A new probe of supernova ALPs in neutrino water Cherenkov detectors

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https://projects.ift.uam-csic.es/thedeas/

arXiv: 2412.09595

arXiv: 2412.19890

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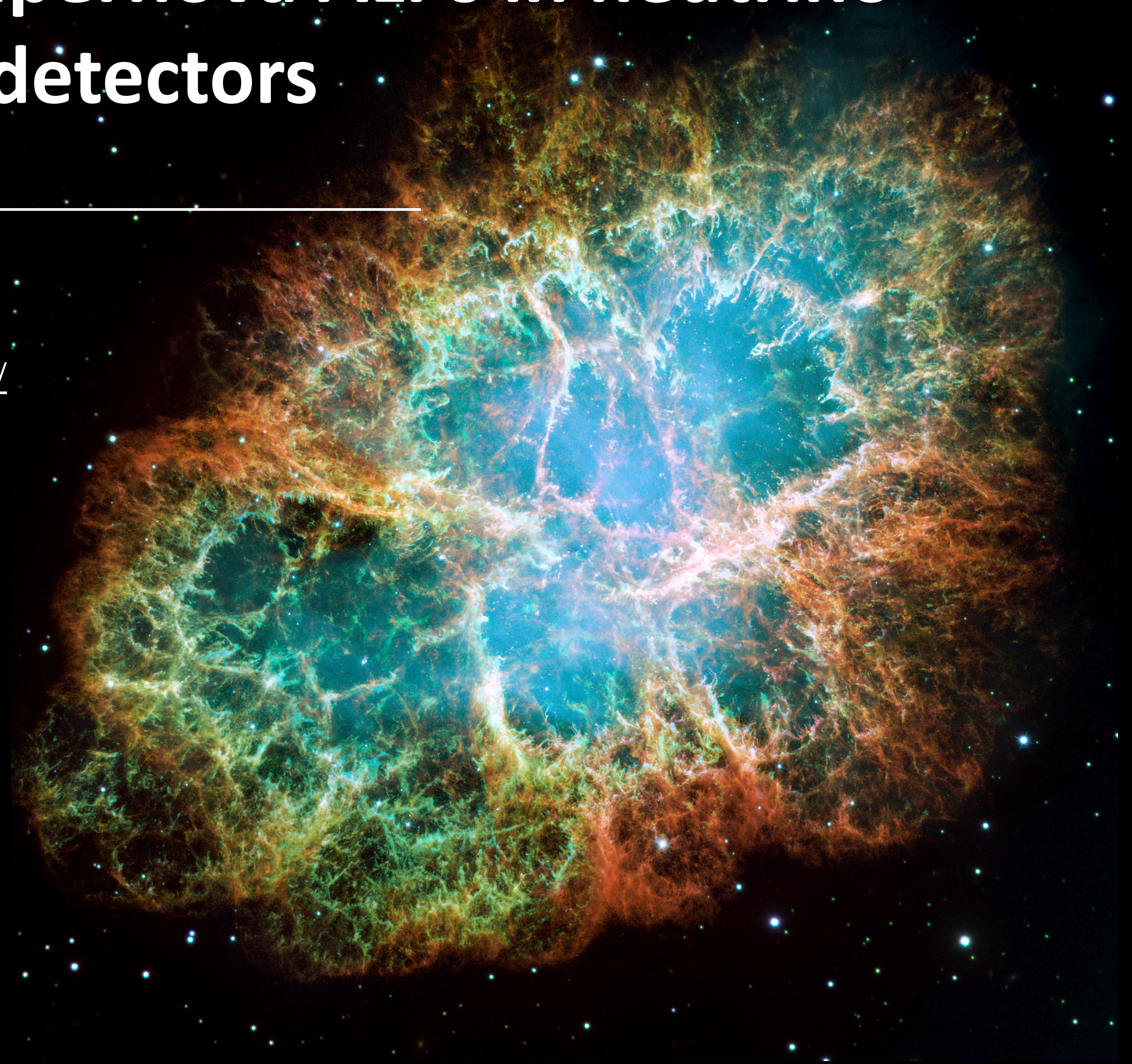
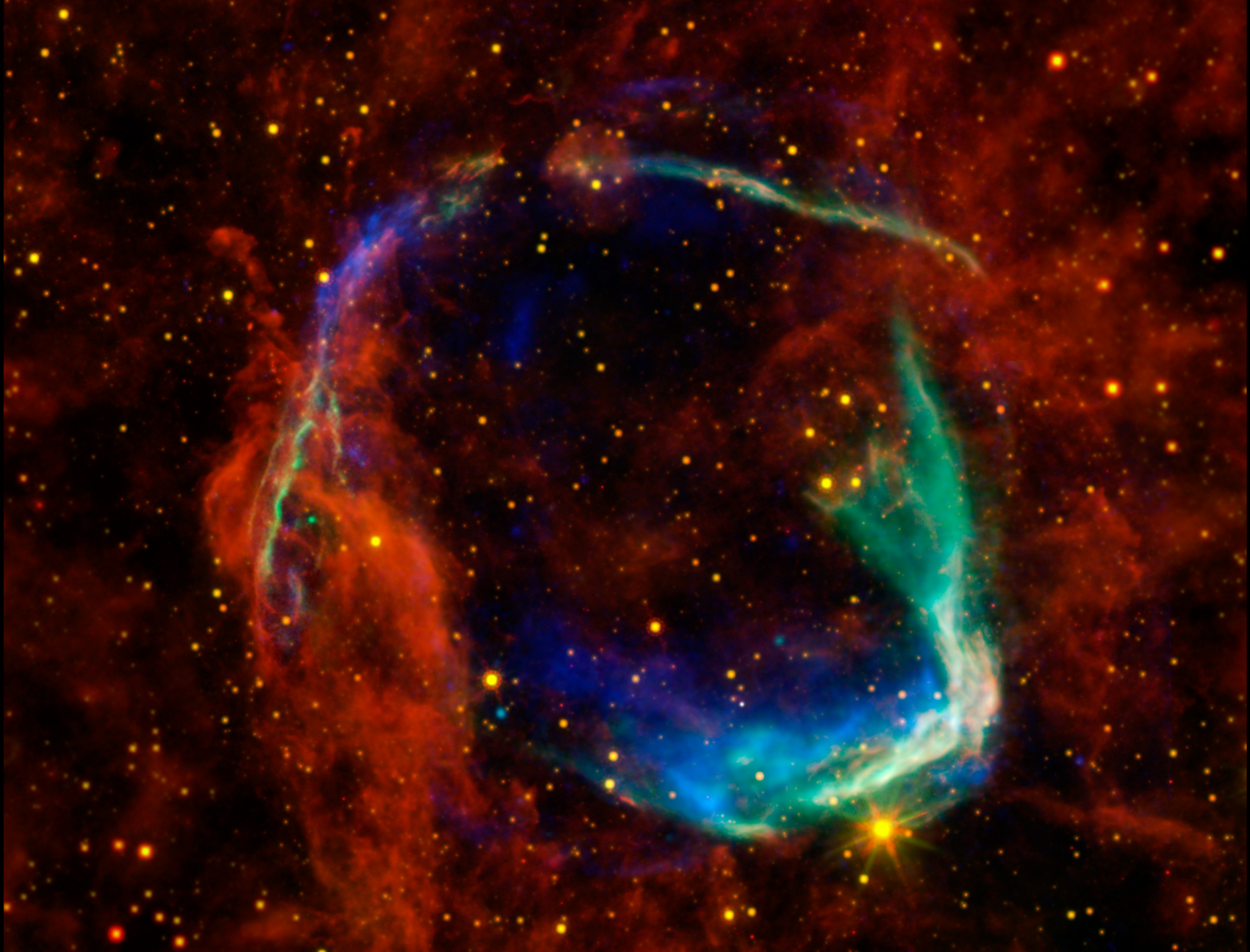
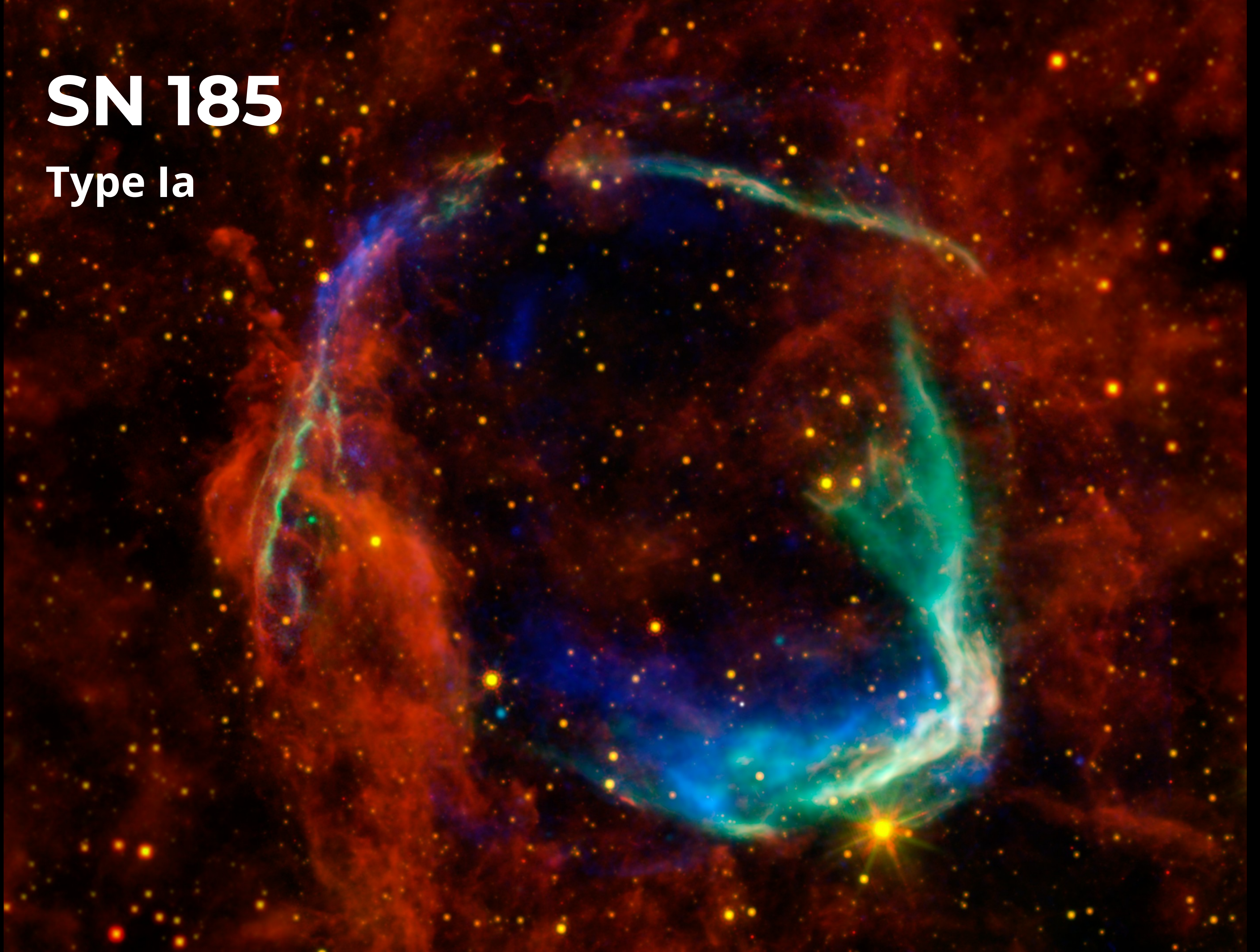


