POINTING WITH PRESUPERNOVA NEUTRINOS

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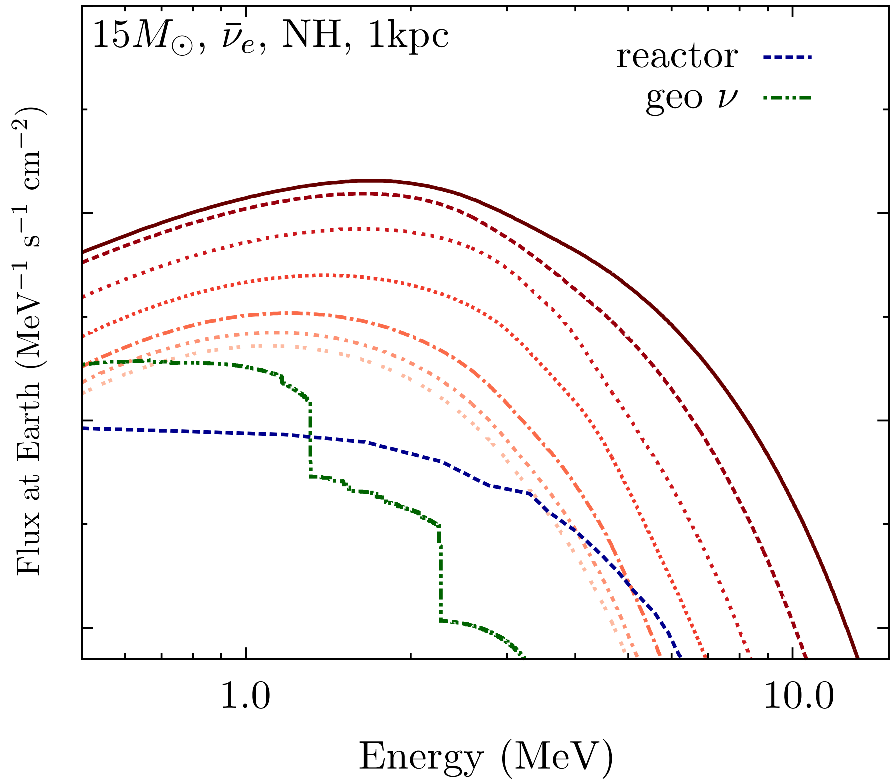
M. Mukhopadhyay, C. Lunardini, F. X. Timmes and K. Zuber,
arXiv:2004.02045, accepted in ApJ.

Introduction

See Chinami Kato's talk at Neutrino2020

Presupernova → collapse → explosion

- Neutrinos from advanced stages of nuclear burning
  - Thermal (pair production)
  - Beta processes (capture, decay)
- 0.1-5 MeV energy
  - Need low threshold detector
- Detectable hours (days?) before collapse neutrinos
  - For near-earth stars (D<1 kpc)



Patton, Lunardini, Farmer & Timmes, 2017, ApJ, 851, 6

Why localization?

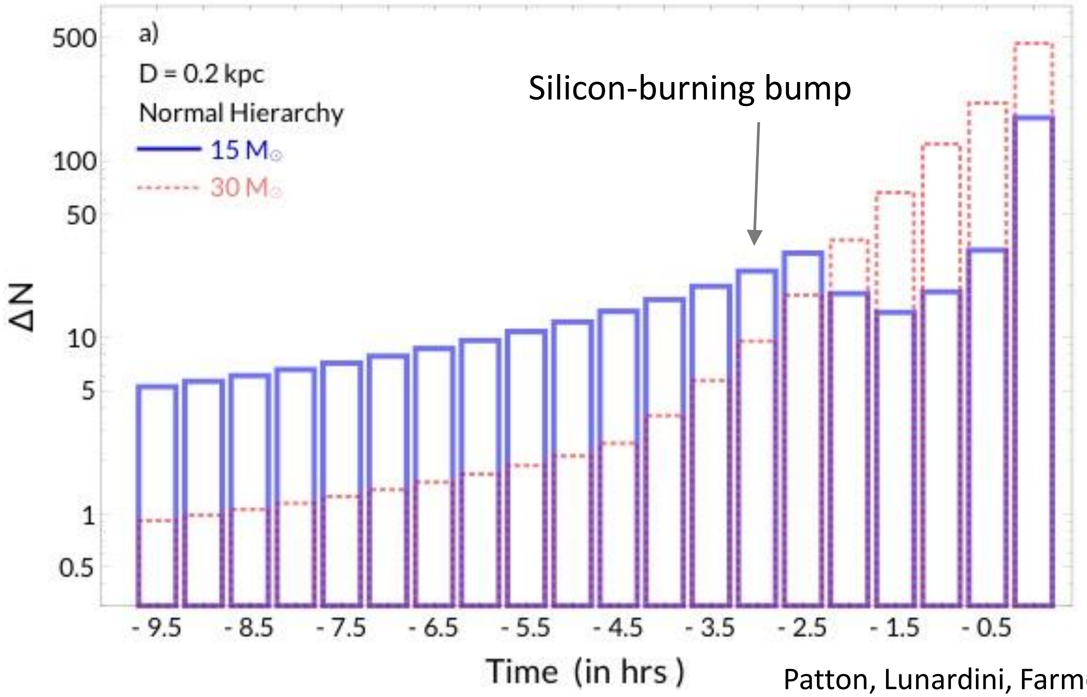
- Rough pointing + list of nearby stars = potential for *progenitor identification*

Li, Li, Wen, & Zhou, 2020, arXiv:2003.03982

- **Motivation 1**: early alert *of collapse*
  - observe a star before and during collapse to test stellar evolution
  - Prepare GW detectors
  - Prepare to observe exotic physics during collapse (e.g., point axion detectors)

- **Motivation 2**: *very early alert* of supernova explosion (or black hole formation)
  - precedes the neutrino burst by hours: useful for decision-making (esp. when human intervention is needed)
  - Can be the *only* useful alert for fast-exploding stars (less than 1 hour from collapse to explosion)

Signal at liquid scintillator detector



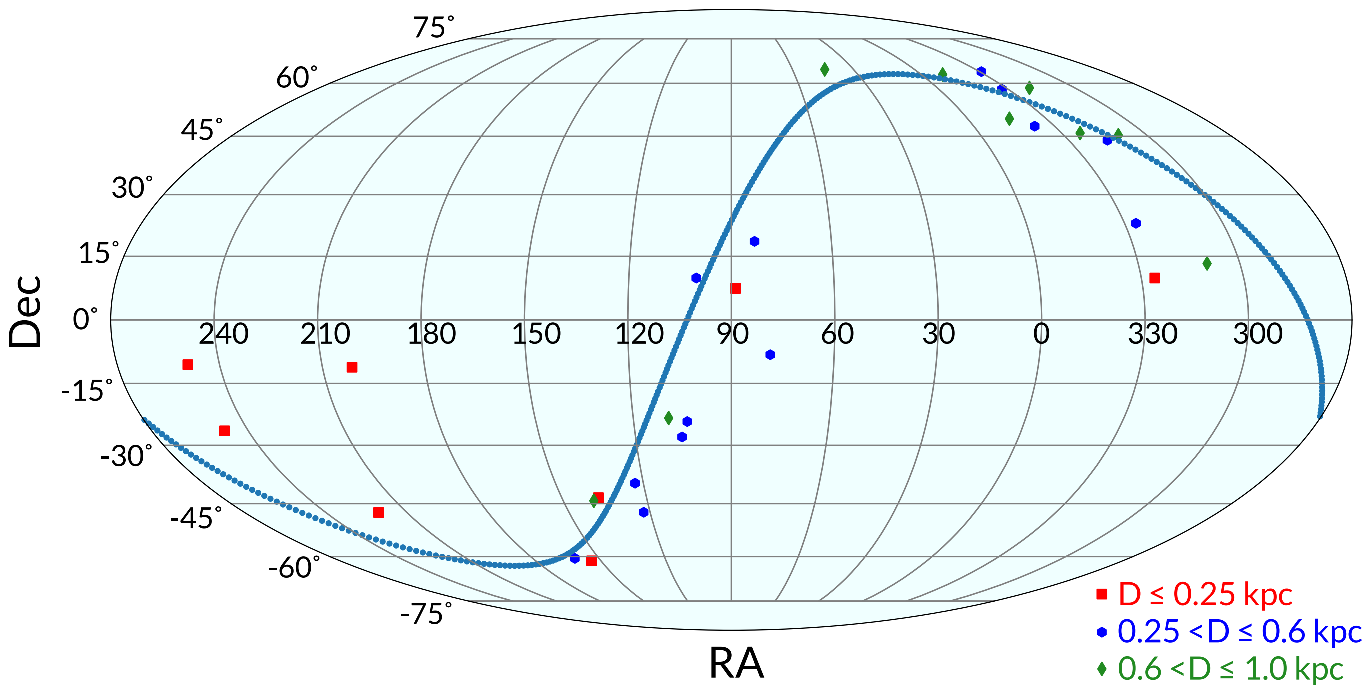
Patton, Lunardini, Farmer & Timmes, 2017, ApJ, 851, 6

