Galactic Neutrinos: Linking the Dynamics of SNe

CNP Day 2023
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Introduction

Galactic CCSNe

Galactic SN rate is ~1-4 per century

The last Galactic supernova (SN) predates the invention of telescopes, neutrino detectors, and gravitational wave

Table 1. Detectable signals, detectors, and their horizons.

Signals		Extremely nearby event @ O(1 kpc) (see Section 4) Detector	Horizon	Galactic event @ O(10 kpc) (see Section 3) Detector	Horizon	Extragalactic event @ O(1 Mpc) (see Section 5) Detector	Horizon
Neutrino	Pre-SN $\bar{\nu}_e$	KamLand	<1 kpc	–		–	
		HK (20XX-)	<3 kpc				
	$\bar{\nu}_e$ burst	SK	Galaxy[a]	SK	Galaxy	*HK*	<a few Mpc
	$\bar{\nu}_e$ burst	*JUNO (201X-)*	Galaxy	*JUNO*	Galaxy	–	
	ν_e burst	*DUNE (20XX-)*	Galaxy	*DUNE*	Galaxy	–	
GW	Waveform[c]	H-L-V-K[d]	<several kpc				
	detection			H-L-V-K	$\lesssim$8.5 kpc	*ET (20XX-)*	$\lesssim$100 kpc
EM	Optical	<1 m class		1–8 m class[b]		<1 m class	
	NIR	<1 m class		<1 m class		<1 m class	

Nakamura et al. 2016

CC Supernova Progenitors

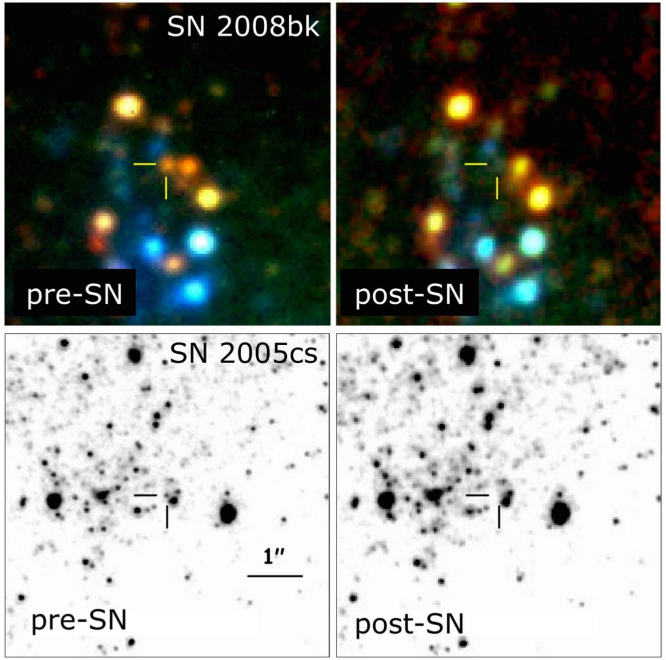


Figure 8.2. The two best cases of RSG SN progenitors detected in pre- and post-explosion imaging. Top panel: adapted from Mattila et al. (2010). The left panel shows pre-explosion VIK_s imaging of the SN 2008bk explosion site (marked with yellow crosshairs) from the VLT, combining V and I band imaging from 16 Sept 2001 with K_s imaging taken on 17 Oct 2005; the right panel shows post-explosion VIK_s imaging of the same site from the NTT, combining V and I band imaging from 16 Sep 2010 with K_s imaging from 29 Oct 2010. Bottom: reproduced from Maund et al. (2014). The left panel shows pre-explosion (0.44 years before discovery) HST ACS/WFC F814W imaging of the SN 2005cs explosion site (marked with crosshairs); the right panel shows HST ACS/WFC F814W imaging of the same site 5.09 years after the discovery of the SN.

Levesque, E. M., 2017

Pre-explosion imaging confirms low mass RSG are the direct progenitors of Type-IIP supernova

Lifetime of RSG phase: 0.5-2 Myr

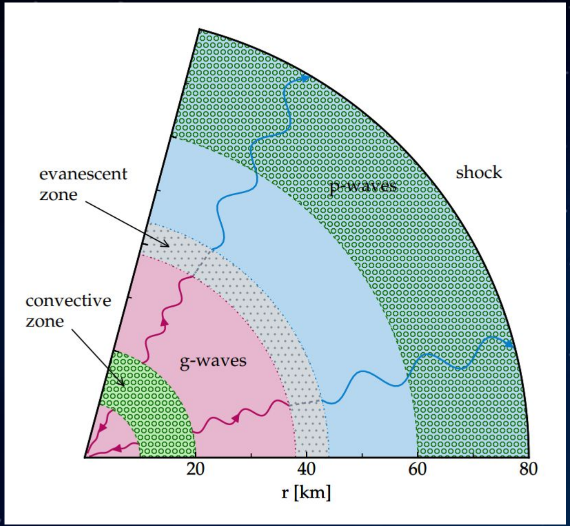
CC triggered when fusion stops and gravity takes over

How is the shock revived?

1. Neutrino mechanism E(neutrino)
   Wilson (1985), ...
2. Phase transition E(gravity)
   Migdal et al (1971), ...
3. Magneto-rotational E(rotation)
   Bisnovatyi-Kogan (1976), ...

