Workshop on Gravitational Waves and
High-Energy Neutrinos@Paris, May 18, 2009

Joint emitters of GW and HEν: What and how frequent are they?

Shin'ichiro Ando
California Institute of Technology

Requirements for potential sources

- Massive
- Violent (time scale less than sec)
- Energetic
- Contain rich baryons (to produce neutrinos)
- Close enough
- Frequent enough

List of GW+HEν sources

- Galactic sources
  - Soft γ repeaters
  - Micro quasars
- Extragalactic sources
  - Long GRBs
  - Short GRBs
  - Low-luminosity GRBs

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Stellar collapase
(supernova, hypernova)

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HEν	jets (particle acceleration)

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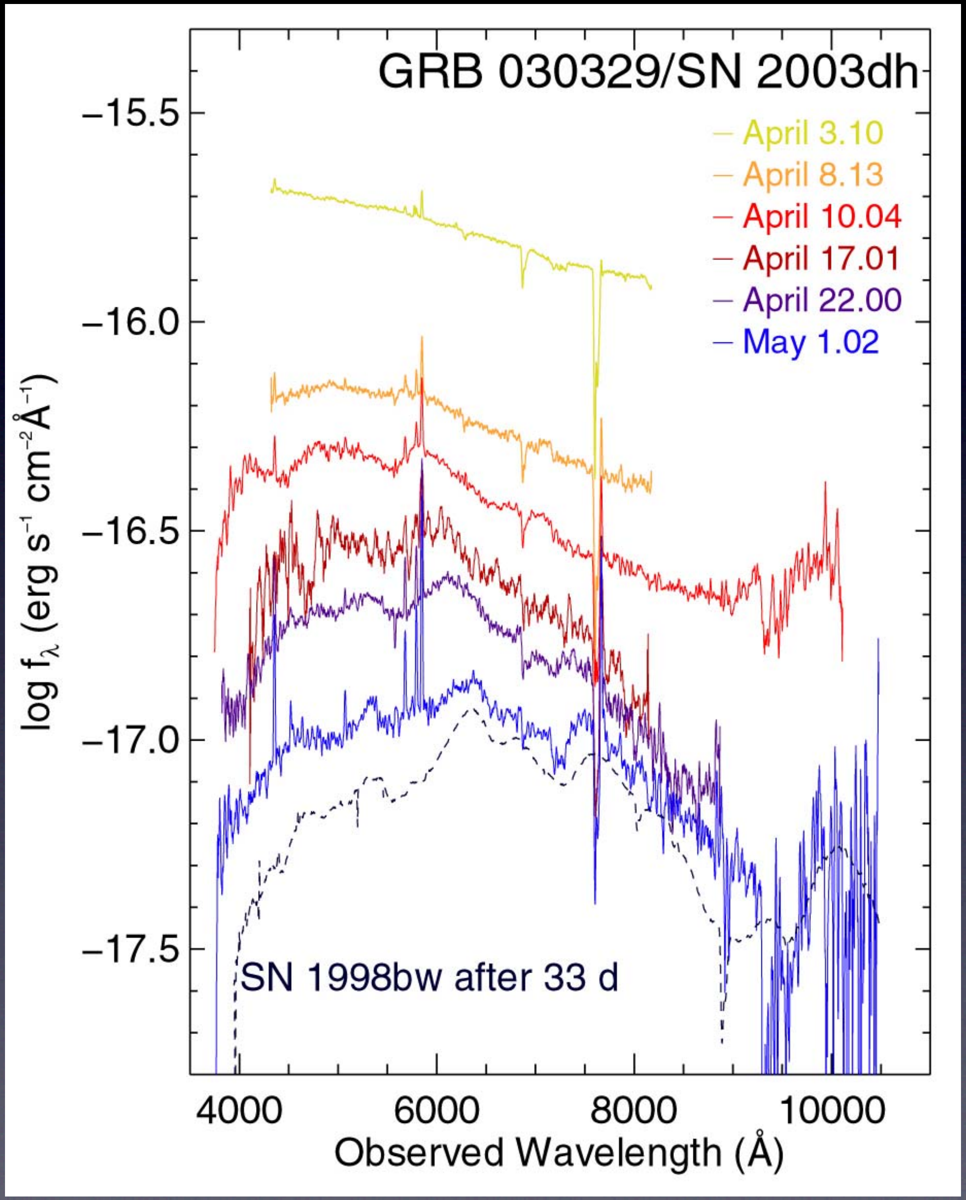
- Luminous collapse
  - GRBs, supernovae, hypernovae
  - Also bright in photons and MeV neutrinos (if in the Galaxy), providing valuable timing information
- Dark collapse: unidentified
  - Potentially interesting for GW/HEν search

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?

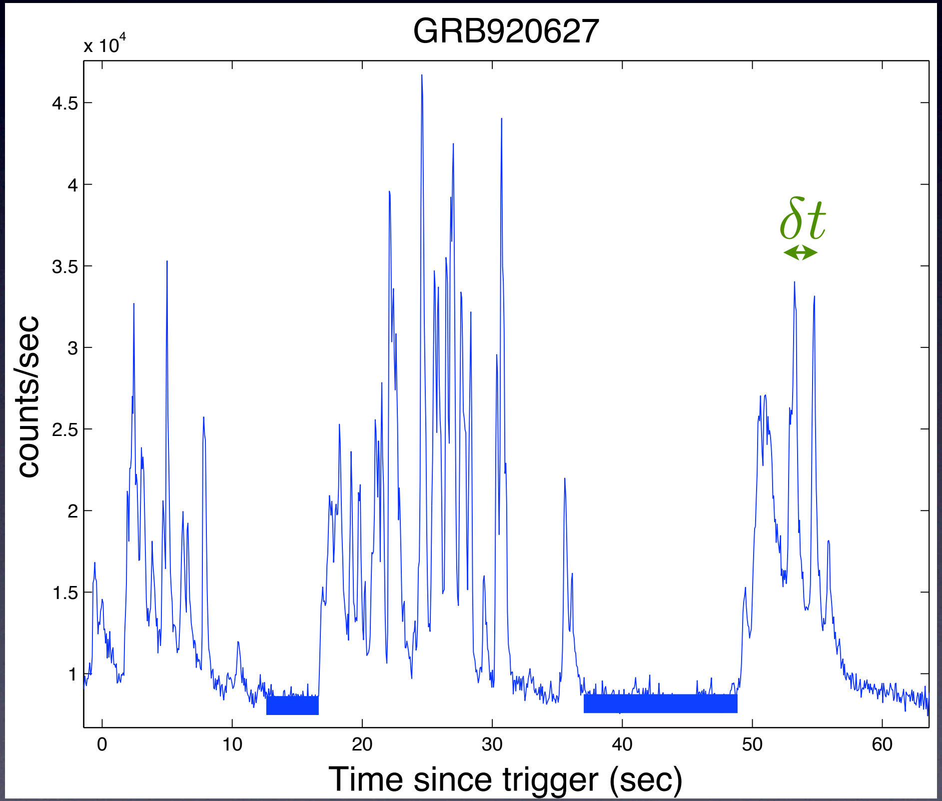
	SN	GRB
Energy	10^{51} erg	10^{51} erg
Rate	~1 cen^{-1} gal^{-1}	~1 Myr^{-1} gal^{-1}
Γ	~1	~100–10^3

Are there sources in between?

Why GRBs luminous and nonthermal?

- Why are GRB jets relativistic? — compactness problem

E.g., Piran 2005



Without relativistic effect:

- Size of the emitting region

$$\lesssim c\delta t$$

- Density of photons

$$\frac{4\pi d^2 F}{\bar{E}_\gamma c^3 \delta t^2}$$

- Opacity for γγ absorption

$$\frac{f_e \sigma_T 4\pi d^2 F}{\bar{E}_\gamma c^2 \delta t} \approx 10^{15}$$

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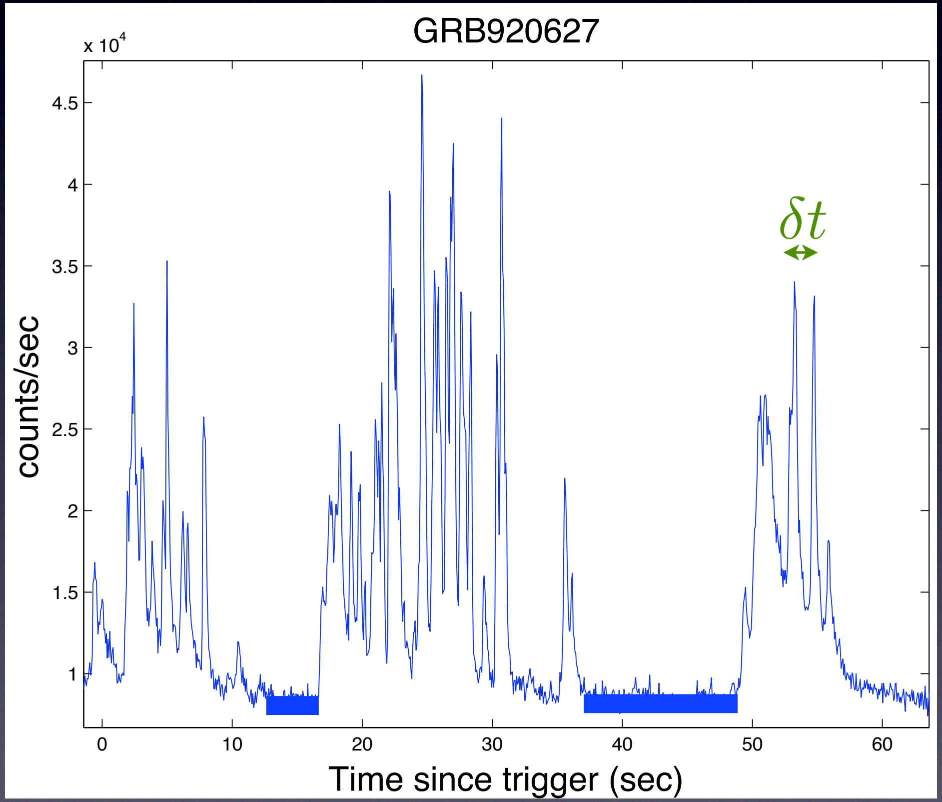

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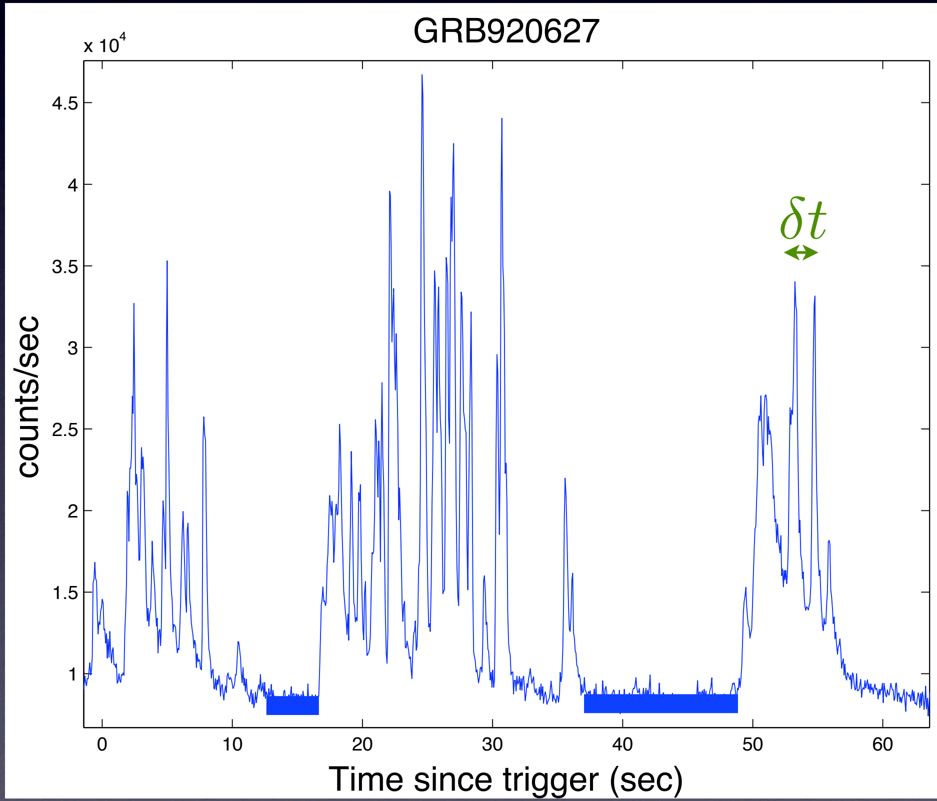

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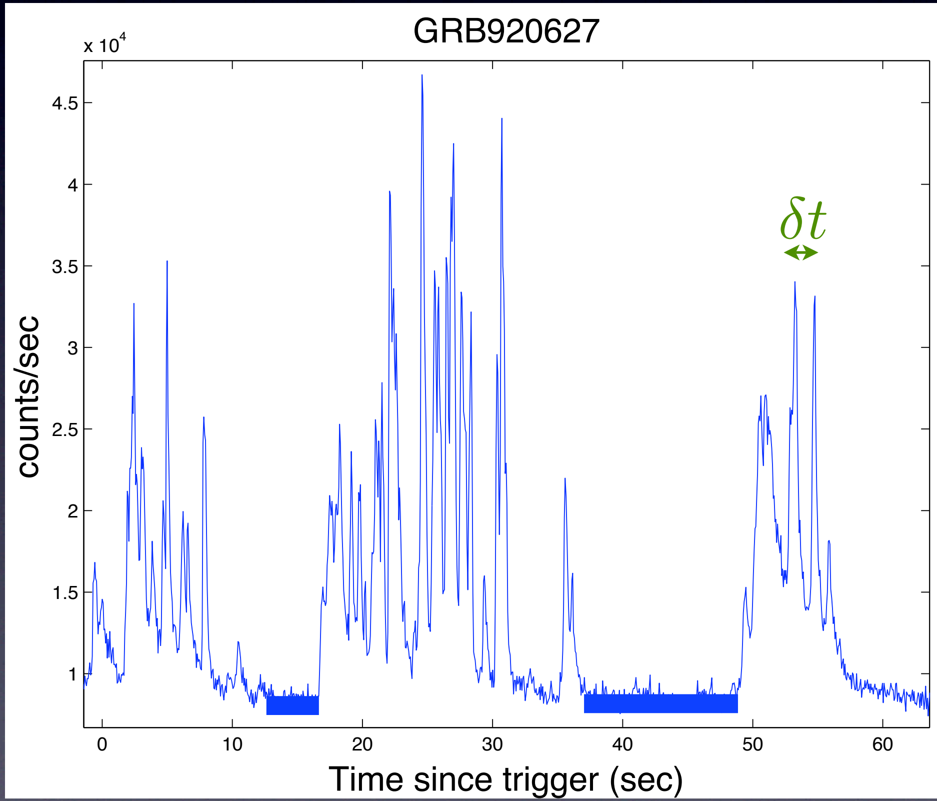

