Improved nuclear physics for supernovae

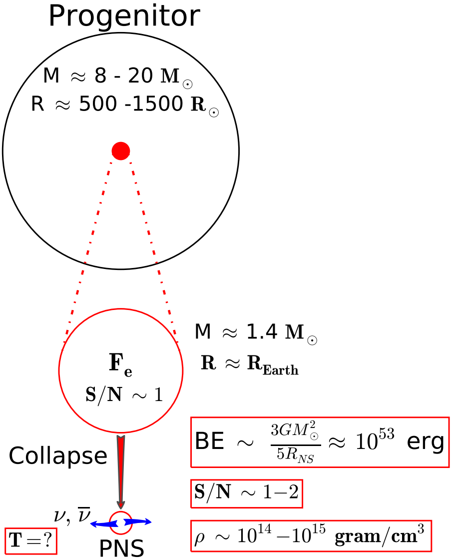
Implications for neutrino spectra, nucleosynthesis and dark matter

Ermal Rrapaj

University of Washington, Seattle

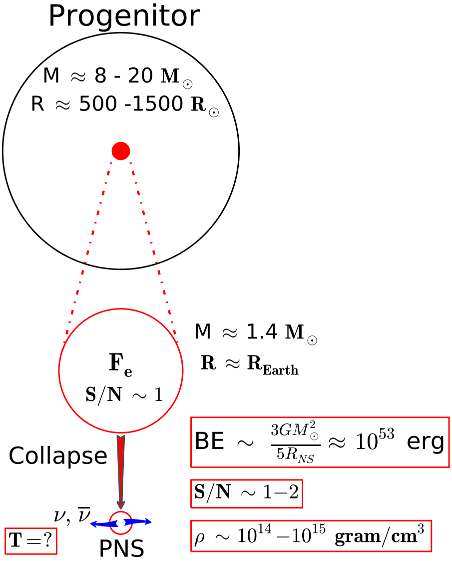
December 16, 2015

Core Collapse Supernovae



Core Collapse Supernovae

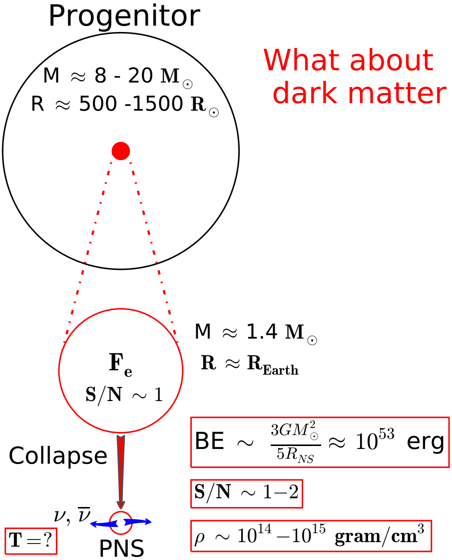
The binding energy is carried away by $\nu, \overline{\nu}$



Core Collapse Supernovae

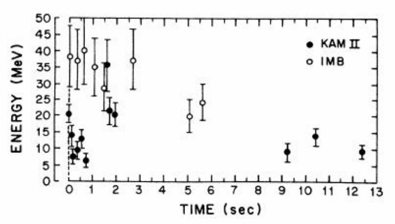
What about dark matter ?

The binding energy is carried away by $\nu, \overline{\nu}$



Detection of SN87A

Hirata et al, Phys. Rev. Lett. 58, (1490)



12 events in the burst sample observed in Kamiokande-II, and 8 events in the burst sample observed in the IMB detector

Dark Matter, Why ?

Astron.Astrophys. 571 (2014) A16

Energy composition of our universe: Planck Data

- Dark Energy: 68.3%
- Dark Matter (DM): 26.8%
- Attomic Matter: 4.8%
- Light: 0.005%
- Neutrinos: 0.0034%

Dark Matter, Why ?