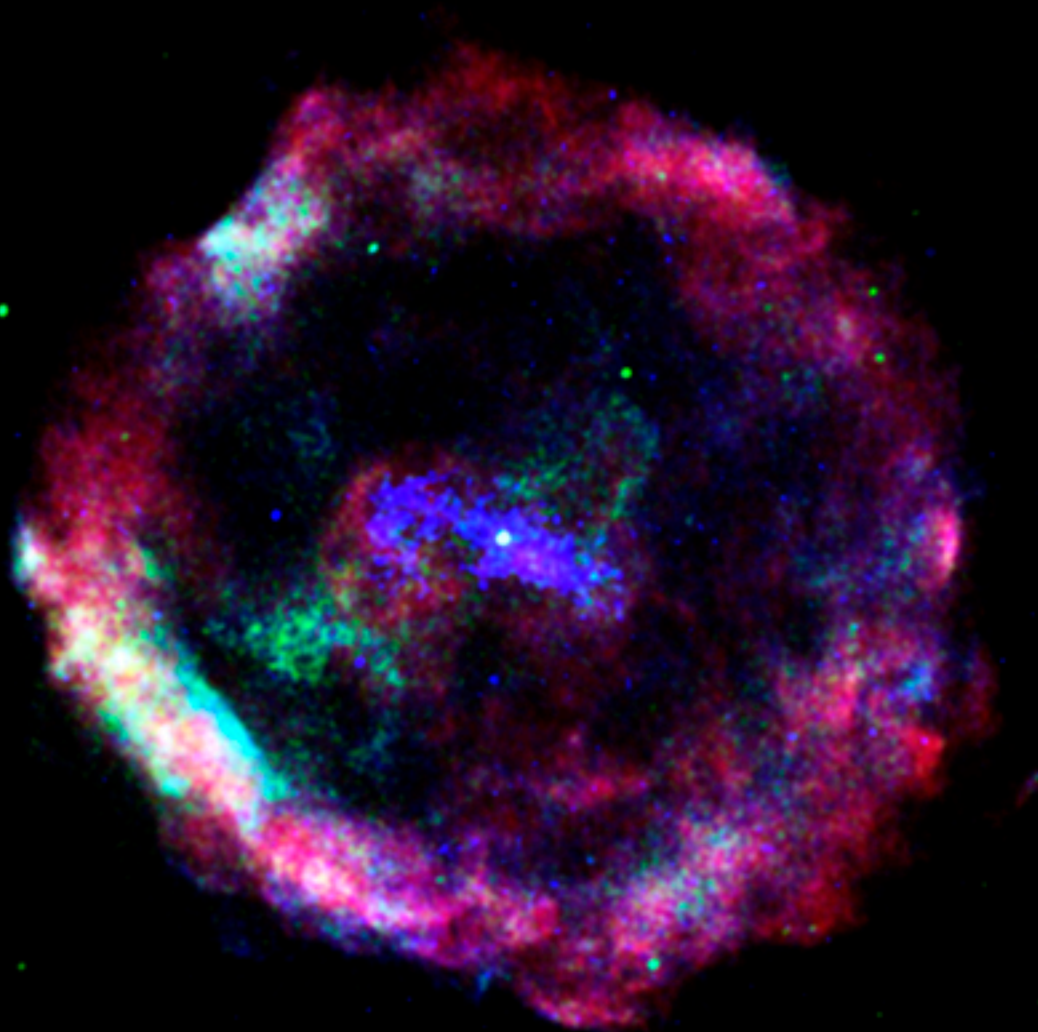




SN 185
Type Ia

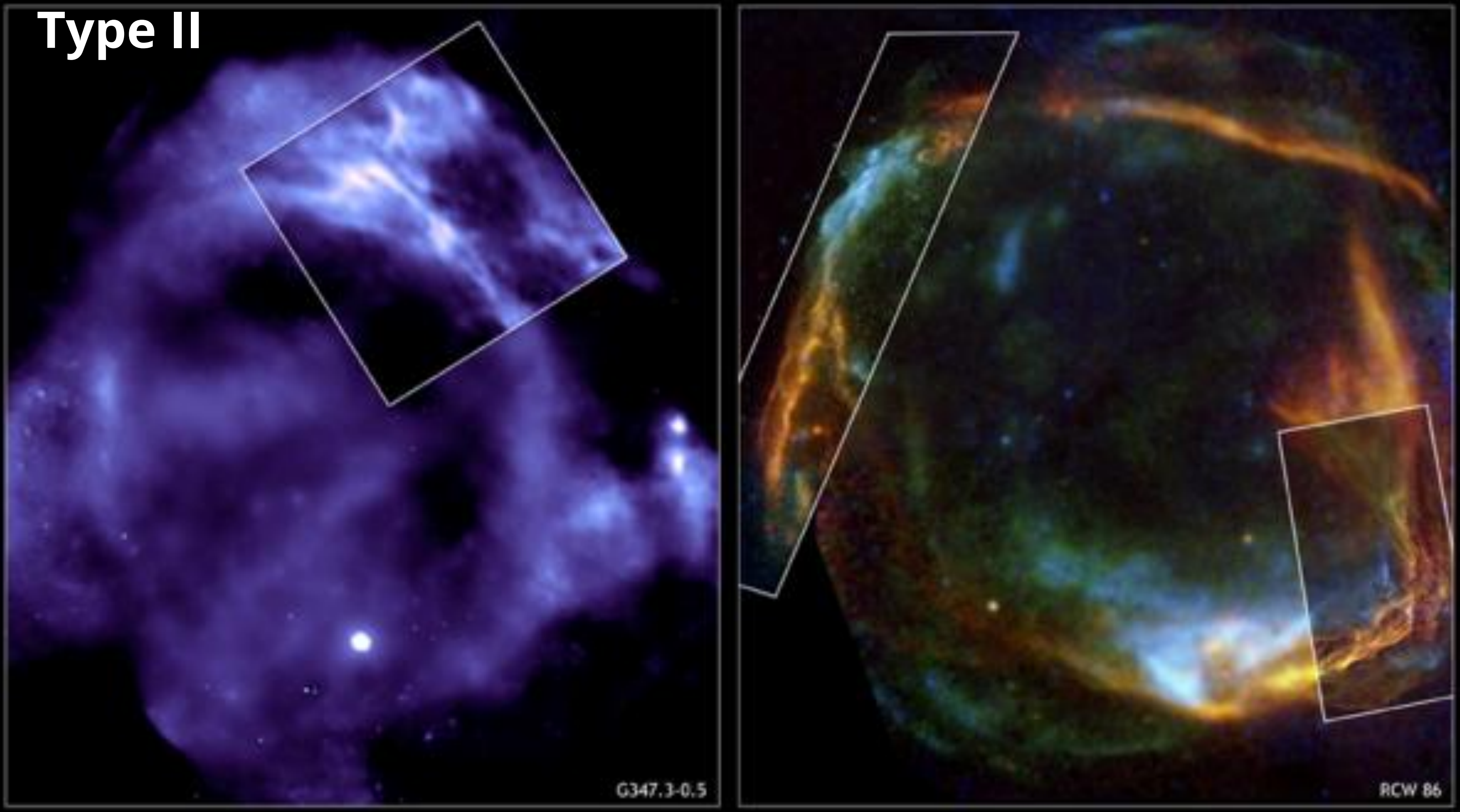
SN 386

Type II



SN 393

Type II



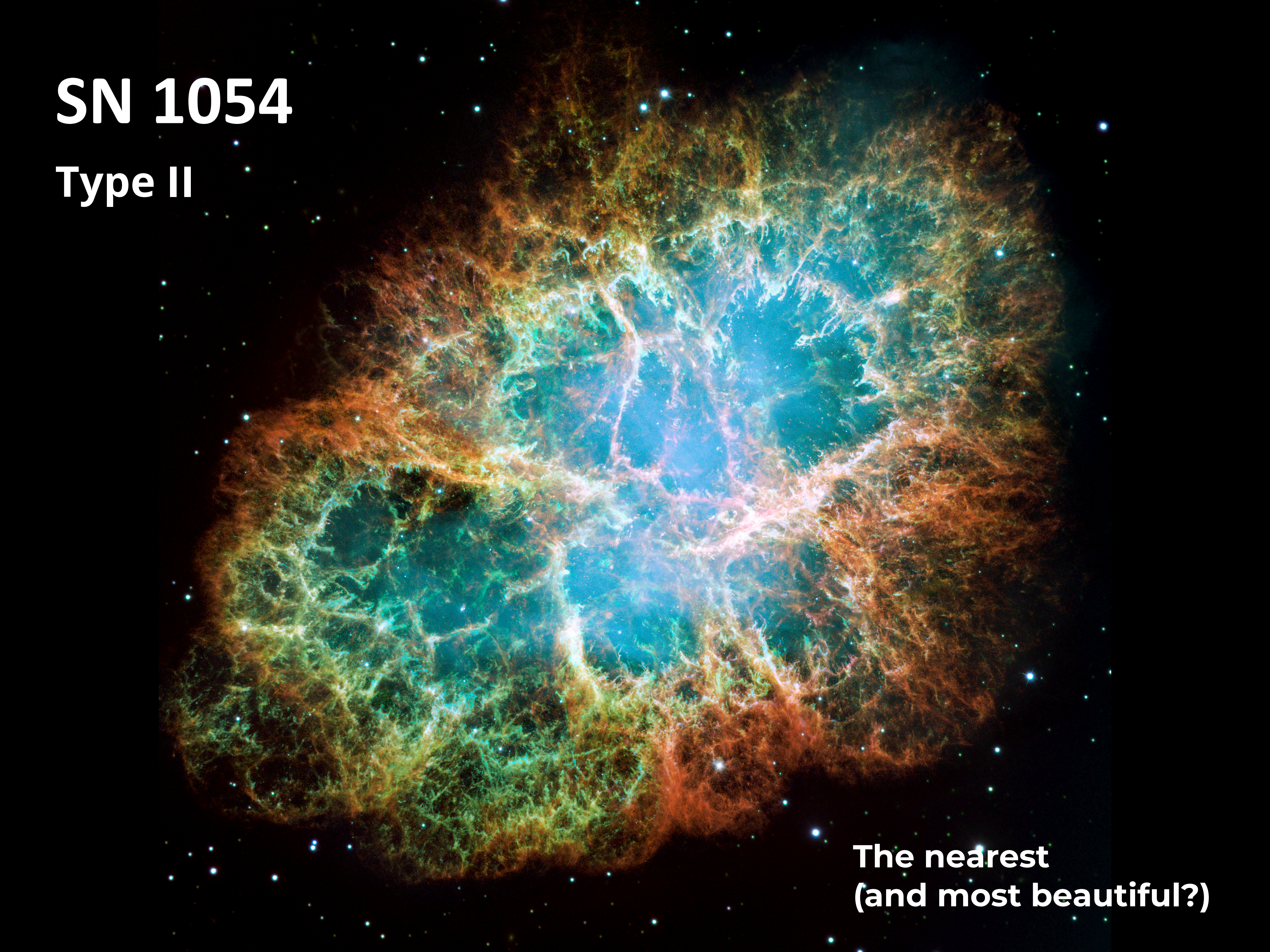
SN 1006

Type Ia

The brightest!!

SN 1054

Type II



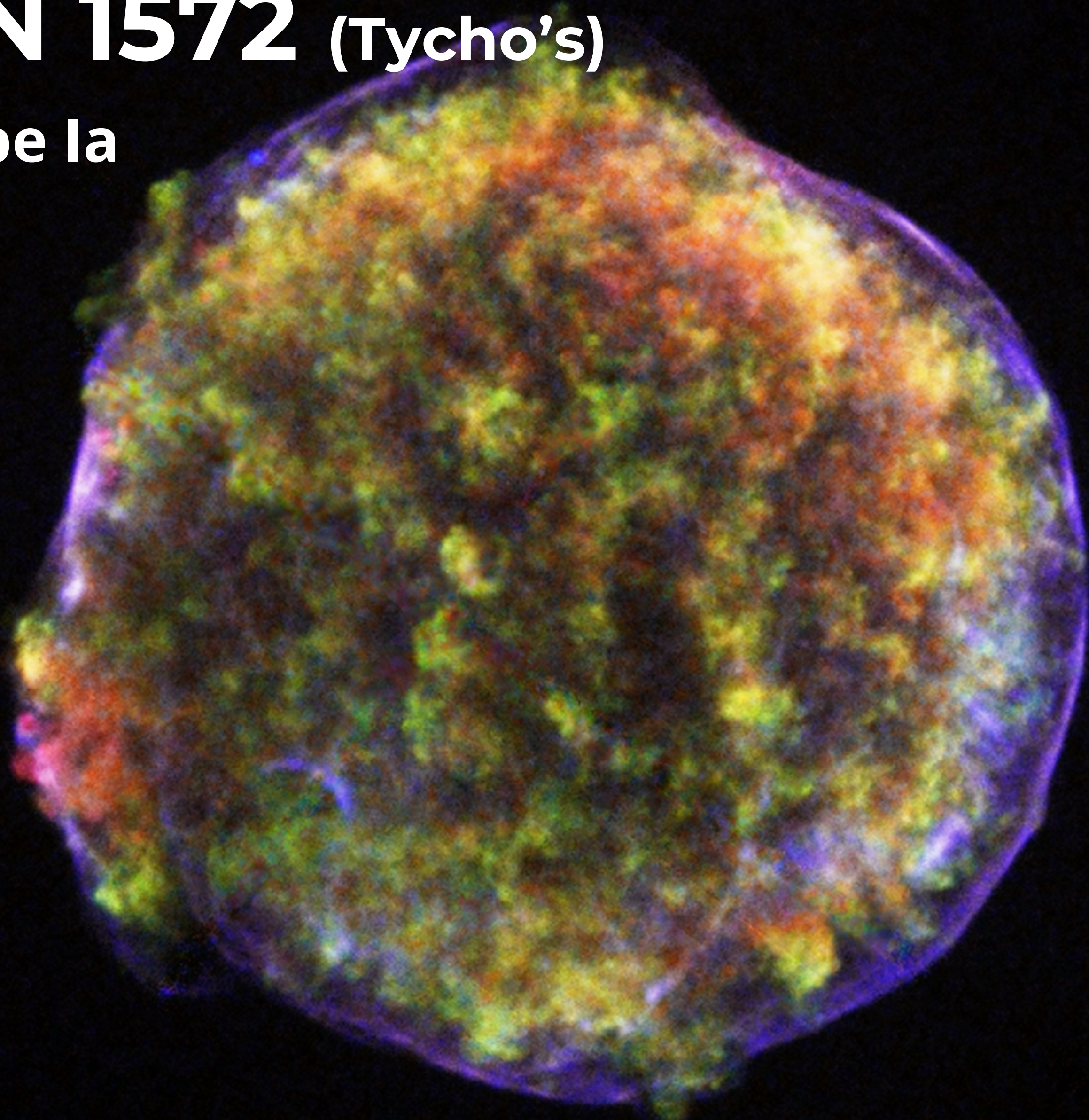
**The nearest
(and most beautiful?)**

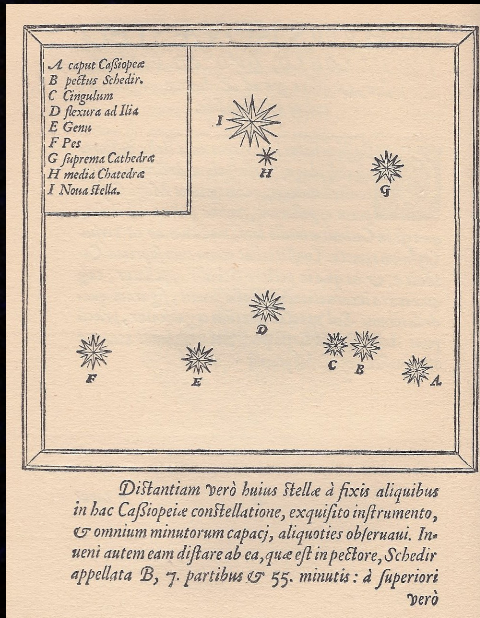
SN 1181

Type Iax

SN 1572 (Tycho's)