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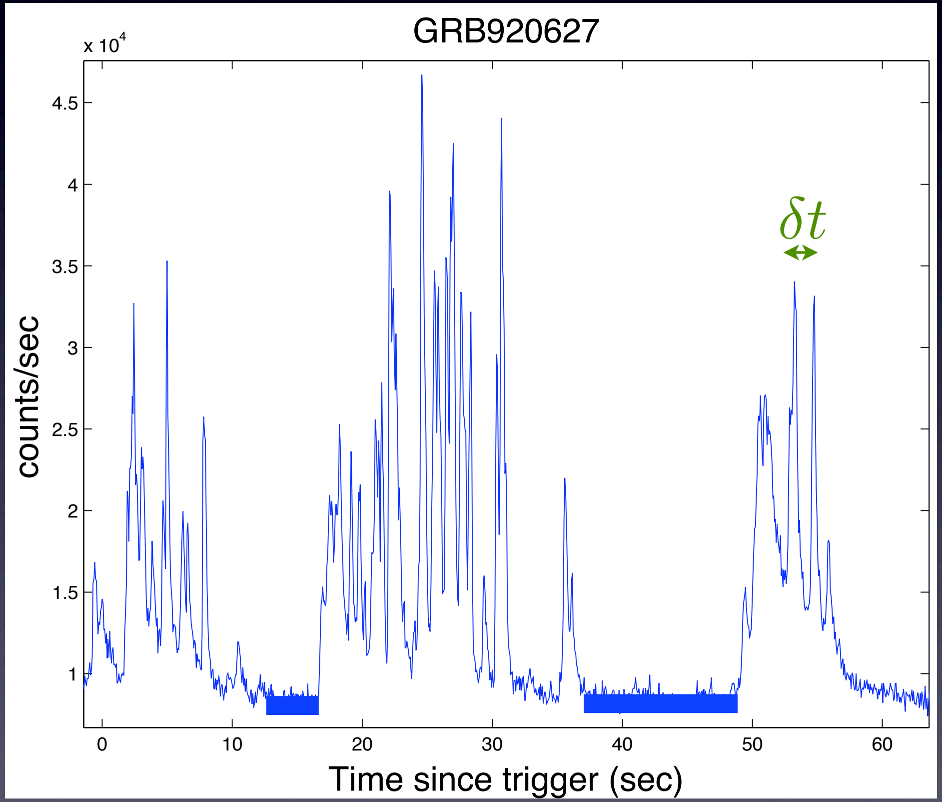

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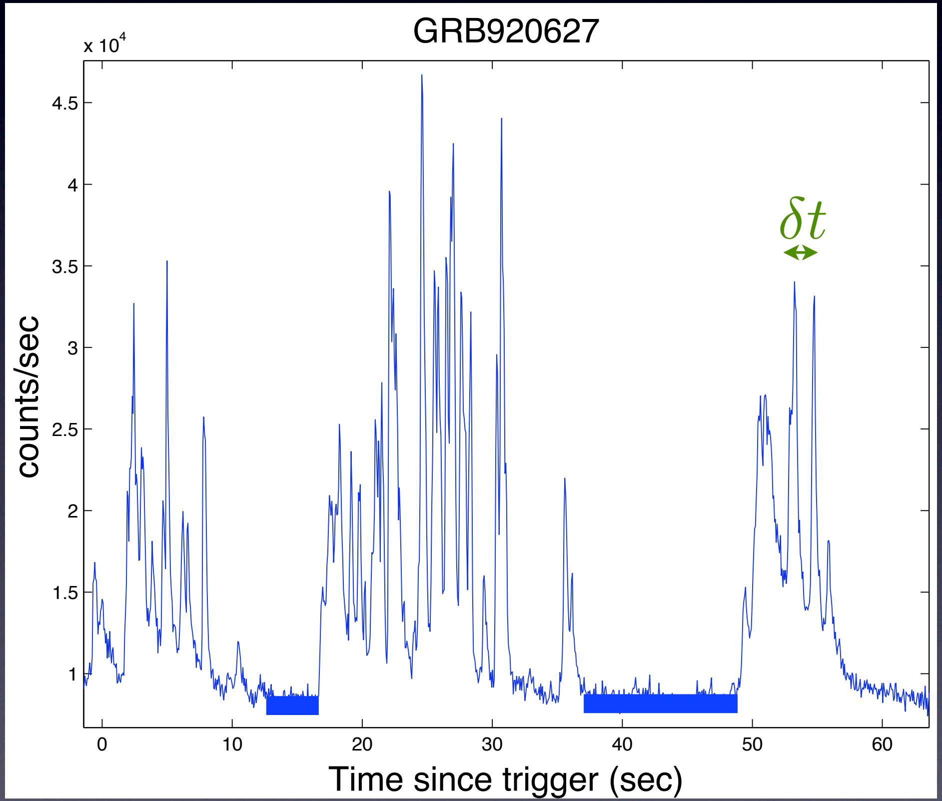

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So, we need $\Gamma = O(100)$ for nonthermal spectra

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

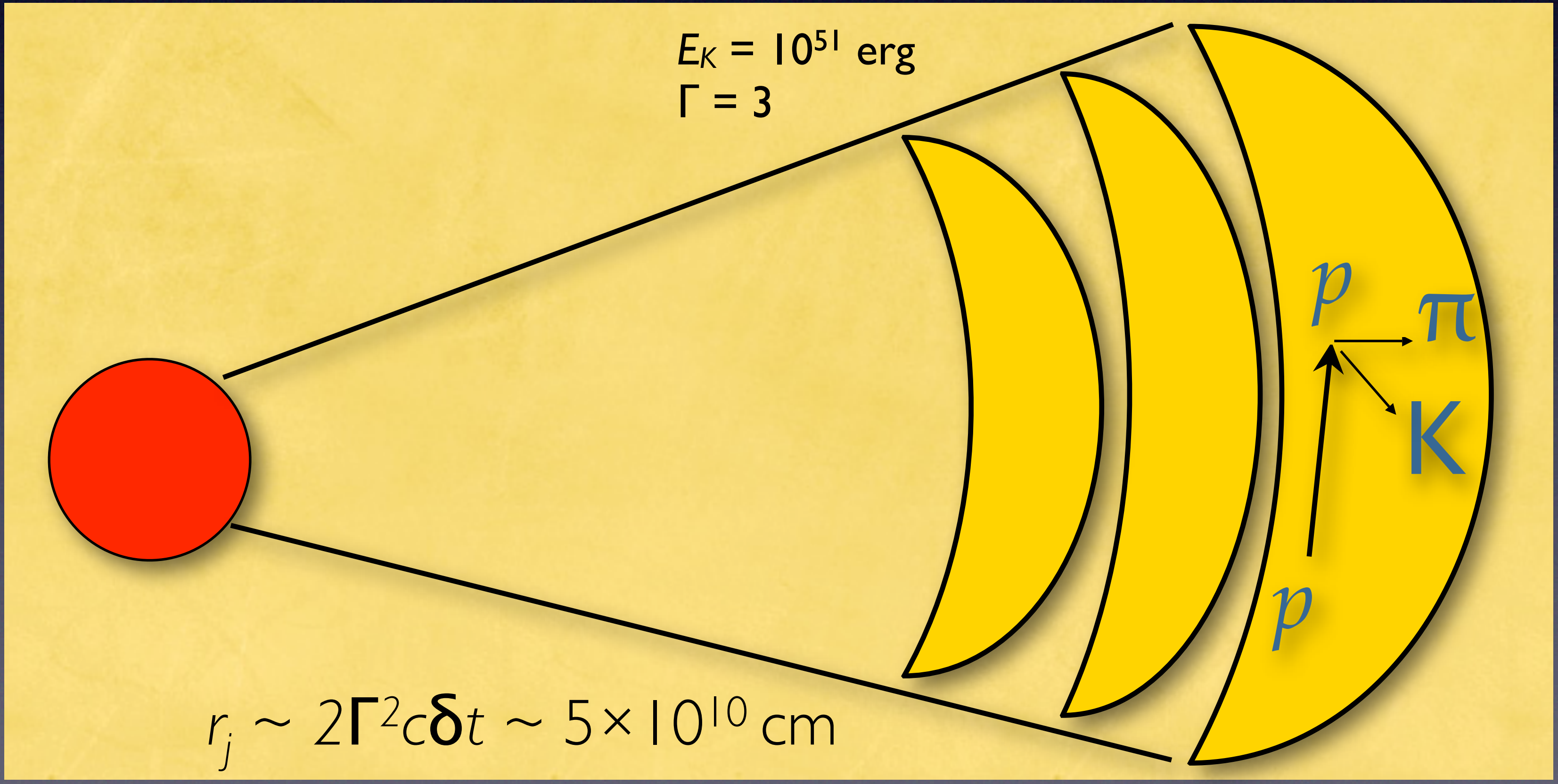
- Evidence of mildly relativistic jets:

  Kulkarni et al. 1998; Berger et al. 2003; Totani 2002; Granot & Ramirez-Ruiz 2004; van Putten 2004; Soderberg et al. 2004, 2006, 2008, etc.

Model

Razzaque, Meszaros, & Waxman (2004)

- Consider internal shocks of E_K = 3x10^{51} erg, Γ = 3 jets ejecta
- Kinetic energy is converted to thermal energy with protons accelerated as E_p^{-2} spectrum
- Some fraction (10%) goes to electrons and magnetic fields



Meson coolings and decays

- Mesons either lose energy or decay
- Energy-loss processes
  - πp, Kp interaction (hadronic cooling)
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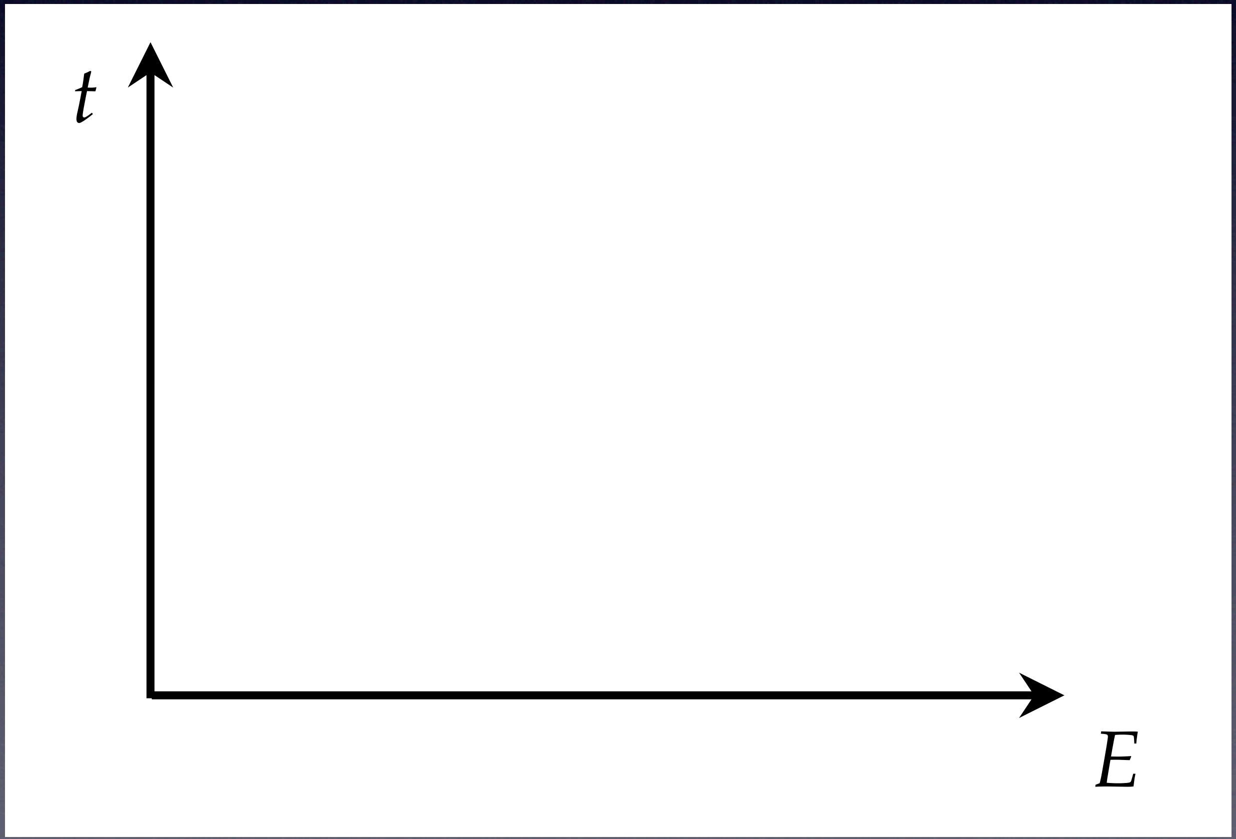

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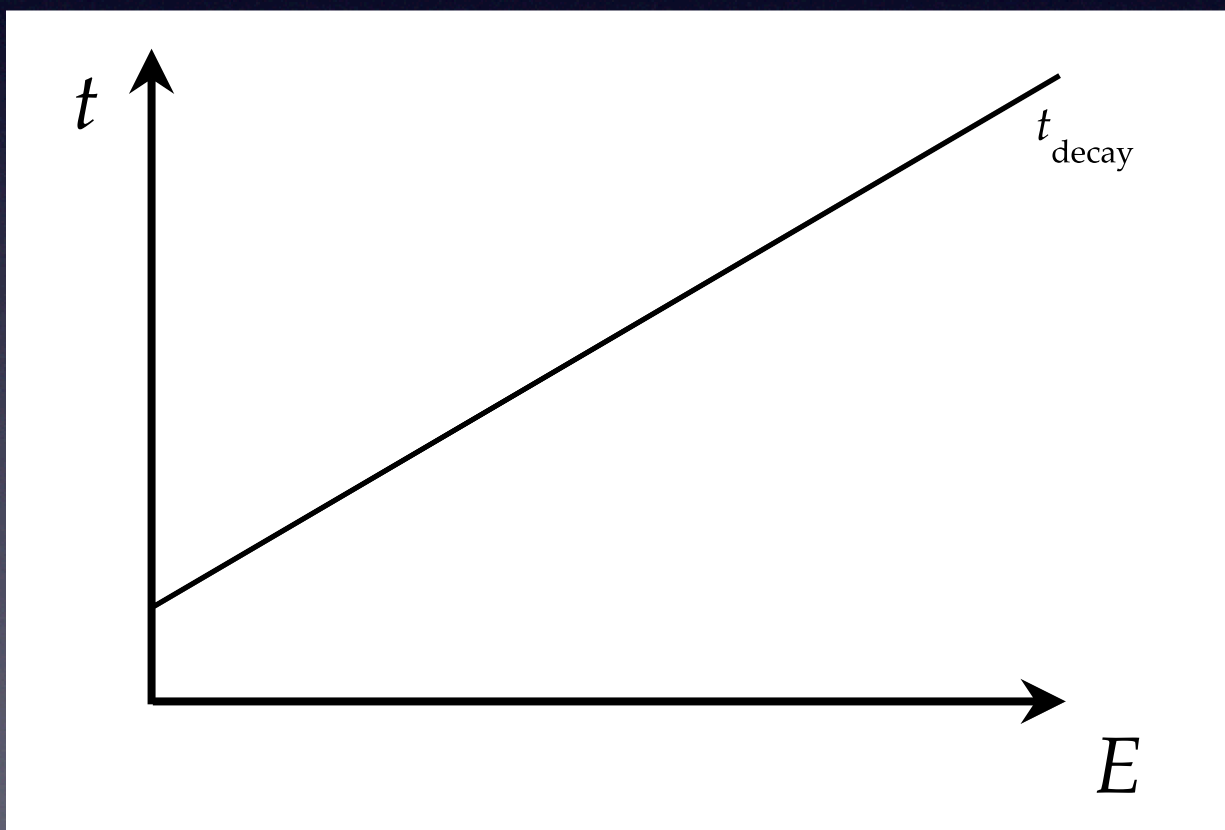

