Supernova Bounds on Hidden Sectors

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

Apr 10, 2018

Fermilab

Supernova Bounds on the QCD axion

(and whatever else I have time for)

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Who is this talk for?

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Nathaniel

Who is this talk for?

Particle phenomenologists!

Who is this talk for?

Particle phenomenologists!

“What can a supernova do for me?”

Who is this talk for?

Particle phenomenologists!

"…and how reliable is it?"

Who is this talk for?

Astrophysicists!

Who is this talk for?

Astrophysicists!

“What’s the deal with axions?”

Who is this talk for?

Astrophysicists!

"…
and wasn't this done ~ 30 years ago?"

Who is this talk for?

Experimentalists!

Who is this talk for?

Experimentalists!

“Where will it ever stop!?”

Executive Summary

- Supernova 1987A reached extremely high temp ~ 30 MeV and density ~ 3×10^{14}g/cm^3 and was necessarily "powered" by neutrinos
- an axion with a large [small] f_a would have not been produced [gotten trapped], but for intermediate f_a would have "defused" the neutrinos

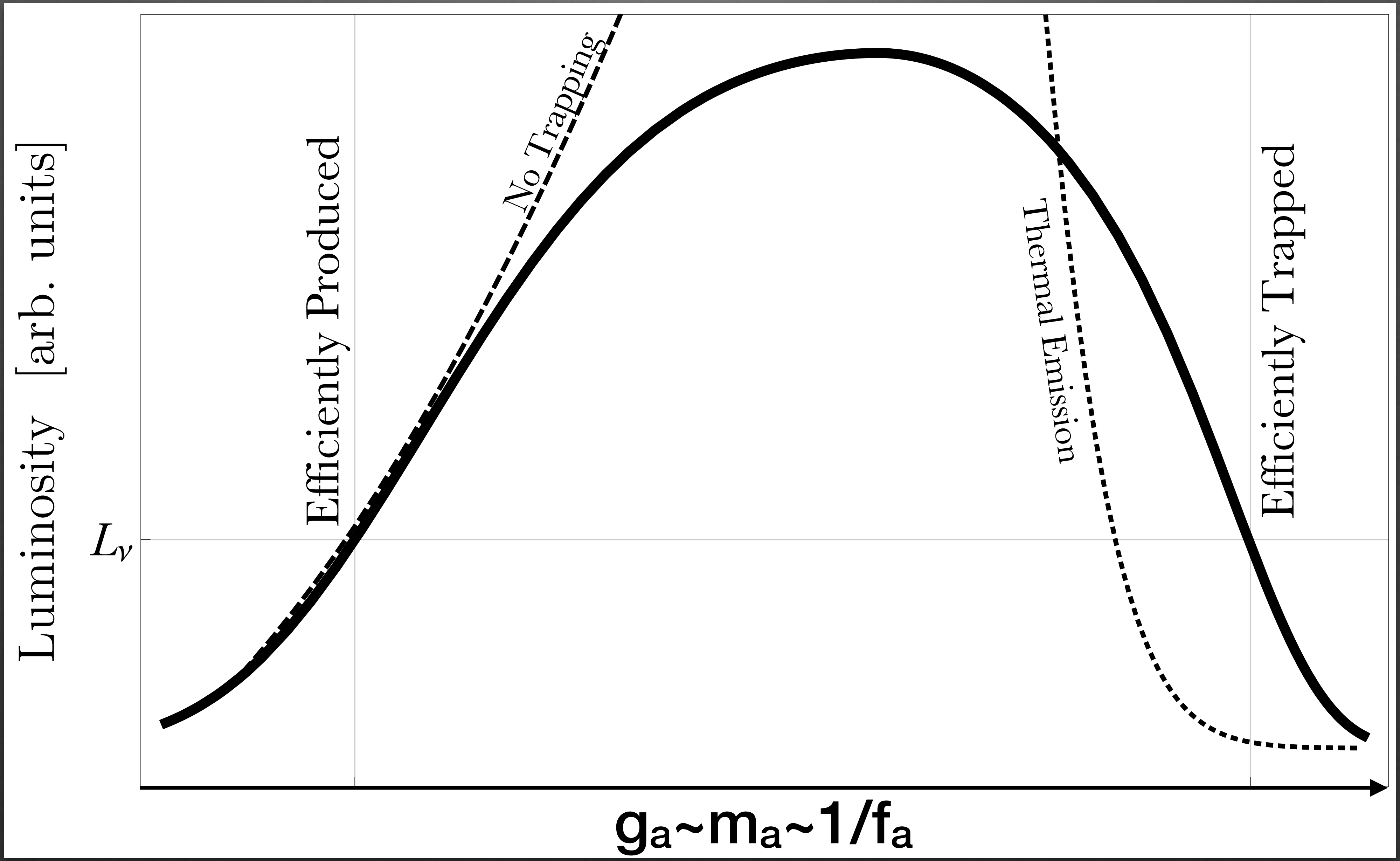
Executive Summary

- $\lambda_{mfp,\nu} \sim 1/(n_N G_F^2 T^2) \sim 1\text{m} \times (\text{radius}/10\text{km})^8 \Longrightarrow$ neutrinos diffuse until a radius ~ 40km, whereupon they are emitted like a blackbody with $L_\nu \sim 10^{52}$ erg/s
- $L_a \sim \text{Vol} \times Y_p C_p^2 n_N^2 \sigma_N T/(f_a/\text{GeV})^2 \sim L_\nu \times (f_a/10^8\,\text{GeV})^2$ $\Longrightarrow$ axions can “compete” if their decay constant is less than approx 10^8 GeV

Executive Summary

- 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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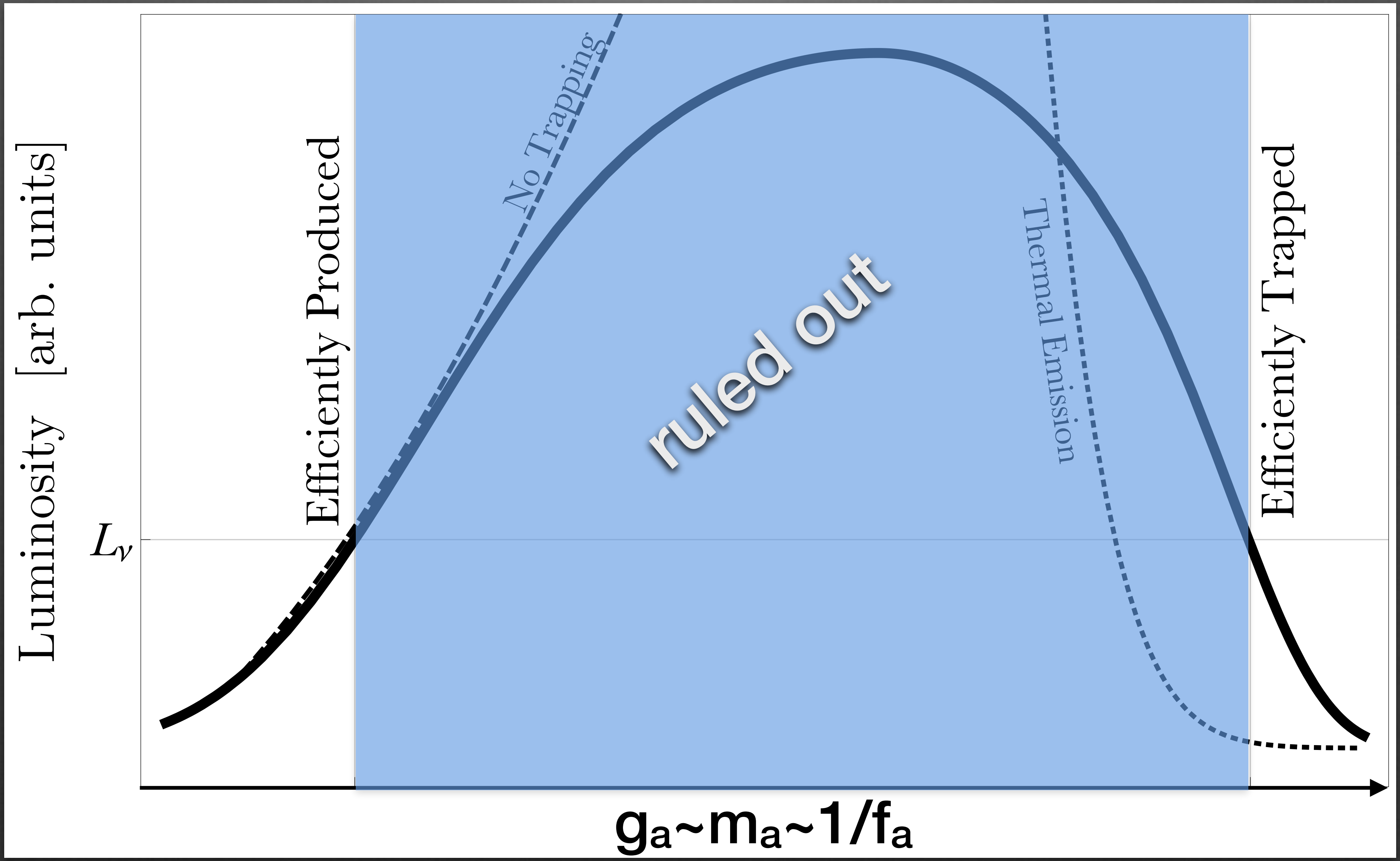

Novelt(ies) in our work(s)

- 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

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extends bounds by ~ order of magnitude at large coupling

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introduces factor ~ few error bar

- Systematic uncertainties from progenitor profile
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- 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

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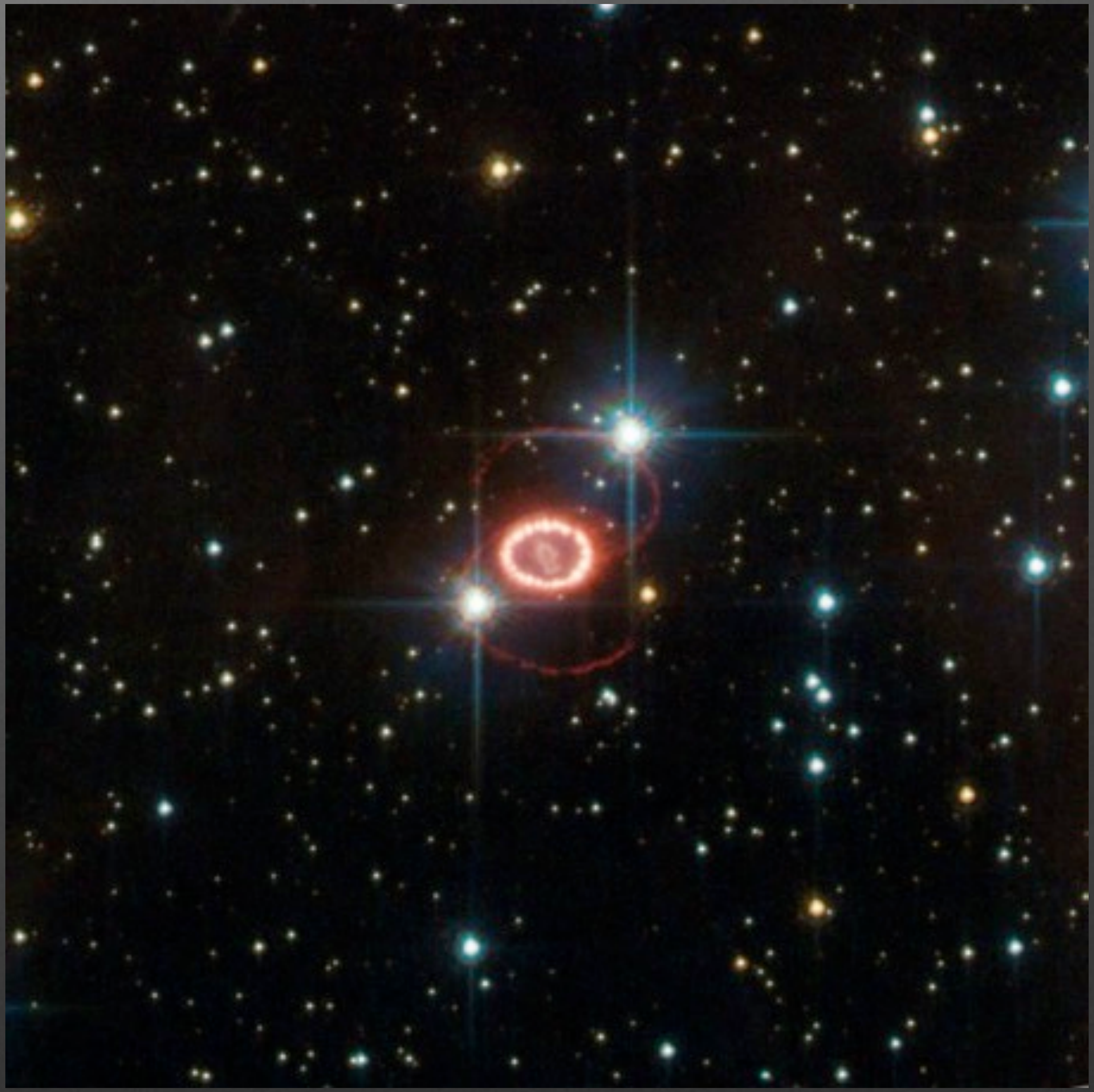
Broad(est possible) Picture

Supernova 1987A:

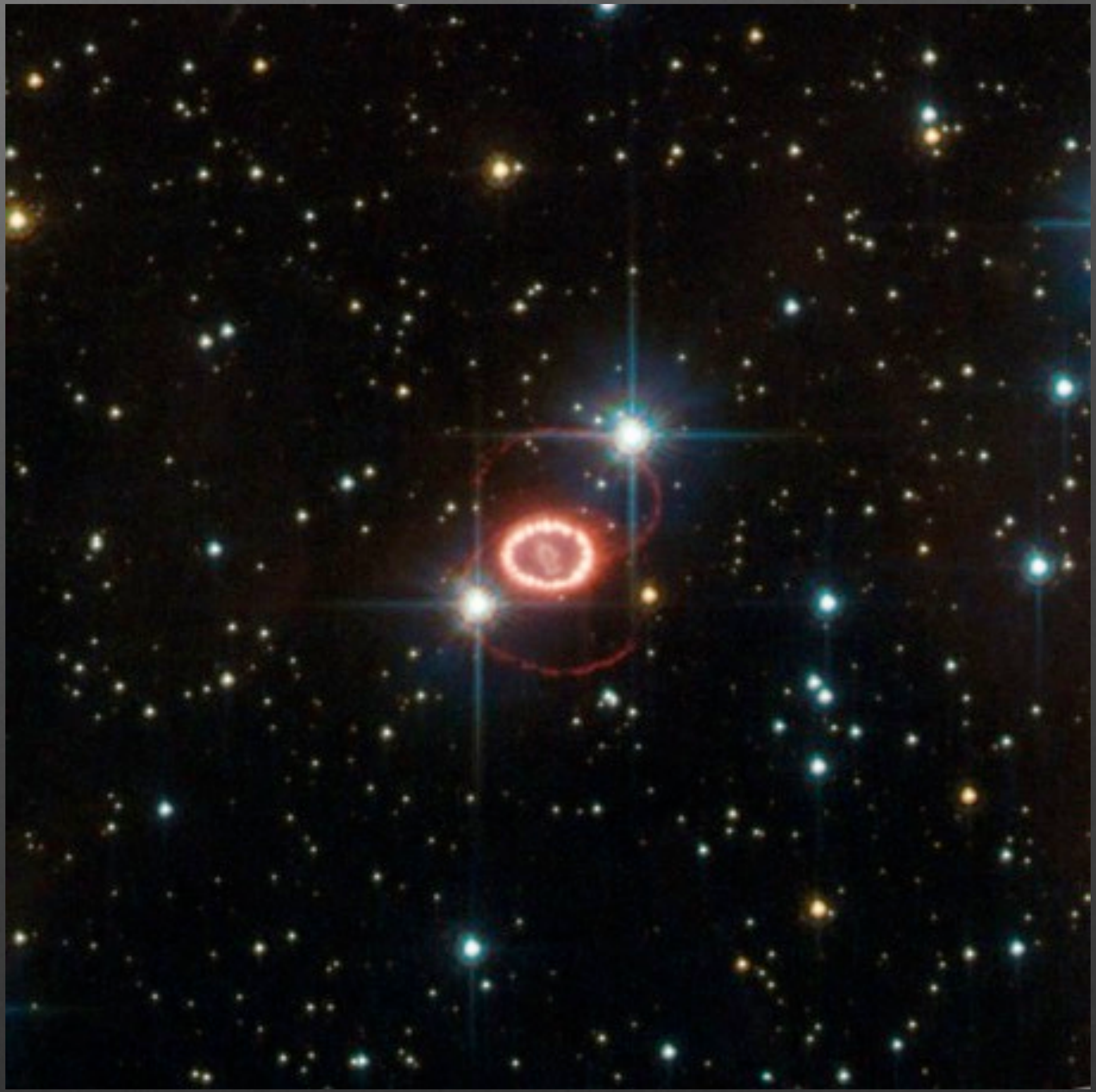
~ 99% of the grav. binding energy of a collapsing blue supergiant radiated away in the form of neutrinos over the course of ~ 10s



spacetelescope.org

Things we know (and do not know) about Supernova 1987A

- Progenitor was a blue supergiant in the Large Magellanic Cloud
- Progenitor mass was $O(10\,M_\odot)$
- Neutrinos arrived over a span of O(10 sec)



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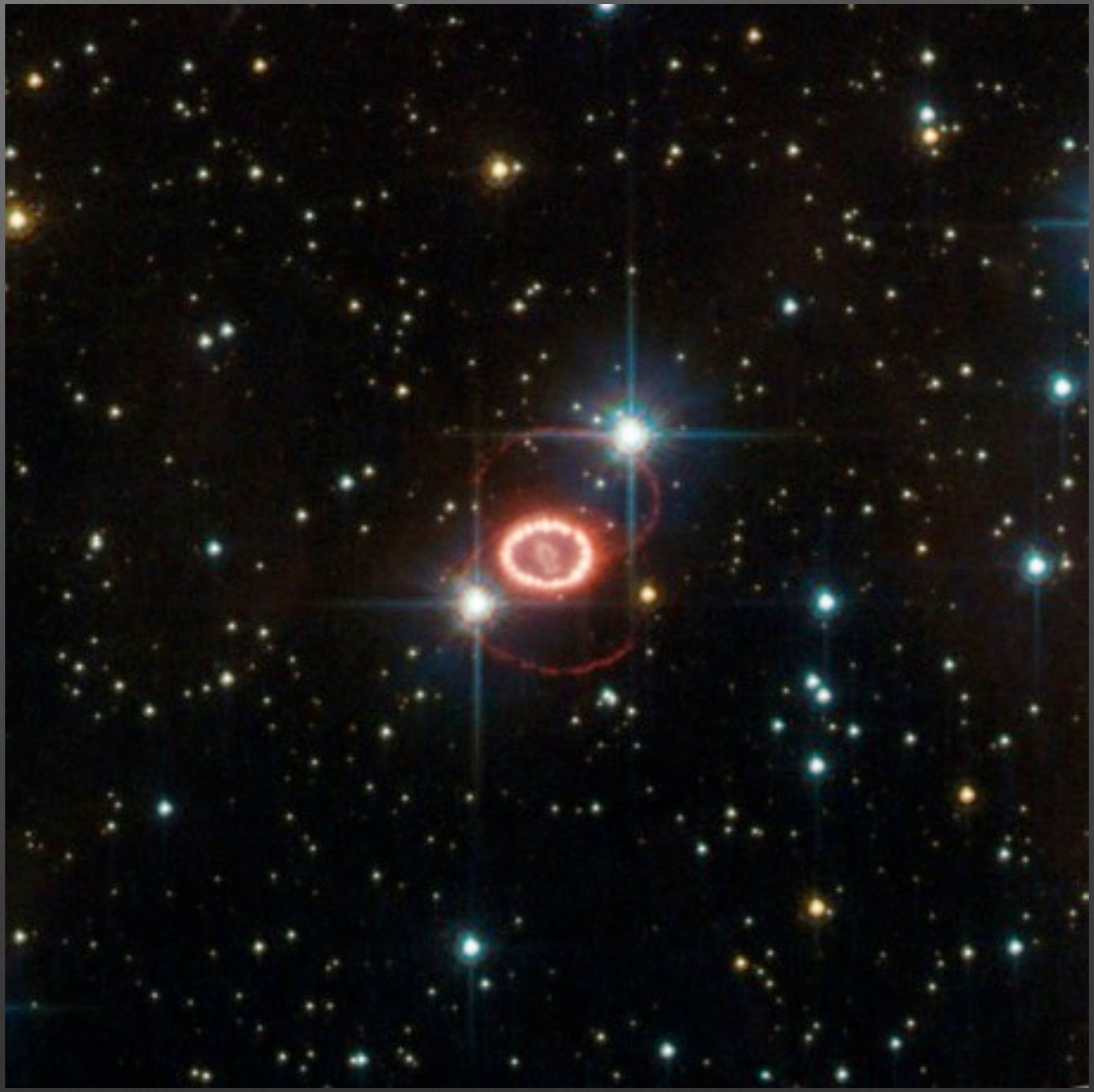

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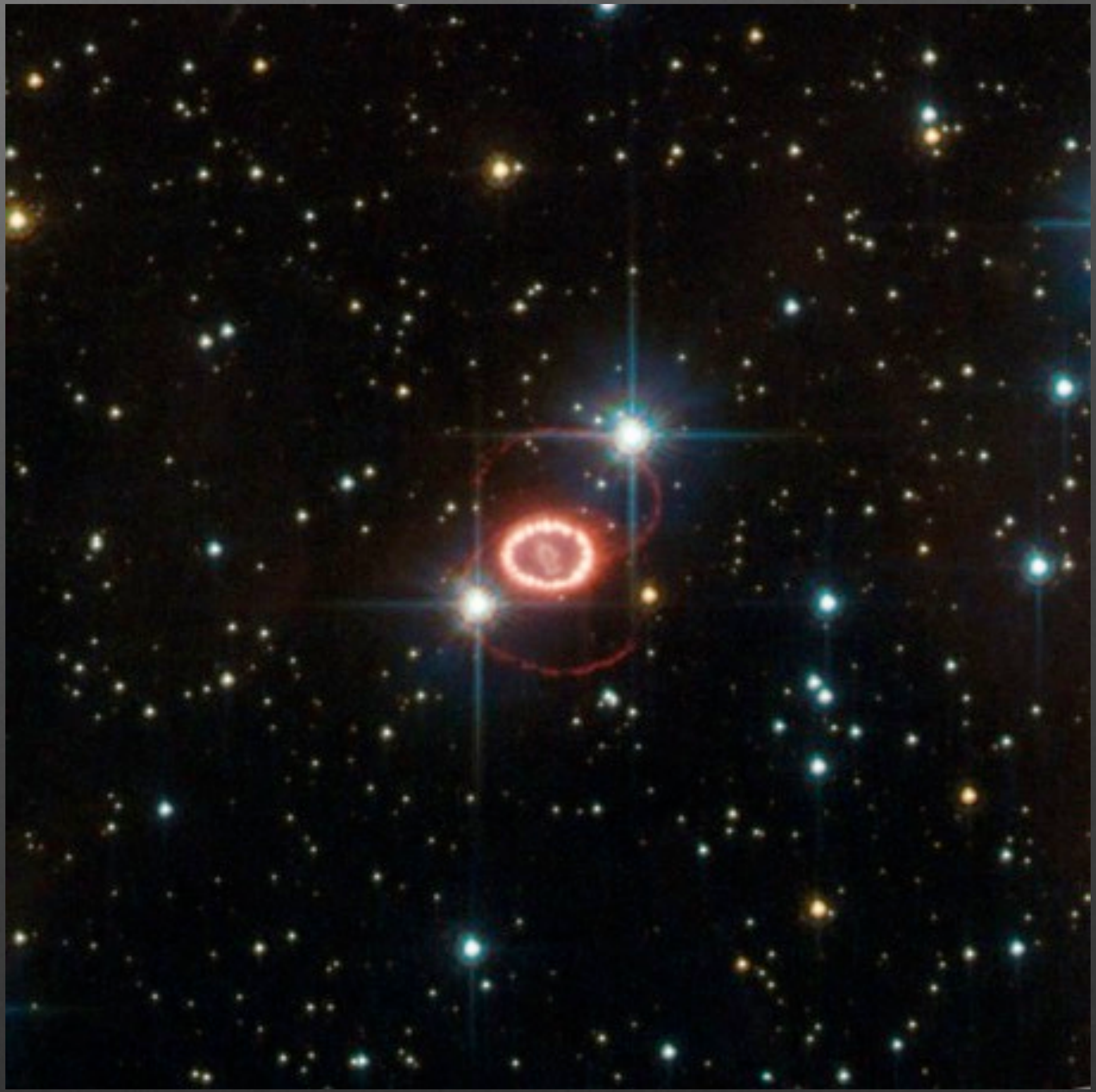

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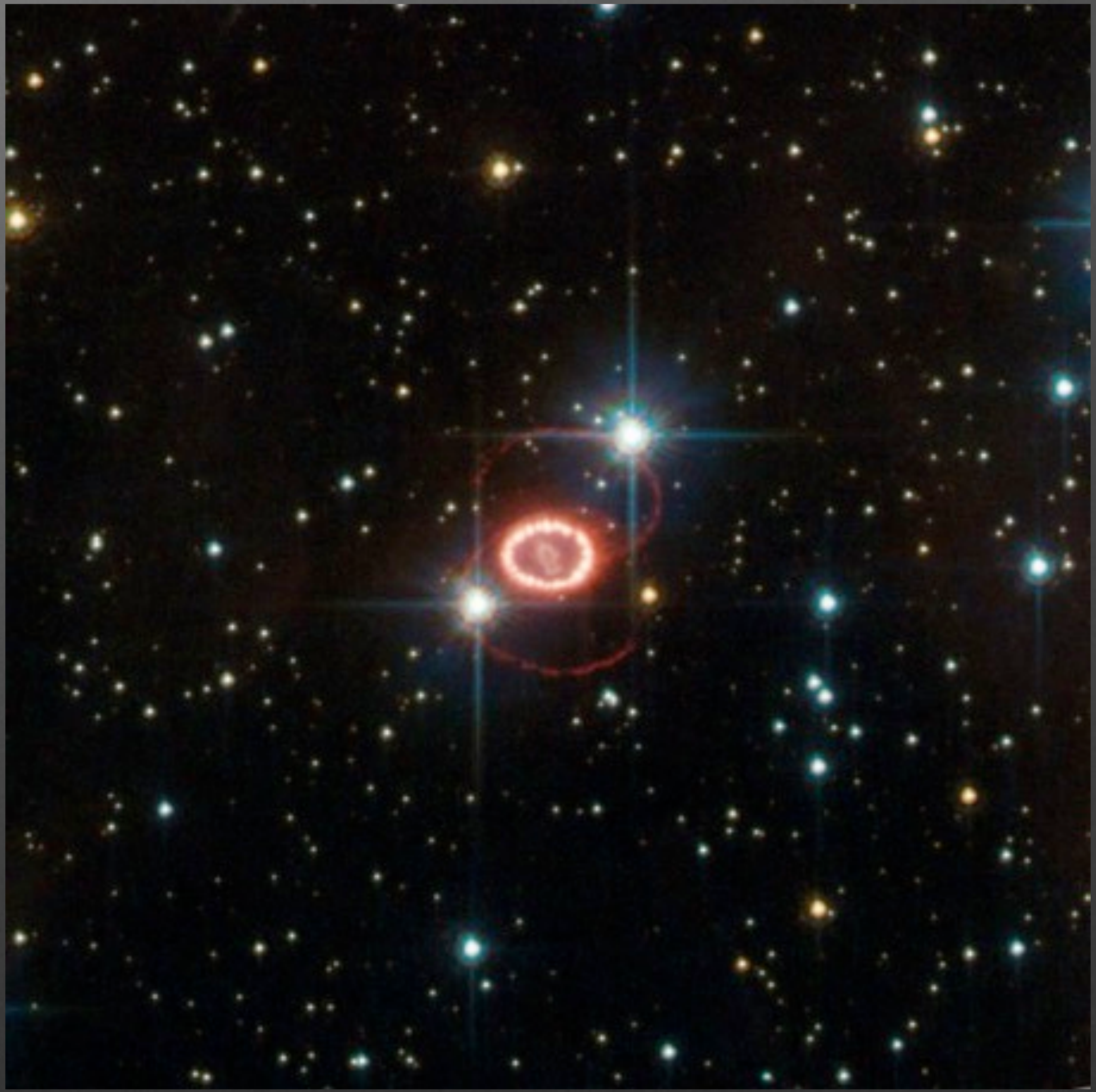