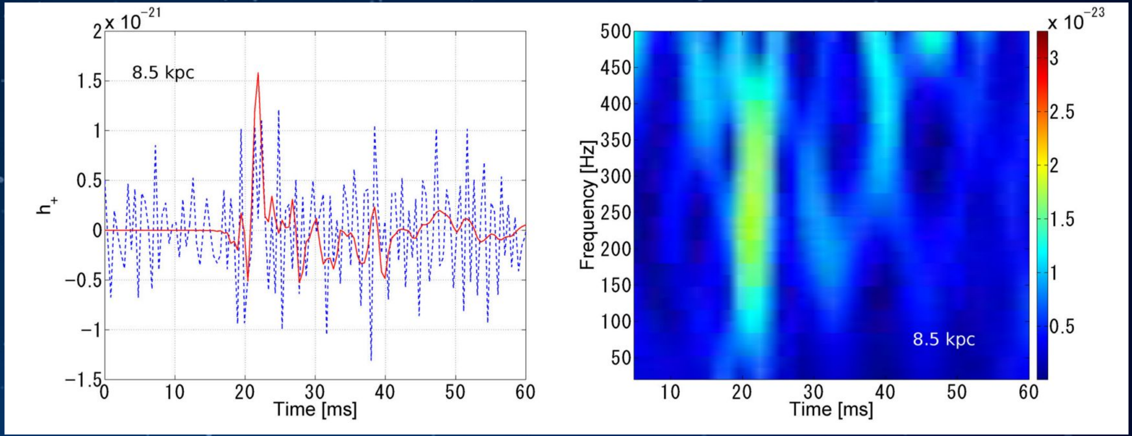
Messenger signals of CCSNe

Gravitational Waves



S. E. Gossan et al. 2019

Only a few times 10^{46} erg released as GW



Nakamura et al. 2016

Frequency range of GWs

- Mechanism of production

Epoch of first emitted GWs

- Estimates of progenitor's rotation rates

Neutrinos

Teresa Undagoitia

Properties of nuclear burning stages in a 15 $M_\odot$ star

Stage	Time Scale	Fuel or Product	Ash or Product	Temperature (10^9K)	Density (gm/cm^3)	Luminosity (solar units)	Neutrino Losses (solar units)
Hydrogen	11 My	H	He	0.035	5.8	28,000	1800
Helium	2.0 My	He	C,O	0.18	1390	44,000	1900
Carbon	2000 y	C	Ne,Mg	0.81	2.8×10^5	72,000	3.7×10^5
Neon	0.7 y	Ne	O,Mg	1.6	1.2×10^7	75,000	1.4×10^8
Oxygen	2.6 y	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,C r,Ti…	Neutron Star	> 7.1	$>7.3 \times 10^9$	75,000	$>3.6 \times 10^{15}$

Woosley and Janka 2005

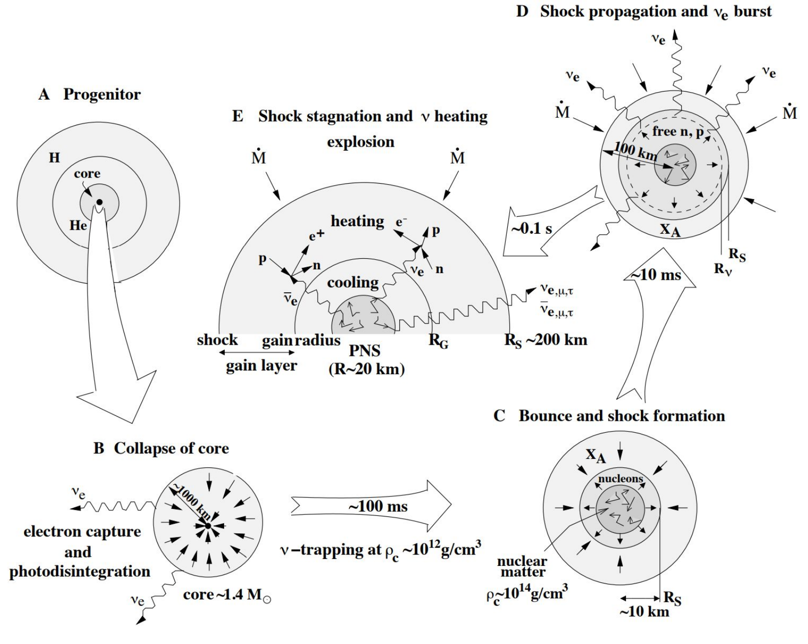


Figure 3. Scheme of a supernova explosion. Figure from F. Kitaura.

Synthesized in the hot, innermost regions → Insights into the unobservable physical processes that initiate the blast

EM Waves

Reveal information about the SN ejecta and the environment

IR

- Nature and spatial distribution of the dust grains

Radio and X-ray

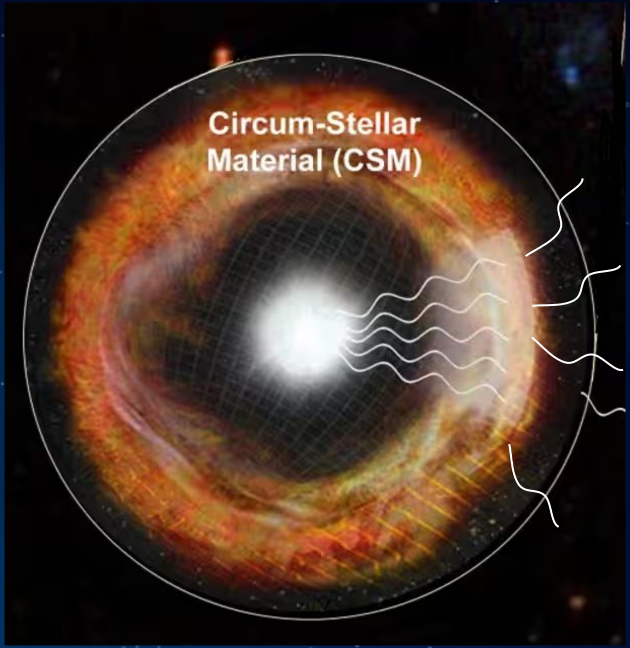
- Mass-loss rates of the progenitor

Spectra

- Line width - wind velocity of the progenitor
- Line strength - relative abundances of the elements in the wind