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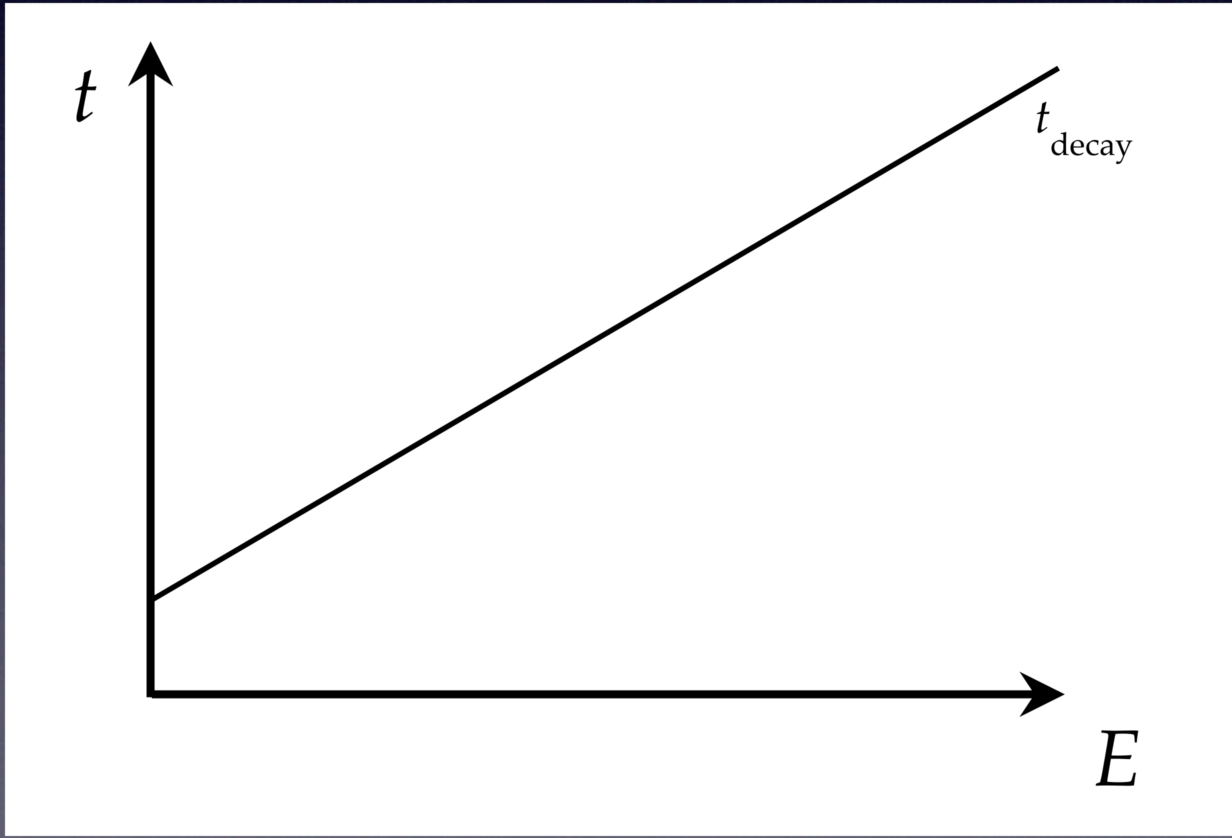

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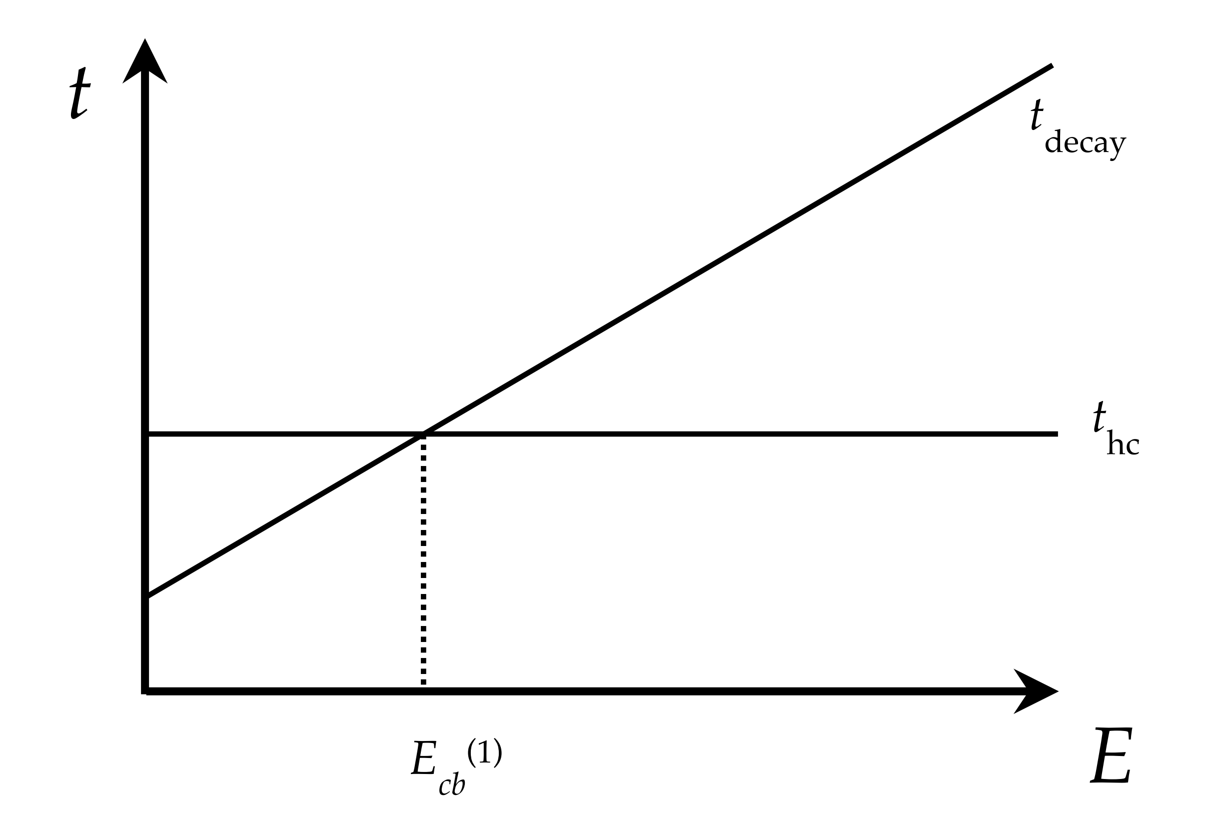

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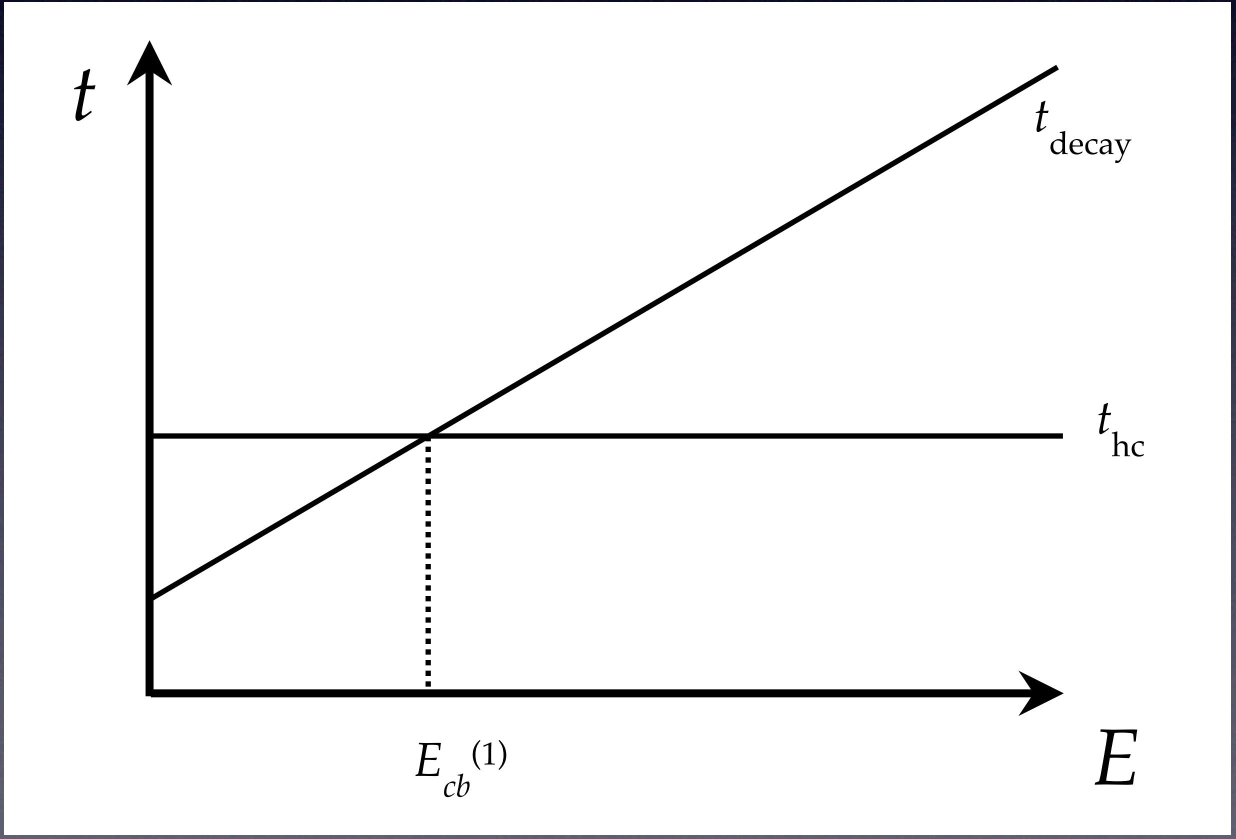

$$t_{\rm decay} = \tau \frac{E}{m}$$

$$t_{\rm hc} = \frac{E}{c\sigma_h n_p \Delta E}$$

$$t_{\rm rc} = \frac{3m^4c^3}{4\sigma_T m_e^2 E(U_\gamma + U_B)}$$

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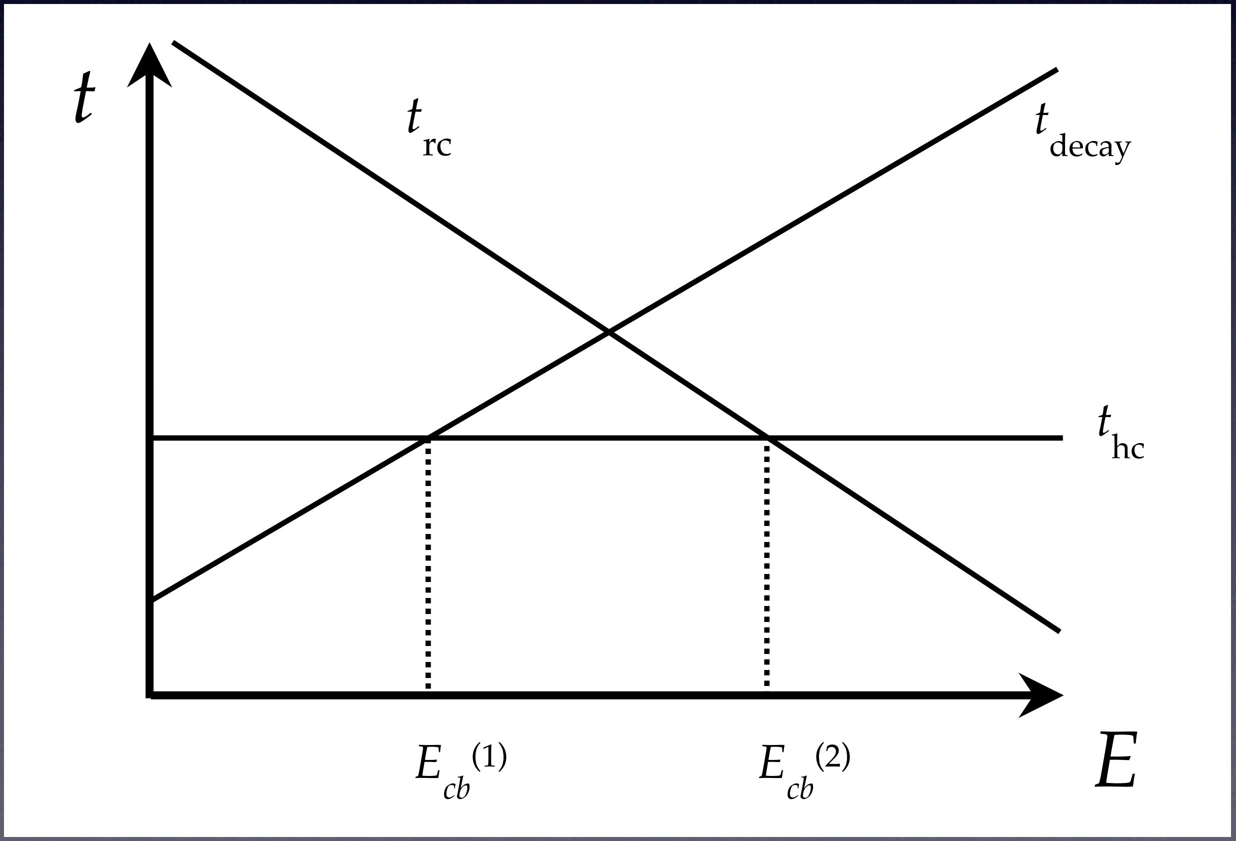

