SCALARS 2025

Neutron star heating by DM in an ALP LFV model

Jaime Hoefken Zink
collaborators: Hooman Davoudiasl, Sebastian Trojanowski

24/09/2025

AGENDA

01
Motivation

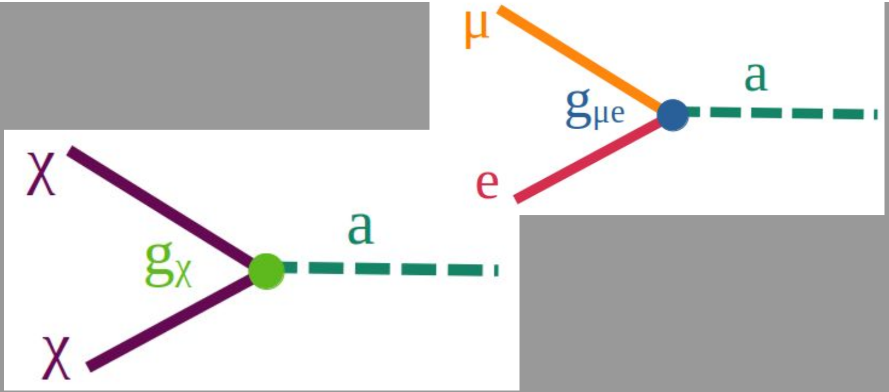
LFV Dark matter model (μe sector)

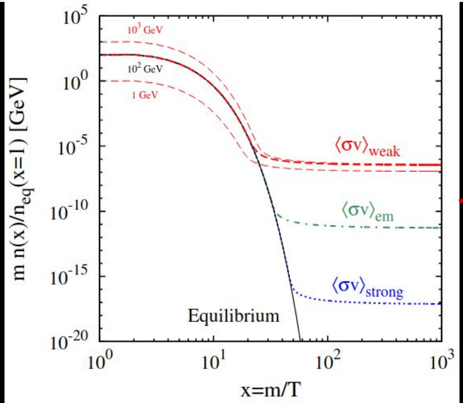
Challenges

$$\mathcal{L} \supset -i g_{e\mu} a \bar{e} \left[\sin\phi + \cos\phi \gamma^5\right] \mu + \text{h.c.}$$

$$\mathcal{L} \supset -i g_{\chi} a \overline{\chi} \gamma^5 \chi$$

1911.06279, 2310.05827, 2407.15942





Credit: 1204.3622

p-wave: χχ ↔ aa 2310.05827

$$\langle \sigma v \rangle_{aa} \simeq \frac{6}{x_{\text{f.o.}}} \frac{g_\chi^4}{24\pi} \frac{m_\chi^2 (m_\chi^2 - m_a^2)^2}{(2m_\chi^2 - m_a^2)^4} \left(1 - \frac{m_a^2}{m_\chi^2}\right)^{1/2}$$

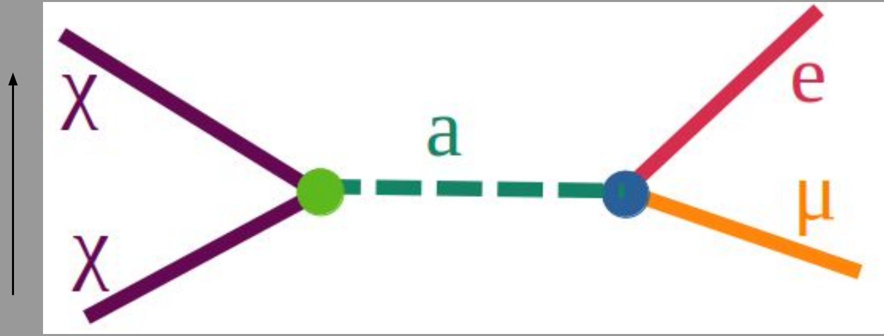
s-wave: χχ ↔ μe 2407.15942

$$\langle \sigma v \rangle_{\mu e} \simeq \frac{g_{\mu e}^2 g_\chi^2}{16\pi} \frac{(4m_\chi^2 - m_\mu^2)^2}{m_\chi^2 (4m_\chi^2 - m_a^2)^2}$$

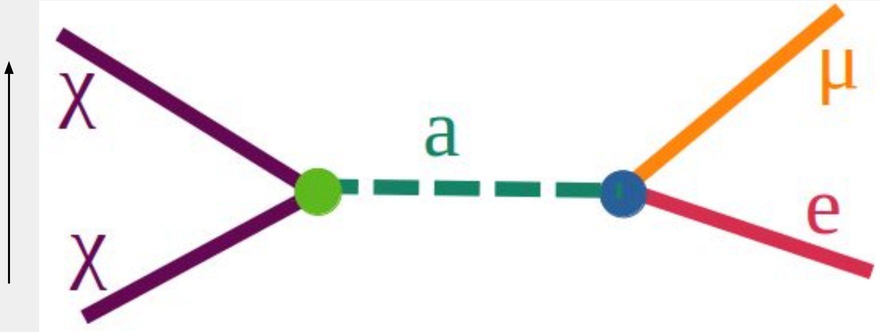
LFV Dark matter model (μe sector)

Difficulties in DM detection

1. No detectors made from muons



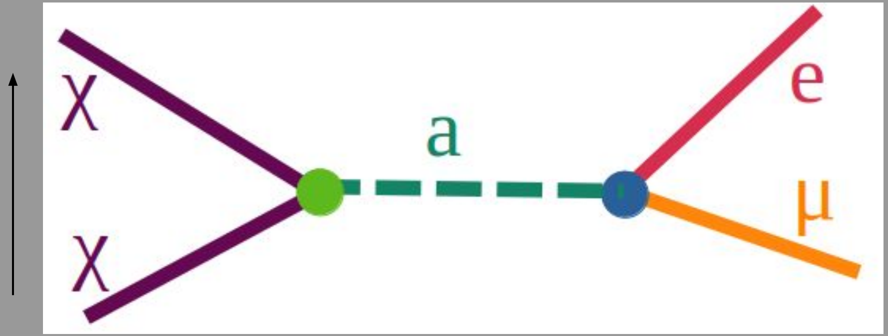
2. Halo DM is not sufficiently boosted to upscatter



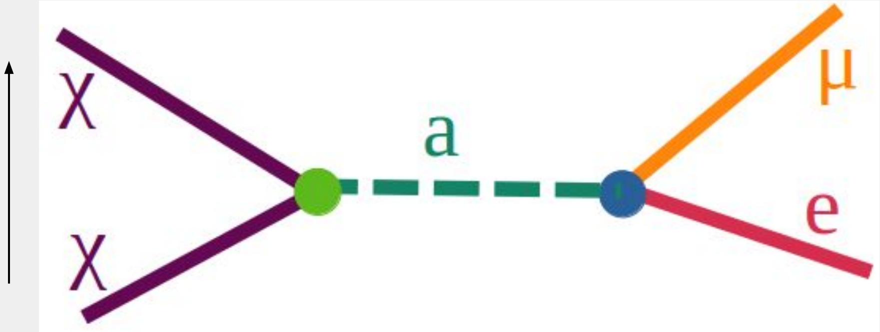
LFV Dark matter model (μe sector)

Advantages of NS as detectors

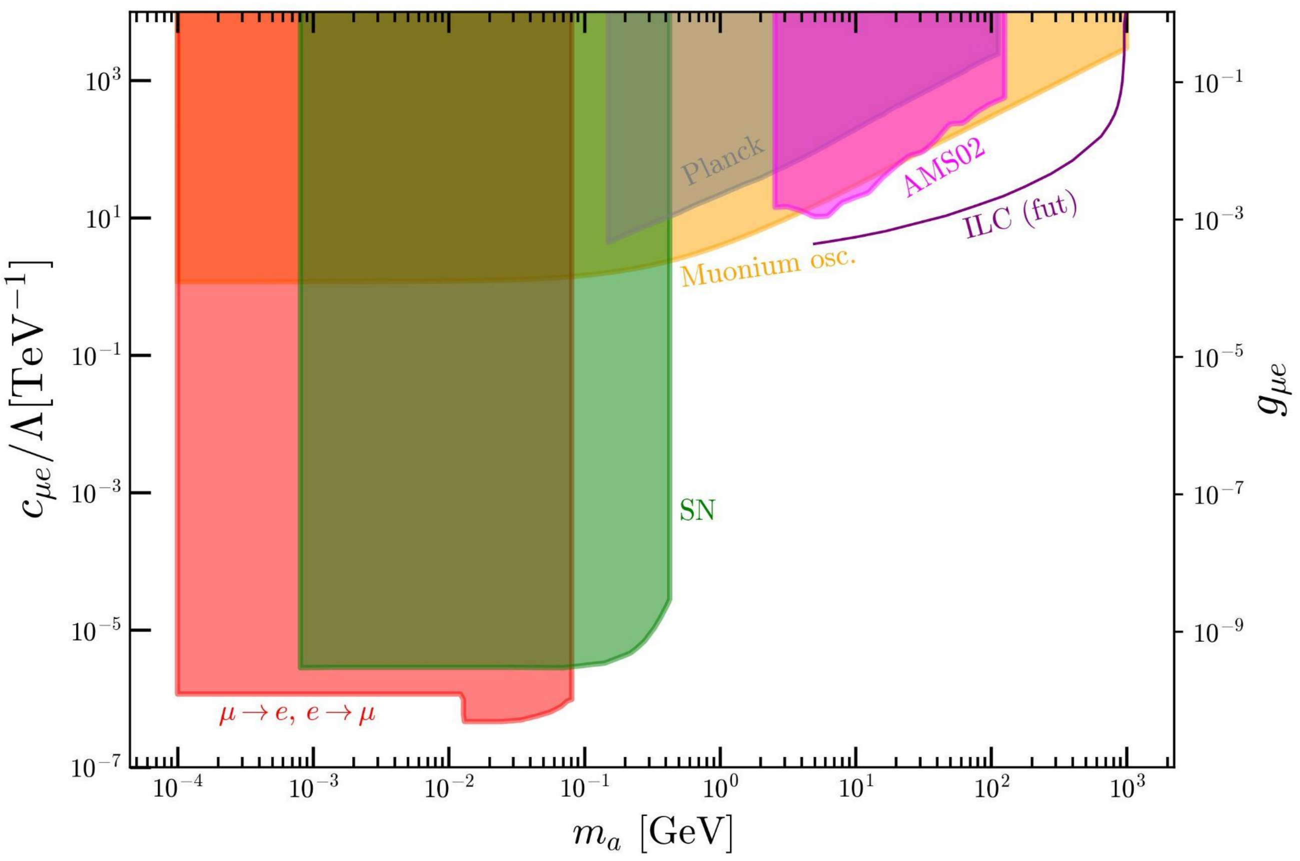
1. There are stable muons in NSs



2. Halo DM is boosted thanks to NS strong gravitational field



Current (and future) bounds



Planck: CMB [1807.06209] (assumption: $\Omega h^2 = 0.12$)

AMS02: annihilation into positrons [2107.10261] (assumption: $\Omega h^2 = 0.12$)

