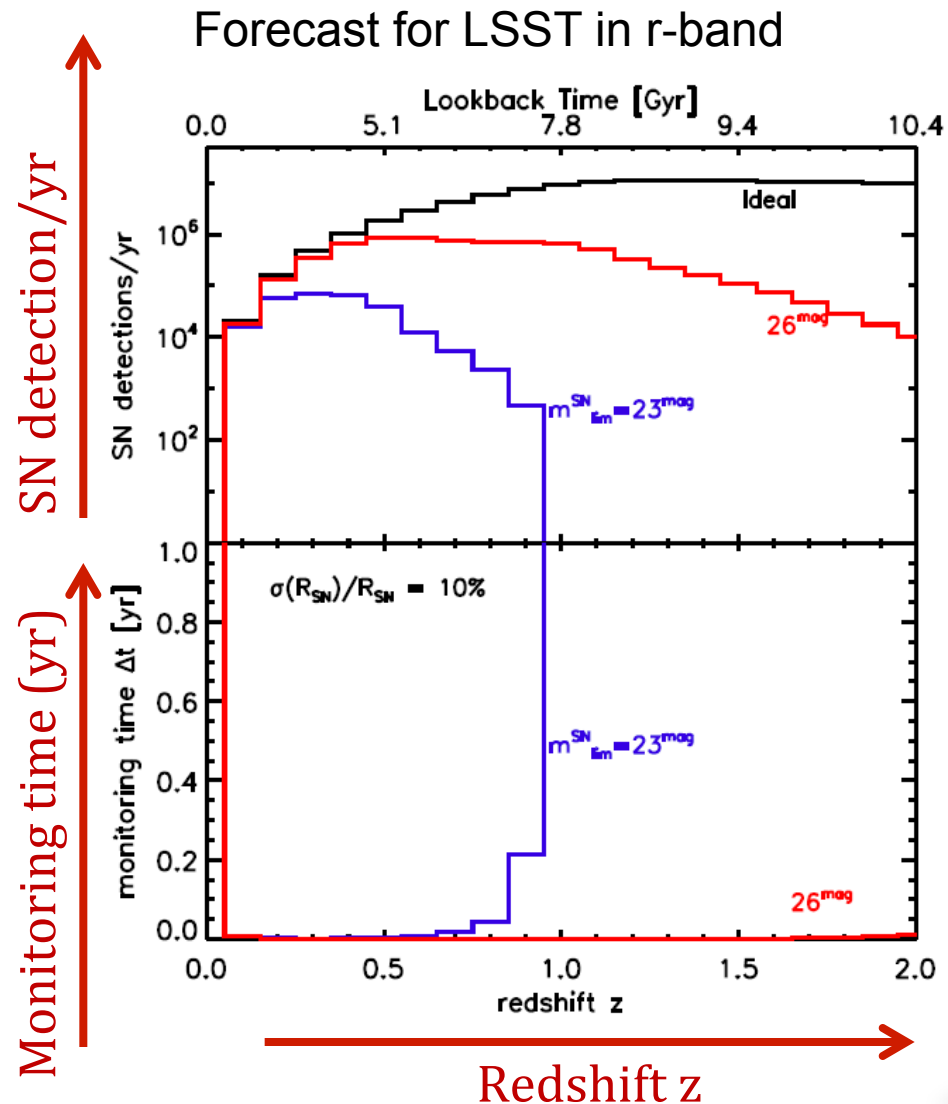


Cosmic Supernova Rate
Lien & Fields (2009)

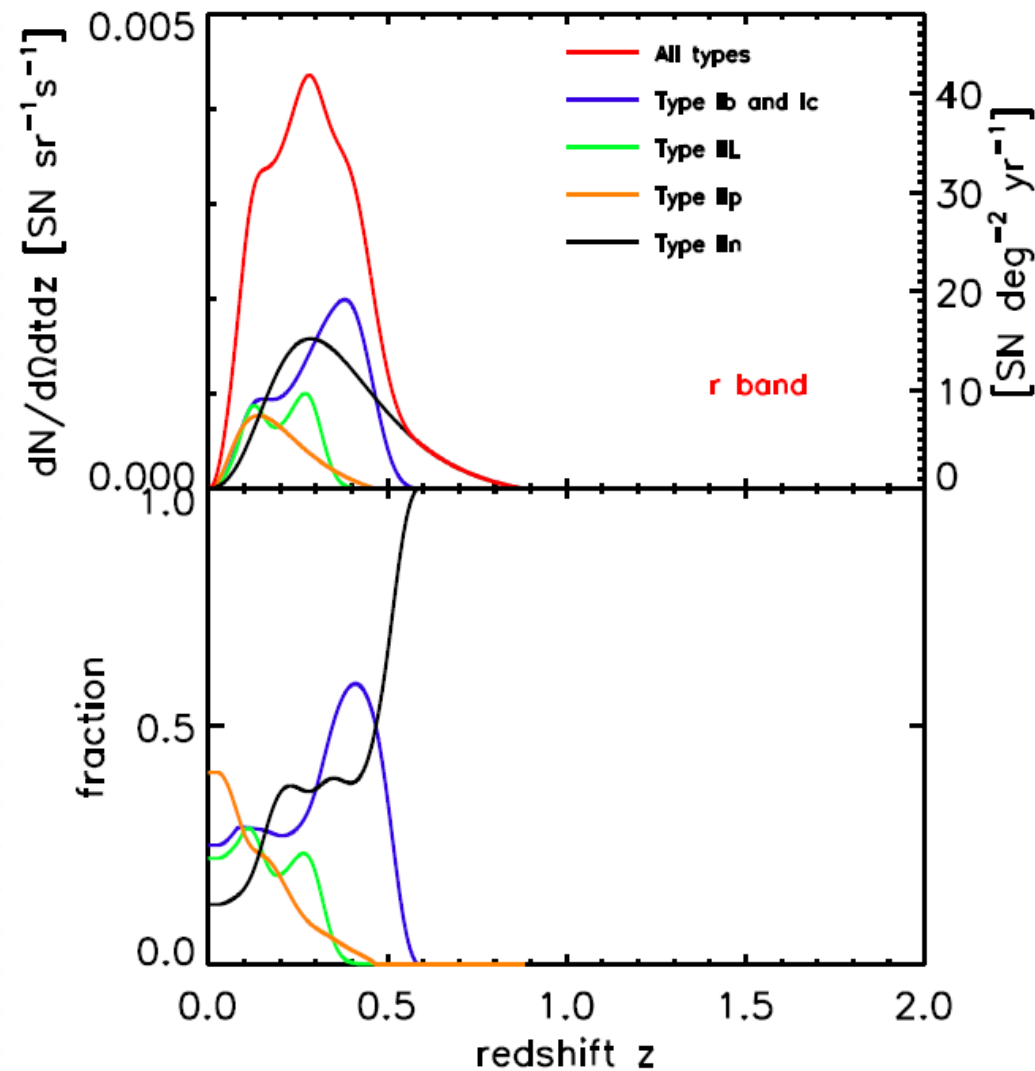
Forecasts for LSST

- 0 $> 10^5$ CC SNe per year to $z \sim 1$.
- 0 SN rate by direct counting!
- 0 $< 10\%$ statistical precision for the CC SNe rate in one year of detection (current uncertainty $> 40\%$).
- 0 LSST plot:
 - 0 Scan area: 20000 deg^2
 - 0 Proposed limiting magnitude for SNe: 23^{mag}
 - 0 Bin size: $\Delta z = 0.1$

Lien & Fields (2009)

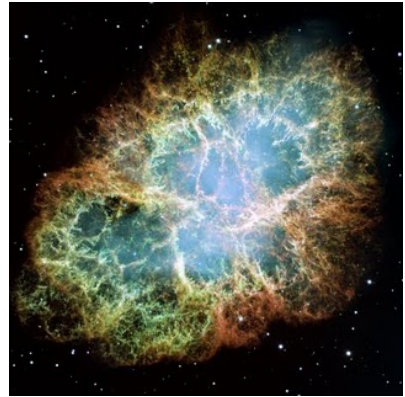
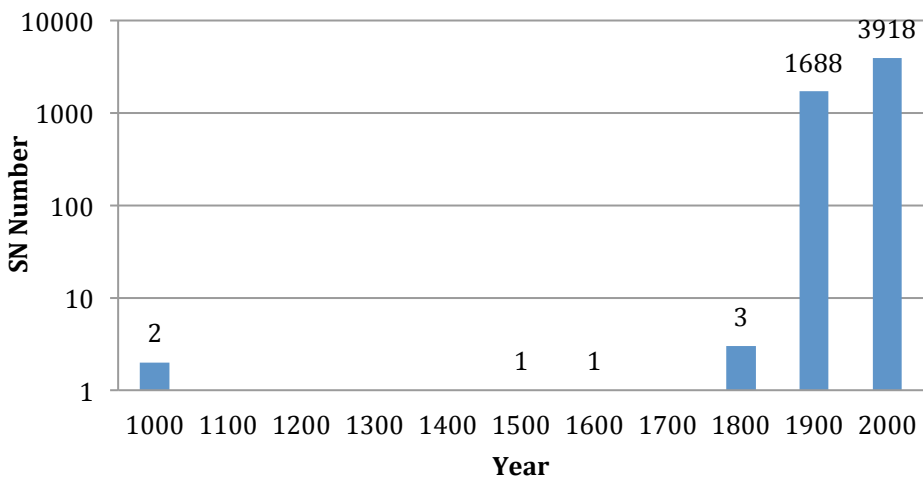


Forecast of SN detection in Types

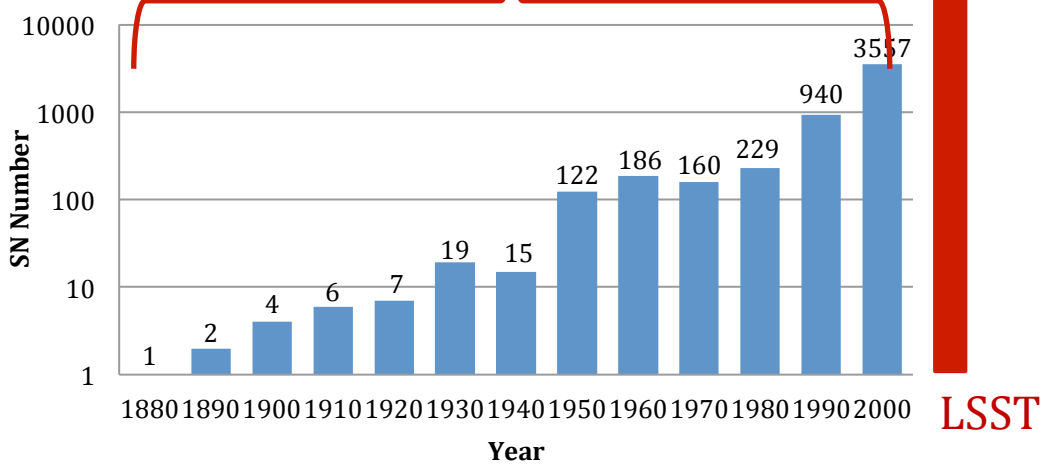


How Many is 1 Million Supernovae?

Historical Supernovae

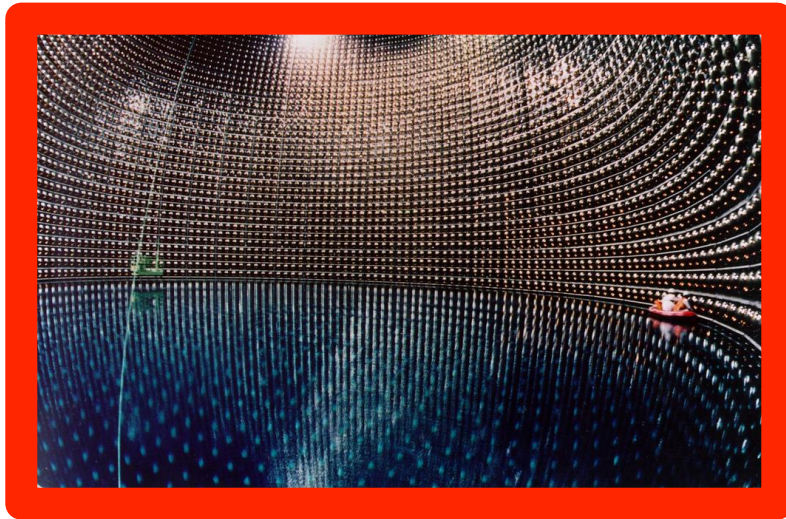


Historical Supernovae

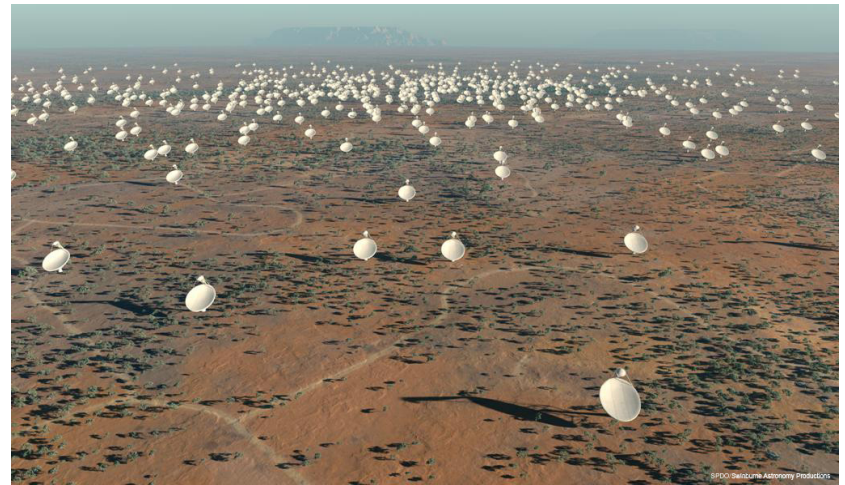


Revealing Optically Invisible Core-Collapse Supernovae

0 Synergies with



Neutrino detectors



Radio Surveys

Diffuse Supernova Neutrino Background (DSNB)

- 0 Neutrinos from supernovae
 - 0 ν & anti- ν of all species
- 0 $\sim 10^{58}$ neutrinos per SN
- 0 Cosmic SNe ~ 10 events/sec (observable univ)
- 0 Add them up $\rightarrow$ DSNB
 - 0 Detectable energy range: 10 - 26 MeV
 - 0 Major detector: Super-Kamiokande

$$\phi_\nu(\epsilon) = c \int_0^\infty (1+z) \left| \frac{dt}{dz} \right| \mathcal{R}_{\text{SN}}(z) N_\nu[(1+z)\epsilon] dz$$

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- Cosmic
- Known
- Line of Sight

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- Known
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- SN rate
- Astro
- Will know (from survey)

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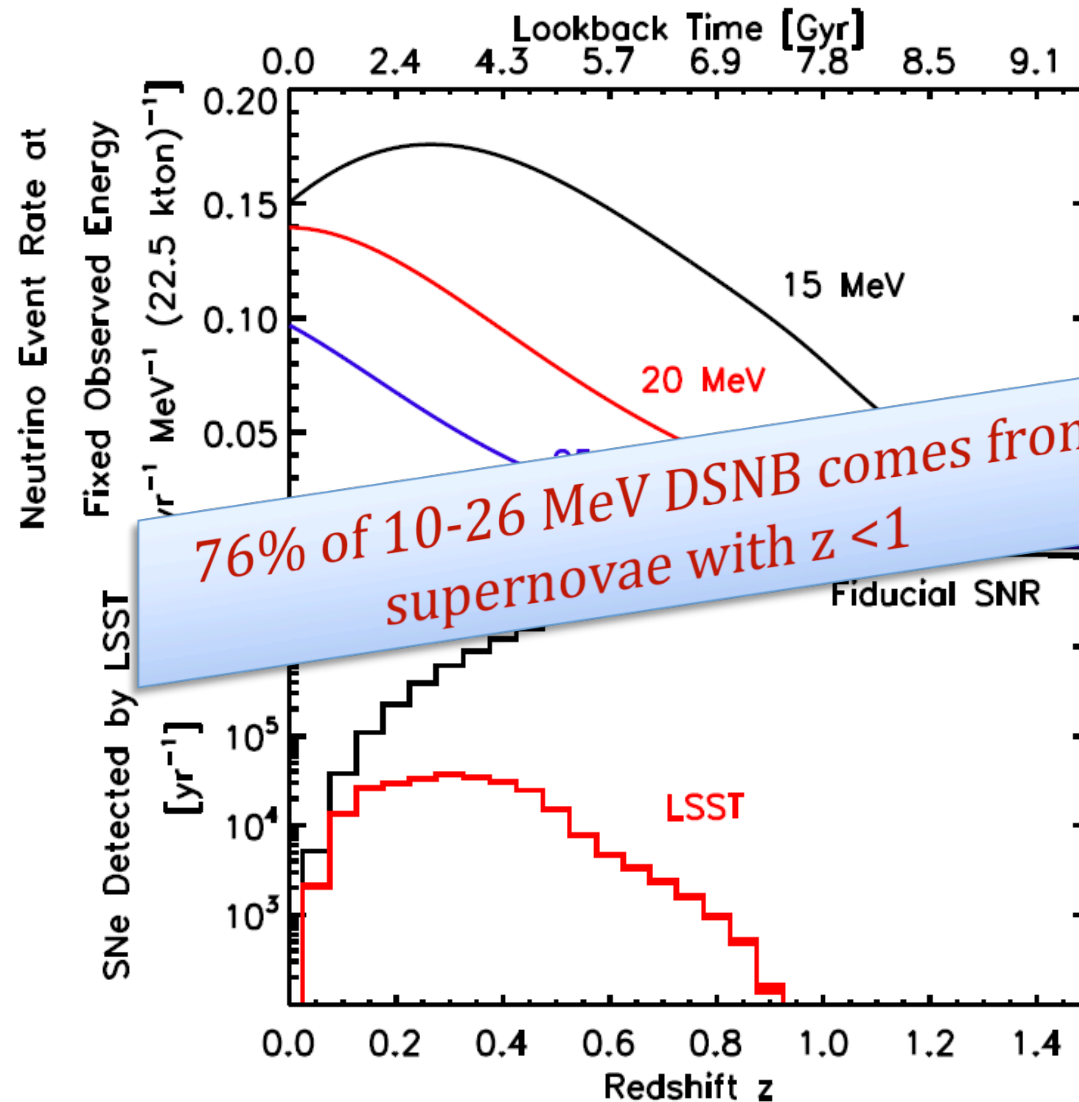
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- Astro
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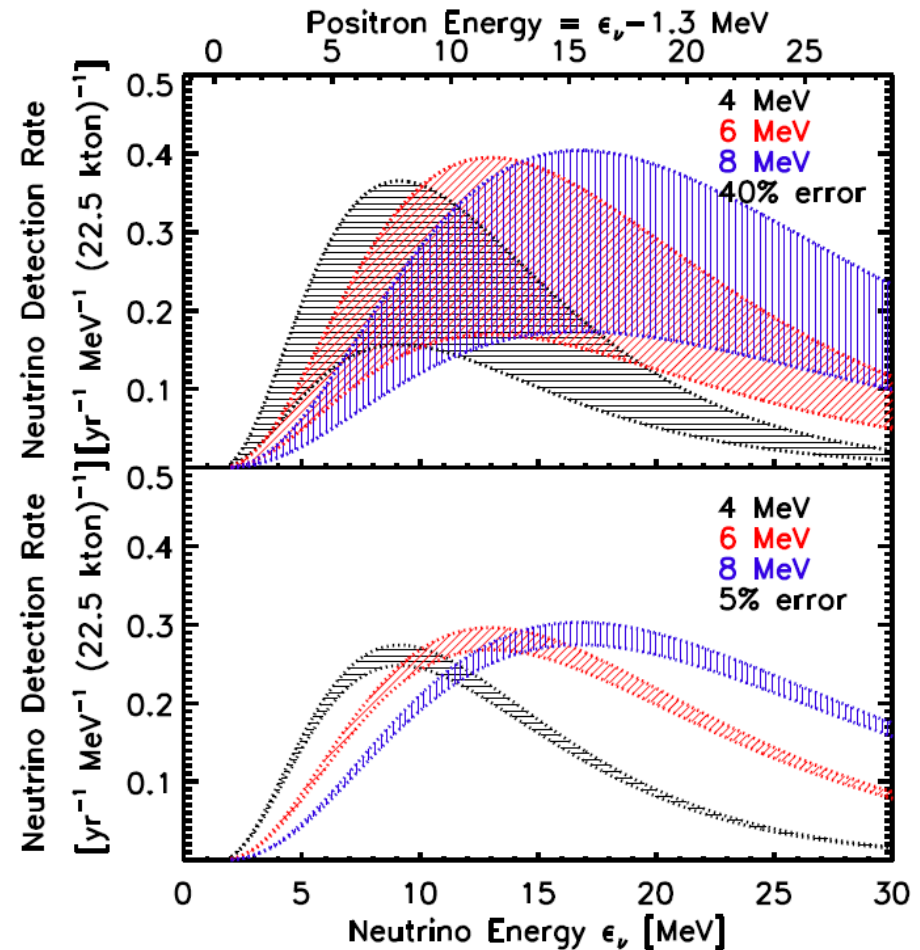
- Neutrino energy spectrum
- SN theory
- Want to know

LSST supernovae and Neutrinos



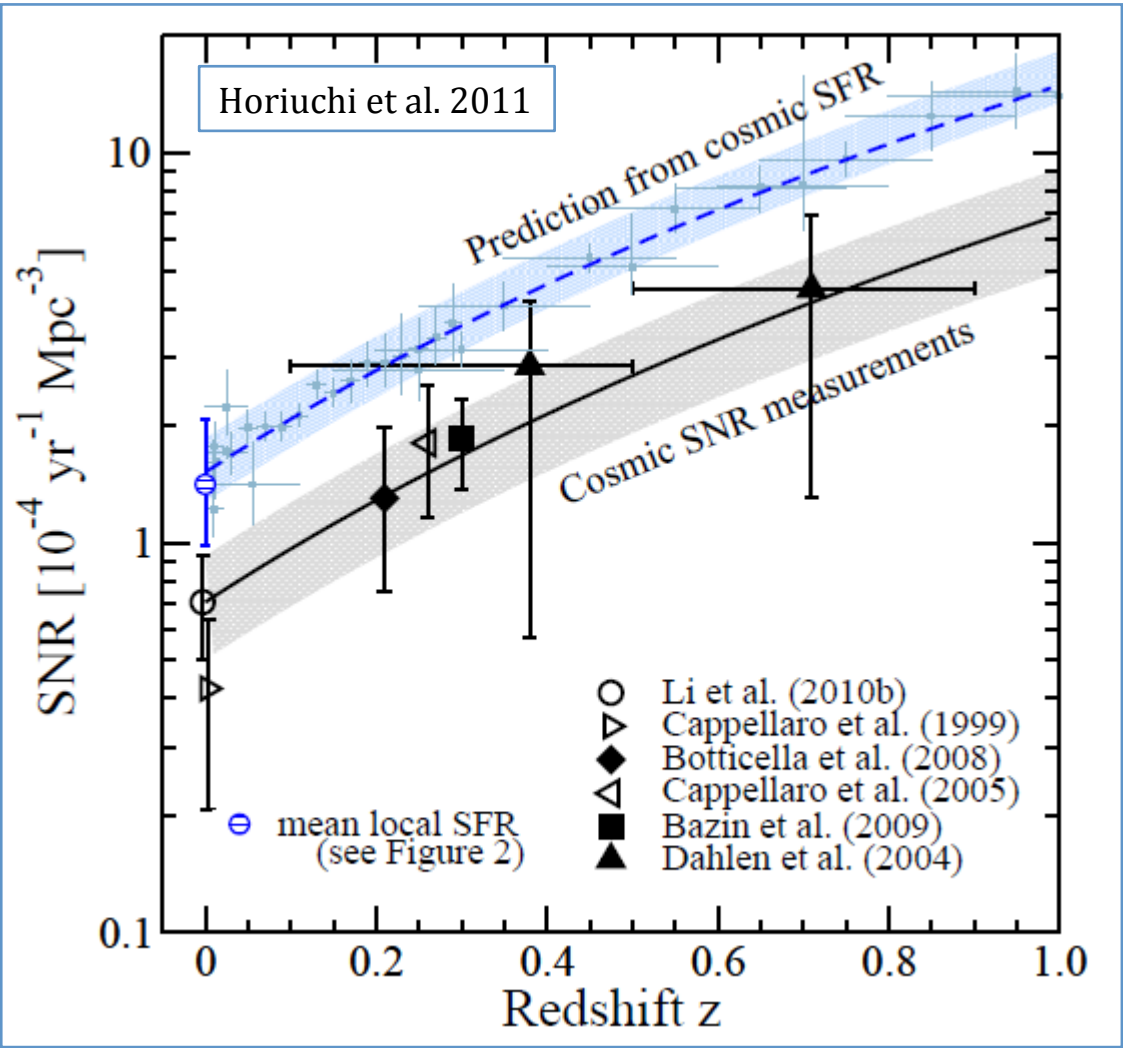
Supernova Neutrino Physics

- 0 Current candidates for the neutrino temperature:
4,6,8 MeV
- 0 Current uncertainty too big to distinguish models
- 0 Future CC SNe data will provide much better precision to distinguish models
- 0 Note: Energy distribution of supernova neutrinos
~ Fermi-Dirac distribution with zero chemical potential, fitted with an effective temperature



Failed Supernovae?