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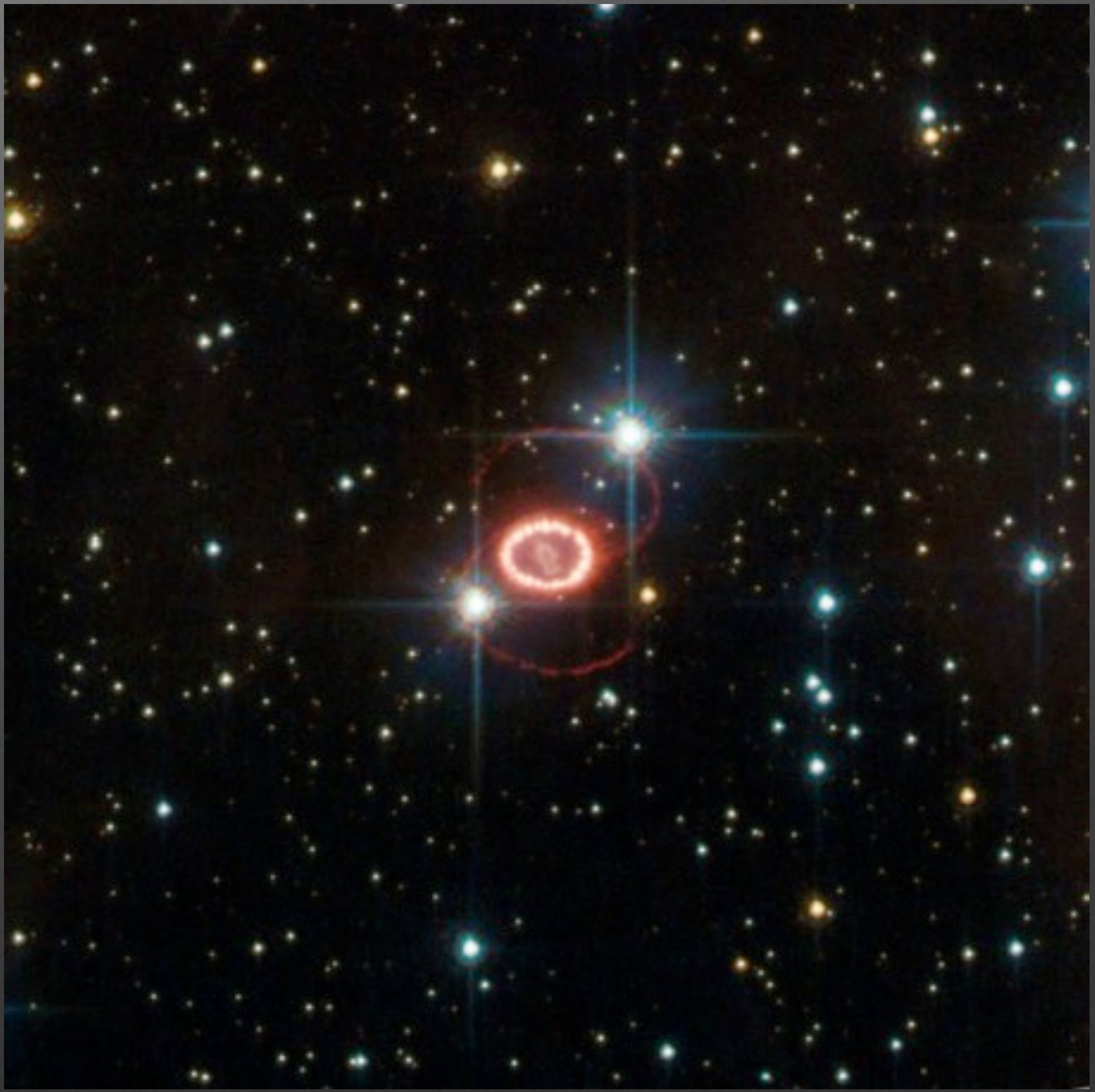
…and we don't see a remnant



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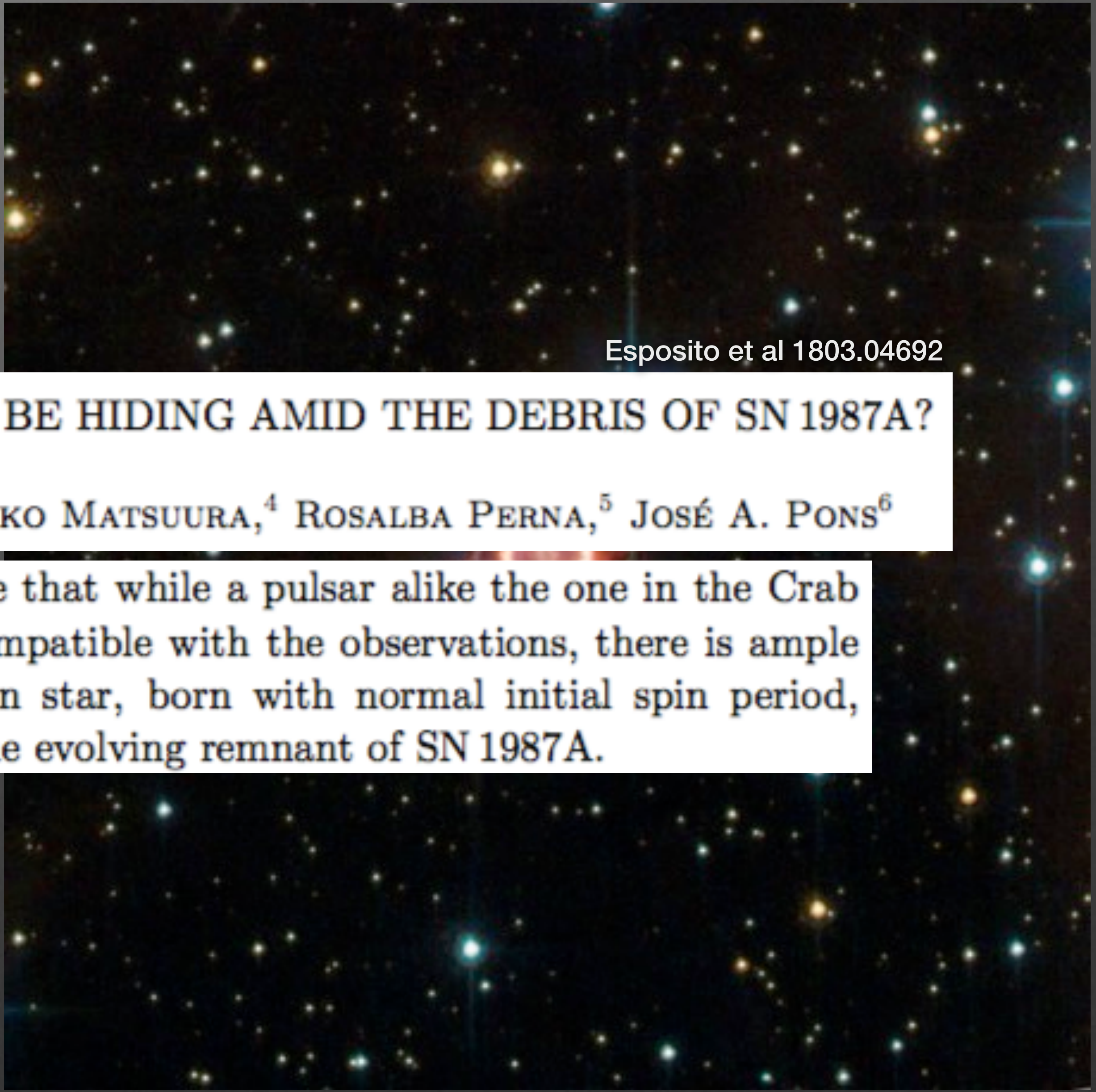

Esposito et al 1803.04692

CAN A BRIGHT AND ENERGETIC X-RAY PULSAR BE HIDING AMID THE DEBRIS OF SN 1987A?

Paolo Esposito,[1] Nanda Rea,[1,2] Davide Lazzati,[3] Mikako Matsuura,[4] Rosalba Perna,[5] José A. Pons[6]

luminosity of the order of $\approx 10^{35}$ erg s^{-1}. We conclude that while a pulsar alike the one in the Crab Nebula in both luminosity and spectrum is hardly compatible with the observations, there is ample space for an 'ordinary' X-ray-emitting young neutron star, born with normal initial spin period, temperature and magnetic field, to be hiding inside the evolving remnant of SN 1987A.

spacetelescope.org

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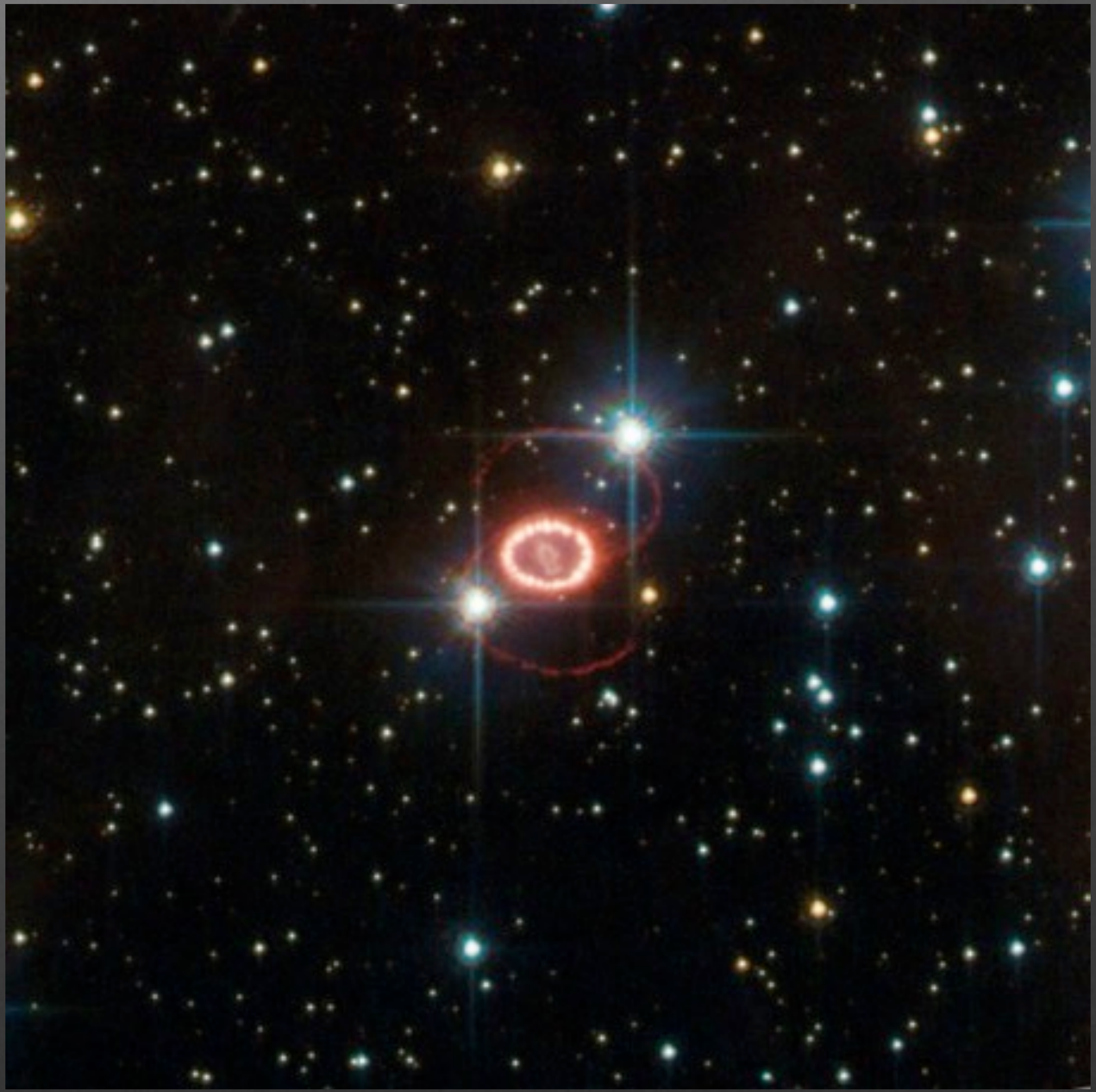

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…and we don’t see a remnant

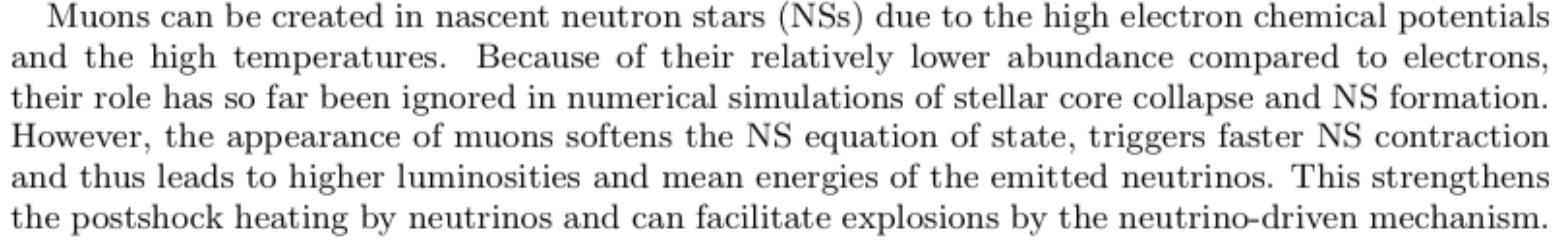
…and shock revival is difficult numerically

Things we know (and do not know) about Supernova 1987A

Bollig et al 1706.04630

Muon creation in supernova matter facilitates neutrino-driven explosions

R. Bollig,[1,2] H.-T. Janka,[1] A. Lohs,[3] G. Martínez-Pinedo,[3,4] C.J. Horowitz,[5] and T. Melson[1]



Muons can be created in nascent neutron stars (NSs) due to the high electron chemical potentials and the high temperatures. Because of their relatively lower abundance compared to electrons, their role has so far been ignored in numerical simulations of stellar core collapse and NS formation. However, the appearance of muons softens the NS equation of state, triggers faster NS contraction and thus leads to higher luminosities and mean energies of the emitted neutrinos. This strengthens the postshock heating by neutrinos and can facilitate explosions by the neutrino-driven mechanism.