Astron.Astrophys. 571 (2014) A16

Energy composition of our universe: Planck Data

- Dark Energy: 68.3%
- Dark Matter (DM): 26.8%
- Attomic Matter: 4.8%
- Light: 0.005%
- Neutrinos: 0.0034%

So, what is Dark Matter?

Can we 'see' dark matter?

Essig et al, arxiv:1311.0029 (2013)

Portal	Particles	Operators
"Vector"	Dark Photons	$-\epsilon e J_\mu^{\rm SM}$
"Axion"	PseudoScalars	$\frac{a}{f_a} G_{\mu\nu}\tilde{G}^{\mu\nu}$, $\frac{a}{f_a} F_{\mu\nu}\tilde{F^{\mu\nu}}$, $\frac{\partial_\mu a}{f_a}\overline{\Psi}\gamma^\mu\gamma^5\Psi$
"Higgs"	Dark Scalars	$(\mu S + \lambda S^2)H^\dagger H$
"Neutrino"	Sterile Neutrinos	$y_N LHN$

Can we 'see' dark matter?

Essig et al, arxiv:1311.0029 (2013)

Portal	Particles	Operators
"Vector"	Dark Photons	$-\epsilon e J_{\mu}^{\mathrm{SM}}$
"Axion"	PseudoScalars	$\frac{a}{f_a} G_{\mu\nu}\tilde{G}^{\mu\nu}$, $\frac{a}{f_a} F_{\mu\nu}\tilde{F^{\mu\nu}}$, $\frac{\partial_\mu a}{f_a}\overline{\Psi}\gamma^\mu\gamma^5\Psi$
"Higgs"	Dark Scalars	$(\mu S + \lambda S^2)H^\dagger H$
"Neutrino"	Sterile Neutrinos	$y_N LHN$

This talk will be focused on Dark Photons!

Dark Photons: How?

Holdom, Phys. Rev. B 166, (1986) 196

High - Energy

$$\mathcal{L} \supset -\frac{1}{4}(B_{\mu\nu})^2 - \frac{1}{4}(F'^{\mu\nu})^2 - \frac{\epsilon_Y}{2\cos\theta_W} B_{\mu\nu} F'^{\mu\nu} + \frac{1}{2} m^2_{A'} A'^2 + g_D J^D_\mu A'^\mu_D$$

Low - Energy

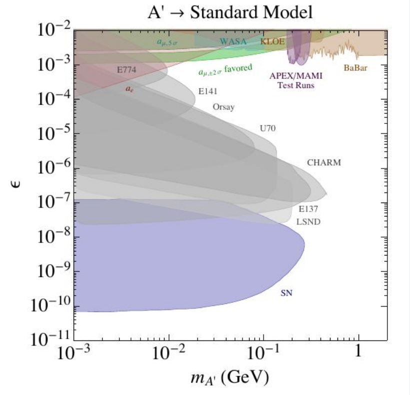
$$\mathcal{L} \supset g_Q A'_\mu J^{\text{EM}}_\mu - \frac{1}{2} m^2_{\gamma Q} A'_\mu A'^\mu + \left[g_B V^B_\mu J^B_\mu - \frac{1}{2} m^2_{\gamma B} (V^B_\mu)^2 \right]$$

Lee, Yang Phys. Rev. 98, 1501 (1955)

Batell, deNerville, McKeen, Pospelov, Ritz Phys. Rev. D 90, 115014 (2014)

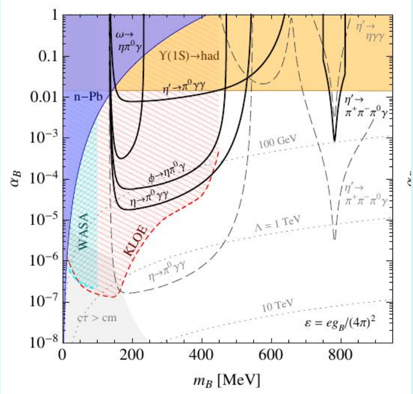
Dark Photons: Why?

