The day before Betelgeuse dies: identifying a near-earth pre-supernova star from its neutrinos

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XIX International Workshop on Neutrino Telescopes
February 25, 2021

Credits: A plume of gas nearly the size of our solar system erupts from Betelgeuse's surface in this artist's illustration of real observations gathered by astronomers using the Very Large Telescope in Chile. European Southern Observatory, L. Calçada

Based on:

arXiv: 2004.02045 - "Presupernova neutrinos: directional sensitivity and prospects for progenitor identification" - MM, C. Lunardini, F. X. Timmes, K. Zuber

(Astrophys.J. 899 (2020) 2, 153)

Work supported by: National Science Foundation (NSF)

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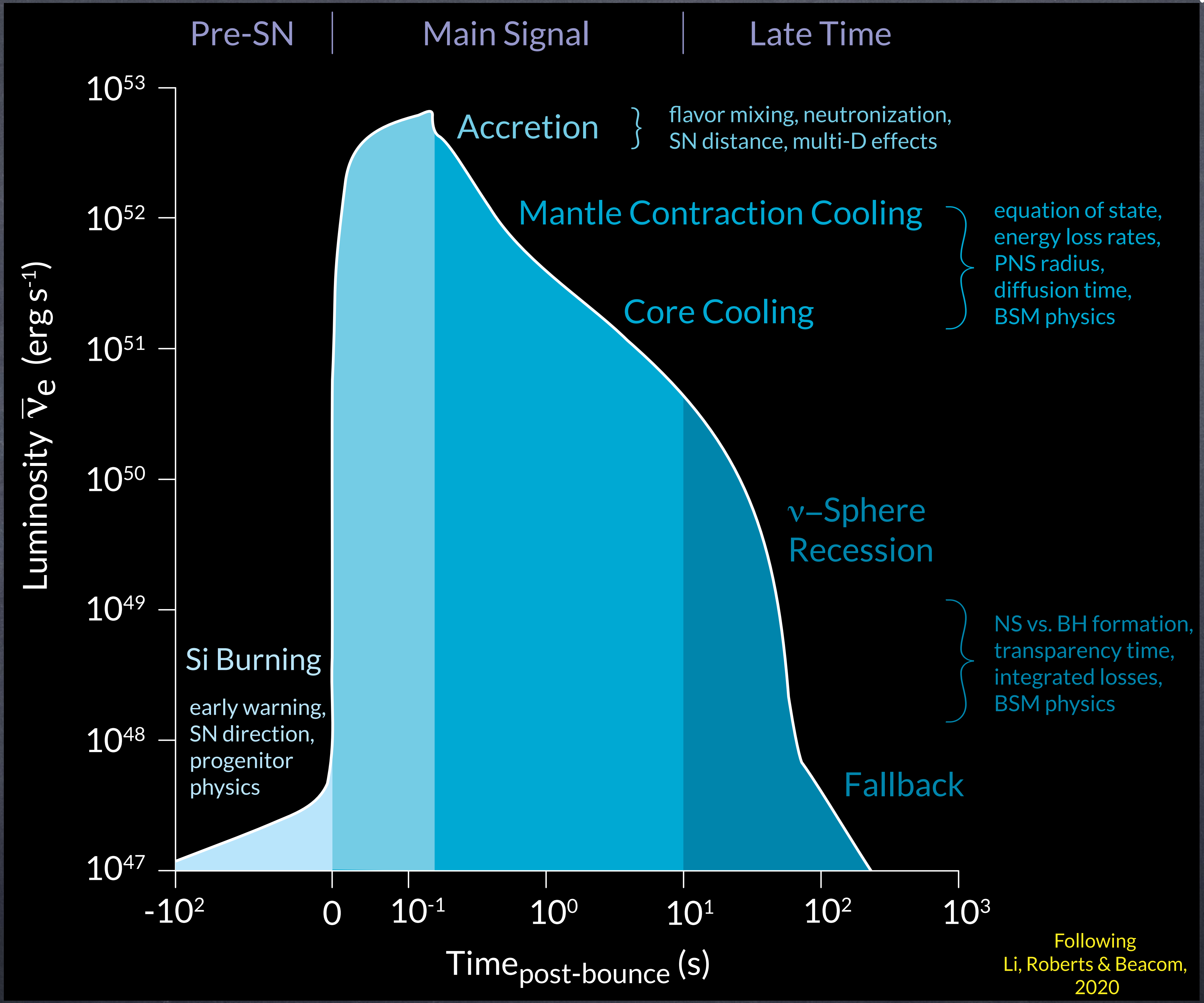
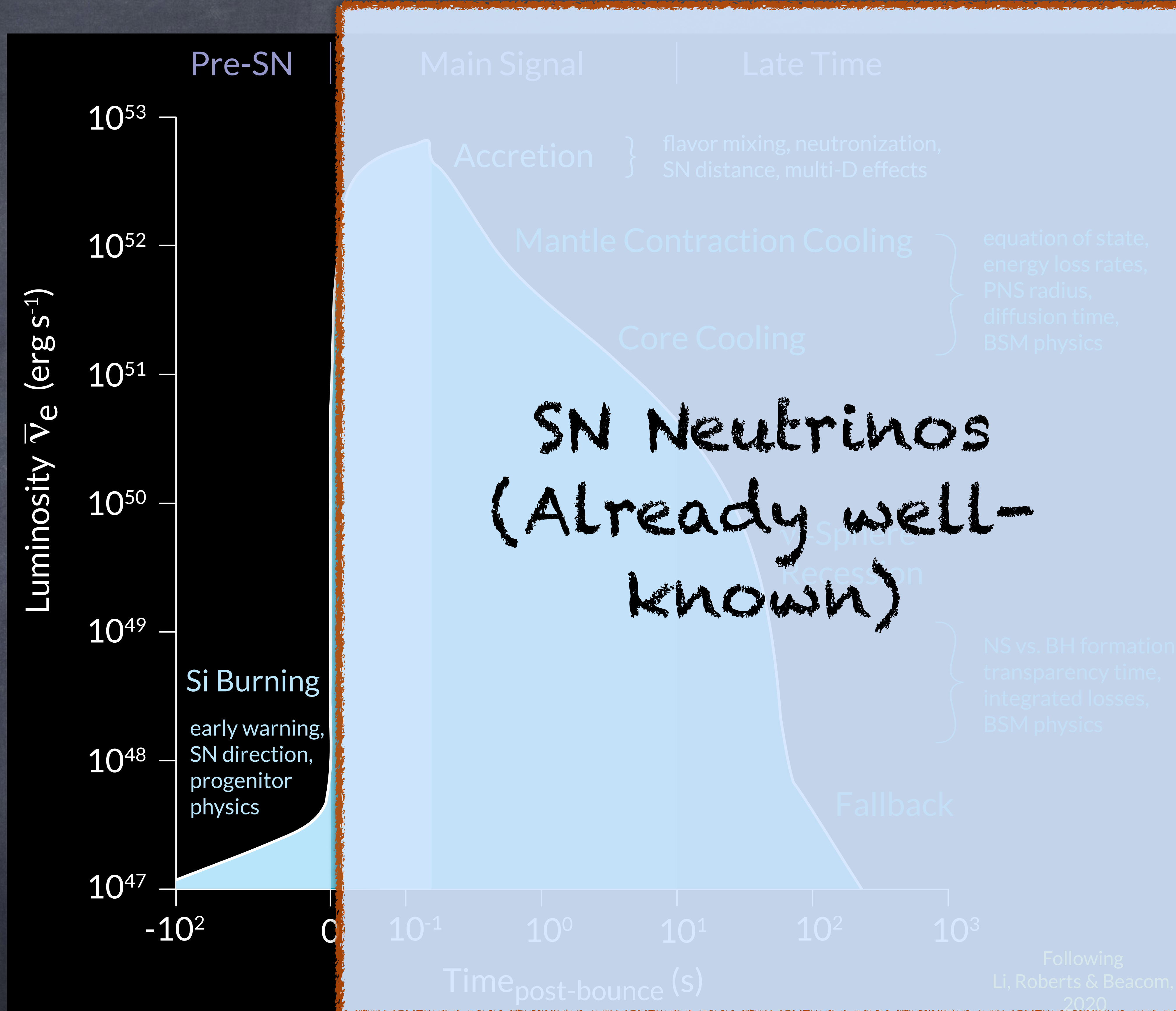


Credits: Frank Timmes

Months, weeks, days, hours....before collapse



Credits: Frank Timmes

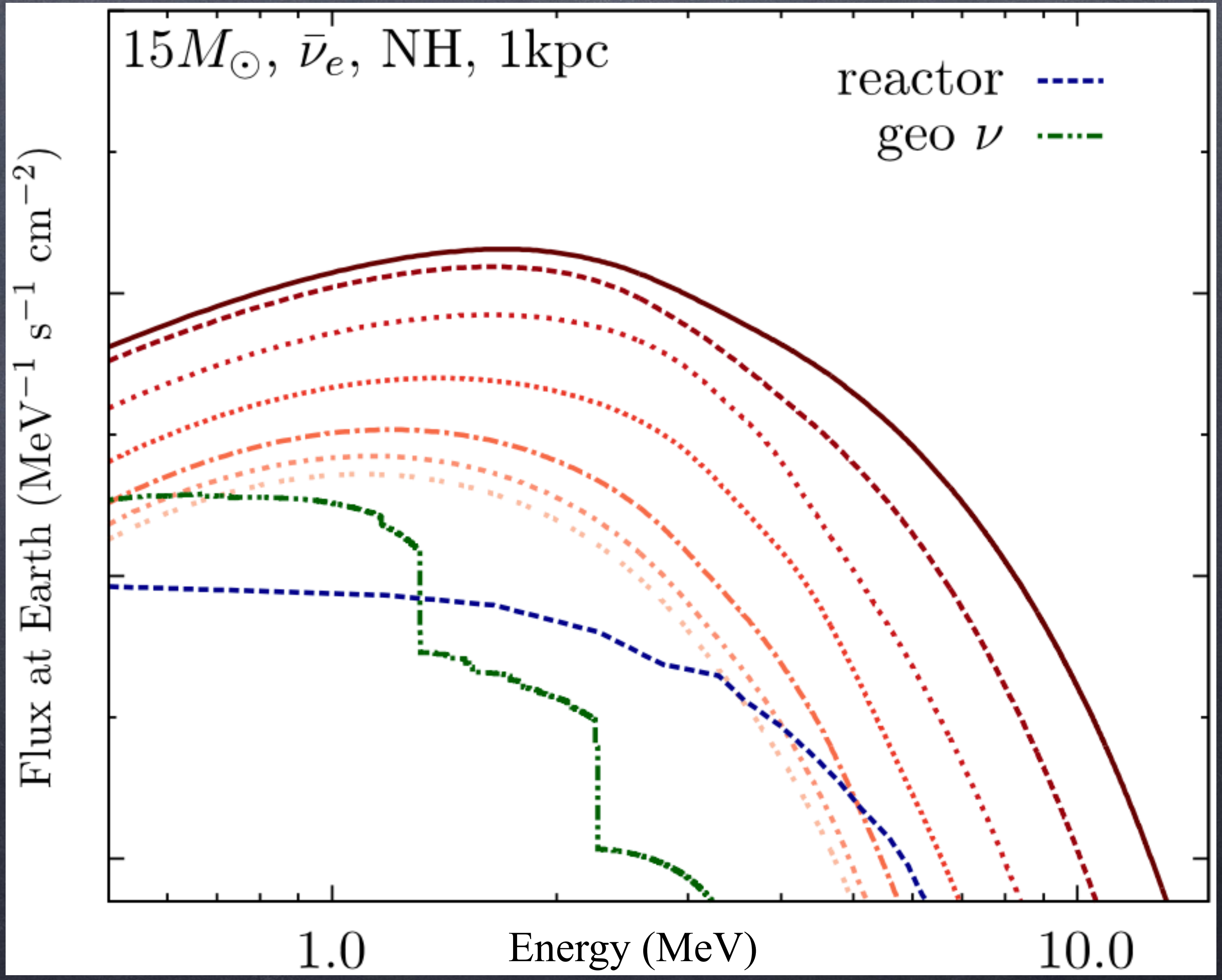
Presupernova Neutrinos

- What?

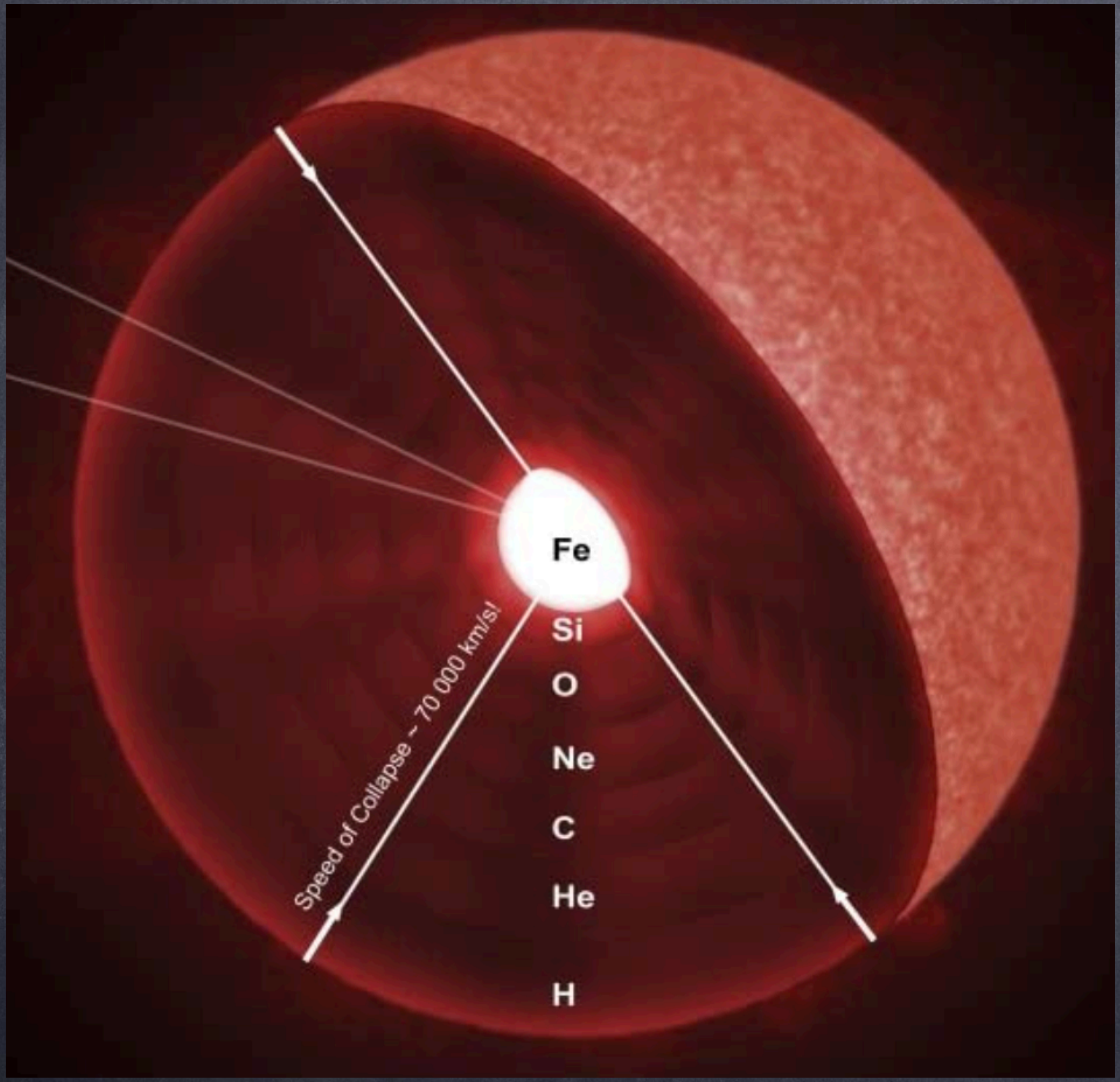
Neutrinos of energy 0.1 - 5 MeV

Low energy neutrinos

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



Presupernova Neutrinos

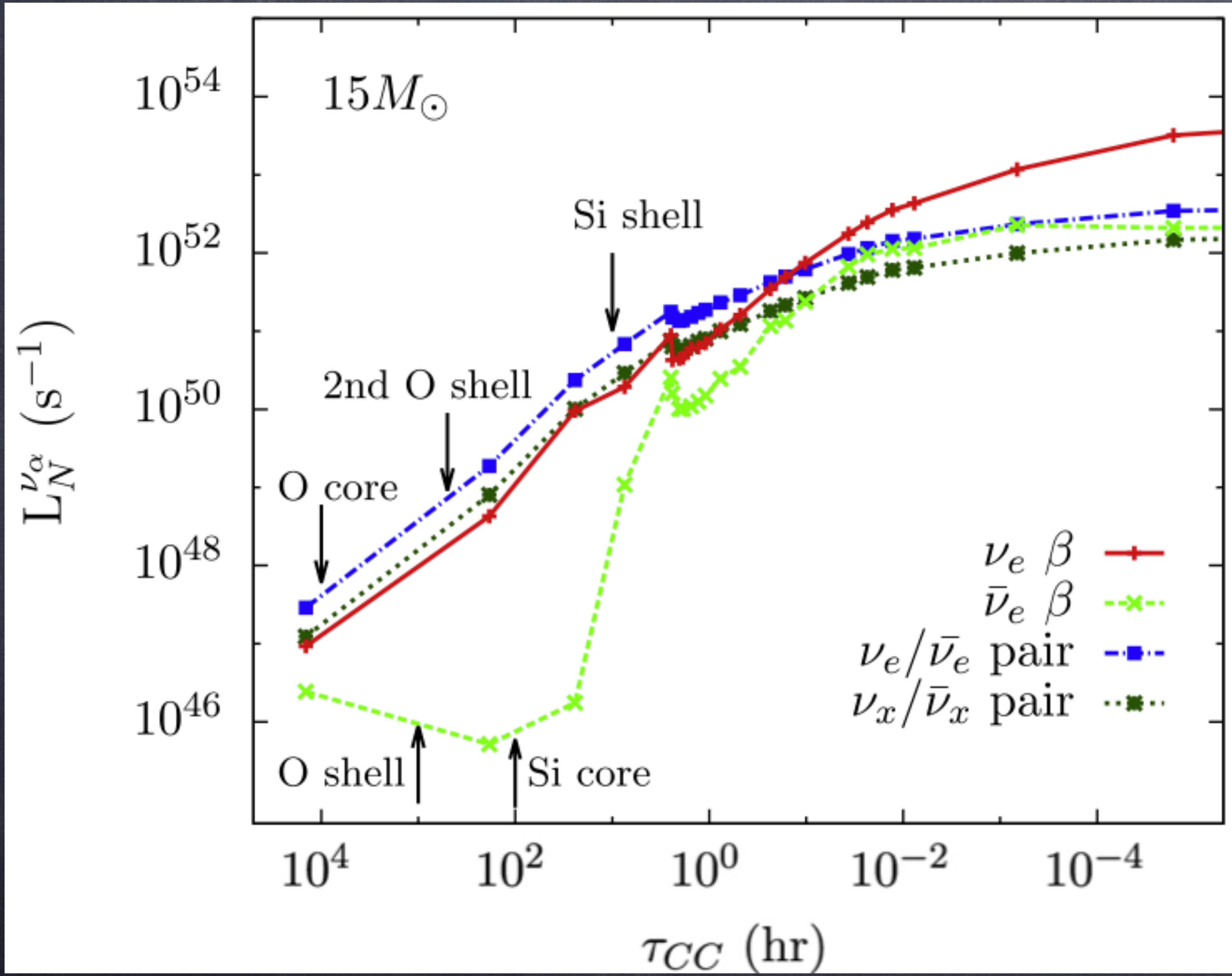


- When?