CSM ionization state

- Amount of ionizing radiation emitted by the explosion



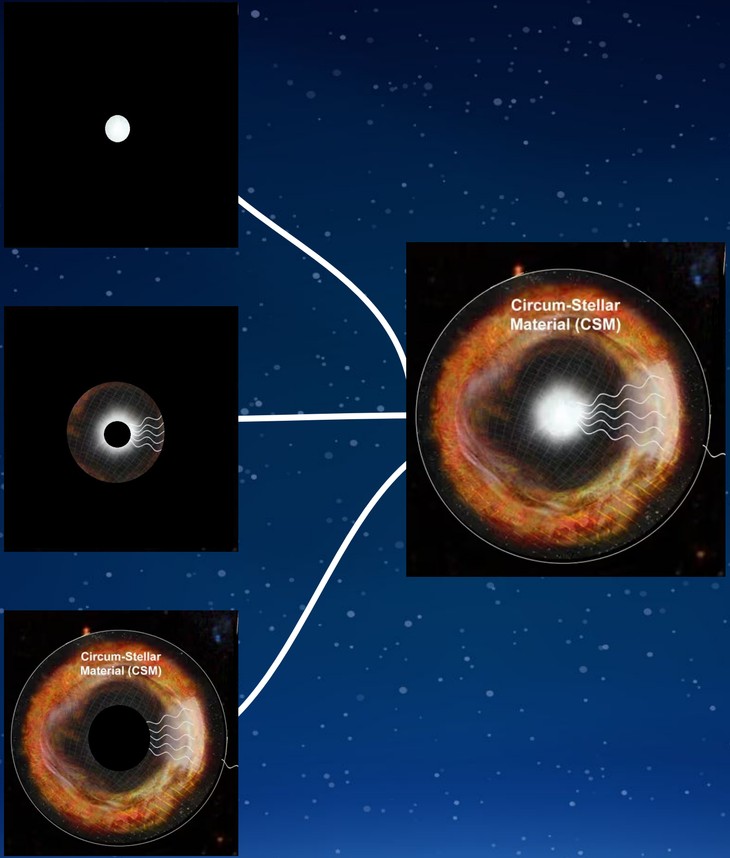
Adapted from Ofer Yaron

Completing the Picture

Gravitational Waves

Neutrinos

Electromagnetic Waves



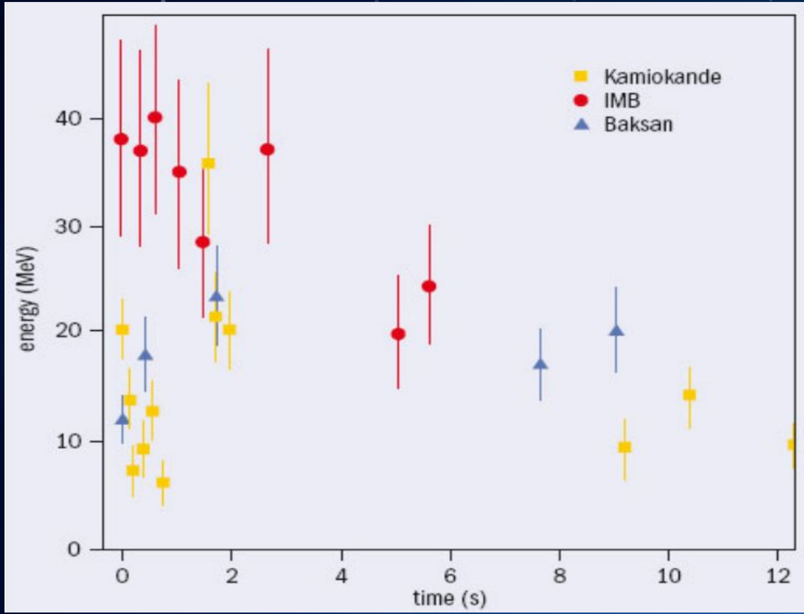
This science cannot be tested with extra-galactic SN

The absolute majority of the supernovae have so far been observed only through their EM signature

