How Astronomers Observe the Supernova Explosions?

- Roles of the Korean Neutrino Observatory (KNO)

2024 July 25

한국천문연구원 Korea Astronomy & Space
Science Institute (KASI)

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M5 = NGC 5904 (https://apod.nasa.gov/apod/ap150620.html)

Contents

- KASI
- Supernovae (SNe) burst – Ia, CC

  KMTNet Telescopes
- SN science – Neutrino science

- Relic SNe
- Failed SNe
- Precursors of SNe

과학기술정보통신부

nst 국가과학기술연구회
National Research Council of Science & Technology

KASI 한국천문연구원
Korea Astronomy & Space Science Institute

과학기술정보통신부

2024

05.27. **우주항공청 출범**

우주항공청
Korea AeroSpace Administration

KASI 한국천문연구원
Korea Astronomy & Space Science Institute

Korea Astronomy & Space Science Institute (KASI)

천문학	우주과학
Universe (우주)	Space (우주)

과학기술정보통신부

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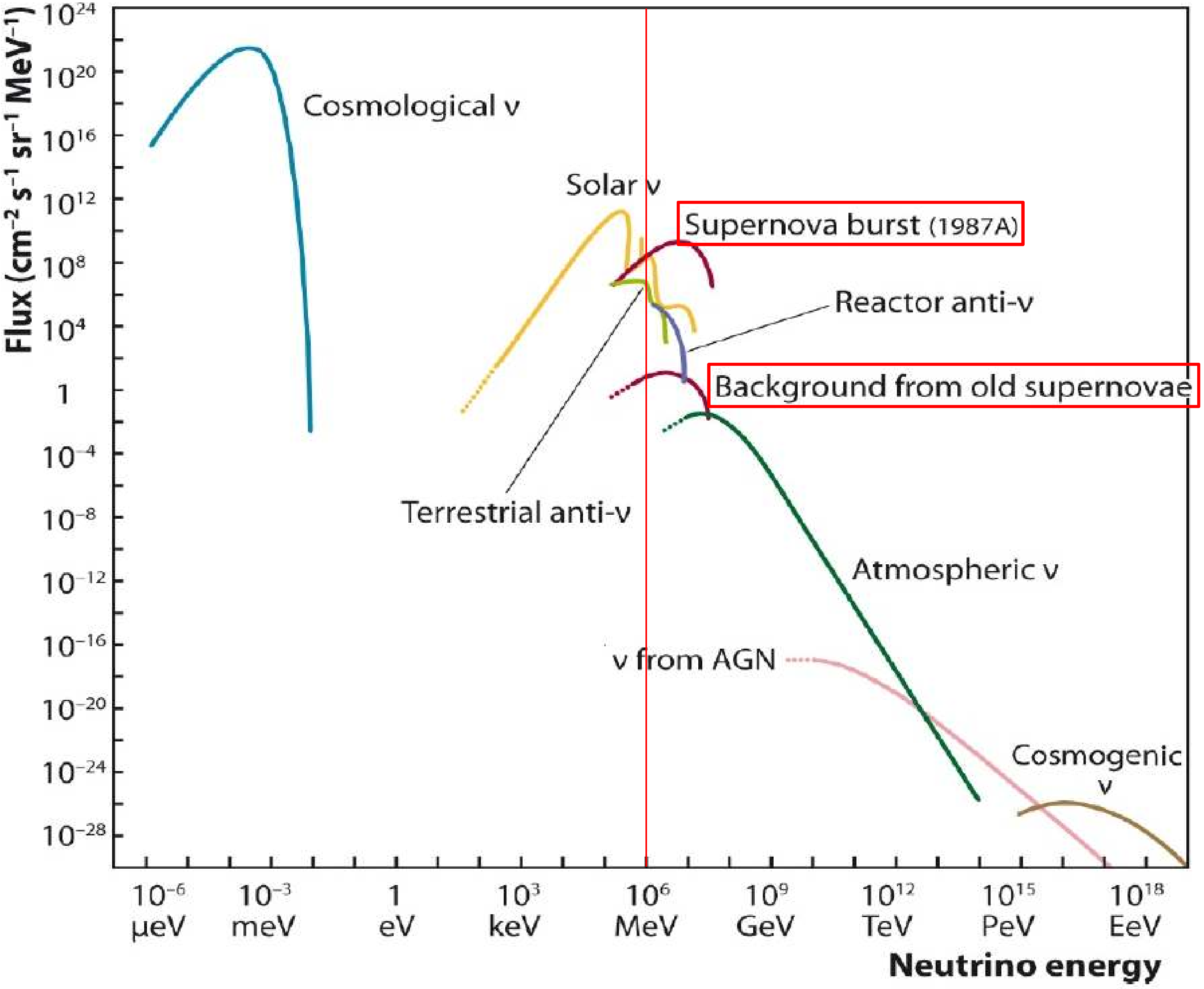
- 광학천문본부
- 전파천문본부
- 우주과학본부
- 대형망원경사업단
- 우주위험감시센터
- 이론천문센터
- 천문우주기술센터
- 고천문연구센터
- 천문전산융합센터

Neutrino Sources



Katz & Spiering (2012, Progress in Particle and Nuclear Physics, 67, 651)

Neutrinos from Supernovae (SNe)

- Nearby core collapse SNe
- Relic SNe
- Failed SNe
- Precursors of SNe (Supergiant Stars)

Nearby Core Collapse SNe

- Neutrino comes out first from the core collapse (CC)

- supernova energy
  - 99% comes as neutrinos
  - ~1% comes as kinetic energy
  - ~0.01% optical emission

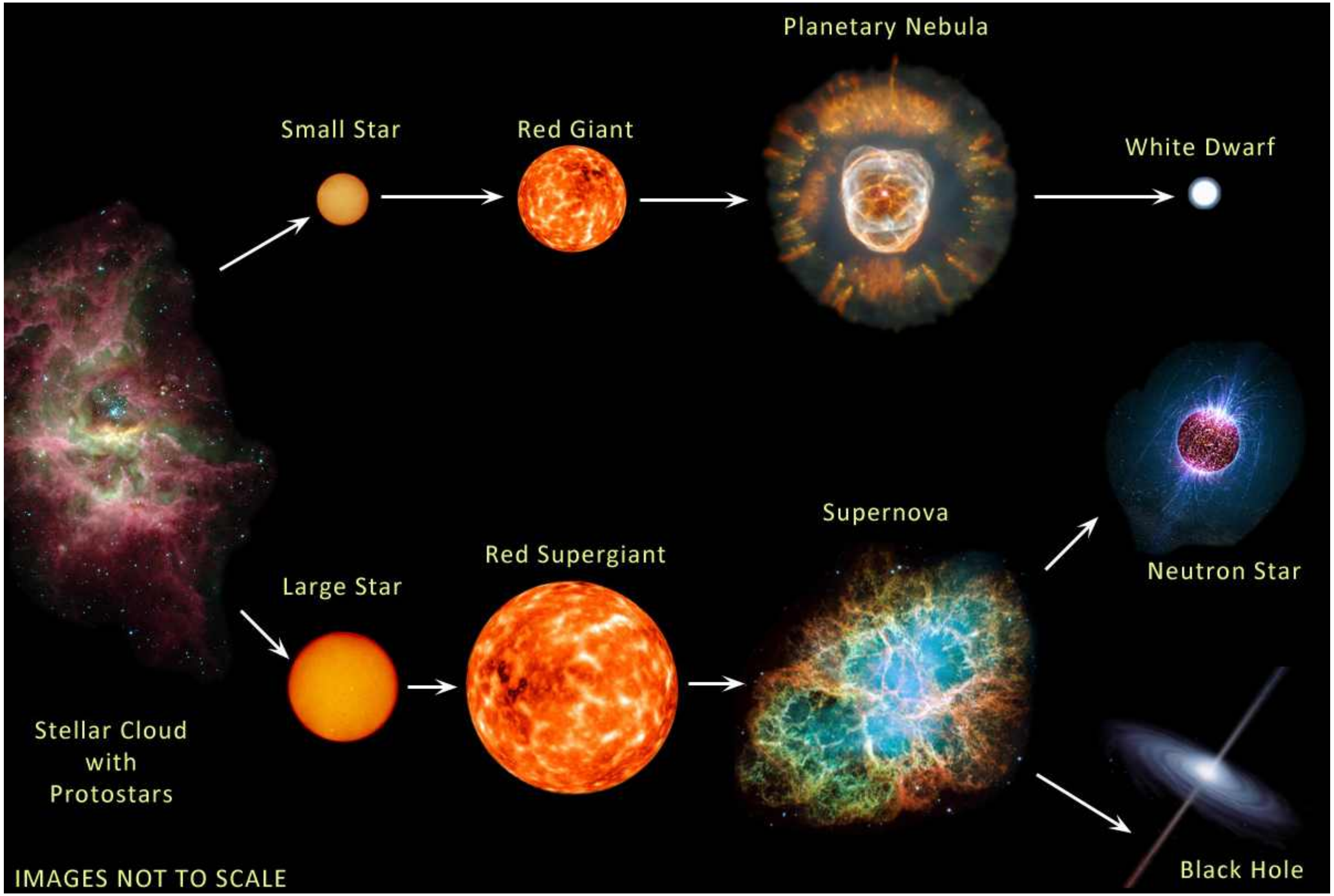
- Neutrino telescope can give fast alert to optical and other λ observatories → need arrival time + direction

- Sciences from SN early detection

  - progenitors
  - explosion mechanism
  - fast decay optical transients

Stellar Evolution

- Mass, Mass loss → final stages
- Low-mass stars → White Dwarfs (WDs), binary system → SN Ia
- Massive ($\geq 8\ M_\odot$) stars → core-collapse SN



http://earthspacecircle.blogspot.kr/2013/07/stellar-evolution.html

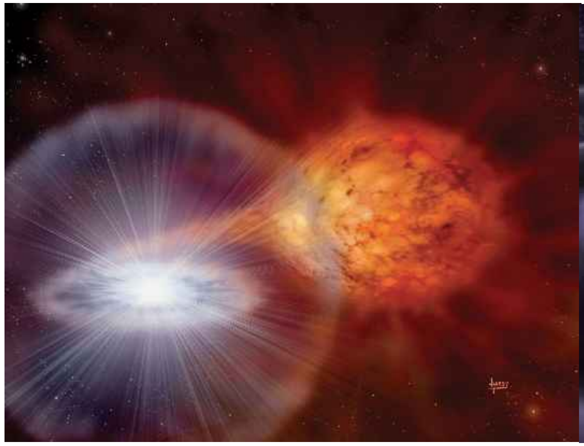
Supernova (SN) types

- Supernovae : Brightest objects in galaxies (M_V = -14 ~ -22)

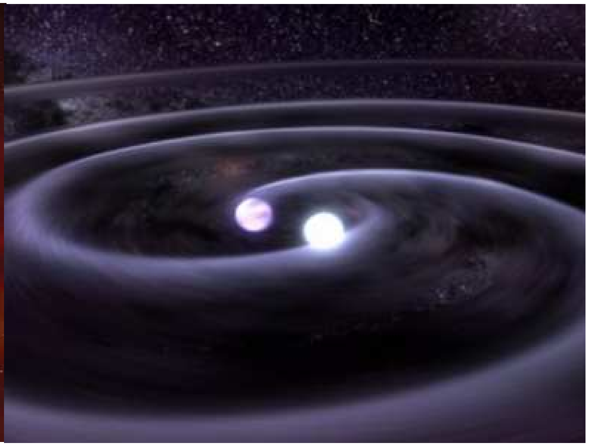
- Typical types

No H lines (pop II) → Type Ia Ib Ic

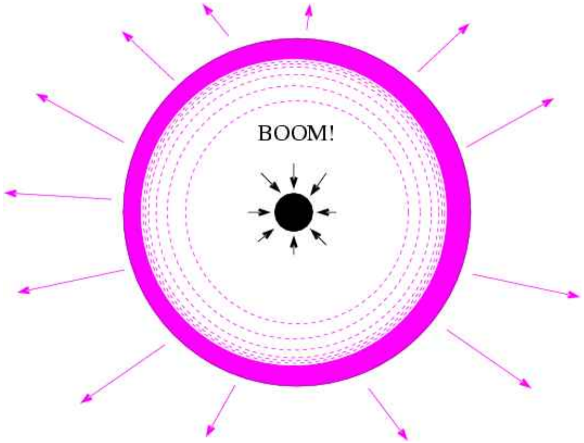
H lines (pop I) → Type II



WD + Giant/MS/He *
(Single Degenerate, SD)



WD + WD
(Double Degenerate, DD)



Core collapse

SNe Ia (thermonuclear stellar explosion)
(WD originated SNe)
백색왜성 기원 초신성

CC SNe

핵붕괴 초신성

http://dujs.dartmouth.edu/2008/05/type-ia-supernovae-properties-models-and-theories-of-their-progenitor-systems
http://wwwmpa.mpa-garching.mpg.de/mpa/research/current_research/hl2013-8/hl2013-8-en.html
http://spiff.rit.edu/richmond/sdss/sn_survey/sn_survey.html

Supernova (SN) types

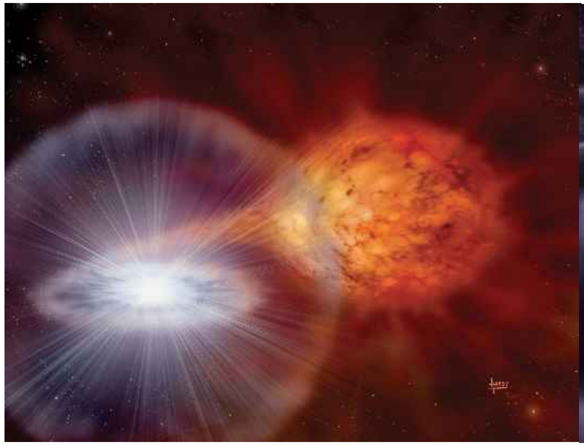
- **Supernovae : Brightest objects in galaxies (M_V = -14 ~ -22)**
- **Typical types**

No H lines (pop II) → Type Ia

H lines (pop I) → Type II

Ib

Ic



WD + Giant/MS/He *
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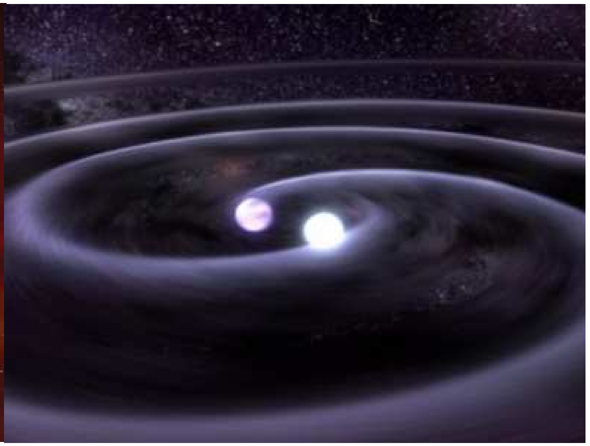
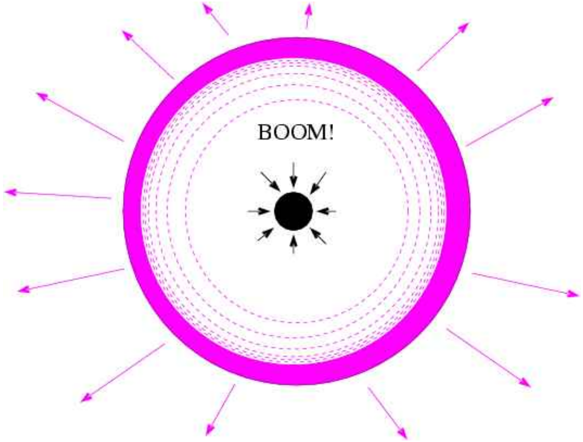


WD + WD
(Double Degenerate, DD)



Core collapse

SNe Ia (thermonuclear stellar explosion)
(WD originated SNe)
백색왜성 기원 초신성

CC SNe

핵붕괴 초신성

http://dujs.dartmouth.edu/2008/05/type-ia-supernovae-properties-models-and-theories-of-their-progenitor-systems
http://wwwmpa.mpa-garching.mpg.de/mpa/research/current_research/hl2013-8/hl2013-8-en.html
http://spiff.rit.edu/richmond/sdss/sn_survey/sn_survey.html

Supernova taxonomy

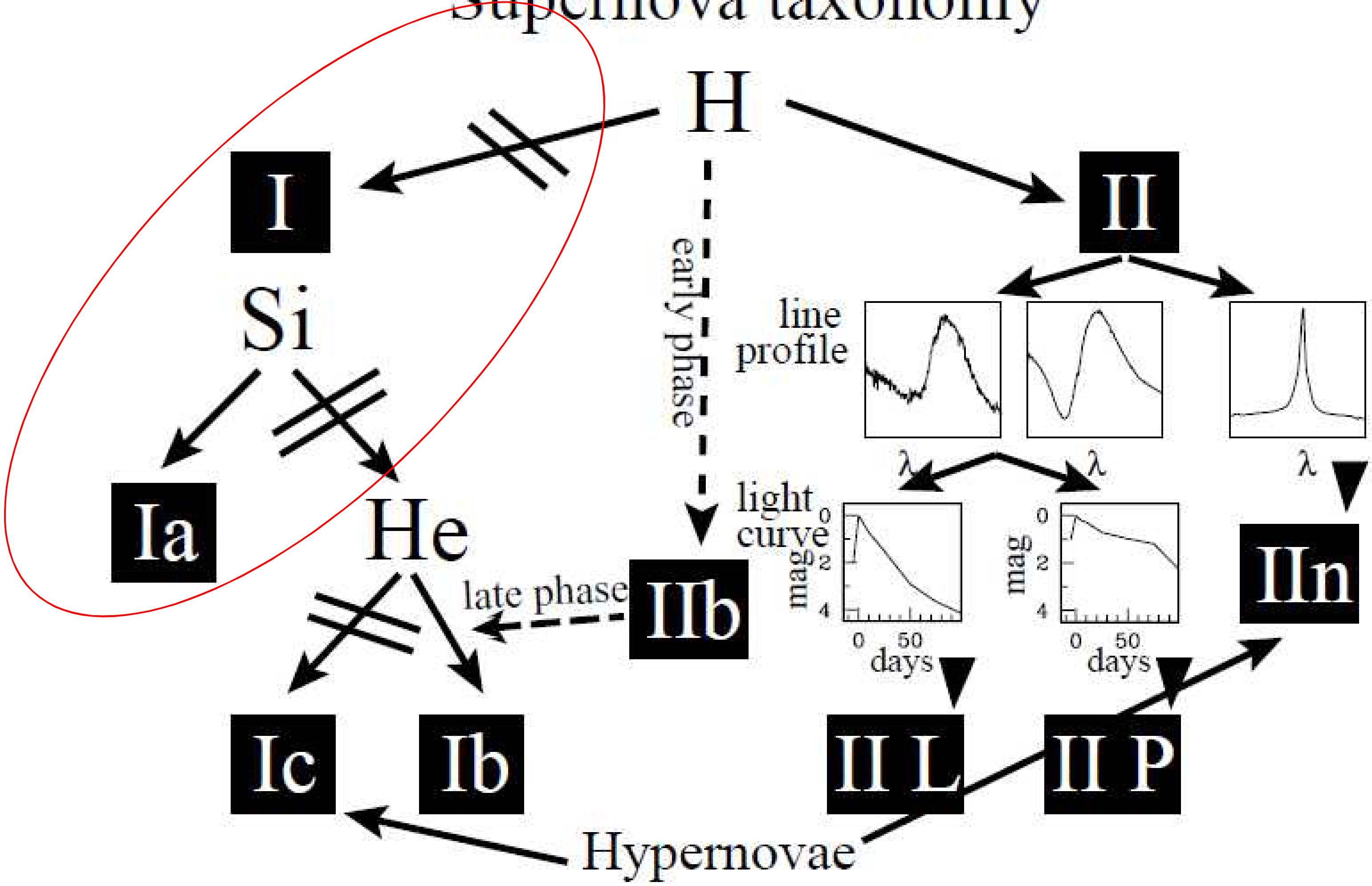


Figure 2. The detailed classification of SNe requires not only the identification of specific features in the early spectra, but also the analysis of the line profiles, luminosity and spectral evolutions

Cappellaro & Turatto (astro-ph/0012455)

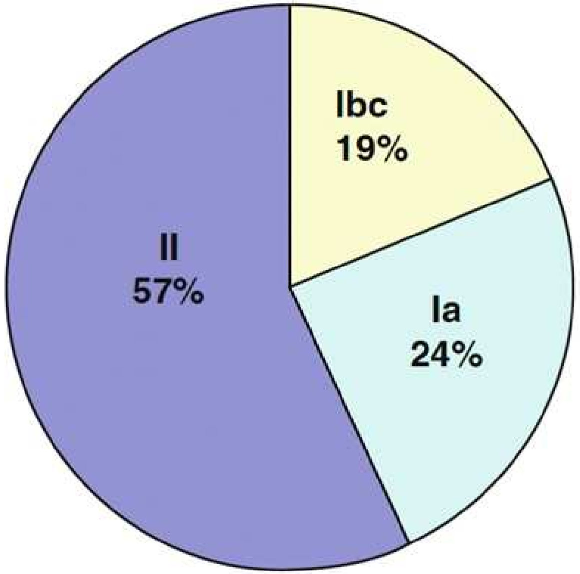
SNe : Ia vs CC

- SN Ia : maximum brightness (peak luminosity)
  $M_V \sim -19.30 \pm 0.03 + 5 \log (H_0/60)$
- A good distance indicator
- Rising time ~ 20 days

