Supernova Bounds on sub-GeV Particles

Sam McDermott
1611.03864 & 1803.00993
with Rouven Essig and Jae Hyeok Chang

Fermilab

Supernova Bounds on the QCD Axion

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- an axion with a large [small] f_a would have not been produced [gotten trapped]
- intermediate f_a would “defuse” neutrinos

*[~ $m_N\times(110\text{ MeV})^3$ ~ $m_N\times0.17\text{fm}^3$]

Axions in SN1987A

- $\lambda_{mfp,\nu} \sim 1/(n_N G_F^2 T^2) \sim 1\text{m} \times (\text{radius}/10\text{km})^8 \Longrightarrow$ neutrinos diffuse until radius ~ 40km
- At r ~ 40km they are emitted with a blackbody spectrum of $L_\nu \sim 10^{52}$ erg/s

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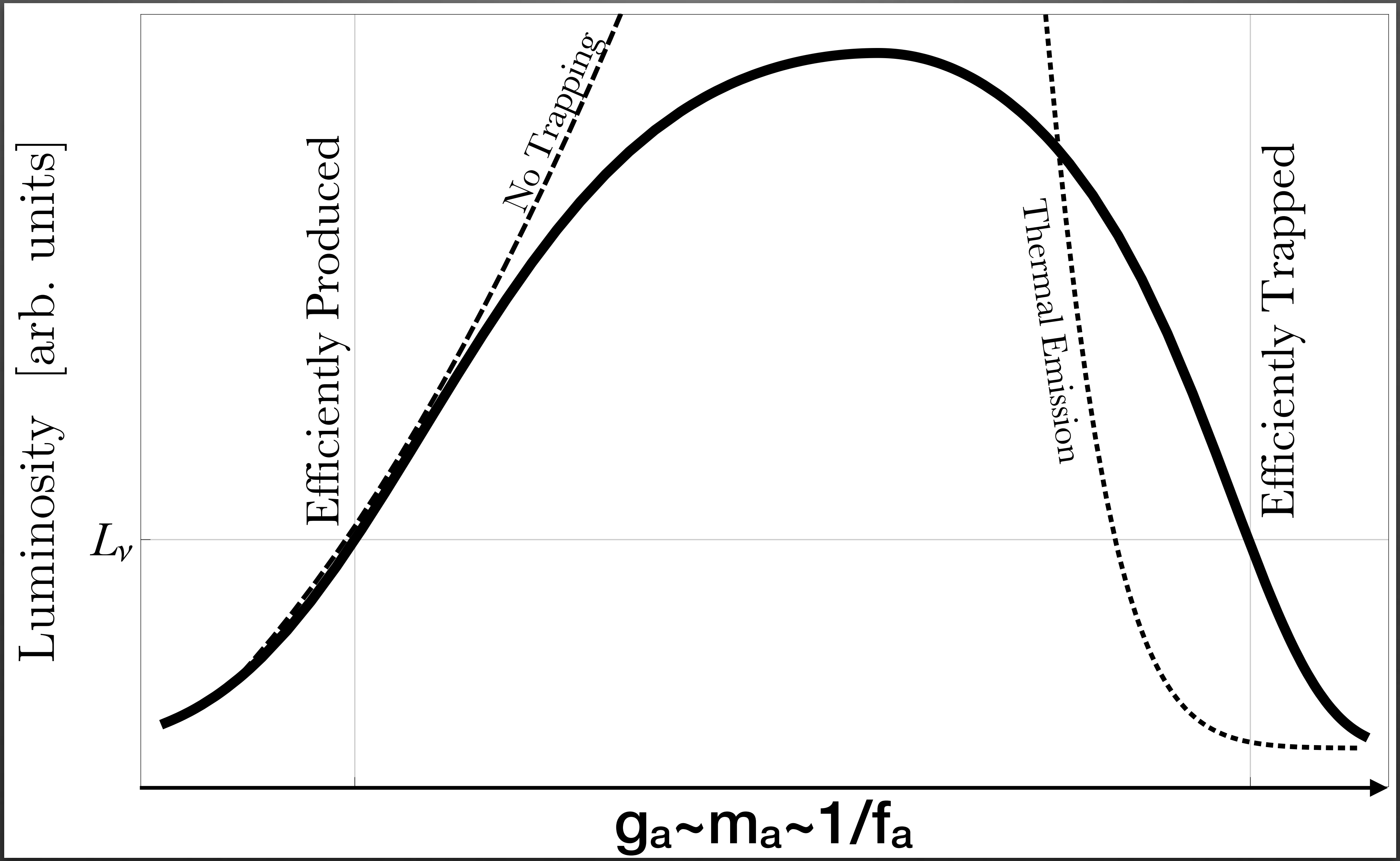
- At r ~ 40km they are emitted with a blackbody spectrum of $L_\nu \sim 10^{52}$ erg/s
- $L_a \sim \mathrm{Vol}\; Y_p\, C_p^2\, n_N^2\, \sigma_N\, T^3 / f_a^2 \sim L_\nu \times (f_a/10^9\ \mathrm{GeV})^2$ $\Longrightarrow$ axions “compete” if their decay constant is $< 10^9$ GeV (or $m_a > 10^{-11}$ GeV = 10^{-2} eV)

Bounds: Expectation

Because the environment is so hot and extreme, but the criterion is so coarse, SN1987A bounds on a given model are generically entirely below the terrestrially accessible regions of parameter space

How the bound works



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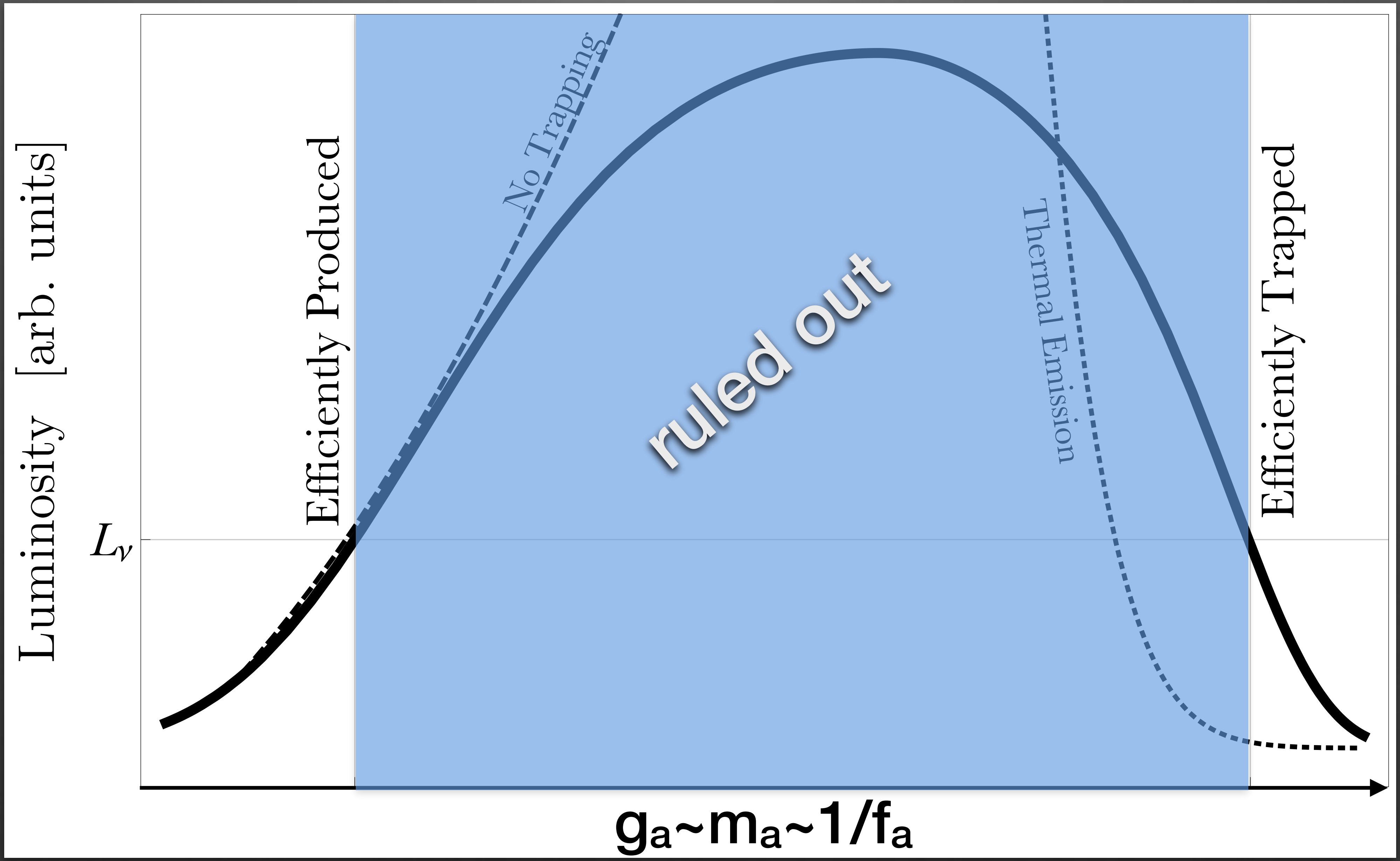

Novelt(ies) in our work(s)

- Novel treatment of large mixing angles (blackbody emission underestimates the emission of bosons, not using optical depth ~ O(1) for fermions)
- Systematic uncertainties from progenitor profile
- Chiral effective theory results for nuclear matrix element to which axion couples

Novelt(ies) in our work(s)

extends bounds by ~ order of magnitude at large coupling

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Novelt(ies) in our work(s)

introduces factor ~ few error bar

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Novelt(ies) in our work(s)

- Novel treatment emission underestimates the emission of bosons, not using optical depth ~ O(1) for fermions)

weakens constraints ~ order of magnitude

- Systematic uncertainties from progenitor profile
- Chiral effective theory results for nuclear matrix element to which axion couples

Outline

I. Knowns and Unknowns of SN1987A

II. Calculating with the QCD Axion

III. Results and Future Directions

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Broad(est possible) Picture

Supernova 1987A:

~ 99% of the grav. binding energy of a collapsing blue supergiant radiated away in the form of neutrinos over the course of ~ 10s

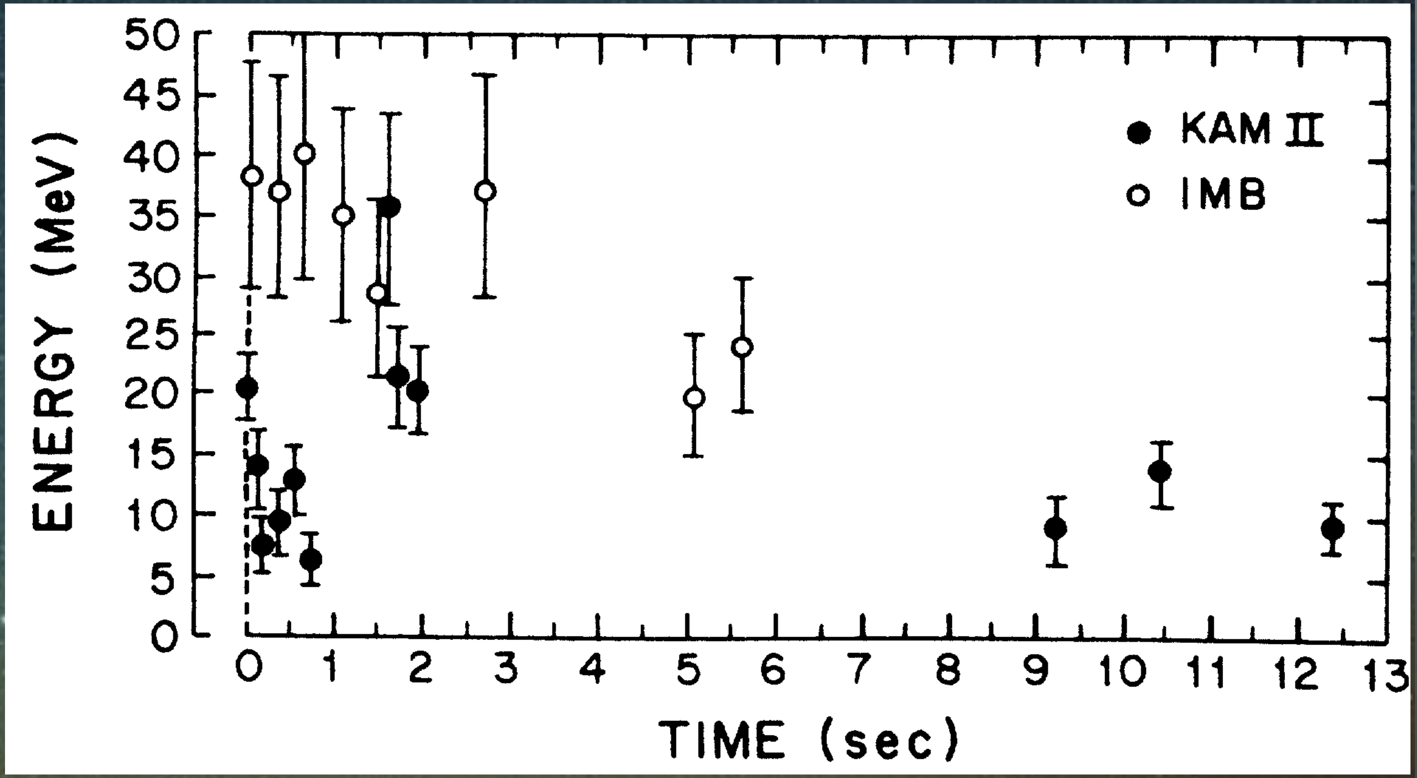
spacetelescope.org

Why Supernova 1987A?

Credit: Colin Legg

- Cooling phase is consistent with analytic expectation
- …but wouldn't be if a new "energy sink" competed with Standard Model processes
- Limited amount of luminosity may be diverted to novel particles $\Longleftrightarrow$ bounds on new coupling with SM

Why Supernova 1987A?