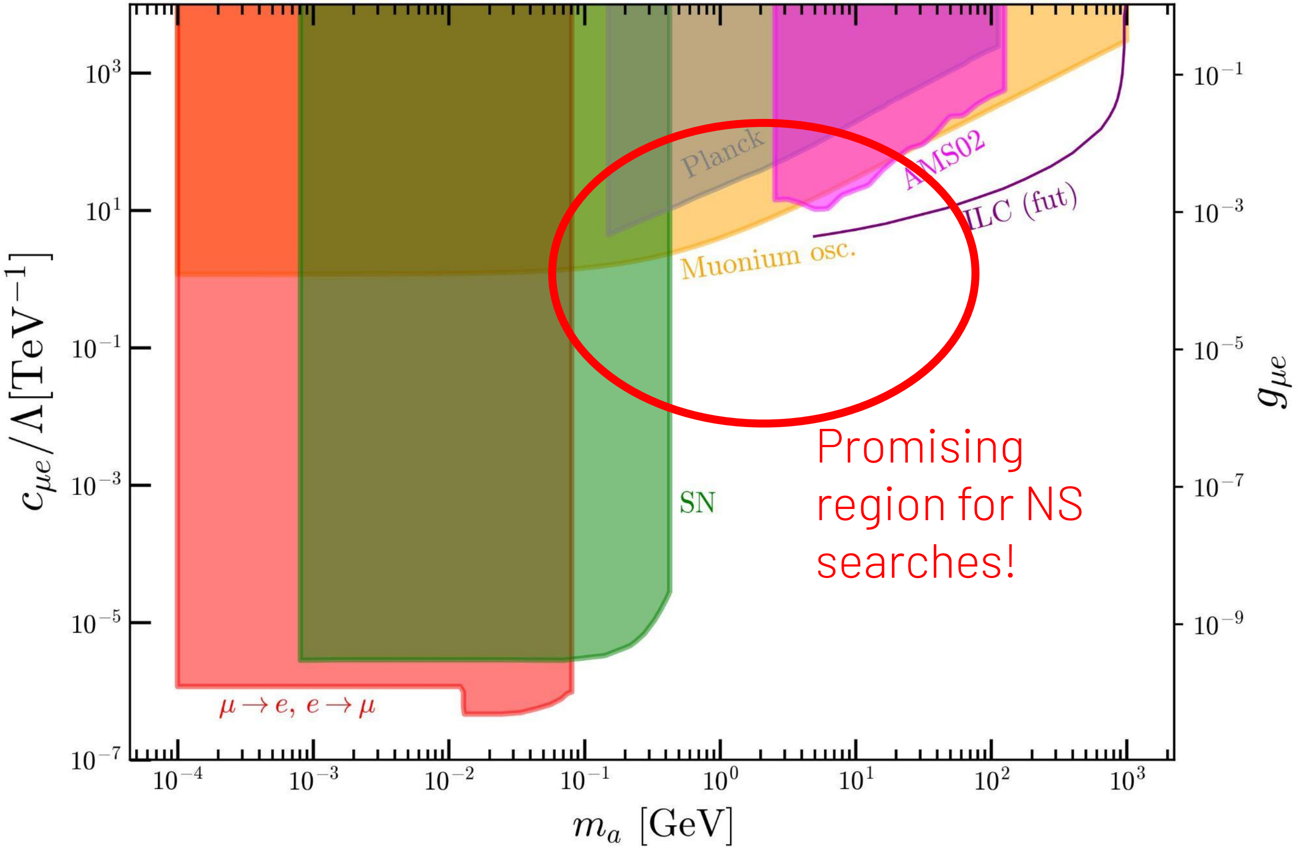
Muonium oscillation: especially from MACS ($\mu^- e^+ \leftrightarrow \mu^+ e^-$) [1711.08430]

μ to e + inv.: from TWIST, SINDRUM, MEG... [1908.00008]

Supernovae: axion emission [2309.03889]

ILC [1711.08430]

Current (and future) bounds



Planck: CMB [1807.06209] (assumption: $\Omega h^2 = 0.12$)

AMS02: annihilation into positrons [2107.10261] (assumption: $\Omega h^2 = 0.12$)

Muonium oscillation: especially from MACS ($\mu^- e^+ \leftrightarrow \mu^+ e^-$) [1711.08430]

μ to e + inv.: from TWIST, SINDRUM, MEG... [1908.00008]

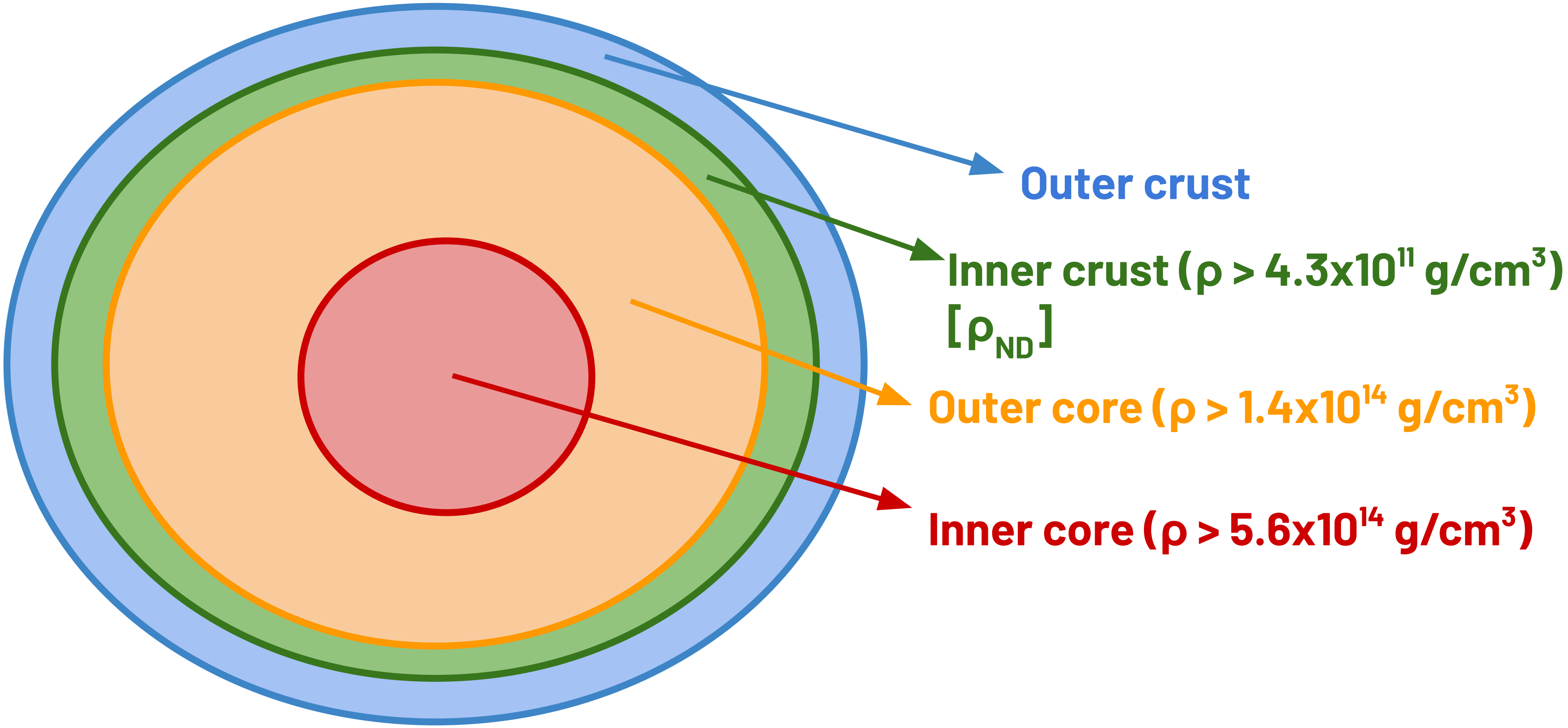
Supernovae: axion emission [2309.03889]

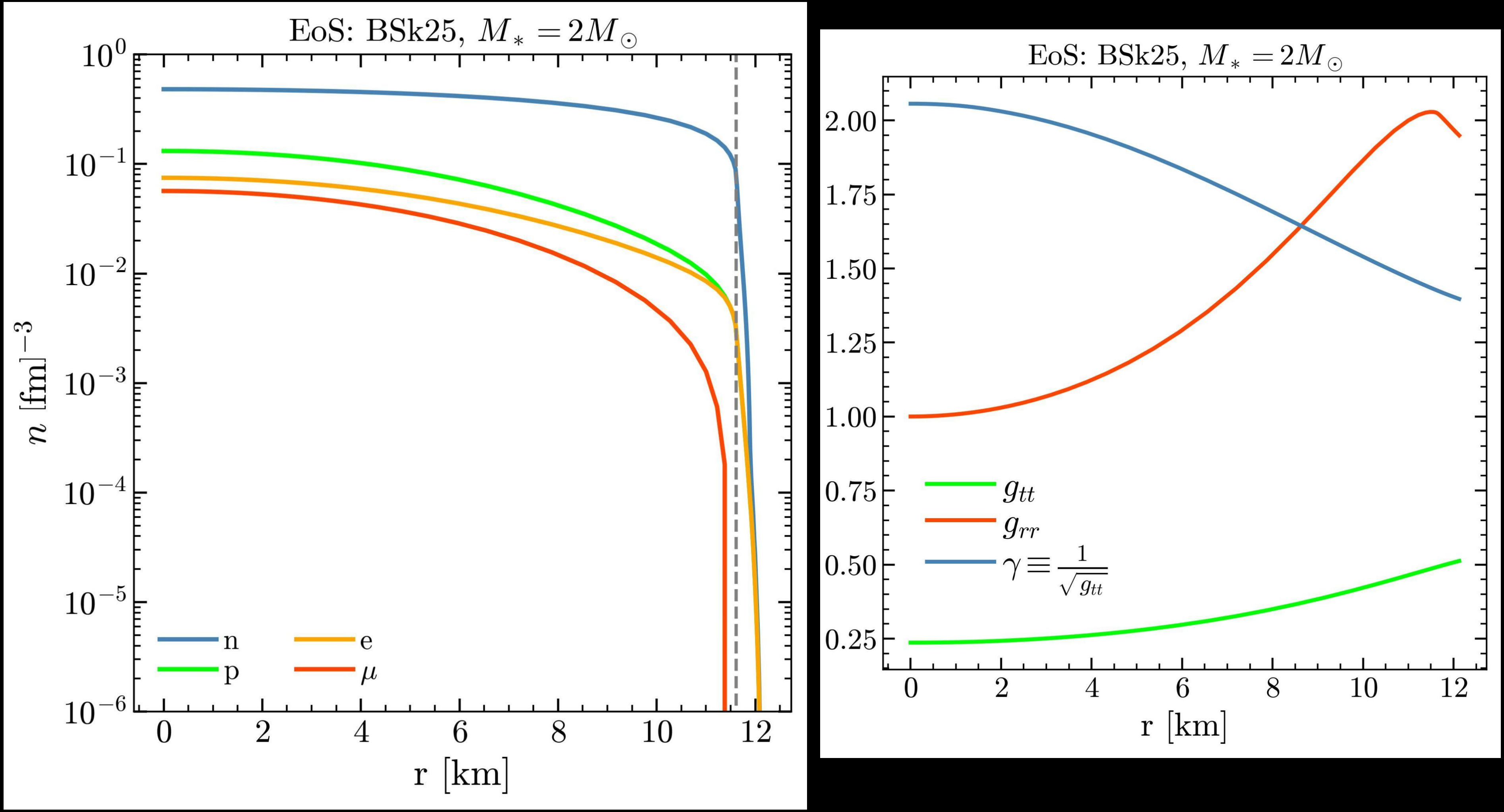
ILC [1711.08430]