Type Ia



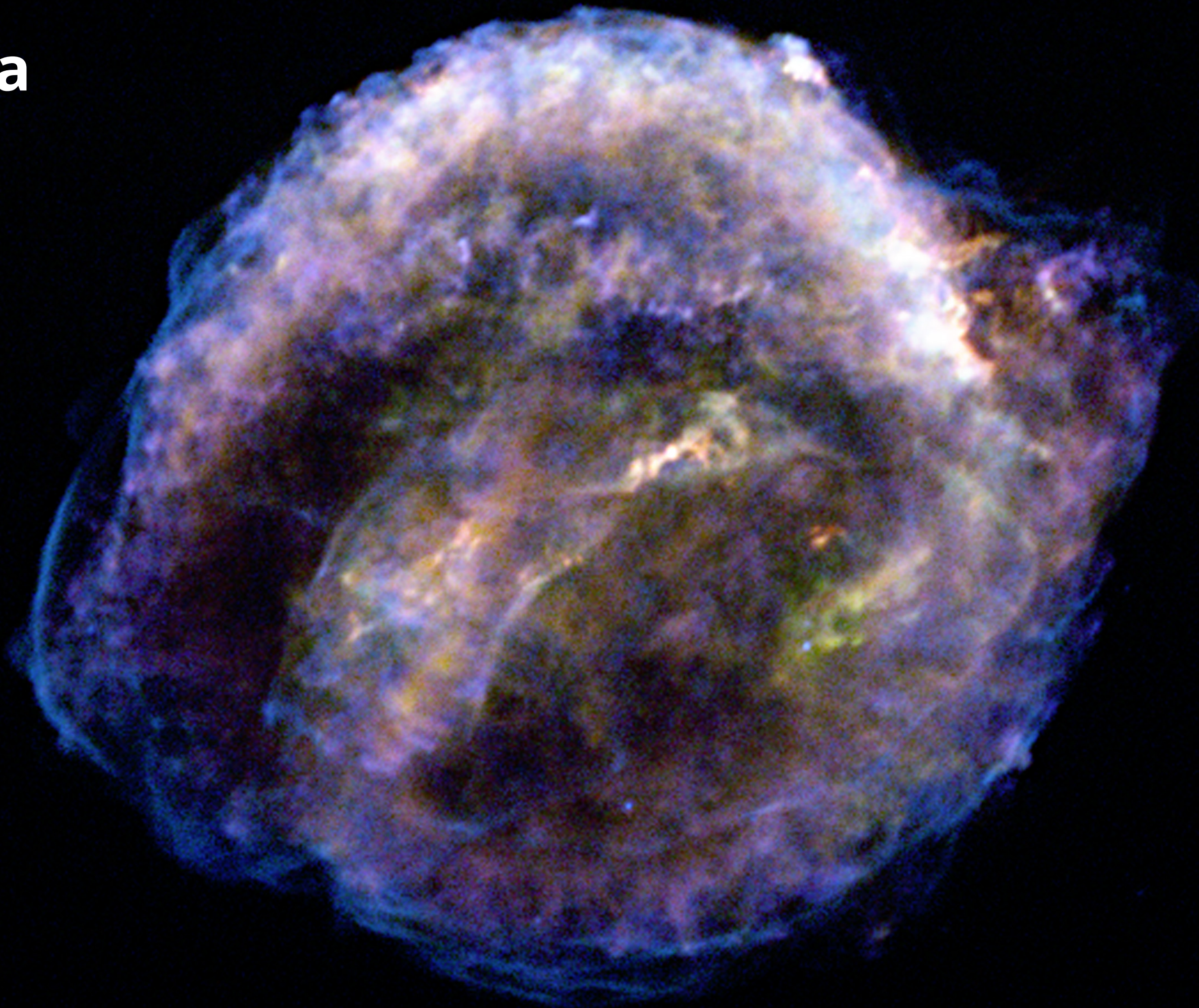


A caput Caßiopeæ
B pectus Schedir.
C Cingulum
D flexura ad Ilia
E Genu
F Pes
G ſuprema Cathedræ
H media Chatedræ
I Noua ſtella.

Diſtantiam verò huius ſtellæ à fixis aliquibus in hac Caßiopeiæ conſtellatione, exquiſito inſtrumento, & omnium minutorum capacj, aliquoties obſeruaui. Inueni autem eam diſtare ab ea, quæ eſt in pectore, Schedir appellata B, 7. partibus & 55. minutis: à ſuperiori verò

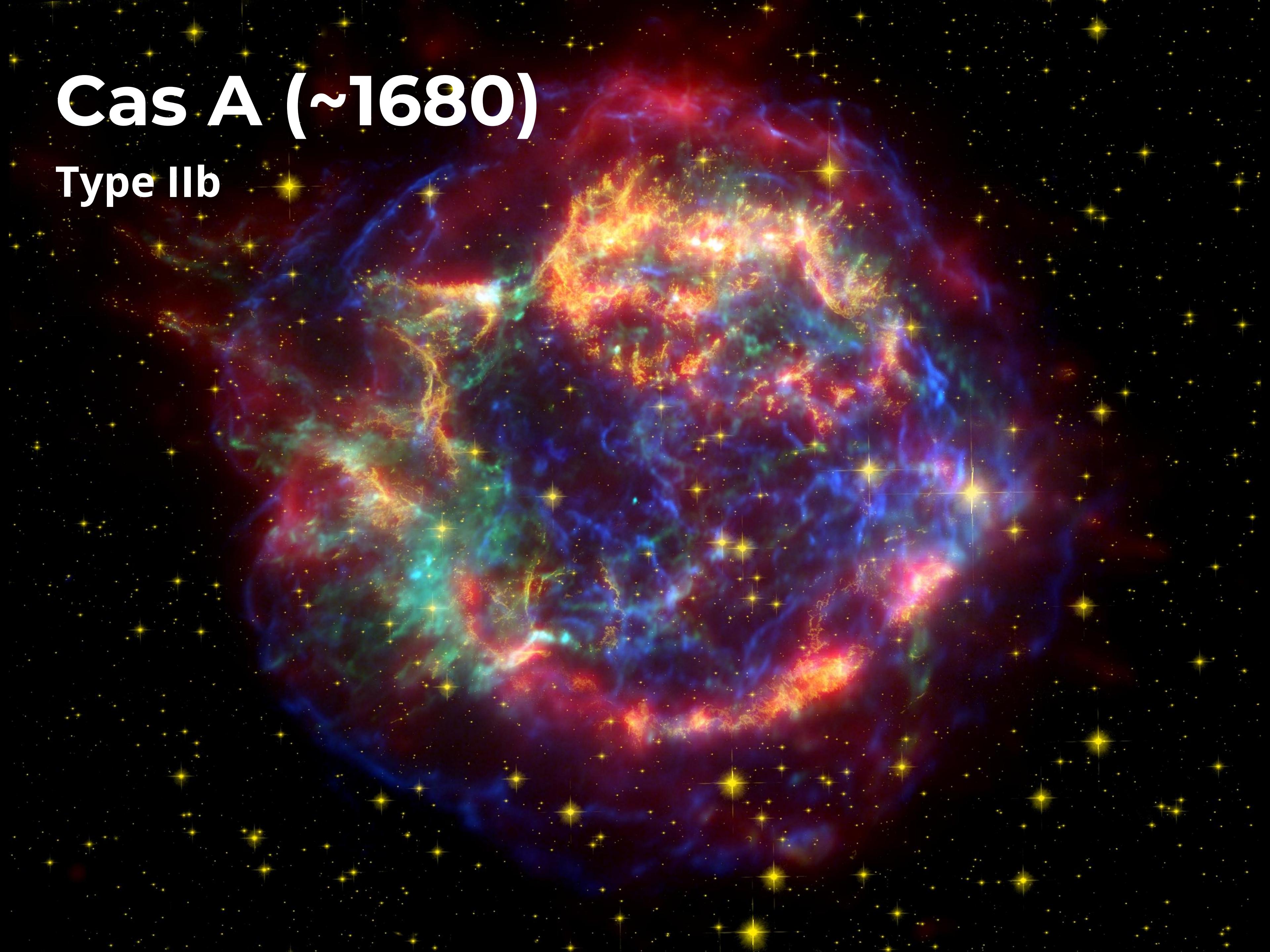
SN 1604 (Kepler's)

Type Ia



1609

Galileo’s Telescope

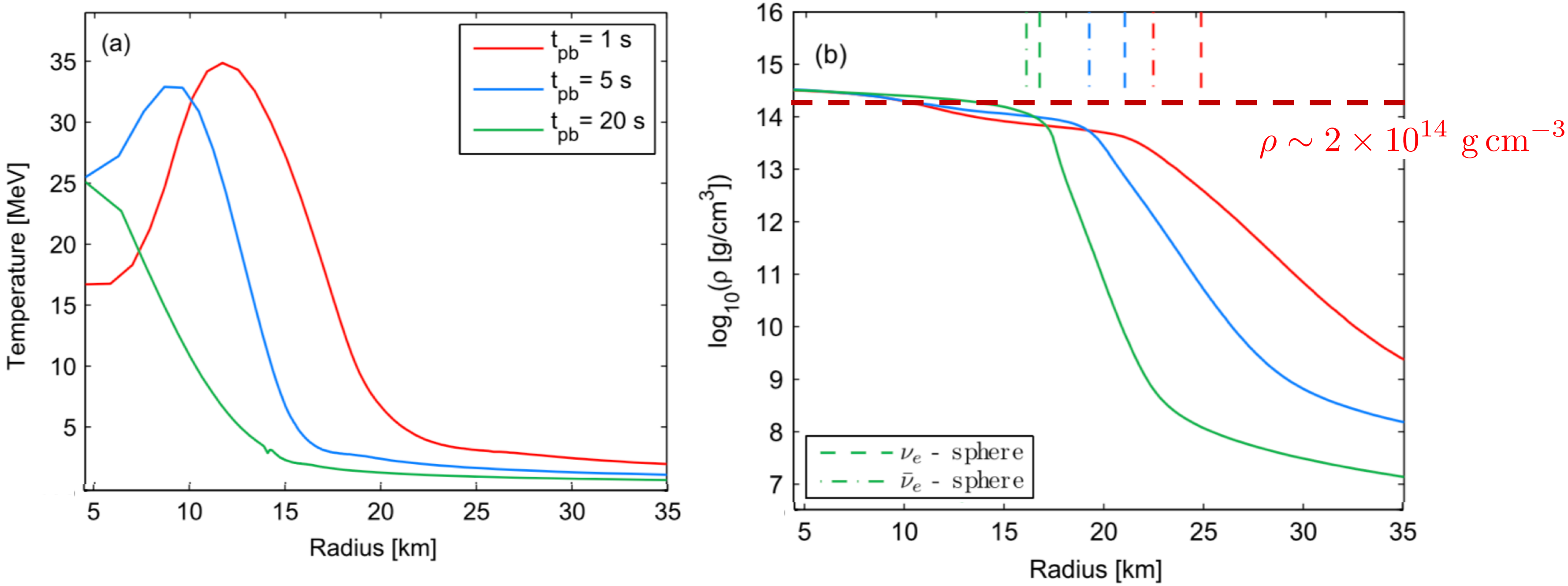

Cas A (~1680)
Type IIb

G1+9+0.3 (~1868)

Type Ia (most likely)

Core-collapse Supernovae

In the first few seconds after the explosion the resulting proto-neutron star core (~20 km) reaches temperatures of the order of 30 MeV and densities exceeding the nuclear one.



Fischer, Martínez Pinedo, Hempel, Liebendörfer 2012

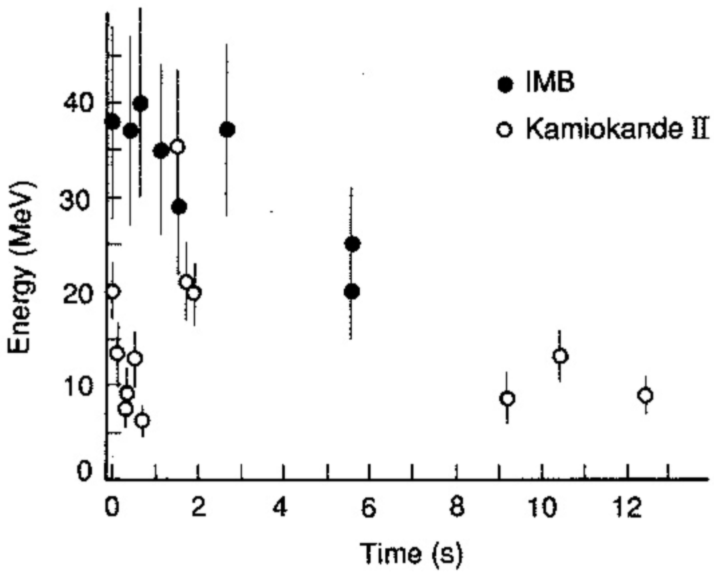
SN 1987A

(d ~ 50 kpc in the Large Magellanic Cloud)

First (and only) supernova neutrinos detected

~ 20 (26) neutrinos in IMB + KII (+ BUST + LSD), which arrived a few hours before optical brightening.

MeV energies and pulse duration ~10s



SN 1987A

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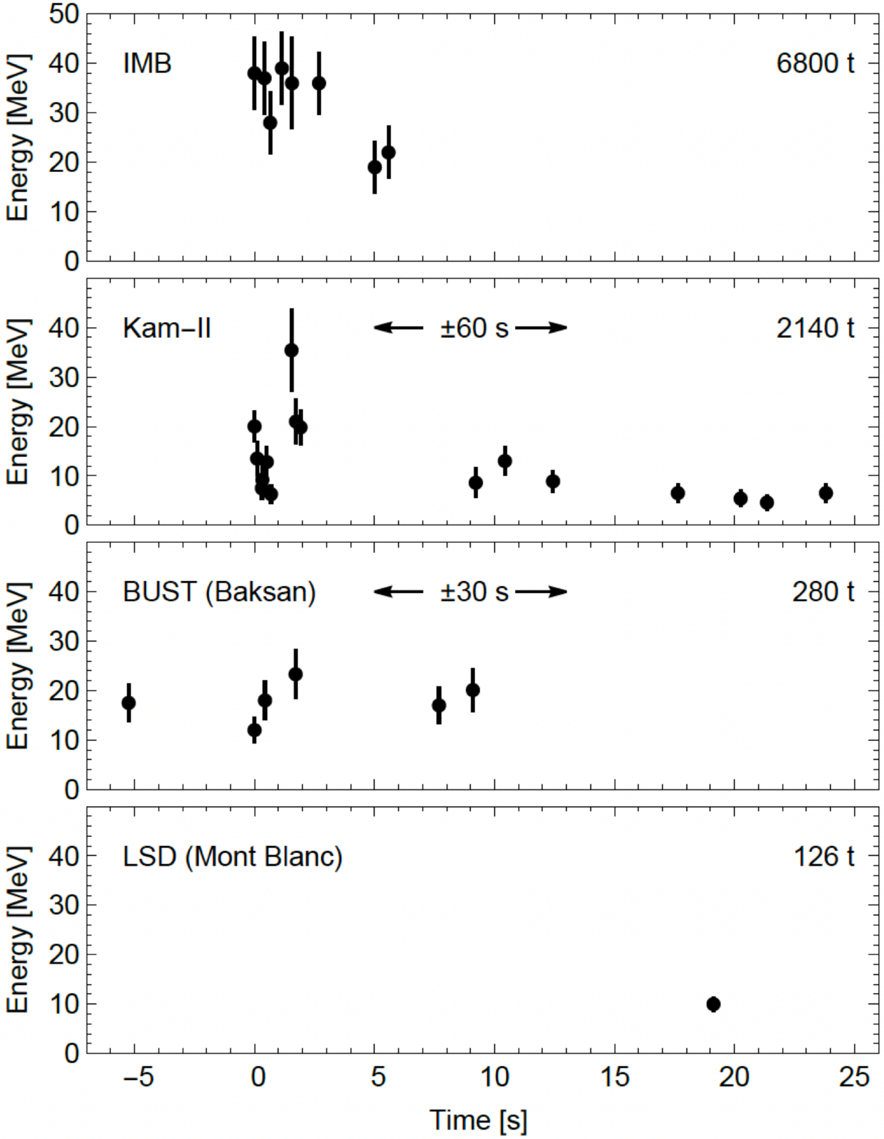
MeV energies and pulse duration ~10s

Model calculations of the neutrino emissions following core collapse with these data obtain reasonable agreement for the total energy, average neutrino energy, and burst duration.