Hirata et al 1988

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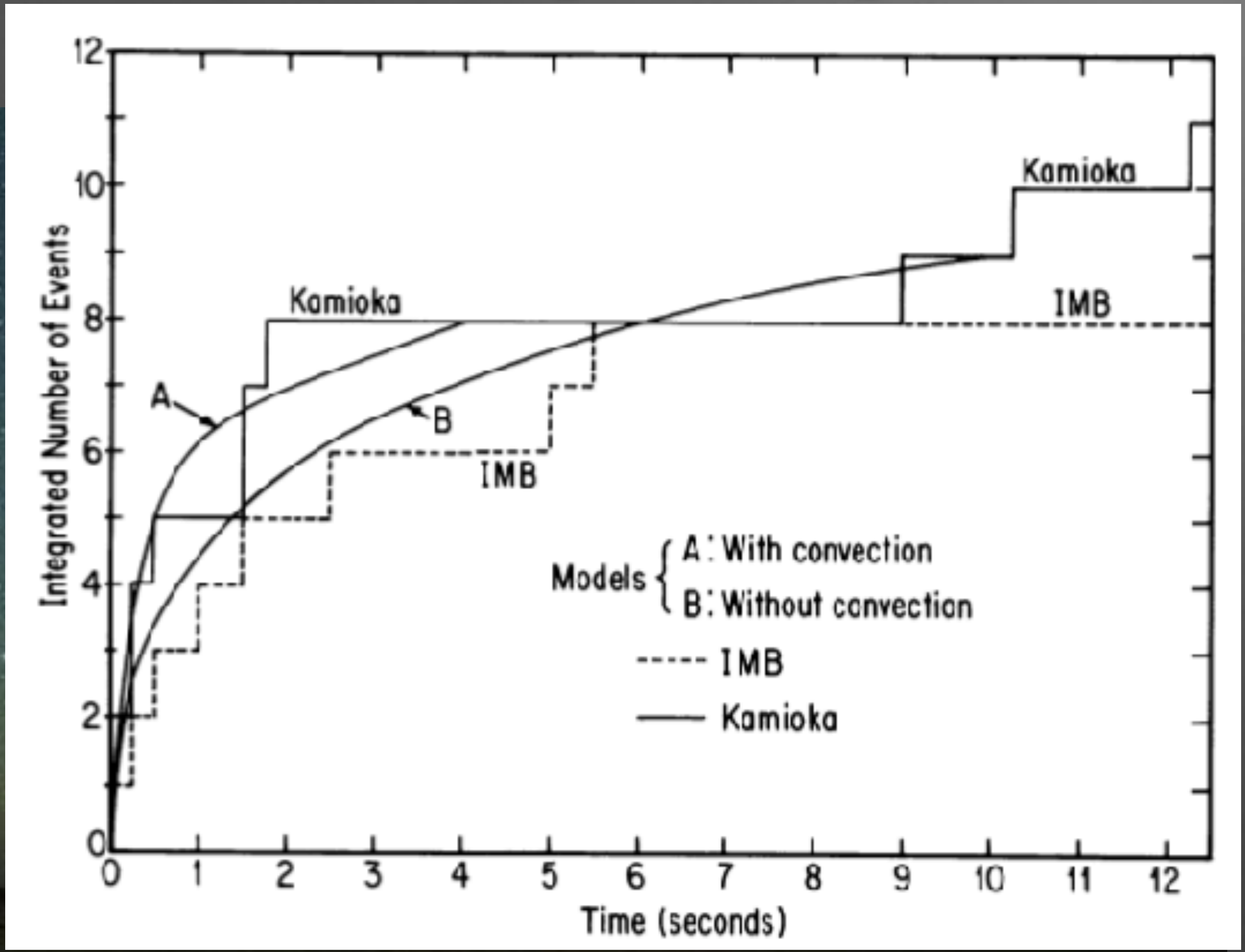

Burrows and Lattimer, 1987

Credit: Colin Legg

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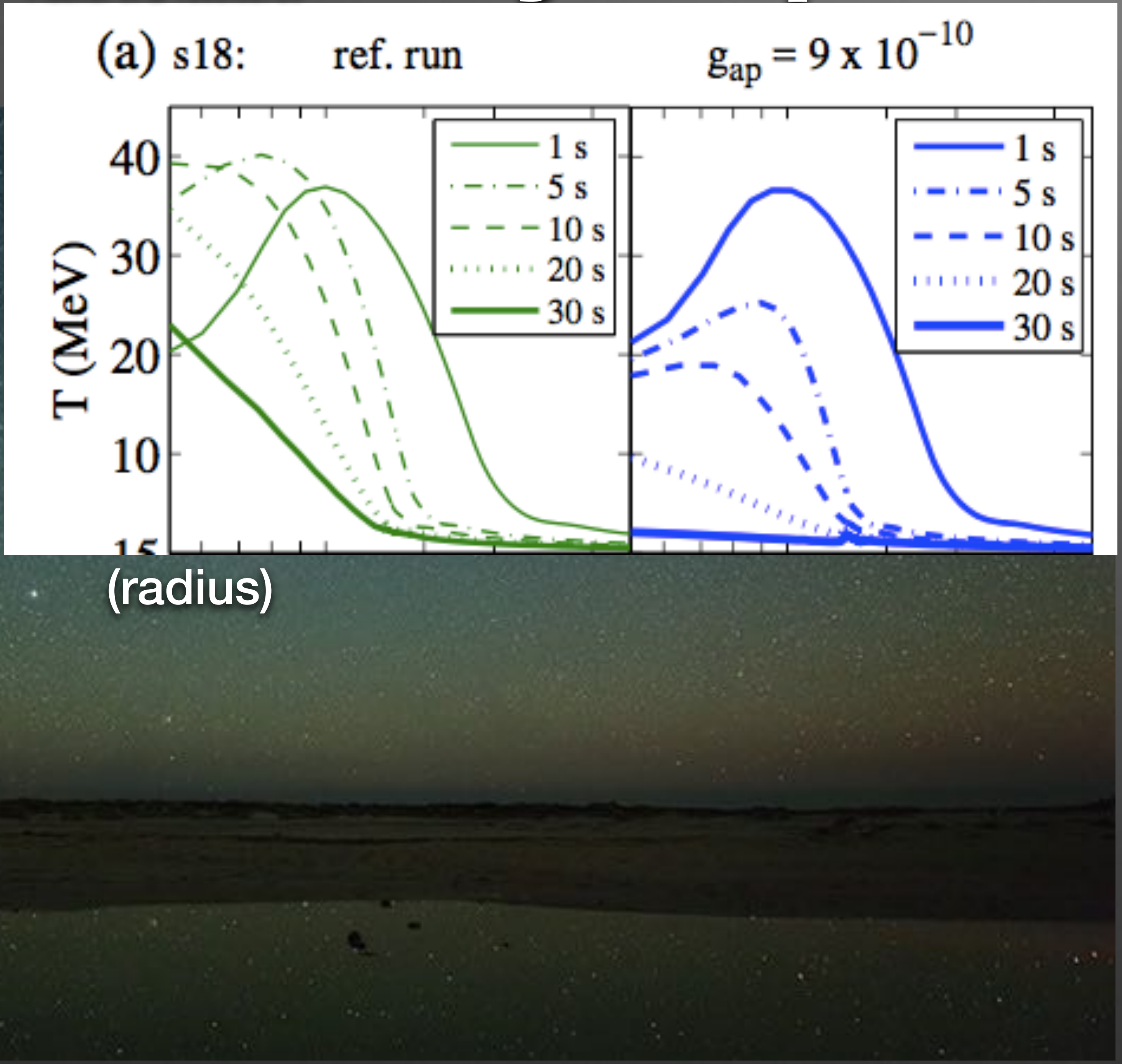
Fischer et al 1605.08780



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“$L_{new} \leq L_{\nu}$”

Credit: *Colin Legg*

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Basics of the QCD Axion

a particle that solves the strong CP problem
can be produced coherently as dark matter

$$\mathcal{L} \supset \frac{\alpha_s}{8\pi} \frac{a}{f_a} G^a_{\mu\nu} \tilde{G}^{a\mu\nu}$$

Basics of the QCD Axion

a particle that solves the strong CP problem
necessarily couples to nucleons at low energy

$$\mathcal{L} \supset \frac{\alpha_s}{8\pi}\frac{a}{f_a}G^a_{\mu\nu}\tilde{G}^{a\mu\nu} \to \frac{C_N}{2f_a}\partial_\mu a\bar{N}\gamma^\mu\gamma_5 N$$

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helpfully, this is the same nucleon current that neutrinos (dominantly) couple to:

$$\mathcal{L} \sim G_F \bar{\nu}\gamma_\mu P_L \nu \bar{N}(C_V - C_A\gamma_5)\gamma^\mu N$$

$$\left|\overline{\mathcal{M}}\right|^2_{\text{nonrel.}} \propto C_A^2 G_F^2$$

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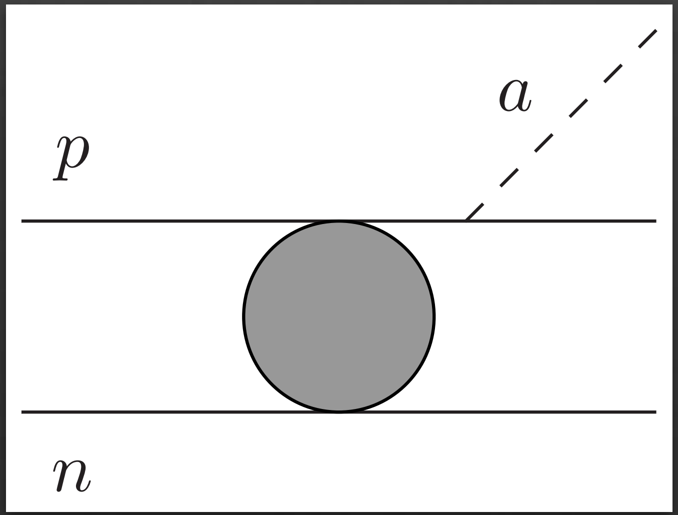
from this, we can get an interaction rate
(equivalently, a mean free path) for bremsstrahlung



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calculate axion rates using this
Lagrangian and the improved matrix
element for the nuclear spin flip rate

Particle Luminosity

$$dL = e^{-\tau} dP$$

Particle Luminosity

energy lost
in a’s per
unit time

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rate at which
a’s are
produced

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odds of
escaping

Power and Optical Depth

differential power is the integral of production rate:

$$\frac{dP}{dV} = \int \frac{d^3k}{(2\pi)^3}\omega\Gamma_{\rm prod}$$

not all power gets out because of a nonzero "optical" depth:

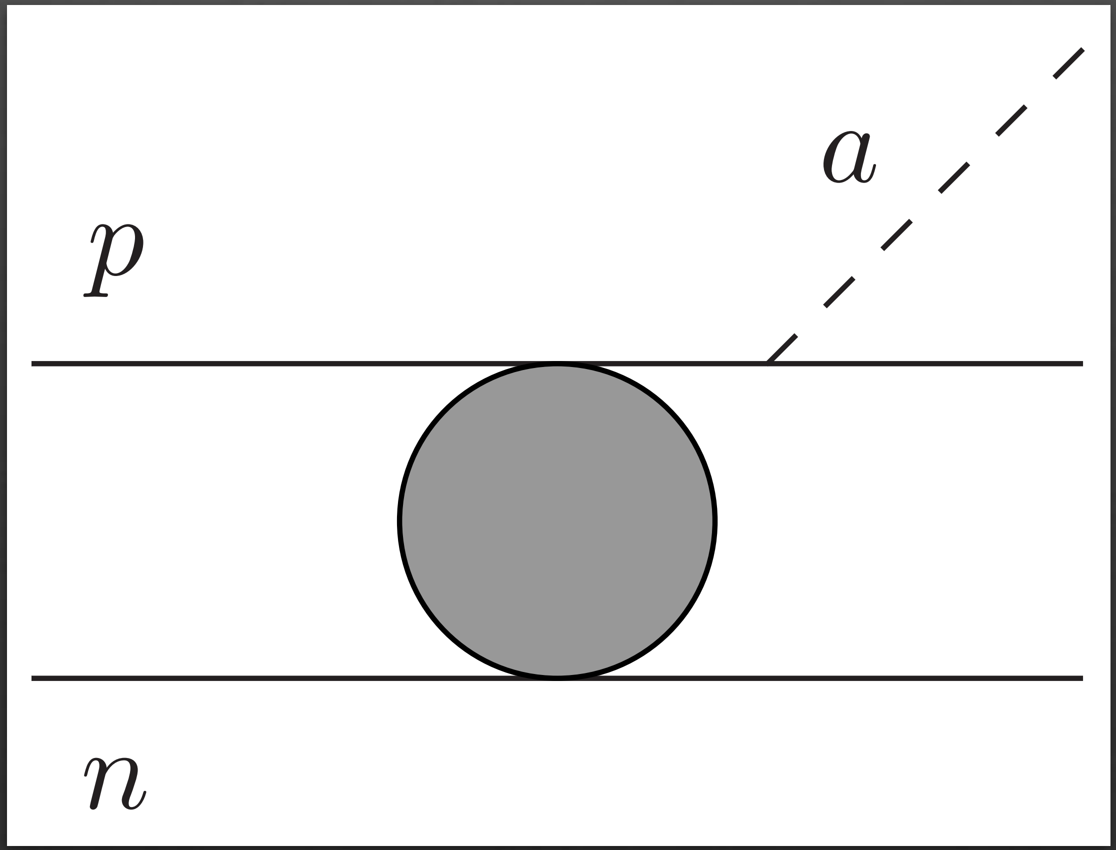
$$\tau = \int_r^{R_{\rm far}} \Gamma_{\rm abs}(r')dr'$$

by detailed balance, $\Gamma_{\rm prod} = e^{-\omega/T}\,\Gamma_{\rm abs}$, so calculate $\Gamma_{\rm abs}$ only

Axion Bremsstrahlung Rate

$$\Gamma_a^{ij} = \frac{C_i^2 Y_i Y_j}{4 f_a^2} \frac{\omega}{2} \frac{n_B^2 \sigma_{np\pi}}{\omega^2} \gamma_{\mathrm{f}} \gamma_{\mathrm{p}} \gamma_{\chi}$$

$$\sigma_{np\pi} = 4\alpha_\pi^2 \sqrt{\pi T / m_N^5}$$



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in the free-streaming limit,

$$\mathrm{Vol} \times \int \frac{d^3 p_a}{(2\pi)^3} \omega \Gamma_a \simeq \frac{10^{56}\,\mathrm{erg}}{\mathrm{sec}} \frac{C^2}{C_{\mathrm{KSVZ}}^2} \left(\frac{m_a}{\mathrm{eV}}\right)^2 \gamma_{\mathrm{f}} \gamma_{\mathrm{p}} \gamma_\chi$$

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in the free-streaming

$$\mathrm{Vol} \times \int \frac{d^3 p_a}{(2\pi)^3} \omega \Gamma_a \simeq \frac{10^{56}\,\mathrm{erg}}{\mathrm{sec}} \frac{C}{C_{\mathrm{KS}}^2}$$

cuts off low-energy divergence

$$\gamma_{\mathrm{f}} \equiv \frac{1}{1 + (n_N \sigma_{np\pi})^2 / 4\omega^2}$$

Axion Bremsstrahlung Rate

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accounts for $m_\pi \neq 0$

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corrects rate to agree with N^{3}LO χEFT calc.

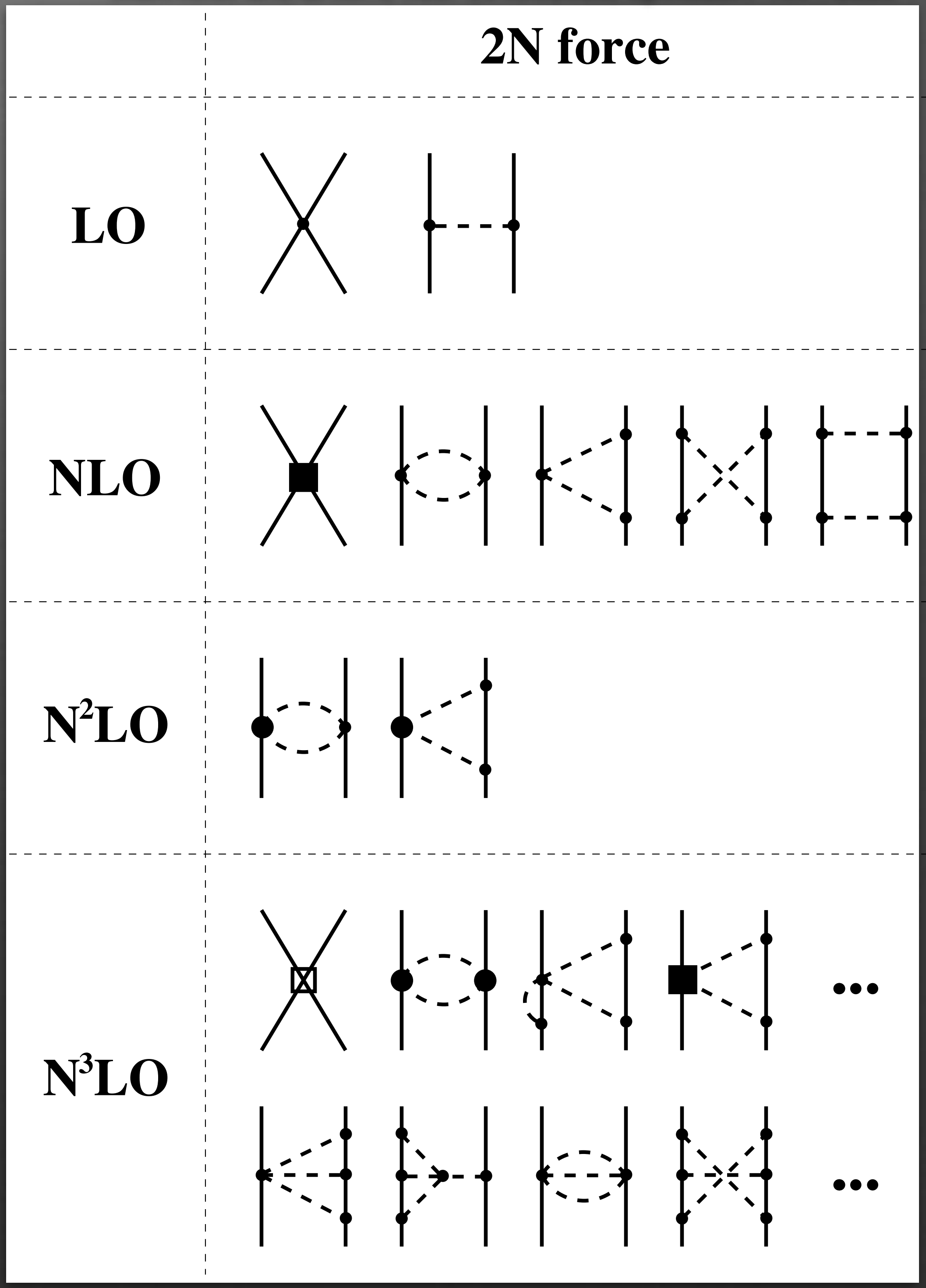
in the free-streaming

series of papers by Schwenk, Pethick, and many collaborators:
0812.0102, 1112.5185, 1403.4114, 1608.05037

$$\int \quad (2\pi)^3 \qquad \mathrm{sec} \qquad C^2_{\mathrm{KSVZ}} \quad (\mathrm{eV})$$

χEFT (& what is γ_χ?)