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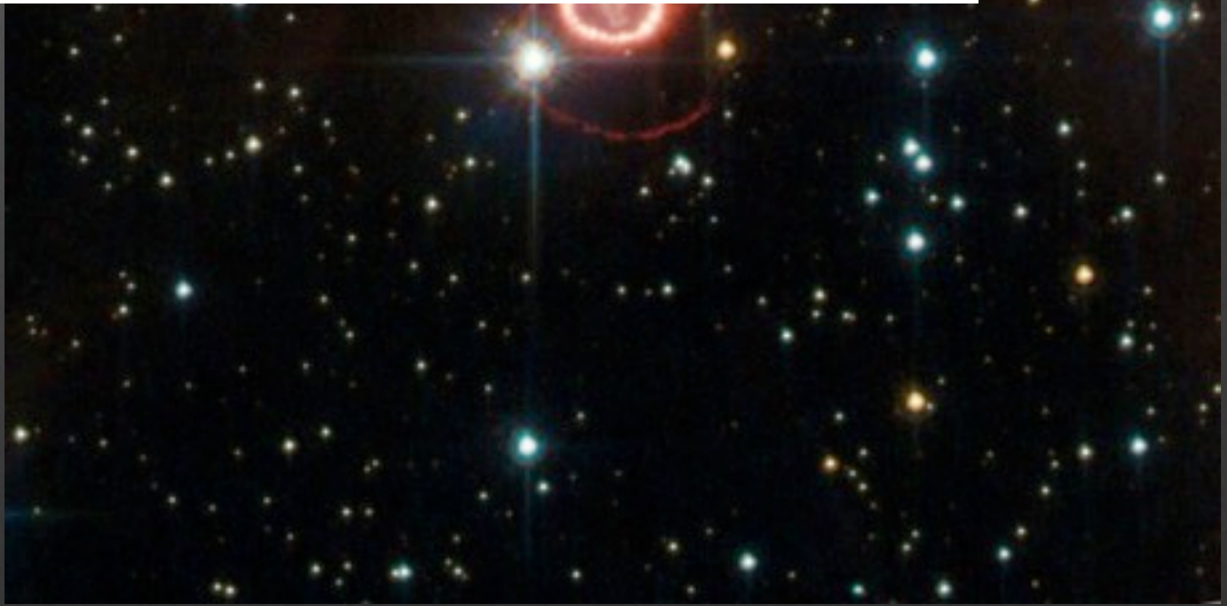

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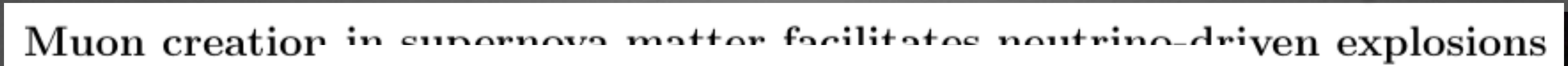

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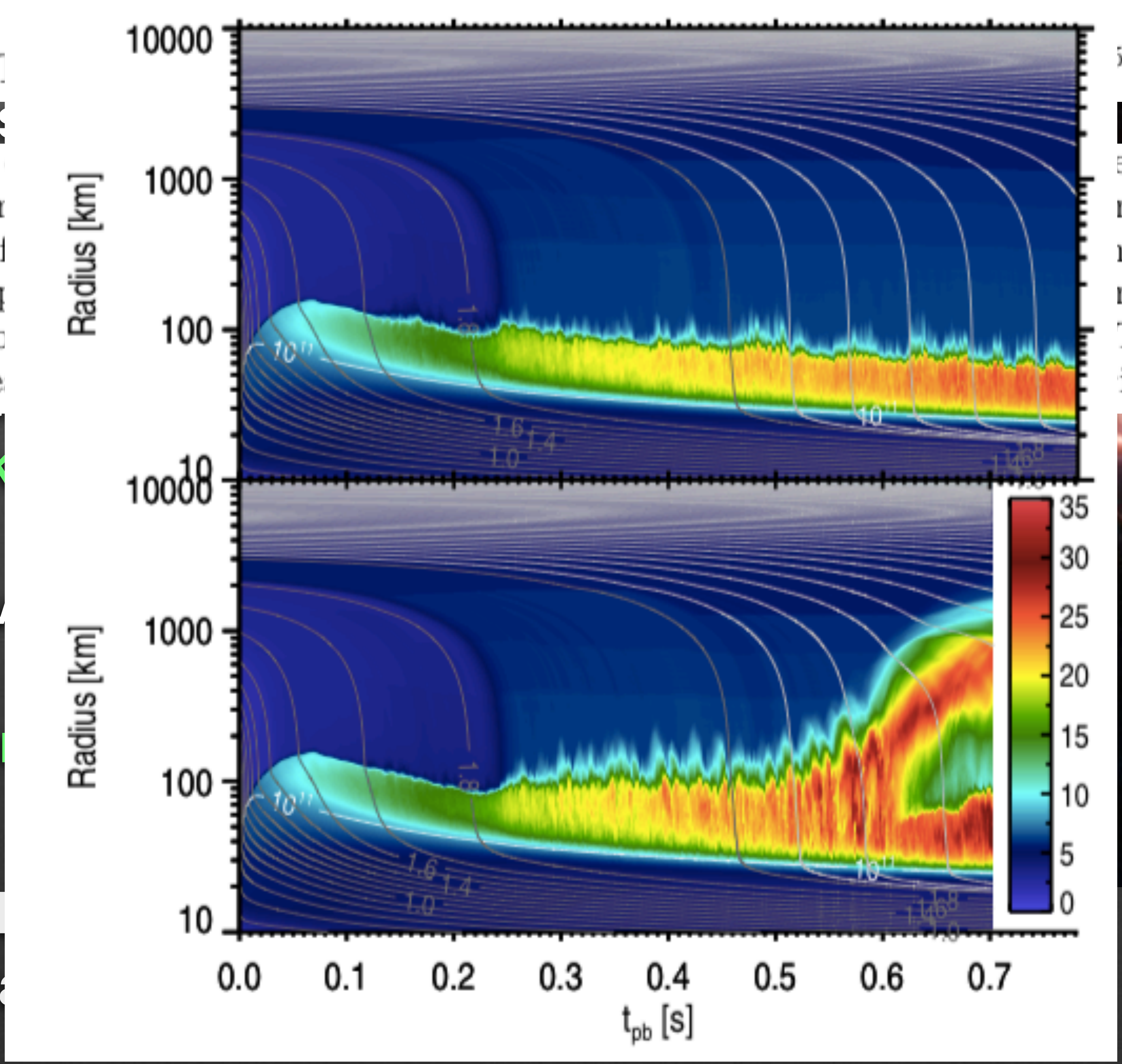

spacetelescope.org

...and we do

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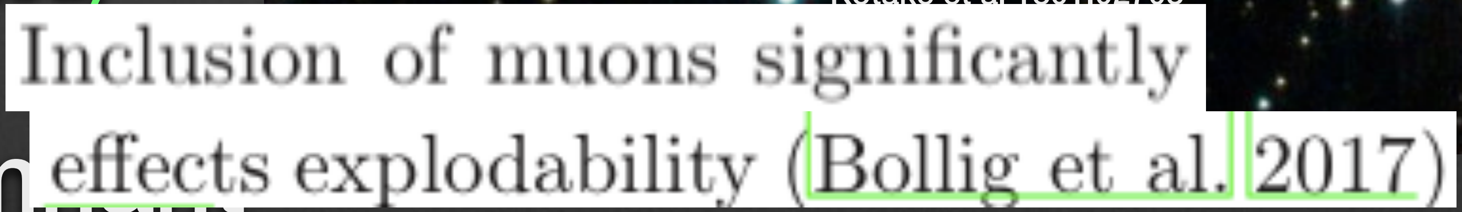
Kotake et al 1801.02703



Inclusion of muons significantly effects explodability (Bollig et al. 2017)

…and we don't see a rem

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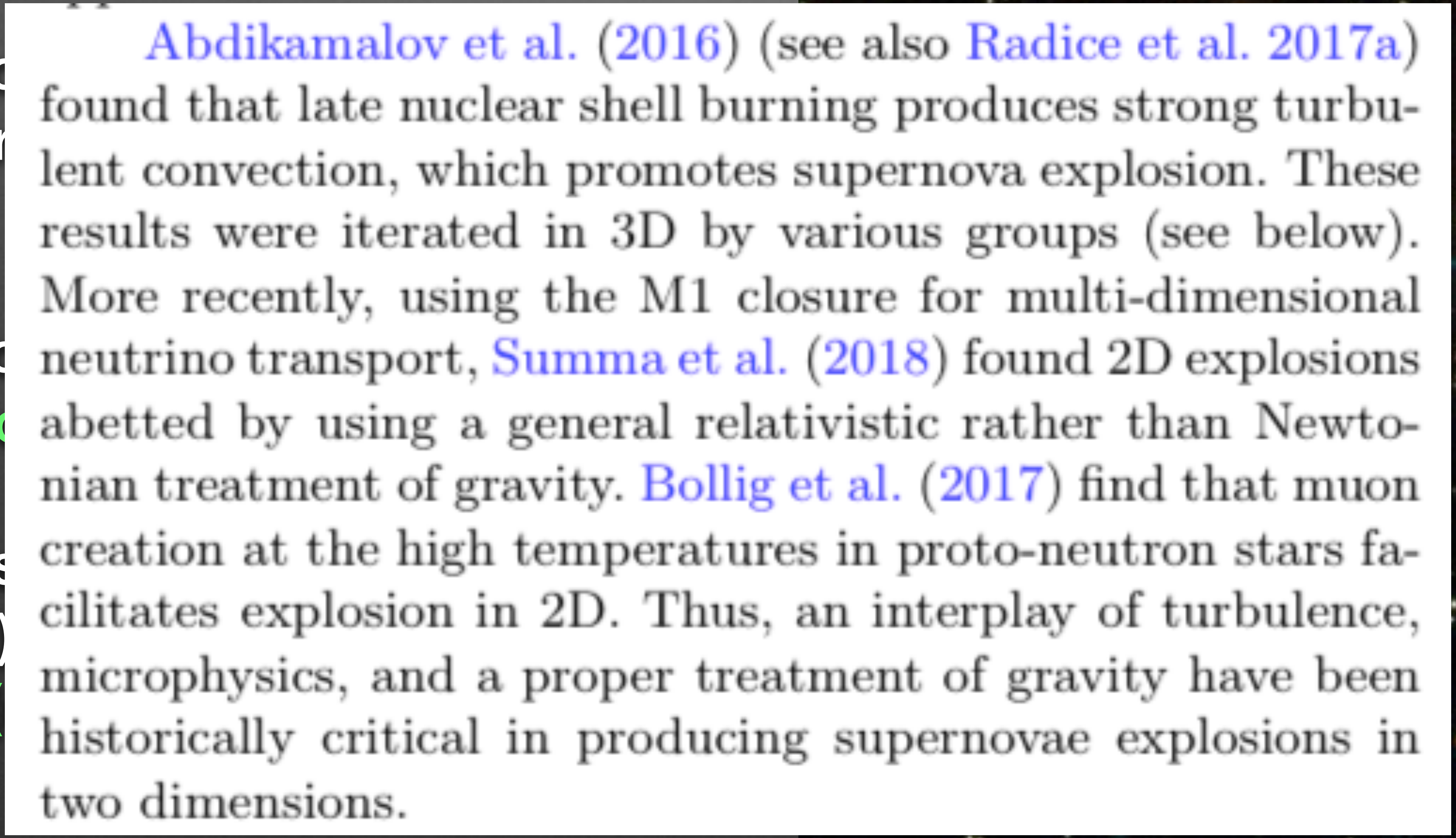

Abdikamalov et al. (2016) (see also Radice et al. 2017a) found that late nuclear shell burning produces strong turbulent convection, which promotes supernova explosion. These results were iterated in 3D by various groups (see below). More recently, using the M1 closure for multi-dimensional neutrino transport, Summa et al. (2018) found 2D explosions abetted by using a general relativistic rather than Newtonian treatment of gravity. Bollig et al. (2017) find that muon creation at the high temperatures in proto-neutron stars facilitates explosion in 2D. Thus, an interplay of turbulence, microphysics, and a proper treatment of gravity have been historically critical in producing supernovae explosions in two dimensions.

Vartanyan et al 1801.08148

spacetelescope.org

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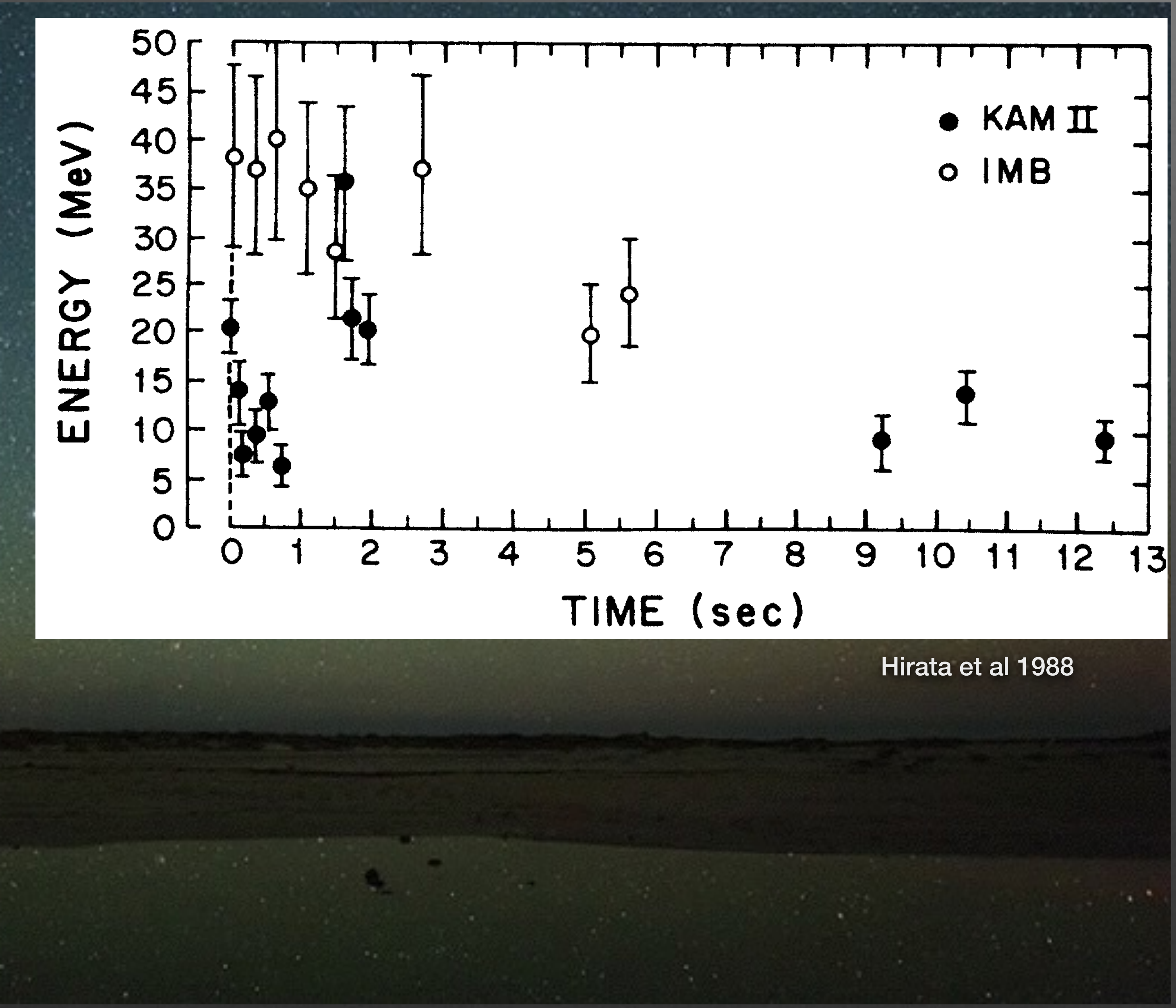
…and shock revival is difficult numerically

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 ⟺ bounds on new coupling with SM

Why Supernova 1987A?