γ_Q Parameter Space



Snowmass report (2013) arXiv:1311.0029

γ_B Parameter Space

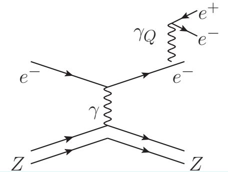


Tulin Phys. Rev. D 89, 11408 (2014)

Dark Photons: Why?

http://hallaweb.jlab.org/experiment/APEX

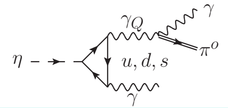
Experimental searches for γ_Q



APEX (spring 2016) at Jefferson Laboratory

- $10^{-2} \lesssim \epsilon_Q \lesssim 10^{-10}$
- $65\ \text{MeV} \leq m_{\gamma_Q} \leq 550\ \text{MeV}$

Experimental searches for γ_B



Jlab Eta Factory (JEF) Experiment

- $10^{-1} \lesssim \alpha_B \lesssim 10^{-7}$
- $140\ \text{MeV} \leq m_{\gamma_B} \leq 550\ \text{MeV}$

https://cnidlamp.jlab.org/RareEtaDecay/JDocDB/system/files/biblio/2015/04/jef-gan-aps-pdf.pdf

And many more other experiments

Implications for supernovae

Dark matter cooling of PNS

1. produced in the hot core
2. light in mass $\longrightarrow$ copious amounts!
3. sap energy from the core
4. reduce neutrino energy and burst duration!

Raffelt's Criteria

Conditions for fiducial calculations:

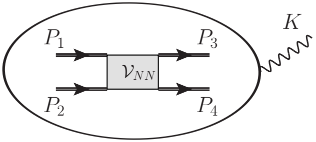
- $T = 30$ MeV
- $\rho = 3 \times 10^{14}$ gram/cm^3

$$\dot{E} \approx 10^{19} \frac{\text{erg}}{\text{gram s}} \implies \text{Neutrino burst duration is halfed!}$$

"Stars as laboratories for fundamental physics: The astrophysics of neutrinos, axions, and other weakly interacting particles" (University of Chicago Press, 1996)

How is light dark matter produced ?

Nucleon Bremsstrahlung



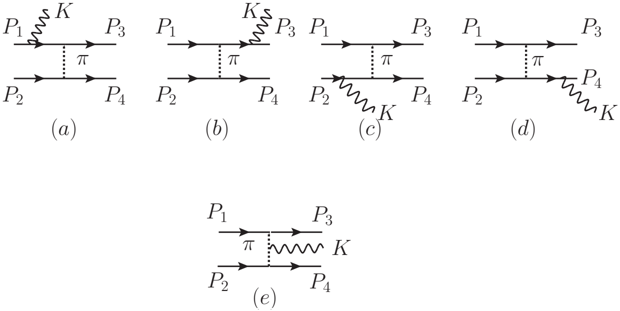
What has been studied so far ?!

- Axions, Burrows, Turner, Brinkman, Phys. Rev. D 39, 1020,(1989)
- Kaluza–Klein gravitons and dilatons, Hannart, Phillips,Reddy, Savage, Nuc. Phys. B 595(2001)
- Neutralinos Dreiner, Hanhart, Langenfeld, Phillips Phys. Rev. D 68, 055004 (2003)
- Dark Photons Dent, Ferrer, Kraus arxiv: 1201.2683 (2012)
  Kazanas, Mohapatra, Nussinov Teplitz, Zhang Nuc. Phys. B. 90, 17, (2014)

Current Dark Photon Constraint: Supernova Cooling

Dent, Ferrer, Kraus arxiv: 1201.2683 (2012)