- γ_χ summarizes χEFT calculations
- calculations ca. 1988 were done for exchange of a single massless π
- this is LO in chiral effective theory



Machleidt and Entem, nucl-th/0503025; Epelbaum 1001.3229

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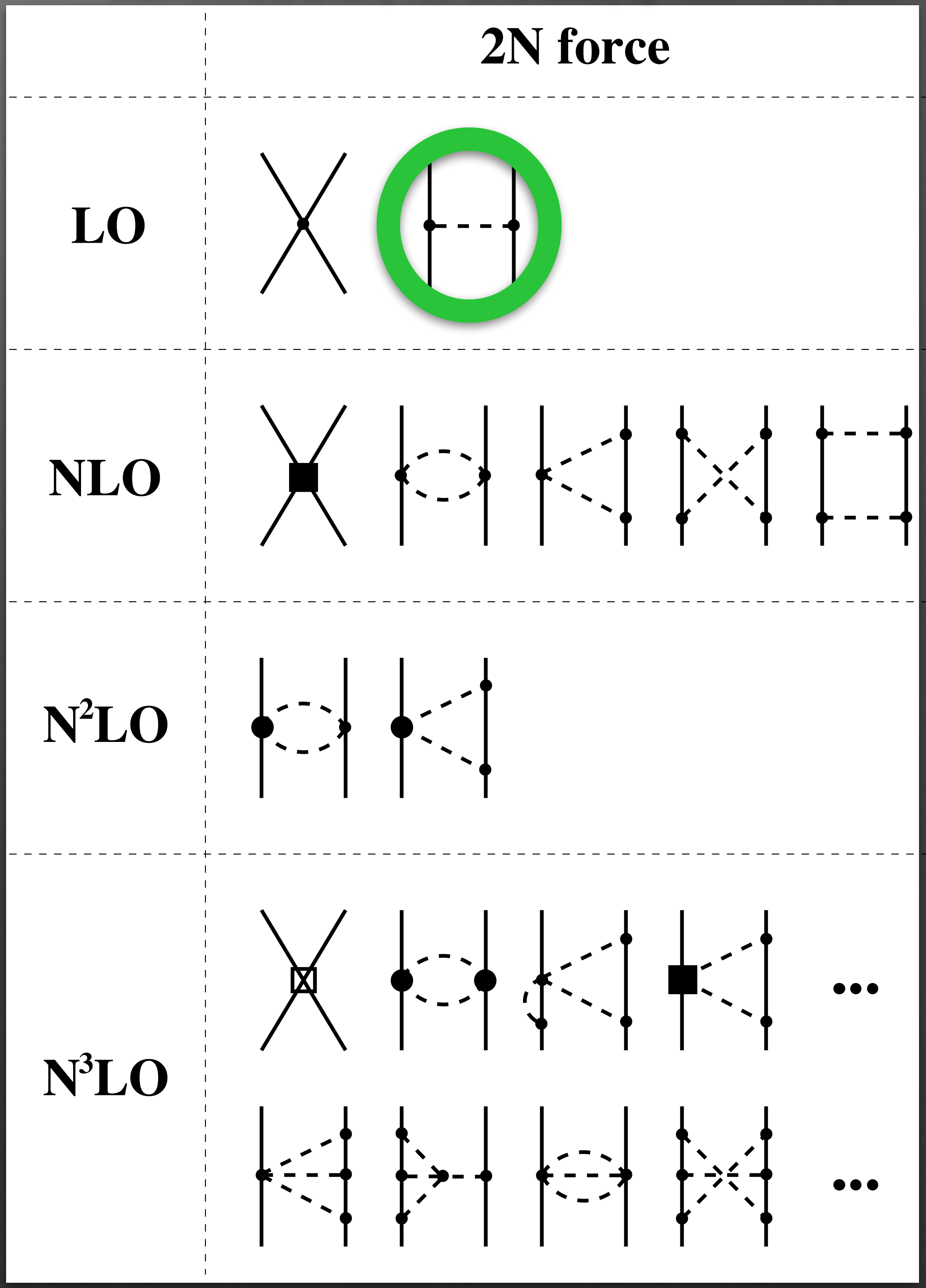
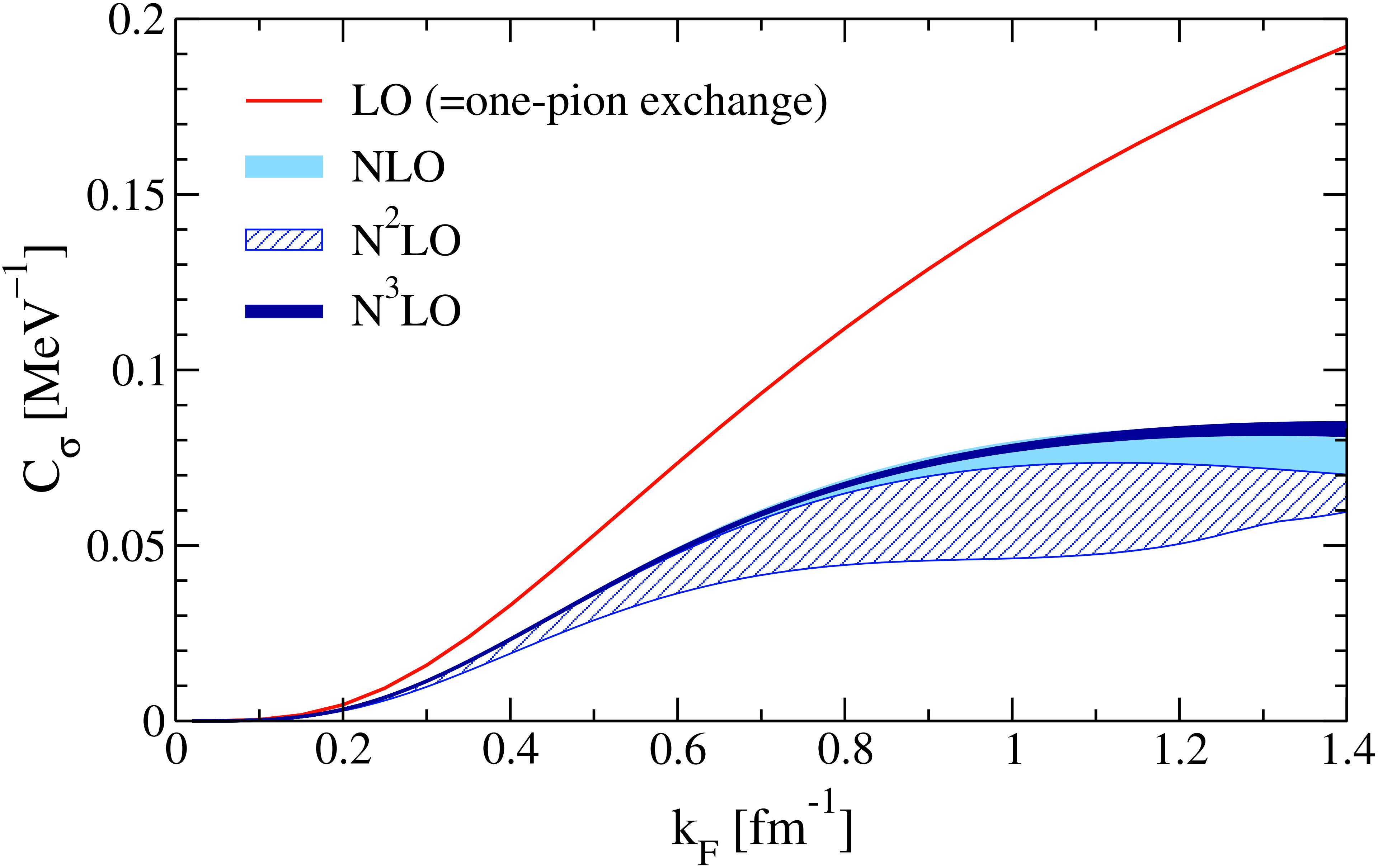


Cancellation in χEFT

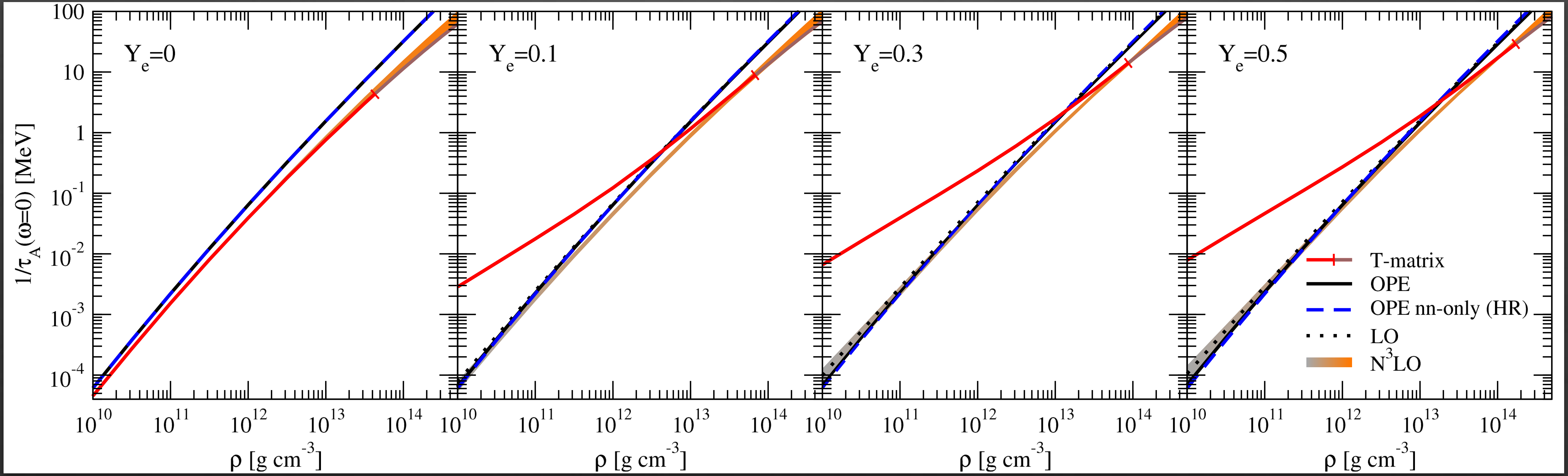
Stable beyond NLO

Bacca, Hally, Pethick, Schwenk
0812.0102



Dependence on Density and Y_p

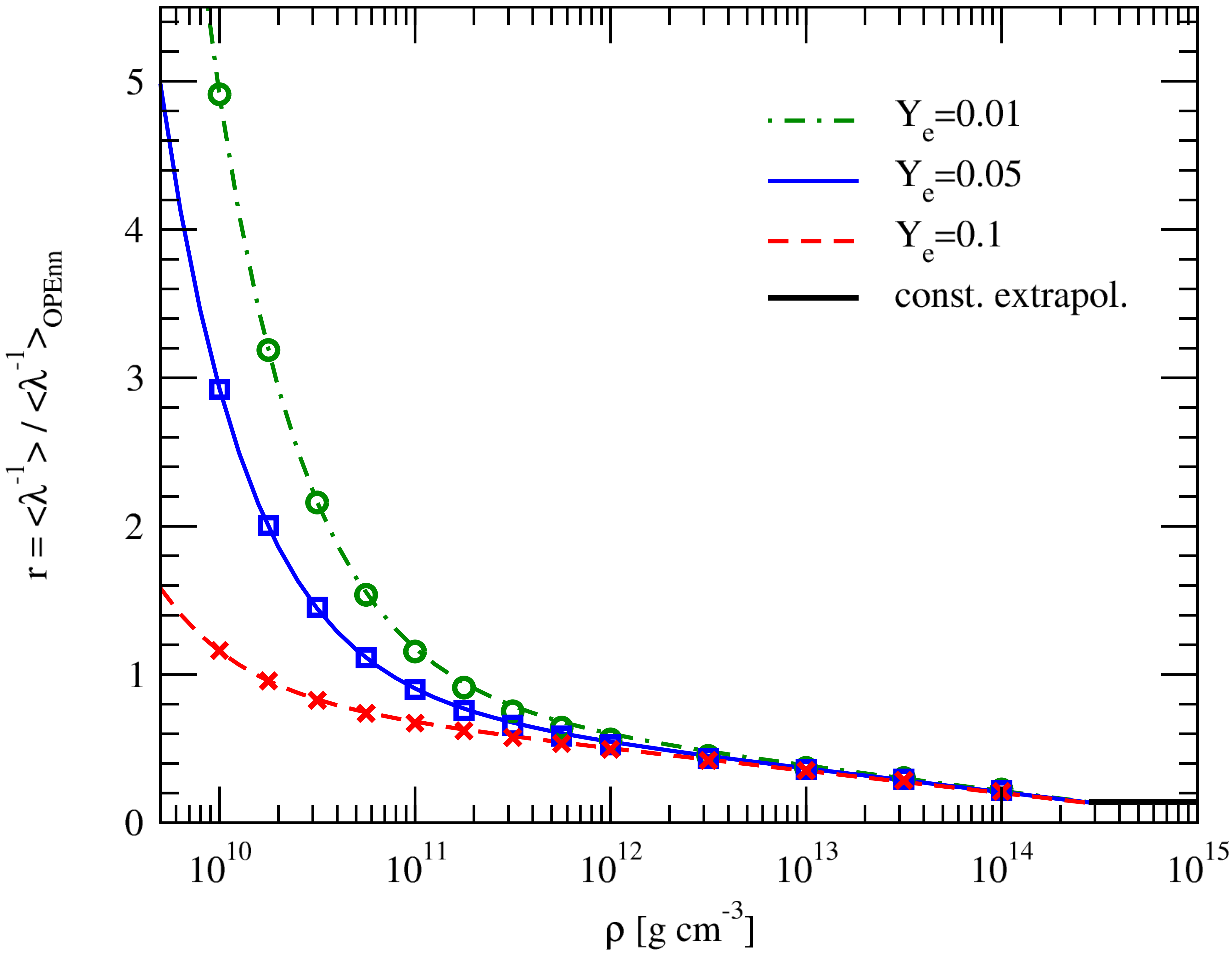
Nontrivial dependence on proton number (deuteron production resonance):



