@ DESY theory workshop

Dark Gauge Bosons in Neutron Stars

Seokhoon Yun
(University of Padova)

"*Cooling of young neutron stars and dark gauge bosons*," Deog Ki Hong (PNU), Chang Sub Shin (CNU), ***SY***
PRD 103 (2021) 12, 123031, arXiv:2012.05427

"*Dark gauge boson production from neutron stars via nucleon-nucleon bremsstrahlung*," Chang Sub Shin (CNU), ***SY***
JHEP 02 (2022) 133, arXiv:2110.03362

Work in progress, Chang Sub Shin (CNU), ***SY***

Outline

01 **Introduction**

- Effective theory of dark gauge boson (in a medium)

02 **Standard NS cooling**

- SN1987A
- (NS1987A)
- Rapid cooling of Cas A
  - superfluidity?

Stellar cooling argument

03 **γ' cooling** [Dark photon / $U(1)_{\mathrm{B-L}}$

- NN-bremsstrahlung
- (Compton pionic)
- Cooper pairing

04 **Constraints on dark gauge bosons**

05 **Conclusion**

Effective theory of Dark gauge boson

- Chiral perturbation theory framework
  - Hadronic interactions
- Thermal field theory framework
  - Plasma effect : mixing & screening
- Two benchmarks : Dark photon & $U(1)_{\mathrm{B-L}}$

Dark $U(1)$ gauge boson

- ◉ Effective γ' couplings at $\mu > \Lambda_{\text{QCD}}$ - *perturbative QCD*

$$\mathscr{L} = \underset{\text{EM field strength}}{-\frac{1}{4}F_{\mu\nu}F^{\mu\nu}} \underset{\text{DP field strength}}{-\frac{1}{4}X_{\mu\nu}X^{\mu\nu}} + \underset{\text{kinetic mixing}}{\frac{\varepsilon}{2}F_{\mu\nu}X^{\mu\nu}} \underset{\gamma'\text{ mass}}{-\frac{1}{2}m_{\gamma'}^2 X_\mu X^\mu} + \underset{\text{EM current}}{eA_\mu J^\mu_{\text{EM}}} + \underset{\substack{\gamma'\text{ current}\\ \text{- quark}\\ \text{- lepton}}}{e'A'_\mu J'^\mu}$$

- ◉ Effective γ' couplings at $\mu < \Lambda_{\text{QCD}}$?
  - ✓ Chiral perturbation theory (ChPT) with hadronic resonances (e.g., nucleons and mesons)
- ◉ Effective γ' couplings in a medium?
  - ✓ Thermal field theory ☞ plasma effect

Hadronic interactions

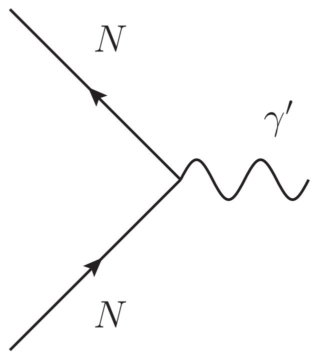
- ◉ Basic principle in ChPT?

  ➡ Matching currents with the same symmetry properties

- ◉ γ' couplings to hadrons from $e'A'_\mu J'^\mu$ $\boxed{J'_\mu = \sum_i q'_i \bar{\psi}_i \gamma_\mu \psi_i}$

[Kroll-Ruderman, 1954]

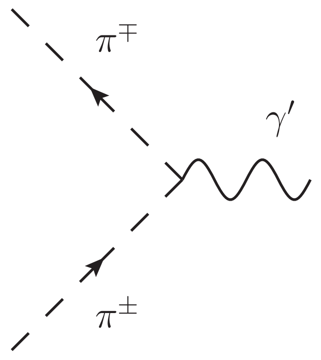
- Nucleon currents



$$e'A'_\mu \sum_N q'_N \bar{N} \gamma^\mu N$$

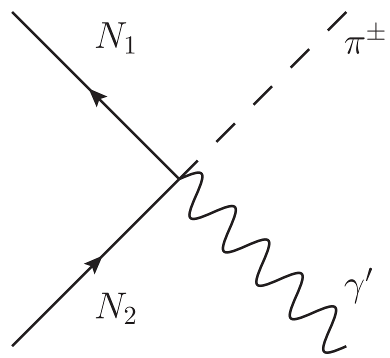
$q'_p = 2q'_u + q'_d \quad q'_n = q'_u + 2q'_d$

- Pion currents



$$e'A'_\mu \boxed{\left(q'_p - q'_n\right)} i\pi^- \overleftrightarrow{\partial^\mu} \pi^+$$

- N+Pion currents



$$-ie'A'_\mu \boxed{\left(q'_p - q'_n\right)} \frac{g_A}{f_\pi} \left[\pi^+ \bar{p} \gamma^\mu \gamma^5 n - \pi^- \bar{n} \gamma^\mu \gamma^5 p\right]$$

Isospin breaking

★ What is effective couplings in a dense medium?

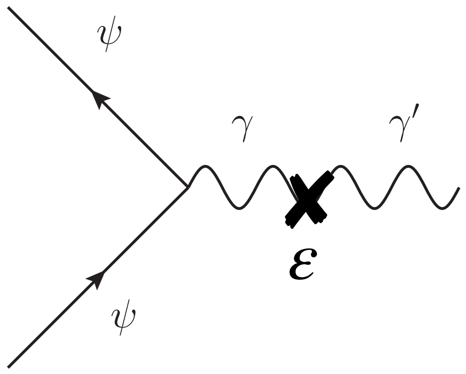
$\left(q'_p \,\&\, q'_n\right)$

Effective coupling of γ' in medium

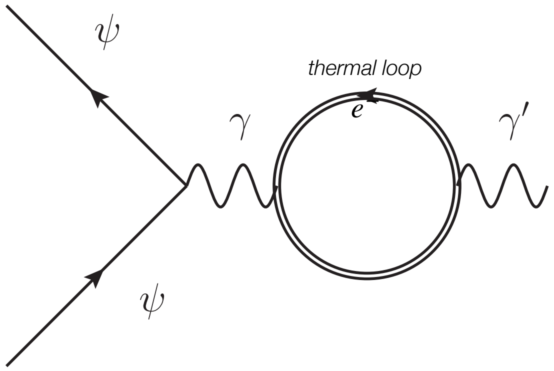
[E. Hardy, R. Lasenby, 16]

[C. S. Shin, D. Hong, SY, 20]

- Kinetic mixing (ε)



- Plasma mixing



$$\boxed{J^\mu_\psi = \bar{\psi}\gamma^\mu\psi}$$

$$\mathscr{M} = e^\psi_{\rm eff} J^\mu_\psi \epsilon'_\mu$$

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

$$e^\psi_{\rm eff} = e'\left(q'_\psi + q'_e q_\psi\right) + \left(\varepsilon e - q'_e e'\right) q_\psi \frac{m^2_{\gamma'}}{m^2_{\gamma'} - \pi_{\rm T,L}}$$

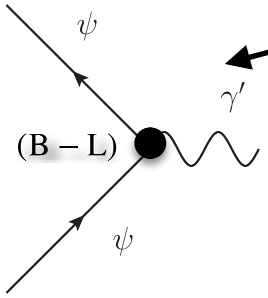
$\left(\mathbf{e q_\psi A_\mu + e' q'_\psi A'_\mu}\right)$

- If the gauge boson field basis coupling to ψ is consistent with that of the electron $\left(\mathbf{e q_e A_\mu + e' q'_e A'_\mu}\right)$ (i.e., ***plasmon***),
  - the first term vanishes, i.e. $q'_\psi + q'_e q_\psi = 0$
  - plasma suppression ($\propto \omega_{\rm pl}^{-2}$) when $\omega_{\rm pl} > m_{\gamma'}$

$U(1)_{\mathrm{B-L}}$ gauge boson

$$\mathscr{L} = -\underbrace{\frac{1}{4}F_{\mu\nu}F^{\mu\nu}}_{\text{EM field strength}} - \underbrace{\frac{1}{4}X_{\mu\nu}X^{\mu\nu}}_{\text{DP field strength}} - \underbrace{\frac{1}{2}m_{\gamma'}^2X_\mu X^\mu}_{\gamma' \text{ mass}} + \underbrace{eA_\mu J^\mu_{\mathrm{EM}}}_{\text{EM current}} + \underbrace{e'A'_\mu J^\mu_{\mathrm{B-L}}}_{\text{B-L current}}$$

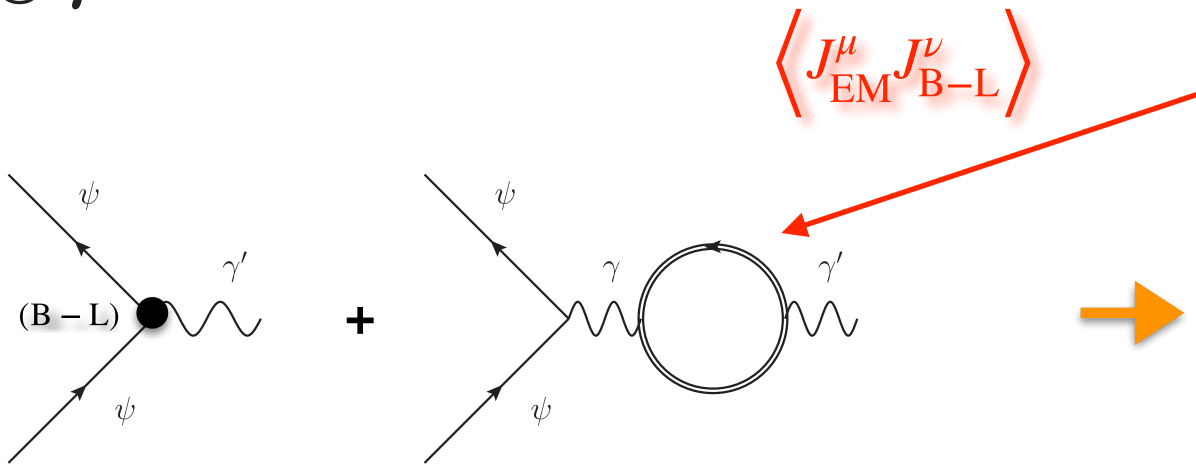
- γ' emission



$U(1)_{\rm B-L}$ gauge boson

$$\mathscr{L} = -\frac{1}{4}\underset{\text{EM field strength}}{F_{\mu\nu}F^{\mu\nu}} - \frac{1}{4}\underset{\text{DP field strength}}{X_{\mu\nu}X^{\mu\nu}} - \frac{1}{2}\underset{\gamma'\text{ mass}}{m^2_{\gamma'}X_\mu X^\mu} + \underbrace{\underset{\text{EM current}}{eA_\mu J^\mu_{\rm EM}} + \underset{\text{B-L current}}{e'A'_\mu J^\mu_{\rm B-L}}}_{☞\ \textbf{plasma mixing}}$$

- ◉ γ' emission



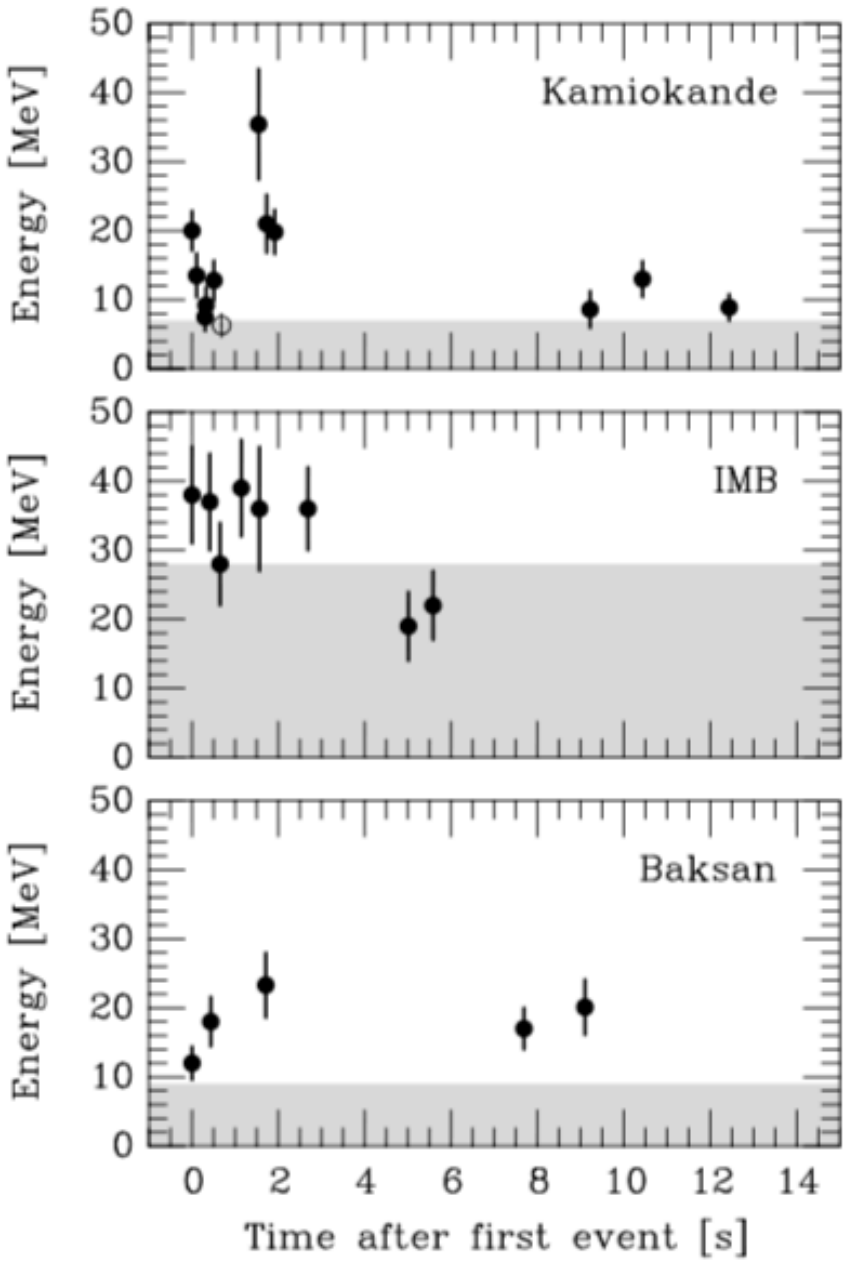
	$e^e_{\rm eff}$	$e^p_{\rm eff}$	$e^n_{\rm eff}$
$U(1)_{\rm DP}$	$-\varepsilon e\dfrac{m^2_{\gamma'}}{m^2_{\gamma'}-\pi_{\rm T,L}}$	$\varepsilon e\dfrac{m^2_{\gamma'}}{m^2_{\gamma'}-\pi_{\rm T,L}}$	n/a
$U(1)_{\rm B-L}$	$-e'\dfrac{m^2_{\gamma'}}{m^2_{\gamma'}-\pi_{\rm T,L}}$	$e'\dfrac{m^2_{\gamma'}}{m^2_{\gamma'}-\pi_{\rm T,L}}$	e'

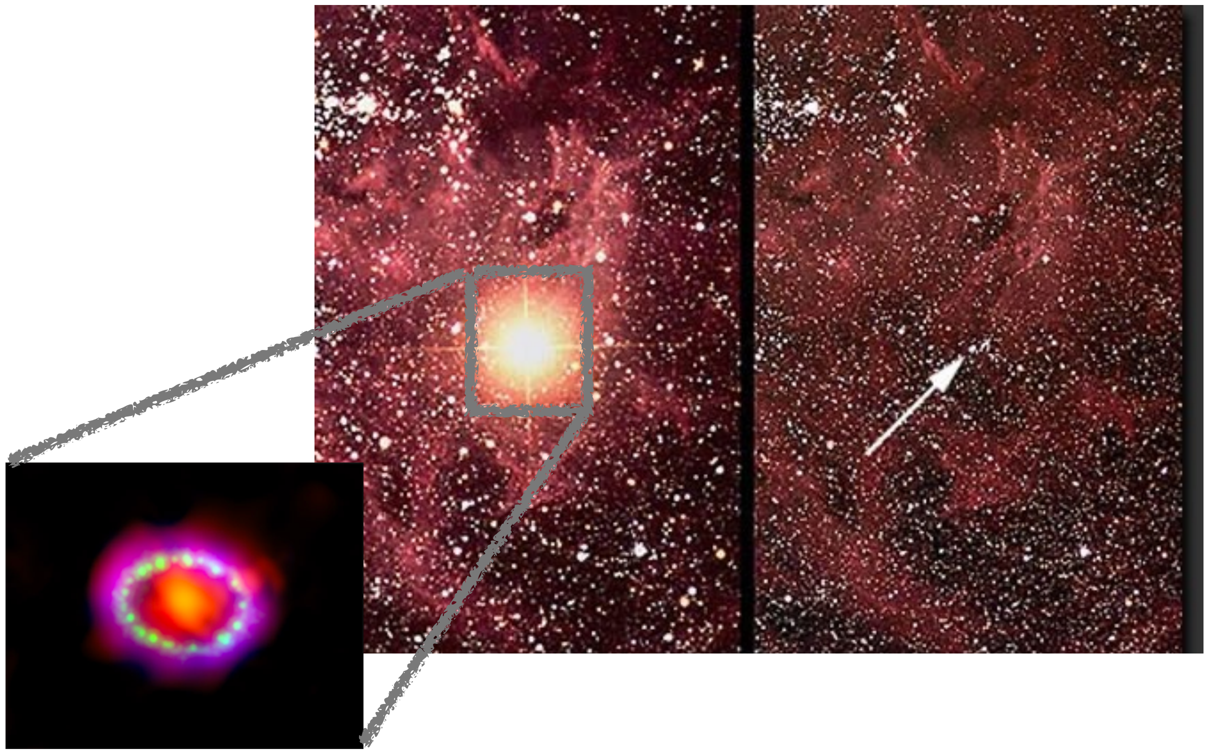
plasma mixing **direct coupling**

Core collapse Supernovae

- Core collapse + the delayed neutrino mechanism
- Supernova neutrino signal of SN1987A
- Reduction of time duration by novel particle emission

SN1987A





[Chandra, 17]

- The only direct observation of neutrinos occurred on 23 February 1987 when the blue supergiant Sanduleak–69 202 in the Large Magellanic Cloud exploded
- Time duration of SN neutrino flux ($\sim 10\,\mathrm{sec}$)

→ $$L_x \lesssim 3 \times 10^{52}\,\mathrm{erg\,s^{-1}}$$

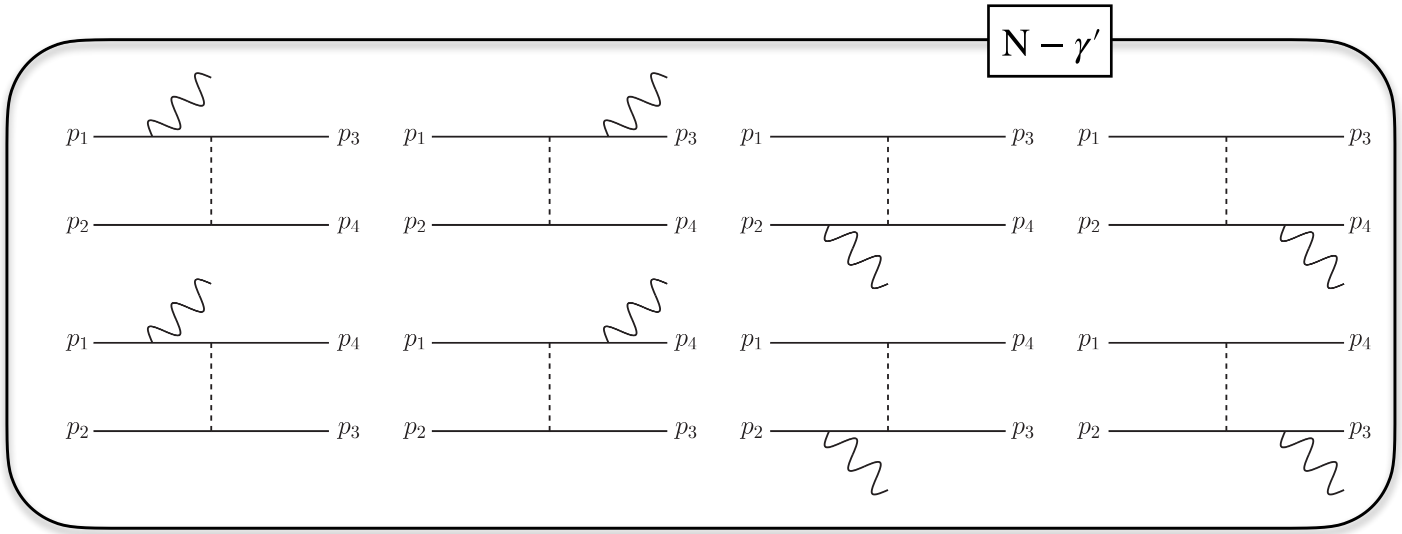
[Raffelt, 96]

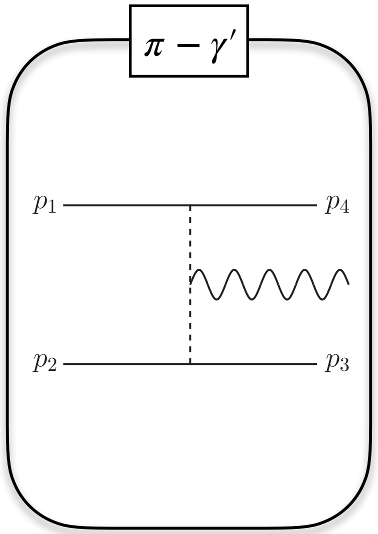
Nucleon-Nucleon Bremsstrahlung

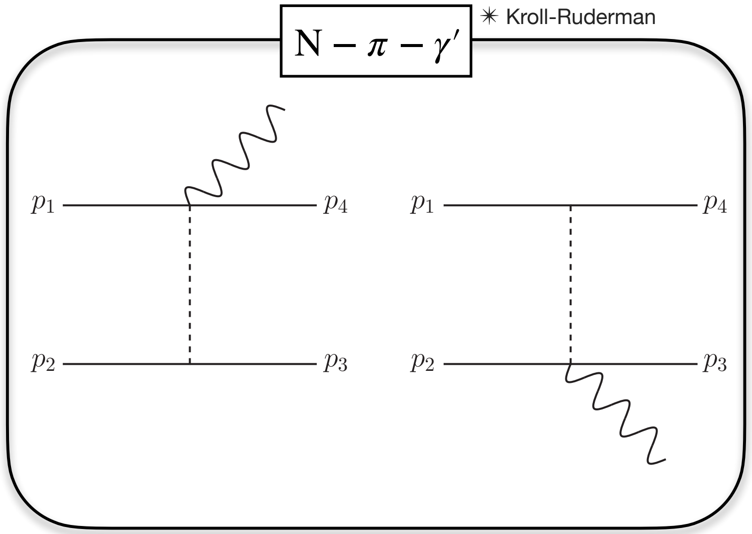
- Electrons in highly degenerate and relativistic limit
  - $p_F \sim 1\,\mathrm{fm}^{-1} \gg T \sim 10\,\mathrm{MeV}$
  - Pauli blocking makes processes associated with electrons (e.g., $e + \gamma \rightarrow e + \gamma'$) sub-dominant
- Nucleons in approximately non-degenerate and non-relativistic limit
  - N-N bremsstrahlung with mediators associated with strong interaction