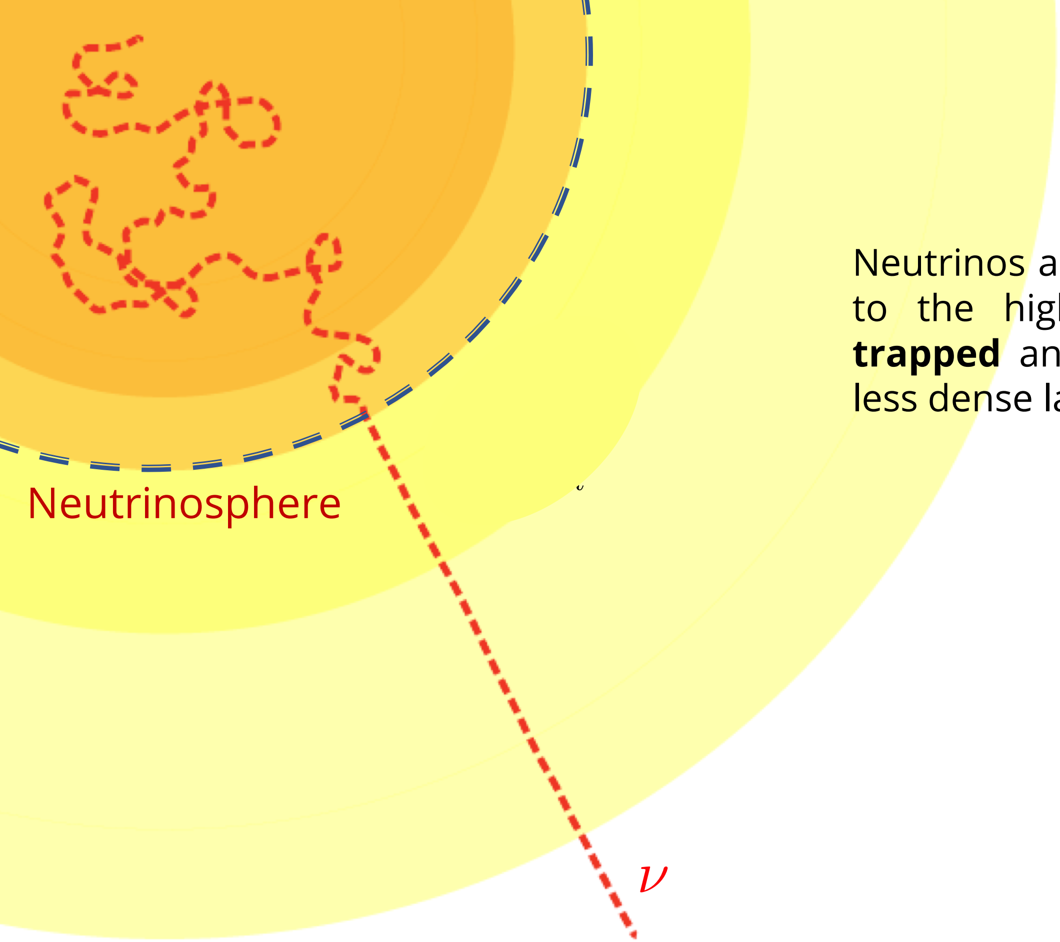
See e.g., Burrows, Lattimer 1987

SN 1987A

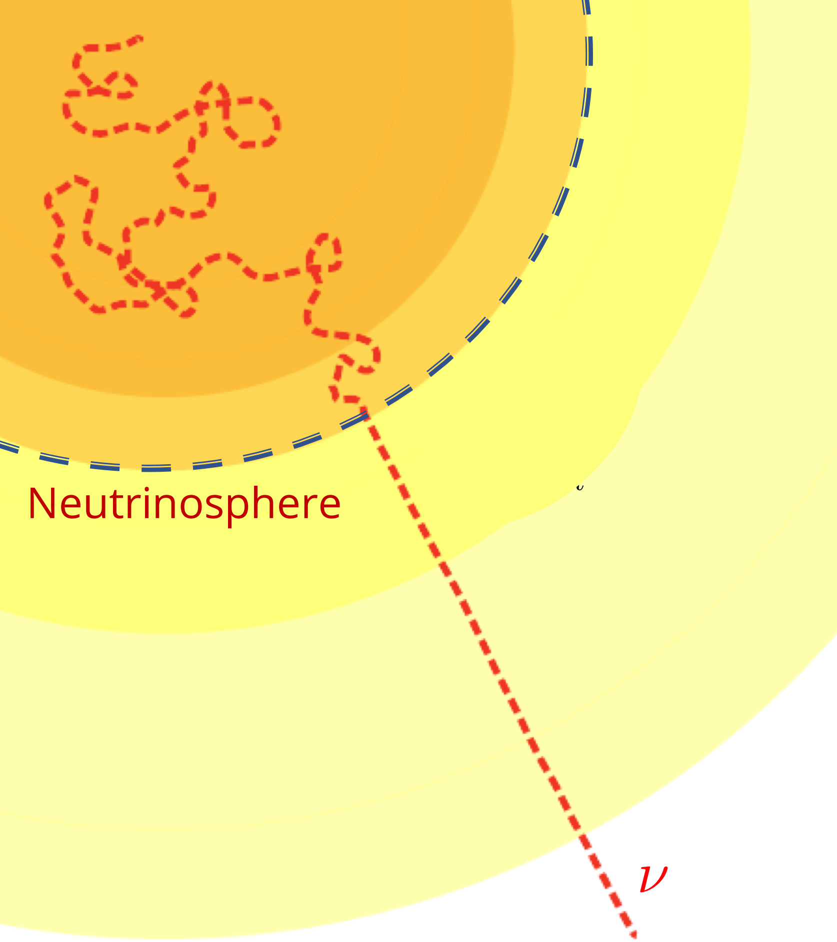
(d ~ 50 kpc in the Large Magellanic Cloud)



The neutrino signal



Neutrinos are produced in the interior of the PNS. Due to the high temperatures and densities, they are **trapped** and diffuse out until they reach colder (and less dense layers)



The neutrino signal

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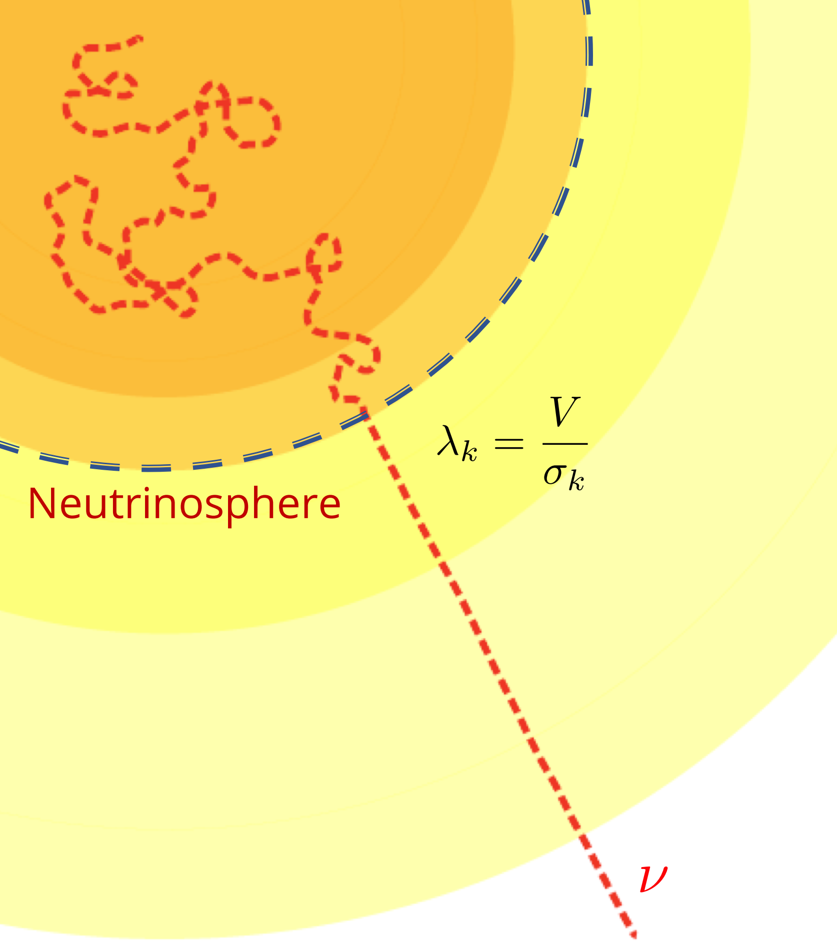
Roughly speaking, the energy released of the neutrino pulse can be estimated as

$$E_{bind} = \frac{3}{5}\frac{GM^2}{R} \sim 1.6 \times 10^{53}\,\mathrm{erg}\left(\frac{M}{M_\odot}\right)^2\left(\frac{R_\odot}{R}\right)$$

$$T = \frac{2}{3}\langle E_{kin}\rangle \sim 10 - 20\,\mathrm{MeV}$$

The neutrino signal



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Neutrinos scatter off nucleons (n, p) on their way out of the proto NS

The mean free-path increases as we move towards outer (less dense – colder) layers

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$$E_{bind} = \frac{3}{5}\frac{GM^2}{R} \sim 1.6 \times 10^{53}\,\mathrm{erg}\left(\frac{M}{M_\odot}\right)^2\left(\frac{R_\odot}{R}\right)$$

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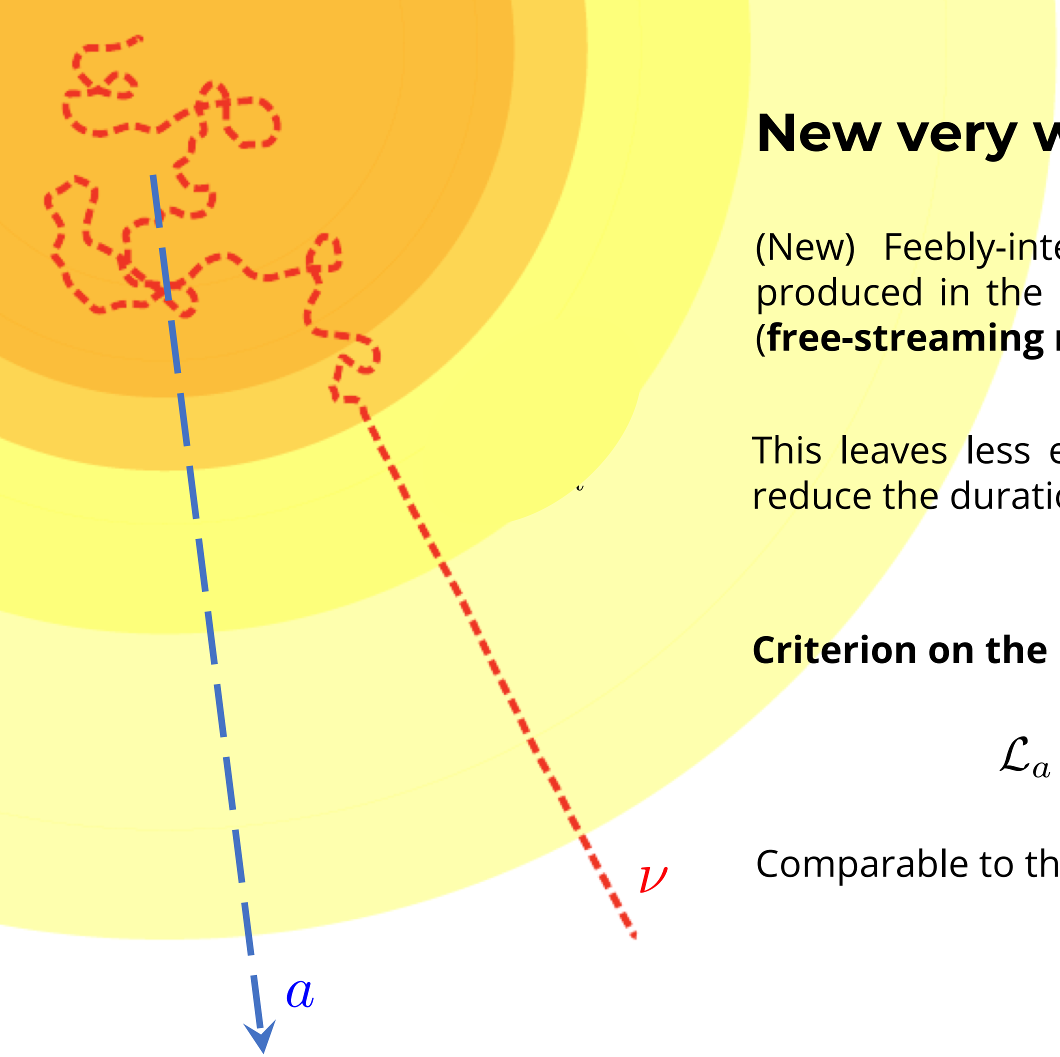
Neutrino diffusion time:

$$c\Delta t_\nu = \frac{R^2}{\lambda_\nu} \qquad \Delta t^{\mathrm{SM}} = 1.1\ \mathrm{s}$$



New very weakly interacting particles

(New) Feebly-interacting particles (e.g. and ALP) can be produced in the PNS and could escape the star unimpeded (**free-streaming regime**), taking away energy.