Last stages of nuclear burning of a massive star

Source: https://images-na.ssl-images-amazon.com/images/I/61yf26rpIXL._AC_SL1000_.jpg

Presupernova Neutrinos



- How?

I) Thermal processes
- Pair production

II) Weak reactions - Beta processes mainly e^-/e^+ captures and nuclear decays

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

Is this talk about the details of presupernova neutrinos?

No.... → Where to look?

Patton et.al. (2017 a,b) and References

References:

A) Odrzywolek, Misiaszek, Kutschera 2004, Astropart. Phys., 21, 303

B) Kutschera, Odrzywolek, Misiaszek, 2009, Acta Physics Polonica B, 40, 3063

C) Kato, Delfan Azari, Yamada, et. al. 2015, ApJ, 808, 168

D) Kato, Nagakura, Furusawa, et. al. 2017, ApJ, 848, 48

E) Yoshida, Takahashi, Umeda, Ishidoshiro 2016, Phys. Rev. D, 93, 123012

F) Guo, Qian, Heger 2019, Phys. Lett., B796, 126

Is this talk about the details of presupernova neutrinos?

No.... → Where to look?

Patton et.al. (2017 a,b) and References → Then what?

Try to use this signature to locate the progenitor in the sky and serve as an early warning system (this talk...)

Also see: Li, Li, Wen and Zhou 2020, arXiv 2003.03982

Motivations

Early alert of collapse :

Observe a star before and during collapse to test stellar evolution.

$\sim$ 100 IBD events for nearby (0.2 kpc) star like Betelgeuse in a detector like JUNO

Motivations

Early alert of collapse :

Observe a star before and during collapse to test stellar evolution.

Aligns with SN neutrino burst warning which is already considered an early warning

Motivations

Very early alert of SN explosion (or BH formation) :

1. Precedes the neutrino burst by hours (or even days): useful for decision making

2. Can be the only useful alert for fast-exploding stars (< 1 hours from collapse to explosion)

Motivations

Prepare GW detectors: multi-messenger observations

Plenary talk by Prof. Barry Barish

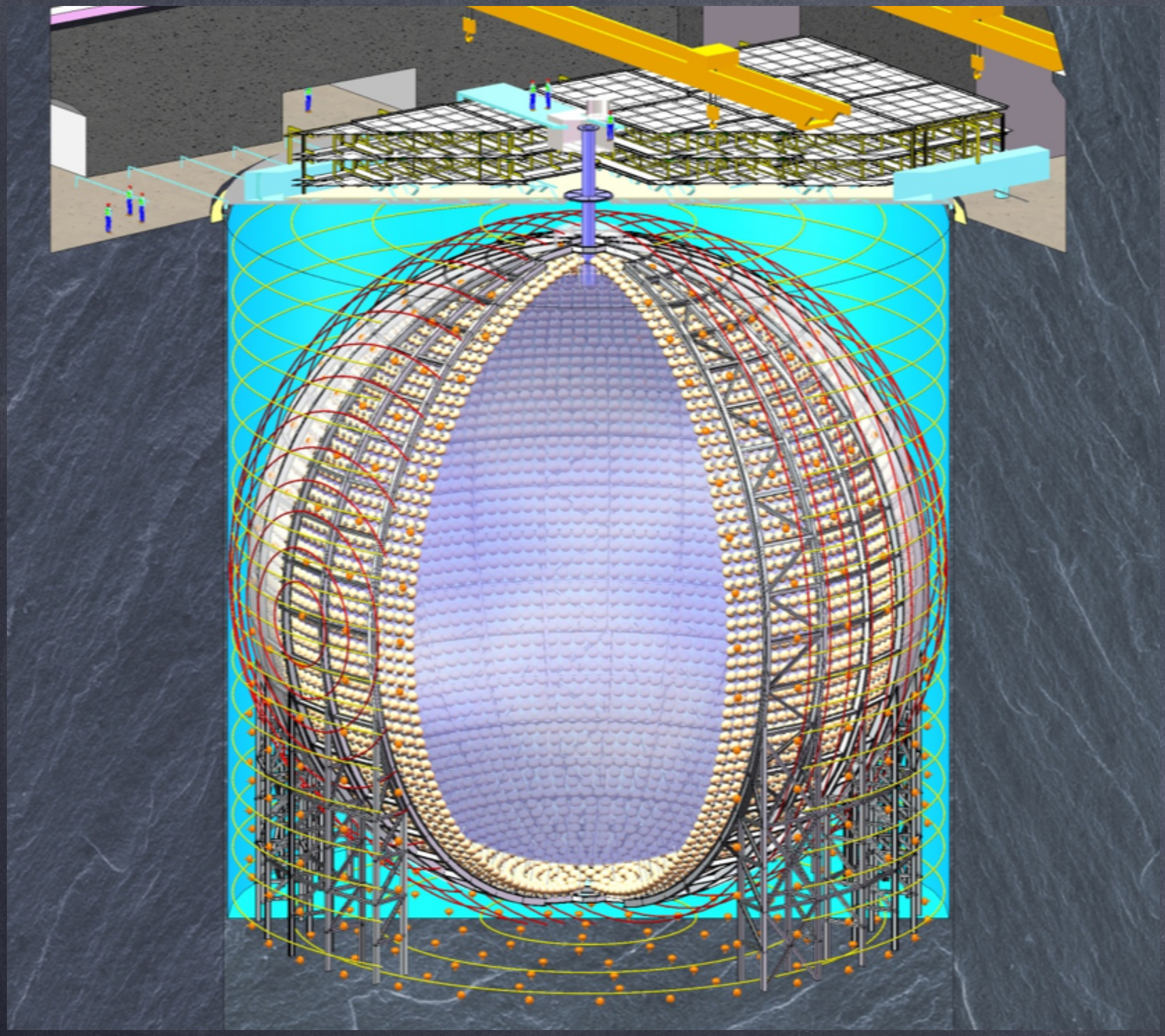
Motivations

Prepare GW detectors: multi-messenger observations

Prepare to observe exotic physics during collapse: point axion detectors

See:- Supernova-scope for the Direct Search of Supernova Axions - Ge, Hamaguchi, Ichimura, Ishidoshiro, Kanazawa, arXiv: 2008.03924

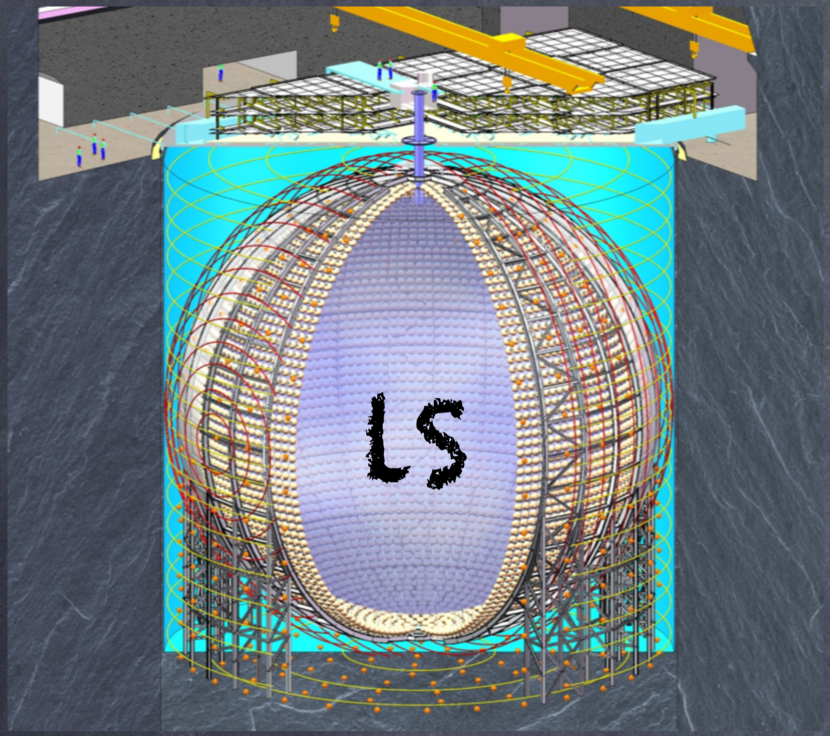
Detectors



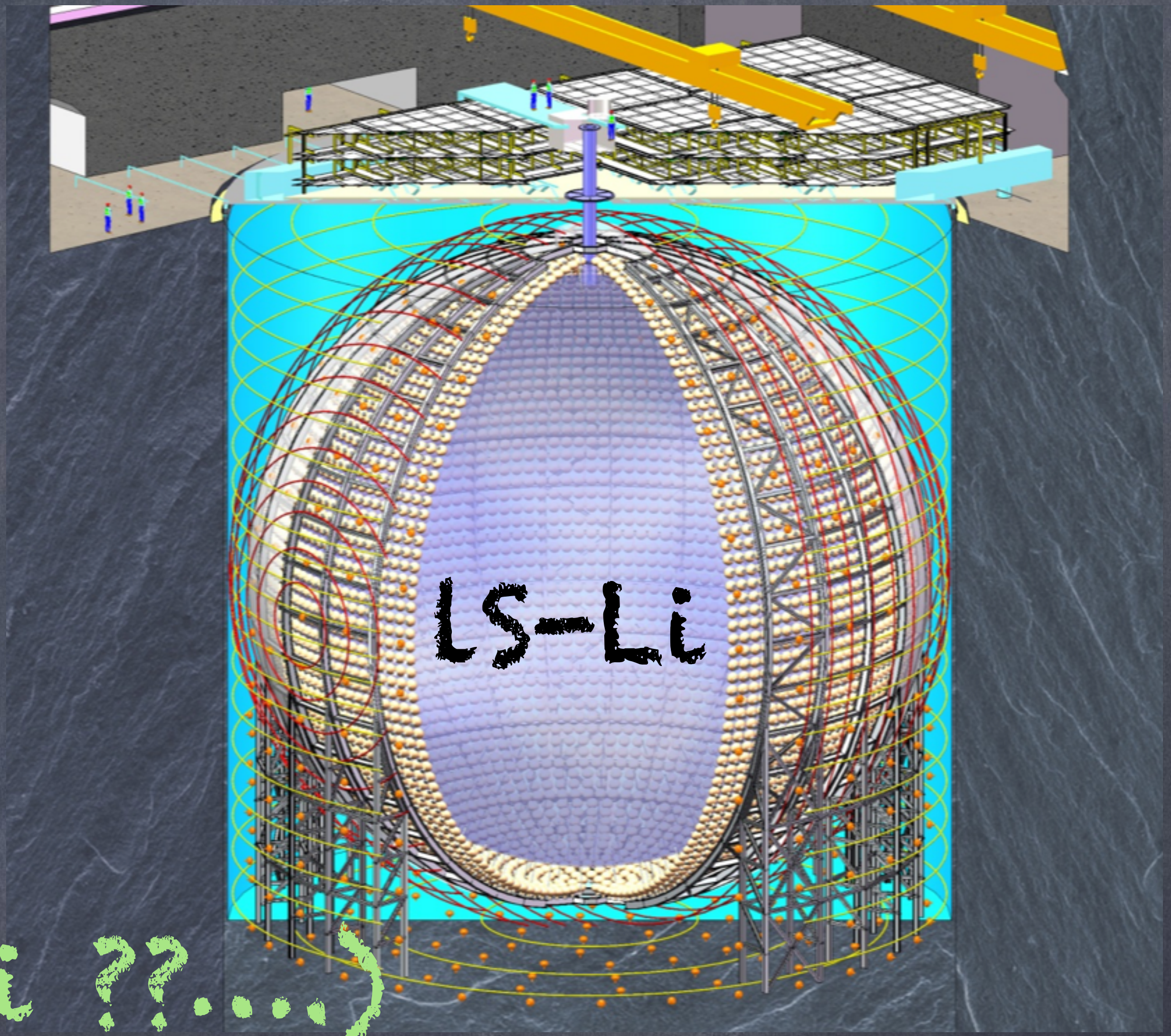
- Fiducial detector mass: 17 kt
- Efficiency: 1
- Liquid Scintillator: LAB (Linear Alkylbenzene)

JUNO (Jiangmen Underground Neutrino Observatory)

Detectors



JUNO



(JUNO-Li ??...)

Hypothetical setup with Li dissolved in liquid scintillator for enhanced angular sensitivity

Tanaka & Watanabe 2014, Scientific Reports, 4, 4708

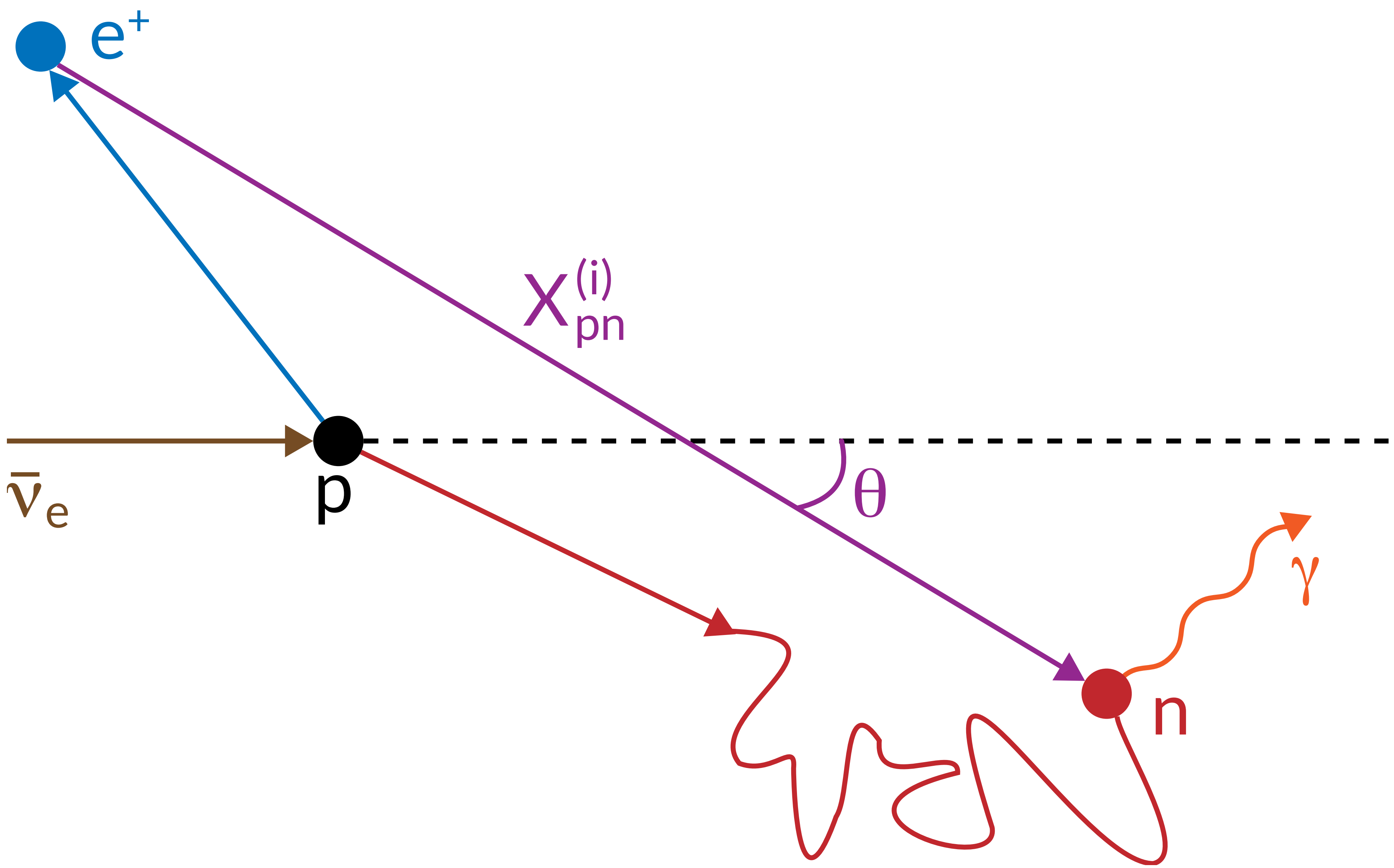
Inverse Beta Decay (IBD)

$$\bar{\nu}_e + p \rightarrow n + e^+$$

Why?

- Low energy threshold (1.8 MeV)
- Timing
- Energy resolution
- Background discrimination performance

Inverse Beta Decay (IBD)



Some details....