- JUNO-like detector (17 kt), inverse beta decay (IBD): $\bar{\nu}_e + p \rightarrow n + e^+$
  - E > 1.8 MeV threshold
  - Background: 2.6 events/hour in reactor-on phase

An, An, An, et al. 2016, Journal of Physics G Nuclear Physics, 43, 030401

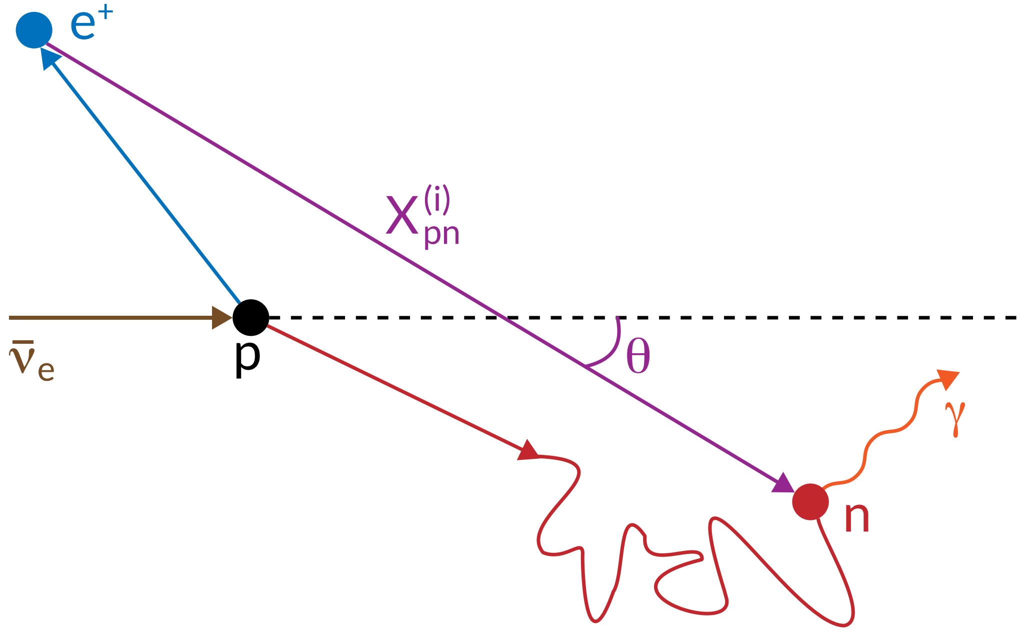
Nearby stars

- 31 supernova-ready stars at D<1 kpc
  - Known distance, mass and type



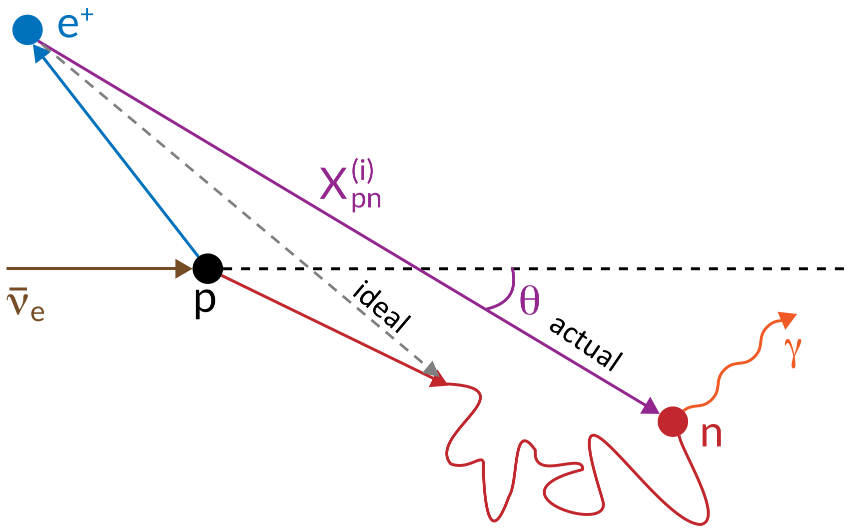
The method

Directionality of IBD



- $X^{(i)}_{pn}$: vector from e^+ annihilation point to n capture point

Experimental sensitivity



- LS : Linear AlkylBenzene (SNO+, JUNO)
  - Directionality limited by neutron thermalizing before capture
  - Resolution of e^+ annihilation also important

- LS-Li : LS with Lithium salts for faster n capture: $^6\text{Li} + n \rightarrow t\,(2.73\ \text{MeV}) + \alpha$
  - Enhanced directionality by shortening neutron capture range

Tanaka & Watanabe, 2014, Scientific Reports, 4, 4708

Key quantities

- N_S : IBD signal events from point source
- N_{Bkg} : background events ; *assumed isotropic*

- Signal-to-background ratio: $\alpha = N_S / N_{\mathrm{Bkg}}$

- **F**orward ($\theta < \pi/2$)-**B**ackward ($\theta > \pi/2$) asymmetry:

$$\frac{a}{2} = \frac{(N_{F,S} + N_{F,\mathrm{Bkg}}) - (N_{B,S} + N_{B,\mathrm{Bkg}})}{(N_{F,S} + N_{F,\mathrm{Bkg}}) + (N_{B,S} + N_{B,\mathrm{Bkg}})}$$

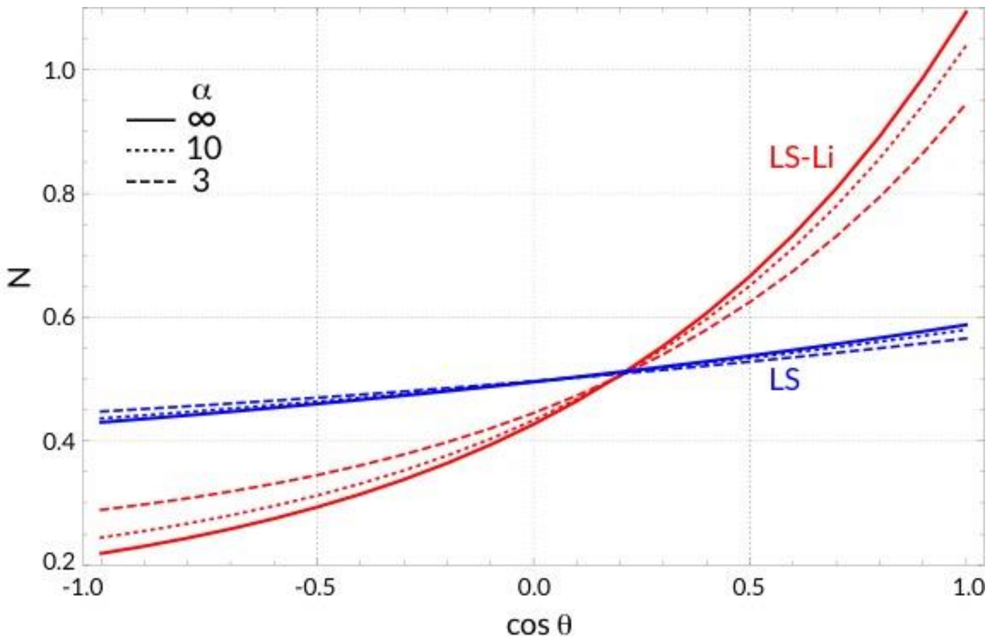
$$N_{B,S} = \frac{N_S}{2}\left(1 - \frac{a_0}{2}\right) \qquad N_{F,S} = \frac{N_S}{2}\left(1 + \frac{a_0}{2}\right)$$