This leaves less energy for neutrinos and can considerably reduce the duration of the neutrino signal.

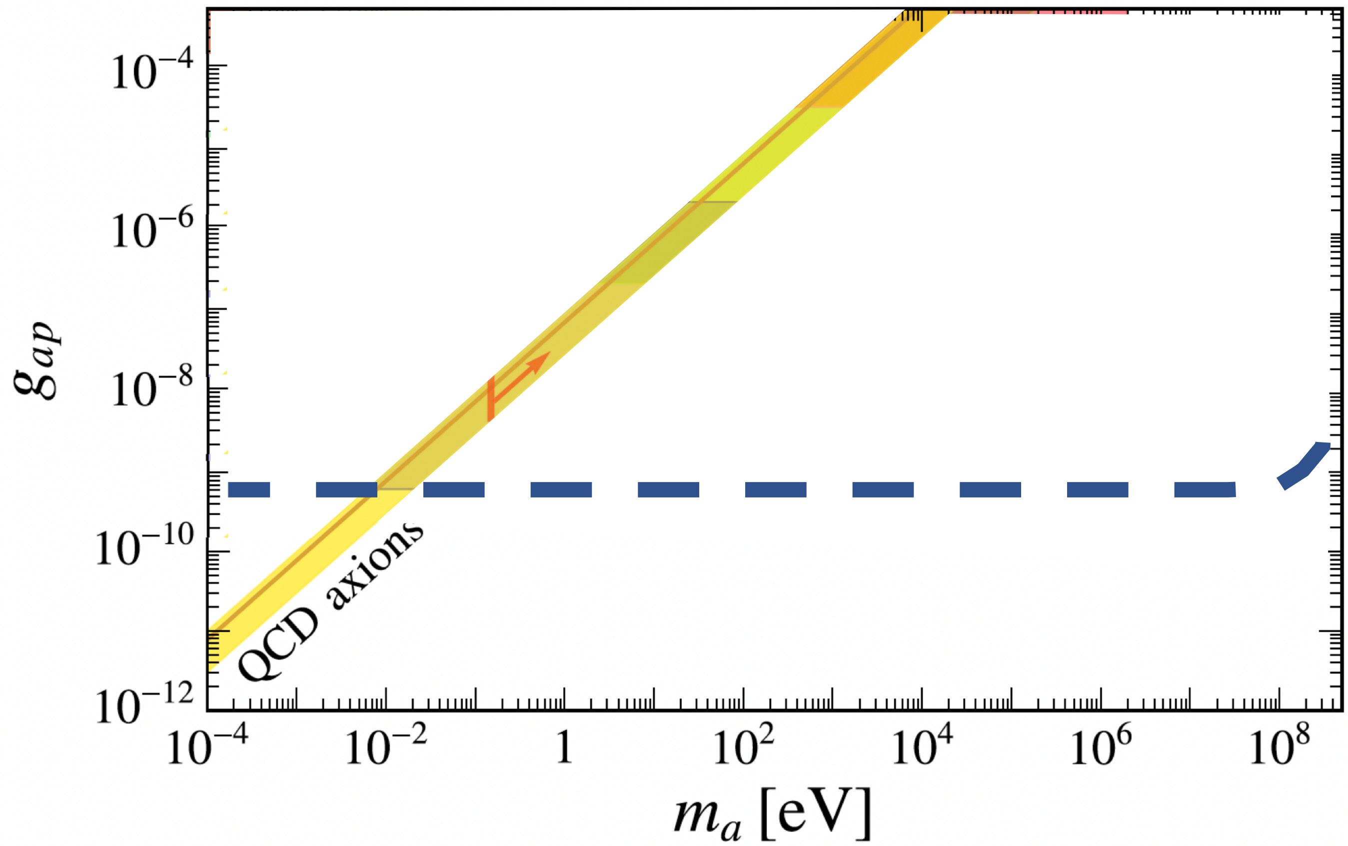
Criterion on the luminosity of a new exotic species:

$$\mathcal{L}_a \lesssim 3 \times 10^{52}\ \mathrm{erg\,s^{-1}}$$

Comparable to that from neutrinos at *t = 1s* post-bounce.

Raffelt, Dearborn 1987
Burrow, Turner, Brinkman 1989
See also Chang, Essig, McDermott 2016

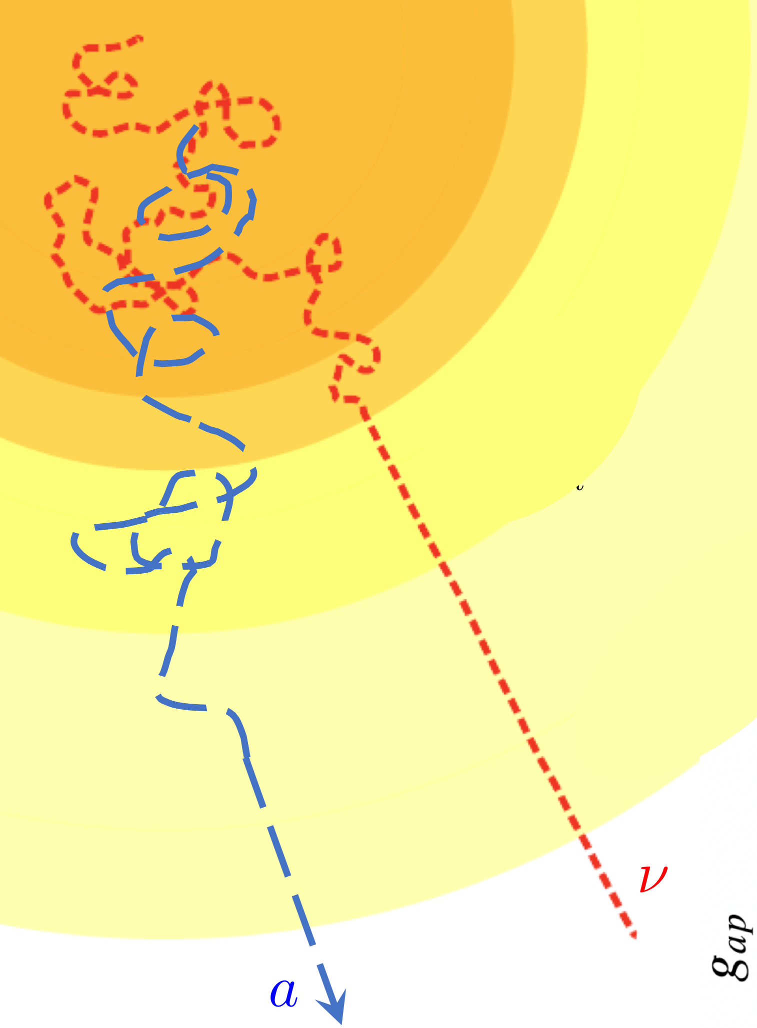
Raffelt's condition leads to an upper bound on the ALP-proton coupling above which ALPs are more copiously produced inside the SN.

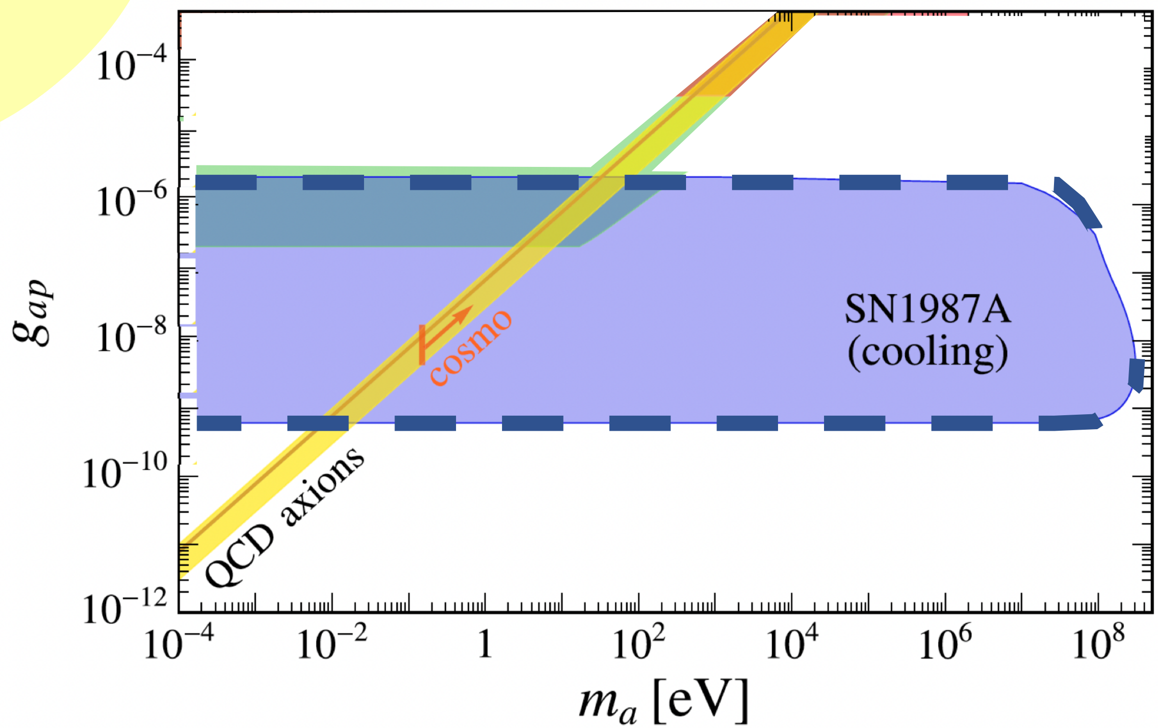


New very weakly interacting particles

However, If the ALP (or other exotic) coupling to matter continues increasing, they become **trapped** inside the SN and the outgoing luminosity decreases.

Eventually, for large enough couplings, the luminosity condition is fulfilled again and particles are not constrained.

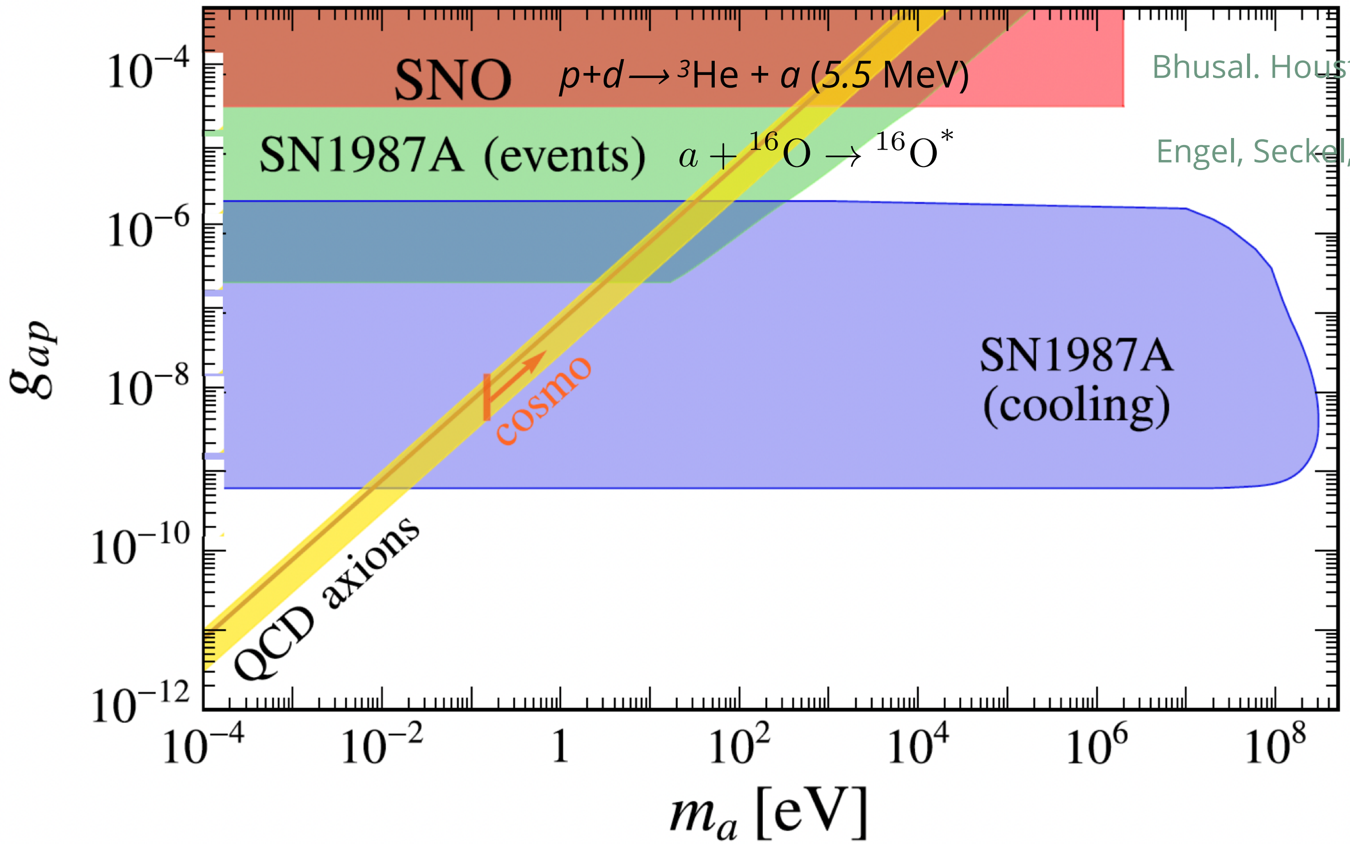




(modified from) Lella et al. PRD 109 (2024)