- 0 Massive without
- 0 Current
- 0 8 M
- 0 Msta
- 0 25 M
- 0 Most c
- 0 energi
- 0 Neutri
- 0 supern
- 0 Horui
- 0 optica

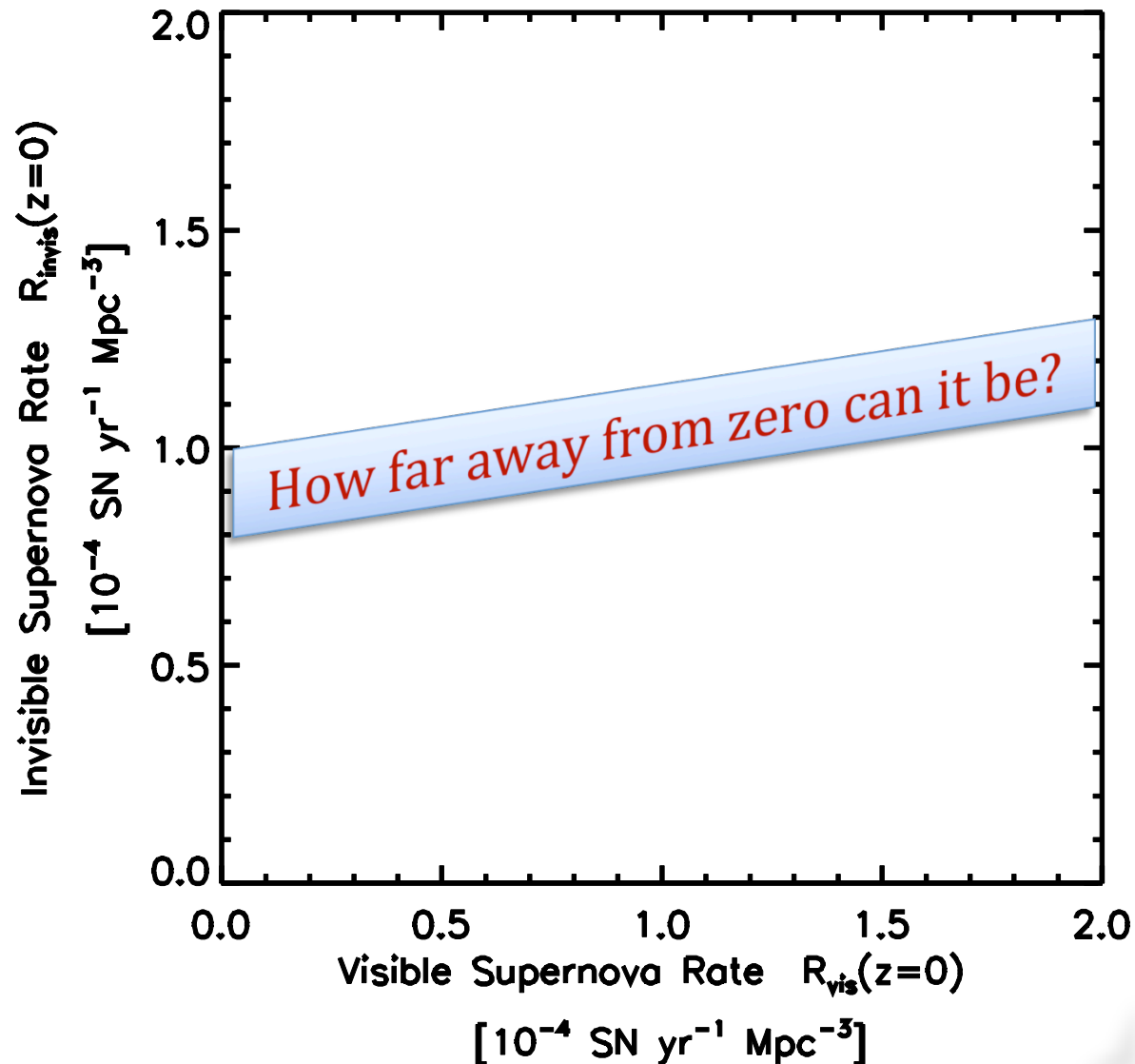


es

a higher

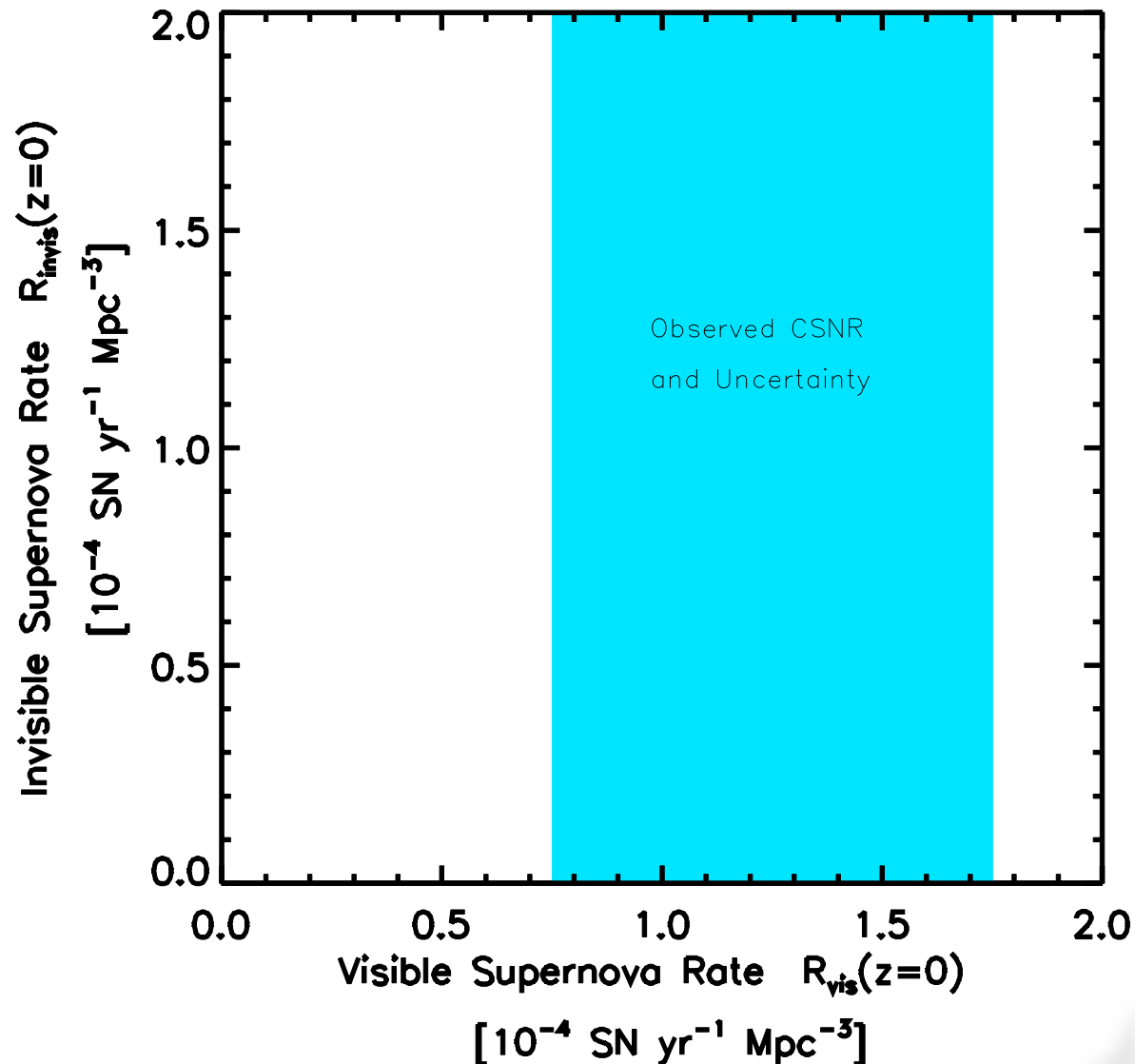
Revealing Failed Supernovae

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



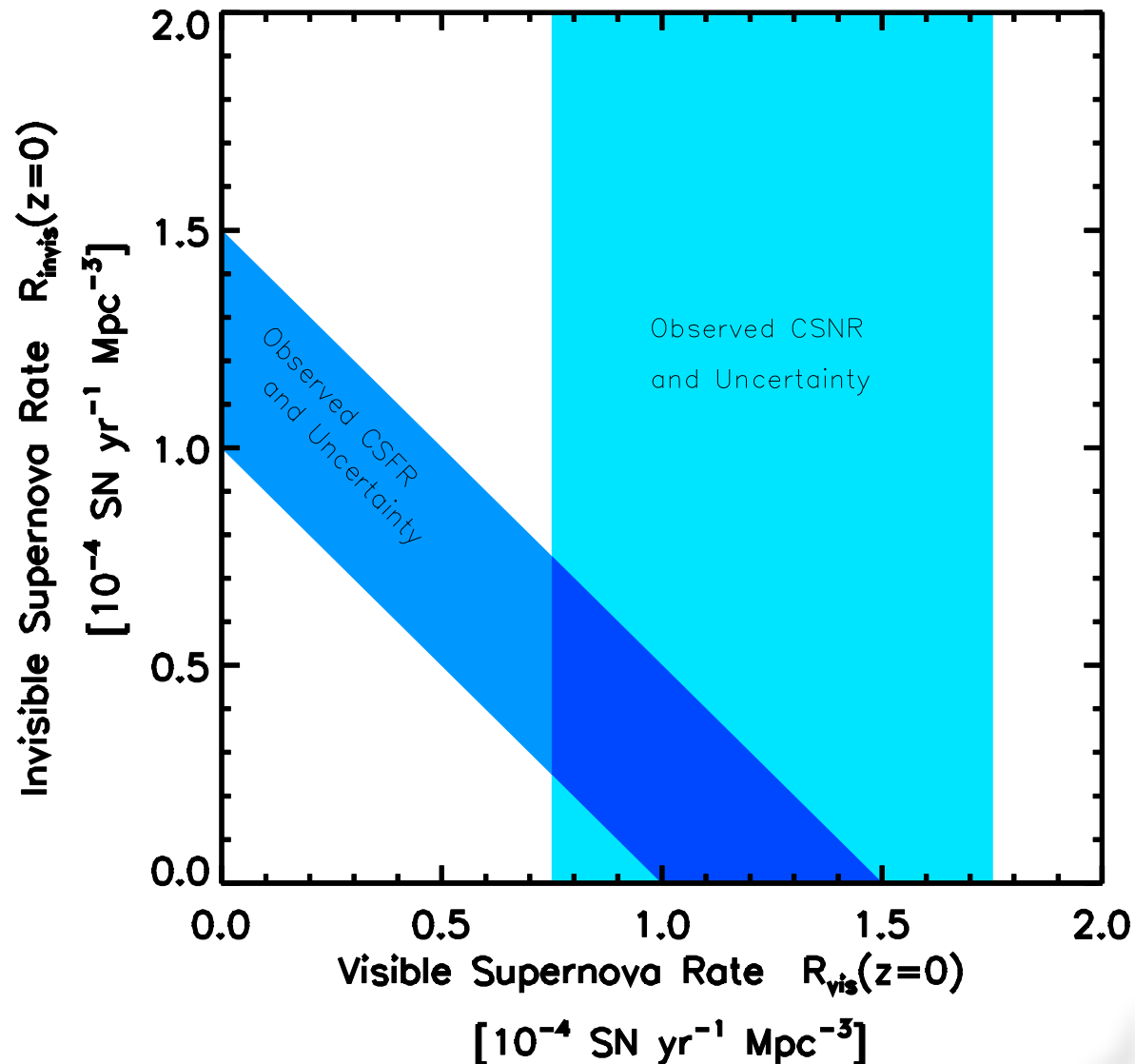
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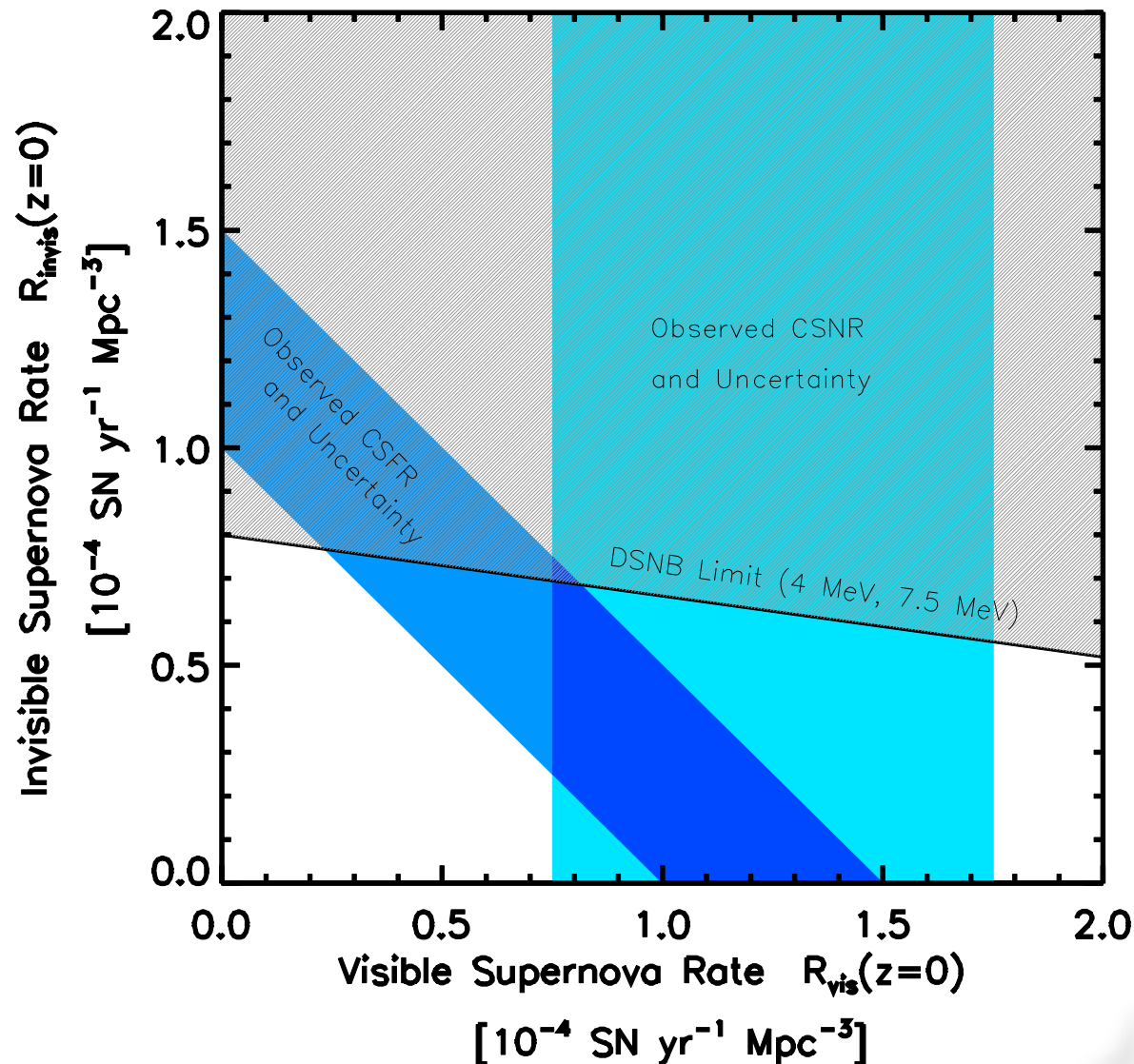
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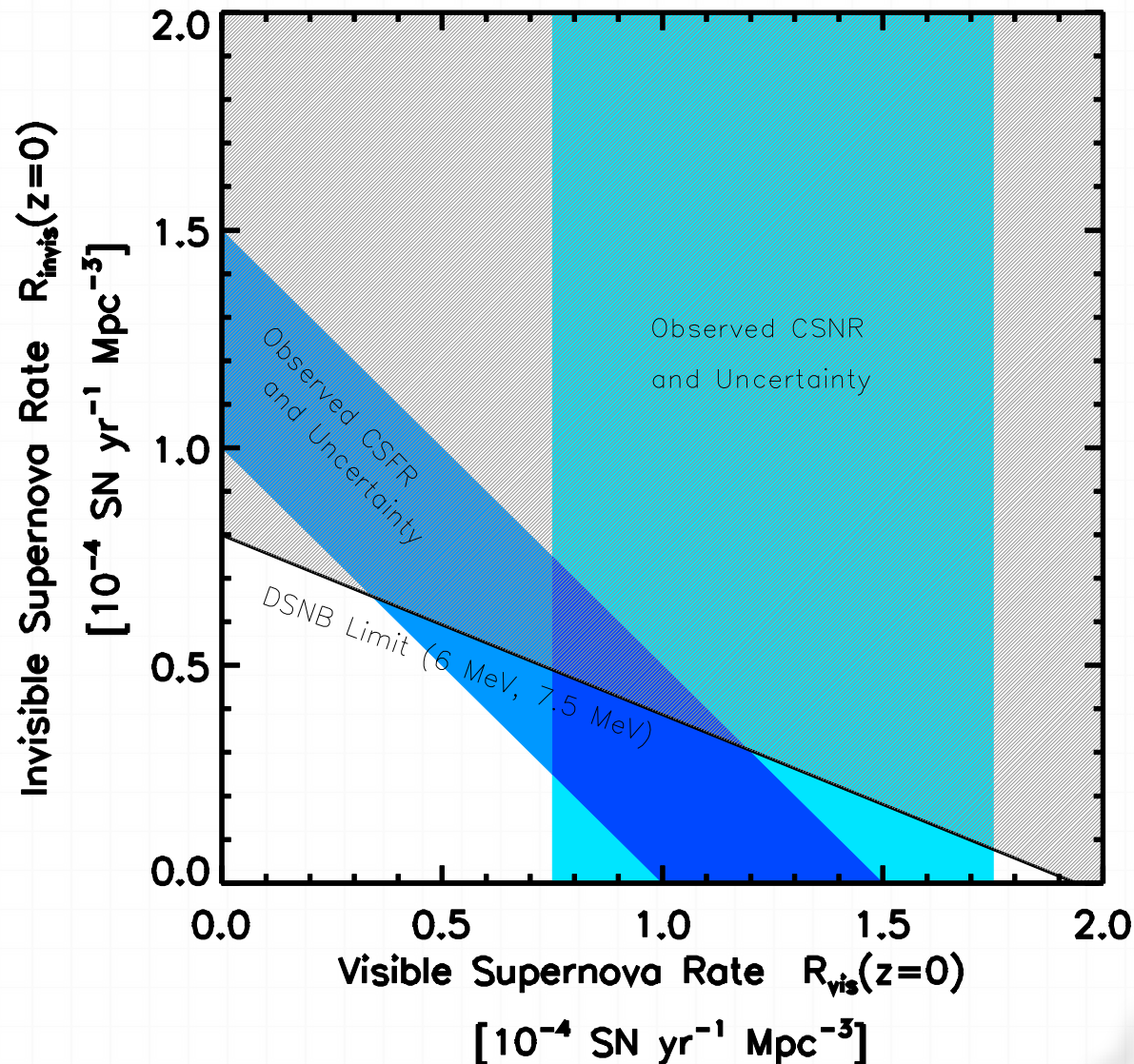
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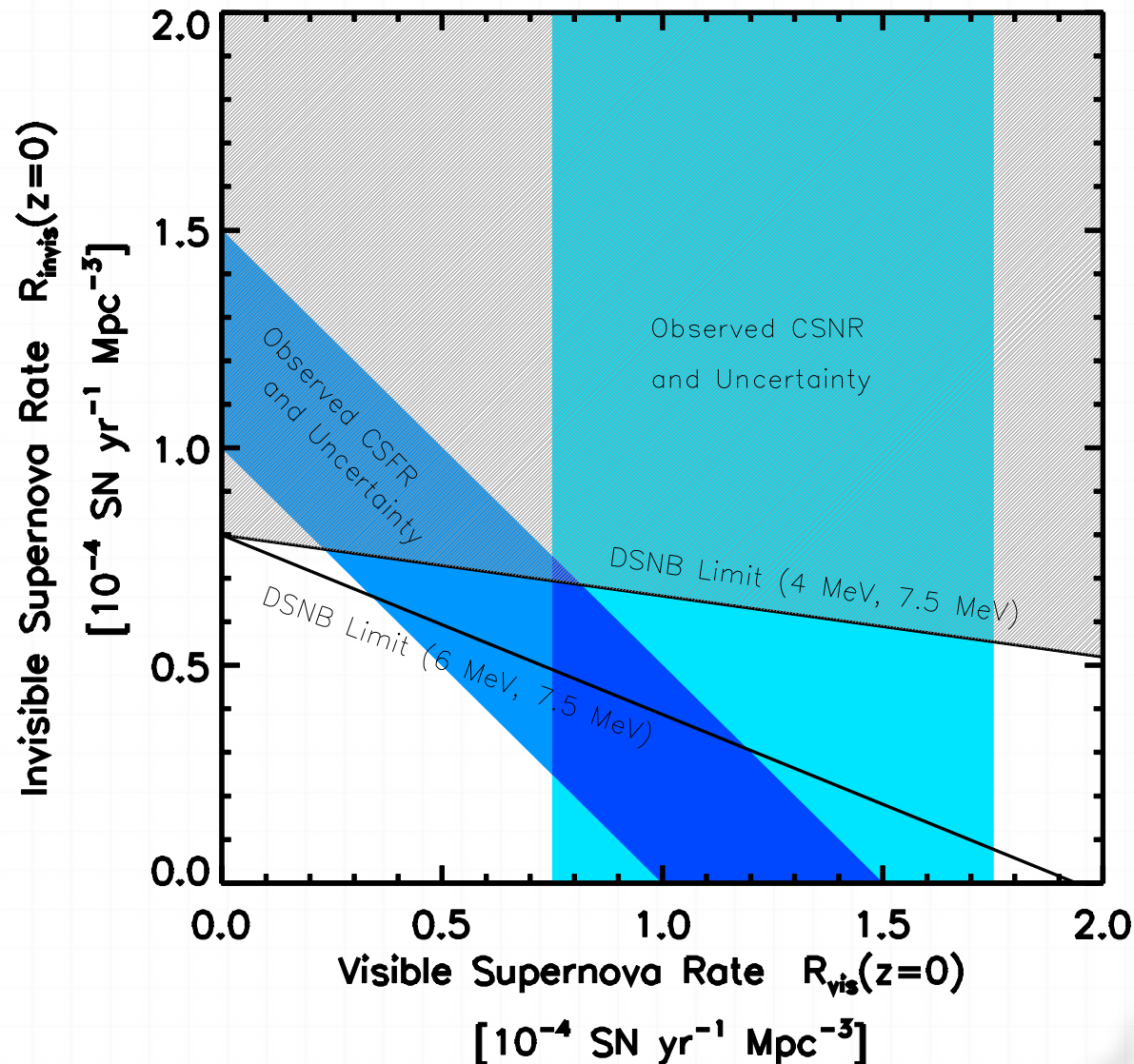
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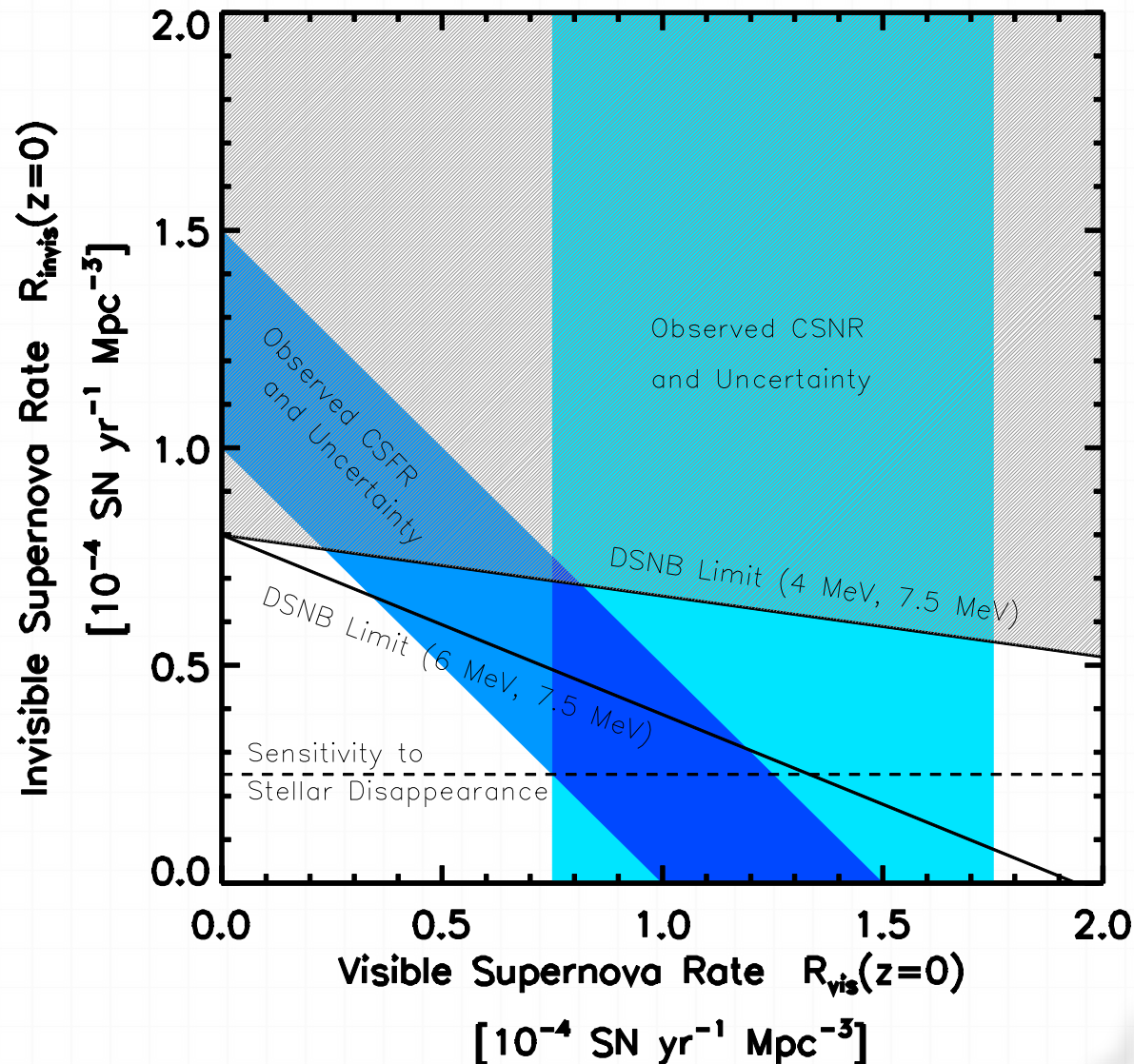
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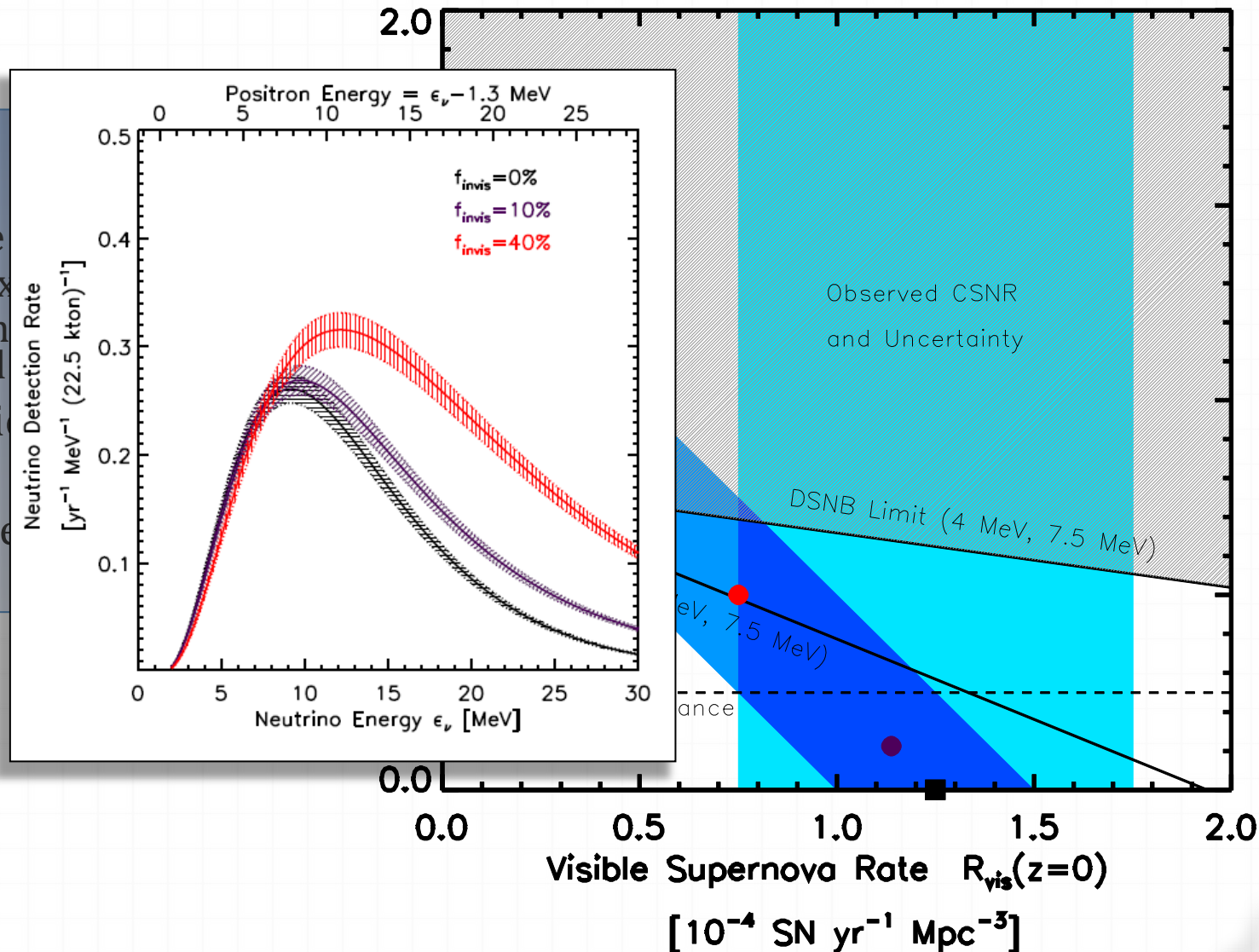
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Revealing Failed Supernovae