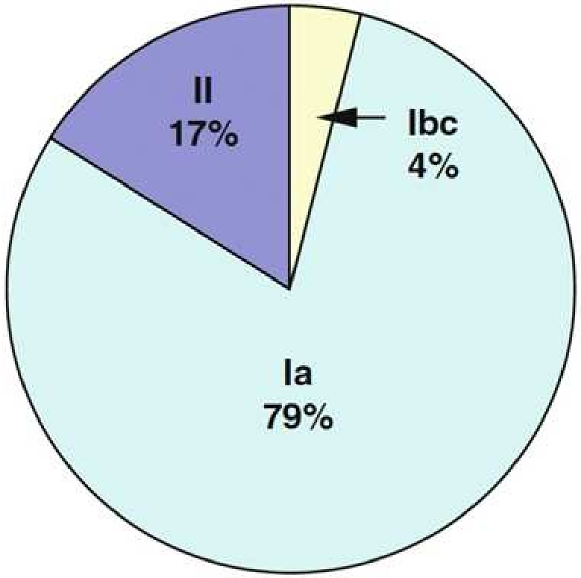
Number ratio

Ia : CC = 24 : 76

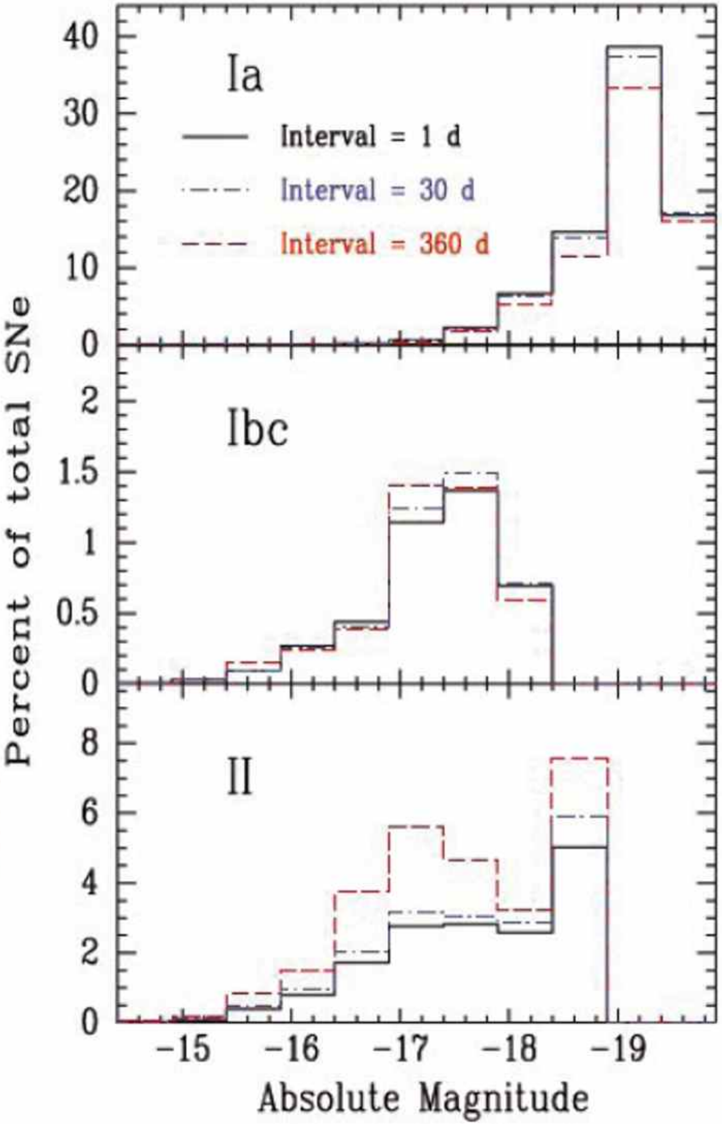
Ia : CC = 79 : 21



Volume-limited sample
$D \leq 60$ Mpc (CC SNe)
$D \leq 80$ Mpc (SNe Ia)



Magnitude-limited sample
(observed rates)



SN Ia : intrinsically brighter than CC SNe

Li et al. 2011, MNRAS 412 1441

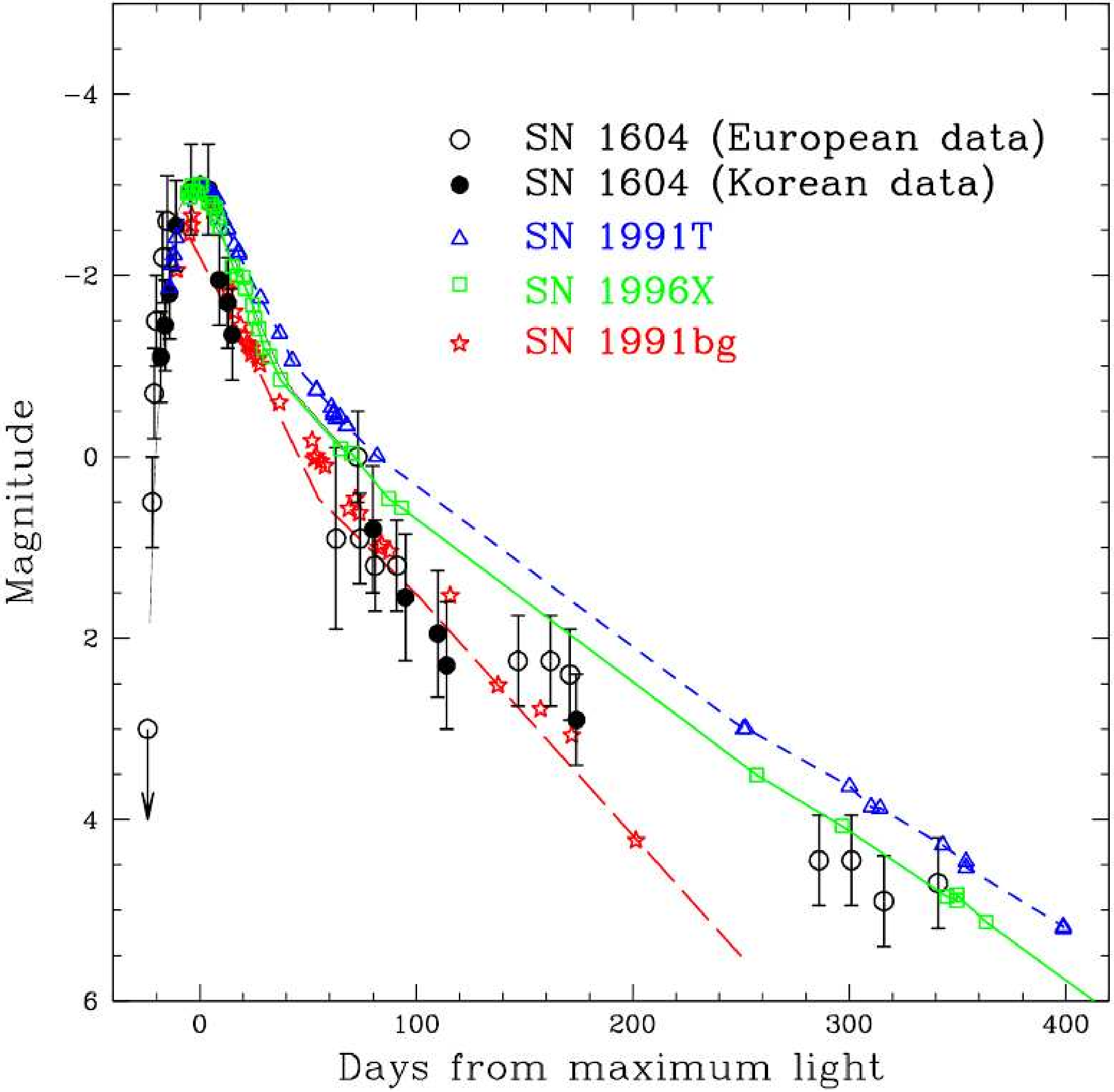
Milky Way SN Rate

(per century)

Method	CC SN	SN Ia	All SNe	Authors
Historical SN	$3.4^{+7.3}_{-2.6}$	$1.4^{+1.4}_{-0.8}$	$4.6^{+7.4}_{-2.7}$	Adams+13 ApJ 778 164
SN statistics	2.30±0.48	0.54±0.12	2.84±0.60	W. Li+11 MN 412 1441
SFR	1-2	…	…	Reed 05 AJ 130 1652
^{26}Al	1.9±1.1	…	…	Diehl+06 Nature 439 45
Pulsar	3.2-3.7	…	…	Faucher-Giguere & Kaspi 06 ApJ 643 332
No neutrino burst	≤11.4	…	…	Agafonova+15 ApJ 802 47

→ Galactic CC SN rate ~ 2-3 SNe/100 years

SN 1604 Oct 8 (type Ia)



(1604 Nov 1)

Kepler

관상감(觀象監)

선조 宣祖 37년

Ruiz-Lapuente 2017 ApJ 842 112

Milky Way Supernovae

- Last (known through SN remnant)
  - 1680 Cassiopeia A (Changbom Park et al. 2016 JKAS 49 233)
  - G1.9+0.3 : year 1899±9 (Chakraborti+16 ApJ 819 37)

- The World is waiting for a new SN!
  And observing extragalactic SNe!

SN Explosion

SN 1987A (II peculiar)

Large Magellanic Cloud (LMC)

Tarantula Nebula

d=49.97 kpc (Pietrzynski+ 13 Natur 495 76) or

51.2 ± 3.1 kpc (Panagia+91 ApJL 380 L23)

1987 Feb 23.316 (UT)

B3 I (supergiant star)

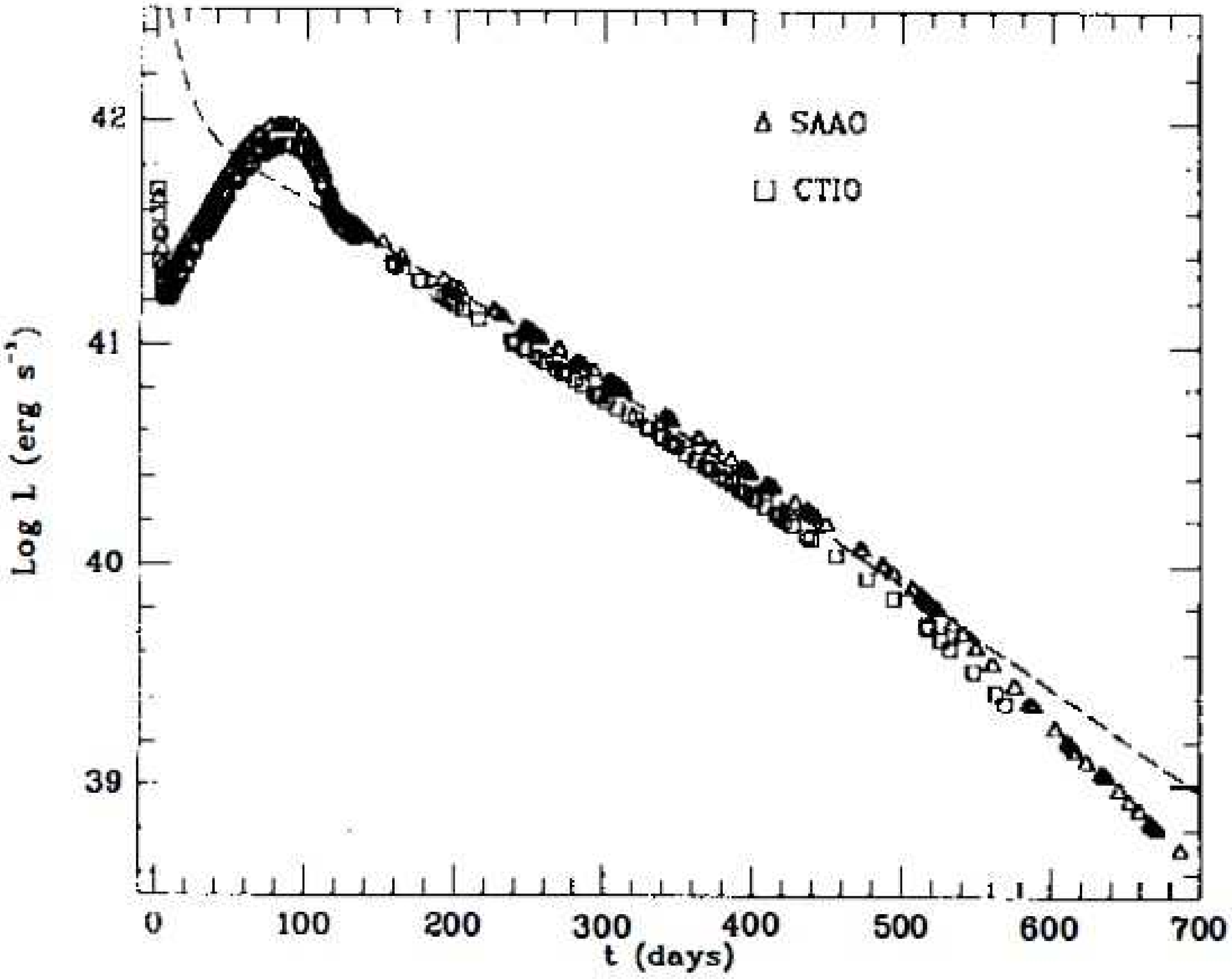
Sanduleak -69° 202

Peak : +2.9 mag

(B-V) = +0.085

$M_{initial} \sim 20\ M_{\odot}$ (N. Smith 07 AJ 133 1034)

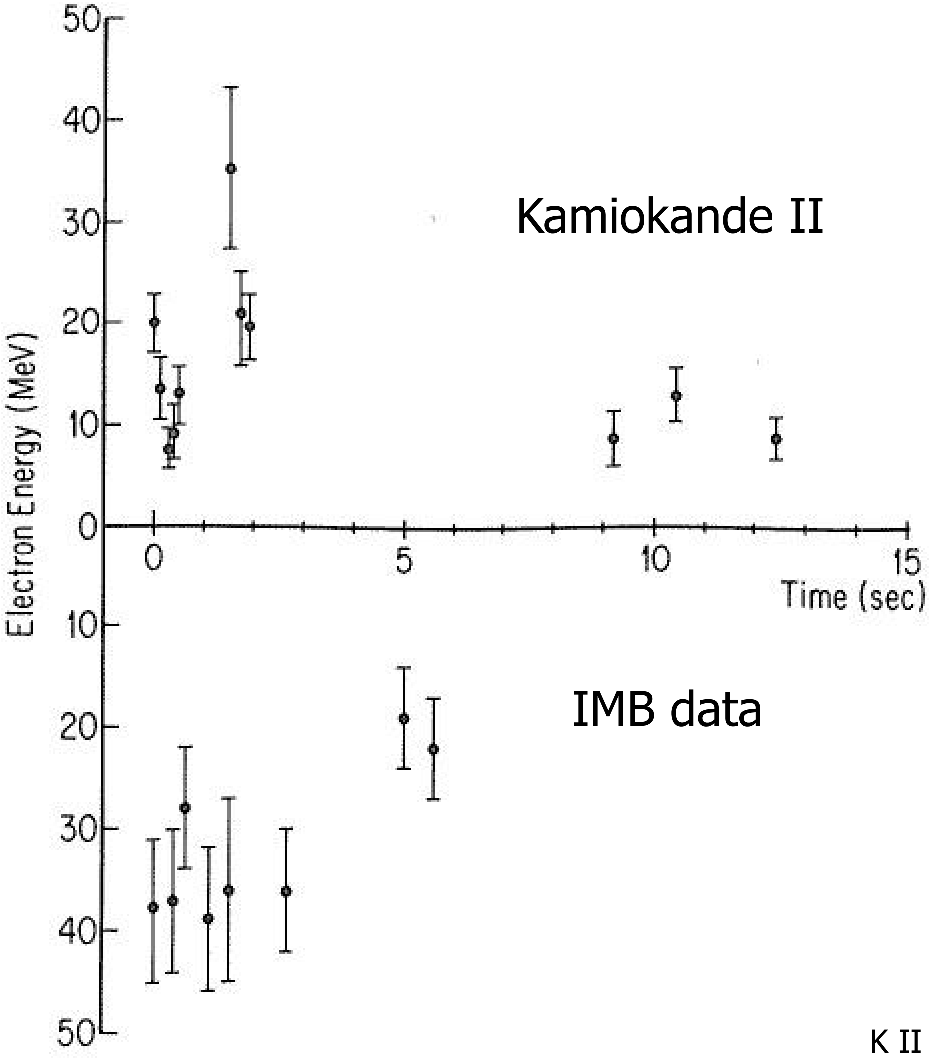
SN 1987A – Bolometric Light Curve



Arnett et al. (1989, ARAA, 27, 629)

10^{58} Neutrinos from SN 1987A

- 1987 Feb 23, 07:35:35 (UT) @ d = 50 kpc
- Kamiokande II – 11 events (12.44 seconds)
- Irvine-Michigan-Brookhaven-3 (IMB, Lake Erie) – 8 events (5.58 seconds)

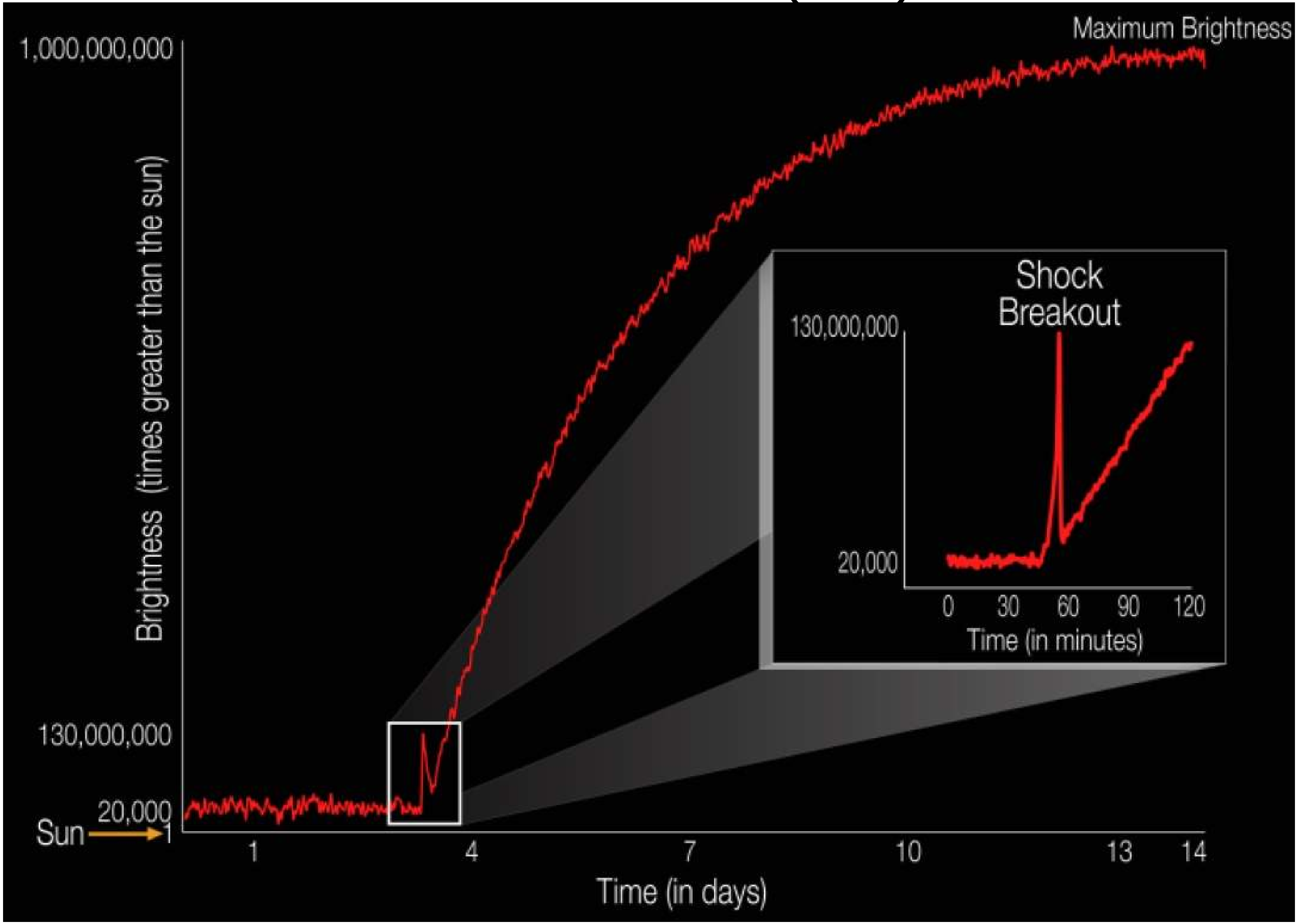


Nobel Prize 2002

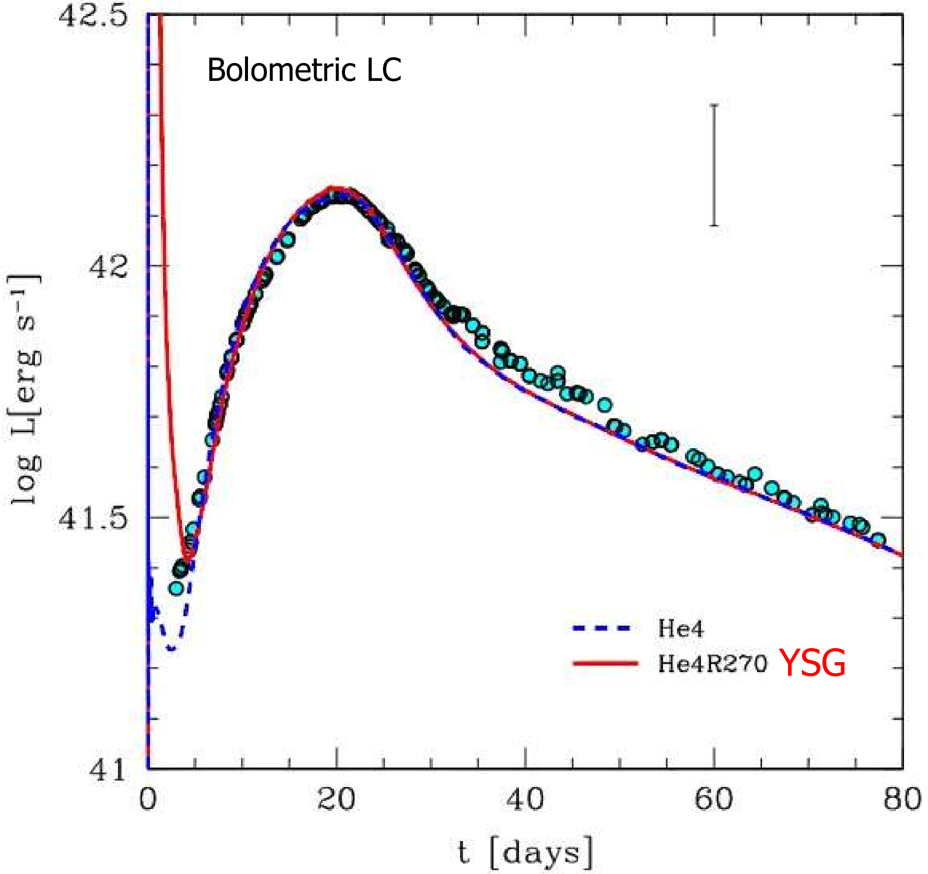
Masatoshi Koshiba
고시바 마사토시(小柴昌俊)
(1926-2020)