N-π^- **scatterings @ Back up**

- Diagrams in one-pion-exchange approximation







✳ Kroll-Ruderman

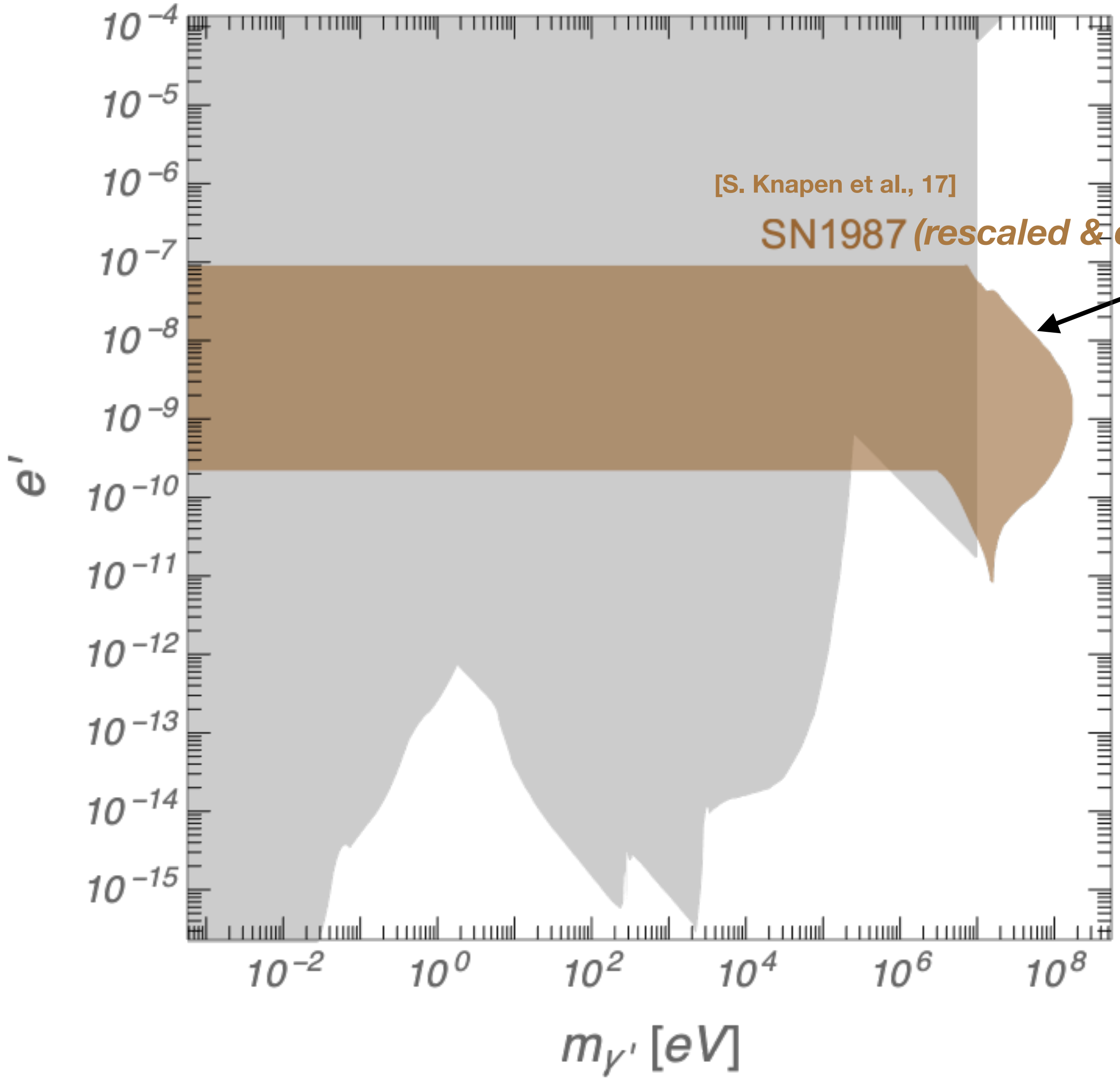
Multipole radiation

- 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 → $\boxed{\text{only for n–p bremsstrahlung}}$
  - Center of charges ≠ Center of masses

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

SN1987A bound on $U(1)_{\mathrm{B-L}}$



[J. H. Chang et al., 16] $m_{\gamma'} > 3\,\mathrm{MeV}$

✦ Dark photon

$$e^n_{\mathrm{eff}} = 0$$

$$e^p_{\mathrm{eff}} = \varepsilon e \frac{m^2_{\gamma'}}{m^2_{\gamma'} - \pi_{\mathrm{T,L}}}$$

→ Dipole

$m_{\gamma'} < 3\,\mathrm{MeV}$ [E. Rrapaj, S. Reddy, 16]

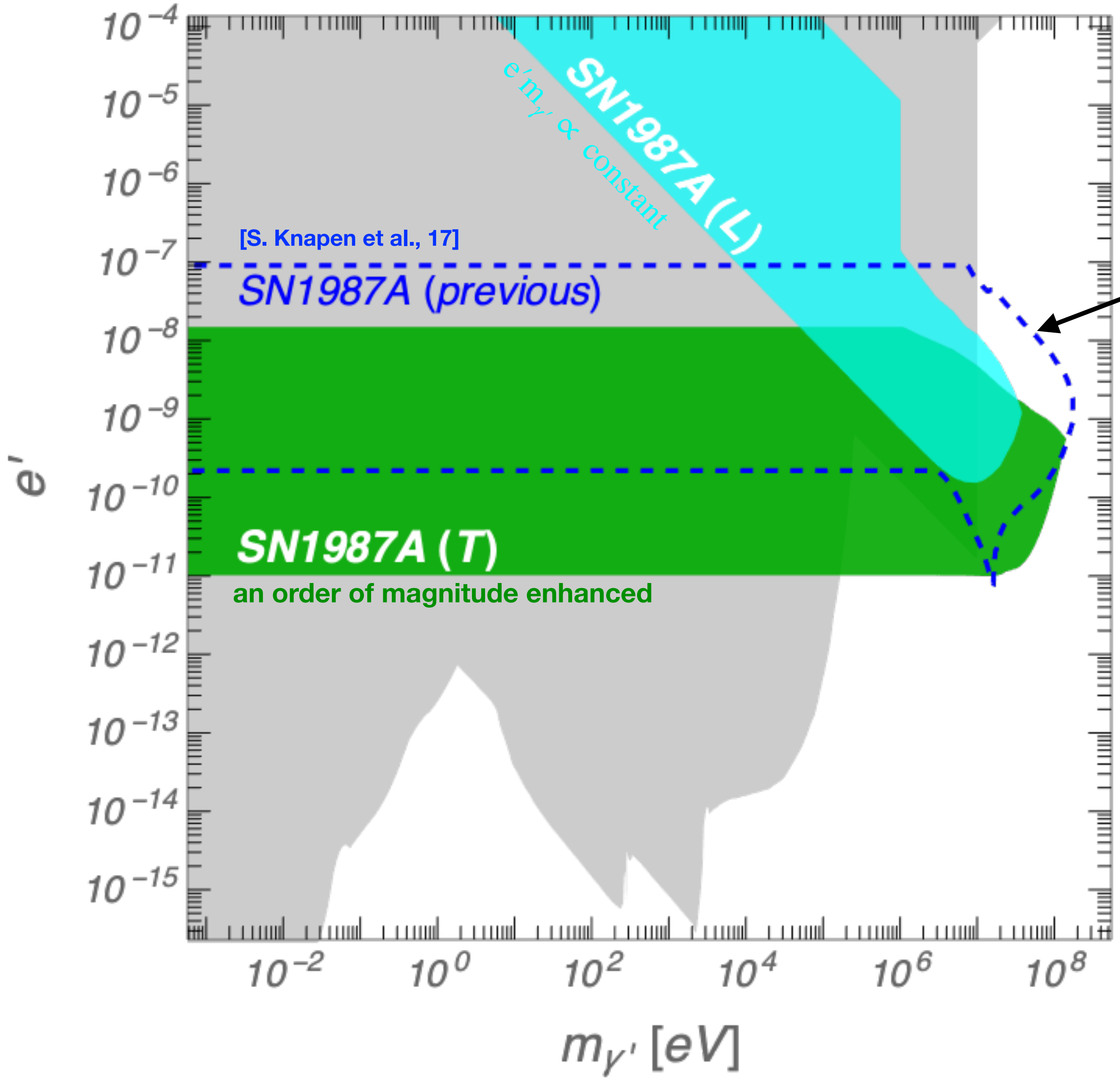
✦ $U(1)_{\mathrm{B}}$

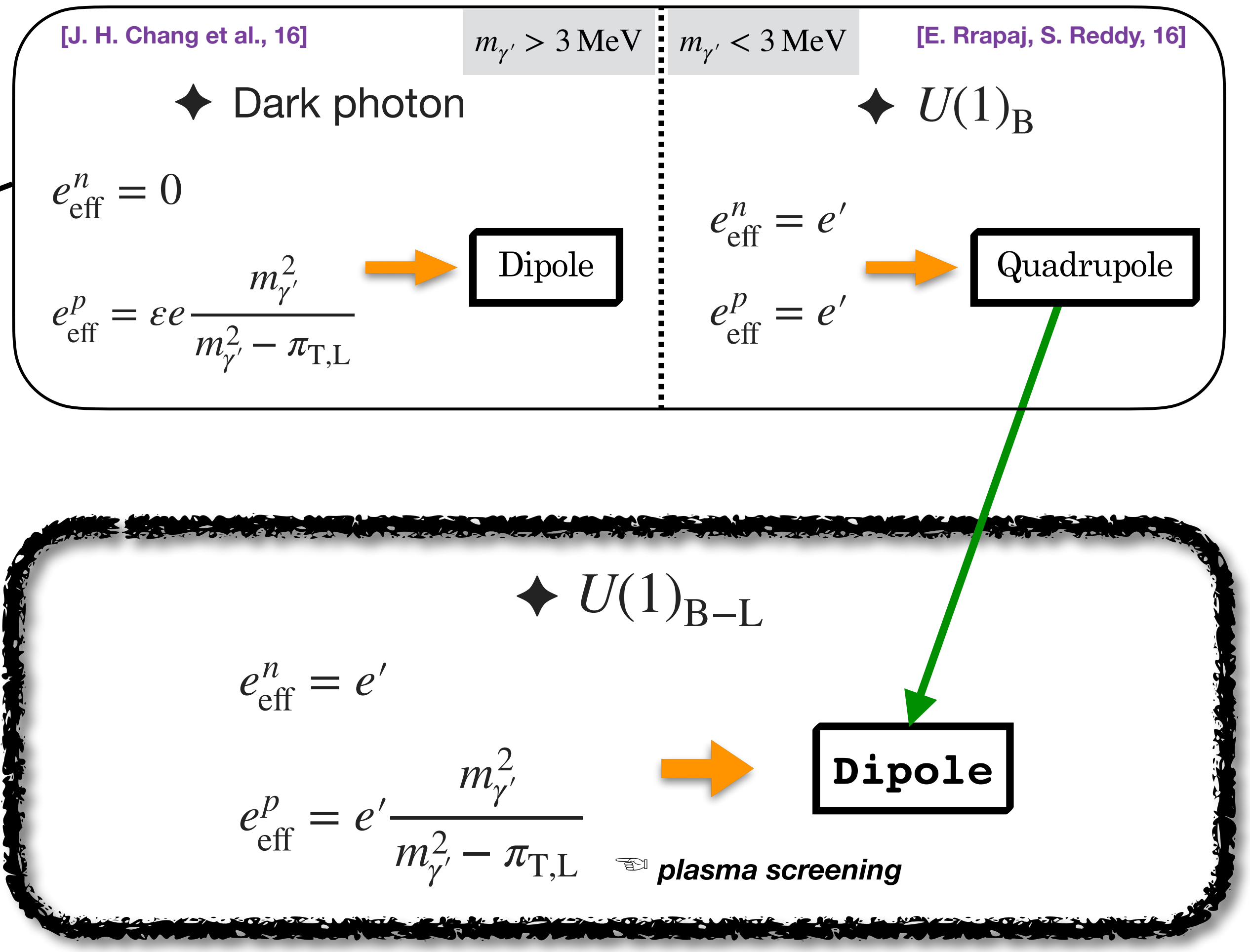
$$e^n_{\mathrm{eff}} = e'$$

$$e^p_{\mathrm{eff}} = e'$$

→ Quadrupole

SN1987A bound on $U(1)_{\rm B-L}$





[J. H. Chang et al., 16] $m_{\gamma'} > 3\,\mathrm{MeV}$

✦ Dark photon

$e^n_{\rm eff} = 0$

$e^p_{\rm eff} = \varepsilon e \dfrac{m^2_{\gamma'}}{m^2_{\gamma'} - \pi_{\rm T,L}}$ → **Dipole**

$m_{\gamma'} < 3\,\mathrm{MeV}$ [E. Rrapaj, S. Reddy, 16]

✦ $U(1)_{\rm B}$

$e^n_{\rm eff} = e'$

$e^p_{\rm eff} = e'$ → **Quadrupole**

✦ $U(1)_{\rm B-L}$

$e^n_{\rm eff} = e'$

$e^p_{\rm eff} = e' \dfrac{m^2_{\gamma'}}{m^2_{\gamma'} - \pi_{\rm T,L}}$ → **Dipole**

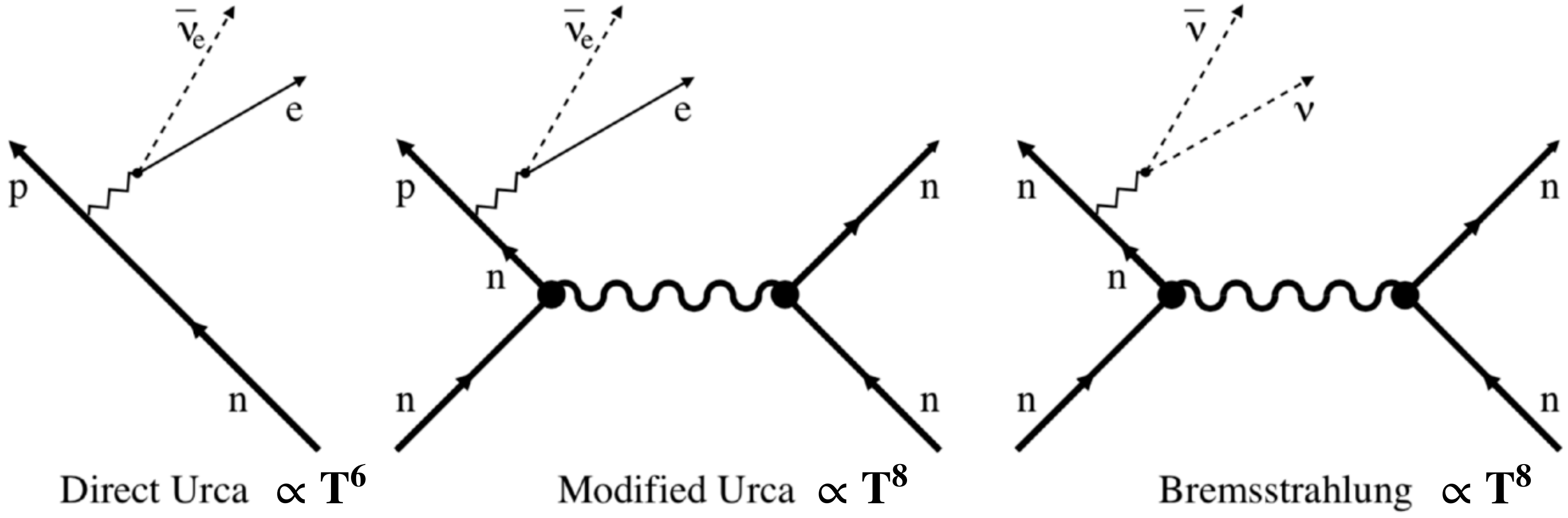
☜ ***plasma screening***

Neutron star cooling

- Minimal cooling scenario
- Observation of rapid cooling at early era (CAS-A)
  - evidence of superfluidity?
- Constraints on novel particles

Young NS cooling

- Neutrino (volume, mostly from core) emission

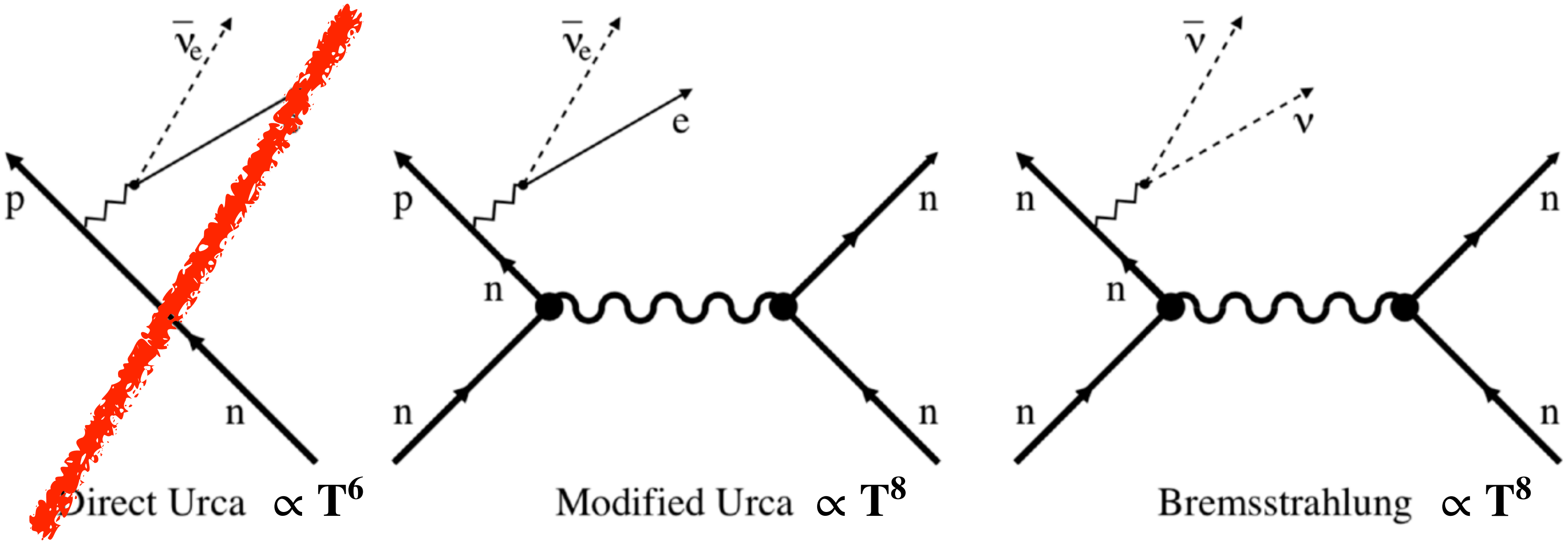


- Photon (surface) emission

Minimal cooling scenario w/o superfluid

Young NS cooling

- Neutrino (volume, mostly from core) emission



only when $> 2M_\odot$

- ~~Photon (surface) emission~~ dominant when $> 10^5$ year

◎ Energy valance equation

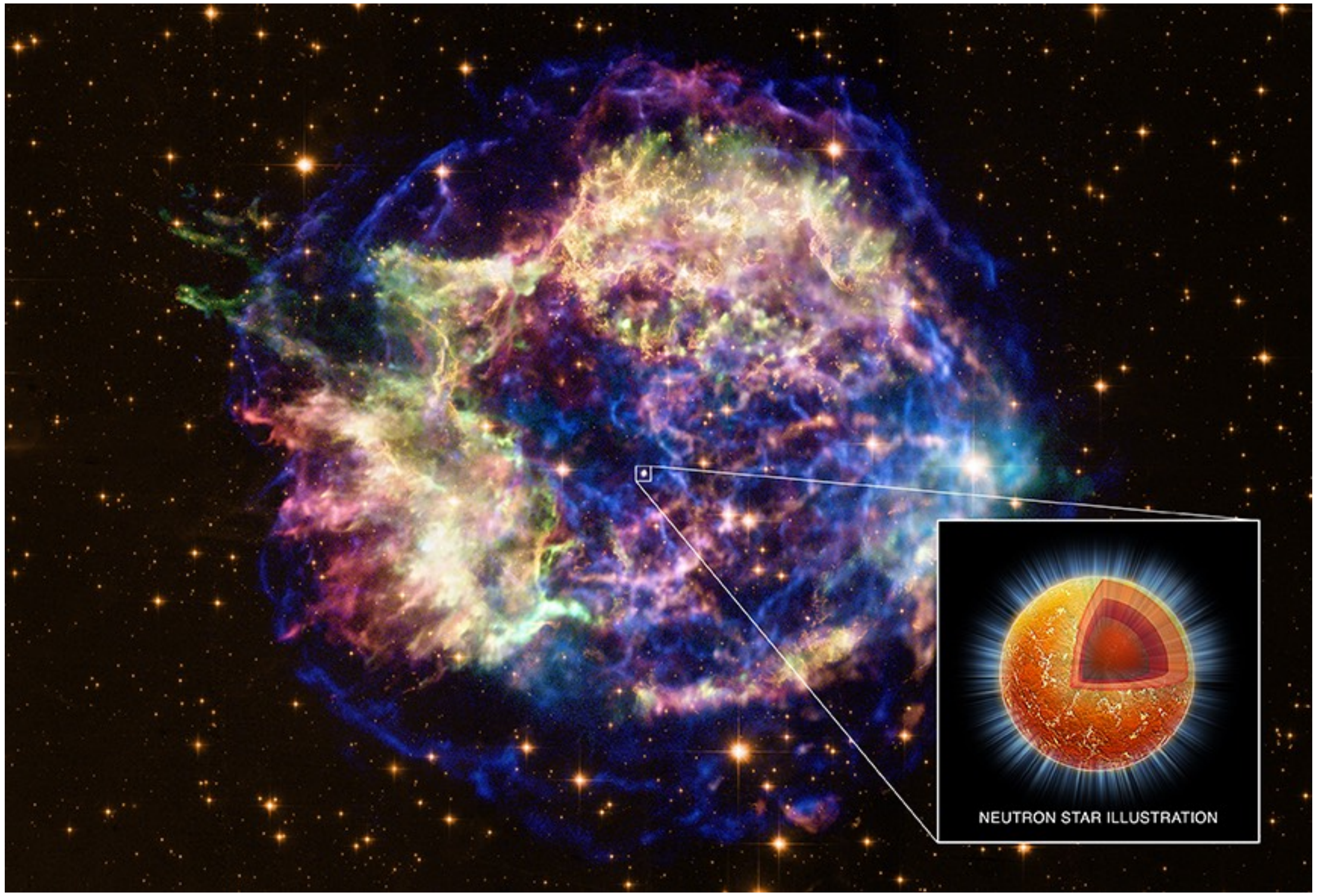
$$C\frac{dT}{dt} = -L_\nu - \cancel{L_\gamma} + \cancel{H}$$

$C \propto T$

$$\frac{\Delta T}{T} \sim -\frac{1}{6}\frac{dt}{t}$$

Cassiopeia A

[Chandra]