Directional IBD signal

$$N_{B,\mathrm{Bkg}} = \frac{N_{\mathrm{Bkg}}}{2} \qquad N_{F,\mathrm{Bkg}} = \frac{N_{\mathrm{Bkg}}}{2}$$

Isotropic background

Directionality: low-to-moderate



	Forward-Backward asymmetry	
↵	LS	LS-Li
1	0.1580	0.7820
10.0	0.1418	0.7165
3.0	0.1170	0.5911

Tanaka & Watanabe, 2014, Scientific Reports, 4, 4708
For geoneutrinos (similar spectrum as pre-SN)

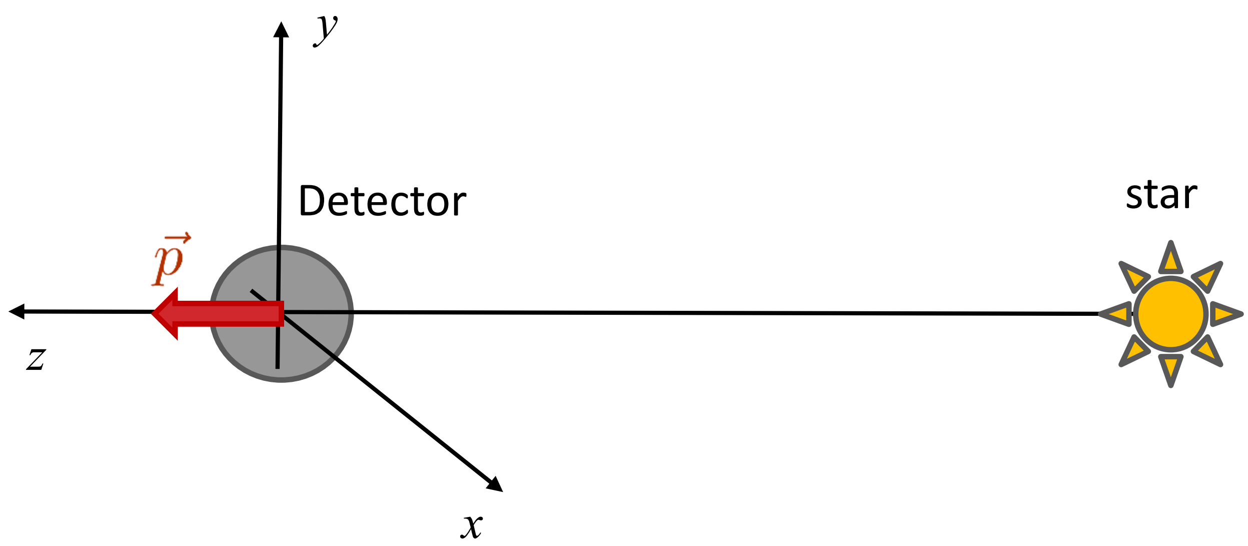
Localization - estimating signal direction

Apollonio, Baldini, Bemporad, et al. 2000, PhRvD, 61, 012001

1. Best estimate of arrival direction: average of unit vectors

$$\vec{p} = \frac{1}{N} \sum_{i=1}^{N} \hat{X}_{pn}^{(i)} \qquad (i = 1, 2, \ldots, N)$$

2. Set direction of p-vector as new z-axis:



Localization – find uncertainty angle β

- Use linearized distribution for cos θ: $f(\cos\theta) = \frac{1}{2}\left(1 + a\cos\theta\right)$

- Study statistical behavior of p-vector:
  - *Mean:*

$$\vec{p}_m = (0, 0, |\vec{p}|) = (0, 0, a/3)$$

  - *Standard deviation:* take distribution of X_{pn} and apply Central Limit theorem to the components of p-vector

$$\sigma_x = \sigma_y = \sigma_z = \sigma = 1/\sqrt{3N}$$

(Note: minor dependence of σ_z on *a* is neglected here)

- Take 3D Gaussian distribution and find cone that contains a given probability:

$$P(p_x, p_y, p_z) = \frac{1}{\left(2\pi\sigma^2\right)^{\frac{3}{2}}} \exp\left(\frac{-p_x^2 - p_y^2 - (p_z - |\vec{p}|)^2}{2\sigma^2}\right)$$

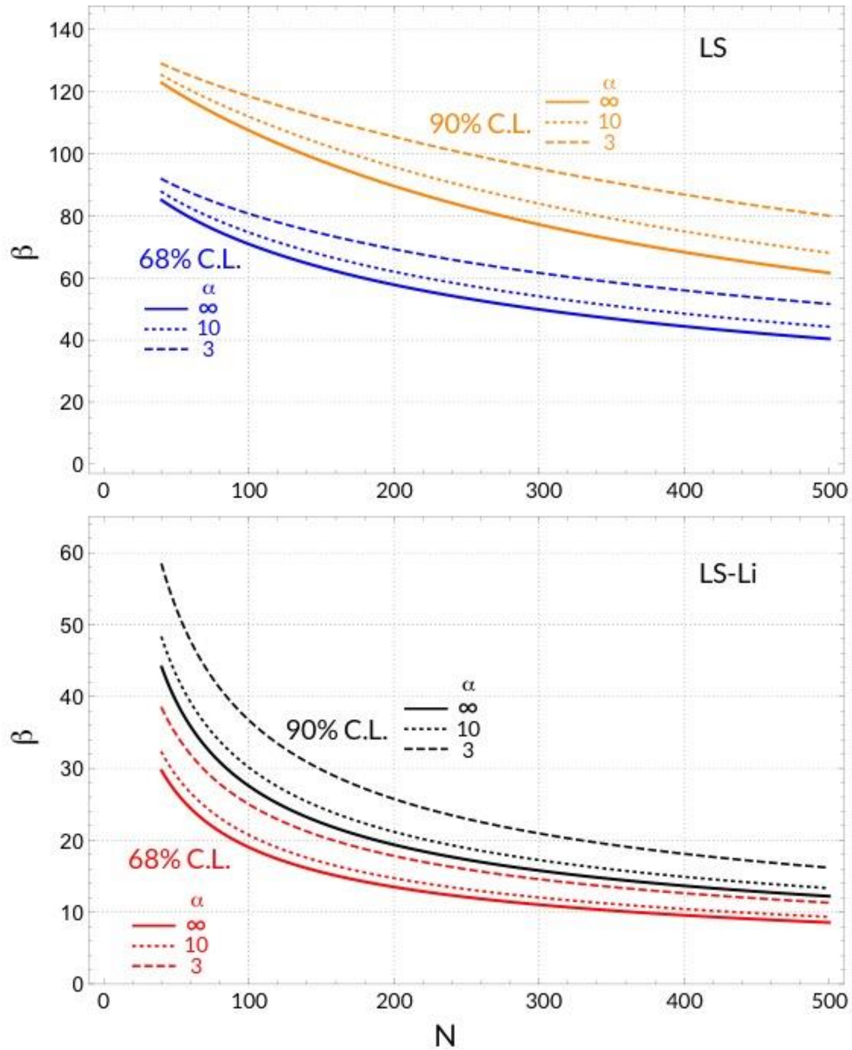
$$\int_0^\infty p^2 dp \int_{\cos\beta}^{1} d\cos\theta \int_0^{2\pi} d\phi \; P(p_x, p_y, p_z) = I \qquad (\, I = 0.68,\, 0.90, 0.99,\, \dots\,)$$

Solve for β, cone half-width

Results – localization prospects

Results: localization angle vs statistics

- For Betelgeuse-like star ($N \sim 200$), 68% C.L. :
  - LS : $\beta \sim 60$ degrees
  - LS-Li : $\beta \sim 15$ degrees



Progenitor identification?

- Goal: reduce the list of candidates for astronomy follow-ups
  - A 4-5 candidates shortlist would be extremely useful to allocate telescope resources
- Idea: combine localization information with:
  - **Distance cut** (from number of events, model-dependent)
  - signals from multiple detectors (improve distance cut and/or triangulation)
  - Clues of stellar type from neutrino time profile (Silicon burning “bump”)
  - Possible unusual stellar activity in days/months prior (dimming, etc.)