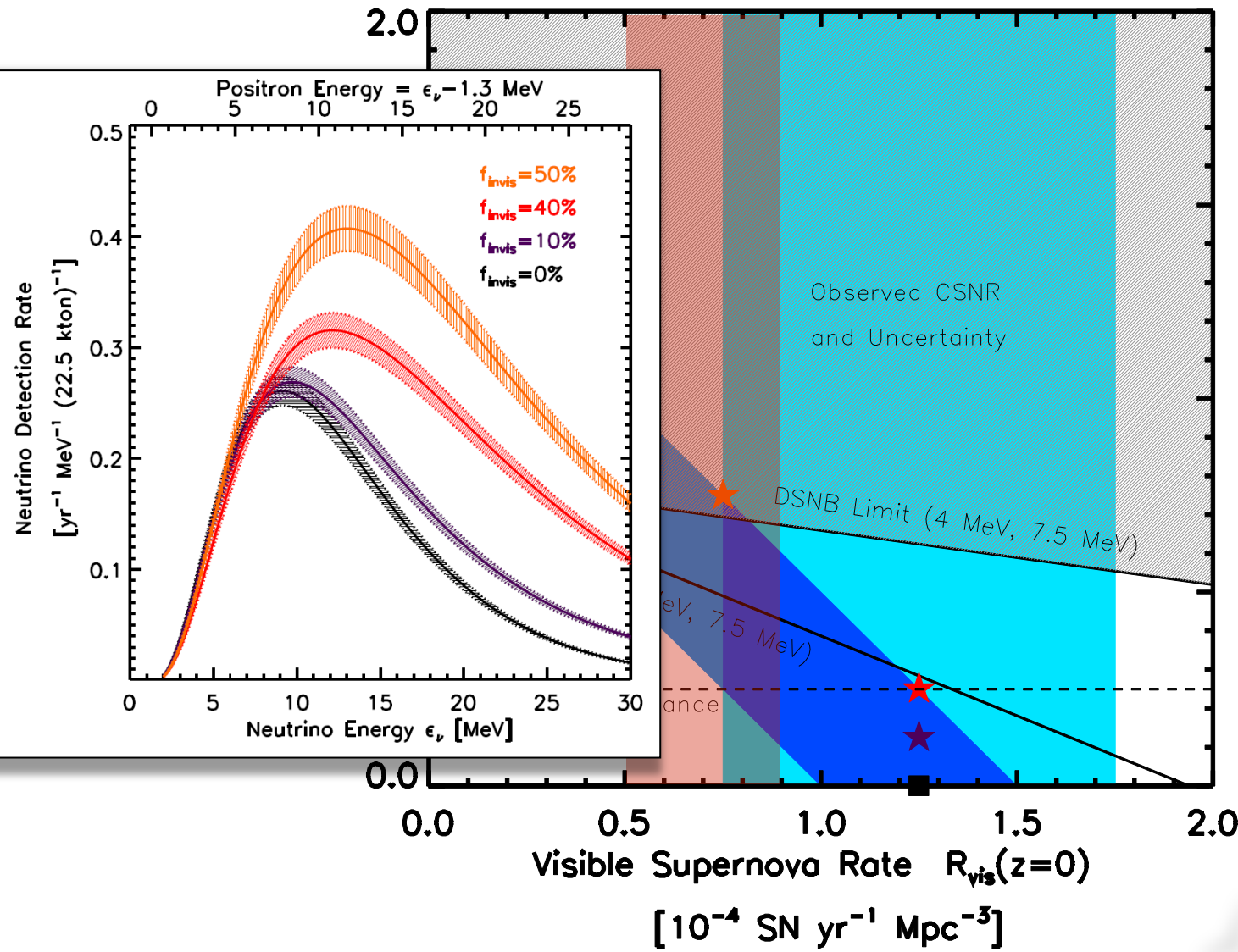
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 - 0 Collapse → Black hole
 - 0 No optical emission
 - 0 Neutrino emission or enhanced
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Revealing Failed Supernovae

Li et al. 2010

- Failed SN
 - Collapse
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 - No optical emission
 - Neutrino emission or enhanced
- Missed in optical surveys
- Detected by neutrino observatories

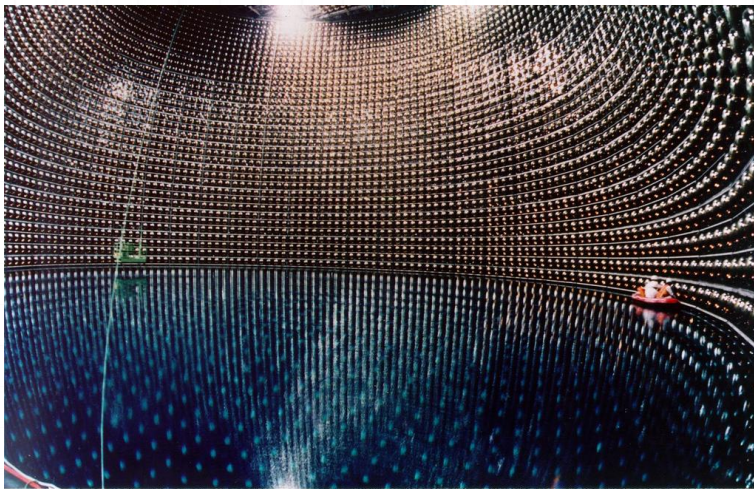


LSST + Neutrinos

- 0 LSST will remove astro uncertainty in DSNB
- 0 LSST + DSNB:
 - 0 Distinguish different supernova neutrino models.
 - 0 Probe failed supernovae.
 - 0 DSNB flux should be at least 10% higher than flux from observed supernovae.
 - 0 GRBs with failed supernovae?

Revealing Optically Invisible Core-Collapse Supernovae

0 Synergies with



Neutrino detectors



Radio Surveys

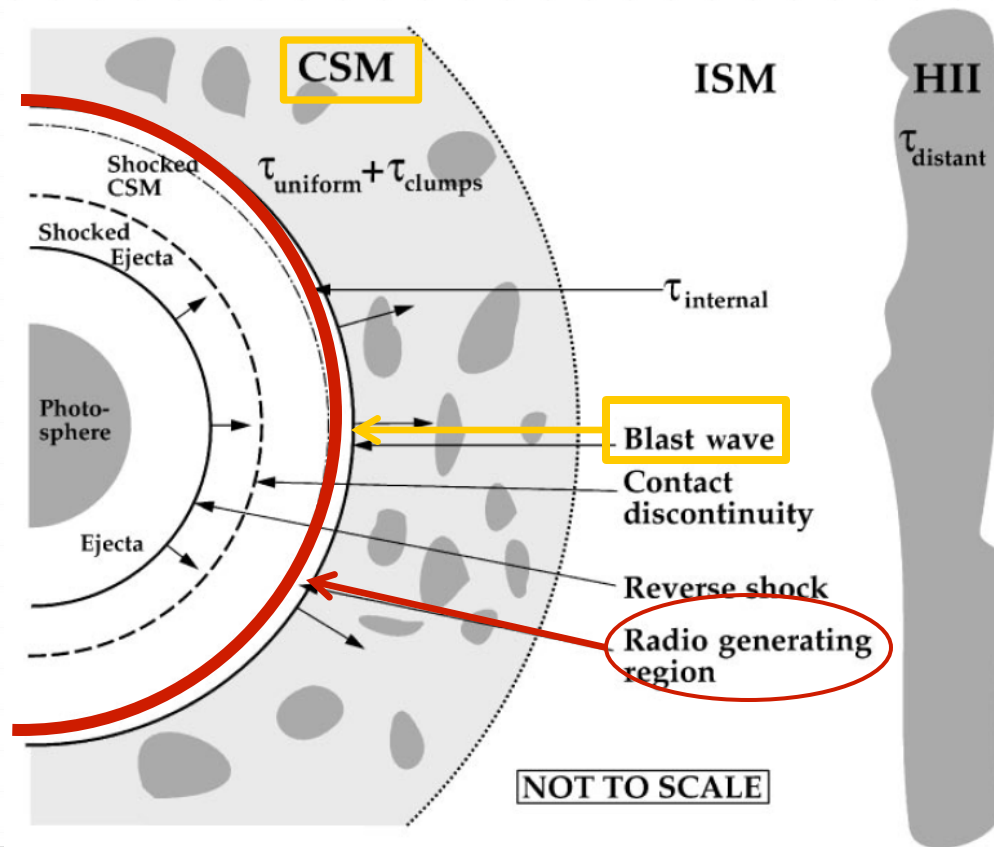
Why are Radio SNe Important?

- 0 Transparent to dust
- 0 GRBs
- 0 Mass loss rate for supernova progenitors
 - 0 Stellar evolution
 - 0 Metallicity in pre-supernova wind
 - 0 Different Type Ia scenarios
- 0 Not much information to date
 - 0 No radio Type Ia
 - 0 ~ 50 radio core-collapse SNe



Supernovae.....In Radio

- 0 Radio emission: interaction between shock and circumstellar medium
- 0 Light curve = nonthermal emission + thermal/nonthermal absorption



Weiler et al.

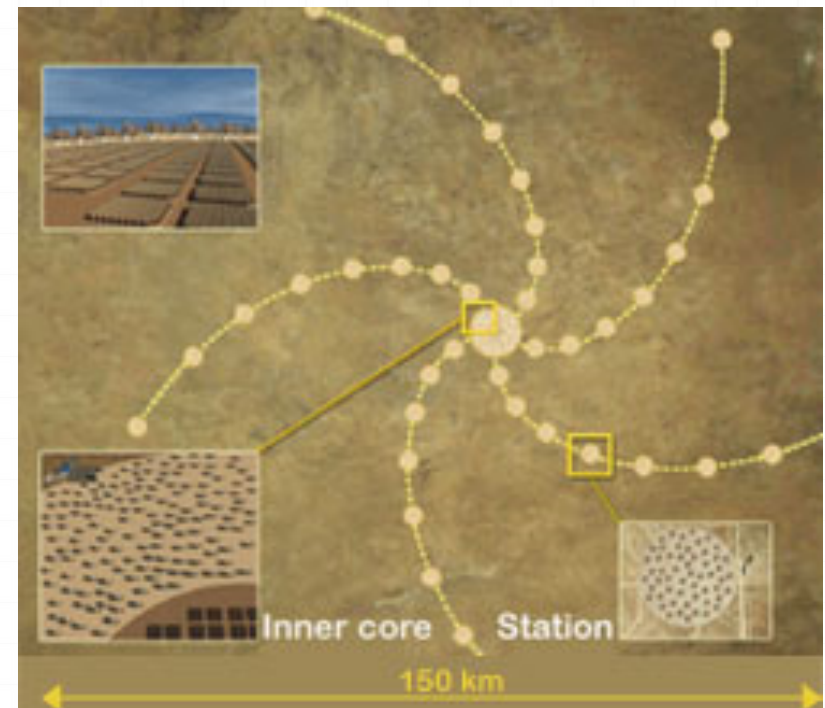
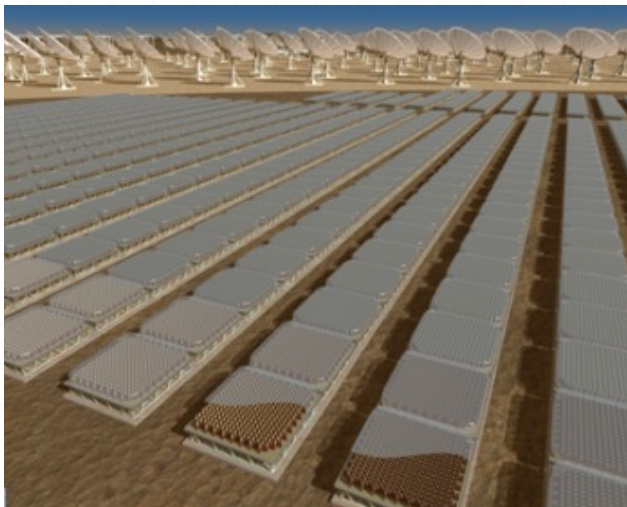
Square Kilometer Array (SKA)

- 0 Number of antennas: **2280**
- 0 Collecting area: $\sim 1 \text{ km}^2$
- 0 Sensitivity: $\sim$ **few nJy**
($1 \text{ Jy} = 10^{-23} \text{ erg/s/cm}^2/\text{Hz}$)
- 0 Frequency range: 0.07 – 10 GHz
- 0 Field of view: $\sim 1 \text{ deg}^2$ at 1.4 GHz

(EVLA:27)

(EVLA: 0.013 km^2)

(EVLA: $\sim \mu\text{Jy}$)



Synoptic Surveys for Radio Supernovae

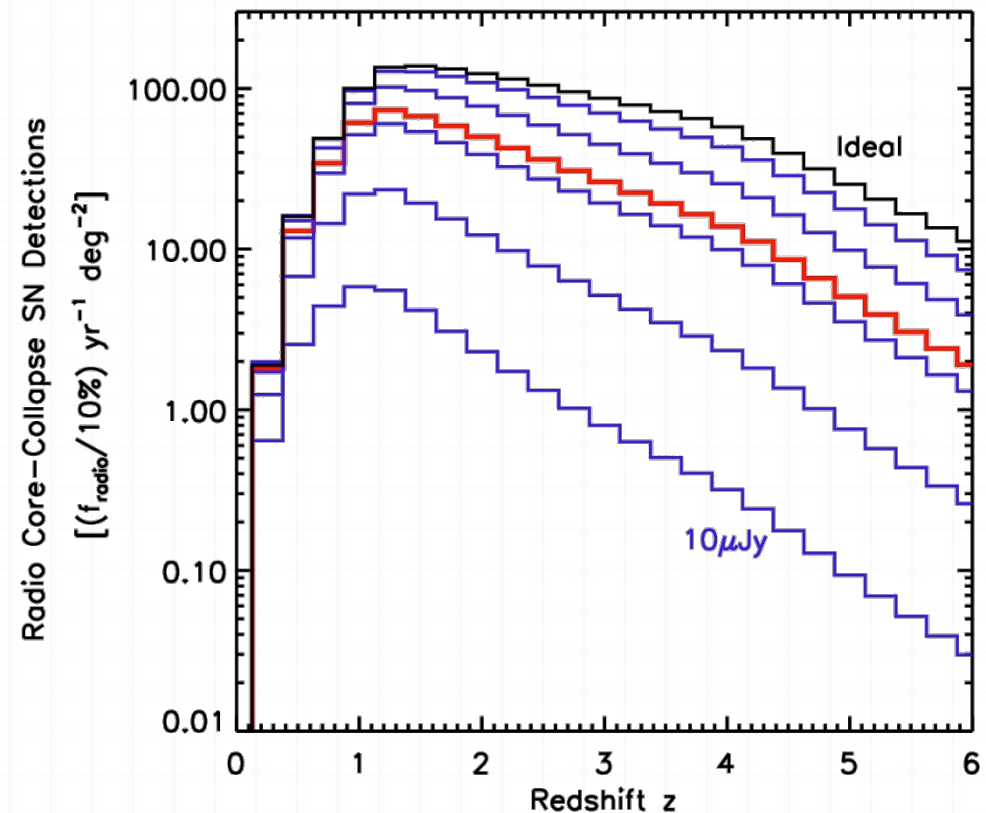
0 Assume $f_{\text{radio}} = 10\%$ of
CC SNe are radio bright
(Berger et al. 2003)