Production by Bremsstrahlung

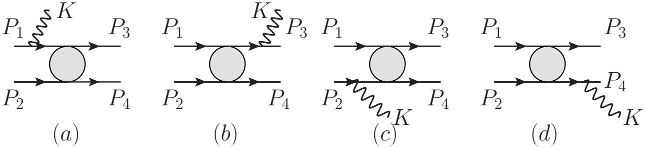


Emissivity

$\mathcal{L}_{\tilde{\gamma}} \leq 10^{53}$ erg/s $\longleftrightarrow$ $\dot{E} \leq 8 \times 10^{22}$ erg/g/s

Bremsstrahlung: Soft Radiation Approximation (SRA)

Low Phys. Rev. 110, 974 (1958)



$$d\sigma_{pp\to pp\tilde{\gamma}} \approx -4\pi\alpha_{\rm em}\epsilon^2 \ \frac{d^3k}{2\omega}(\epsilon^\mu J_\mu)^2 \ d\sigma_{NN\to NN}$$

$$J^{(2)}_\mu = \left(\frac{P_1}{P_1\cdot K} - \frac{P_3}{P_3\cdot K}\right)_\mu , \ J^{(4)}_\mu = \left(\frac{P_1}{P_1\cdot K} + \frac{P_2}{P_2\cdot K} - \frac{P_3}{P_3\cdot K} - \frac{P_4}{P_4\cdot K}\right)_\mu$$

Rrapaj, Reddy arxiv:1511.09136

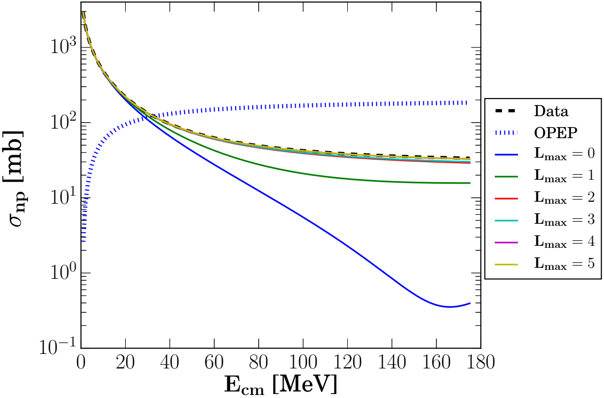
$$\dot{\epsilon}_{np\to np\gamma_Q} = \frac{2\alpha_{\rm em}\epsilon_Q^2}{\sqrt{\pi}}\frac{n_n n_p}{(MT)^{3/2}}T^4\int_{m_{\gamma_Q}/T}^{\infty} dx\ e^{-x}\ x^3\ \mathcal{I}^{(2)}(\frac{m_{\gamma_Q}/T}{x})\ \sigma^{(2)}_{np}(xT)$$

$$\dot{\epsilon}_{ij\to ij\gamma_B} = \frac{2\alpha_{\rm em}\epsilon_B^2}{\sqrt{\pi}}\frac{n_i n_j}{(MT)^{3/2}}T^5\int_{m_{\gamma_B}/T}^{\infty} dx\ e^{-x}\ \frac{x^4}{M}\ \mathcal{I}^{(4)}(\frac{m_{\gamma_B}/T}{x})\ \sigma^{(4)}_{ij}(xT)$$

$$\sigma^{(2)}_{ij} = \int d\cos\theta_{\rm cm}\frac{d\sigma_{n_in_j\to n_in_j}}{d\theta_{\rm cm}}(1-\cos\theta_{\rm cm}),\ \sigma^{(4)}_{ij} = \int d\cos\theta_{\rm cm}\frac{d\sigma_{n_in_j\to n_in_j}}{d\theta_{\rm cm}}(1-\cos^2\theta_{\rm cm})$$