Examples: Betelgeuse, Sigma Canis Majoris

Betelgeuse, D=0.222 kpc, M=15 M_{sun}

					LS			LS-Li		
Time to CC	N_{Total}	N_{Signal}	N_{Bkg}	α	a	68% C.L.	90% C.L.	a	68% C.L.	90% C.L.
4.0 hr	93	78	15	5.20	0.1308	78.43°	116.17°	0.6610	23.24°	33.98°
1.0 hr	193	170	23	7.39	0.1374	63.92°	98.42°	0.6942	15.47°	22.26°
2 min	314	289	25	11.56	0.1435	52.72°	81.79°	0.7254	11.63°	16.67°

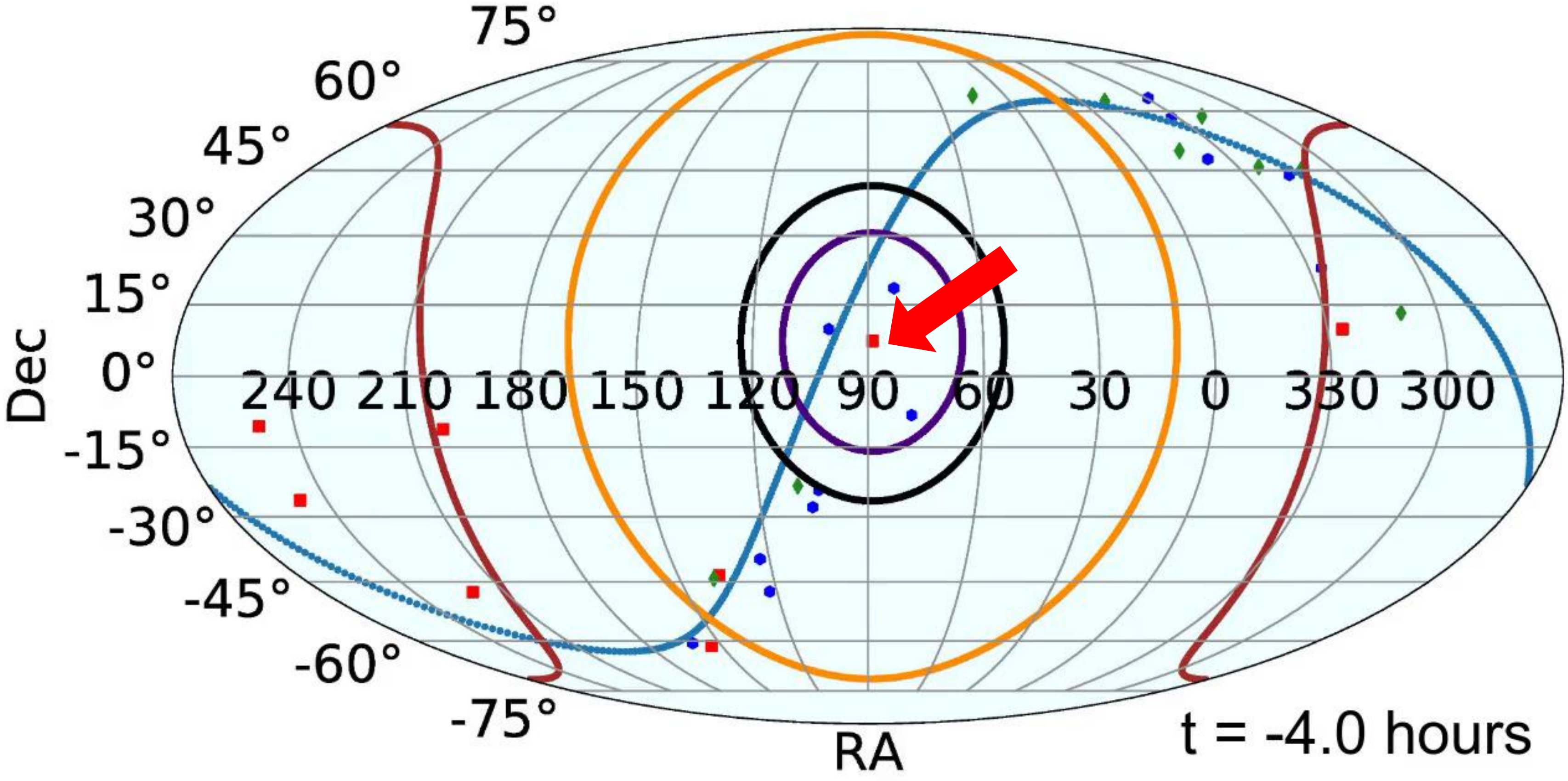
Sigma Canis Majoris, D=0.513 kpc, M=15 M_{sun}

					LS		LS-Li	
Time to CC	N_{Total}	N_{Signal}	N_{Bkg}	α	a	68 % C.L.	a	68 % C.L.
2.0 hr	31	11	20	0.55	0.0553	103.28°	0.2797	71.43°
1.0 hr	36	13	23	0.56	0.0560	102.54°	0.2829	68.32°
2 min	58	33	25	1.32	0.0887	93.56°	0.4484	41.57°

Betelgeuse

D=0.222 kpc, M=15 M_{sun}

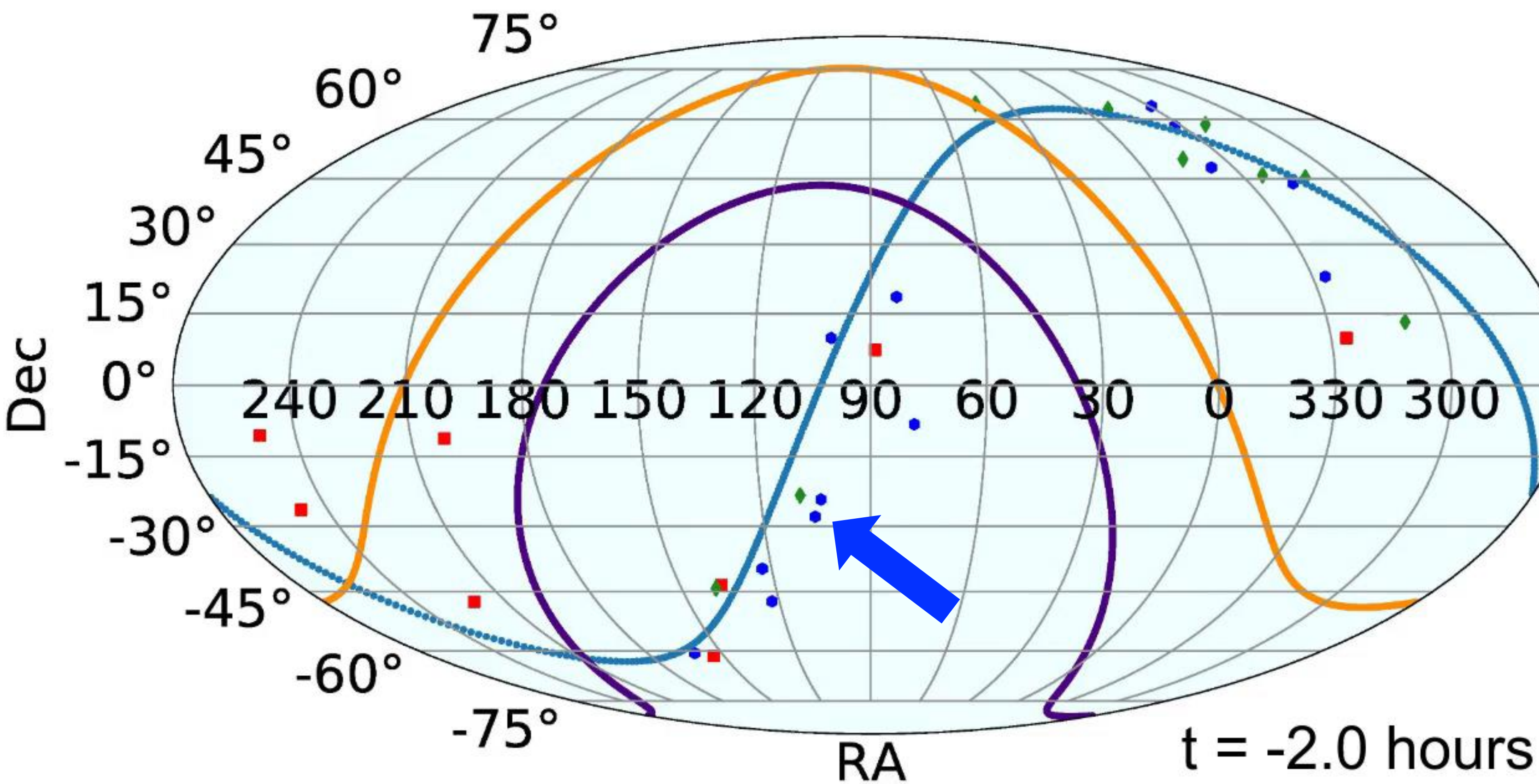
Inner contours: LS-Li, 68%,90% CL
Outer contours : LS, 68%,90% CL