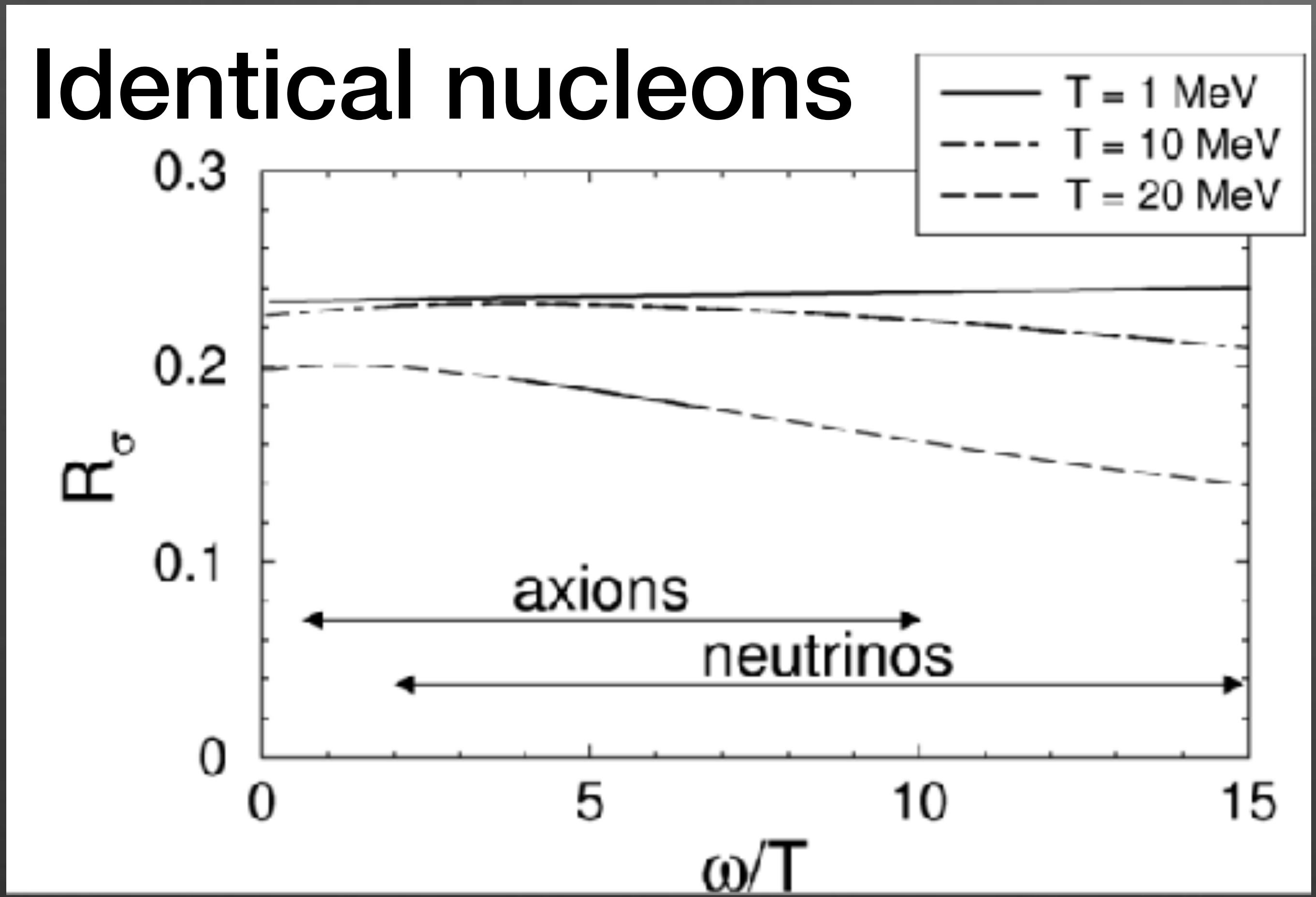
Bartl, Pethick, Schwenk 1403.4114

Ratio vs the LO result

Bartl, Bollig,
Janka, Schwenk
1608.05037

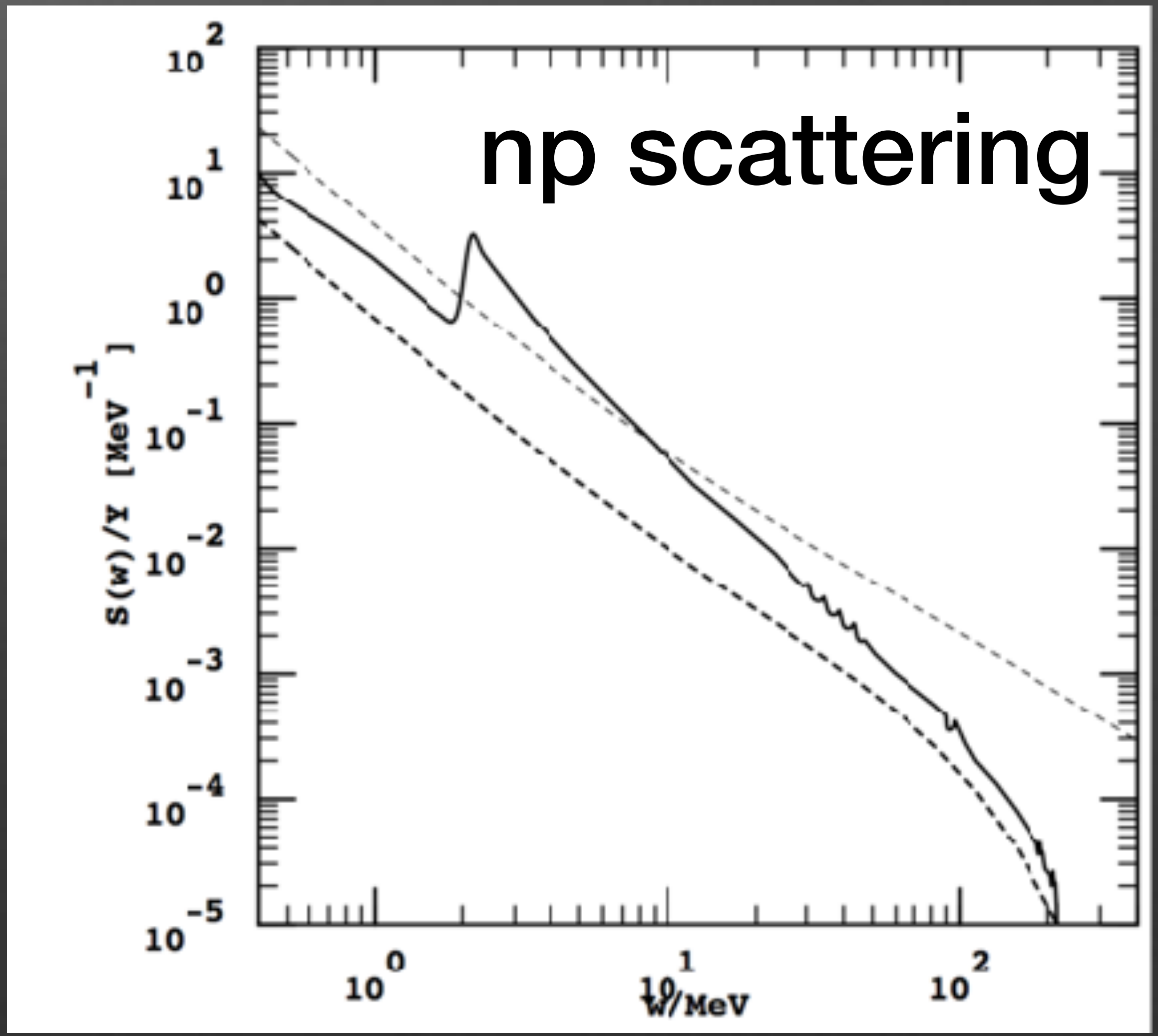


Similar physics known for ~O(20 years)



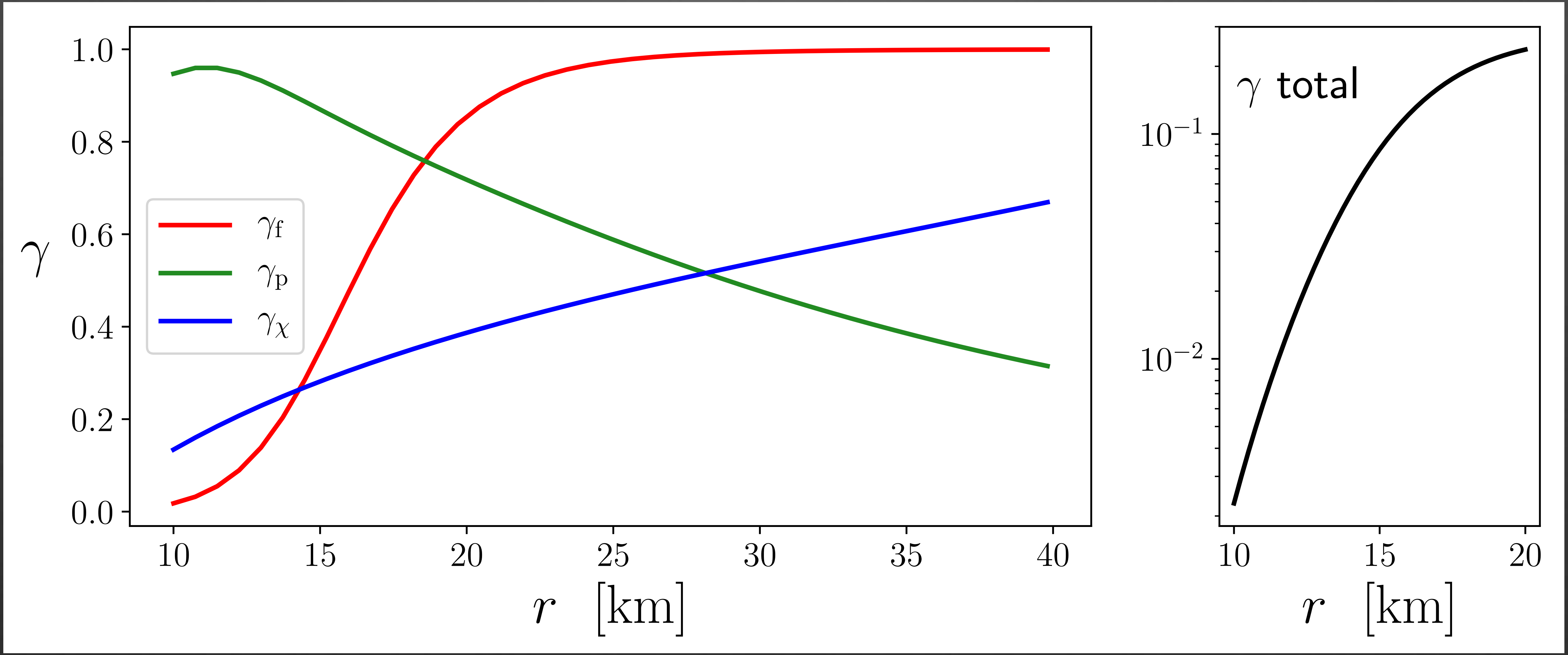
Hanhart, Phillips, Reddy 2000

Sigl 1997



Correction Factors

$$\Gamma_a^{ij} = \frac{C_i^2 Y_i Y_j}{4 f_a^2} \frac{\omega}{2} \frac{n_B^2 \sigma_{np\pi}}{\omega^2} \gamma_{\rm f} \gamma_{\rm p} \gamma_\chi$$



Supernova Thermo

“fiducial model” (Raffelt, 1995)

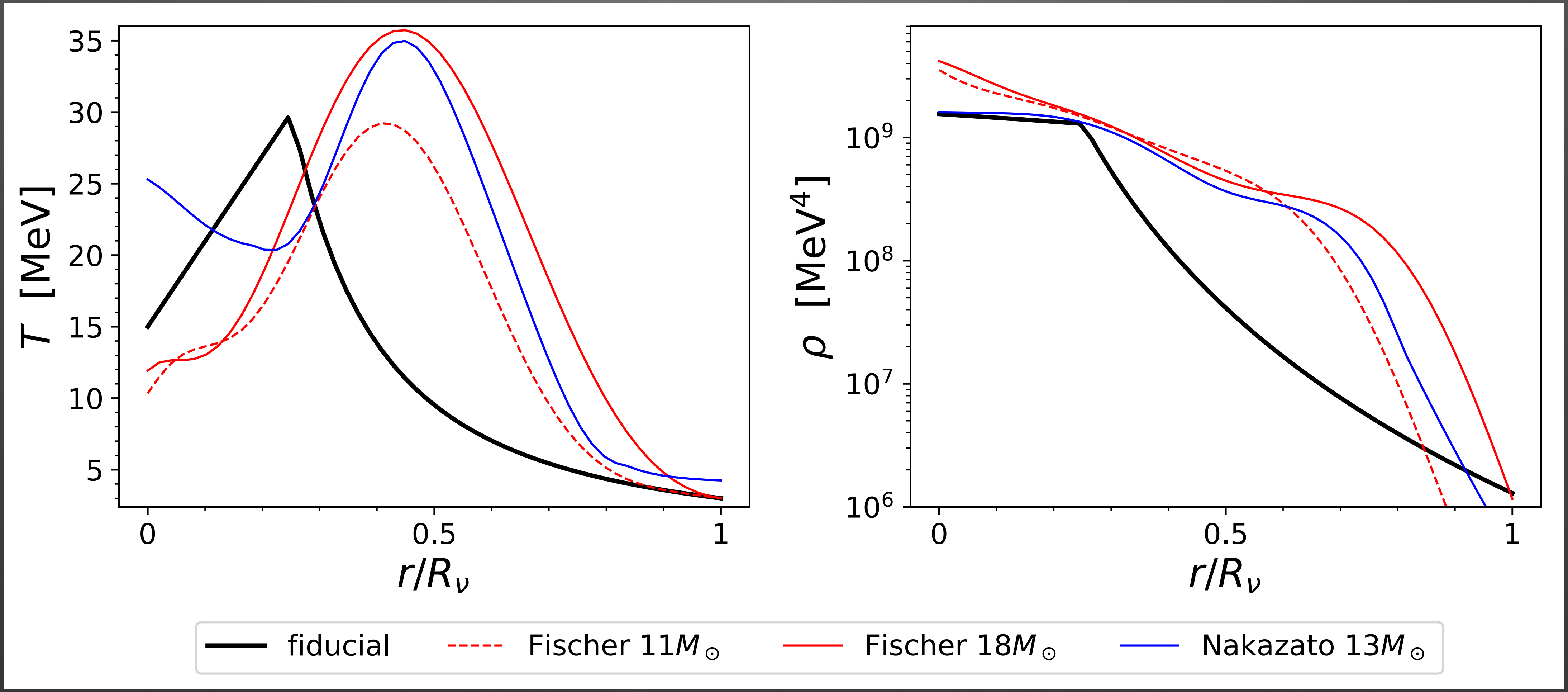
$\rho_c \approx m_N(100\text{ MeV})^3$, $T_c = 30$ MeV, $Y_p \approx 0.3$

$$\rho(r) = \rho_c \times \begin{cases} 1 + k_\rho(1 - r/R_c) & r < R_c \\ (r/R_c)^{-\nu} & r \geq R_c \end{cases}$$

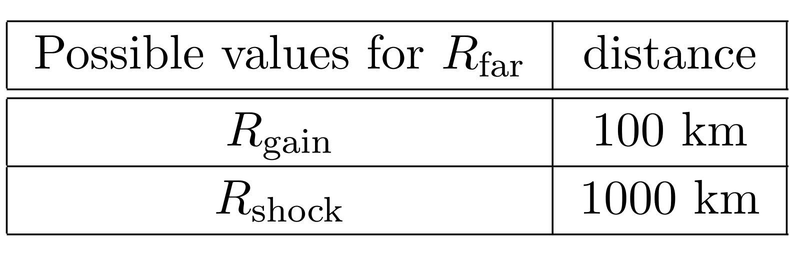
$$T(r) = T_c \times \begin{cases} 1 + k_T(1 - r/R_c) & r < R_c \\ (r/R_c)^{-\nu/3} & r \geq R_c \end{cases}$$

Uncertainties

"fiducial model" differs from sims by ~O(few):



value of R_f (important for optical depth, $\tau(r)=\int_r^{R_f} \Gamma'(r')\, dr'$)