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

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

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

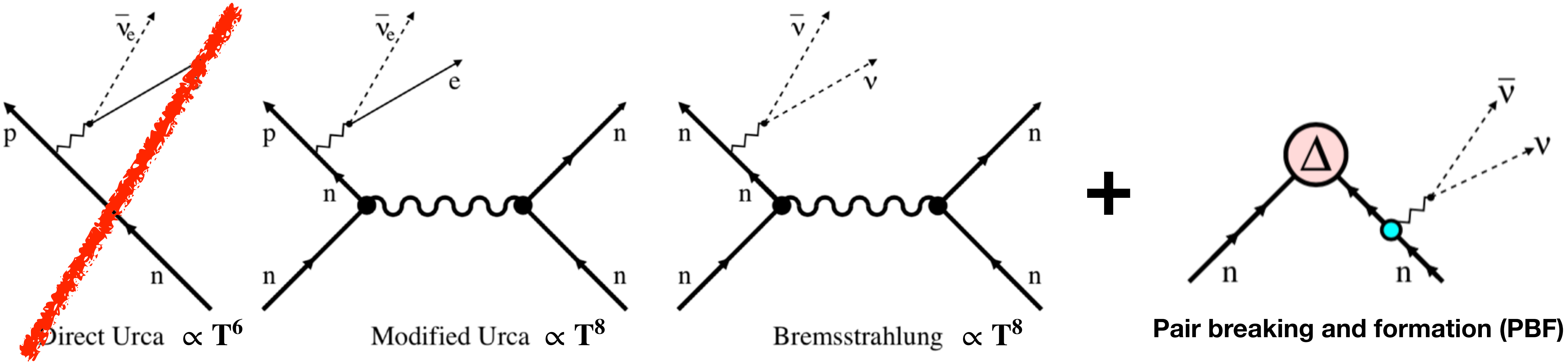
2~3% for 10 yr decline rate

expectation w/o superfluidity

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

Young NS cooling

- Neutrino (volume) emission



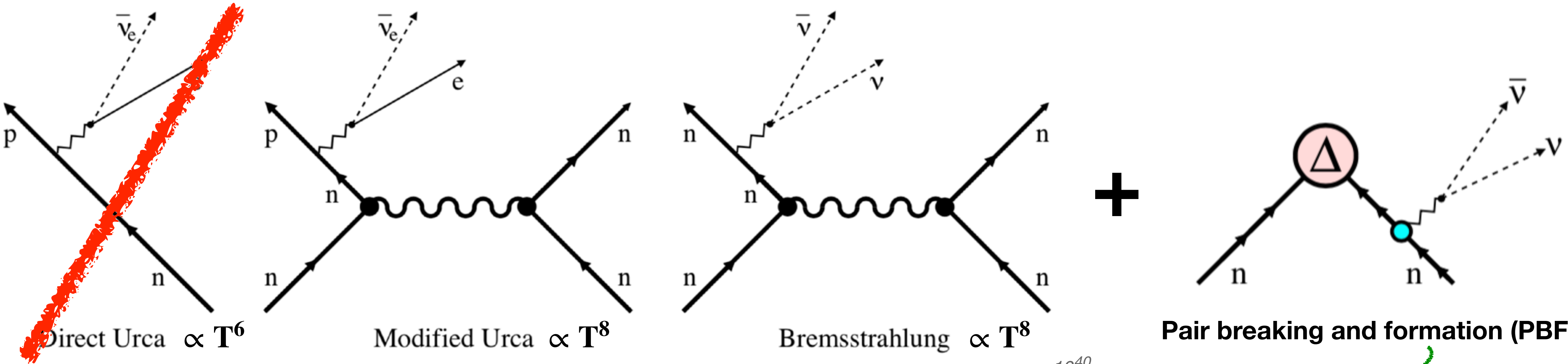
only when $> 2M_\odot$

- ~~Photon (surface) emission~~

dominant when $> 10^5$ year

Young NS cooling

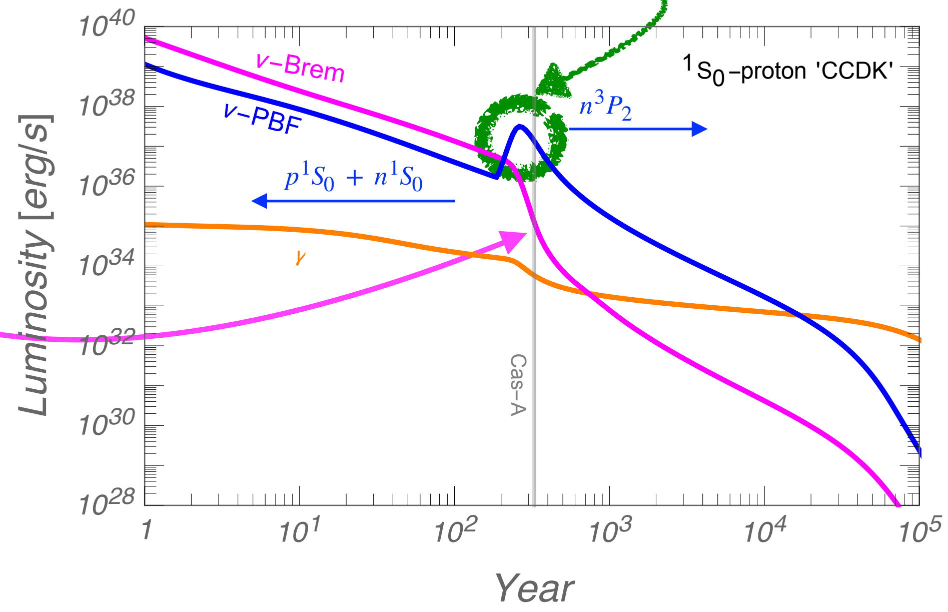
- Neutrino (volume) emission



only when $> 2M_\odot$

Suppressed at $T < T_c$

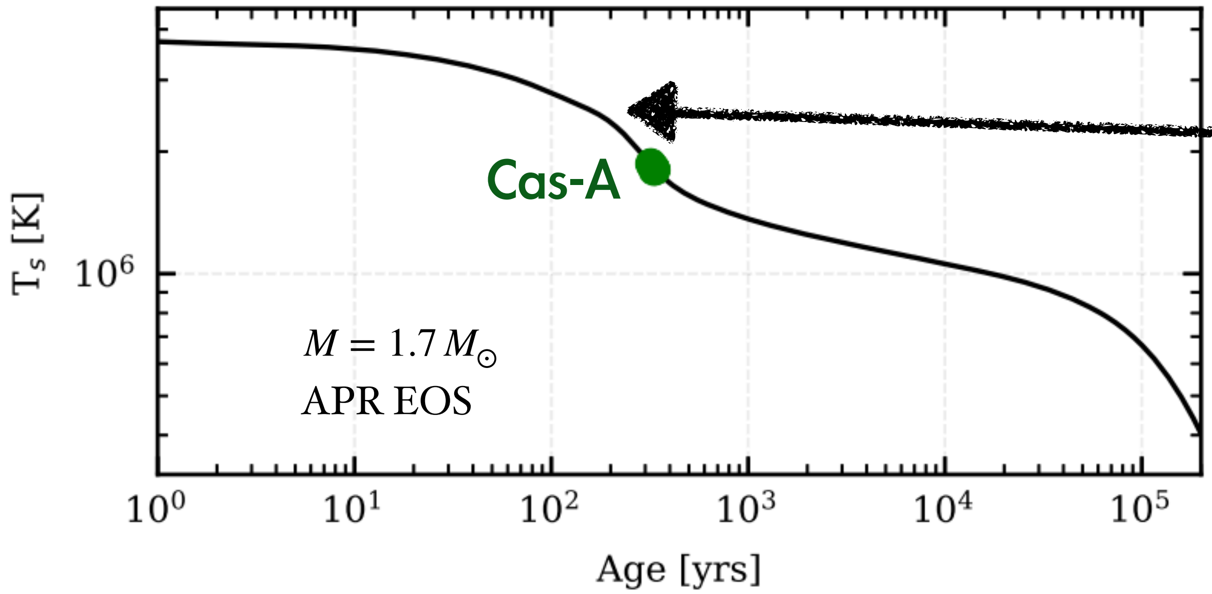
Pair breaking and formation (PBF)



- ~~Photon (surface) emission~~

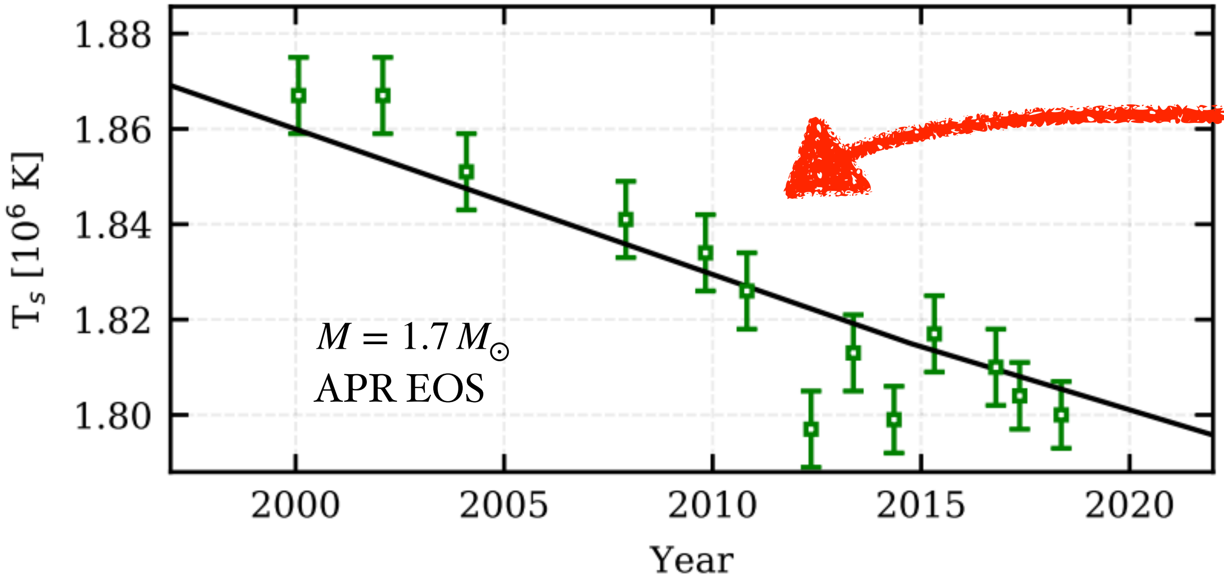
dominant when $> 10^5$ year

Evidence for superfluidity?



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

Rapid cooling by ***PBF***



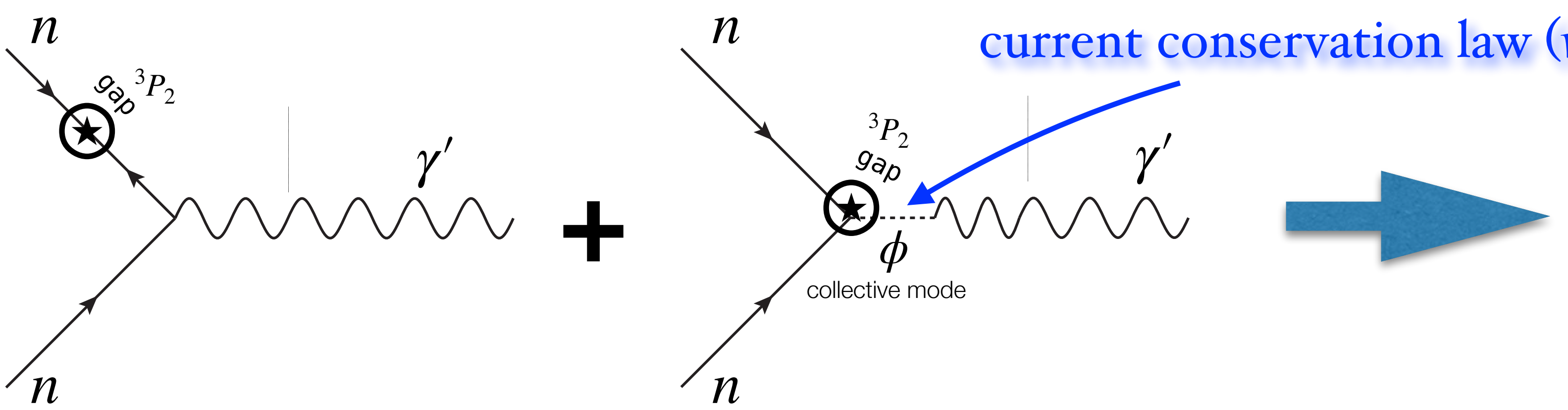
Minimal cooling scenarios with superfluidity fit well to the data

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

$U(1)_{\rm B-L}$ gauge boson in NS

- Emission processes through the nucleon current :
  - nn- or np-bremsstrahlung : $nn\,(np) \to nn\,(np) + \gamma'$ (dominant for very young NS)
  - Neutron singlet PBF in crust
  - Neutron triplet PBF in core → ***Dominant!!*** ***(after ~200 yr)***

◎ Neutron triplet ***PBF*** in core



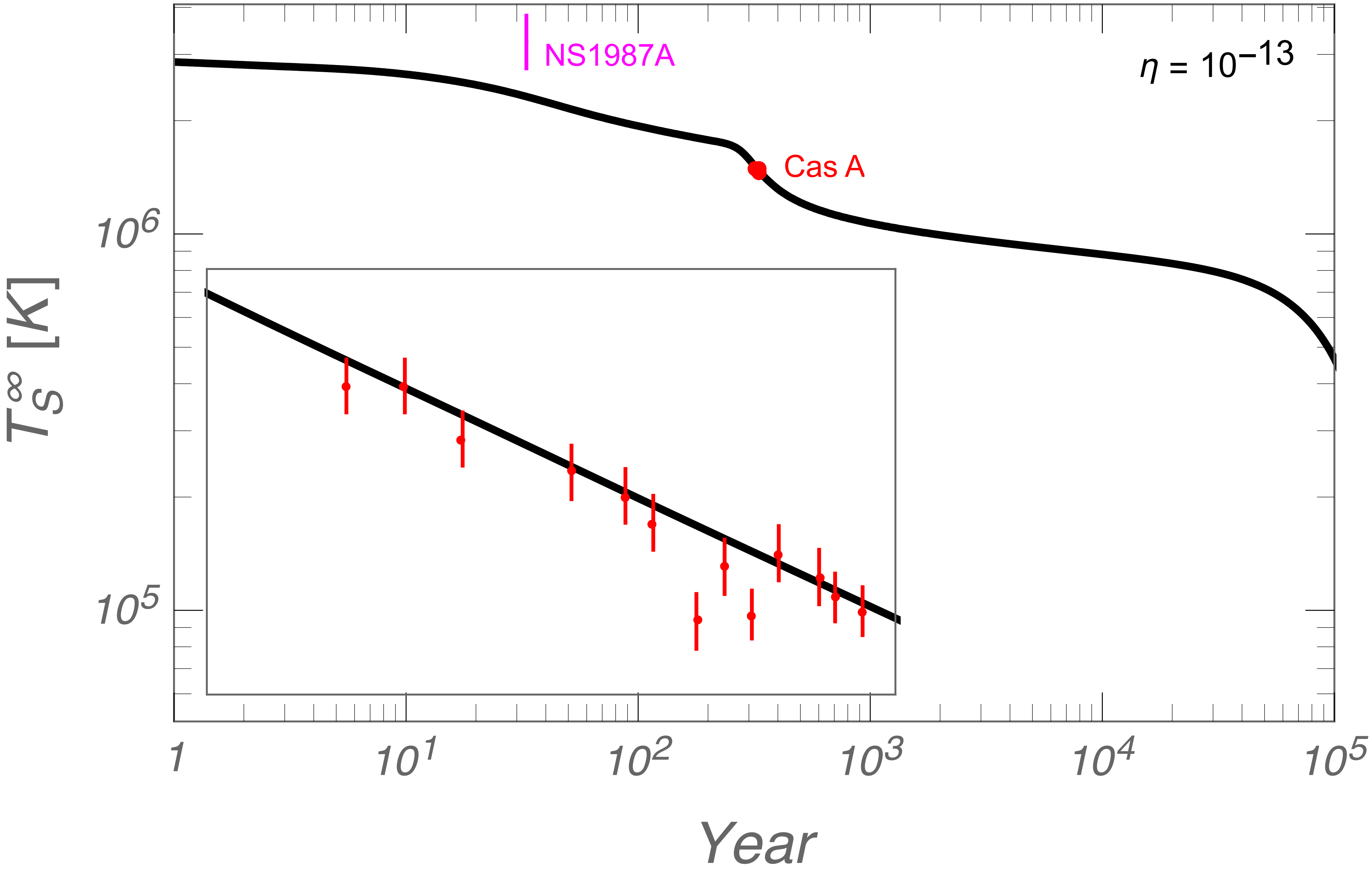
current conservation law (v_F^2 suppression)

$$\propto v_F^4 T^3$$

w/o plasma suppression

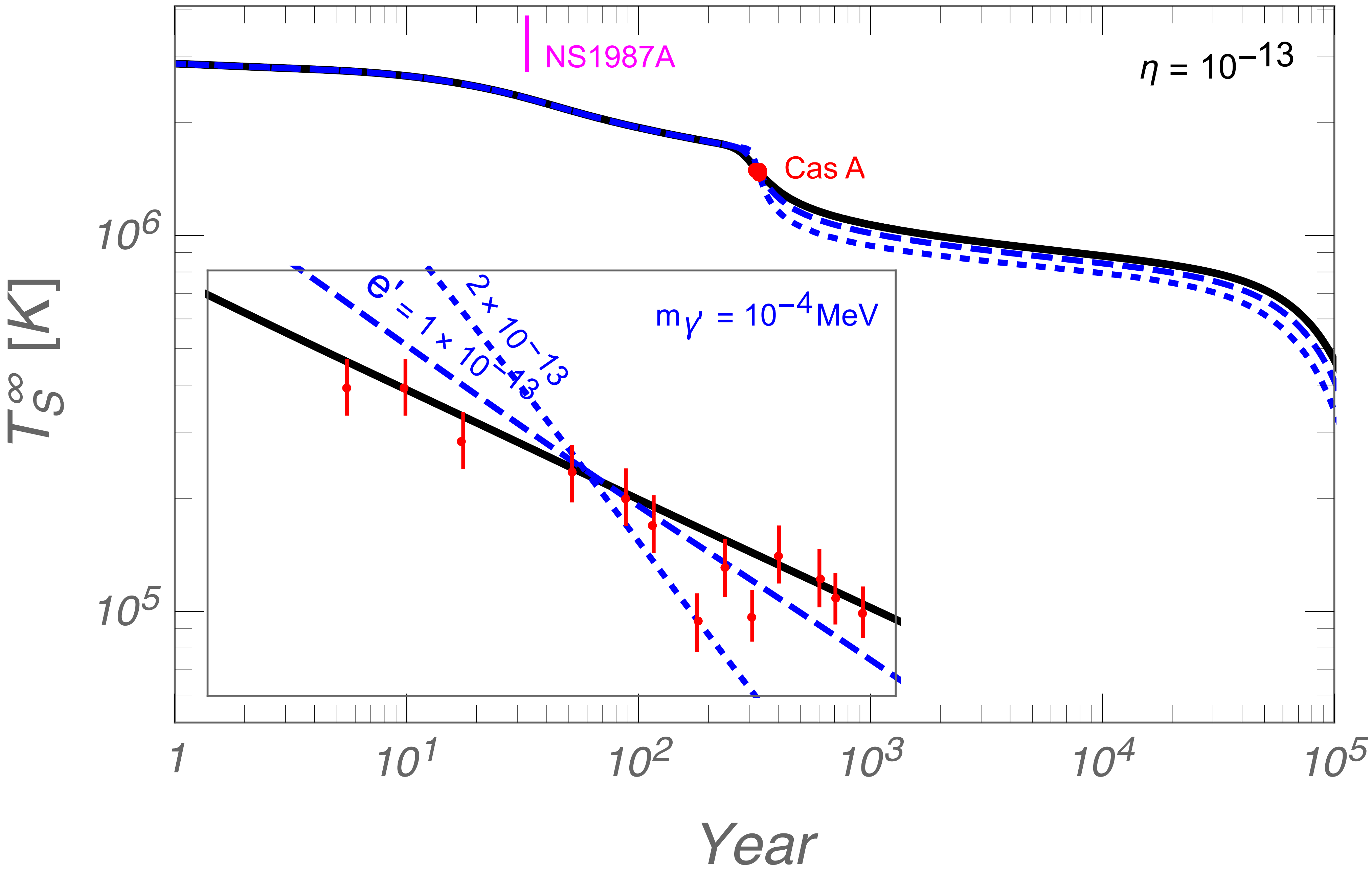
"NSCool" code

$U(1)_{\mathrm{B-L}}$ gauge boson cooling

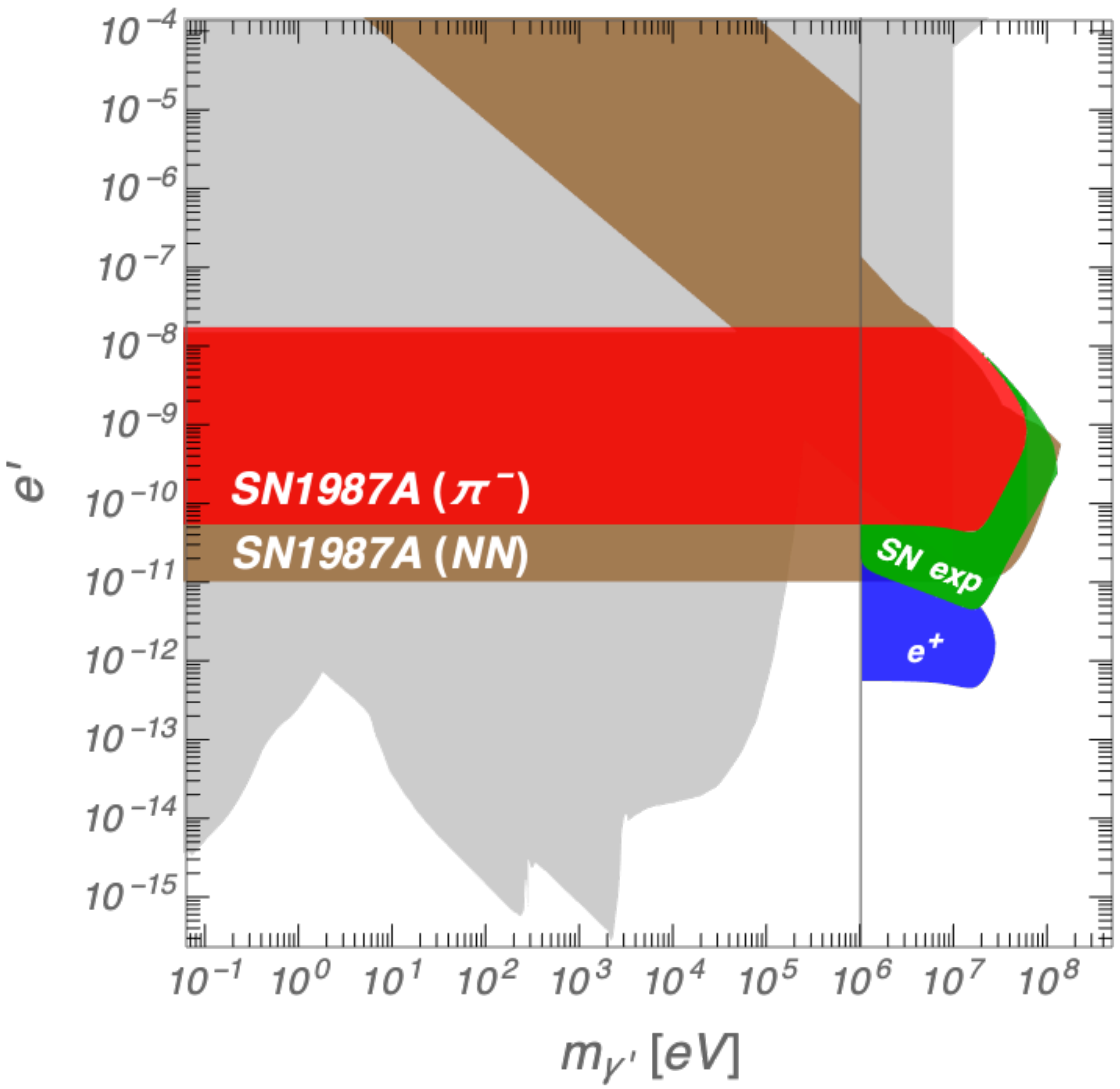


“NSCool” code

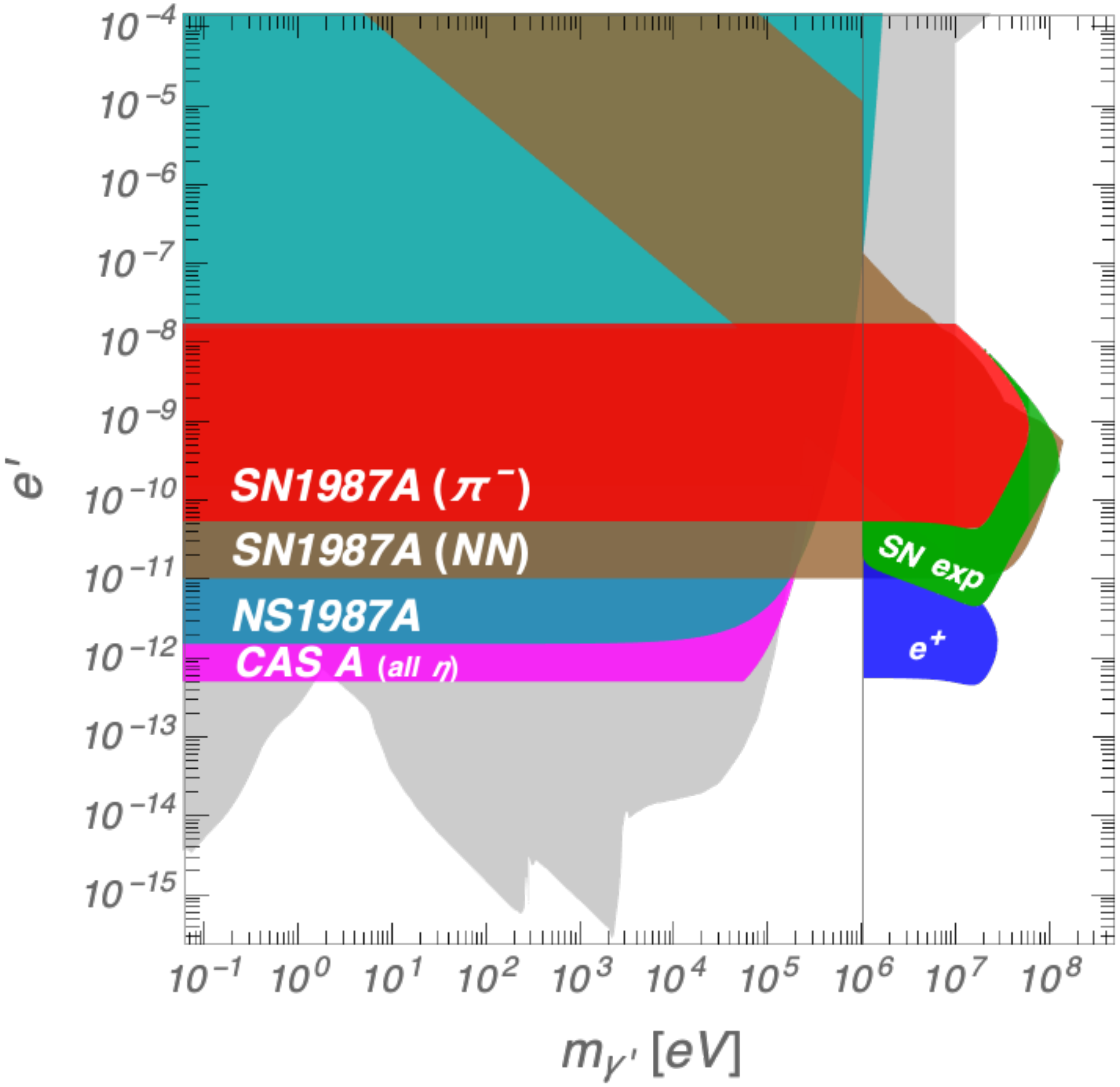
$U(1)_{\mathrm{B-L}}$ gauge boson cooling