Sigma Canis Majoris

D=0.513 kpc, M=15 M_{sun}

Inner contour: LS-Li, 68% CL
Outer contour : LS, 68% CL



Discussion

Pointing at 10-kt scale LS detectors

- Sensitivity up to 1 kpc; angular error ~70°
  - Can provide shortlist of 4-10 candidates, about 1 hour prior to collapse

- Possible long term improvements:
  - ~30° with THEIA (100 kt)
  - ~10° with LS-Li

Questions

- When to issue localization information?
  - Publish as soon as possible and keep updating…
  - Best compromise between accumulating statistics and have enough time before collapse? Roughly, when you reach *100 events*.
- Protocol to identify a slow-rising (hours/days) signal?
  - Use directionality for early identification?
- Extremely high potential for public engagement
  - Impact on the general public? How to handle?

Thank you!

BACKUP

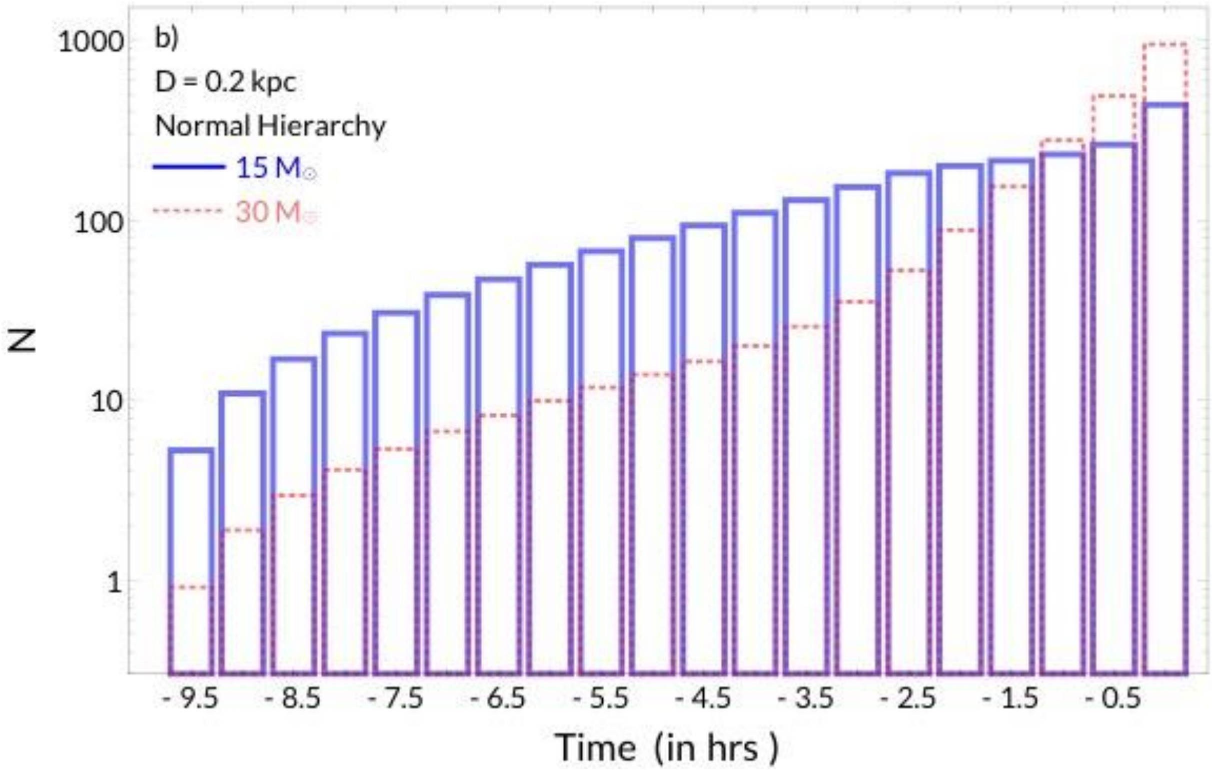
New compilation of candidates

Table A1. Candidate Pre-supernova Stars.

N	Catalog Name	Common Name	Constellation	Distance (kpc)	Mass ($M_\odot$)	RA	Dec
1	HD 116658	Spica/α Virginis	Virgo	0.077 ± 0.004 [a]	$11.43^{+1.15}_{-1.15}$ [b]	13:25:11.58	−11:09:40.8
2	HD 149757	ζ Ophiuchi	Ophiuchus	0.112 ± 0.002 [a]	20.0 [g]	16:37:09.54	−10:34:01.53
3	HD 129056	α Lupi	Lupus	0.143 ± 0.003 [a]	$10.1^{+1.0}_{-1.0}$ [f]	14:41:55.76	−47:23:17.52
4	HD 78647	λ Velorum	Vela	0.167 ± 0.003 [a]	$7.0^{+1.5}_{-1.0}$ [h]	09:07:59.76	−43:25:57.3
5	HD 148478	Antares/α Scorpii	Scorpius	0.169 ± 0.030 [a]	11.0 − 14.3 [l]	16:29:24.46	−26:25:55.2
6	HD 206778	ϵ Pegasi	Pegasus	0.211 ± 0.006 [a]	$11.7^{+0.8}_{-0.8}$ [f]	21:44:11.16	+09:52:30.0
7	HD 39801	Betelgeuse/α Orionis	Orion	0.222 ± 0.040 [d]	$11.6^{+5.0}_{-3.9}$ [m]	05:55:10.31	+07:24:25.4
8	HD 89388	q Car/V337 Car	Carina	0.230 ± 0.020 [c]	$6.9^{+0.6}_{-0.6}$ [f]	10:17:04.98	−61:19:56.3
9	HD 210745	ζ Cephei	Cepheus	0.256 ± 0.006 [c]	$10.1^{+0.1}_{-0.1}$ [f]	22:10:51.28	+58:12:04.5
10	HD 34085	Rigel/β Orion	Orion	0.264 ± 0.024 [a]	$21.0^{+3.0}_{-3.0}$ [j]	05:14:32.27	−08:12:05.90
11	HD 200905	ξ Cygni	Cygnus	0.278 ± 0.029 [c]	8.0 [r]	21:04:55.86	+43:55:40.3
12	HD 47839	S Monocerotis A	Monoceros	0.282 ± 0.040 [a]	29.1 [i]	06:40:58.66	+09:53:44.71
13	HD 47839	S Monocerotis B	Monoceros	0.282 ± 0.040 [a]	21.3 [i]	06:40:58.57	+09:53:42.20
14	HD 93070	w Car/V520 Car	Carina	0.294 ± 0.023 [c]	$7.9^{+0.1}_{-0.1}$ [f]	10:43:32.29	−60:33:59.8
15	HD 68553	NS Puppis	Puppis	0.321 ± 0.032 [c]	9.7 [f]	08:11:21.49	−39:37:06.8
16	HD 36389	CE Tauri/119 Tauri	Taurus	0.326 ± 0.070 [c]	$14.37^{+2.00}_{-2.77}$ [k]	05:32:12.75	+18:35:39.2
17	HD 68273	γ^2 Velorum	Vela	0.342 ± 0.035 [a]	$9.0^{+0.6}_{-0.6}$ [o]	08:09:31.95	−47:20:11.71
18	HD 50877	o^1 Canis Majoris	Canis Major	0.394 ± 0.052 [c]	$7.83^{+2.0}_{-2.0}$ [f]	06:54:07.95	−24:11:03.2
19	HD 207089	12 Pegasi	Pegasus	0.415 ± 0.031 [c]	$6.3^{+0.7}_{-0.7}$ [f]	21:46:04.36	+22:56:56.0
20	HD 213310	5 Lacertae	Lacerta	0.505 ± 0.046 [a]	$5.11^{+0.18}_{-0.18}$ [q]	22:29:31.82	+47:42:24.8
21	HD 52877	σ Canis Majoris	Canis Major	0.513 ± 0.108 [c]	$12.3^{+0.1}_{-0.1}$ [f]	07:01:43.15	−27:56:05.4
22	HD 208816	VV Cephei	Cepheus	0.599 ± 0.083 [c]	$10.6^{+1.0}_{-1.0}$ [f]	21:56:39.14	+63:37:32.0
23	HD 196725	θ Delphini	Delphinus	0.629 ± 0.029 [c]	$5.60^{+3.0}_{-3.0}$ [n]	20:38:43.99	+13:18:54.4
24	HD 203338	V381 Cephei	Cepheus	0.631 ± 0.086 [c]	12.0 [s]	21:19:15.69	+58:37:24.6
25	HD 216946	V424 Lacertae	Lacerta	0.634 ± 0.075 [c]	$6.8^{+1.0}_{-1.0}$ [p]	22:56:26.00	+49:44:00.8
26	HD 17958	HR 861	Cassiopeia	0.639 ± 0.039 [c]	$9.2^{+0.5}_{-0.5}$ [f]	02:56:24.65	+64:19:56.8
27	HD 80108	HR 3692	Vela	0.650 ± 0.061 [c]	$12.1^{+0.2}_{-0.2}$ [f]	09:16:23.03	-44:15:56.6
28	HD 56577	145 Canis Major	Canis Major	0.697 ± 0.078 [c]	$7.8^{+0.5}_{-0.5}$ [f]	07:16:36.83	−23:18:56.1
29	HD 219978	V809 Cassiopeia	Cassiopeia	0.730 ± 0.074 [c]	$8.3^{+0.5}_{-0.5}$ [f]	23:19:23.77	+62:44:23.2
30	HD 205349	HR 8248	Cygnus	0.746 ± 0.039 [c]	$6.3^{+0.7}_{-0.7}$ [f]	21:33:17.88	+45:51:14.5
31	HD 102098	Deneb/α Cygni	Cygnus	0.802 ± 0.066 [e]	$19.0^{+4.0}_{-4.0}$ [e]	20:41:25.9	+45:16:49.0