0 Supernovae at high
redshift

0 SKA detections:
 $\sim 620/\text{yr}/\text{deg}^2$

0 Complement to LSST

Lien et al. (2011)



Survey sensitivities: $\{10 \mu\text{Jy}, 1 \mu\text{Jy}, 100 \text{ nJy}, 50 \text{ nJy}, 10 \text{ nJy}, 1 \text{ nJy}\}$

Synoptic Surveys for Radio Supernovae

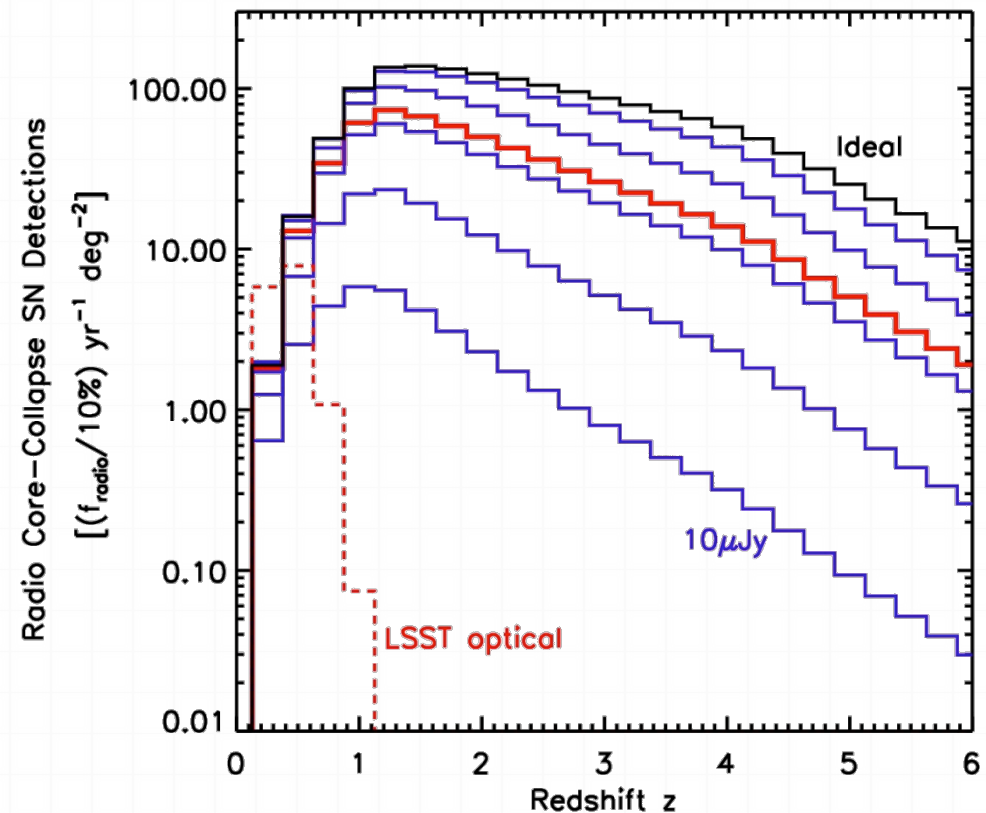
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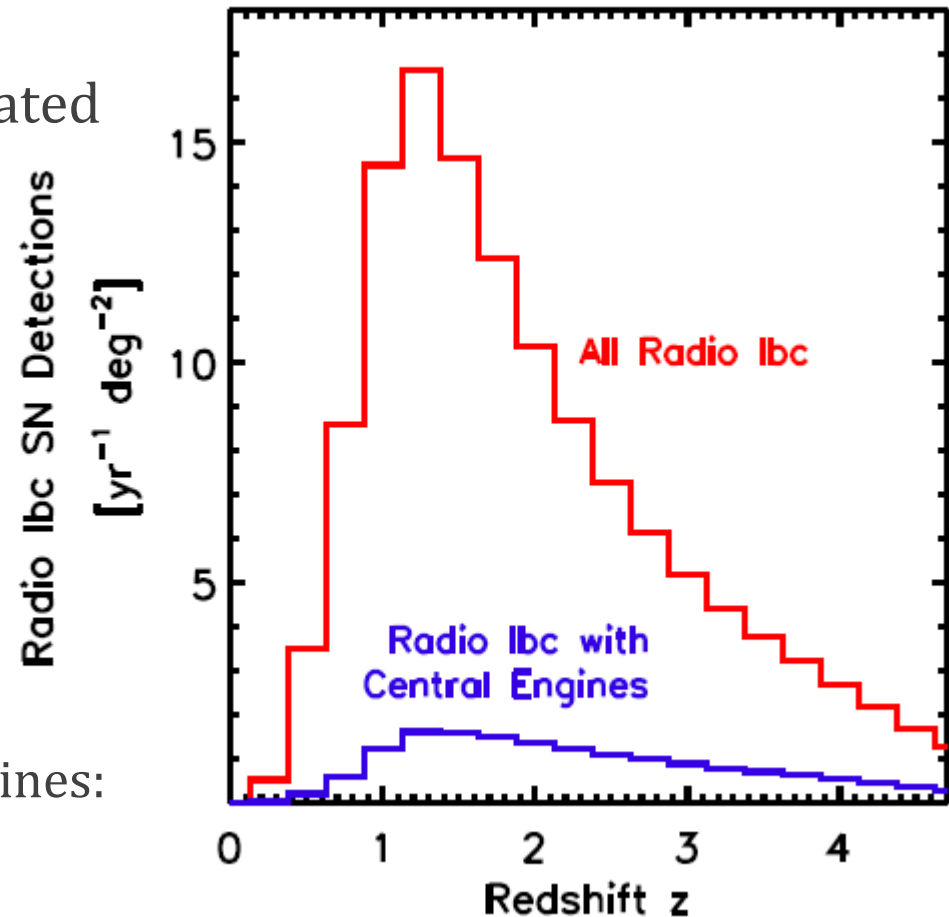
Lien et al. (2011)



Survey sensitivities: $\{10 \mu\text{Jy}, 1 \mu\text{Jy}, 100 \text{ nJy}, 50 \text{ nJy}, 10 \text{ nJy}, 1 \text{ nJy}\}$

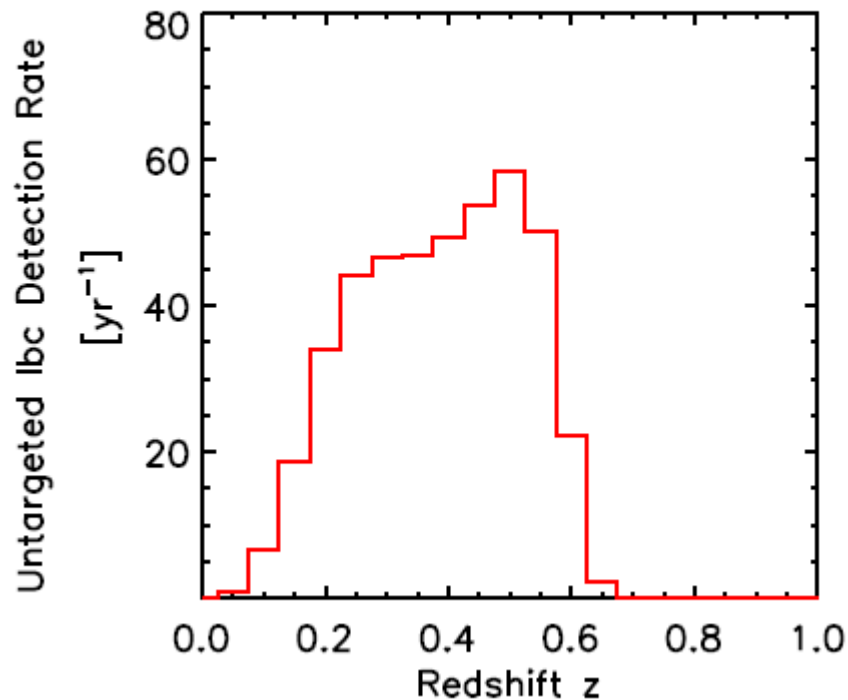
Estimated Type Ibc detections for SKA

- 0 Some Type Ibc SNe are related to GRBs
- 0 Ibc/CC $\sim 25\%$ (Li et al. 2010)
- 0 (Radio Ibc)/Ibc $\sim 12\%$ (Berger et al. 2003)
- 0 (Radio Ibc with central engine)/Ibc $\sim 0.5\%$ (Berger et al. 2003)
- 0 SKA detections:
 - 0 Radio Ibc : $\sim 130/\text{yr}/\text{deg}^2$
 - 0 Radio Ibc with central engines: $20/\text{yr}/\text{deg}^2$



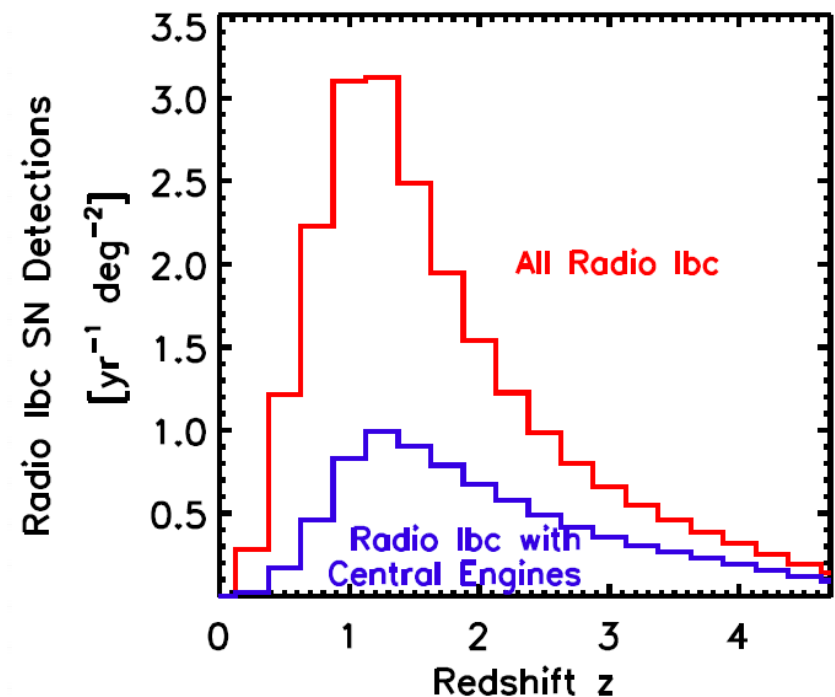
Ibc Predictions for Current Surveys

Prediction for DES



Total number: $\sim 430 \text{ yr}^{-1}$

Prediction for EVLA



Total number:

- All: $\sim 20 \text{ yr}^{-1} \text{ deg}^{-2}$
- With central engines: $\sim 8 \text{ yr}^{-1} \text{ deg}^{-2}$

LSST + SKA

- 0 SKA is a high-redshift supernova factory
- 0 Probe optically invisible supernovae to high redshift
 - 0 Star formation
 - 0 Supernova progenitors and environment
 - 0 Dust evolution
- 0 Explore the SN-GRB relation
- 0 Search for radio Type Ia

Conclusions

LSST SNe

- 0 Measure
- 0 Star-form

ting

Future Prospect

- 0 Probing SN-GRB relation with multi-messenger observations
- 0 Fermi, Swift, DES/LSST, EVLA/SKA, neutrinos...etc.
- 0 GRBs from failed SNe?

LSST

- 0 Remove
- in the D
- 0 Distinguish
- superno
- models.
- 0 Probe failed supernovae.

Radio

or radio

visible

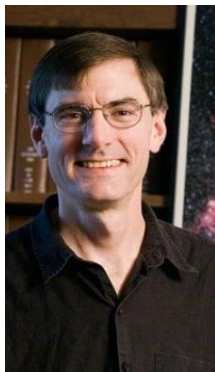
h redshift

- 0 Stellar evolution and dust at high redshift

Thank You

Back-up Slides

Special Thanks to



Brian Fields
(U of Illinois)



John Beacom
(Ohio State University)



Nachiketa Chakraborty
(U of Illinois)



Athol Kemball
(U of Illinois)

And the proof-reading Group:



Brett Hayes
(U of Illinois)



Jana Bilikova
(U of Illinois)

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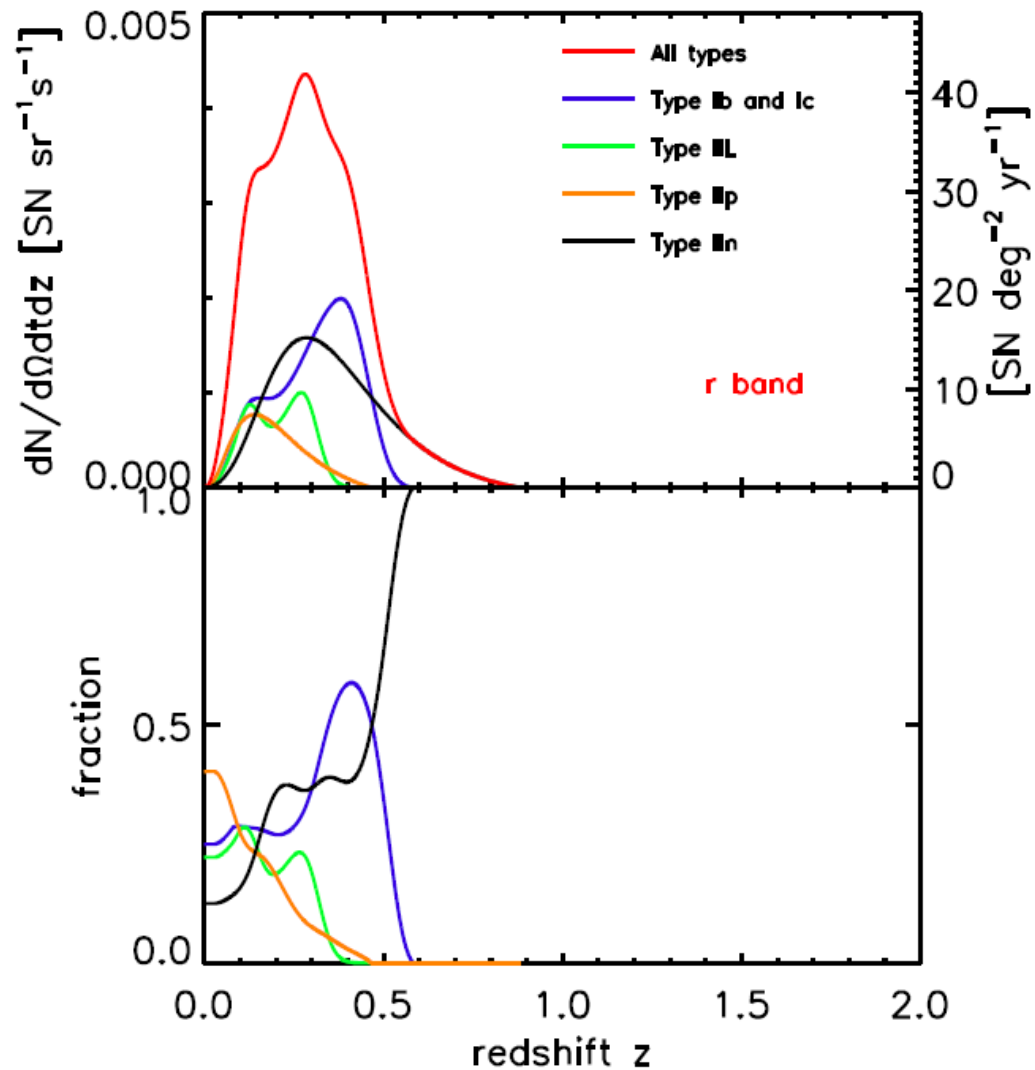
Part 1: LSST SNe

Table 1: Current and Future Synoptic Sky Surveys and Their Discovery Potential in r -band.

Survey Name	Scan Area $\Delta\Omega_{\text{scan}}$ [deg ²]	SN Depth $m_{\text{lim}}^{\text{sn}}$ [mag]	Expected Operation	Expected Total 1-year SNII Detections	SNII Redshift Range
SDSS-II*	300	21.5	2005–2008	1.70×10^2	$0.03 < z < 0.37$
DES	40	24.2	2011–2016	2.74×10^3	$0.06 < z < 1.20$
Pan-STARRS	30000	23	2010–2020	5.14×10^5	$0.01 < z < 0.89$
LSST	20000	23–25	2014–2024	3.43×10^5	$0.01 < z < 0.89$

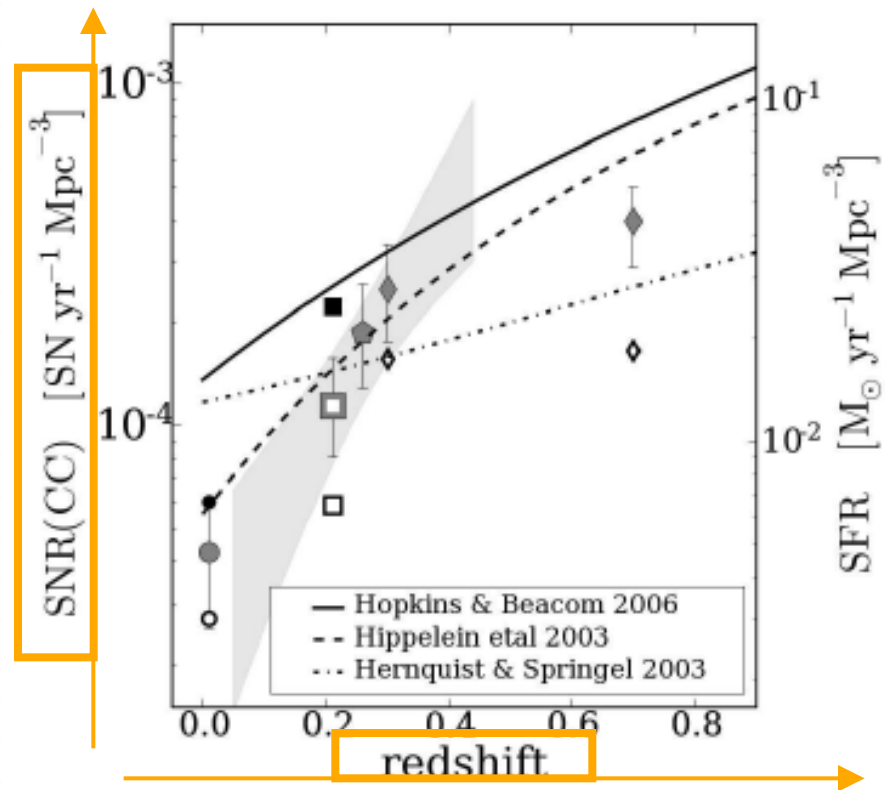
Note: *Reflects SDSS-II supernova scan season of 3 months per calendar year.

Forecast of SN detection in Types



The Cosmic CC SNe Rate from Direct Supernova Counts

- 0 The shaded area:
1 σ confidence level
 - 0 Open symbols:
No correction for dust
 - 0 Closed symbols:
High dust correction
 - 0 Different shape:
Estimation made by different groups
- (Cappellaro et al. 1999,
Dahlen et al. 2004,
Cappellaro et al. 1999,
Botticella et al. 2007)



Supernova Synoptic Surveys

- ▶ Synoptic: repeated scans, large sky coverage
- ▶ SDSS-II (current)
 - ▶ Pan-STARRS
- ▶ DES
 - ▶ LSST

Table 1: Current and Future Synoptic Sky Surveys

Survey Name	Scan Area $\Delta\Omega_{\text{scan}}$ [deg ²]	SN Depth $m_{\text{lim}}^{\text{sn}}$ [mag]	Scan Region	Expected Operation
SDSS-II	300	21.2	SDSS southern equatorial strip	2005–2008
DES	40	24.2	South Galactic Cap	2011–2016
Pan-STARRS	150	23	~ 75% of the Hawai'ian sky	2010–2020
LSST	3800	23–25	southern hemisphere	2014–2024

Supernova Synoptic Surveys

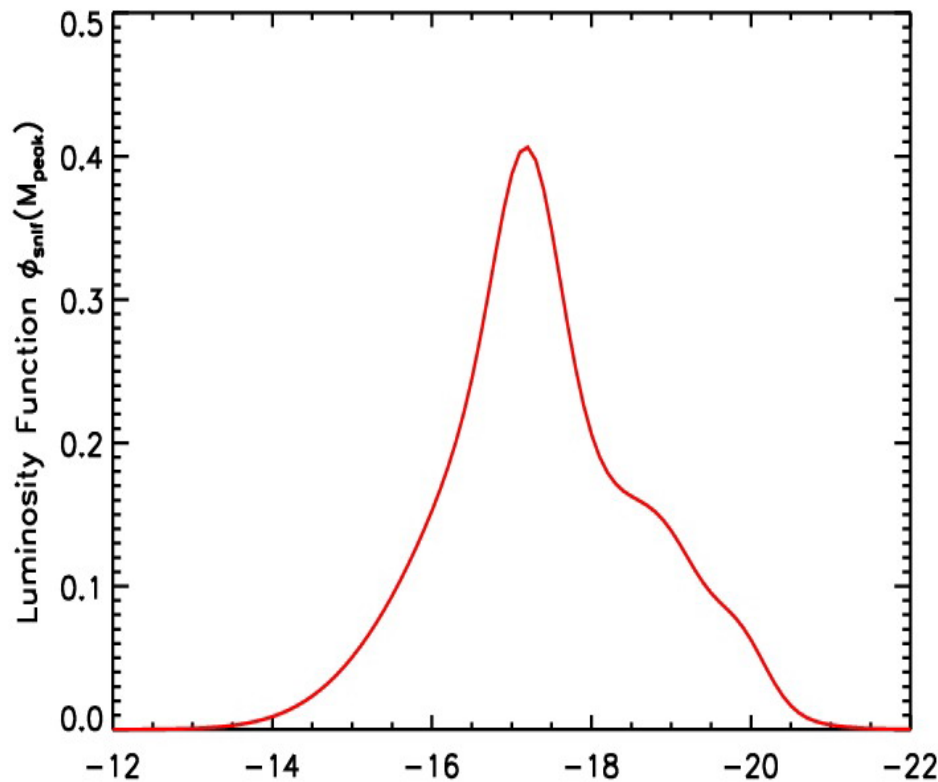
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Note: *Reflects SDSS-II supernova scan season of 3 months per calendar year.