Constraints on ALP-proton coupling

Bounds on axions and ALPs can also be obtained from other sources (e.g., solar axions at SNO, SN axions at Kamiokande II)



Bhusal. Houston, Li PRL 126 (2021)

Engel, Seckel, Hayes PRL 65 (1990)

Lella et al. PRD 109 (2024)

ALP-nucleon interactions

$$\mathcal{L}_{int} = g_a \frac{\partial_\mu a}{2\, m_N} \Big[C_{ap}\, \bar{p}\, \gamma^\mu\, \gamma_5\, p + C_{an}\, \bar{n}\, \gamma^\mu\, \gamma_5\, n \; + \frac{C_{a\pi N}}{f_\pi} \left(i\, \pi^+\, \bar{p}\, \gamma^\mu\, n - i\, \pi^-\, \bar{n}\, \gamma^\mu\, p \right)$$

$$+ C_{aN\Delta} \left(\bar{p}\, \Delta^+_\mu + \bar{\Delta}^+_\mu\, p + \bar{n}\, \Delta^0_\mu + \bar{\Delta}^0_\mu\, n \right) \Big]$$

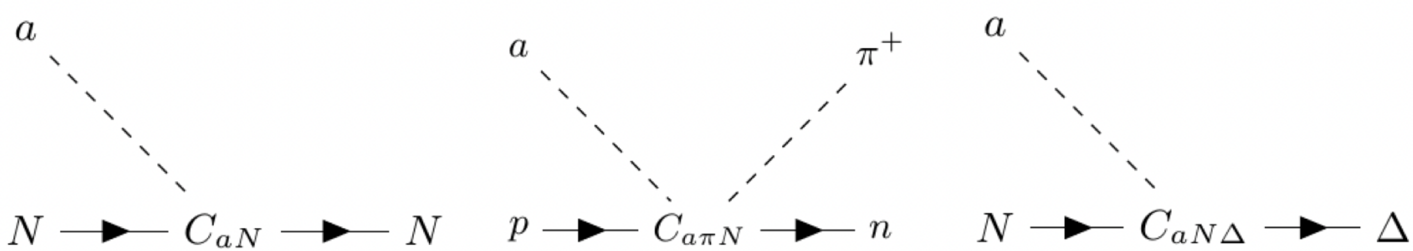
Chang, Choi PLB 316 (1993)
See also Di Luzio et al. Phys Rep. 870 (2020)

$$C_{a\pi N} = (C_{ap} - C_{an})/\sqrt{2} g_A$$

$$C_{aN\Delta} = -\sqrt{3}/2(C_{ap} - C_{an})$$

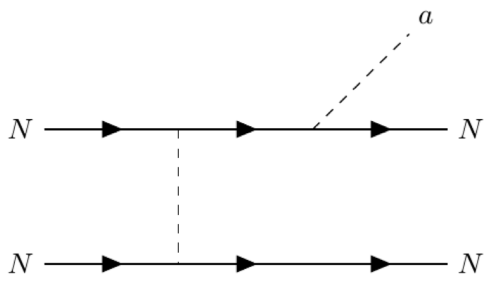
C_{aN} are model-dependent axion-nucleon couplings (generally *O(1)*) $g_{aN} = g_a C_{aN},\, N = p, n$

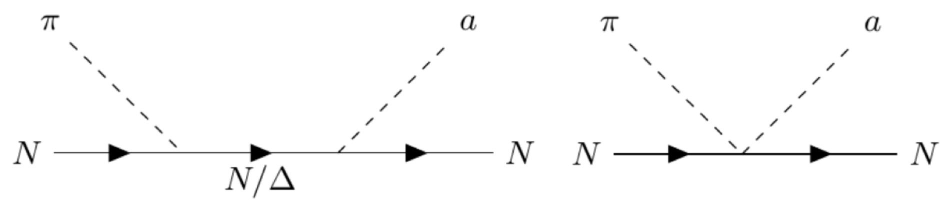
$g_A \simeq 1.28$ the axial coupling, $f_\pi = 92.4$ MeV pion decay constant



ALP production in SN

This allows for different production mechanisms inside the supernova





NN bremsstrahlung

With corrections beyond one-pion-exchange approximation
Carenza et al. JCAP 10 (2019)

Pionic Compton processes

Lella et al. PRD 107 (2023)
Choi et al. JHEP 02 (2022)
Ho et al. PRD 107 (2023)

ALP produced spectrum (number density per unit time and energy)

$$\frac{d^2 n_a}{dE_a dt} = \prod_i \int \frac{d^3 \vec{p}_i}{(2\pi)^3 2E_i} \prod_{j \neq a} \int \frac{d^3 \vec{p'}_j}{(2\pi)^3 2E'_j} (2\pi)^4 \delta^4 \Big(\sum_k p_k - \sum_{l \neq a} p'_l - p_a \Big) \frac{|\vec{p}_a|}{4\pi^2} |\overline{\mathcal{M}}|^2 \mathcal{F}(E_i, E'_j)$$

$$\mathcal{F}(E_i, E'_j) = f_i(E_i)[1 - f_j(E'_j)]$$

ALP flux attenuation

As ALPs travel out of the proto-NS they can be reabsorbed in the nuclear medium through the reverse processes $N + N + a \longrightarrow N + N$ and $N + a \longrightarrow N + \pi$.

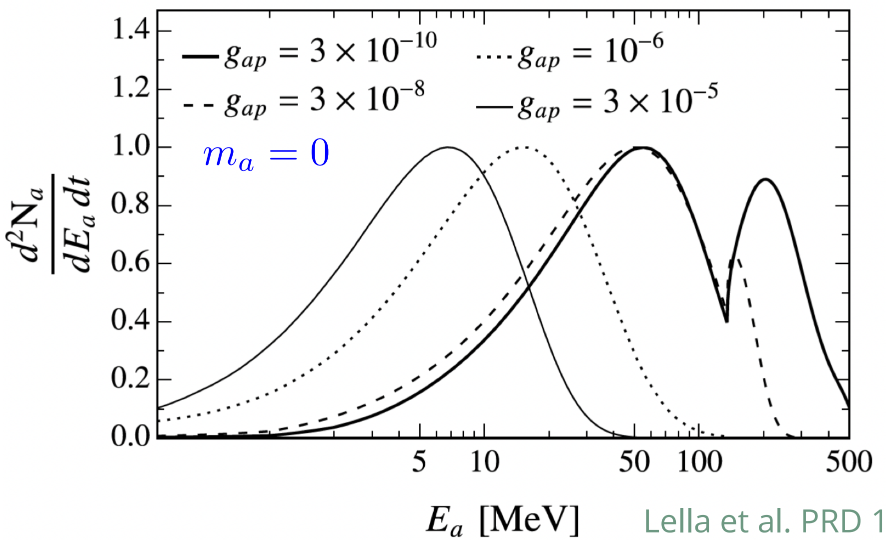
$$\frac{d^2 N_a}{dE_a dt} = \int_0^\infty 4\pi r^2 dr \left\langle e^{-\tau(E_a^*, r)} \right\rangle \frac{d^2 n_a}{dE_a dt}(E_a, r)$$

The absorption effects are averaged over the cosine of the emission angle

$$\left\langle e^{-\tau(E_a^*, r)} \right\rangle = \frac{1}{2} \int_{-1}^{+1} d\mu \, e^{-\int_0^\infty ds \Gamma_a\left(E_a^*, \sqrt{r^2 + s^2 + 2rs\mu}\right)}$$

reduced absorption rate

Caputo, Raffelt, Vitagliano PRD 105 (2022)



Lella et al. PRD 109 (2024)

As the coupling grows, both production **and absorption** become more efficient.

Inverse pion conversion very efficient for energies above 100 MeV.

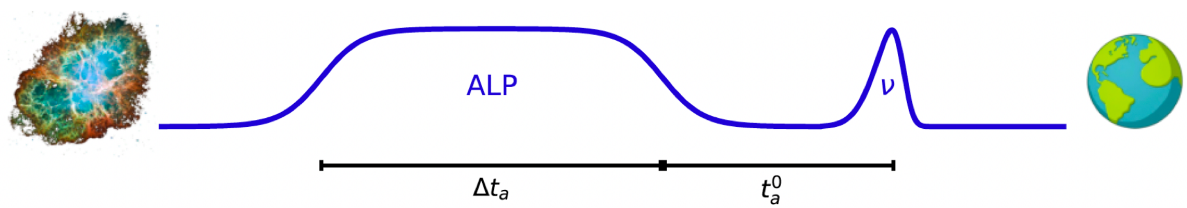
The NN bremmstrahlung peak reflects the temperature of the region where escaping ALPs are produced.

A diffuse Galactic flux of ALPs from SN

ALPs with masses above ~1 MeV would be produced in core-collapse SN with semi-relativistic velocities. They would travel to Earth with a spread in velocities, resulting in a difference in arrival times from the high- and low-velocity ALPs.

In fact, ALPs would arrive some time after SN neutrinos are measured.

Galactic SN



$$\Delta t_a \sim 5 \times 10^2 - 5 \times 10^3 \text{ years}$$

Since the rate of Galactic SN is **~1.63 per century**, we expect that the fluxes of ~ 10 – 100 SN overlap at Earth, resulting in a near constant **diffuse ALP flux**. This flux would be anisotropic, peaking towards the Galactic Centre.

This is analogous to the argument of DeRocco et al PRD 100 (2019) for dark photons.

Diffuse galactic SN ALP flux at Earth

Spectral fluence of ALPs from an isotropic production spectrum far away from **one** SN

$$\frac{dN_a}{dE_a^{*\infty}} = \int_{t_{\min}}^{t_{\max}} dt \int_0^{\infty} \alpha(r)^{-1} 4\pi r^2 dr \, \left\langle e^{-\tau(E_a^*, r)} \right\rangle \frac{d^2 n_a}{dE_a dt} \left(r, t, \alpha(r)^{-1} E_a^{*\infty}\right)$$

$E_a^{*\infty} = \alpha(r) E_a$ is the observed energy at infinity (the detector)

$\alpha(r) \leq 1$ is the lapse function that accounts for gravitational redshift inside and outside the star

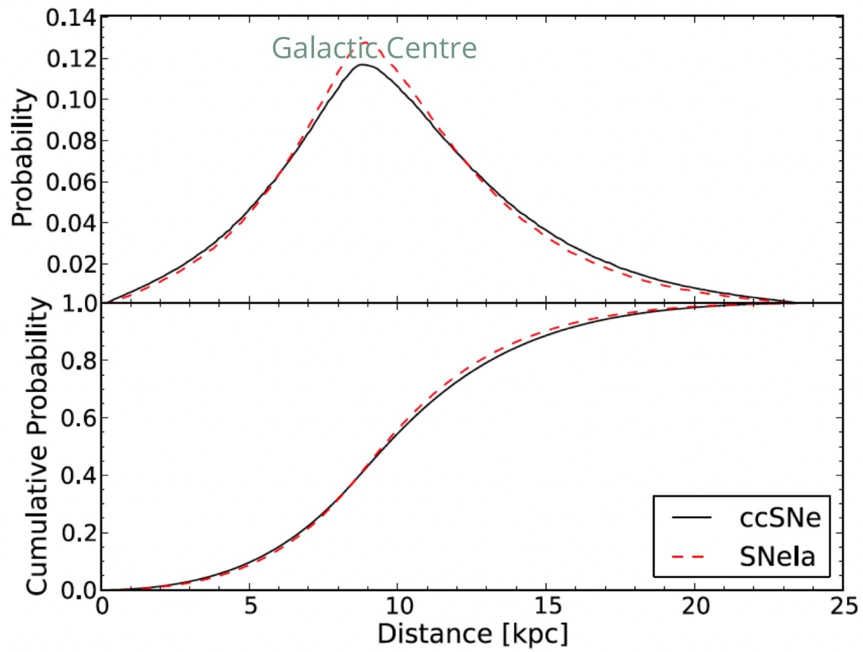
$R_d \sim 2.6$ kpc

Must integrate to **all** Galactic SN, with the corresponding distribution

$$\frac{dn_{SN}}{dt} = A\, e^{-\frac{r}{R_d}}\, e^{-\frac{|z|}{H}},$$

For Type II SN $R_d \sim 2.6$ kpc, $H \sim 0.3$ kpc

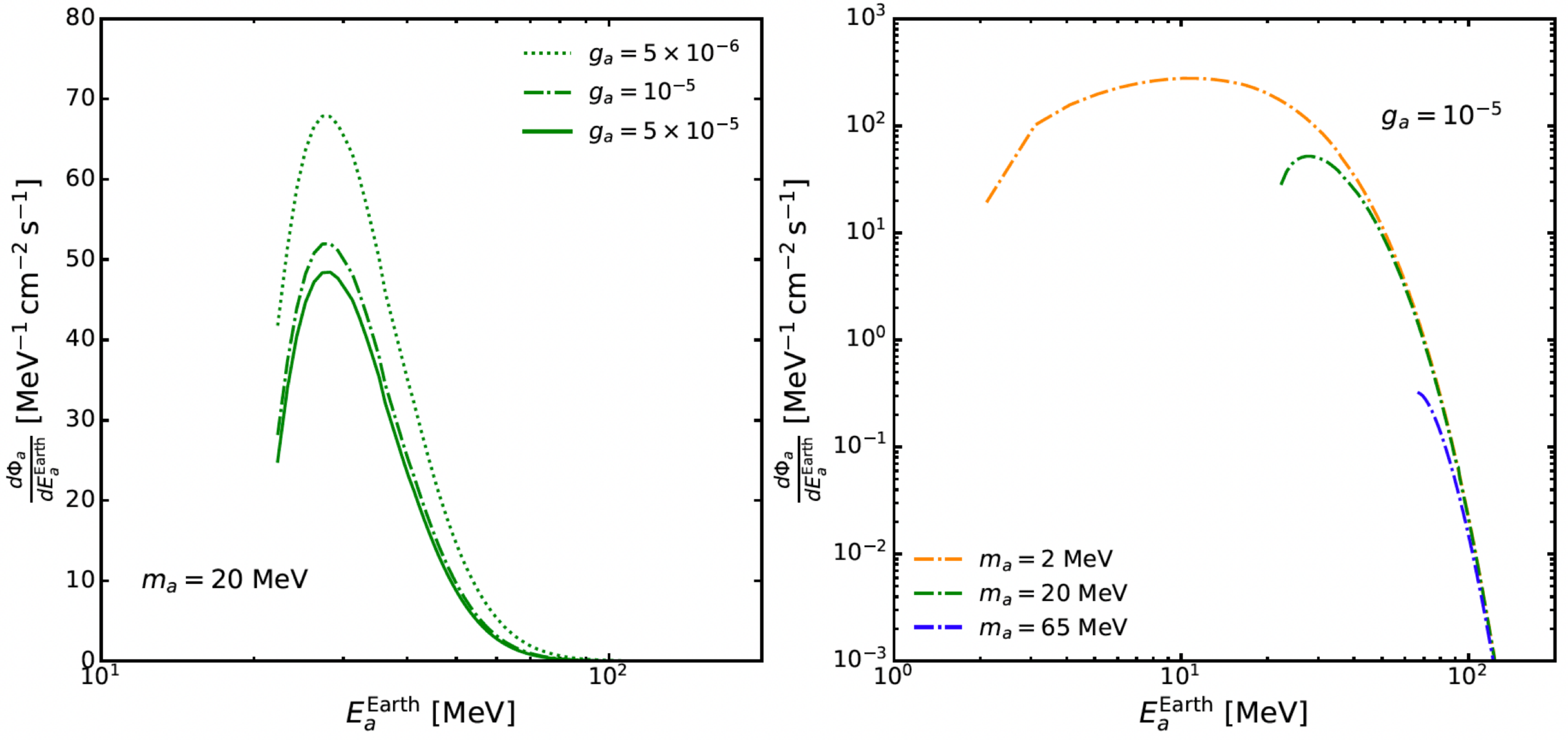
$$A = 1.65 \times 10^{-3}\ \mathrm{kpc}^{-3}\,\mathrm{yr}^{-1}$$