Partial Wave Expansion vs OPEP

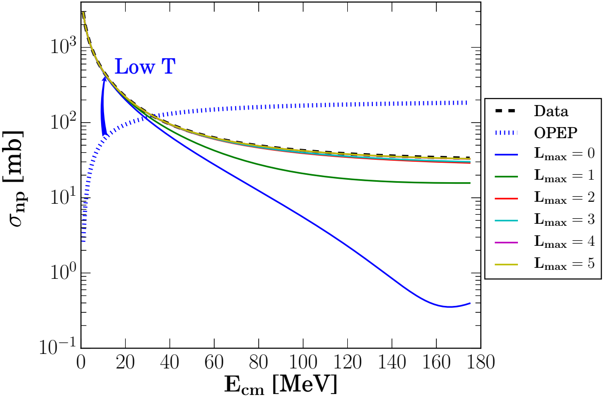
Rrapaj, Reddy arxiv:1511.09136



Data from Nijmegen University database

Partial Wave Expansion vs OPEP

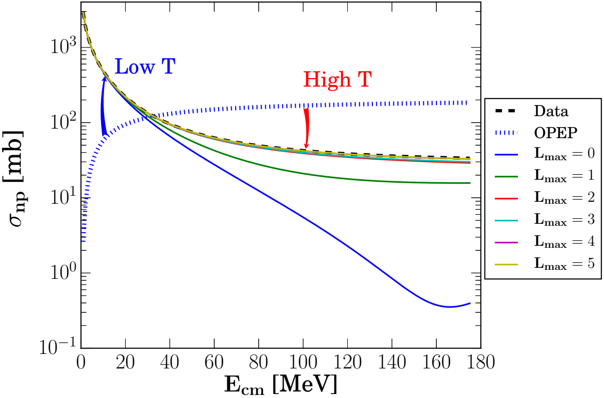
Rrapaj, Reddy arxiv:1511.09136



Data from Nijmegen University database

Partial Wave Expansion vs OPEP

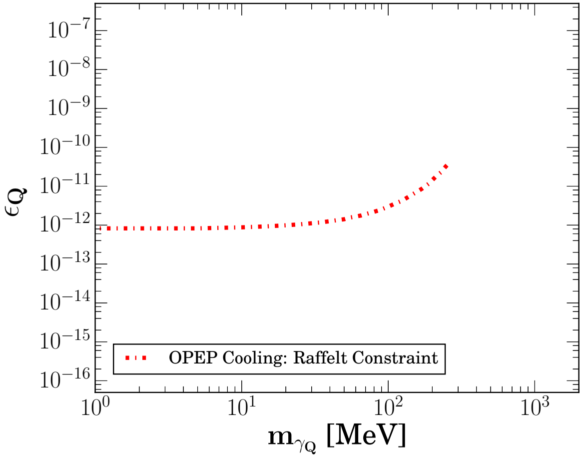
Rrapaj, Reddy arxiv:1511.09136



Data from Nijmegen University database

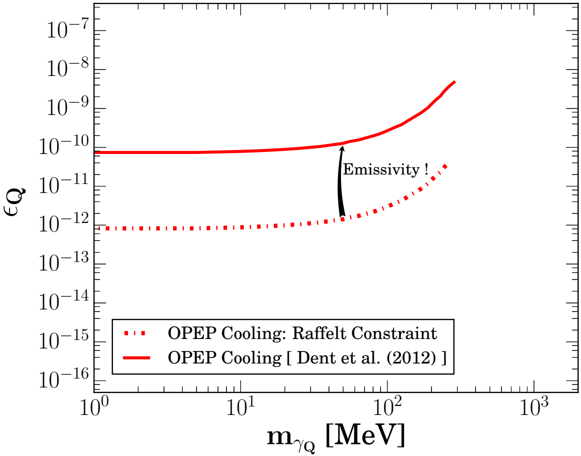
Dark Photon Constraint

Rrapaj, Reddy arxiv:1511.09136



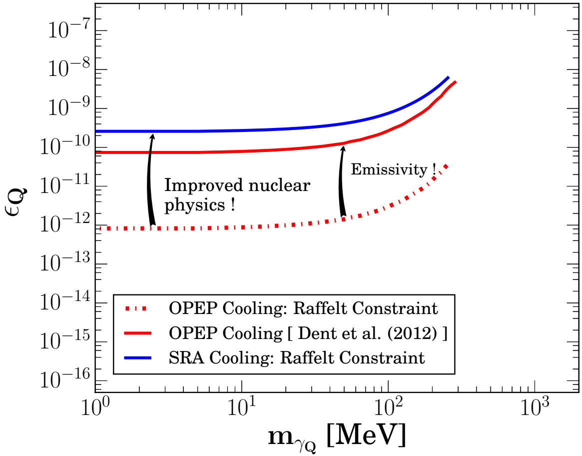
Dark Photon Constraint

Rrapaj, Reddy arxiv:1511.09136



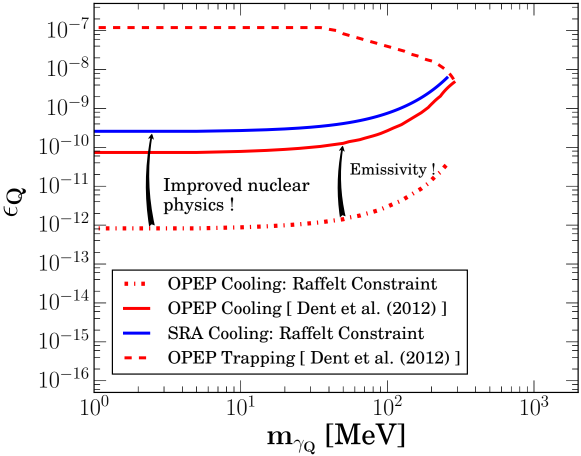
Dark Photon Constraint

Rrapaj, Reddy arxiv:1511.09136



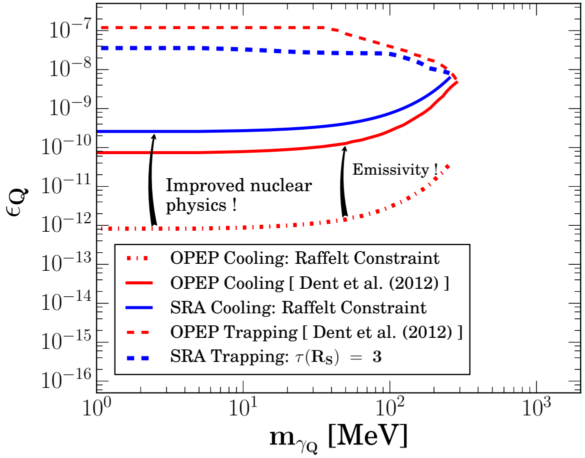
Dark Photon Constraint

Rrapaj, Reddy arxiv:1511.09136



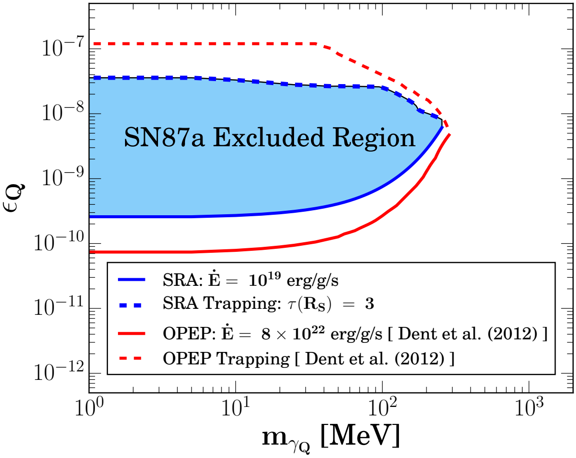
Dark Photon Constraint

Rrapaj, Reddy arxiv:1511.09136



Dark Photon Constraint

Rrapaj, Reddy arxiv:1511.09136

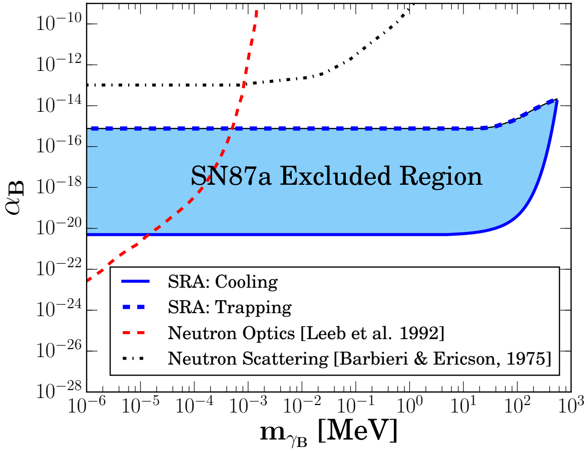


What about the dark leptophobic photon ?!