02

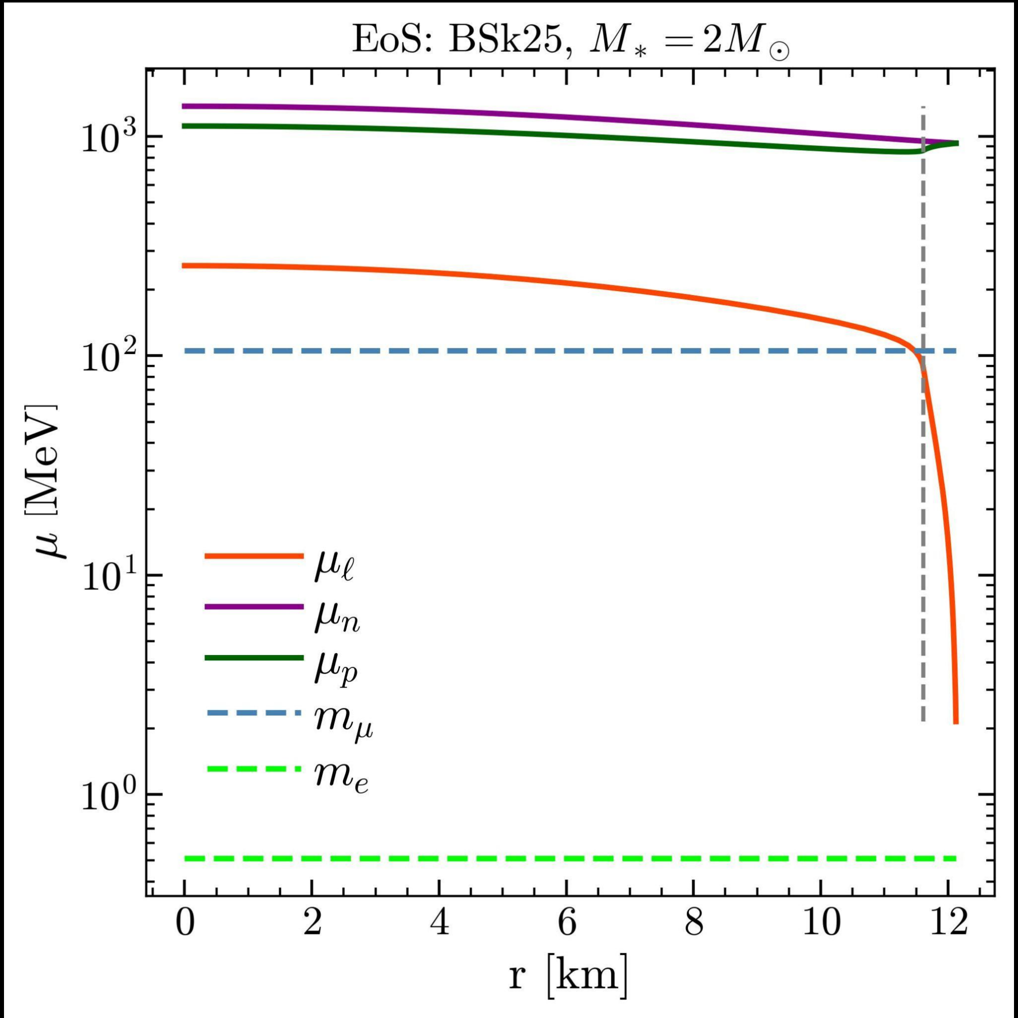
Neutron stars

Parts of a Neutron Star



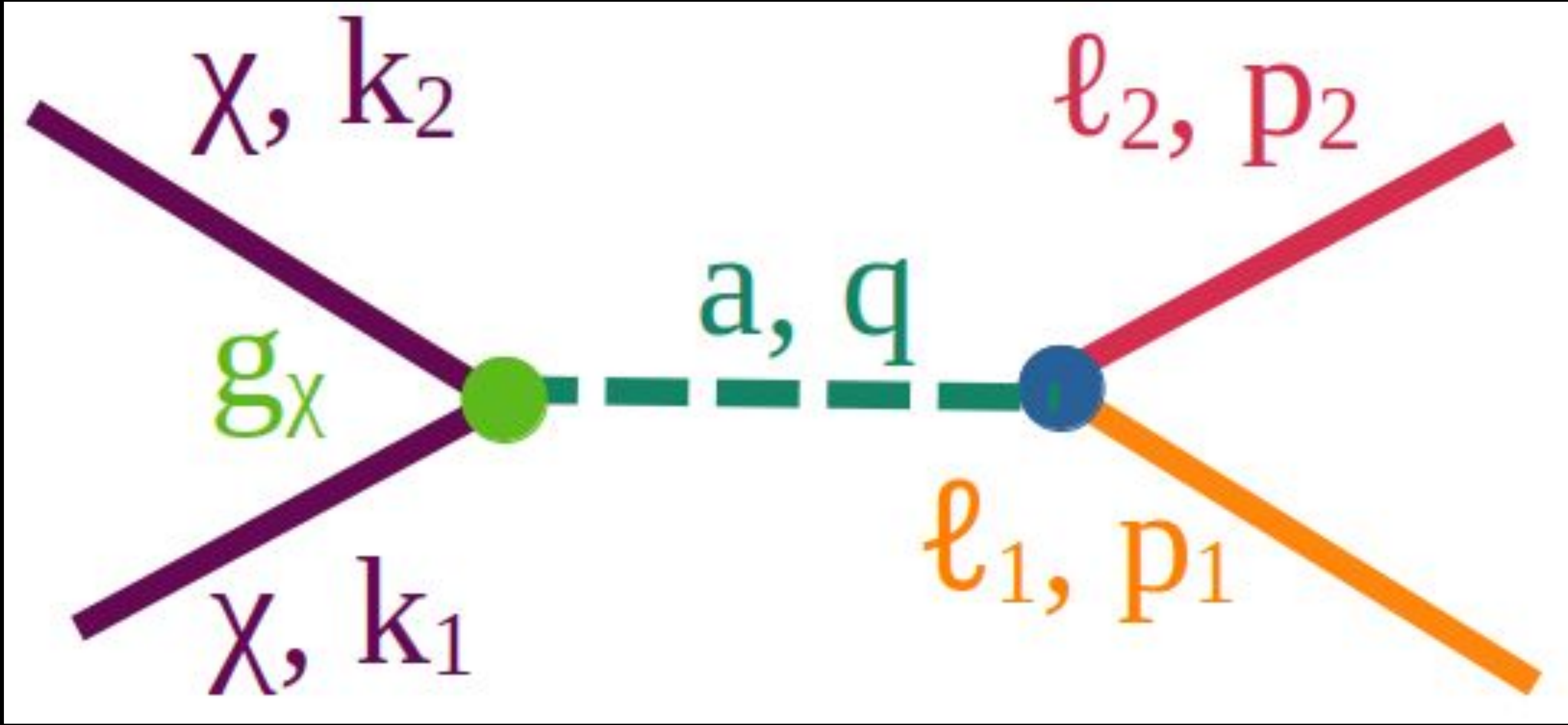


EoS: BSk25, $M_* = 2M_\odot$
n [fm]$^{-3}$
r [km]
n
p
e
μ
EoS: BSk25, $M_* = 2M_\odot$
r [km]
g_{tt}
g_{rr}
$\gamma \equiv \frac{1}{\sqrt{g_{tt}}}$


EoS: BSk25, $M_* = 2M_\odot$
μ [MeV]
r [km]
10^3
10^2
10^1
10^0
0
2
4
6
8
10
12
μ_ℓ
μ_n
μ_p
m_μ
m_e

03

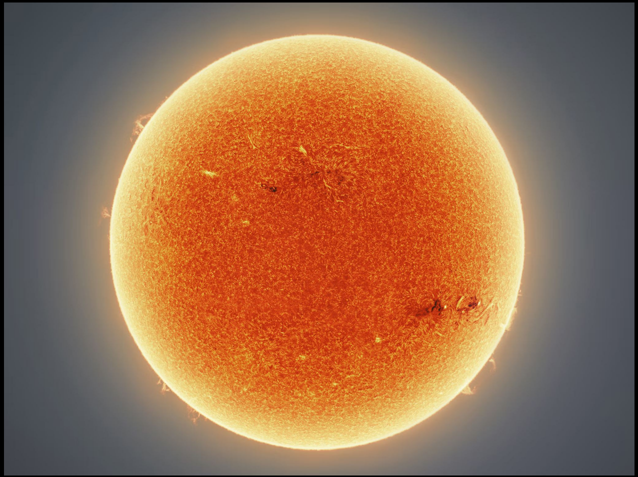
Capture of DM by NSs



$\chi e \rightarrow \chi \mu$ $\chi \mu \rightarrow \chi e$

What to measure?

