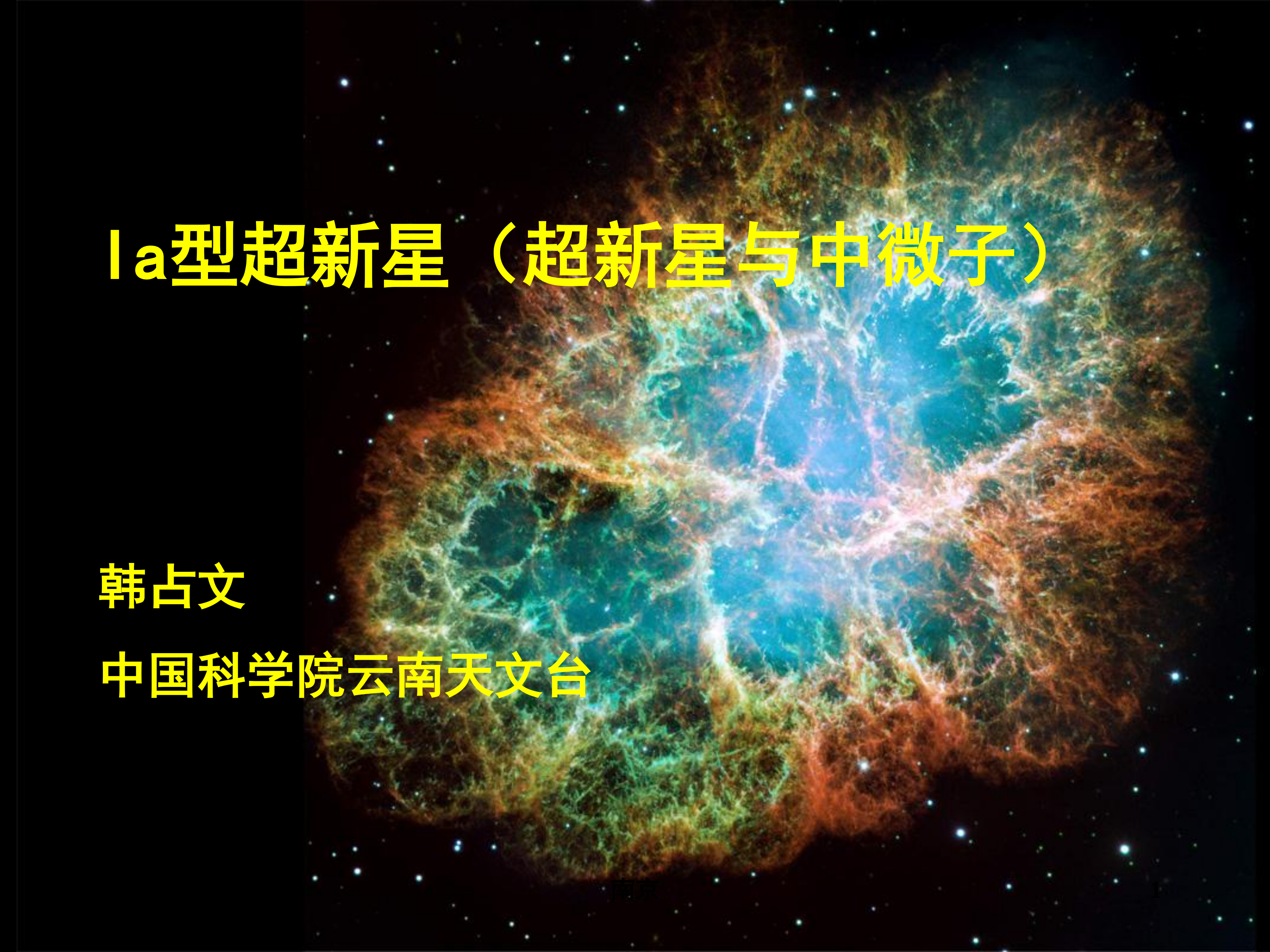


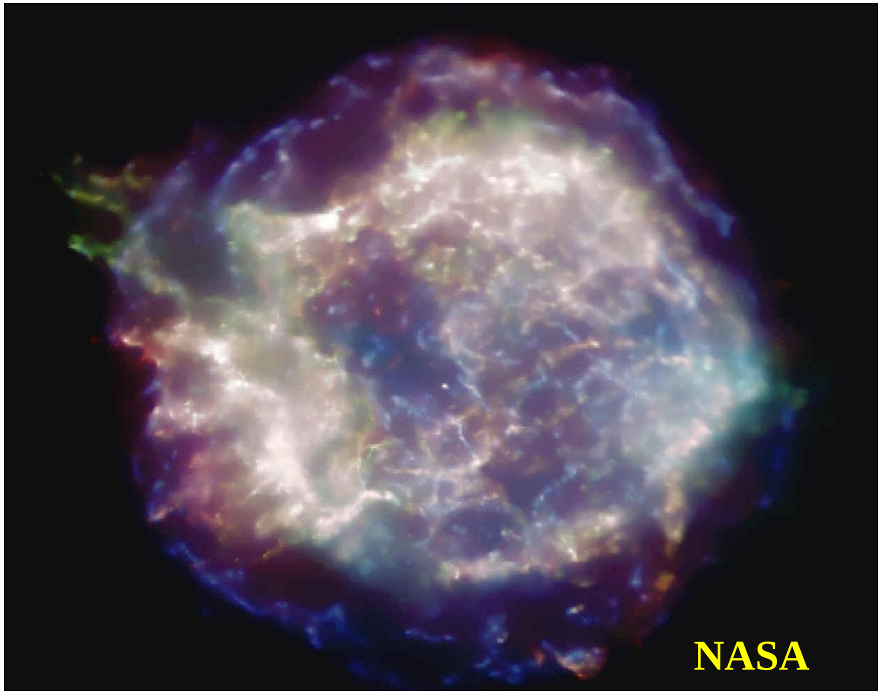
Ia型超新星（超新星与中微子）

韩占文

中国科学院云南天文台

什么是超新星？

- 超新星：恒星死亡时的剧烈爆炸



星ナビ
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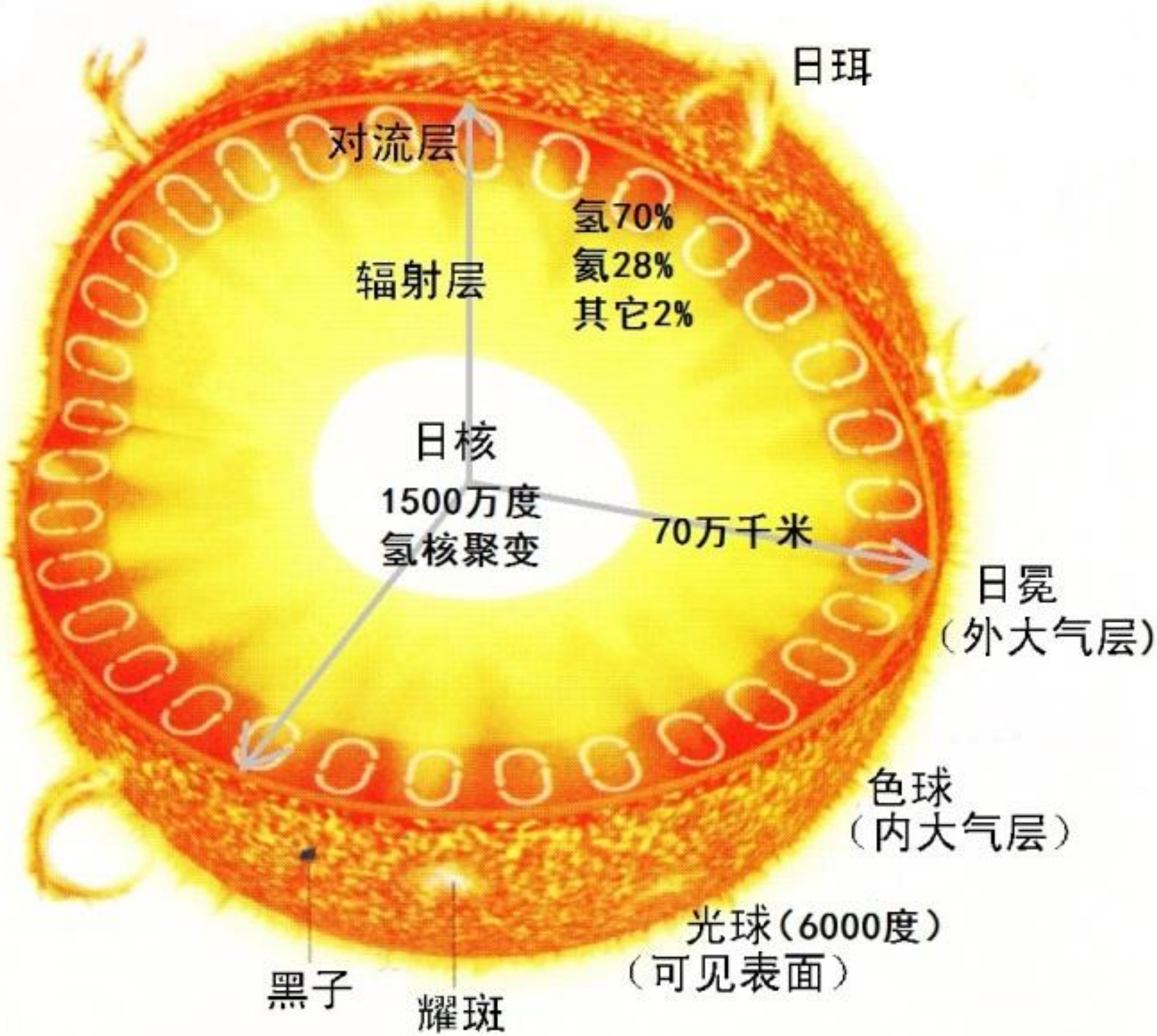
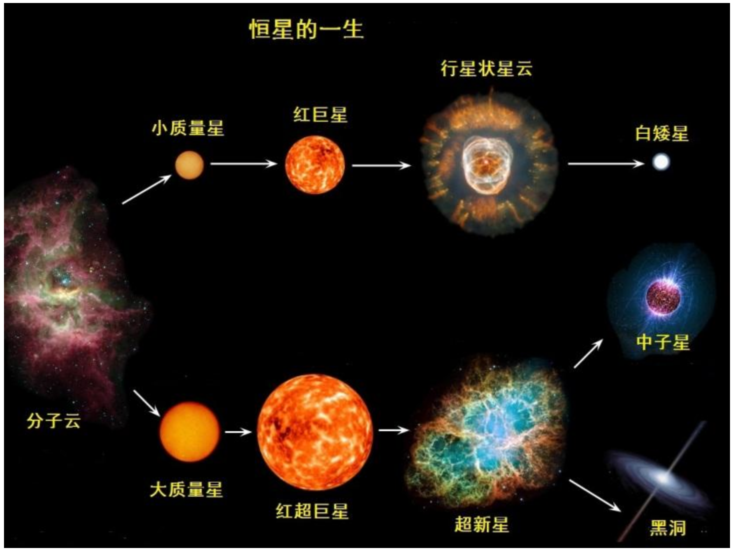
南京

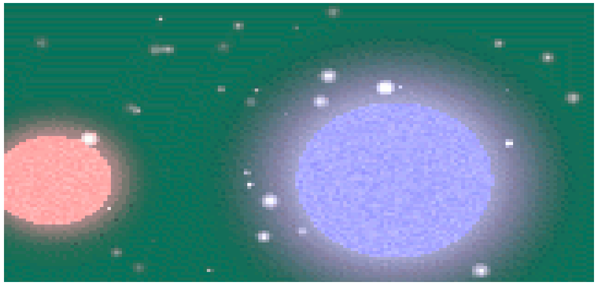

日珥
对流层
氢70%
氦28%
其它2%
辐射层
日核
1500万度
氢核聚变
70万千米
日冕
（外大气层）
色球
（内大气层）
光球（6000度）
（可见表面）
黑子
耀斑

绝大多数（99.99%）发光的天体都是恒星！

恒星结构和演化理论是天体物理的两大理论体系之一。

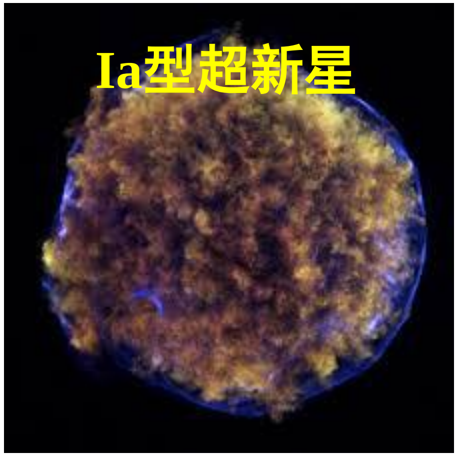


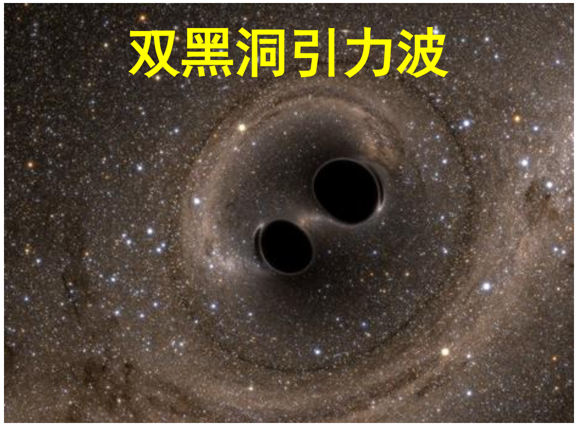
双星约占50%

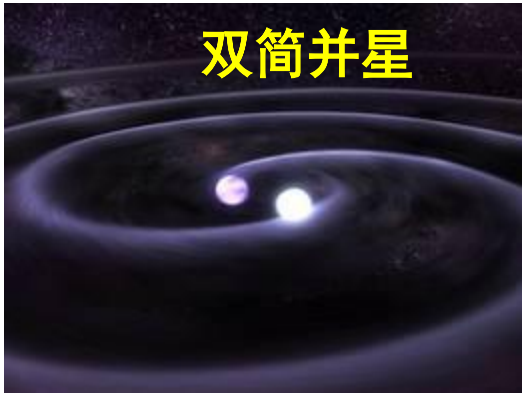


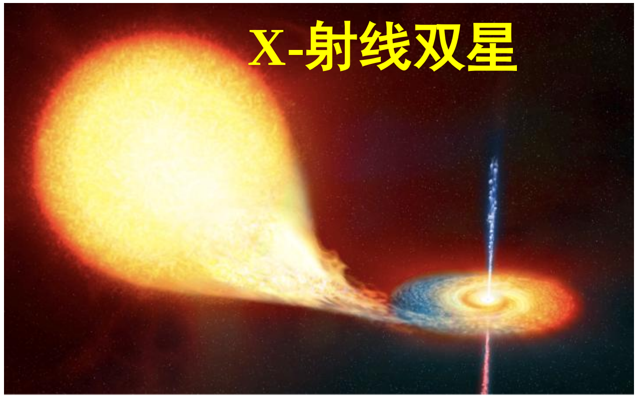
双 星

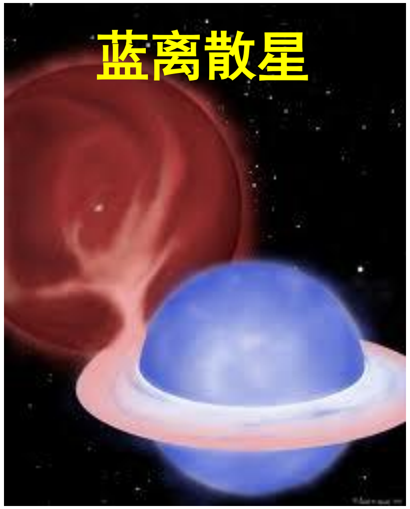
双星演化使恒星世界丰富多彩！



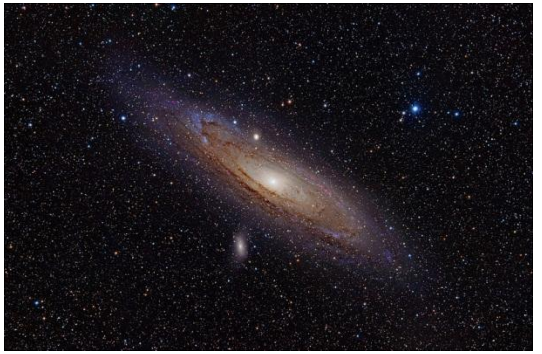








- 商代甲骨卜辞中就记载着公元前14世纪出现于天蝎座α星（我国称做心宿二）附近的一颗新星：“七日己巳夕……新大星并火。”



- 《汉书·天文志》中记有：“元光元年五月，客星见于房。”

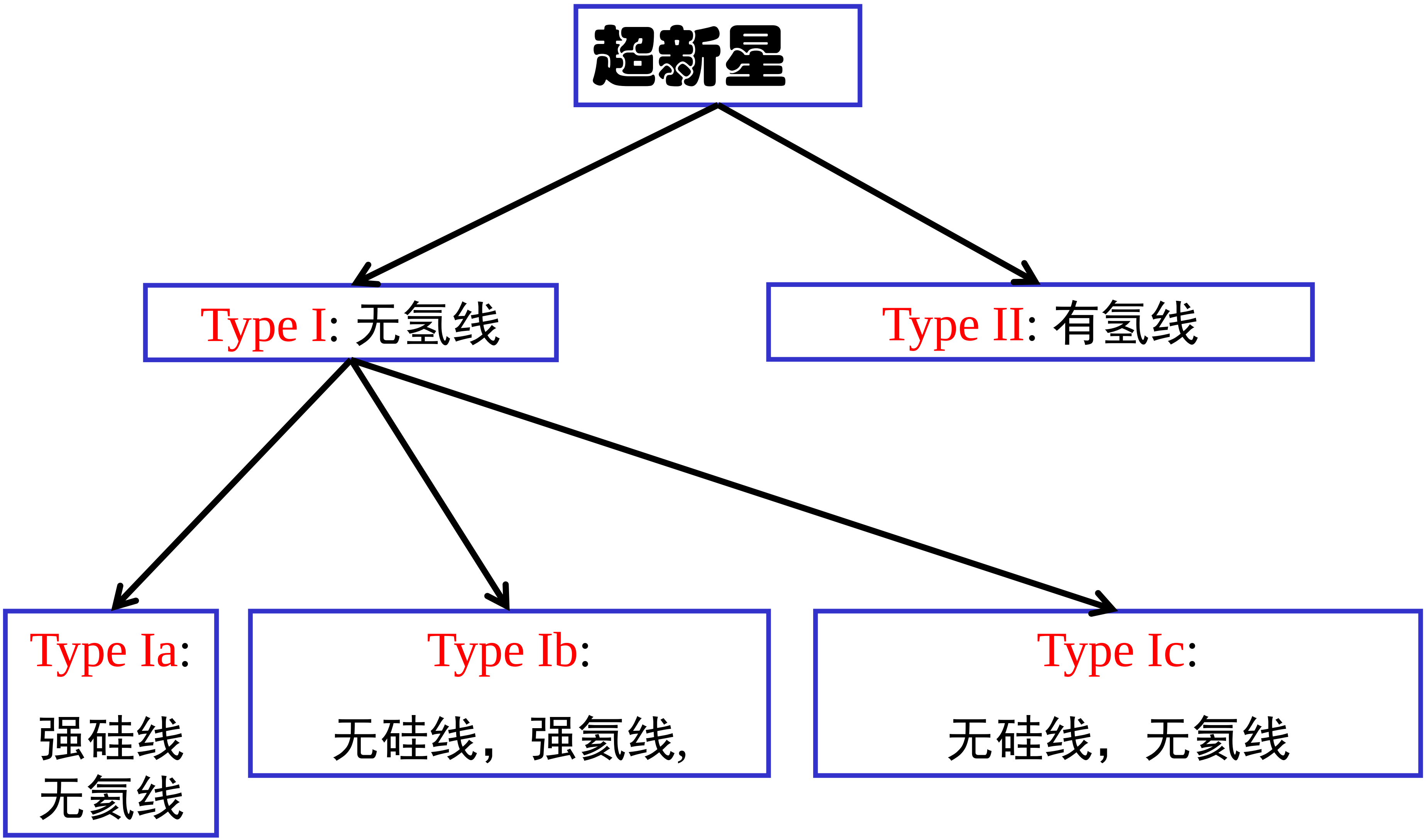
- 具有现代意义的超新星研究始于1885年8月31日 Hartwig在仙女座星云（M31）中发现了一颗新星，其在18个月后消失。