NOTE— [a]van Leeuwen (2007), [b]Tkachenko et al. (2016), [c]Gaia Collaboration et al. (2018), [d]Harper et al. (2017), [e]Schiller & Przybilla (2008), [f]Tetzlaff et al. (2011), [g]Howarth & Smith (2001), [h]Carpenter et al. (1999), [i]Cvetkovic et al. (2009), [j]Shultz et al. (2014), [k]Montargès et al. (2018), [l]Ohnaka et al. (2013), [m]Neilson et al. (2011), [n]van Belle et al. (2009); Malagnini et al. (2000), [o]North et al. (2007), [p]Lee et al. (2014), [q]Baines et al. (2018), [r]Reimers & Schroeder (1989), [s]Tokovinin (1997)

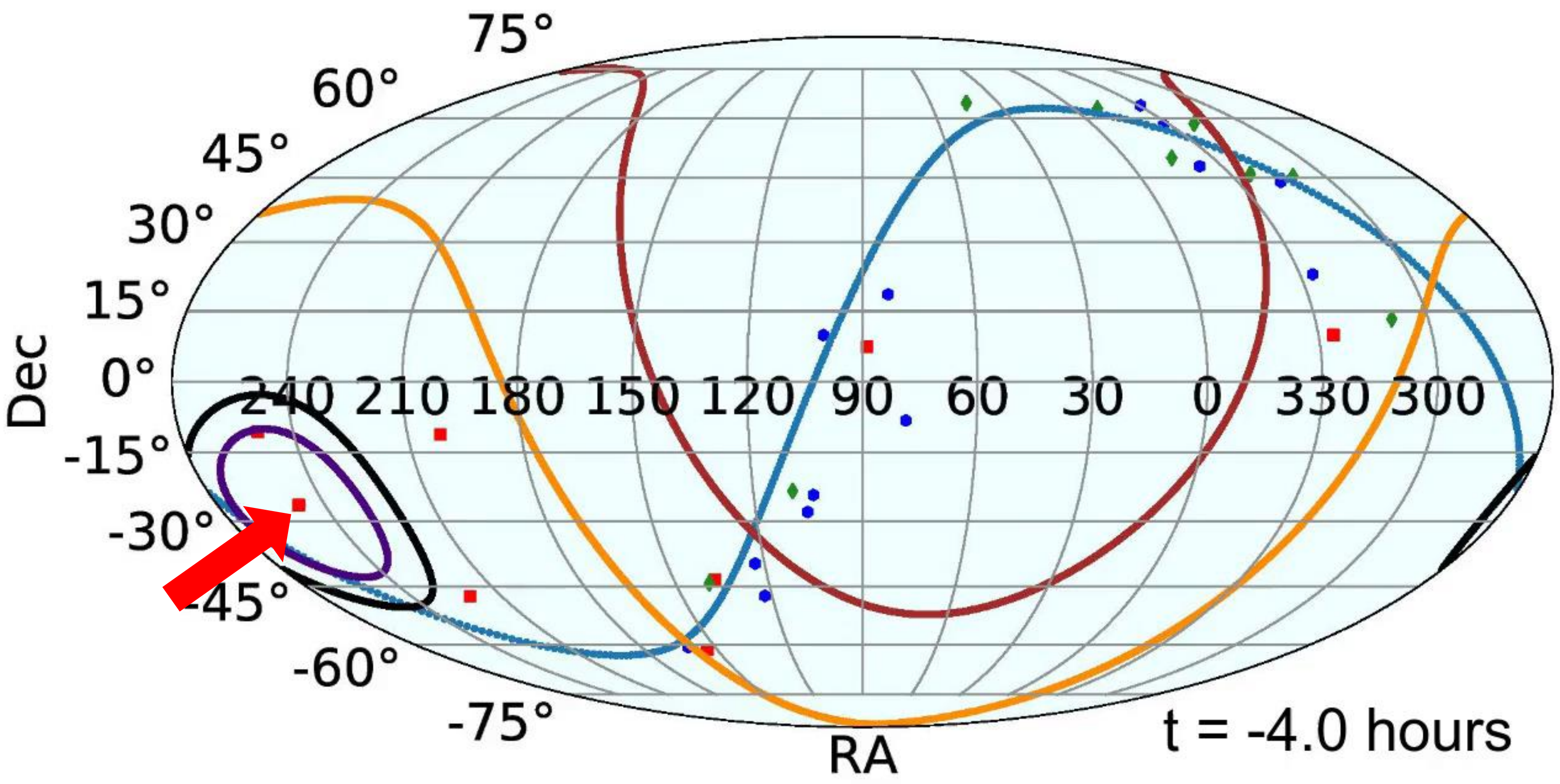
- Includes red and blue supergiants;
- updated distance/mass info


b)
D = 0.2 kpc
Normal Hierarchy
15 $M_\odot$
30 $M_\odot$
1000
100
10
1
N
- 9.5
- 8.5
- 7.5
- 6.5
- 5.5
- 4.5
- 3.5
- 2.5
- 1.5
- 0.5
Time (in hrs)