Calculate f_{maglim}



Peak Absolute magnitude M_{peak}

Dim

Bright

0 Supernovae luminosity function (SNLF)

a. Richardson et al. (2002)

b. Peak magnitude

c. Normalized

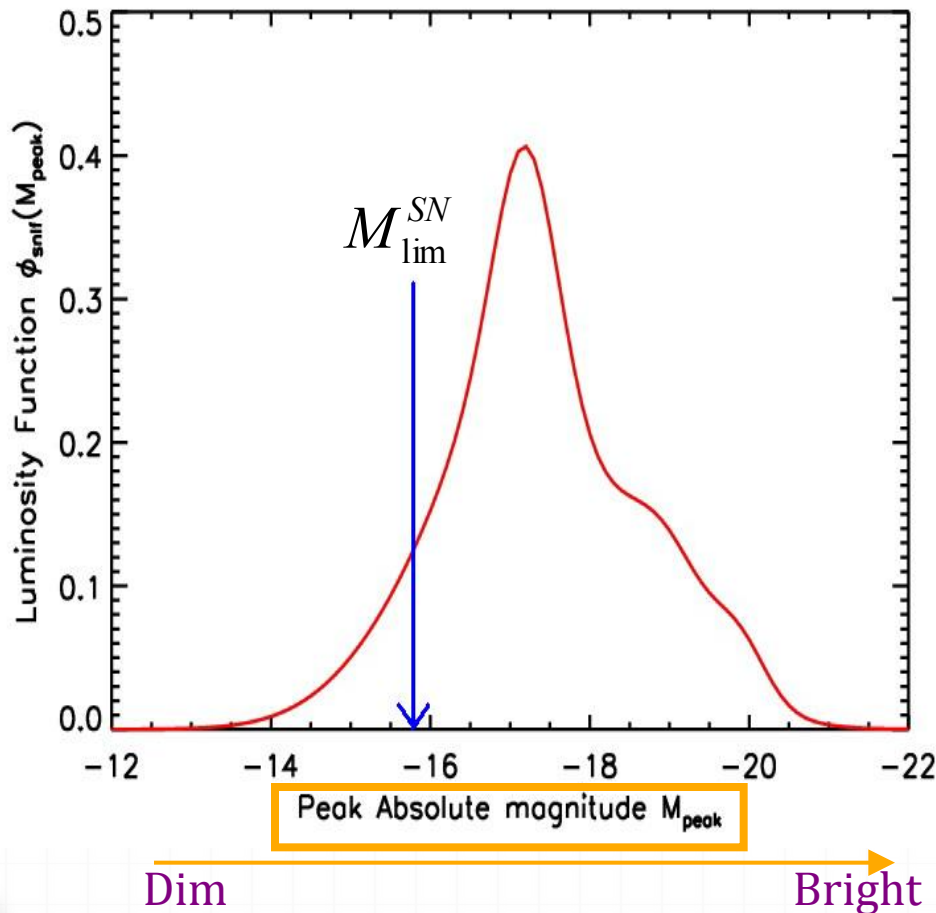
d. Four types of supernovae

0 Find the absolute magnitude in B-band corresponds to m_{lim} in x-band

$$M_B = m_x - \mu(z) - K_x(z) - \eta_{xB}$$

0 Integrate over SNLF to m_{lim} and find the cumulative fractional number of CC SNe

Calculate f_{maglim}

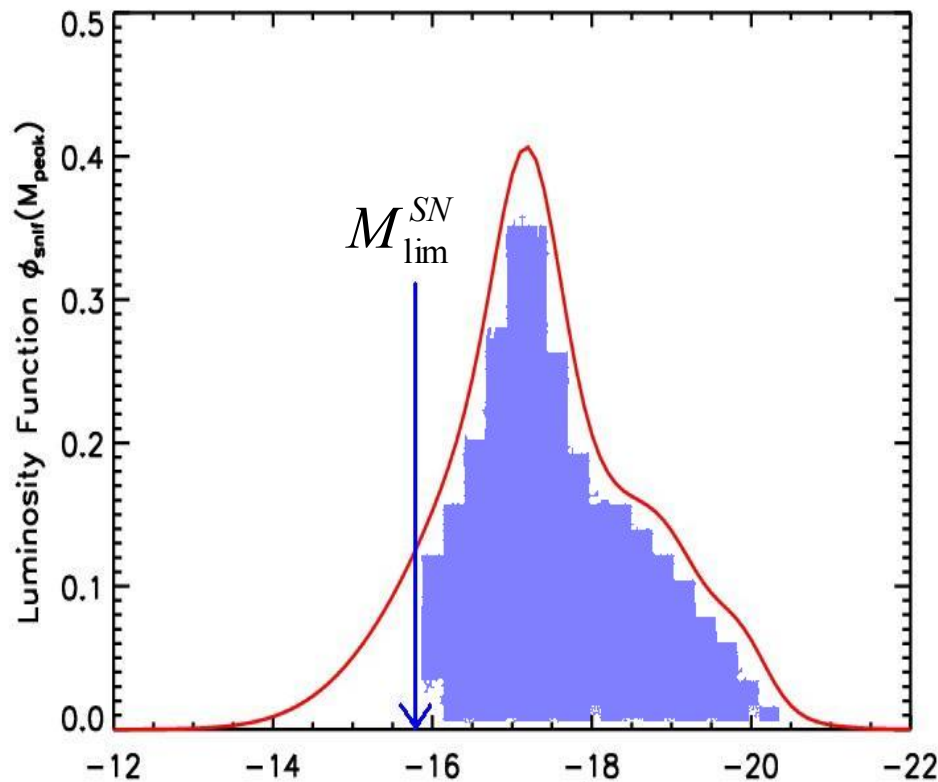


- Supernovae luminosity function (SNLF)
 - a. Richardson et al. (2002)
 - b. Peak magnitude
 - c. Normalized
 - d. Four types of supernovae
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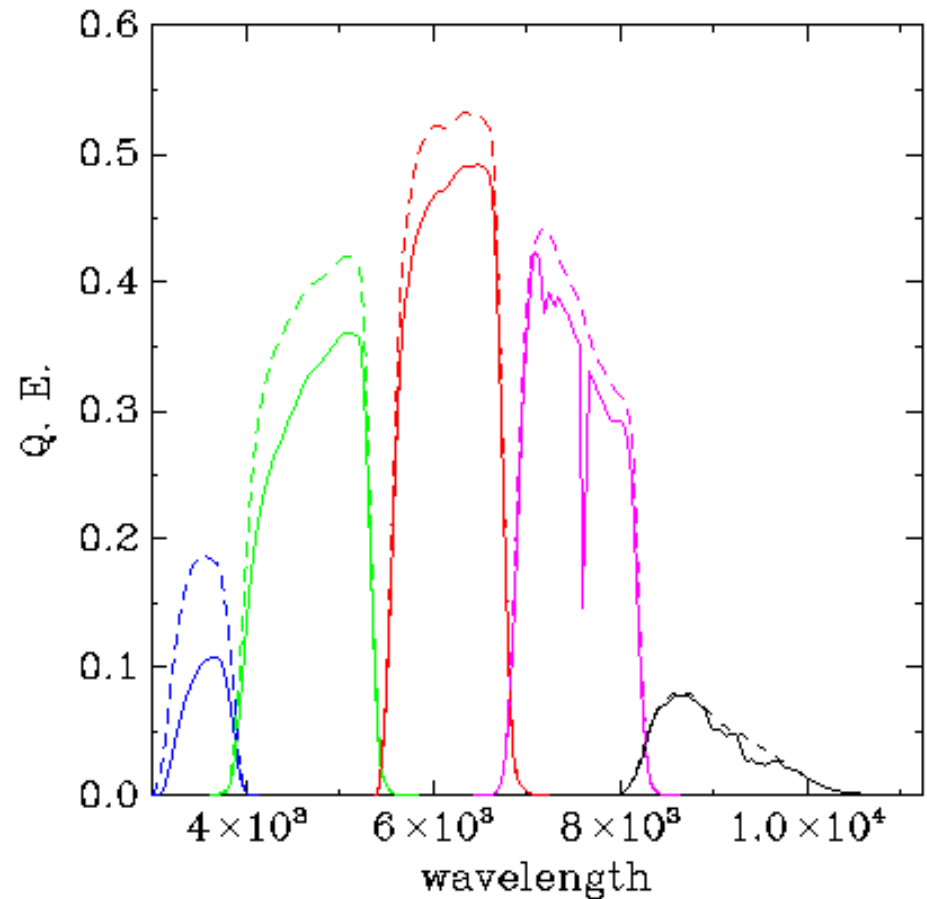
Dim

Bright



SDSS Instrumental Efficiency

- 0 u (3551 Å)
- 0 g (4686 Å)
- 0 r (6165 Å)
- 0 i (7481 Å)
- 0 z (8931 Å)
- 0 Solid: including atmospheric extinction (what we use)
- 0 Dashed: not including atmospheric extinction



K-Correction

0 Relation between apparent magnitude and absolute magnitude in x-filter

$$m_x(z) = M_z + \mu(z) + K_x(z)$$

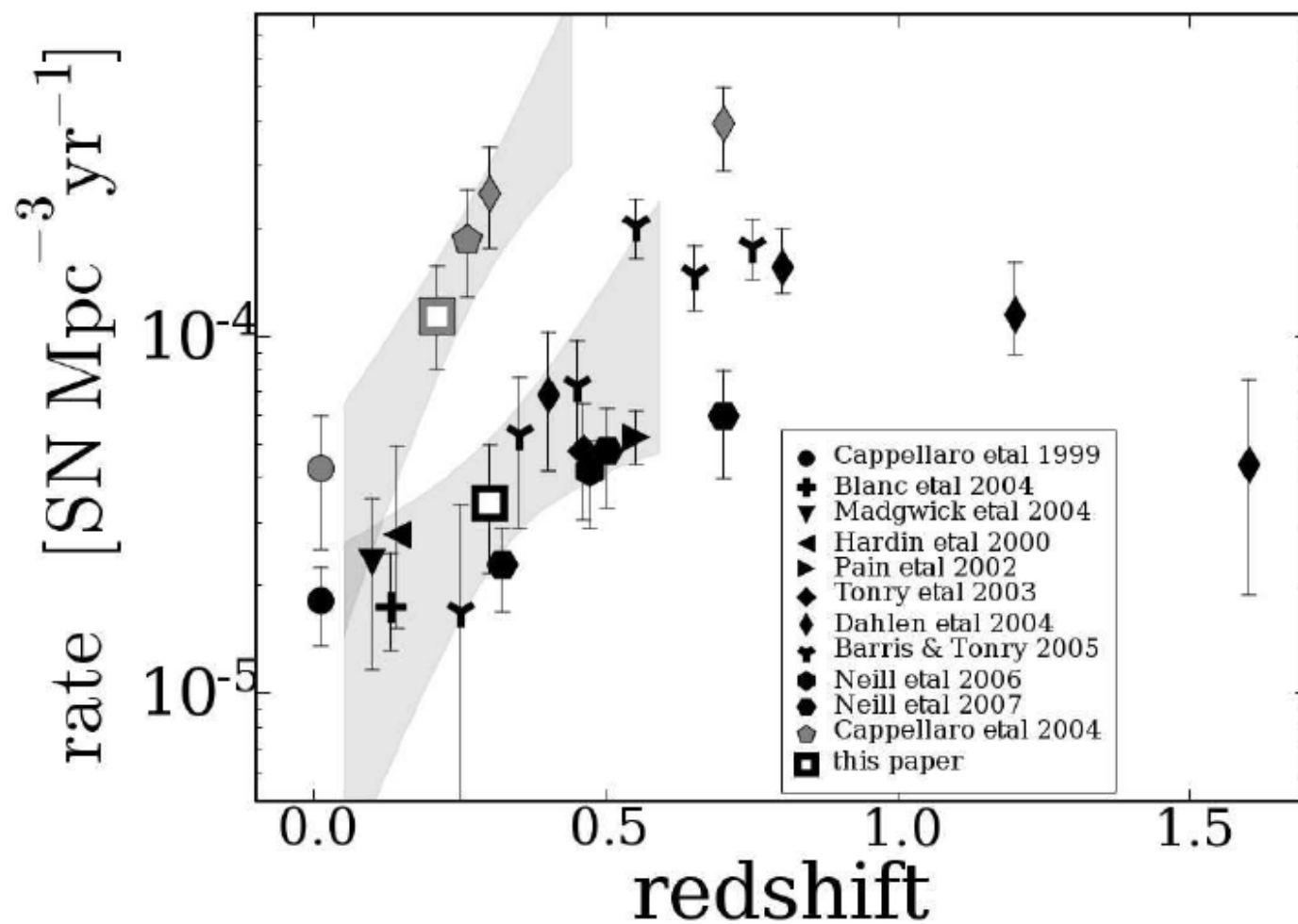
$$\mu = 5\log_{10}(d_L/10\text{pc})$$

0 K-correction (Kim et al. 1996)

$$K_x = 2.5\log(1+z) + 2.5\log \frac{\int F(\lambda) S_x(\lambda) d\lambda}{F(\lambda/(1+z)) S_x(\lambda) d\lambda}$$

Different type of CC SNe

- 0 They show great diversity in their observed properties and are sorted by their light
- 0 curves and spectra. Type-L supernovae show a steady linear decay after explosion, whereas type-P
- 0 supernovae show a plateau phase where the luminosity remain close to a constant for some time.
- 0 Type-L and type-P are both in the type II category, which display hydrogen in their spectra. Most
- 0 of the spectra line of type II supernovae have the P Cygni profile and are very broad, implying
- 0 a rapid explosion with high expanding velocity. However, there are a kind of type II supernovae
- 0 which has narrow spectrum line without P Cygni profile. This kind of supernovae is called type
- 0 II-n. In type I category supernovae, type Ib and Ic are also core-collapse supernova, which are lack
- 0 of hydrogen in their spectra. Type Ic also shows a lack of helium in its spectrum



Botticella et al. (2007)

Black: Type Ia
Gray: CC

Supernova Remnant

- 0 Velocity of the ejected matter $\sim 10^4 \text{ km/s } E_{51}^{1/2} (M/M_{\text{sun}})^{-1/2}$
- 0 Medium density $\sim 1 \text{ hydrogen atom per cm}^3$
- 0 Different phase:

1. Free expansion: $r \propto t$

Until

$$r_f \cong 2pc \left(\frac{M_{ej}}{M_{sun}} \right)^{1/3} \left(\frac{\rho_{ISM}}{2 \times 10^{-24} \text{ gm cm}^{-3}} \right)^{-1/3}$$

$$t_f \cong \frac{r_f}{v_{ej}} \approx 200 \text{ yr} \left(\frac{M_{ej}}{M_{sun}} \right)^{5/6} E_{51}^{-1/2} \left(\frac{\rho_{ISM}}{2 \times 10^{-24} \text{ gm cm}^{-3}} \right)^{-1/3}$$

Cont.

0 2. Sedov phase: $r \propto t^{2/5}$

$$r \cong \left(\frac{E}{\rho}\right)^{1/5} t^{2/5} \cong 0.3 pc E_{51}^{1/5} n_H^{-1/5} t_{yr}^{2/5}$$

$$v \cong 5000 km s^{-1} \left(\frac{r}{2 pc}\right)^{-3/2} E_{51}^{1/2} n_H^{-1/2}$$

$$T \cong 6 \times 10^8 k (50 keV) \left(\frac{r}{2 pc}\right)^{-3} E_{51} n_H^{-1}$$

$$\cong 10^6 k (100 eV) E_{51}^{2/5} n_H^{-2/5} \left(\frac{t}{3 \times 10^4 yr}\right)^{-6/5}$$

$$t_{sedov} \cong 3 \times 10^4 T_6^{-5/6} E_{51}^{1/3} n_H^{-1/3}$$

End when radiative cooling is significant.

Cont.

0 3. Snowplow phase:

- start when $t_{cool} < t_{sedove}$
- shock become isothermal
- hot interior & cool dense shell
- shock move with approx. constant radial momentum
- conservation of momentum

$$t_{cool} \cong 4 \times 10^4 \frac{T_6^{3/2}}{n_H} \text{ yr}$$

$$\dot{r} \propto T^{1/2} < 200 \text{ km s}^{-1} (E_{51} n_H^2)^{1/14}$$

$$\frac{4\pi}{3} \rho R^3 \dot{R} = \frac{4\pi}{3} \rho_0 R_0^3 v_0$$

$$R = R_0 \left[1 + 4 \frac{v_0}{R_0} (t - t_0) \right]^{1/4} \quad v = v_0 \left[1 + 4 \frac{v_0}{R_0} (t - t_0) \right]^{-3/4}$$

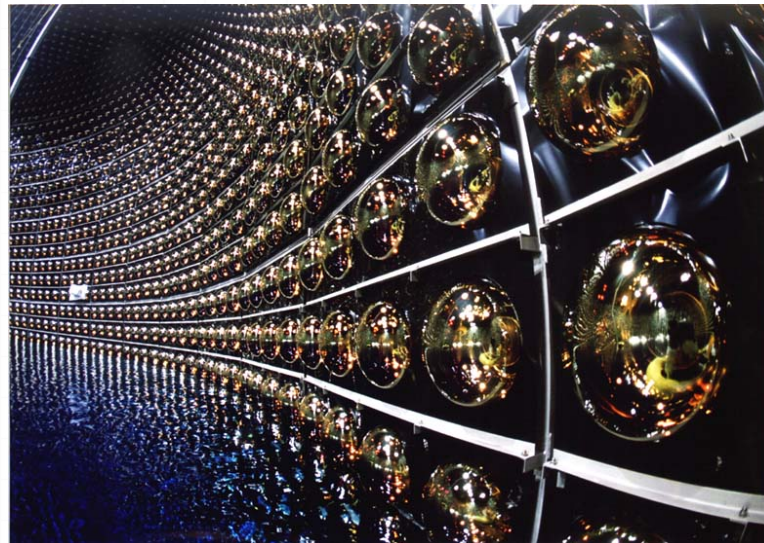
Back-up Slides

Part 2:

SNe + neutrinos

Supernova Neutrinos

- 0 ν & anti- ν of all species
- 0 Detectable energy range $\sim 10\text{-}30$ MeV
- 0 Major detector: Super-Kamiokande
- 0 Detection **anti-nu**: $\bar{\nu}_e + p \rightarrow n + e^+$
- 0 Expect to have first detection of supernova neutrino background in the next ten years

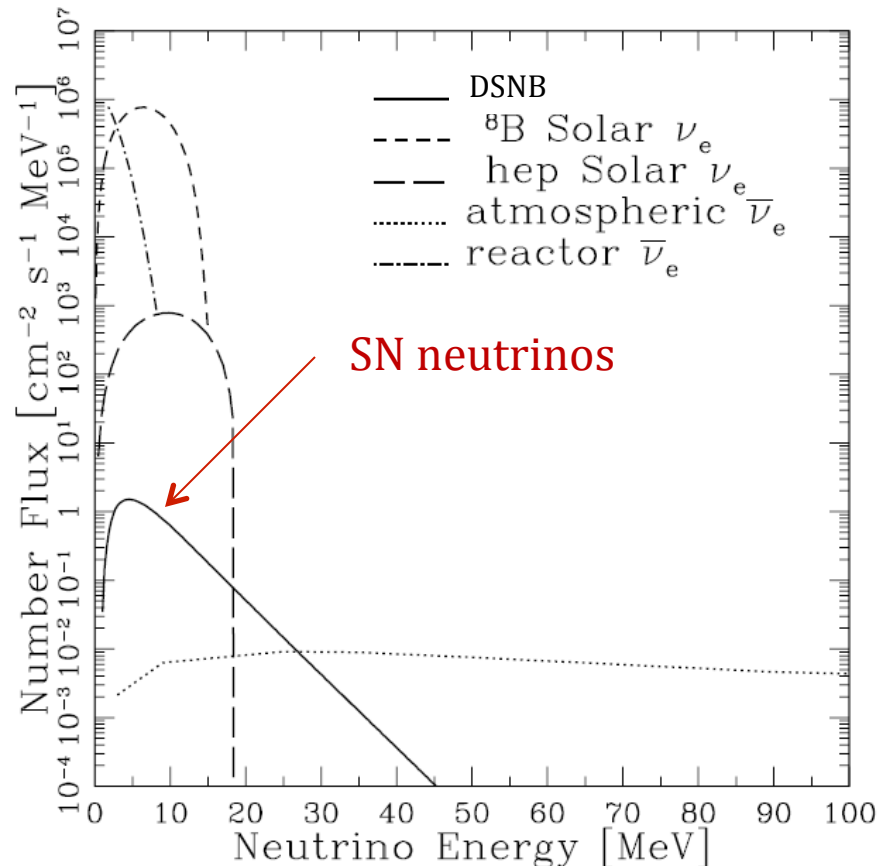


Neutrino Sources from Earth & Sky

Main neutrino background sources:

- 0 Supernovae (10-30 MeV)
- 0 Sun (create ν_e , not anti ν_e)
- 0 Atmospheric (from interaction with cosmic ray particles)
- 0 Artificial (nuclear reactors)
- 0 Earth (similar to reactors)
- 0 High energy cosmic neutrinos (10^{12} eV)
- 0 Cosmic background radiation neutrino (1.7×10^{-4} eV)

Ando et al. (2002)