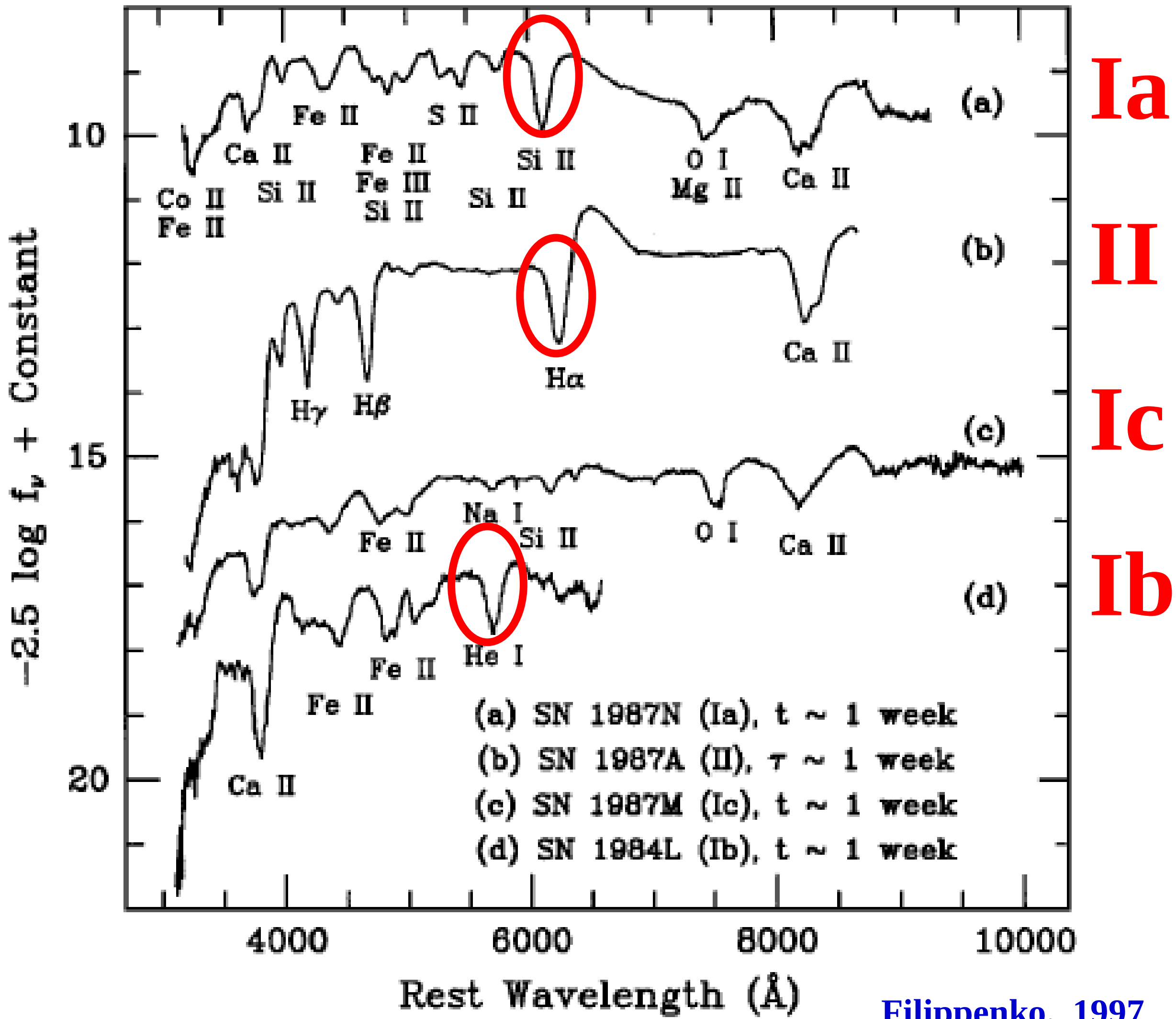
- 1919年Lundmark估计一下M31到地球的距离约70万光年，这就意味着Hartwig的新星比一般的新星亮1000倍。

- 1934年将超新星从经典新星中分出来。

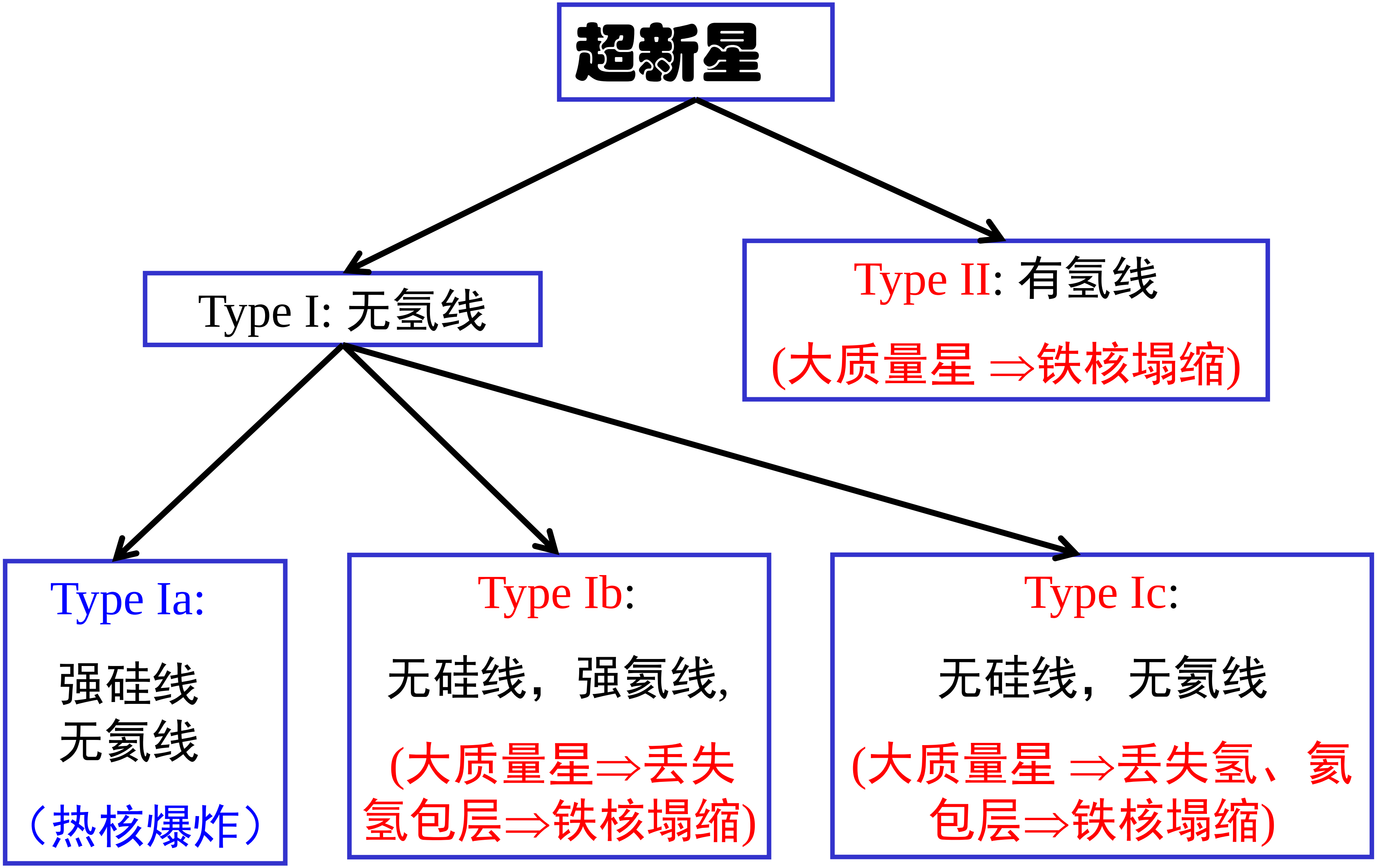
- 1940年超新星有了不同的分类 。

  Minkowski将有类似SN1937c光谱的称为I型超新星，将有类似SN1940c光谱的称为II型超新星。

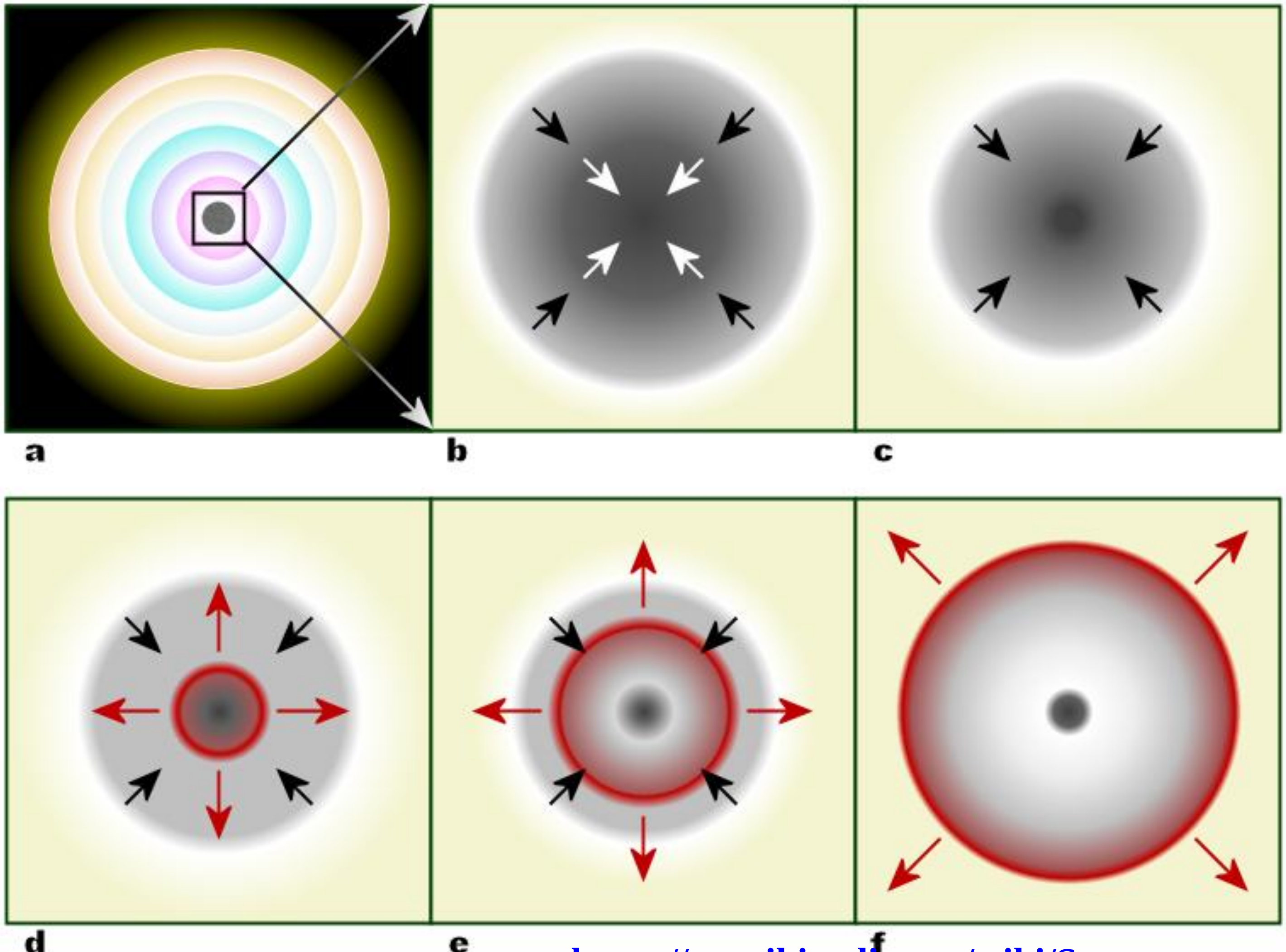

超新星
Type I: 无氢线
Type II: 有氢线
Type Ia:
强硅线
无氦线
Type Ib:
无硅线，强氦线,
Type Ic:
无硅线，无氦线



Filippenko, 1997


超新星
Type I: 无氢线
Type II: 有氢线
(大质量星 ⇒铁核塌缩)
Type Ia:
强硅线
无氦线
（热核爆炸）
Type Ib:
无硅线，强氦线,
(大质量星⇒丢失
氢包层⇒铁核塌缩)
Type Ic:
无硅线，无氦线
(大质量星 ⇒丢失氢、氦
包层⇒铁核塌缩)

核塌缩超新星（II, Ib, Ic）



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

中国超新星

公元1054年超新星爆发：

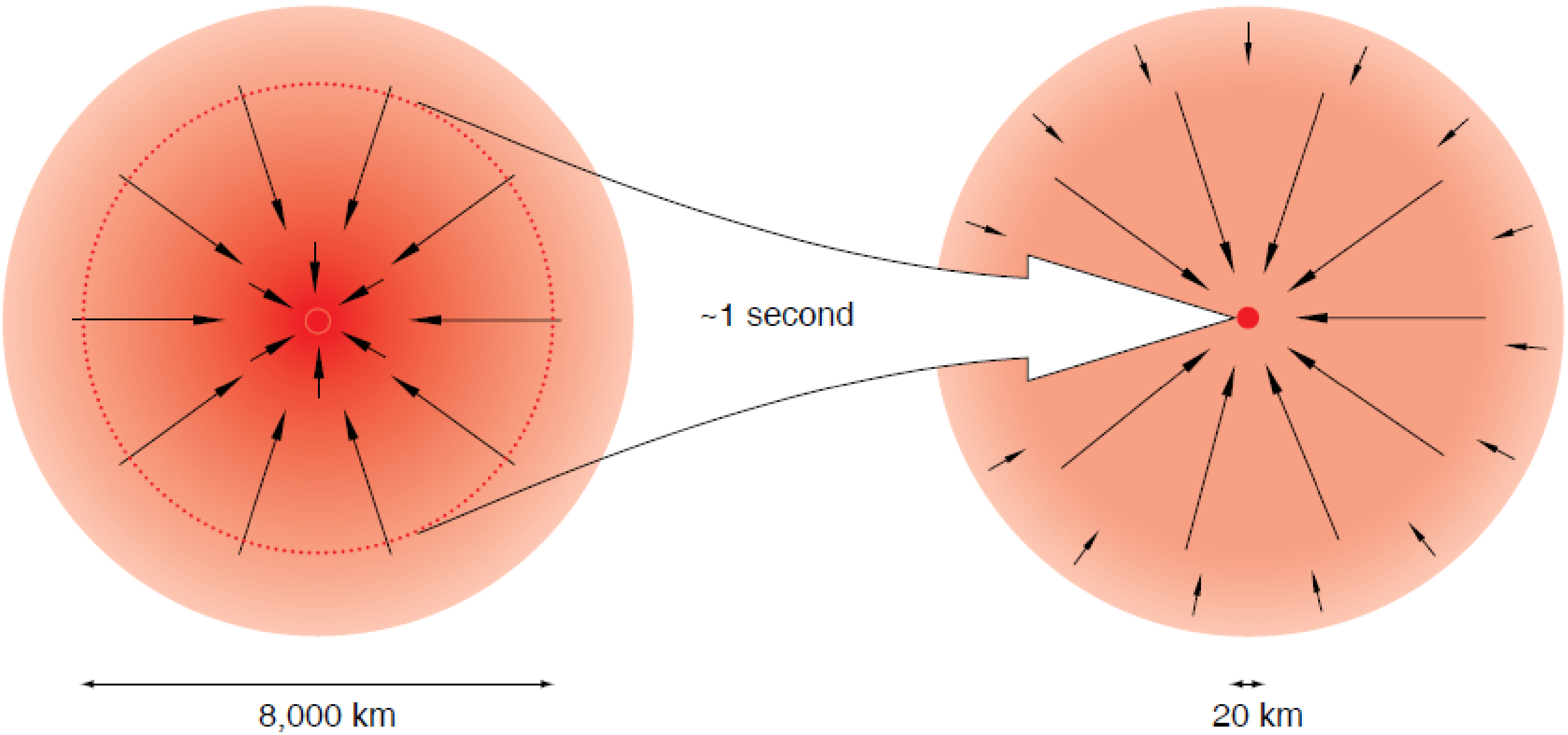
《宋会要》："至和元年七月二十二日守将作监致仕杨惟德：伏睹客星出现，其星上微有光彩，黄色。"；"嘉佑元年三月，司天监言：'客星没'，初，至和元年五月，晨出东方，守天关，昼见如太白，芒角四出，色赤白，凡见二十三日"