N_s : No. of IBD signal events in detector

N_{Bkg} : Background events (Assumption: Isotropic background)

$$\alpha = \frac{N_s}{N_{Bkg}}$$: Signal to Background ratio

Asymmetry Factor

$$\frac{a_0}{2} = \frac{N_F - N_B}{N_F + N_B}$$

Backward $(\theta > \frac{\pi}{2})$

Forward $(\theta < \frac{\pi}{2})$

Signal

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

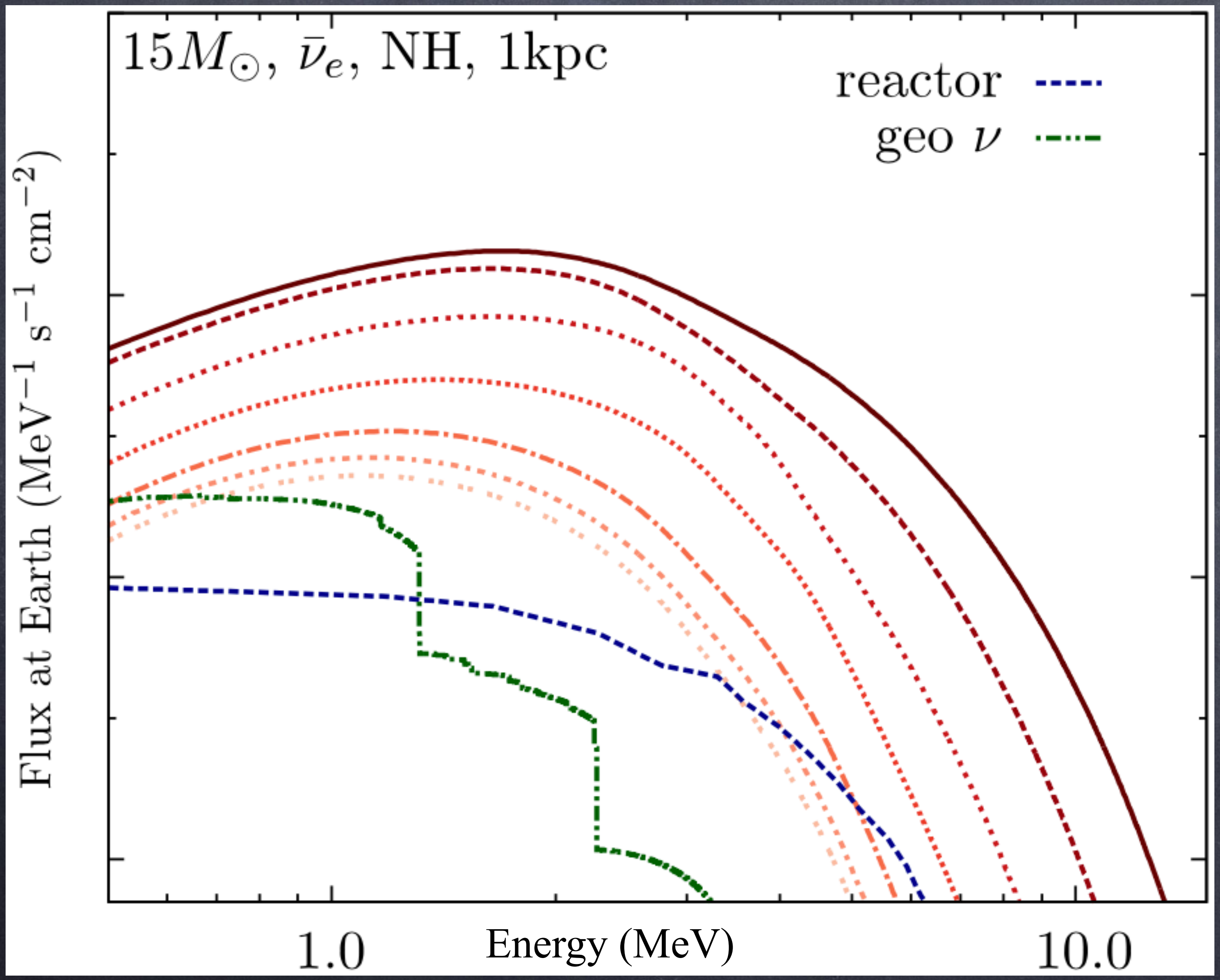
Background

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

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

Background

Recall...



Main background sources:

Reactor ν

Geo ν

Background

Main background sources:

Reactor ν

Geo ν

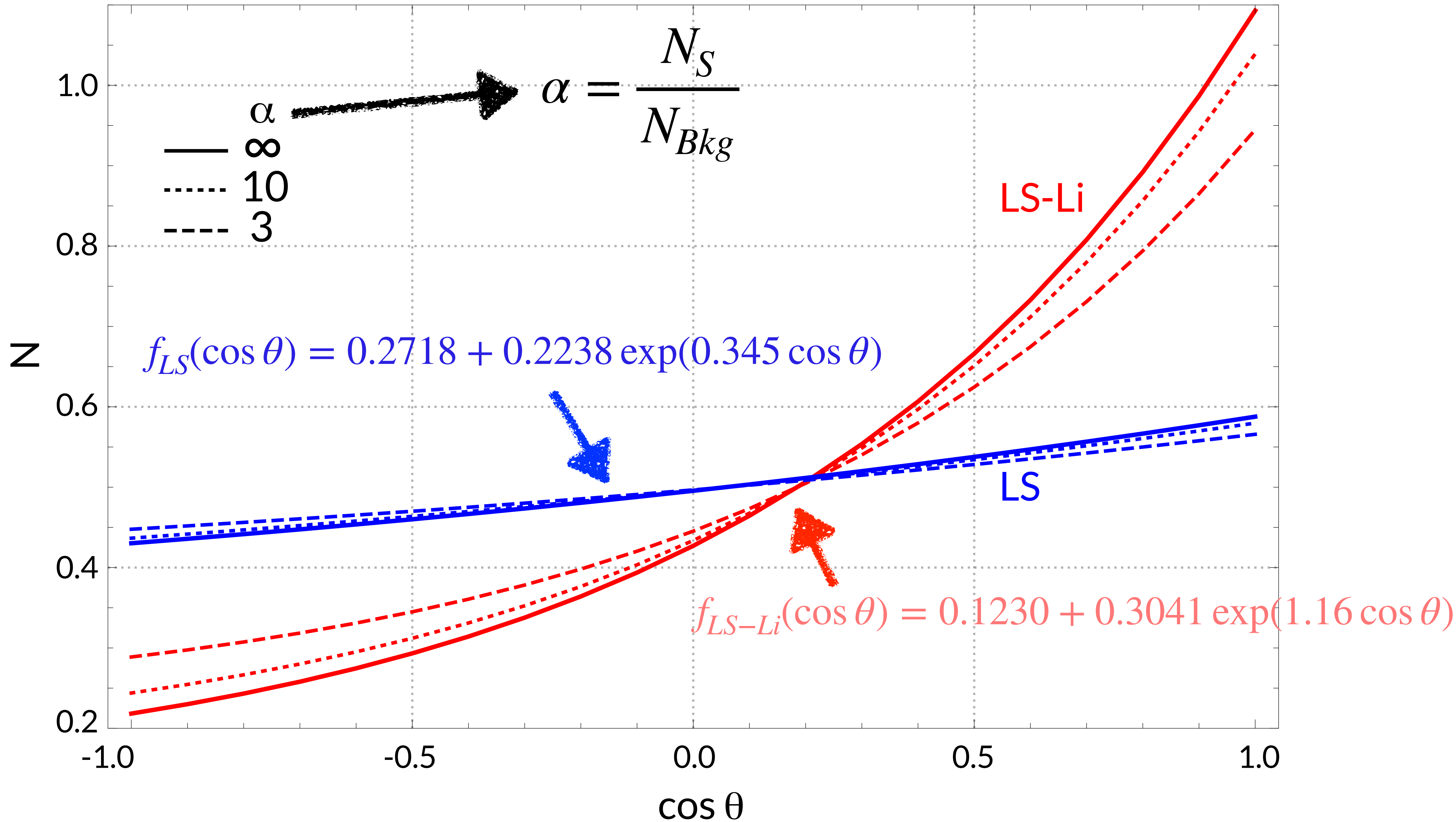
Assumption: Isotropic

2.6 events/hour in reactor-on phase for JUNO

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

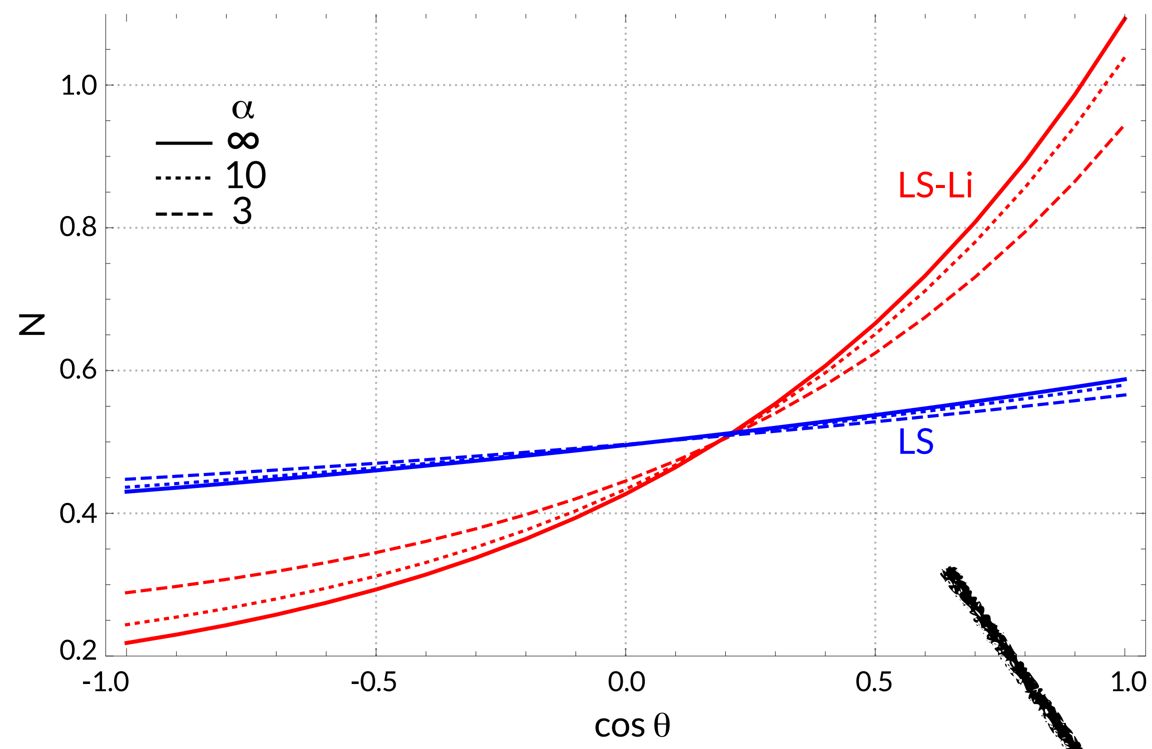
Yoshida, Takahashi, Umeda, Ishidoshiro 2016, Phys. Rev. D, 93, 123012

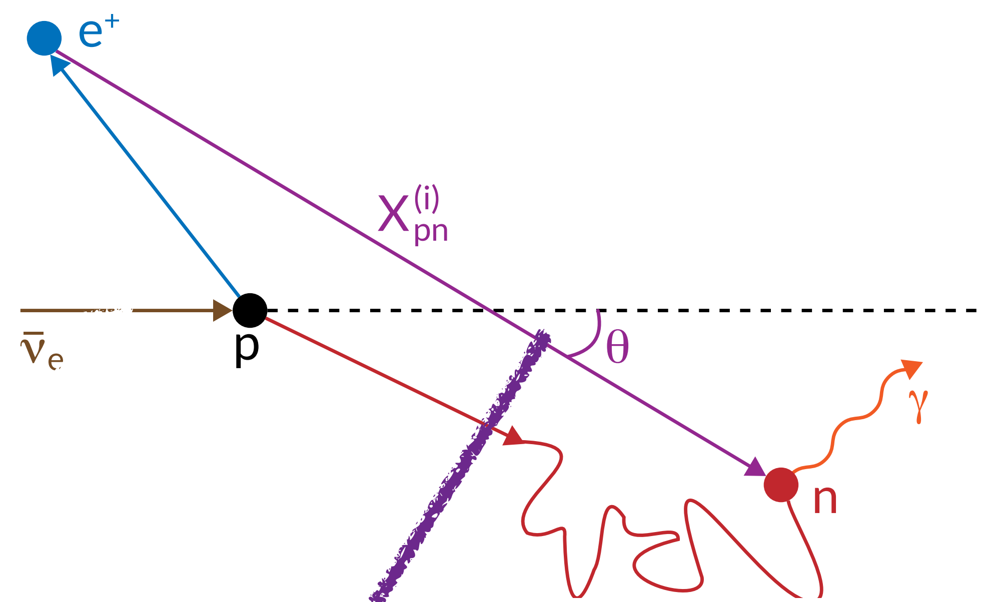
Normalized Distribution of $\cos\theta$



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

Normalized Distribution of $\cos\theta$





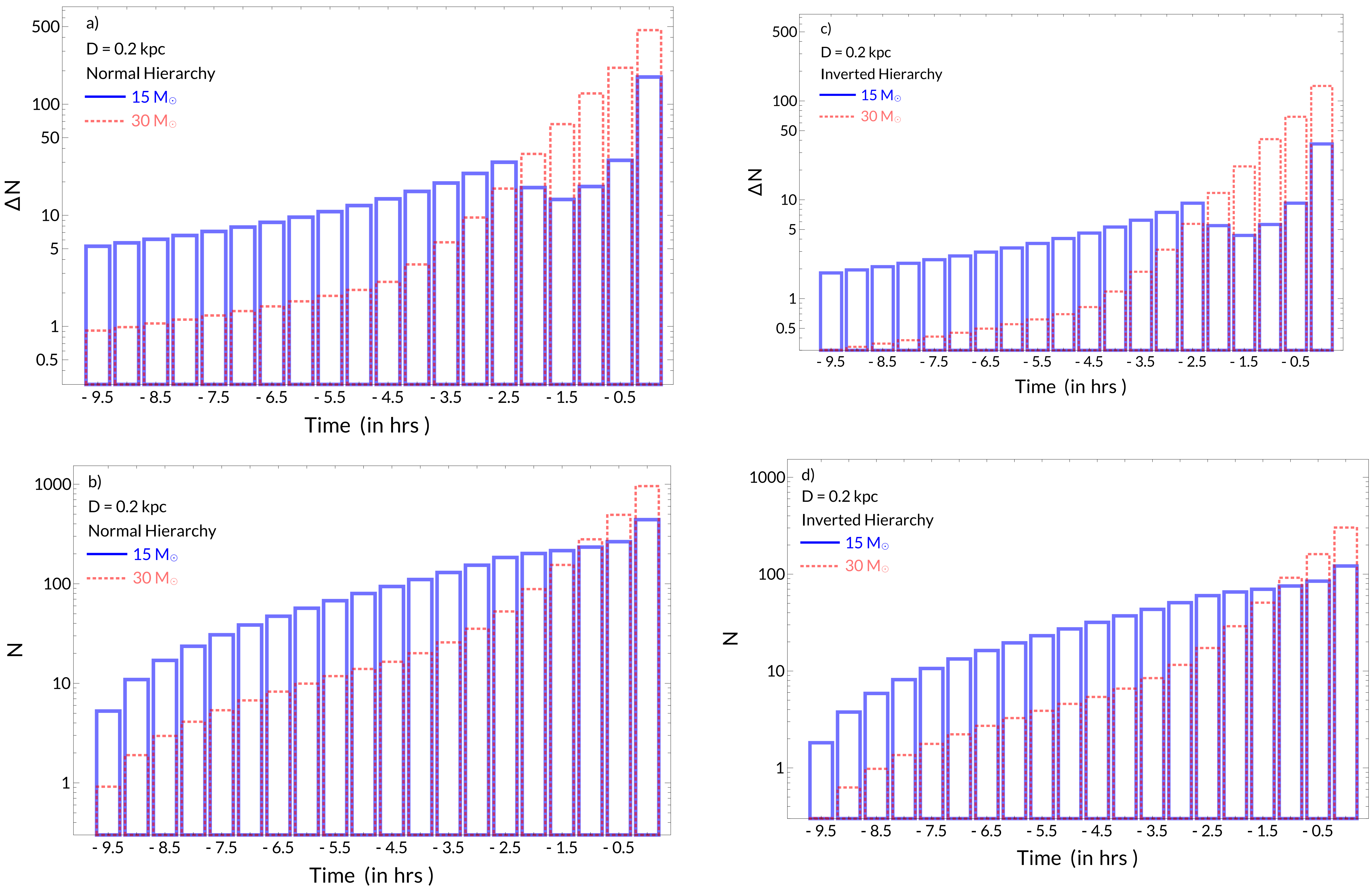
$$\frac{a_0}{2} = \frac{N_F - N_B}{N_F + N_B}$$