No Current Supernova constraint!

Dark photon coupled only to baryonic current

Rrapaj, Reddy arxiv:1511.09136



So, did we ‘solve’ this issue?

So, did we 'solve' this issue?

NOPE

Uncertainties in establishing constraints

Scattering Rate: Bremsstrahlung

- SRA valid only for $\omega/E_{\mathrm{CM}} \ll 1$
  (perhaps effective field theories and two body currents)
- medium effects not included
  (rescattering, nucleon excitation lifetimes)
- ...

Uncertainties in establishing constraints

Scattering Rate: Bremsstrahlung

- SRA valid only for $\omega/E_{\mathrm{CM}} \ll 1$
  (perhaps effective field theories and two body currents)
- medium effects not included
  (rescattering, nucleon excitation lifetimes)
- ...

Supernova environment

- $S/N \sim 1-2$
- $\rho_0 = 0.16 \text{ fm}^{-3} \leq \rho_C \leq ? \longrightarrow$ Equation of State (EoS)
- $T = ? \longrightarrow$ Specifit heat $\longrightarrow$ EoS$\longrightarrow$?

$T = 0$: Equation of State

Constraining mean field models

- Saturation density properties   Dutra, Lourenco, Martins,Delfino, Phys.Rev.C 85, 035201 (2012)