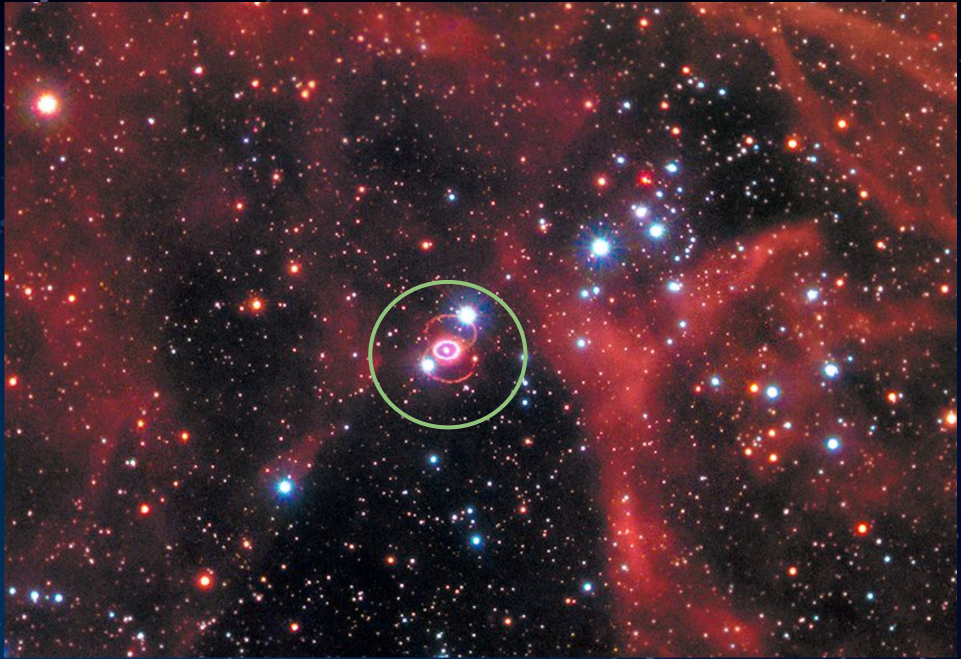
Supernova 1987A

Occurred in LMC

Blue supergiant progenitor



CERN courier



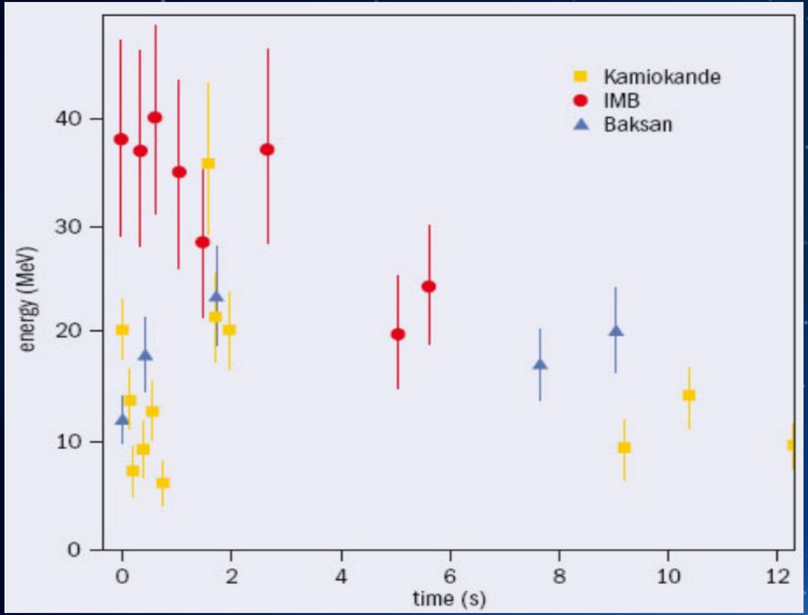
HST, NASA, ESA

Detections in EM waves including X-rays, γ-rays, and neutrinos

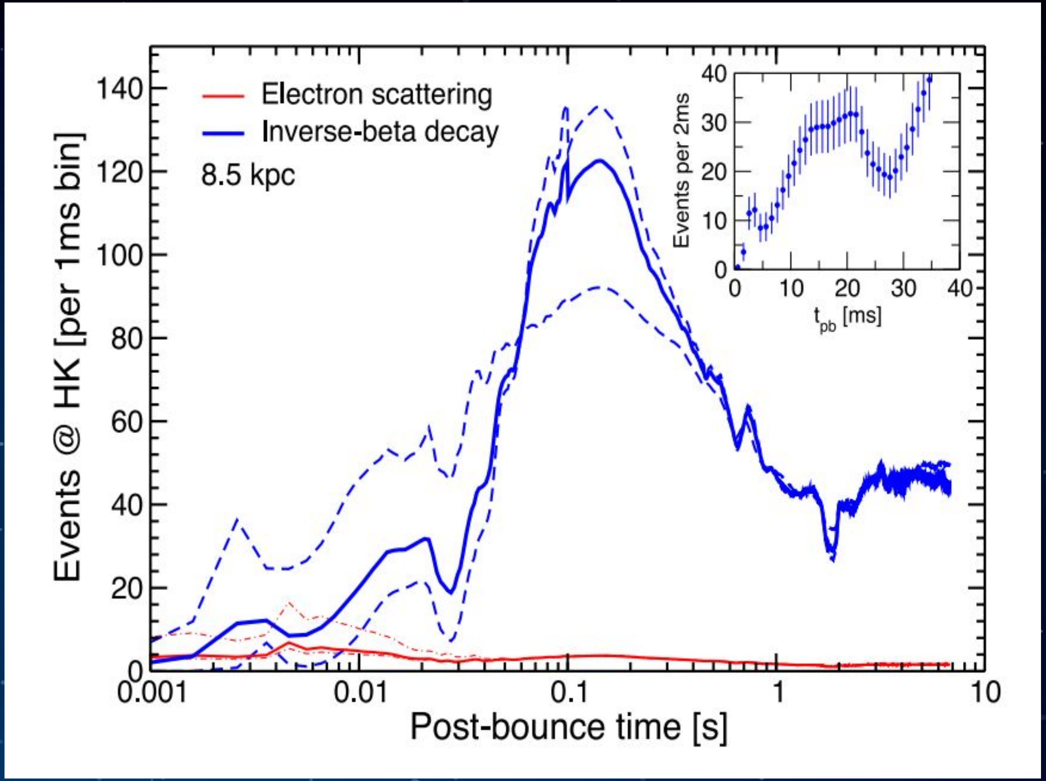
Supernova 1987A

Occurred in LMC

Blue supergiant progenitor



CERN courier

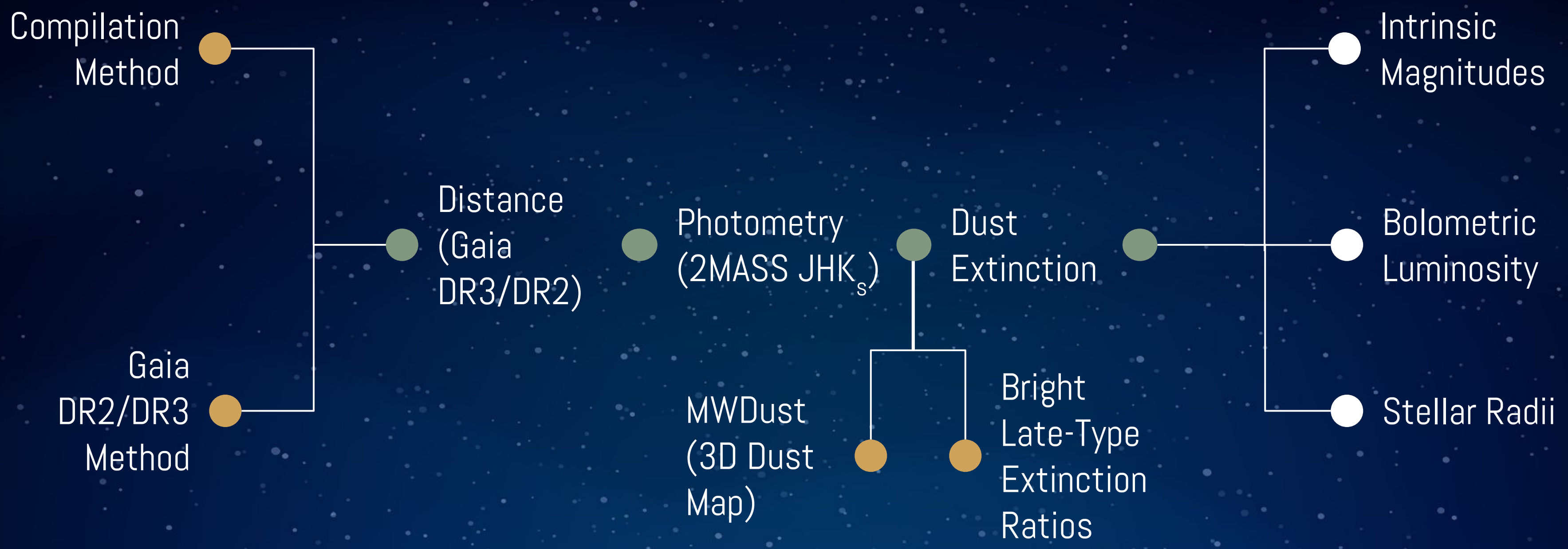


Nakamura et al. 2016

Detections in EM waves including X-rays, γ-rays, and neutrinos

What we are doing to prepare

Compiling List of Progenitors



$$BC_{K_s} = 5.574 - 0.7589\left(\frac{T_{eff}}{1000}\right)$$

$$M = m - 5\log_{10}\left(\frac{D}{10}\right)$$

$$M_{Bol} = M_{K_s} + BC_{K_s}$$

$$\log_{10}\left(\frac{L}{L_\odot}\right) = -\frac{(M_{Bol} - 4.8)}{2.5}$$

Multimessenger Astronomy

SNEWS SUPERNOVA EARLY WARNING SYSTEM & aavso

Interpretation of joint observation of multiple messengers to optimize science