Adams et al. ApJ 778 (2013)
Rozwadowska et al. New Astron 83 (2021)
McMillan MNRAS 466 (2017)

Diffuse galactic SN ALP flux at Earth

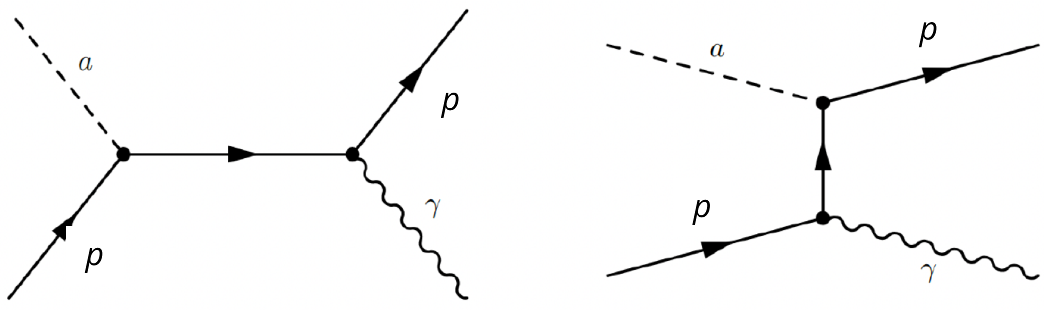
$$\frac{d\Phi_a}{dE_a^{\rm Earth}} = \frac{dN_a}{dE_a^{\rm Earth}} \int_{-\infty}^{\infty} \int_0^{2\pi} \int_0^{\infty} \frac{dn_{SN}}{dt} \frac{r}{(\vec{r} - \vec{R}_E)^2} \, dr \, d\theta \, dz \; = 2.69 \times 10^{-54} \ {\rm cm}^{-2} \ {\rm s}^{-1} \frac{dN_a}{dE_a^{\rm Earth}}$$



Since we are in the trapping regime, the flux **decreases** when increasing the ALP-proton coupling.

Detection in neutrino Cherenkov detectors

These semi-relativistic ALPs can be observed in neutrino Cherenkov detectors. We propose a search based on **photoproduction** from their scattering off free protons.



The emitted photon takes almost all the energy of the ALP. The expected rate is

$$\frac{d\,N_\gamma}{dE_\gamma} = N_t \int_{E_a^{\rm min}(E_\gamma)}^{E_a^{\rm max}(E_\gamma)} dE_a^{\rm Earth} \frac{d\Phi_a}{dE_a^{\rm Earth}} \frac{d\,\sigma_{ap}}{d\,E_\gamma}$$

where $E_a^{max} \sim E_a^{min} \sim E_\gamma$

This signature has not been exploited before.

The rate is smaller than oxygen excitation $a + {}^{16}\mathrm{O} \to {}^{16}\mathrm{O}^*$

However, the released photon is more energetic and the signal is **almost background free**

Detection in neutrino Cherenkov detectors

Simulated signal for Super Kamiokande phase IV (Exposure: 22.5 x 2970-kton·day)

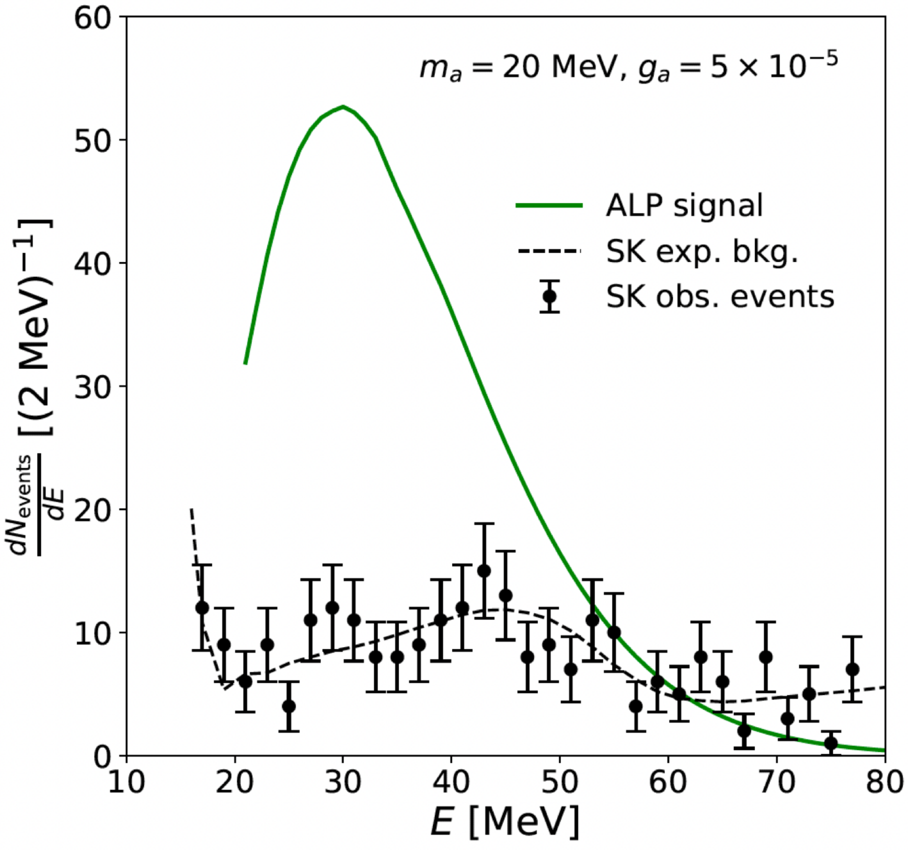
Energy window [16-80] MeV optimized to search for the DSNB by identifying positrons from inverse beta decay.

Super Kamiokande Phys. Rev. D 104 (2021)

Background mainly from invisible or low-energy muons that decay into electrons (and neutrinos)

and charged current interactions of atmospheric neutrinos.

The background increases considerably below ~ 16 MeV



Alonso-González, Cermeño, Cerdeño, Perez 2412.09595

Bounds from SK and expectations for HK

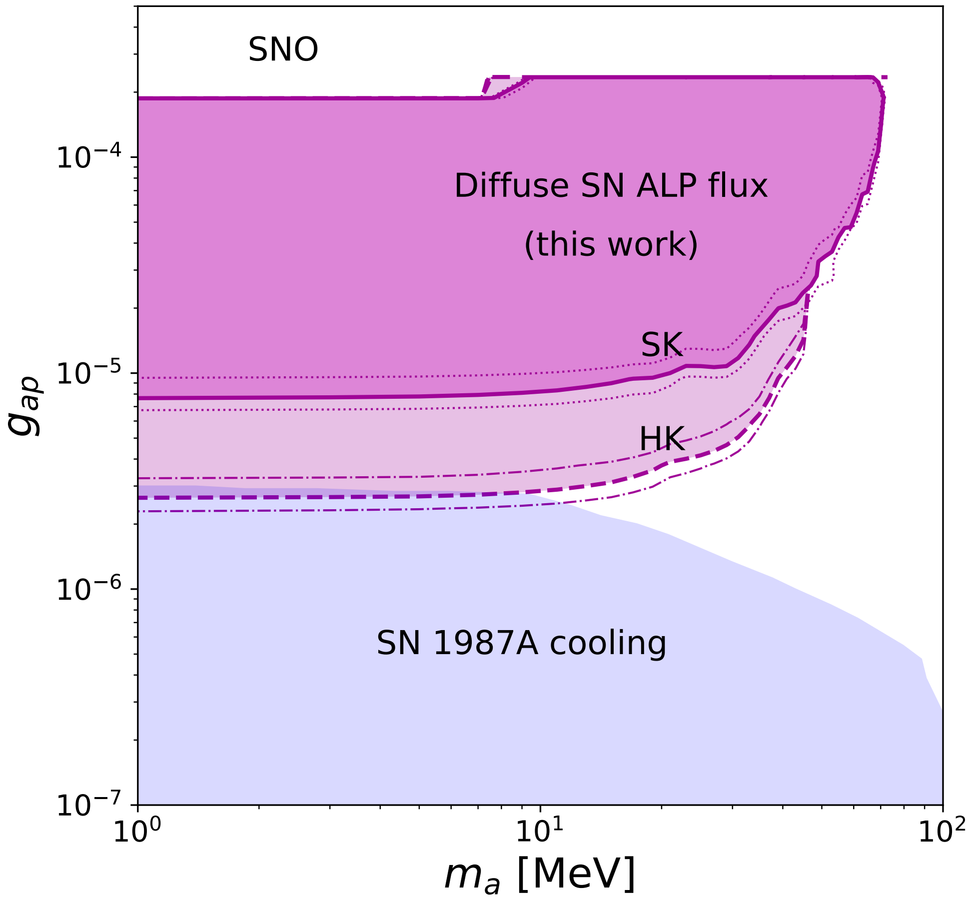
We derive bounds on the ALP-proton coupling based on the non-observation of anomalous signals in SK.

We apply it to all SK exposure, although the results are dominated by phase IV.

Binned analysis ~ 2MeV

For the future Hyper Kamiokande we use the background from the HK report, which is limited to [16-50] MeV (hence we do not get to probe heavy ALPs)

* For alps with m_a > 3 MeV the coupling to the photon must be very suppressed to guarantee their stability.

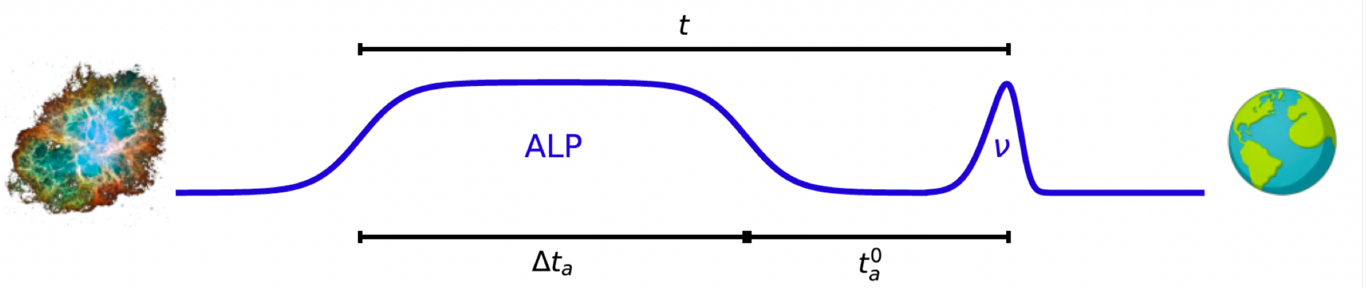


Alonso-González, Cermeño, Cerdeño, Perez 2412.09595

What happens with lighter ALPs

For alps with m_a < *1* MeV the hypothesis of a diffuse ALP background does not hold. They travel rather fast to the Earth and we would be integrating over less than 10 Galactic Supernovae.