Hirata et al 1988

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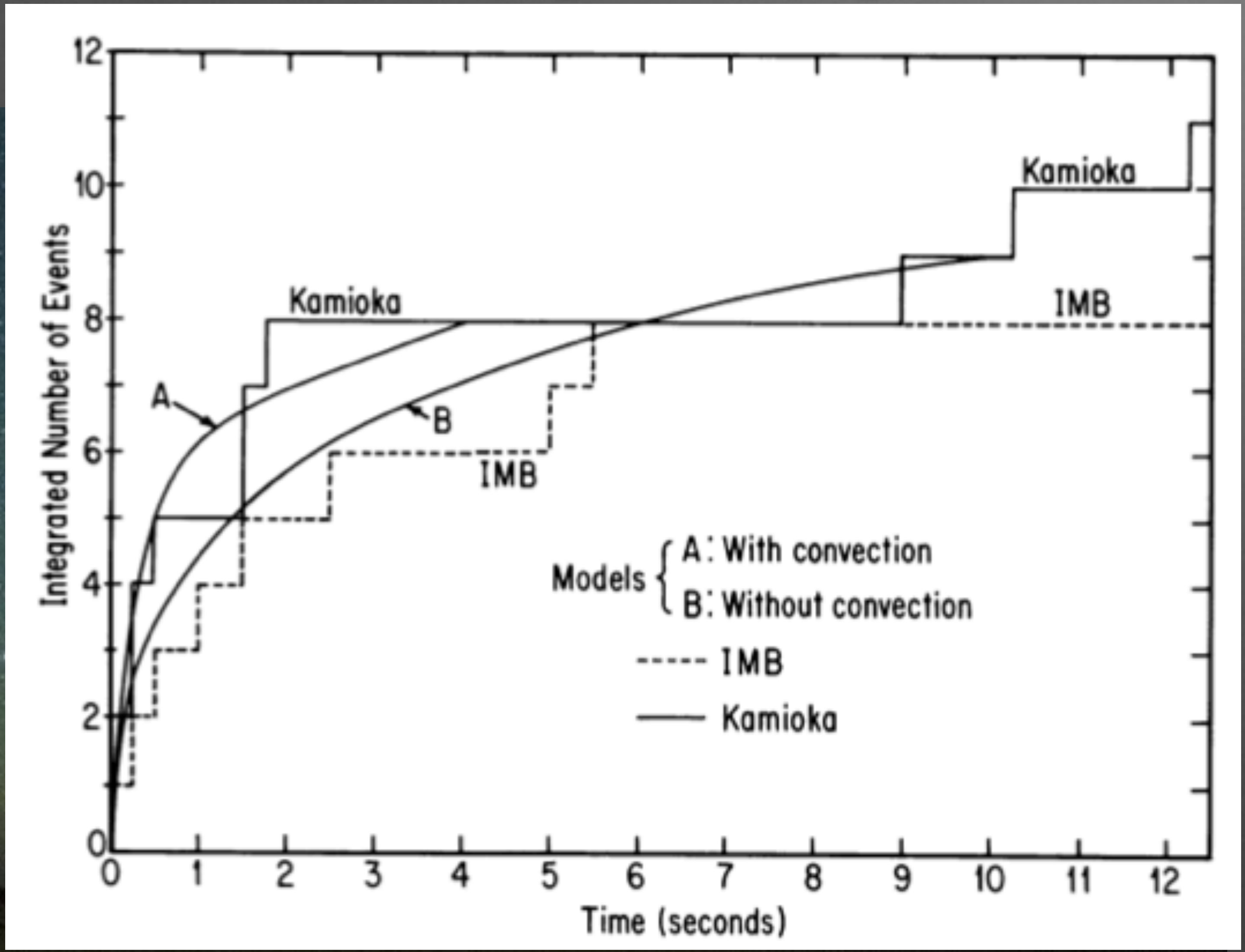

Burrows and Lattimer, 1987

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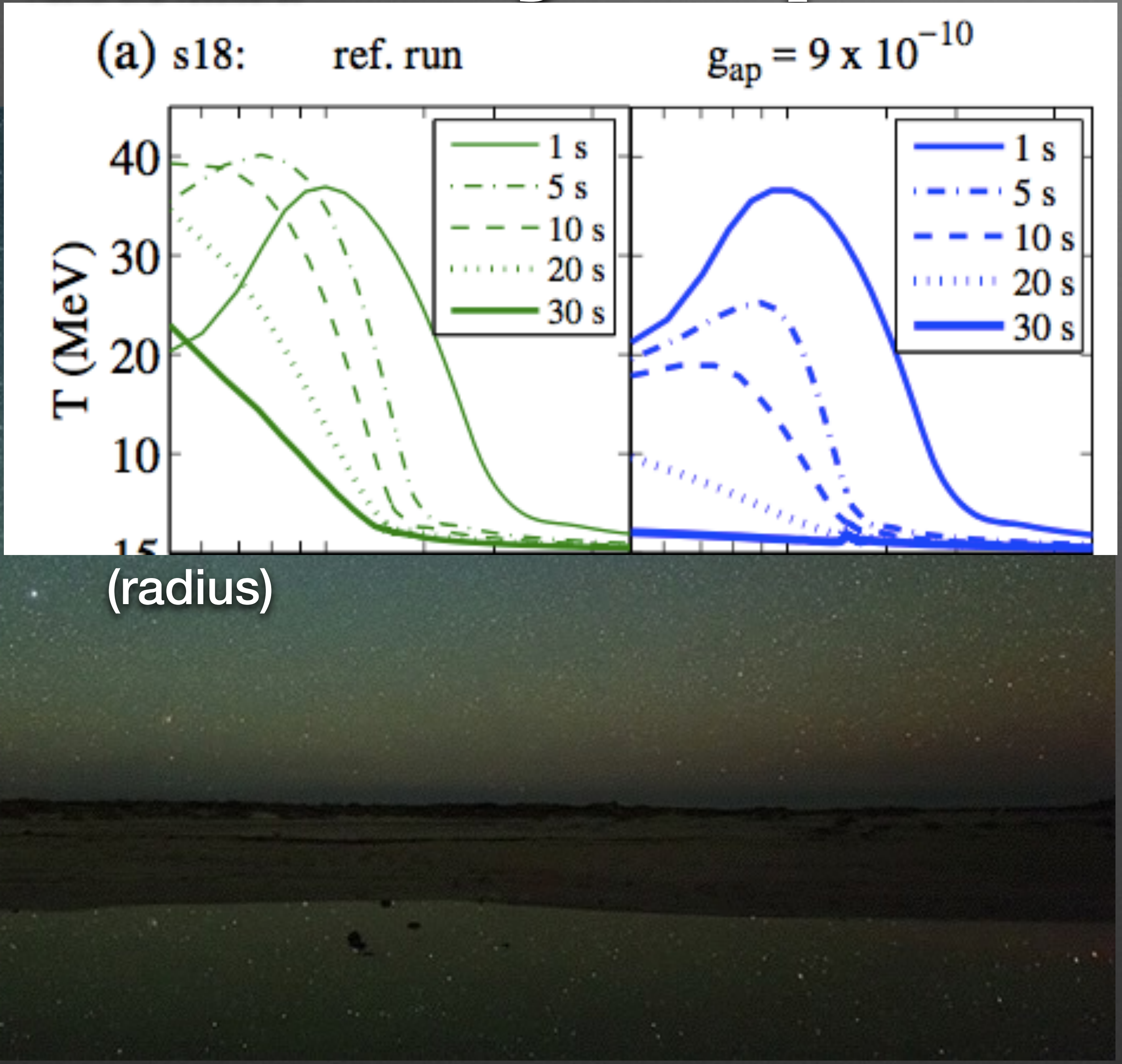
Fischer et al 1605.08780



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“$L_{new} \leq L_\nu$”

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Outline

I. Crash Course on SN1987A

II. Calculating with the QCD Axion

III. Results

Basics of the QCD Axion

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

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

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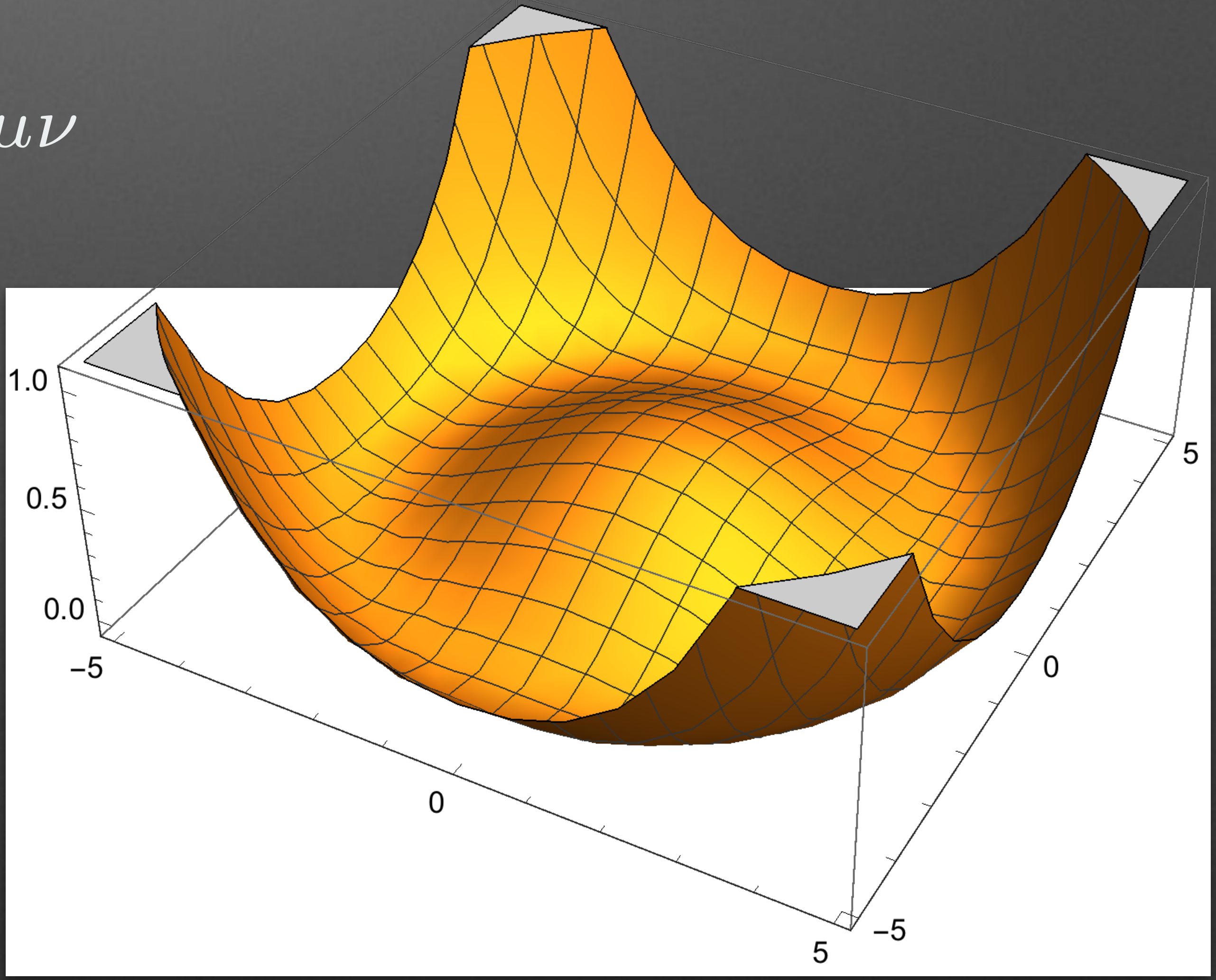

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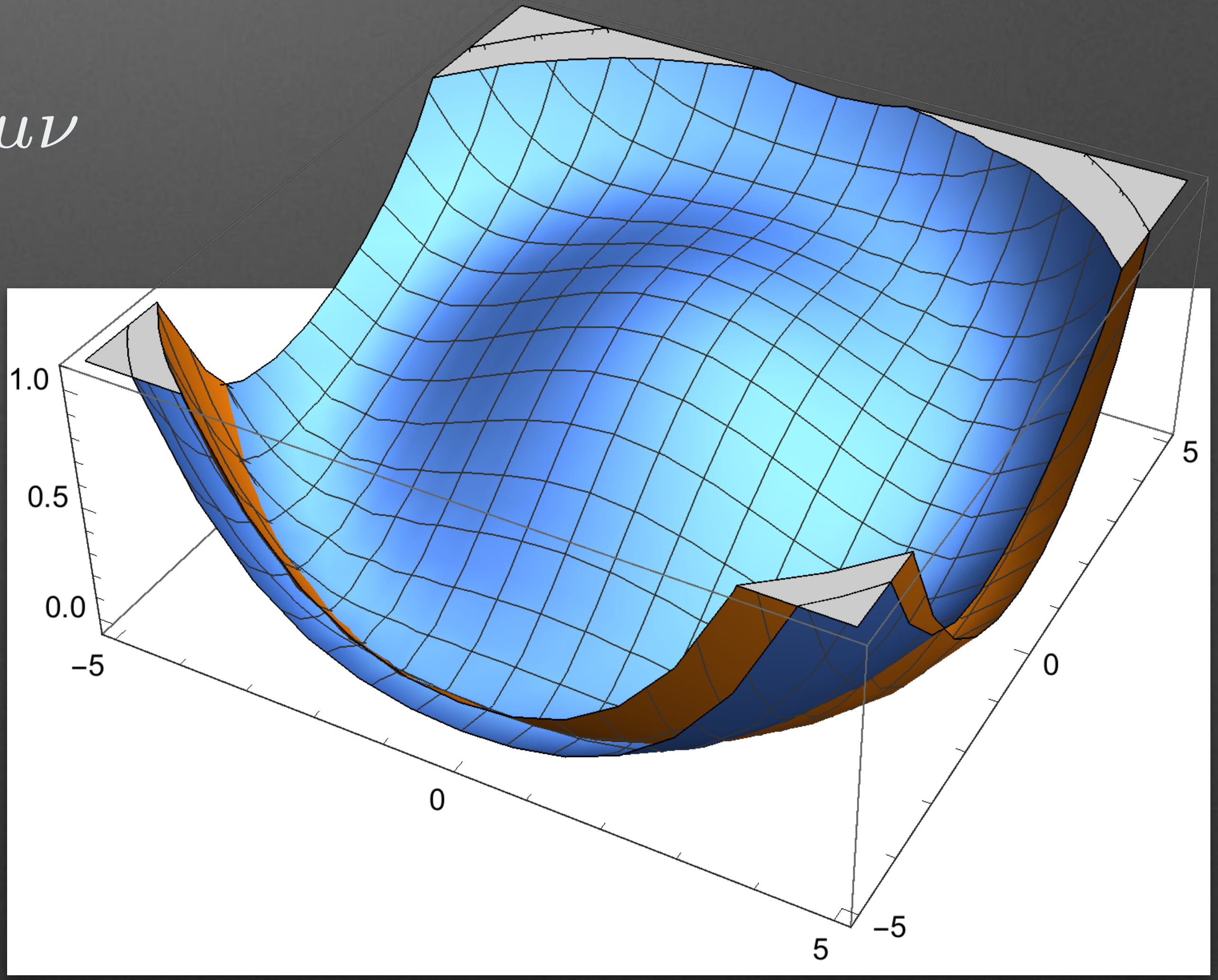

