BSM Probes from Stars

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Outline

01 Introduction
- Stellar objects to probe BSM – Involving neutrino detection?

02 Core-collapse supernova
- Duration of neutrino signal
- Delayed energetic neutrino flux

03 The Sun
- MeV-ish novel particle emission from nuclear reaction

04 Conclusion

Stellar object

> “ **Star**
>
> From Wikipedia, the free encyclopedia
>
> *This article is about the astronomical object. For other uses, see Star (disambiguation).*
>
> A **star** is an astronomical object consisting of a luminous spheroid of plasma held together by its own gravity. ”

- can be used as laboratories to probe fundamental interactions.
  - observed photon or neutrino signal

    e.g. γ-ray spectral modulation which can be explained by axion-photon oscillations

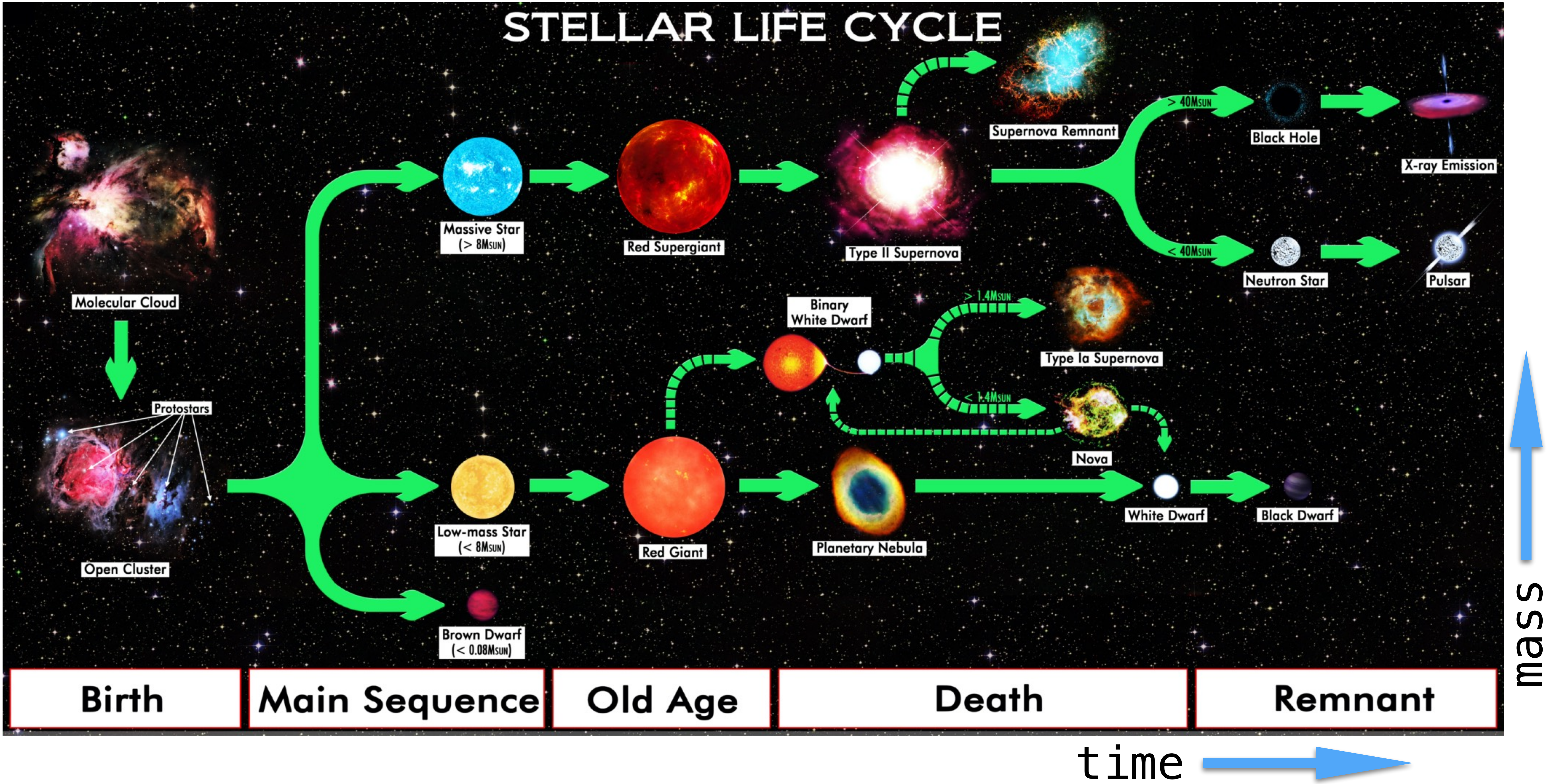
  - Stellar evolution

    extra energy leakage/realease could change
    the evolutionary path which fits well to the standard scenario

⋮

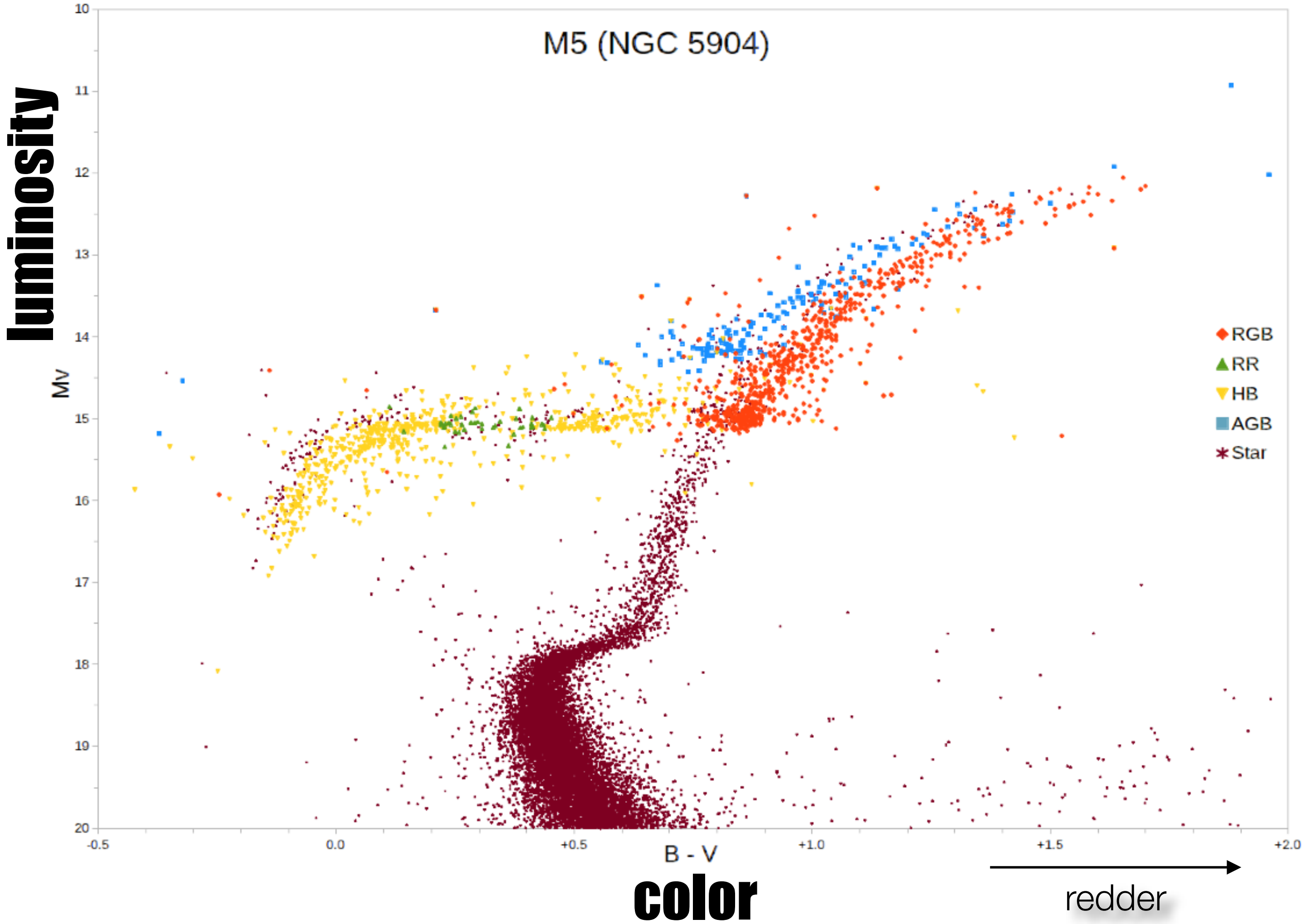
Stellar evolution

[image from Wikipedia]

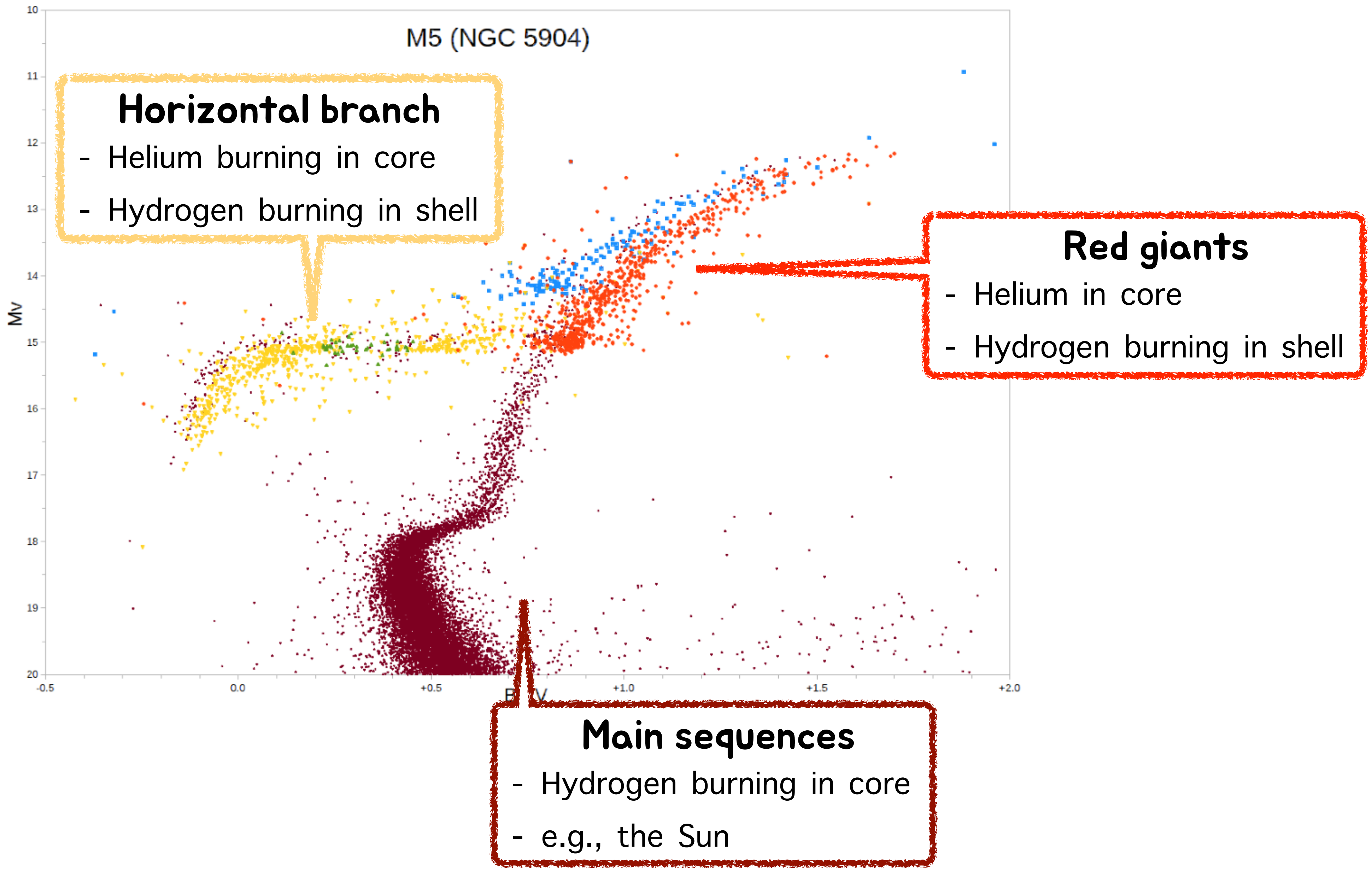


Globular cluster

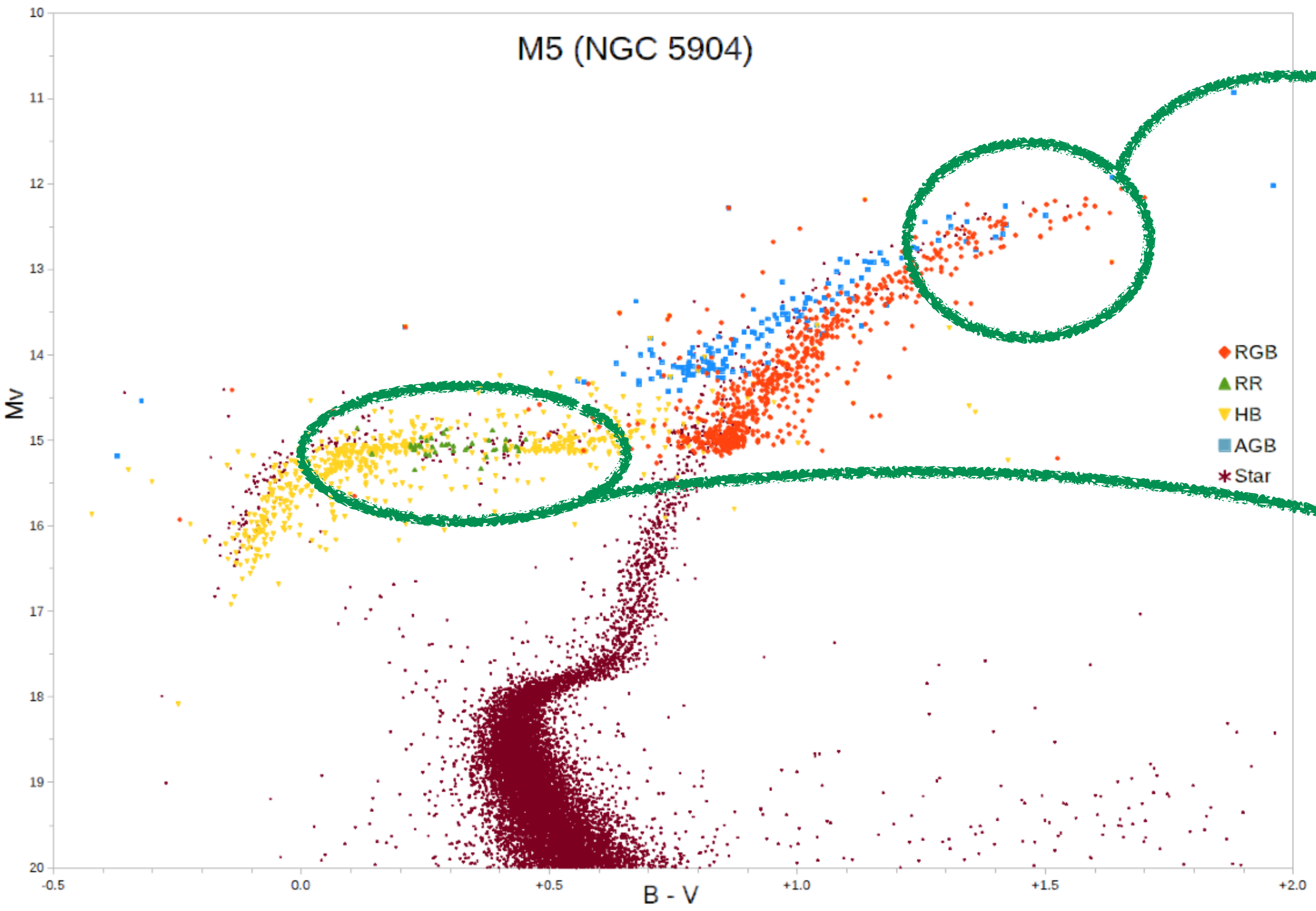
- Very clean laboratories for studies of stellar evolution
- Coeval and almost equal chemical compositions
- Only different initial mass



Main evolutionary phases



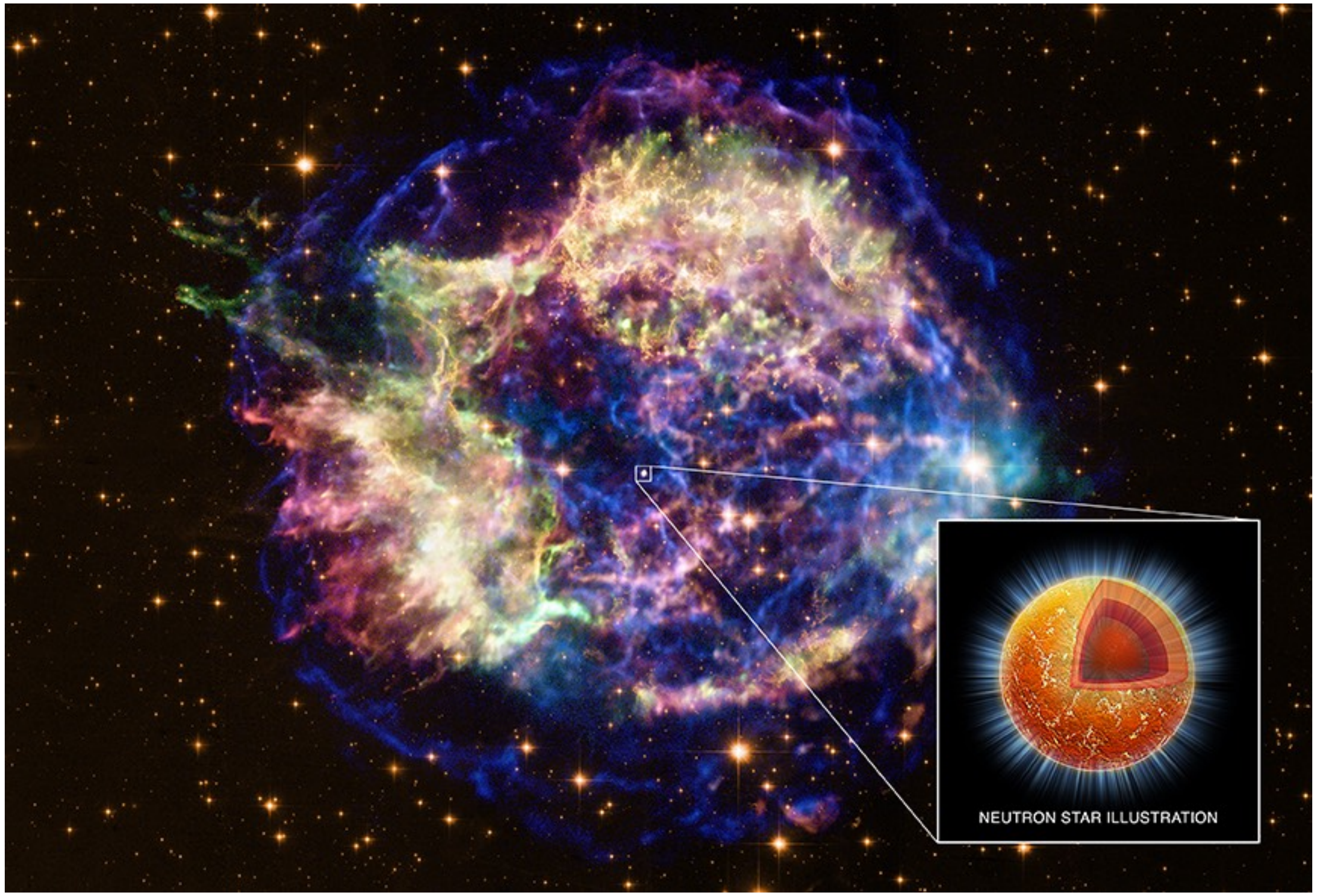
Observables to probe BSM?



- Helium ignition in red-giant phase
  - brightness at the tip of a red-giant branch
  - determined by core mass at helium ignition
- Lifetime of stars on horizontal-branch
  - duration of helium burning
  - the number ratio of stars on HB vs. RGB
  - determined by triple-alpha reaction rate

Cassiopeia A

[Chandra]



- Exploded 340 years ago (ν-cooling)
- Carbon (light element) atmosphere

- Rapid cooling of surface temperatures derived from X-ray observations

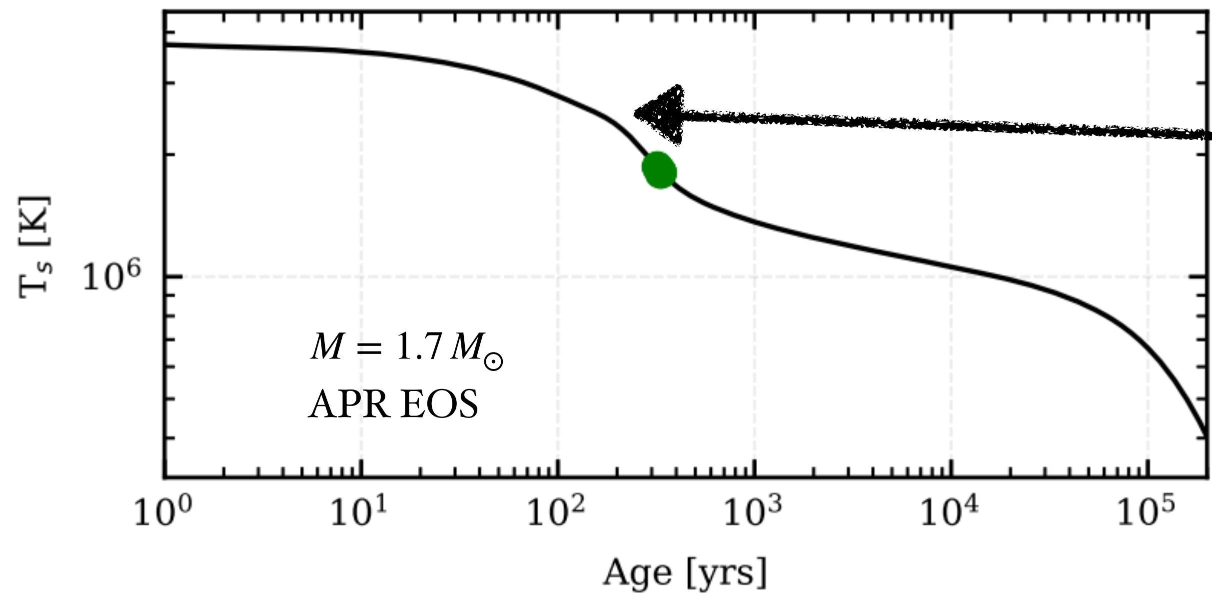
[M. J. P. Wijngaarden et al, 2019]

2~3% for 10 yr decline rate

expectation w.o. superfluidity

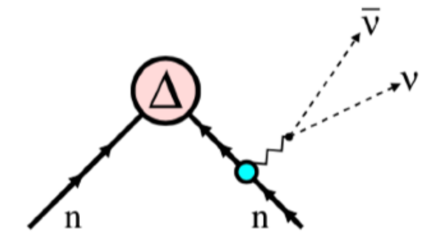
$$\gg \frac{\Delta T}{T} \sim -\frac{1}{6}\frac{dt}{t} \sim 0.5\,\%$$

Evidence for superfluidity?