01



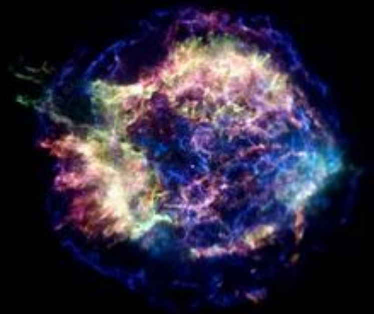
Mass accumulation

02

Heating of star

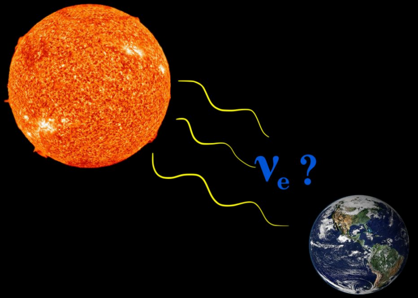
01a

Gravitational effects



01b

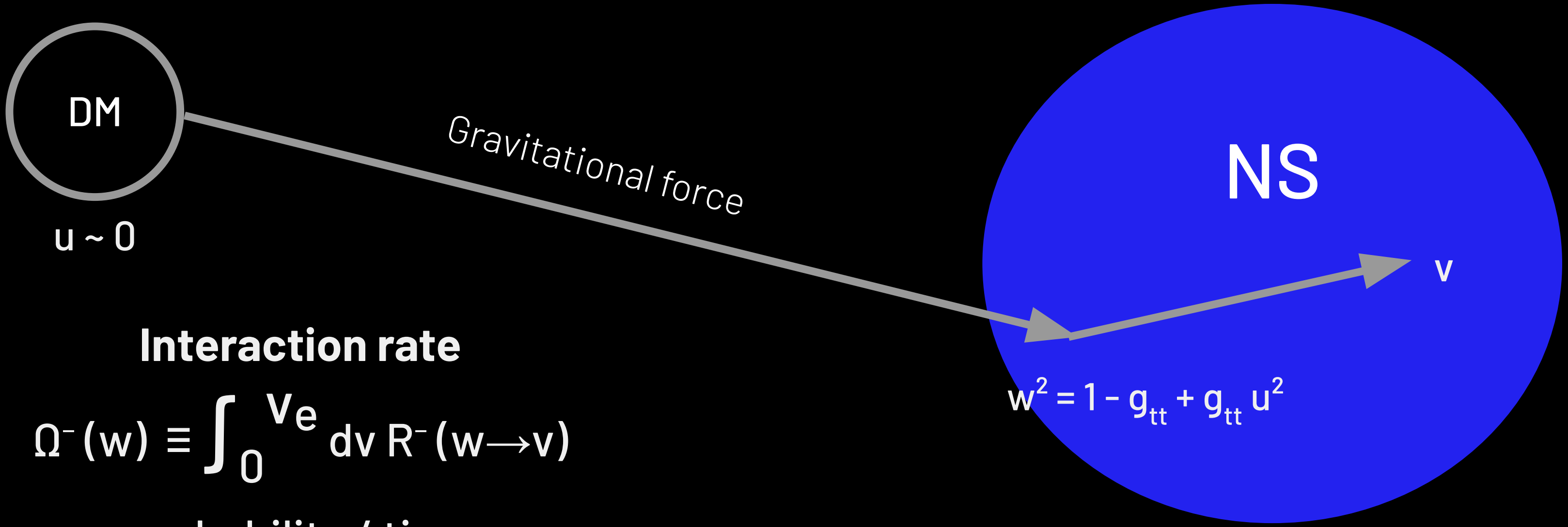
Emission of SM particles



CAPTURE MECHANISM

Sources for capture rates in compact stars: 1703.07784, 2010.00601, 2108.02525, 1807.02840, 1904.09803, 2004.14888, 2010.13257, 2012.08918, 2212.09785, 2312.11892, 2206.06667, 2408.03759, 2408.00594, 2404.16272, 2410.13908, 0709.1485, 1004.0586, 1001.2737, 1309.1721, 1703.04043, 1906.10145, 1812.08773, 2307.14435, 2404.10039, 1704.01577, 2208.07770...

What happens?



Interaction rate

$$\Omega^-(w) \equiv \int_0^{v_e} dv\, R^-(w \to v)$$

:: probability / time ::

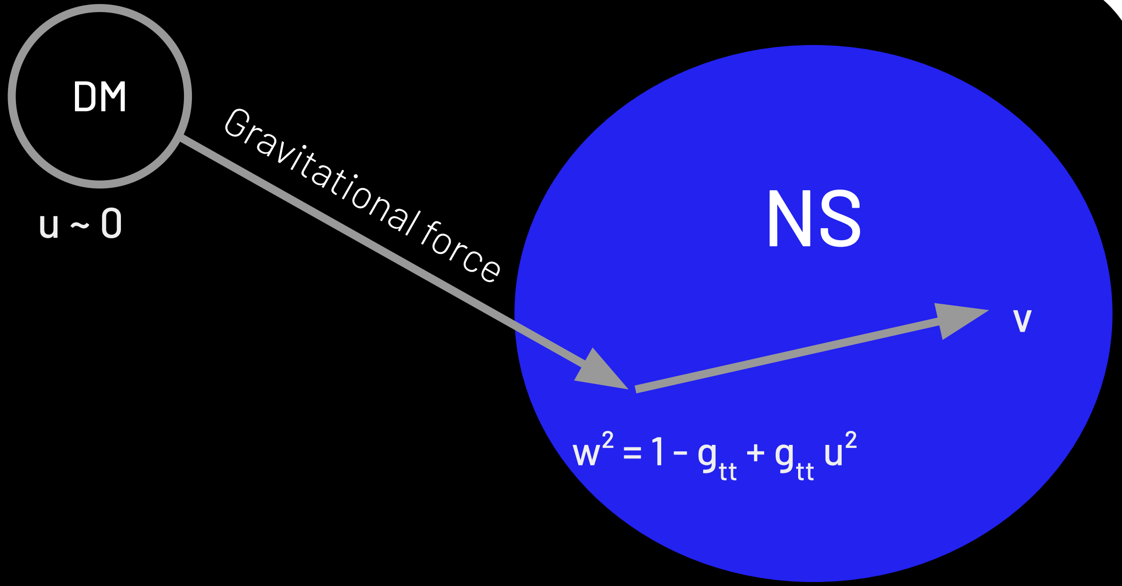
CAPTURE MECHANISM

What happens?

$$R^- \propto d\sigma/dv$$

$$\Omega^- \propto \sigma(v<v_e)$$

$$v_e = (1 - g_{tt})^{0.5}$$



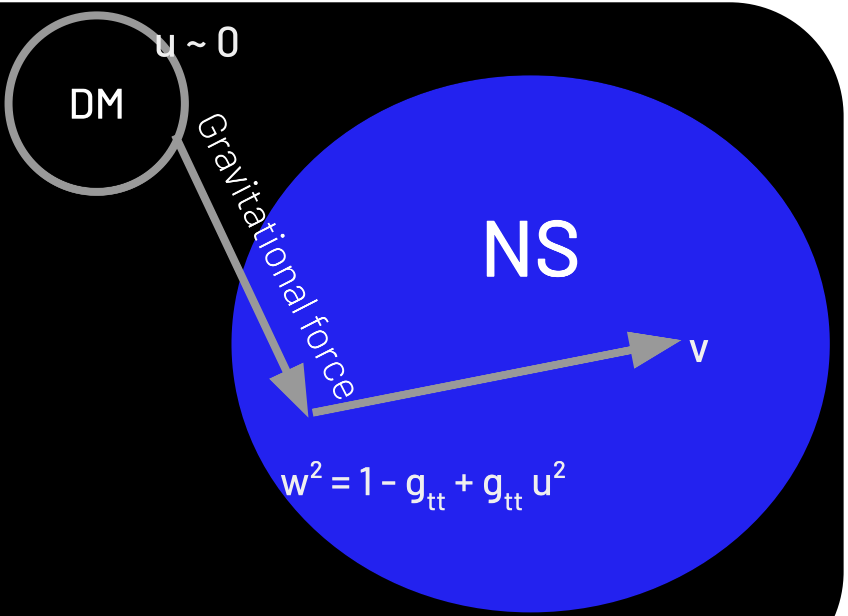
CAPTURE MECHANISM

v_{NS} = 230 km/s
v_d = 270 km/s
ρ_χ = 0.4 GeV/cm^3

What happens?

$$\Omega^-_{\alpha\to\beta} = \frac{\zeta}{32\pi^3 m_\chi}\sqrt{\frac{g_{tt}}{1-g_{tt}}} \times \int_{m_\alpha}^{\mu_l} dE_{p_1} E_{p_1} \int_{s_{\min}}^{s_{\max}} \frac{s\,ds}{\gamma_s(m_\alpha)\beta_s} \times \int_{t_{\min}}^{t_{\max}} dt \langle|\mathcal{M}|^2_{\rm cm}\rangle_{\alpha\to\beta}(t)\Theta(E_{p_2}-\mu_l)$$

$$C = \frac{4\pi}{v_{NS}}\frac{\rho_\chi}{m_\chi}\mathrm{Erf}\left(\sqrt{\frac{3}{2}}\frac{v_{NS}}{v_d}\right) \times \int_0^{R_{NS}} r^2 \frac{\sqrt{1-g_{tt}(r)}}{g_{tt}(r)}\Omega^-(r)\ \eta(r)dr$$



CAPTURE MECHANISM

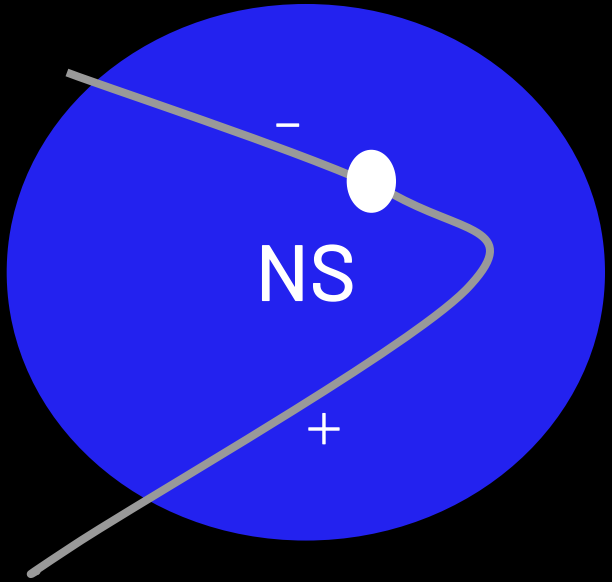
Optical factor

What happens?

$$\eta(r) = \frac{1}{2}\int_0^1 \frac{y\,dy}{\sqrt{1-y^2}}\left(e^{-\tau_\chi^-(r,y)} + e^{-\tau_\chi^+(r,y)}\right)$$

$$\tau_\chi^-(r,y) = \int_r^{R_{\rm NS}} dr' \frac{\Omega^-(r')}{\sqrt{1-g_{tt}(r')}\sqrt{1-y^2\frac{J^2_{\rm max}(r)}{J^2_{\rm max}(r')}}},$$

$$\tau_\chi^+(r,y) = \tau_\chi^-(r,J) + 2\int_{r_{\rm min}}^{r} dr' \frac{\Omega^-(r')}{\sqrt{1-g_{tt}(r')}\sqrt{1-y^2\frac{J^2_{\rm max}(r)}{J^2_{\rm max}(r')}}}.$$