- Low density neutron matter, ab-inito methods   Brown,Schwenk Phys.Rev.C 91,049902 (2015)

  Compare many-body perturbation and Monte Carlo using χEFT

  Rrapaj, Roggero, Holt arxiv:1510.00444 (2015)

$T = 0$: Equation of State

Constraining mean field models

- Saturation density properties   Dutra, Lourenco, Martins,Delfino, Phys.Rev.C 85, 035201 (2012)
- Low density neutron matter, ab-inito methods   Brown,Schwenk Phys.Rev.C 91,049902 (2015)

  Compare many-body perturbation and Monte Carlo using χEFT

  Rrapaj, Roggero, Holt arxiv:1510.00444 (2015)

Found mean field models consistent with all constraints!

$T = 0$: Equation of State

Constraining mean field models

- Saturation density properties Dutra, Lourenco, Martins,Delfino, Phys.Rev.C 85, 035201 (2012)
- Low density neutron matter, ab-inito methods Brown,Schwenk Phys.Rev.C 91,049902 (2015)

  Compare many-body perturbation and Monte Carlo using χEFT

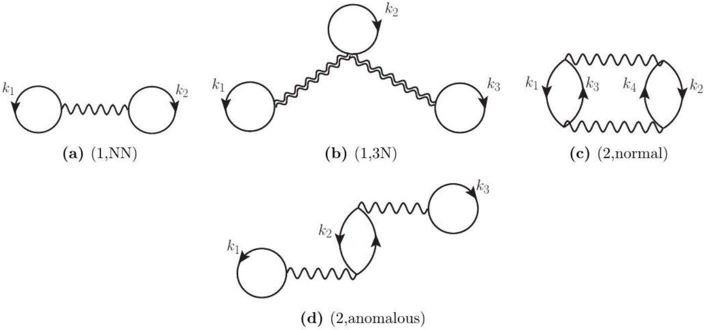
  Rrapaj, Roggero, Holt arxiv:1510.00444 (2015)

Found mean field models consistent with all constraints!