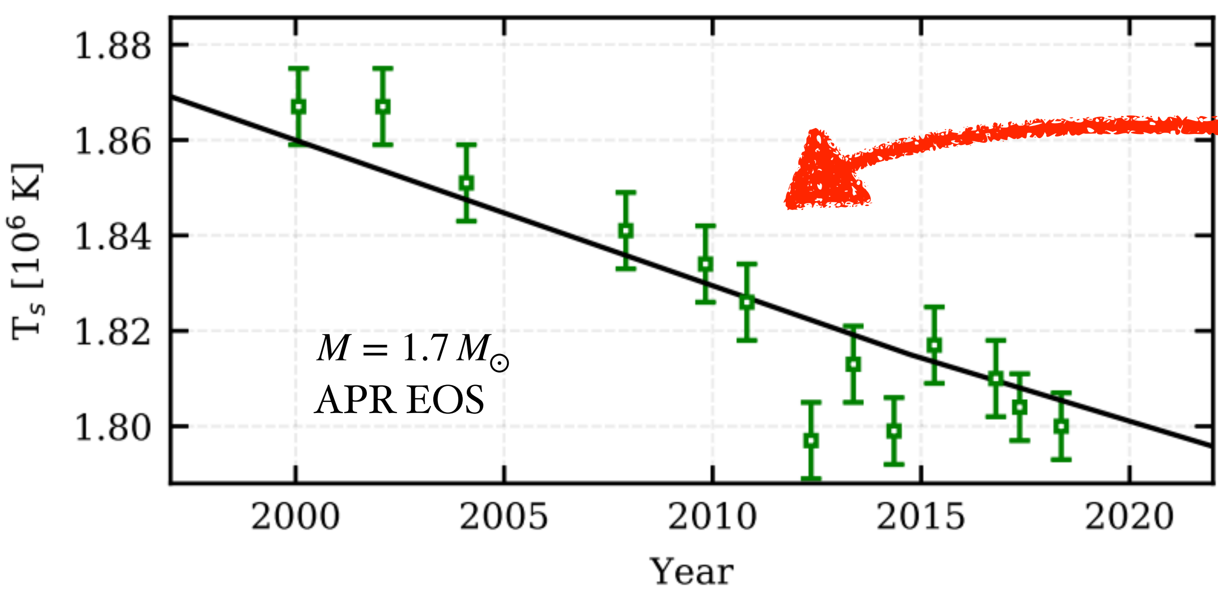


$T = T_c \sim 5.9 \times 10^8\,\mathrm{K}$ for $^3P_2$

Rapid cooling by



'Pair breaking and formation'



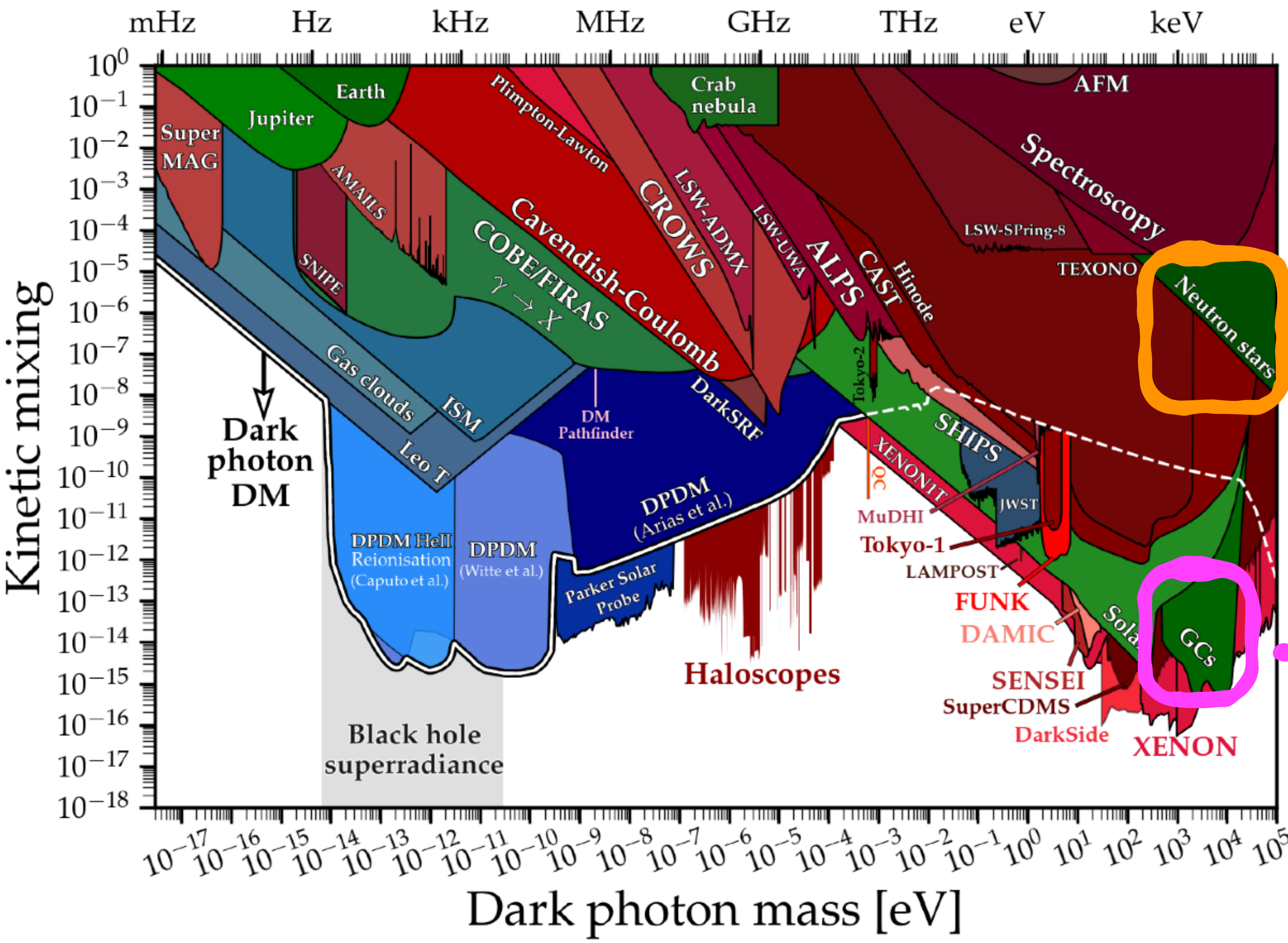
Minimal cooling scenarios with superfluidity fit well to the data

[M. J. P. Wijngaarden et al, 2019]

Cooling argument

No involving ν detection

[https://cajohare.github.io/AxionLimits/docs/dp.html]



- Dominantly ν-cooling in the SM

Extra energy leakage

[D. K. Hong, C. S. Shin, SY, 2021]

$$\epsilon_x \lesssim \epsilon_{\rm PBF}$$

To be consistent with the standard cooling scenario

Extra energy leakage

$$\epsilon_x \lesssim 10\,{\rm erg\,g^{-1}\,s^{-1}}$$

"Raffelt's criterion"

To be consistent with the SM prediction

Conditions to involve ν detection

✓ Energy should exceed $\mathcal{O}(1)\,\mathrm{MeV}$ due to a detection efficiency

✓ High luminosity?

→ **Core-collapse Supernovae**

✓ Close distance?

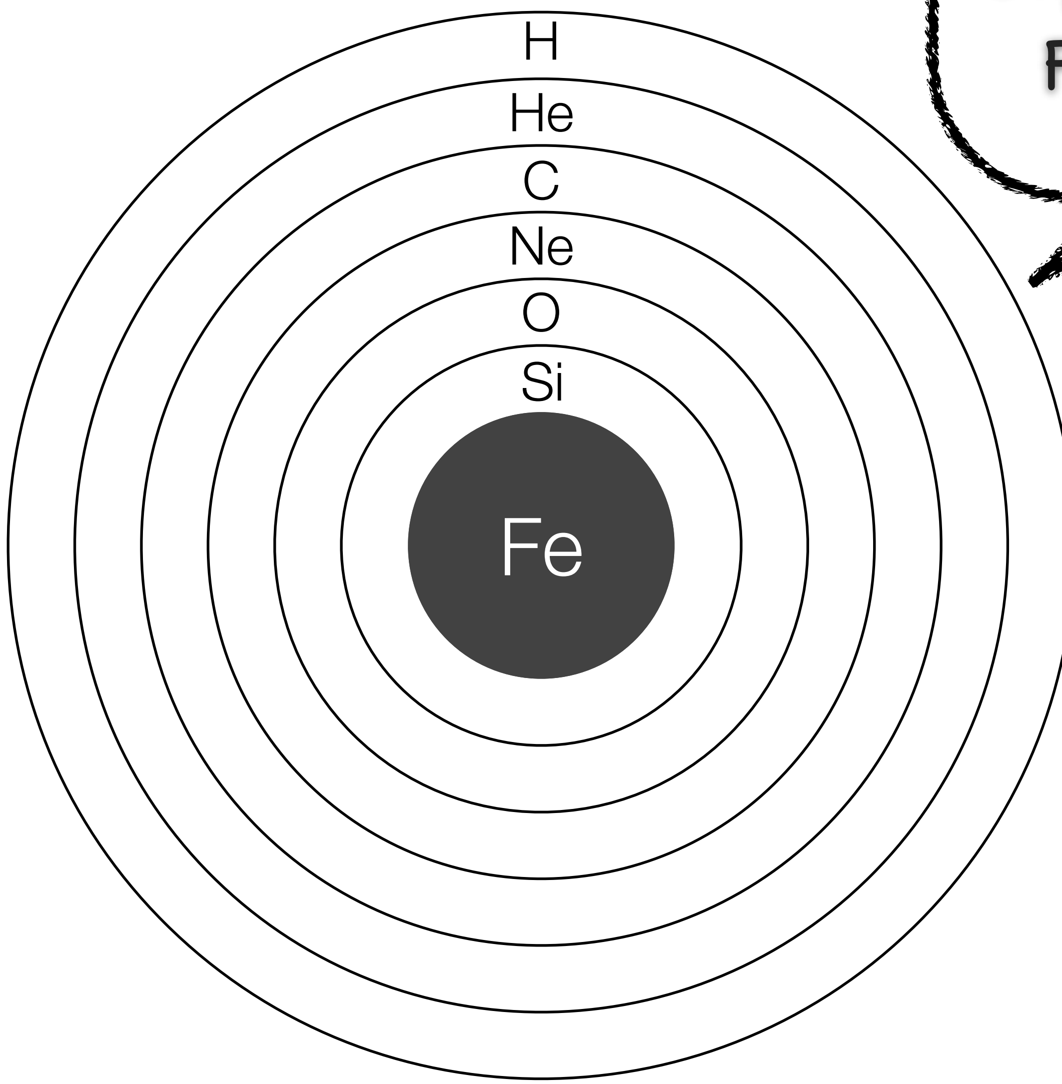
→ **The Sun**

◉ Also powerful source to generate energetic novel particles

Core collapse Supernovae

- Core collapse + the neutrino-driven explosion
- Neutrino signal of SN1987A for a few seconds
  - Reduction of time duration by novel particle emission
- No energetic($\sim \mathcal{O}(100)\,\mathrm{MeV}$) neutrino detection
  - Energetic and delayed ν from novel particle's decay

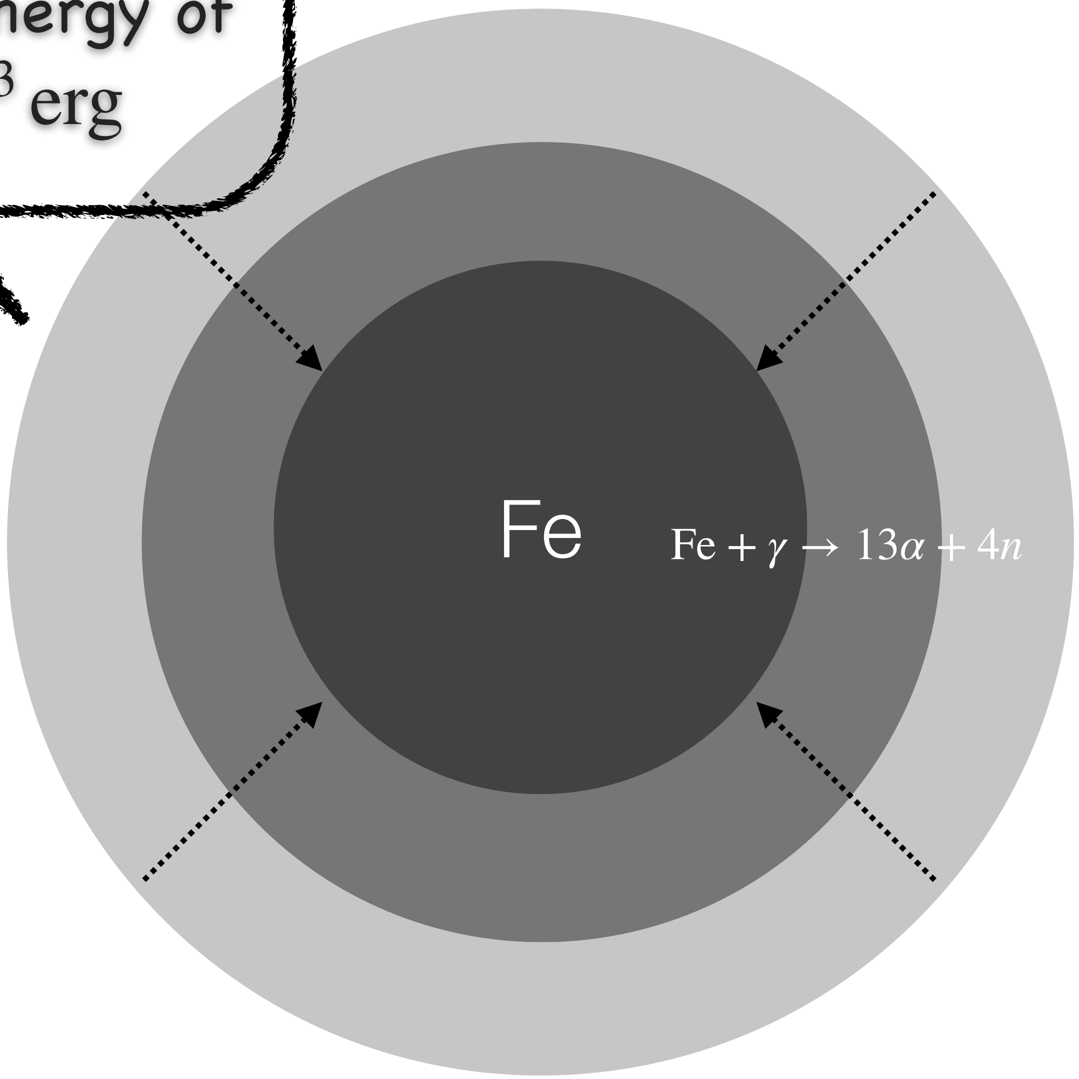
Core-collapse supernova



Supergiant w/ $M_i > 8M_\odot$
Fusion up to iron core

Core-collapse supernova

"Chandrasekhar limit"
At $M_c \sim 1.4 M_\odot$, iron core collapses w/ gravitational binding energy of $E_{\rm tot} \sim G M_c^2 / R_c = 10^{53}\,{\rm erg}$



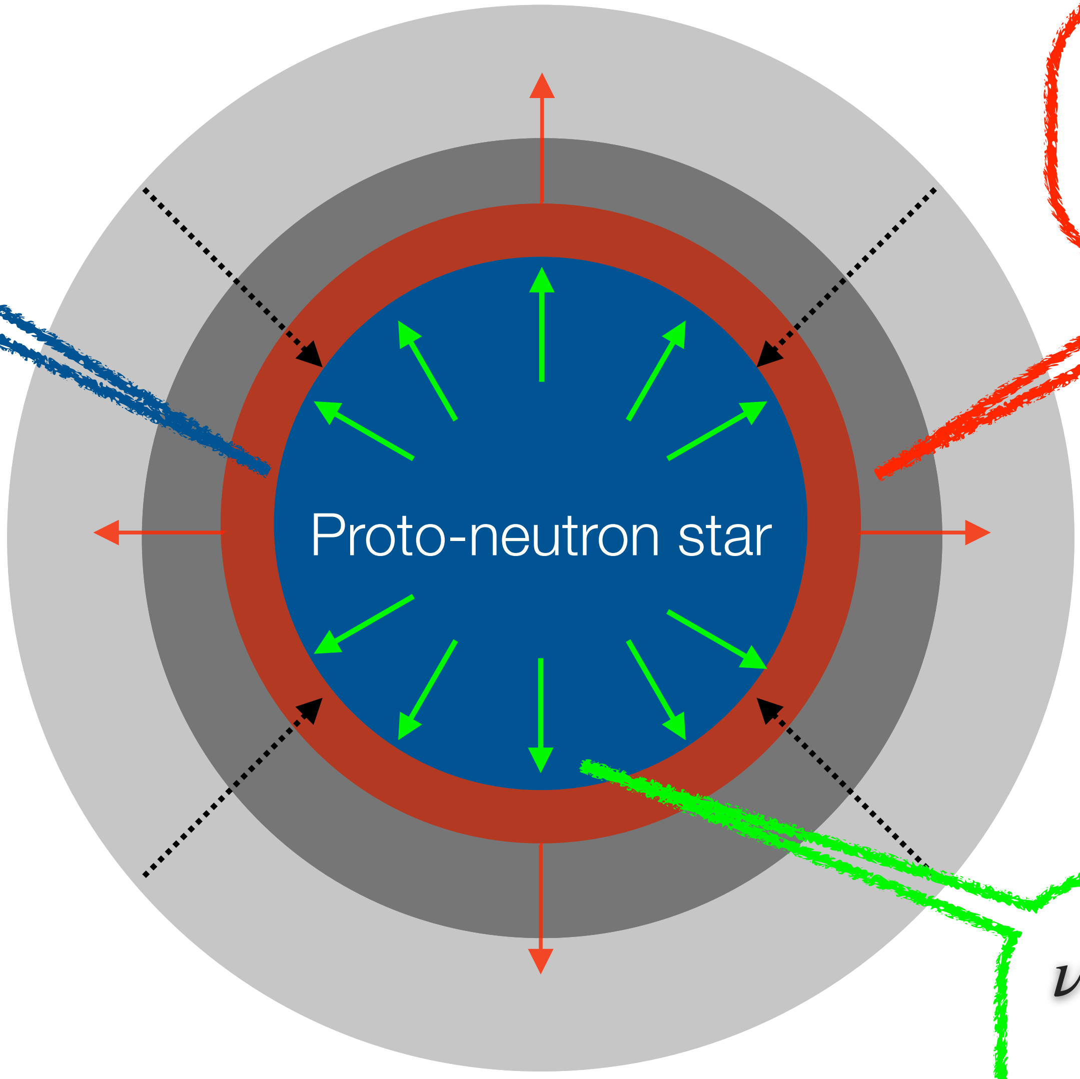
Core-collapse supernova

i.e., typical nucleon distance $\sim \mathrm{fm}$

At $\rho_c \sim \rho_{\mathrm{sat}}$, EoS stiffens

Core size $\sim 10\,\mathrm{km}$

Temperature $\sim 30\,\mathrm{MeV}$



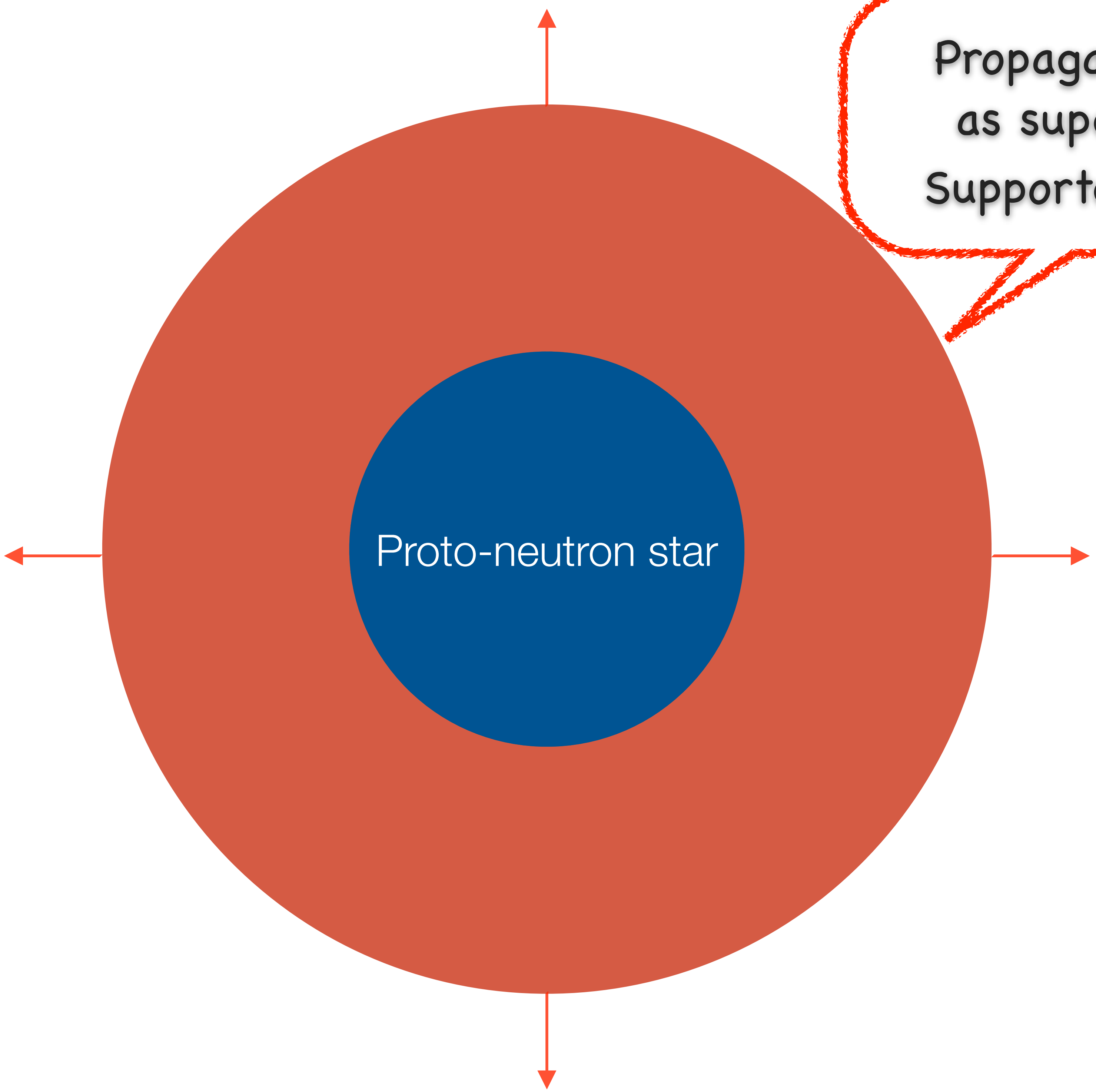
Bounce shock wave stall due to dissociation & accretion