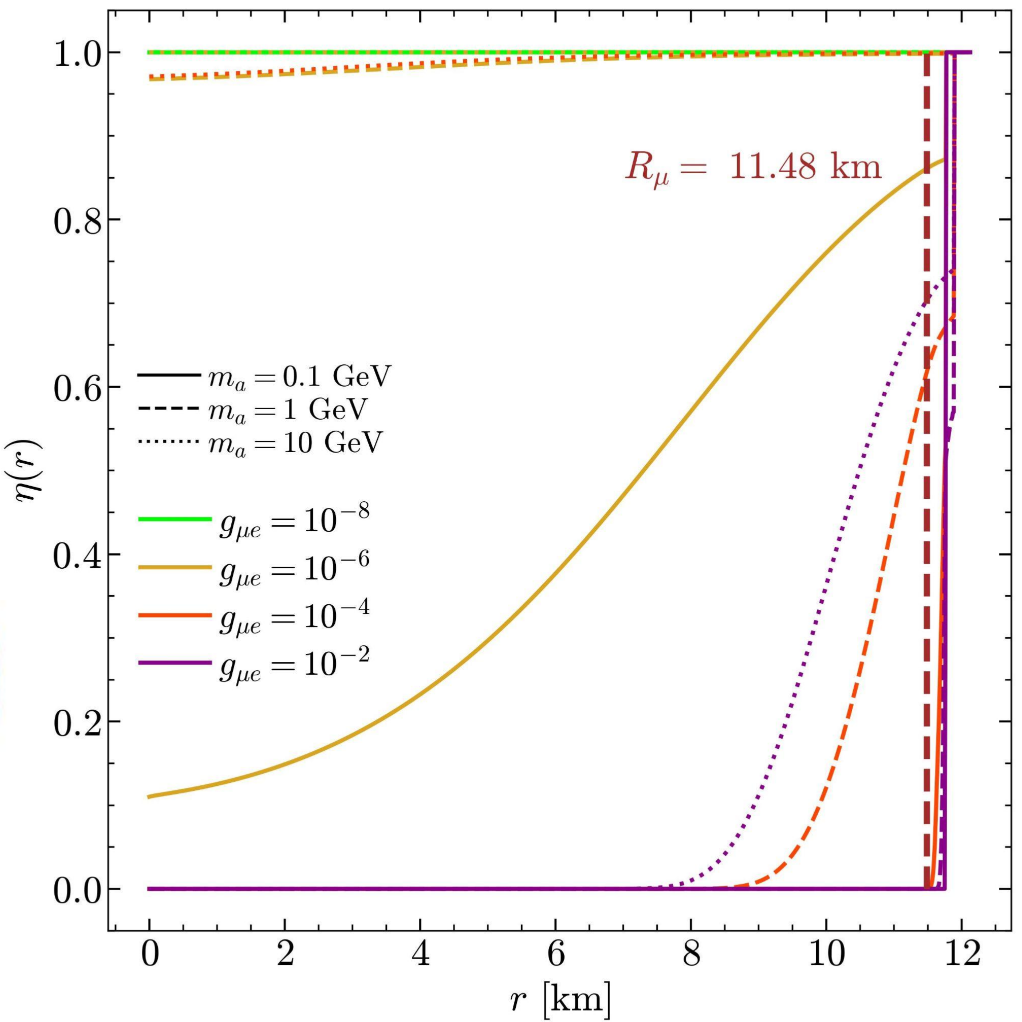
Optical factor

Case: $m_\chi = 2\, m_a$

Limits:

- Saturation limit
- Geometric limit

$$C_{\rm NS} = \frac{\pi R_{\rm NS}^2 (1 - B(R_{\rm NS}))}{v_{\rm NS} B(R_{\rm NS})} \frac{\rho_\chi}{m_\chi} {\rm Erf}\left(\sqrt{\frac{3}{2}} \frac{v_{\rm NS}}{v_d}\right)$$



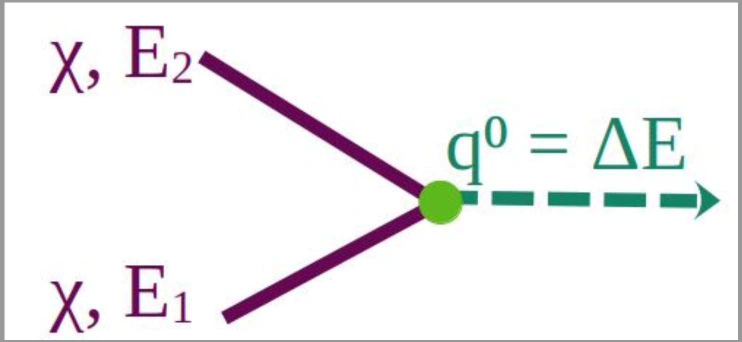
04
Kinetic energy deposition and heating

Kinetic energy deposition: heating NSs

Expected T of NSs: 10^3 K (20 Myr) and ~ 100 K (1 Gyr)
Sensitivities in the future: 2000-4000 K (JWST, TMT, E-ELT) [2403.07496]

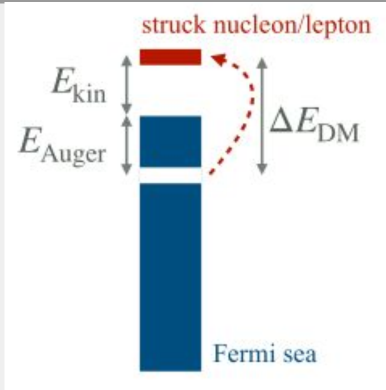
What to do?

We need to add the kinetic energy lost for each point in parameter space to the innermost integrand of the capture rate to find the energy rate deposited into the NS.



What happens to the leptons?

The target lepton is removed from the thermal distribution. The outgoing lepton is produced with an energy, E > μ, and loses its extra energy reconverts into the original flavor, respecting the thermal distributions.



Credits: 2307.14435

Kinetic energy deposition

Approaches

Just first interaction

$$E_k = E_{k_1} - E_{k_2}$$

Thermal first interaction

$$E_k = E_{k_1} - m_\chi$$

All energy lost on the surface

$$E_k = \left(\frac{1}{\sqrt{g_{tt}(R_{\mathrm{NS}})}} - 1 \right) m_\chi$$

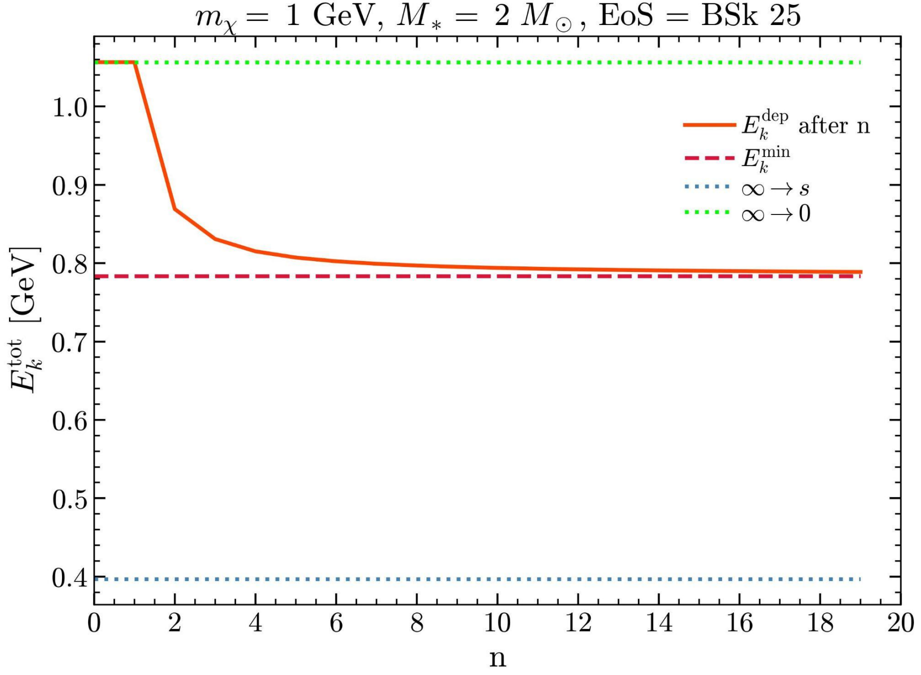
1704.01577

All energy lost at the center of NS

$$E_k = \left(\frac{1}{\sqrt{g_{tt}(0)}} - 1 \right) m_\chi$$

2312.11892

Lower bound: Infinite interactions losing all E_k



$$
\begin{aligned}
E_k^{min} &= E_s + \lim_{n\to\infty} \sum_{i=0}^{n} (E_i - m_\chi)\,, \\
&= m_\chi(\gamma_s - 1) + \lim_{n\to\infty} \sum_{i=1}^{n} m_\chi \left(\frac{\gamma(r_i)}{\gamma(r_{i-1})} - 1 \right), \\
&= m_\chi(\gamma_s - 1) + \int m_\chi \frac{\gamma(r_i) - \gamma(r_{i-1})}{\gamma(r_{i-1})}, \\
&= m_\chi(\gamma_s - 1) + m_\chi \int_{\gamma_s}^{\gamma_0} \frac{d\gamma}{\gamma}, \\
&= m_\chi \left(\gamma_s - 1 + \ln \frac{\gamma_0}{\gamma_s} \right),
\end{aligned}
$$

(Im)possibility of thermalizing

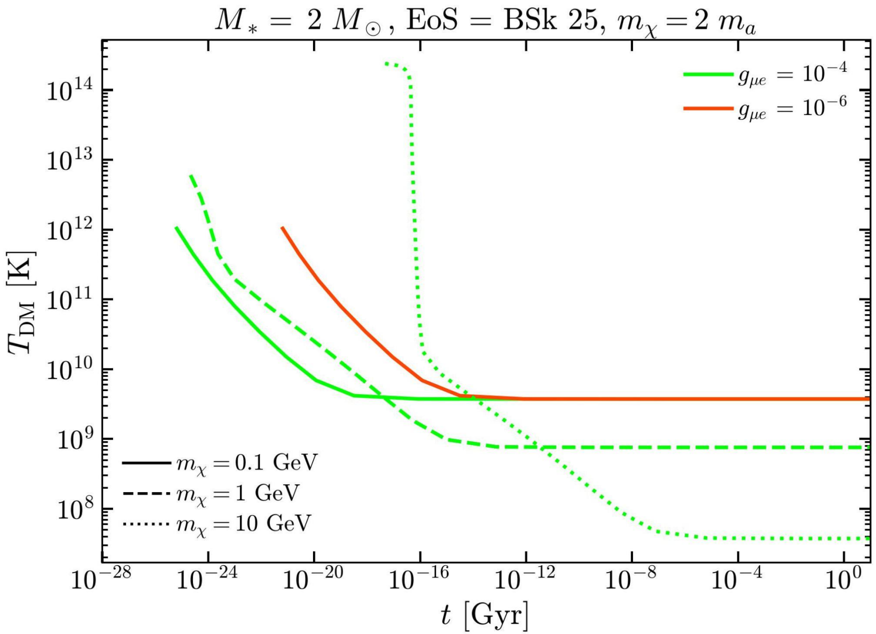
$$\Gamma = 2 \int \mathcal{D}p_1 \mathcal{D}k_2 \mathcal{D}p_2 \frac{\sum_{\text{spins}} |\mathcal{M}|^2}{2E_{k_1}} (2\pi)^4 \delta^{(4)}(k_1 + p_1 - k_2 - p_2) n_F(E_{p_1})(1 - n_F(E_{p_2}))$$