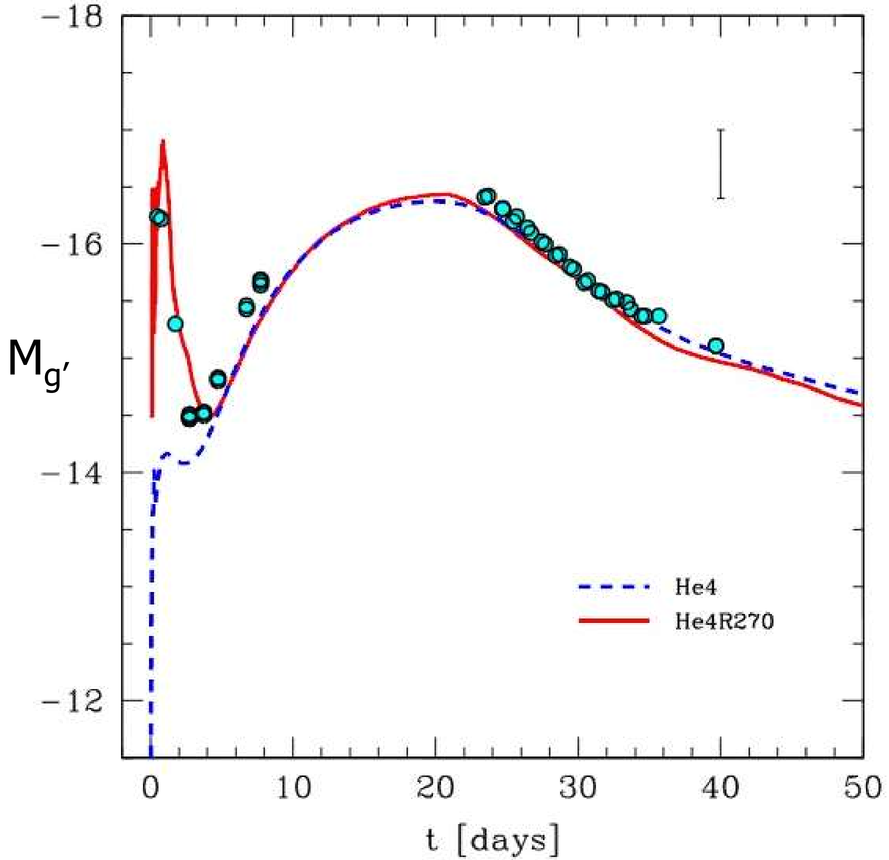
K II : Hirata+ 87 Phys. Rev. Lett. 58, 1490
IMB : Bionta+ 87 Phys. Rev. Lett. 58, 1494

Shock Breakout (SBO)



Early bolometric light curve(LC)





SN 2011dh
(IIb, M51)

Radius effect – noticeable before t~5 days
(compact 2 $R_\odot$ vs extended 270 $R_\odot$)

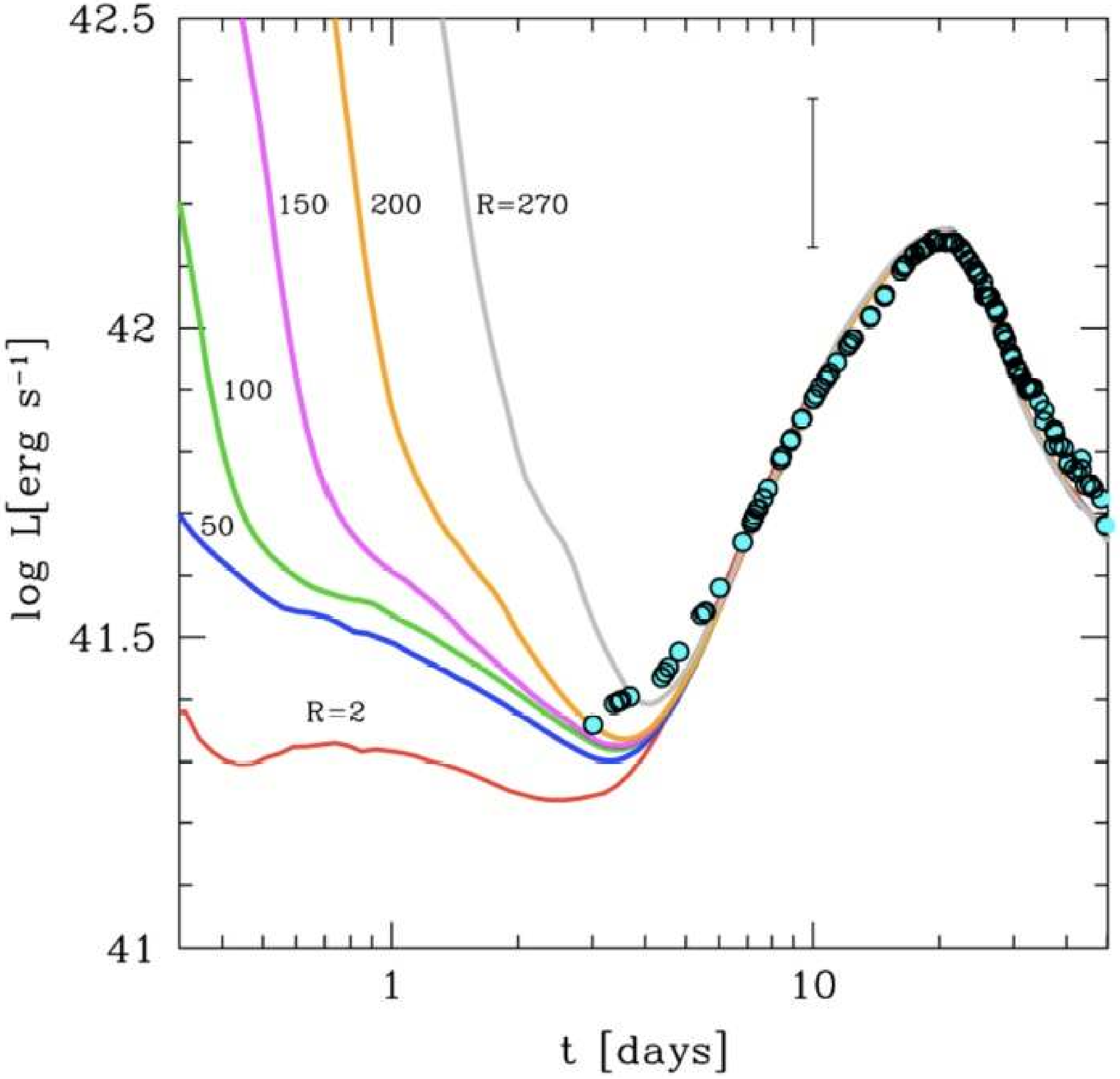
Bersten+12 ApJ 757 31

Early bolometric light curve(LC)

Models

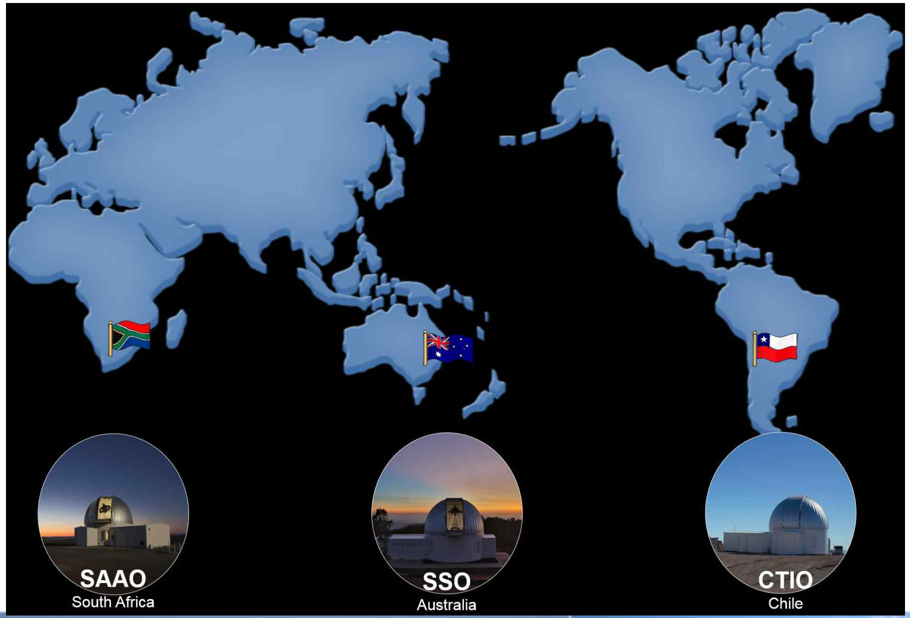
- Same explosion energy
- Different initial radius

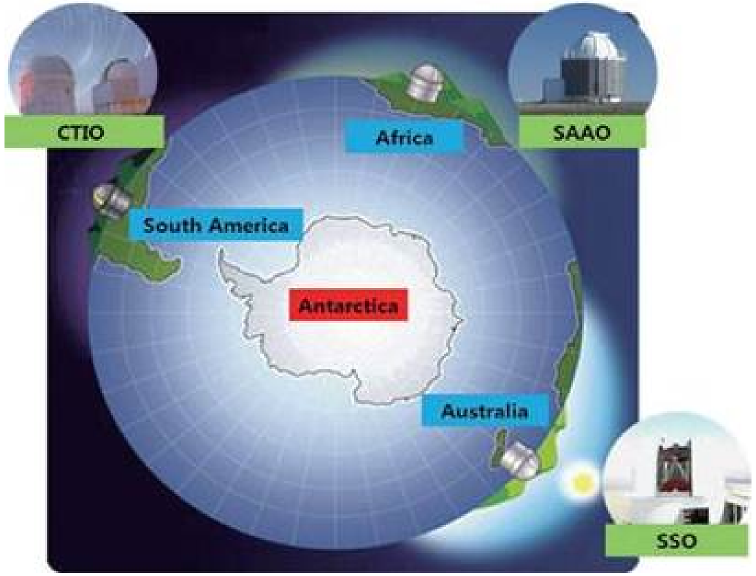
● : SN 2011dh (IIb, M51)



Bersten+12 ApJ 757 31

To avoid the effect of Earth rotation





KMTNet - 24hour coverage!

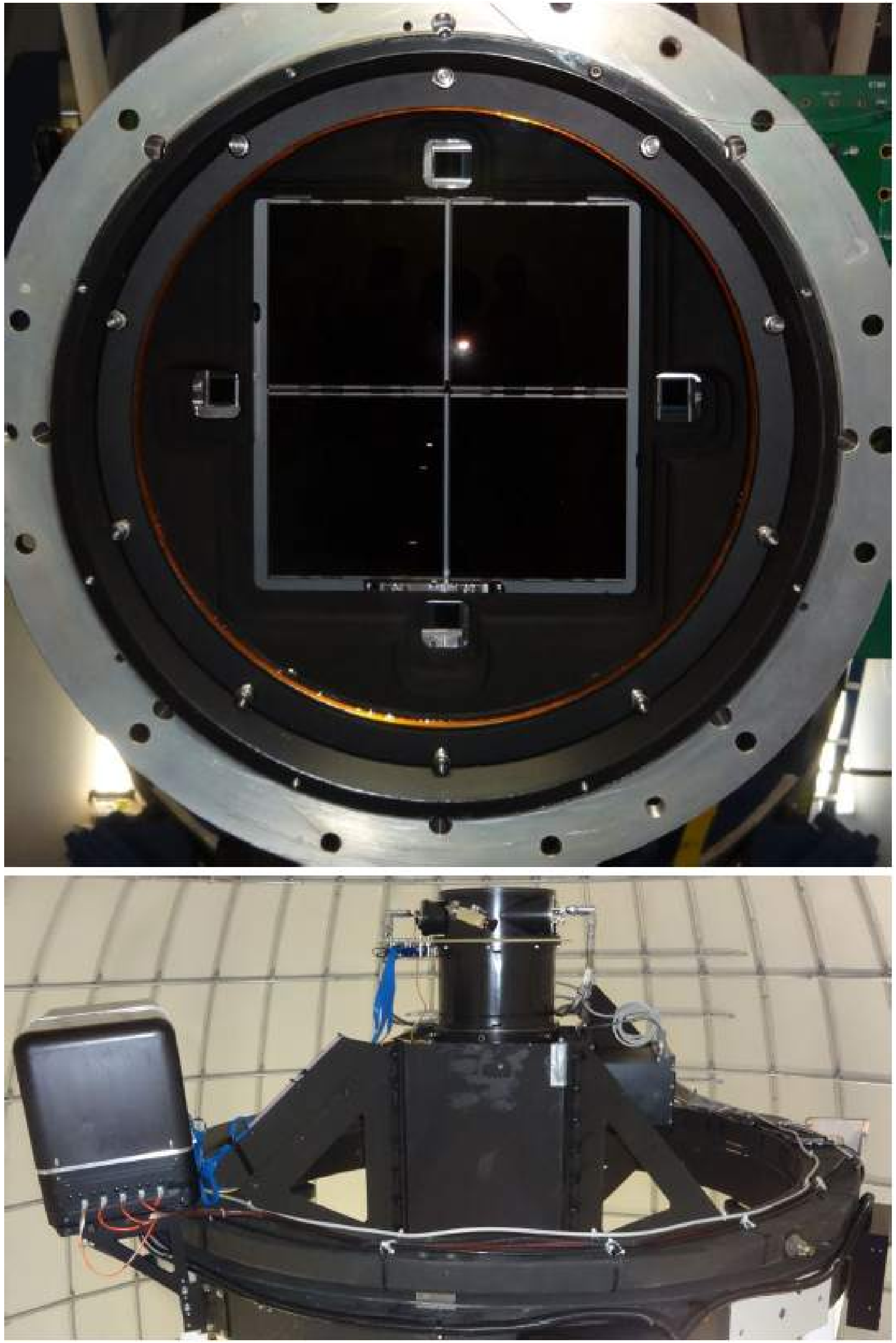
- **K**orea **M**icrolensing **T**elescope **Net**work
- Three Identical Observing Systems:
  CTIO in Chile, SAAO in South Africa,
  SSO in Australia
- **24-hours Monitoring** of night sky at Southern Hemisphere
- Primary Mirror with 1.6m Diameter

KMTNet – Wide-field!

- 4 Chips with 9K x 9K pixels
- 0.4 arcsec/pixel,
- **2°x2° wide-field of view** (FOV)

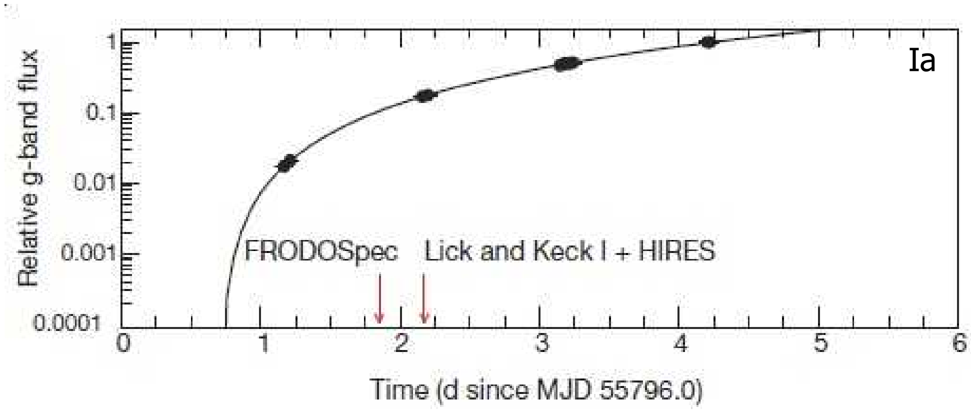
"Star never sets on the KMTNet"