《续资治通鉴长篇》："至和元年五月己丑客星出天关之东南可数寸，岁余消没"；"嘉佑元年三月辛未司天监言：自至和元年五月，客星晨出东方，守天关，至是没"。

参宿四

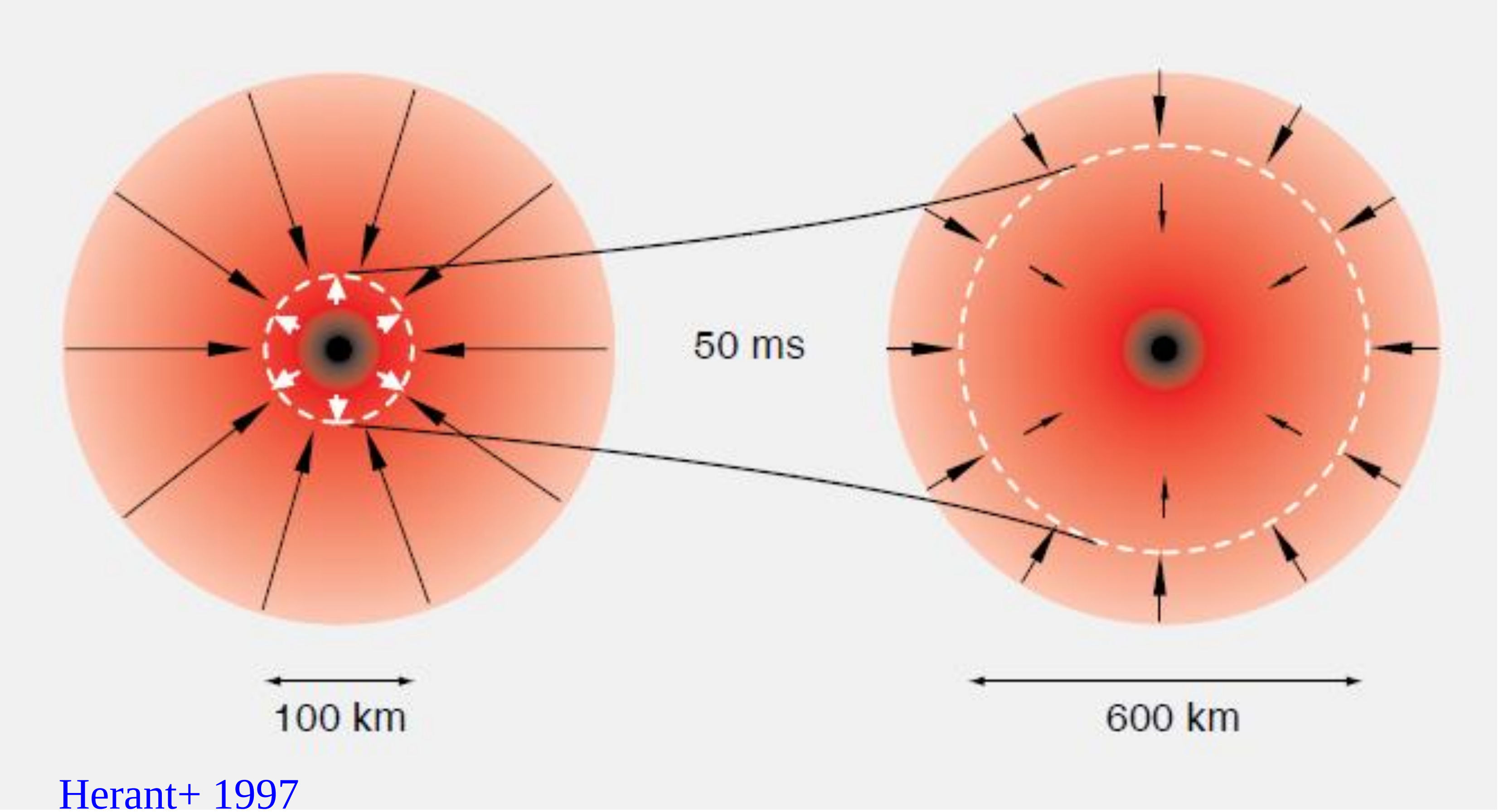
https://keelyandthomas.wordpress.com/

中微子在核塌缩超新星中的作用



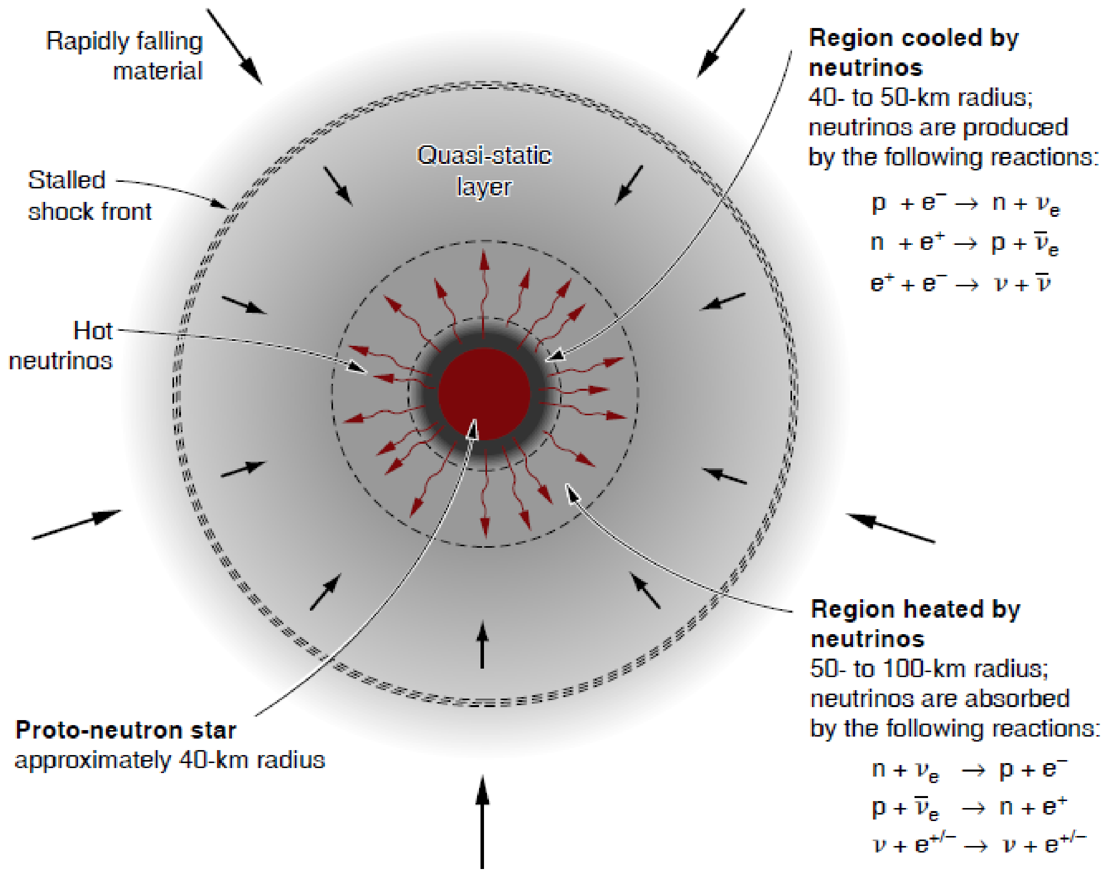
Herant+ 1997

中微子在核塌缩超新星中的作用



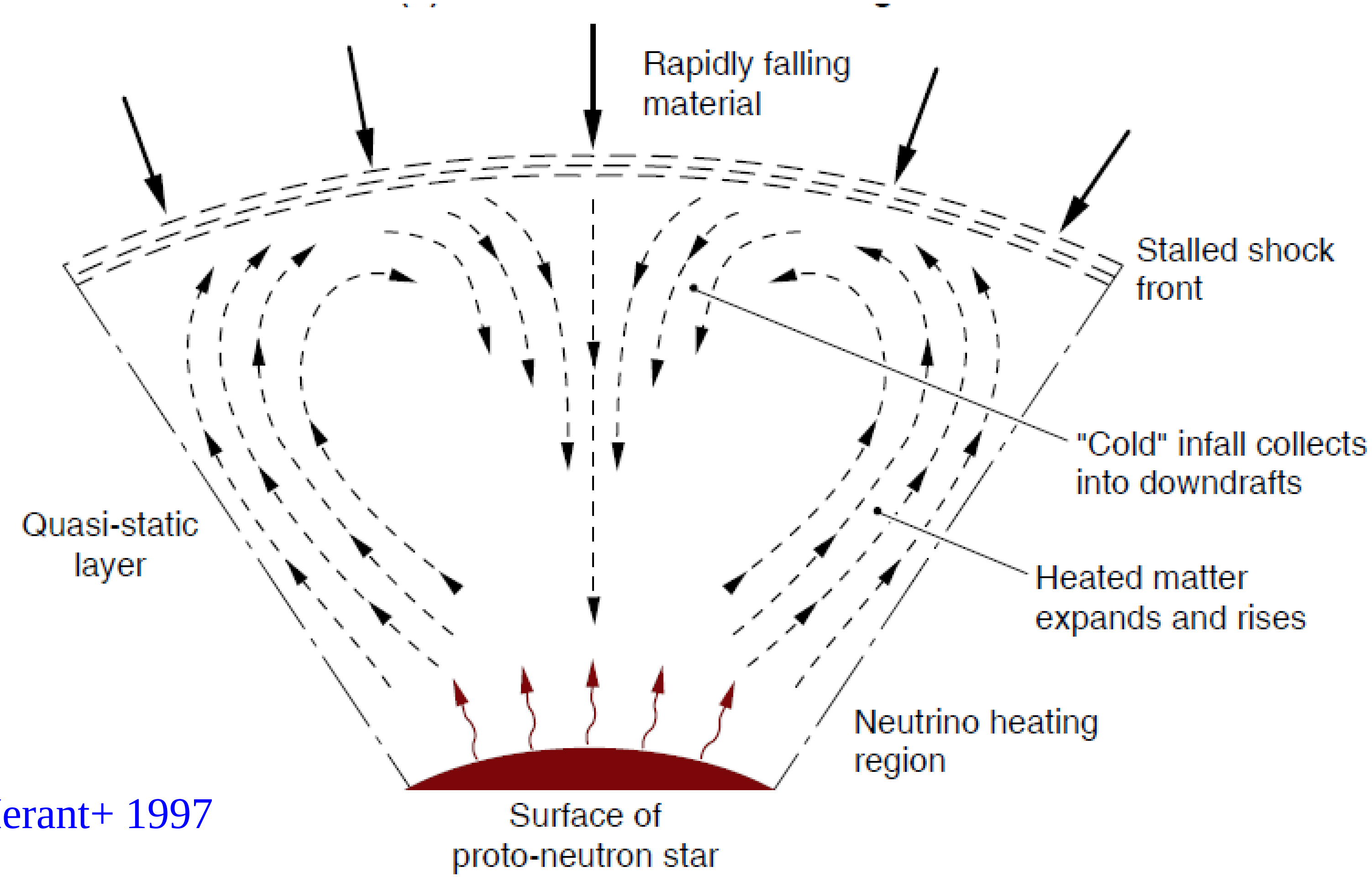
Herant+ 1997

中微子在核塌缩超新星中的作用



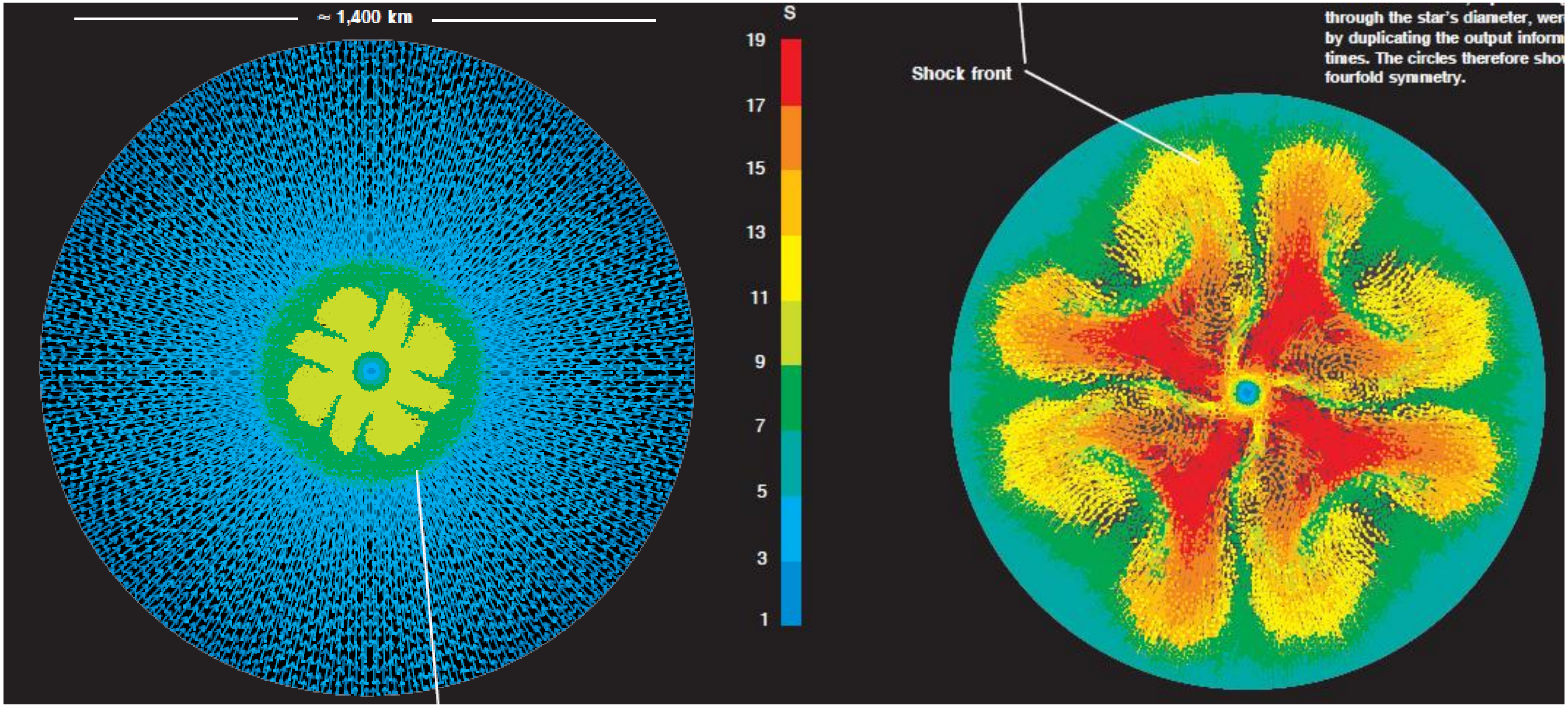
Herant+ 1997

中微子在核塌缩超新星中的作用



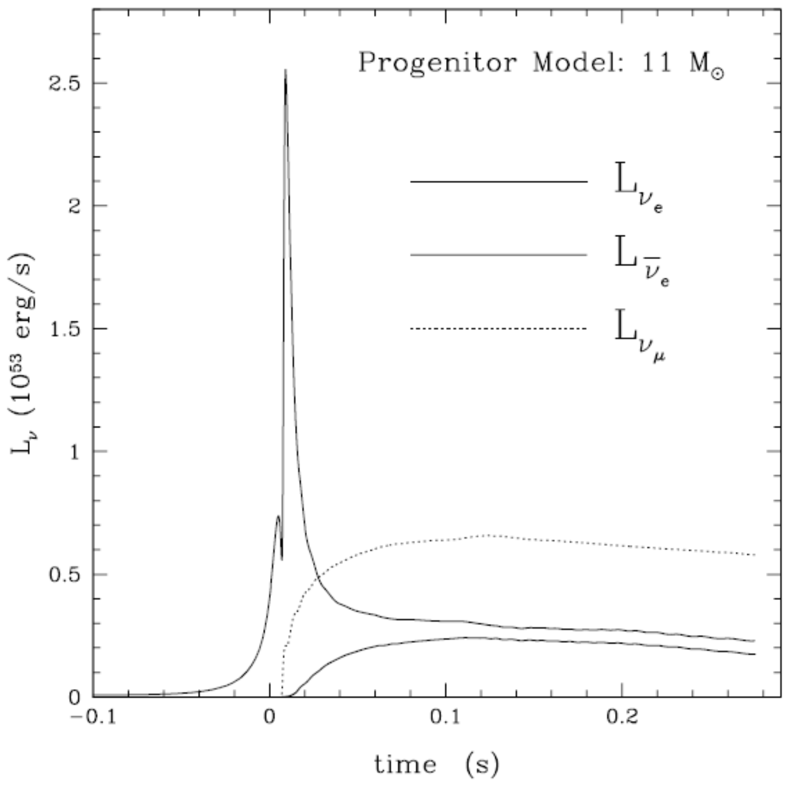
Herant+ 1997

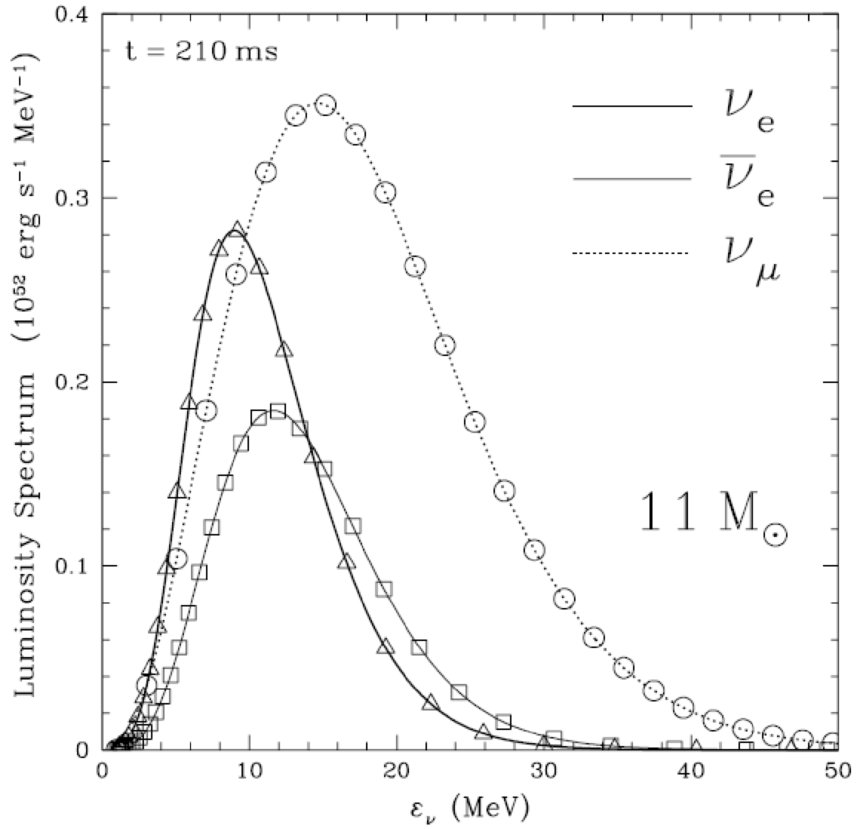
中微子在核塌缩超新星中的作用



Herant+ 1997

核塌缩超新星的中微子流量和谱





Thompson+ 2003

SN 1987A

日本Kamiokande（12个中微子）、美国IMB（8个中微子）

Hirata+ 1987

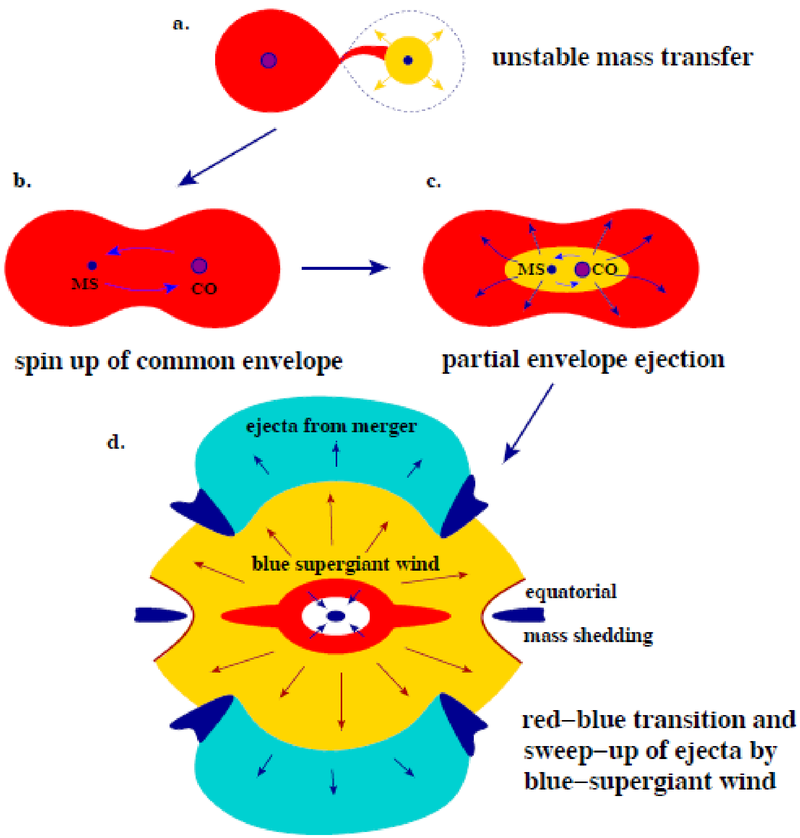
Bionta+ 1987

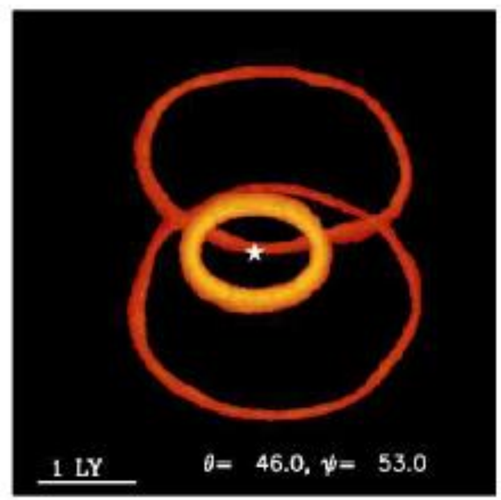
中微子的能量(10-40Mev)：原中子星的温度

持续时间（10s）：原中子星的冷却时间

总能量：1.4Msun、15km的中子星

SN 1987A的前身星

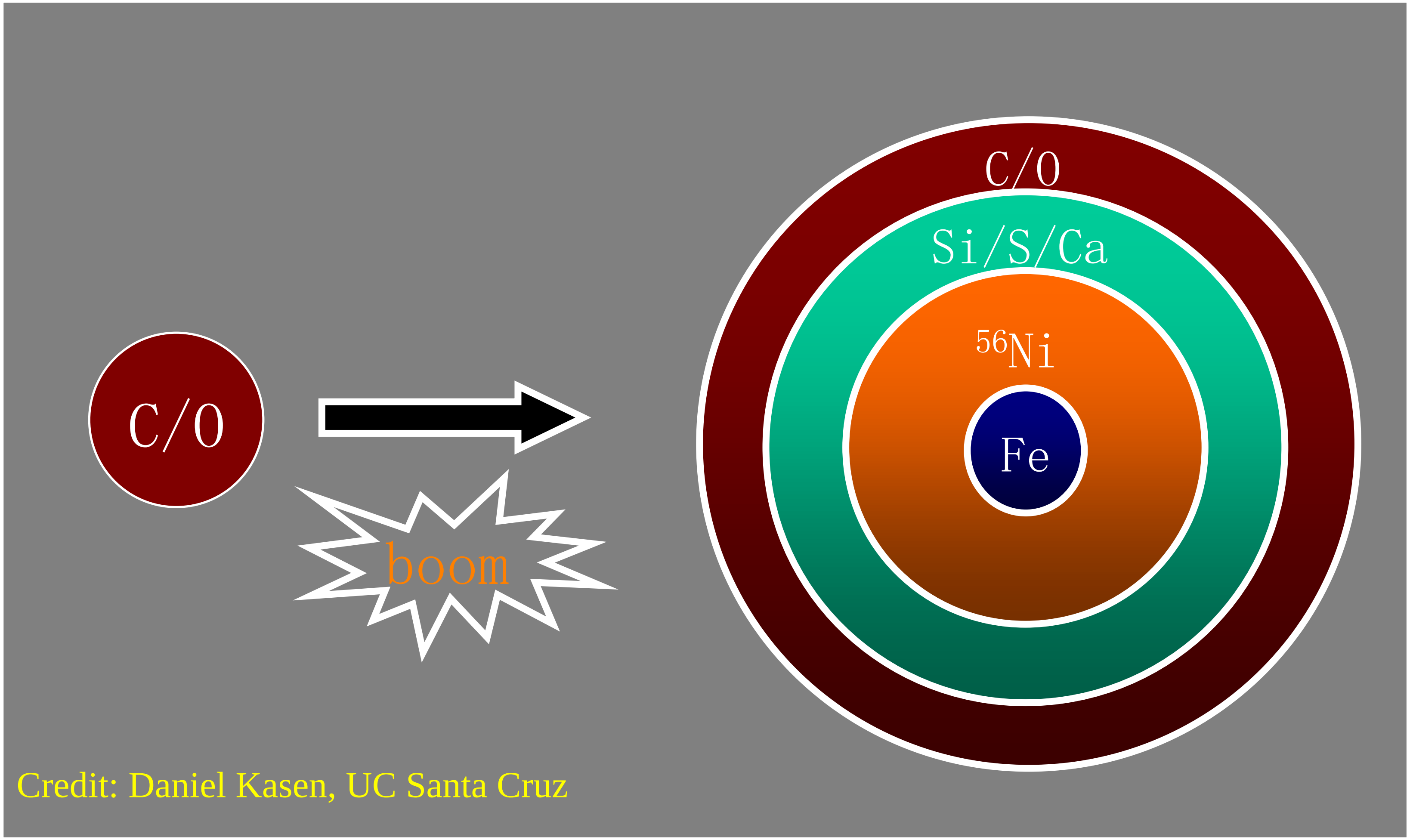




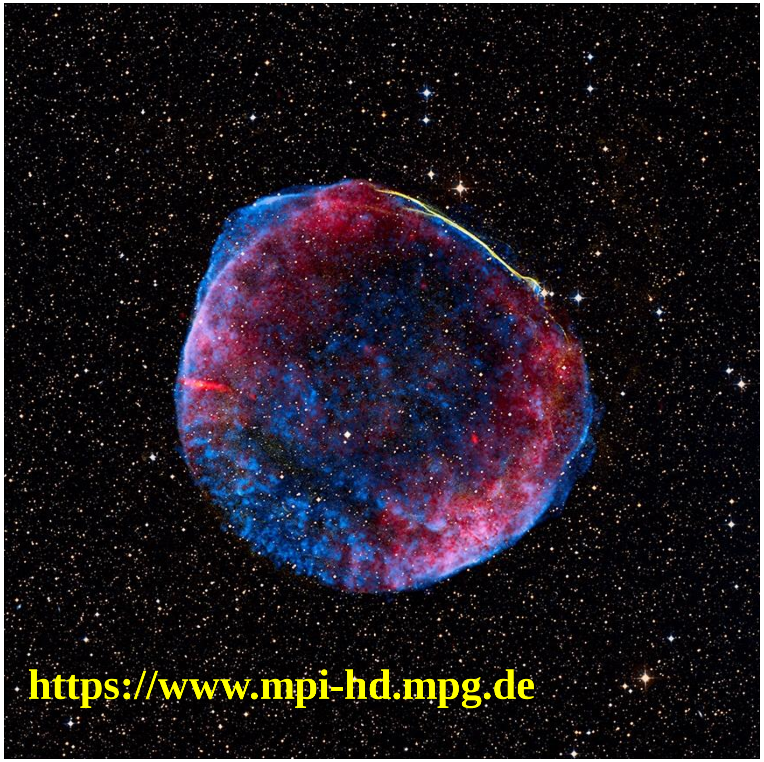
Morris+ 2007

热核爆炸超新星（Ia）

(Chandrasekhar质量极限的碳氧白矮星)



SN 1006



公元1006年超新星爆发

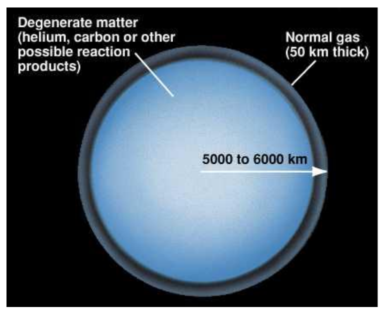
《宋会要辑稿》：“（景德三年）四月二日夜初更，见大星，色黄，出库楼东，骑官西，渐渐光明，测在氐三度。”

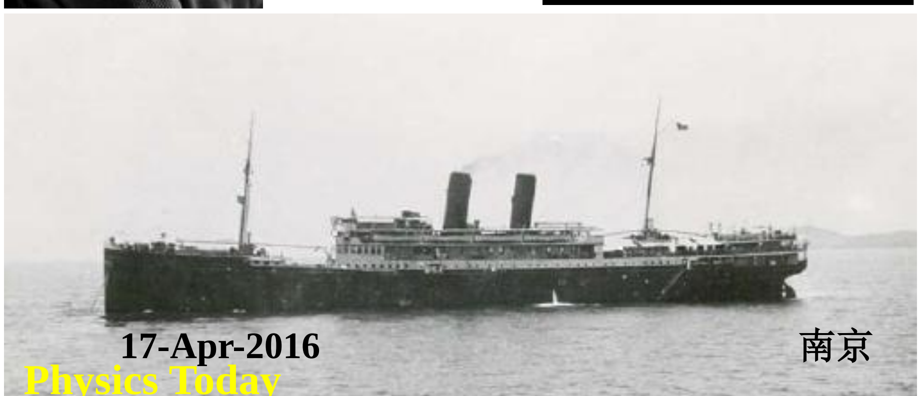
《宋史·天文志》：“状如半月，有芒角，煌煌然可以鉴物》”

Chandrasekhar质量极限-

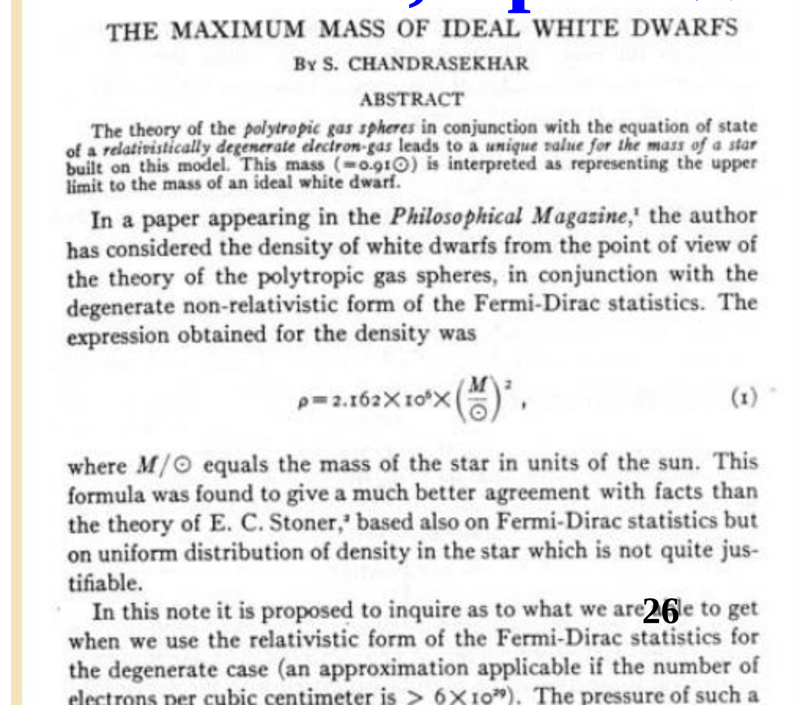
电子简并压所能支撑的最大质量

- 1930年19岁的Chandrasekhar乘轮船去英国剑桥大学读书
- 正常恒星（气体压）、白矮星（电子简并压）、中子星（简并中子压）、黑洞
- 电子：量子力学：牛顿力学到狭义相对论：质量越大，密度越高





1931, ApJ （2页）



THE MAXIMUM MASS OF IDEAL WHITE DWARFS

By S. CHANDRASEKHAR

ABSTRACT

The theory of the *polytropic gas spheres* in conjunction with the equation of state of a *relativistically degenerate electron-gas* leads to a *unique value for the mass of a star* built on this model. This mass ($=0.91\odot$) is interpreted as representing the upper limit to the mass of an ideal white dwarf.