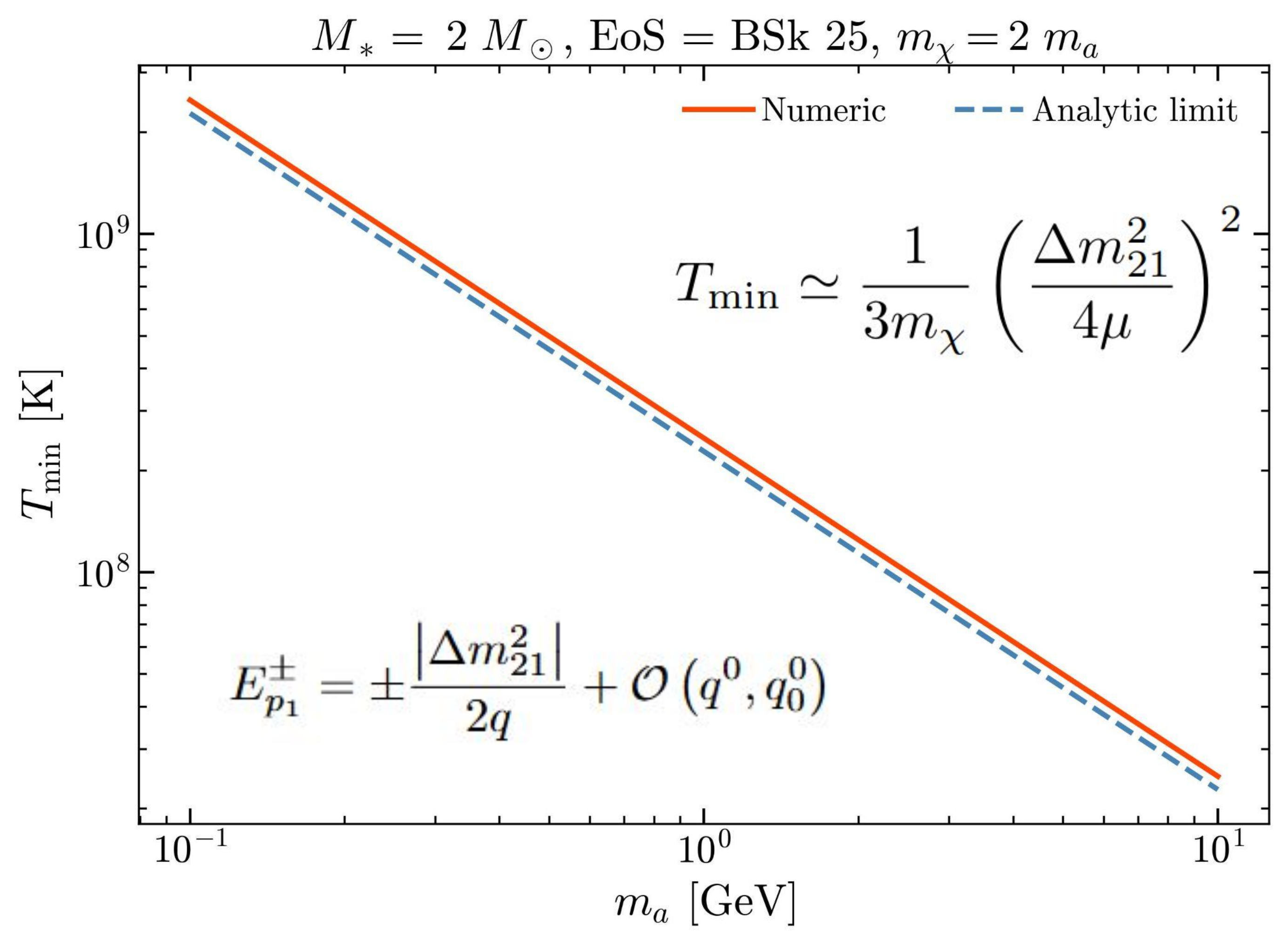
Scattering rate: $\Gamma(E_1)$

$\Delta\tau_{th} = 1/\Gamma$

until **$\langle E_1 - m_\chi \rangle \sim 3/2\ T$**

$$\langle K \rangle = \frac{1}{\Gamma} \int dq_0 q_0 \frac{d\Gamma}{dq_0}$$





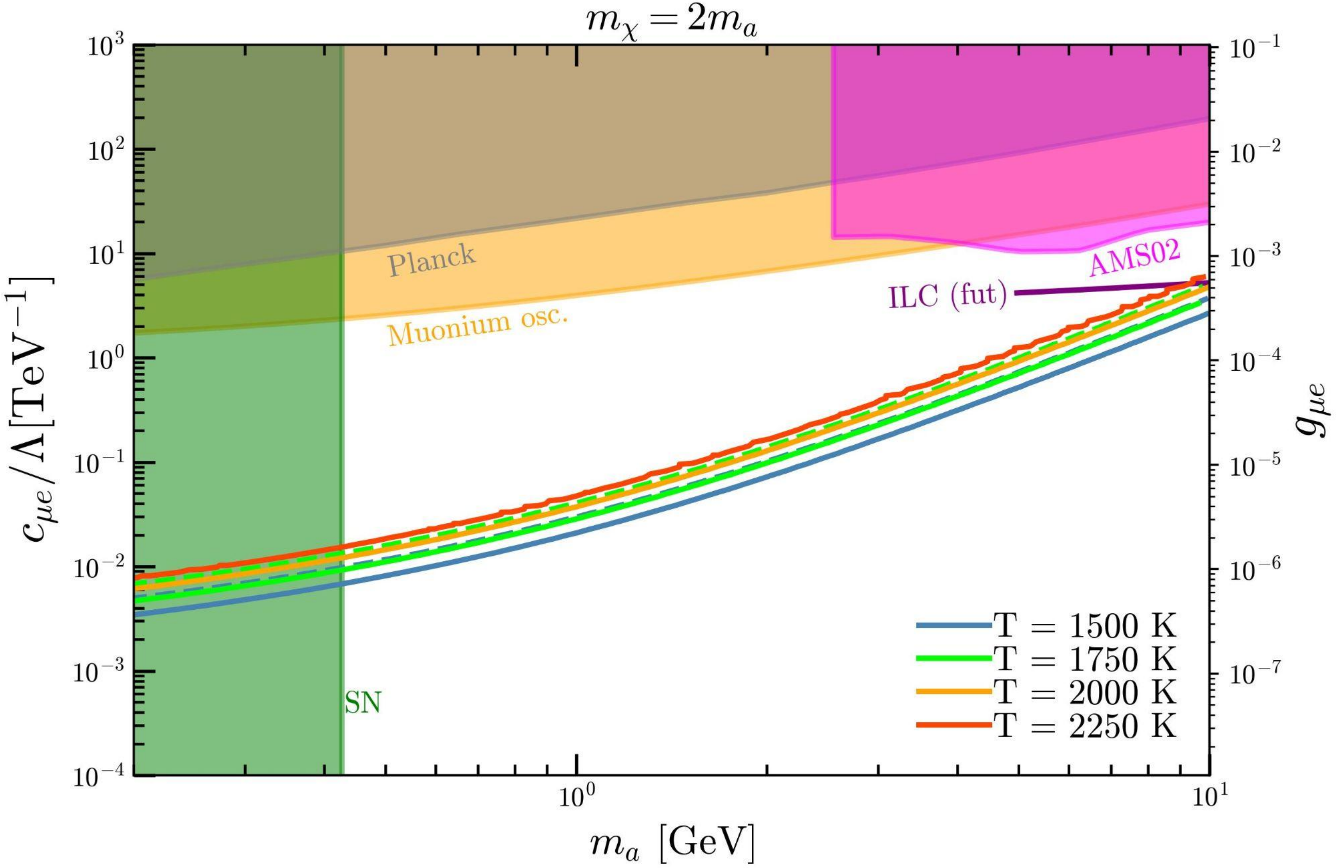
$M_* = 2\ M_\odot$, EoS = BSk 25, $m_\chi = 2\ m_a$
Numeric
Analytic limit
$T_{\rm min} \simeq \frac{1}{3m_\chi}\left(\frac{\Delta m_{21}^2}{4\mu}\right)^2$
$E_{p_1}^{\pm} = \pm\frac{|\Delta m_{21}^2|}{2q} + \mathcal{O}\left(q^0, q_0^0\right)$
$T_{\rm min}$ [K]
10^9
10^8
10^{-1}
10^0
10^1
m_a [GeV]

05

Results

Thermal case

$$g_\chi = 0.097 \times (m_a \,/\, \mathrm{GeV})^{1/2}$$



$$c_{\mu e}/\Lambda \equiv \frac{g_{\mu e}}{m_\mu[\mathrm{TeV}]}$$

06

Conclusions

CONCLUSIONS

What was shown	● Mechanism of capture rate of dark particles in NSs. ● Different approaches to compute the heating of a NS. ● **Context**: LFV ALP model.
What we found	● We can set limits based on sensitivities of infrared telescopes in the near future (hopefully), including the Thirty Meter Telescope (TMT), and the European Extremely Large Telescope (E-ELT) and also the James Webb Space Telescope (JWST).
Future prospects	● Study the thermalization time, in order to know whether the thermalization limits can be used and where in parameter space. ● Analyze the possibility of emissions from the star.

THANK YOU

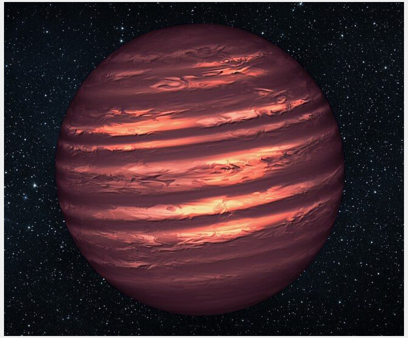
07

Extra slides

End of life of stars

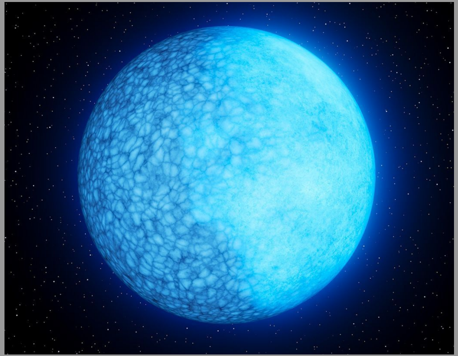
Brown dwarf

$13 - 80\ M_J$



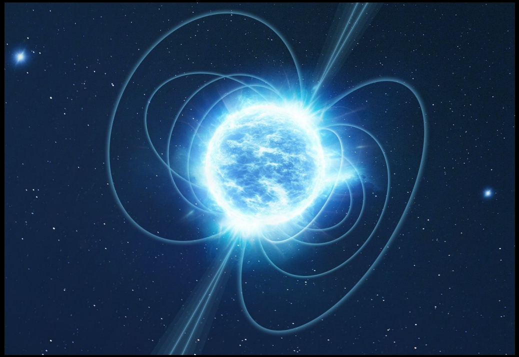
White dwarf

$0.17 - 1.33\ M_\odot$

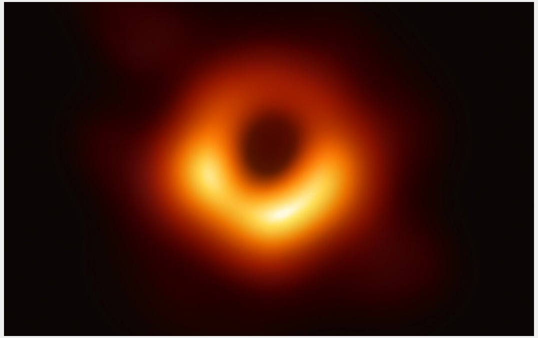


Neutron star

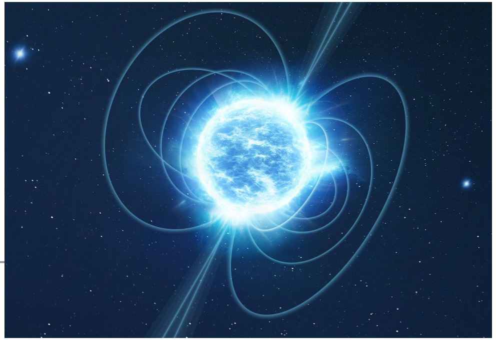
$1.1 - 2.3\ M_\odot$



Black hole



Main characteristics of NS



Density	• Up to 10^{15}-10^{16} g/cm^3. • Core made of npeμ or exotic matter
Mass	• 1.1 - 2.3 $M_\odot$
How to model	• EoS + **TOV equations** (Tolman-Oppenheimer-Volkoff) / Hartle and Thorne / Komatsu-Eriguchi-Hachisu
EoS	• *Ab initio* • Pheno: BMF (Brussels-Montreal Functionals, BSk), RMF (Relativistic Mean Field) • ...