KOREA MICRO-LENSING TELESCOPE NETWORK ★



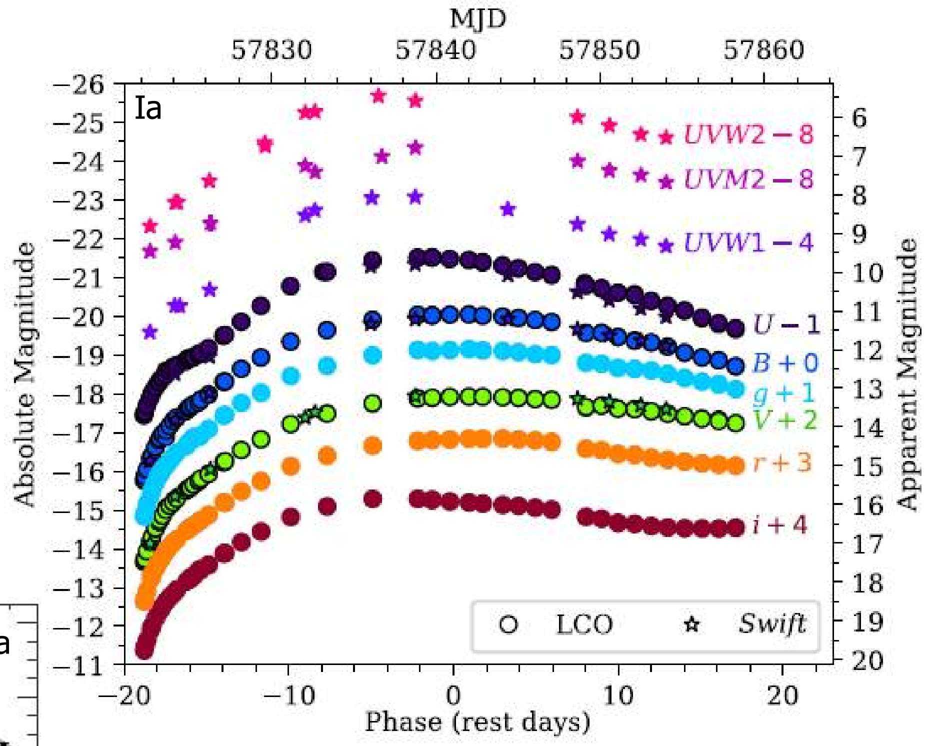
Efforts to detect early SNe Ia

Nugent+11 (Natur 480 344) SN 2011fe



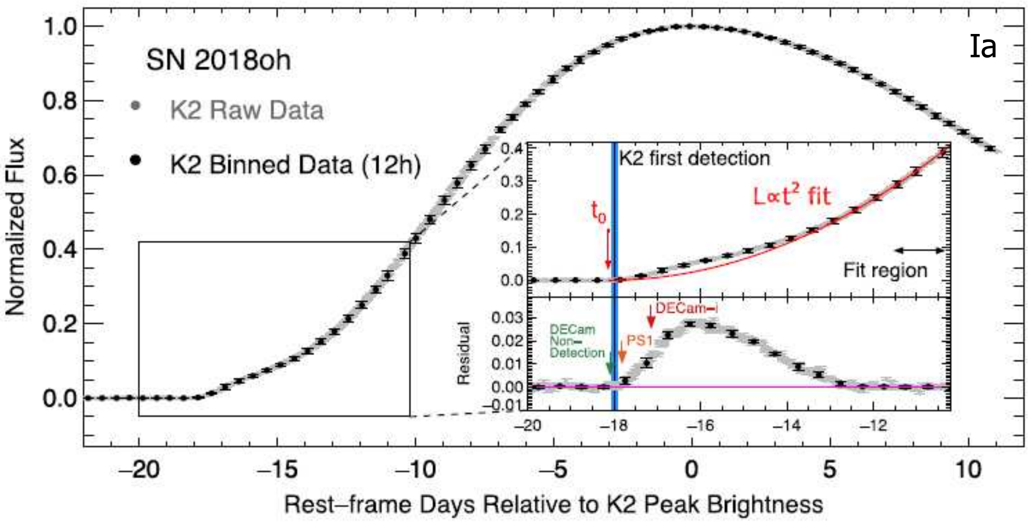
11 h after explosion

Hosseinzadeh+17 (ApJL 845 L11) SN 2017cbv



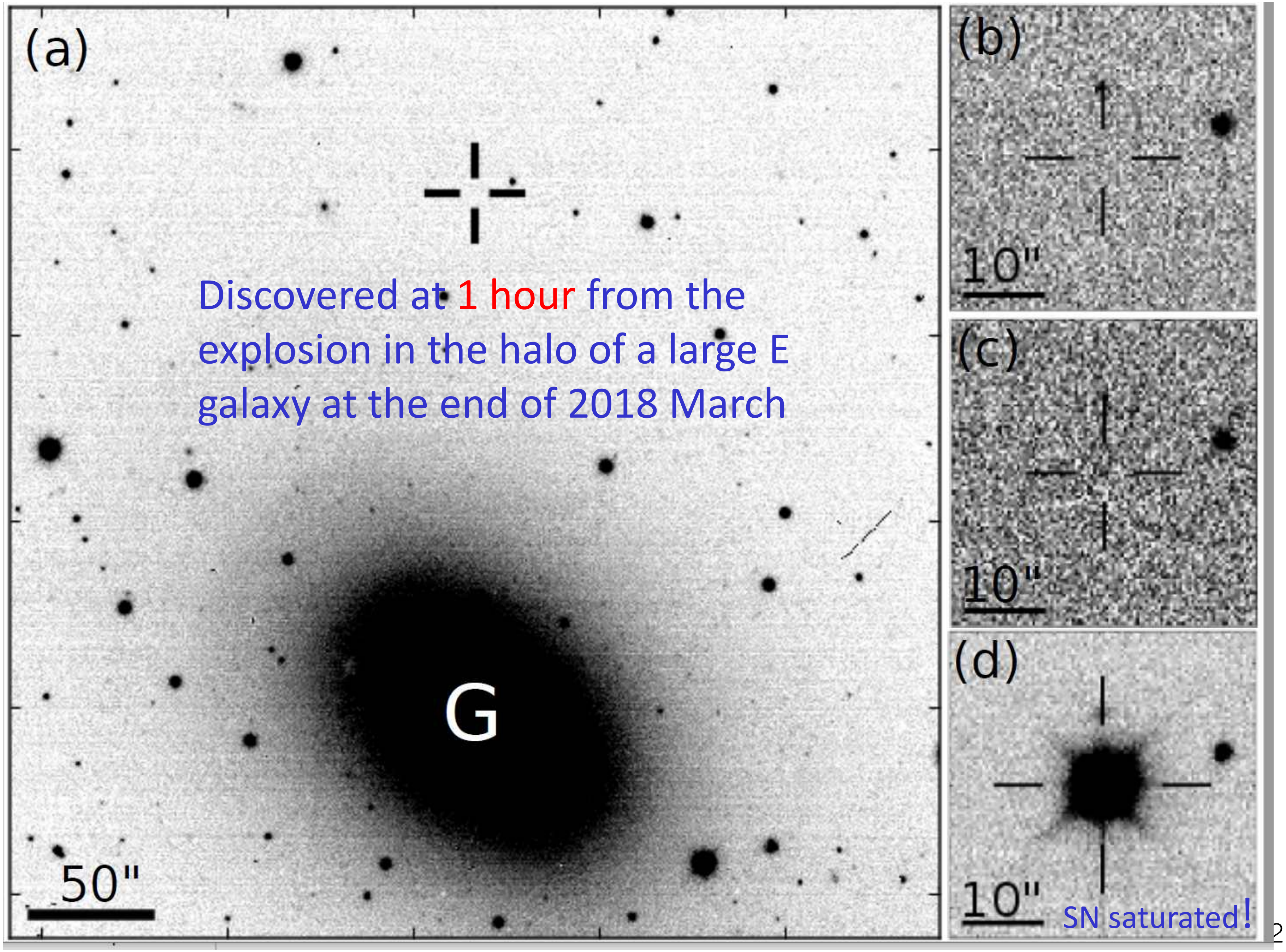
7 h after explosion

Dimitriadis+19 (ApJL 870 L1) SN 2018oh



3.6 h after explosion

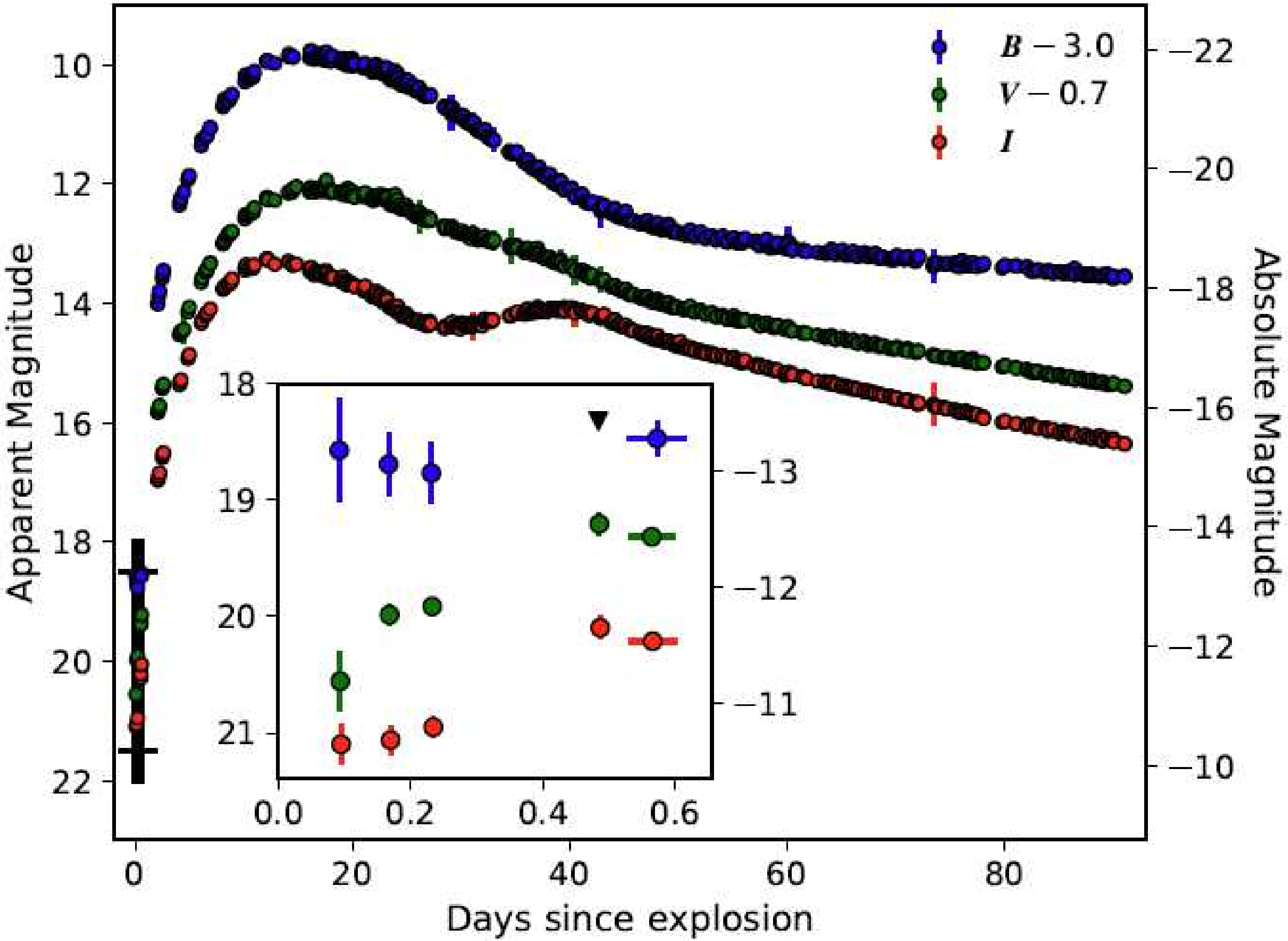
SN 2018aoz: Earliest (Type Ia) SN (KSP-N3923-2-2018-ku, Ni+22 NatAs 6 568)



Discovered at 1 hour from the explosion in the halo of a large E galaxy at the end of 2018 March

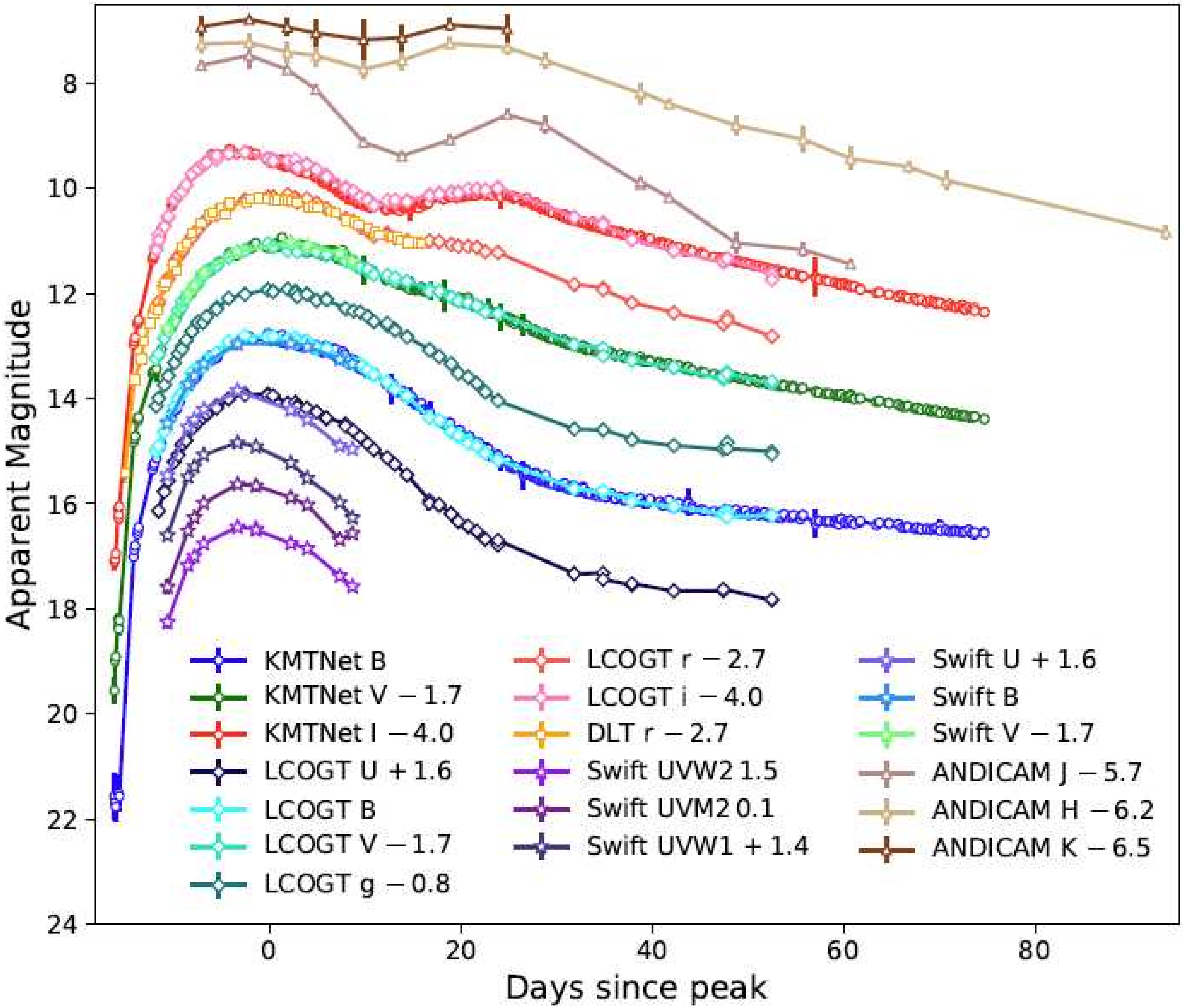
SN saturated!

SN 2018aoz: Earliest (Type Ia) SN (KSP-N3923-2-2018-ku, Ni+22 NatAs 6 568)



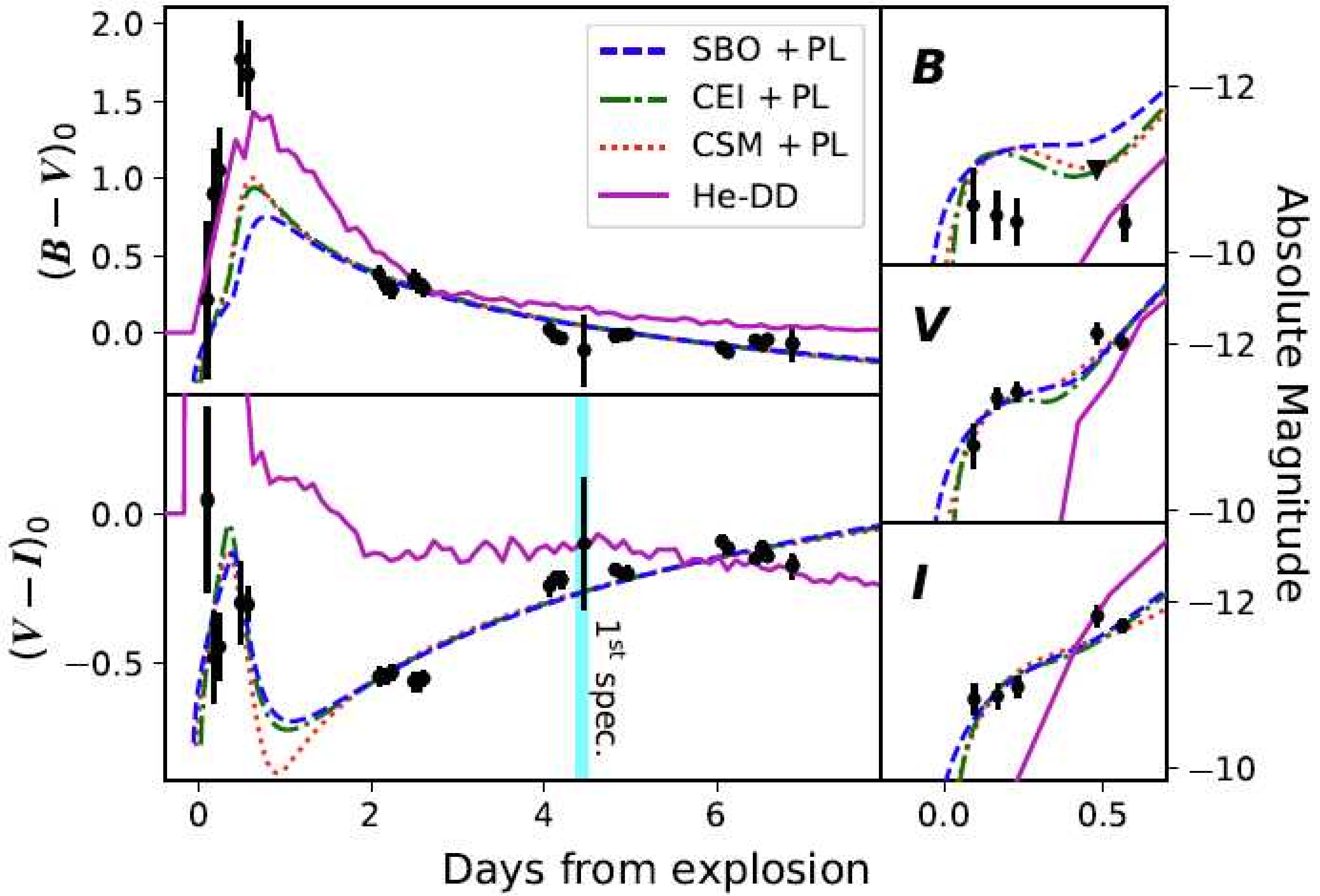
KMTNet light curves reveal early reddening – never seen before

SN 2018aoz: Earliest (Type Ia) SN (KSP-N3923-2-2018-ku, Ni+22 NatAs 6 568)



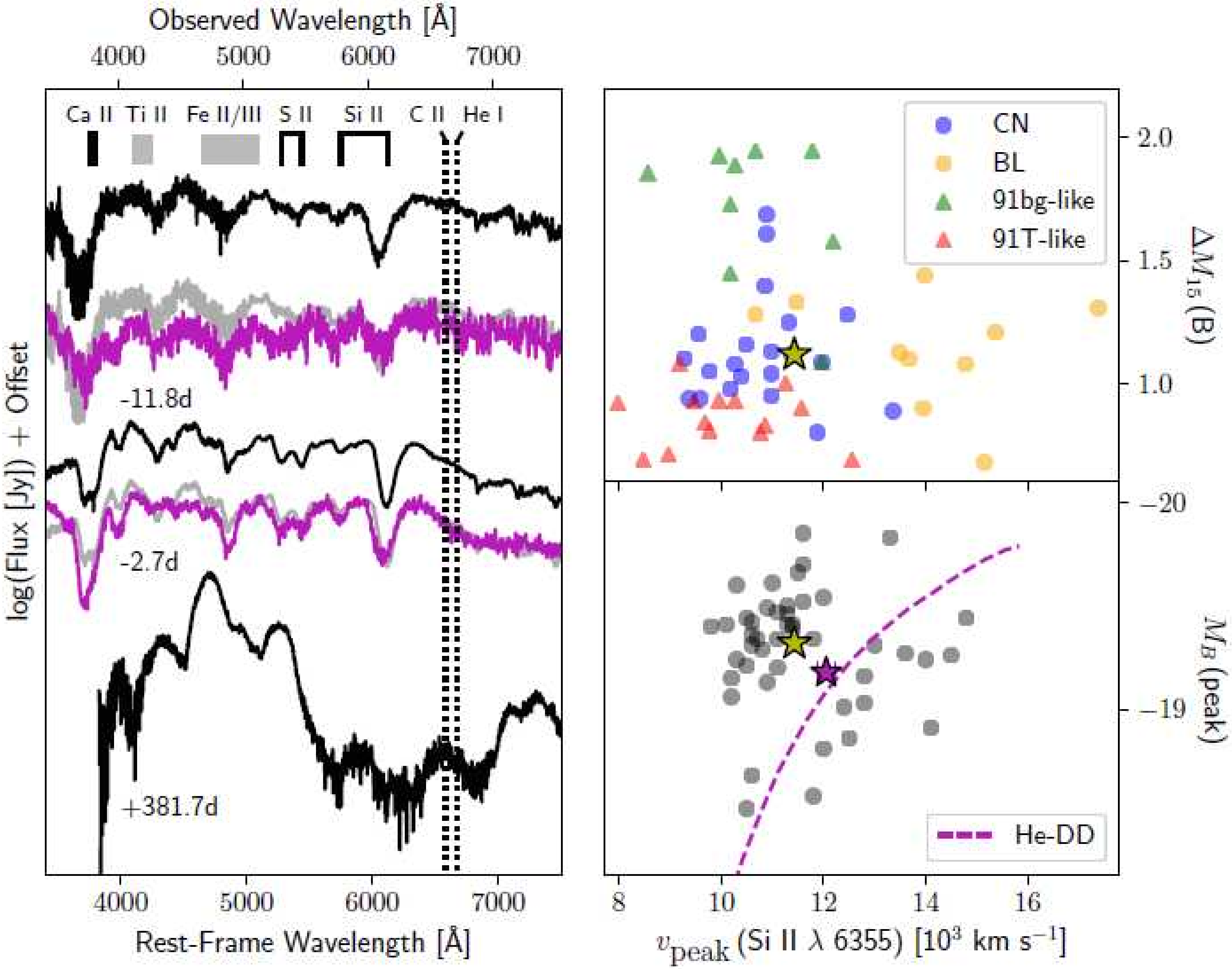
Data from multi-wavelength campaign

SN 2018aoz: Earliest (Type Ia) SN (KSP-N3923-2-2018-ku, Ni+22 NatAs 6 568)



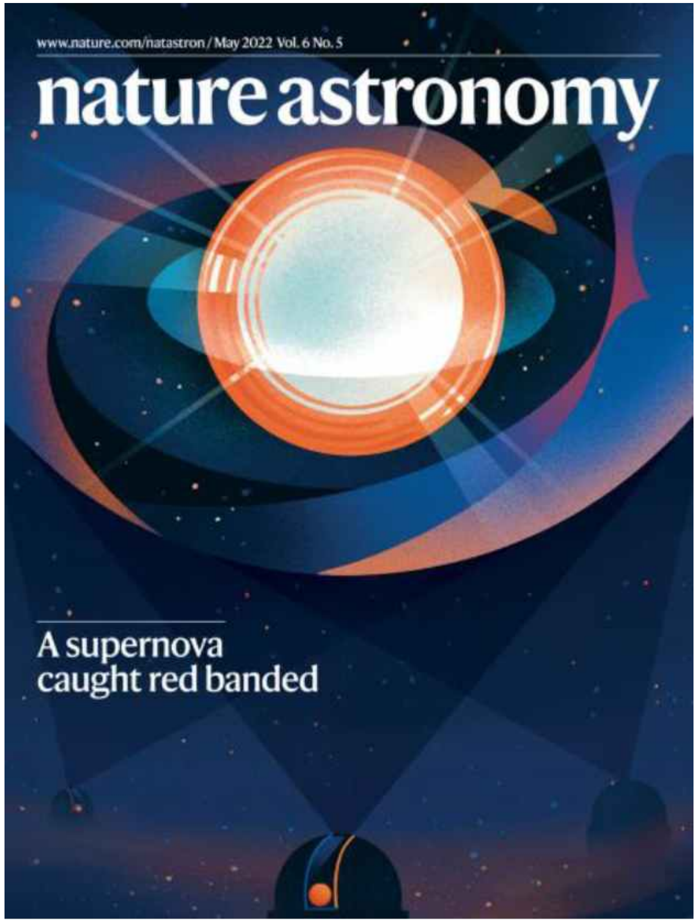
Comparison with various models: Shock Break Out, Companion-Ejecta Interaction, Circumstellar Emission and He Double Detonation