ν **produced, but trapped**

$\langle E_\nu \rangle \sim 10\,\mathrm{MeV}$

$t_{\mathrm{diff}} \sim 10\,\mathrm{sec}$

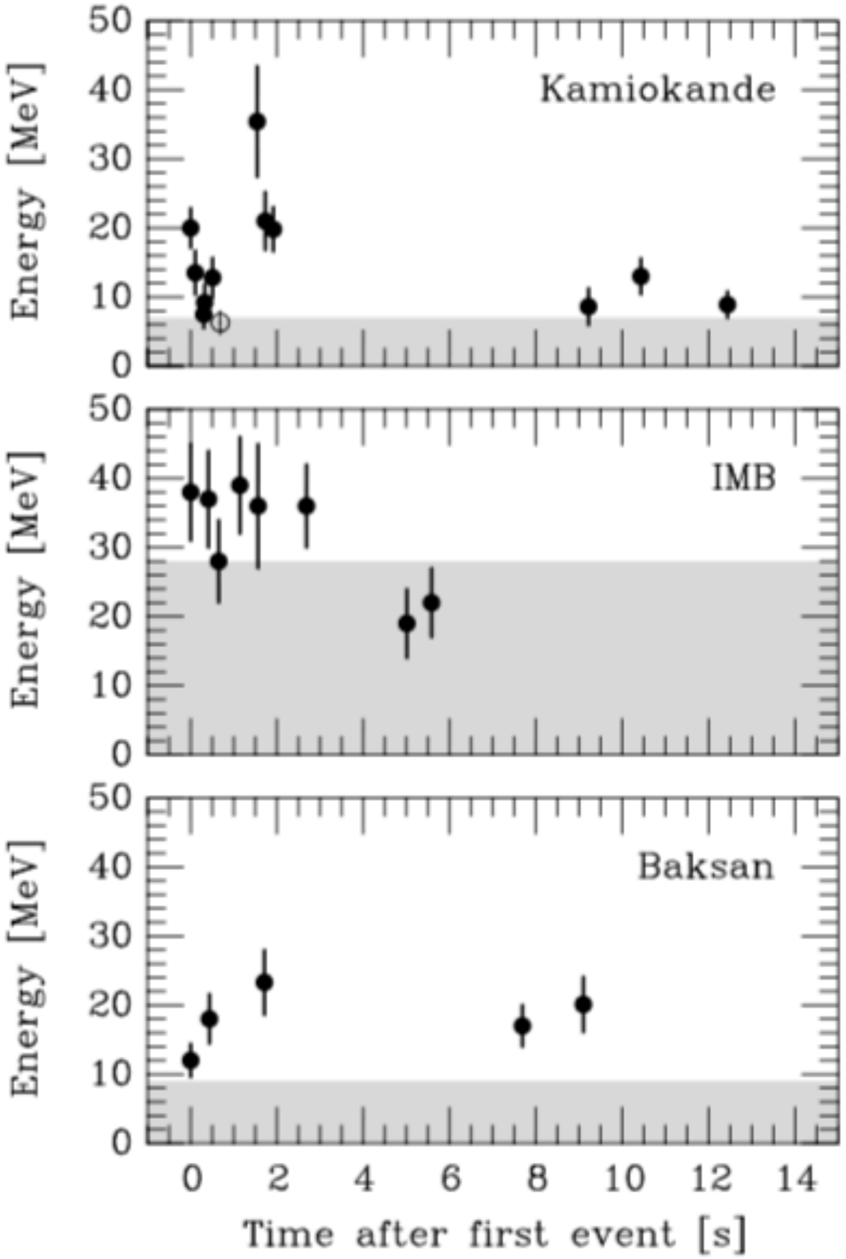
Core-collapse supernova

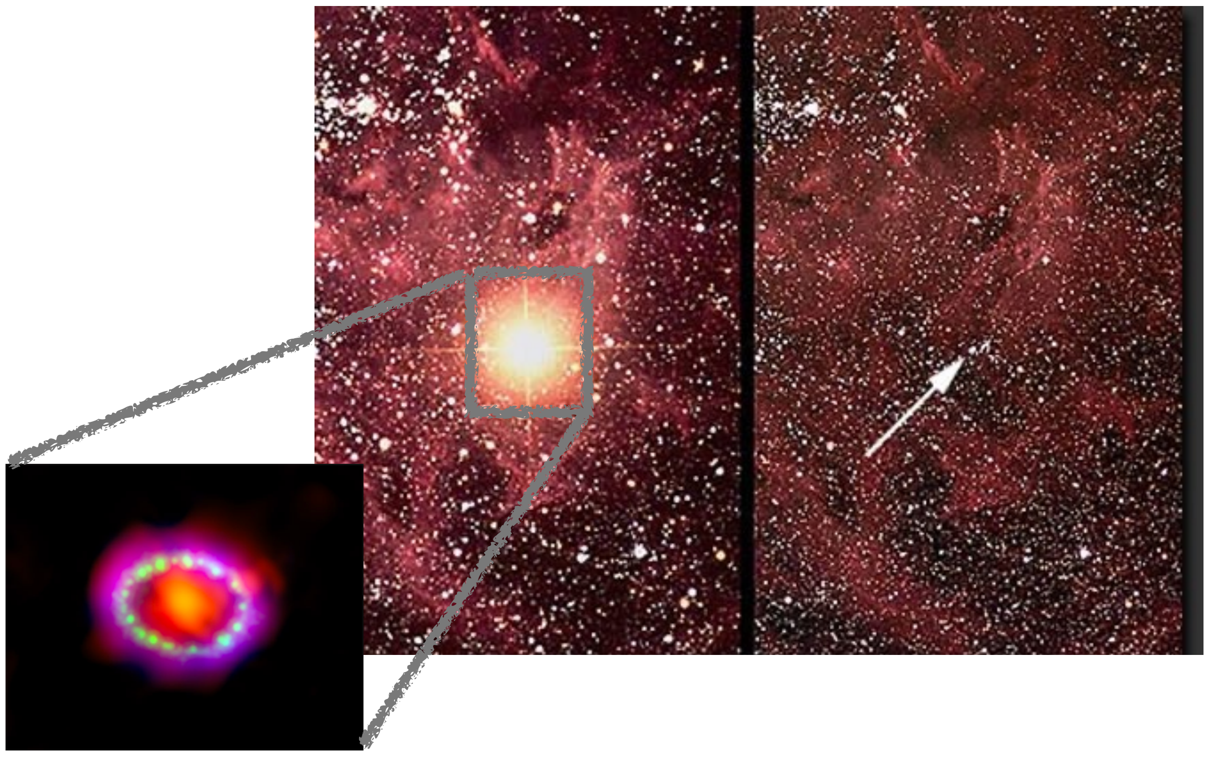


Propagate to outer layer
as supernova explosion
Supported by ν transport

SN1987A

[Raffelt, 95]



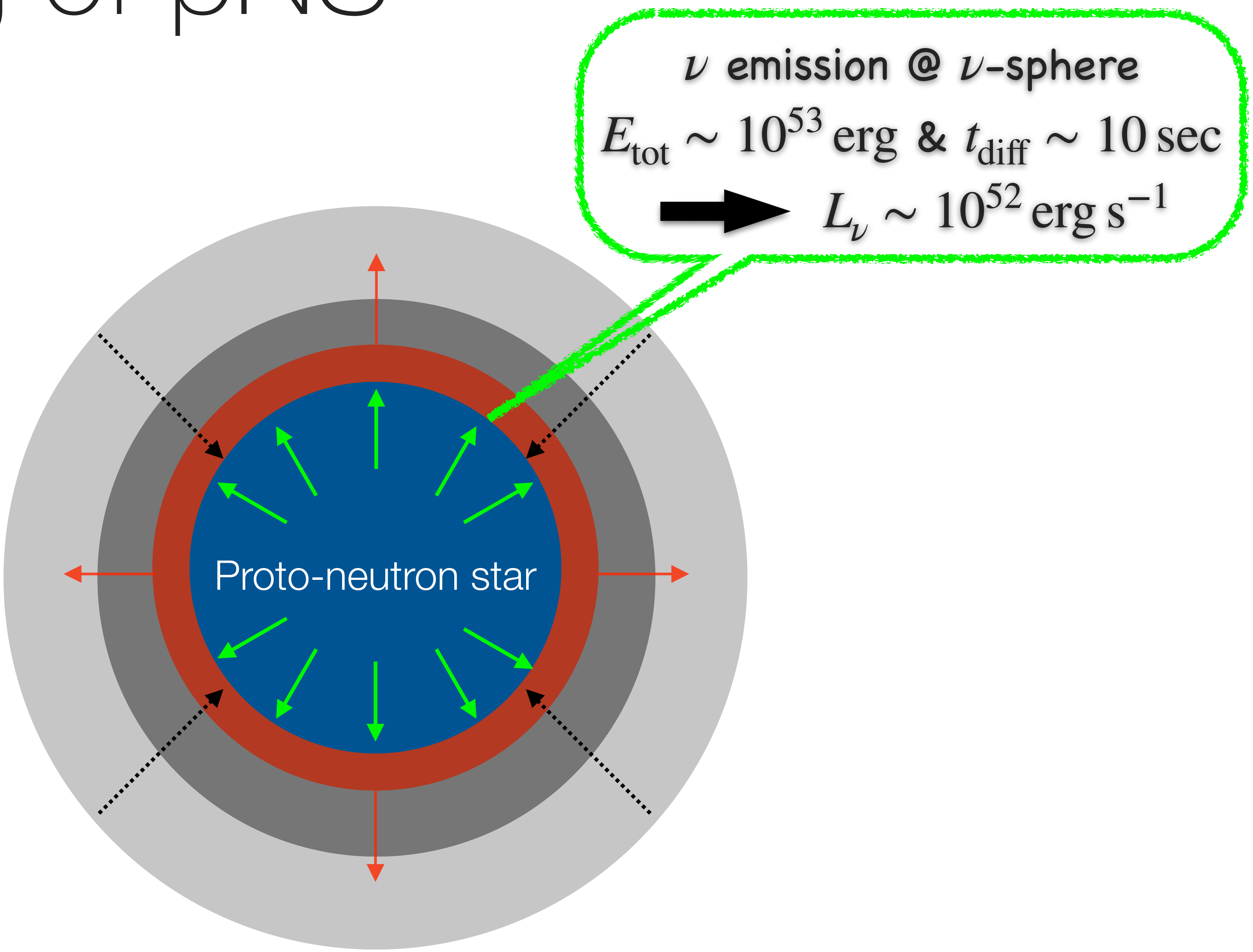


[Chandra]

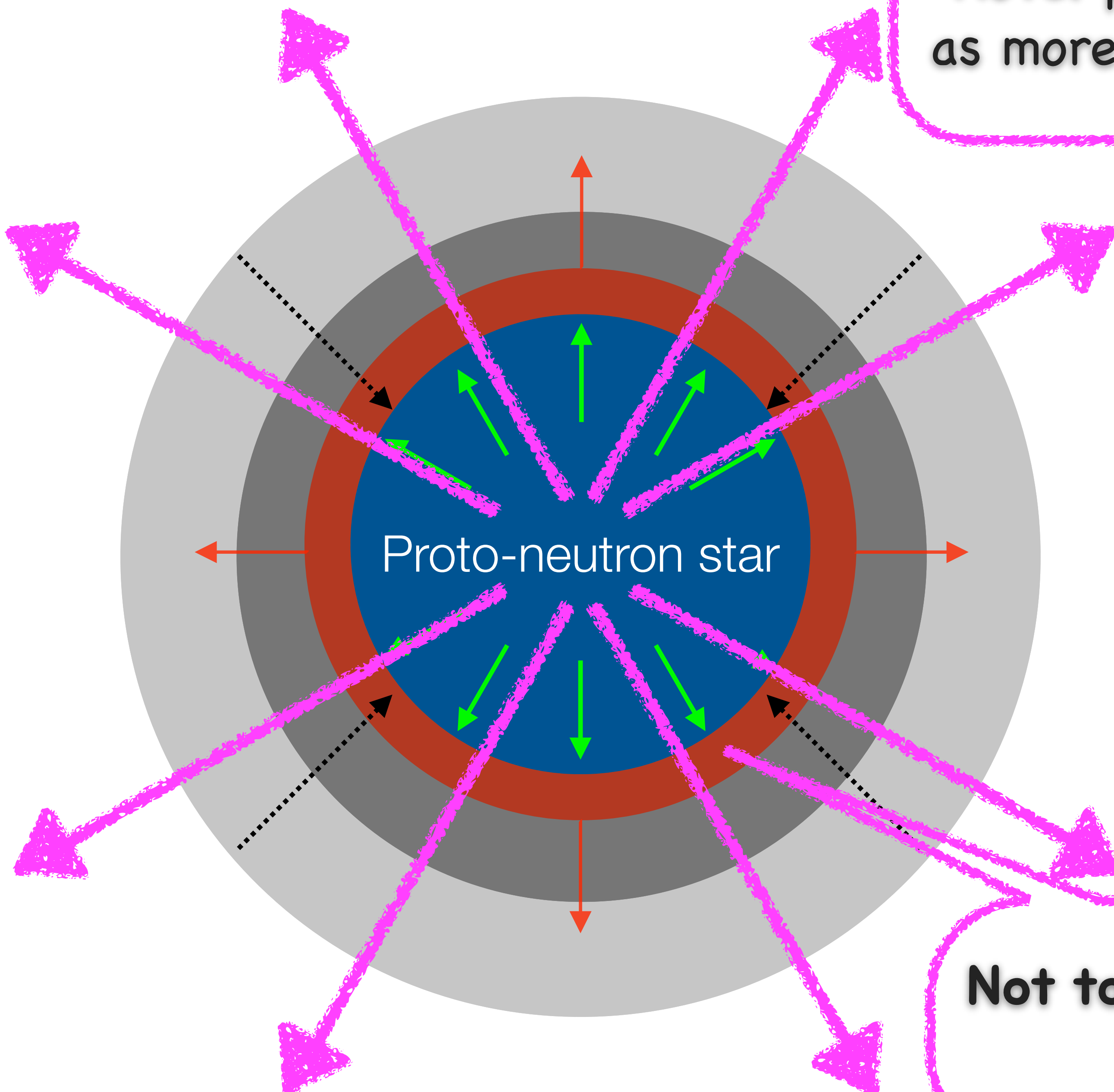
- The only direct observation of neutrinos occurred on 23 February 1987 when the blue supergiant Sanduleak–69 202 in the Large Magellanic Cloud exploded

Observational neutrino signal consistent with simulation fit

ν-cooling of pNS



Cooling argument on SNe

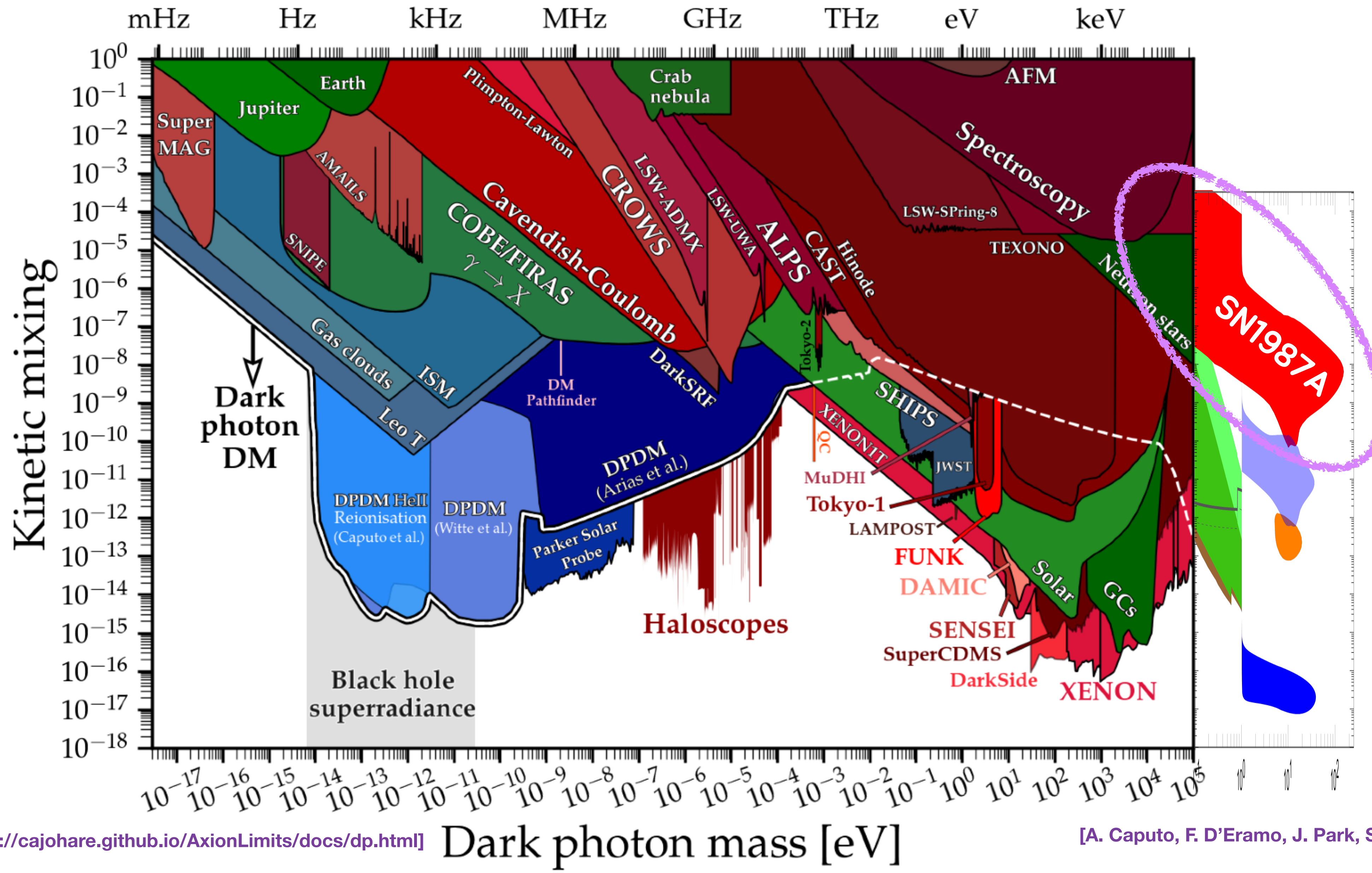


Novel particle can free-stream as more efficient cooling channel

Not to reduce ν-signal duration

$L_X < L_\nu \sim 10^{52}\,\mathrm{erg\,s^{-1}}$

SN cooling bound on DP



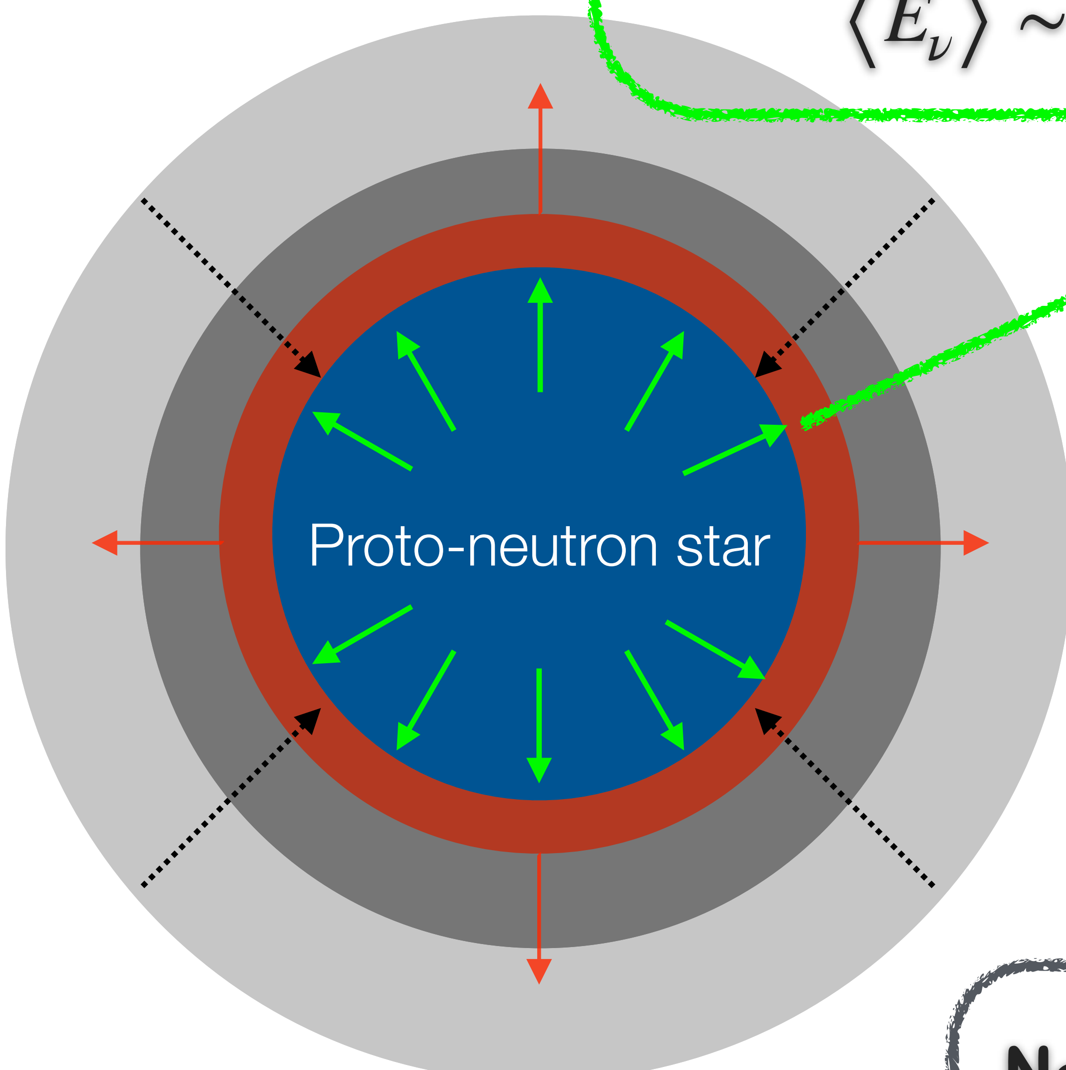
[https://cajohare.github.io/AxionLimits/docs/dp.html]