Not currently used in supernovae simulations!

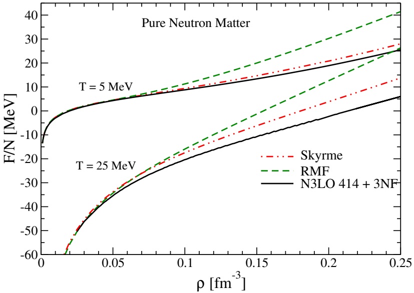
Many-body perturbation theory , $T > 0$

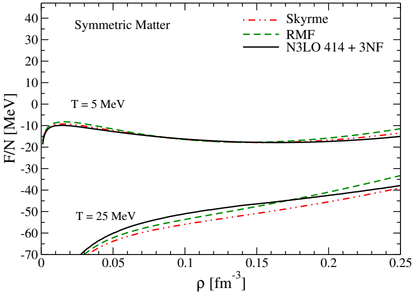
Wellenhofer, Holt, Kaiser, Weise Phys. Rev. C 89, 064009 (2014)



$T > 0$ EoS: Skyrme interactions and relativistic models

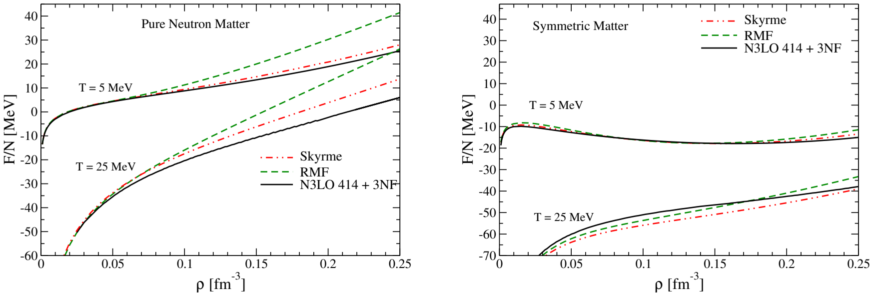
Rrapaj, Roggero, Holt arxiv:1510.00444 (2015)





$T > 0$ EoS: Skyrme interactions and relativistic models

Rrapaj, Roggero, Holt arxiv:1510.00444 (2015)

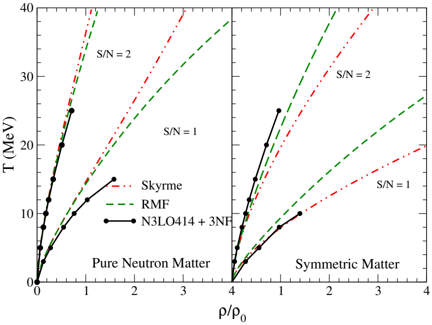


'Qualitatively' comparable with many-body calculations

Thermal Properties

Rrapaj, Roggero, Holt arxiv:1510.00444 (2015)

S = *const* trajectories

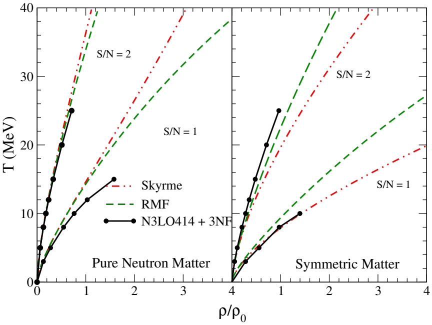


Core temperature uncertain!

Thermal Properties

Rrapaj, Roggero, Holt arxiv:1510.00444 (2015)

$S = const$ trajectories



Beyond mean field signature !

Collaborators

Thank You

- Sanjay Reddy
- Jeremy Holt
- Alessandro Roggero
- Alexander Bartl
- Achim Schwenk