In a paper appearing in the *Philosophical Magazine*,[1] the author has considered the density of white dwarfs from the point of view of the theory of the polytropic gas spheres, in conjunction with the degenerate non-relativistic form of the Fermi-Dirac statistics. The expression obtained for the density was

$$\rho = 2.162 \times 10^6 \times \left(\frac{M}{\odot}\right)^2 , \quad (1)$$

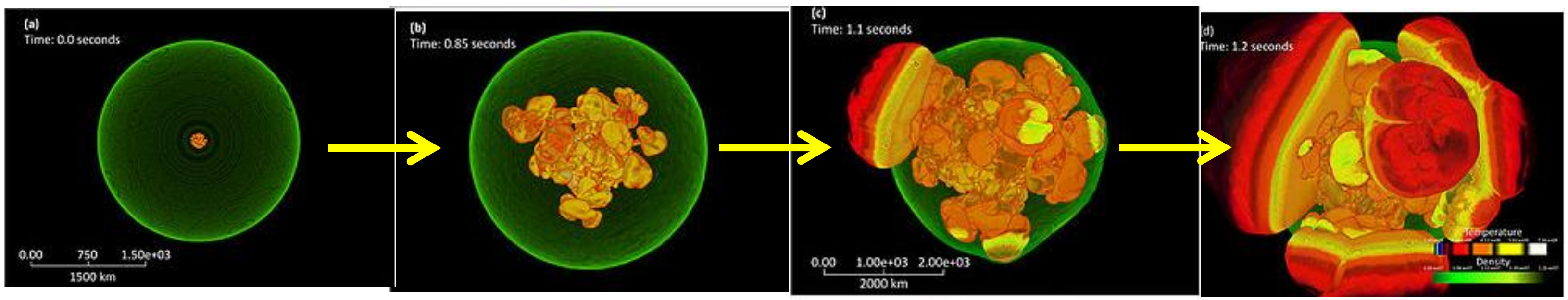
where $M/\odot$ equals the mass of the star in units of the sun. This formula was found to give a much better agreement with facts than the theory of E. C. Stoner,[2] based also on Fermi-Dirac statistics but on uniform distribution of density in the star which is not quite justifiable.

In this note it is proposed to inquire as to what we are able to get when we use the relativistic form of the Fermi-Dirac statistics for the degenerate case (an approximation applicable if the number of electrons per cubic centimeter is $> 6\times10^{29}$). The pressure of such a

1983：获诺贝尔奖
1999年：NASA发射Chandra X-射线天文台

热核爆炸超新星（Ia）

碳氧白矮星（～1.4M⊙）的热核爆炸，



是太阳亮度的1000亿倍，性质惊人的一致。

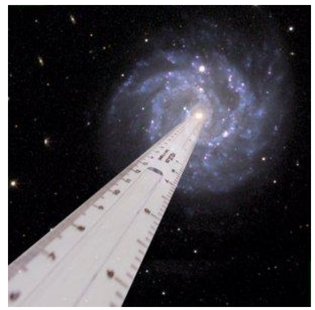
2011年诺贝尔物理学奖

S. Perlmutter, B.P. Schmidt, A.G. Riess

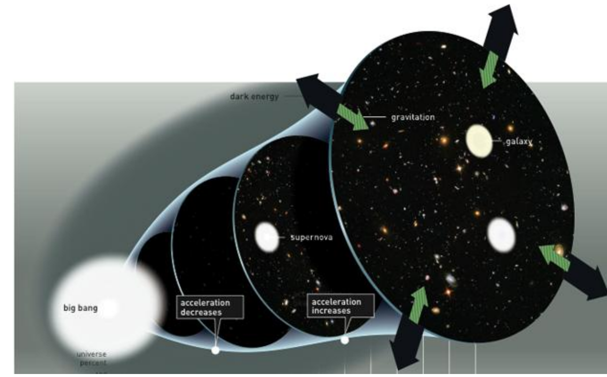
三位科学家通过对遥远的超新星的观测发现宇宙加速膨胀。瑞典皇家科学院称该发现“震动了宇宙学的基础”。

宇宙距离指示器

http://www.universeadventure.org

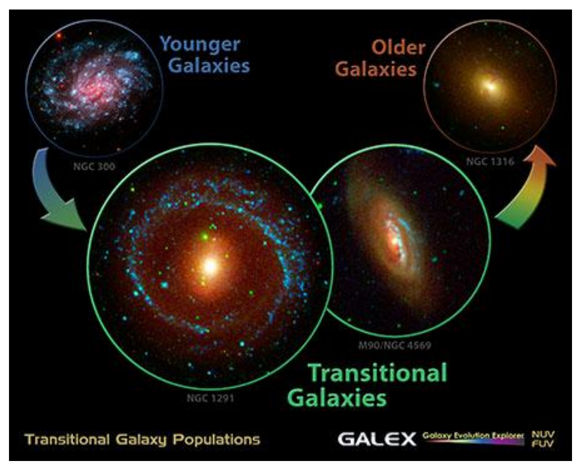


http://www.schoolsobservatory.org.uk/



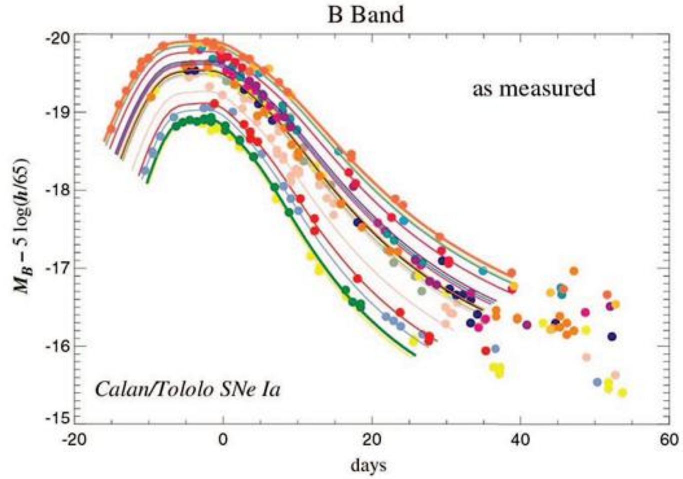
http://arstechnica.com

铁、动能（星系演化）



标定 SNe Ia

观测的Ia型超新星的光变曲线



经“Phillips关系”定标

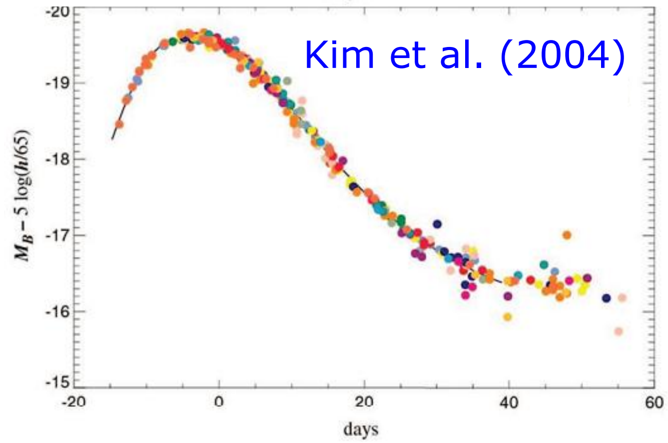


TABLE 2

Fits to the Color Parameter versus Luminosity Relation Using $M_{max} = M_0 + R\Delta C_{12}$

Bandpass	M_0[a]	R[a]	σ (mag)	n[b]
B	−19.96(07)	1.94(13)	0.099	30
V	−19.72(07)	1.46(12)	0.070	30
I	−19.23(07)	1.03(13)	0.072	27

[a] Error estimates in parentheses are in units of ±0.01 mag.
[b] The sample number of SNe Ia selected.