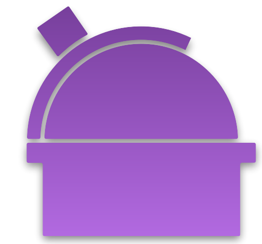
[A. Caputo, F. D'Eramo, J. Park, SY, in progress]

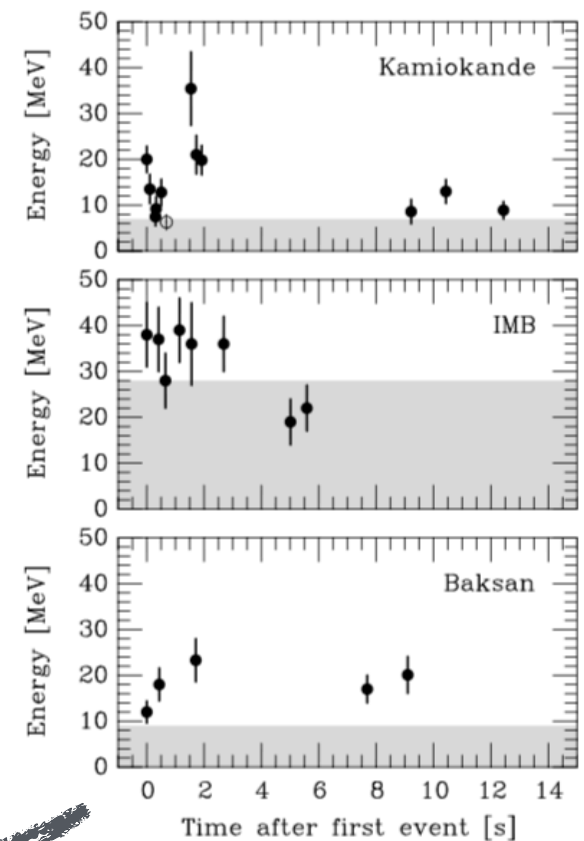
No energetic SN ν signal

ν emission @ ν-sphere

$$\langle E_\nu \rangle \sim T \sim 10\,\mathrm{MeV}$$





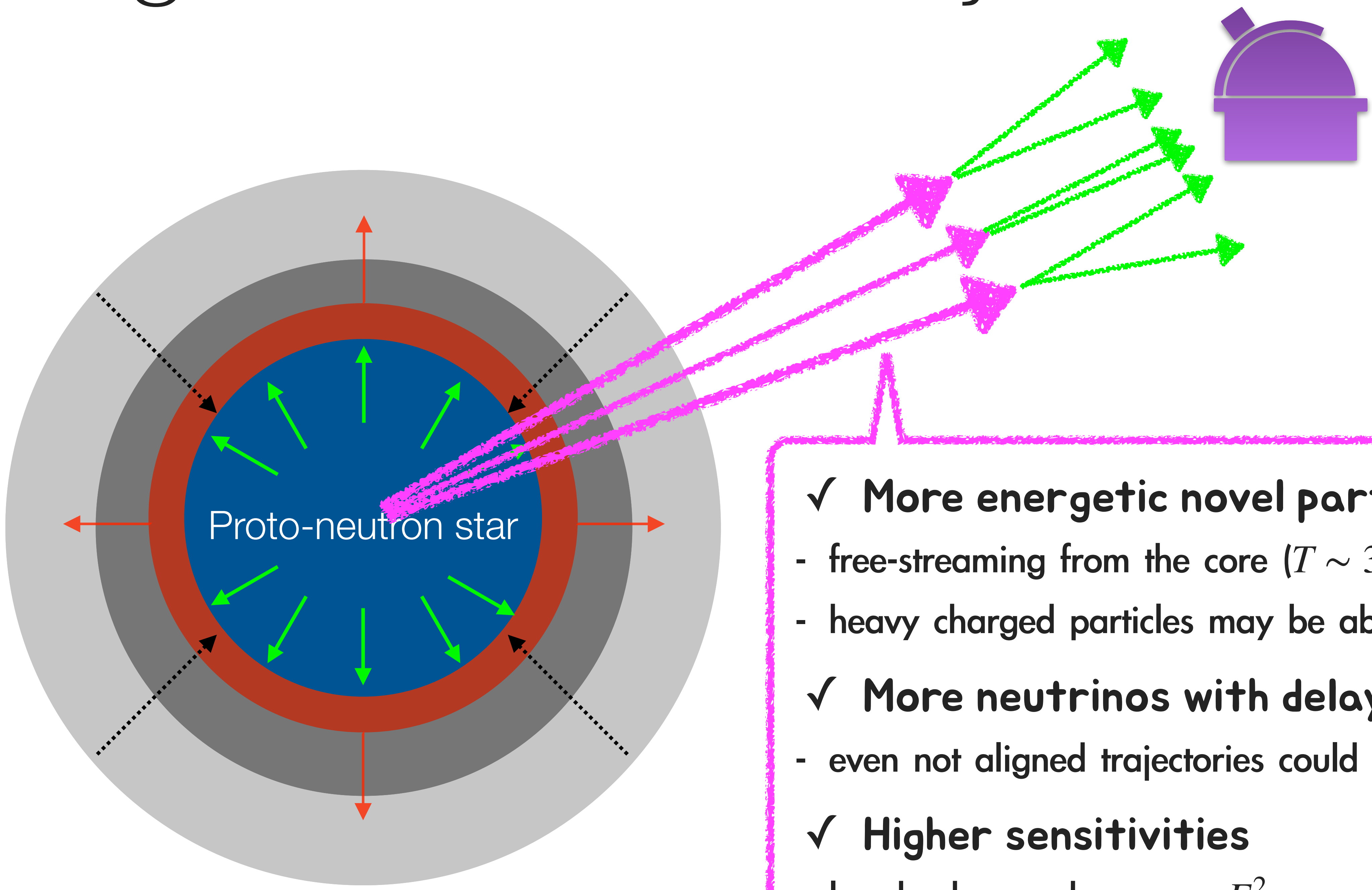


[Raffelt, 95]

No energetic ν signal

$$E_\nu \gtrsim 100\,\mathrm{MeV}$$

Energetic ν from decay



✓ More energetic novel particles

- free-streaming from the core ($T \sim 30\,\mathrm{MeV}$)
- heavy charged particles may be abundant

✓ More neutrinos with delay

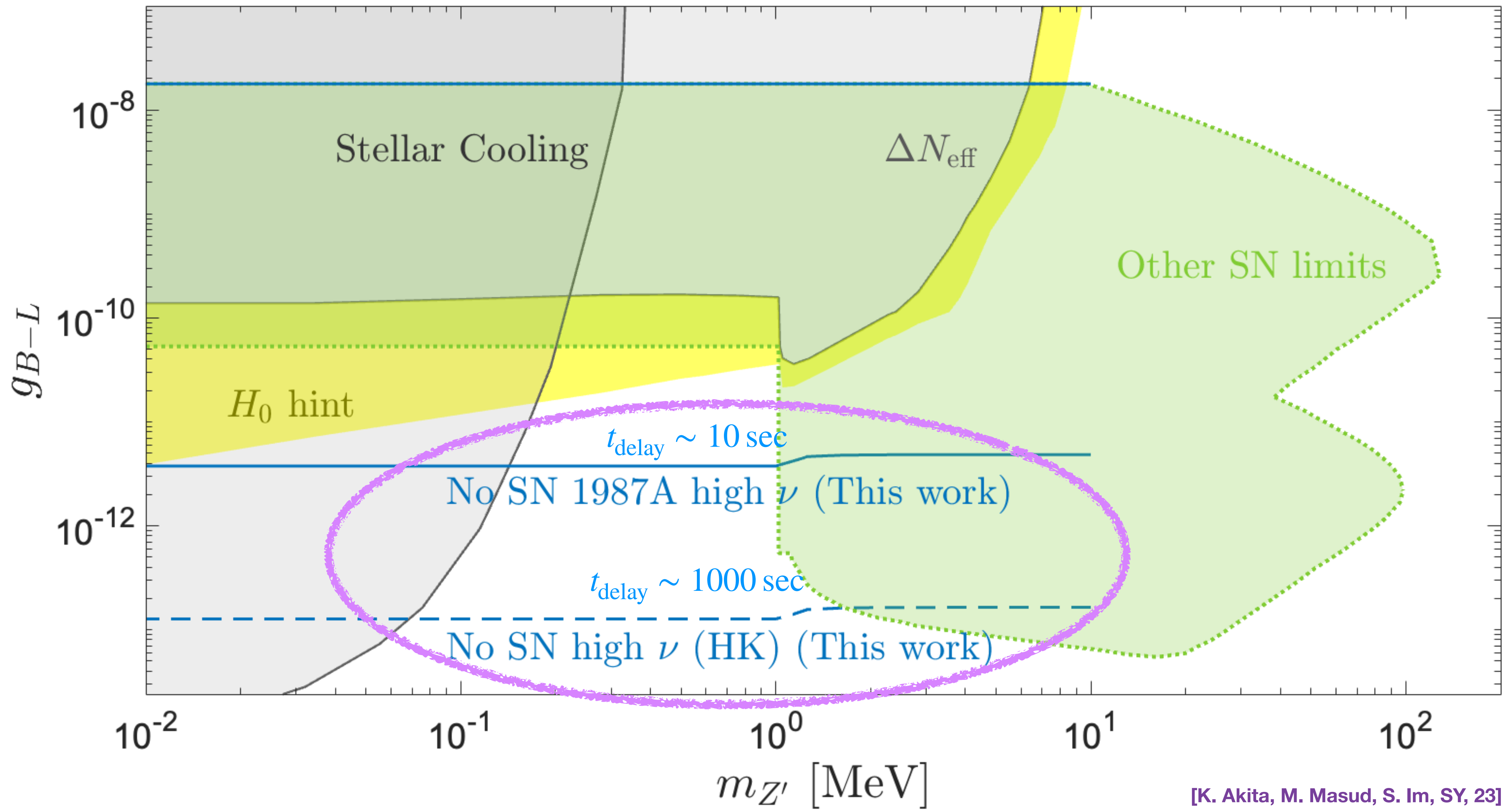
- even not aligned trajectories could contribute

✓ Higher sensitivities

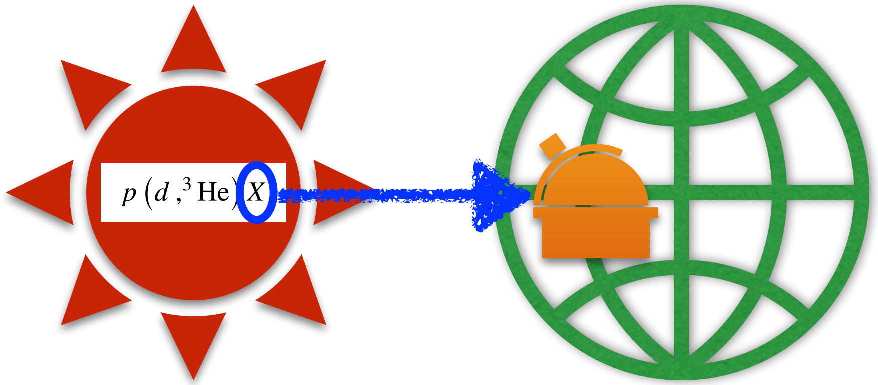
- less background + $\sigma_{\nu \mathrm{A}} \propto E_\nu^2$

[K. Akita, M. Masud, S. Im, 22] [D. Fiorillo, G. Raffelt, E. Vitagliano, 23] [K. Akita, M. Masud, S. Im, SY, 23]

Constraints on the $U(1)_{\mathrm{B-L}}$ model



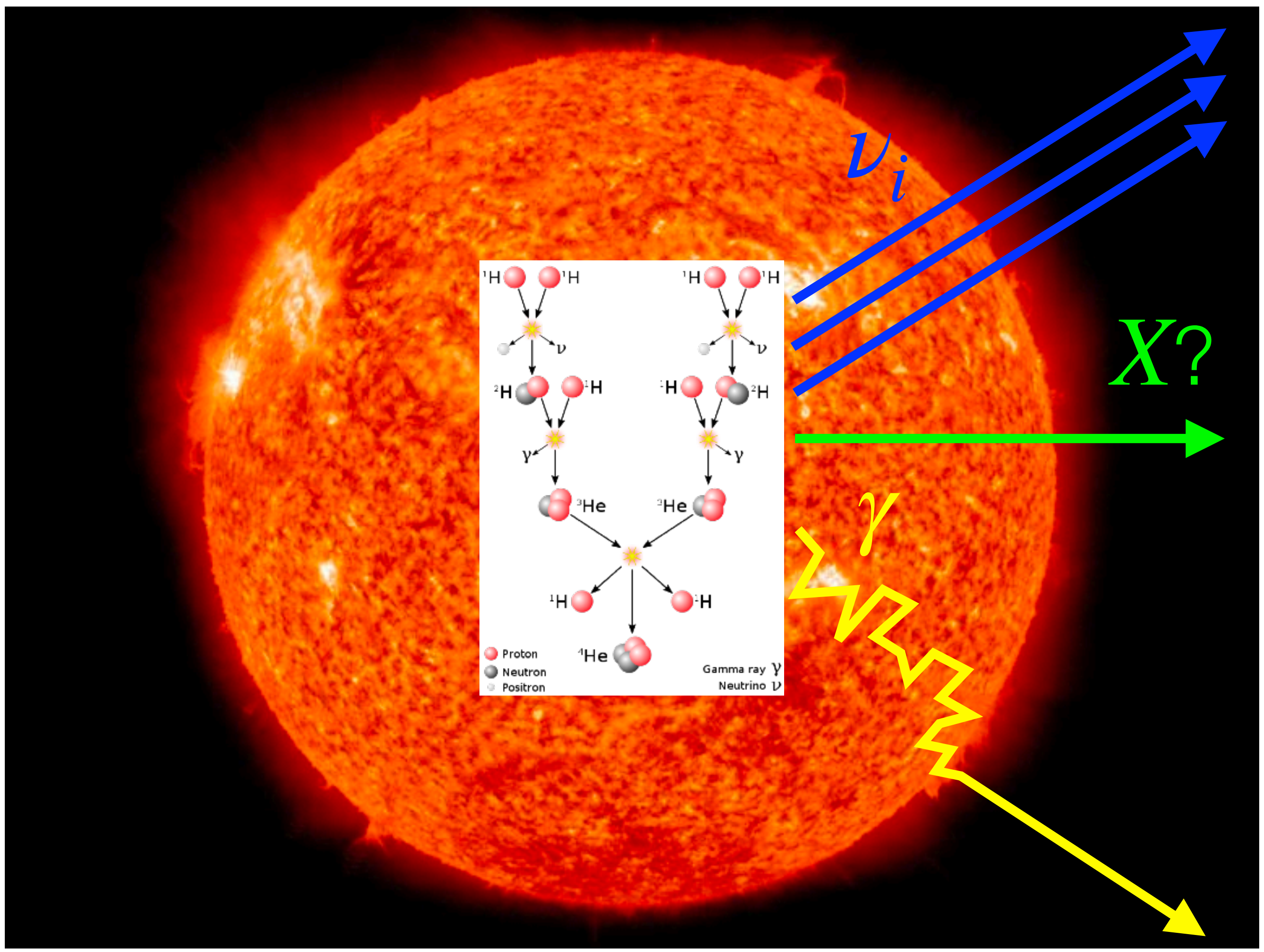
[K. Akita, M. Masud, S. Im, SY, 23]



Solar nuclear reaction

- Deuterium fusion $p + d \to {}^3\mathrm{He} + X\,(5.49\,\mathrm{MeV})$
- Predominantly isovector (i.e., isospin breaking)
- Axion as a magnetic mode & Dark photon by a mixing

Sun

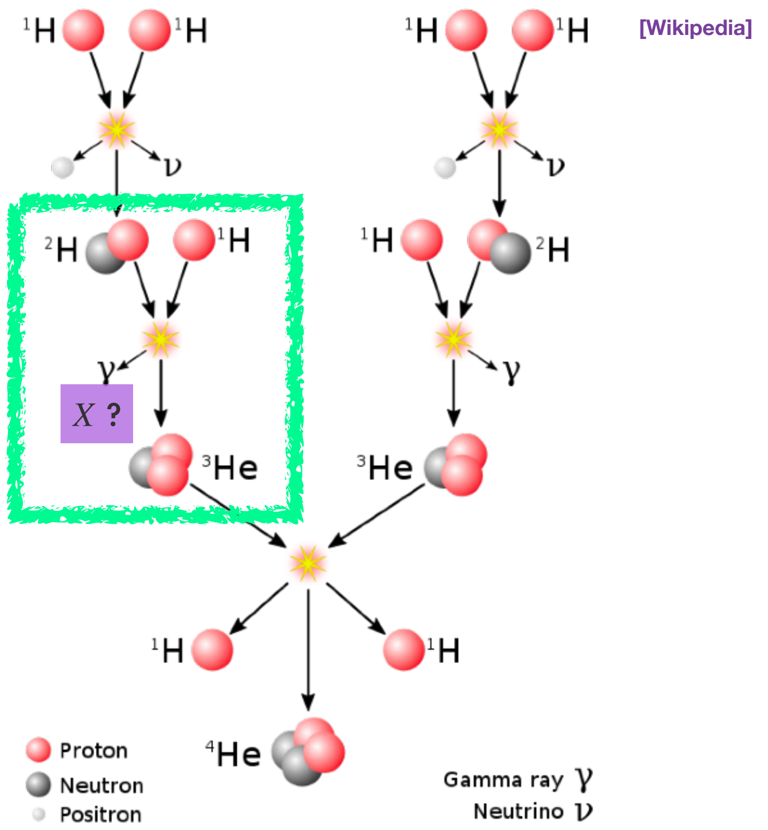


[NGC]

- Closest star to Earth
  - as a good and natural laboratory to probe new physics
- Dominant energy release by nuclear reaction (p-p chain)
  - **Neutrino** (volume emission)
  - **Photon** (surface emission)
  - ***Novel particles?***
    - thermal : $E \Downarrow$ ($\sim T = \mathcal{O}(1)\,\mathrm{keV}$), $\Phi \Uparrow$
    - N-reaction : $E \Uparrow$ ($\sim \mathcal{O}(1)\,\mathrm{MeV}$), $\Phi \Downarrow$