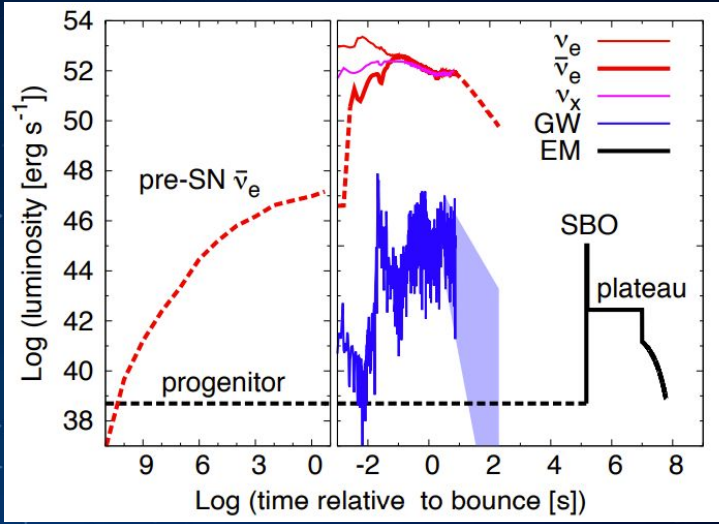
SuperNova Early Warning System (SNEWS)

- First established multi-messenger networks
- Uses supernova neutrinos

American Association of Variable Star Observers (AAVSO)

- Monitoring candidates long before collapse

Warning is imperative to getting complete observations of progenitors and SNe



Nakamura et al. 2016

Neutrino Triangulation

The supernova can be pointed to by use of multiple detectors around the earth and relative timing of signals

Needs for calculation

- Large statistics
- High flux component of the signal

Needs for detection

- coordination between multiple detectors or future mega-detectors

Two detectors:

gives ring on the sky in which the supernova is located

Three detectors:

Location of the supernova is given as two spots

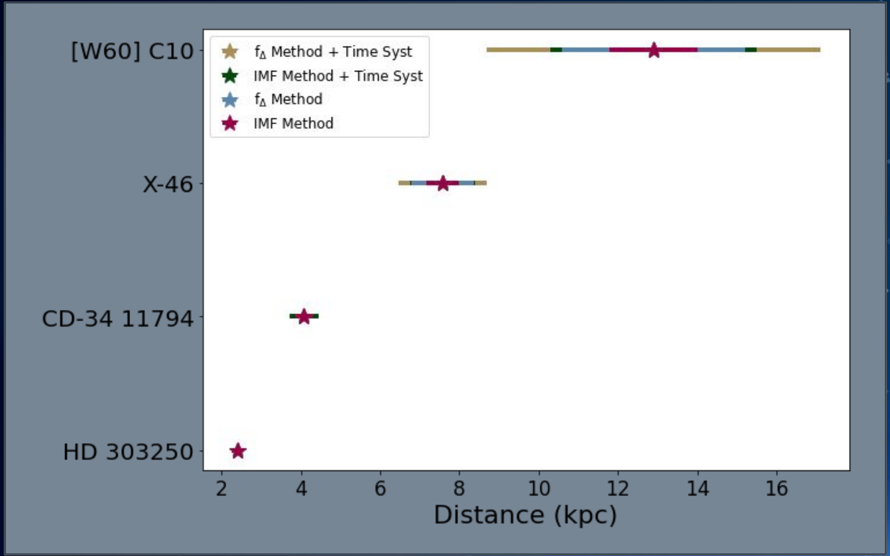
Four detectors:

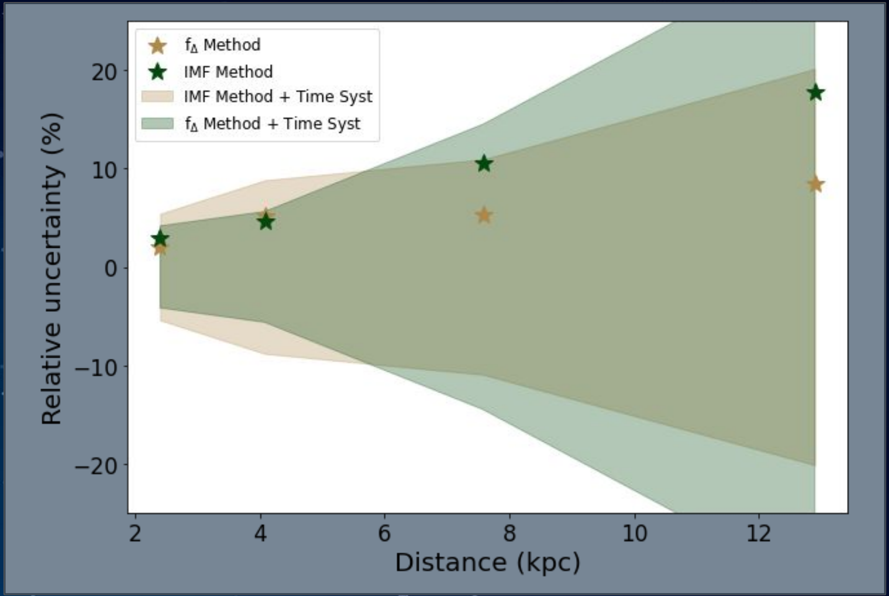
A single spot on the sky determines location

Distance Estimates from Neutrinos

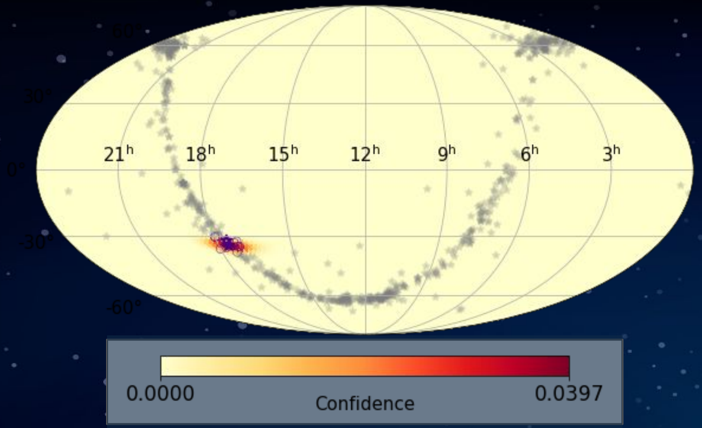
Two method utilized in snewpdag

1. IMF Method
   Compares the observed number of events (n_{50}) to the expected value weighted over the initial mass function

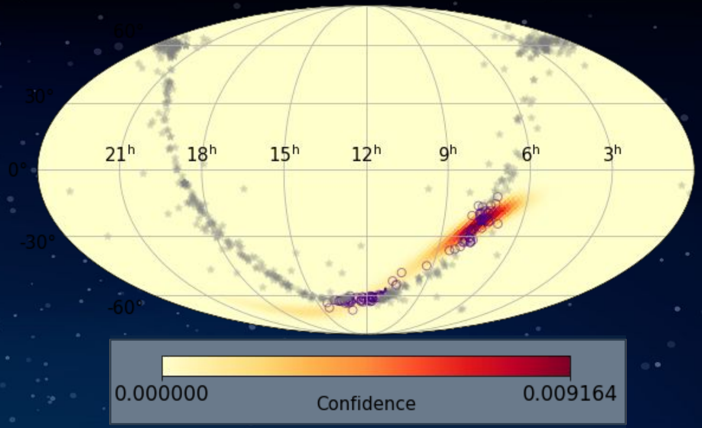




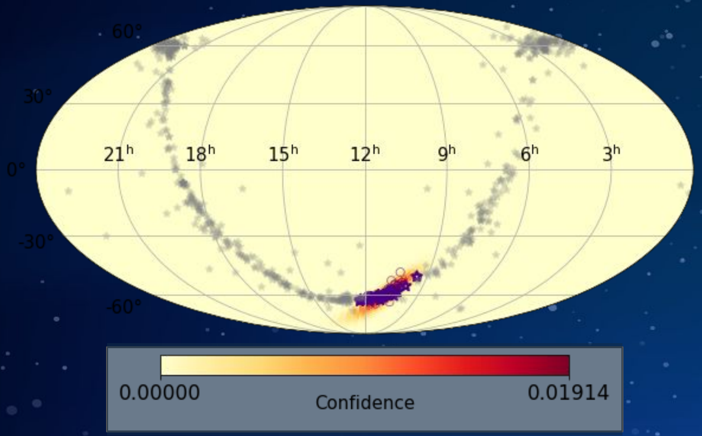
2. The f_Δ Method
   Compares $f_\Delta = N(50)/N(100\text{-}150)$ and its linear relation with n_{50}



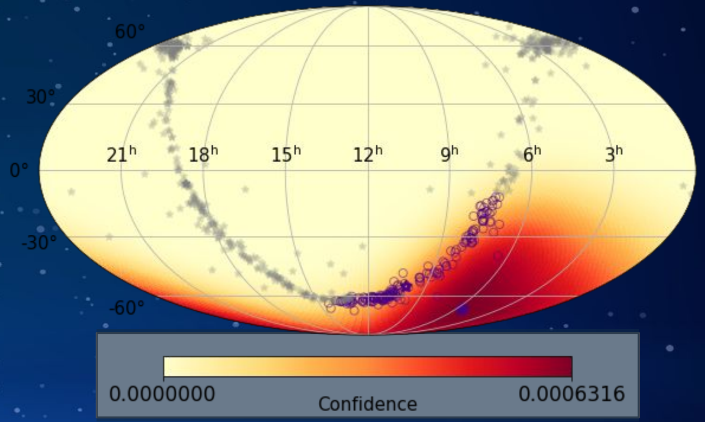
Calculations based on CD-34 11794 (263°, -34°, and 4.1 kpc) as the progenitor. 13 stars lie within the 90% credible region with 2 of those matching the combined distance estimation and angular resolution.