SN 2018aoz: Earliest (Type Ia) SN (KSP-N3923-2-2018-ku, Ni+22 NatAs 6 568)



Observed spectra confirm that it is a normal Type Ia supernova from He Double Detonation

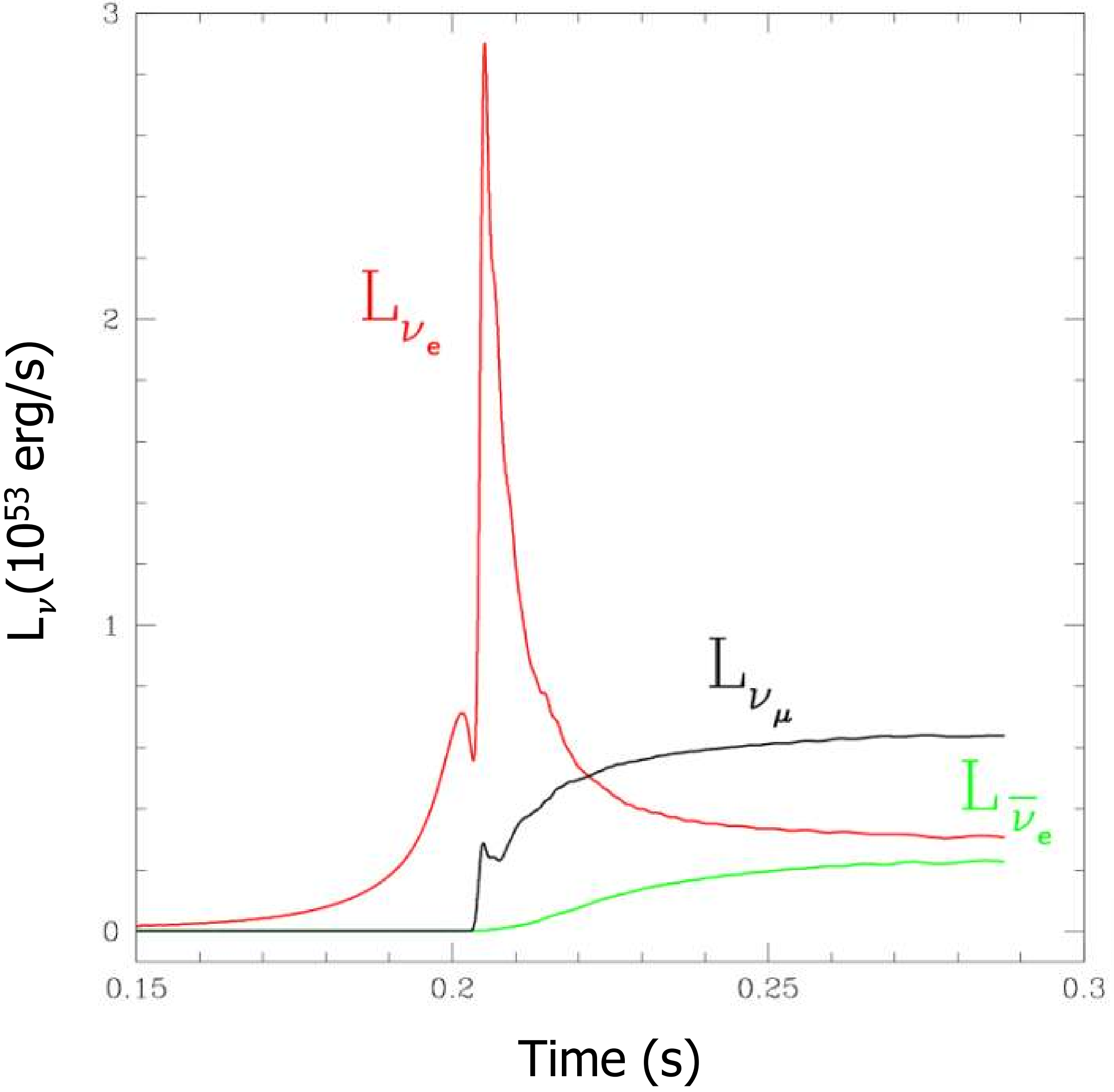
SN 2018aoz: Earliest (Type Ia) SN (KSP-N3923-2-2018-ku, Ni+22 NatAs 6 568)



- SN 2018aoz : originated from helium-shell double detonation
- Triggered by a WD companion
- The origin of normal Type Ia SNe!

Using Neutrinos for SNe Science

Neutrino Emission

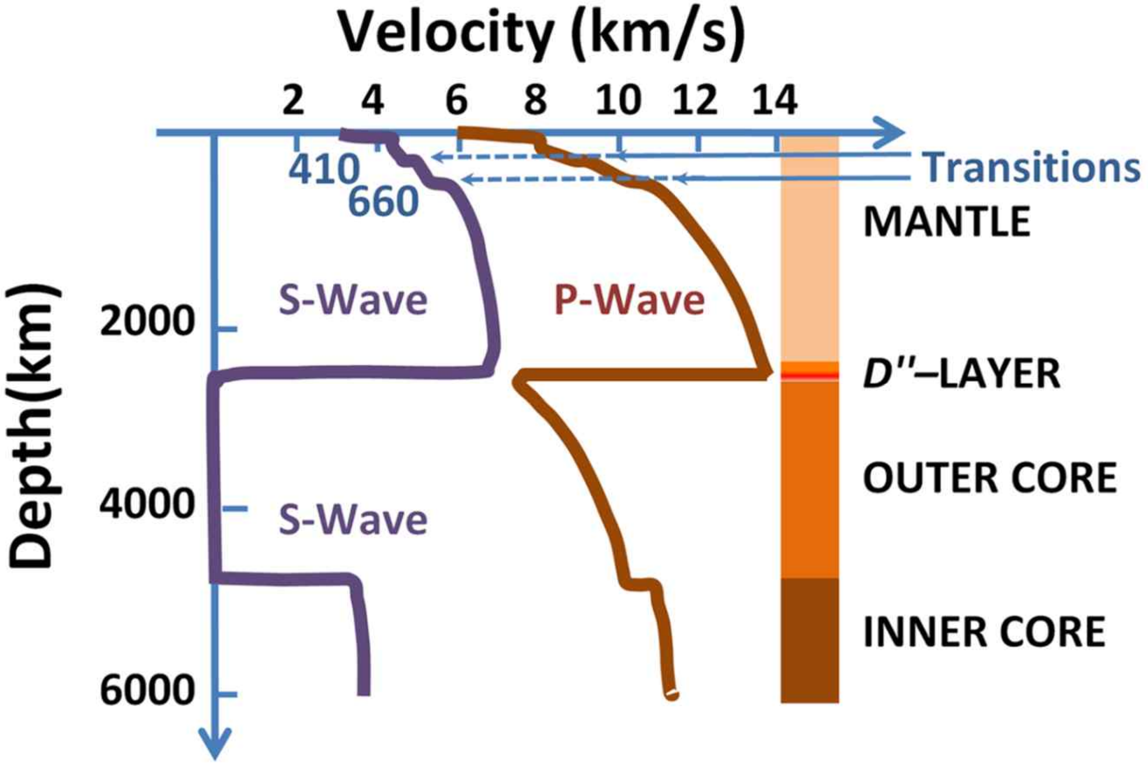


Burrows 2013 (RvMP 85, 245)

Progenitor model : 11 $M_\odot$

SNEWS:
SuperNova Early Warning System

- Similar to “Seismic waves in(on) the Earth”



Seismic wave	파동	Speed	통과물질	피해
Primary wave	종파	**5-8 km/s**	고,액,기체	Minor
Secondary wave	횡파	3-4 km/s	고체	Huge

https://en.wikipedia.org/wiki/Supernova_Early_Warning_System

SNEWS:
SuperNova Early Warning System

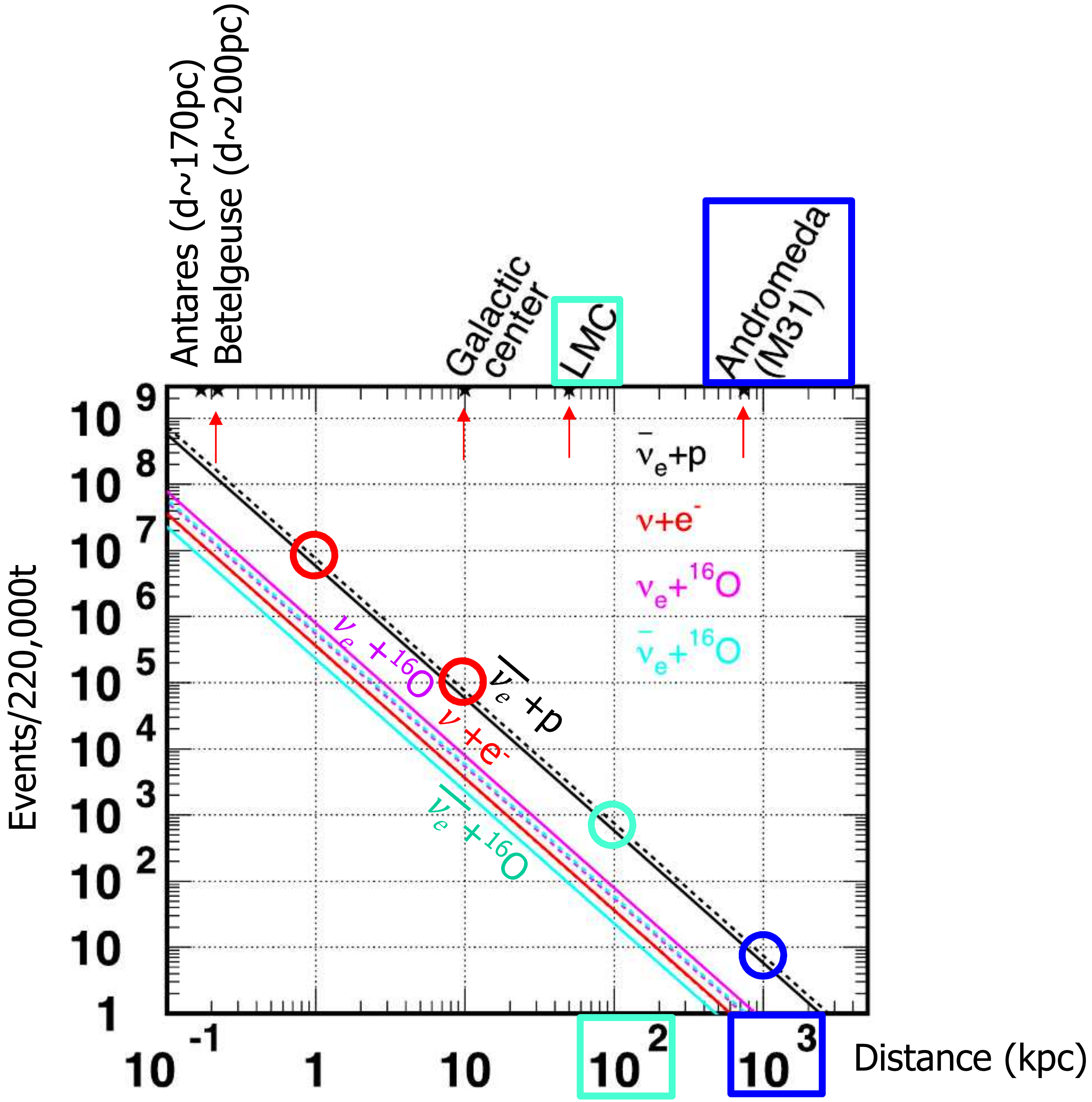
- http://snews.bnl.gov/
- A network of 7 neutrino detectors
  - Borexino, Daya Bay, KamLAND, HALO, IceCube, LVD, Super-Kamiokande
  - began automatic operation in 2005
  - reports gather + identify SNe at Brookhaven National Laboratory
    → need signals at ≥ 2 detectors within 10 seconds
- To make early warning for CC SNe from the Milky Way, or nearby galaxies (e.g. LMC, Canis Major dwarf)
- Neutrino pulses from SN 1987A – arrived 3 hours before the photons

https://en.wikipedia.org/wiki/Supernova_Early_Warning_System

Studying the Neutrinos Themselves

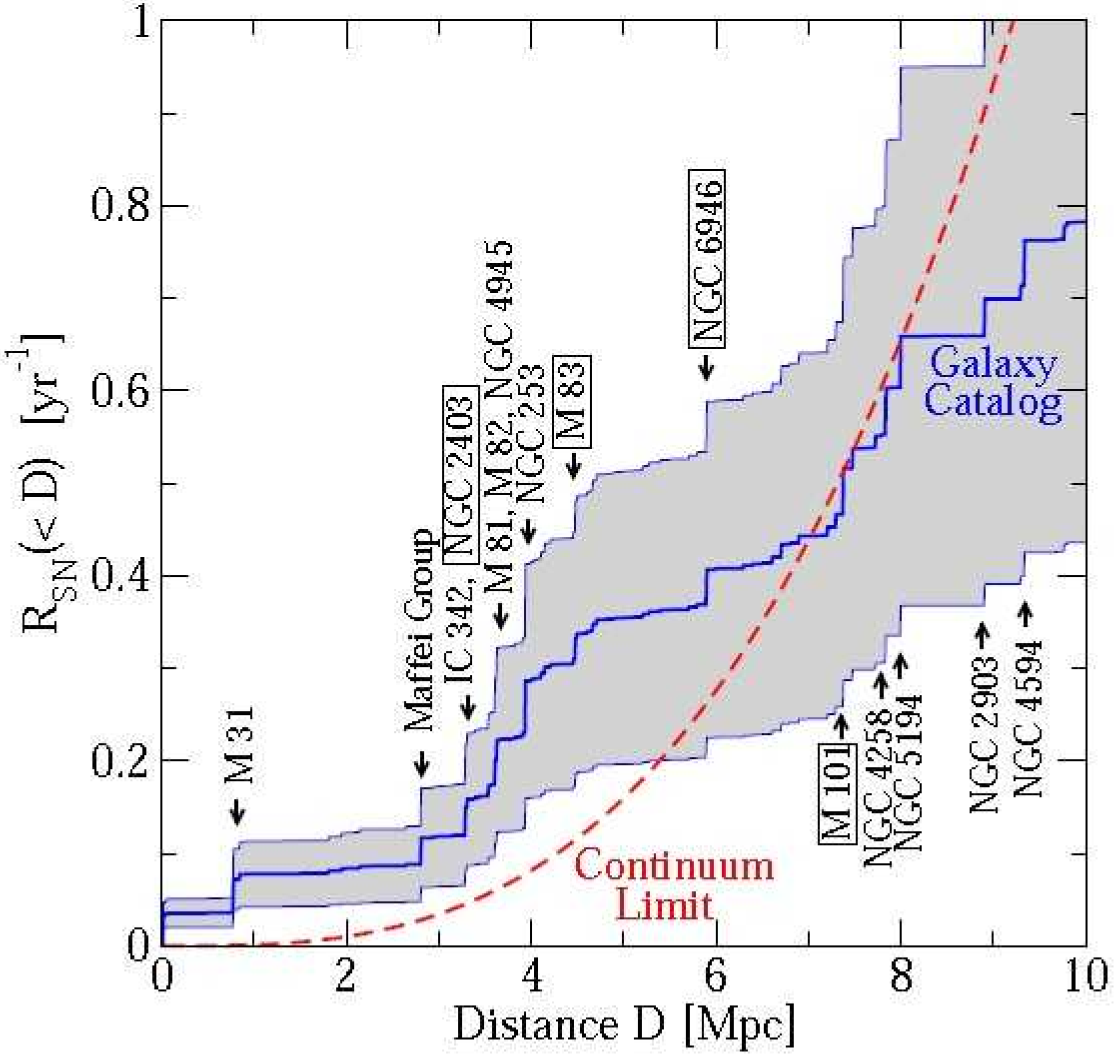
- Nearby CC SNe!

SN burst observation by KNO



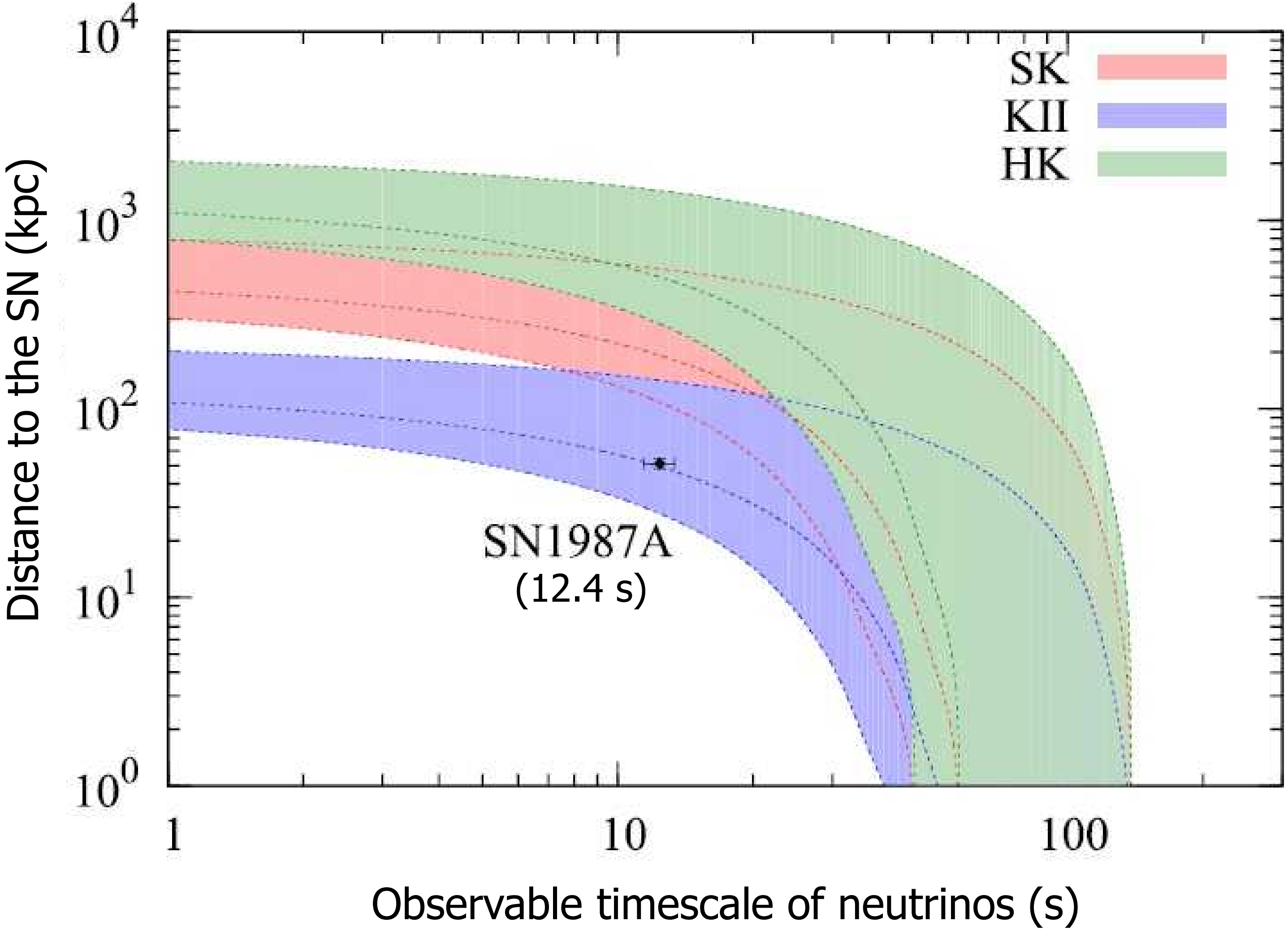
Abe+21 (ApJ 916 15)

CC SN Rate



Ando et al. (2005, PRL, 95, 171101)

Nearby CC SNe



Y. Suwa 19 ApJ 881 139

If There is No SN…

Then What?