Deuterium fusion

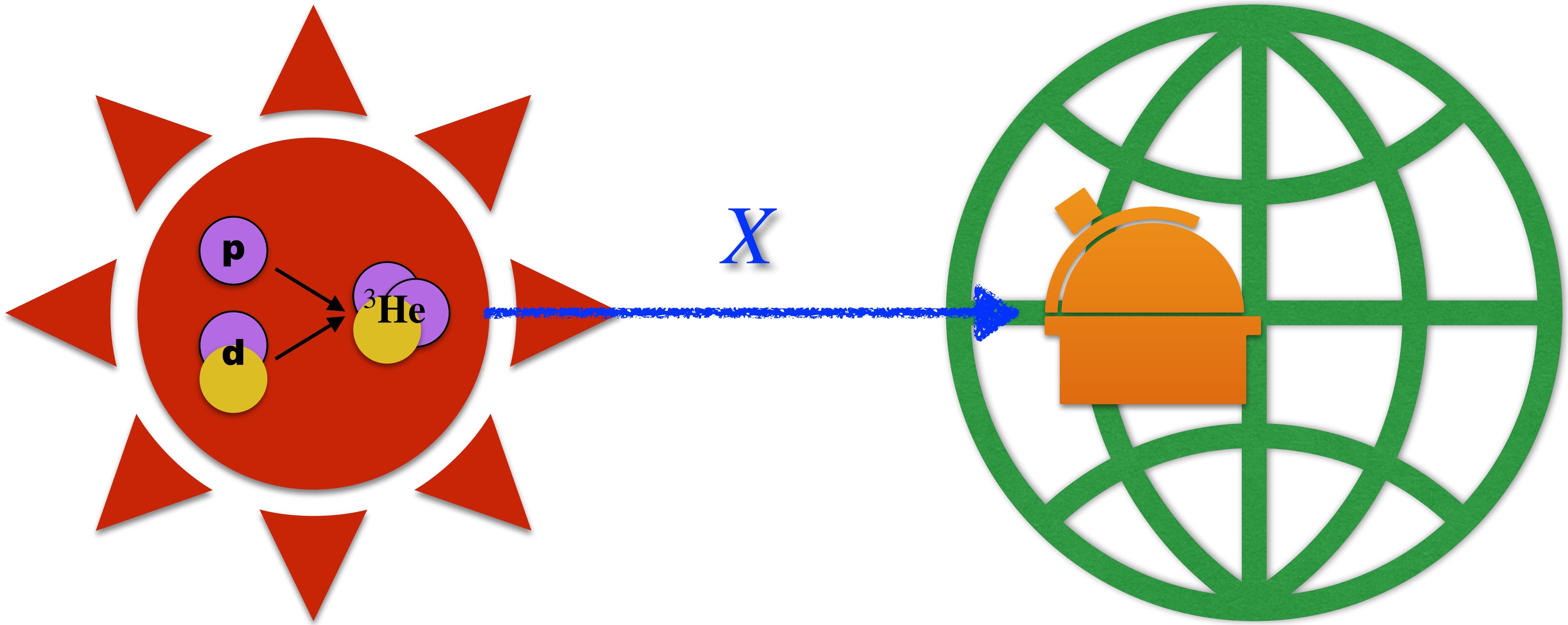
$$p + d \rightarrow {}^{3}\mathrm{He} + \gamma\,(5.49\,\mathrm{MeV})$$



- The second stage of solar pp fusion chain
  - $1.7 \times 10^{38}\,\mathrm{s}^{-1}$ at the innermost region (core) of the Sun

- 5.49 MeV energy release through the electromagnetic radiation
  - X instead of γ ? (possibility for axion have been discussed)

- In terms of multipole expansion (relevant to non-relativistic regime)
  - Electric- & Magnetic-dipole transition dominant
  - Due to the proton and deuteron as the pure isospin eigenstates
  - Controlled by **isovector** charge (i.e., difference between the couplings to nucleons)



Production

- Effective theory of γ' in a medium
  - *i. Kinetic mixing*
  - *ii. Plasma mixing*
- $p + d \to {}^3\mathrm{He} + \gamma' \left(5.49\,\mathrm{MeV}\right)$
  - ✓ *Multipole expansion - (E1 & M1)*
  - ✓ *Isovector*

Detection

- Compton-like $e^-\gamma' \to e^-\gamma$
  - ✓ *Polarized cross-section*
- In-flight decay $\gamma' \to e^-e^+$
  - ✓ *allowed for* $m_{\gamma'} \geq 2m_e$

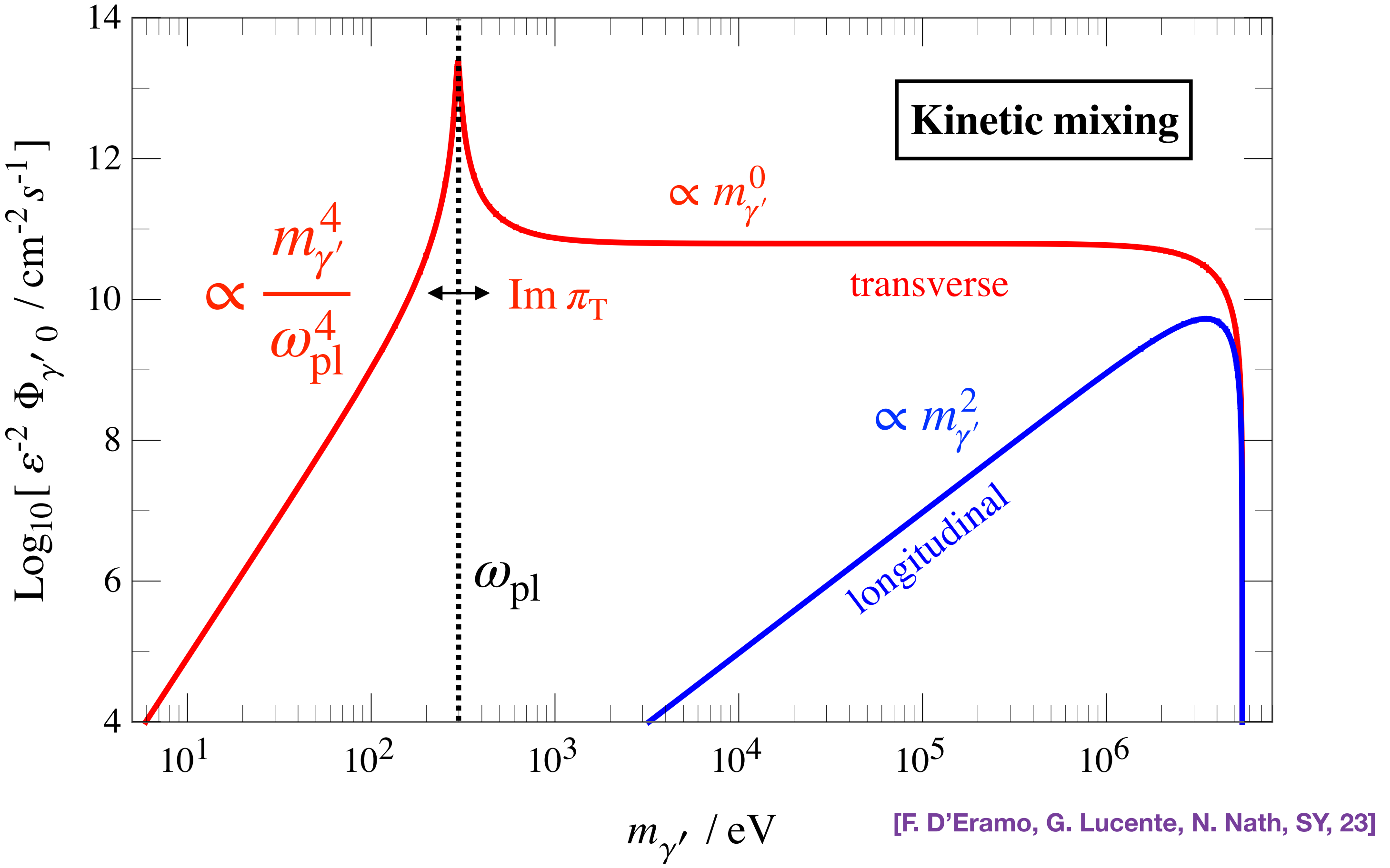
Solar **5.49 MeV** γ' flux (kinetic mixing)

$1.7 \times 10^{38}\,\mathrm{s}^{-1}$ **for** $p\,(d\,,^3\mathrm{He})\,\gamma$

γ-γ' **mixing**

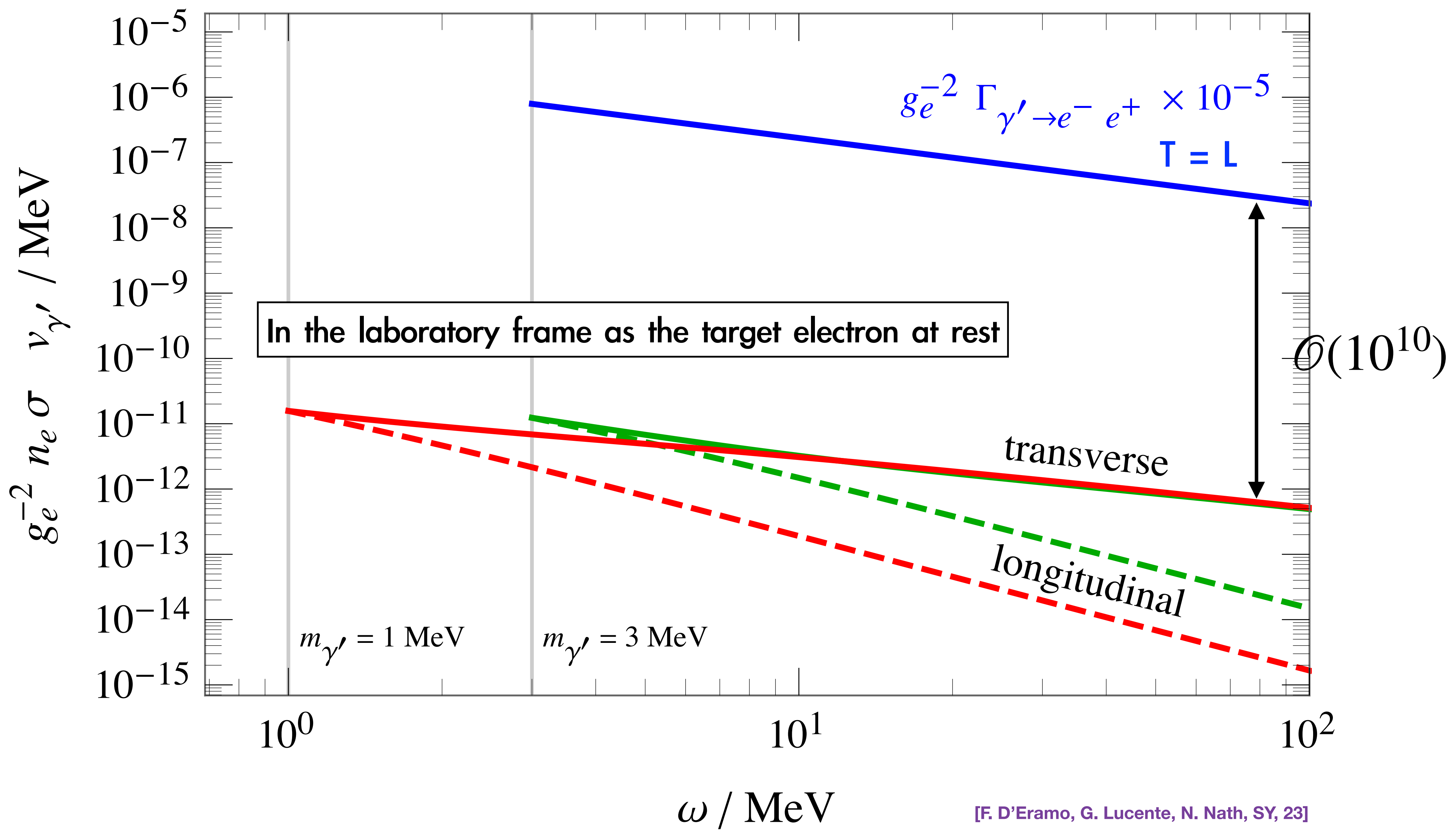
$$\left[\Phi_{\gamma'}\right]_{\mathrm{T,L}} = \frac{1}{4\pi d_\odot^2}\phi_\gamma \frac{k^3}{\omega^3}\left|\varepsilon \frac{m_{\gamma'}^2}{m_{\gamma'}^2 - \pi_{\mathrm{T,L}}}\right|^2 \times \left[\frac{m_{\gamma'}^2}{\omega^2}\right]_{\mathrm{L}}$$

(current conservation)



[F. D'Eramo, G. Lucente, N. Nath, SY, 23]

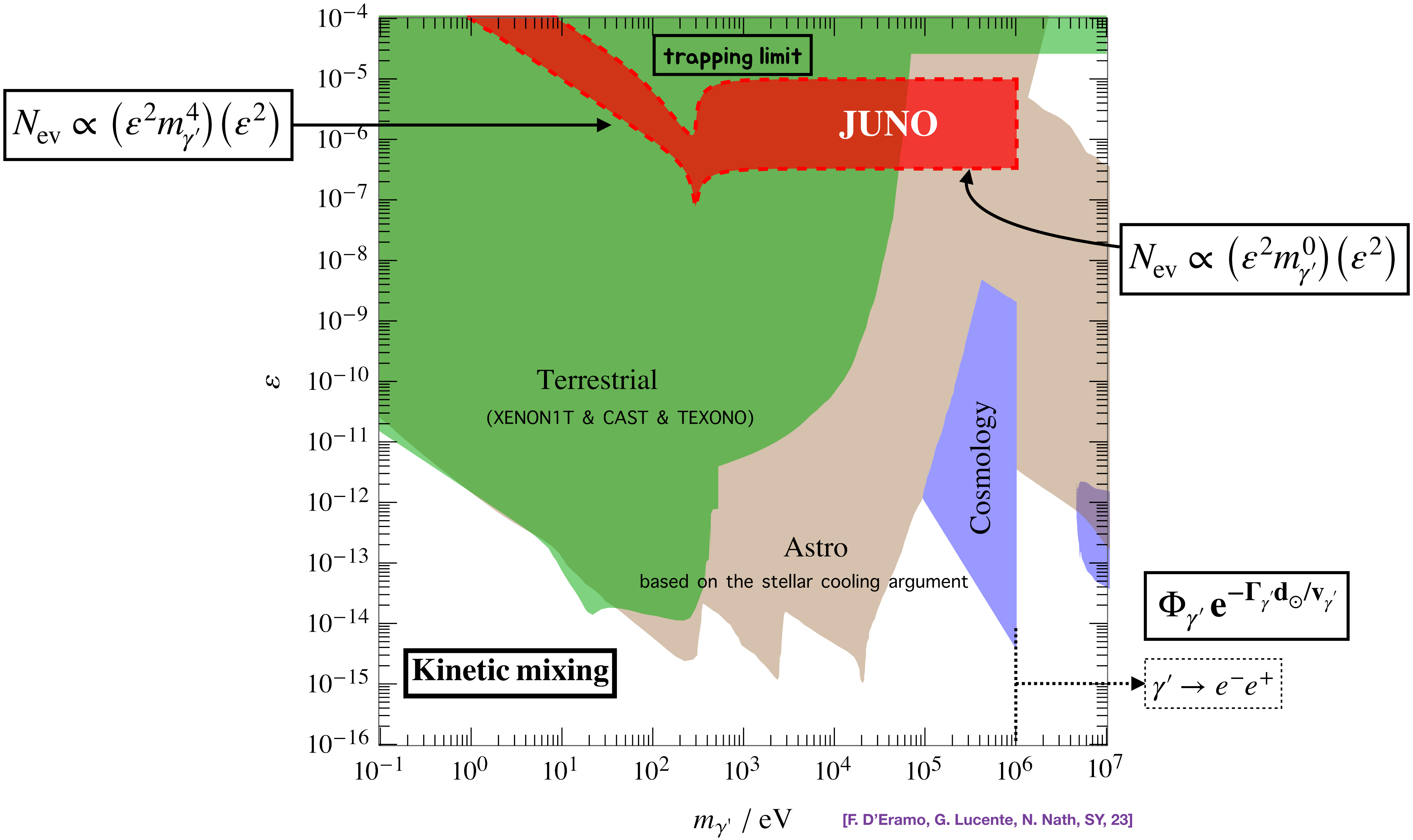
Detection rate



[F. D'Eramo, G. Lucente, N. Nath, SY, 23]

$N_{ev} < N_{ev}^{lim} = 97$ @ 90 % C.L.

JUNO constraint on Kinetic mixing



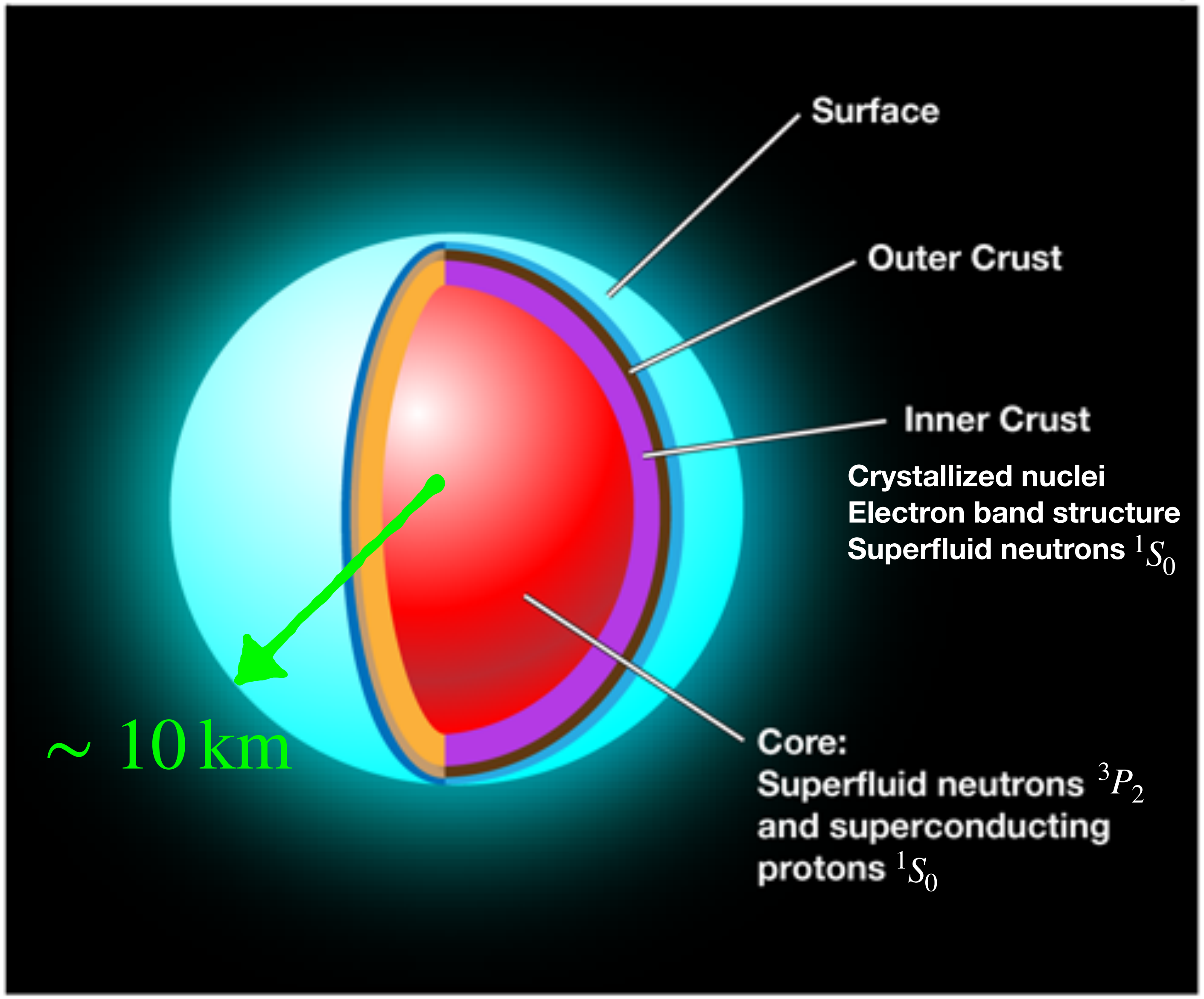
[F. D'Eramo, G. Lucente, N. Nath, SY, 23]

Conclusion

- Stellar objects as a good way to probe BSM signals
  - e.g., stellar evolution path as a conventional approach
  - With involving ν detection, supernovae & the Sun are relevant objects
- Core-collapse supernovae
  - Time duration of ν signals for stellar cooling argument
  - Improved by energetic & delayed ν signal, if $X \to \nu\bar{\nu}$
- Solar nuclear reaction
  - 5.49 MeV production via the deuterium fusion reaction
  - can be probed by terrestrial ν detectors
  - sensitive to the solar interior condition (any BSM impact?)