Calculations based on X-46 (113°, -22° and 7.6 kpc) as the progenitor. 105 stars lie within the 90% credible region with 2 of those matching the combined distance estimation and angular resolution.



Calculations based on HD 303250 (161°, -58°, and 2.4 kpc) which lies within cluster CAR OB1 as the progenitor. 85 stars lie within the 90% credible region with 20 of those matching the combined distance estimation and angular resolution.



Calculations based on [W60] C10 (83°, -67°, 12.9 kpc) as the progenitor. 186 stars lie within the 90% credible region with 3 of those matching the combined distance estimation and angular resolution.

Summary

The next galactic SN gives us the chance to gain the most complete data set for CCSN.

EM waves, Neutrinos, and gravitational waves together give a complete picture of the SN

We have prepared by compiling a list of possible candidates, and worked with SNEWS to inform their coincidence network, including pointing and distance estimations.

Extra Slides

Neutrino Pointing

Neutrino burst signal can be used for pointing

Does require two things:

1. The interaction detected to have an intrinsic directionality
2. The detector being able to exploit that directionality

Channel	Observable(s)
$\nu_x + e^- \rightarrow \nu_x + e^-$	C
$\bar{\nu}_e + p \rightarrow e^+ + n$	C, N, A

Neutrino-Electron elastic scattering

- Most promising method
- Electron gets kicked in the direction of the neutrino
- Photon can be detected
- Relatively small cross section

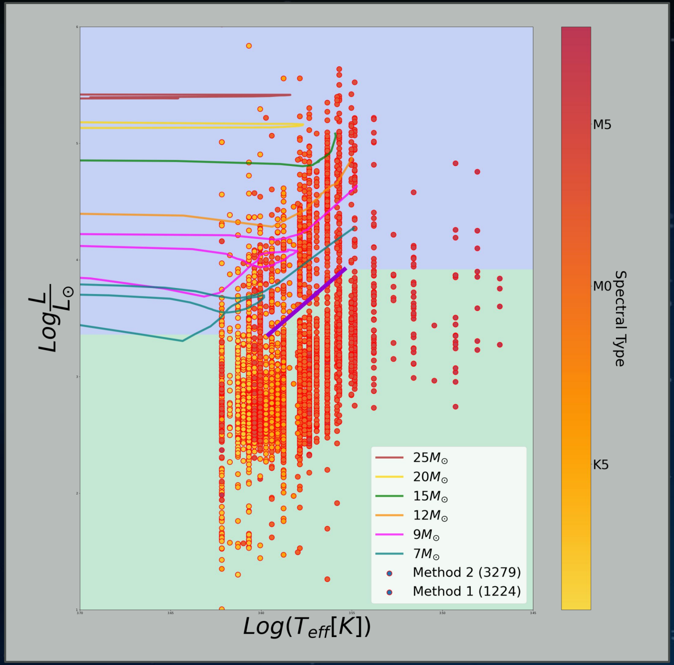
We compiled a catalog of 676 Milky Way RSGs candidates

- Using two complementary methods for obtaining T_{eff}
- Determined bolometric luminosity
- Compared to stellar evolutionary tracks and galactic AGB surveys
- Took into account uncertainties (79)

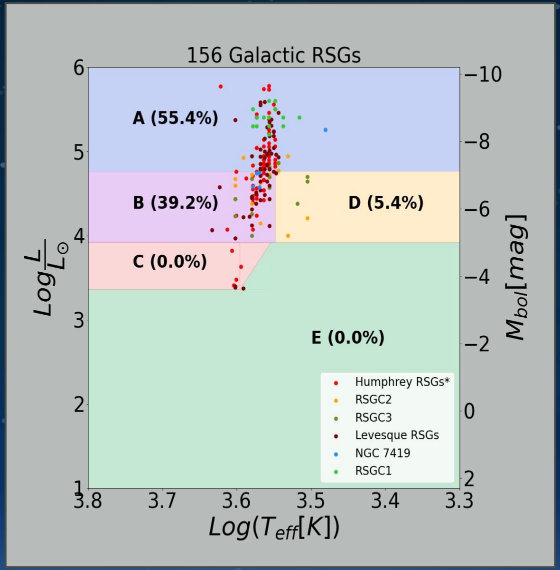
Included details of each star's known characteristics

Exploration of the RSG's stellar radii range and mass-loss rates match predicted values and its spatial distribution shows current limitations

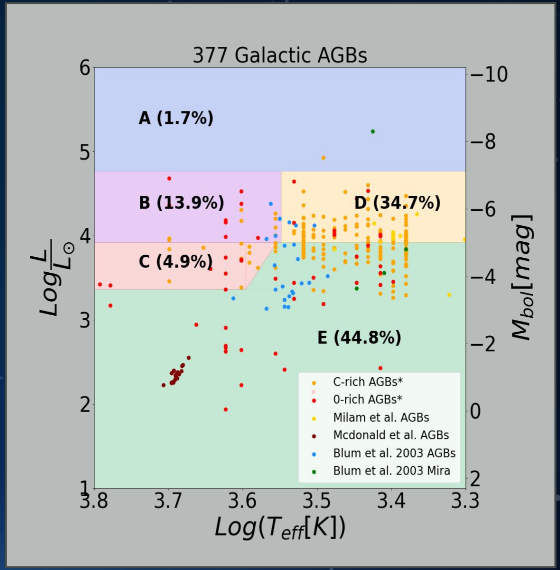
In combination with the intense neutrino burst from CC, our RSG catalog can help in prioritizing locations to observe