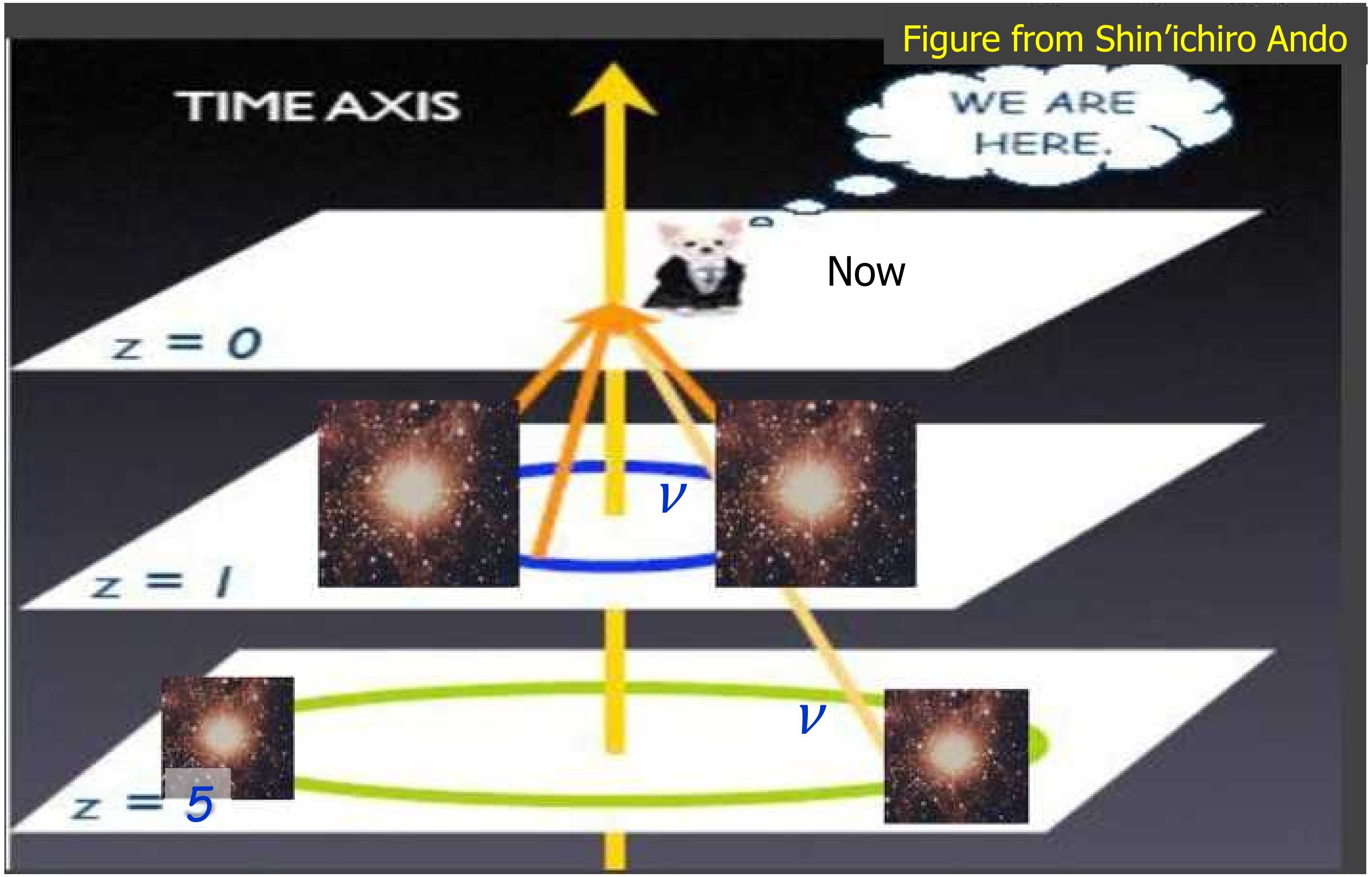
Neutrinos from SNe

- Relic SNe
- Failed SNe
- Precursors of SNe (Supergiant Stars)

Neutrinos from Relic SNe

- Supernova Relic Neutrino (SRN) : Neutrinos emitted from past SNe since the beginning of the Universe – esp. below 20 MeV

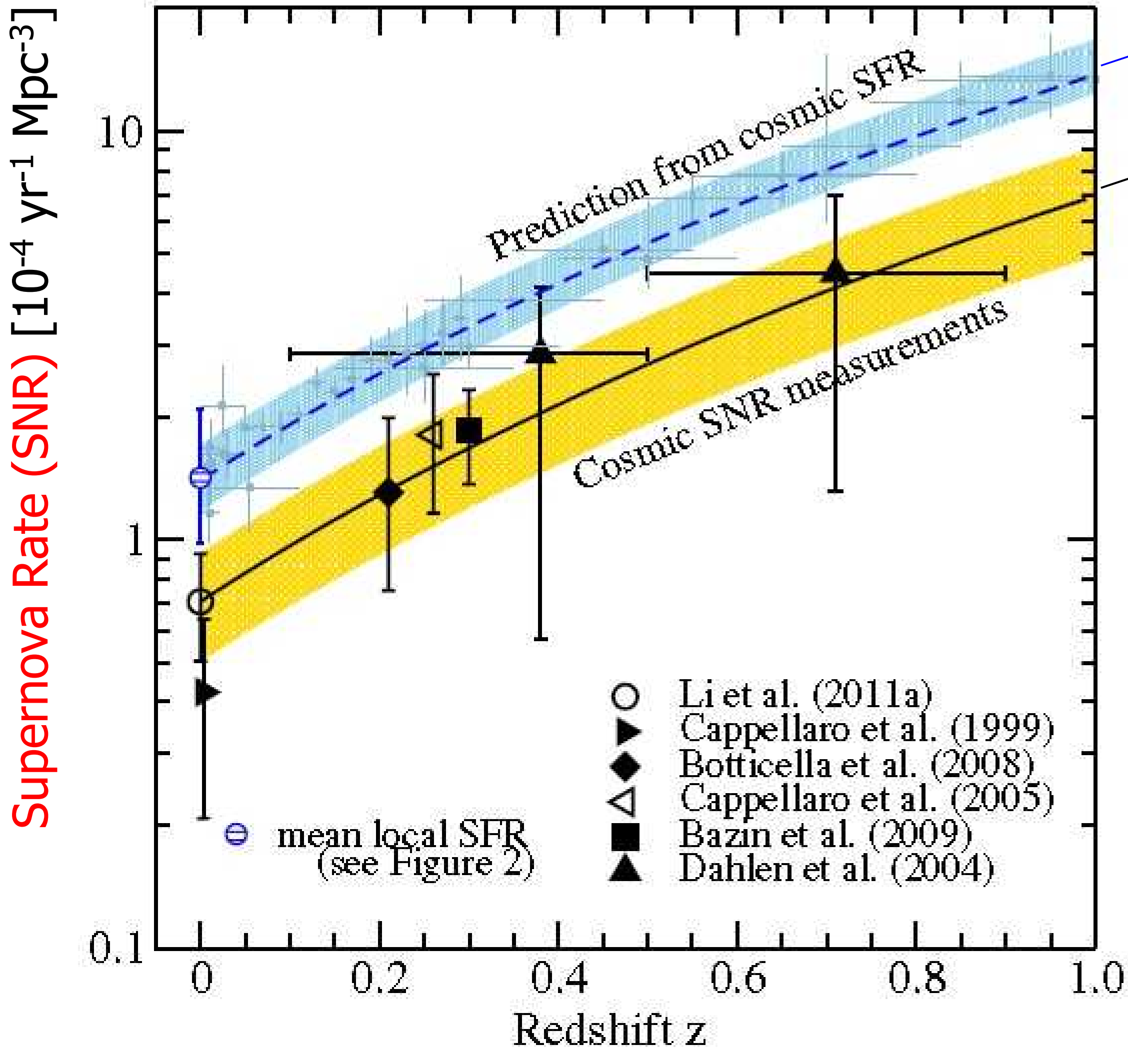
~ Diffuse Supernova Neutrino Background (DSNB, or flux DSNνF)



https://slidesplayer.net/slide/14162575/

Neutrinos from Relic SNe

Physics motivation : supernova rate (SNR) problem



Theoretical estimation
from cosmic Star Formation Rate

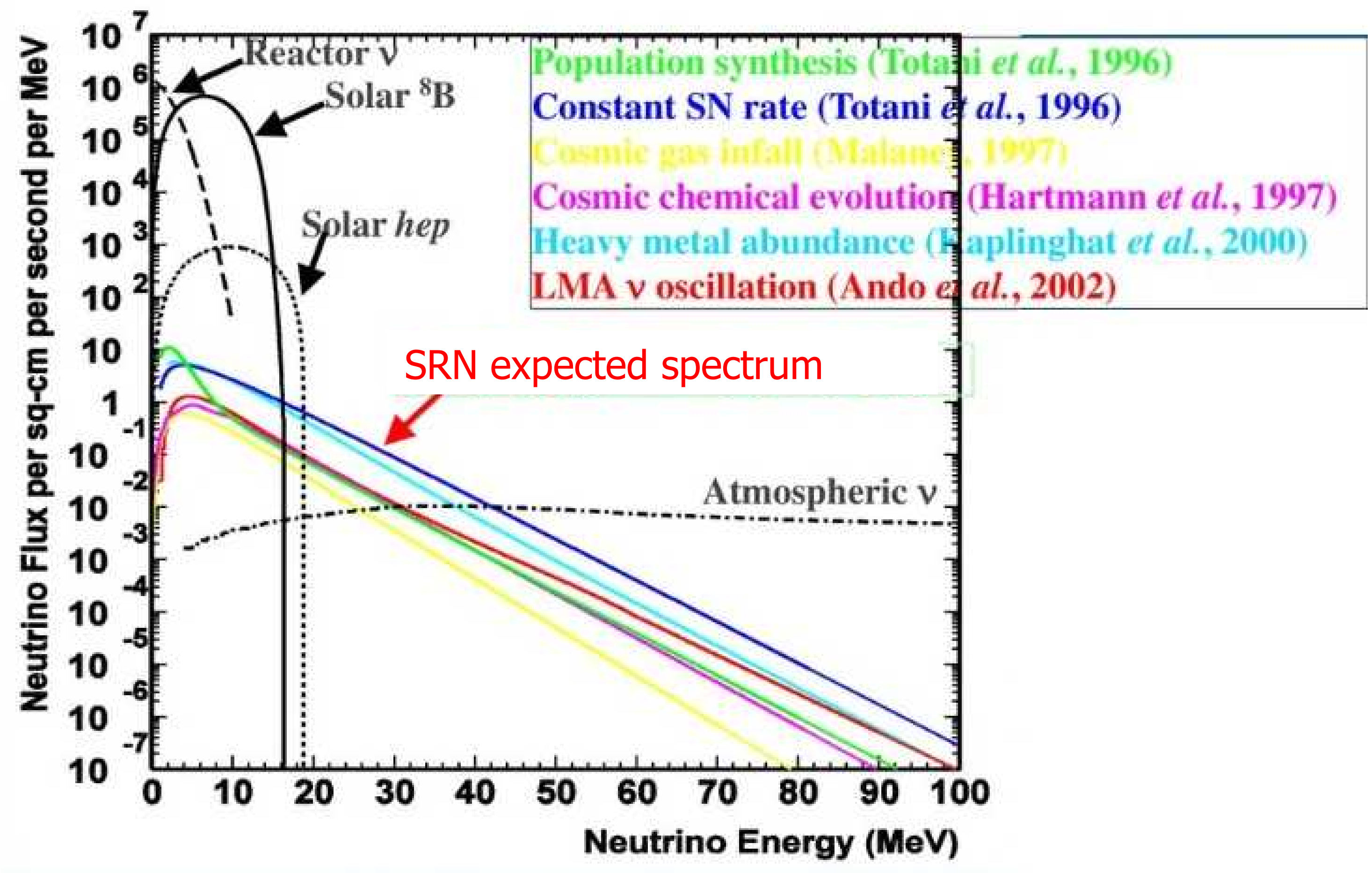
Observational SN Rate

Horiuchi+11 ApJ 738 154

Neutrinos from Relic SNe

- Supernova Relic Neutrino (SRN) : Neutrinos emitted from past SNe since the beginning of the Universe – esp. below 20 MeV

→ SRN energy spectrum measurement, history of SN bursts

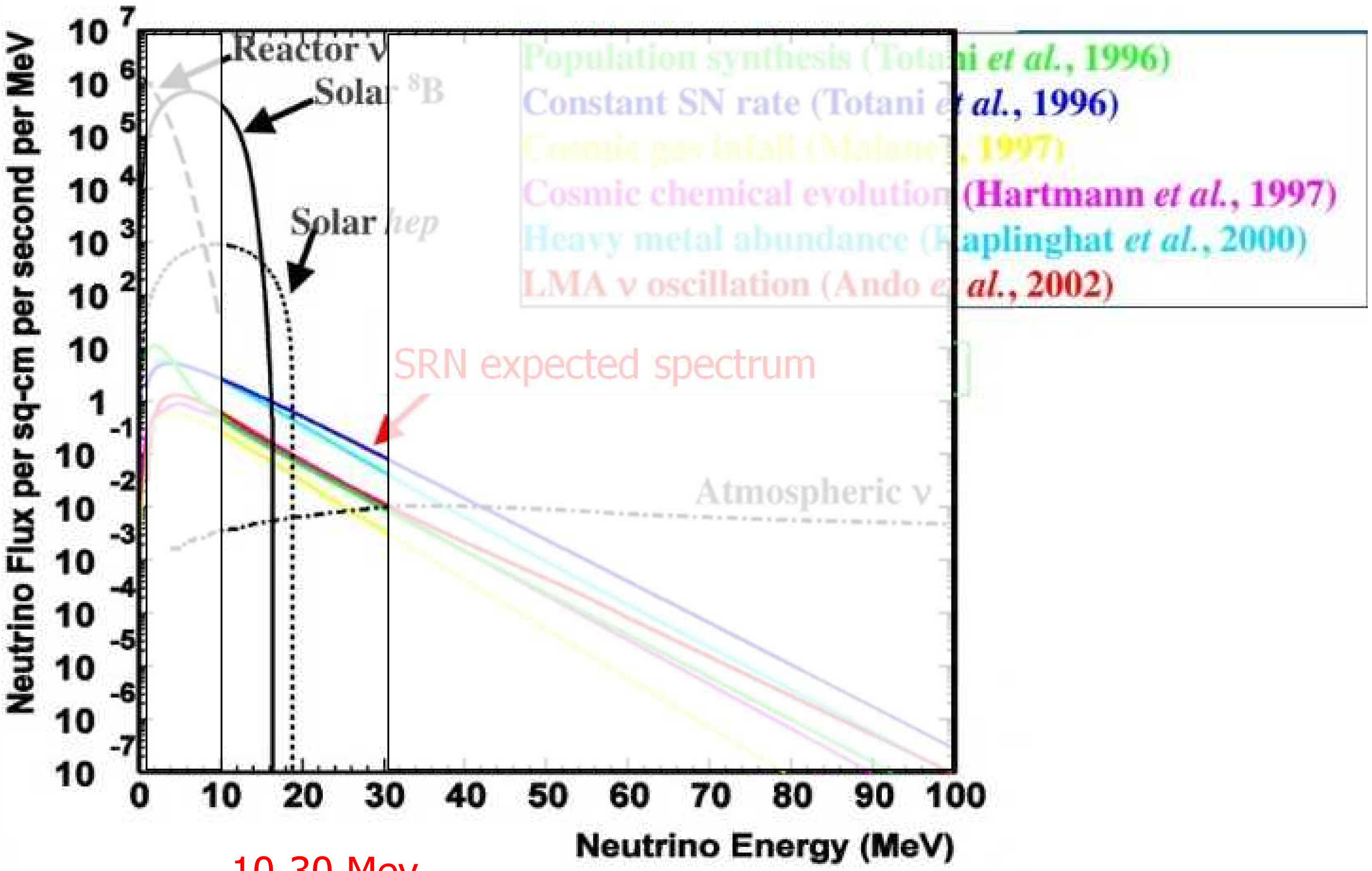


https://slidesplayer.net/slide/14162575/

Neutrinos from Relic SNe

- Supernova Relic Neutrino (SRN) : Neutrinos emitted from past SNe since the beginning of the Universe – esp. below 20 MeV

→ SRN energy spectrum measurement, history of SN bursts



~10-30 Mev

Neutrinos from Relic SNe

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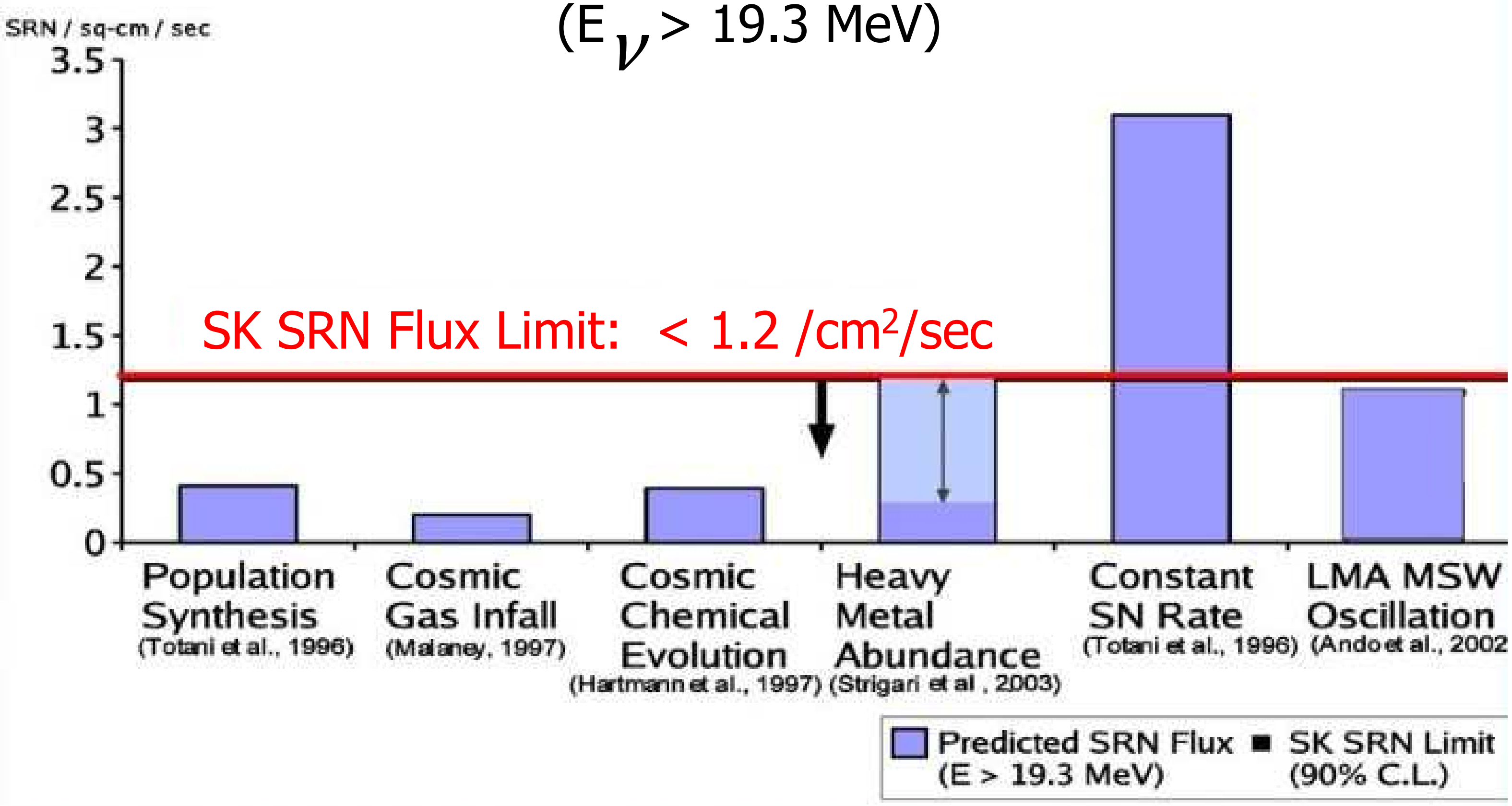
  → SRN energy spectrum measurement, history of SN bursts

SK SRN Flux Limits vs. Theoretical Predictions

(E_ν > 19.3 MeV)



SK SRN Flux Limit: < 1.2 /cm^2/sec

Neutrinos from SNe

- Relic SNe
- Failed SNe (fSNe)
- Precursors of SNe (Supergiant Stars)

Neutrinos from Failed SNe (fSNe)

- Massive stars : $M_i \geq 8\ M_\odot$
- Evolution – Fe core + envelope
- explosion → core-collapse supernova
- Failed explosion → black hole

Neutrinos from Failed SNe (fSNe)