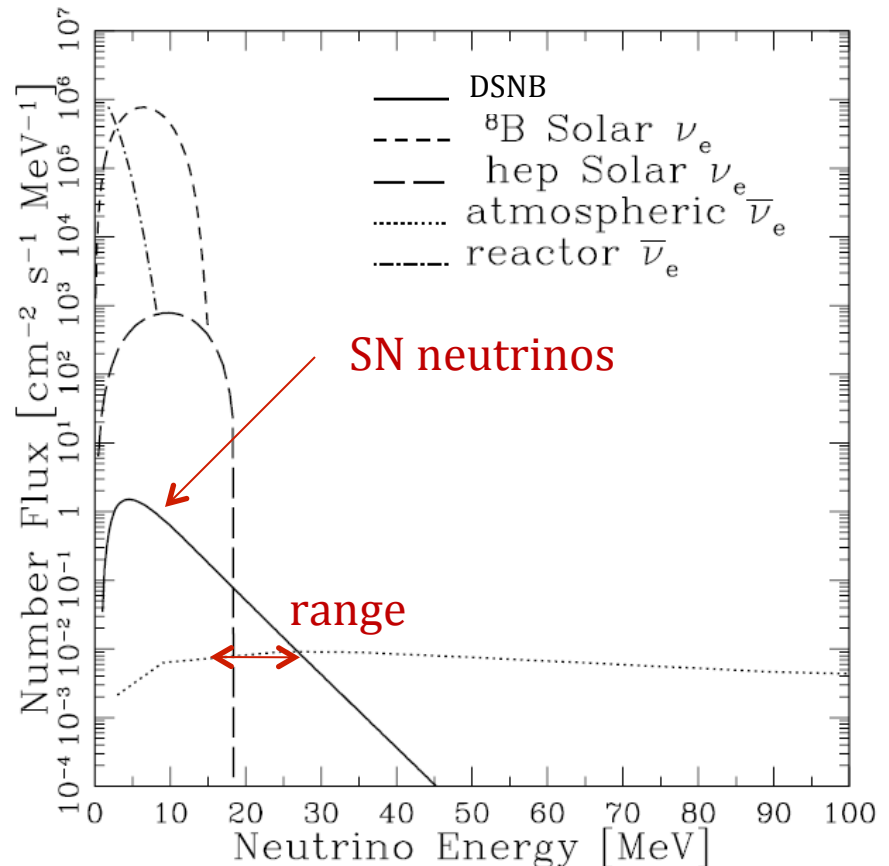


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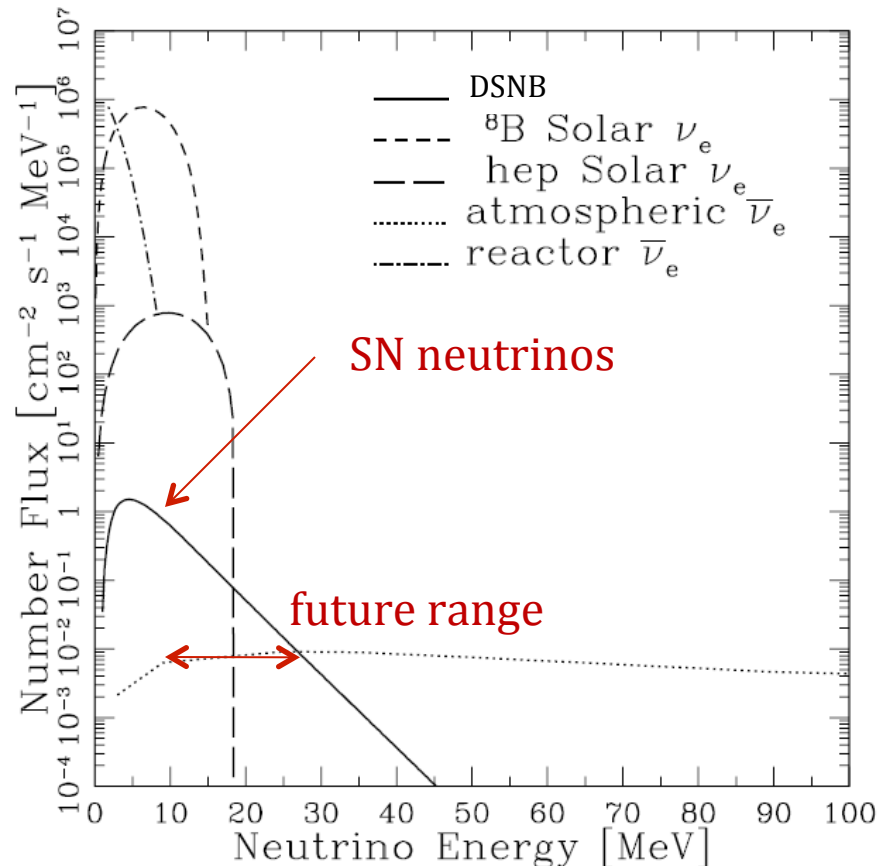


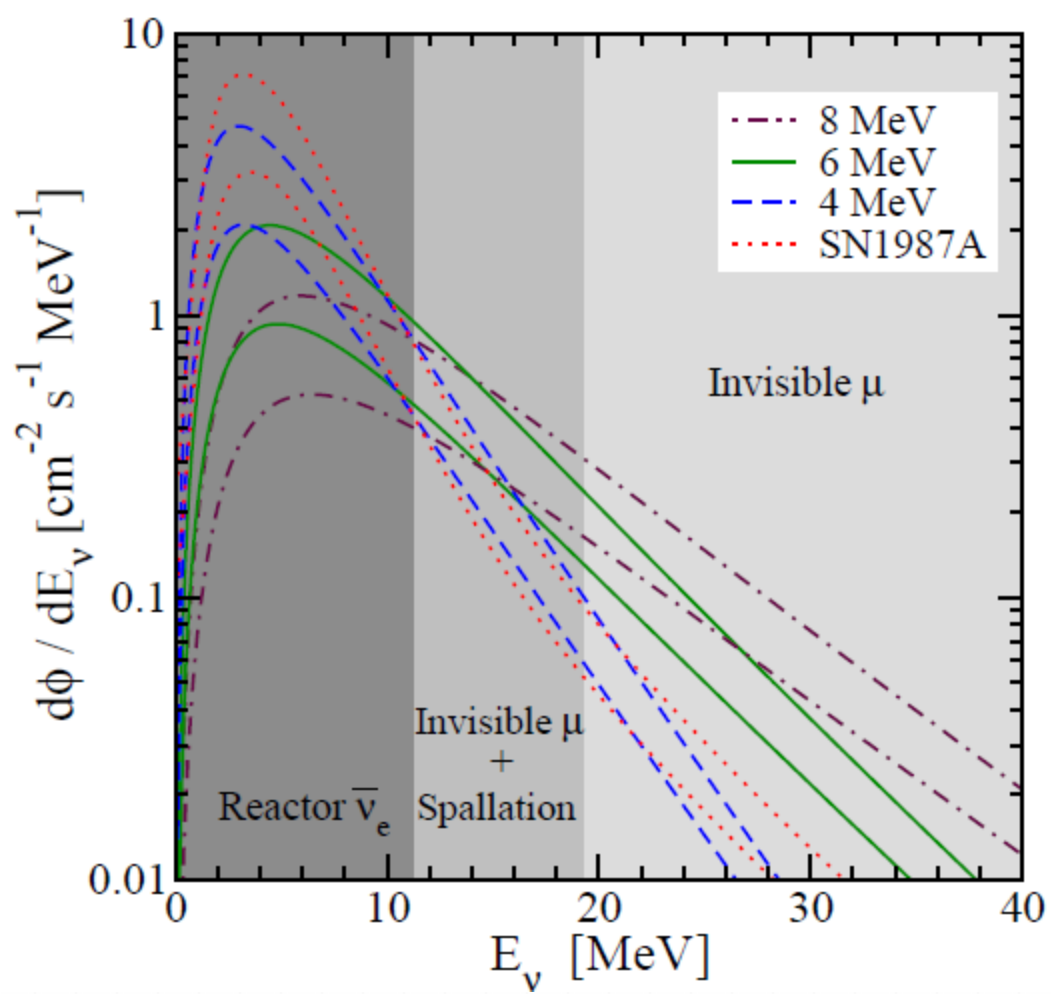
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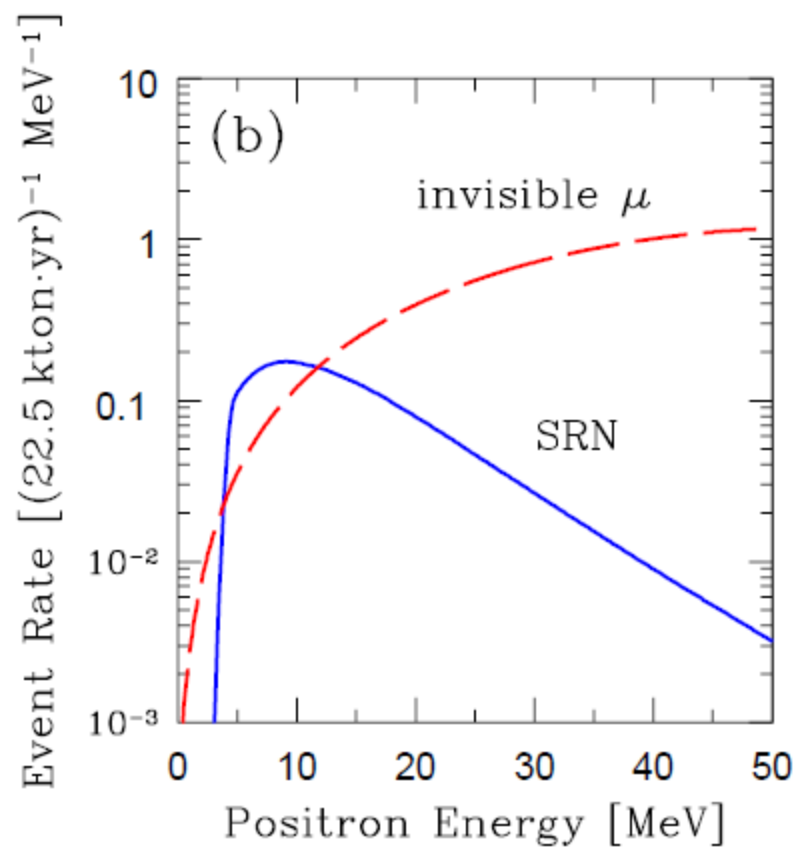
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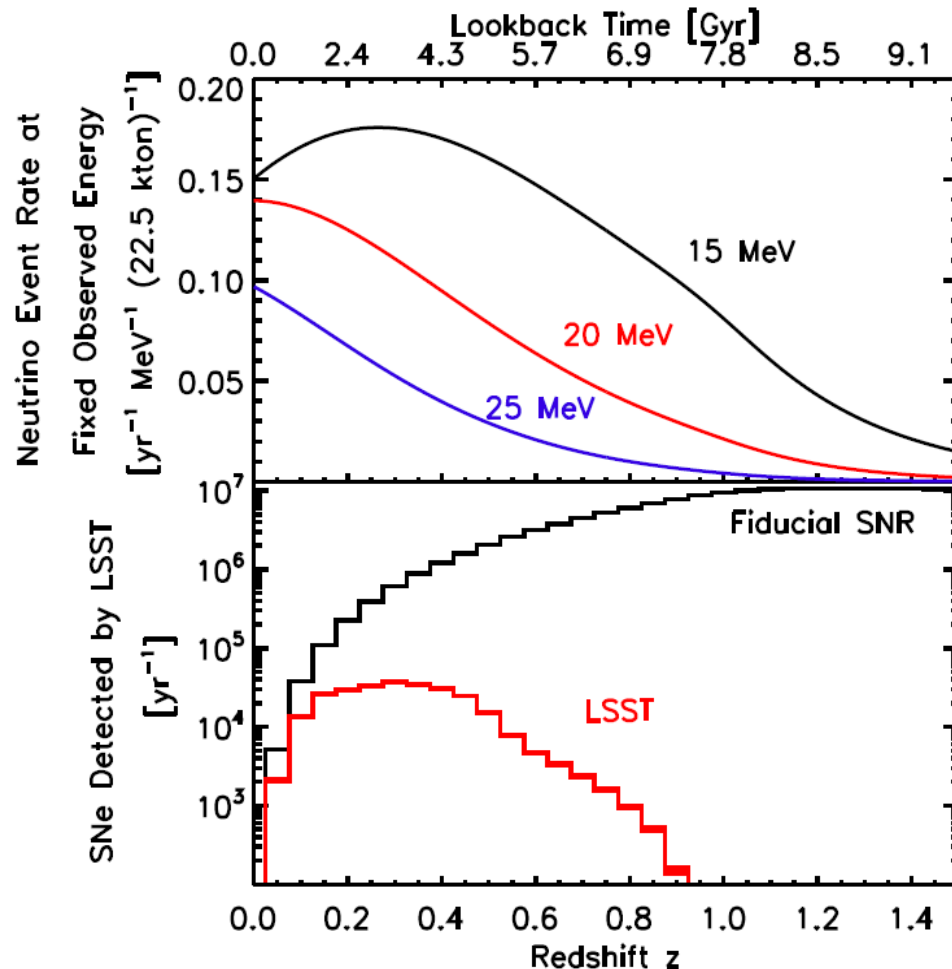
Ando et al. (2002)







Supernova Surveys and Neutrinos



0 Main upcoming SN survey:

LSST

0 Scan area: 20000 deg^2

0 SN survey deepness: 23 mag

0 Main neutrino detector: Super-Kamiokande (Super-K)

0 Detection energy range: 18-26 MeV

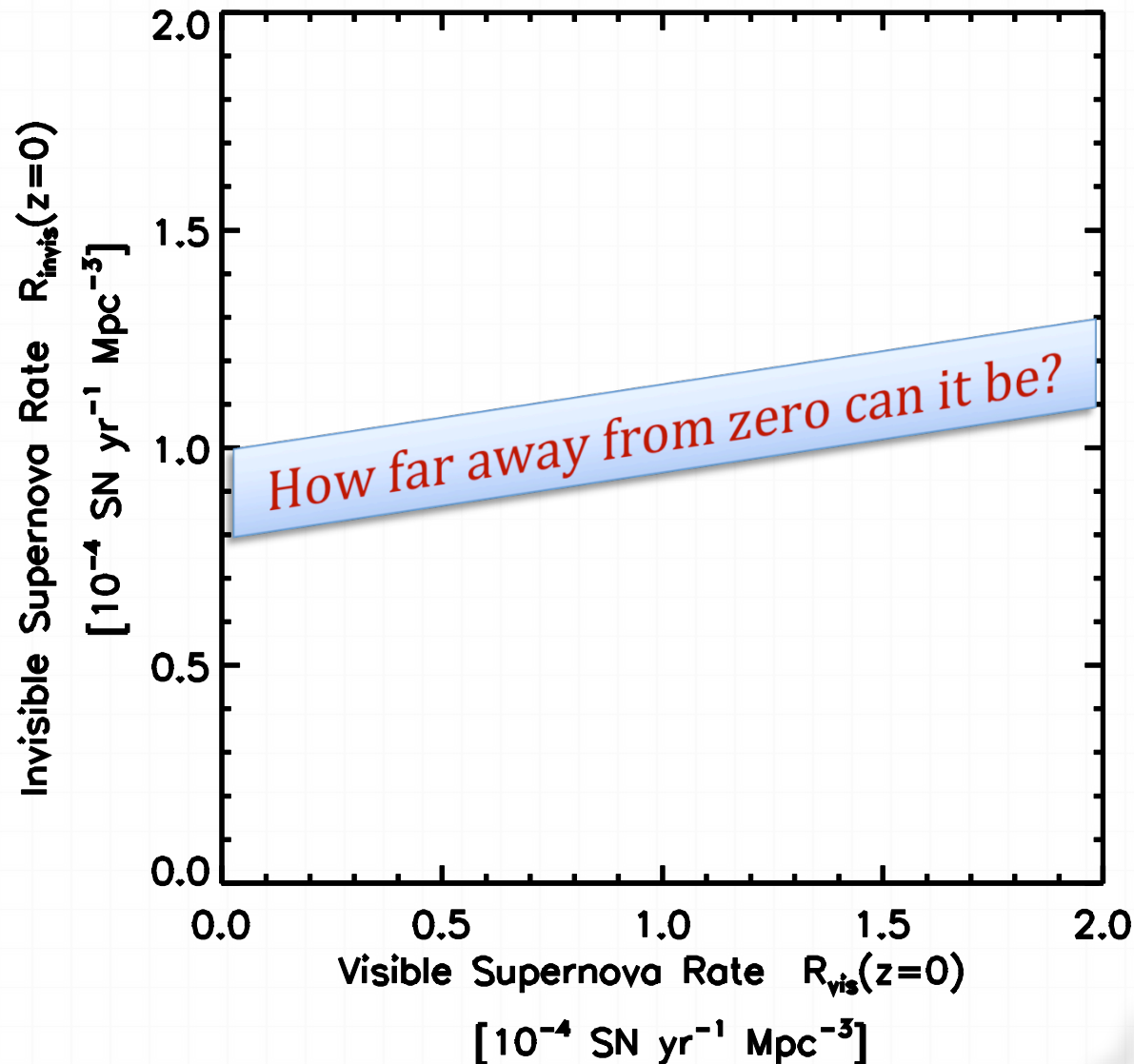
0 Possible future detection energy range: 10-26 MeV