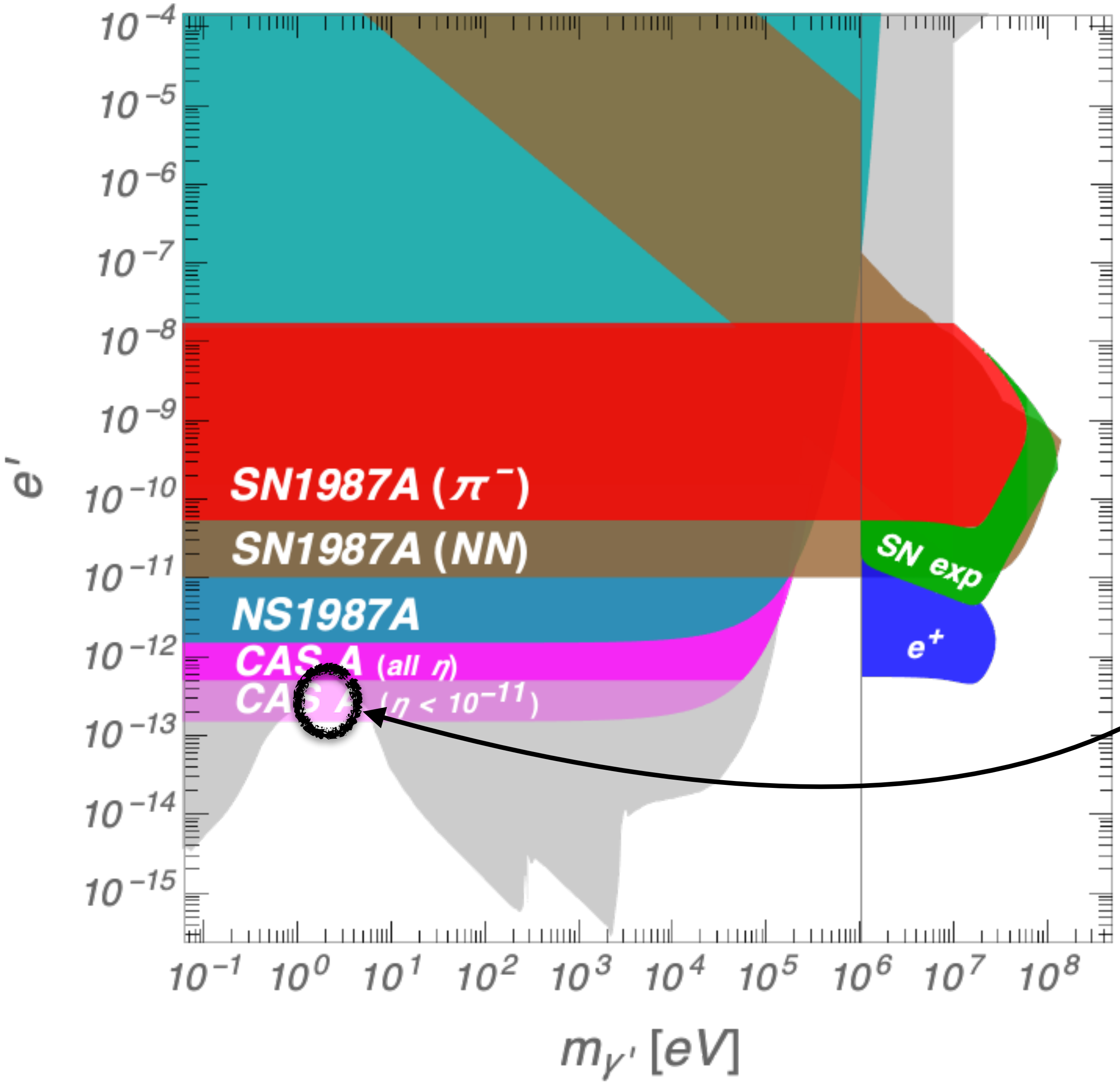
$U(1)_{\mathrm{B-L}}$ gauge boson constraints



$U(1)_{\mathrm{B-L}}$ gauge boson constraints

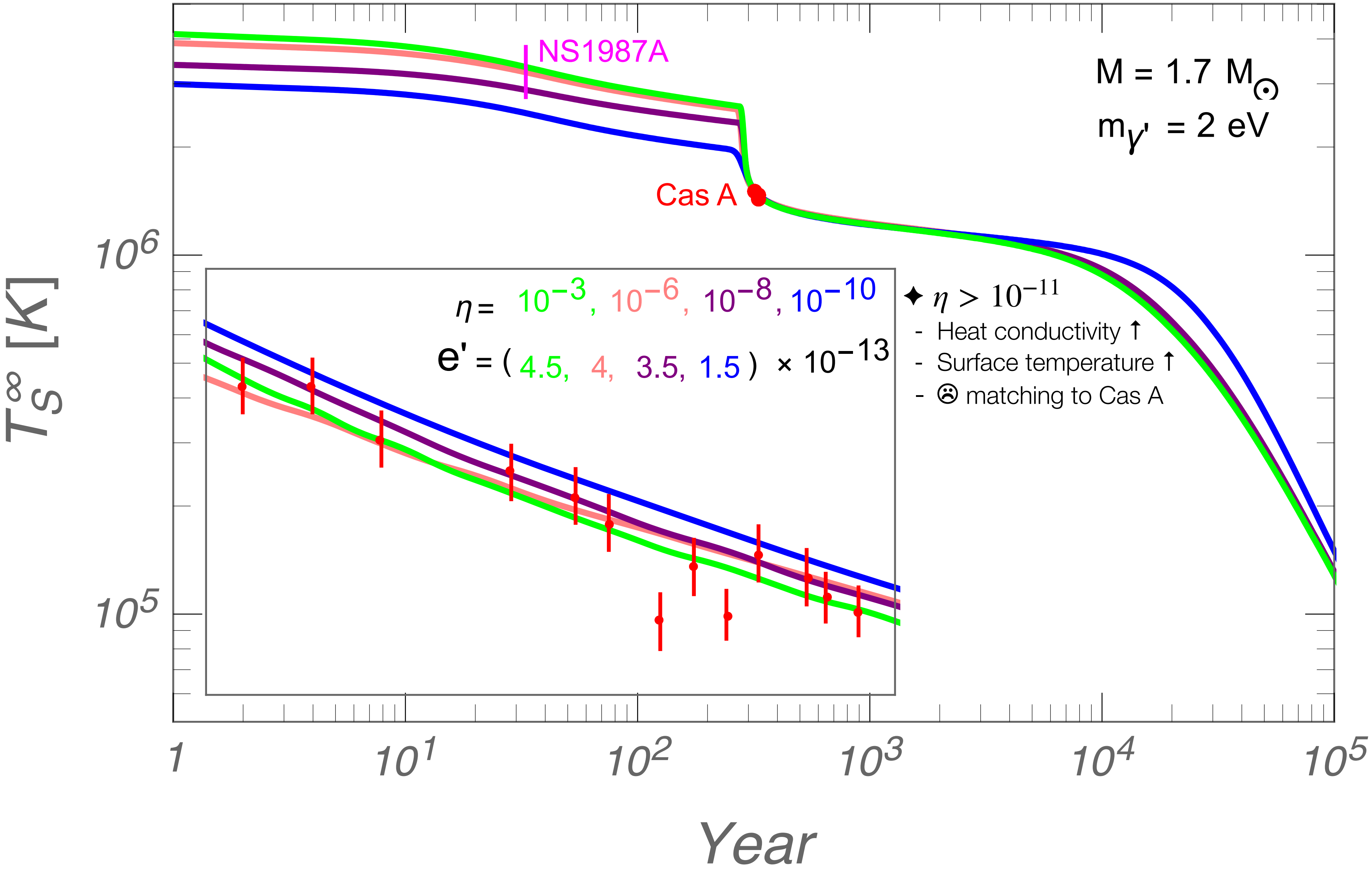


$U(1)_{\mathrm{B-L}}$ gauge boson constraints



Implications?

$U(1)_{\mathrm{B-L}}$ gauge boson implications



✦ $\eta > 10^{-11}$
- Heat conductivity ↑
- Surface temperature ↑
- ☹ matching to Cas A

Conclusion

- Neutron stars are attractive objects to probe fundamental interactions
- Stellar cooling argument on young neutron star cooling

1. Revisited SN1987A bound on $U(1)_{\mathrm{B-L}}$ gauge bosons
   - ChPT & Plasma effect
   - NN-brem (multipole rad)
   - Pion-induced

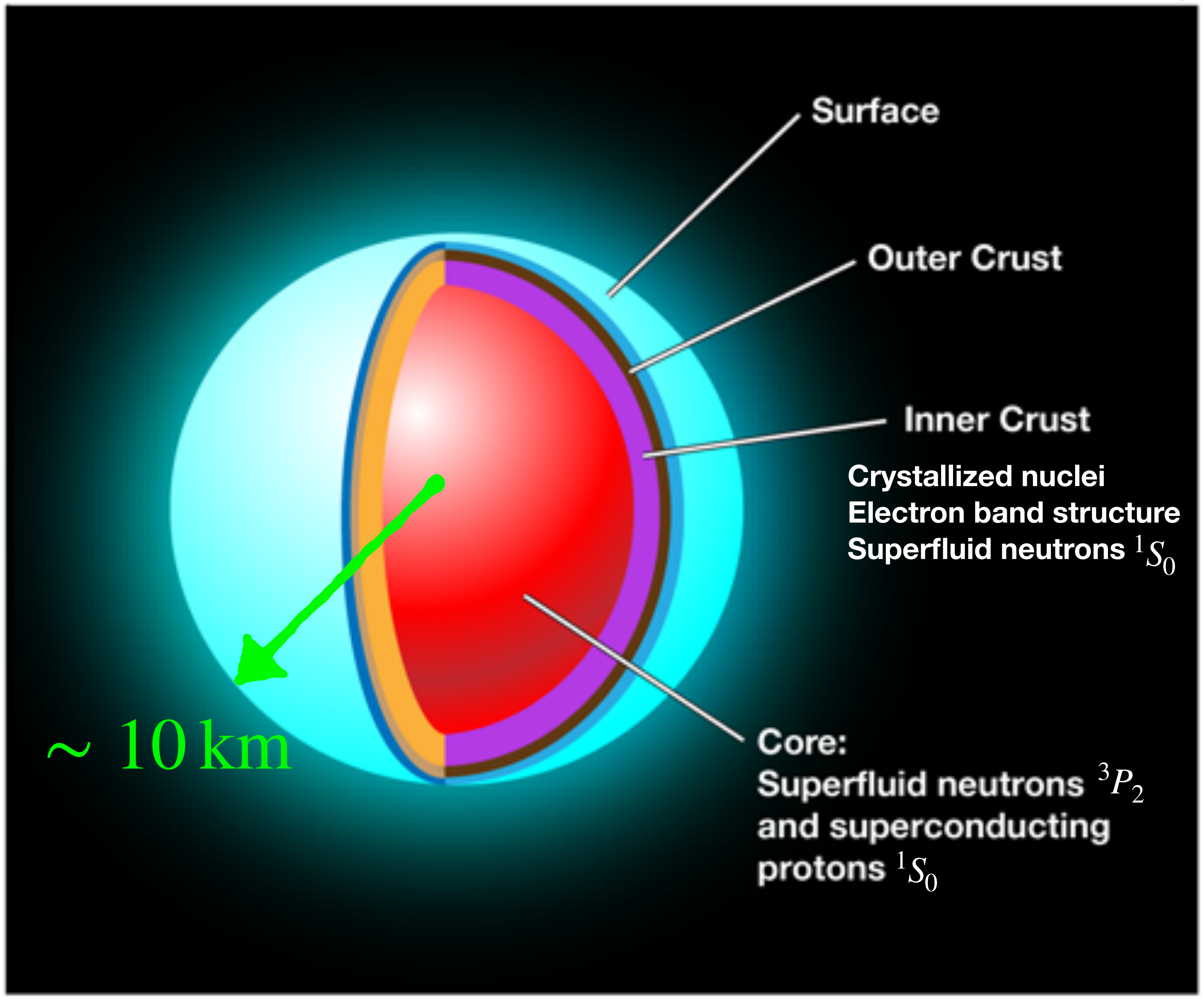
An order of magnitude enhanced!

2. Direct evidence of superfluidity from the rapid cooling of Cas A → minimal scenario with superfluidity fits well to datas (incl. NS1987A?)

New stringent constraints on dark gauge bosons!

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?

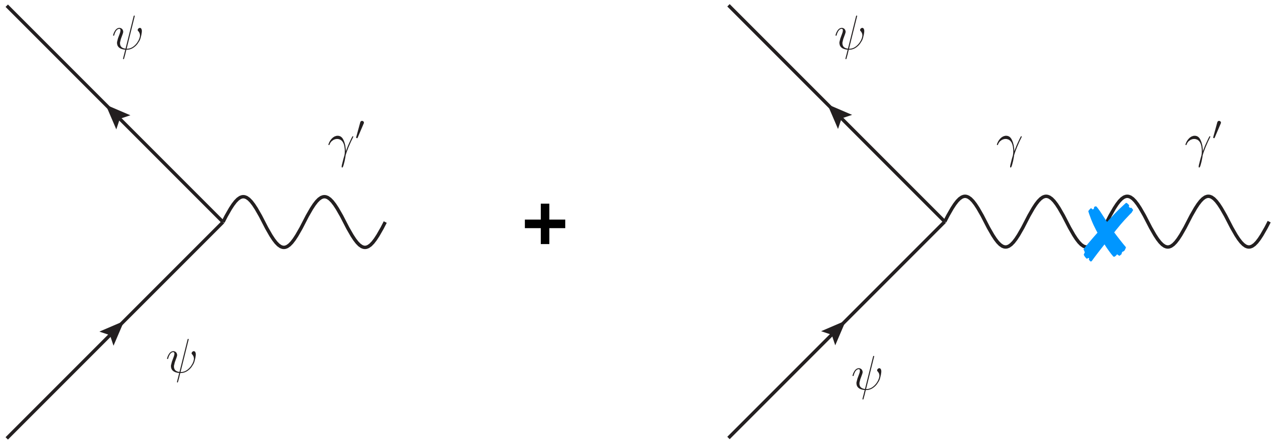
In medium (+ kinetic) mixing

- Effective γ' couplings within ChPT framework

$$\mathcal{L} = -\underbrace{\frac{1}{4}F_{\mu\nu}F^{\mu\nu}}_{\text{EM field strength}} - \underbrace{\frac{1}{4}X_{\mu\nu}X^{\mu\nu}}_{\text{DP field strength}} + \underbrace{\frac{\varepsilon}{2}F_{\mu\nu}X^{\mu\nu}}_{\text{kinetic mixing}} - \underbrace{\frac{1}{2}m_{\gamma'}^2 X_\mu X^\mu}_{\gamma'\text{ mass}} + \underbrace{eA_\mu J^\mu_{\text{EM}}}_{\text{EM current}} + \underbrace{e'A'_\mu J'^\mu}_{\gamma'\text{ current}}$$

- hadron (ChPT)
- lepton

- Effective γ' couplings: direct + indirect (mixing)



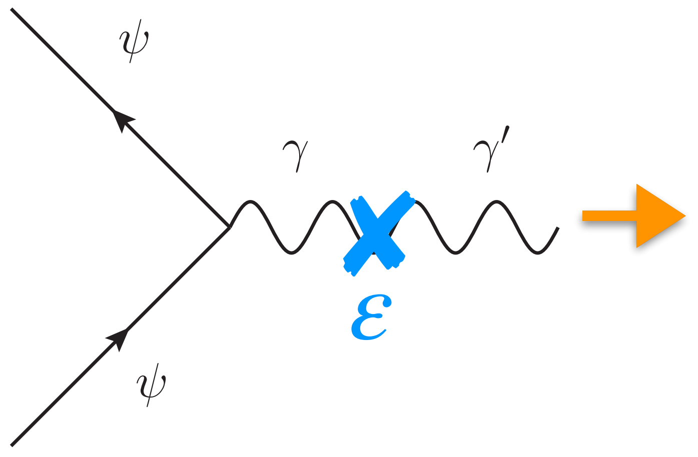
Direct coupling

Indirect coupling
- kinetic mixing
- plasma mixing

Dark photon (vector portal)

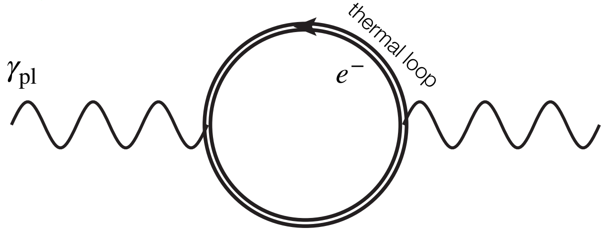
$$\mathscr{L}_{\rm eff} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}X_{\mu\nu}X^{\mu\nu} + \frac{\varepsilon}{2}F_{\mu\nu}X^{\mu\nu} - \frac{1}{2}\overset{\left\langle J^{\mu}_{\rm EM}J^{\nu}_{\rm EM}\right\rangle}{\Pi^{\mu\nu}} A_\mu A_\nu - \frac{1}{2}m^2_{\gamma'}X_\mu X^\mu$$

EM field strength DP field strength ***kinetic mixing*** ***plasmon*** DP mass



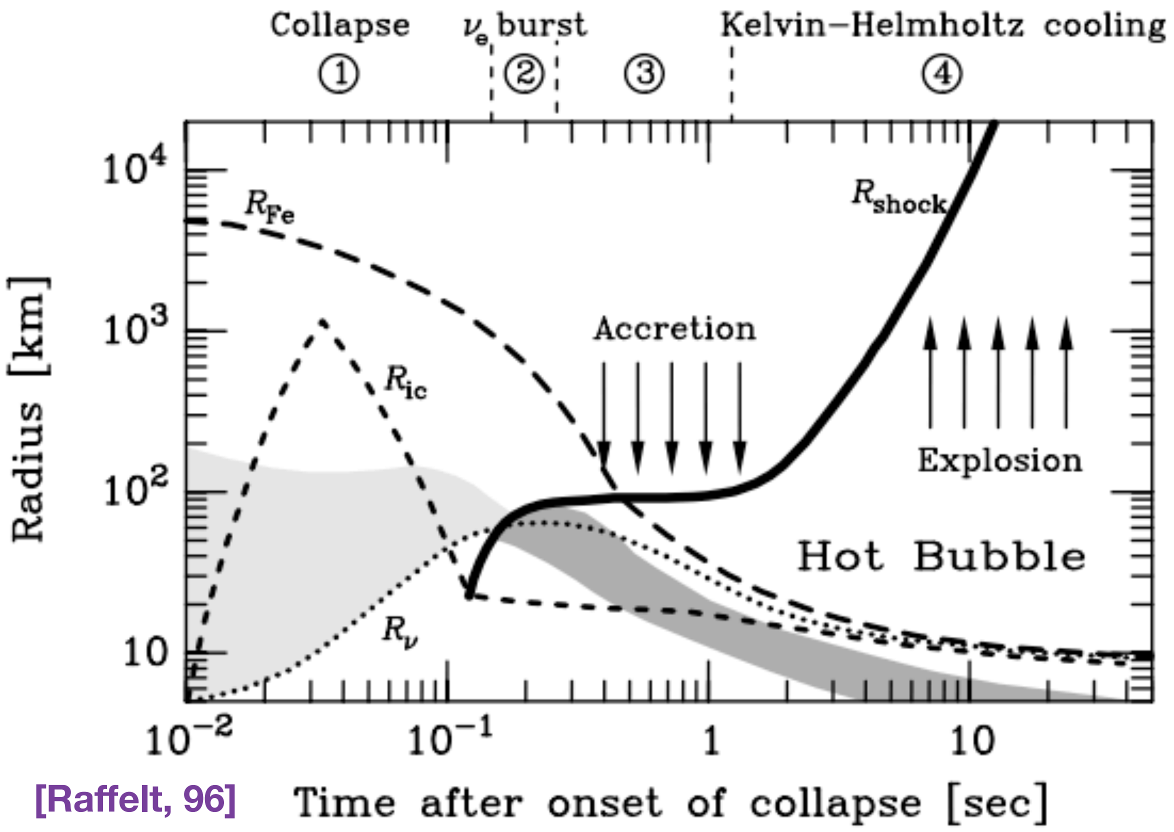
$$\mathscr{M} = \underbrace{\frac{\varepsilon e m^2_{\gamma'}}{m^2_{\gamma'} - \pi_{\rm T,L}}}_{e^{\psi}_{\rm eff}} \left[J^{\mu}_{\rm EM}\right] \epsilon'_\mu$$

*medium effect



$$\pi_{\rm T,L} = \begin{cases} \text{transverse} & \omega^2_{\rm pl}\left(1 + \frac{1}{2}G(v_*^2k^2/\omega^2)\right) \\ \text{longitudinal} & \omega^2_{\rm pl}\frac{m^2_{\gamma'}}{\omega^2}\frac{1 - G(v_*^2k^2/\omega^2)}{1 - v_*^2k^2/\omega^2} \end{cases}$$

Raffelt’s criterion for SN1987A



[Raffelt, 96]

- The “***delayed explosion scenario***” (***DνM***)
  - Thermal relaxation of the proto-neutron star as the source of neutrino emission for > 5sec
  - the energy deposition of the neutrino flow causes the explosion ($\mathcal{O}(1)$% of total neutrino bulk energy)

$$\Rightarrow \quad L_x \lesssim 3 \times 10^{52}\,\mathrm{erg\,s^{-1}}$$

SN1987A bound

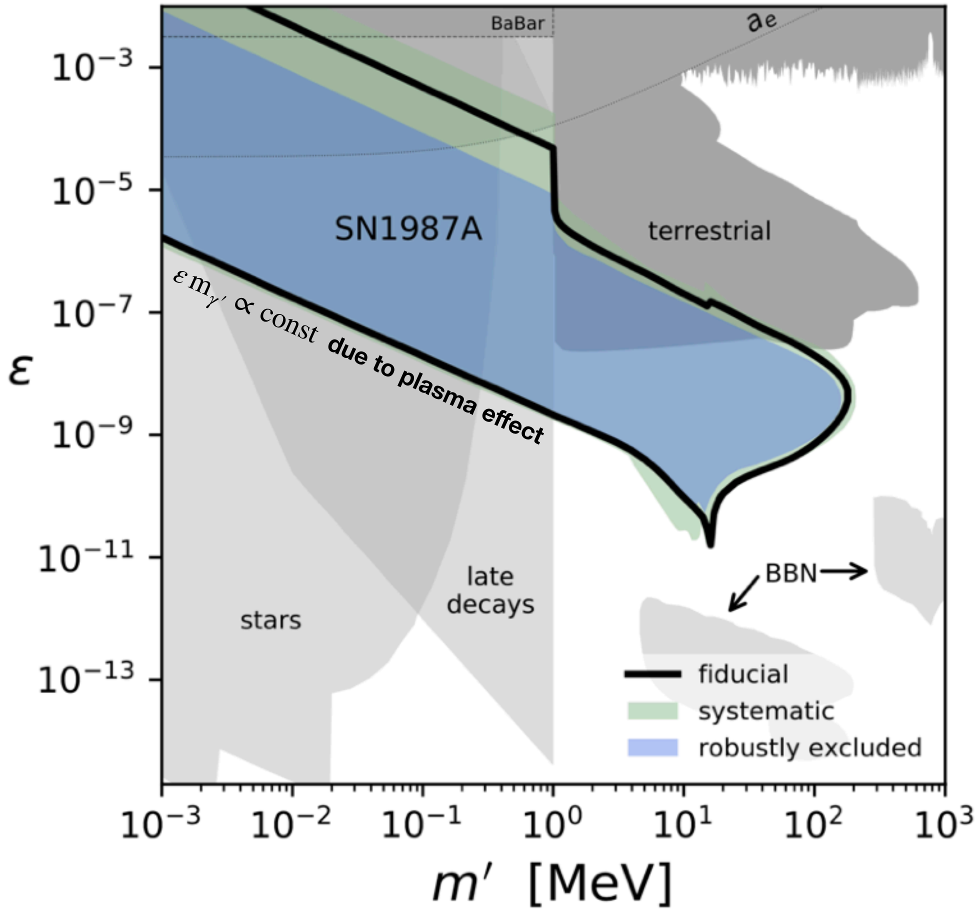
✦ Dark photon

$$e^n_{\text{eff}} = 0$$

$$e^p_{\text{eff}} = \varepsilon e \frac{m^2_{\gamma'}}{m^2_{\gamma'} - \pi_{\text{T,L}}}$$