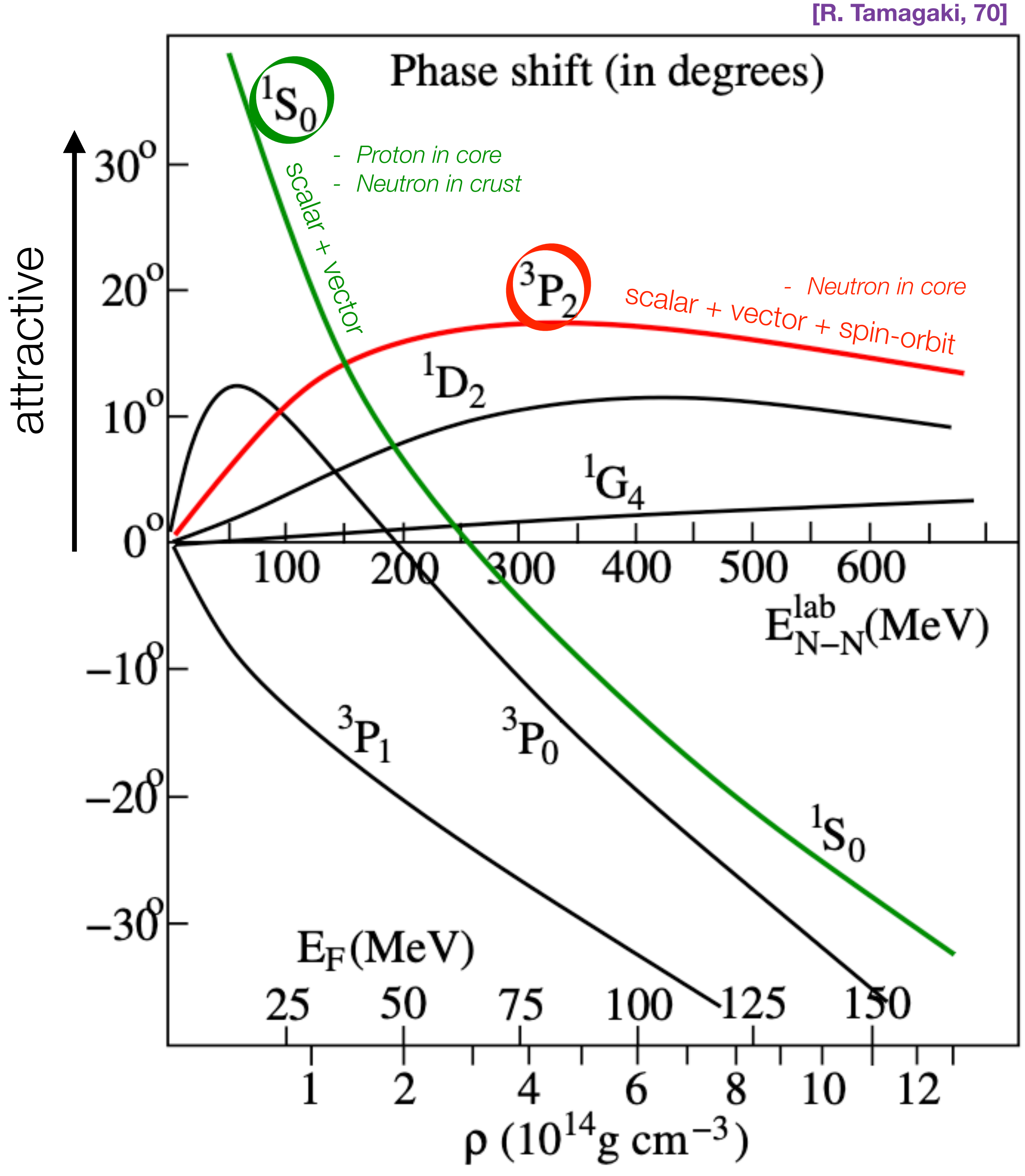
Back up

Neutron stars

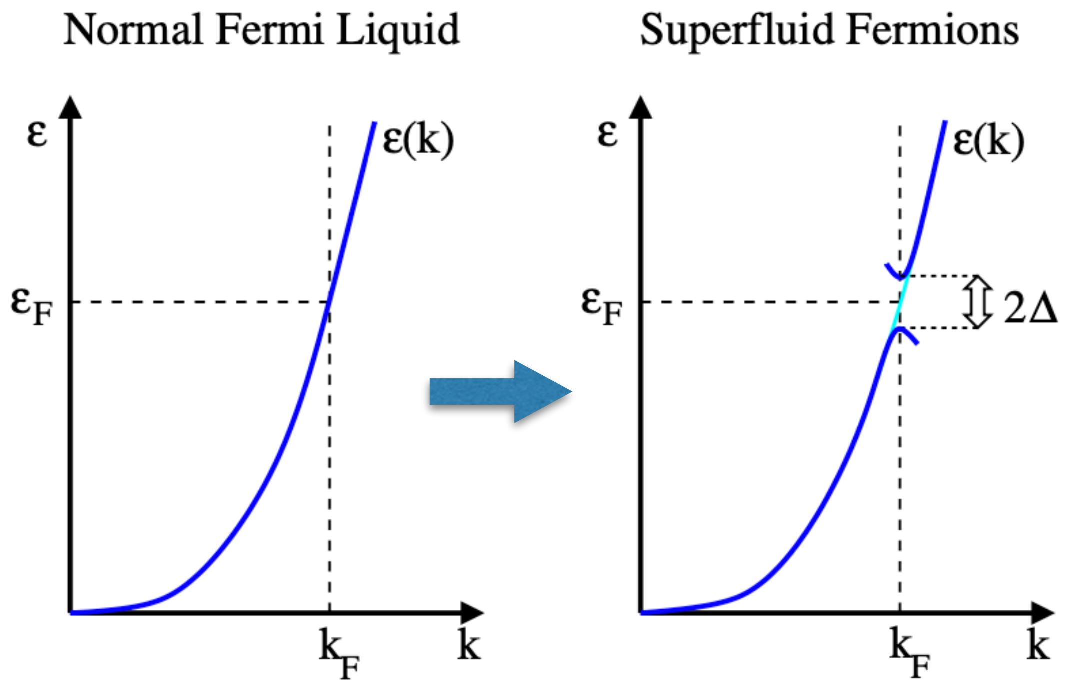


- Remnant core of a massive star after a type-II supernovae explosion
  - Neutrino signal for a few seconds (SN1987A)
  - Lack of prompt gamma-ray signal
- Young neutron star cooling
  - Neutrino (volume) emission
  - Photon (surface) emission $> 10^{4\text{-}5}\,\mathrm{yr}$
  - Superfluidity?
- Etc.
  - Strong magnetic field
  - Gravitational source?

Superfluidity of nucleon



- N-N interaction by exchange of meson
  - Scalar (attractive)
  - Vector (repulsive)
  - Spin-orbit (attractive or repulsive)
- Below T_c, nucleons form the pairs
- Appearance of a gap in the momentum spectrum

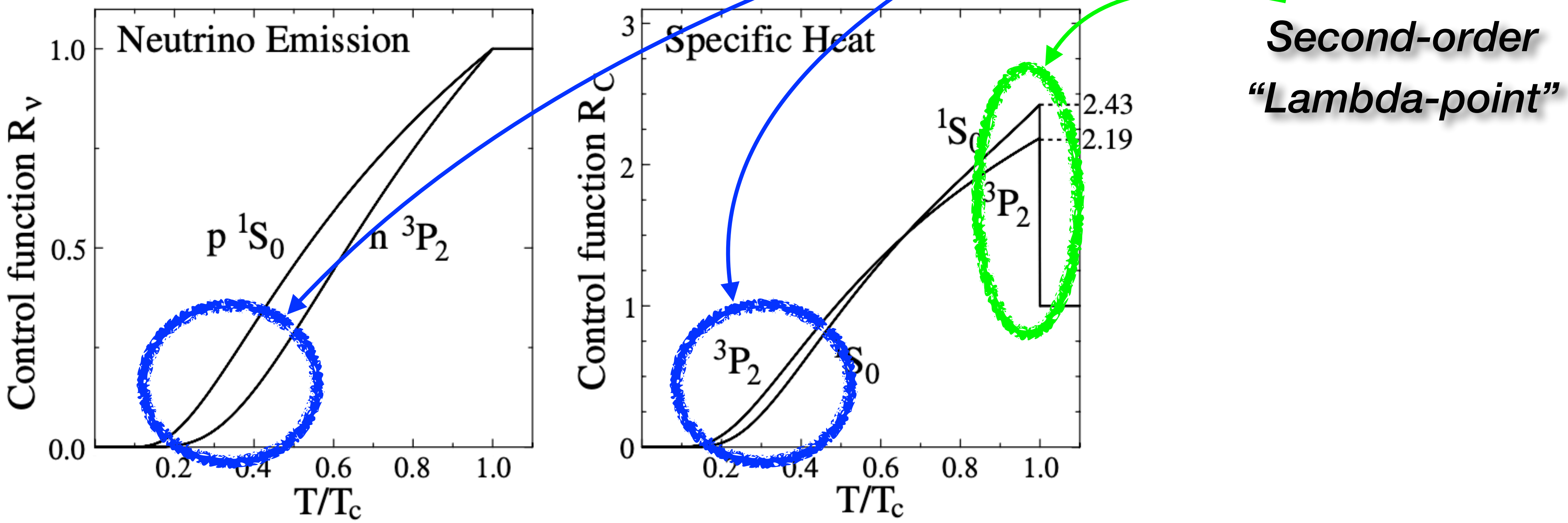


Effect of pairing for NS cooling

1. Suppression of the emissivity
2. Modification of the heat capacity

phase space suppression $e^{-2\Delta/T}$

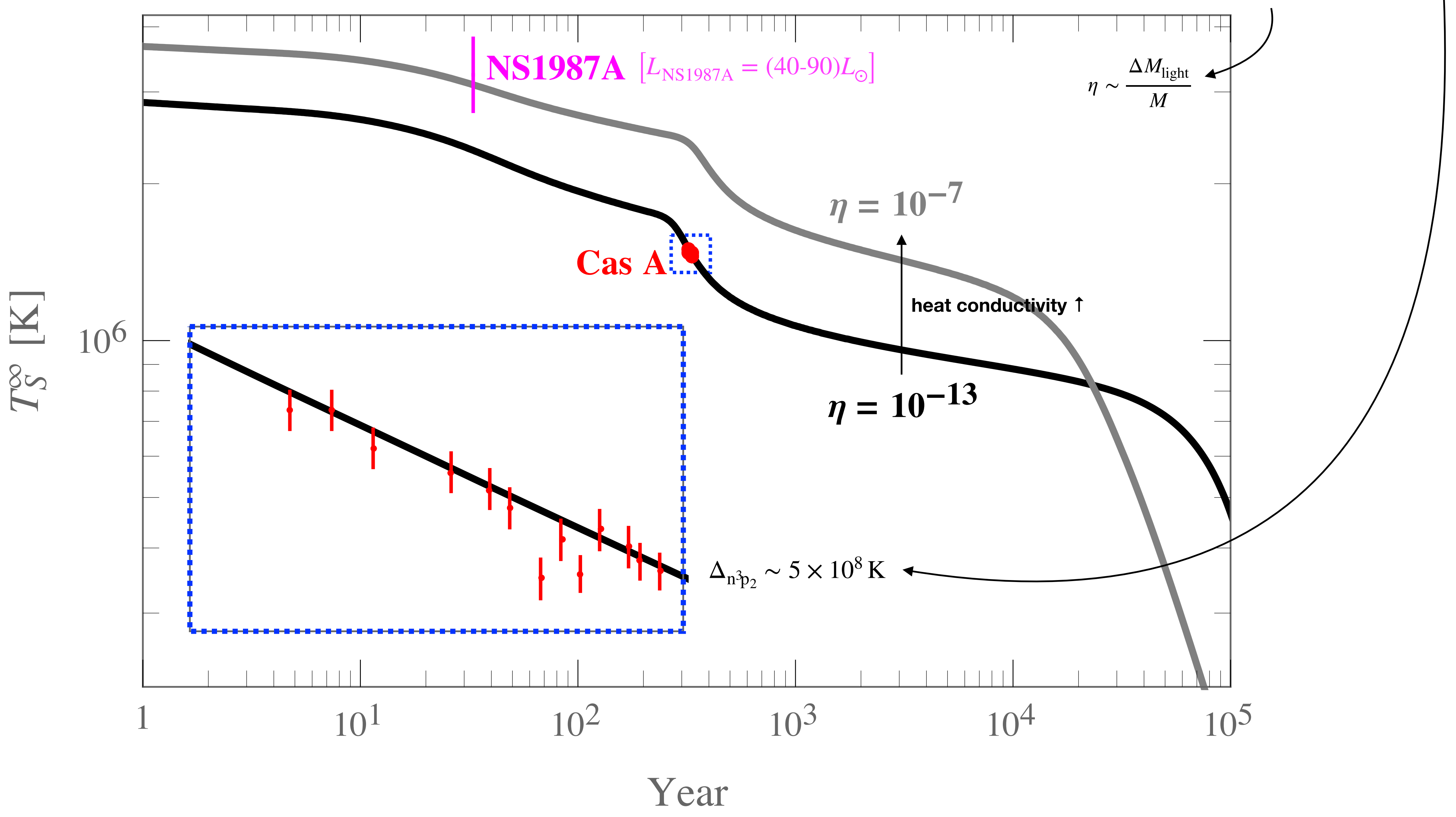
$\epsilon \to R_\nu \epsilon$ $\quad$ $c_v \to R_C c_v$



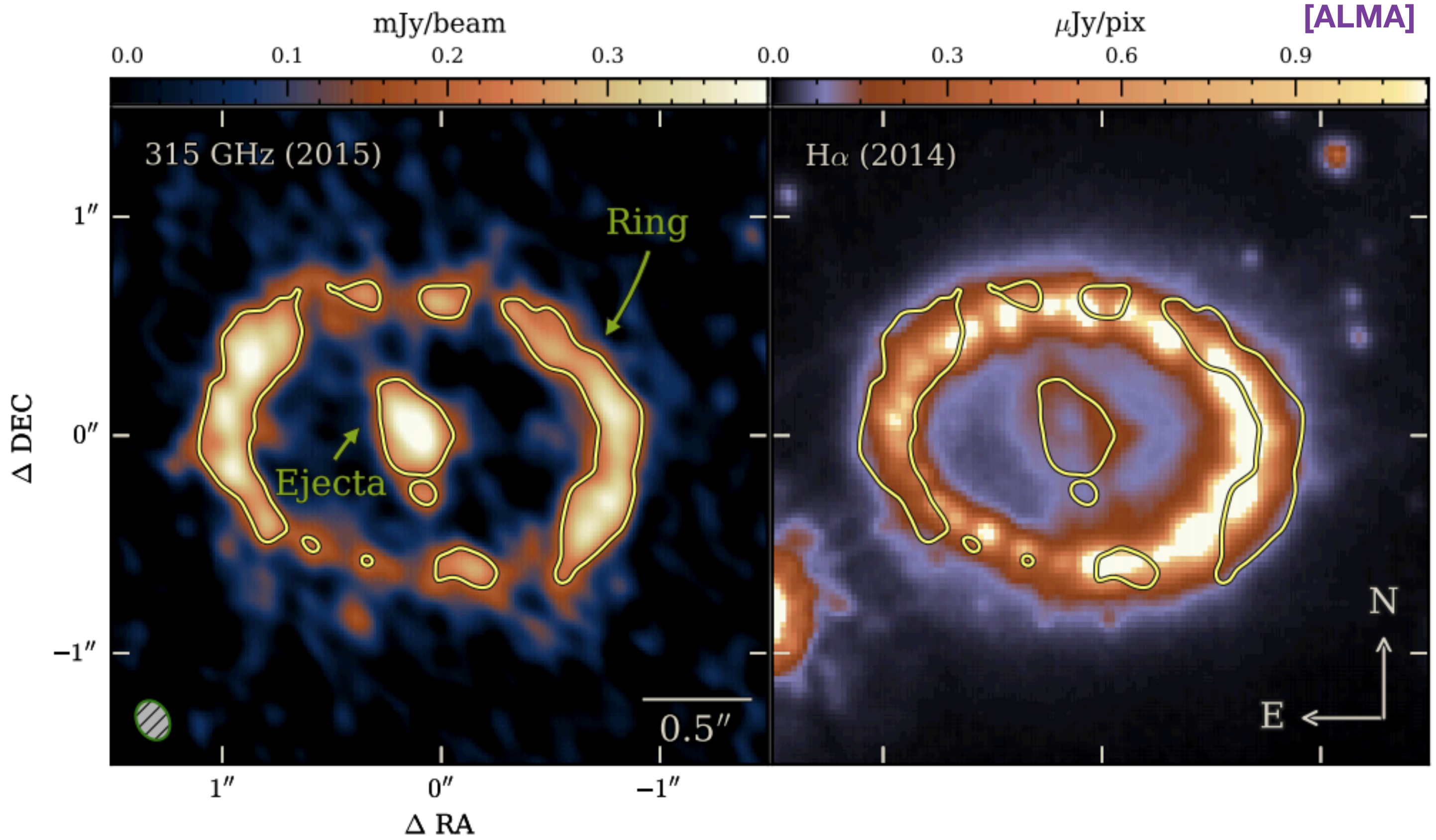
3. Triggering of the "pair breaking and formation" (PBF) emission

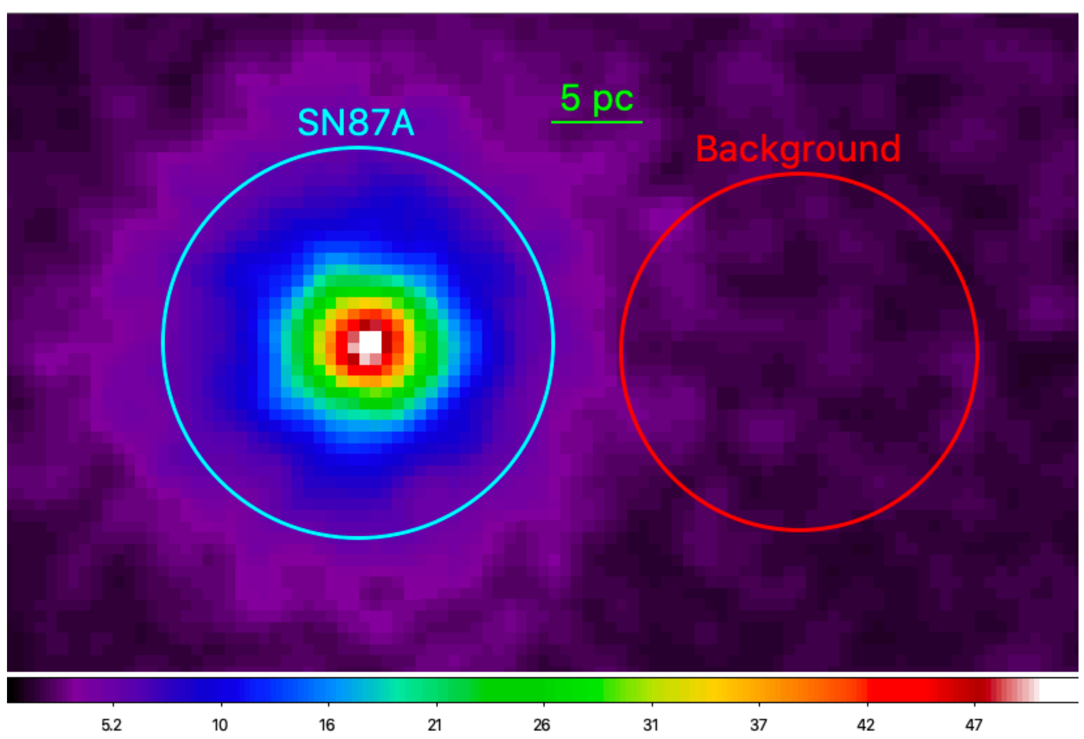
Minimal cooling scenario

◉ Model parameters?
- pairing gap: width, height, position?
- amount of light elements



Remnant of SN1987A?