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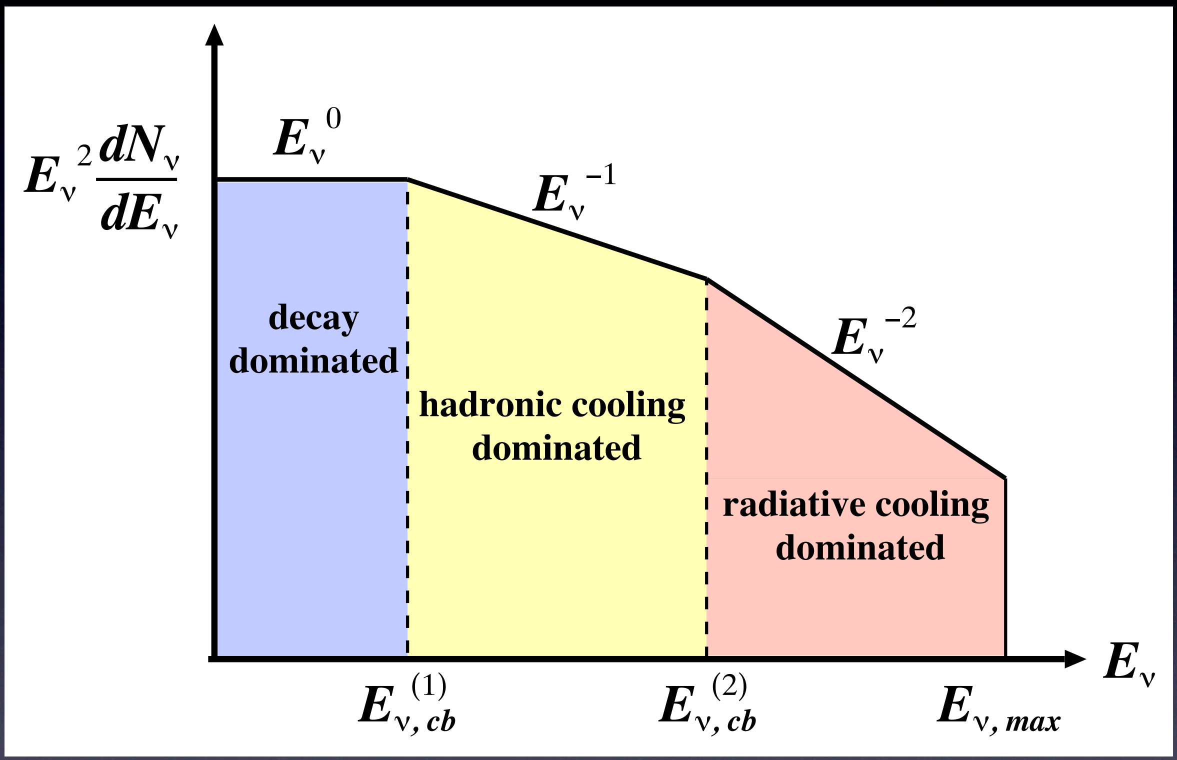
Neutrino spectrum

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

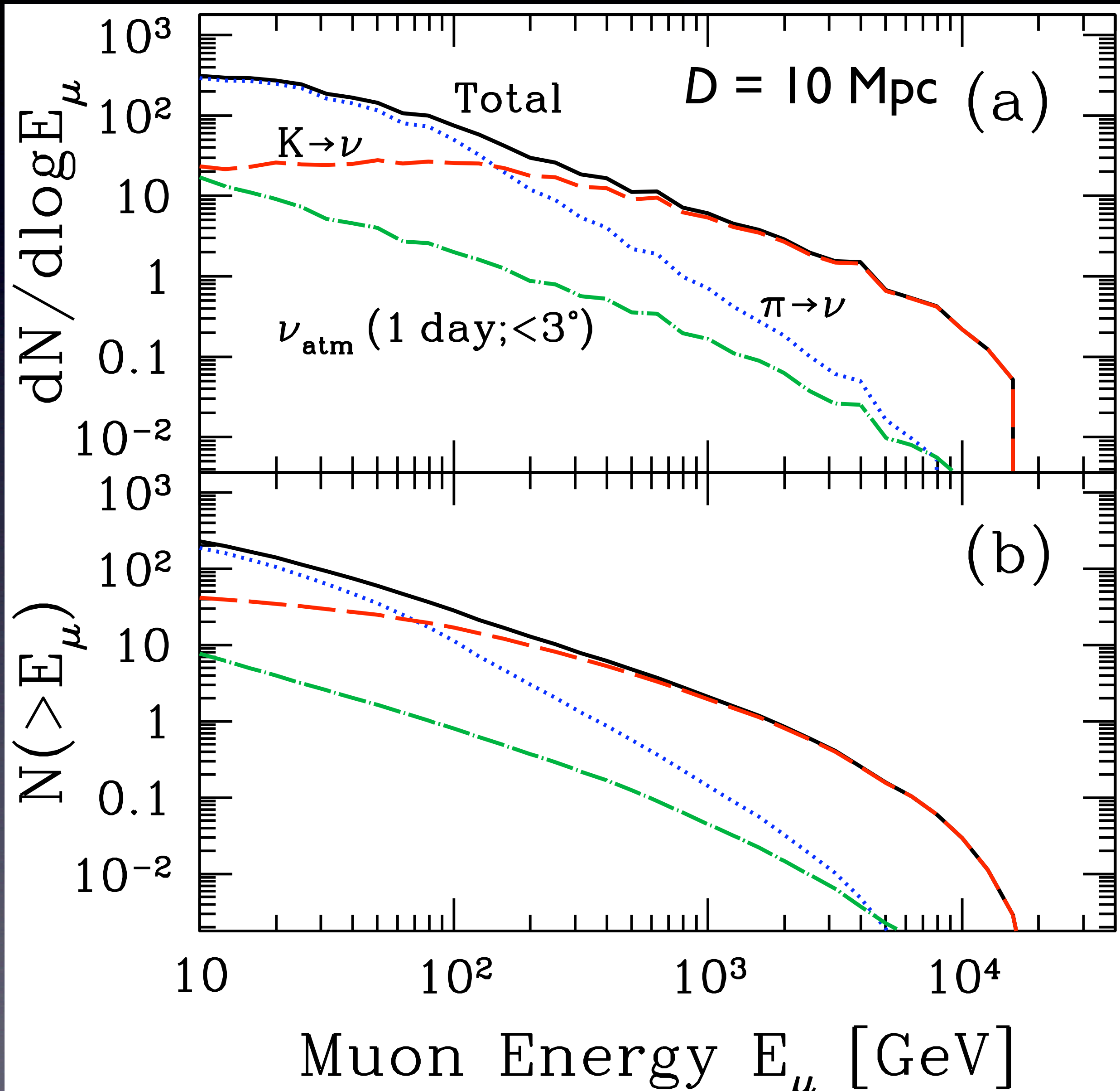


	$E_{cb}^{(1)}$ [GeV]	$E_{cb}^{(2)}$ [GeV]
π	30	100
K	200	20,000

- K-decay neutrinos have higher break energies because
  - Lifetime is twice shorter
  - 4 times massive, significantly less radiative loss (t_{rc}~m^4)
  - Neutrino carries larger fraction of meson energy

Events at km^3 detectors

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



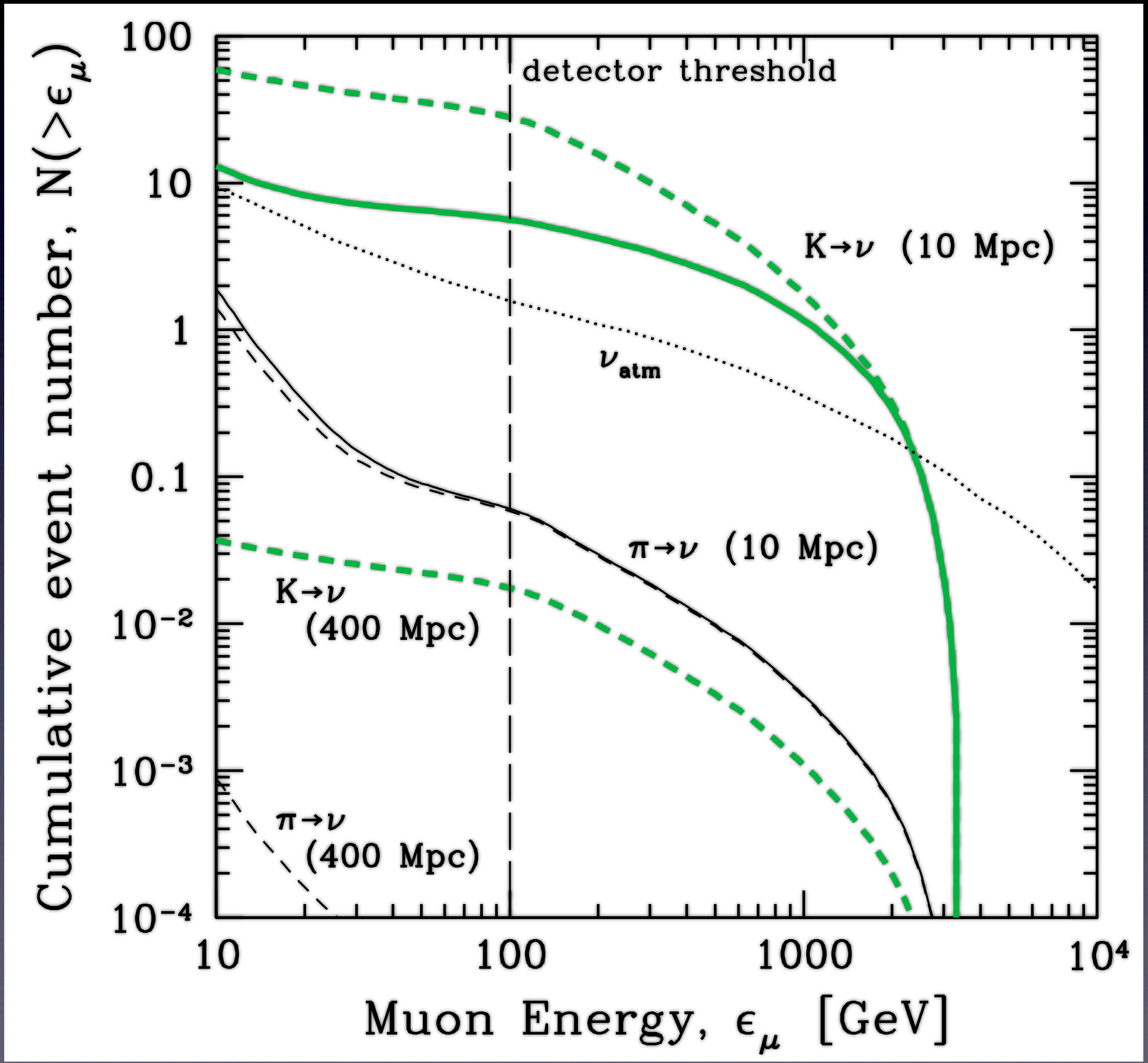
- Kaon contribution dominates
- Expected events above 100 GeV:

  ~30 @ 10 Mpc

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

Neutrinos from reverse shocks

Horiuchi & Ando, *Phys. Rev. D* **77**, 063007 (2008)



- Particles are accelerated in reverse shocks during propagation
- Events predicted

  ~10 @ 10 Mpc

How frequent are they?

- Neutrino horizon for km^3 detectors: 10–30 Mpc
- Core-collapse supernova rate sets the upper limit
- Estimate of R_{SN}
  - UV/opt/IR luminosity conversion
  - Direct number count
  - 1.8 MeV ^{26}Al line (Galactic)
  - Count of supernova remnants (Galactic)
  - Etc.

Summary of Galactic supernova rate estimate

Diehl et al., *Nature* **439**, 45 (2006)

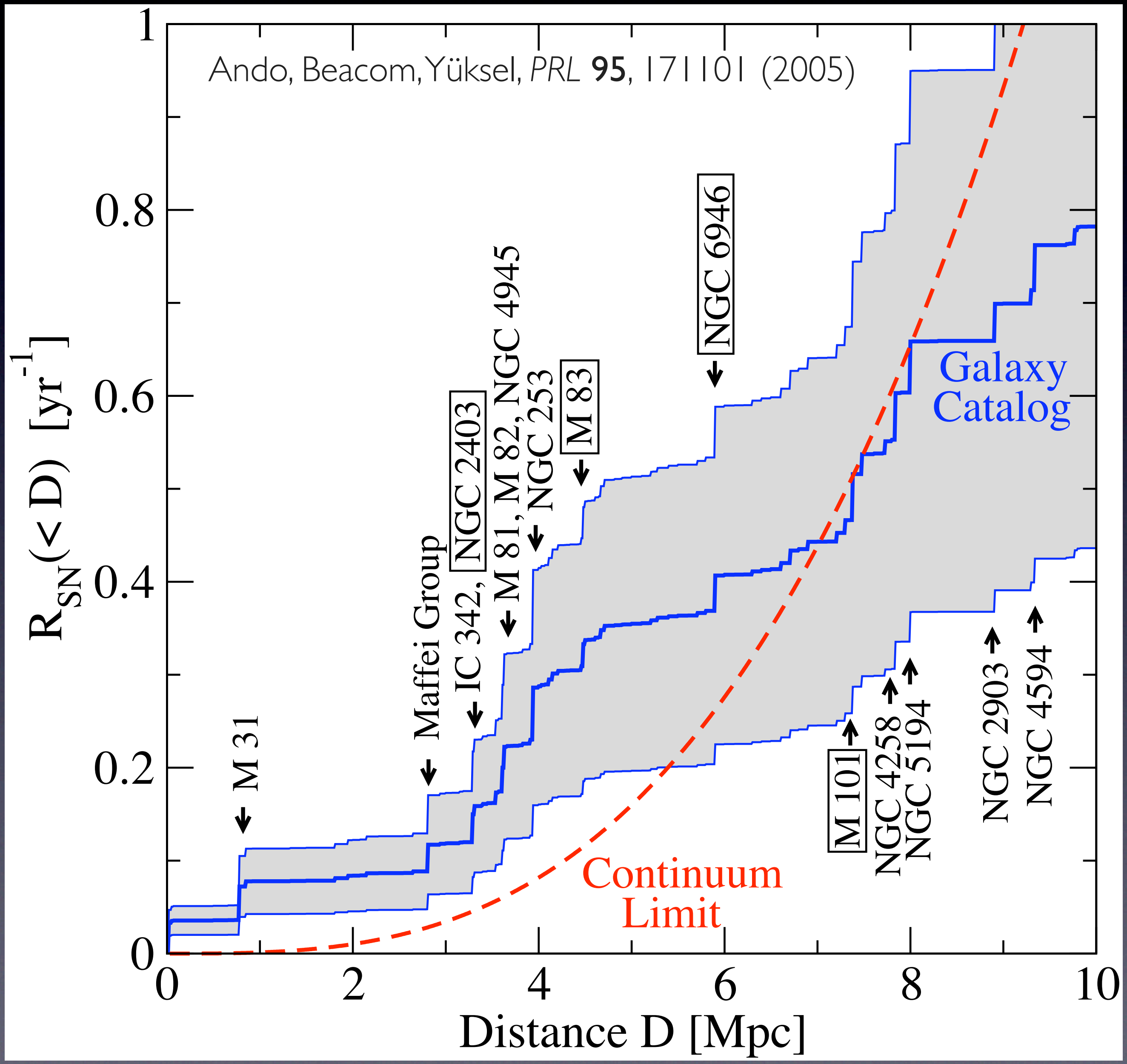
Authors	SFR [$M_\odot y^{-1}$]	SNR [$century^{-1}$]	Comments
Smith et al. 1978	**5.3**	2.7	
Talbot 1980	**0.8**	0.41	
Guesten et al. 1982	**13.0**	6.6	
Turner 1984	**3.0**	1.53	
Mezger 1987	**5.1**	2.6	
McKee 1989	**3.6** (R) **2.4** (IR)	1.84 1.22	
van den Bergh 1990	2.9 ± 1.5	**1.5 ± 0.8**	„the best estimate“
van den Bergh & Tammann 1991	7.8	**4**	extragalactic scaling
Radio Supernova Remnants	6.5 ± 3.9	**3.3 ± 2.0**	very unreliable
Historic Supernova Record	11.4 ± 4.7	**5.8 ± 2.4**	very unreliable
Cappellaro et al. 1993	2.7 ± 1.7	**1.4 ± 0.9**	extragalactic scaling
van den Bergh & McClure 1994	4.9 ± 1.7	**2.5 ± 0.9**	extragalactic scaling
Pagel 1994	**6.0**	3.1	
McKee & Williams 1997	**4.0**	2.0	used for calibration
Timmes, Diehl, Hartmann 1997	5.1 ± 4	**2.6 ± 2.0**	based on ^{26}Al method
Stahler & Palla 2004	**4 ± 2**	2 ± 1	Textbook
Reed 2005	2-4	**1-2**	
Diehl et al. 2005	3.8 ± 2.2	**1.9 ± 1.1**	this work

Table 1: *Star formation and core-collapse supernova rates from different methods.*

- All methods converge at R_{SN} ~ a few / century
- No neutrino burst in the last 25 years sets upper limit: < 9.2 / century (90% CL)

  Alekseev & Alekseeva 2002; Raffelt 2007

Supernova rate with galaxy catalog



- Galaxy catalog (name, distance, morphology, luminosity, etc.) by Karachentsev et al. (2004)
- Conversion to SN rate with calibration by Cappellaro et al. (1999)
  - Underestimating starbursts?
- R_{SN} ~ 1 / yr within 10 Mpc

Direct supernova count in nearby galaxies

List of Supernovae

As of May 13, 2009 at
www.cfa.harvard.edu/iau/lists/Supernovae.html

This page gives details on all supernovae reported since 1885, as well as four earlier galactic supernovae. All coordinates given in the table below are J2000.0 positions. Date refers to the date of discovery, Mag. to the magnitude at discovery and Offset to the offset from the nucleus of the host galaxy as reported at time of discovery. Disc. Ref. is the reference to the discovery report, Posn. Ref. is the source of the accurate position and Type is the supernova's type (as reported at or near the time of discovery). Note that the preferred hierarchy for host-galaxy catalogue designations is M/NGC/IC, UGC, MCG; all other catalogues are considered "Anon" below.