Dipole radiation

[J. H. Chang et al., 16]



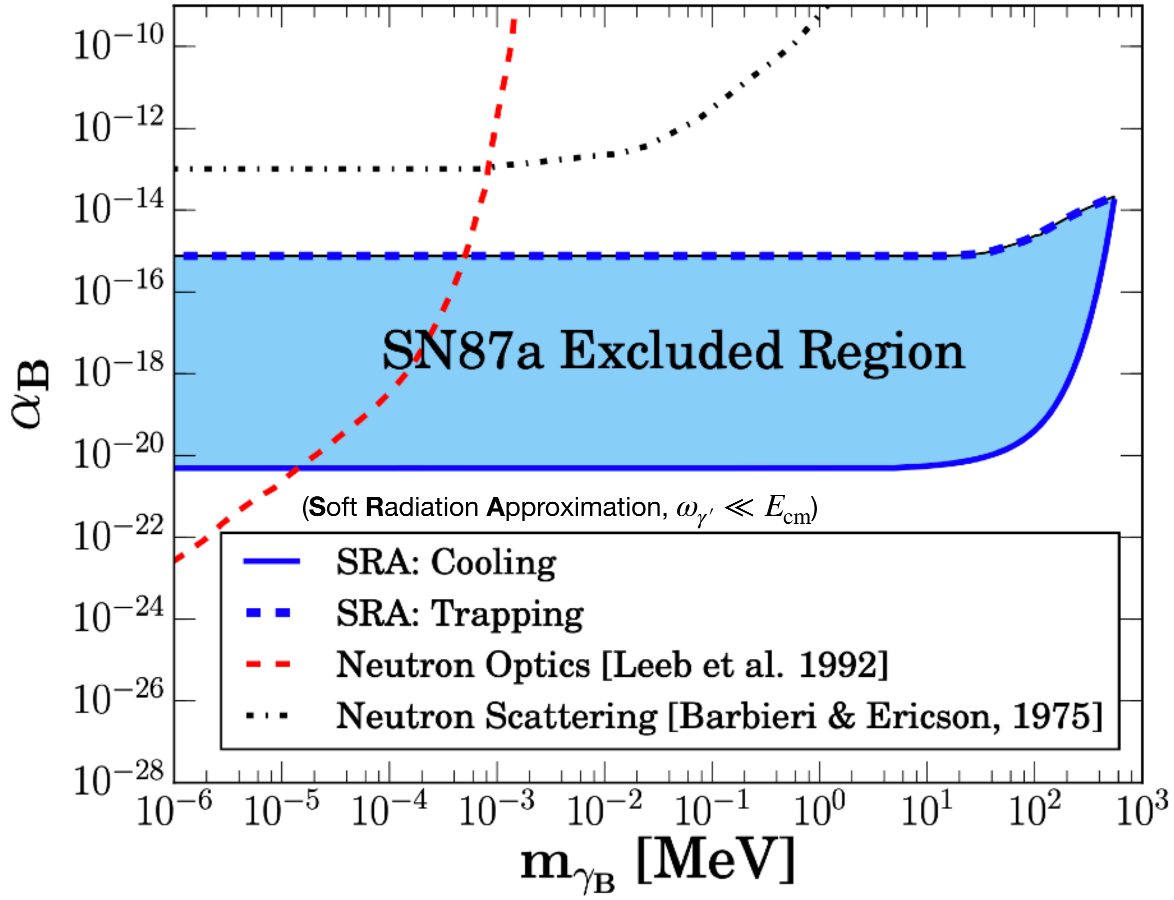
✦ $U(1)_{\text{B}}$

$$e^n_{\text{eff}} = 1$$

$$e^p_{\text{eff}} = 1$$

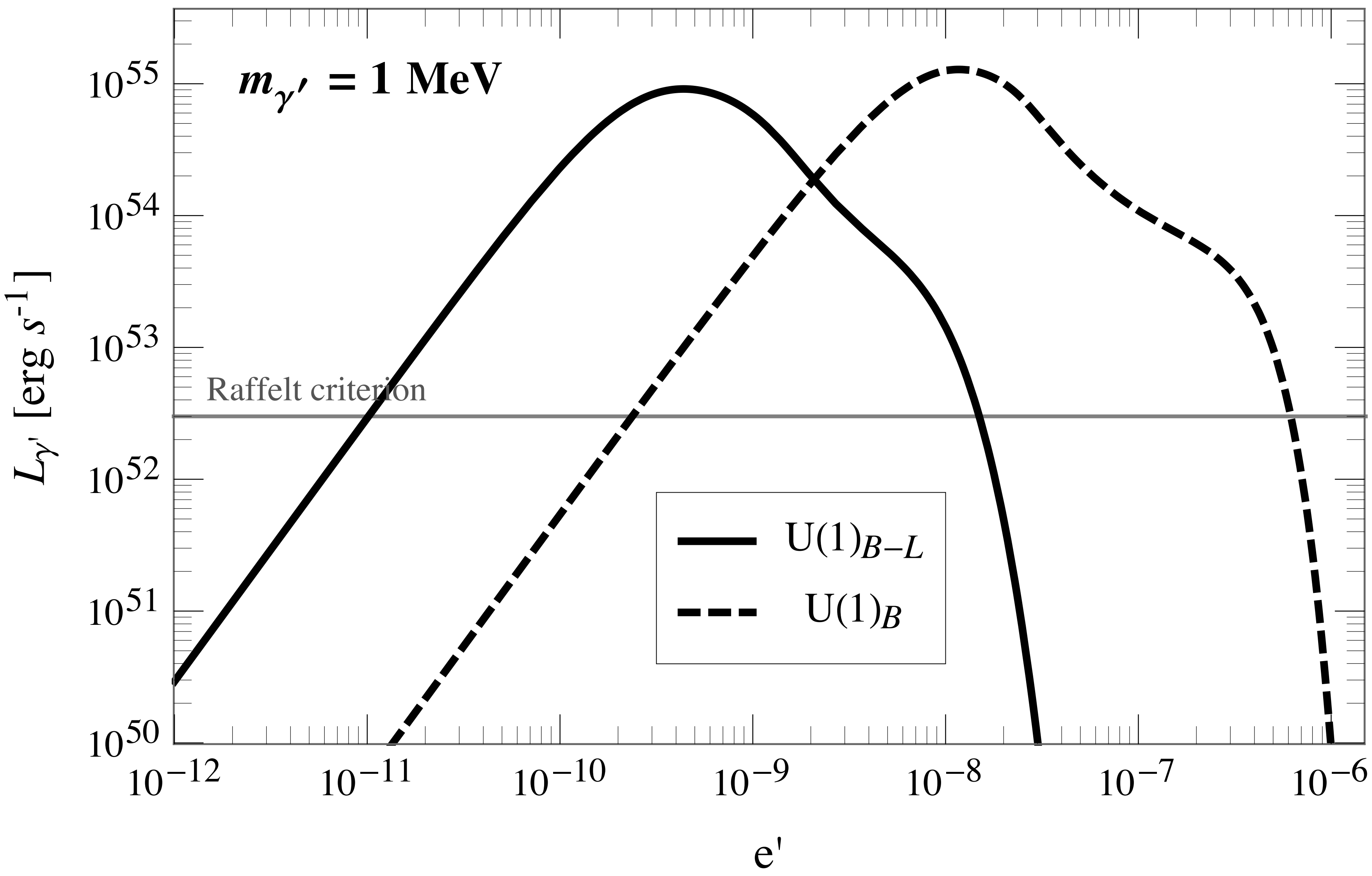
Quadrupole radiation

[E. Rrapaj, S. Reddy, 16]

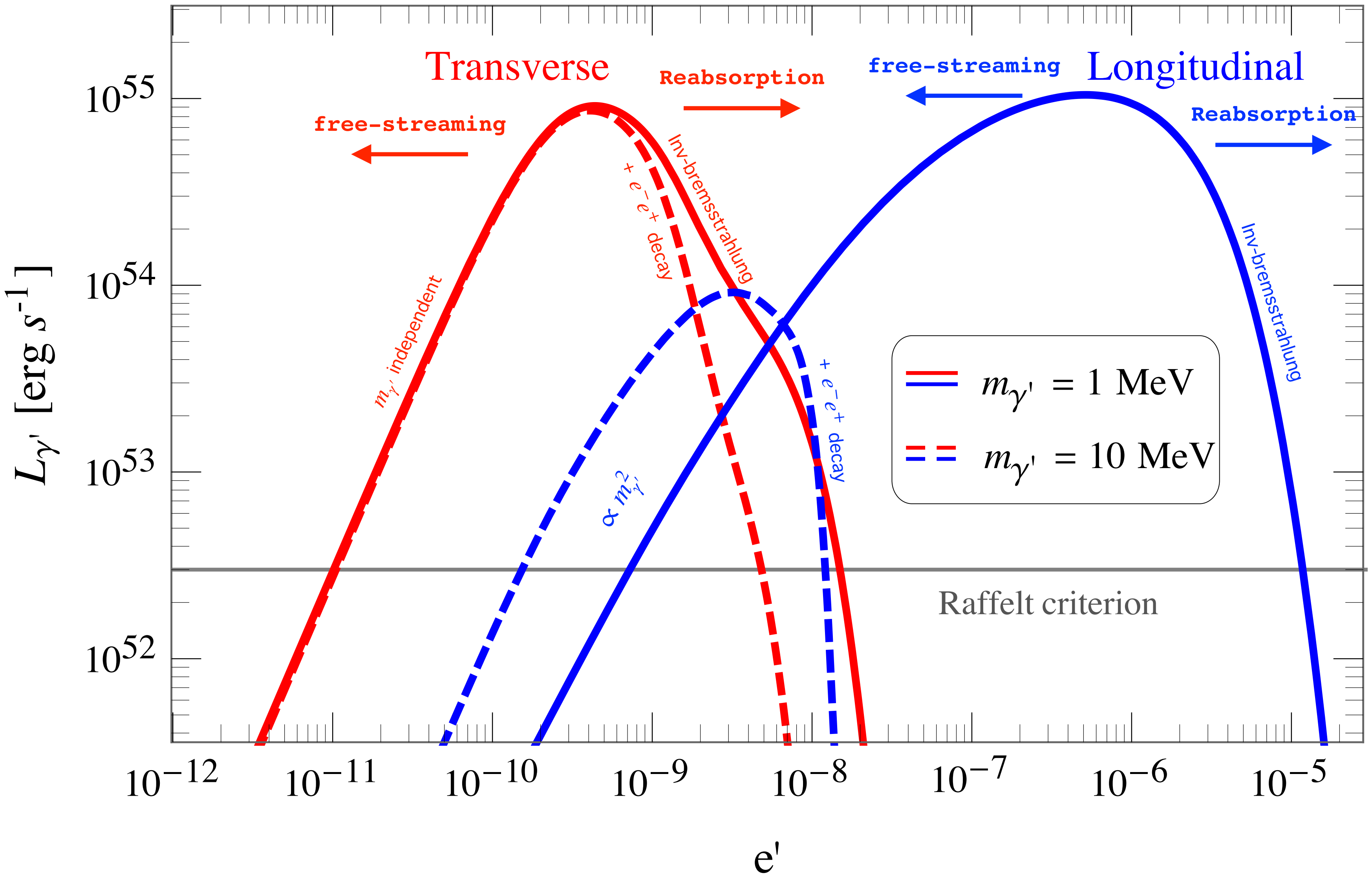


$U(1)_{\mathrm{B-L}}$ vs $U(1)_{\mathrm{B}}$ in SN1987A

✳ only transverse



$U(1)_{\mathrm{B-L}}$ luminosity in SN1987A



Dark gauge boson via Pion-induced reaction

- Thermal π^- abundance
- Dominant production during supernovae @ $\omega \sim m_\pi$
- Constraints from

  i) SN1987A (cooling)

  ii) SN explosion energy

  iii) galactic e^+ injection

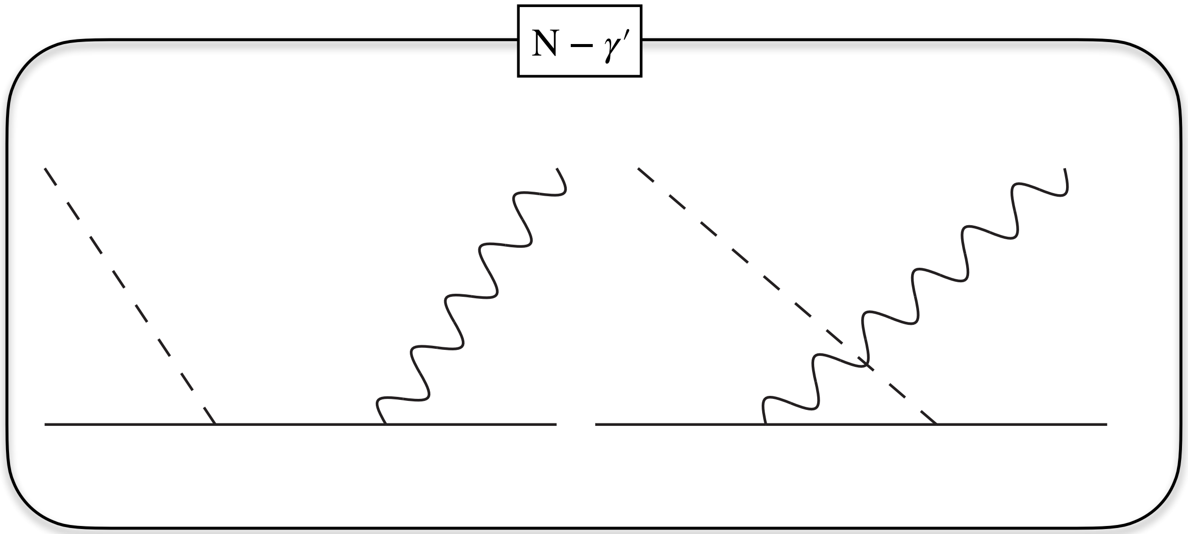
  iv) Absence of prompt SN γ-ray

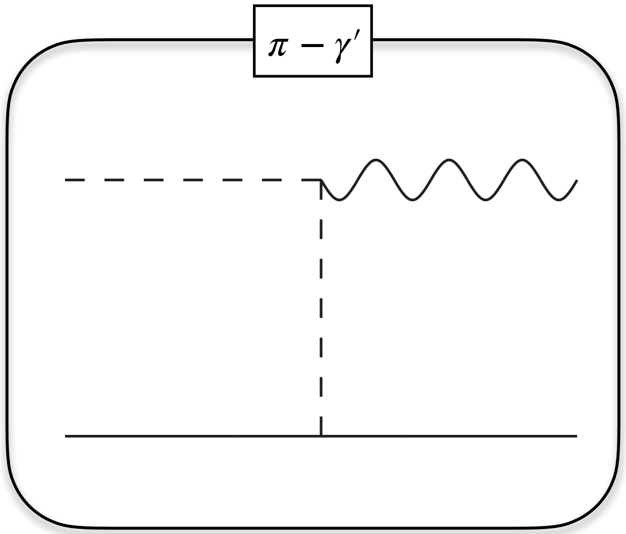
Thermal π^--induced production

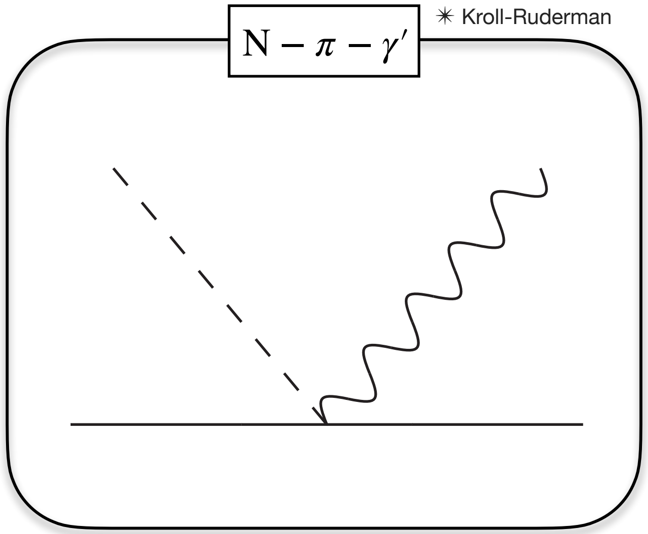
- Large $\mu_\mathrm{n} - \mu_\mathrm{p}$ & temperature ($\sim 30\,\mathrm{MeV}$)
  - source for negatively charged particles (e.g., e^-, μ^-, π^-)
  - thermal pion abundance with $n_{\pi^-}/n_B \sim \mathcal{O}(1)\,\%$ **[B. Fore, S. Reddy, 19]**
- Strong interactions with nucleons
  - modification of thermodynamics
  - effective dispersion relation of π^-

$\Rightarrow$ **Viral expansion**

- Diagrams of Compton-like processes







✴ Kroll-Ruderman

Phenomenological implications?

◉ Cooling argument on SN1987A

- comparable constraints to the results based on NN-bremsstrahlung
- If absorbed within $r_{\rm far} \sim 10^{2\text{-}3}\,{\rm km}$, no efficient cooling
- $L_{\gamma'}\, e^{-(m_{\gamma'}/\omega_{\gamma'})\,\Gamma_{\gamma'}\, v_{\gamma'}\, r_{\rm far}} < 10^{19}\,{\rm erg\, g^{-1}\, s^{-1}}$ “Raffelt criterion”

$m_{\gamma'} > 2m_e$

◉ High energy galactic e^+ injection

[W. DeRocco, et al., 19] [F. Calore, et al., 21]

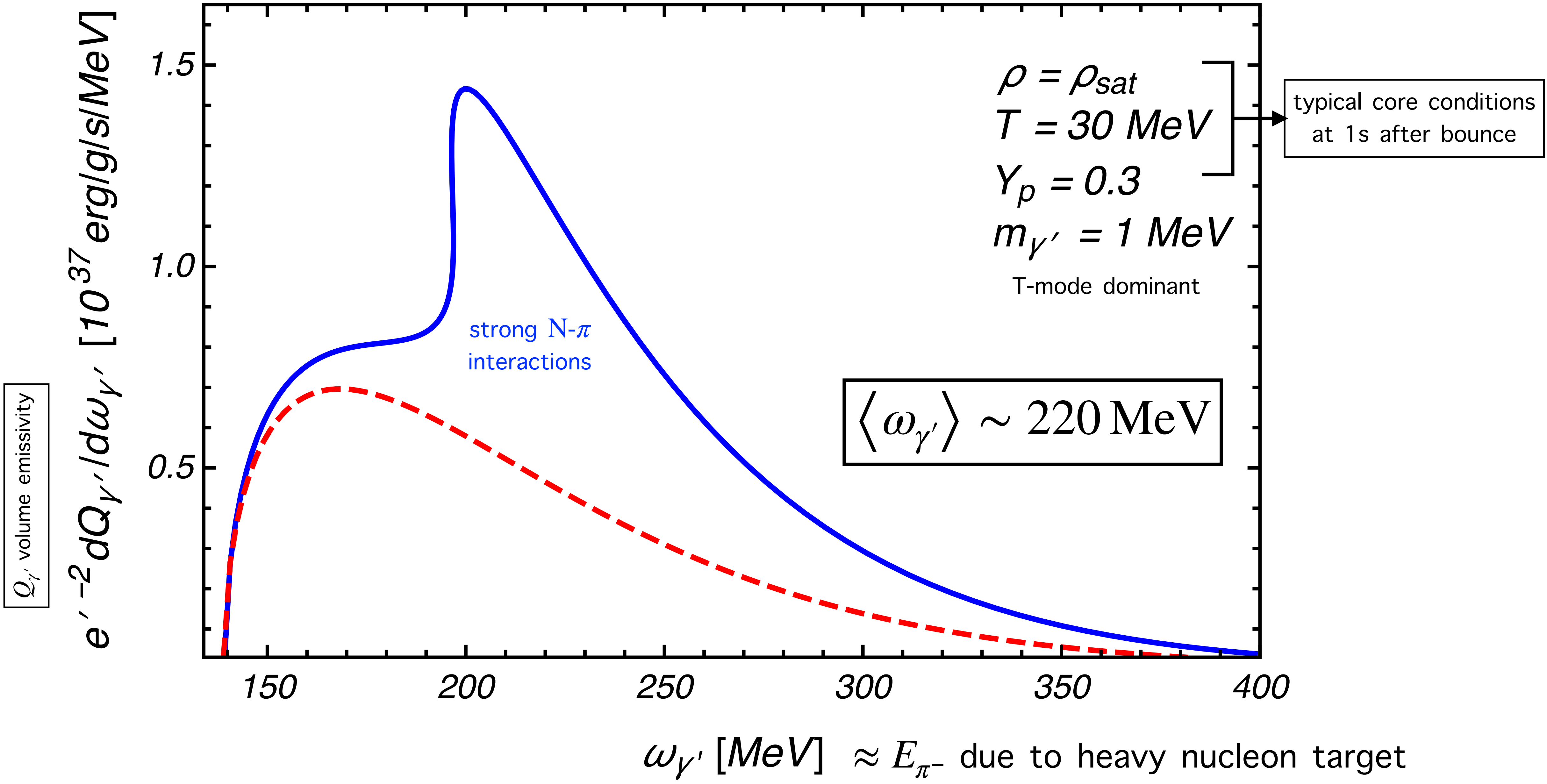
- No excess of the galactic gamma ray flux ⇒ constrain new e^+ sources [J. F. Beacom, et al., 06] [P. Sizun, et al., 06]
- $N_{\gamma'}\, e^{-(m_{\gamma'}/\omega_{\gamma'})\,\Gamma_{\gamma'}\, v_{\gamma'}\, r_{\rm esc}} < 10^{52}\, e^+$ for $\omega_{e^+} = 100\,{\rm MeV}$ & $r_{\rm esc} \sim 10^9\,{\rm km}$ (type-II SN)