$$f(\cos\theta) = \frac{1}{2}\Big(1 + a_0 \cos\theta\Big)$$

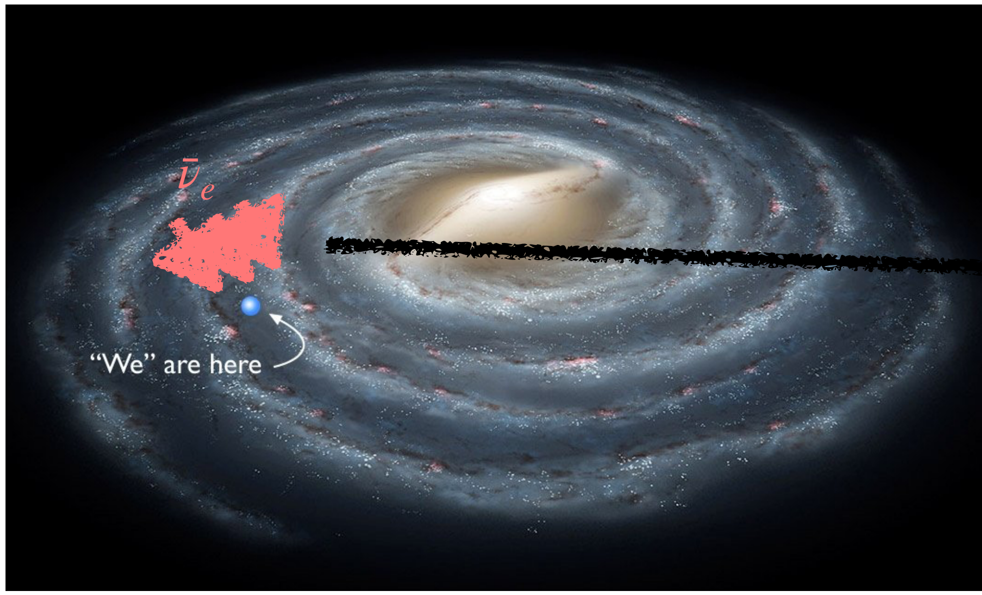
Asymmetry Factor

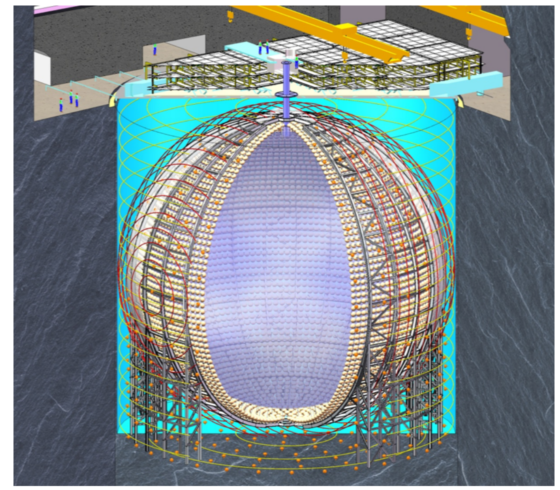
Event Rates

Patton et. al. 2017b

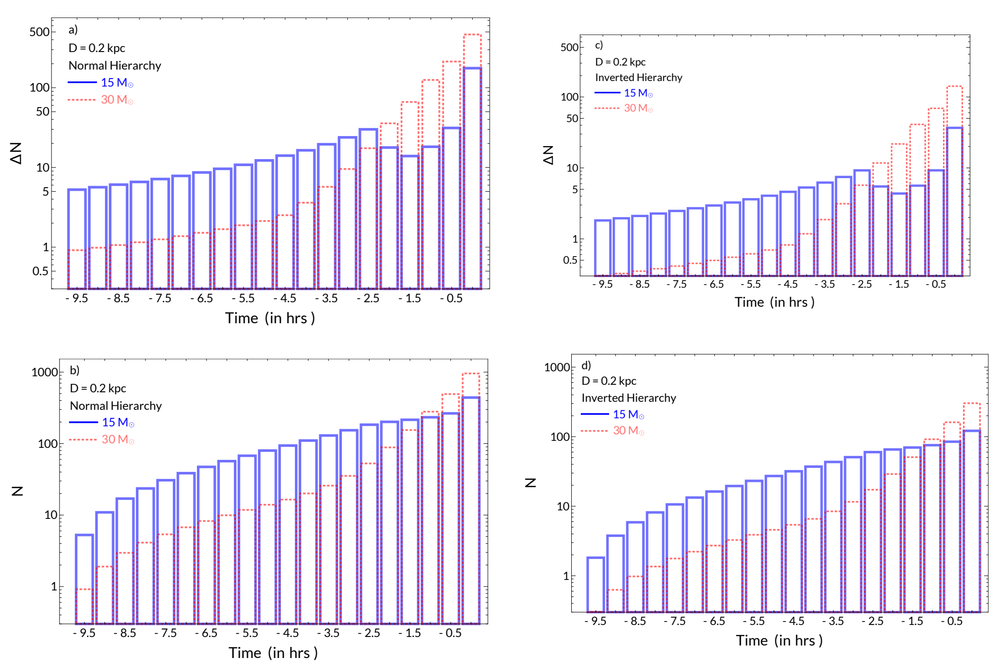


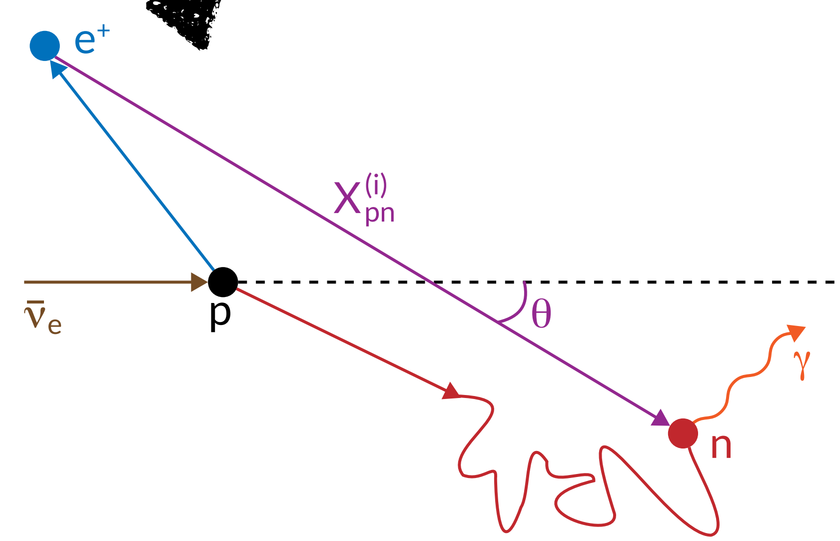
Pointing to the progenitor



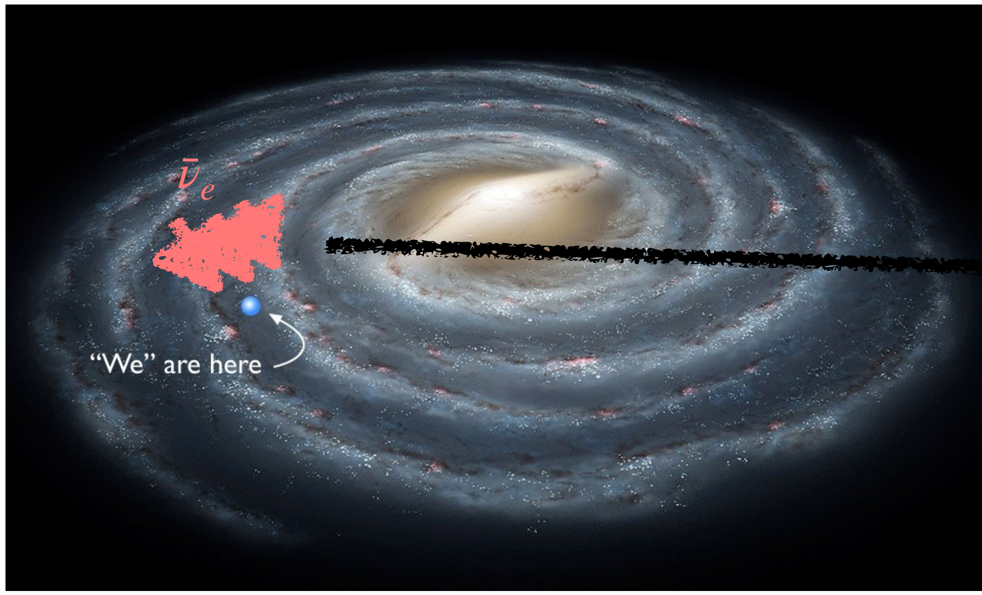


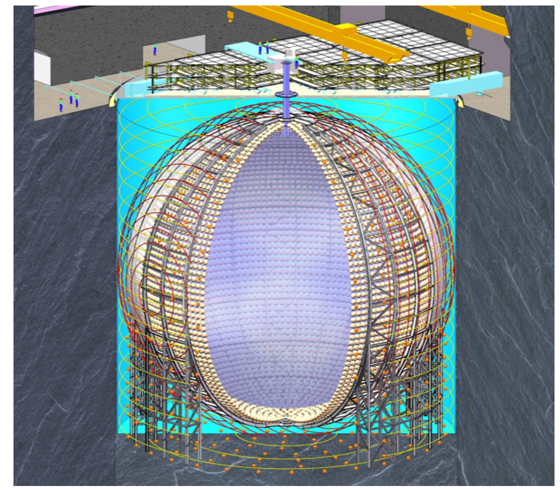
N
Events





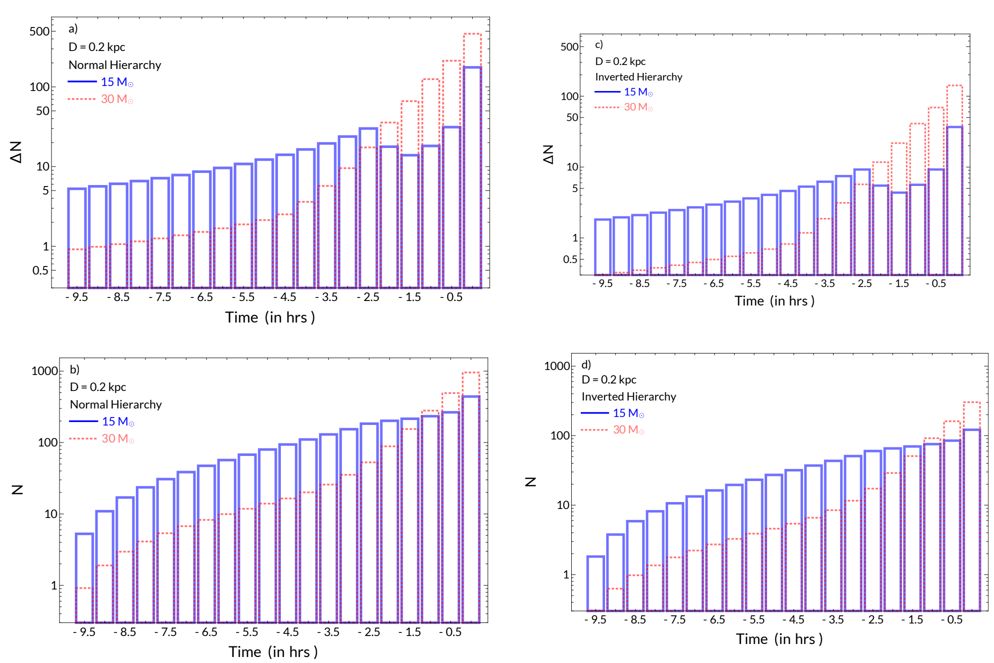
Pointing to the progenitor

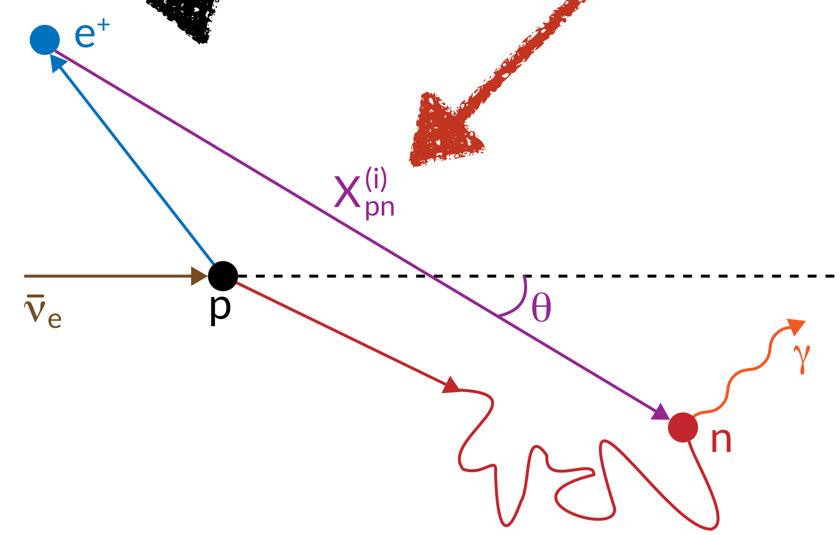




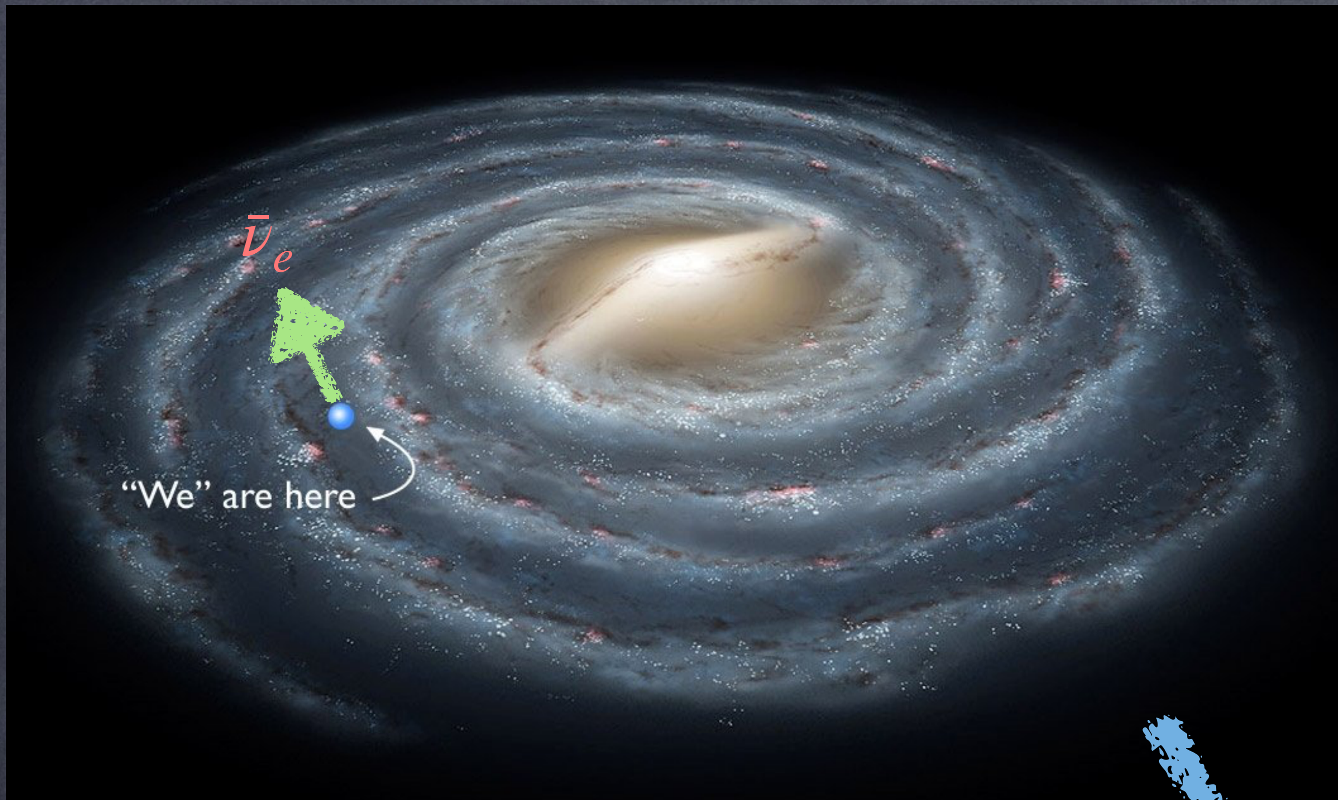
$$\vec{p} = \frac{1}{N}\sum_{i=1}^{N} \hat{X}_{pn}^{(i)}$$

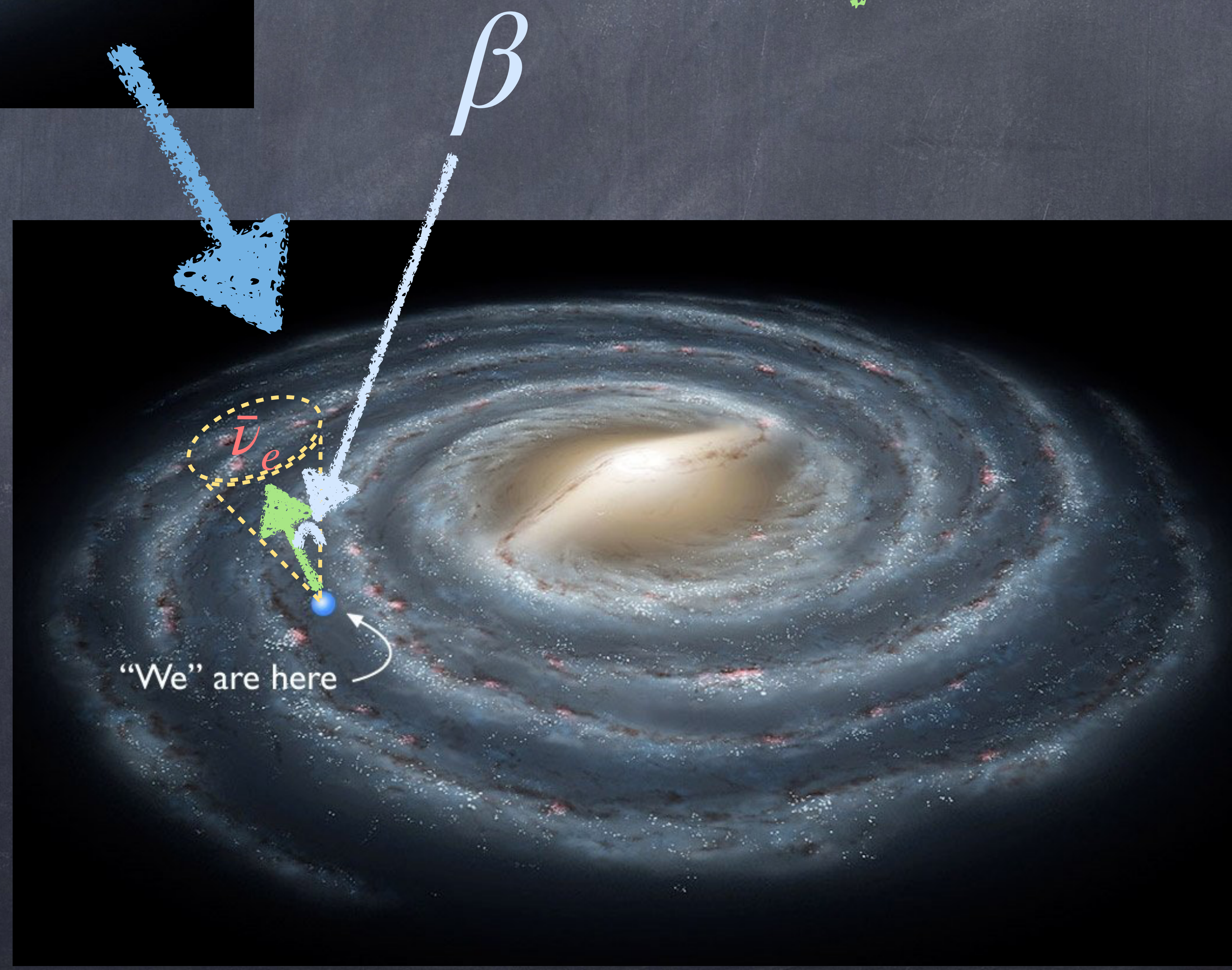
N
Events





Apollonio, Baldini, Bemporad et. al. 2000, Phys. Rev. D, 61, 012001
Fischer, Chirac, Lasserre et. al. 2015, JCAP, 032