Wang+, ApJ, 2005

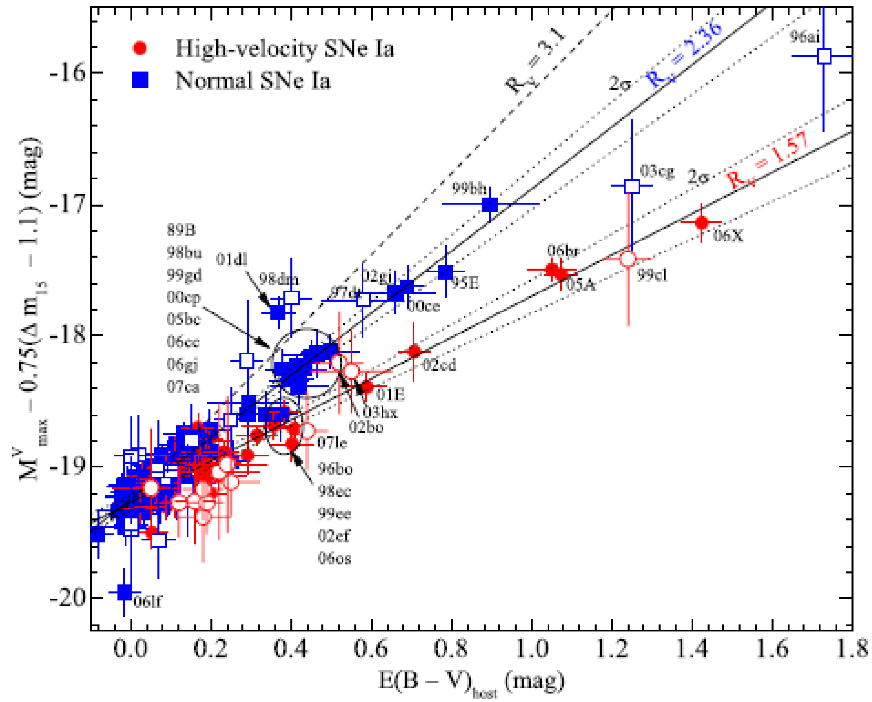
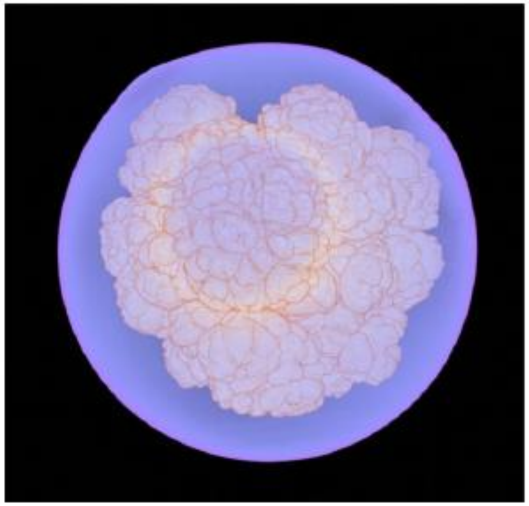


Figure 4. Δm_{15}-corrected absolute V mag at maximum brightness vs. the host-galaxy reddening. The filled symbols are SNe with $z \gtrsim 0.01$ or Cepheid-based distances, and the open symbols are nearby objects that were not included in the fit. The two solid lines show the best-fit R_V for SNe in the HV and Normal groups, with dotted lines indicating 2σ uncertainties. The dashed line represents the Milky Way reddening law.

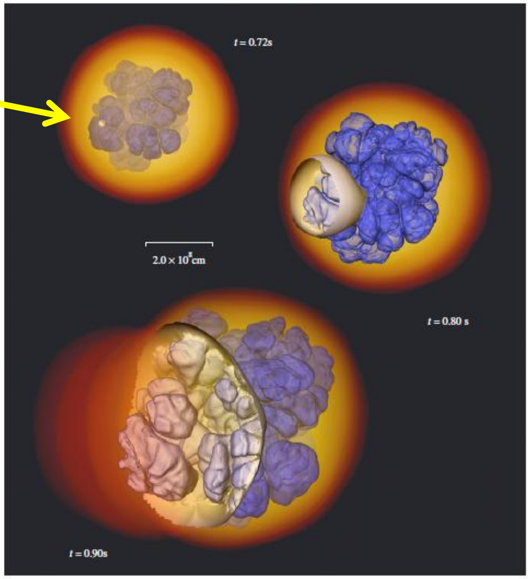
Wang+, ApJ, 2009

1.38Msun的CO白矮星的热核爆炸 -> SN Ia

carbon ignition under degenerate conditions ⟶
thermonuclear runaway ⟶
incineration and complete destruction of the star



10^{51}**ergs**

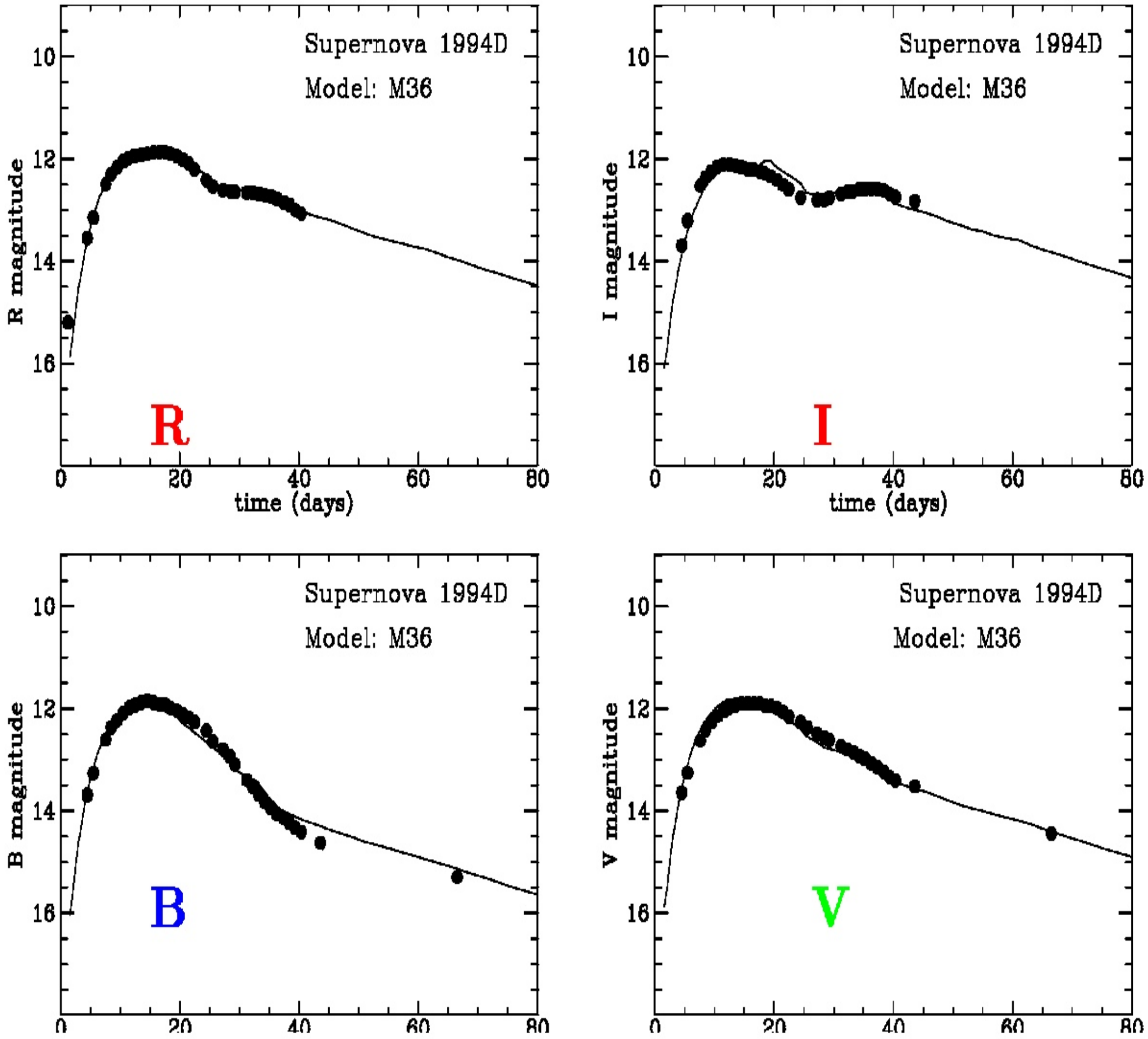


Pure deflagration in a Chandrasekhar-mass CO WD: snapshot of the flame propagation 1.0 s after ignition in multiple sparks around the star's center.

Delayed detonation.At t = 0.72 s the detonation triggers. Subsequently it burns the remaining fuel wrapping around the ashes left behind from the initial deflagration.

Ropke et al. 2011,
Progress in Particle and Nuclear Physics (Review)

(Hoeflich 1995, ApJ 443, 89) **Data obtained by CfA group**



LCs up to day 80

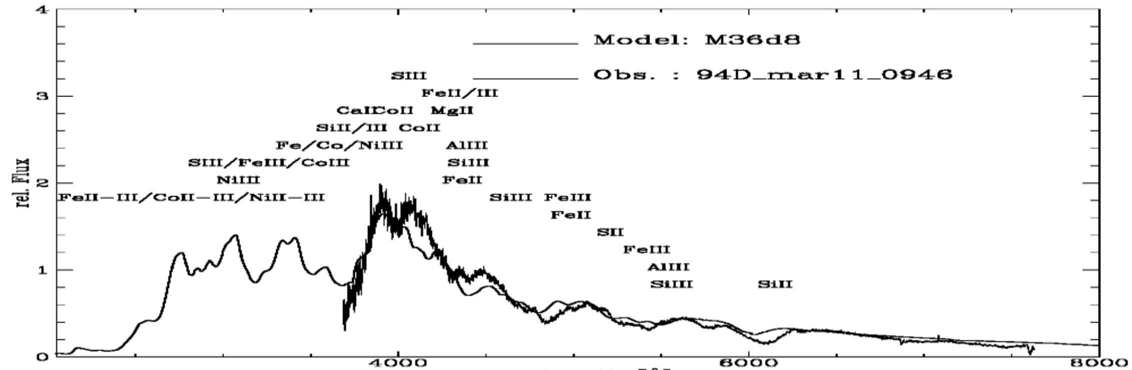
C/O WD with

rho(c)=2.E9g/ccm

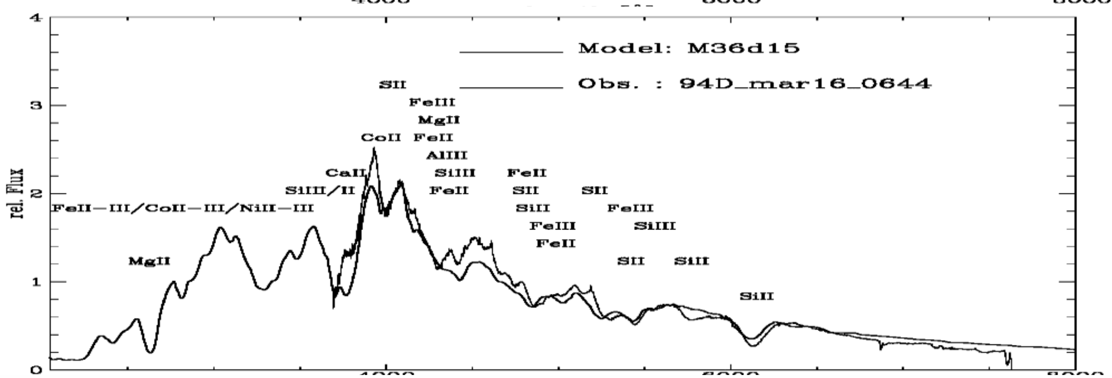
rho(tr)=2.4E7 g/ccm

Spectra between 3000 and 8000 A: SN94D vs. M36

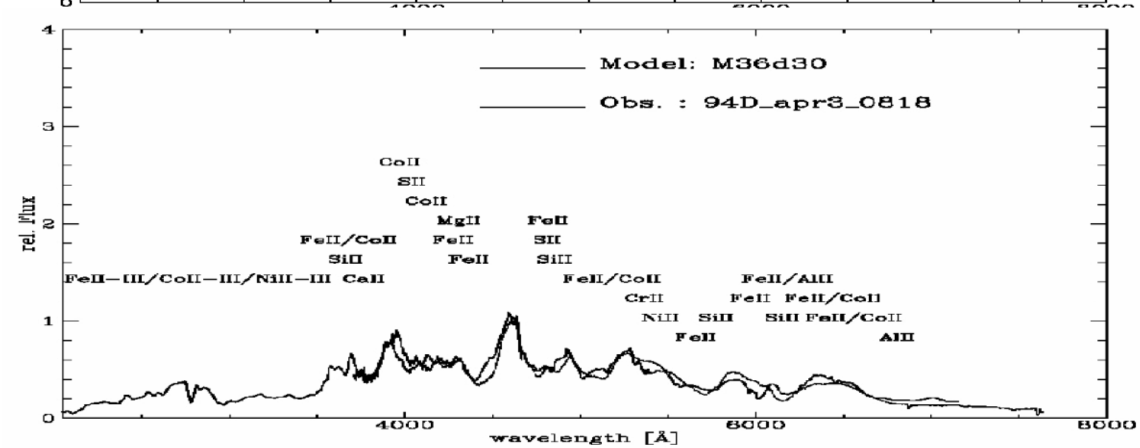
C/O WD; rho(c)=2.E9g/ccm; rho(tr)=2.4E7 g/ccm (H95)



- 8 days after explosion
 = -8 days before maximum
 - spectrum is dominated by
 intermediate mass elements (S,Si)
 + iron group elements



- 16 days after the explosion
 = -2 d before maximum light
 - spectrum is dominated by
 Si, S, Ca + iron group elements
 (formed in transition layer
 between Si and Ni/Co/Fe



- 31 days after explosion
 = 2 weeks after maximum
 - spectrum is formed in inner
 Ni/Co/Fe core

不清楚的

- 前身星模型（最重要的）.
- 爆炸模型.
- 随红移的演化.
- 光度弥散的起源.

前身星模型:

1. WD吸积模型（单简并星模型）

(Hachisu et al. 1996; Li & van den Heuvel 1997;
Han & Podsiadlowski 2004, 2006; Han 2008;
Chen & Li 2007; Meng et al. 2009; Lv et al. 2009;
Wang et al. 2009a,b；Wang, Li & Han 2009)

CO WD + MS

CO WD + RG

CO WD + He star

单简并SD

双简并DD

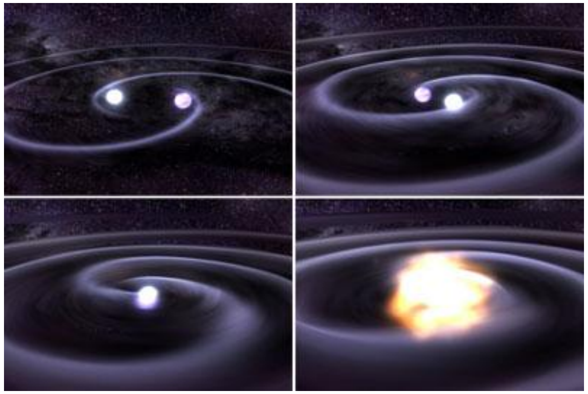


Image Credit: NASA/Tod Strohmayer (GSFC)/Dana Berry (Chandra X-Ray Observatory)

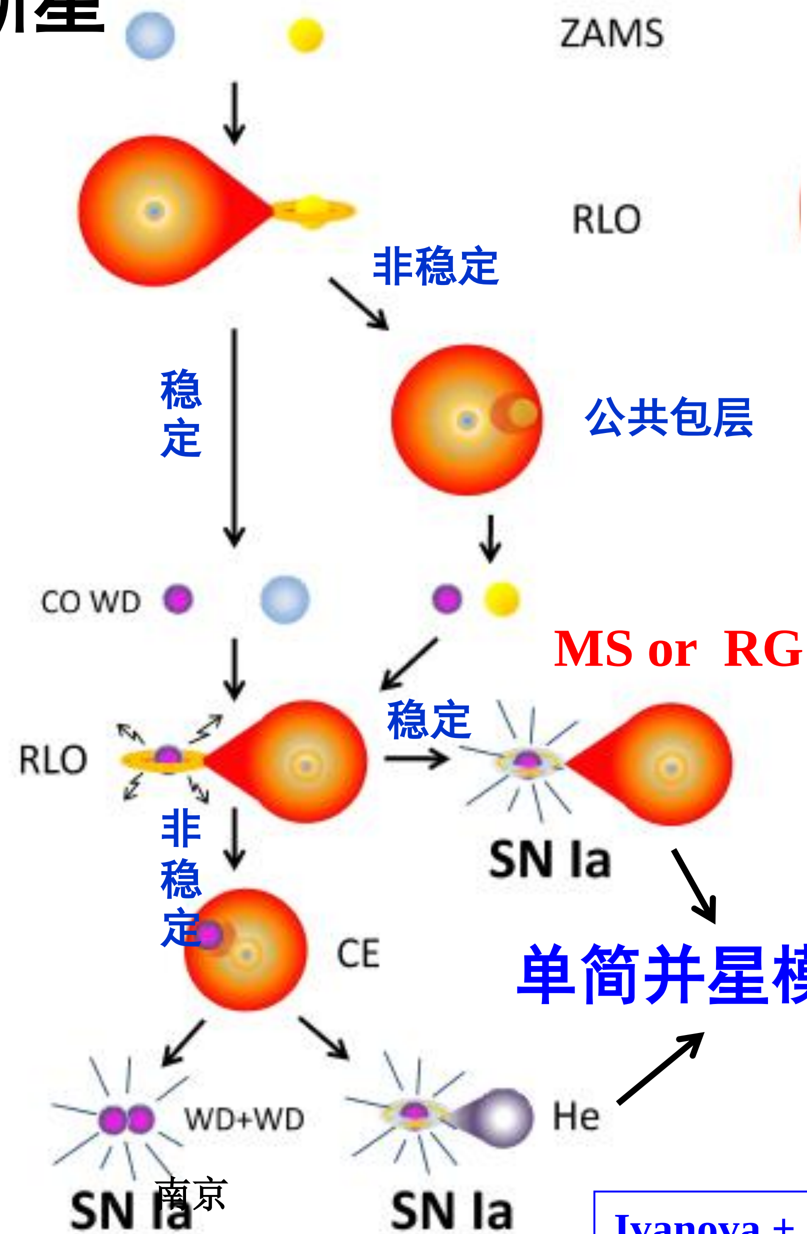
2. 双WD并合模型（双简并星模型）

(Iben & Tutukov 1984; Webbink 1984; Han 1998)