◉ Trigger of supernova explosion

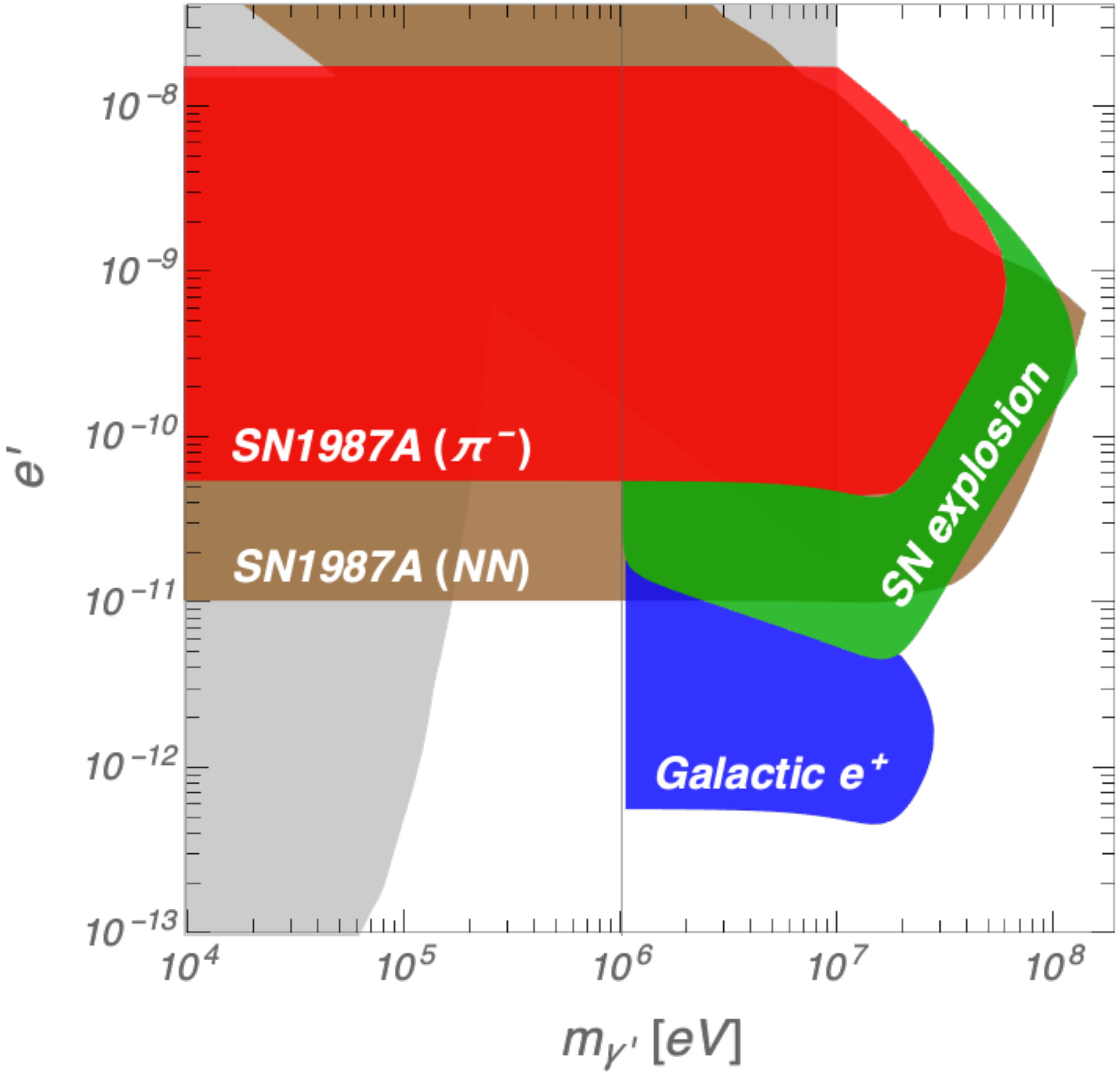
[S. W. Falk et al., 78] [A. Sung, et al., 19] [A. Caputo et al., 22]

- trapping or reabsorption within $r_{\rm far} < r < r_{\rm esc}$ can transfer energy
- inferred SN explosion energy $< 10^{51}\,{\rm erg}$ ⇒ constrain new energy transfer sources [K. Nomoto, et al., 13] [S. W. Bruenn, et al., 14]
- $L_{\gamma'} \left(e^{-(m_{\gamma'}/\omega_{\gamma'})\,\Gamma_{\gamma'}\, v_{\gamma'}\, r_{\rm far}} - e^{-(m_{\gamma'}/\omega_{\gamma'})\,\Gamma_{\gamma'}\, v_{\gamma'}\, r_{\rm esc}} \right) < 10^{17}\,{\rm erg\, g^{-1}\, s^{-1}}$

π^--induced γ' spectrum

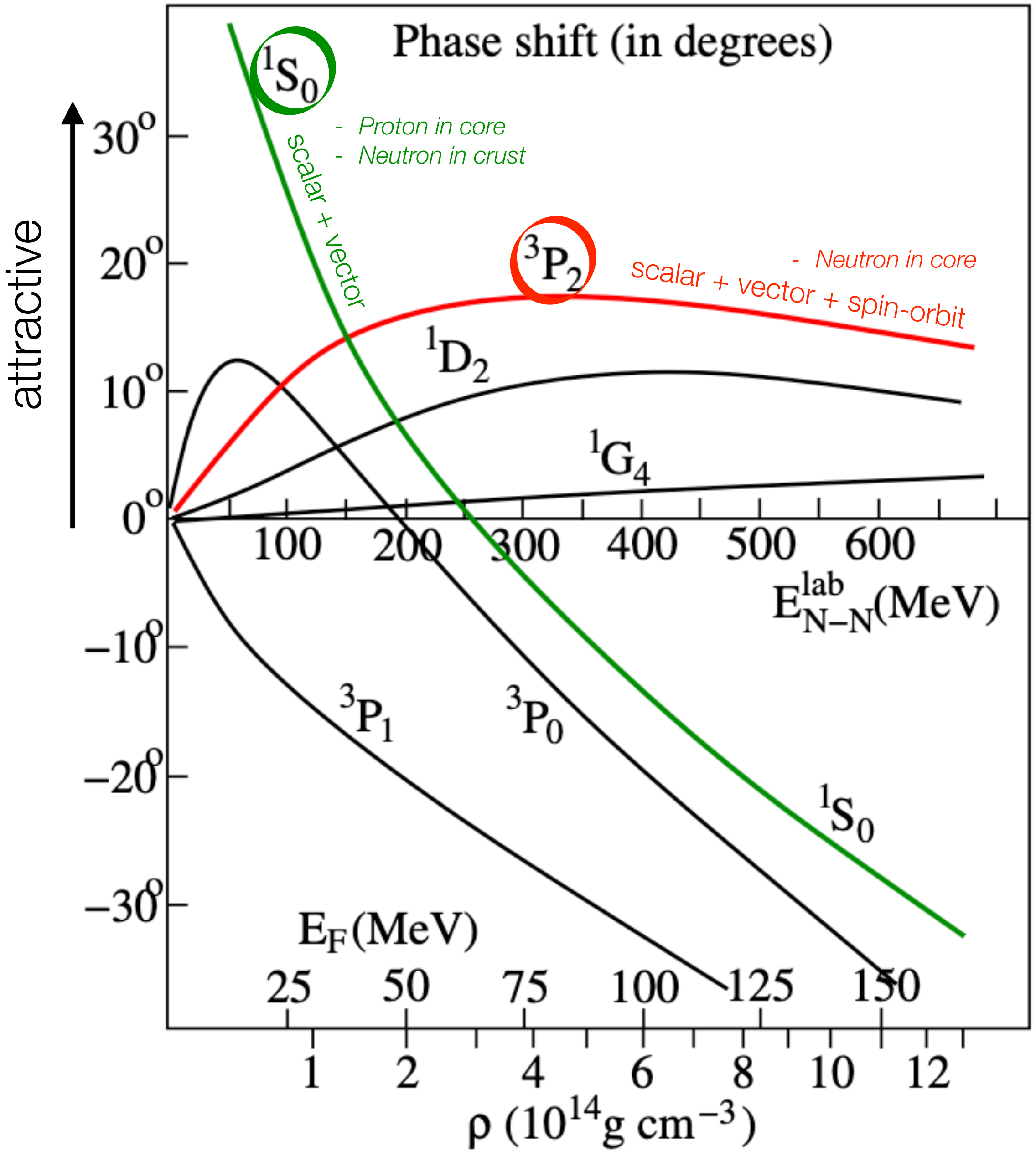


$U(1)_{\mathrm{B-L}}$ gauge boson constraints

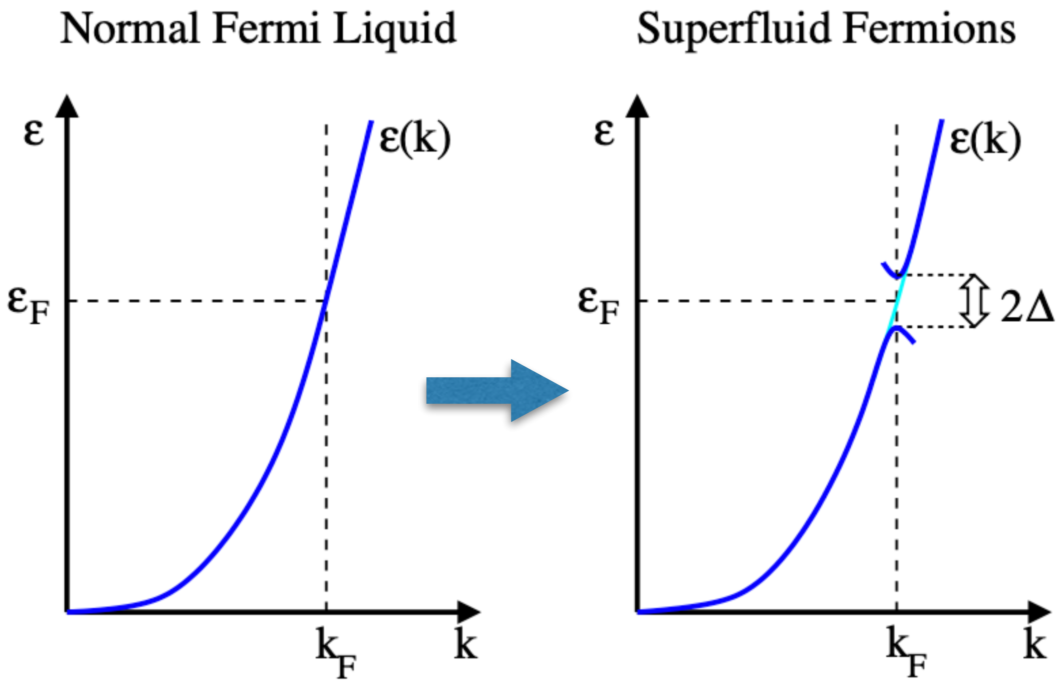


Superfluidity of nucleon

[R. Tamagaki, 70]



- 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

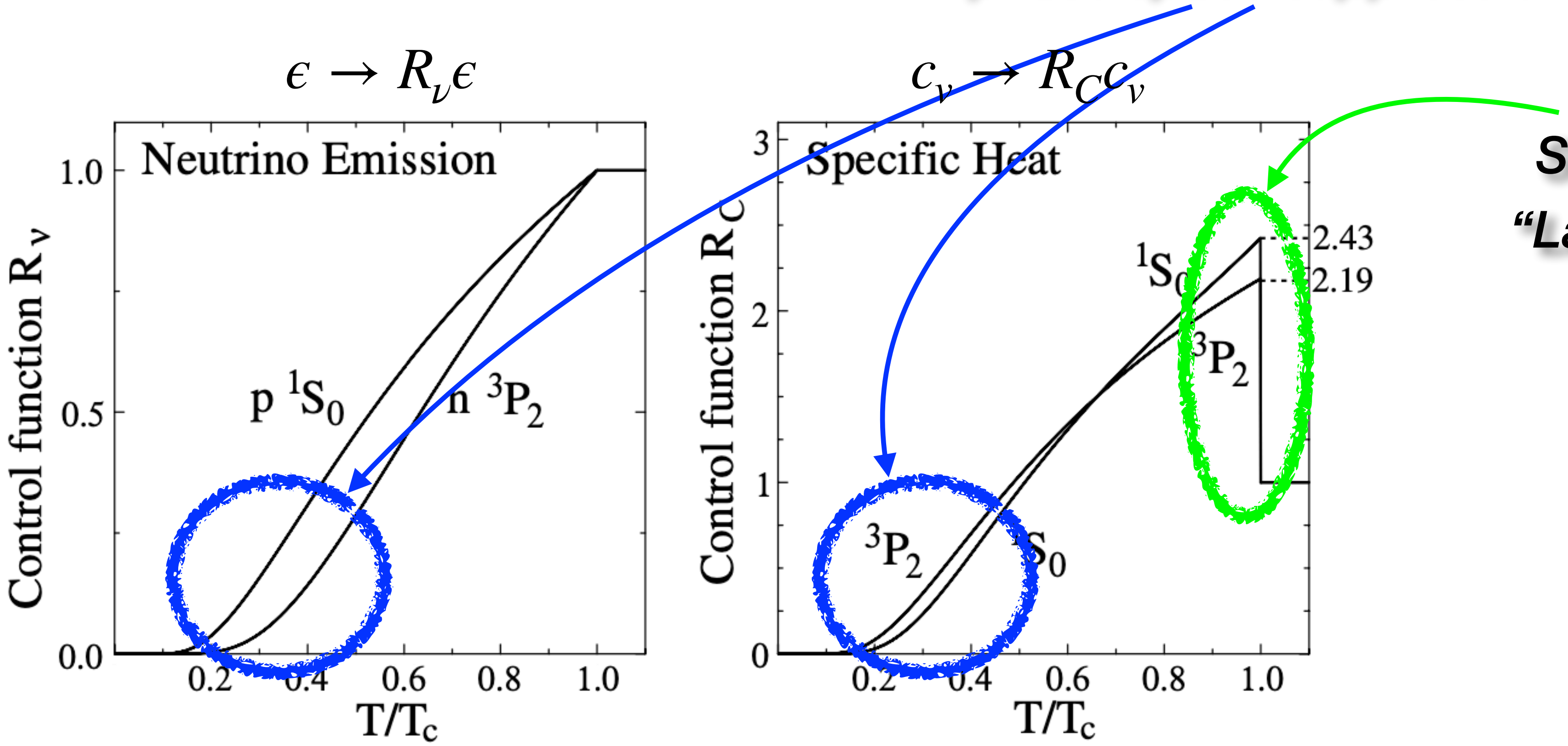


Effect of pairing for NS cooling

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

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

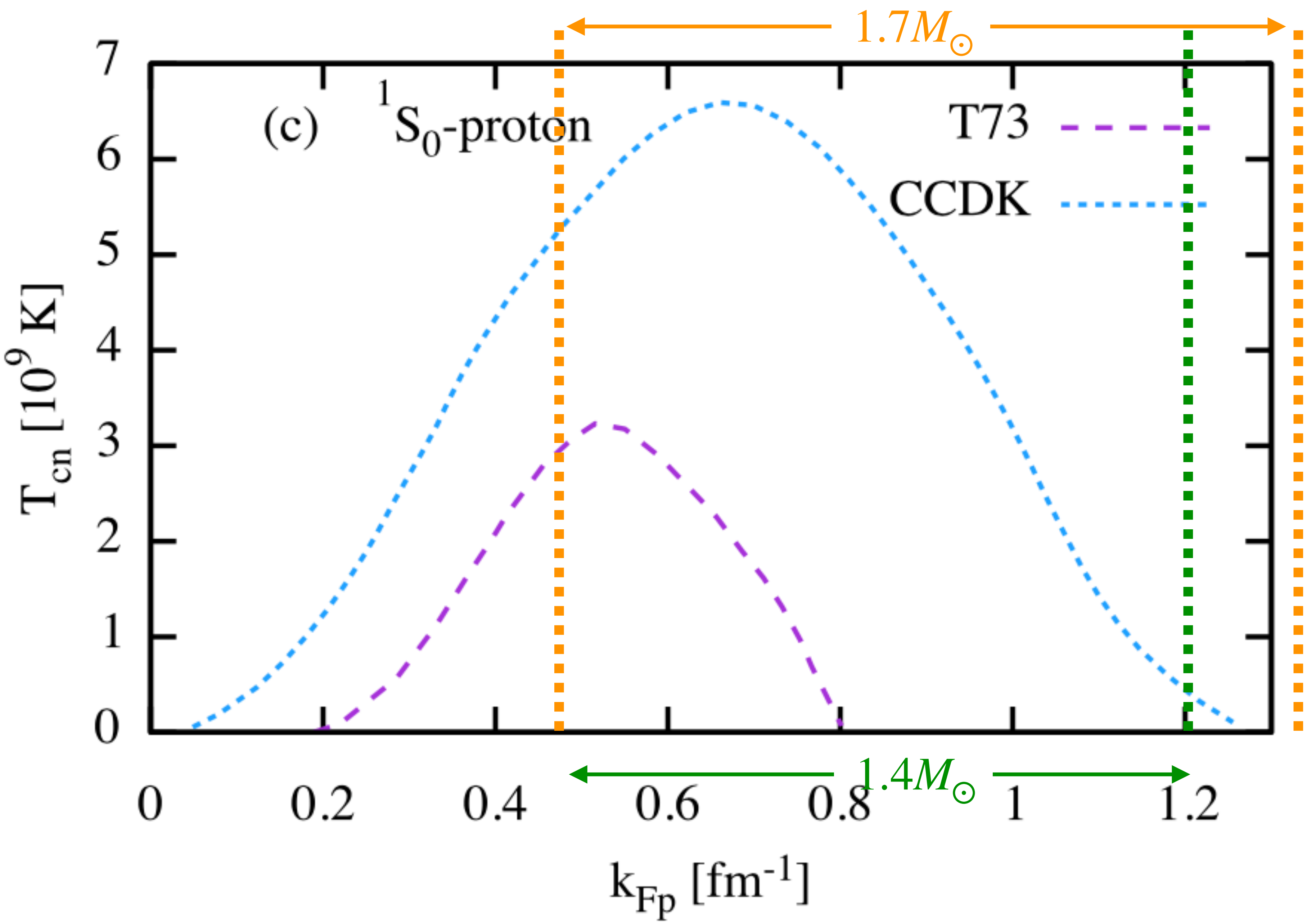
$\epsilon \rightarrow R_\nu \epsilon$ $c_v \rightarrow R_C c_v$



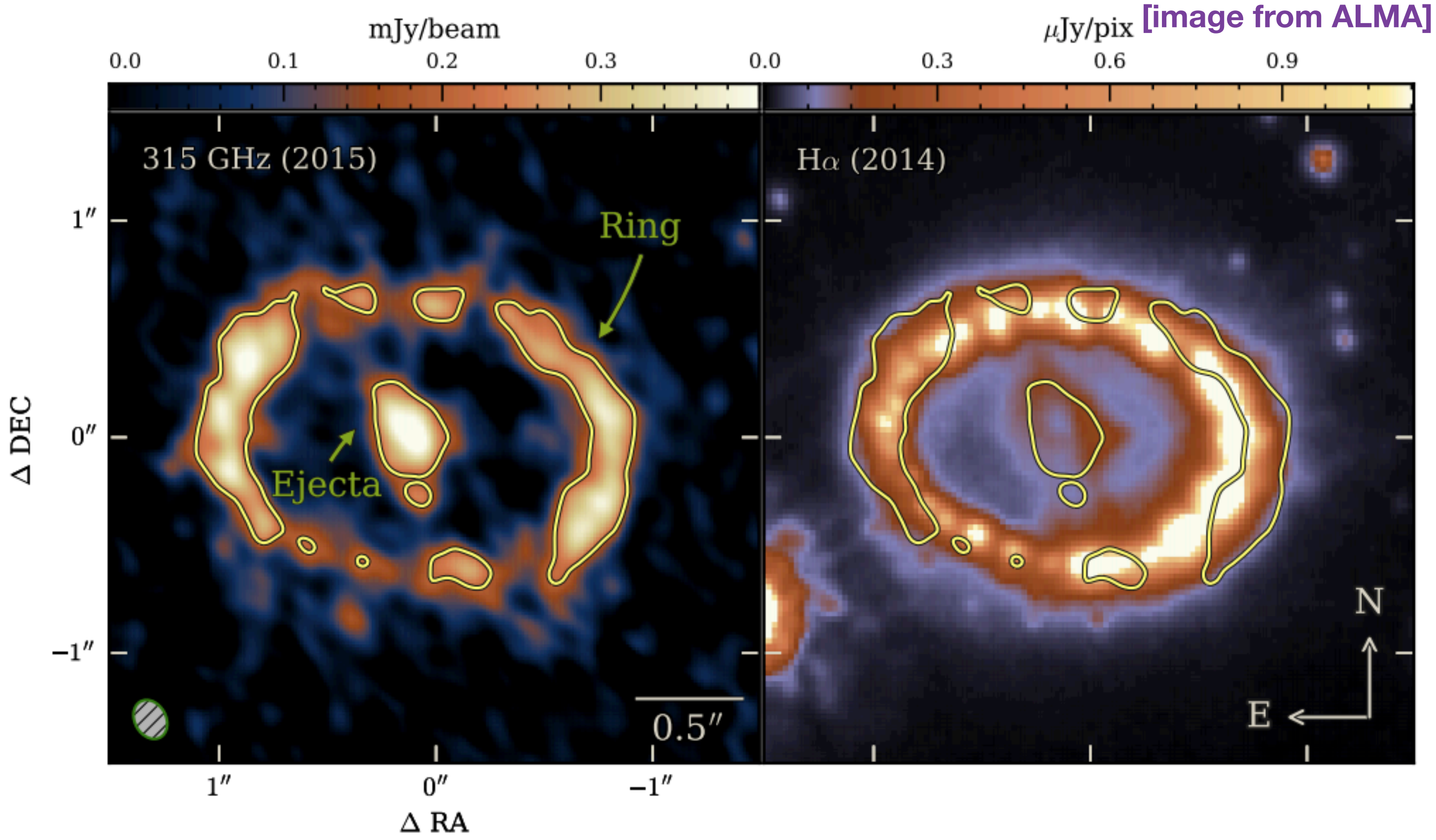
Second-order "Lambda-point"

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

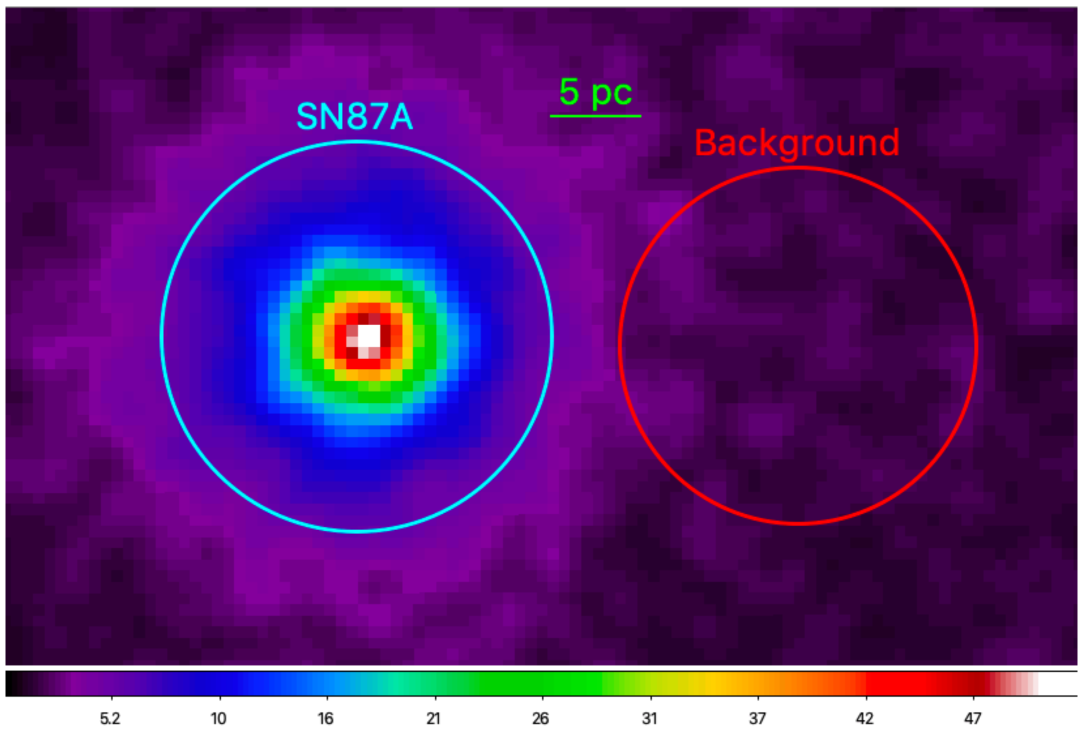
Proton singlet pairing models



Remnant of SN1987A?