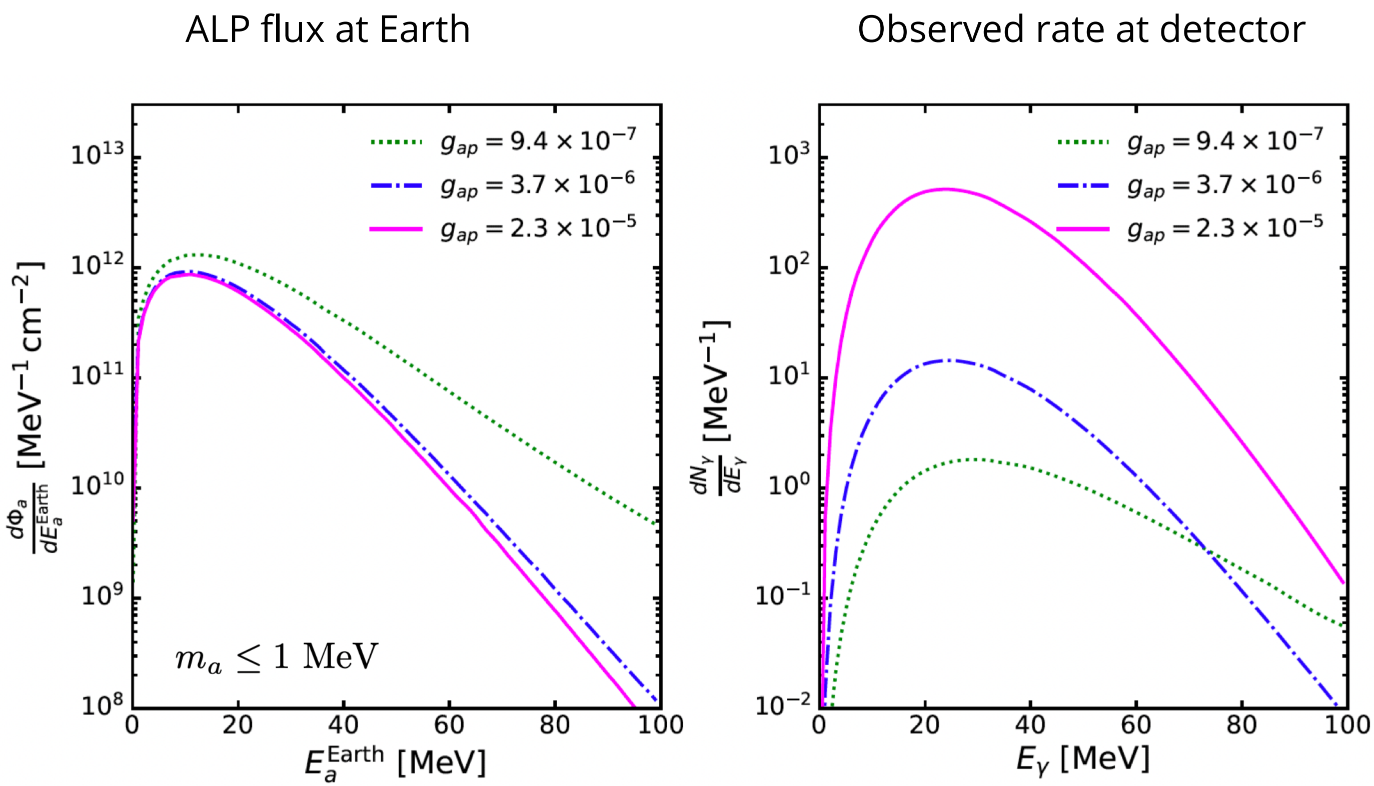
However, we can still apply our analysis to a **single future supernova.**



$$\frac{d\Phi_a}{dE_a^{\mathrm{Earth}}} = \frac{1}{4\pi d_{SN}^2} \int_{t_{\min}}^{t_{\max}} dt \int_0^{\infty} \alpha(r)^{-1} 4\pi r^2 dr \, \left\langle e^{-\tau(E_a^*, t, r)} \right\rangle \frac{d^2 n_a}{dE_a^{\mathrm{loc}} dt} \left(r, t, \alpha(r)^{-1} E_a^{\mathrm{Earth}}\right)$$

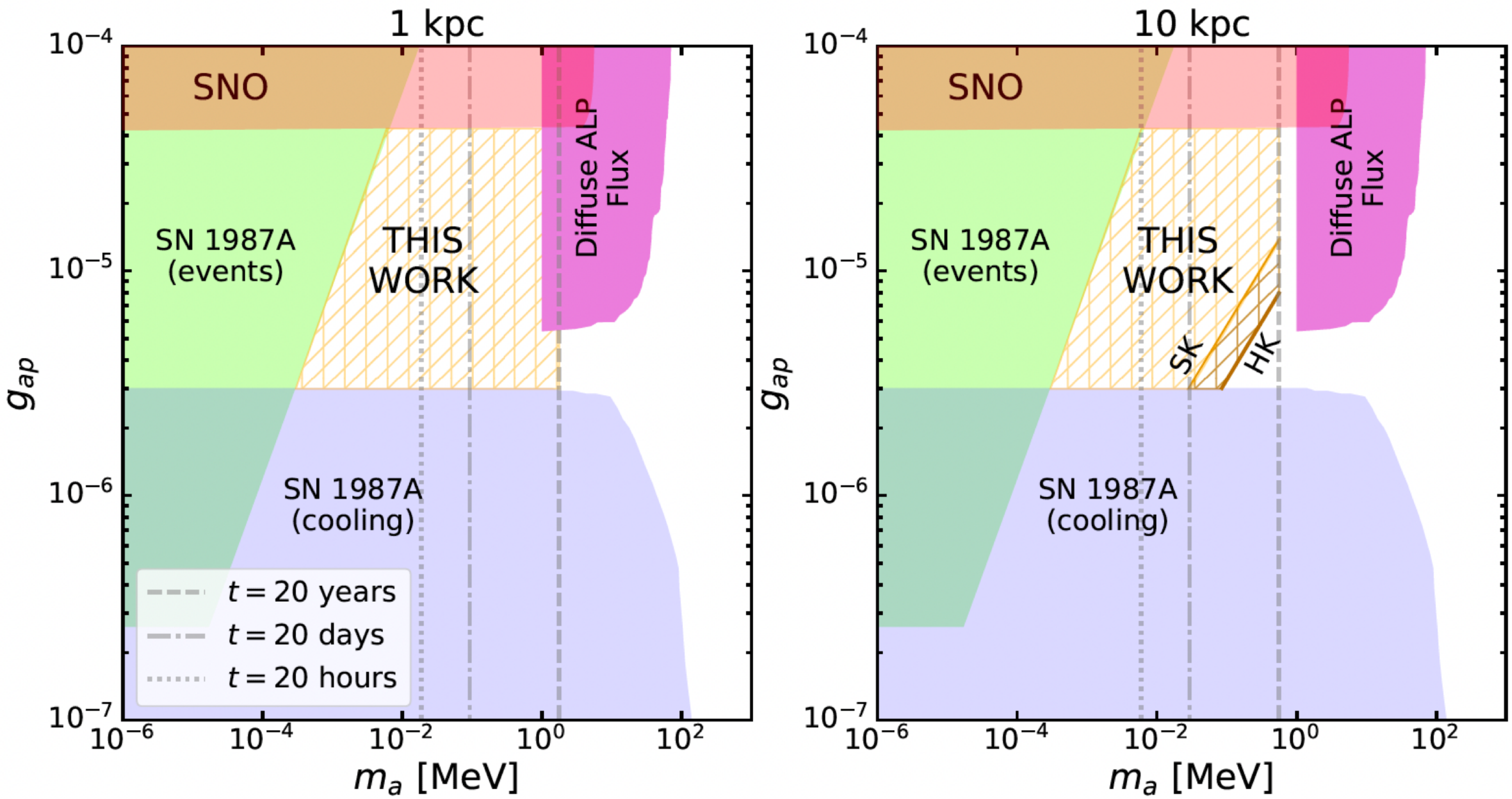
ALP flux at the detector

$$\frac{dN_\gamma}{dE_\gamma} = N_t \int_{E_a^{\min}(E_\gamma)}^{E_a^{\max}(E_\gamma)} dE_a^{\rm Earth} \frac{d\Phi_a}{dE_a^{\rm Earth}} \frac{d\,\sigma_{ap}}{d\,E_\gamma},$$



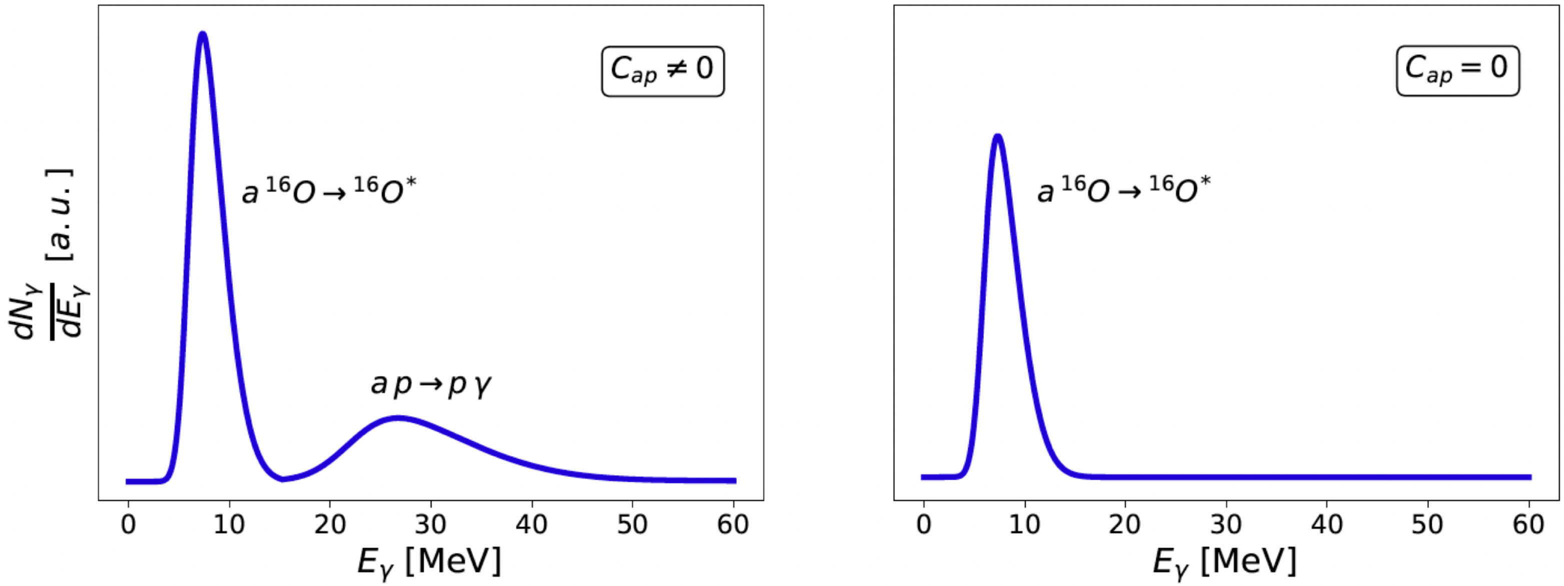
Region of ALP couplings that can be probed

The accessible region depends on the distance of the Supernova. The gap above cooling bounds could be explored (closed?). We do not need a bigger experiment (SK would do), but we do need a supernova...



Distinguishing ALP couplings to neutron and protons

Our signature is only sensitive to the ALP-proton coupling, whereas Oxygen excitation depends on both the ALP-proton and –neutron coupling. In a future observation, the comparison of both channels can be used to measure the ratio of both couplings.



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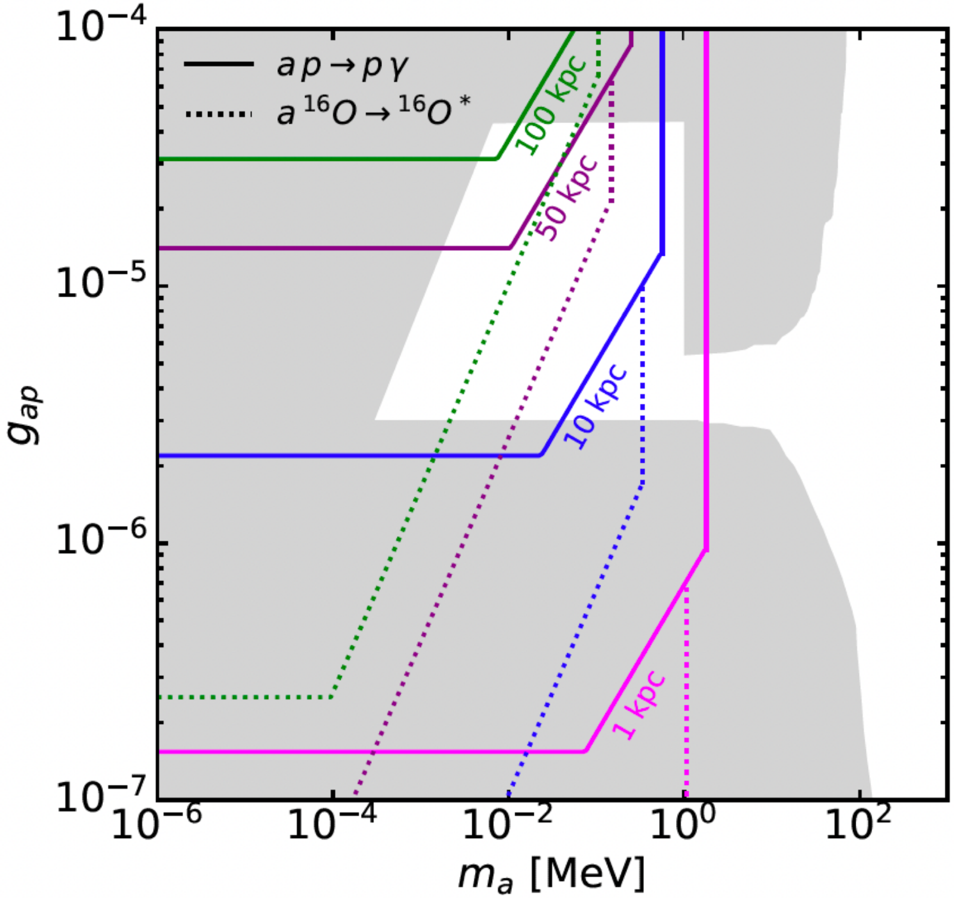
This can be applied to a wide area of the parameter space!

And to supernovae just **outside** our Galaxy (up to ~100 kpc)



Conclusions

If axion-like particles couple to protons, they can be produced in supernovae and detected through the process $a + p \longrightarrow p + \gamma$ in neutrino water Cherenkov detectors.

- ALPs in the mass range $m_a = 1\text{-}100$ MeV would be produced with semirelativistic energies, giving rise to a diffuse ALP flux.

  Bounds using Super Kamiokande II data exclude new areas of the ALP-proton coupling

- ALPs lighter than $m_a < 1$ MeV could be detected from single neighbouring supernovae. The comparison of the signals from $a + p \longrightarrow p + \gamma$ and $a + {}^{16}O \longrightarrow {}^{16}O^*$ can be used to disentangle the ALP coupling to neutrons and protons.

  This can be done for supernovae as distant as ~ 100 kpc.

Energies, not forms, not figures (chant)

Comunidad de Madrid
GOBIERNO DE ESPAÑA
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Thank you

Remembering
Rebecca Collins III

WEEK OF SOUND

Stolen Voices and Parameters for Uncertainty – Concert

7pm

Tuesday 18 February

West Court

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