Confirmed black holes and mass determinations

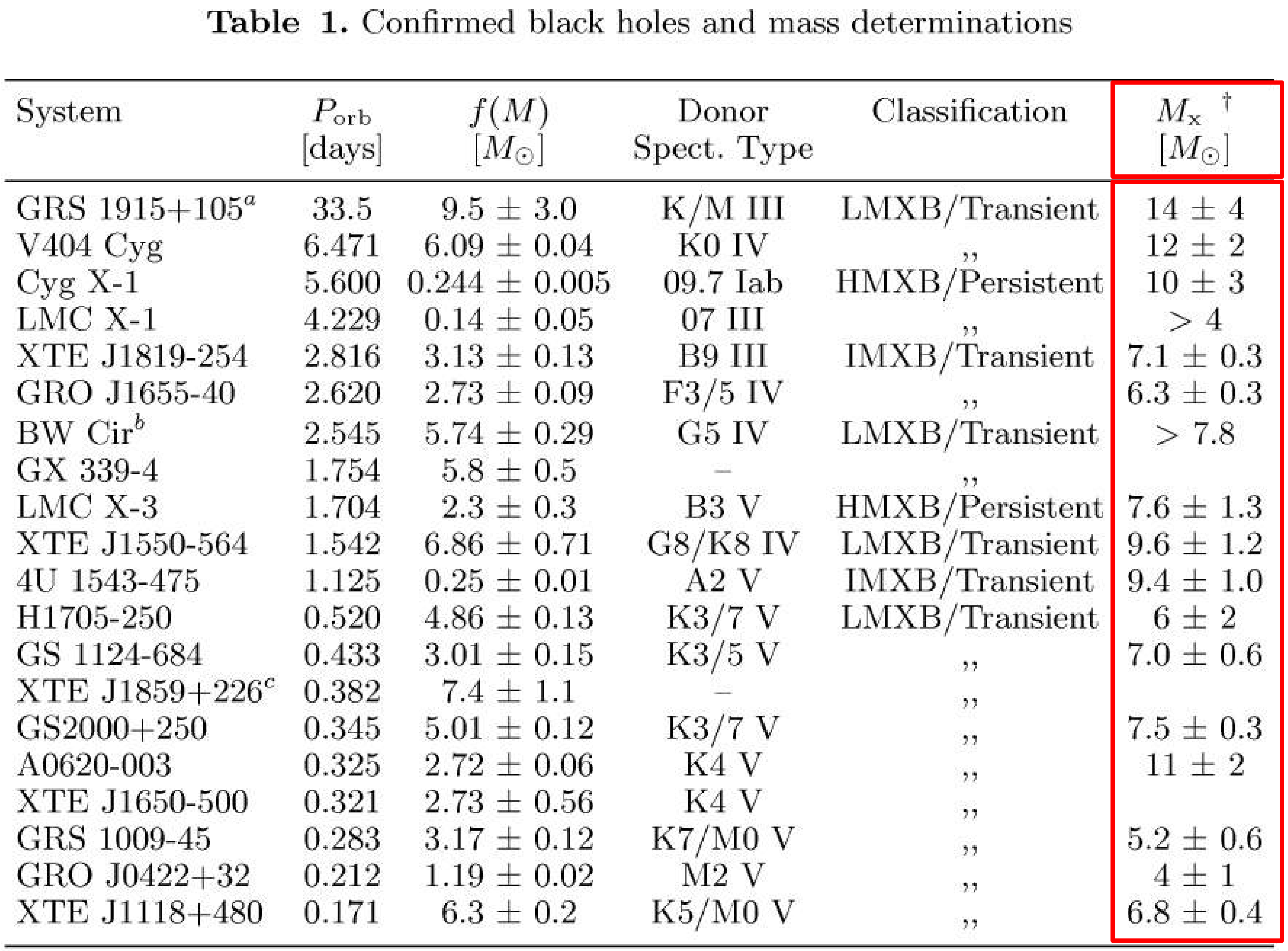


Table 1. Confirmed black holes and mass determinations

System	$P_{\rm orb}$ [days]	$f(M)$ [$M_\odot$]	Donor Spect. Type	Classification	$M_{\rm x}$ † [$M_\odot$]
GRS 1915+105[a]	33.5	9.5 ± 3.0	K/M III	LMXB/Transient	14 ± 4
V404 Cyg	6.471	6.09 ± 0.04	K0 IV	,,	12 ± 2
Cyg X-1	5.600	0.244 ± 0.005	09.7 Iab	HMXB/Persistent	10 ± 3
LMC X-1	4.229	0.14 ± 0.05	07 III	,,	> 4
XTE J1819-254	2.816	3.13 ± 0.13	B9 III	IMXB/Transient	7.1 ± 0.3
GRO J1655-40	2.620	2.73 ± 0.09	F3/5 IV	,,	6.3 ± 0.3
BW Cir[b]	2.545	5.74 ± 0.29	G5 IV	LMXB/Transient	> 7.8
GX 339-4	1.754	5.8 ± 0.5	–	,,	
LMC X-3	1.704	2.3 ± 0.3	B3 V	HMXB/Persistent	7.6 ± 1.3
XTE J1550-564	1.542	6.86 ± 0.71	G8/K8 IV	LMXB/Transient	9.6 ± 1.2
4U 1543-475	1.125	0.25 ± 0.01	A2 V	IMXB/Transient	9.4 ± 1.0
H1705-250	0.520	4.86 ± 0.13	K3/7 V	LMXB/Transient	6 ± 2
GS 1124-684	0.433	3.01 ± 0.15	K3/5 V	,,	7.0 ± 0.6
XTE J1859+226[c]	0.382	7.4 ± 1.1	–	,,	
GS2000+250	0.345	5.01 ± 0.12	K3/7 V	,,	7.5 ± 0.3
A0620-003	0.325	2.72 ± 0.06	K4 V	,,	11 ± 2
XTE J1650-500	0.321	2.73 ± 0.56	K4 V	,,	
GRS 1009-45	0.283	3.17 ± 0.12	K7/M0 V	,,	5.2 ± 0.6
GRO J0422+32	0.212	1.19 ± 0.02	M2 V	,,	4 ± 1
XTE J1118+480	0.171	6.3 ± 0.2	K5/M0 V	,,	6.8 ± 0.4

Casares 2007 IAU Symp. 238, p. 3

Neutrinos from Failed SNe (fSNe)

Compact objects mass distributions

NS (M≈1.4 $M_\odot$)

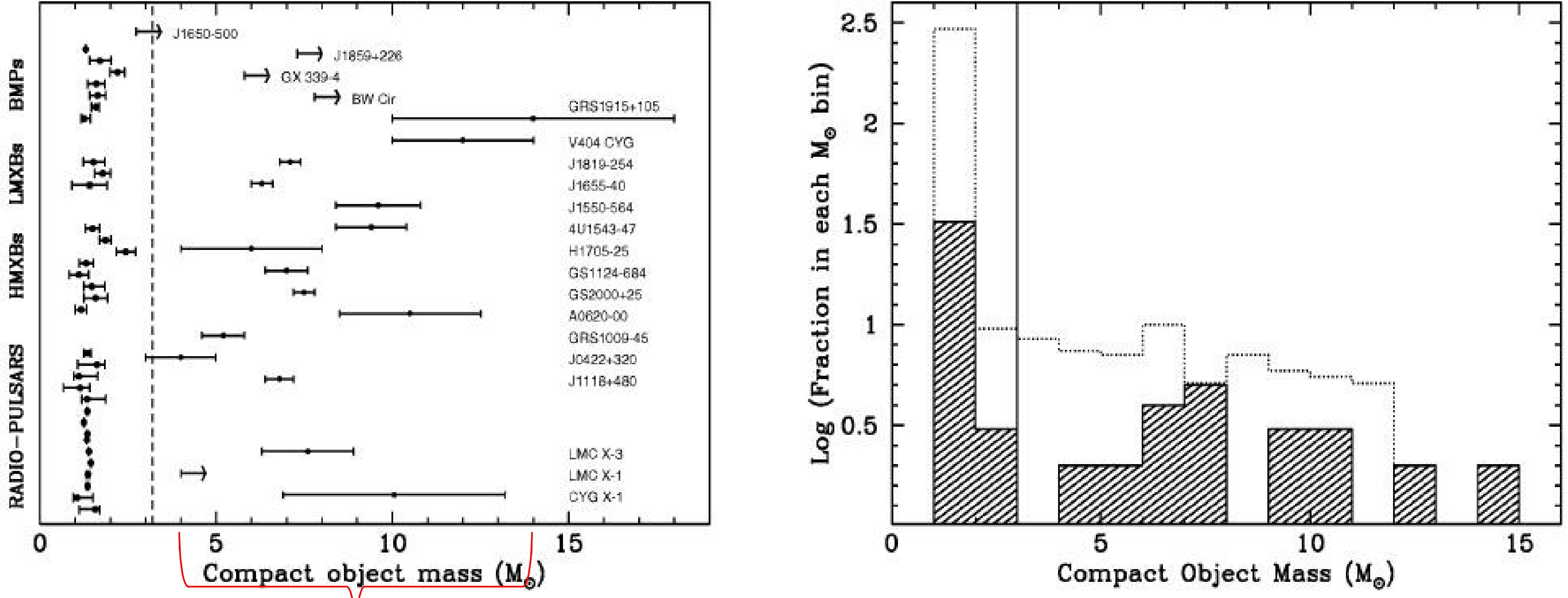


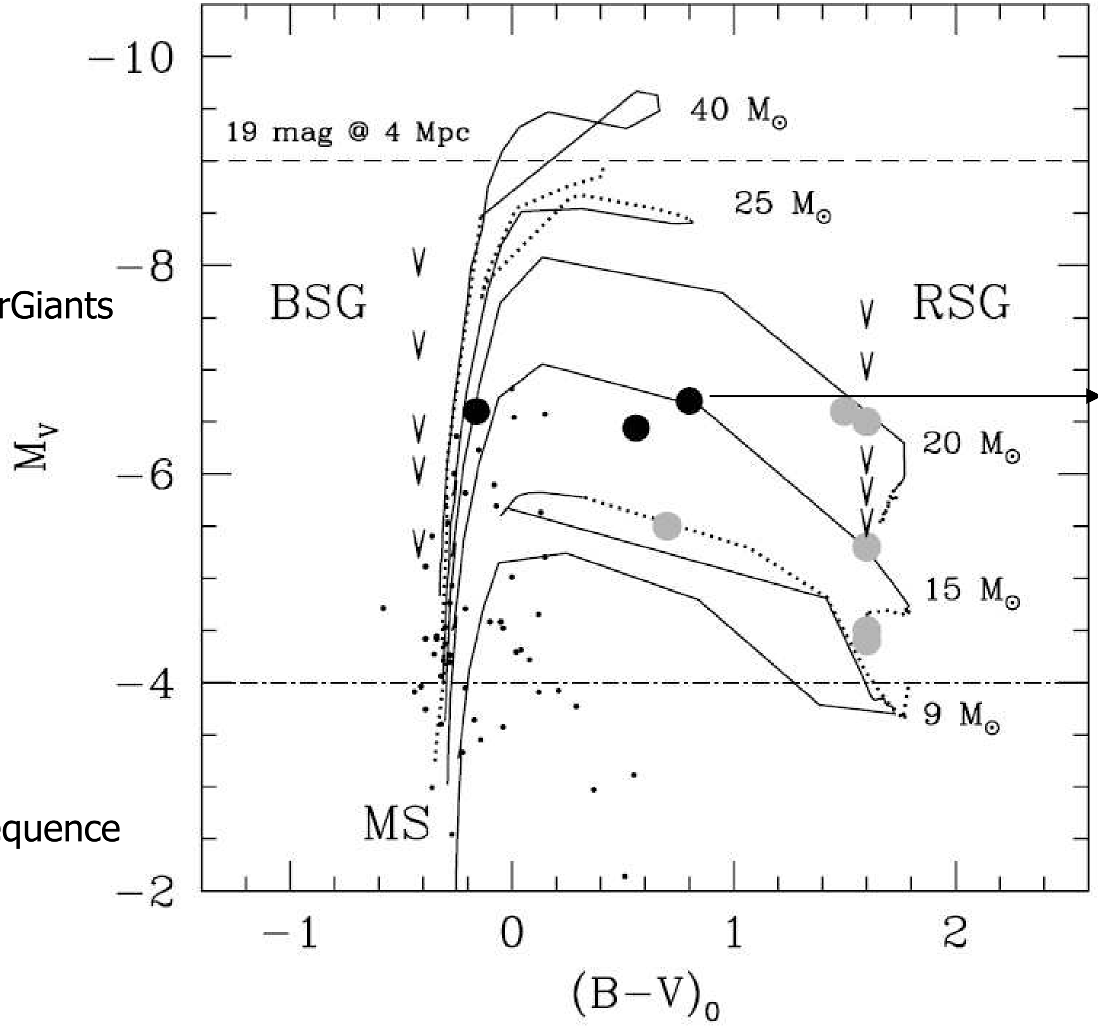
Figure 4. Left: Mass distribution of compact objects in X-ray binaries. Arrows indicate lower limits to BH masses. Right: observed mass distribution of compact objects in X-ray binaries (shaded histogram), compared to the theoretical distribution computed in Fryer & Kalogera (2001) for the "Case C + Winds" scenario (dotted line). Mass-loss rates by Woosley, Langer & Weaver (1995) were used in the computations. The model distribution has been re-scaled for clarity.

$4 \leq M \leq 14\ M_\odot$

Casares 2007 IAU Symp. 238, p. 3

Neutrinos from Failed SNe (fSNe)

Color-magnitude diagram (~HR diagram) of massive stars + evolutionary tracks



Typical depth of a SN survey

Blue SuperGiants

Red SuperGiants

Progenitors in pre-explosion images : 1987A, 2004et, 1993J

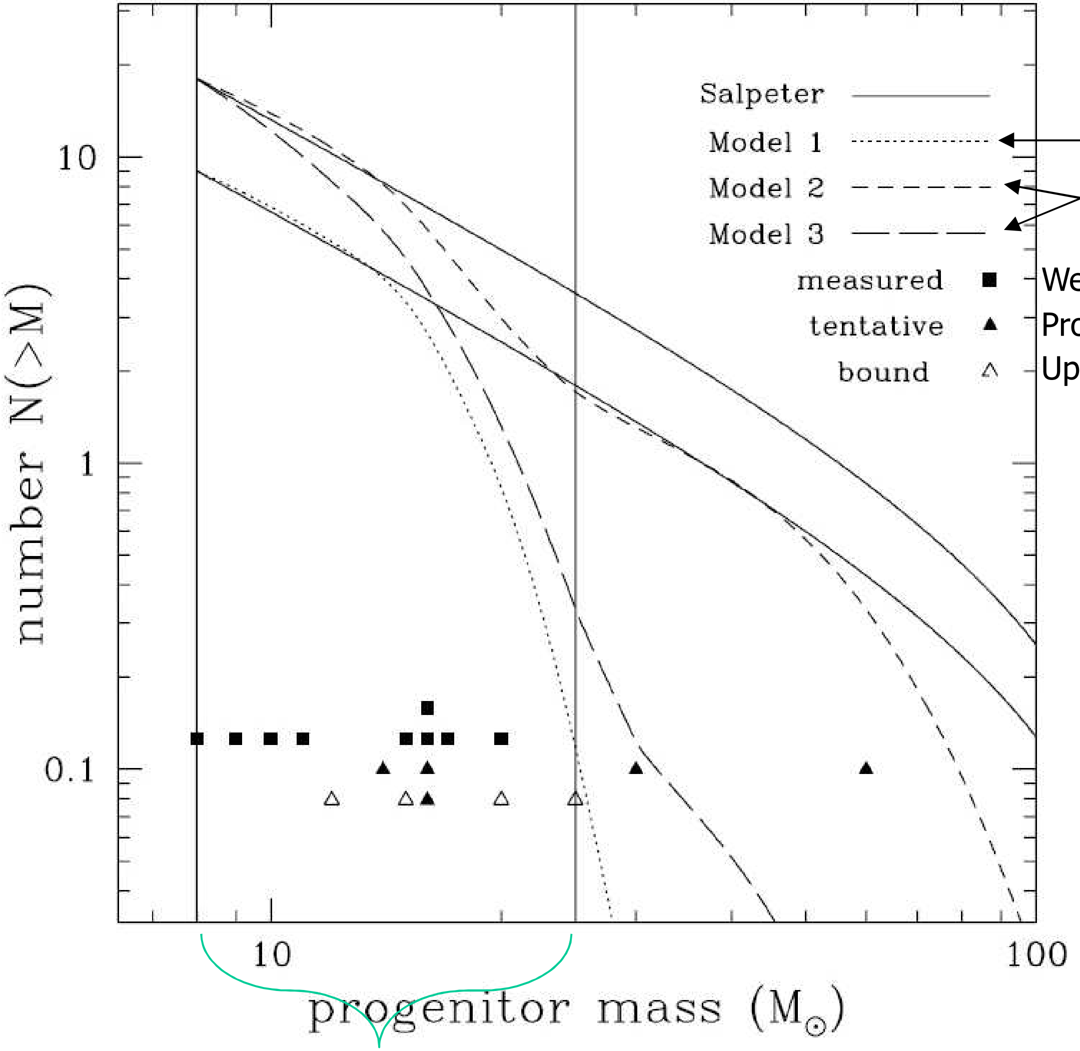
Depth required for a survey for failed SNe

Main Sequence

Kochanek+08 ApJ 684 1336

Neutrinos from Failed SNe (fSNe)

Supernova progenitor mass distributions N(>M)



■ N=9

All 18 Treat △as measurements
Treat △as upper bounds

Well-estimated

Probable

Upper-bounds on the mass from Li+07 (ApJ 661 1013)

SN mass range
$8 \leq M \leq 25\ M_\odot$

Deficit of high-mass progenitors!

$M \geq 25\ M_\odot$,

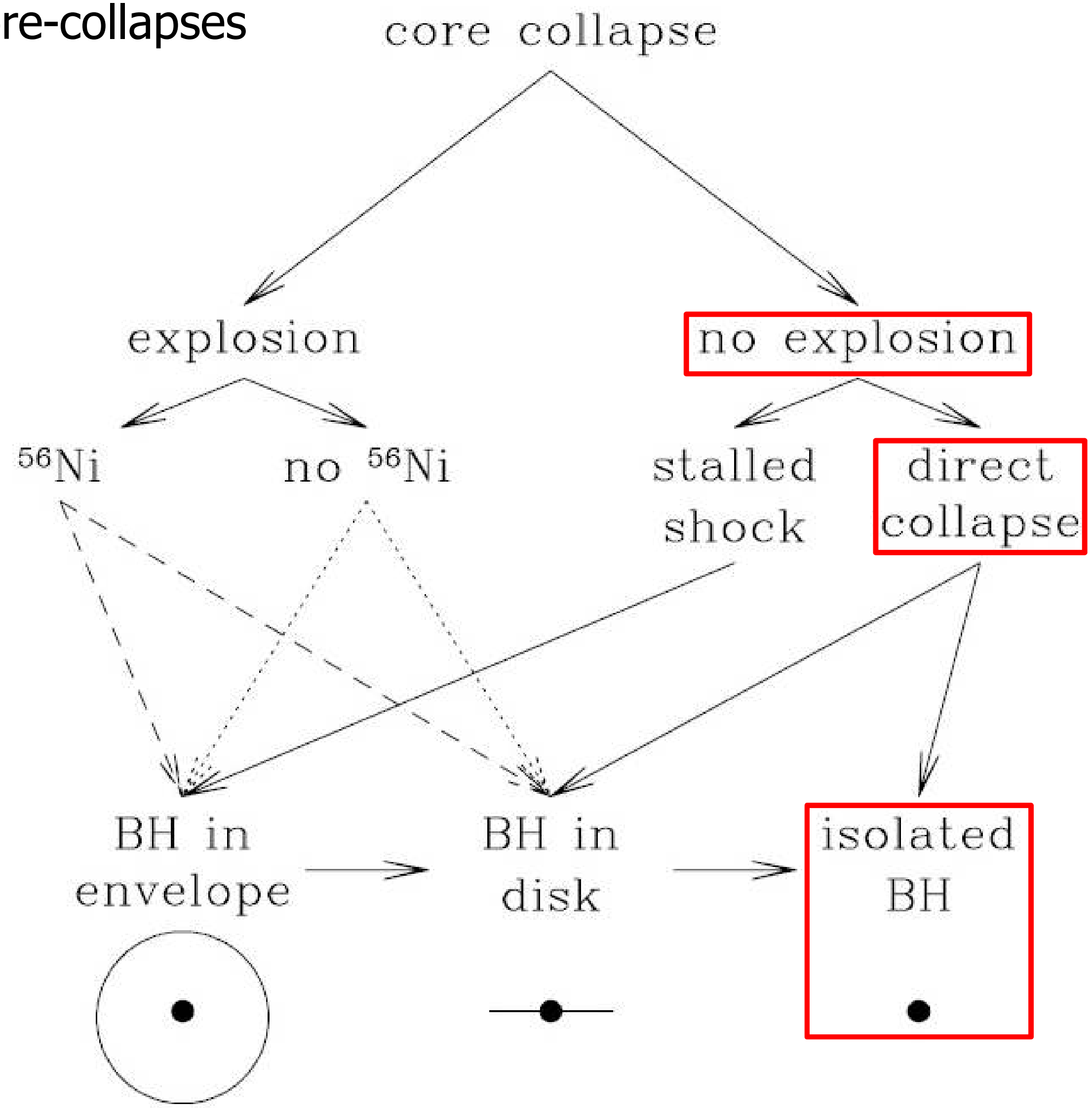
Expect : $\frac{1.8}{9} = \frac{3.6}{18} = 0.2$

Data : $\frac{0.5}{9} = 0.05$ or $\frac{2}{18} = 0.11$

Kochanek+08 ApJ 684 1336

Neutrinos from Failed SNe (fSNe)

black hole formation from core-collapses



Kochanek+08 ApJ 684 1336

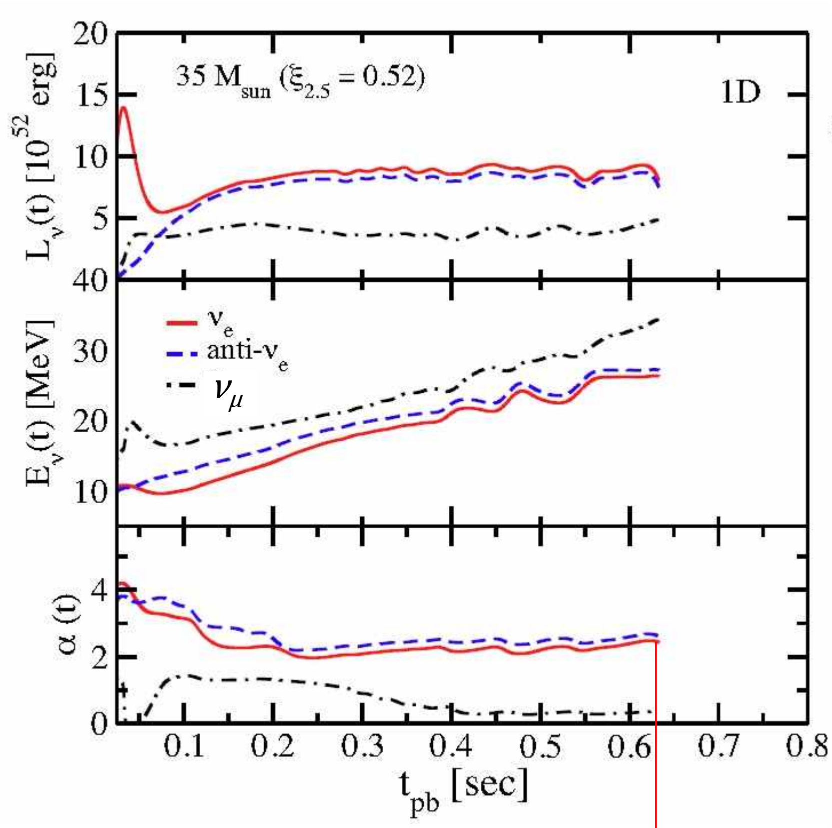
Neutrinos from Failed SNe (fSNe)