[image from ALMA]



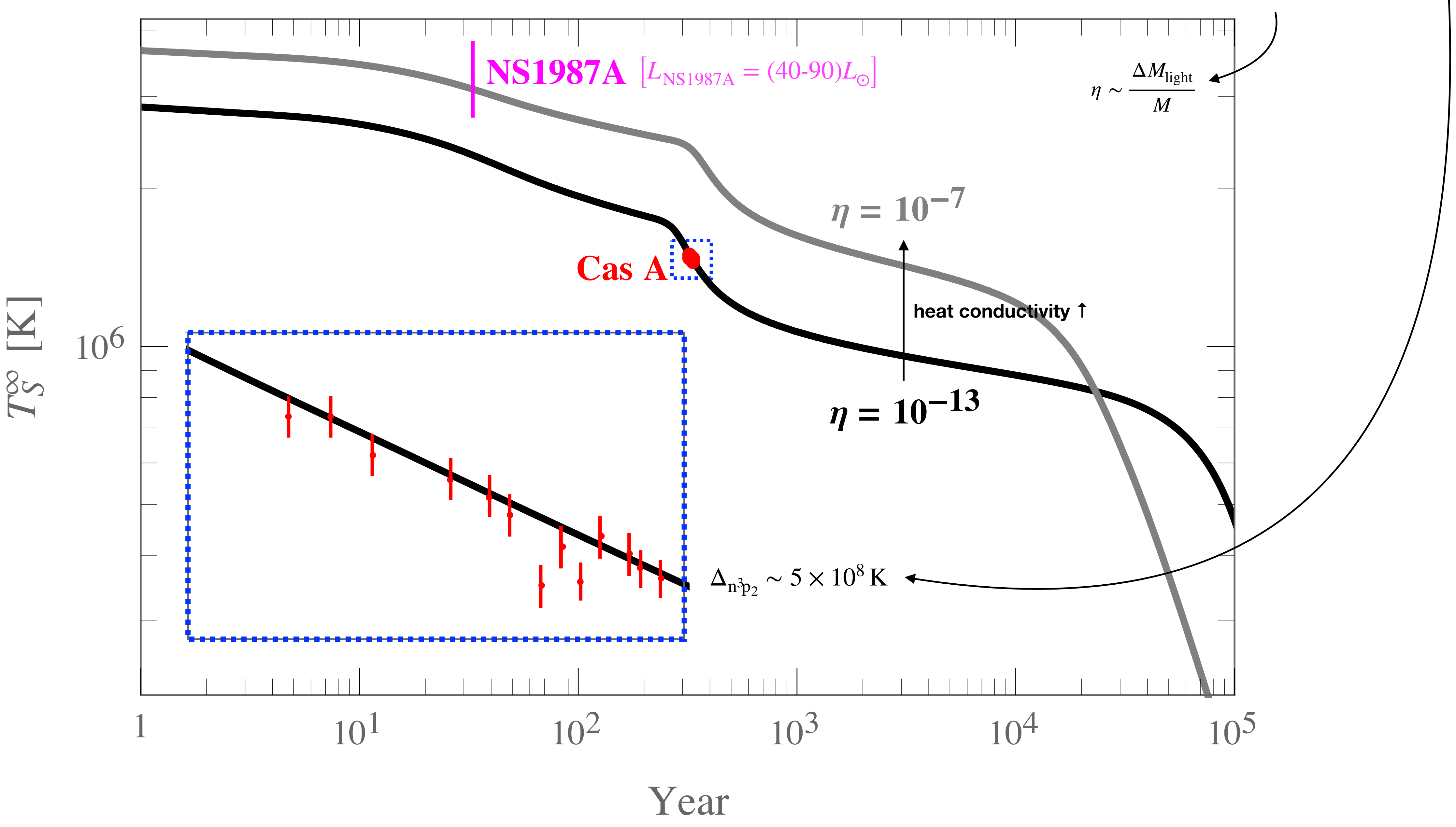
[image from NuSTAR]

- Presence of a compact source in the remnant is indicated.
  - heated dust clump (at the predicted position) + the hard X-ray spectrum
  - a neutron star rather than a black hole is likely to have formed

→ ***‘NS1987A’***

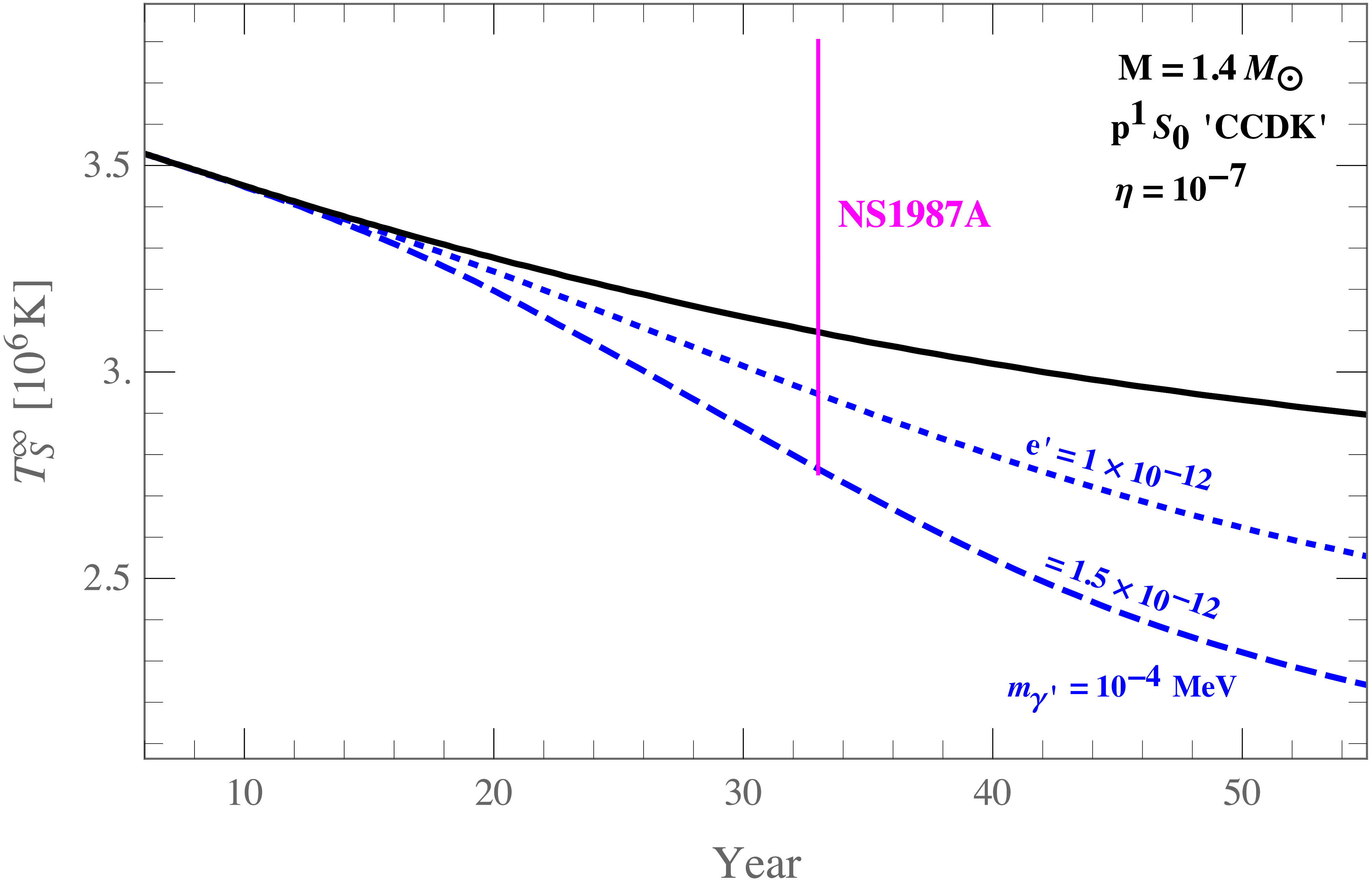
Minimal cooling scenario

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



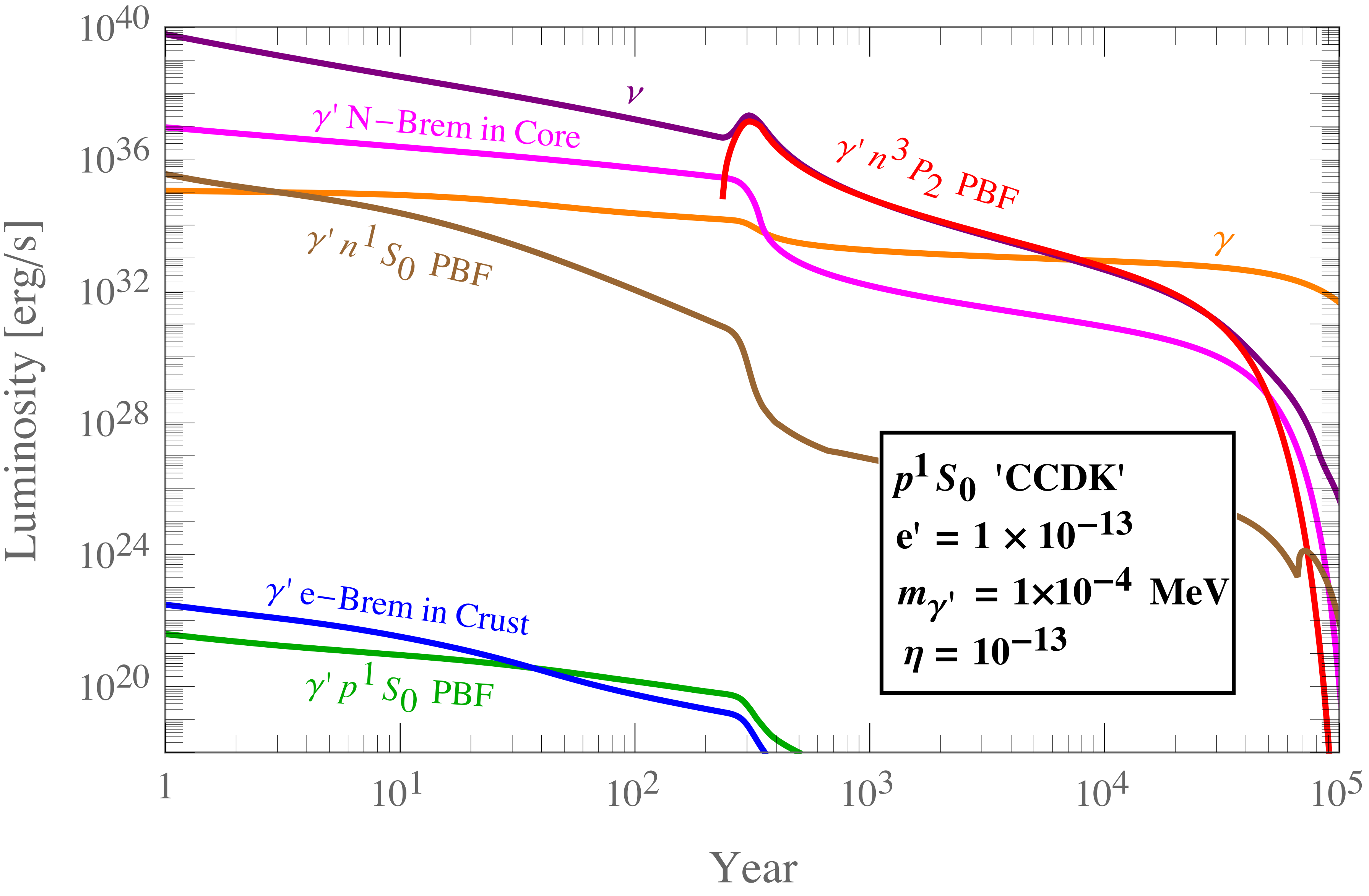
“NSCool” code

$U(1)_{\mathrm{B-L}}$ gauge boson cooling



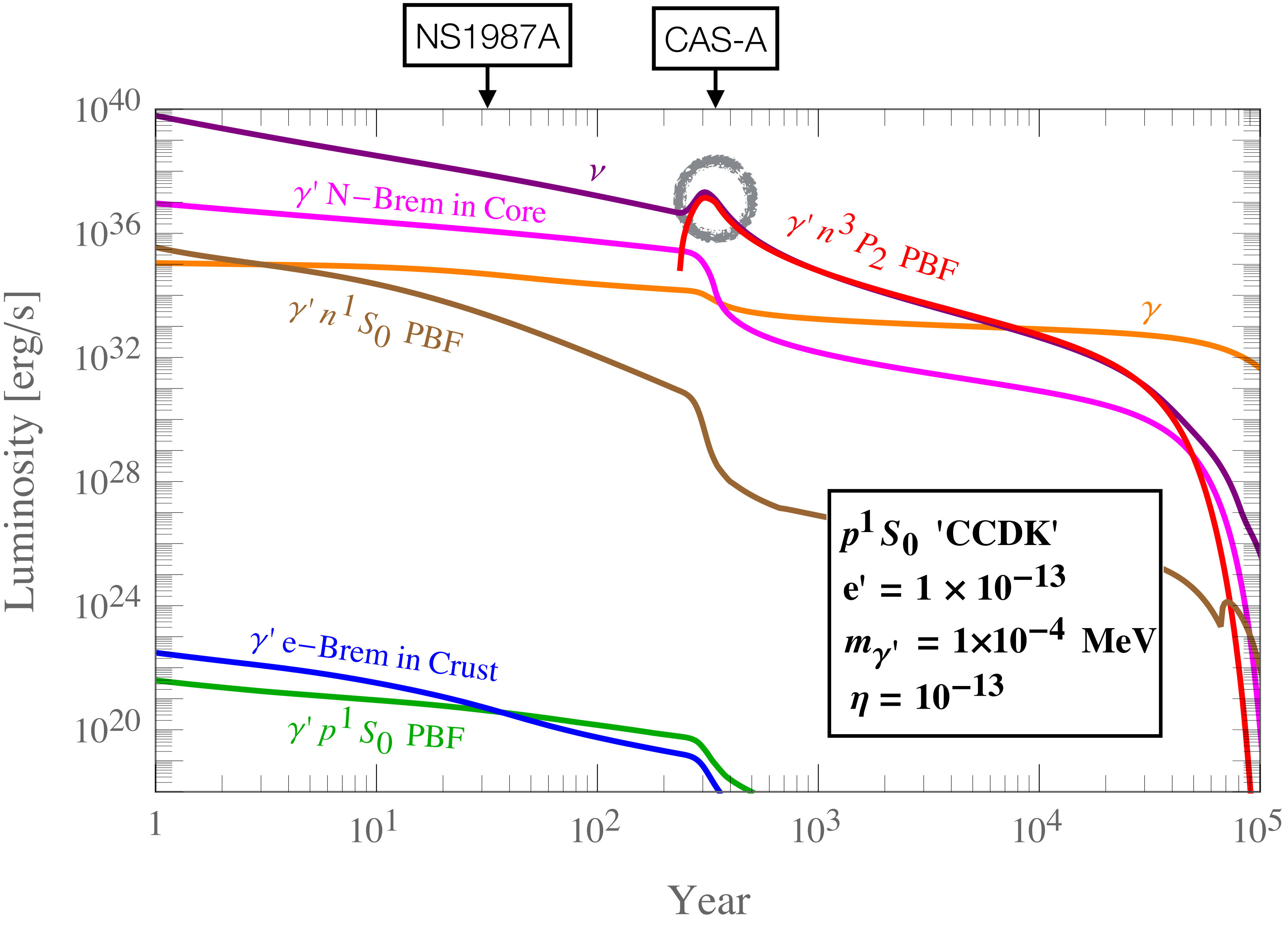
Luminosity of $U(1)_{\mathrm{B-L}}$ (vs. ν)

✻ Stellar cooling argument



Luminosity of $U(1)_{B-L}$ (vs. ν)

✻ Stellar cooling argument

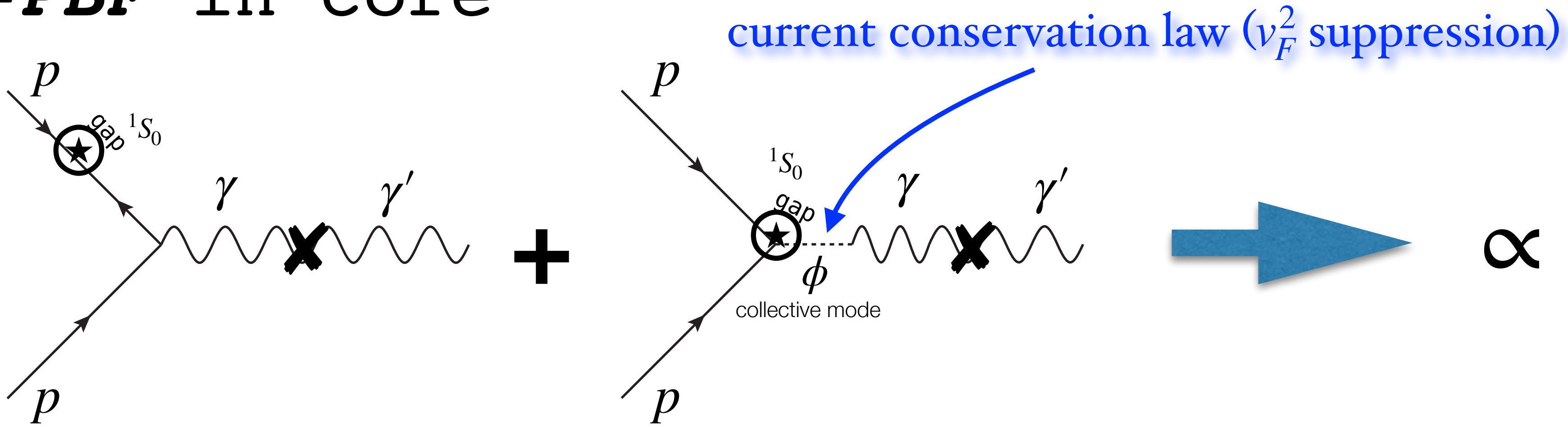


Dark photon in NS

◎ ***Longitudinal*** emission is dominant

$$\epsilon_{\rm L} \propto \varepsilon^2 m_{\gamma'}^2 T^2 \gg \epsilon_{\rm T} \propto \varepsilon^2 m_{\gamma'}^4$$

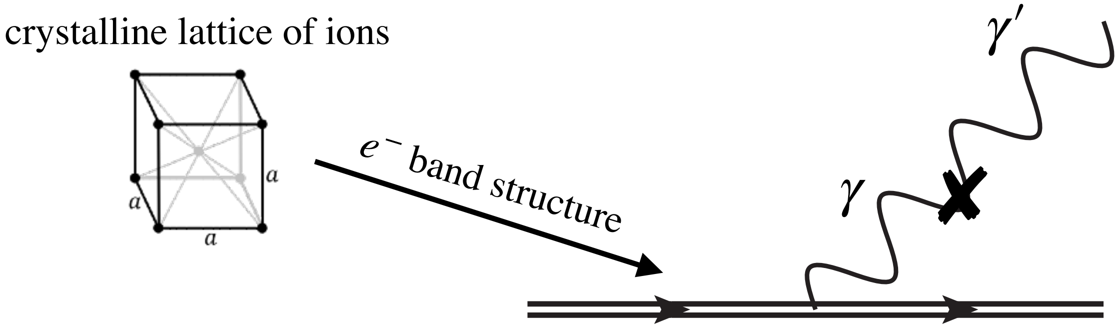
1. p-***PBF*** in core



current conservation law (v_F^2 suppression)