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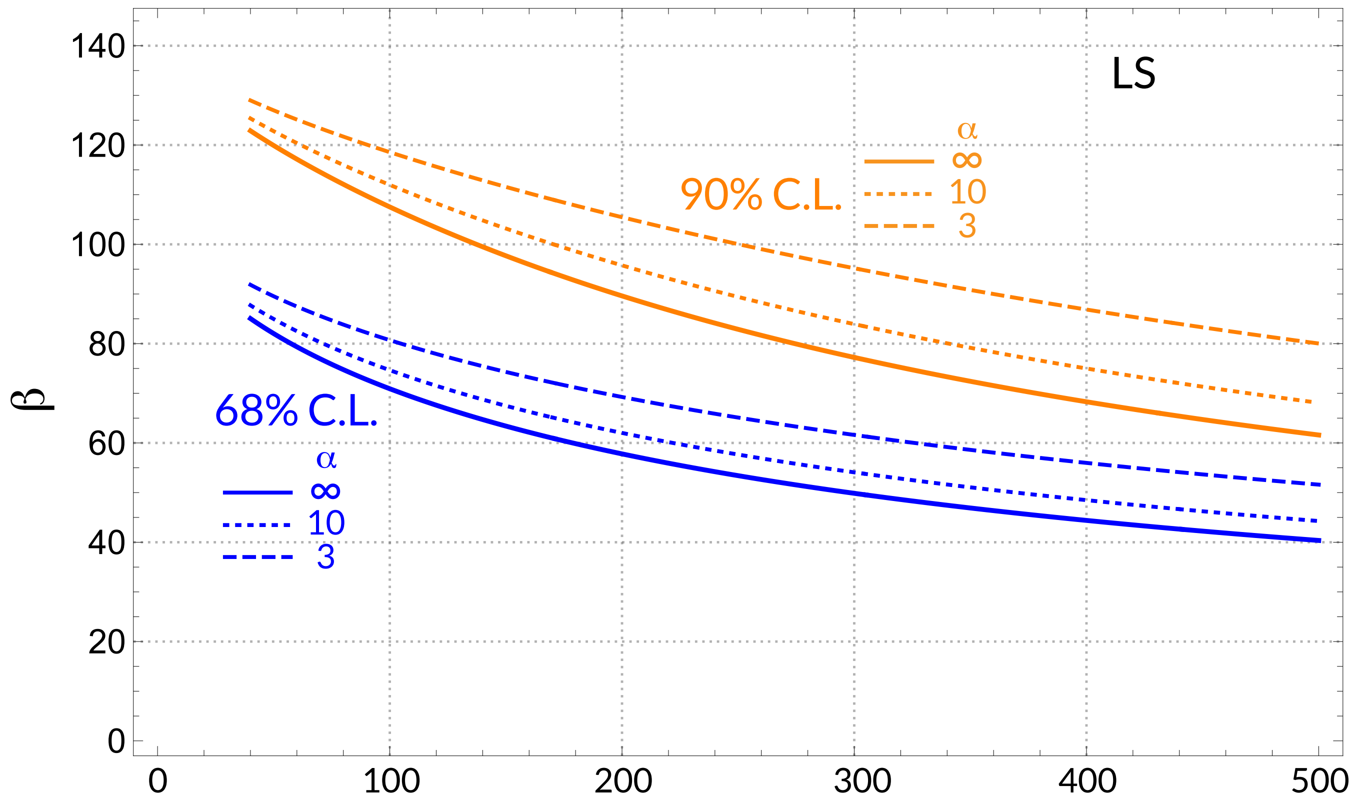
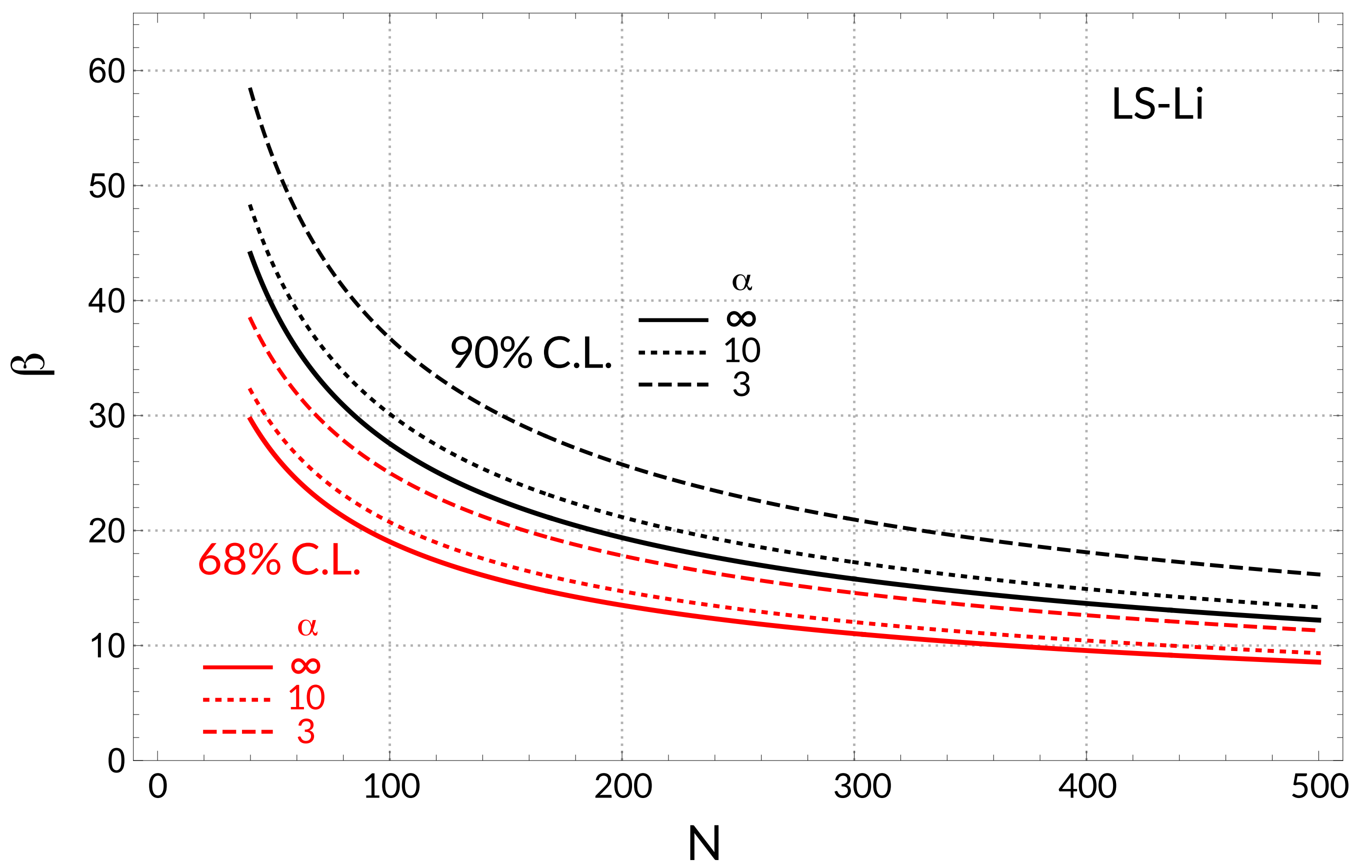
Apollonio, Baldini, Bemporad et. al. 2000, Phys. Rev. D, 61, 012001

β as a function of N



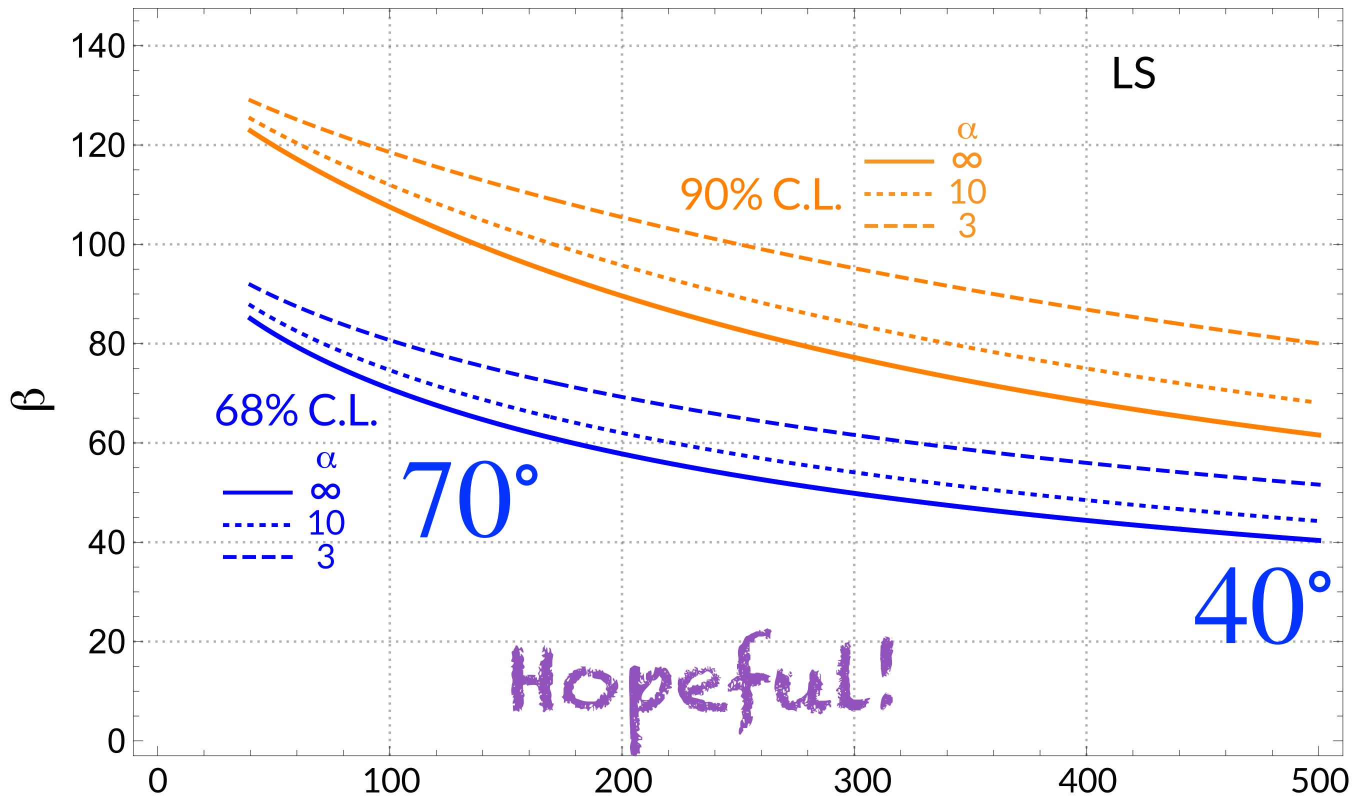


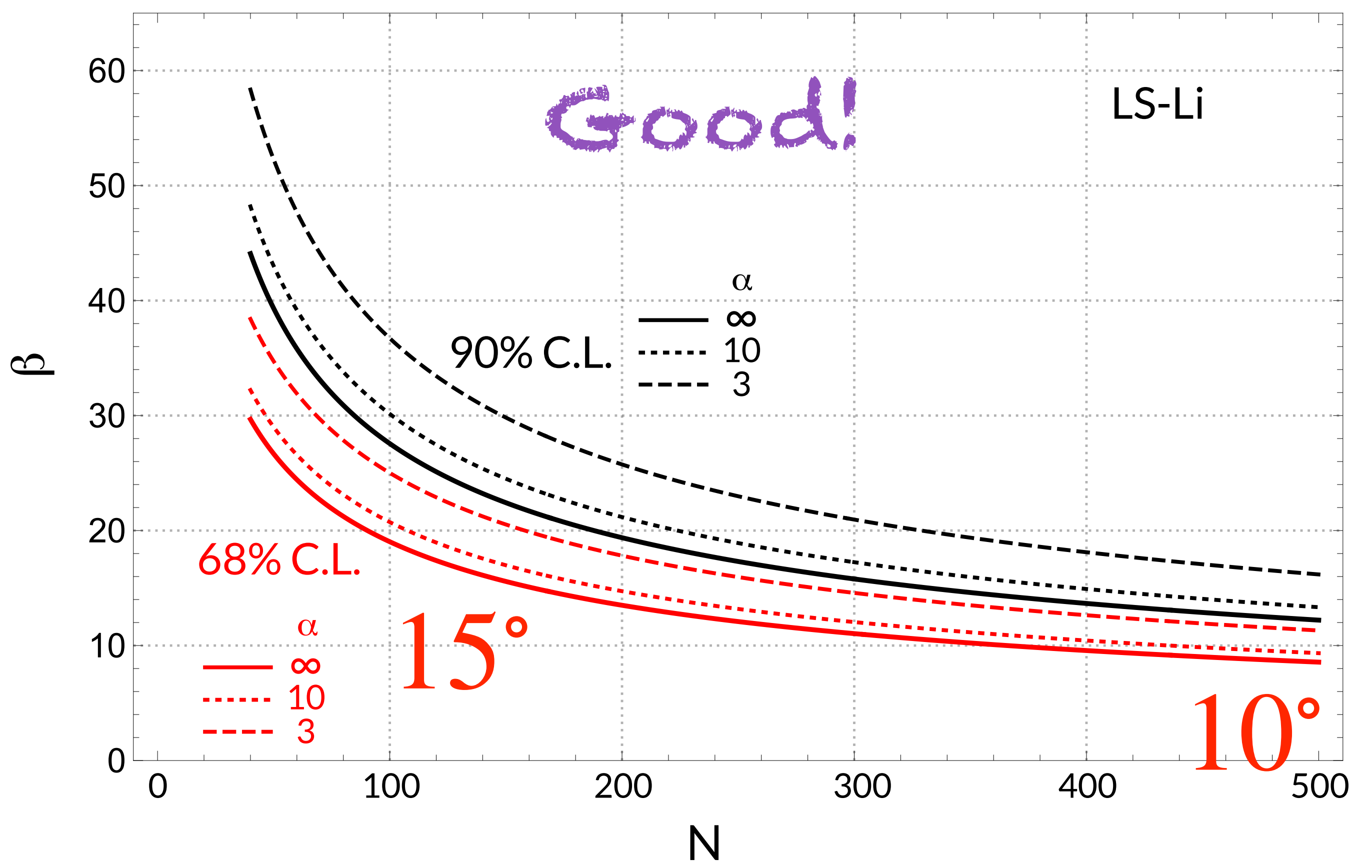
Standard LS localizes to $\approx 70^\circ$ after 100 events