CO WD + CO WD

双星演化产生Ia型超新星

目前几乎所有关于Ia型超新星前身星模型的研究都基于此框架和白矮星吸积过程的研究。



单简并星模型SD

双简并星模型DD

Ivanova +, 2013

Li & van den Heuvel, 1997,A&A, 322, L9

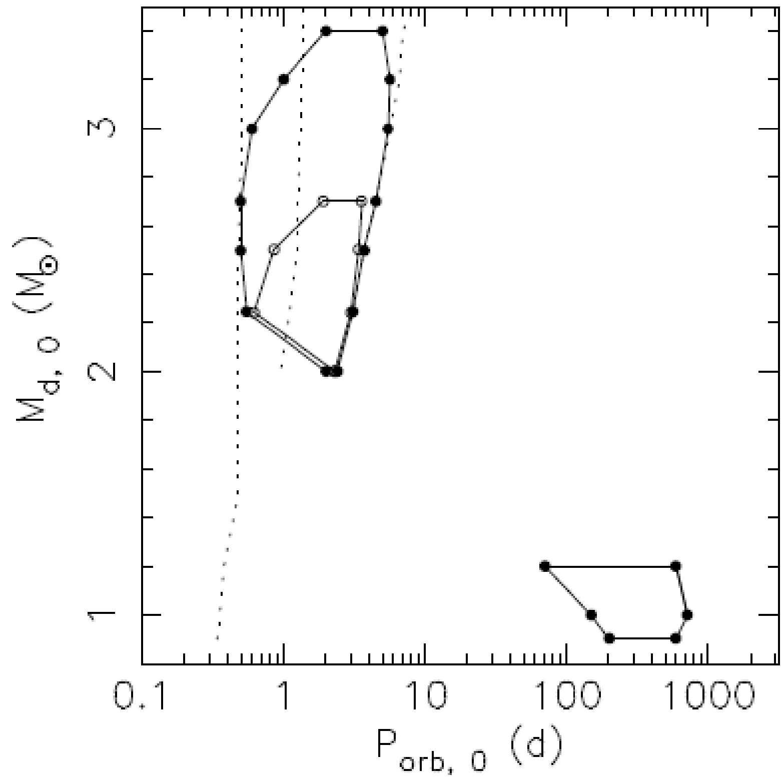
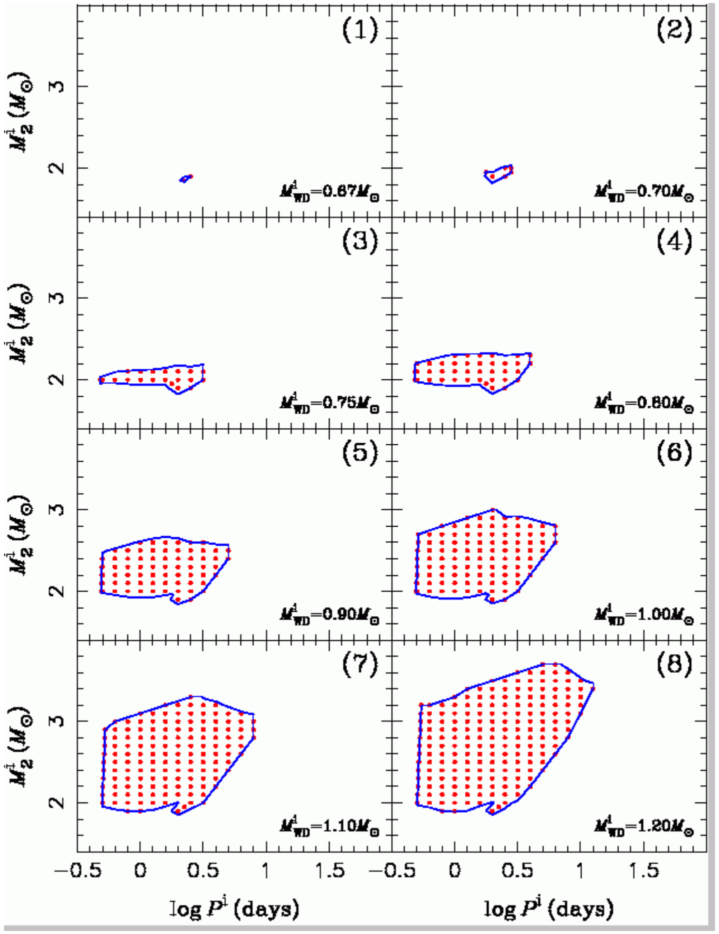
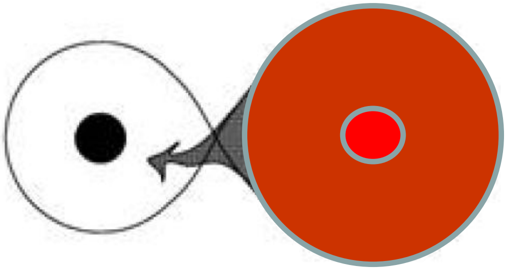


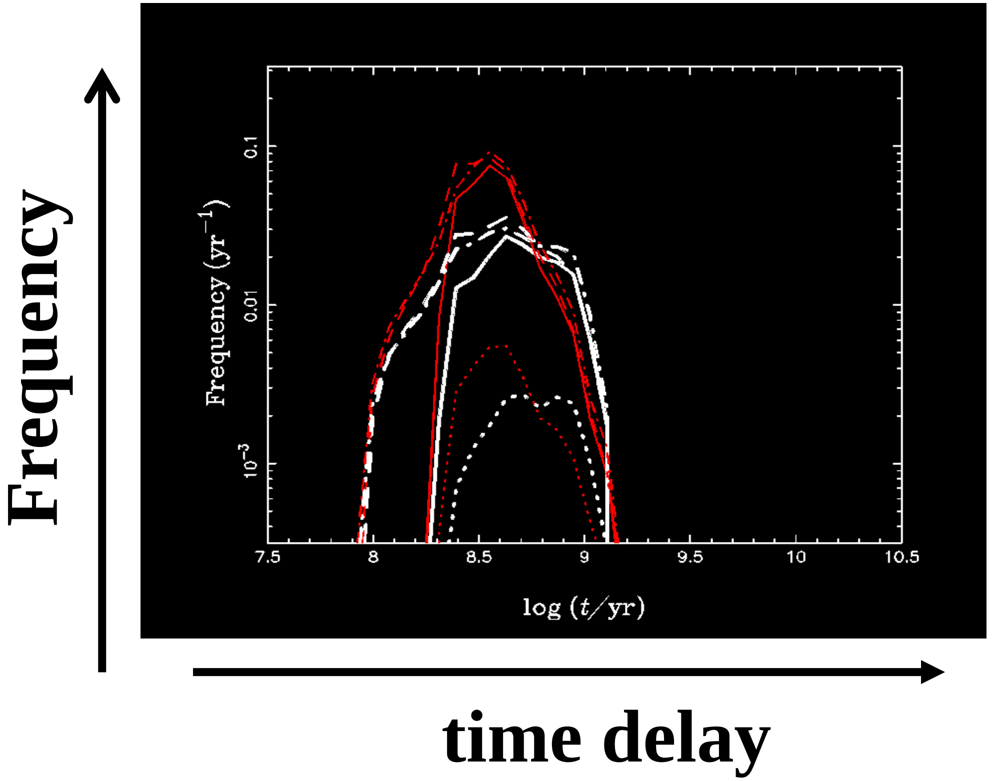
Fig. 3. Distribution of the progenitors of SNe Ia in the $M_{d,0} - P_{orb,0}$ diagram. The filled dots denote the boundary of the initial orbital period at the beginning of the mass transfer, for a white dwarf of $1.2 M_\odot$ initial mass with a specific companion star, and circles for $1 M_\odot$ white dwarfs. The dotted lines represent the boundary of mass transfer in Case A and Case B (from left to right).

WD+MS：哪些双星可以产生SNe Ia？

Han+ 2004, MNRAS

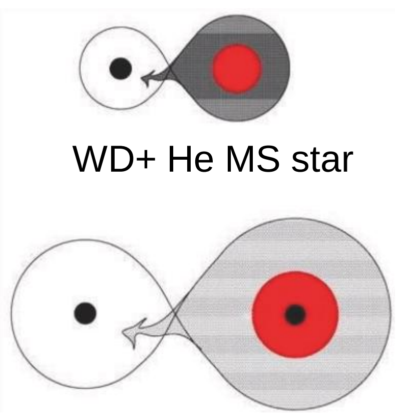






年轻的SNe Ia (~0.1Gyr)占一半，怎么产生的?