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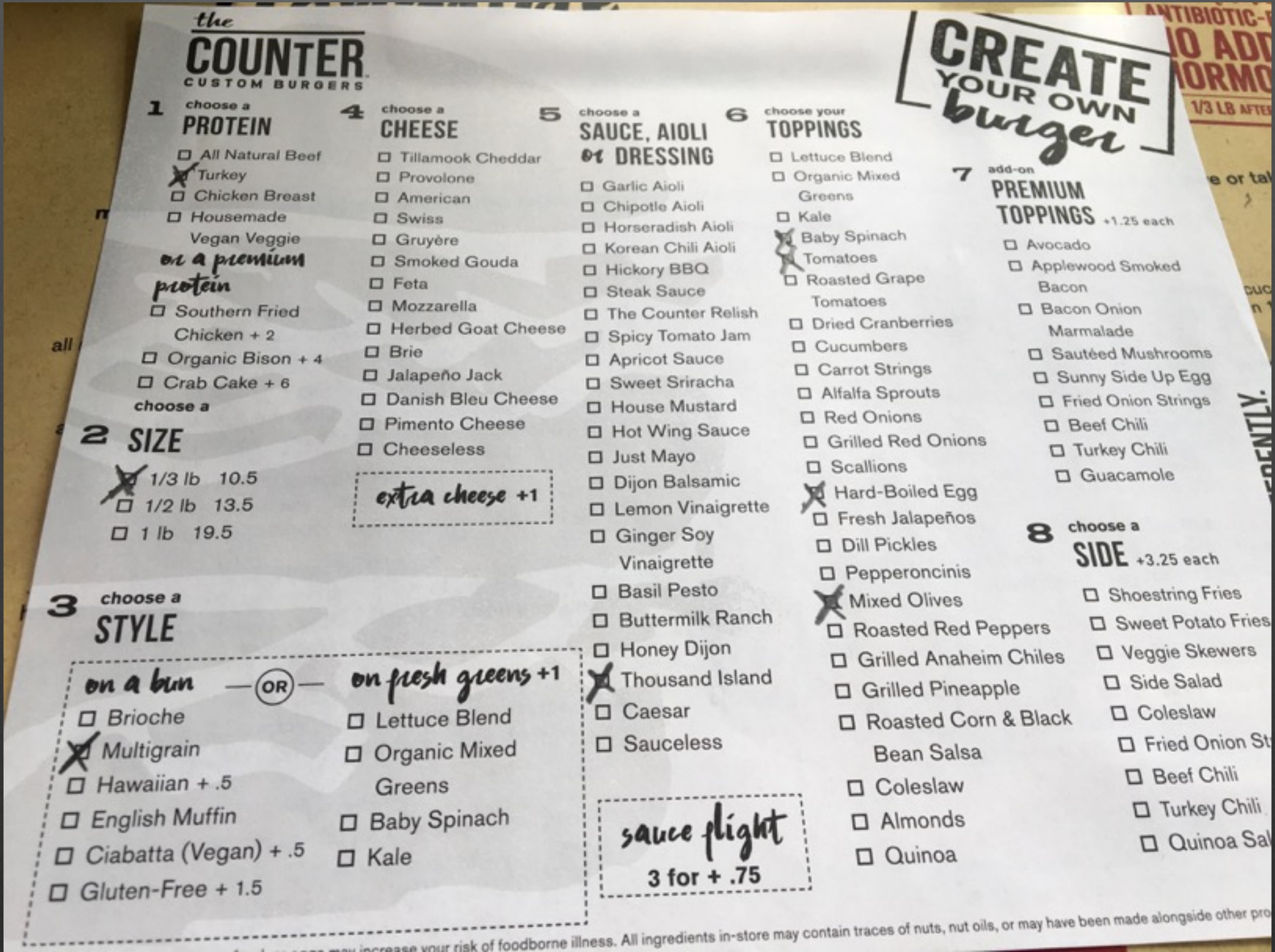

the
COUNTER
CUSTOM BURGERS

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

—OR—

on fresh greens +1
- ☐ Lettuce Blend
- ☐ Organic Mixed Greens
- ☐ Baby Spinach
- ☐ Kale

4 choose a
CHEESE
- ☐ Tillamook Cheddar
- ☐ Provolone
- ☐ American
- ☐ Swiss
- ☐ Gruyère
- ☐ 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

Basics of the QCD Axion

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

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

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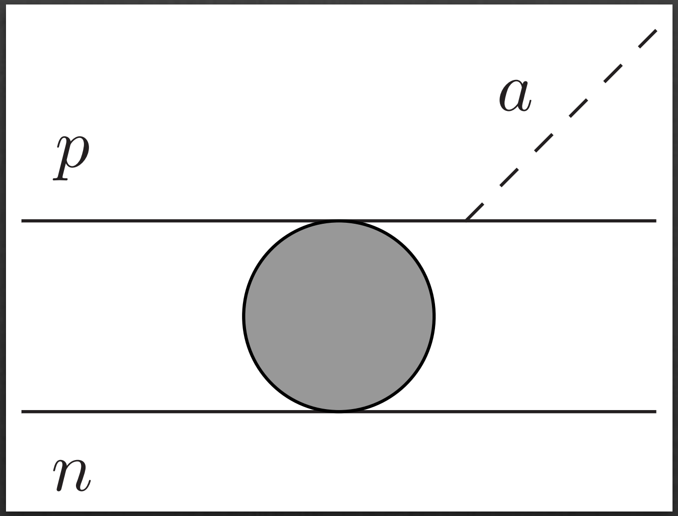
from this, we can get an interaction rate (equivalently, a mean free path) for bremsstrahlung



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helpfully, this is the same nucleon
current that neutrinos 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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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

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

Particle Luminosity

energy lost
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rate at which
a’s are
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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:

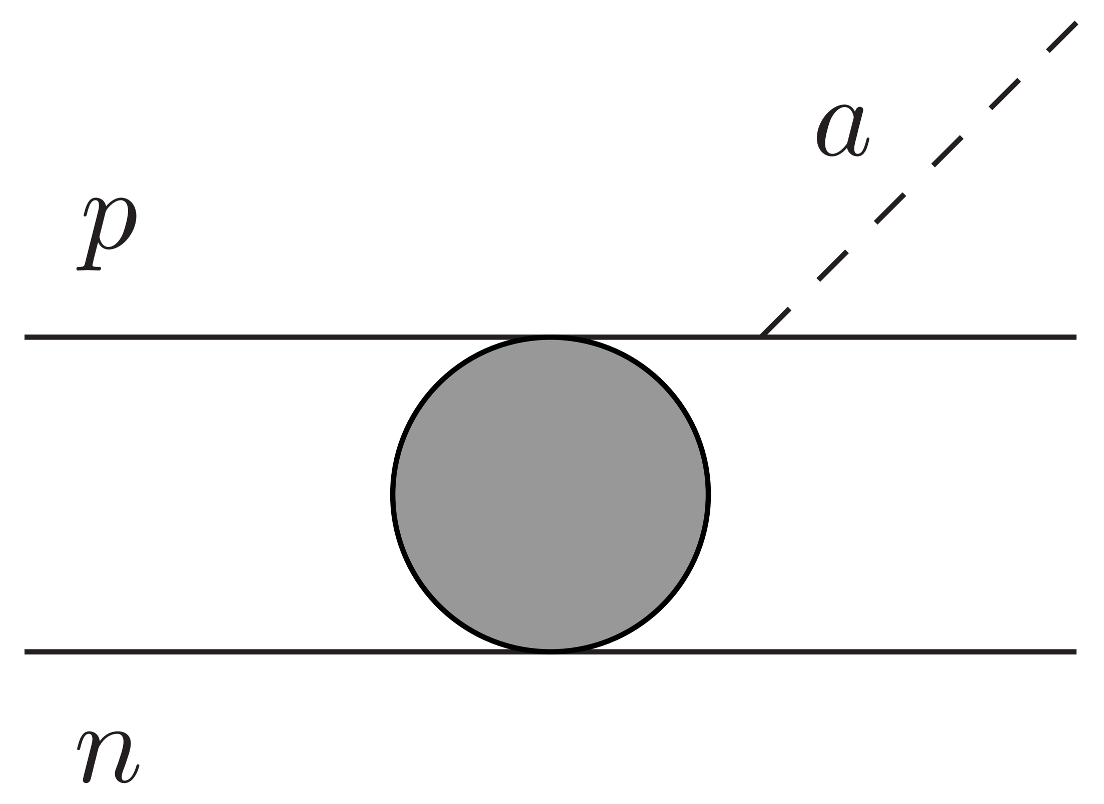
$$\tau = \int_r^{R_{\rm far}} \Gamma_{\rm abs}(r')dr'$$

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

Axion Bremsstrahlung Rate

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

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



Axion Bremsstrahlung Rate

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

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

in the free-streaming limit,

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

Axion Bremsstrahlung Rate

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

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

in the free-streaming

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

cuts off low-energy divergence

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

Axion Bremsstrahlung Rate

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

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

accounts for $m_\pi \neq 0$

in the free-streaming limit,

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

Axion Bremsstrahlung Rate

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

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

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

in the free-streaming

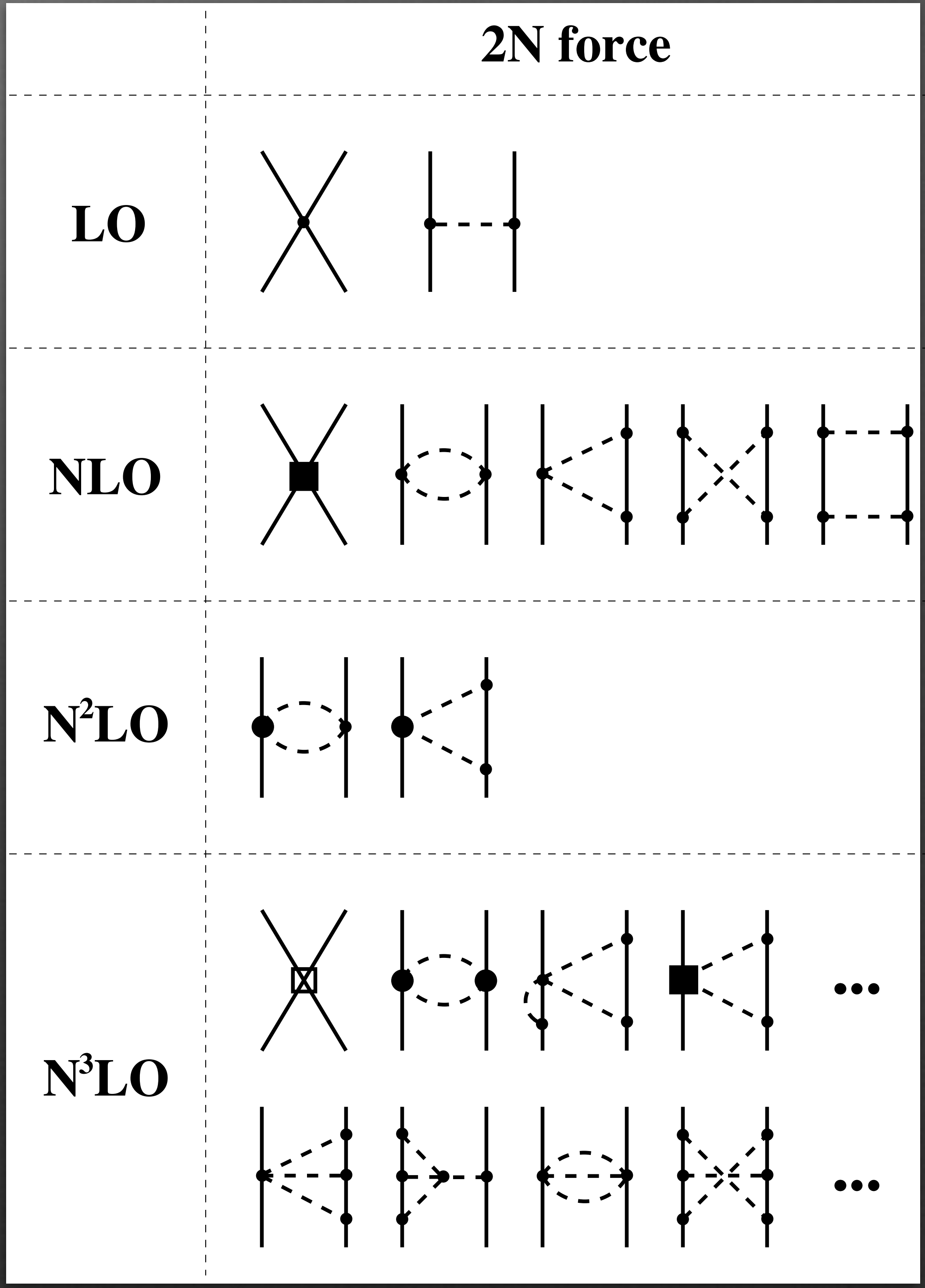
series of papers by Schwenk, Pethick, and many collaborators:
0812.0102, 1112.5185, 1403.4114, 1608.05037