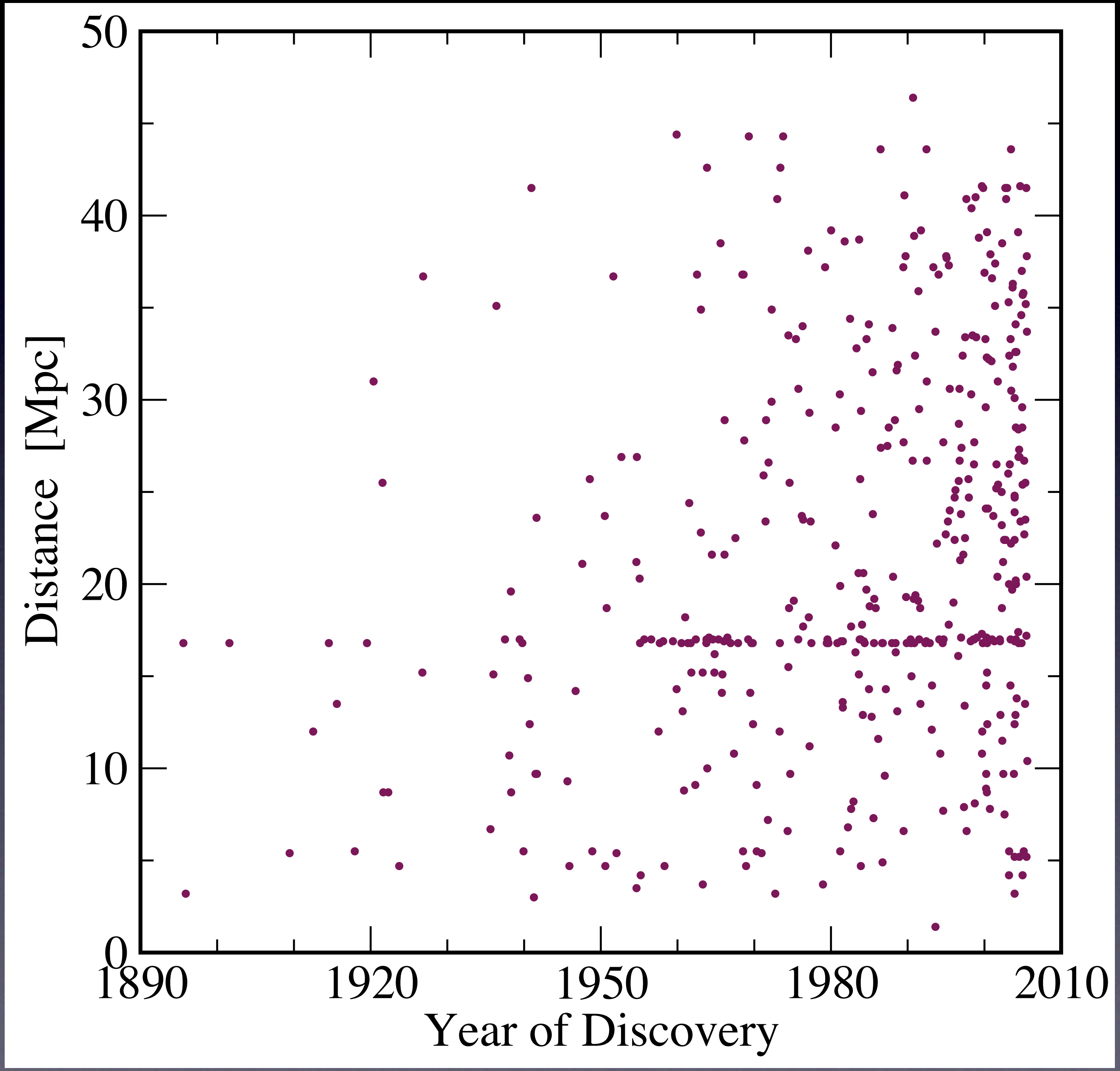
Links are provided to the references, but access to recent circulars requires a subscription.

This list may be freely pointed-to from your own Web site, but must not be copied to your own site or otherwise redistributed. If you use information from this list in the preparation of any publication, please acknowledge this URL and CBAT.

A list of recent supernovae is also available.

SN	Host Galaxy	Date	R.A.	Decl.	Offset	Mag.	Disc. Ref.	SN Position	Posn. Ref.	Type	SN	Discoverer(s)
2009el	ESO 269-74	2009 05 12	13 14.3	-46 07		15.3	CBET 1797	13 14 20.47 -46 06 44.9	CBET 1797	?	2009el	Pignata et al. (CHASE)
2009ek	Anon.	2009 04 23	15 19.8	+48 32	1E 0S	20.7	CBET 1796	15 19 46.76 +48 31 50.6	CBET 1796	Ia	2009ek	Sands et al.
2009ej	Anon.	2009 04 22	15 11.0	+06 33	1E 3S	19.0	CBET 1796	15 10 59.53 +06 33 10.0	CBET 1796	Ia	2009ej	Sands et al.
2009ei	Anon.	2009 04 22	14 32.3	+25 36		20.9	CBET 1796	14 32 17.26 +25 36 15.8	CBET 1796	Ia	2009ei	Sands et al.
2009eh	Anon.	2009 04 03	15 20.6	+07 40	1E 2S	21.2	CBET 1796	15 20 38.08 +07 39 32.5	CBET 1796	Ia	2009eh	Sands et al.
2009eg	Anon.	2009 03 31	14 54.3	+18 58	7W 1N	17.6	CBET 1796	14 54 15.47 +18 57 52.8	CBET 1796	Ia	2009eg	Sands et al.
2009ef	Anon.	2009 03 23	15 19.2	+06 21	2E 1N	21.8	CBET 1796	15 19 12.57 +06 21 29.2	CBET 1796	Ib	2009ef	Sands et al.
2009ee	IC 2738	2009 05 09	11 21.4	+34 20	28E 61S	17.5	CBET 1795	11 21 25.30 +34 20 23.3	CBET 1795	?	2009ee	LOSS
2009ed	Anon.	2009 04 24	09 23.7	+50 24	3W 22S	17.9	CBET 1792	09 23 41.42 +50 24 11.2	CBET 1792	?	2009ed	Drake et al. (CRTS)
2009ec	Anon.	2009 04 19	11 06.5	+24 05	2W 0N	18.3	CBET 1792	11 06 28.89 +24 05 15.4	CBET 1792	?	2009ec	Drake et al. (CRTS)
2009eb	Anon.	2009 04 17	09 54.7	+19 11	1E 3N	17.7	CBET 1792	09 54 40.35 +19 11 12.7	CBET 1792	?	2009eb	Drake et al. (CRTS)
2009ea	Anon.	2009 04 03	14 47.1	+09 58	2E 10N	18.1	CBET 1792	14 47 02.39 +09 57 37.4	CBET 1792	?	2009ea	Drake et al. (CRTS)
2009dz	Anon.	2009 04 03	12 35.6	+01 52	2E 5N	18.1	CBET 1792	12 35 35.77 +01 52 12.6	CBET 1792	?	2009dz	Drake et al. (CRTS)
2009dy	Anon.	2009 04 22	15 01.1	+43 13	1E 0S	18.4	CBET 1791	15 01 04.03 +43 13 13.9	CBET 1791	Ia	2009dy	Drake et al. (CRTS)
2009dx	Anon.	2009 04 21	16 49.4	+05 53	0W 4S	18.8	CBET 1791	16 49 25.67 +05 52 48.1	CBET 1791	Ia	2009dx	Drake et al. (CRTS)
2009dw	Anon.	2009 04 21	13 36.2	+34 03	2W 1S	19.2	CBET 1791	13 36 09.45 +34 03 19.0	CBET 1791	IIP	2009dw	Drake et al. (CRTS)
2009dv	Anon.	2009 04 18	13 24.7	+16 34	14E 13N	19.3	CBET 1791	13 24 40.15 +16 34 05.5	CBET 1791	IIP	2009dv	Drake et al. (CRTS)
2009du	Anon.	2009 04 17	13 39.8	-21 27		19.4	CBET 1791	13 39 46.36 -21 27 19.1	CBET 1791	Ia	2009du	Drake et al. (CRTS)
2009dt	IC 5169	2009 04 28	22 10.2	-36 06	9W 24S	17.2	CBET 1785	22 10 09.27 -36 05 42.6	CBET 1785	Ic	2009dt	Pignata et al. (CHASE)
2009ds	NGC 3905	2009 04 28	11 49.1	-09 44	12W 3N	16.8	CBET 1784	11 49 04.11 -09 43 44.9	CBET 1784	Ia	2009ds	Itagaki
2009dr	Anon.	2009 04 17	14 44.7	+49 44		20.3	CBET 1783	14 44 42.08 +49 43 44.9	CBET 1783	Ia?	2009dr	"Palomar Transient Factory" co
2009dq	IC 2554	2009 04 24	10 08.8	-67 02	2W 3S	15.2	CBET 1781	10 08 49.94 -67 01 57.3	CBET 1781	IIb	2009dq	Pignata et al. (CHASE)

Direct supernova count: recent progress



Efficiency of SN discovery improved in late-1990s

Direct supernova count: productive galaxies

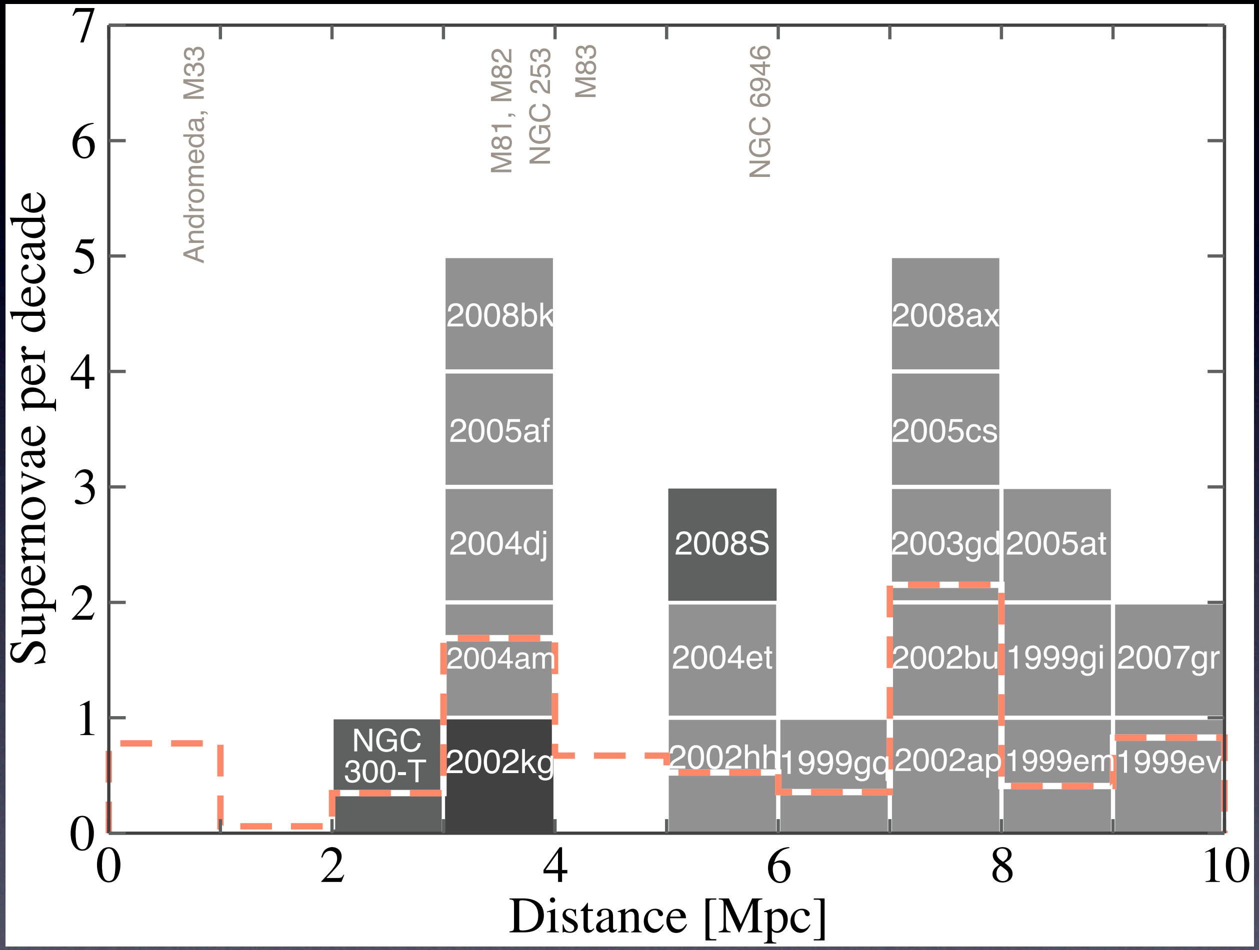
Galaxy	Distance (Mpc)	Known supernova
NGC 2403	3.3	1954J, 2002kg, 2004dj
NGC 5236 (M 83)	4.5	1923A, 1945B, 1950B, 1957D, 1968L, 1983N
NGC 6946	5.6	1917A, 1939C, 1948B, 1968D, 1969P, 1980K, 2002hh, 2004et, 2008S
NGC 5457 (M 101)	7.4	1909A, 1951H, 1970G