Possible values for R_{far}	distance
R_{gain}	100 km
R_{shock}	1000 km

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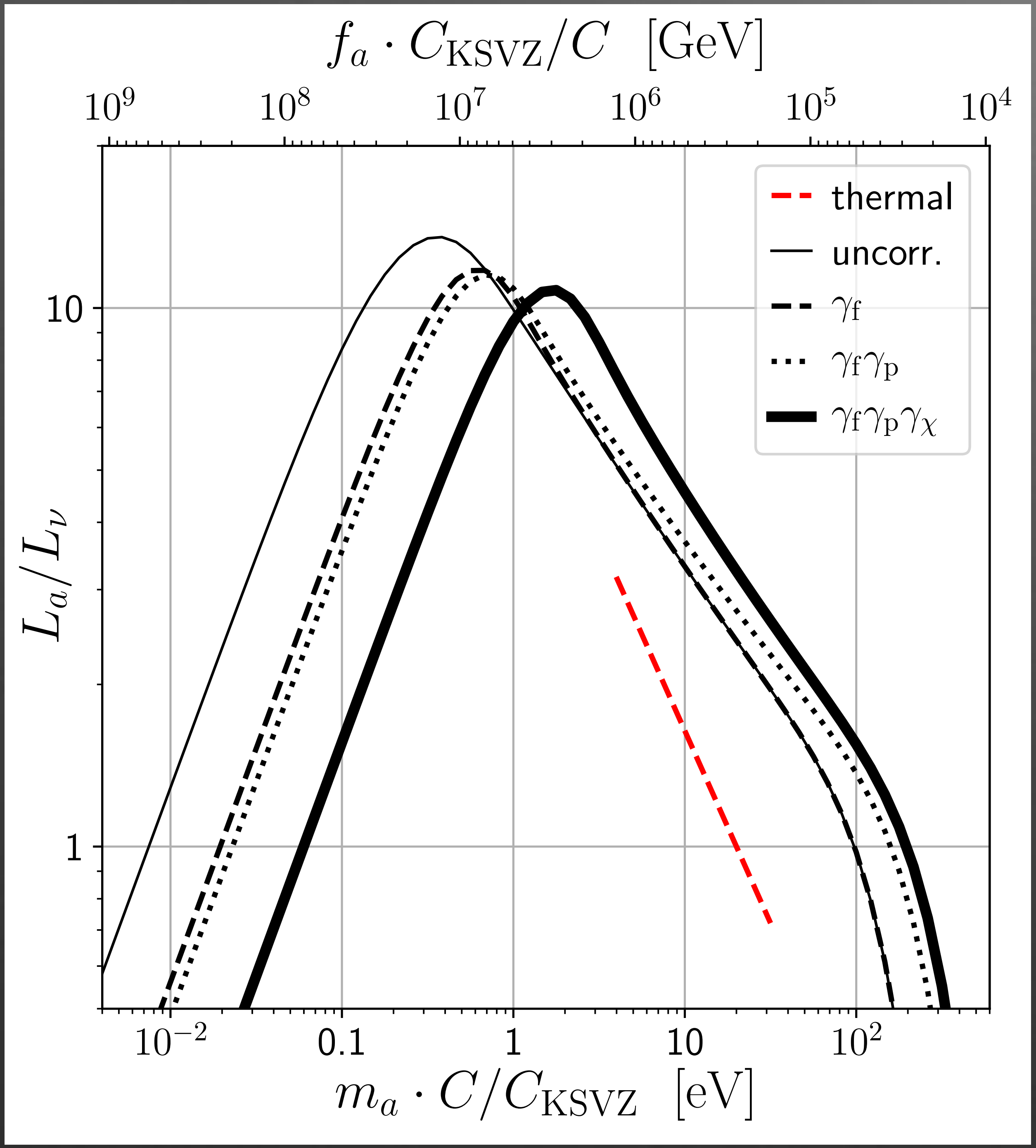
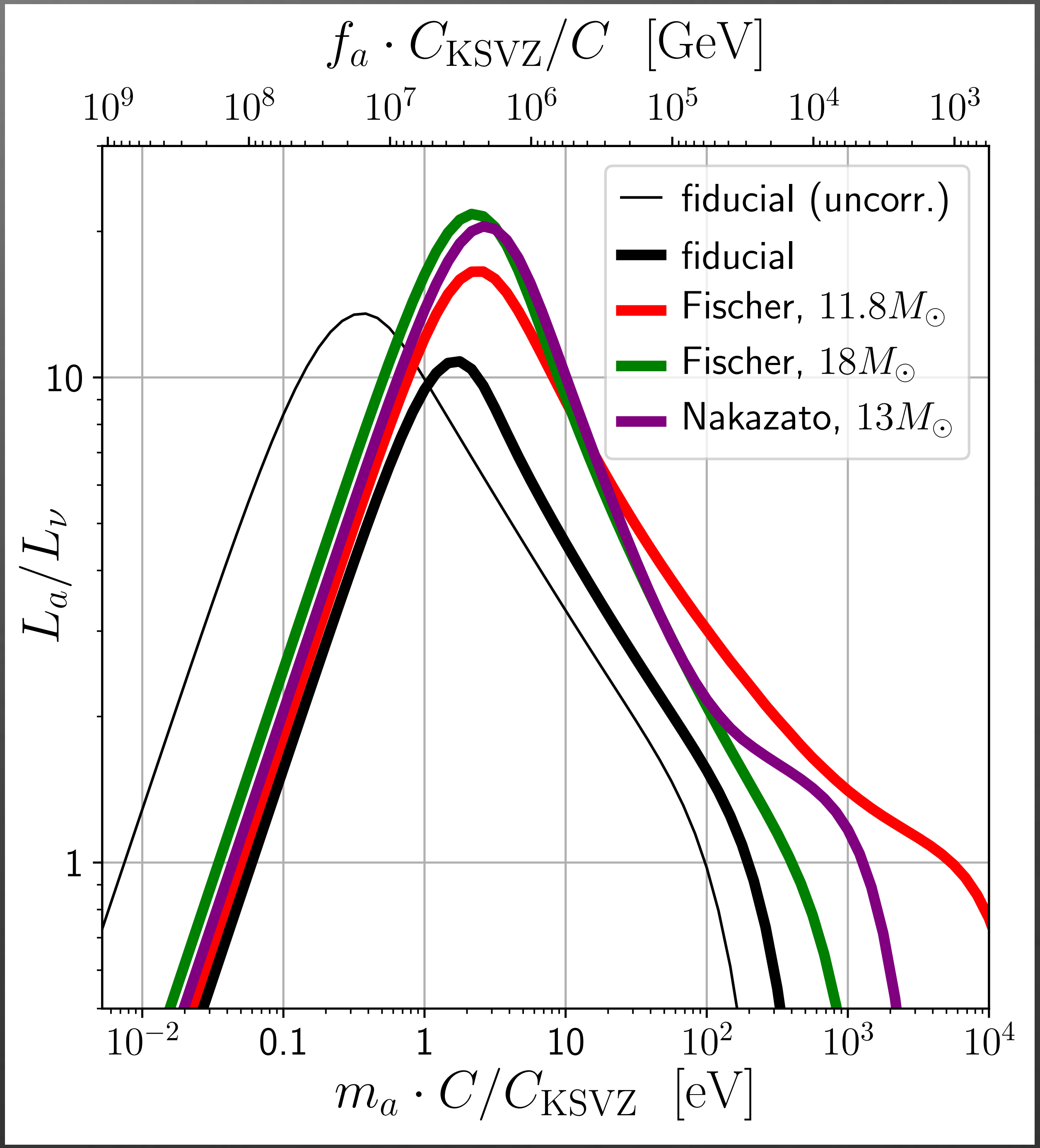
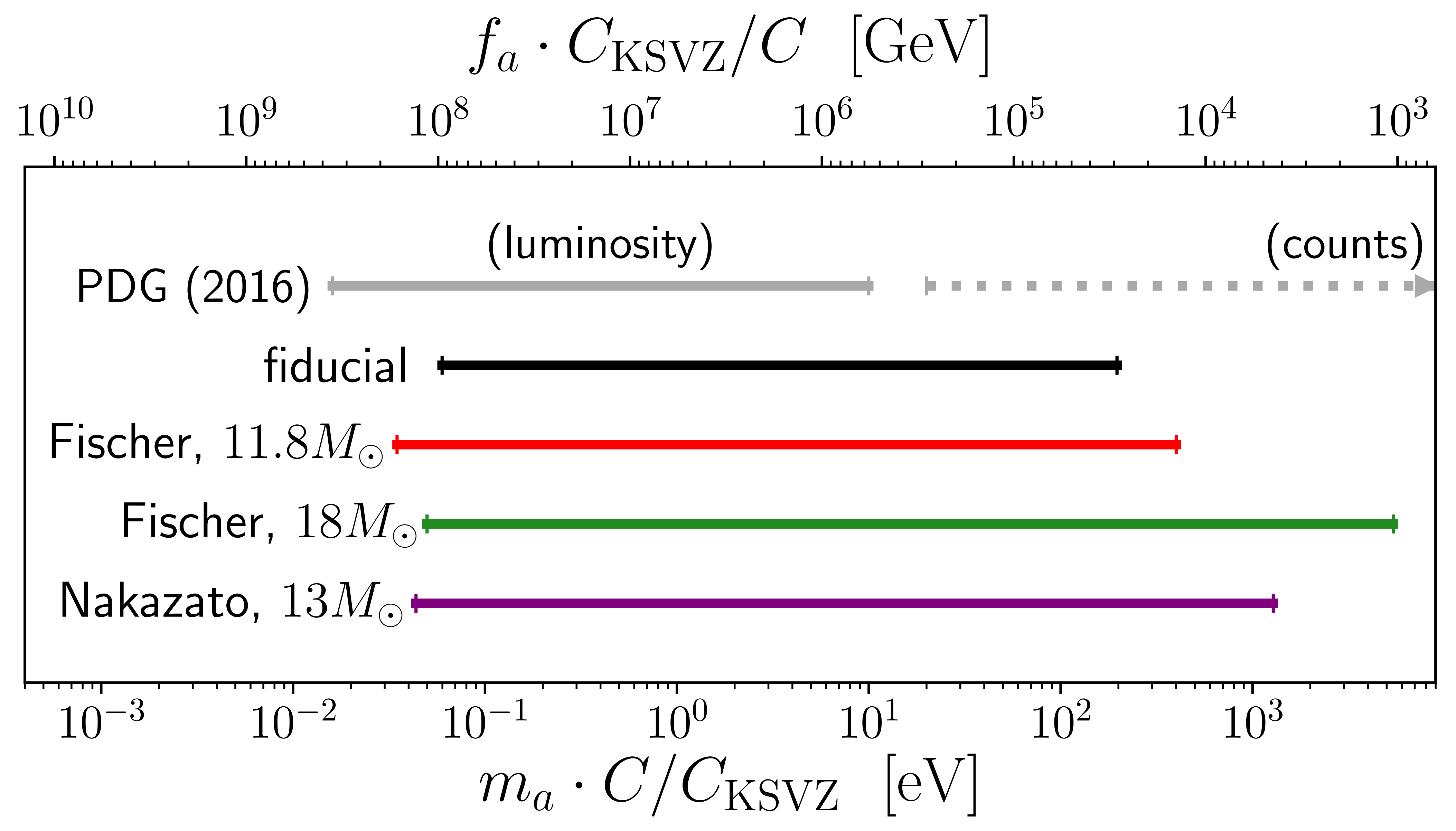
Luminosity vs. Coupling