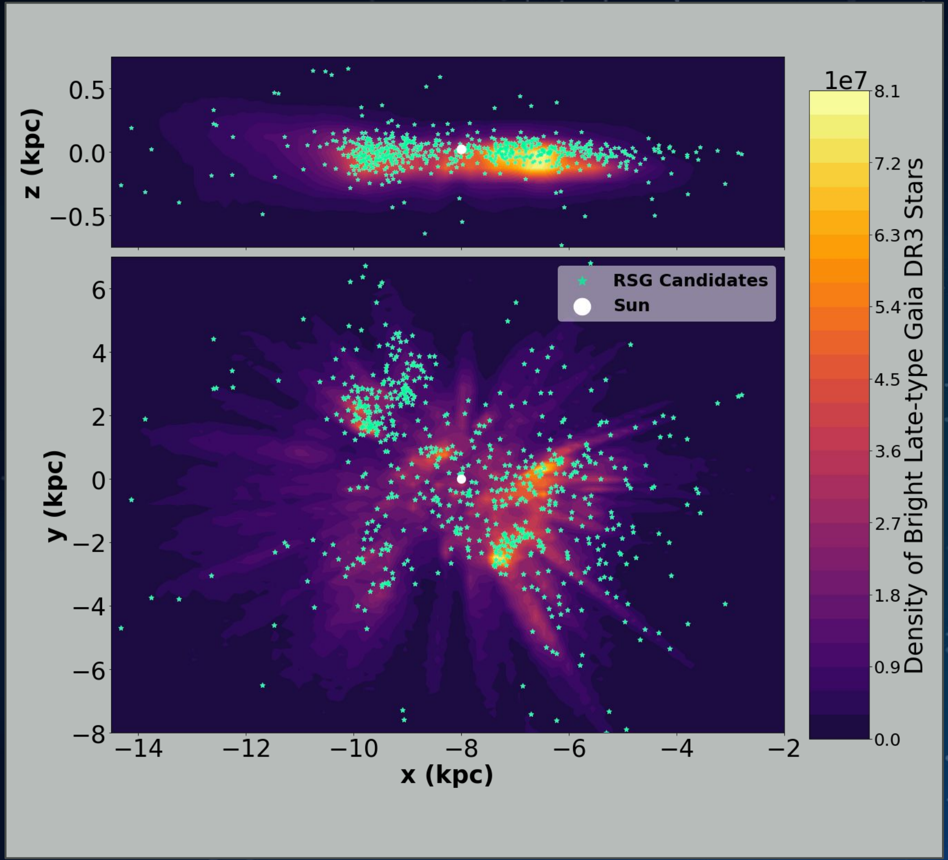
25$M_\odot$
20$M_\odot$
15$M_\odot$
12$M_\odot$
9$M_\odot$
7$M_\odot$
Method 2 (3279)
Method 1 (1224)
M5
M0
K5
Spectral Type
$Log\frac{L}{L_\odot}$
$Log(T_{eff}[K])$

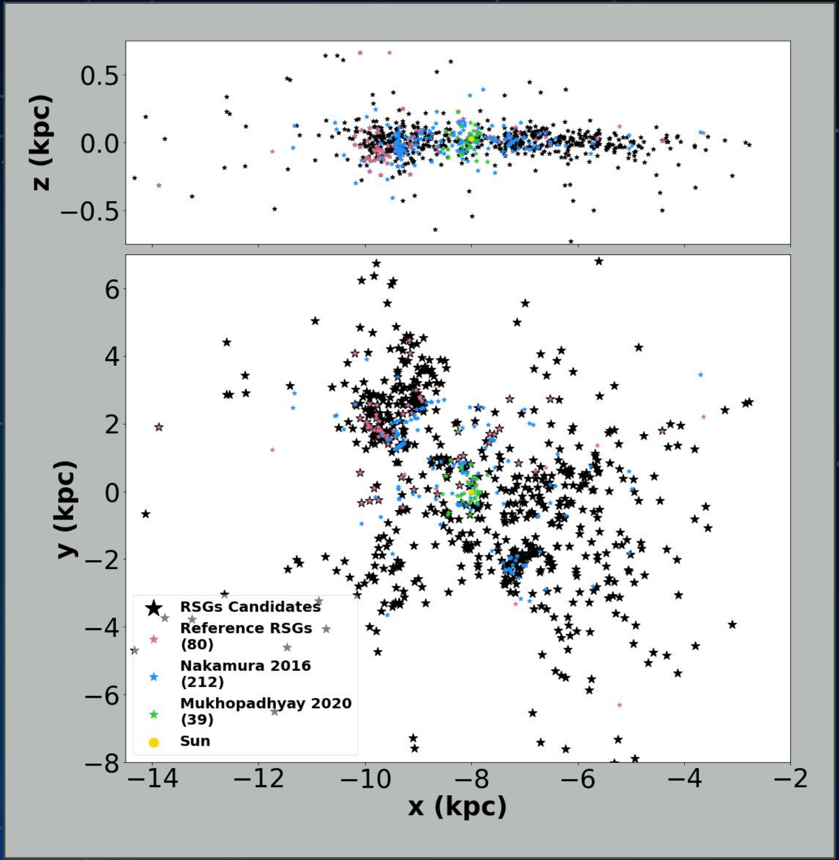


156 Galactic RSGs
A (55.4%)
B (39.2%)
C (0.0%)
D (5.4%)
E (0.0%)
Humphrey RSGs*
RSGC2
RSGC3
Levesque RSGs
NGC 7419
RSGC1
$Log\frac{L}{L_\odot}$
$M_{bol}[mag]$
$Log(T_{eff}[K])$



377 Galactic AGBs
A (1.7%)
B (13.9%)
C (4.9%)
D (34.7%)
E (44.8%)
C-rich AGBs*
0-rich AGBs*
Milam et al. AGBs
Mcdonald et al. AGBs
Blum et al. 2003 AGBs
Blum et al. 2003 Mira
$Log\frac{L}{L_\odot}$
$M_{bol}[mag]$
$Log(T_{eff}[K])$


z (kpc)
y (kpc)
x (kpc)
RSG Candidates
Sun
1e7
Density of Bright Late-type Gaia DR3 Stars


z (kpc)
y (kpc)
x (kpc)
RSGs Candidates
Reference RSGs (80)
Nakamura 2016 (212)
Mukhopadhyay 2020 (39)
Sun