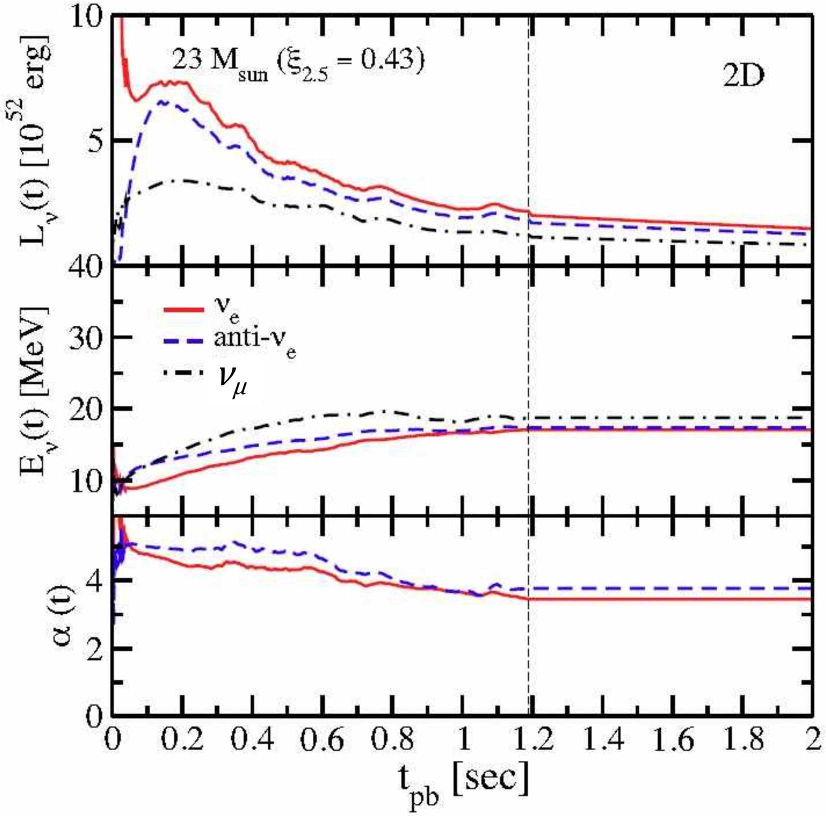
Horiuchi+18 MNRAS 475 1363

Neutrino luminosity

Mean energy

Shape parameter





Collapse of a 35 $M_\odot$ star
1-Dim

Collapse of a 23 $M_\odot$ star
2-Dim

Black hole

Neutron star

Neutrinos from Failed SNe (fSNe)

- Massive stars : $M_i \geq 8\ M_\odot$
- Evolution – Fe core + envelope
- explosion → core-collapse supernova → neutron star
- Failed explosion → black hole
- Neutrino detection from this direct BH formation → observational evidence of a BH formation

- Failed explosion contribution : important ingredient for precise modeling of Supernova Relic Neutrino (SRN) (Diffuse Supernova Neutrino Background, DSNB) (Keehn & Lunardini 2012)

- Fraction of massive stars undergoing collapse to BHs ≥ 20% (Horiuchi+18)
- A search for the disappearances of massive stars (Kochanek+08) → failed explosion fraction ~ 4 – 43% (Horiuchi+18, Adams+17)

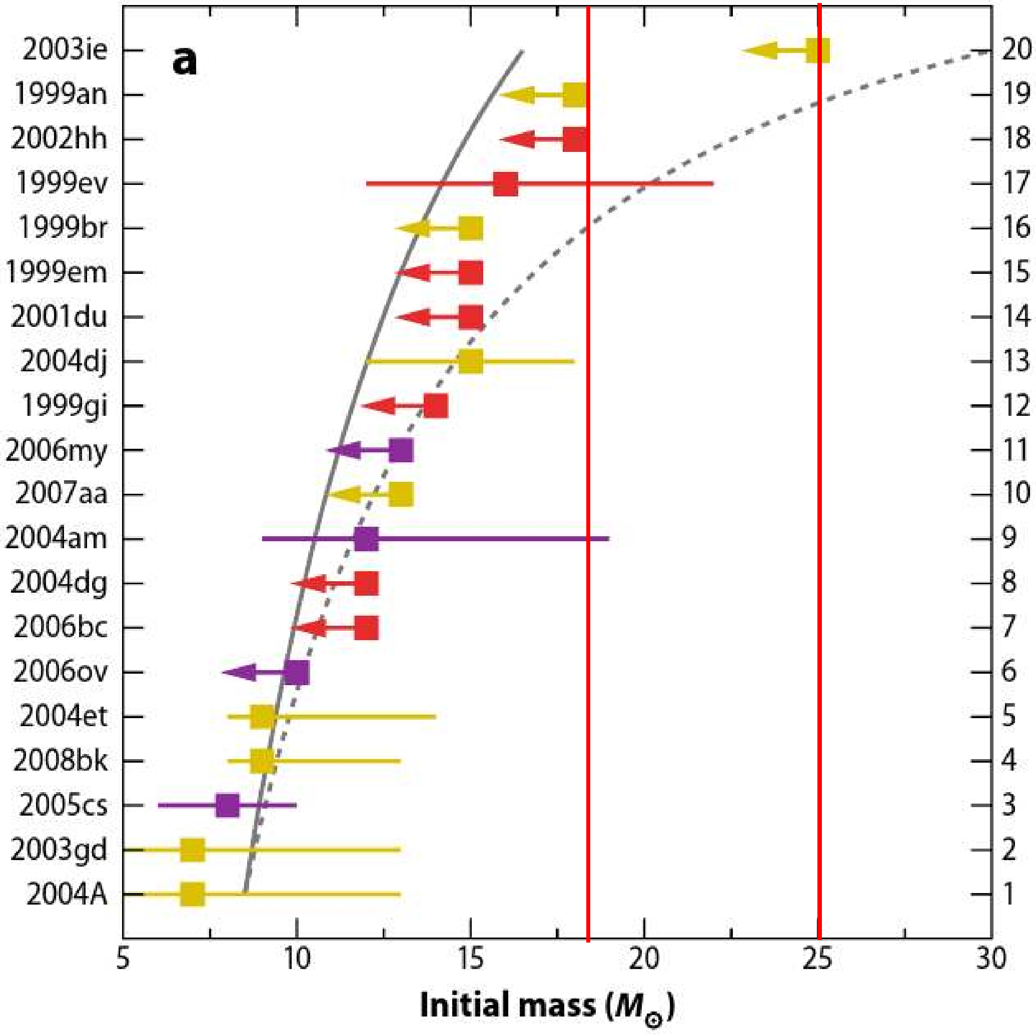
→ valuable constraint on the SRN

Neutrinos from Supernovae (SNe)

- Relic SNe
- Failed SNe
- Precursors of SNe (Supergiant Stars)

Neutrinos from Supergiant Stars

- Red supergiant (RSG) problem : RSGs from CC SNe observations → progenitor initial masses ≤ 17 $M_\odot$
- Theory predicts the upper limit ~ 25 $M_\odot$ (Smartt 2009, 2015)

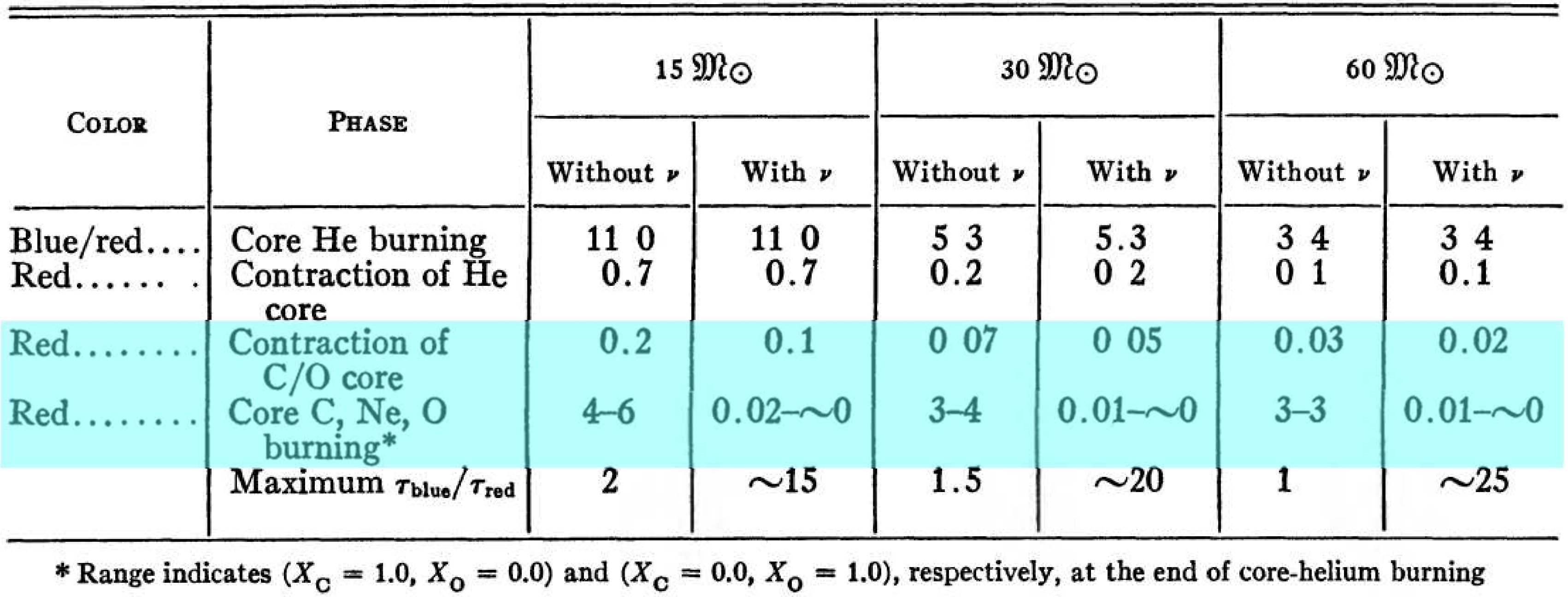


- Possible that RSGs with M ≥ 17 $M_\odot$ end as failed SNe (Hidaka+16)

Smartt 09 ARAA 47, 63

Neutrinos from Supergiant Stars

Theoretical Evolutionary Timetable for Massive Stars
[10^5 years]



COLOR	PHASE	$15\ \mathfrak{M}_\odot$		$30\ \mathfrak{M}_\odot$		$60\ \mathfrak{M}_\odot$	
		Without ν	With ν	Without ν	With ν	Without ν	With ν
Blue/red....	Core He burning	11 0	11 0	5 3	5.3	3 4	3 4
Red...... .	Contraction of He core	0.7	0.7	0.2	0 2	0 1	0.1
Red........	Contraction of C/O core	0.2	0.1	0 07	0 05	0.03	0.02
Red........	Core C, Ne, O burning*	4–6	0.02–~0	3–4	0.01–~0	3–3	0.01–~0
	Maximum $\tau_{\mathrm{blue}}/\tau_{\mathrm{red}}$	2	~15	1.5	~20	1	~25

* Range indicates ($X_C = 1.0$, $X_O = 0.0$) and ($X_C = 0.0$, $X_O = 1.0$), respectively, at the end of core-helium burning

- Detection of neutrinos from nearby supergiant stars
- Evolutionary lifetimes of each stage

Stothers 69 ApJ 155 935

Thermonuclear Energy Generation Stages

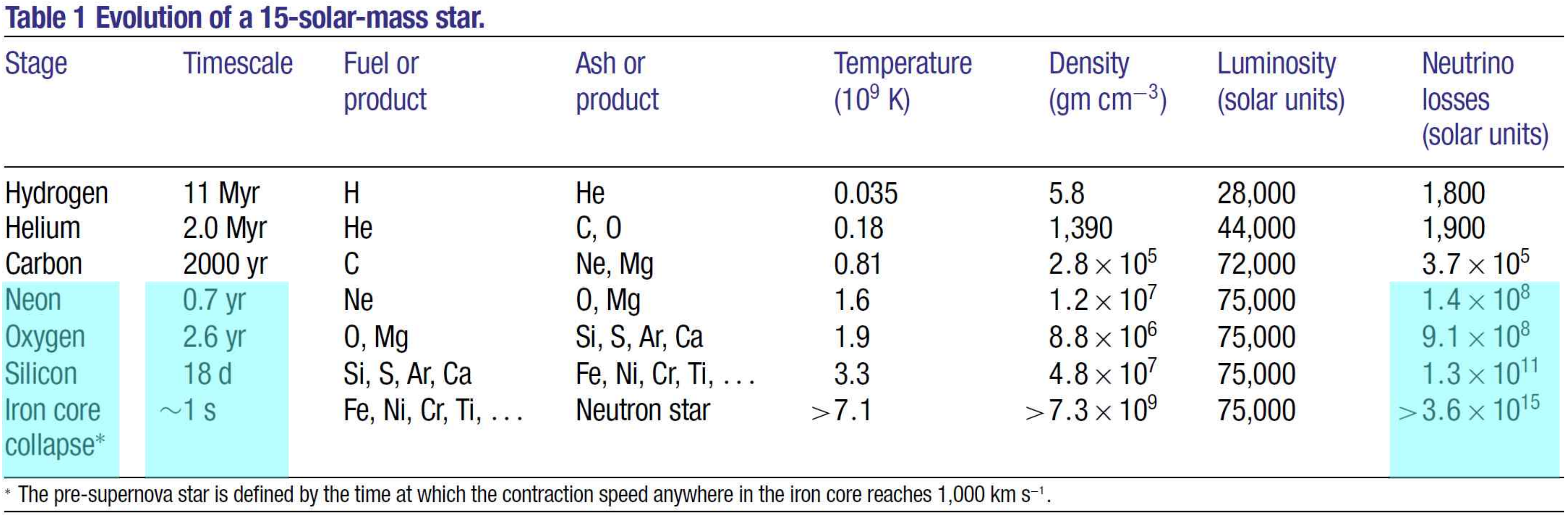


Table 1 Evolution of a 15-solar-mass star.

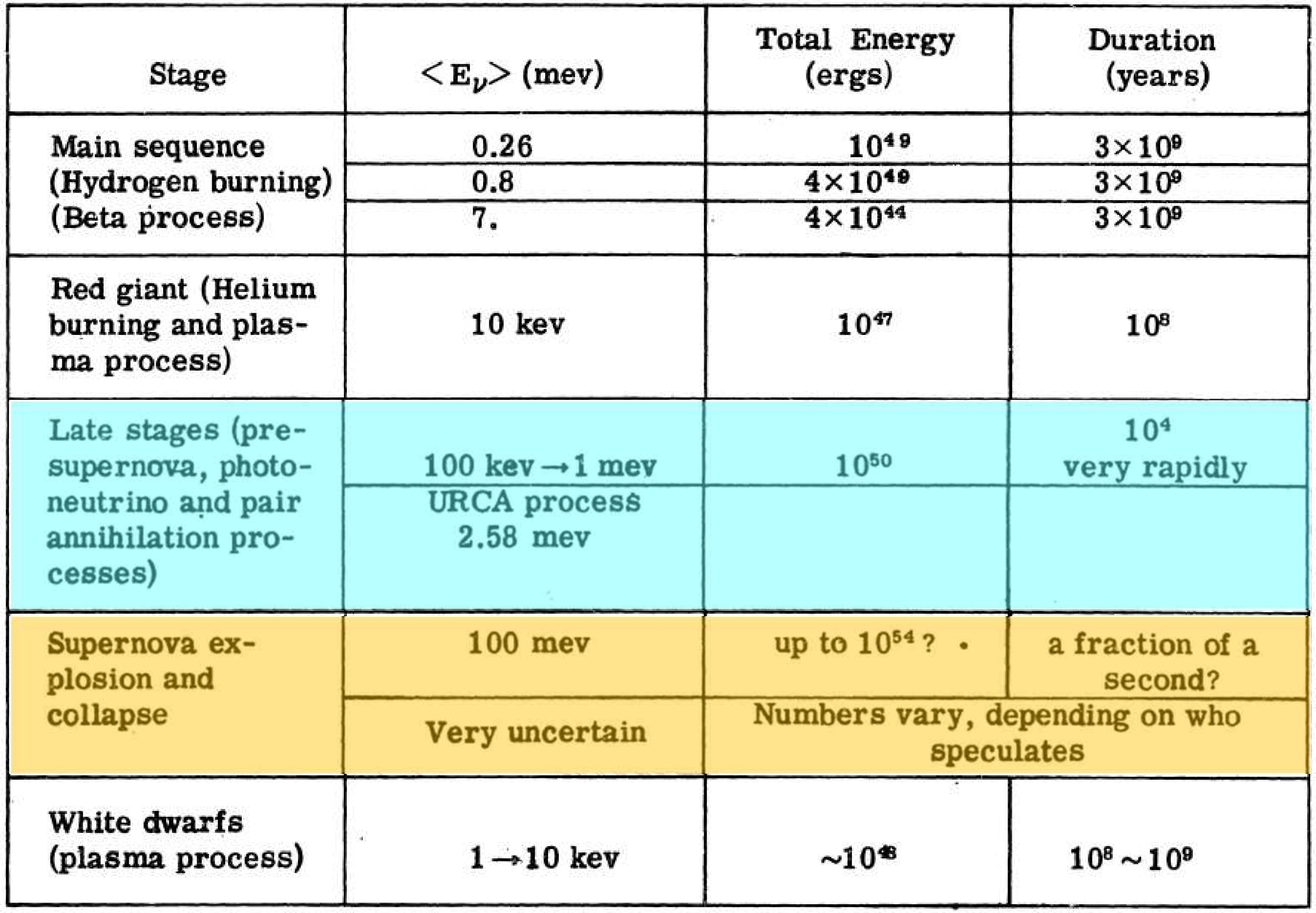
Stage	Timescale	Fuel or product	Ash or product	Temperature (10^9 K)	Density (gm cm^{-3})	Luminosity (solar units)	Neutrino losses (solar units)
Hydrogen	11 Myr	H	He	0.035	5.8	28,000	1,800
Helium	2.0 Myr	He	C, O	0.18	1,390	44,000	1,900
Carbon	2000 yr	C	Ne, Mg	0.81	2.8×10^5	72,000	3.7×10^5
Neon	0.7 yr	Ne	O, Mg	1.6	1.2×10^7	75,000	1.4×10^8
Oxygen	2.6 yr	O, Mg	Si, S, Ar, Ca	1.9	8.8×10^6	75,000	9.1×10^8
Silicon	18 d	Si, S, Ar, Ca	Fe, Ni, Cr, Ti, . . .	3.3	4.8×10^7	75,000	1.3×10^{11}
Iron core collapse*	~1 s	Fe, Ni, Cr, Ti, . . .	Neutron star	>7.1	$>7.3 \times 10^9$	75,000	$>3.6 \times 10^{15}$

* The pre-supernova star is defined by the time at which the contraction speed anywhere in the iron core reaches 1,000 km s^{-1}.

Woosley & Janka 05 Nature Physics 1 147

Neutrinos from Supergiant Stars

Stellar neutrino emission



Stage	$<E_\nu>$ (mev)	Total Energy (ergs)	Duration (years)
Main sequence (Hydrogen burning) (Beta process)	0.26	10^{49}	3×10^9
	0.8	4×10^{49}	3×10^9
	7.	4×10^{44}	3×10^9
Red giant (Helium burning and plasma process)	10 kev	10^{47}	10^8
Late stages (pre-supernova, photo-neutrino and pair annihilation processes)	100 kev → 1 mev	10^{50}	10^4 very rapidly
	URCA process 2.58 mev		
Supernova explosion and collapse	100 mev	up to 10^{54} ? •	a fraction of a second?
	Very uncertain	Numbers vary, depending on who speculates	
White dwarfs (plasma process)	1 → 10 kev	$\sim10^{48}$	$10^8\sim10^9$

The average lifetime = 3×10^9 yr,

Total optical energy output = 3×10^{50} erg

Chiu 63 Proc. 8th International Cosmic Ray Conference 8 131

Summary

Neutrino research - Astronomical applications

- Core-collapse supernovae in the Milky Way and Nearby Galaxies (probably in the Local Group) within a few Mpc
  → Win-Win (both for SN science + Neutrino science)
- Detection of failed explosion to form BHs
- Supernova relic neutrinos (SRN) → SRN energy spectrum measurement, history of SN bursts, cosmic star formation rate (SFR)

Thank you.

Sensitivity

Hyper-Kamiokande

arXiv:1805.04163v1

Design Report
(Dated: May 9, 2018)

TABLE I. Expected sensitivities of the Hyper-Kamiokande experiment assuming 1 tank for 10 years.

Physics Target	Sensitivity	Conditions
– Supernova burst ν	52,000–79,000 ν's	@ Galactic center (10 kpc)
	~10 ν's	@ M31 (Andromeda galaxy)
– Supernova relic ν	70 ν's / 10 years	10–30 MeV, 4.2σ non-zero significance