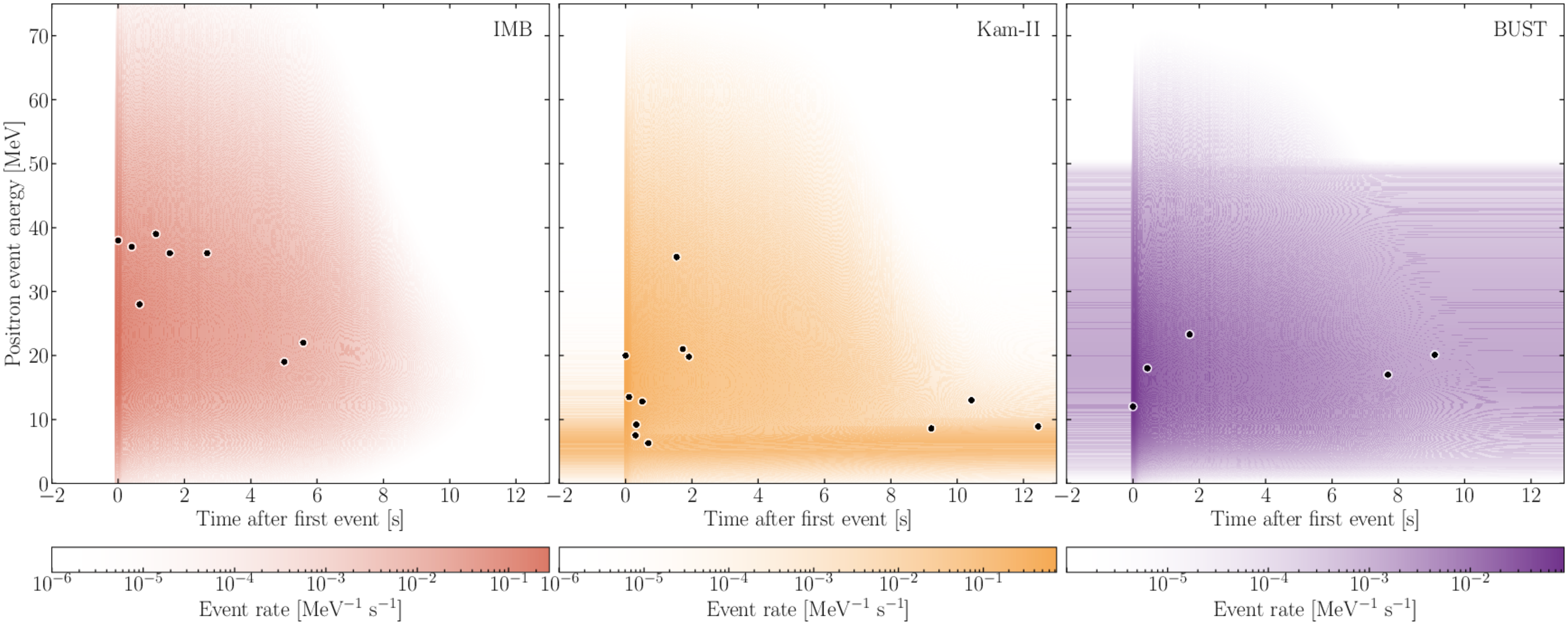




- Presence of a compact source in the remnant is strongly indicated.
  - a neutron star rather than a black hole is likely to have formed
  - small remnant core mass + small fallback mass due to high explosion energy

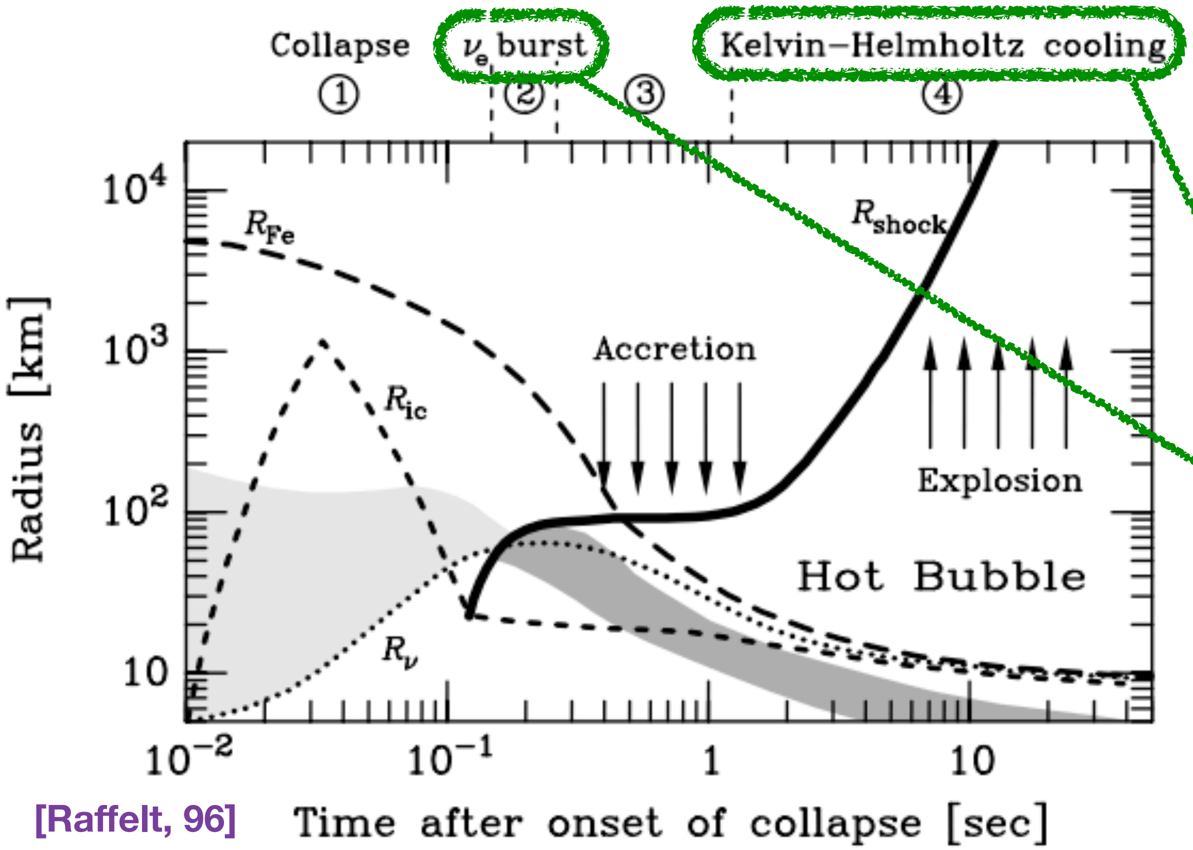
→ ***'NS1987A'***

SN1987A simulation fit



[D.F.G. Fiorillo, M. Heinlein, H.-T. Janka, G. Raffelt, E. Vitagliano and R. Bollig, 23]

Neutrino driven explosion

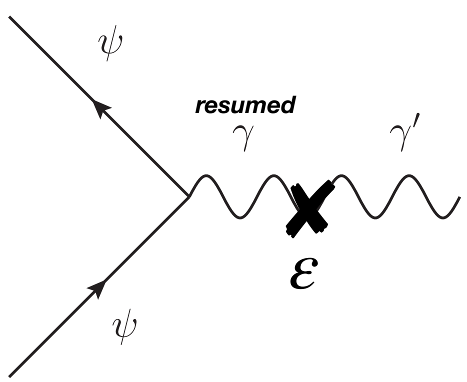


[Raffelt, 96]

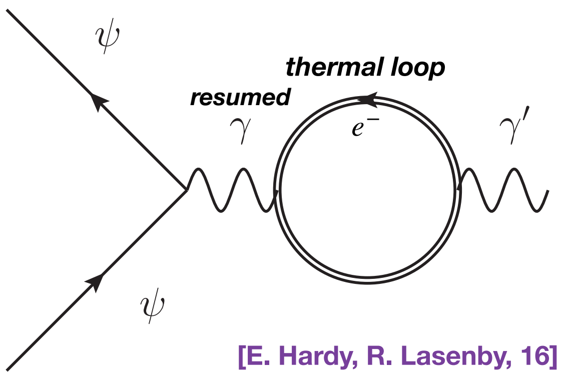
- The “***delayed explosion scenario***”
  - Thermal relaxation of the proto-neutron star as the source of neutrino emission for $\mathcal{O}(10)$ sec
  - the energy deposition of the neutrino flow causes the explosion ($\mathcal{O}(1)$% of total neutrino bulk energy)

Effective coupling of γ' in medium

✓ Kinetic mixing (ε)



✓ Plasma mixing



[E. Hardy, R. Lasenby, 16]
[C. S. Shin, D. Hong, SY, 20]

$$\mathscr{L}_{\varepsilon}^{\text{eff}} = \varepsilon e \frac{m_{\gamma'}^2}{m_{\gamma'}^2 - \pi_{\text{T,L}}} J_{\text{EM}}^{\mu} A'_{\mu}$$

$$\mathscr{L}_{\Pi}^{\text{eff}} = - e' q'_e \frac{\pi_{\text{T,L}}}{m_{\gamma'}^2 - \pi_{\text{T,L}}} J_{\text{EM}}^{\mu} A'_{\mu}$$

- q : EM charge
- q' : dark $U(1)$ charge

$\mu_e \ll T \;\&\; T \ll m_e$

$$\text{Re}\left[\pi_{\text{T}}\right] = \omega_{\text{pl}}^2$$

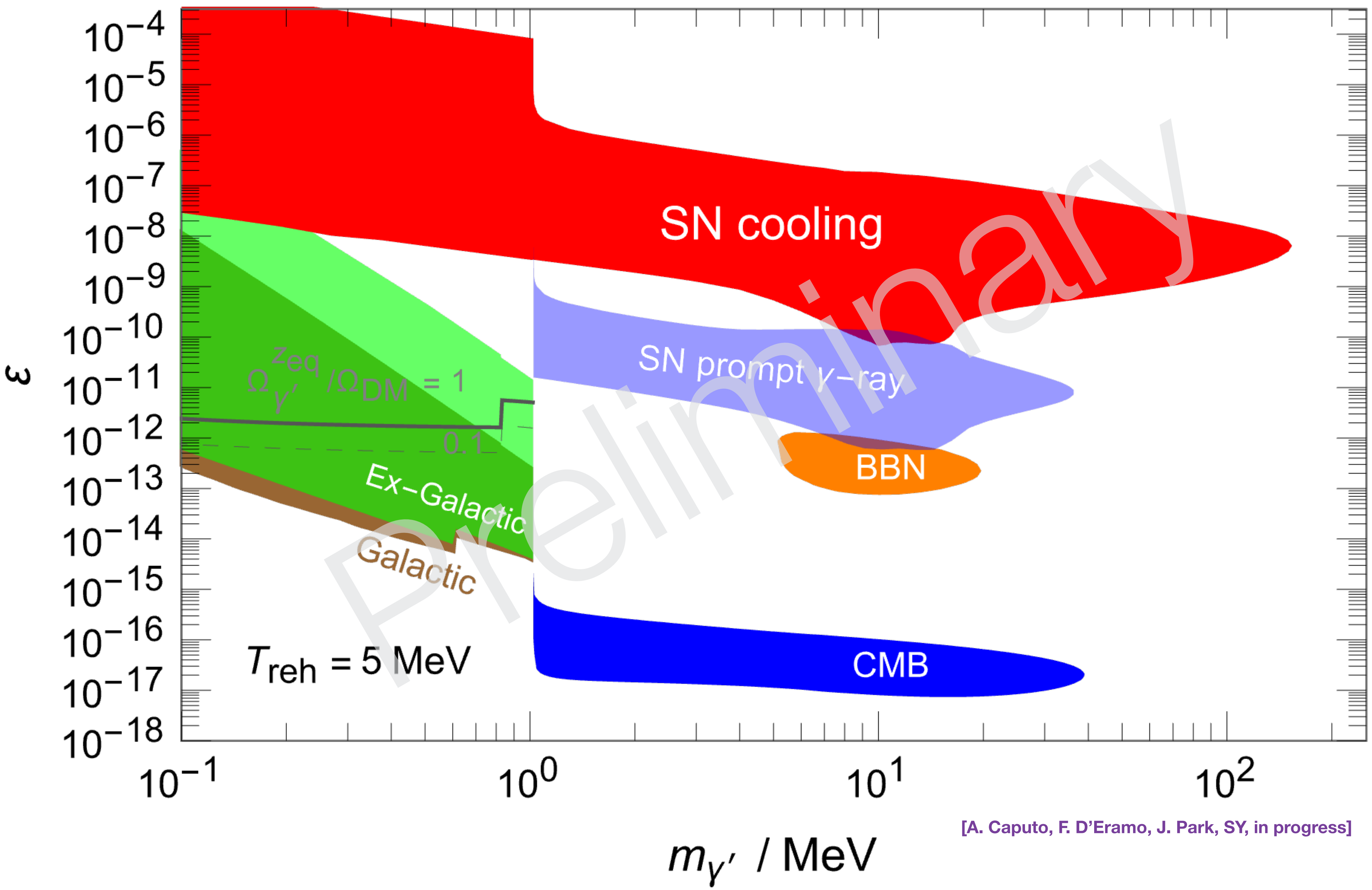
$$\text{Re}\left[\pi_{\text{L}}\right] = \frac{m_{\gamma'}^2}{\omega^2}\omega_{\text{pl}}^2$$

In the solar medium

$$\omega_{\text{pl}} = 0.3\,\text{keV}\left(\frac{n_e}{n_\odot}\right)^{1/2}$$

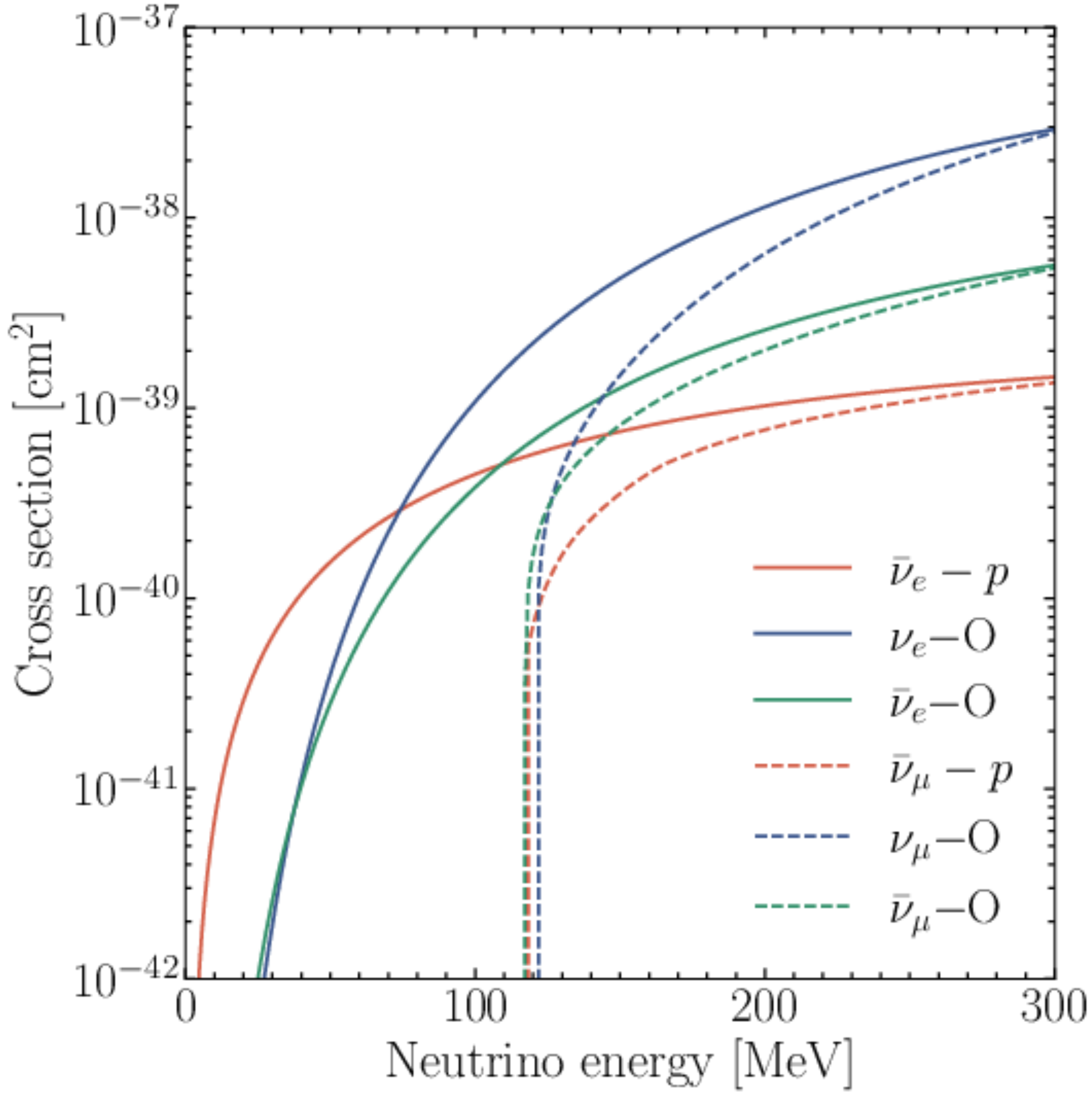
$$\text{Im}\,\pi_{\text{T}} = -\,\omega\left(1 - e^{-\omega/T}\right)\frac{8\pi\alpha^2}{3m_e^2}n_e$$

Model-independent Bound on DP



[A. Caputo, F. D'Eramo, J. Park, SY, in progress]

ν-σ in a water Cherenkov detector



[D. Fiorillo, G. Raffelt, E. Vitagliano, 23]

Multipole radiation

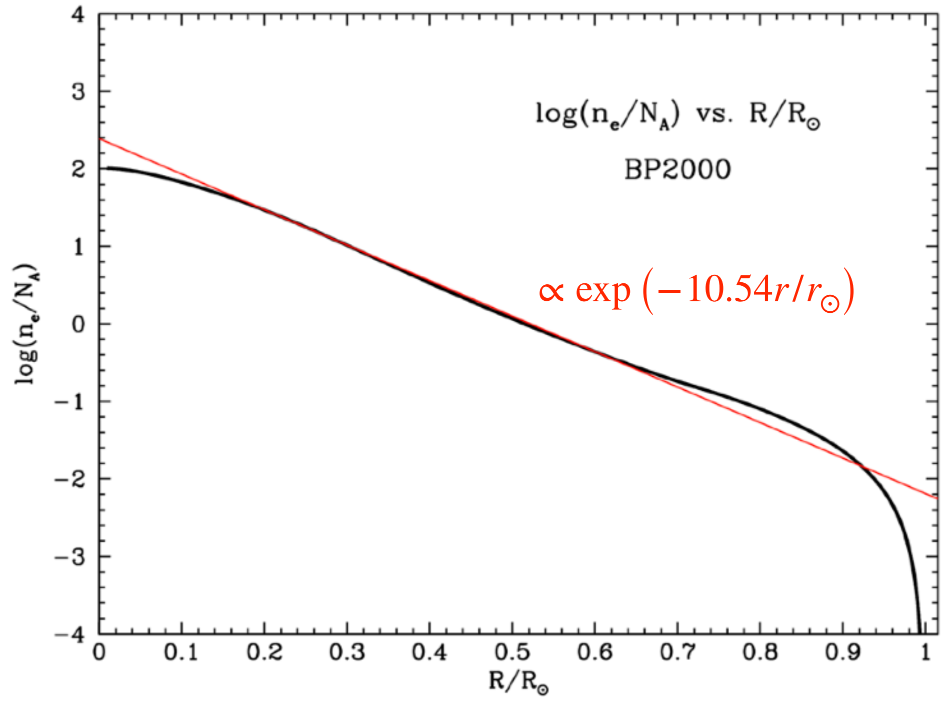
- Velocity as a good order parameter in expansion for scatterings

- Dipole radiation
  - Leading order
  - $\mathscr{M}_{\text{dipole}} \propto (e_{\text{eff}}^{N_1} - e_{\text{eff}}^{N_2})$ of ***isospin breaking*** combination
  - Center of charges ≠ Center of masses

- Quadrupole radiation
  - Next-leading order
  - $\mathscr{M}_{\text{quadrupole}}$ as $\left|\frac{\mathscr{M}_{\text{quadrupole}}}{\mathscr{M}_{\text{dipole}}}\right| \sim v_N$
  - Center of charges = Center of masses

Trapping limit

[J. N. Bahcall et al., 01]



- Absorption into the solar medium?
  - scatterings with charged particles (e.g., electrons) $\propto n_e$
  - due to exponential decrease in r, mostly occurs near core
  - optical depth $\tau_{\gamma'} = \int_0^{r_\odot} dr\, n_e \sigma v_{\gamma'}$ ☞ $\Phi_{\gamma'} e^{-\tau_{\gamma'}}$

- Conversion $\gamma' \to \gamma$?
  - resonant at $m_{\gamma'}^2 = \omega_{\rm pl}^2(r) \propto n_e$ (only for $m_{\gamma'} < 0.3\,{\rm keV}$)
  - $P^{\rm res}_{\gamma' \leftrightarrow \gamma} = 1 - \exp\left(-\pi \gamma_{\rm ad}/2\right)$ (second term as level-crossing probability)
  - adiabaticity $\gamma_{\rm ad} = \dfrac{\Delta_{\rm osc}}{|d\theta/dr|}$

Expected # of solar γ' event signals

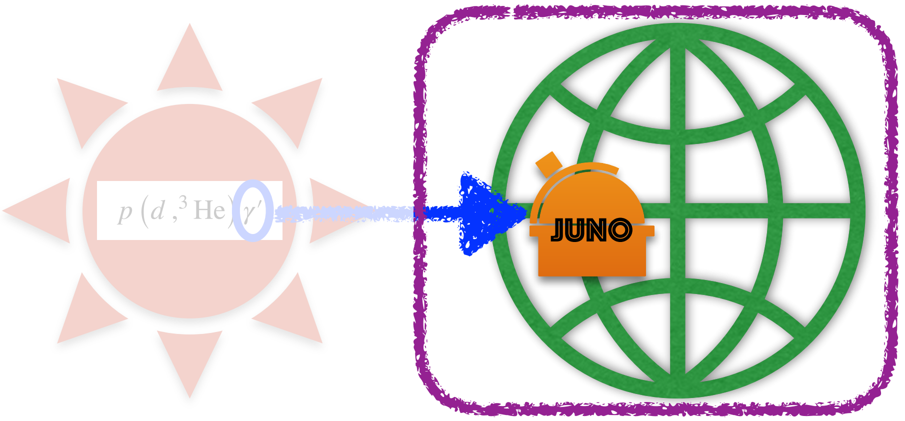
- Net flux reduced by decays
  - visible (e^-e^+ & 3γ) + invisible ($\nu\bar{\nu}$)

10 years

$$N_{\rm ev} = \sum_{i={\rm T,L}} \left[\Phi_{\gamma'0} e^{-\tau_i}\right]_i e^{-\Gamma_{\gamma'} d_\odot / v_{\gamma'}} \left[N_e \sigma_i + \frac{V_f \Gamma_{\gamma'} \, {\rm Br}\left(\gamma' \to {\rm vis}\right)}{v_{\gamma'}}\right] t$$