Antares

D=0.169 kpc, M=15 M_{sun}

Inner contours: LS-Li, 68%,90% CL
Outer contours : LS, 68%,90% CL



References

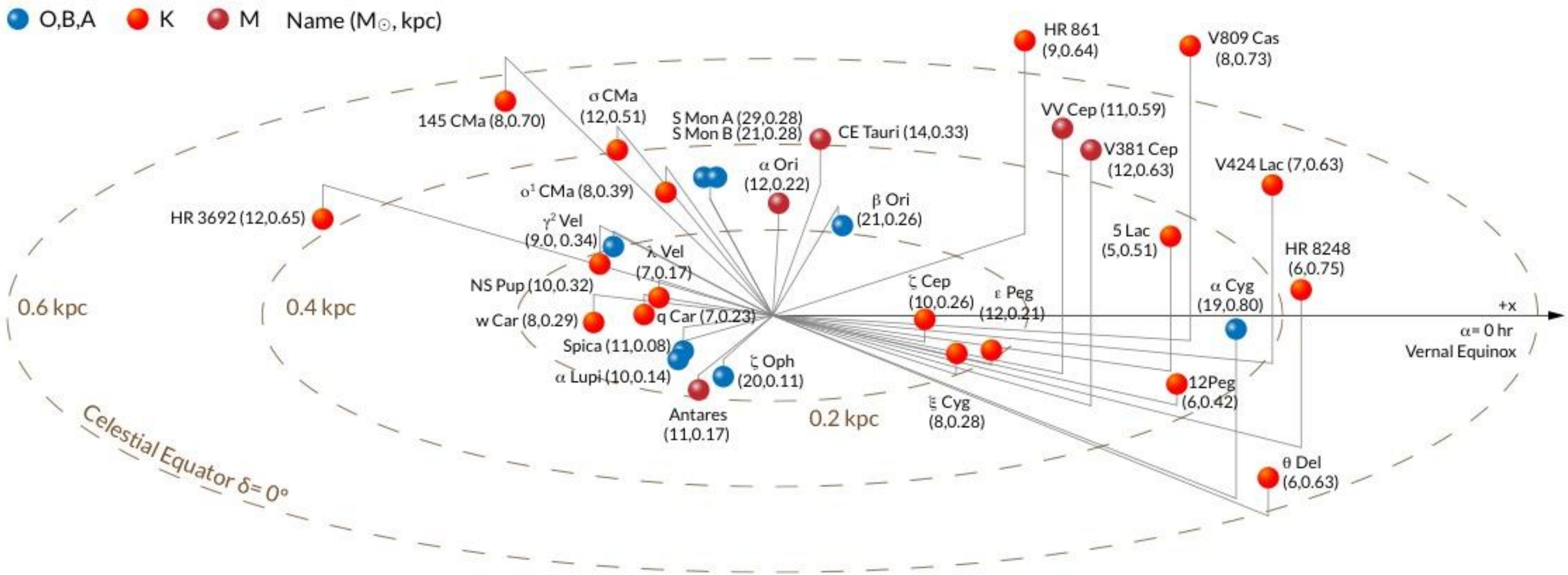
Pre-SN numerical model: Patton, Lunardini, Farmer & Timmes, 2017, ApJ, 851, 6
Zenodo, doi 10.5281/zenodo.2626645 (tables)

Exploratory study of pointing: Li, Li, Wen, & Zhou, 2020, arXiv:2003.03982

Enhancing pointing with LS + Lithium: Tanaka & Watanabe, 2014, Scientific Reports, 4, 4708

Pointing method: Apollonio, Baldini, Bemporad, et al. 2000, PhRvD, 61, 012001

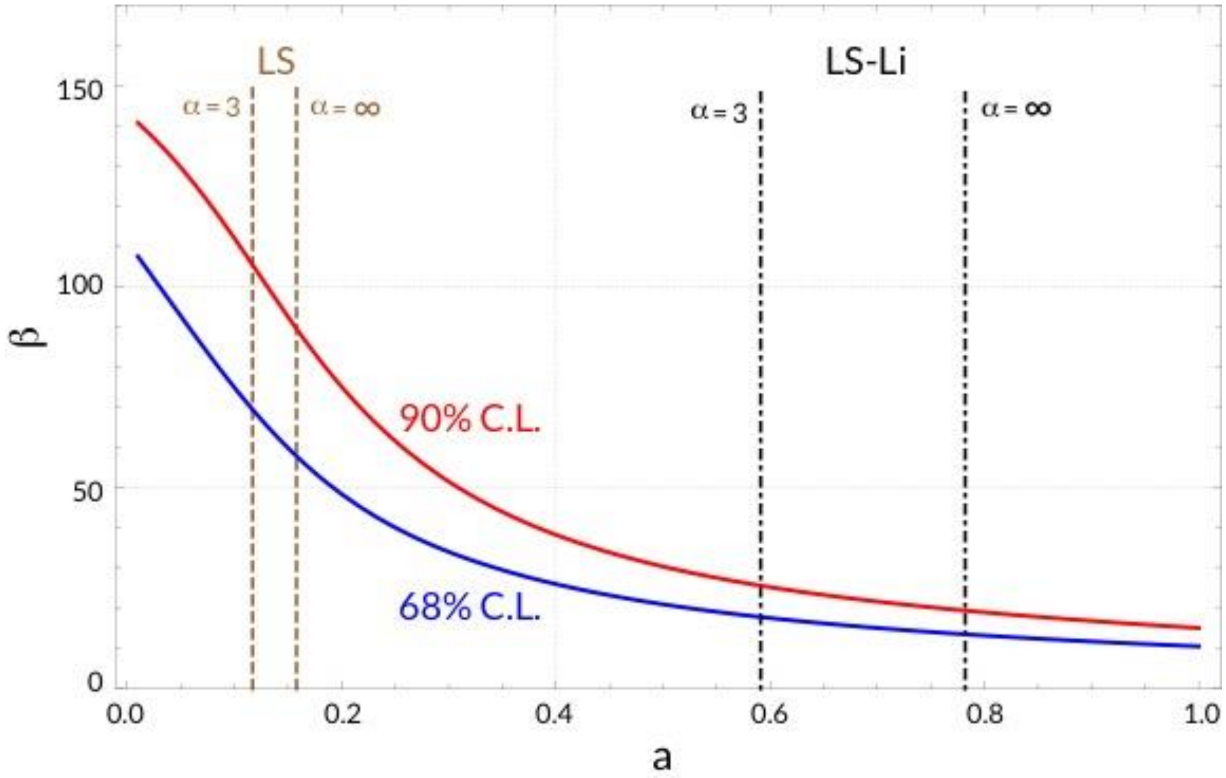
JUNO-specific information: An, An, An, et al. 2016, Journal of Physics G Nuclear Physics, 43, 030401

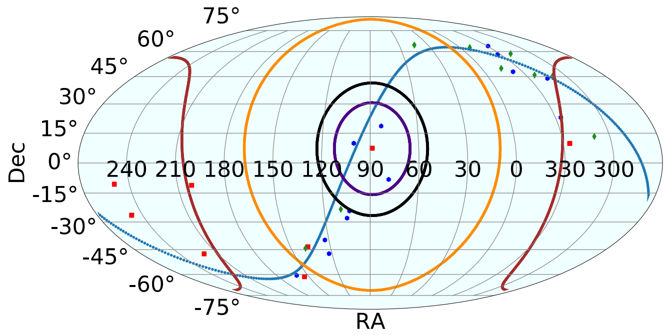


O,B,A
K
M
Name (M☉, kpc)
HR 861 (9,0.64)
V809 Cas (8,0.73)
145 CMa (8,0.70)
σ CMa (12,0.51)
S Mon A (29,0.28)
S Mon B (21,0.28)
CE Tauri (14,0.33)
VV Cep (11,0.59)
V381 Cep (12,0.63)
V424 Lac (7,0.63)
α Ori (12,0.22)
o¹ CMa (8,0.39)
β Ori (21,0.26)
HR 3692 (12,0.65)
γ² Vel (9.0, 0.34)
5 Lac (5,0.51)
λ Vel (7,0.17)
HR 8248 (6,0.75)
NS Pup (10,0.32)
ζ Cep (10,0.26)
ε Peg (12,0.21)
α Cyg (19,0.80)
0.6 kpc
0.4 kpc
w Car (8,0.29)
q Car (7,0.23)
+x
α= 0 hr
Vernal Equinox
Spica (11,0.08)
ζ Oph (20,0.11)
α Lupi (10,0.14)
12Peg (6,0.42)
ξ Cyg (8,0.28)
Antares (11,0.17)
0.2 kpc
Celestial Equator δ= 0°
θ Del (6,0.63)

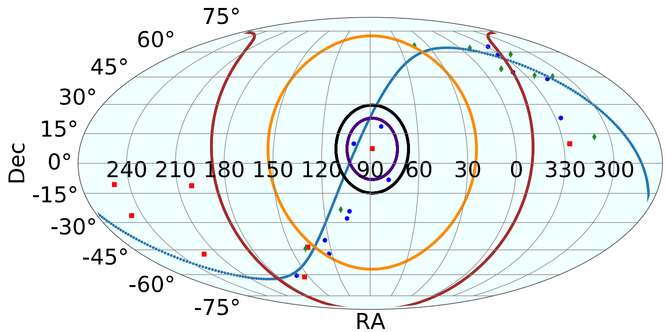
Table A2. Minimum Angular Separation Between Pre-supernova Candidates.