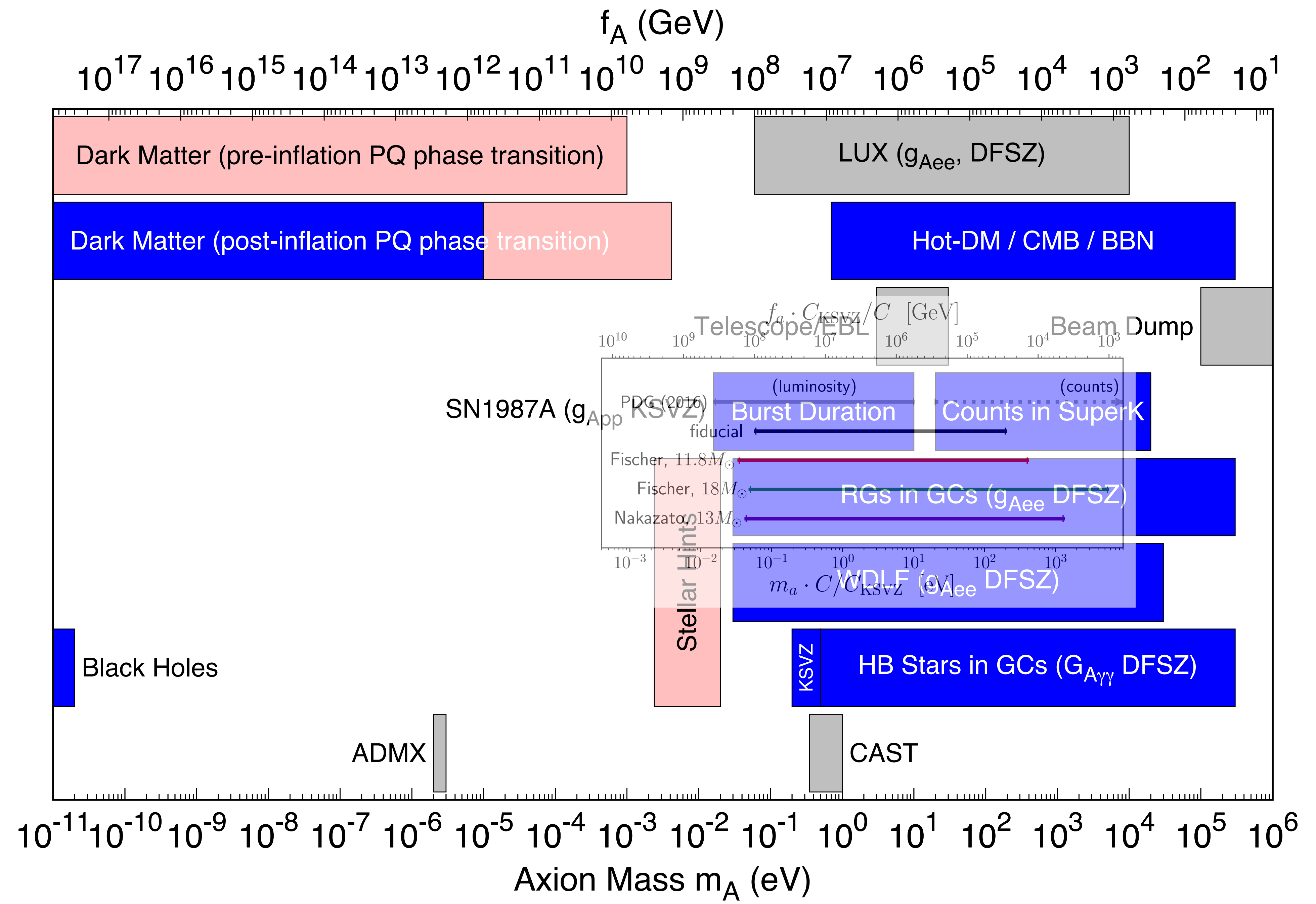




Constraints



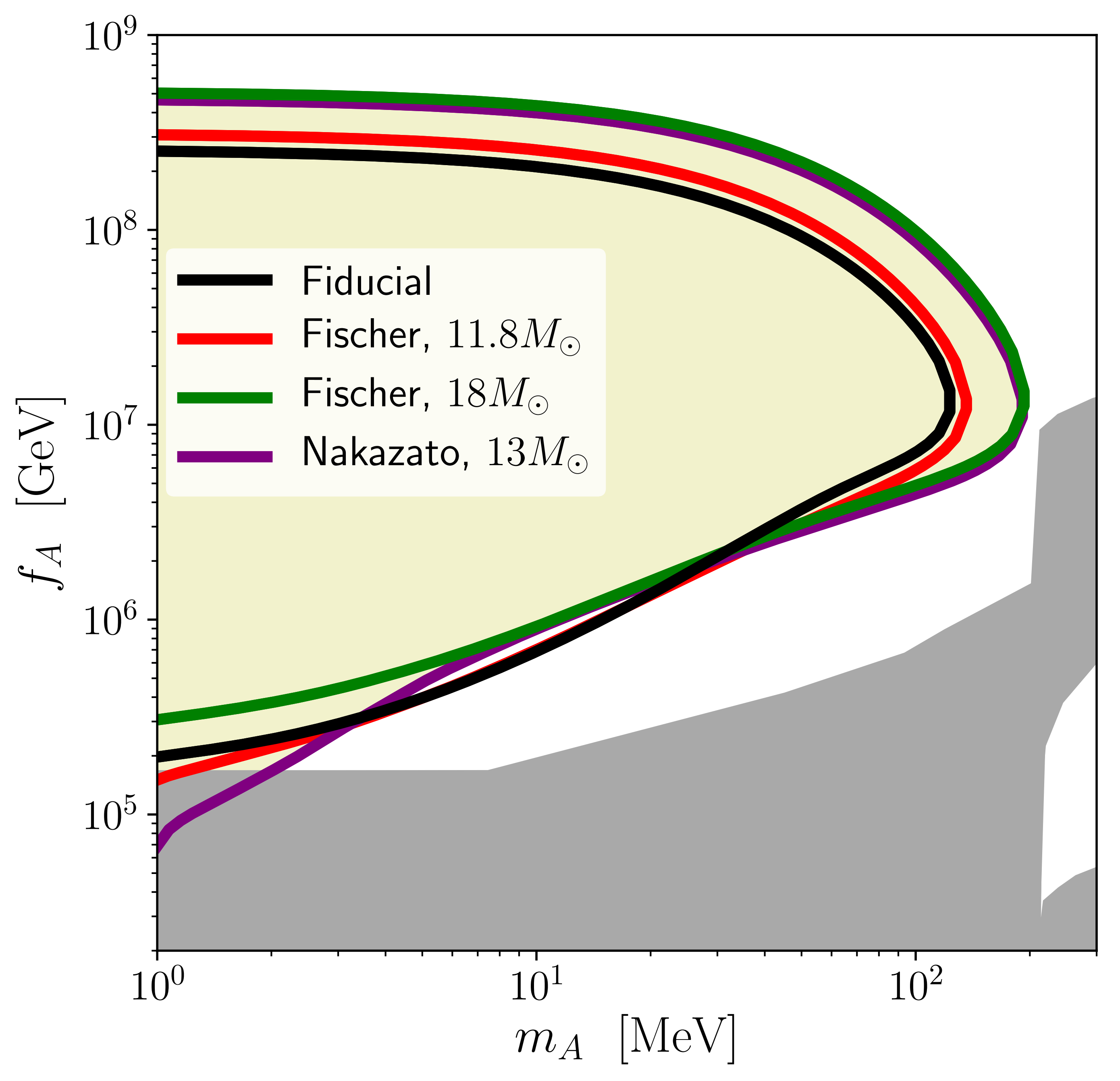
Hadronic Axion



“hadronic axion window” seems to be ruled out

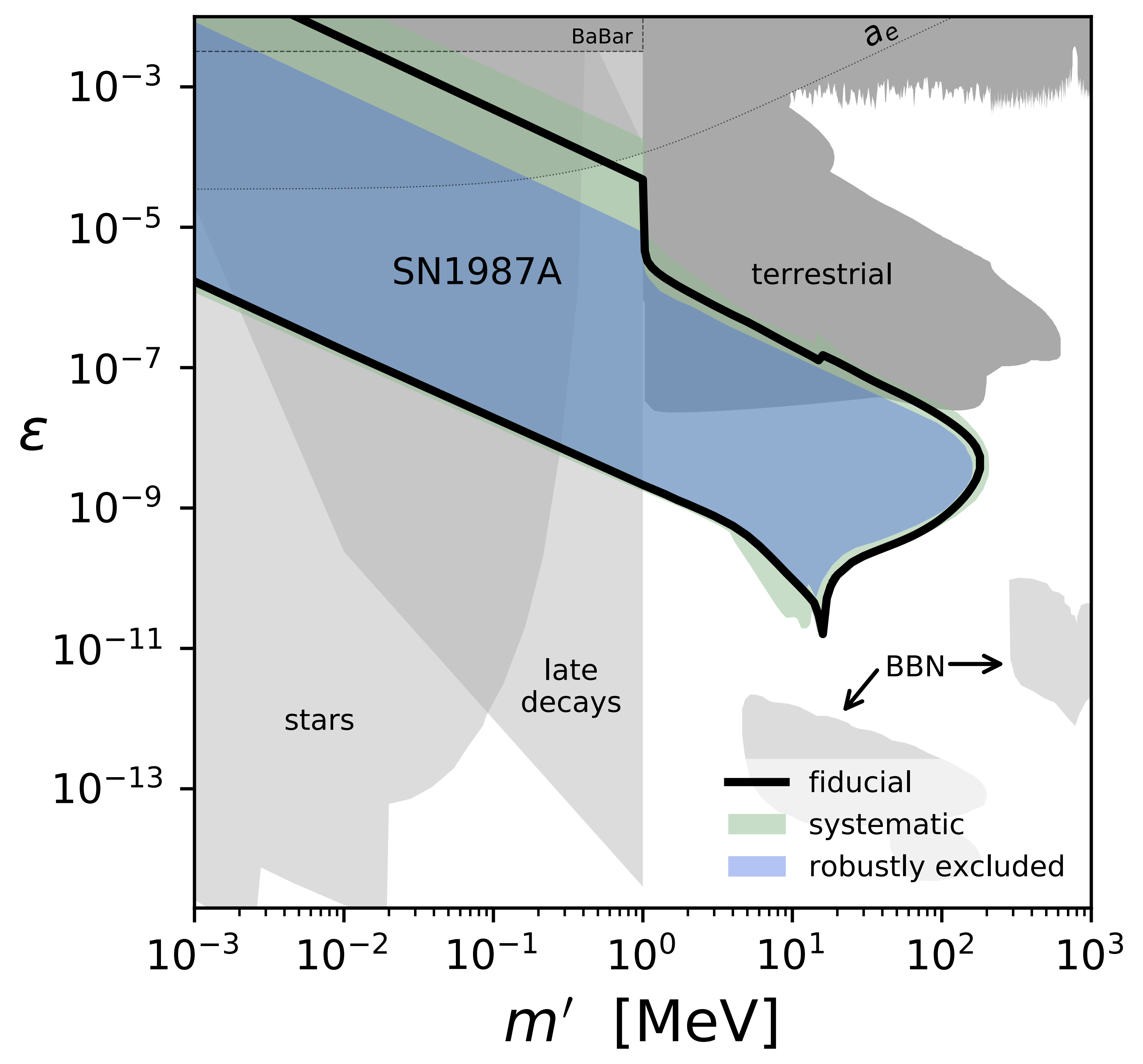
Different Models Lightning Round!

Axion-Like Particle

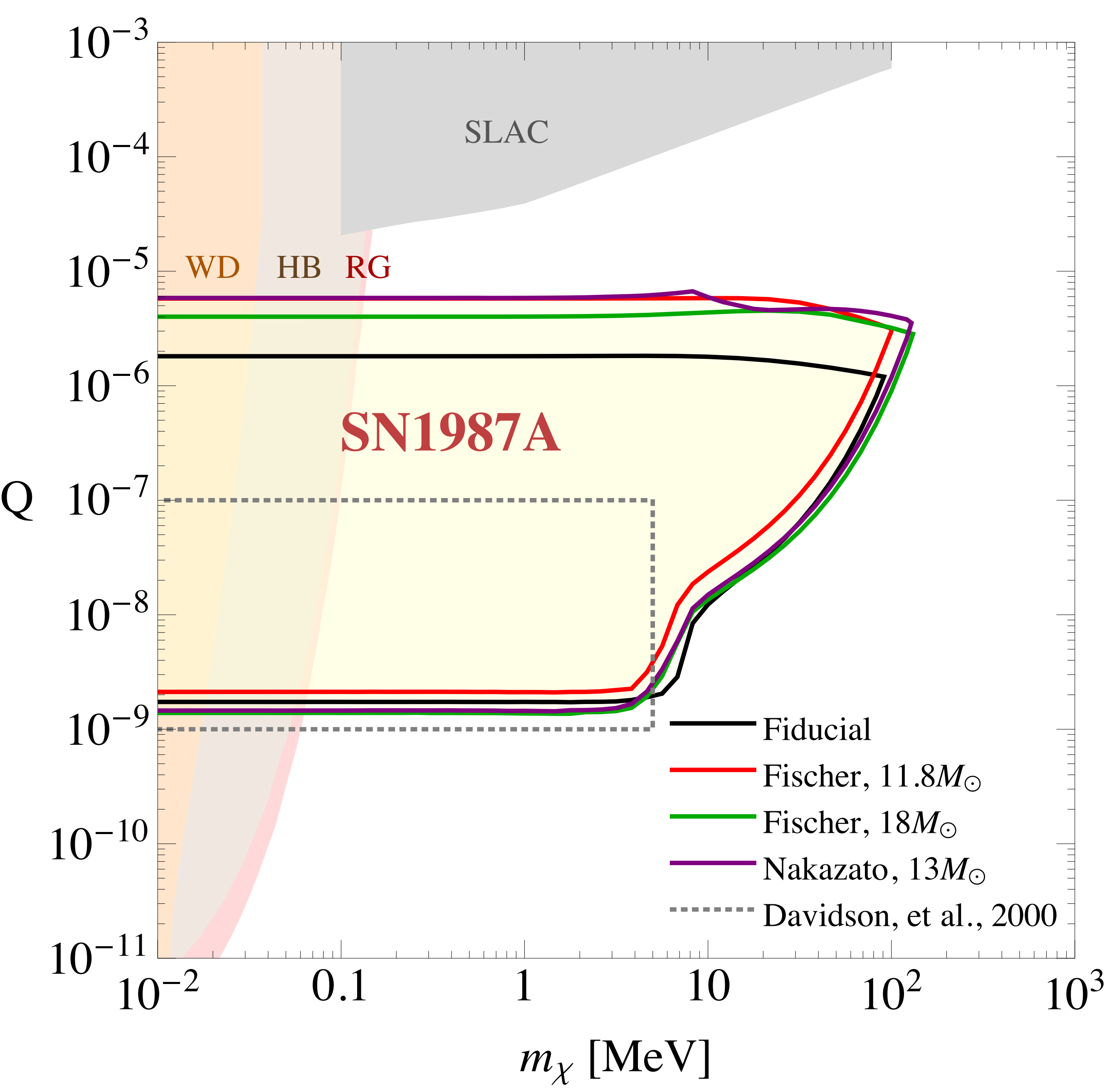


couples to all SM fermions ~ mass but $m_A f_A \neq m_\pi f_\pi$

Dark Photon

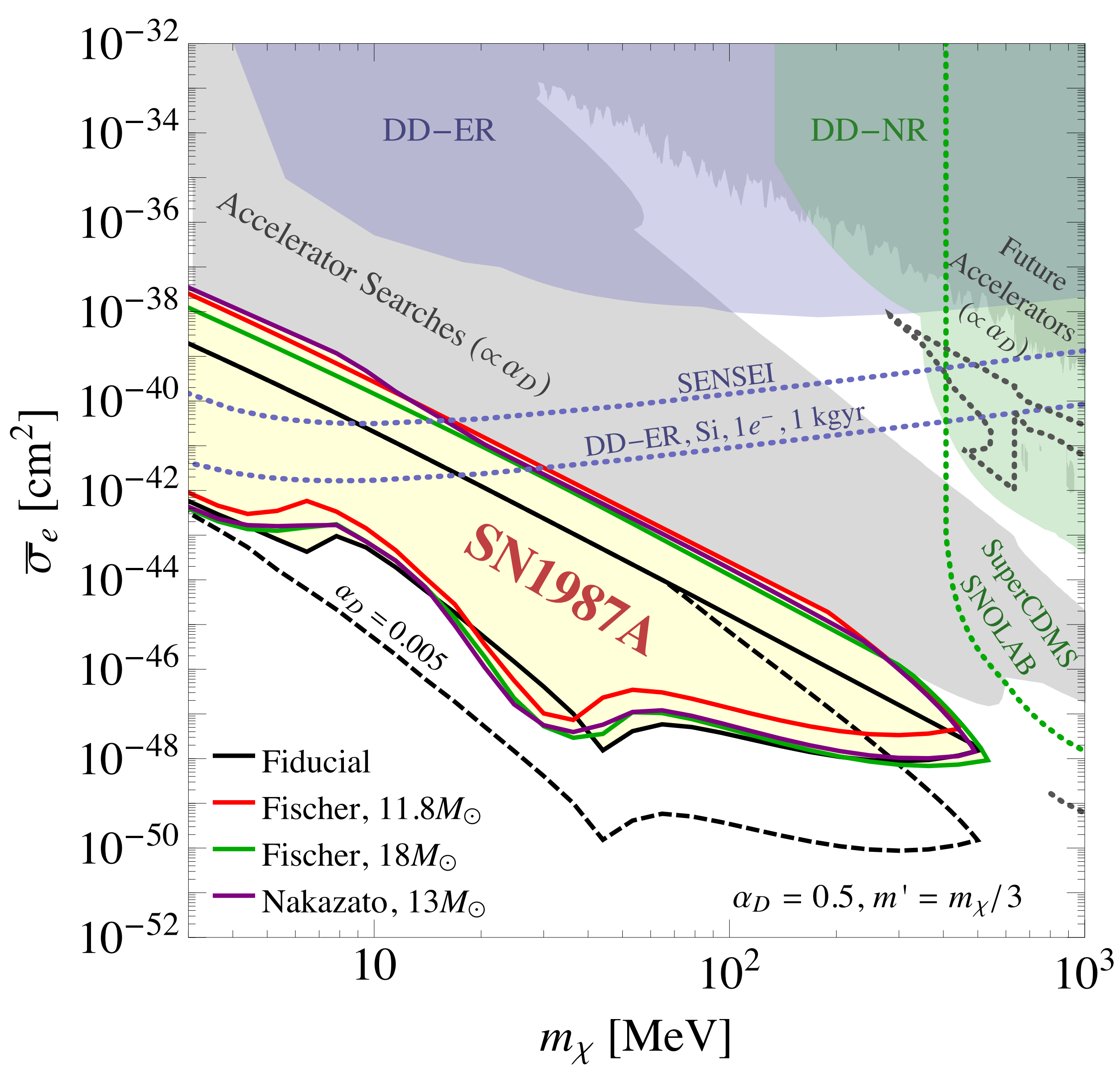

BaBar
a_e
SN1987A
terrestrial
stars
late decays
BBN
fiducial
systematic
robustly excluded
ε
10^{-3}
10^{-5}
10^{-7}
10^{-9}
10^{-11}
10^{-13}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
m' [MeV]