$68\,\%\,C.L.$

Enhanced LS-Li localizes to $\approx 15^\circ$ after 100 events

β as a function of N



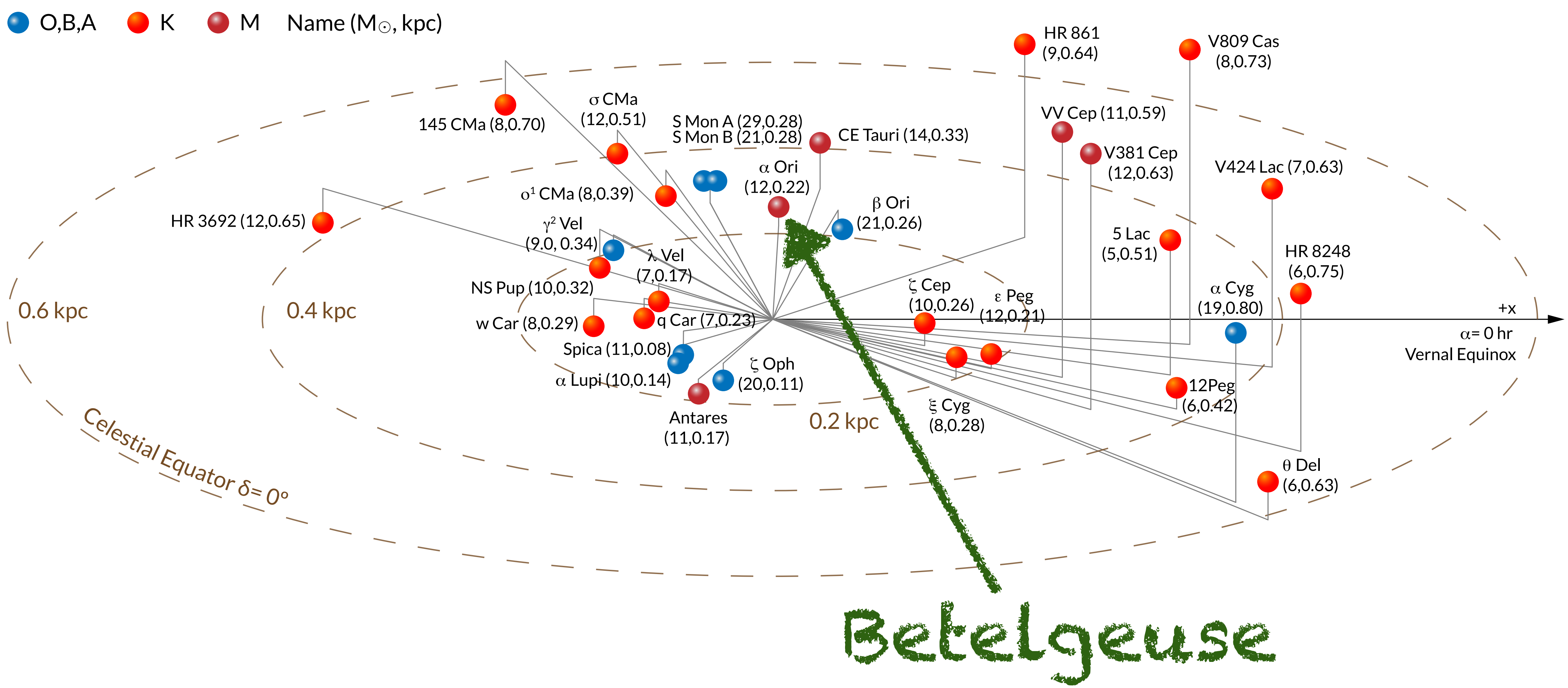


Standard LS localizes to $\approx 70°$ after 100 events

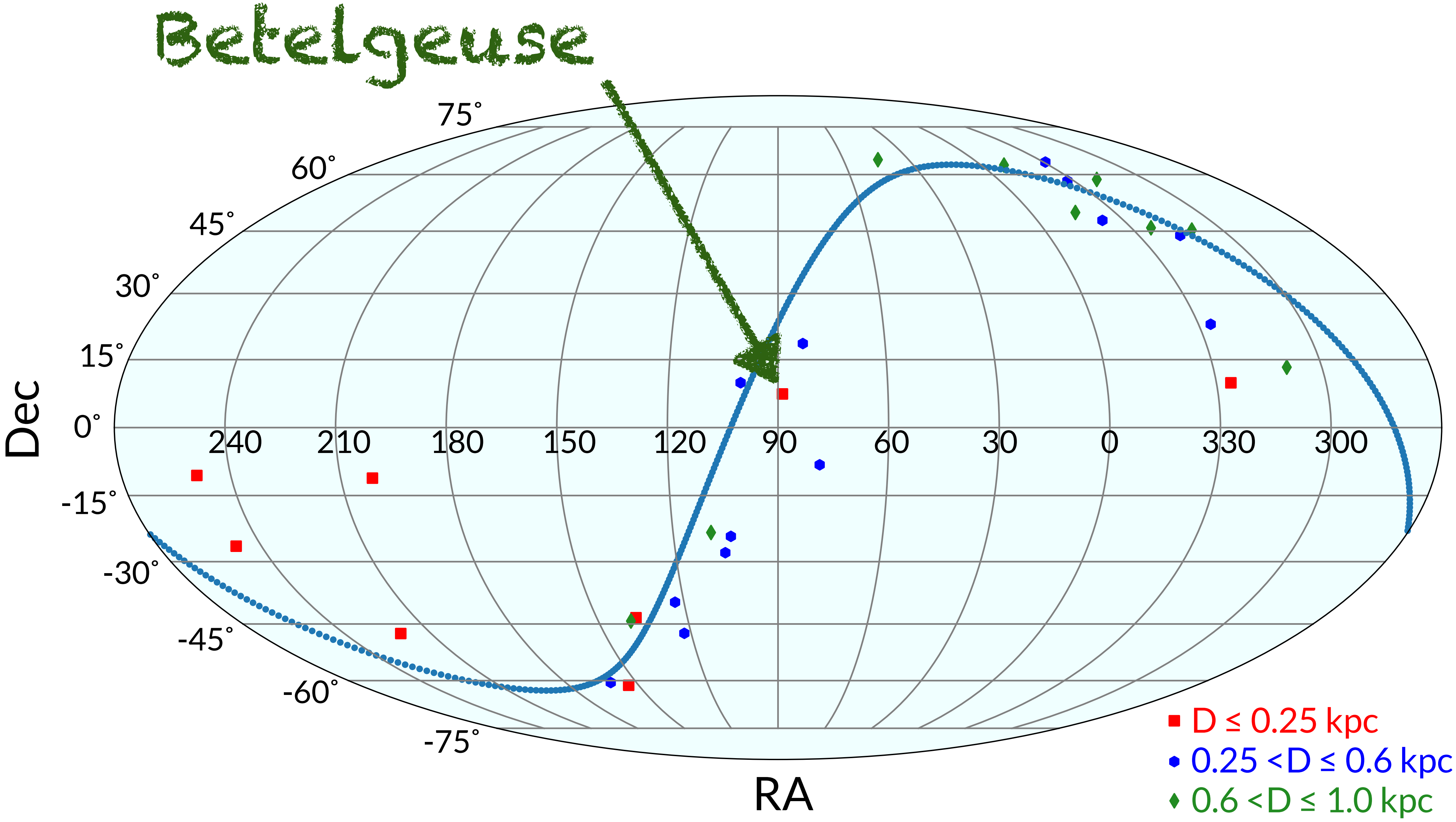
$68\,\%\,C.L.$

Enhanced LS-Li localizes to $\approx 15°$ after 100 events

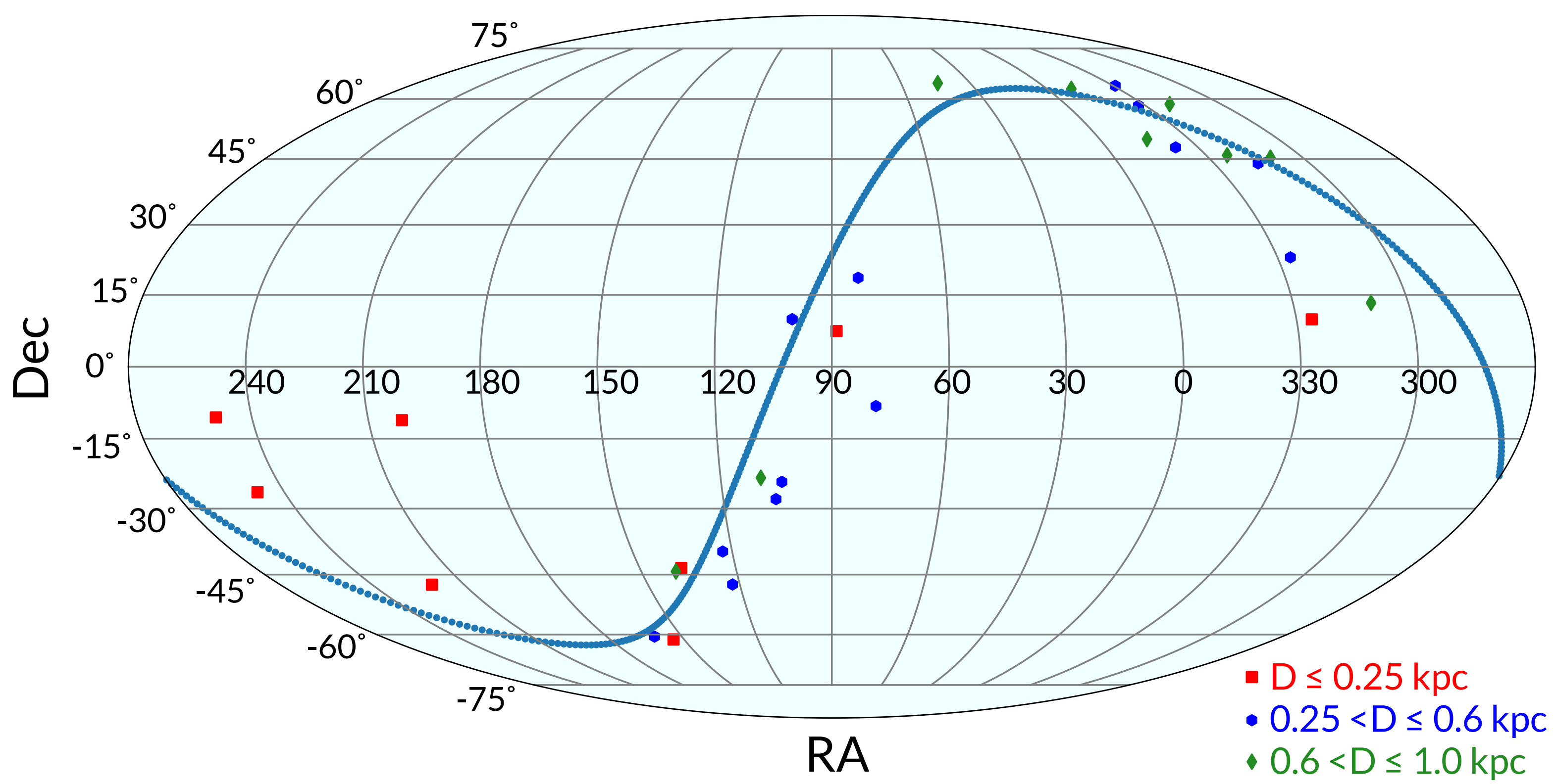
Candidates


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)
λ Vel (7,0.17)
5 Lac (5,0.51)
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)
Betelgeuse

Candidates: Mollweide Projection



Candidates: Mollweide Projection

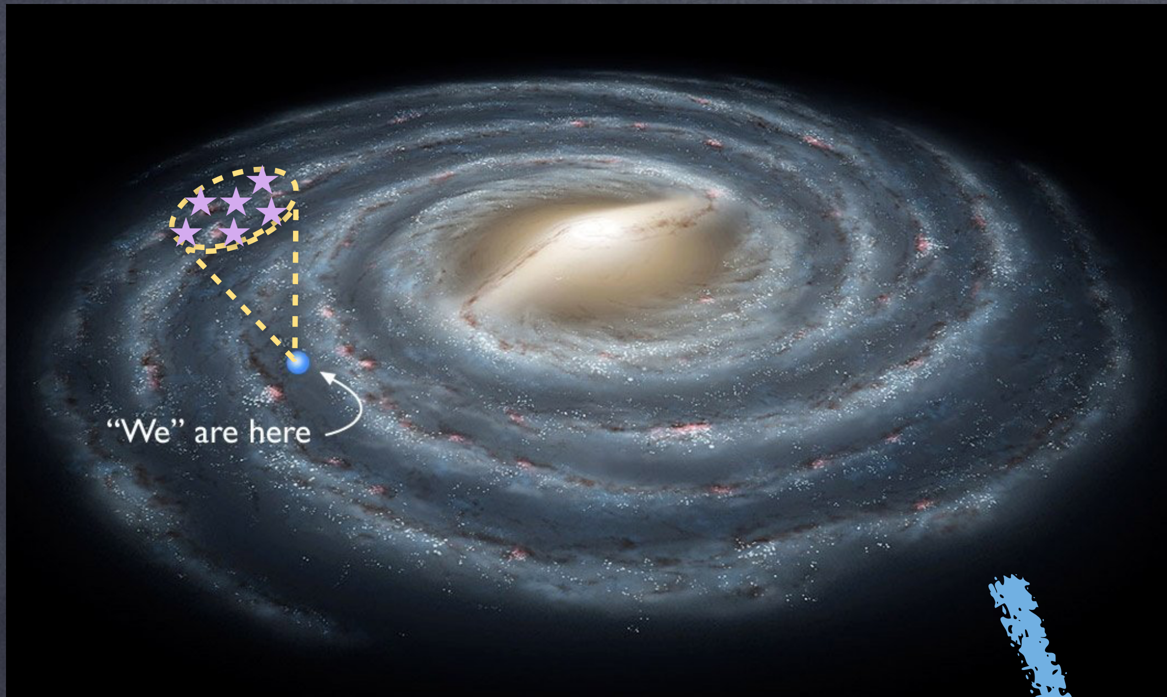


Why 1 kpc?

ν Flux $\sim \dfrac{1}{r^2}$

No considerable flux for large distances

$\sim$ 31 stars in D < 1 kpc



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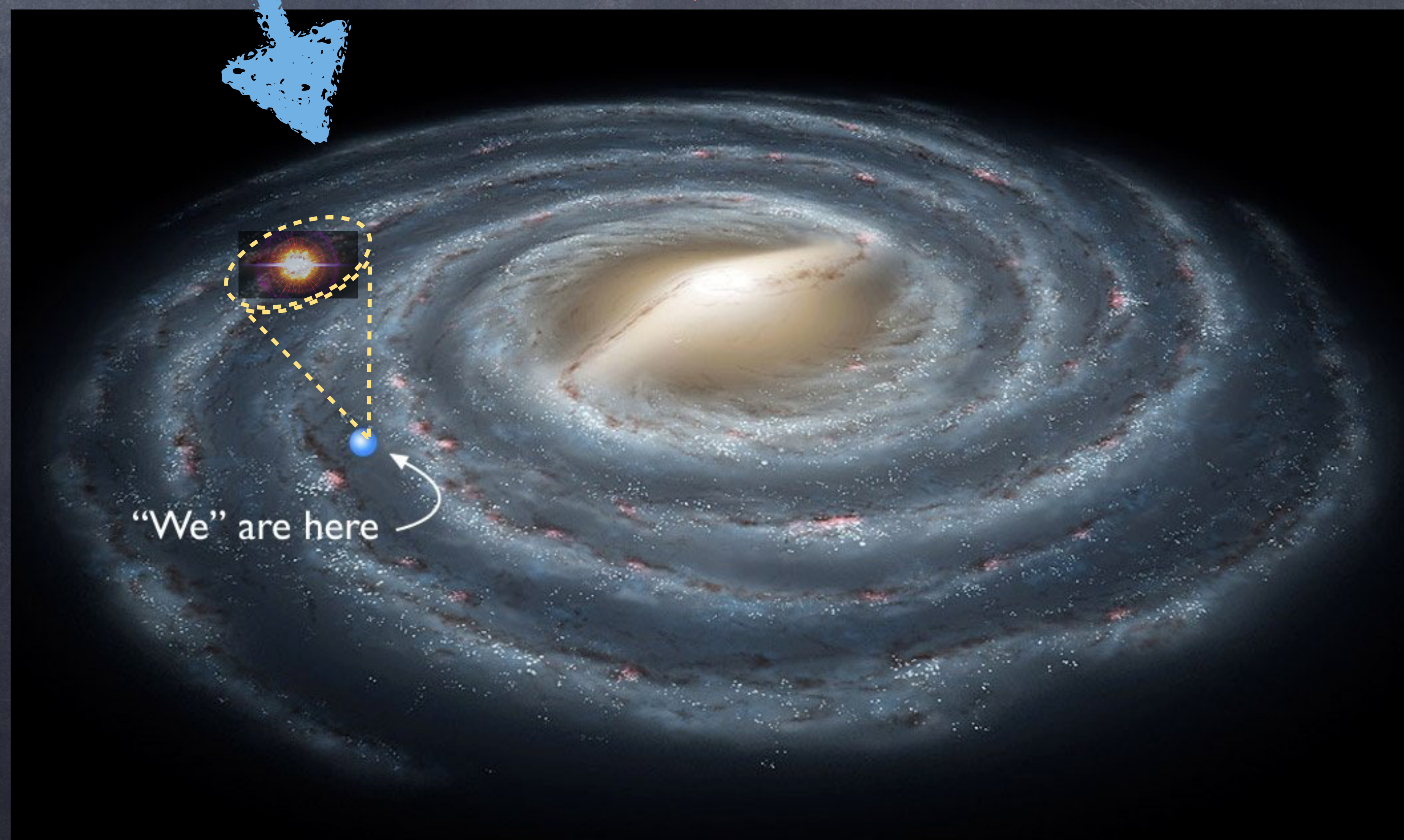
Telescopes....

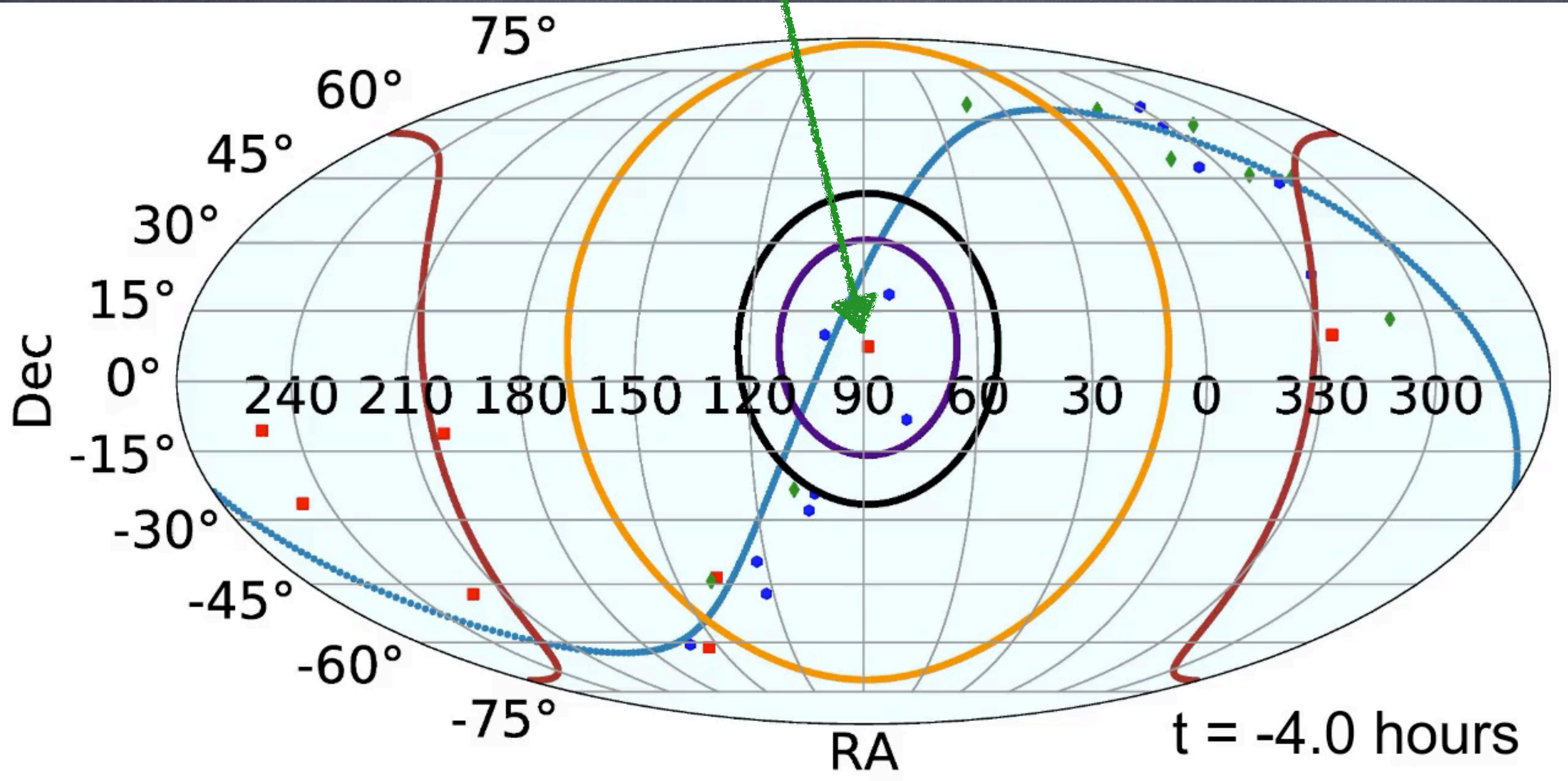


What if it is Betelgeuse?

Distance : $D = 0.222\ kpc$

Mass : $M \approx 15\ M_{Solar}$

Betelgeuse

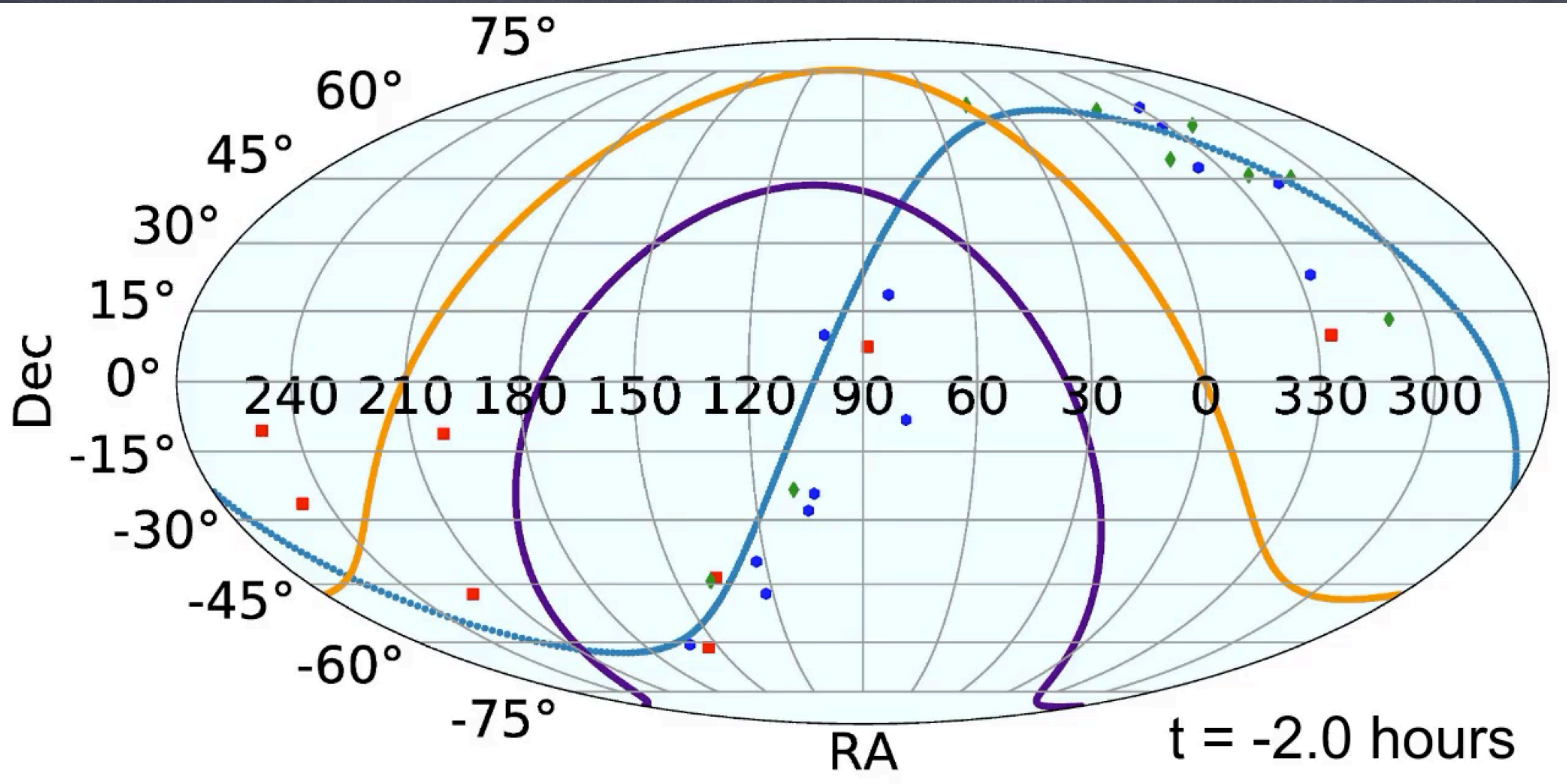

75°
60°
45°
30°
15°
0°
-15°
-30°
-45°
-60°
-75°
Dec
240 210 180 150 120 90 60 30 0 330 300
RA
t = -4.0 hours

What if we are unlucky: a far away star?

σ Canis Majoris

Distance : $D = 0.513\ kpc$

Mass : $M \approx 15\ M_{Solar}$



We only have considerable signal 2 hours before the collapse.....Huge uncertainty even with LS-Li (Only $68\,\%\, C.L.$)

Future prospects

Low energy threshold

Good directional sensitivity

Repeating the analysis for a 100 kt detector like THEIA....