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

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

Epelbaum 1001.3229



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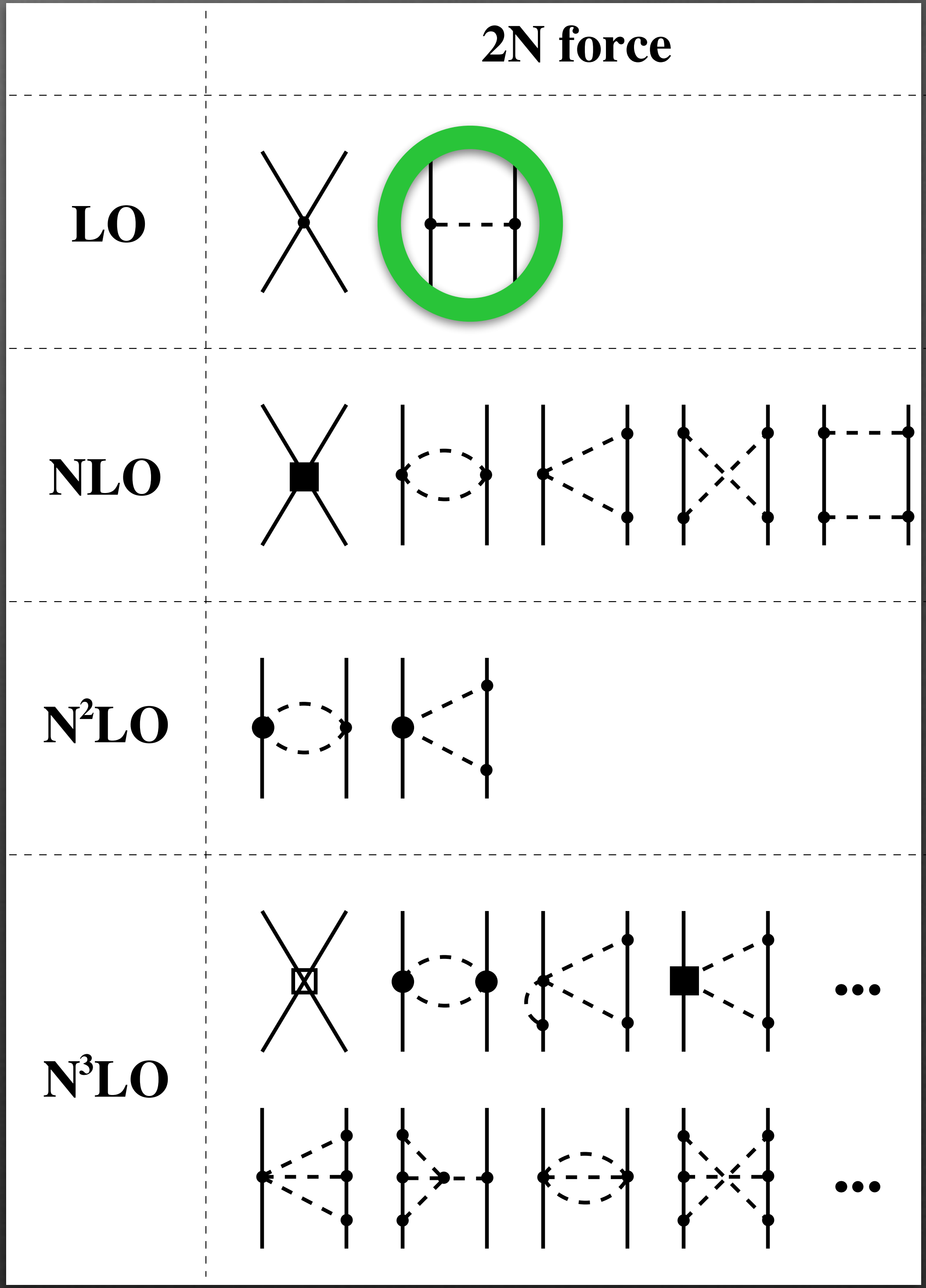
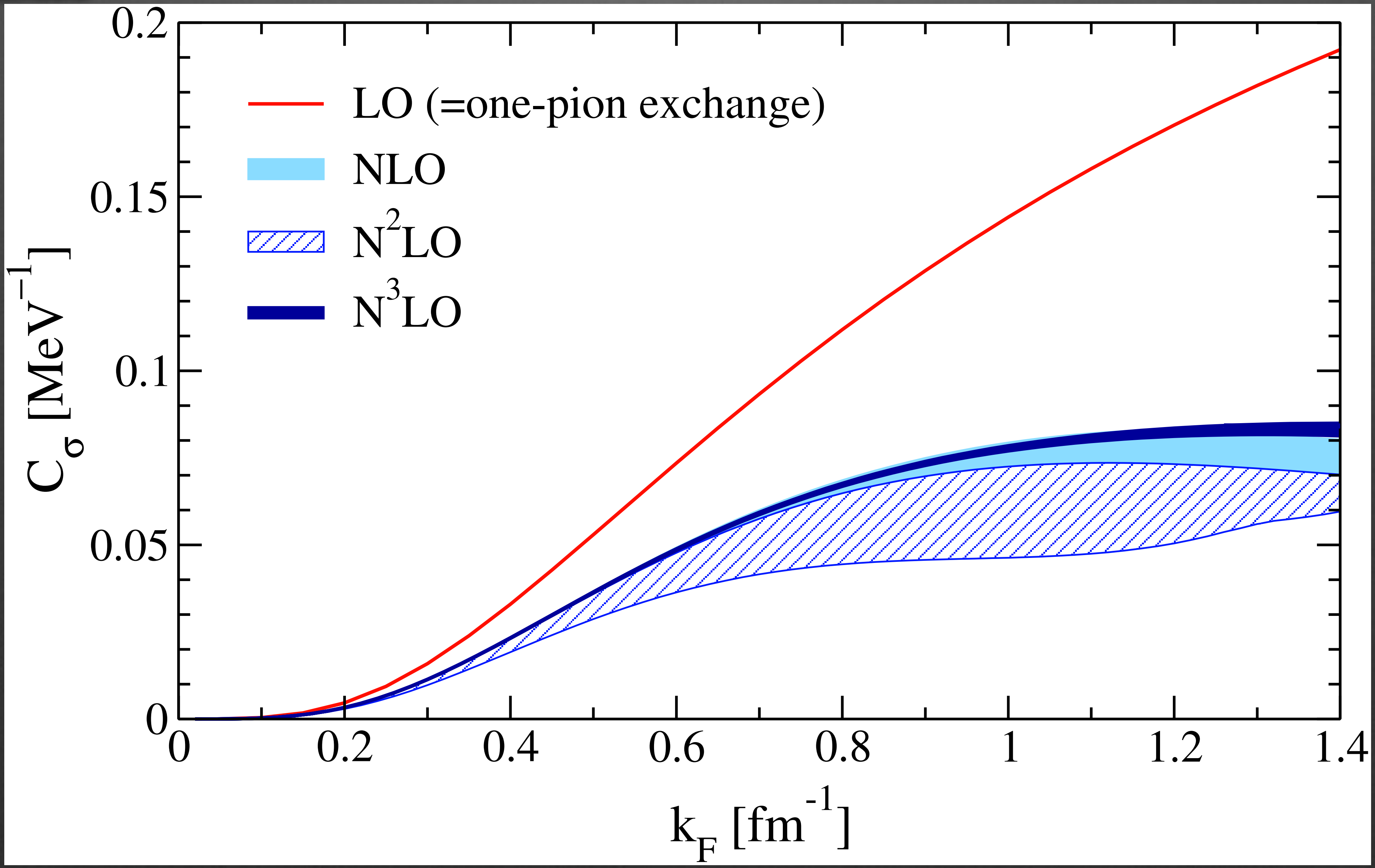


Epelbaum 1001.3229

Cancellation in χEFT

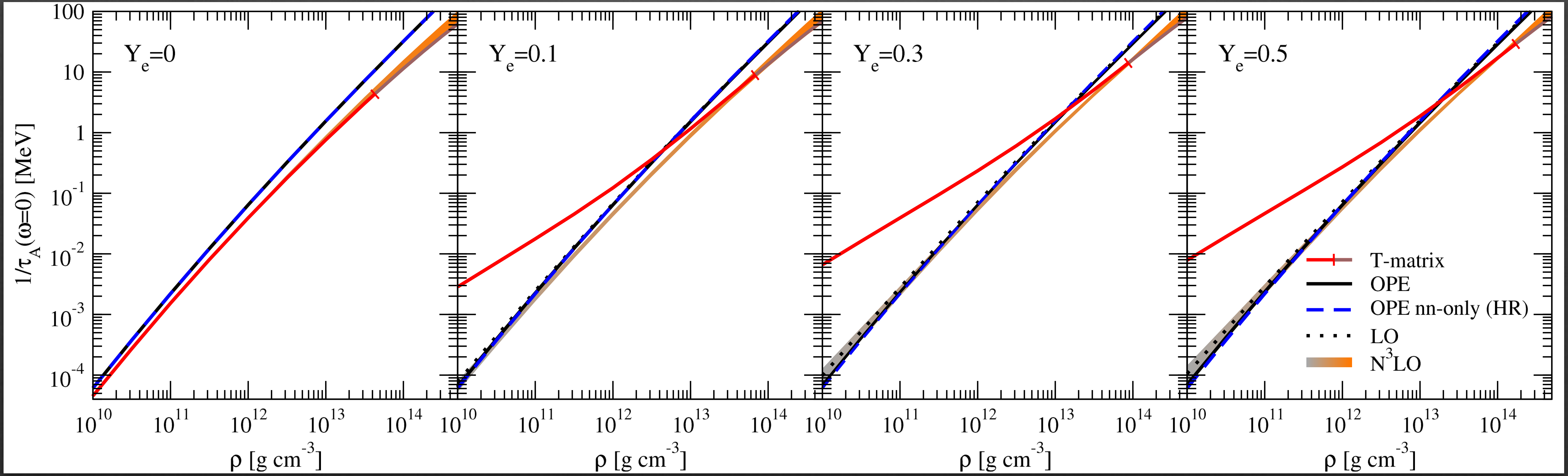
Stable cancellation; seen first at NLO

Bacca, Hally, Pethick, Schwenk
0812.0102



Dependence on Density and Y_p

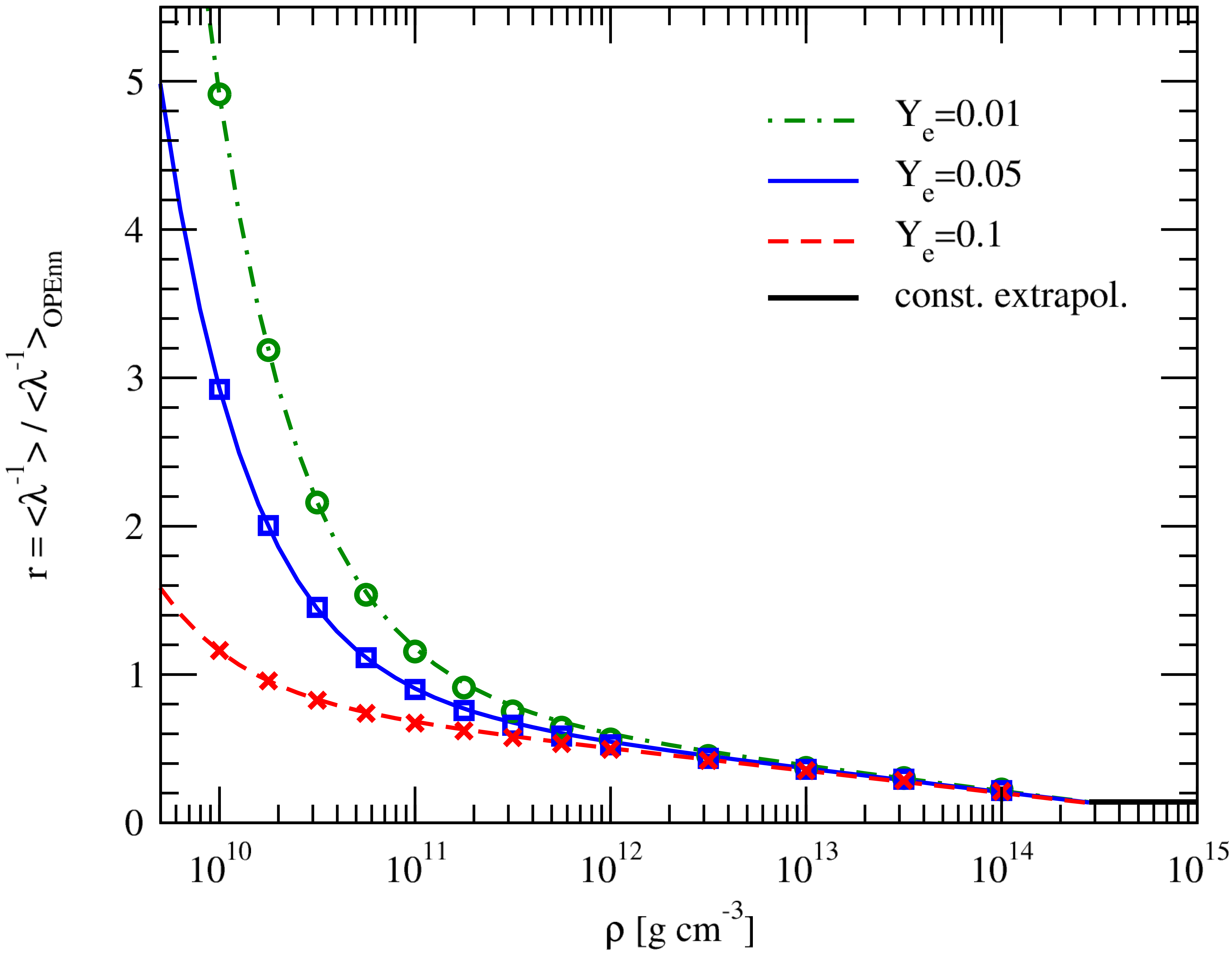
Nontrivial dependence on proton number (deuteron production resonance):