Brussels-Montreal Functionals

BSk-N EoS

Effective forces

1. Skyrme form (16 parameters)
2. Pairing force
3. Wigner terms (esp. for small A)
4. Collective energy correction

Fitting parameters

To nuclear masses (2353, Atomic Mass Evaluation, AME 2012) using the Hartree-Fock-Bogoliubov method (multistate as Slater determinant + pairing correlations)
Neutron matter (NeuM) is modelled a (NS-core) EoS (usually using 3 body-forces).

$$v_{ij} = t_0(1+x_0P_\sigma)\delta(\boldsymbol{r}_{ij}) + \frac{1}{2}t_1(1+x_1P_\sigma)\frac{1}{\hbar^2}\left[p_{ij}^2\,\delta(\boldsymbol{r}_{ij}) + \delta(\boldsymbol{r}_{ij})\,p_{ij}^2\right] + t_2(1+x_2P_\sigma)\frac{1}{\hbar^2}\boldsymbol{p}_{ij}.\delta(\boldsymbol{r}_{ij})\,\boldsymbol{p}_{ij}$$
$$+\frac{1}{6}t_3(1+x_3P_\sigma)\,n(\boldsymbol{r})^\alpha\,\delta(\boldsymbol{r}_{ij}) + \frac{1}{2}t_4(1+x_4P_\sigma)\frac{1}{\hbar^2}\left[p_{ij}^2\,n(\boldsymbol{r})^\beta\,\delta(\boldsymbol{r}_{ij}) + \delta(\boldsymbol{r}_{ij})\,n(\boldsymbol{r})^\beta\,p_{ij}^2\right]$$
$$+t_5(1+x_5P_\sigma)\frac{1}{\hbar^2}\boldsymbol{p}_{ij}.n(\boldsymbol{r})^\gamma\,\delta(\boldsymbol{r}_{ij})\,\boldsymbol{p}_{ij} + \frac{\mathrm{i}}{\hbar^2}W_0(\boldsymbol{\sigma_i}+\boldsymbol{\sigma_j})\cdot\boldsymbol{p}_{ij}\times\delta(\boldsymbol{r}_{ij})\,\boldsymbol{p}_{ij},$$

DOI: 10.1103/PhysRevC.88.024308

Brussels-Montreal Functionals

BSk-N EoS

Effective forces

1. Skyrme form (16 parameters)
2. Pairing force
3. Wigner terms (esp. for small A)
4. Collective energy correction

Fitting parameters

To nuclear masses (2353, Atomic Mass Evaluation, AME 2012) using the Hartree-Fock-Bogoliubov method (multistate as Slater determinant + pairing correlations)
Neutron matter (NeuM) is modelled a (NS-core) EoS (usually using 3 body-forces).

Symmetry coefficient

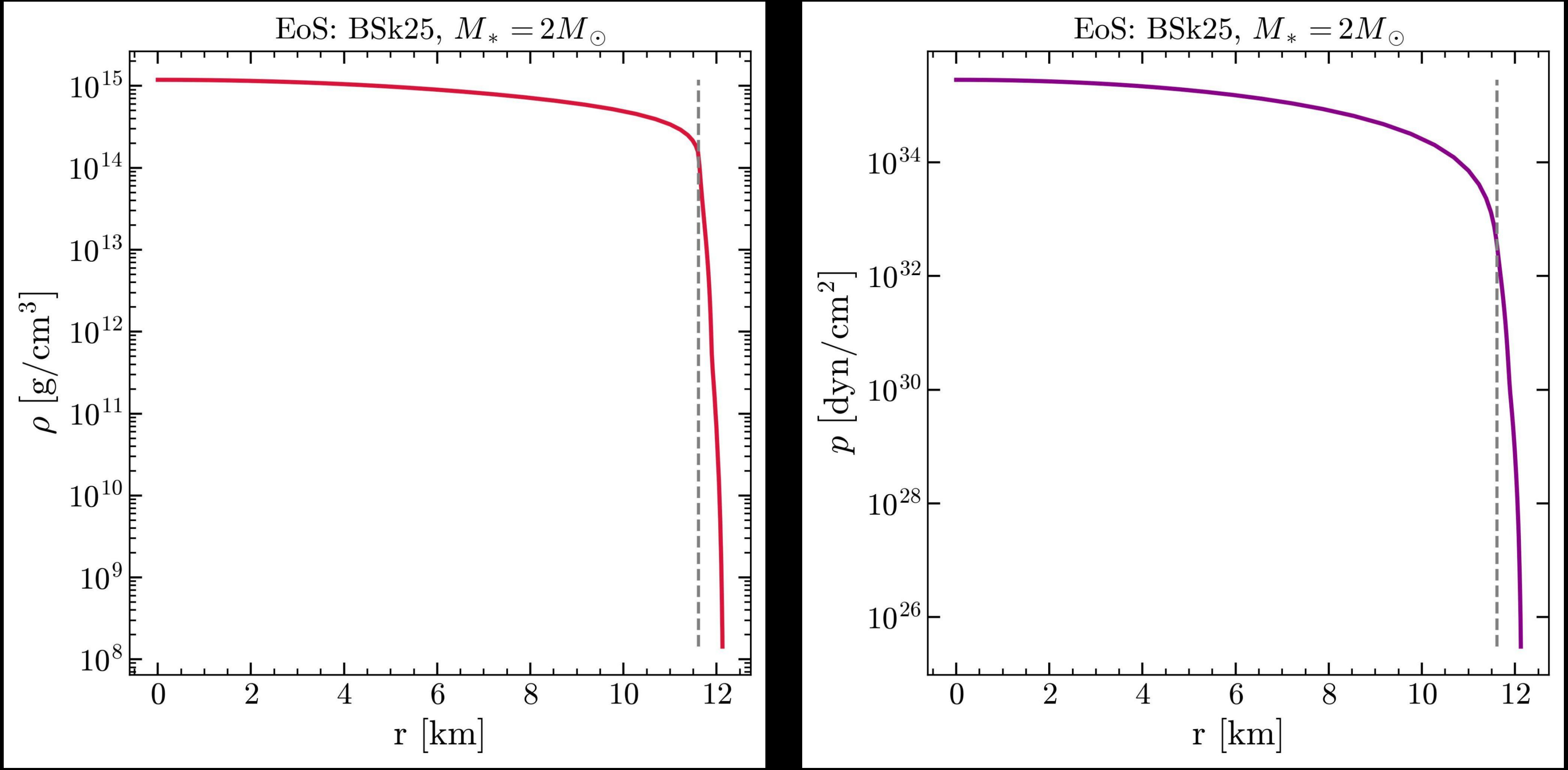
J = $E_{sym}(n_0 = 0.16\ \text{fm}^{-3})$ => n_0: nuclear saturation density, ~ 30 MeV

$$\delta = \frac{N-P}{A}$$

$$E_{sym} = \frac{1}{2}\frac{\partial^2 E(n,d)}{\partial \delta^2}\bigg|_{\delta=0}$$

Other assumptions

1. Equal filling approximation (EFA) for pairing force => if A is odd: |k(t)⟩ ⟶ (|k(t)⟩ + | k(-t)⟩) / 2
2. Coulomb exchange term for protons is dropped (fits are better).


EoS: BSk25, $M_* = 2M_\odot$
ρ [g/cm^3]
r [km]
EoS: BSk25, $M_* = 2M_\odot$
p [dyn/cm^2]
r [km]

EFFECT OF HYPOTHETICAL, WEAKLY INTERACTING, MASSIVE PARTICLES ON ENERGY TRANSPORT IN THE SOLAR INTERIOR

David N. Spergel and William H. Press
Harvard-Smithsonian Center for Astrophysics
Received 1984 December 28; accepted 1985 January 28

ABSTRACT

A possible solution to the solar neutrino problem is to posit a massive, stable, neutral particle as part of the Sun's primordial composition. If that particle has a mass between 5 and 60 GeV, then it will populate only the inner "solar neutrino unit–producing" core and not the larger luminosity-producing region. If it has a scattering cross section on protons of 4×10^{-36} cm^2, then a fractional abundance of 10^{-12} will have order-unity effect on the Sun's thermal transport, in the direction of decreasing the expected neutrino signature. For smaller cross sections, the required abundance rises in inverse proportion, so that cross sections as small as 10^{-46} cm^2 are effective if the concentration is as large as $\sim 10^{-2}$. The photino is a possible candidate particle; mirror neutrinos may also be candidates.

Subject headings: elementary particles — neutrinos — nucleosynthesis — Sun: interior

I. INTRODUCTION

e discuss in this paper an unlikely, but possible, solution to the solar neutrino problem. (For recent reviews of this problem Bahcall *et al.* 1982; Bahcall 1985.) Our solution is unlikely only in requiring the existence in the Sun of a stable, neutral pa a mass in the range of 5–60 GeV, and with a scattering cross section on protons in the range of 10^{-26} to 10^{-46} cm^2. e required range of cross sections is intermediate between strong and weak cross sections of ordinary, nonexotic pa ics. There are, however, hints that significant aspects of particle physics in the required mass range are not now comp rstood: On the experimental side, monojet events, and other events in the UA1 collaboration at CERN (Arnison *et al.* pia 1984), lack theoretical explanation (Ellis 1984; Hall, Jaffe, and Rosner 1984). On the theoretical side, stable particles i ed mass range can arise as "mirror neutrinos" in left-right symmetric theories and vector-like theories (Bagger and D

Spergel and Press (1985)

and solar neutrino problem

WEAKLY INTERACTING, MASSIVE PARTICLES AND THE SOLAR NEUTRINO FLUX[1]

John Faulkner
Lick Observatory, Board of Studies in Astronomy and Astrophysics, University of California, Santa Cruz
and
Ronald L. Gilliland
High Altitude Observatory, National Center for Atmospheric Research[2]
Received 1985 April 18; accepted 1985 June 3

ABSTRACT

If the Sun contained even a small mass fraction of weakly interacting massive particles, there could be significant effects on central solar structure. The long mean free paths associated with such particles make them very efficient energy conductors. Consequently, an essentially isothermal core can be produced, which removes the central temperature peak responsible for the bulk of the predicted solar neutrinos in Davis's ^{37}Cl neutrino capture experiment. We explore the solar evolutionary consequences of both imposed isothermal core models and models including energy transport by a specific class of weakly interacting particles. In particular, a relative mass fraction, 10^{-8}, of 4 GeV particles reduces predicted neutrino count rates by more than a factor of 3.