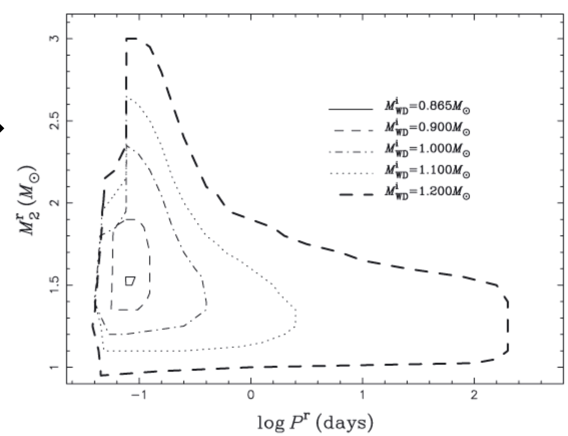
我们提出了氦双星模型 （**Wang+ 2009, 2010**）

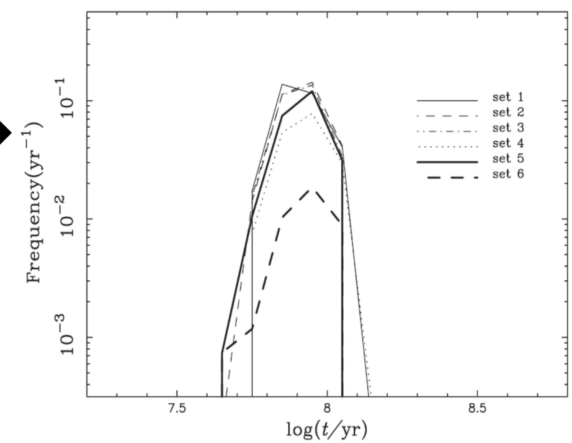


WD+ He MS star

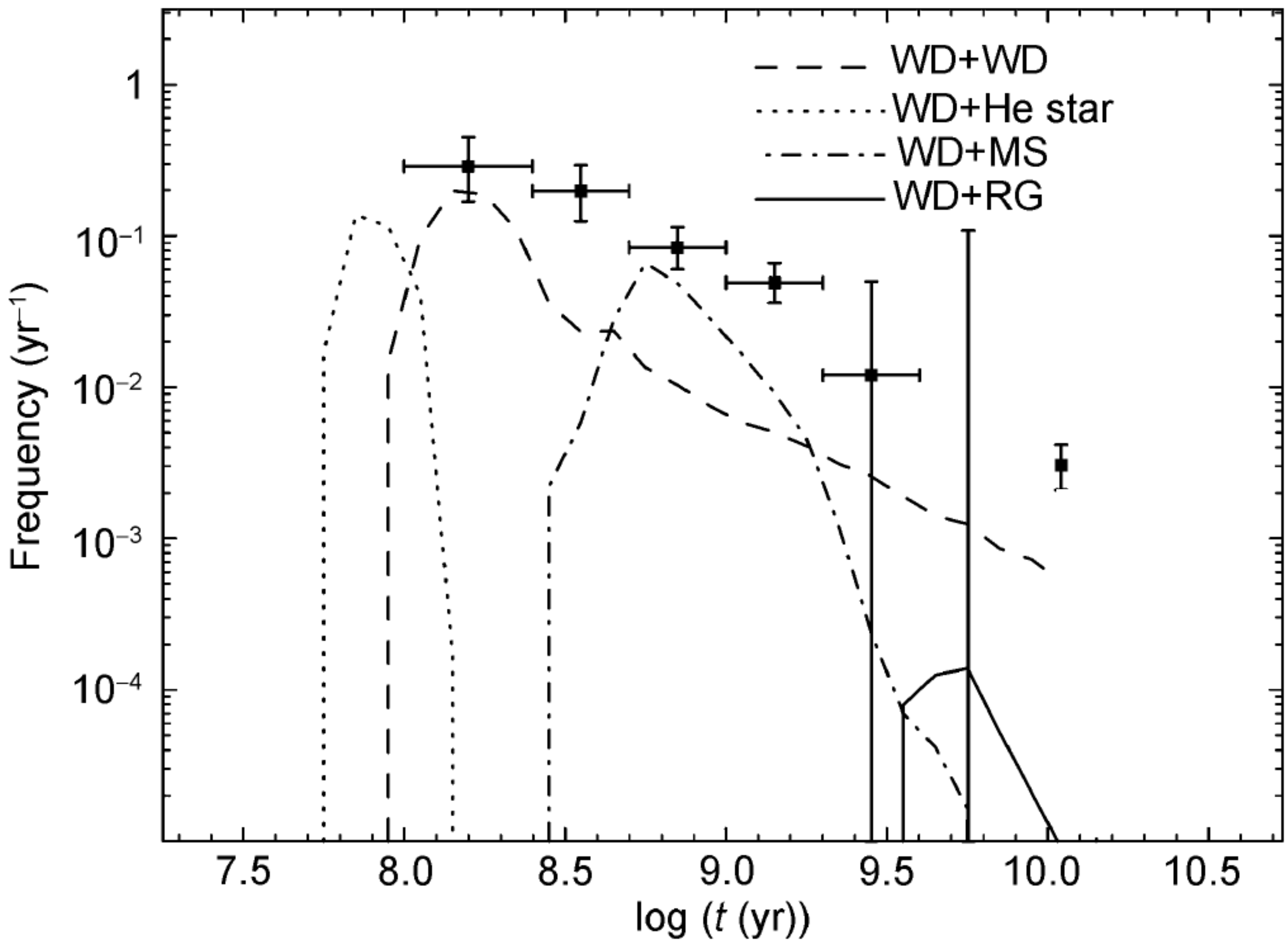
WD + He Giant

Binary Parameter
space leading to SNe Ia





SNe Ia的诞生率（时间延迟函数）

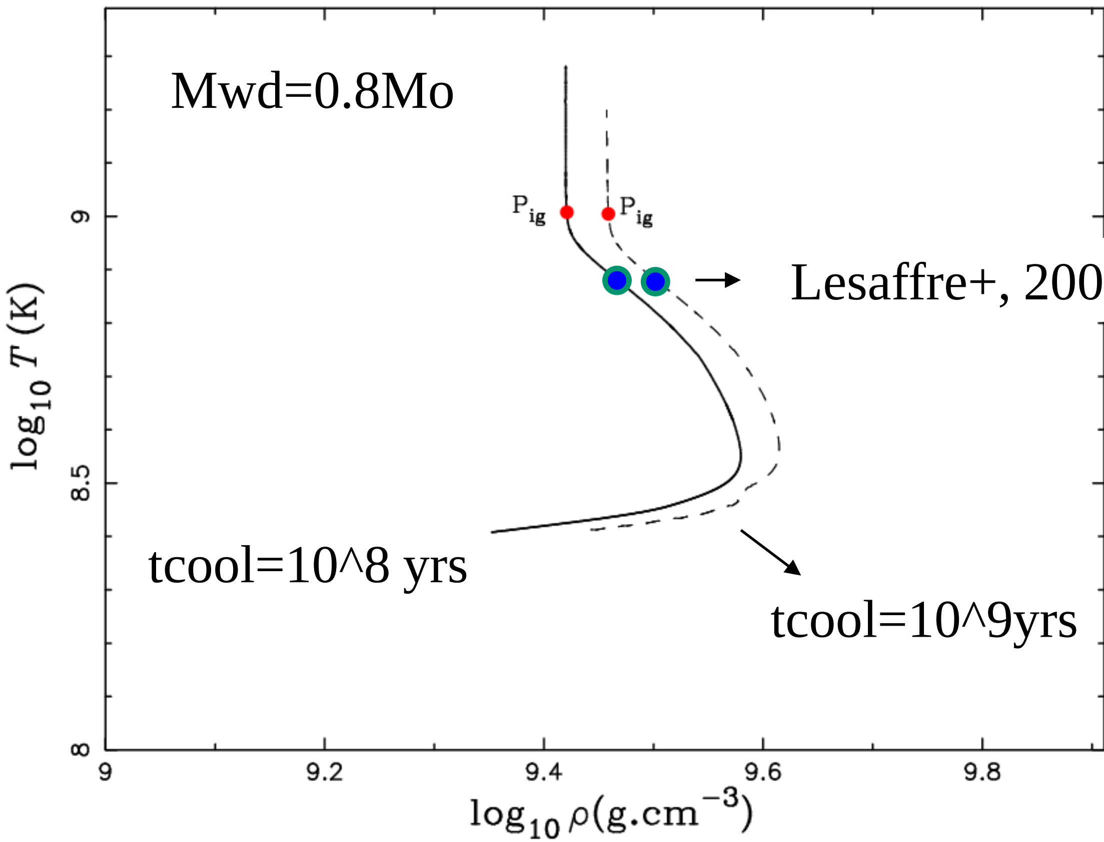


SN Ia rate for single star burst

白矮星诞生时的质量最大为1.1Msun

Chen+ 2014, MNRAS

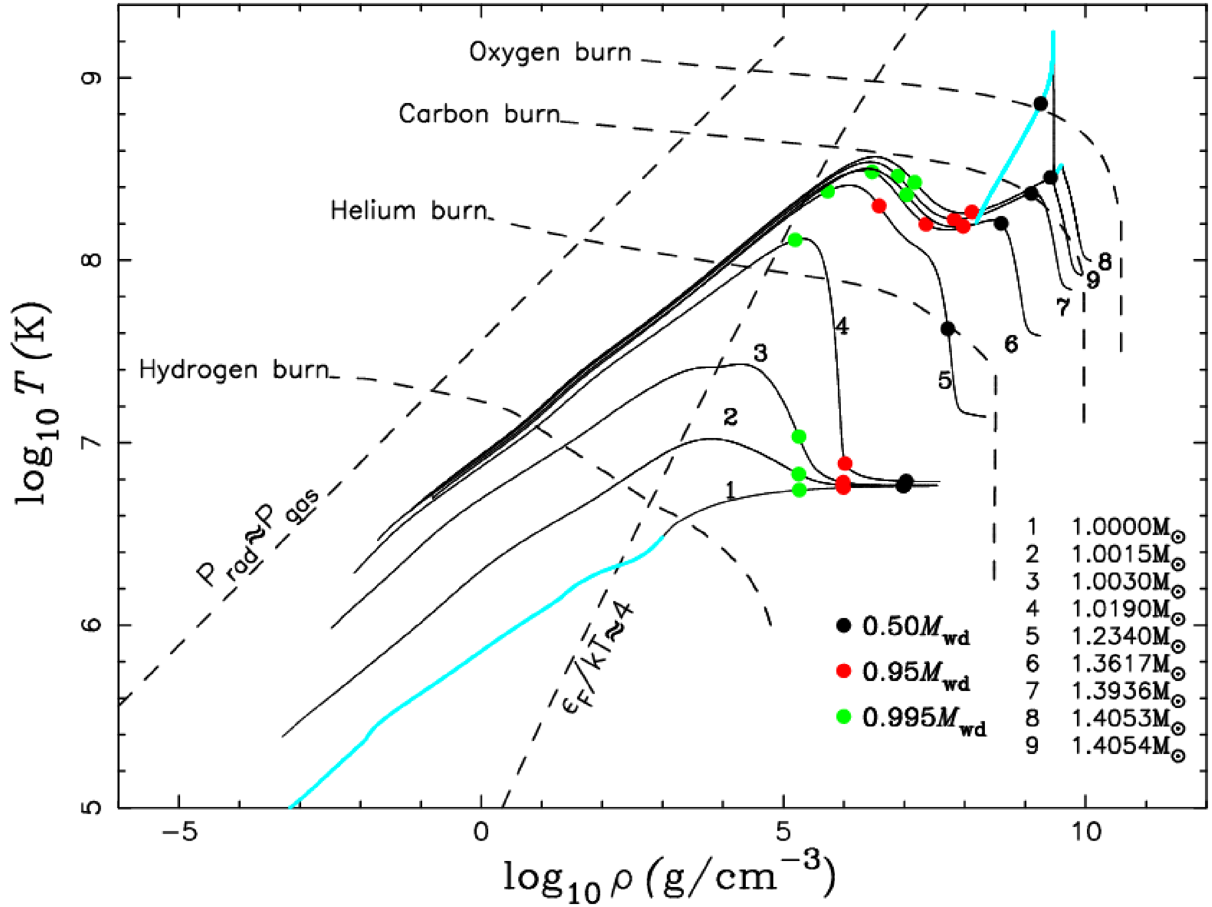
When does C ignition occur ? Tmax ↑ while keeping ρ constant.



$$t_b = \alpha t_c$$

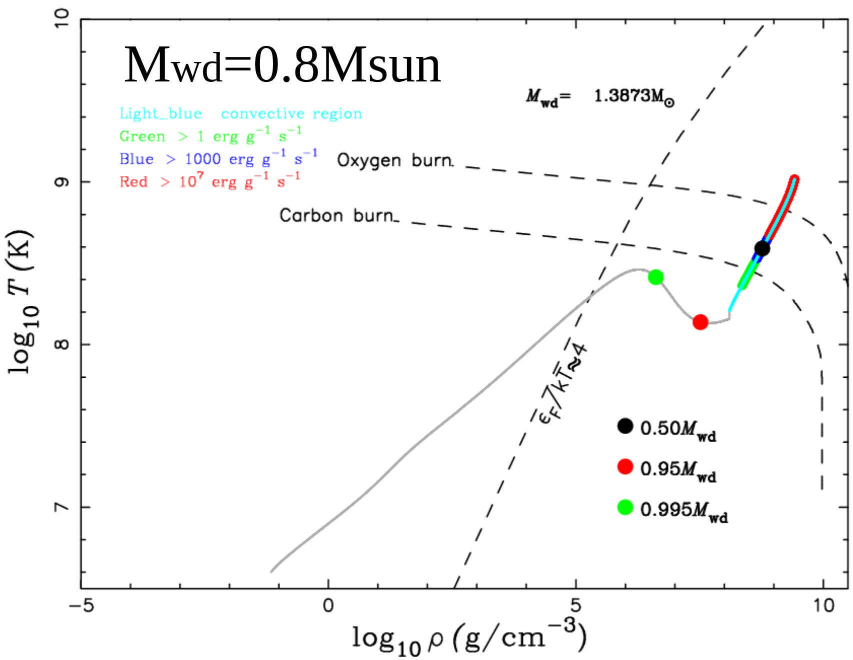
白矮星诞生时的质量最大为1.1Msun

Chen+ 2014, MNRAS



T-rho profile at the C ignition

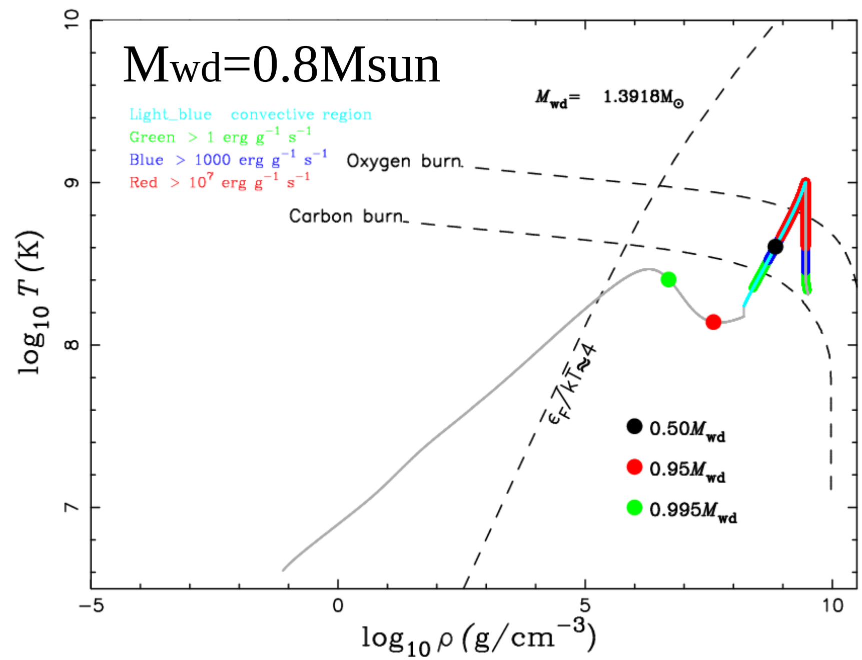
center ignition



tcool=10^8 yrs

Vc=0.036 Vsound

off-center ignition

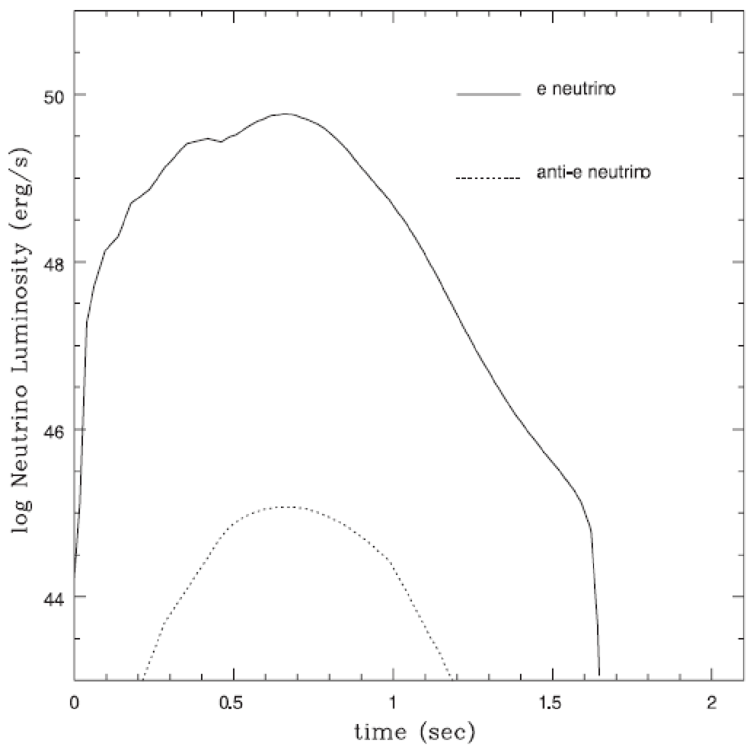


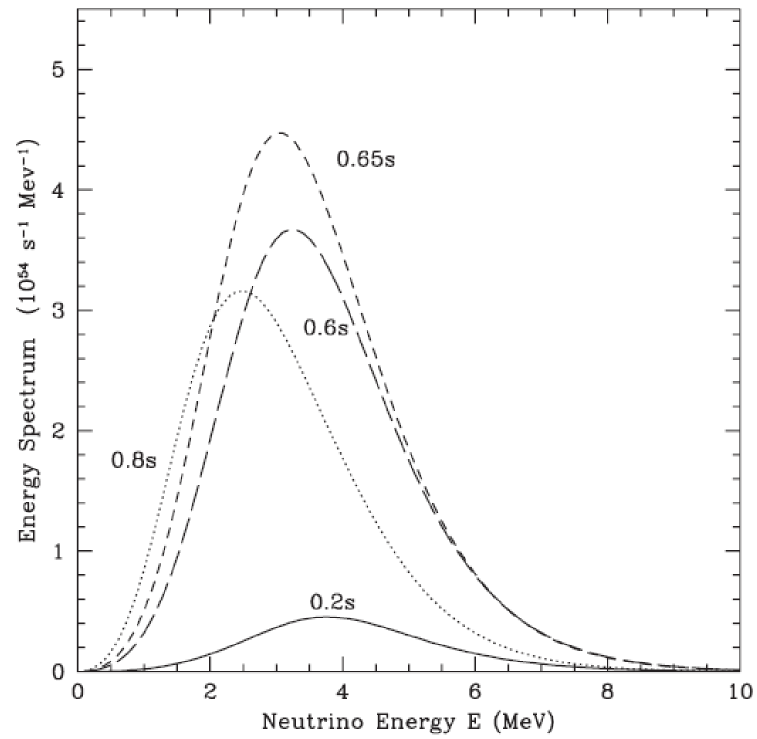
tcool=10^9 yrs

Vc=0.029 Vsound

SN Ia中微子

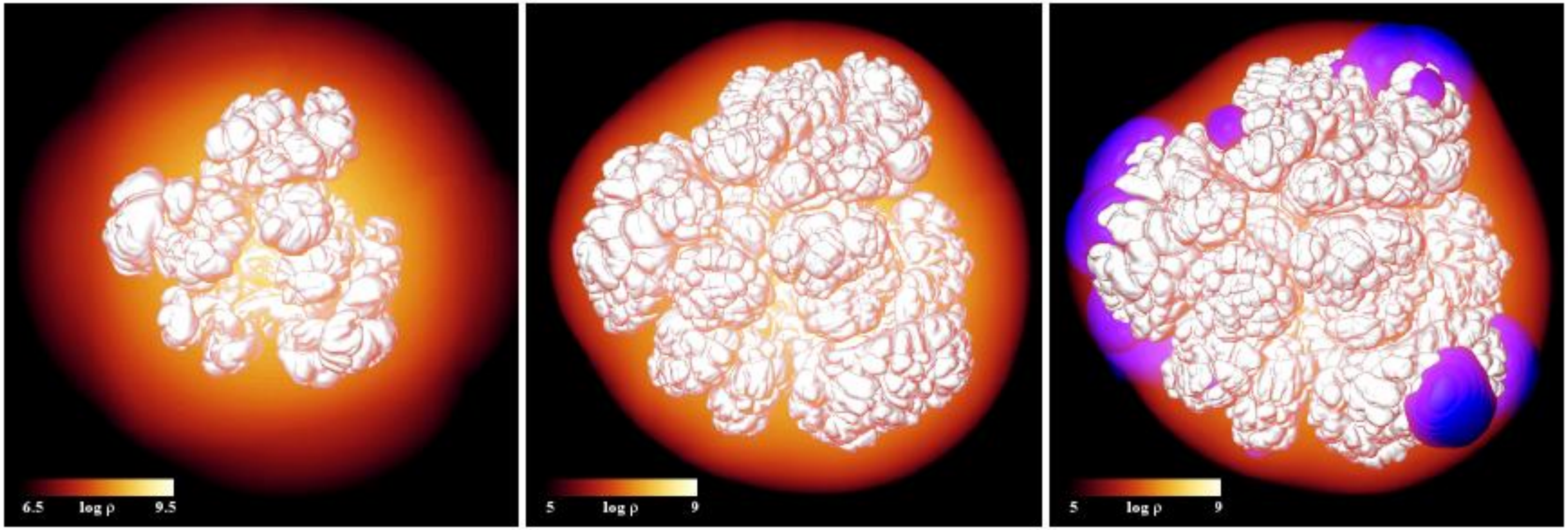
质子、核子捕获中子产生中微子





Kunugise+ 2007，利用W7模型（Nomoto+ 1984）

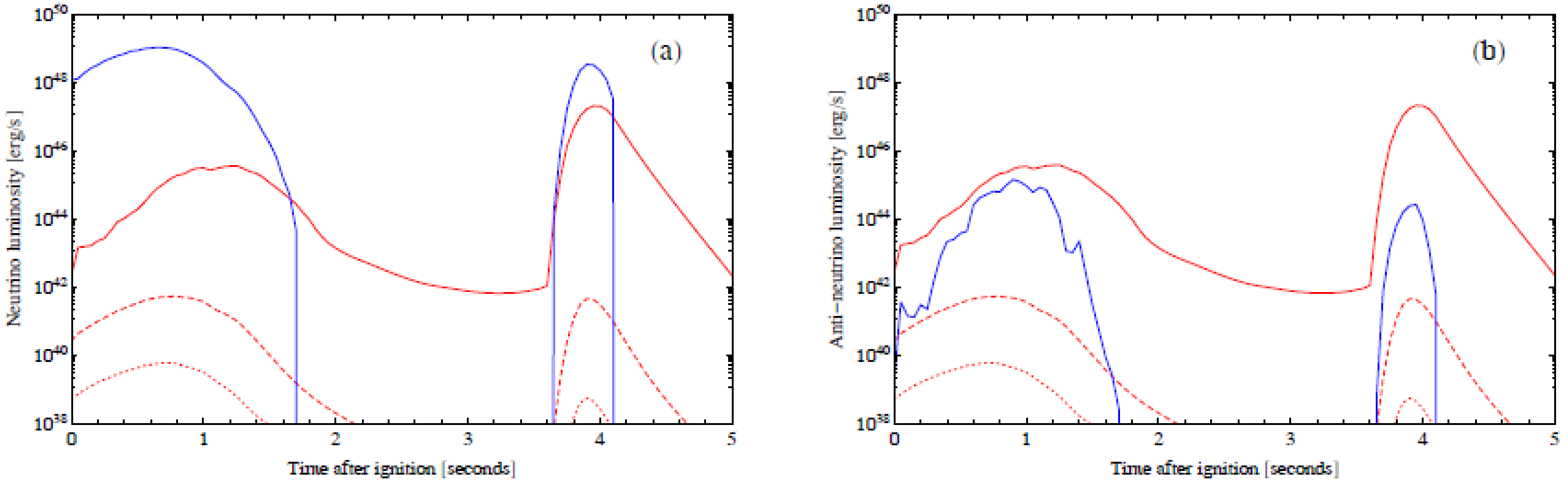
暴燃+暴轰？



Hillebrandt+ 2013

SN Ia中微子（暴燃+暴轰？）

质子、核子捕获中子产生中微子



Odrzywolek+ 2011

前身星模型的观测验证

SN Ia host galaxies

Birthrates

Delay time distributions

Candidate progenitors

Surviving companion stars

Stripped mass of companions

Circumstellar material after SN explosion

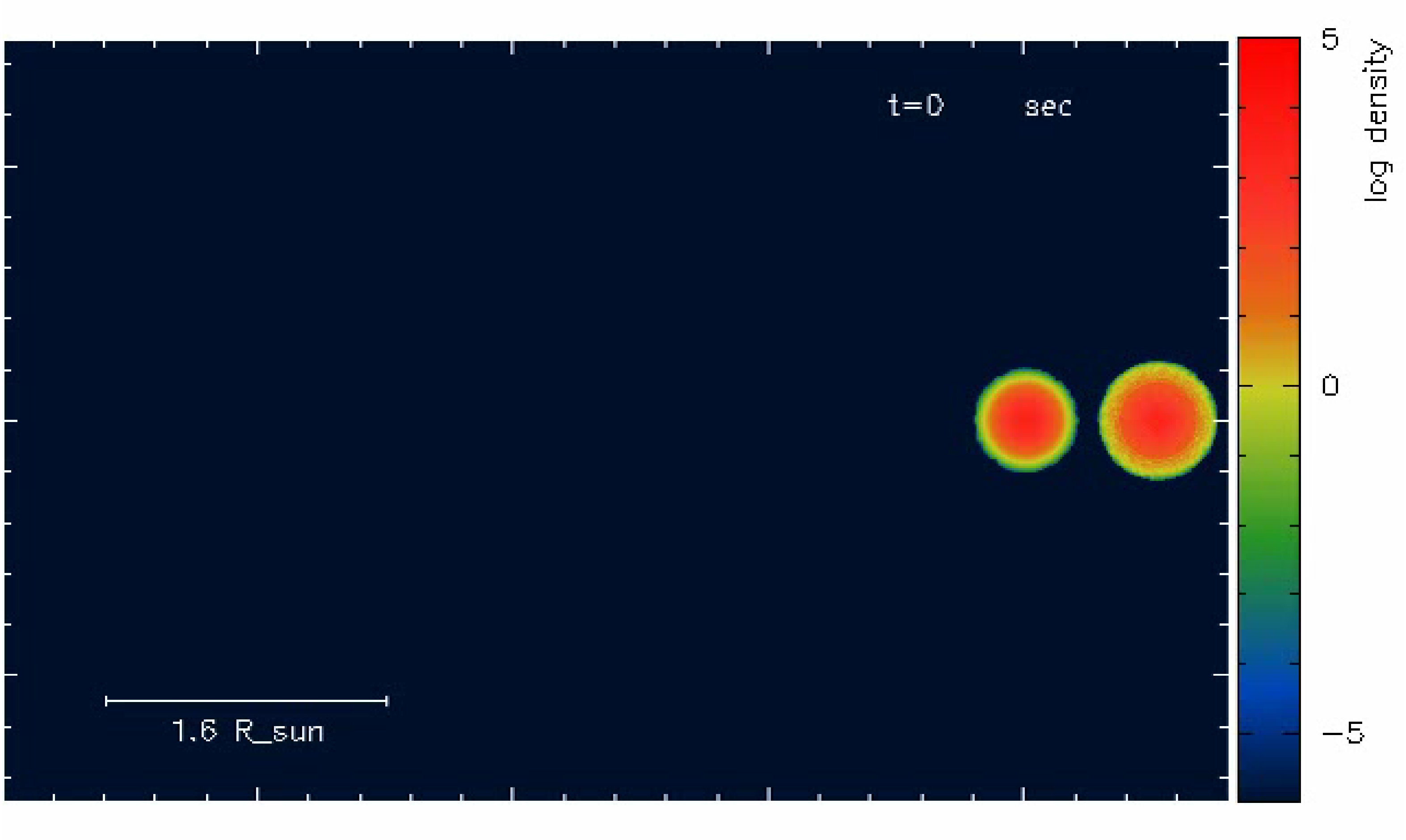
Early optical and UV emission of SNe Ia (collision with companion)