0 Neutrino detection peak at similar redshift range of SN surveys

0 76% of 10-26 MeV DSNB comes from SN with $z < 1$

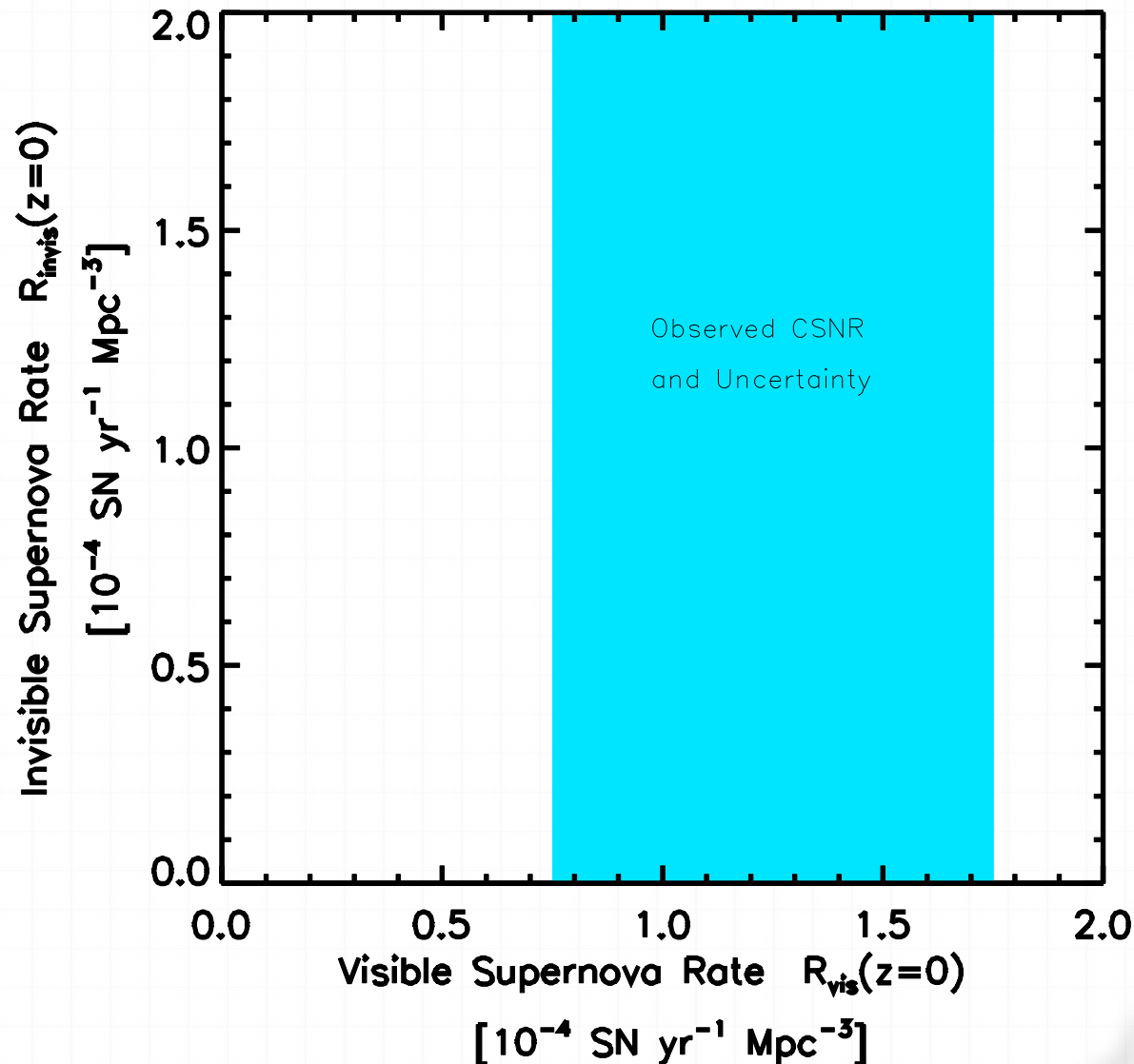
Revealing Failed Supernovae

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



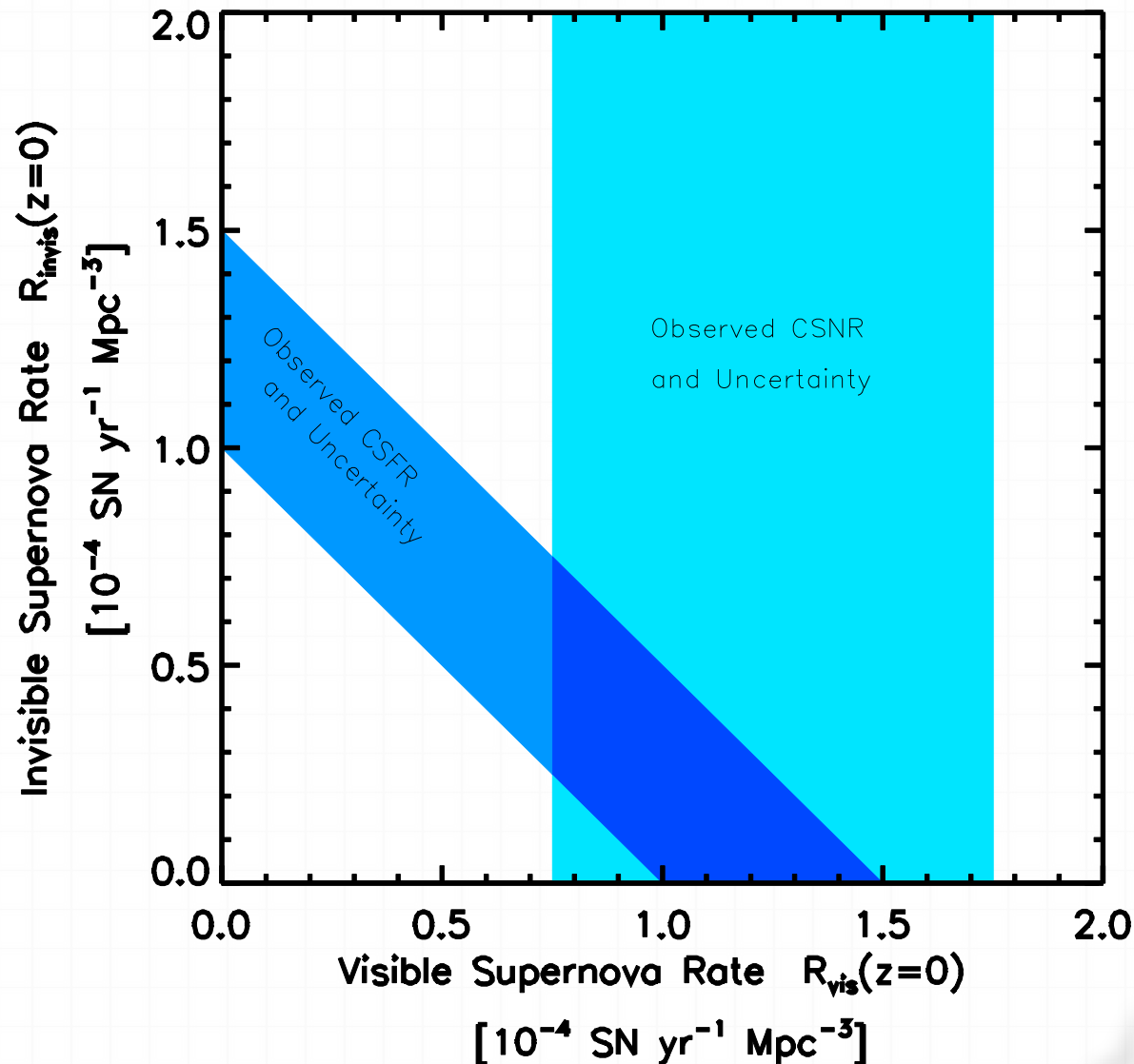
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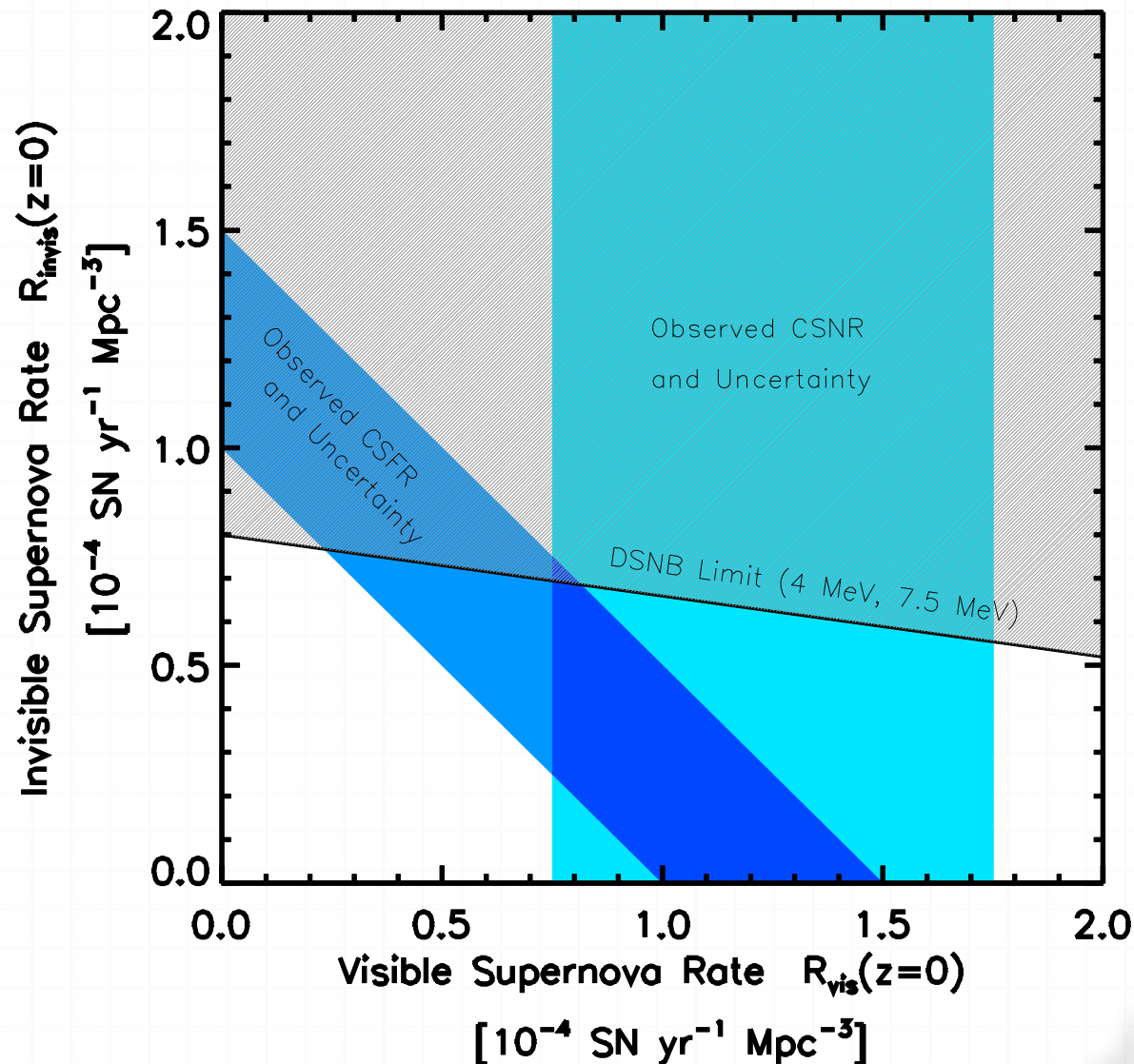
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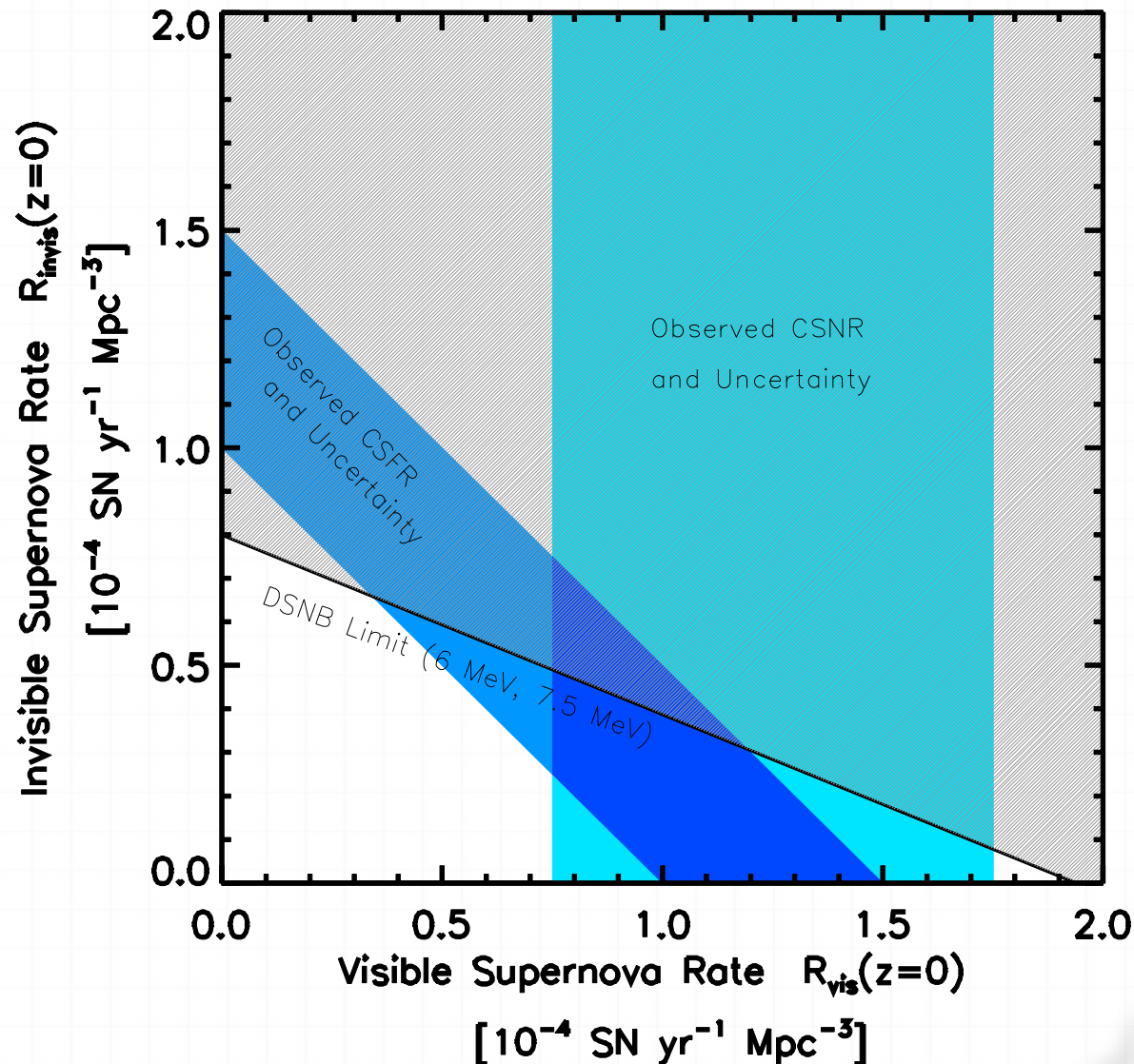
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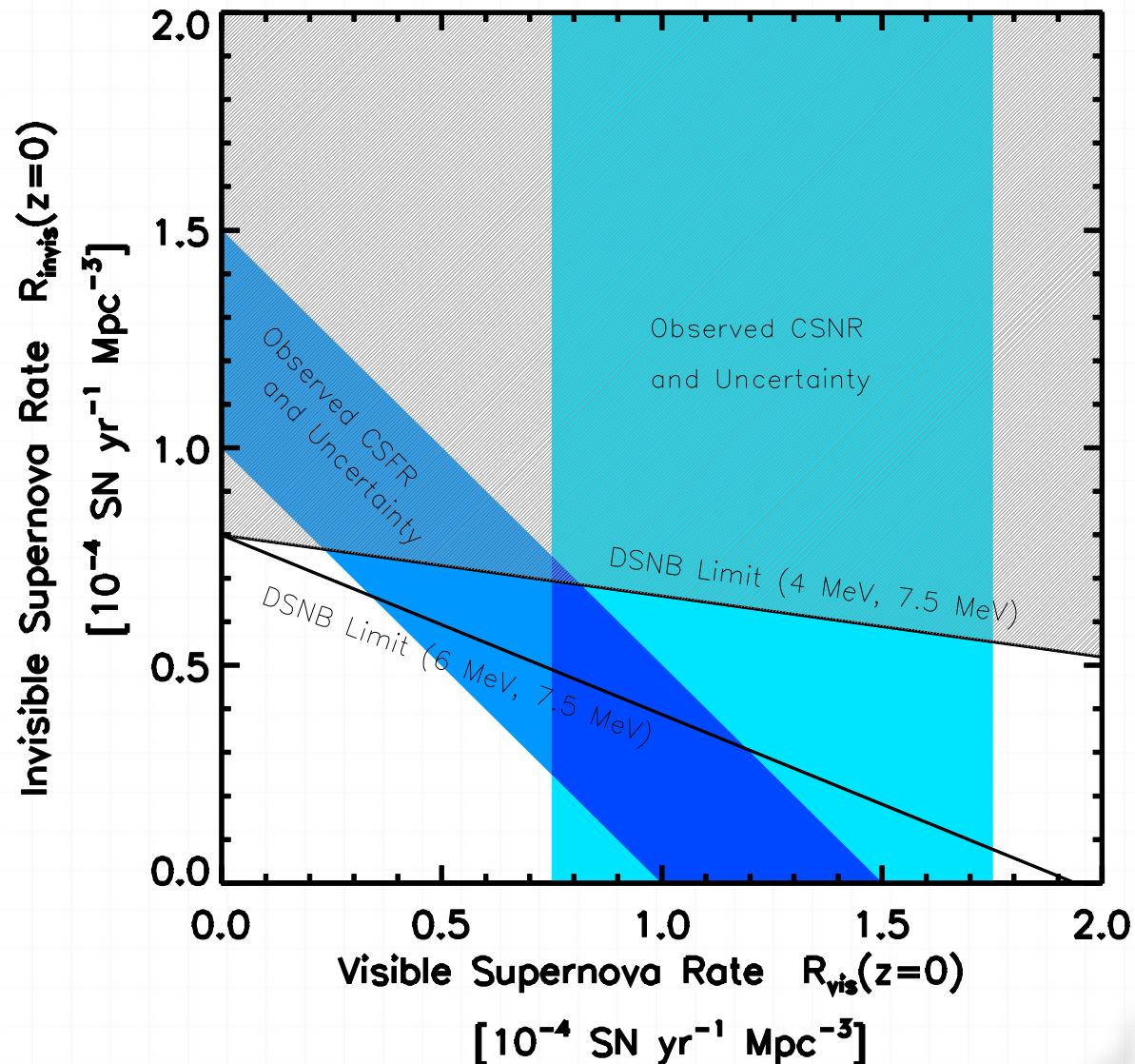
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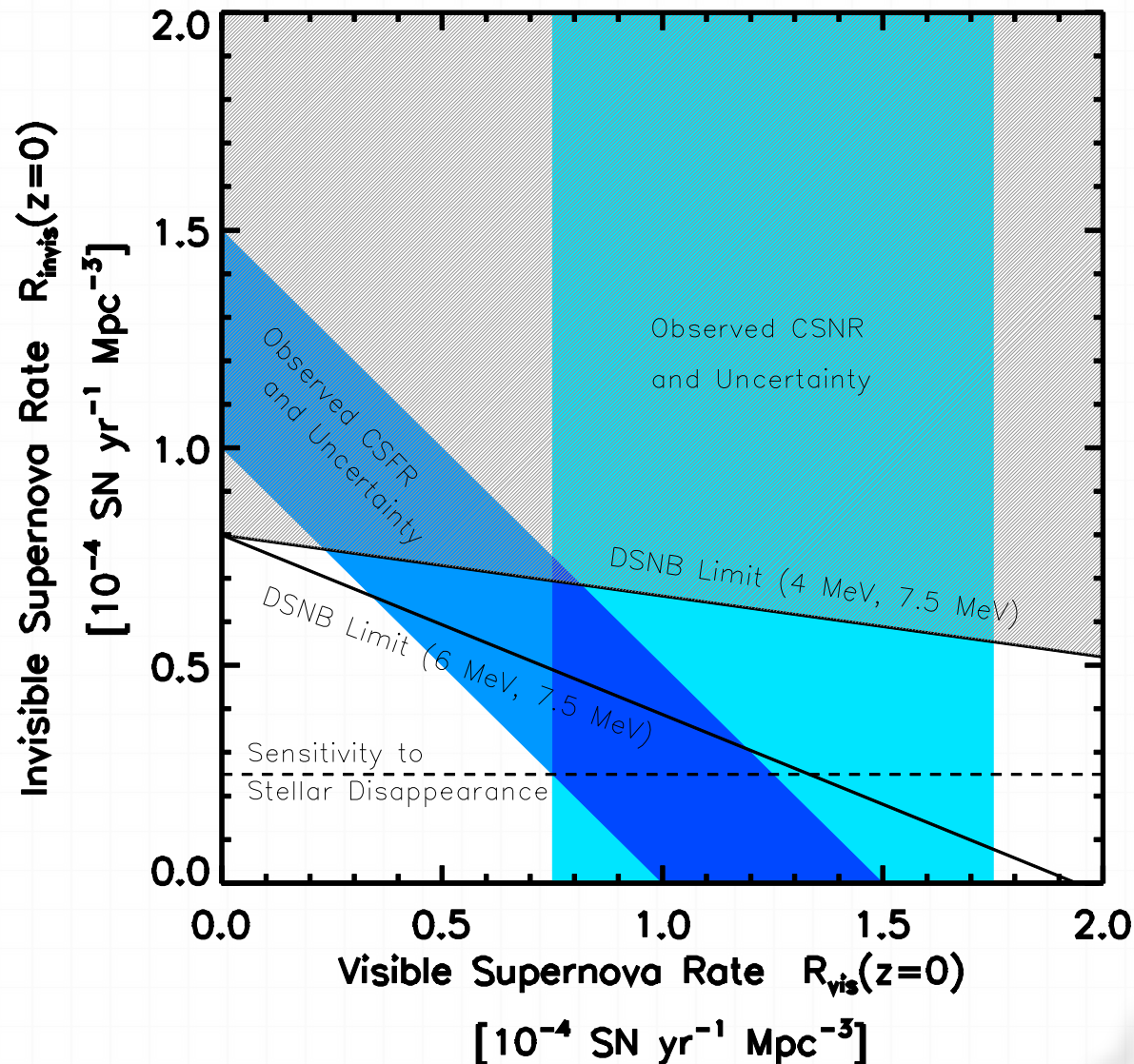
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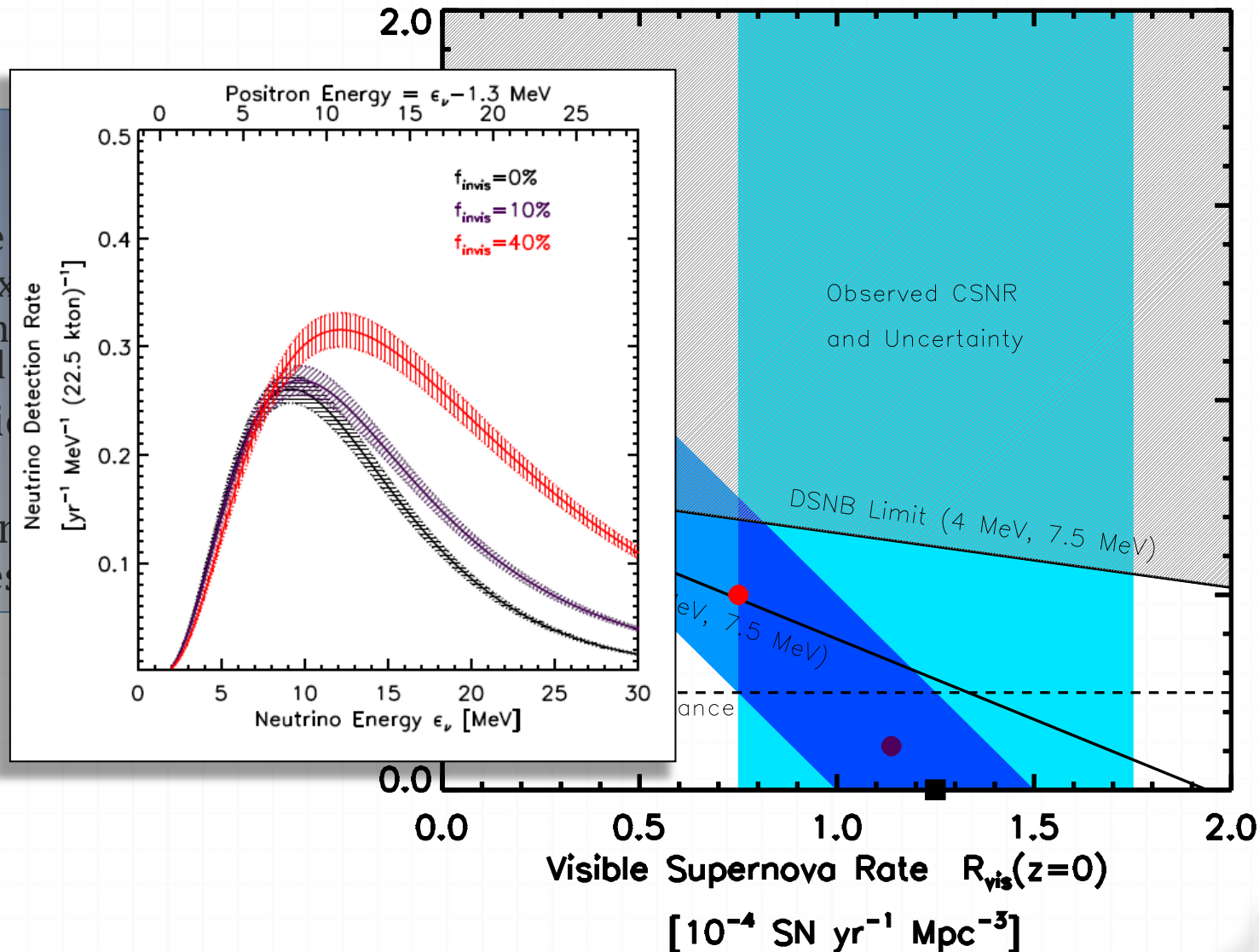
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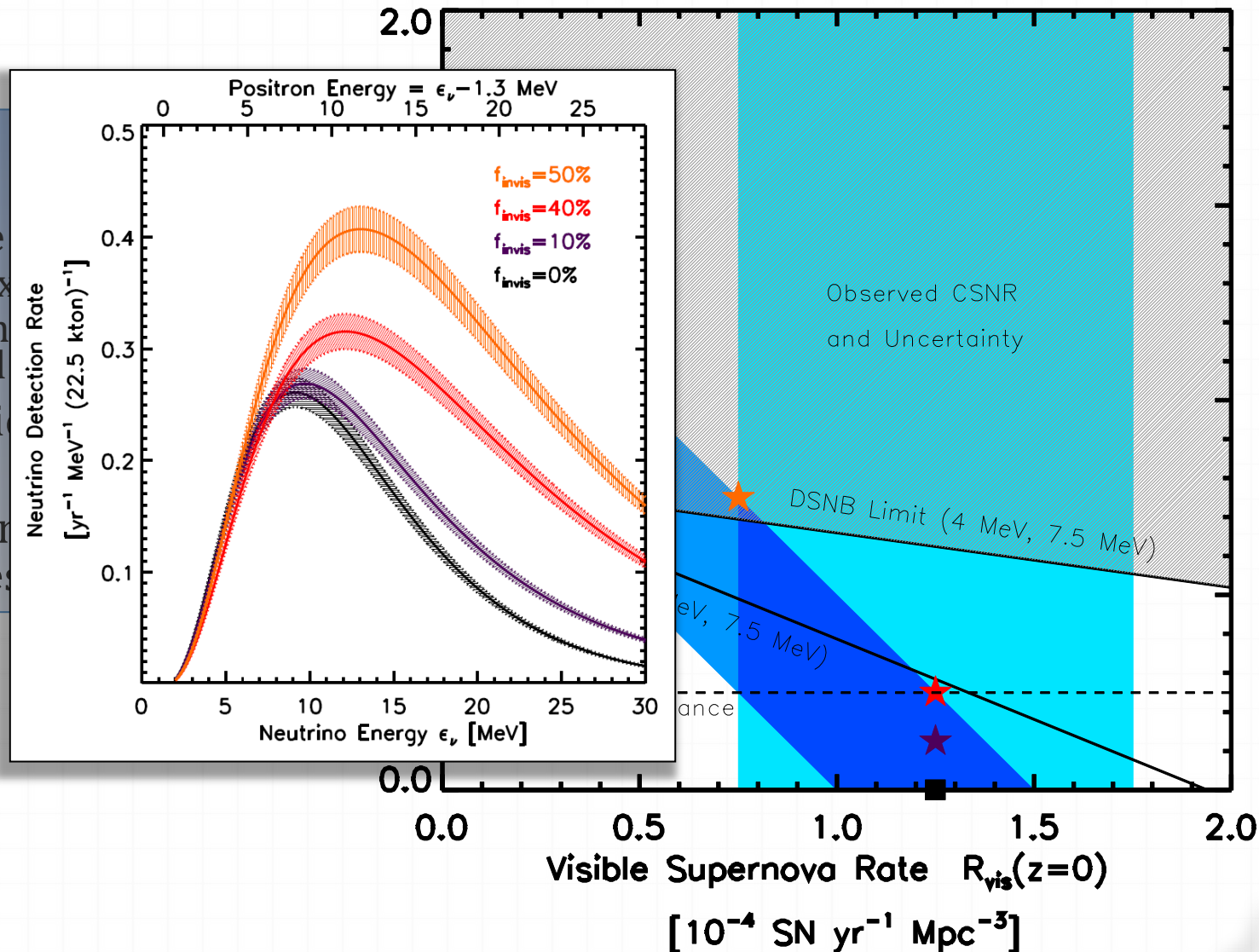
Revealing Failed Supernovae

- 0 Failed SN
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 - Detected by radio observatories



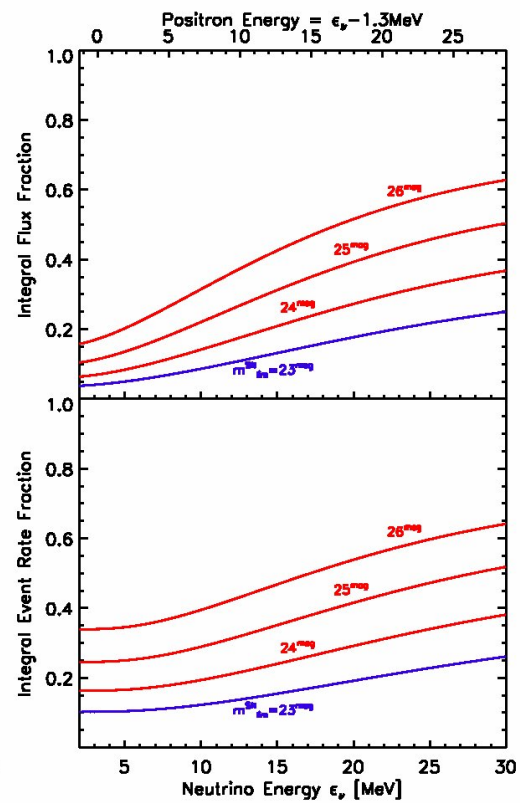
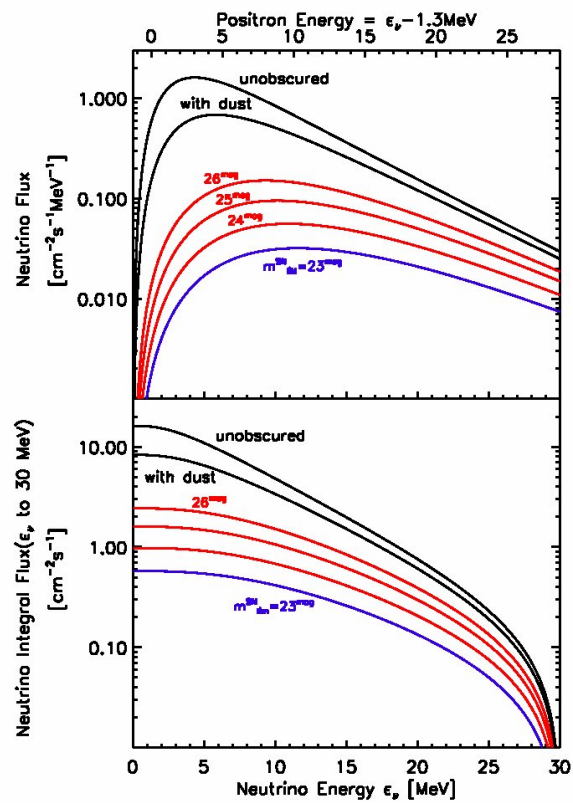
Revealing Failed Supernovae

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Dust?