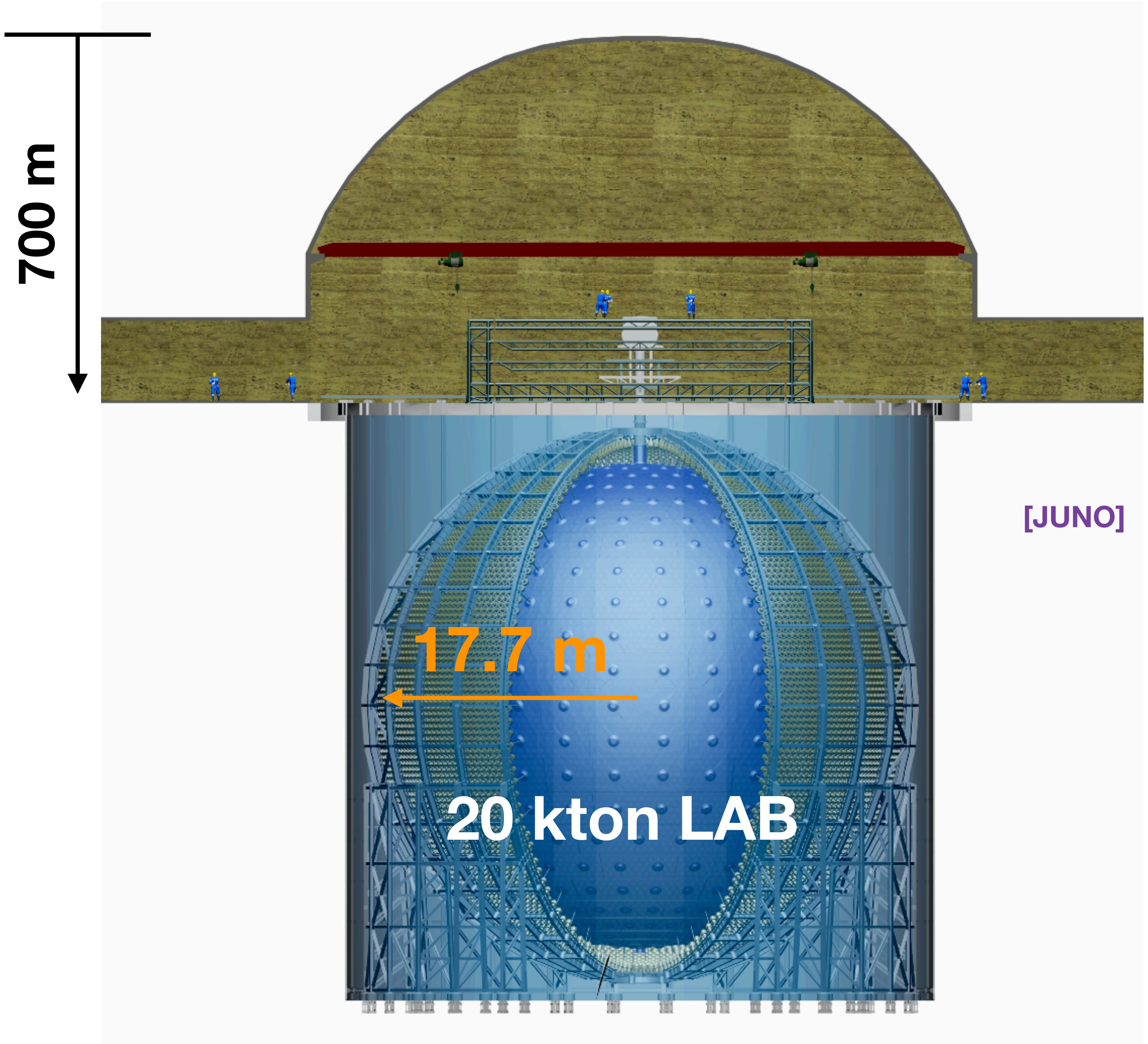
- Solar 5.49 MeV γ' flux on Earth
  - isovector deuterium fusion reaction
  - free-streaming out at $g_e < \mathcal{O}(10^{-7})$ i.e., $\tau_i \ll 1$ $[\, g_e = \varepsilon e - e' q'_e \,]$

- Detection at JUNO
  - Compton-like scatterings (first)
  - in-flight decays into visible channels (second)
  - fiducial volume V_f of 16.2 kton for $E > 5\,{\rm MeV}$
  - the total # of electrons $N_e \simeq 5.5 \times 10^{33}$



JUNO detector

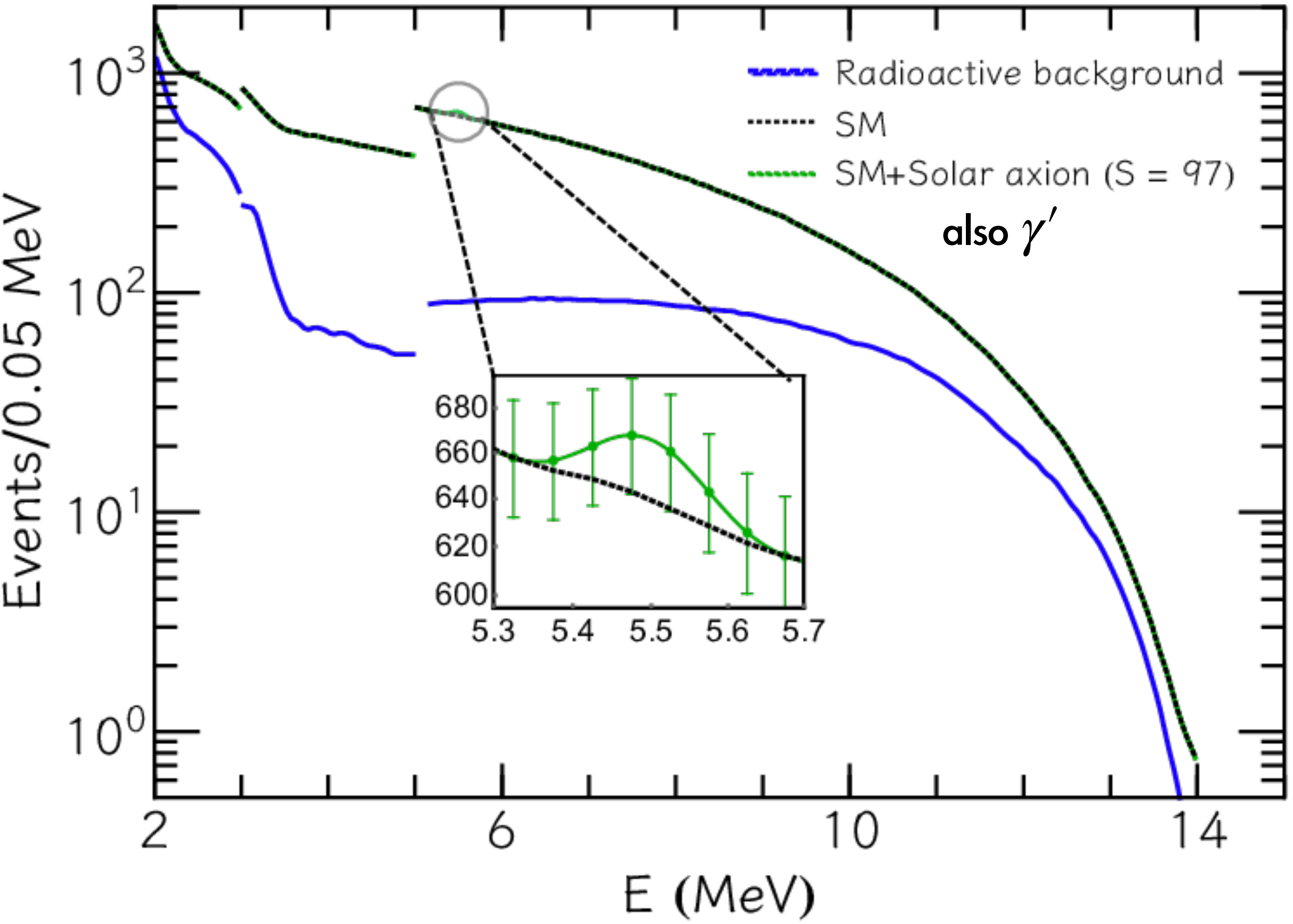
Jiangmen Underground Neutrino Observatory

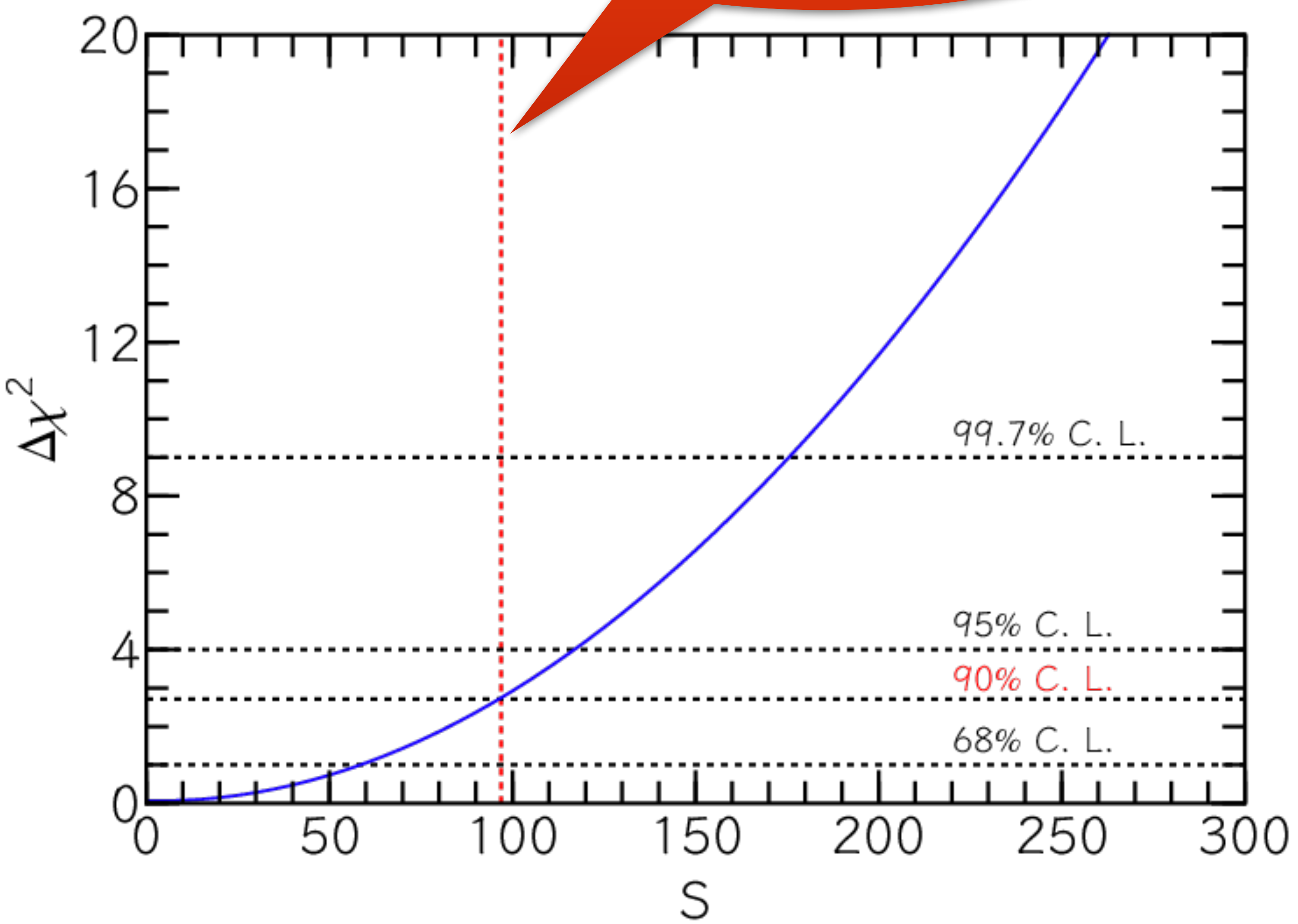


- Multi-purpose liquid scintillator detector
  - aims to determine neutrino mass ordering & precision measurement of PMNS parameters
  - SN, atmospheric, geo-ν
  - also exotic (astroparticle) searches
- Better sensitivity
  - than the previous ones such as Borexino
  - energy threshold $2\,\mathrm{MeV}$
  - under construction, begin taking data 2023

Fitting procedure

$N_{\rm ev}^{\rm lim} = 97$ at 90 % C.L.





[G. Lucente et al., 22]

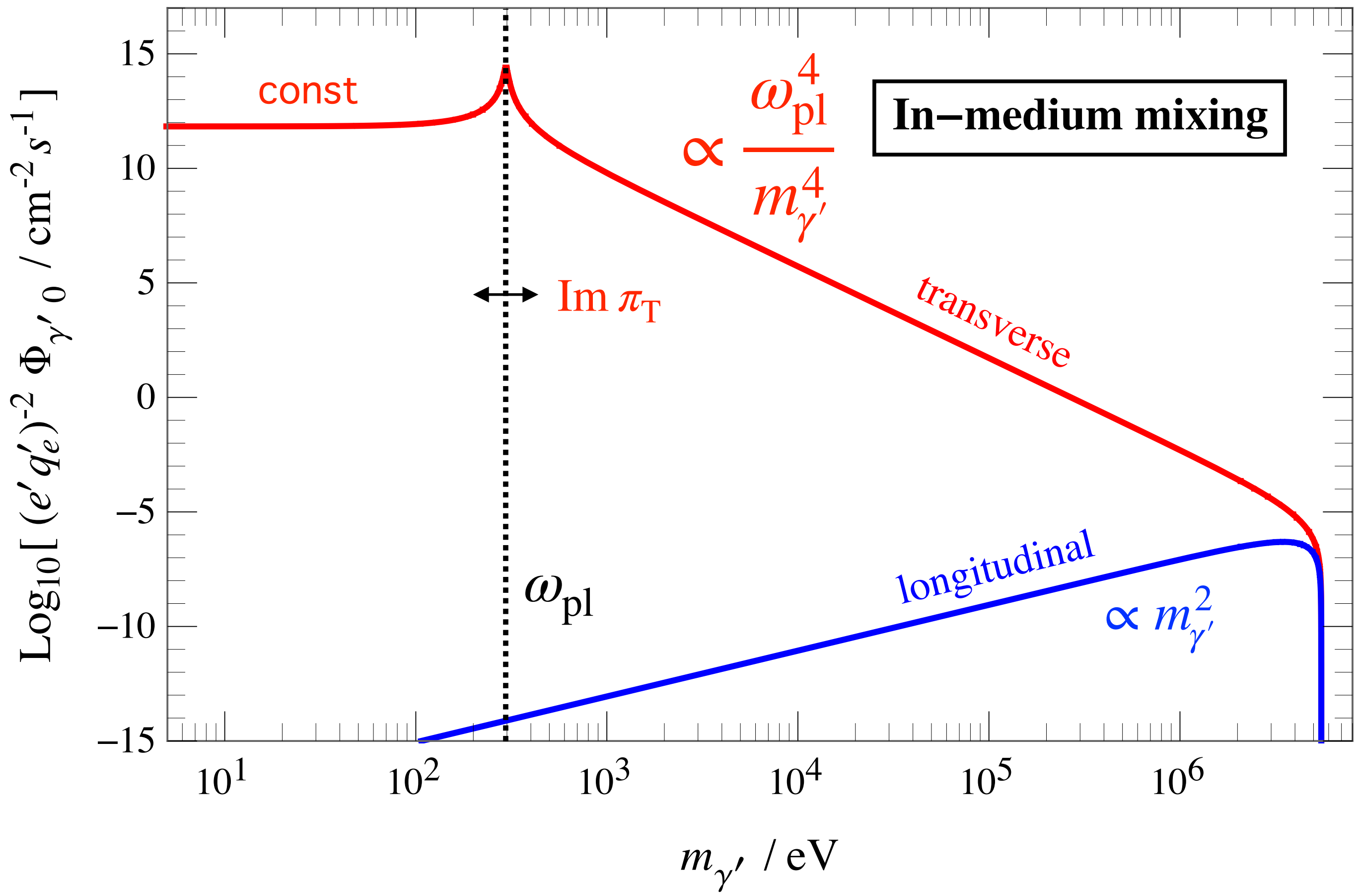
Solar $\mathbf{5.49\,MeV}$ γ' flux (In-medium)

$1.7 \times 10^{38}\,\mathrm{s}^{-1}$ **for** $p\,(d\,,^3\mathrm{He})\,\gamma$

γ-γ' **mixing**

$$\left[\Phi_{\gamma'}\right]_{\mathrm{T,L}} = \frac{1}{4\pi d_\odot^2}\phi_\gamma \frac{k^3}{\omega^3}\left|\frac{e'q_e'}{eq_e}\frac{\pi_{\mathrm{T,L}}}{m_{\gamma'}^2 - \pi_{\mathrm{T,L}}}\right|^2 \times \left[\frac{m_{\gamma'}^2}{\omega^2}\right]_{\mathrm{L}}$$

(current conservation)



Numerical Procedure: χ^2 is defined as

$$\chi^2 = 2 \times \sum_{i=1}^{240} \left(N^i_{pre} - N^i_{obs} + N^i_{obs} \times \log \frac{N^i_{obs}}{N^i_{pre}} \right) + \left(\frac{\varepsilon_s}{\sigma_s} \right)^2 + \left(\frac{\varepsilon_b}{\sigma_b} \right)^2 ,$$

$$N^i_{pre} = (1 + \varepsilon_s) \times T_i + (1 + \varepsilon_b) \times B_i + \frac{S}{\sqrt{2\pi}\sigma} \times e^{-\frac{(E_{5.5} - E_i)^2}{2\sigma^2}} ,$$

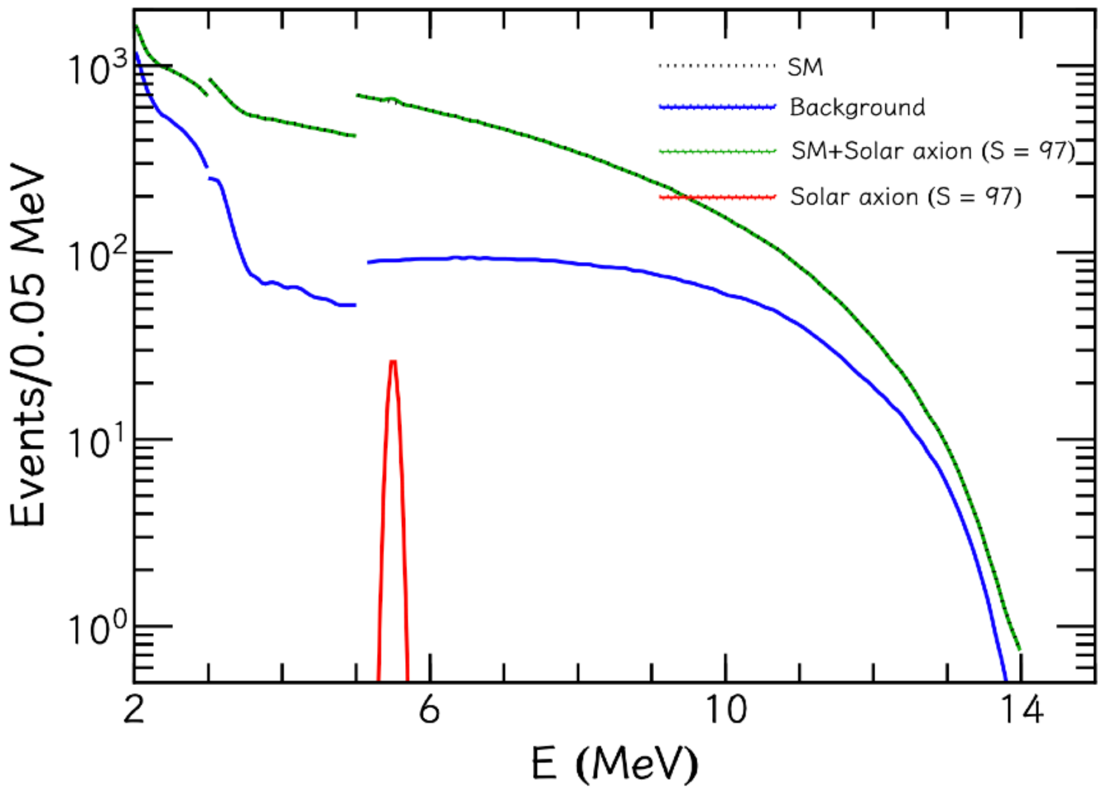
Total signal

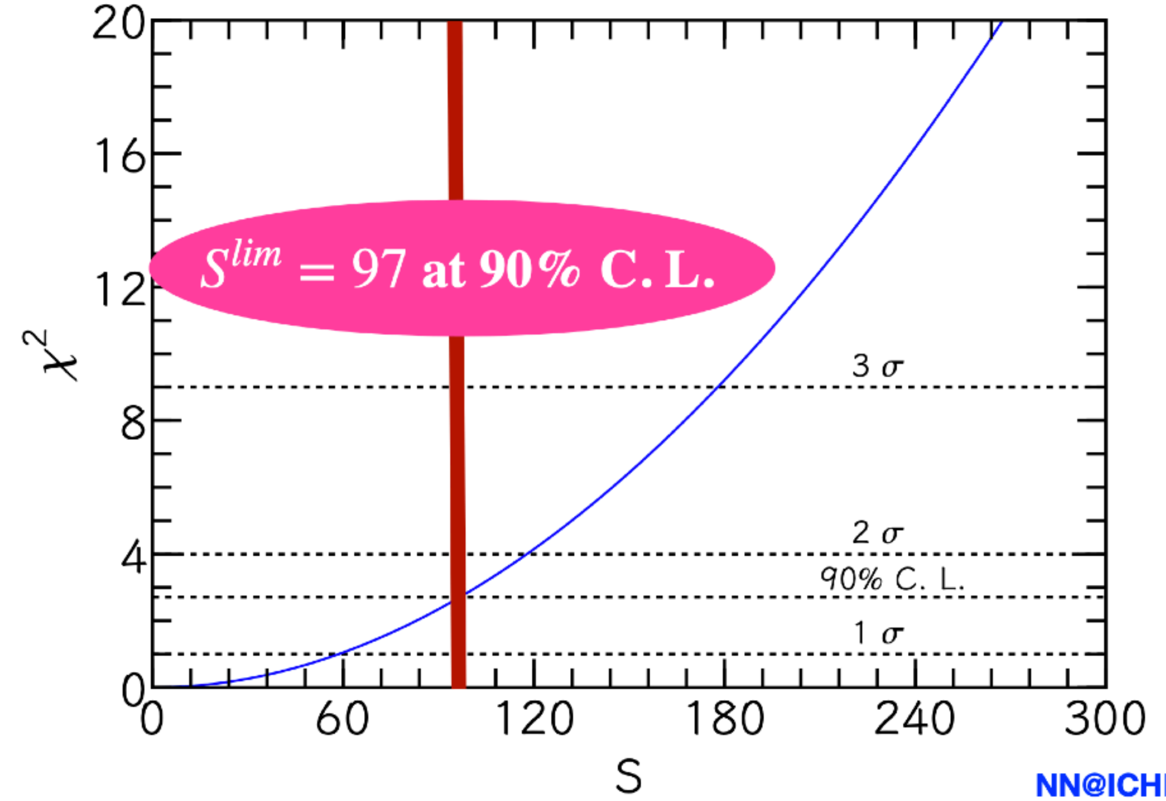
Total Background

Axion peak Intensity

Nuisance parameters

Signal and background Uncertainties, 5% & 15 %





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[N. Nath's slide]