$\propto v_F^4 T^5$

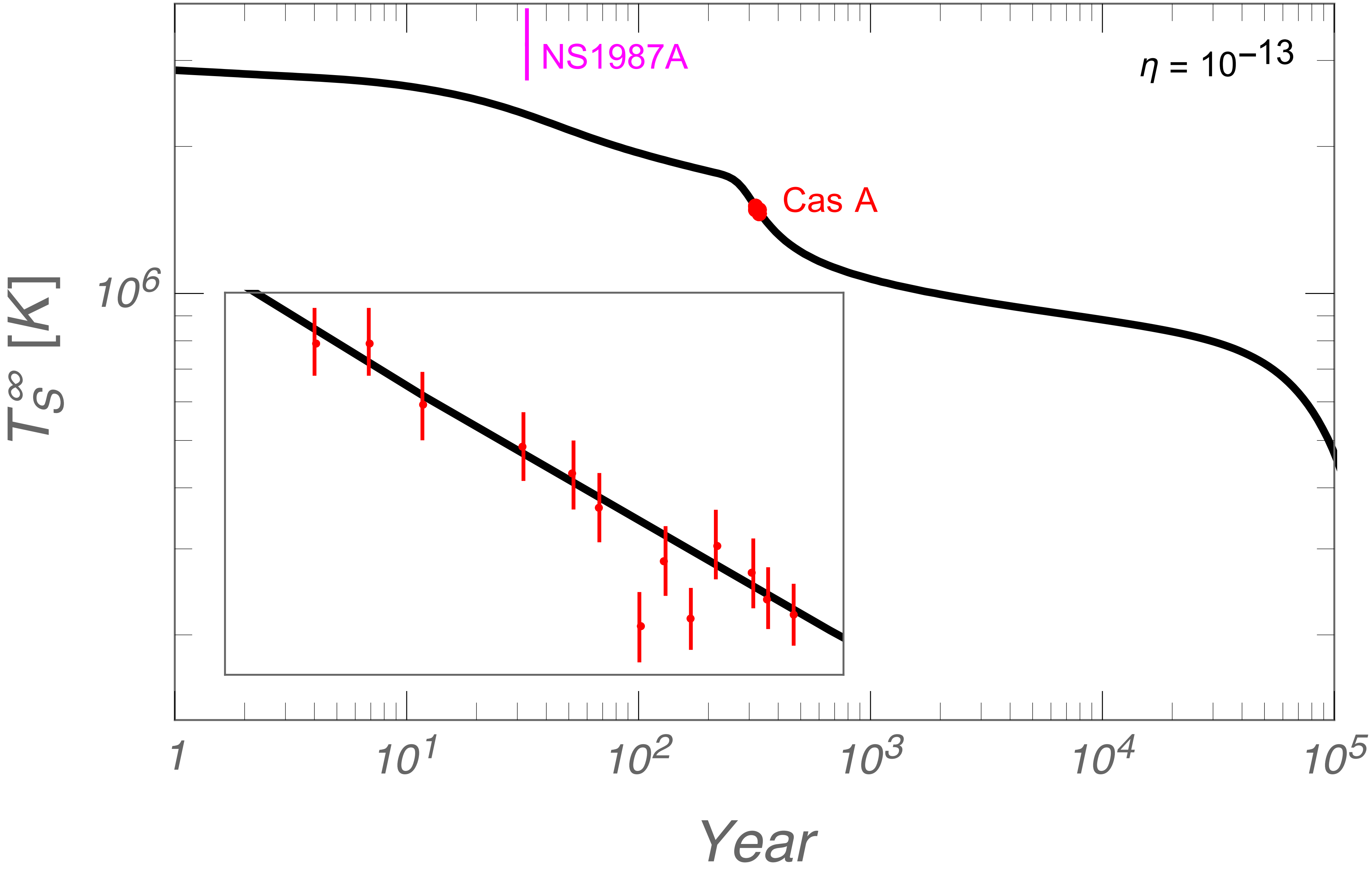
2. ***e-Bremsstrahlung*** in crust



$\propto T^6$

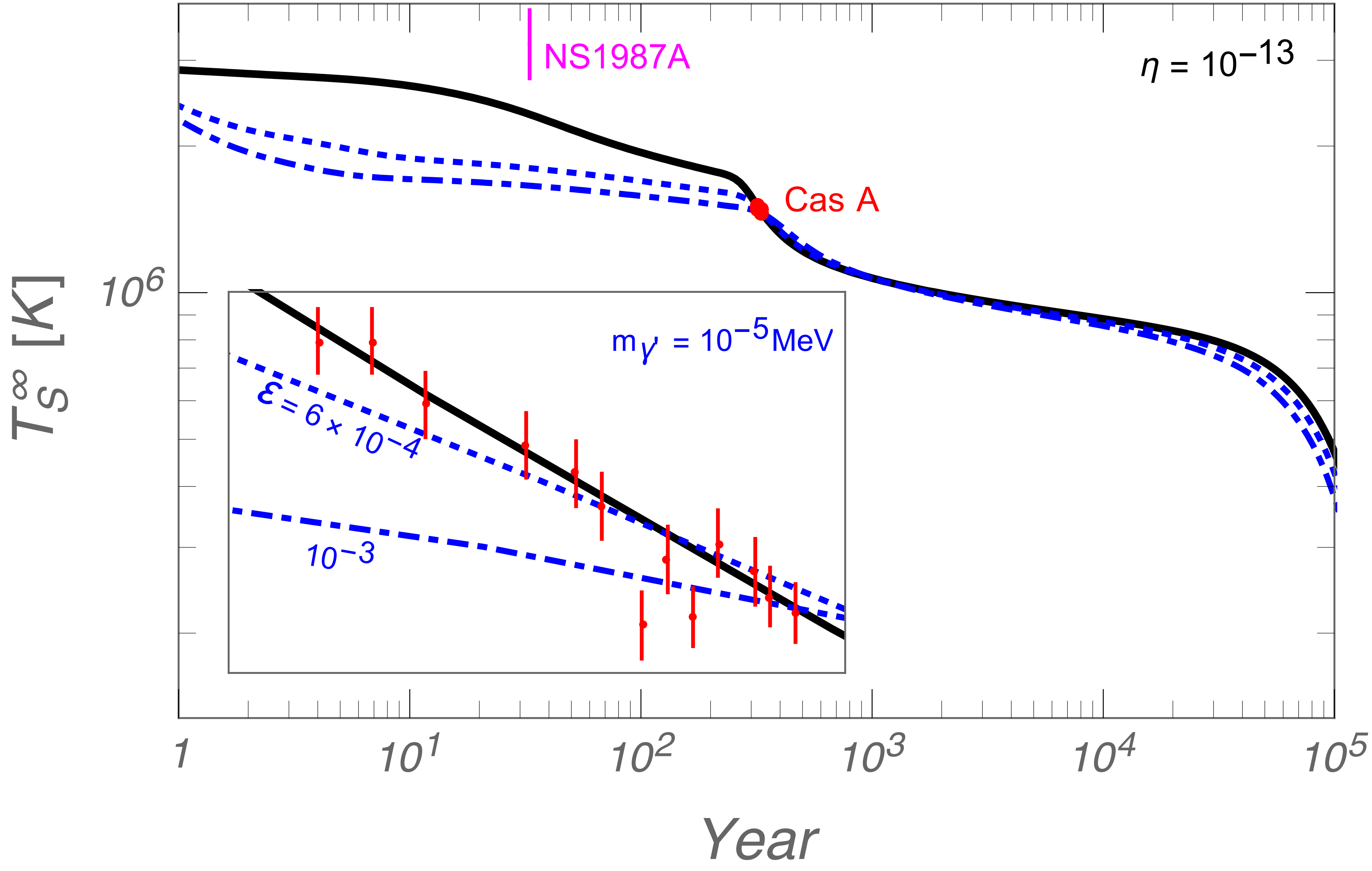
“NSCool” code

Dark photon cooling



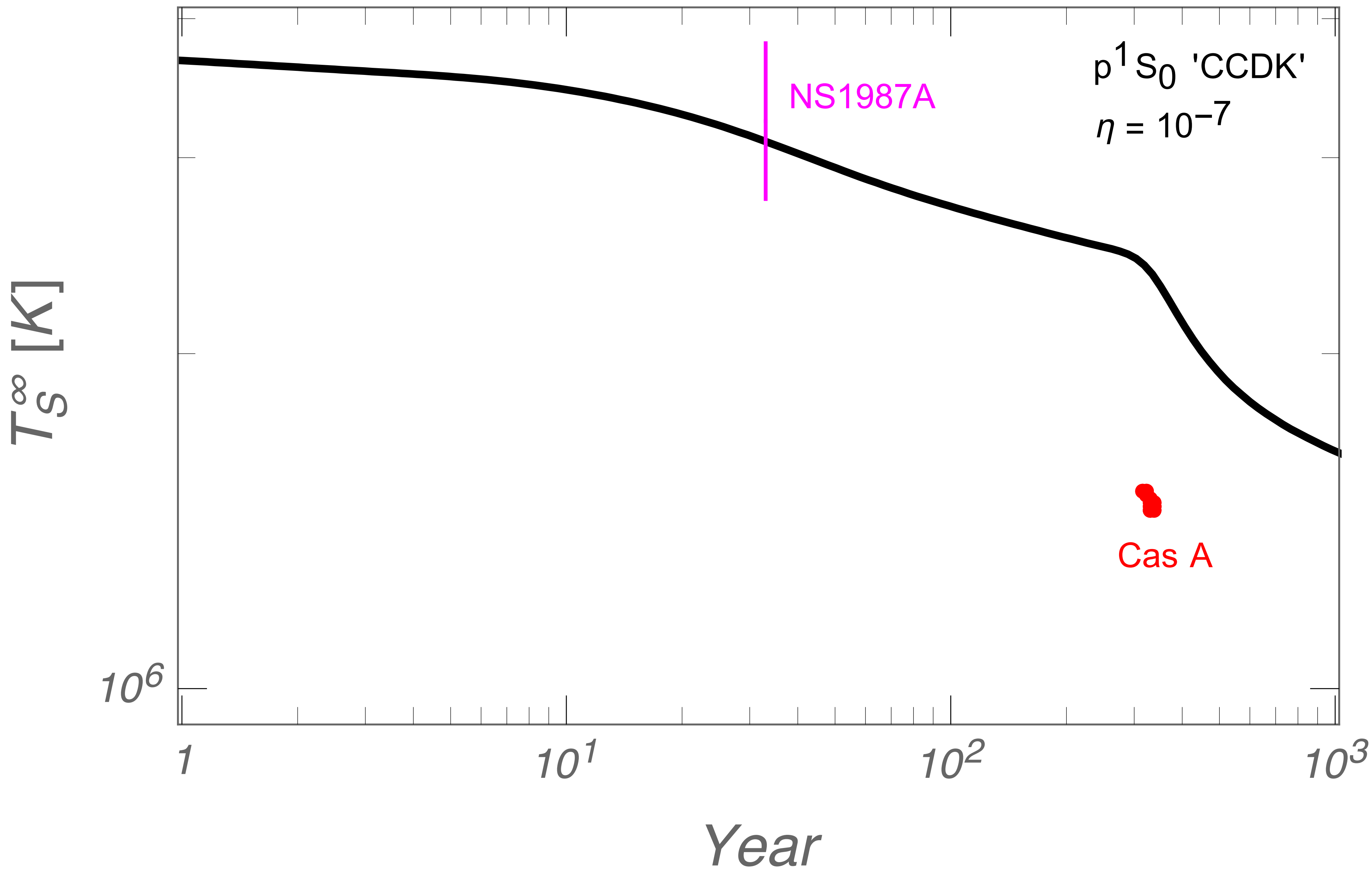
“NSCool” code

Dark photon cooling



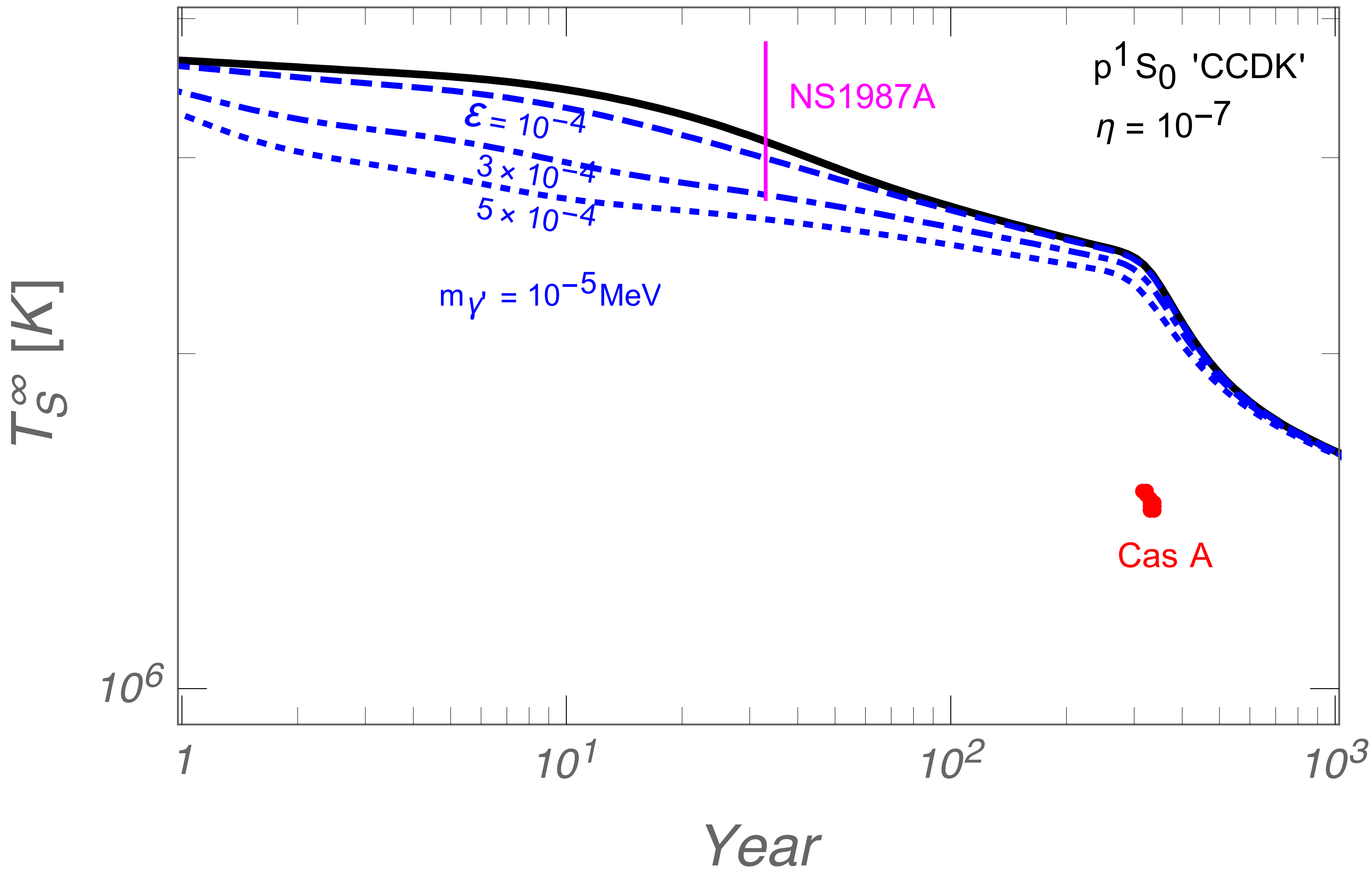
“NSCool” code

Dark photon cooling



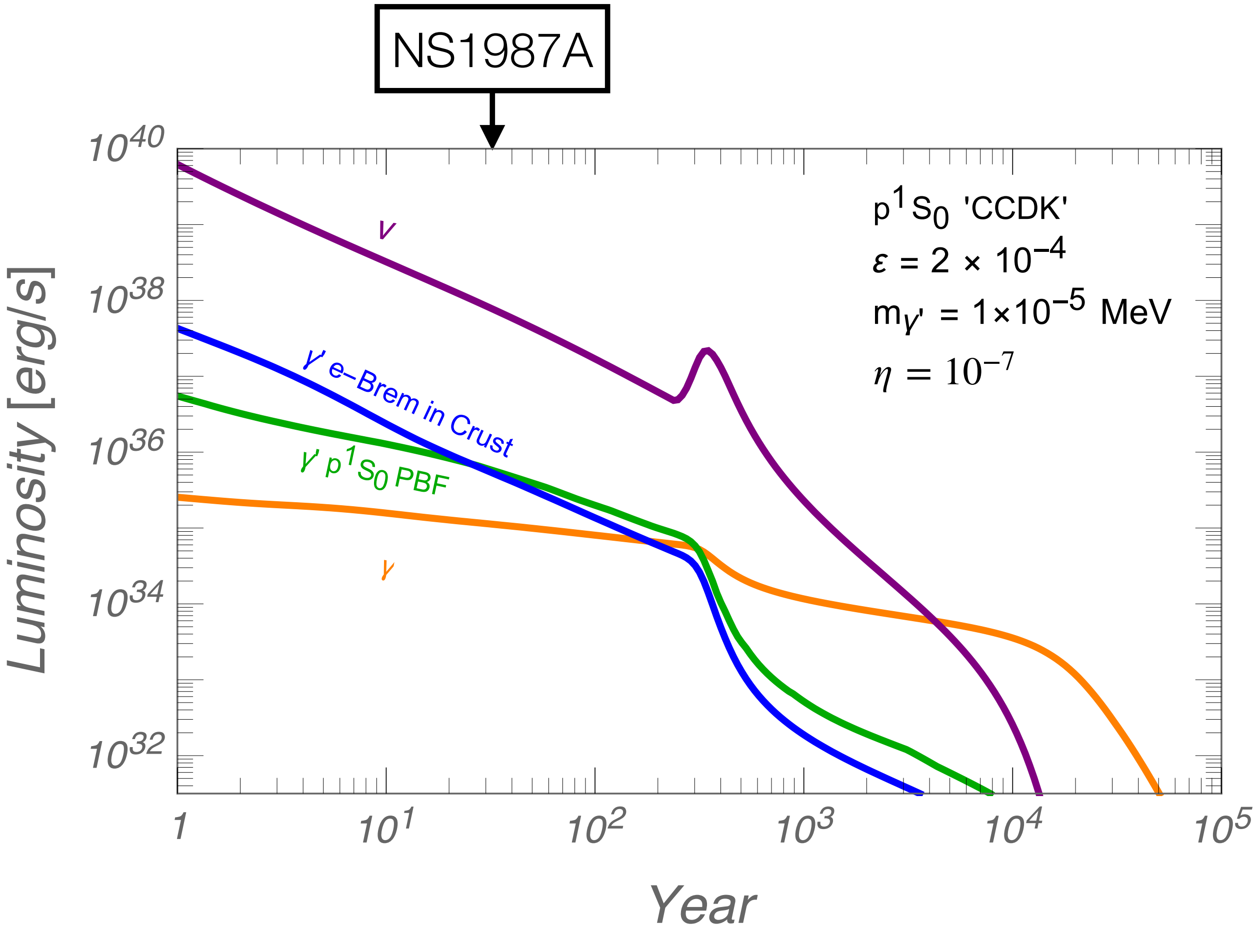
“NSCool” code

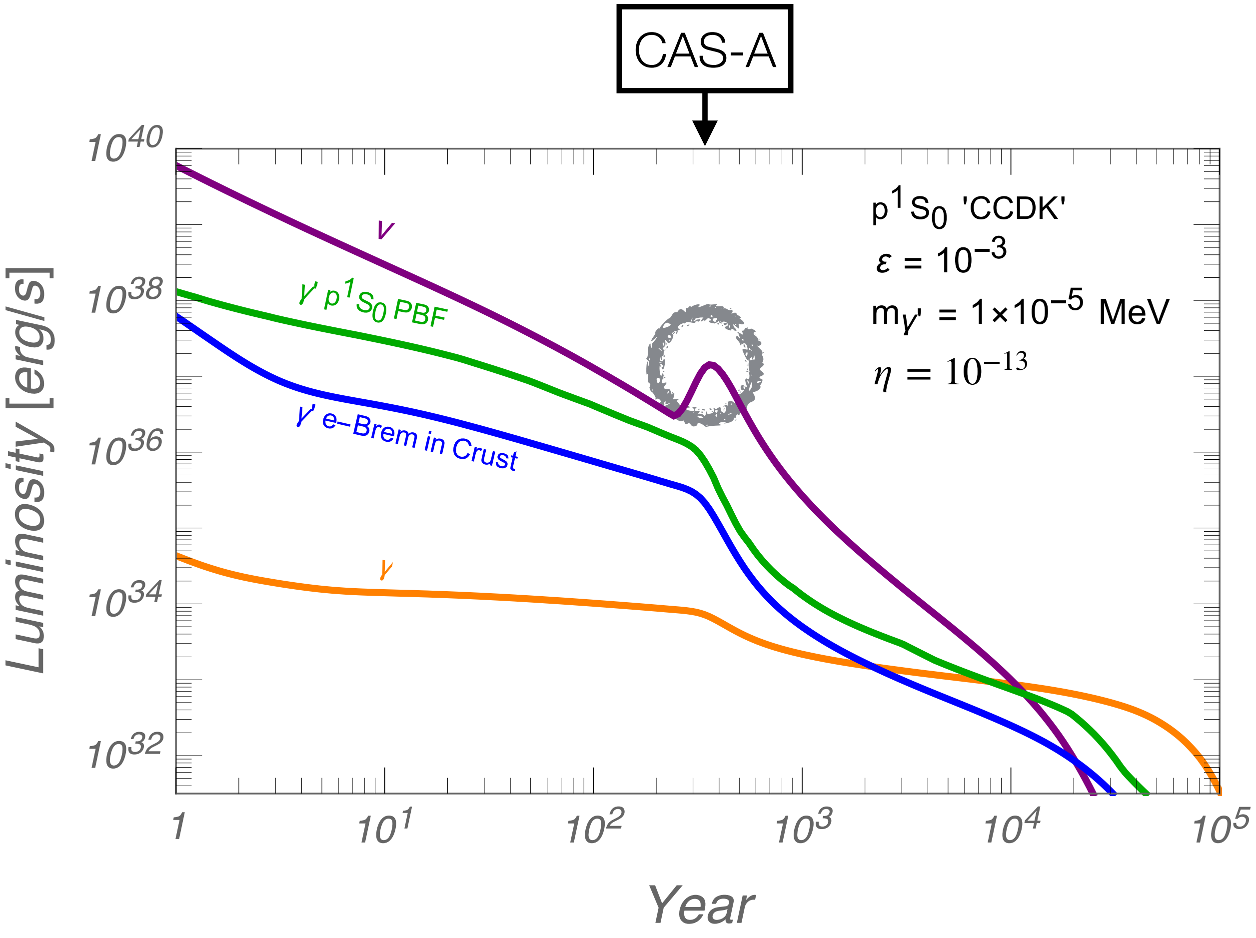
Dark photon cooling



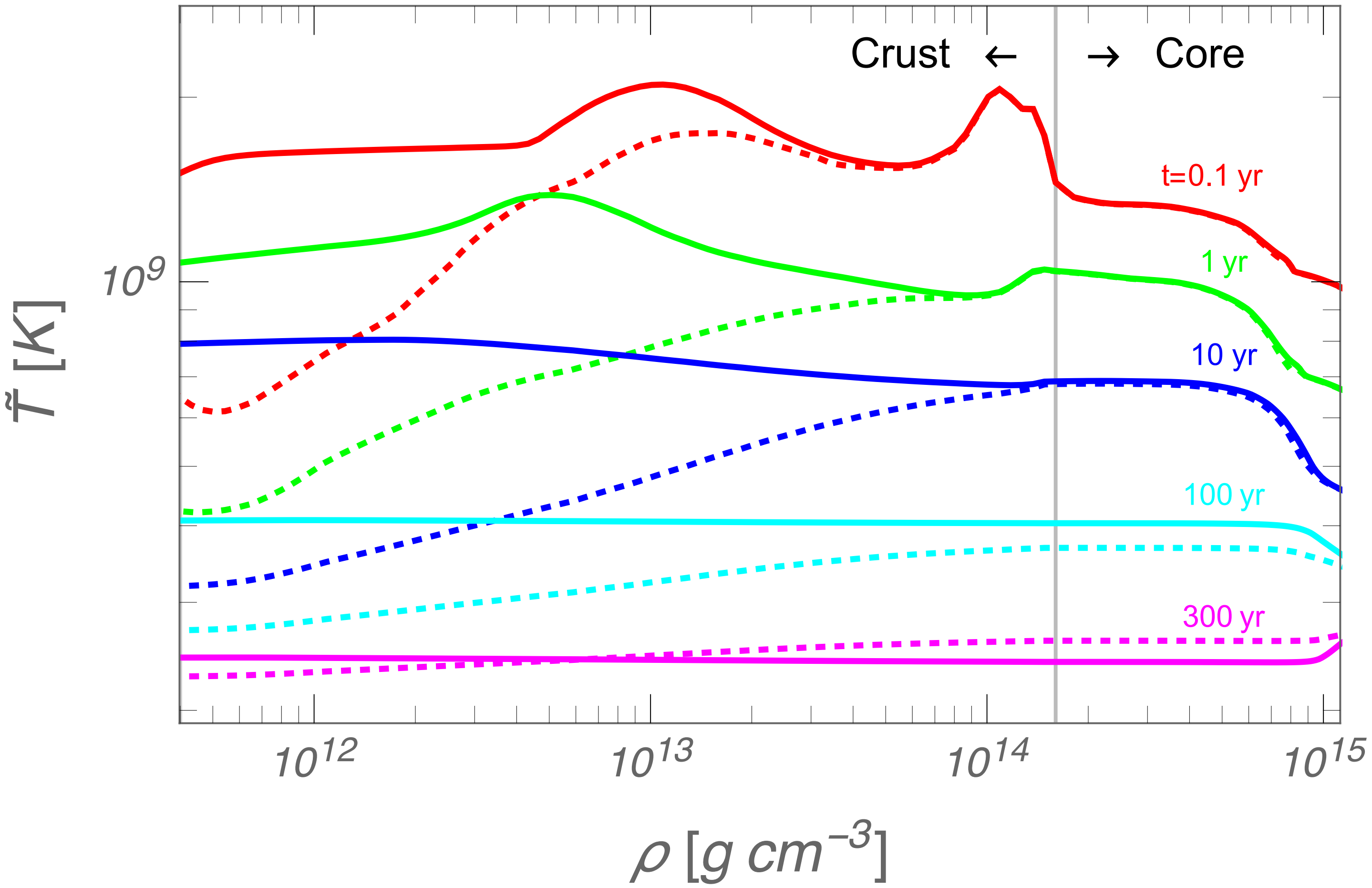
Luminosity of dark photon (vs. ν)

✻ Stellar cooling argument



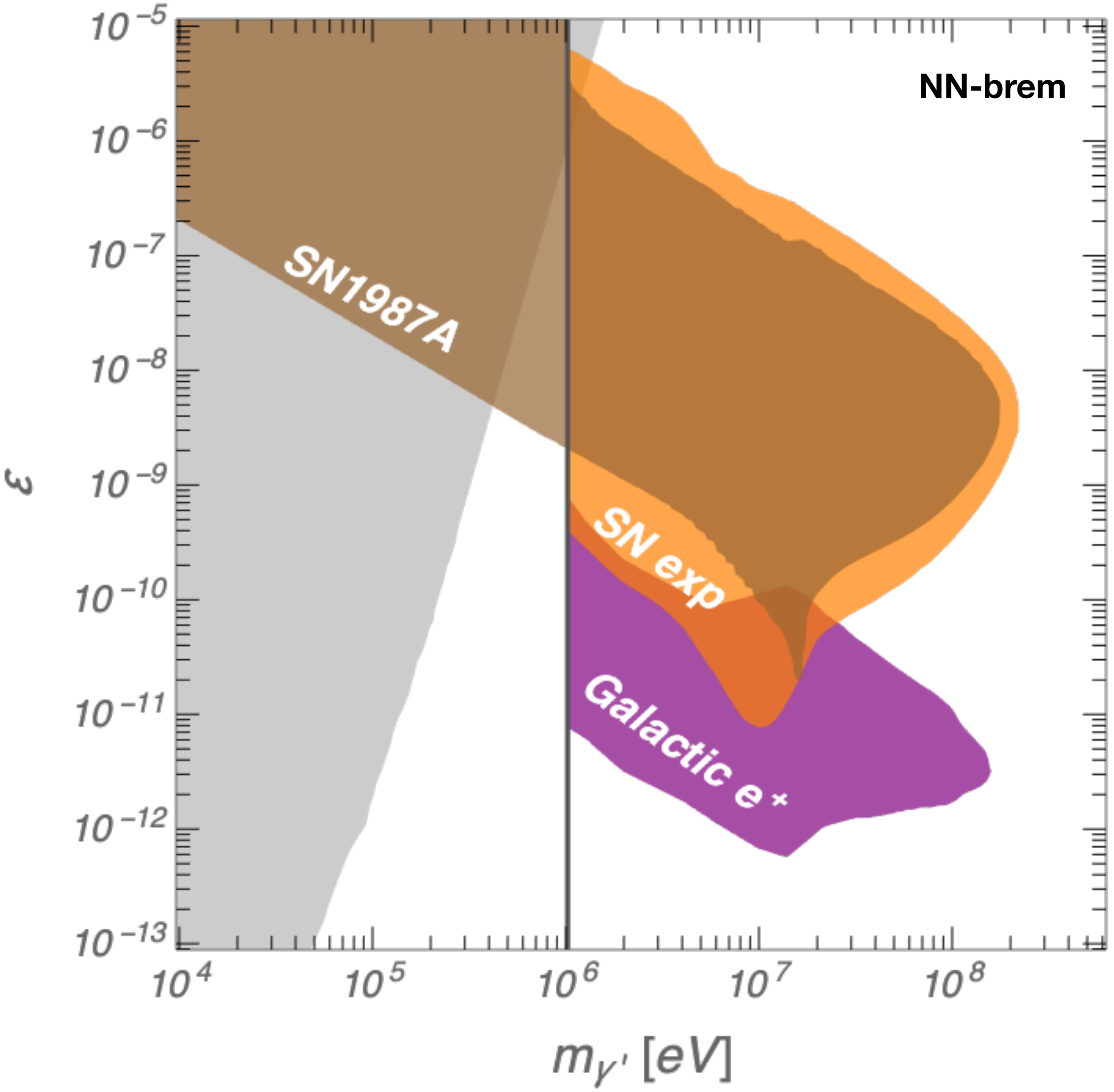


Temperature profiles



- Before thermal relaxation (~ 20 years), the surface temperature is mainly determined by the crust
- Due to small neutrino emission at the crust, the dark photon cooling could be efficient before thermal relaxation
- $m_\gamma^2 \propto n_e \propto \rho$, thus plasma suppression becomes weaker at outer part

Dark photon constraints



Dark photon constraints