Things to keep in mind:

ES + IBD events

The sheer size of it can help with the number of events observed in each channel

Picture courtesy: THEIA: an advanced optical neutrino detector - Askins et. al.

Future prospects

Repeating the analysis for a 100 kt detector like THEIA...

Most optimistic
$\sim 4^\circ - 6^\circ$ error cone

Should significantly help with directional pointing!

Picture courtesy: THEIA: an advanced optical neutrino detector - Askins et. al.

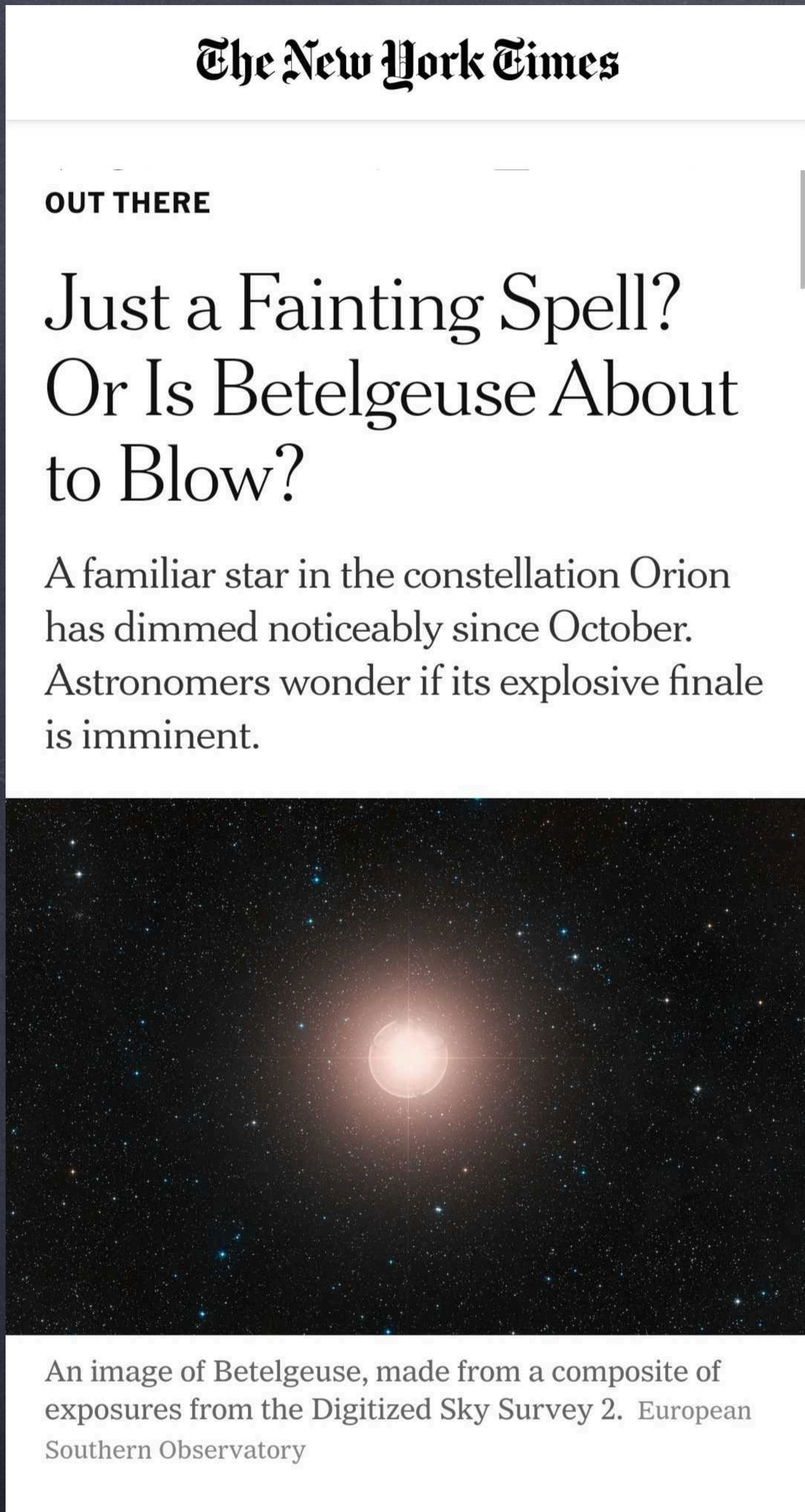
Summary

-> Pre-SN neutrinos: emitted months, days, hours prior to collapse and are detectable. Even earlier than the known SN neutrino burst

-> Directional sensitivity: Can help with locating the progenitor about to collapse

-> Serves as an early warning system and multi-messenger observations. Useful for GW, neutrino and astronomy community. Can help in testing exotic particle physics - axions….

-> Error cones: $\sim 70^{\circ}$ for standard LS detectors, shortlists $\sim$ 10 - 12 candidates and $\sim 20^{\circ}$ for enhanced LS detectors, shortlists $\sim$ 4 - 5 candidates



The New York Times

OUT THERE

Just a Fainting Spell? Or Is Betelgeuse About to Blow?

A familiar star in the constellation Orion has dimmed noticeably since October. Astronomers wonder if its explosive finale is imminent.

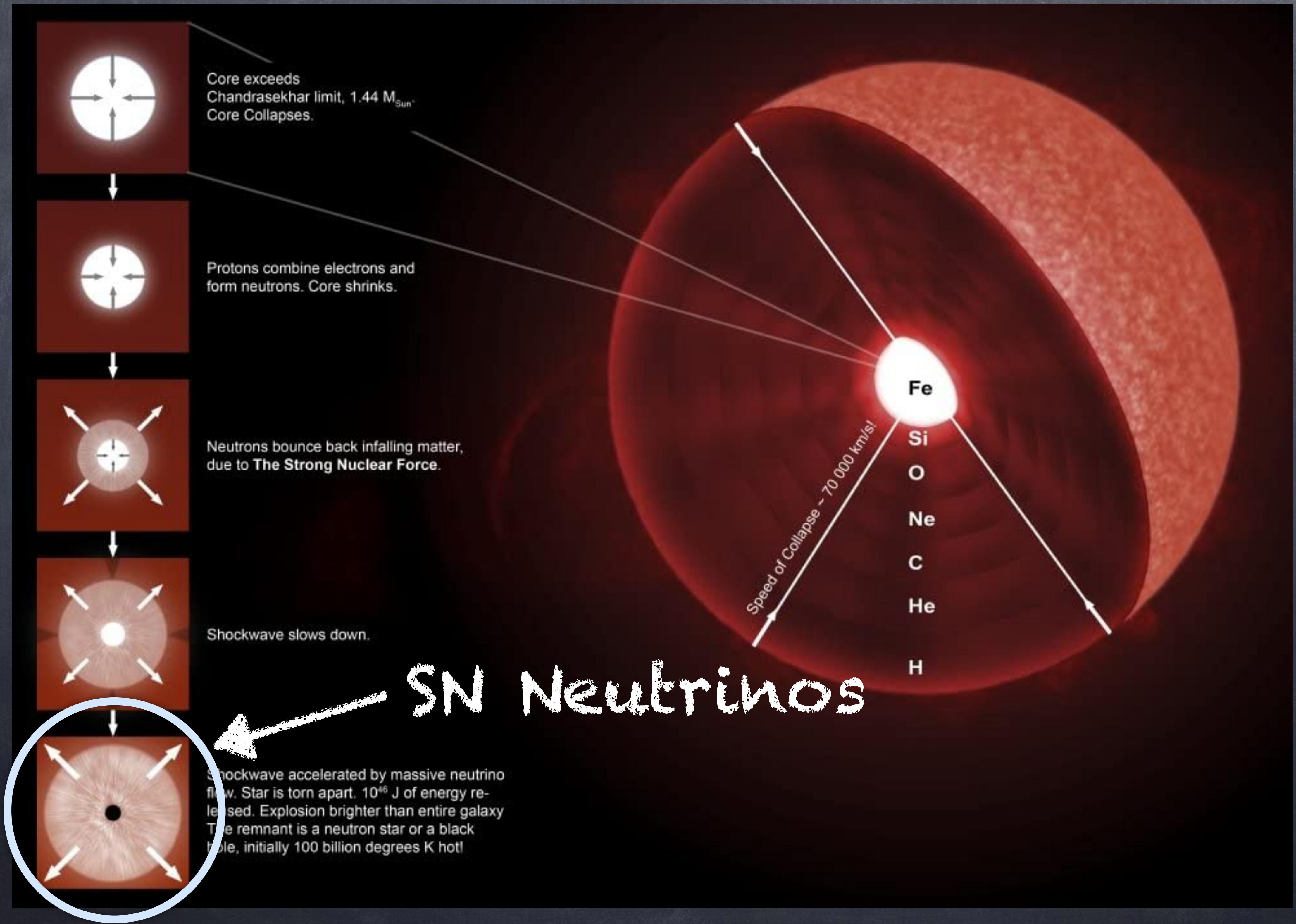
An image of Betelgeuse, made from a composite of exposures from the Digitized Sky Survey 2. European Southern Observatory

Hopefully, we will be able to know at least a few hours (may be even days) in advance through our very early messengers: pre-supernova neutrinos!

Thank You...

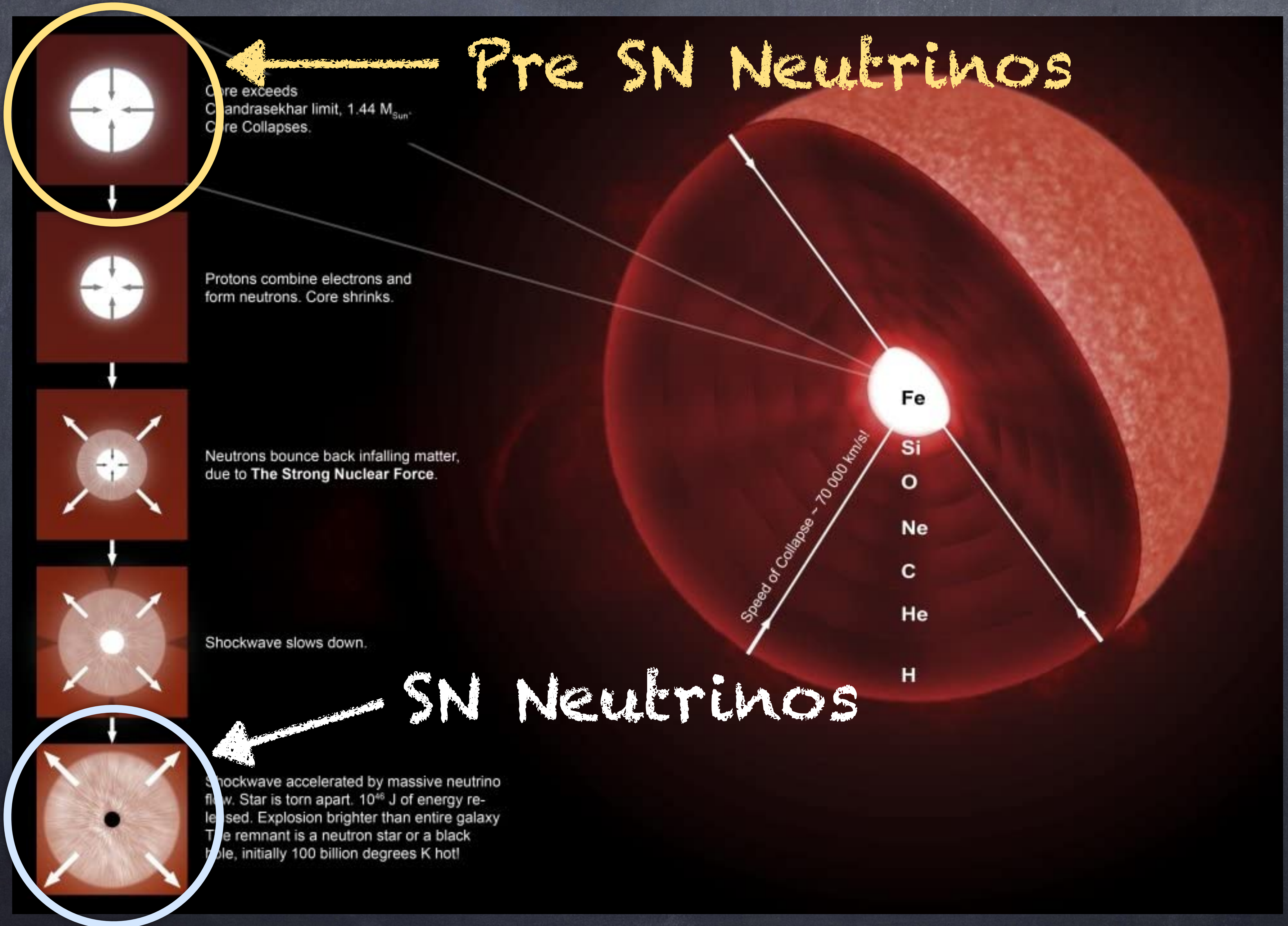
Backup Slides

SN Explosion 101

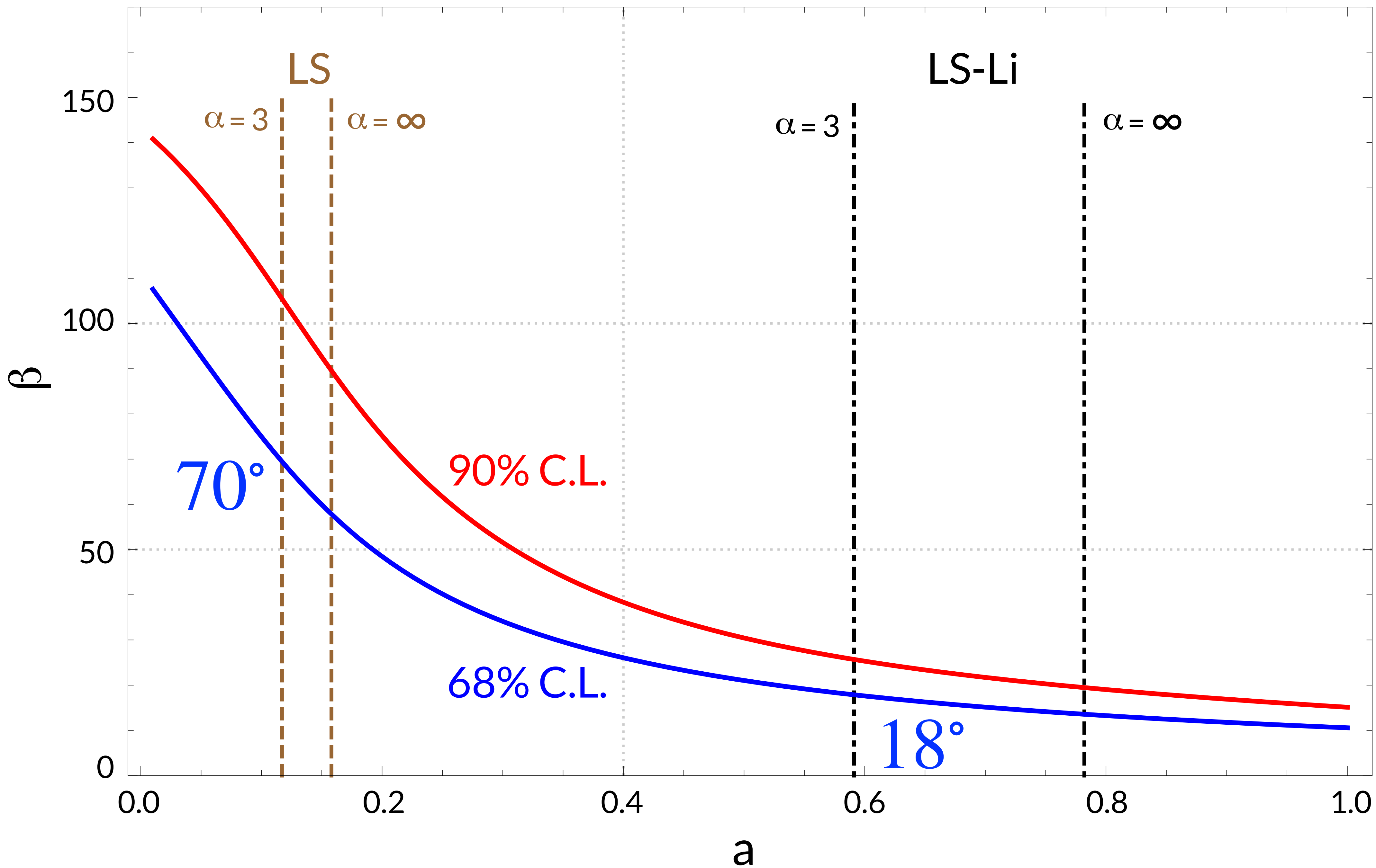


Source: https://images-na.ssl-images-amazon.com/images/I/61yf26rpIXL._AC_SL1000_.jpg

SN Explosion 101

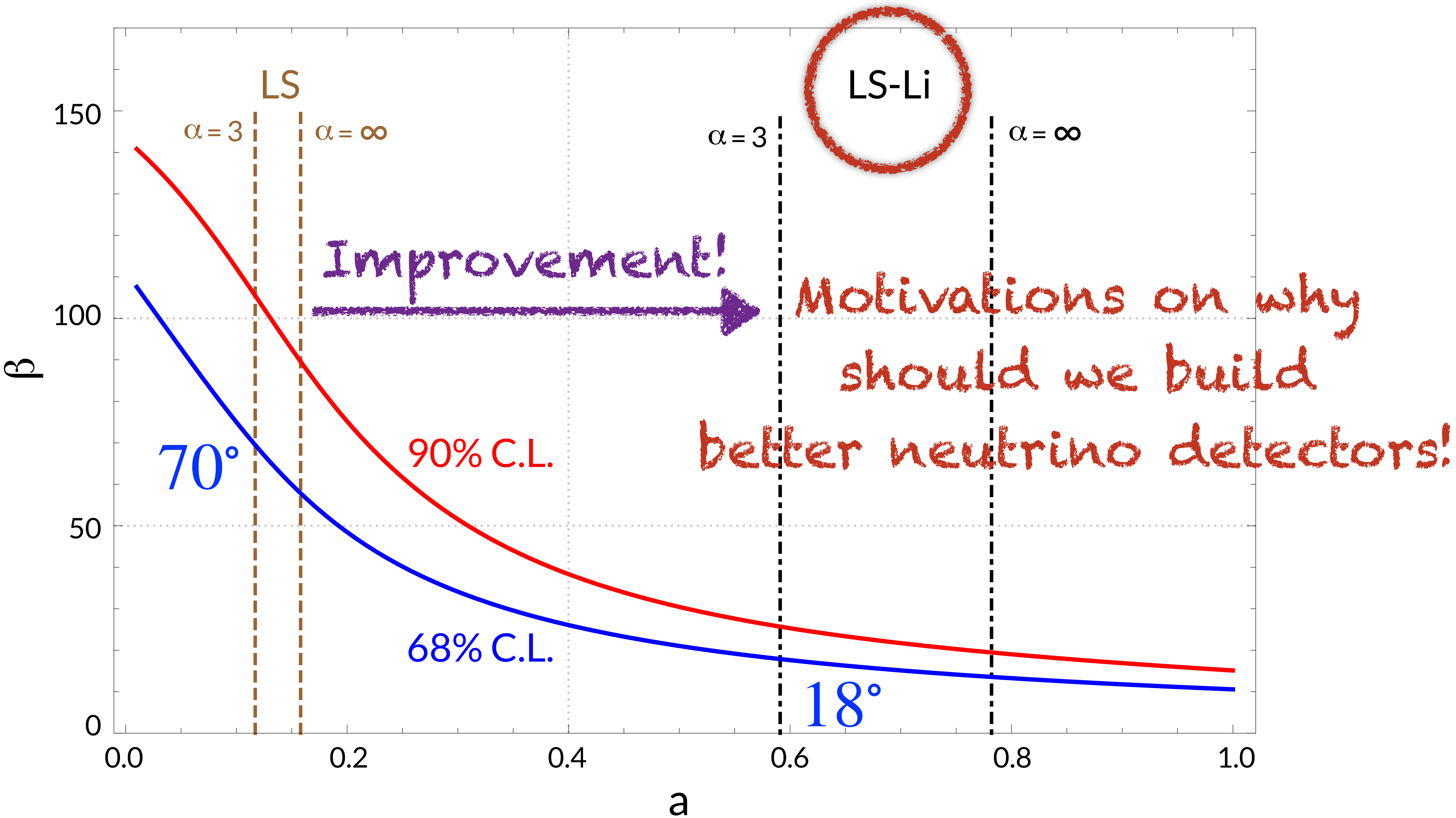


β as a function of 'a'