- 0 Between two extreme dust model, the Super-K detection rates change from 0.42 and 0.39 events per year
- 0 Assuming we know luminosity function $\rightarrow$ 2.46 and 1.78 events per year of the Super-K detection rates
- 0 Not likely to probe dust so far



Connecting the two: Diffuse Supernova Neutrino Background (DSNB)

- 0 Neutrino flux from supernovae
 - 0 ν & anti- ν of all species
 - 0 10-30 MeV
- 0 Estimating DSNB by adding up neutrinos contributed by detected supernovae
- 0 Impacts on SNe and cosmology
 - 0 High-energy flux from nearby SNe:
tests supernova and neutrino physics
 - 0 Low-energy flux:
SN & star formation at $z > 1$
- 0 Neutrinos “see” missing SNe
 - 0 SNe collapse into black hole

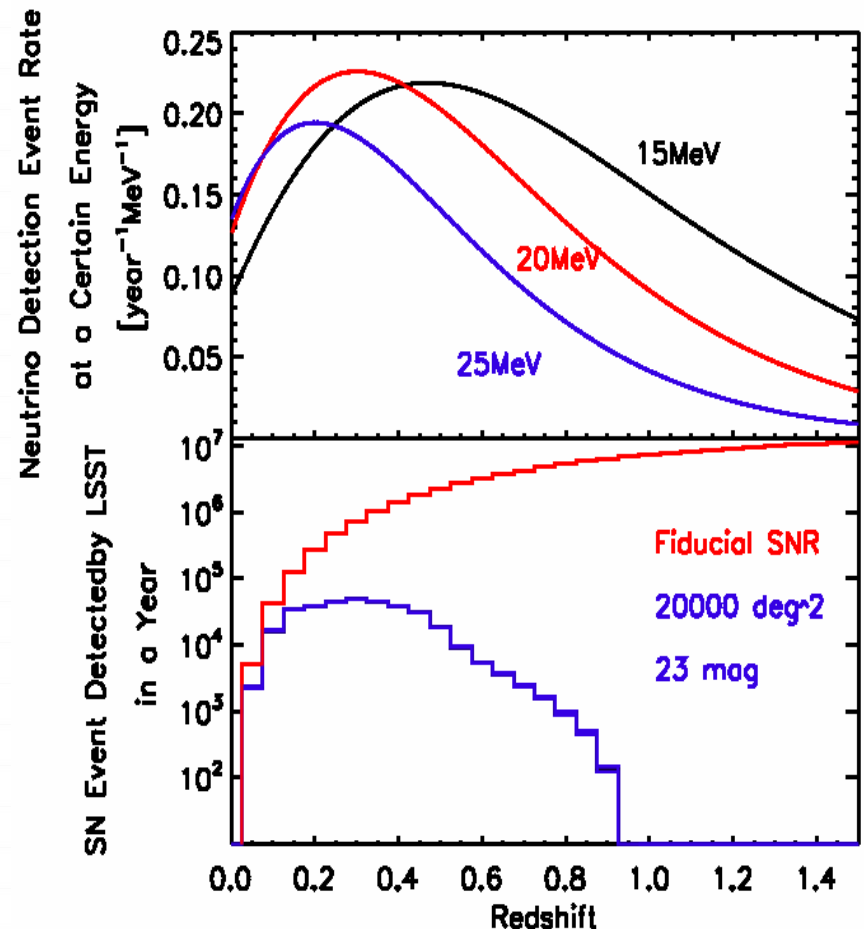
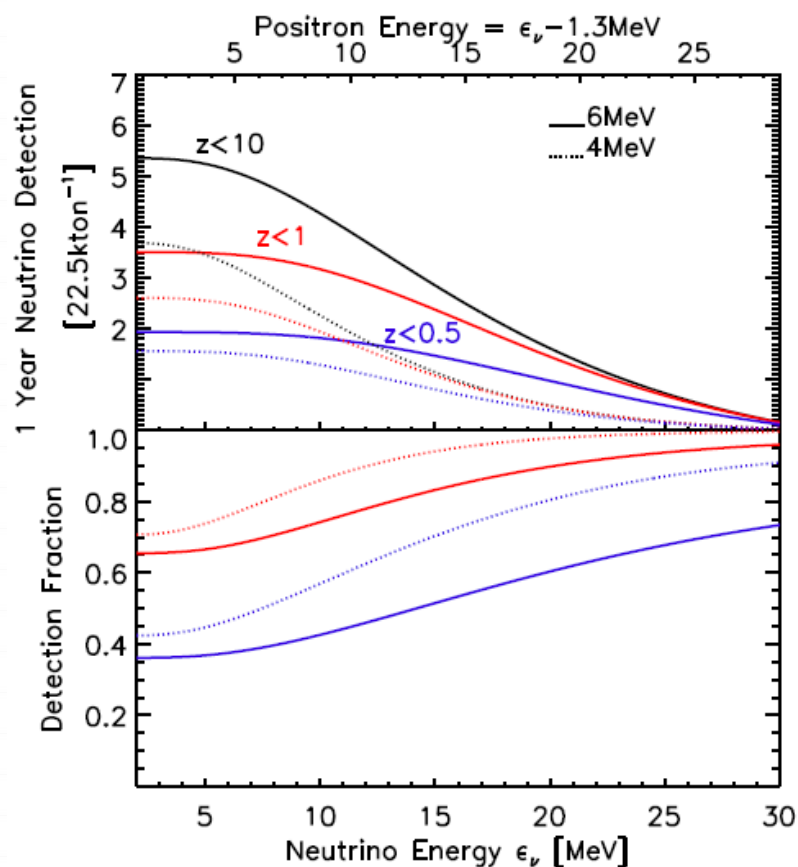


TABLE IV: Integrated DSNB event rates in the positron energy range 18–26 MeV for the current SK and 10–26 MeV for a gadolinium-enhanced SK. The uncertainties reflect the upper and lower R_{CCSN} , defined from the CSFH.

$\bar{\nu}_e$ 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

Neutrino from Different Redshifts



Looking to the future

- 0 Neutrino detections

- 0 Should have the first detection in the next decade.

- 0 Strategy/Attitude

- 0 Imaging that we will be able to measure SN rate out to $z \sim 1$

- 0 Dust effects and SN luminosity distribution understood

- 0 Expecting a 5% precision

Connecting the Two....

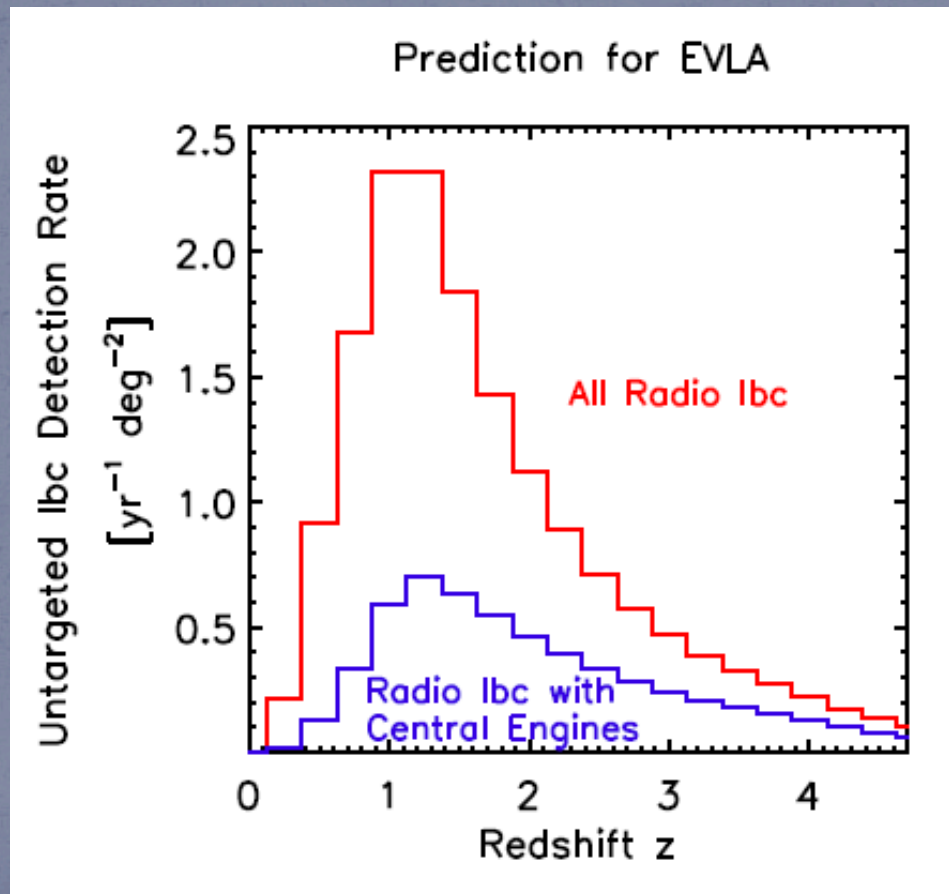
- 0 **Predict** $\phi_{\nu}^{\text{survey}}$ neutrino flux from supernova surveys :
Add neutrinos from all observed supernovae
- 0 **Measure** neutrino flux from neutrino detectors
- 0 Compare $\phi_{\nu}^{\text{survey}}$ and $\phi_{\nu}^{\text{detect}}$
- 0 We hope to $\phi_{\nu}^{\text{survey}}$ in $\phi_{\nu}^{\text{detect}}$
 - 0 Supernova and neutrino physics
 - 0 Failed supernovae
 - 0 Dust? Weak constraint

Back-up Slides

Part 3:

SNe + Radio

Radio Synoptic Survey with EVLA



Current Studies of Radio Supernovae

- 0 VLA/EVLA

- 0 Type Ia – **no detections** so far...

- 0 Core-collapse supernovae – about 50 detections

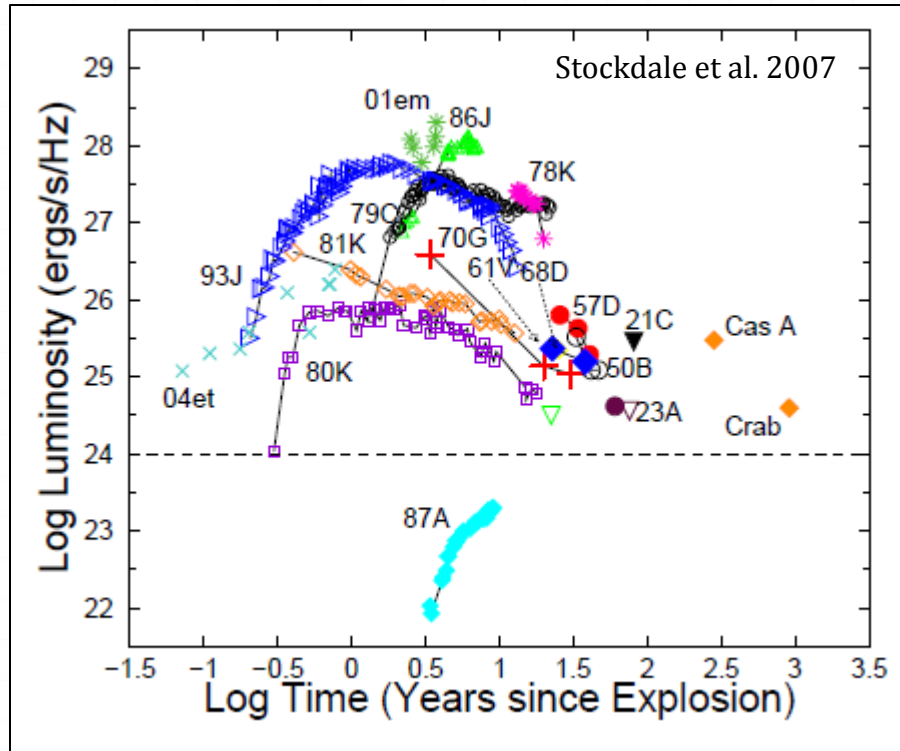
- 0 No synoptic surveys for radio supernovae exist.....
yet



Tge Crazy Radio Light Curve Equation

$$L(t, \nu) = L_1 \left(\frac{\nu}{5 \text{ GHz}} \right)^\alpha \left(\frac{t}{1 \text{ day}} \right)^\beta e^{-\tau_{\text{external}}} \left(\frac{1 - e^{-\tau_{\text{CSM}_{\text{clumps}}}}}{\tau_{\text{CSM}_{\text{clumps}}}} \right) \left(\frac{1 - e^{-\tau_{\text{internal}}}}{\tau_{\text{internal}}} \right)$$

Basic characteristics for core-collapse supernovae



0 Type IIc seems to have the brightest peak luminosity

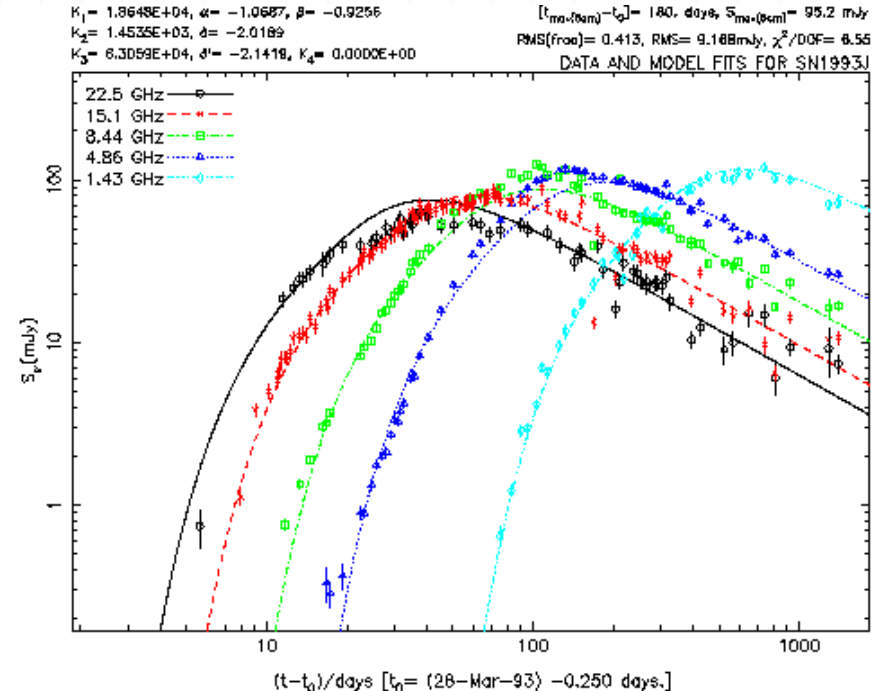


Figure 2.3: Light curves at multiple radio frequencies for a recent, nearby Type IIb, SN 1993J in M81 (NGC 3031), only 3.6 Mpc distant.

Credit: SKA science book 1999

Continue.....

0 Type Ib/c

(Weiler et al. 2002, Berger et al. 2003)

0 Steep spectral indices

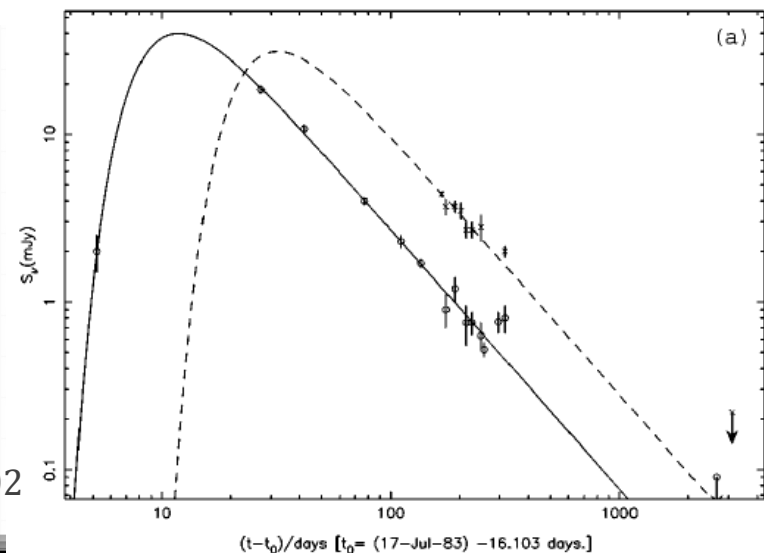
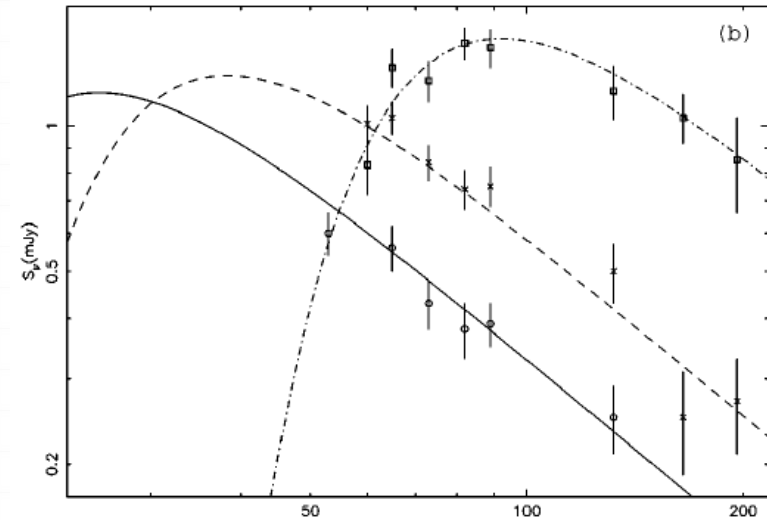
$$S \propto \nu^{+\alpha}$$

0 Fast turn on/off

0 Usually peaking at 6cm before/ near optical maximum

0 About 12% of type Ib/c have detectable radio emission

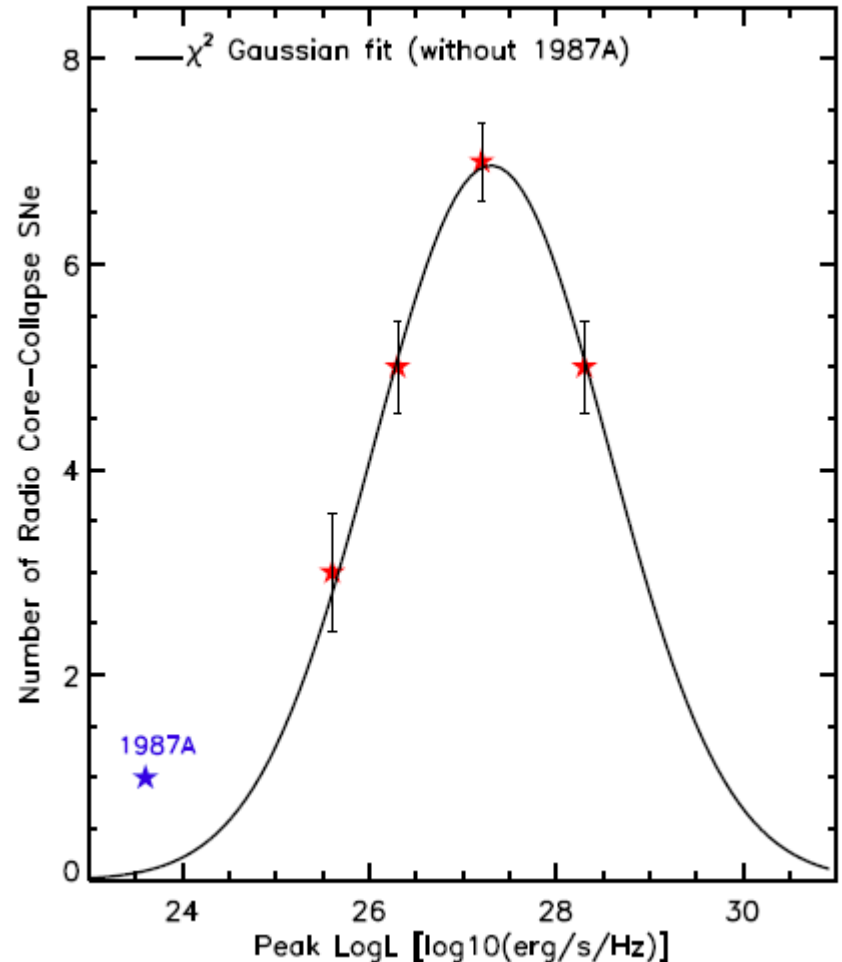
0 About 0.5% of Type Ib/c have central engines (might related to GRBs)



Figures: Weiler et al. 2002

Luminosity Function for Radio Supernovae

- ✖ At 6 cm (5 GHz)
- ✖ Total Radio SNe:
21 + 1987A
- ✖ Average luminosity:
 1.35×10^{28} erg/s/Hz
 $\text{Log}(L)_{\text{avg}} = 27.1$
- ✖ Sigma for Log(L): 1.04



Synoptic Surveys for Radio Supernovae

- 0 Currently:
 - 0 ~ 50 radio CC SNe
 - 0 NO radio Ia
 - 0 When SKA comes up:
 - 0 Sensitivity improves > 50 times
 - 0 Complement to LSST
 - 0 Probe upernovae at high redshift
 - 0 SKA detections:
 - 0 All CC SNe ~620/yr
 - 0 Ibc: ~ 116/yr
- (Assume $f_{\text{radio}} = 10\%$ of CCSNe are radio bright)