NGC 6946

http://www.astronomyphotos.com

Direct supernova count: Last decade

Kistler, Yüksel, Ando, Beacom, & Suzuki, arXiv:0810.1959



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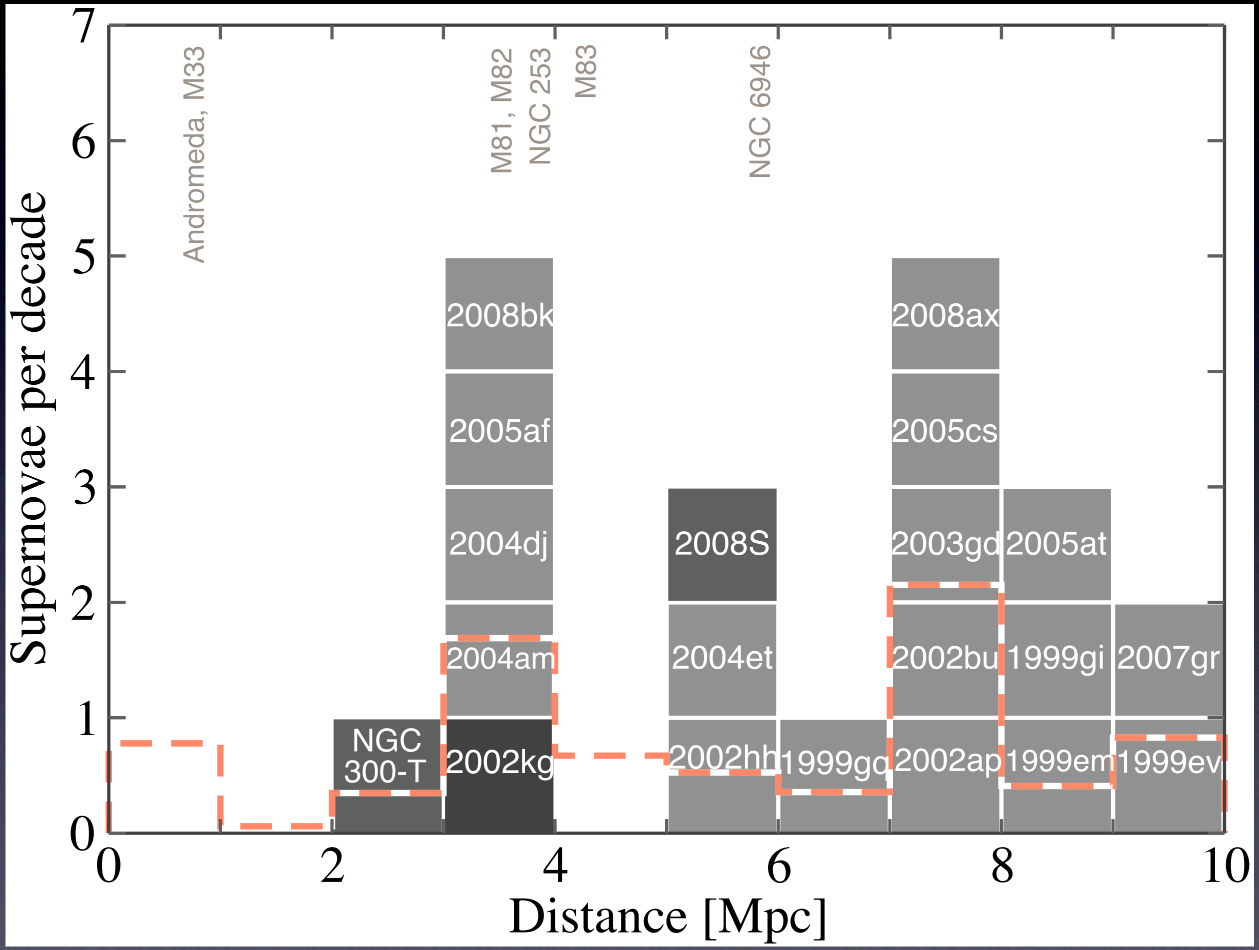
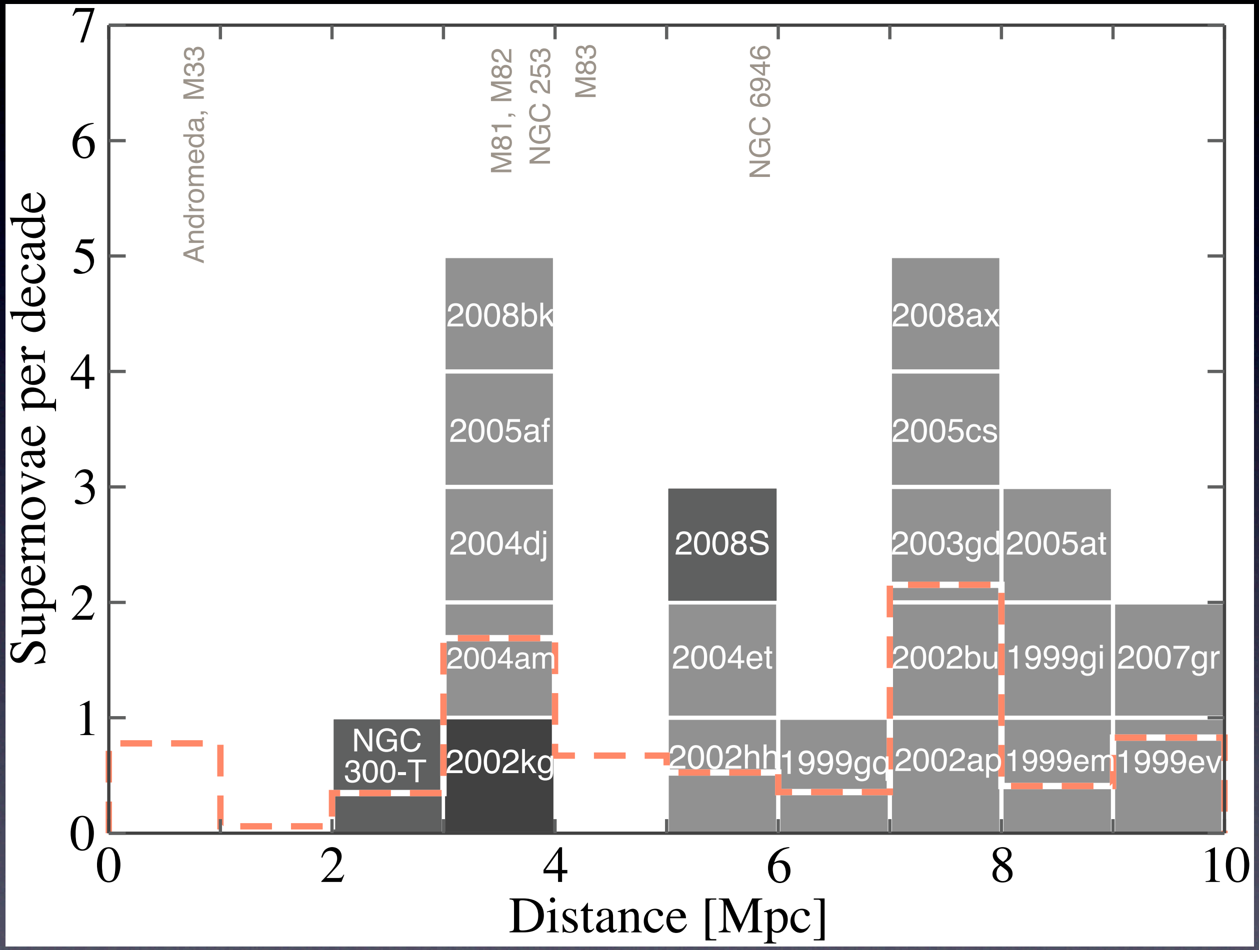


- 20 (6) SNe within 10 (4) Mpc in the last decade (most likely lower limit)

Direct supernova count: Last decade

Kistler, Yüksel, Ando, Beacom, & Suzuki, arXiv:0810.1959



- 20 (6) SNe within 10 (4) Mpc in the last decade (most likely lower limit)
- Within 10 Mpc, $R_{SN} > 2–3\ yr^{-1}$, much larger than previous estimate 1 / yr

Nearby starburst: NGC 253

- Edge-on galaxy at 2.5–3.9 Mpc

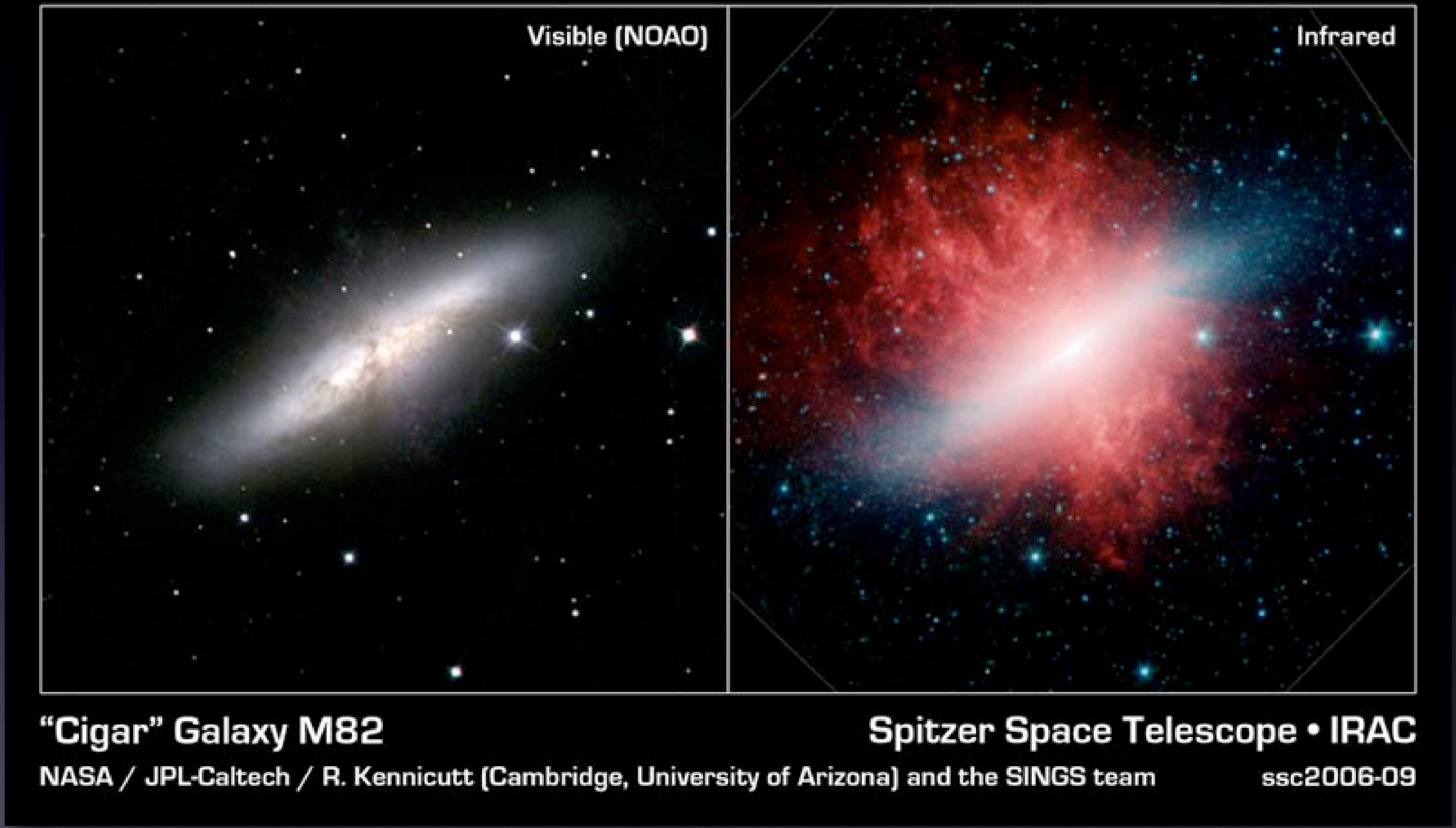
  Mauersberger et al. 1996; Karachentsev et al. 2004

- Heavily dusty starburst galaxy, very bright in IR band

- Estimated SN rate = 0.1 / yr
- However, only one SN (1940E) has been discovered