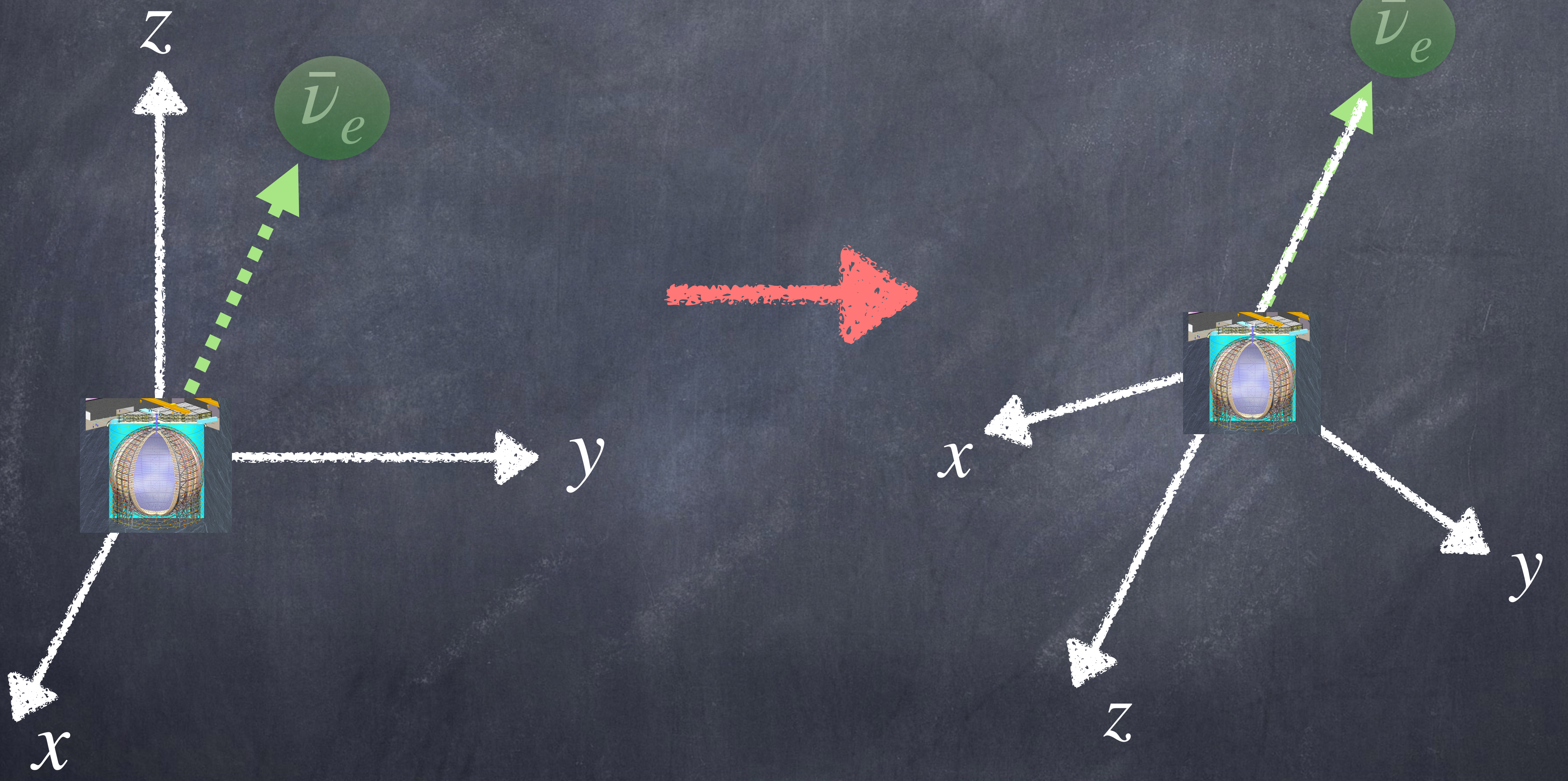
N = 200

β as a function of 'a'

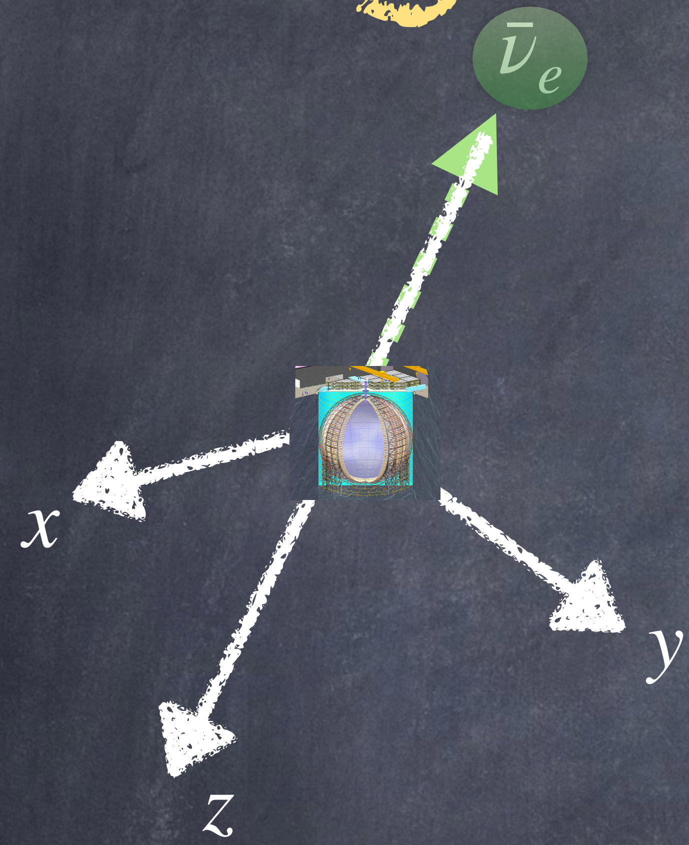


N = 200

Angular Uncertainty (β)



Angular Uncertainty (β)



$$\hat{X}_{pn}^{(i)}$$

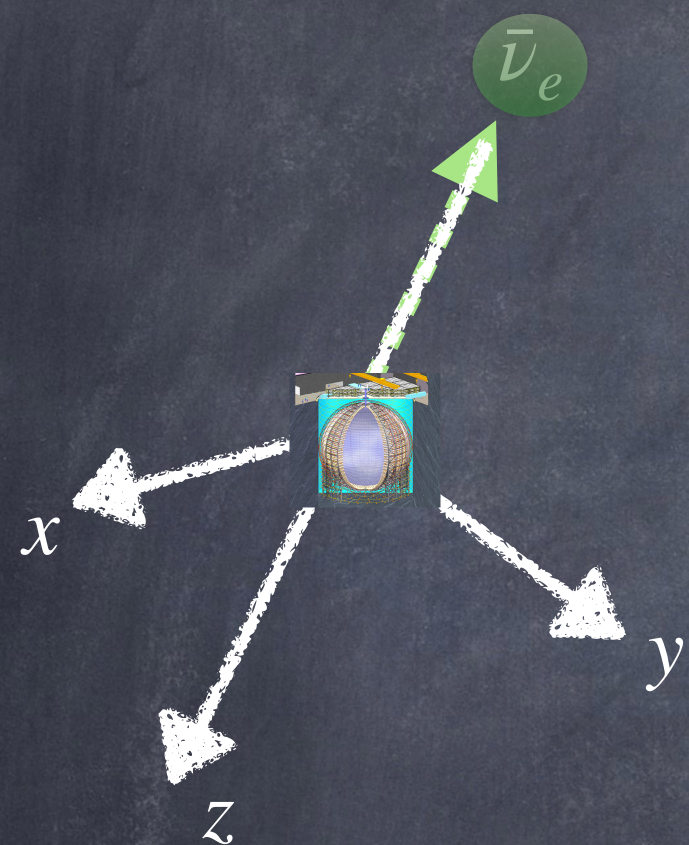
$$x \qquad y \qquad z$$

$$\langle x \rangle = 0 \qquad \langle y \rangle = 0 \qquad \langle z \rangle = \frac{a}{3} \qquad N \to \infty$$

Mean of $\overrightarrow{p}$: $\longleftarrow$ $\overrightarrow{p} = \frac{1}{N} \sum_{i=1}^{N} \hat{X}_{pn}^{(i)}$

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

Angular Uncertainty (β)



Mean of $\overrightarrow{p}$:

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

$$f(\cos\theta) = \frac{1}{2}\left(1 + a\cos\theta\right)$$

$\overrightarrow{p}$

p_x p_y p_z

Central Limit Theorem

Gaussian Distribution

$$\sigma = \frac{1}{\sqrt{3N}}$$

Angular Uncertainty (β)

$$\overrightarrow{p} = \frac{1}{N}\sum_{i=1}^{N} \hat{X}_{pn}^{(i)}$$

Probability distribution of $\overrightarrow{p}$

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

Angular Uncertainty (β)

$$\int P(p_x, p_y, p_z)\, dp_x\, dp_y\, dp_z = I$$

$I = 0.68$

$68\,\%\ C.L.$

$I = 0.90$

$90\,\%\ C.L.$

Black Box (Transform to spherical coordinates…)

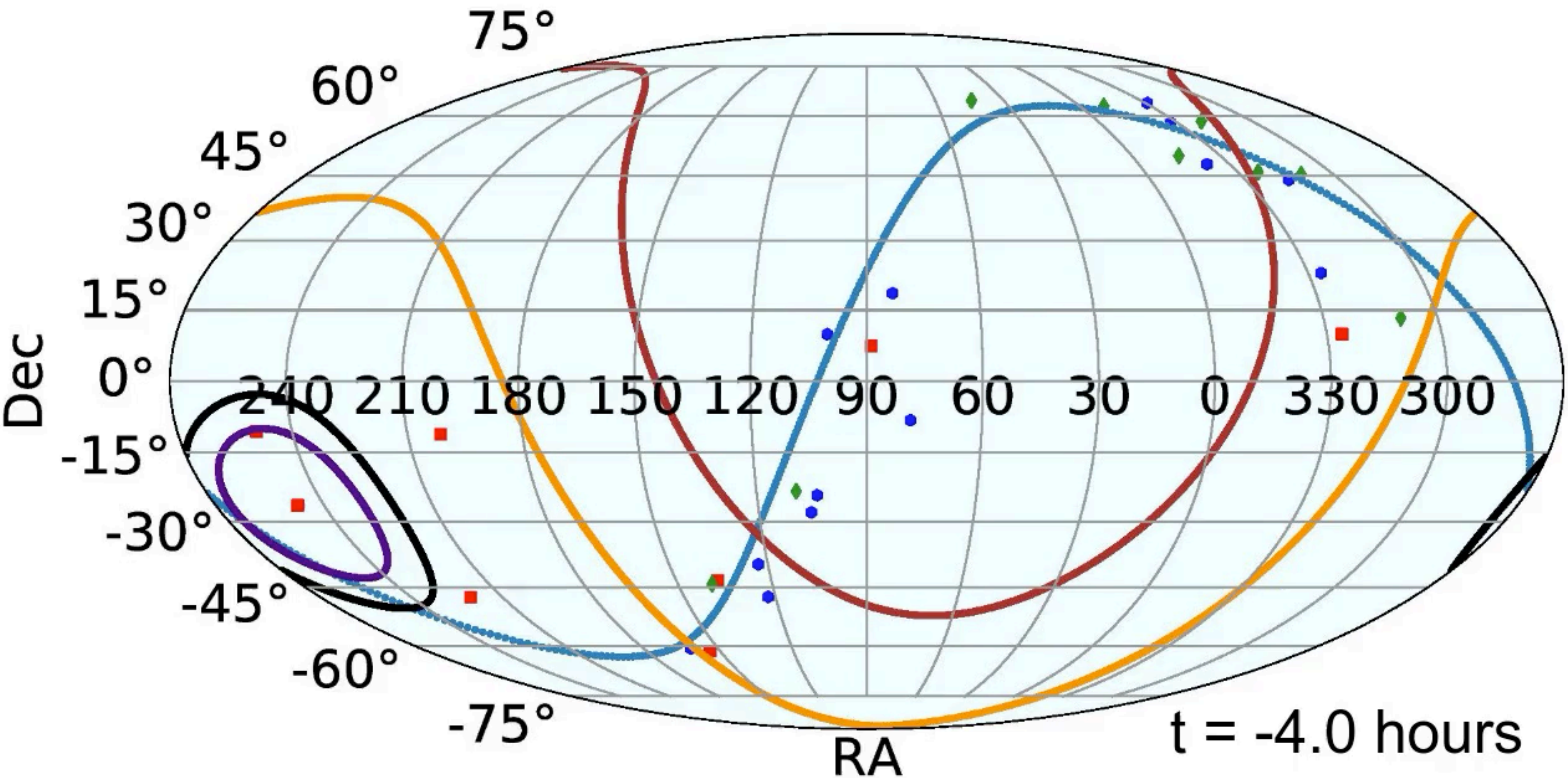
Nice analytical expression!

(Hush work in progress!)

What if it is Antares?

Distance : $D = 0.169\ kpc$

Mass : $M \approx 15\ M_{Solar}$


75°
60°
45°
30°
15°
0°
-15°
-30°
-45°
-60°
-75°
Dec
240 210 180 150 120 90 60 30 0 330 300
RA
t = -4.0 hours

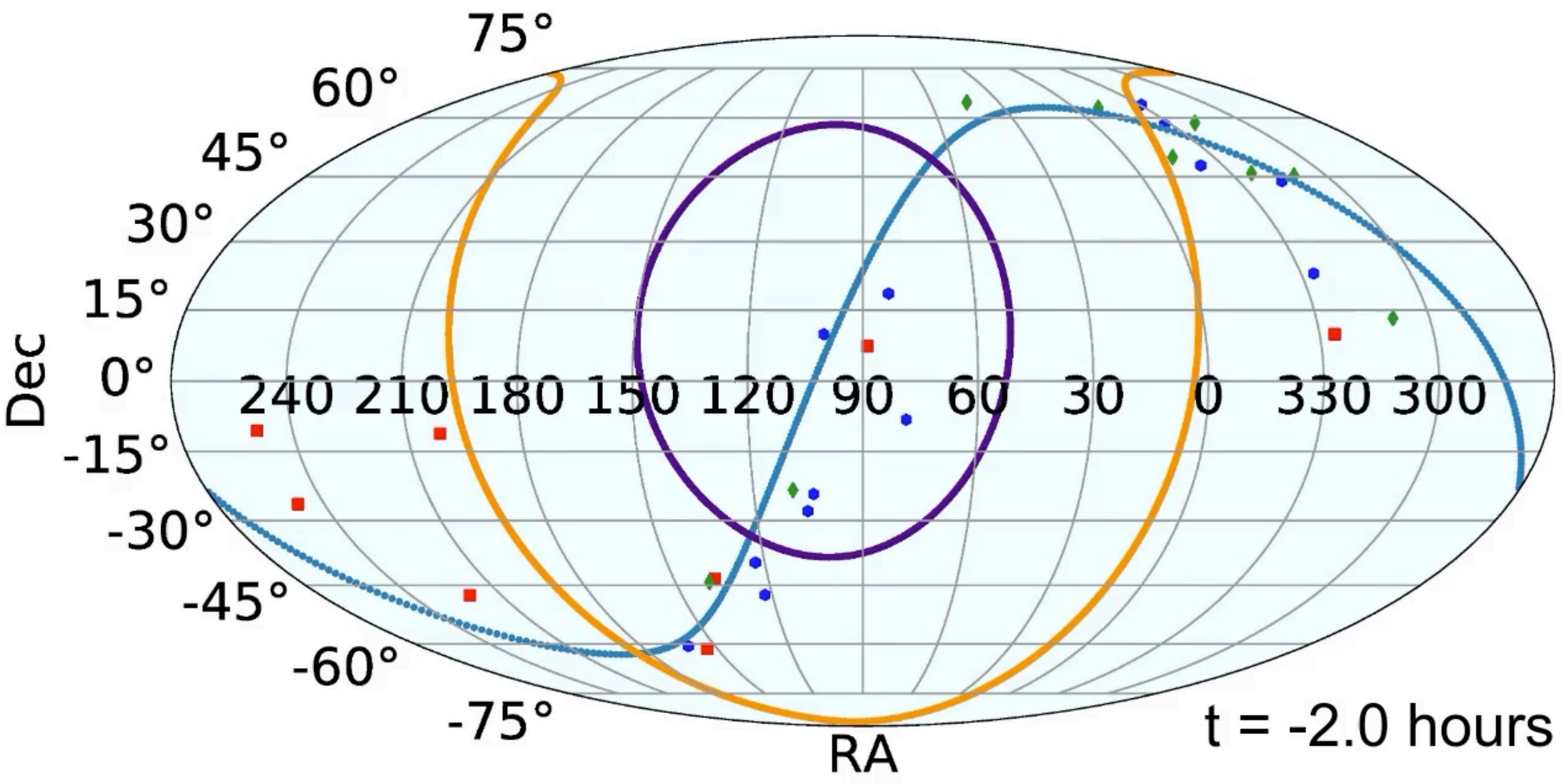
What if it is a huge star?

S Monocerotis A

Distance : $D = 0.282\ kpc$

Mass : $M \approx 30\ M_{Solar}$

Huge!



Pointing greatly improves towards the end because of event (flux) distribution (Only $68\,\%\,C.L.$)