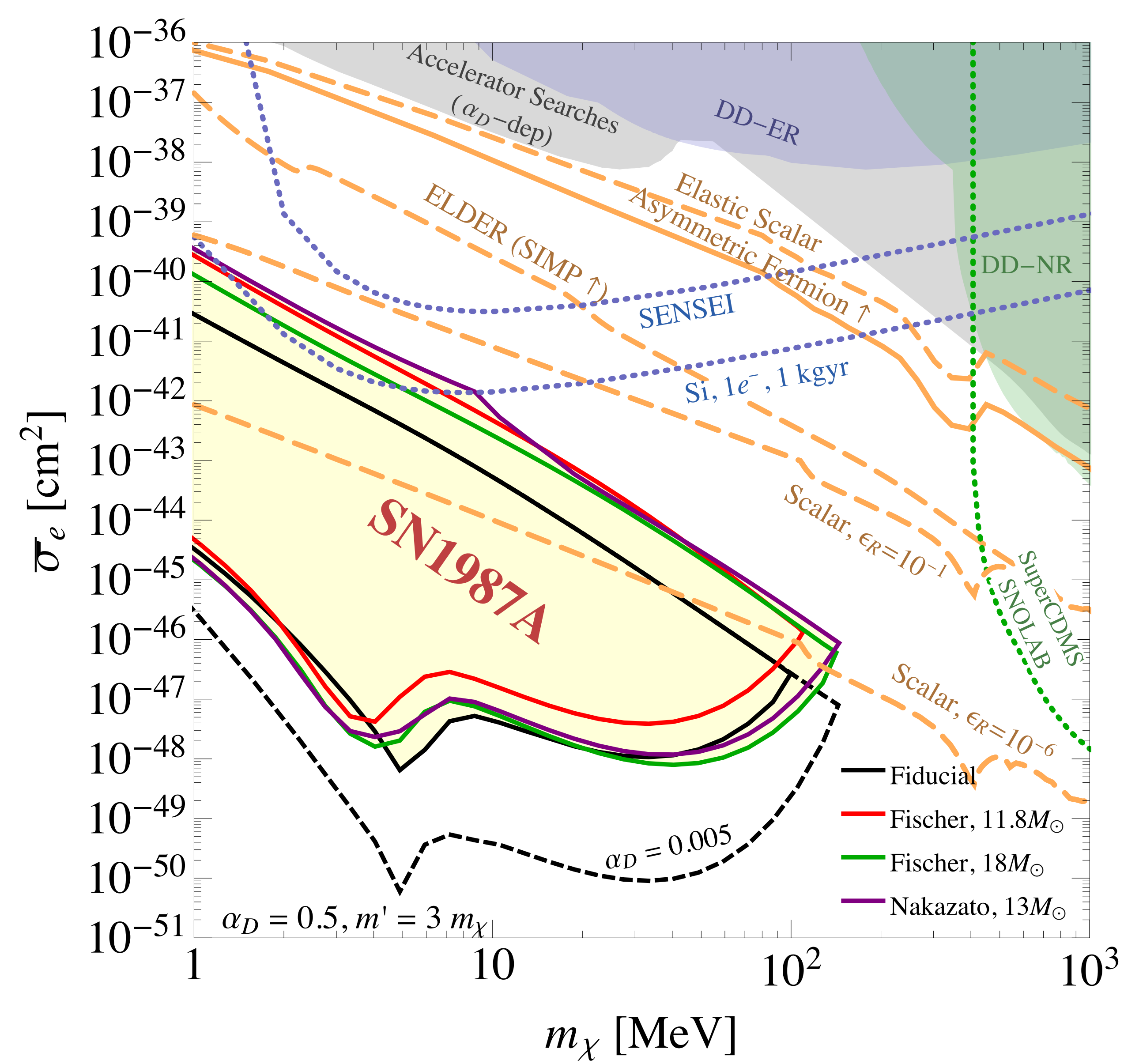
Millicharged Particle



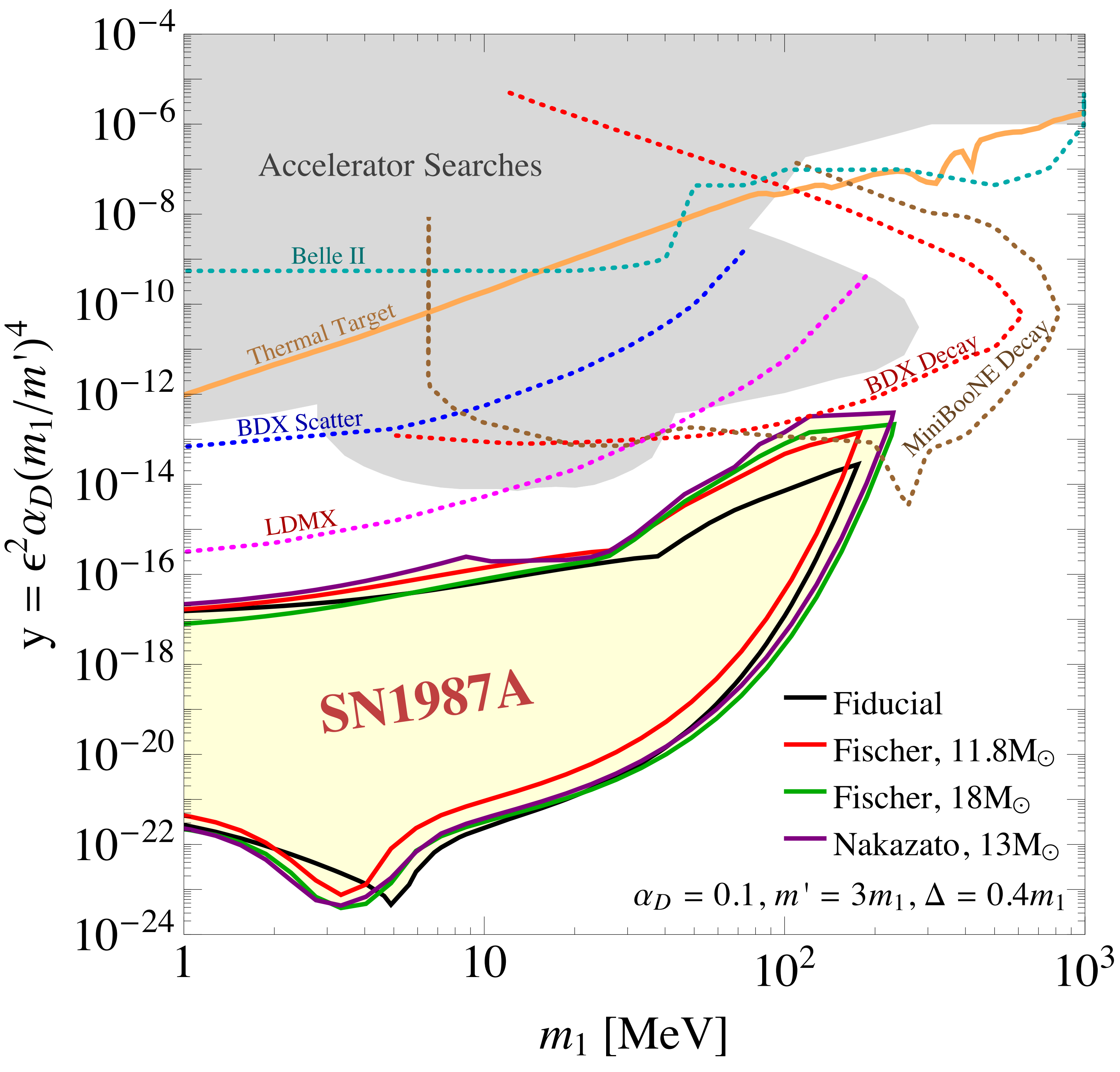
different bounds (or signals!) if it is the dark matter

Dark Photon + Dark Matter

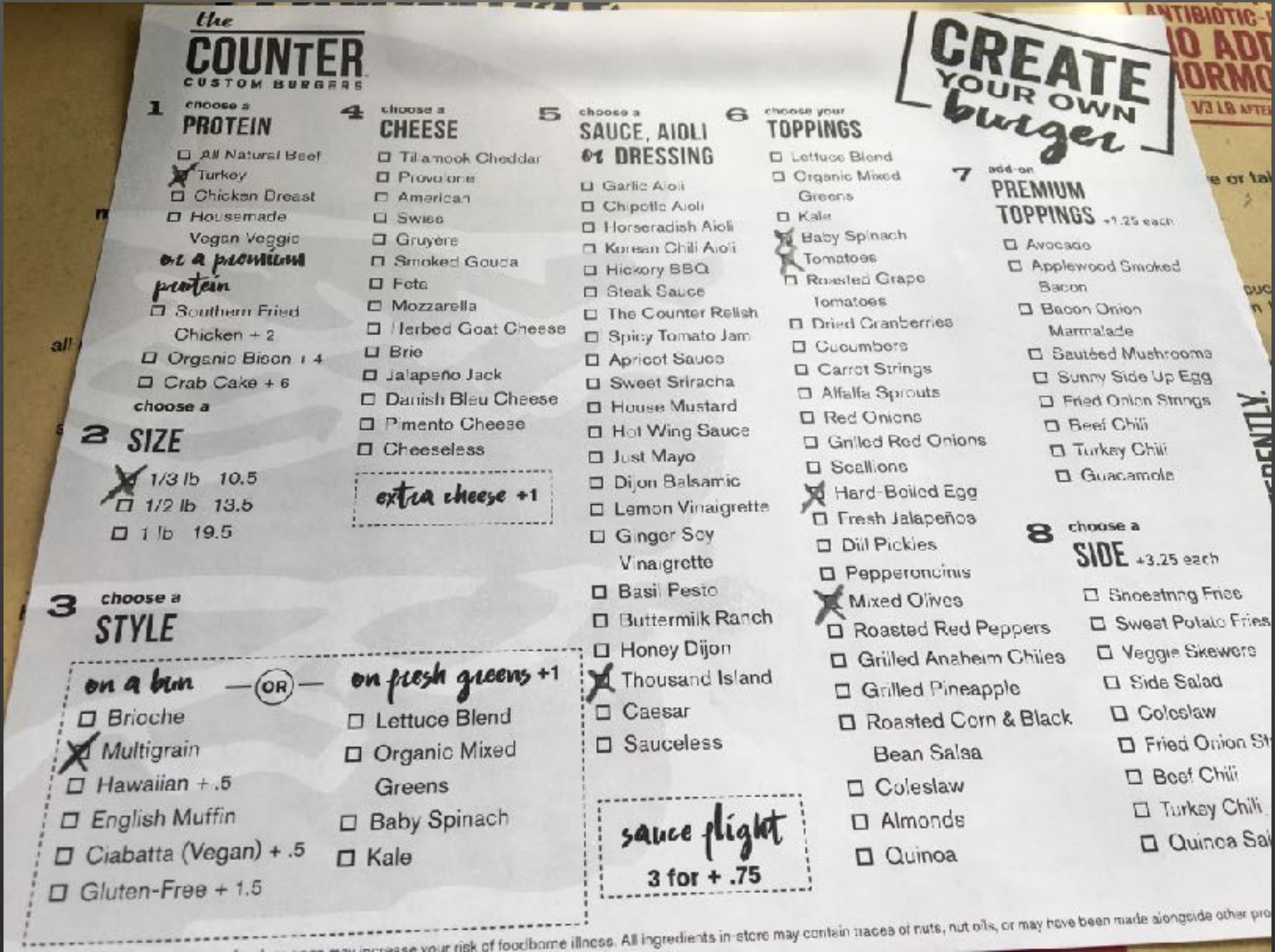




Inelastic Dark Matter



A note on (very) high mixing



the
COUNTER
CUSTOM BURGERS

CREATE YOUR OWN burger

1 choose a
PROTEIN

☐ All Natural Beef
☒ Turkey
☐ Chicken Breast
☐ Housemade Vegan Veggie

or a premium protein

☐ Southern Fried Chicken + 2
☐ Organic Bison + 4
☐ Crab Cake + 6

choose a
2 **SIZE**

☒ 1/3 lb 10.5
☐ 1/2 lb 13.5
☐ 1 lb 19.5

3 choose a
STYLE

on a bun —(OR)— on fresh greens +1

☐ Brioche
☒ Multigrain
☐ Hawaiian + .5
☐ English Muffin
☐ Ciabatta (Vegan) + .5
☐ Gluten-Free + 1.5

☐ Lettuce Blend
☐ Organic Mixed Greens
☐ Baby Spinach
☐ Kale

4 choose a
CHEESE

☐ Tillamook Cheddar
☐ Provolone
☐ American
☐ Swiss
☐ Gruyere
☐ Smoked Gouda
☐ Feta
☐ Mozzarella
☐ Herbed Goat Cheese
☐ Brie
☐ Jalapeño Jack
☐ Danish Bleu Cheese
☐ Pimento Cheese
☐ Cheeseless

extra cheese +1

5 choose a
SAUCE, AIOLI or DRESSING

☐ Garlic Aioli
☐ Chipotle Aioli
☐ Horseradish Aioli
☐ Korean Chili Aioli
☐ Hickory BBQ
☐ Steak Sauce
☐ The Counter Relish
☐ Spicy Tomato Jam
☐ Apricot Sauce
☐ Sweet Sriracha
☐ House Mustard
☐ Hot Wing Sauce
☐ Just Mayo
☐ Dijon Balsamic
☐ Lemon Vinaigrette
☐ Ginger Soy Vinaigrette
☐ Basil Pesto
☐ Buttermilk Ranch
☐ Honey Dijon
☒ Thousand Island
☐ Caesar
☐ Sauceless

sauce flight
3 for + .75

6 choose your
TOPPINGS

☐ Lettuce Blend
☐ Organic Mixed Greens
☐ Kale
☒ Baby Spinach
☒ Tomatoes
☐ Roasted Grape Tomatoes
☐ Dried Cranberries
☐ Cucumbers
☐ Carrot Strings
☐ Alfalfa Sprouts
☐ Red Onions
☐ Grilled Red Onions
☐ Scallions
☒ Hard-Boiled Egg
☐ Fresh Jalapeños
☐ Dill Pickles
☐ Pepperoncinis
☒ Mixed Olives
☐ Roasted Red Peppers
☐ Grilled Anaheim Chiles
☐ Grilled Pineapple
☐ Roasted Corn & Black Bean Salsa
☐ Coleslaw
☐ Almonds
☐ Quinoa

7 add-on
PREMIUM TOPPINGS +1.25 each

☐ Avocado
☐ Applewood Smoked Bacon
☐ Bacon Onion Marmalade
☐ Sautéed Mushrooms
☐ Sunny Side Up Egg
☐ Fried Onion Strings
☐ Beef Chili
☐ Turkey Chili
☐ Guacamole

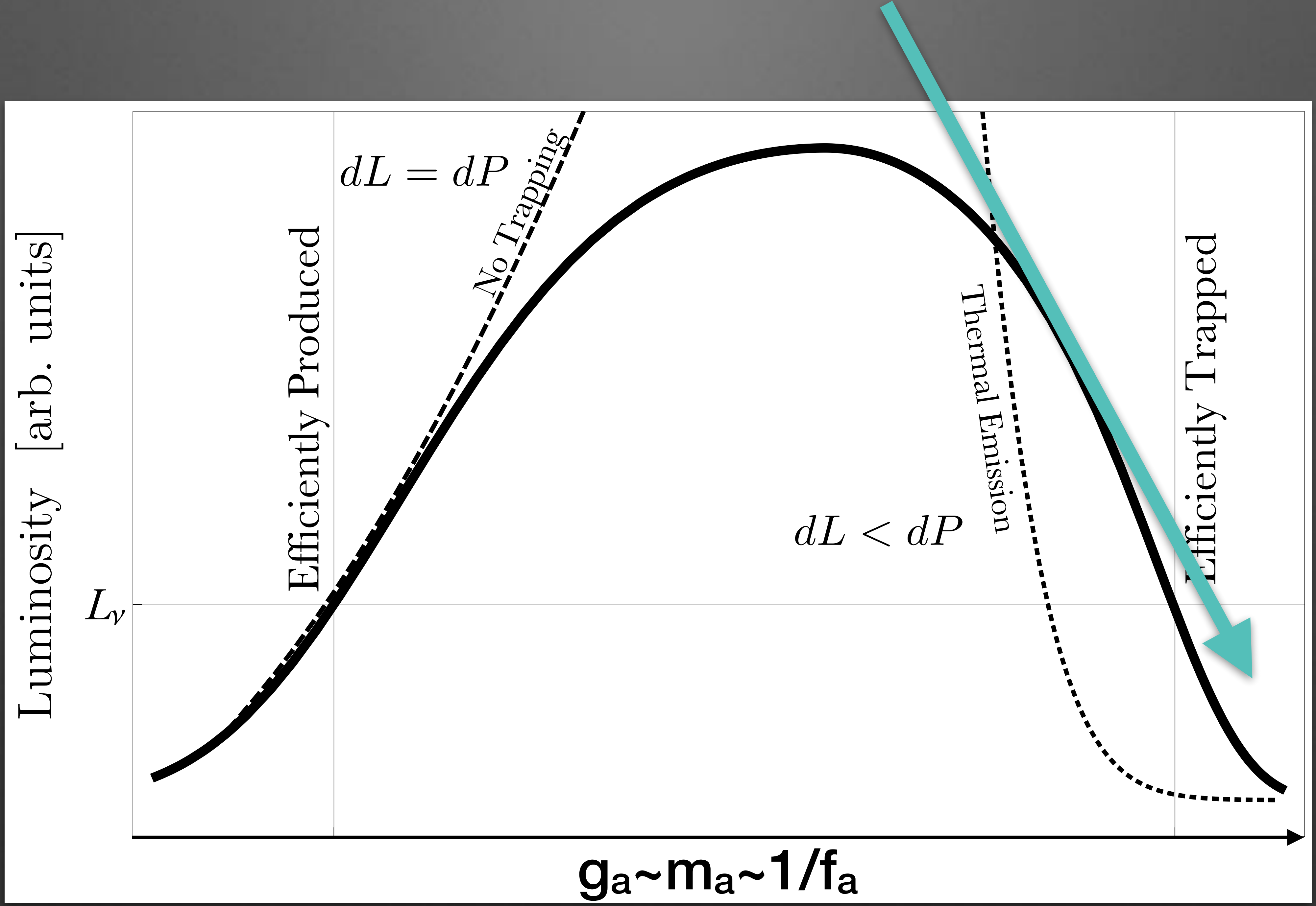
8 choose a
SIDE +3.25 each

☐ Shoestring Fries
☐ Sweet Potato Fries
☐ Veggie Skewers
☐ Side Salad
☐ Coleslaw
☐ Fried Onion St
☐ Beef Chili
☐ Turkey Chili
☐ Quinoa Sal

may increase your risk of foodborne illness. All ingredients in-store may contain traces of nuts, nut oils, or may have been made alongside other pro