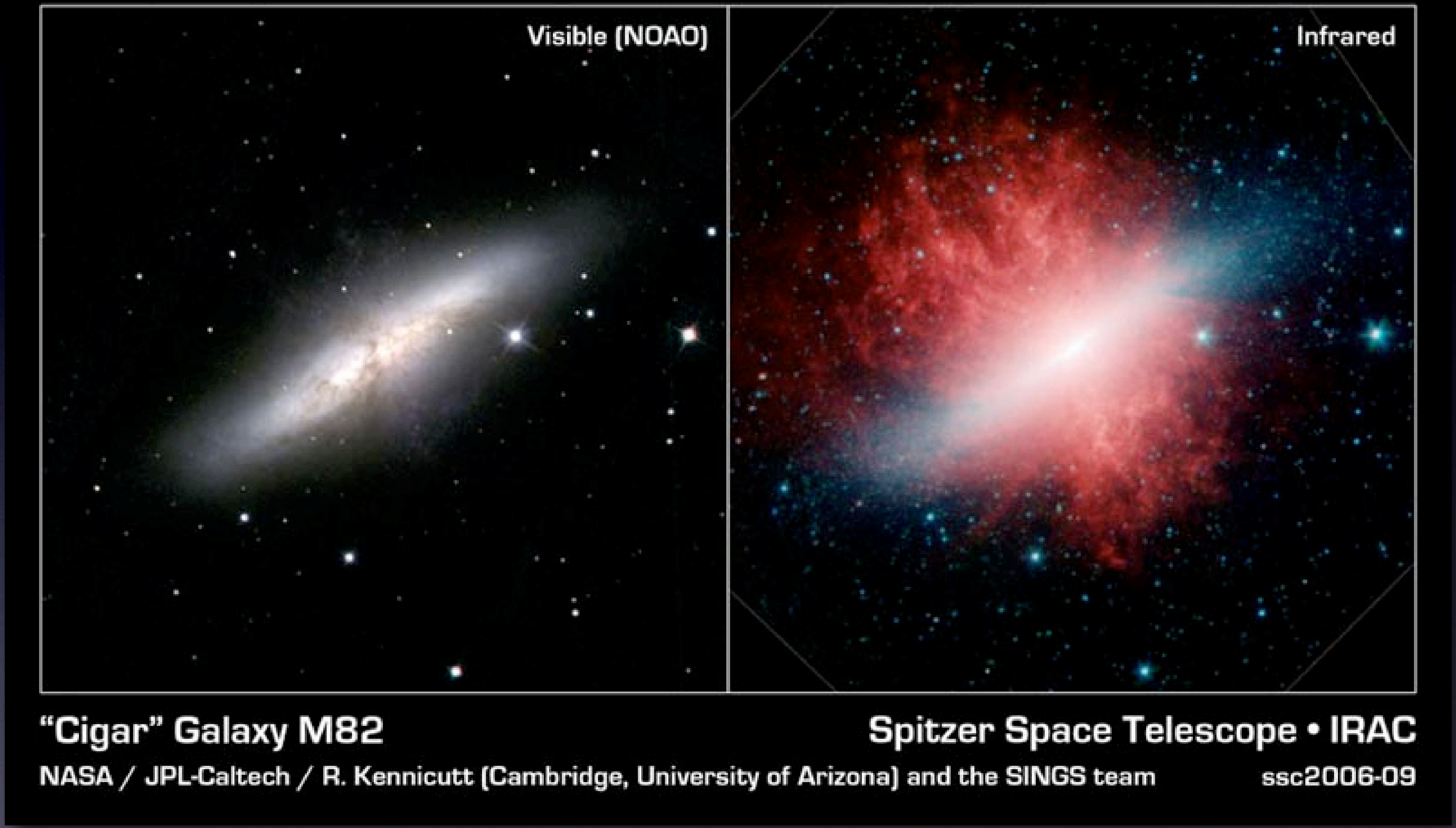
http://www.astronomyphotos.com

Nearby starburst: M82



- Same as NGC 253, but at 3.5 Mpc
- Two SNe (1986D; 2004am) so far

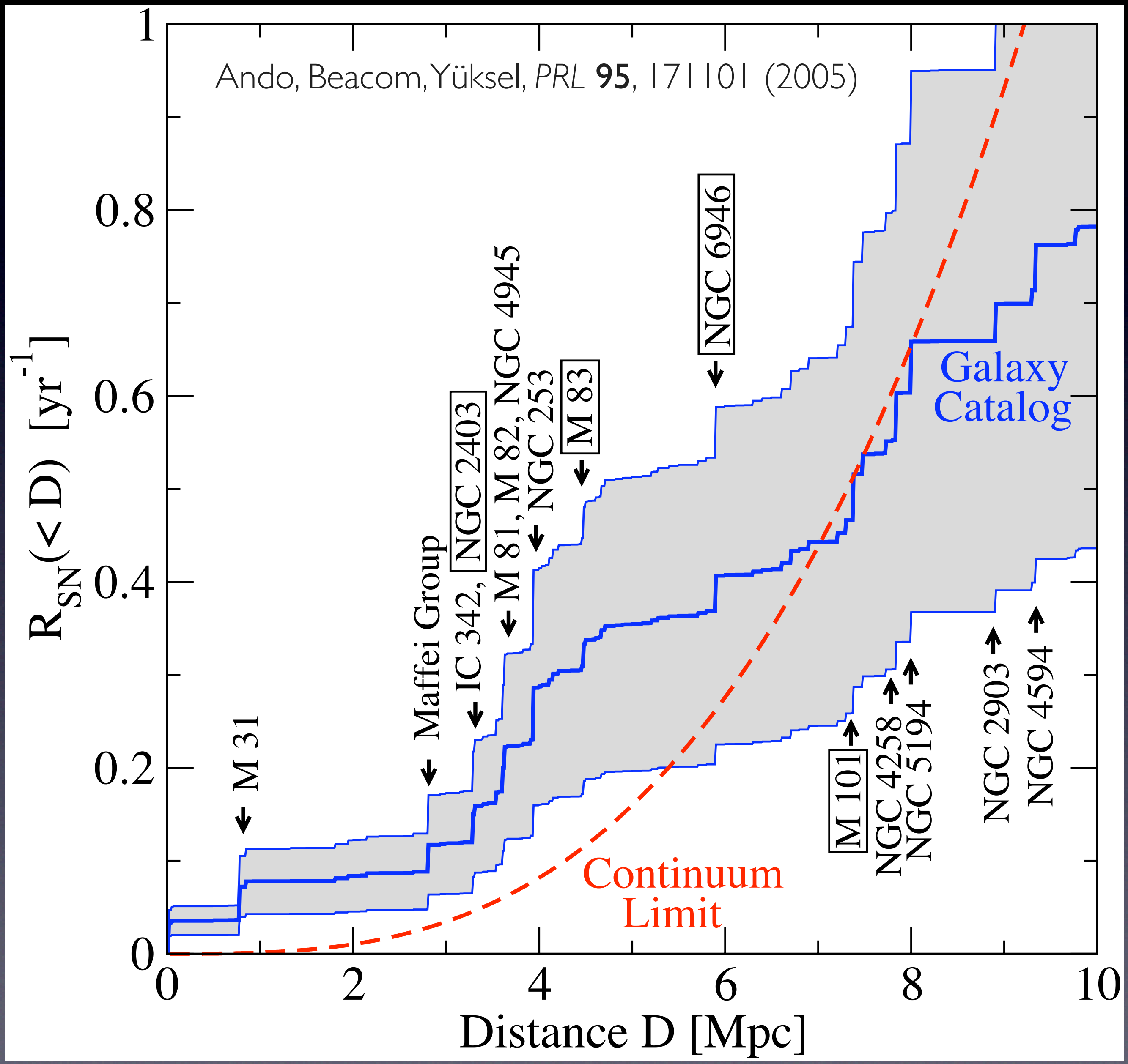
Nearby starburst: M82



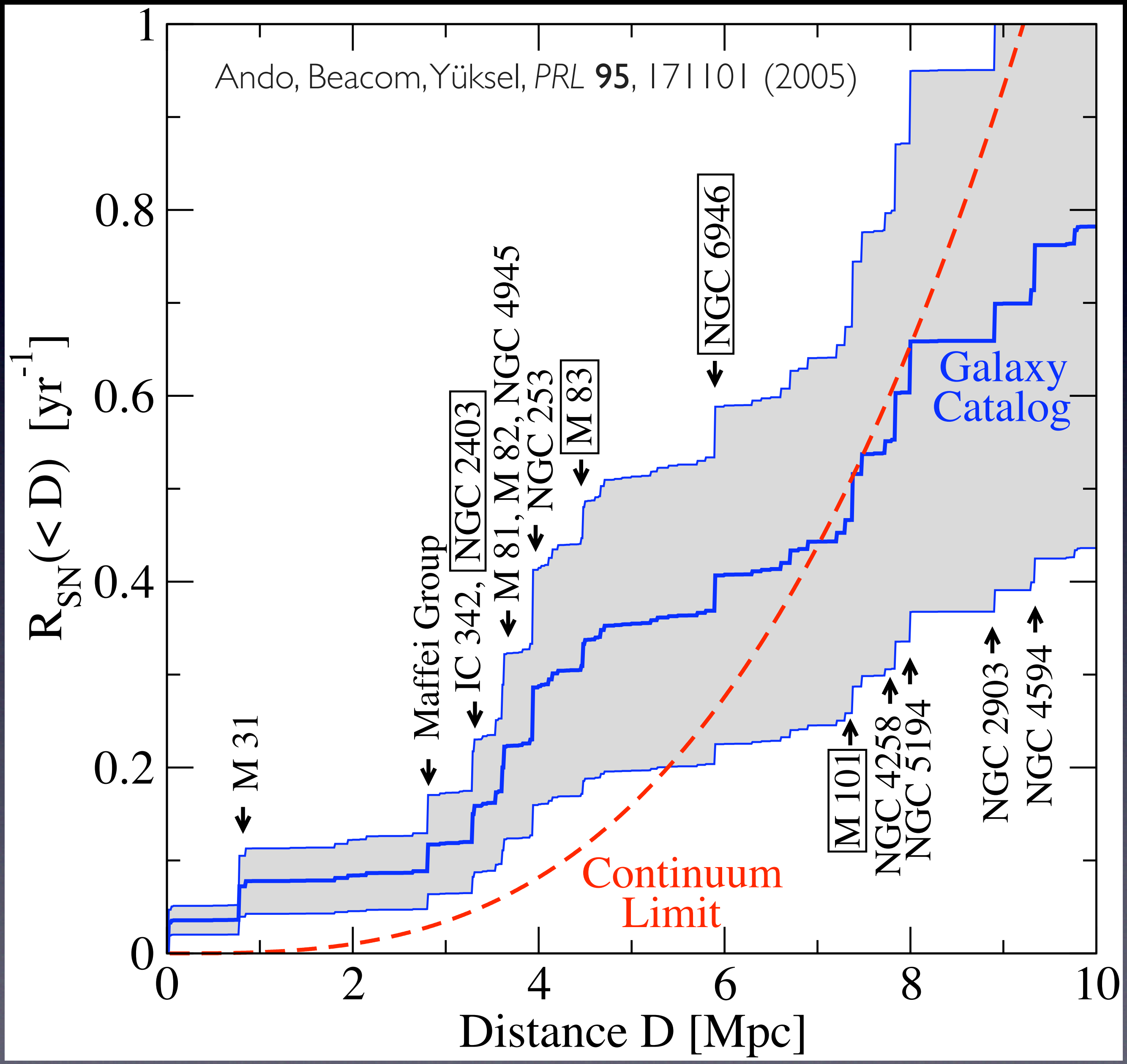
- Same as NGC 253, but at 3.5 Mpc
- Two SNe (1986D; 2004am) so far

Many SNe have likely been missed by dust extinction!!

Summary of supernova rate in nearby galaxies

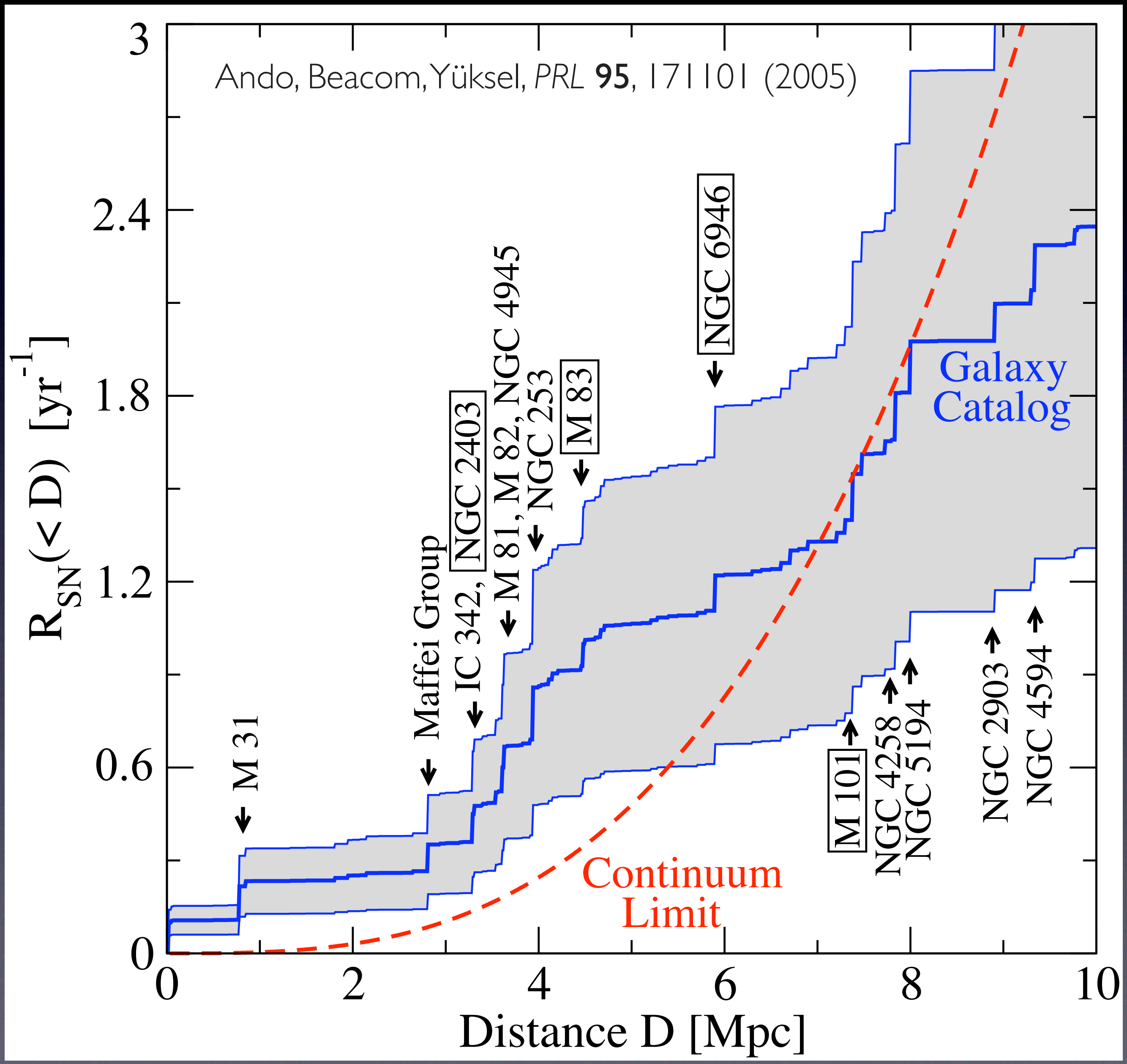


Summary of supernova rate in nearby galaxies



- Using galaxy luminosity is likely significant underestimate of the true rate

Summary of supernova rate in nearby galaxies



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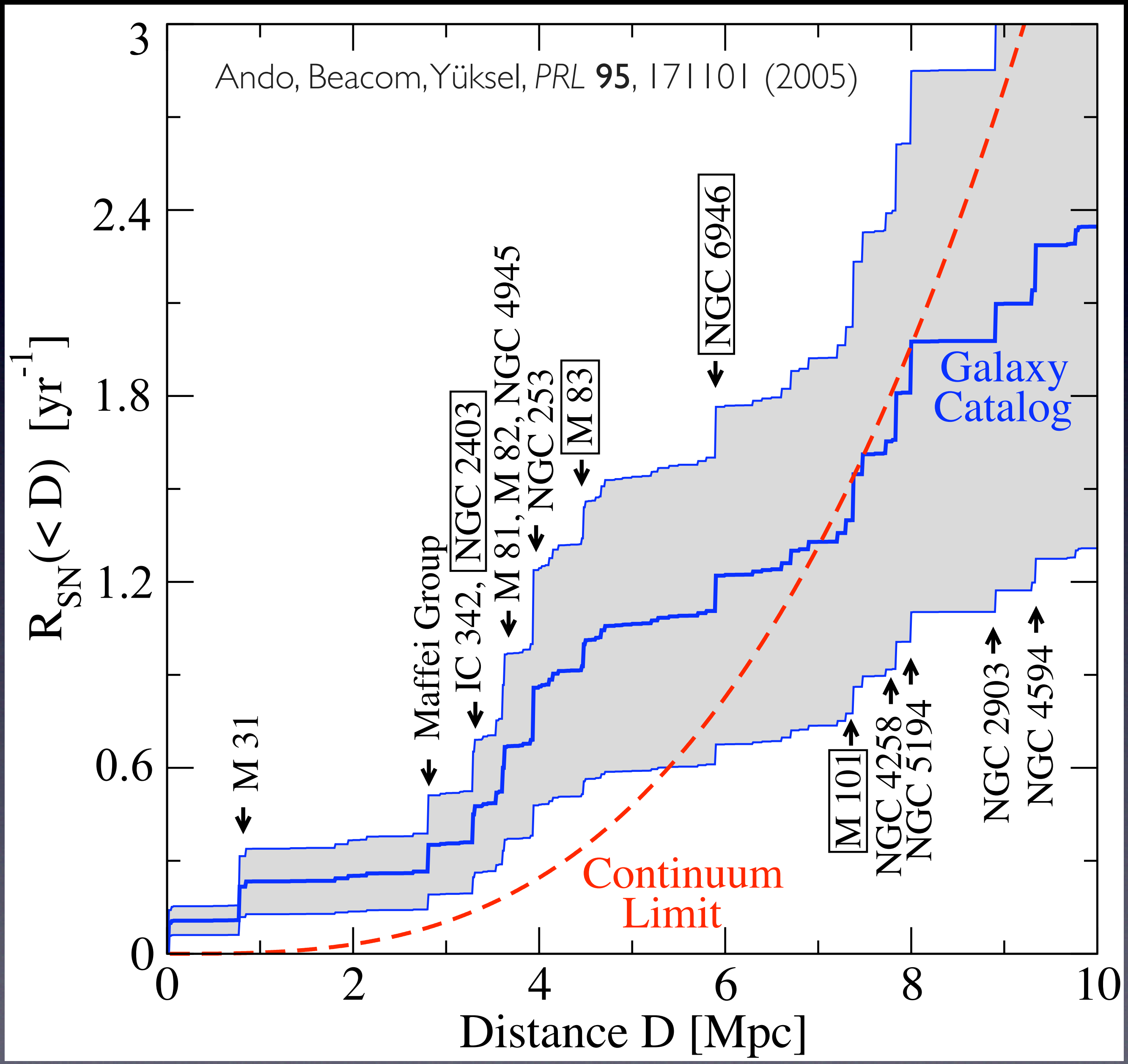