Subject headings: elementary particles — neutrinos — Sun: interior

I. INTRODUCTION

e classical solar neutrino problem has now been with us lmost two decades (see Bahcall and Davis 1982 for a rical review and Bahcall 1985 for the most recent ssion). In essence, there is a persistent discrepancy, of three, between the predicted and observing counting

(where they constitute much of § V*c*), the full details were n published. This was in part because other, rapid developm in cosmology and particle physics seemed to rule out the vival of particles in the range of real interest to the s situation. Although we realized that a sufficient mass frac of suitable WIMPs (ideally, with $m_w \gtrsim 4$ GeV and σ_w

Faulkner and Gilliland (1985)

and solar neutrino problem

Gaisser et al. (1986)

and DM

Limits on cold-dark-matter candidates from deep underground detectors

T. K. Gaisser and G. Steigman
Bartol Research Foundation, University of Delaware, Newark, Delaware 19716
S. Tilav
Department of Physics, University of Delaware, Newark, Delaware 19716
(Received 2 July 1986)

Weakly interacting massive particles which are candidates for the dark mass in the halo of the Galaxy would be captured by the Sun, accumulate in the solar core, and annihilate. We present a systematic evaluation of the neutrino signal produced by such annihilations. Since most annihilations occur in the dense solar interior, only prompt neutrinos escape with sufficiently high energy to be readily observable in deep underground detectors. We find that existing underground experiments are capable of finding—or excluding—several possible cold-dark-matter candidates.

I. INTRODUCTION

e mass in the Universe is dark, the nonlumi-

energy spectrum of the neutrinos at produc this with the correct energy dependence of interaction cross section in the detector to

RESONANT ENHANCEMENTS IN WEAKLY INTERACTING MASSIVE PARTICLE CAPTURE BY THE EARTH

Andrew Gould
Stanford Linear Accelerator Center, Stanford University
Received 1987 March 2; accepted 1987 March 17

ABSTRACT

The exact formulae for the capture of weakly interacting massive particles (WIMPs) by a massive body are derived. Capture by the Earth is found to be significantly enhanced whenever the WIMP mass is roughly equal to the nuclear mass of an element present in the Earth in large quantities. For Dirac neutrino WIMPs of mass 10–90 GeV, the capture rate is 10–300 times that previously believed. Capture rates for the Sun are also recalculated and found to be from 1.5 times higher to 3 times lower than previously believed, depending on the mass and type of WIMP. The Earth alone or the Earth in combination with the Sun is found to give a much stronger annihilation signal from Dirac neutrino WIMPs than the Sun alone over a very large mass range. This is particularly important in the neighborhood of the mass of iron where previous analyses could not set any significant limits.

Subject headings: elementary particles — neutrinos

I. INTRODUCTION

part of their argument that weakly interacting massive particles (WIMPs) could explain both the "dark matter problem solar neutrino problem," Press and Spergel (1985) gave an estimate of the capture rate by a massive body of WIMP well-Boltzmann distribution in the Galactic halo or Galactic disk. Their argument made admittedly crude assumptions IP phase space which they hoped would introduce errors of no more than a factor of 2. They were satisfied with this le racy because of the "order of magnitude" character of their argument. The Press and Spergel calculation was equally the probability of a given WIMP interacting with the body was of order 1, and when it was much less than 1. This w rtant feature for Press and Spergel because, to solve the solar neutrino problem, it is best to have WIMPs with much weak interaction cross sections.
bsequently a number of workers have realized that if WIMPs and anti–WIMPs were both present in the Galactic halo ld tend to collect in the Sun (Silk, Olive, and Srednicki 1985; Gaisser, Steigman, and Tilav 1986; Srednicki, Olive, and Silk

Gould (1987)

and capture by the Earth (+Sun)

Brief history of the topic

It started with the SOLAR COSMION (WIMP) to solve the solar neutrino problem and the missing mass problem (DM), due to their efficiency in energy transport.

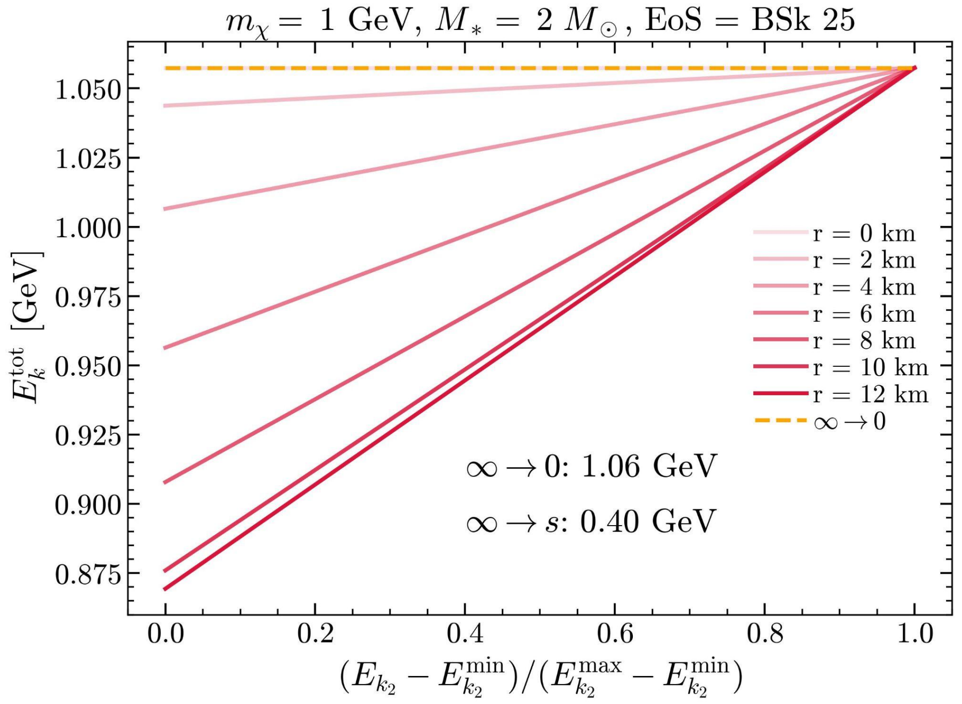
Is the last expression valid?

$$E_k = \left(\frac{1}{\sqrt{g_{tt}(0)}} - 1 \right) m_\chi$$

$$E_a = \sqrt{\frac{g_{tt}^b}{g_{tt}^a}} E_b$$

Local energy is NOT conserved!

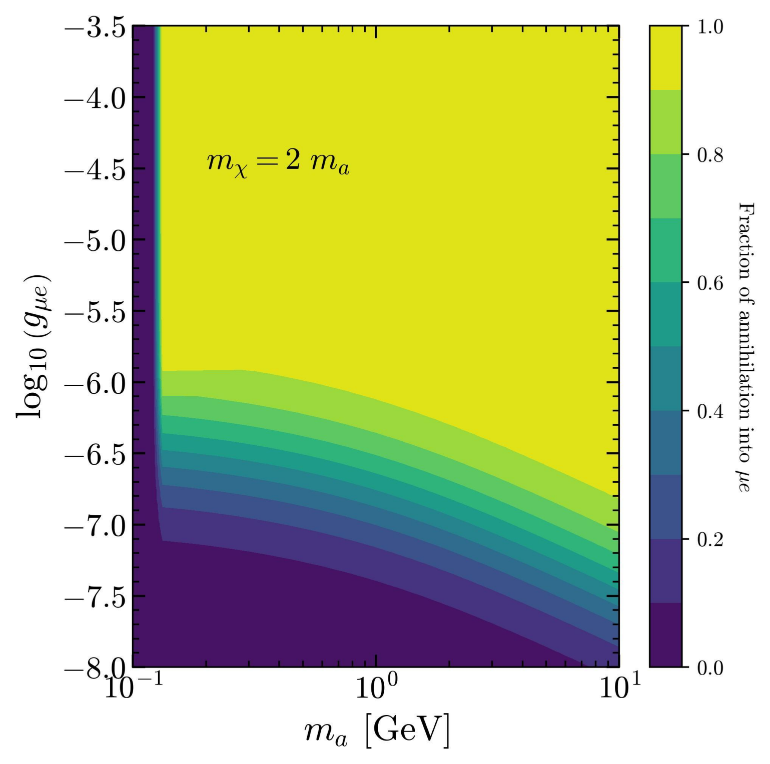
Strategy for lower bound:
1. Large number of interactions
2. Deposit all the energy on each.



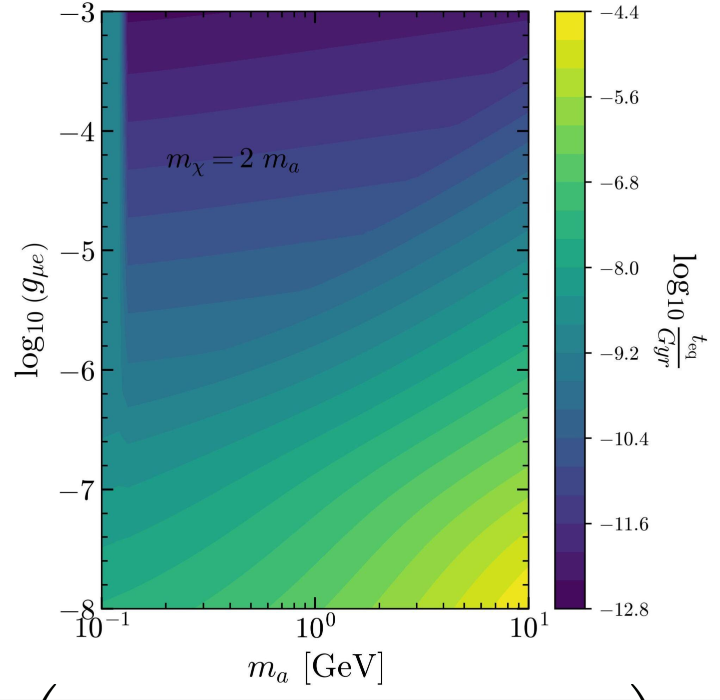
Annihilation energy deposition

Channels

$$\chi\overline{\chi} \to aa \quad \chi\overline{\chi} \to \mu^{\pm}e^{\mp}$$



If equilibrium is reached (C - A)



$$E_k = \left(\frac{1}{\sqrt{g_{tt}(R_{NS})}} + \frac{1}{2} \ln \frac{g_{tt}(R_{NS})}{g_{tt}(0)} \right) m_\chi$$

Different approaches: 1750 K