N	Catalog/Common Name	Min. Ang. Separation (degree)	Nearest Neighbor Name	Nearest Neighbor Number
1	HD 116658/Spica	39.66	HD 129056/α Lupi	3
2	HD 149757/ζ Ophiuchi	15.97	HD 148478/Antares	5
3	HD 129056/α Lupi	29.73	HD 148478/Antares	5
4	HD 78647/λ Velorum	1.73	HD 80108/HR 3692	27
5	HD 148478/Antares	15.97	HD 149757/ζ Ophiuchi	2
6	HD 206778/ϵ Pegasi	13.08	HD 207089/12 Pegasi	19
7	HD 39801/Betelgeuse	11.59	S Mono A/B	12/13
8	HD 89338/q Car	3.30	HD 93070/w Car	14
9	HD 210745/ζ Cephei	5.69	HD 208816/VV Cephei	22
10	HD 34085/Rigel	18.60	HD 39801/Betelgeuse	7
11	HD 200905/ζ Cygni	4.39	HD 102098/Deneb	31
12	HD 47839/S Mono A	11.60	HD 39801/Betelgeuse	7
13	HD 47839/S Mono B	11.60	HD 39801/Betelgeuse	7
14	HD 93070/w Car	3.30	HD 89338/q Car	8
15	HD 68553/NS Puppis	7.72	HD 68273/γ^2 Velorum	17
16	HD 36389/119 Tauri	12.50	HD 39801/Betelgeuse	7
17	HD 68273/γ^2 Velorum	7.72	HD 68553/NS Puppis	15
18	HD 50877/o^1 Canis Majoris	4.12	HD 52877/σ Canis Majoris	21
19	HD 207089/12 Pegasi	13.08	HD 206778/ϵ Pegasi	6
20	HD 213310/5 Lacertae	4.88	HD 216946/V424 Lacertae	25
21	HD 52877/σ Canis Majoris	4.12	HD 50877/o^1 Canis Majoris	18
22	HD 208816/VV Cephei	5.69	HD 210745/ζ Cephei	9
23	HD 196725/θ Delphini	16.39	HD 206778/ϵ Pegasi	6
24	HD 203338/V381 Cephei	6.72	HD 208816/VV Cephei	22
25	HD 216946/V424 Lacertae	4.88	HD 213310/5 Lacertae	20
26	HD 17958/HR 861	23.49	HD 219978/V809 Cassiopeia	29
27	HD 80108/HR 3692	1.73	HD 78647/λ Velorum	4
28	HD 56577/145 Canis Majoris	5.22	HD 50877/o^1 Canis Majoris	18
29	HD 219978/V809 Cassiopeia	9.33	HD 208816/VV Cephei	22
30	HD 205349/HR 8248	5.38	HD 200905/ζ Cygni	11
31	HD 102098/Deneb	4.39	HD 200905/ζ Cygni	11

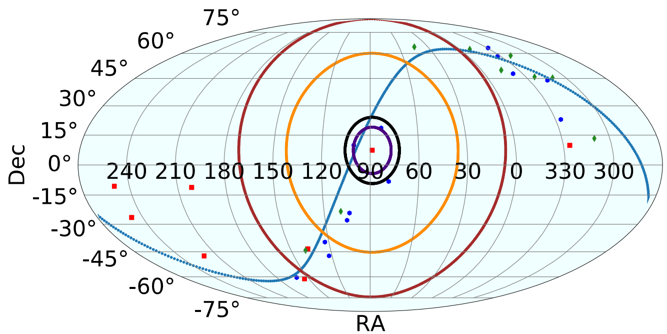

LS
LS-Li
α = 3
α = ∞
α = 3
α = ∞
150
100
50
0
β
90% C.L.
68% C.L.
0.0
0.2
0.4
0.6
0.8
1.0
a



t = -4.0 hours

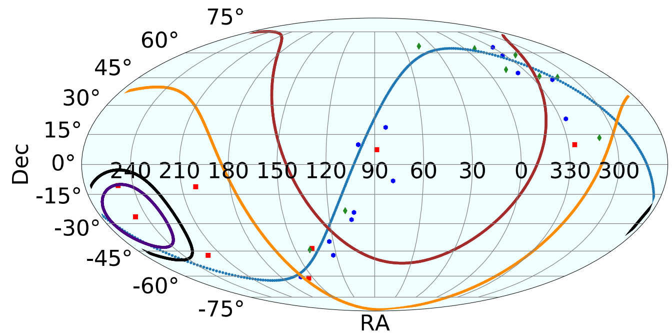


t = -1.0 hour

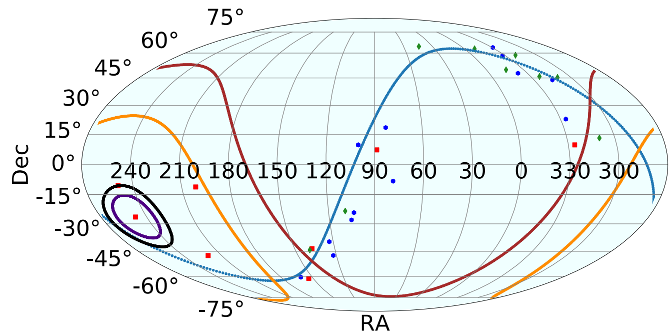


t = -2 minutes

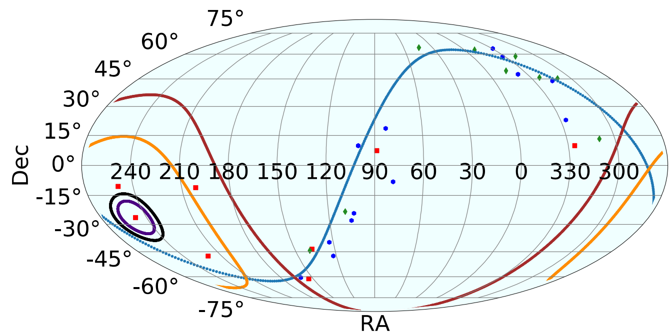
Antares, D=0.169 kpc, M=15 M_{sun}



t = -4.0 hours

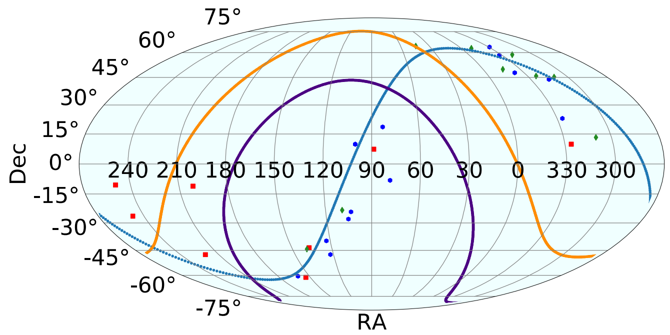


t = -1.0 hour

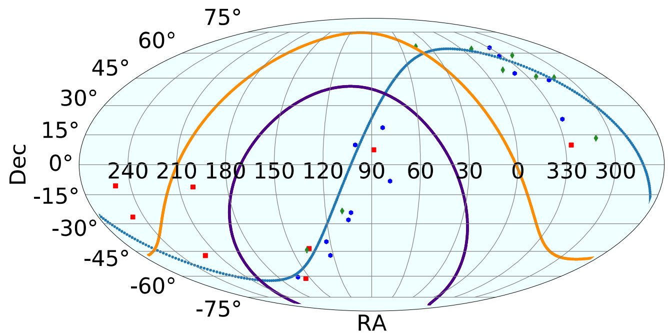


t = -2 minutes

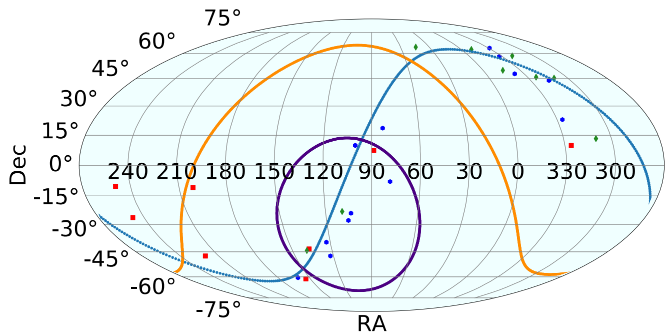
Sigma Canis Majoris, D=0.513 kpc, M=15 M_{sun}



t = -2.0 hours



t = -1.0 hour



t = -2 minutes