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- Direct count implies that lower limit is 2–3 yr^{-1} within 10 Mpc

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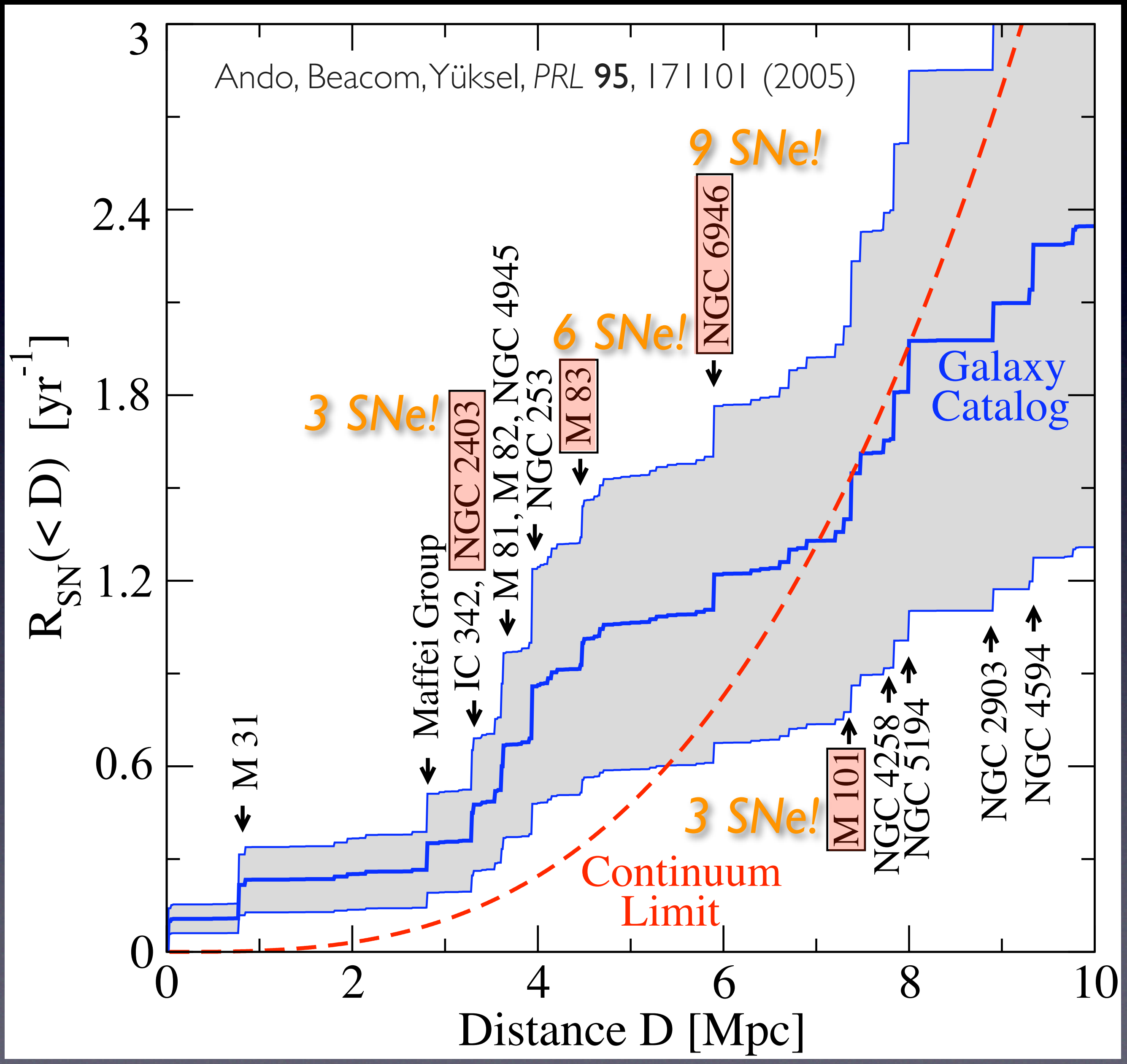

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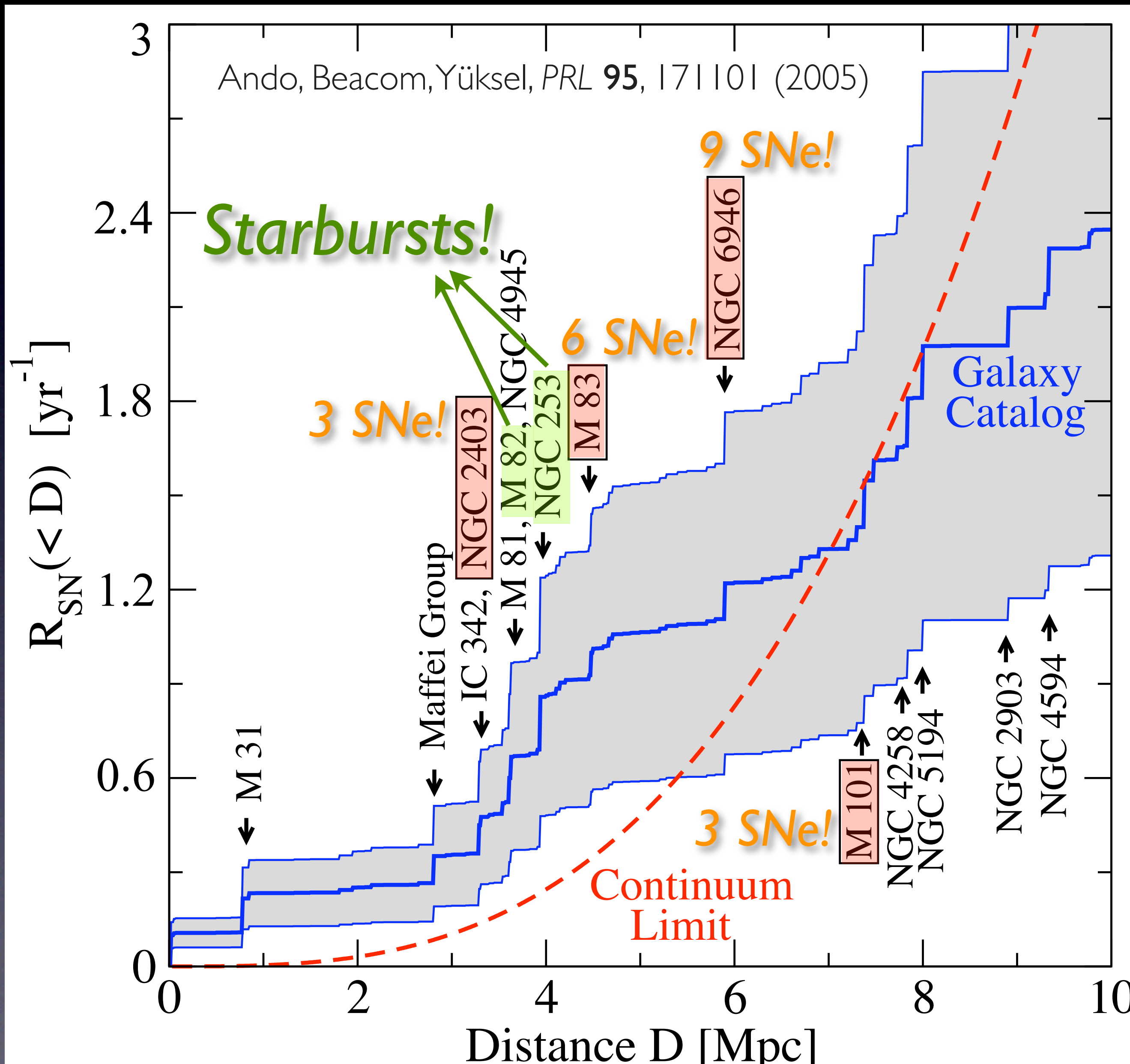

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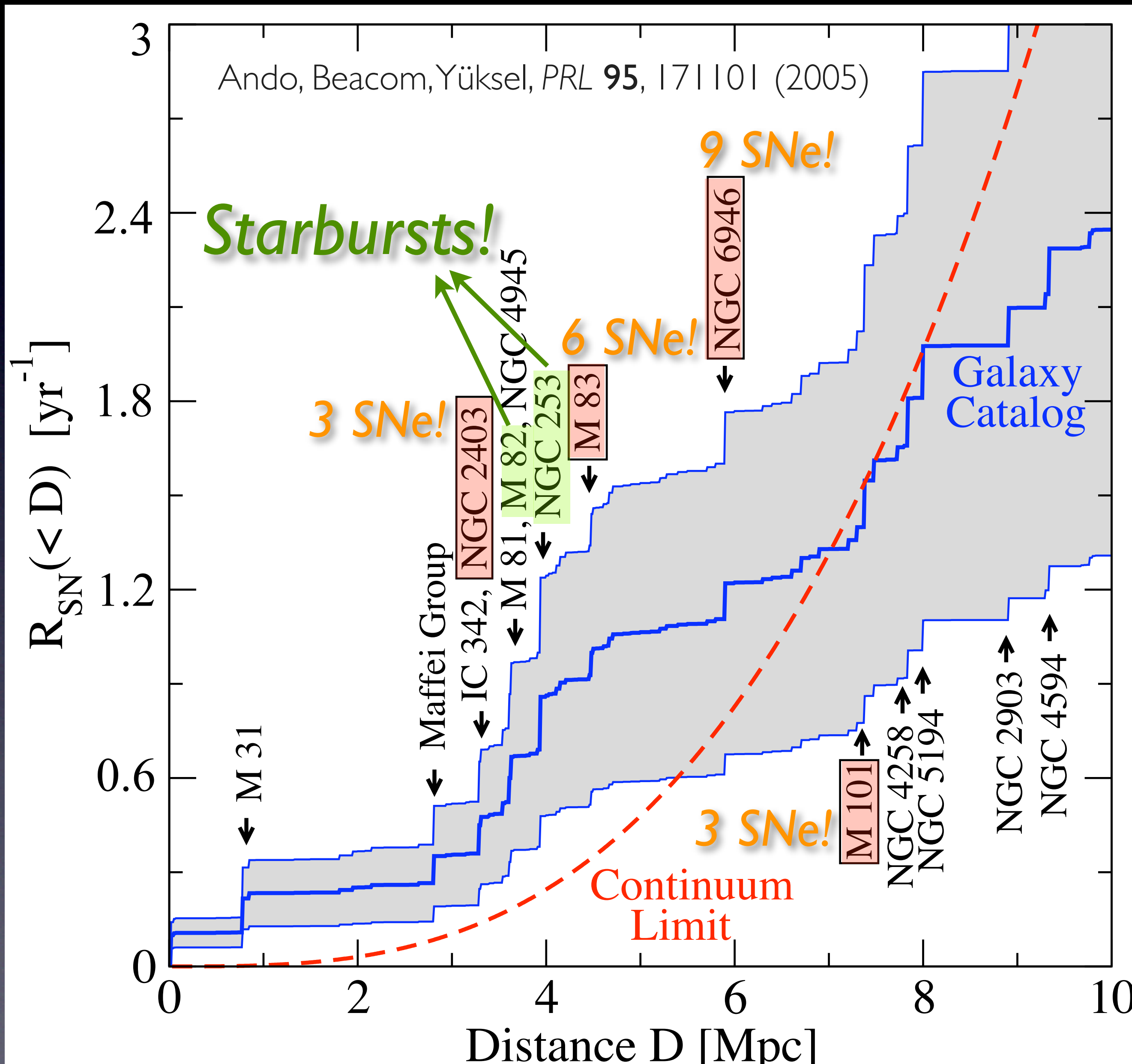

- Using galaxy luminosity is likely significant underestimate of the true rate
- Direct count implies that lower limit is 2–3 yr^{-1} within 10 Mpc
- Many SNe in starbursts have likely been missed
- The true rate could be significantly larger!

Fraction of jetted population in SNe

- We expect $R_{SN}(< 10\ \mathrm{Mpc}) \sim 3\ \mathrm{yr}^{-1}$, $R_{SN}(< 30\ \mathrm{Mpc}) \sim 90\ \mathrm{yr}^{-1}$
- But what fraction of SNe have relativistic jets?
  - Determined by mass, rotation, magnetic fields, etc...(?)
  - If only mass determines it:

Mass threshold	$R_{SN}(<10\ \mathrm{Mpc})$	$R_{SN}(<30\ \mathrm{Mpc})$
$> 8\ M_{sun}$	$3\ \mathrm{yr}^{-1}$	$90\ \mathrm{yr}^{-1}$
$> 30\ M_{sun}$	$0.4\ \mathrm{yr}^{-1}$	$10\ \mathrm{yr}^{-1}$
$> 50\ M_{sun}$	$0.2\ \mathrm{yr}^{-1}$	$6\ \mathrm{yr}^{-1}$
$> 70\ M_{sun}$	$0.1\ \mathrm{yr}^{-1}$	$3\ \mathrm{yr}^{-1}$

Conclusions 1

- Stellar collapse is promising source for GW/HEν
- Baryon-rich (failed) GRB
    - Rate can be very large
    - Good for neutrino production
- For the model with E_K=3x10^{51} erg and Γ=3, we expect ~30 neutrino events at km^3 detectors from a 10-Mpc burst
- Kaon decays give important contribution than π decays

Conclusions 2

- Supernova rate in the Galaxy is ~1–3 century^{-1}
- Supernova rate in the local Universe is ~1–3 yr^{-1} (within 10 Mpc)
- But it could be much larger because of
  - Starbursts (M 82, NGC 253) around 3 Mpc
  - Virgo cluster around 17 Mpc
- Good fraction might be associated with jets
- If 10%, then $R_{\text{failed GRB}}$ ~ 10 yr^{-1} within 30 Mpc

Appendix

Supernova Search: KAIT (since 1998)

http://astro.berkeley.edu/~bait/kait.html

- PI: Alex Filippenko (UC Berkeley)
- Robotic telescope of 76-cm diameter, dedicated for supernova search
- Discovering ~80–100 SNe each year
- No comparable effort in southern hemisphere