Early raido and X-ray emission of SNe Ia (collision with CSM)

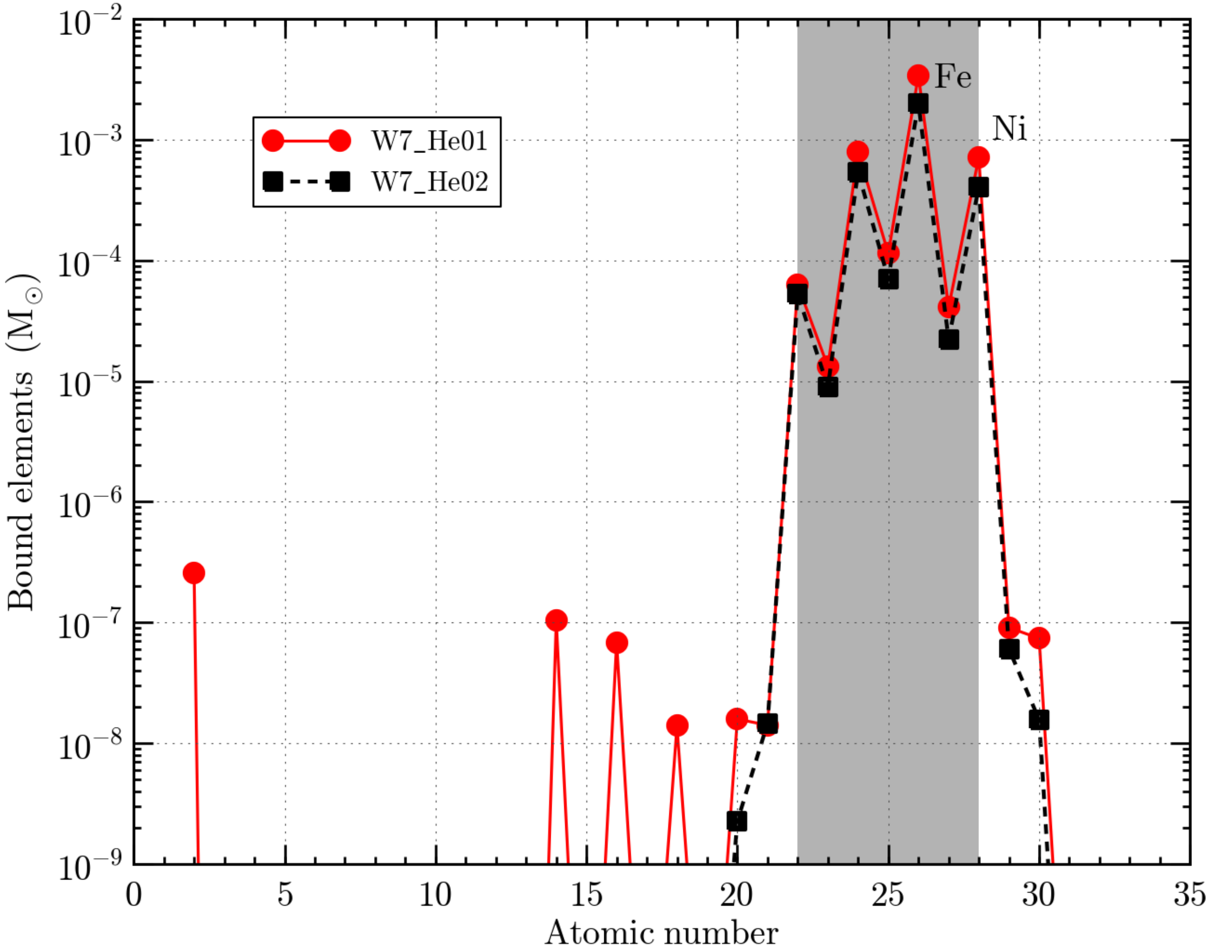
Pre-explosion images

Polarization of SNe Ia

WD+He

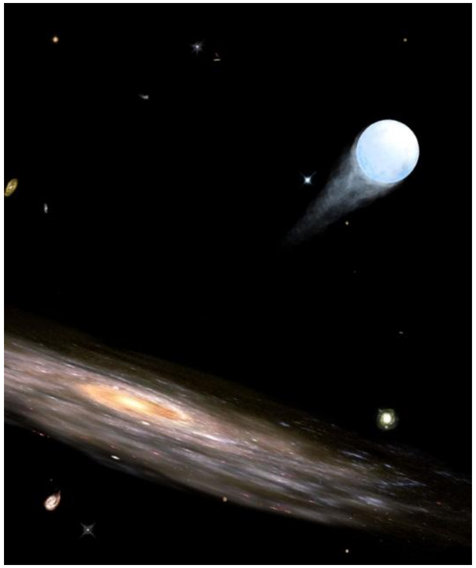


Contamination of SN ejecta onto helium star



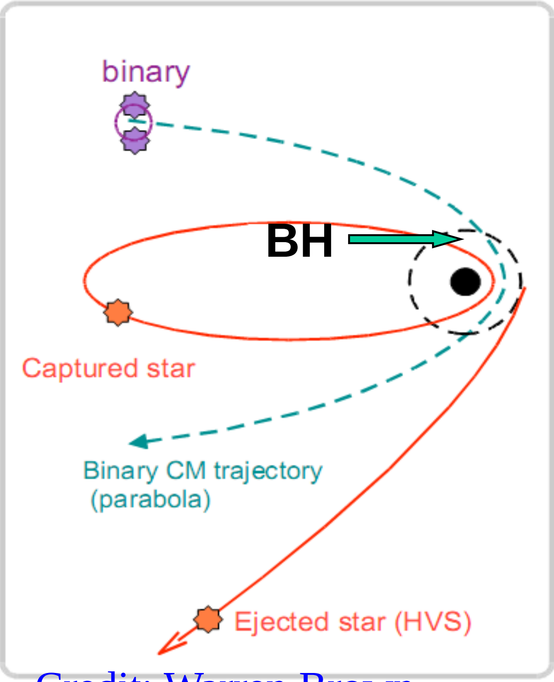
超高速星

- Discovered in 2005 (Brown et al. 2005)
- ~20
- Galactic halo
- > escape velocity



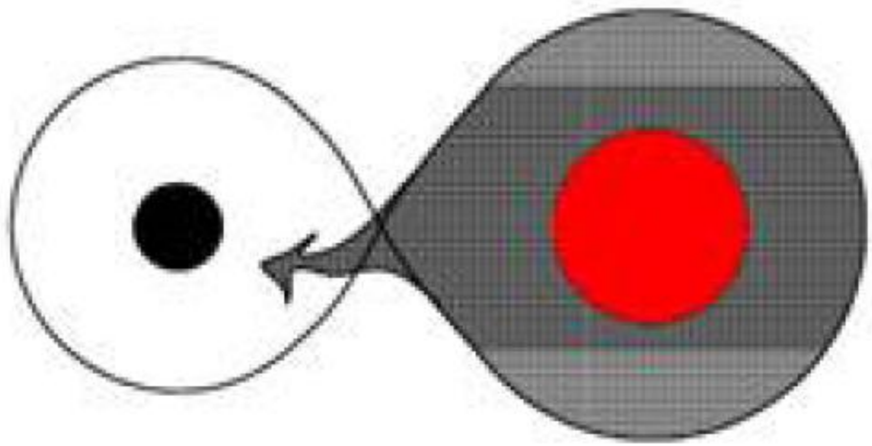
Origin?

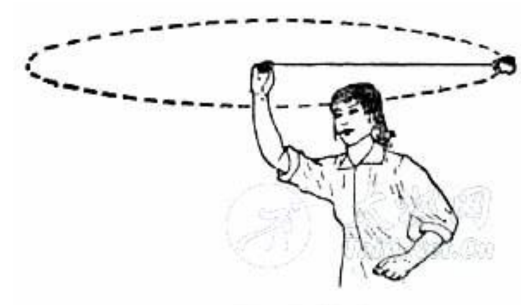
- Interaction of Binary + BH



Credit: Warren Brown

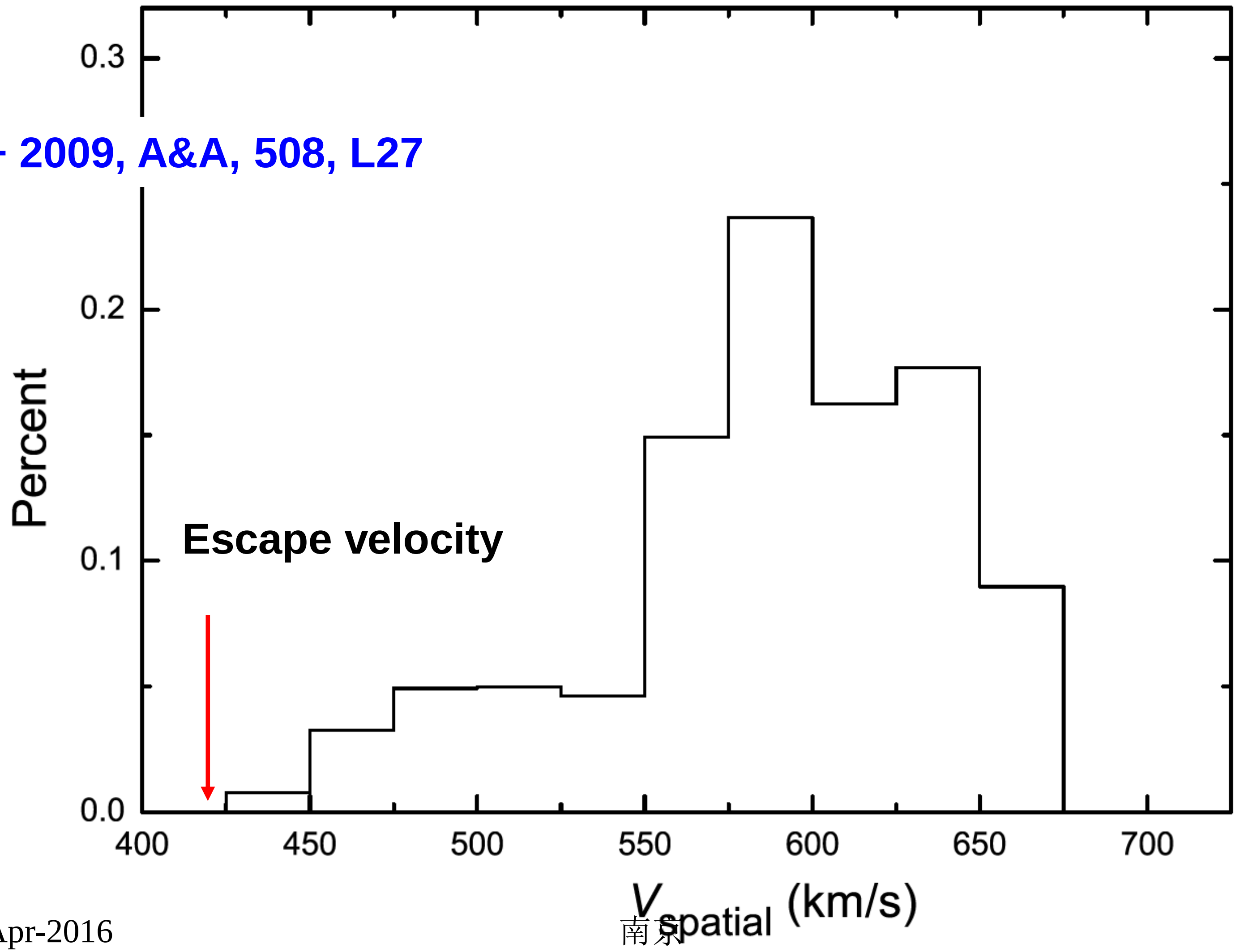
- Alternatively
  remanant star of SNe Ia from WD+He channel.





Remnant velocity distribution of SNe Ia from WD+He channel

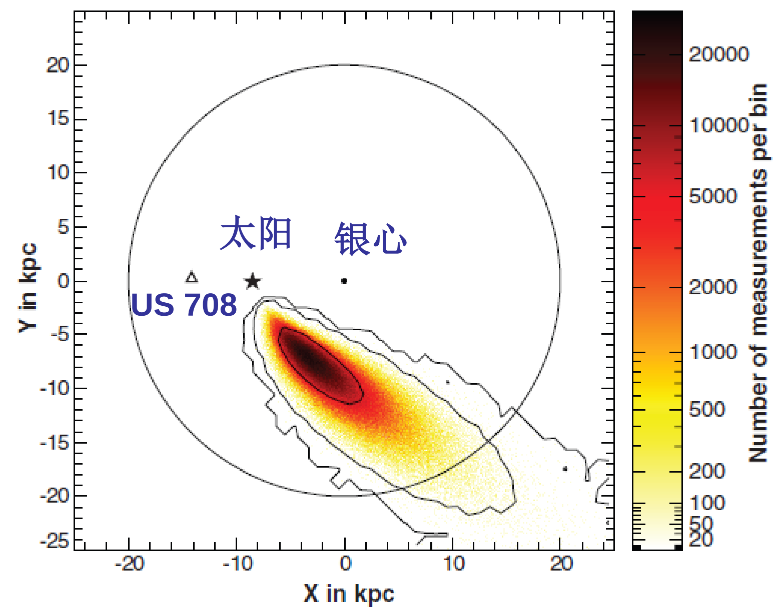
Wang+ 2009, A&A, 508, L27



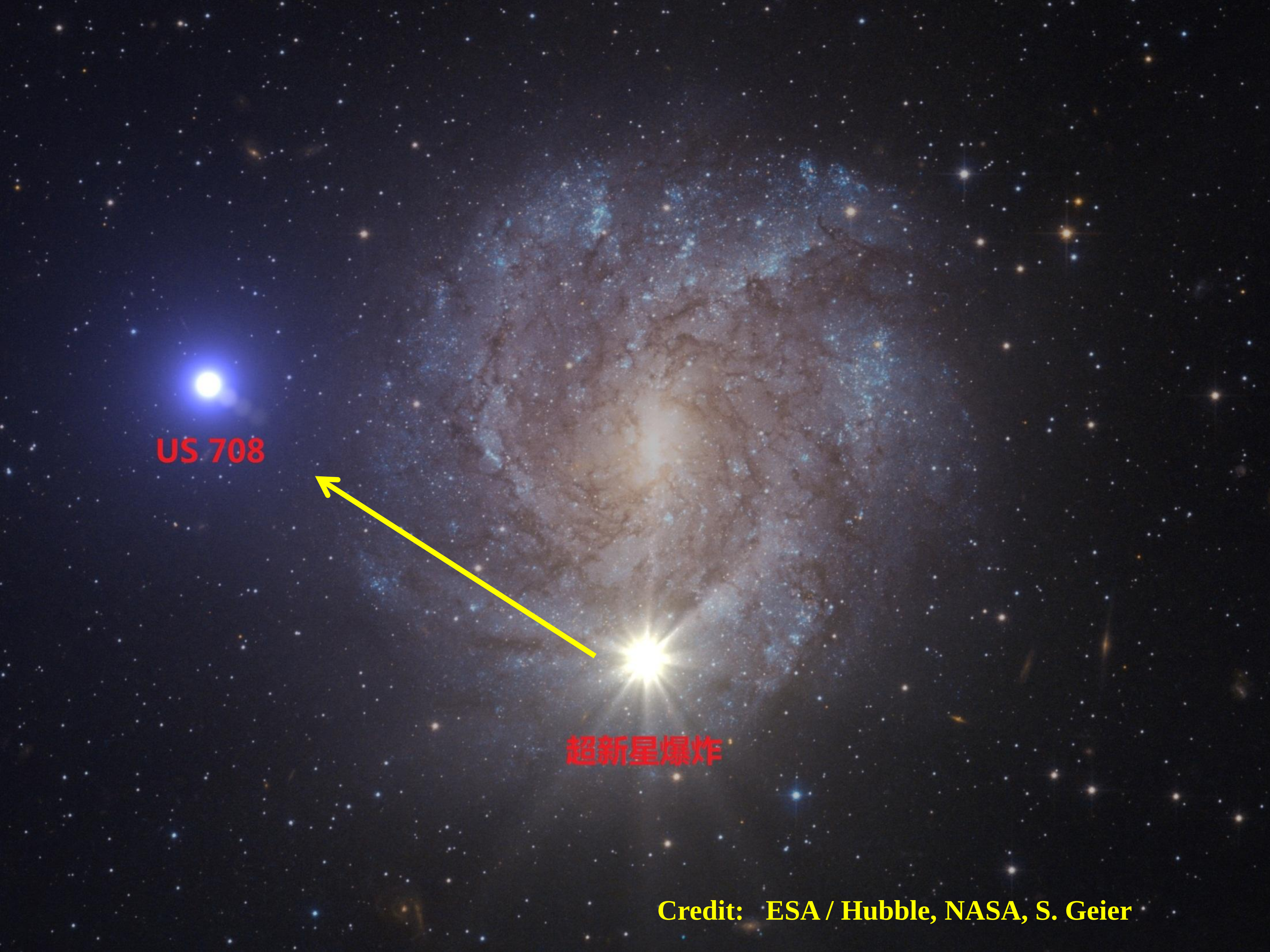
银河系最高速度超高速星的起源

The fastest unbound star in our Galaxy ejected by a thermonuclear supernova
S. Geier *et al.*
Science **347**, 1126 (2015);
DOI: 10.1126/science.1259063

US 708 is a hypervelocity helium star with a space velocity of 1200km/s，it is not from the Galactic centre.



It may be ejected by a thermonuclear supernova!
(from a WD + He system)


US 708
超新星爆炸
Credit: ESA / Hubble, NASA, S. Geier


Thanks !