Natalia Toro, KITP Particle Physics at the Sensitivity Frontier Conf., 2018

A note on (very) high mixing



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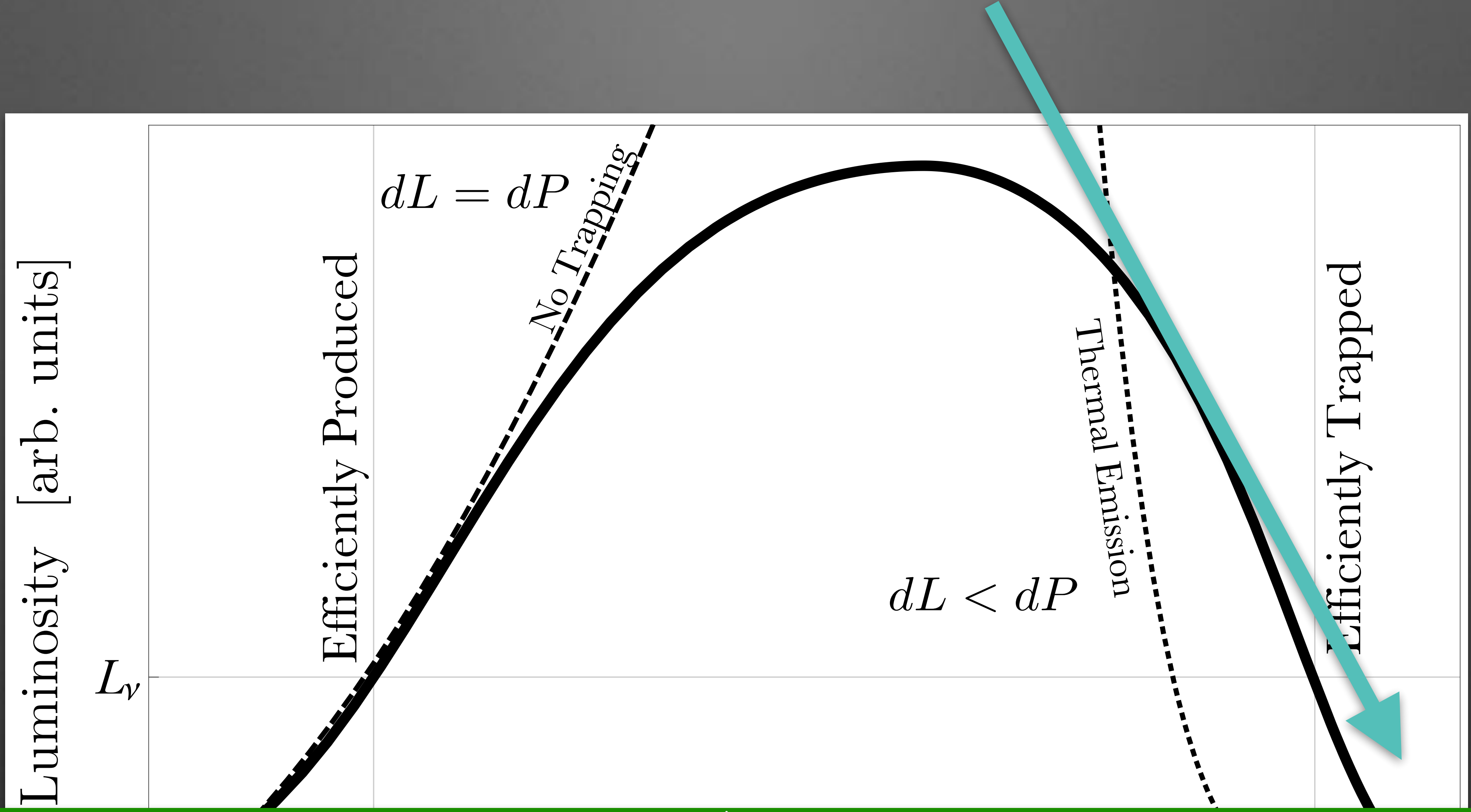

$$T_{\mathrm{BSM}} = T_{\mathrm{SM}} \left(\frac{\sum_{i \in \mathrm{SM}} g_i}{\sum_i g_i} \right)^{1/3} \approx T_{\mathrm{SM}} \left(1 - \frac{1}{3} \frac{\sum_{i \in \mathrm{BSM}} g_i}{\sum_{i \in \mathrm{SM}} g_i} \right)$$

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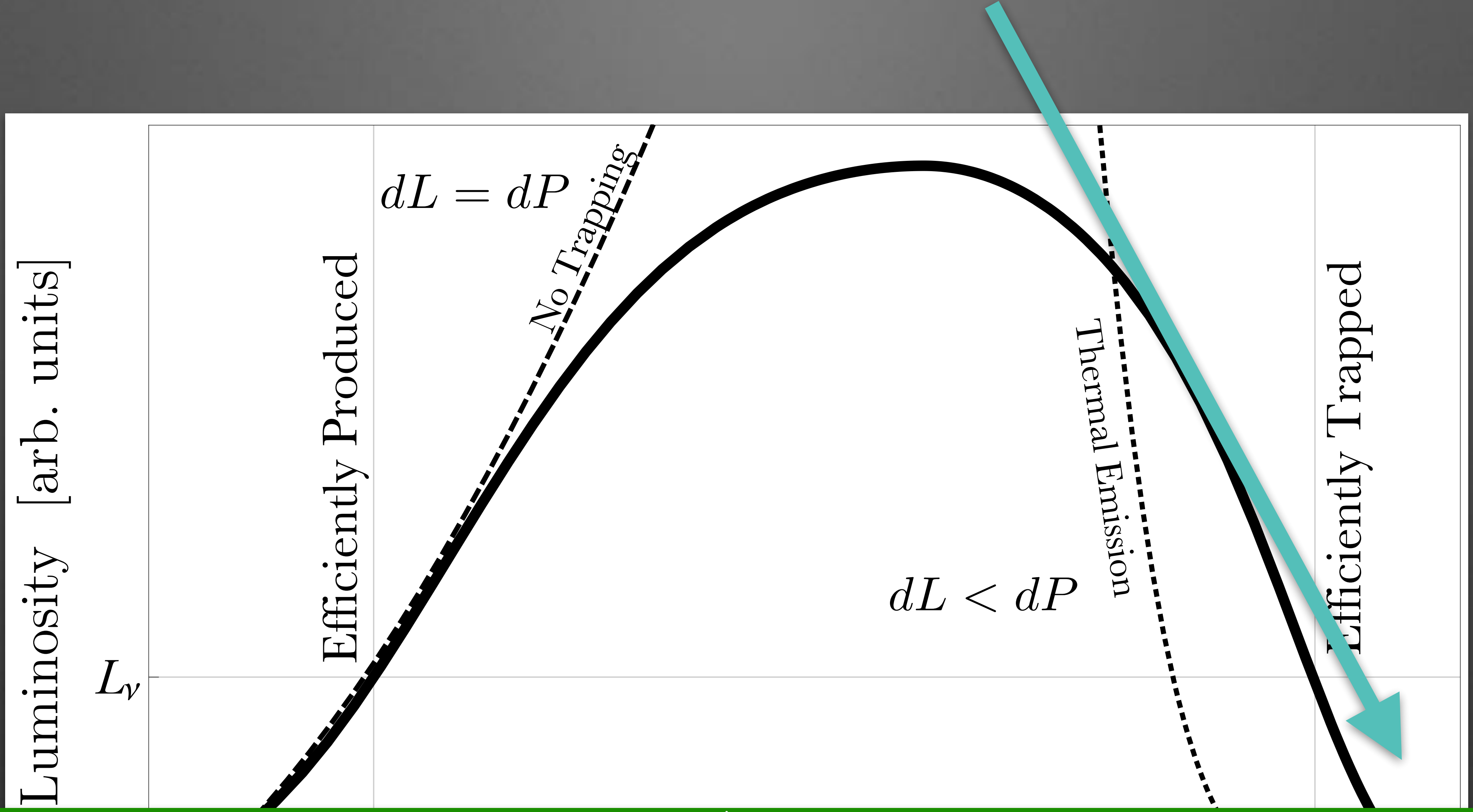

$$T_{\rm BSM} = T_{\rm SM}\left(\frac{\sum_{i\in{\rm SM}} g_i}{\sum_i g_i}\right)^{1/3} \approx T_{\rm SM}\left(1 - \frac{1}{3}\frac{\sum_{i\in{\rm BSM}} g_i}{\sum_{i\in{\rm SM}} g_i}\right)$$

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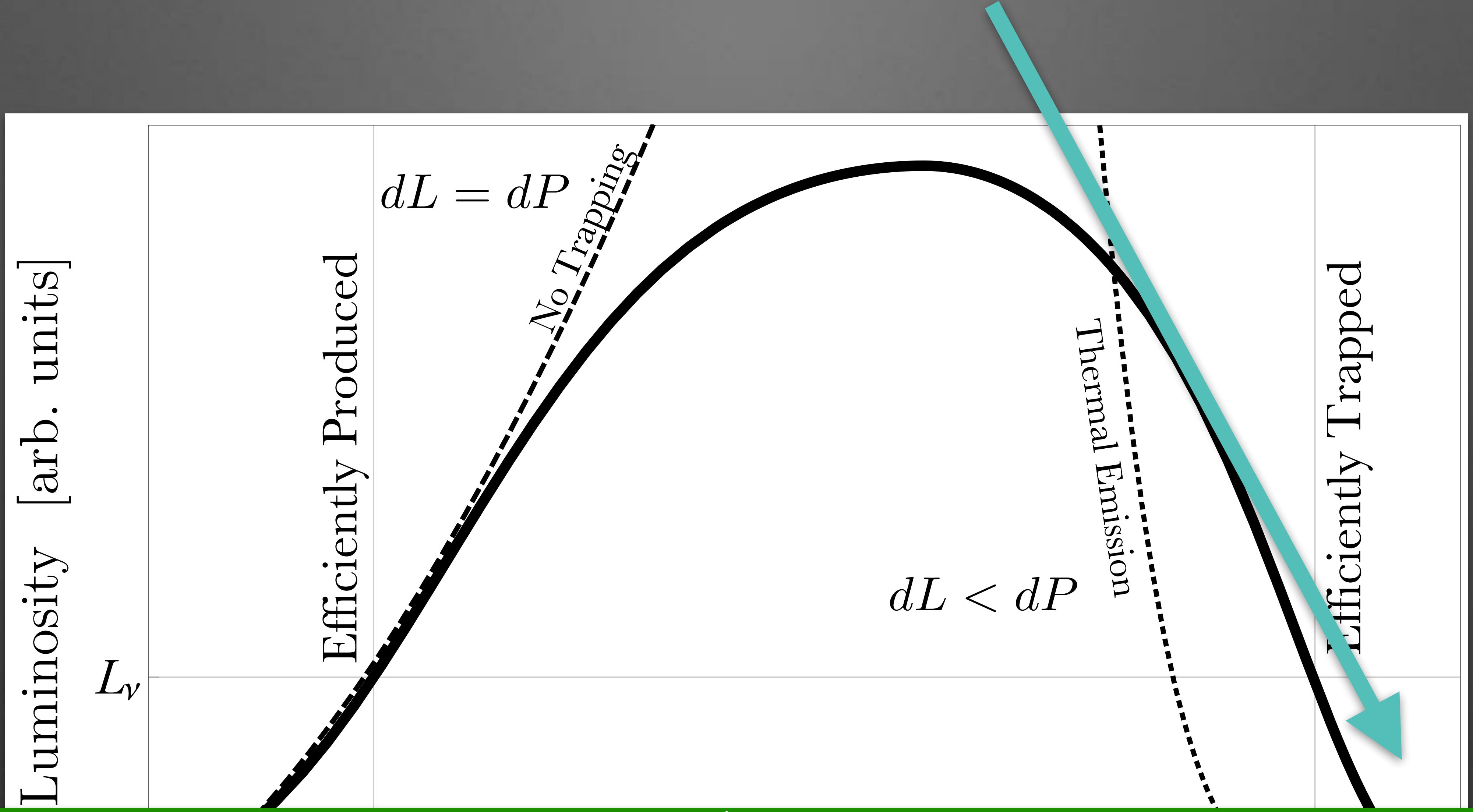
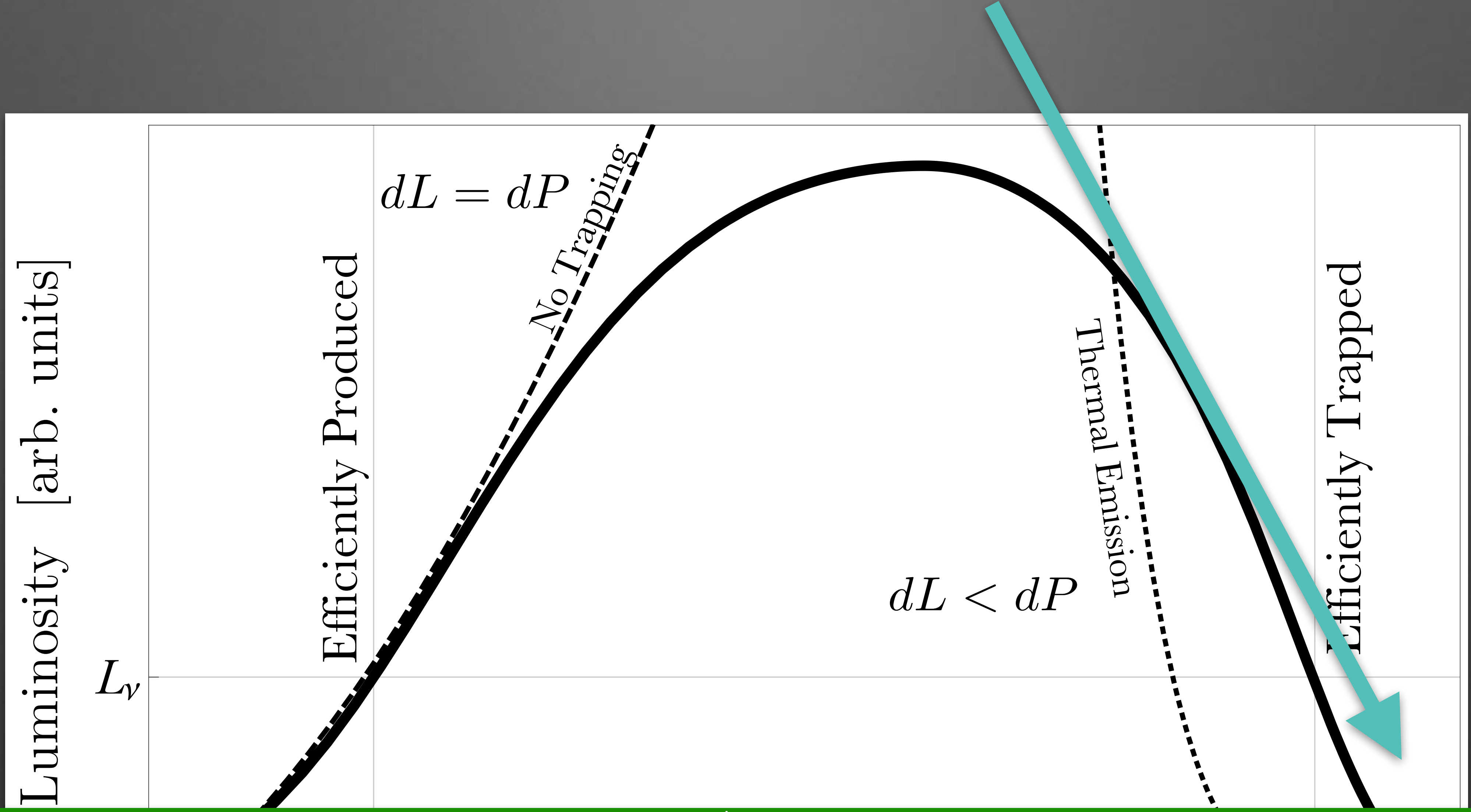


axion:
~1

$$T_{\rm BSM} = T_{\rm SM}\left(\frac{\sum_{i\in{\rm SM}} g_i}{\sum_i g_i}\right)^{1/3} \approx T_{\rm SM}\left(1 - \frac{1}{3}\frac{\sum_{i\in{\rm BSM}} g_i}{\sum_{i\in{\rm SM}} g_i}\right)$$

~20

A note on (very) high mixing



dark sector: ~6.5

$$T_{\text{BSM}} = T_{\text{SM}} \left(\frac{\sum_{i \in \text{SM}} g_i}{\sum_i g_i} \right)^{1/3} \approx T_{\text{SM}} \left(1 - \frac{1}{3} \frac{\sum_{i \in \text{BSM}} g_i}{\sum_{i \in \text{SM}} g_i} \right)$$

~20

Conclusions

- Supernova 1987A provides a unique and powerful probe of light and weakly coupled physics
- Provides strongest bounds for wide variety of modern models of BSM particle physics
- Exciting possibilities to combine cutting edge astrophysics, nuclear physics, and particle physics