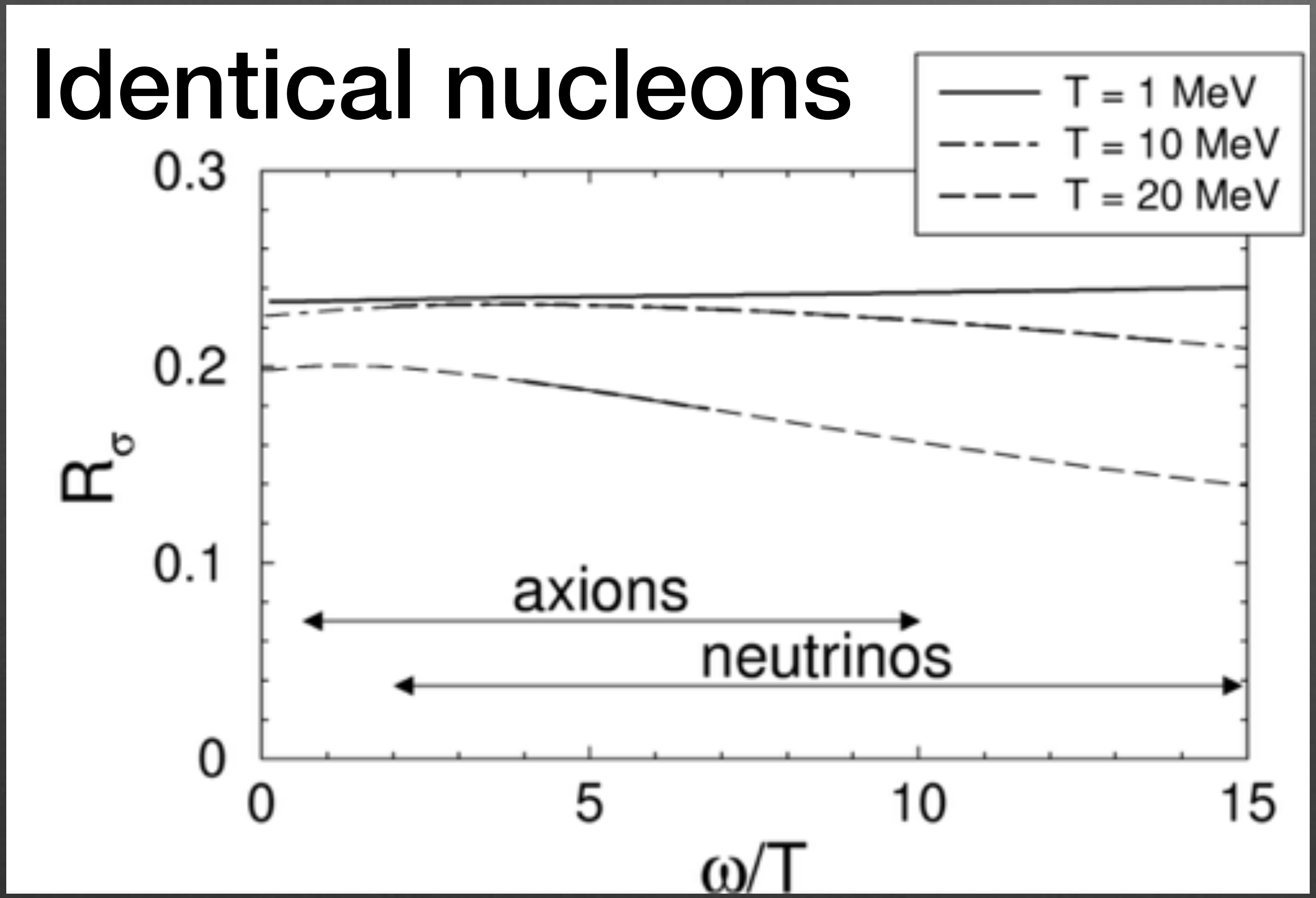
Bartl, Pethick, Schwenk 1403.4114

Ratio vs the LO result

Bartl, Bollig,
Janka, Schwenk
1608.05037

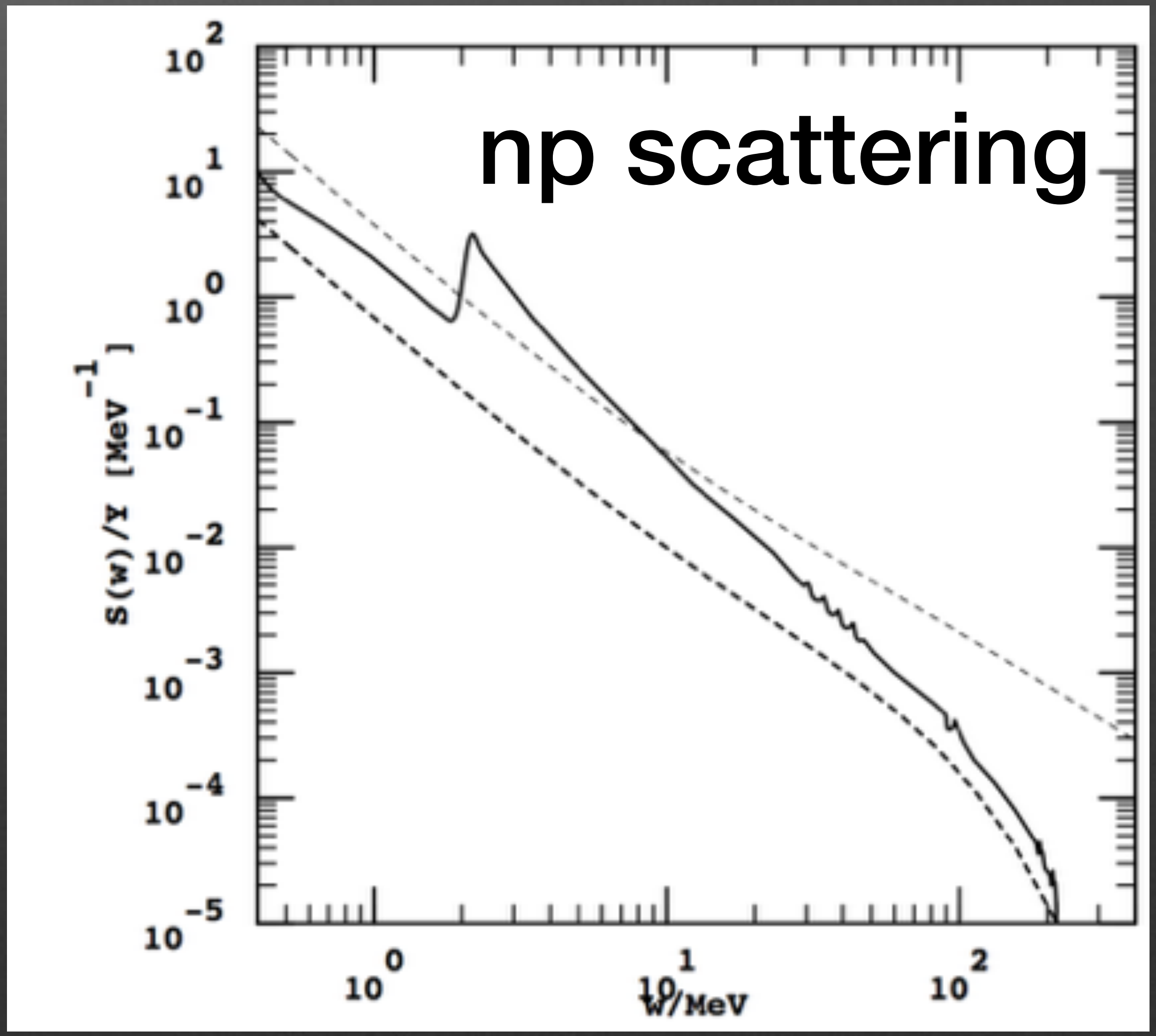


Similar physics known for ~O(20 years)


Identical nucleons

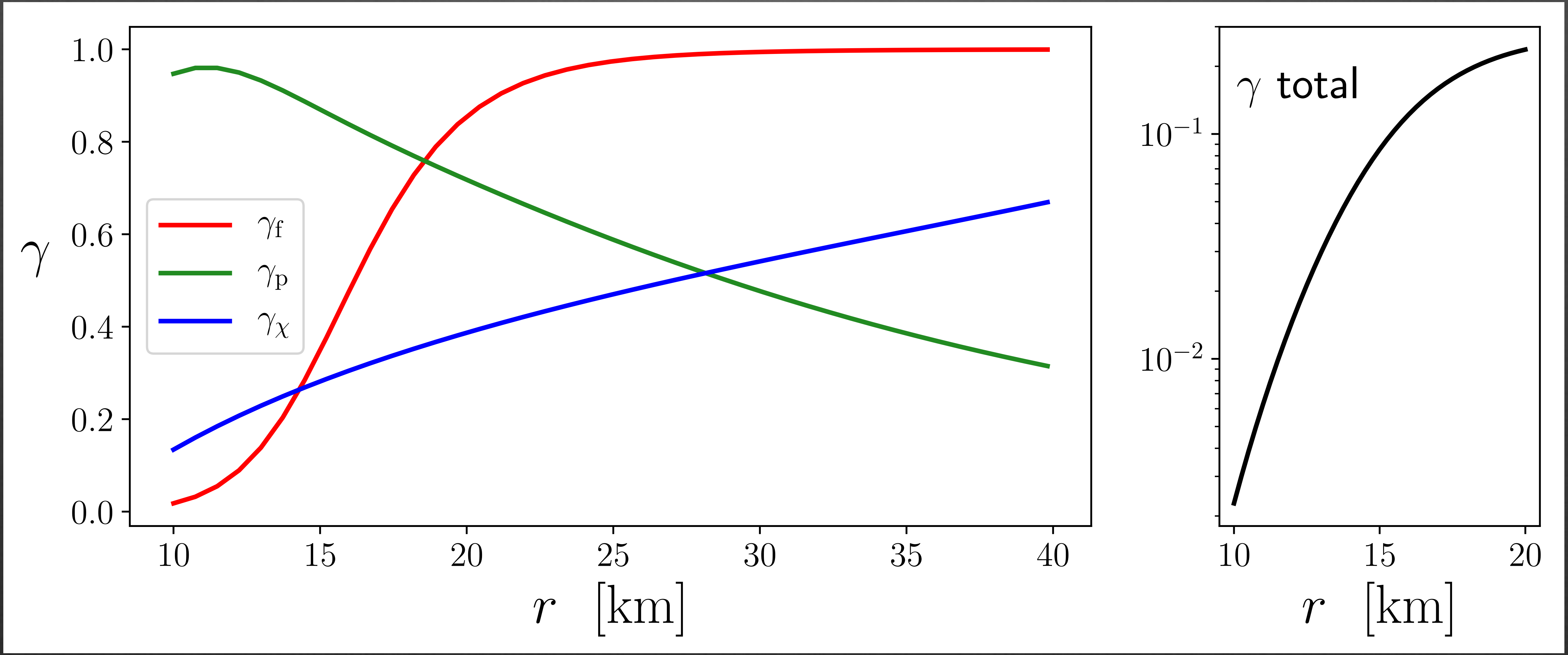
Hanhart, Phillips, Reddy 2000

Sigl 1997


np scattering

Correction Factors

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



Supernova Thermo

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

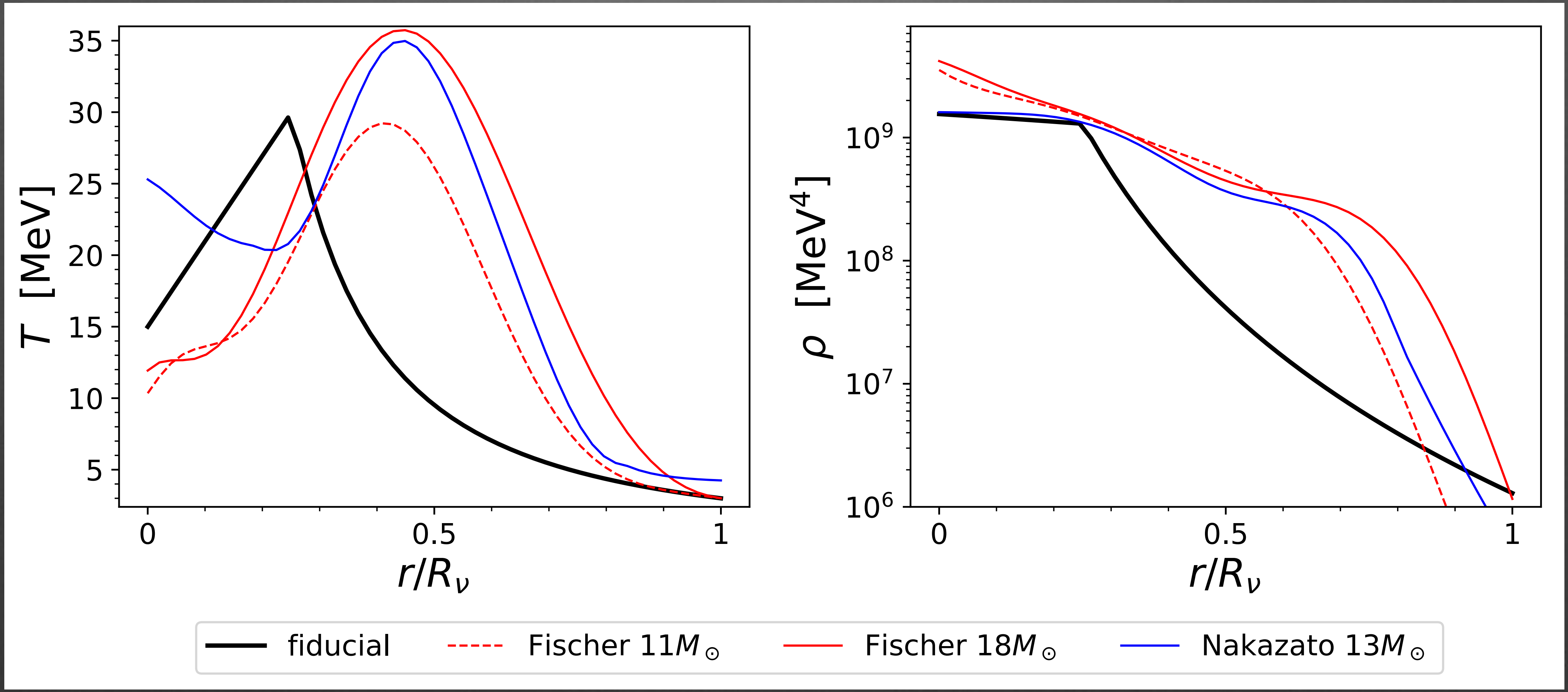
$$\rho(r) = \rho_c \times \begin{cases} 1 + k_\rho(1 - r/R_c) & r < R_c \\ (r/R_c)^{-\nu} & r \geq R_c \end{cases}$$

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

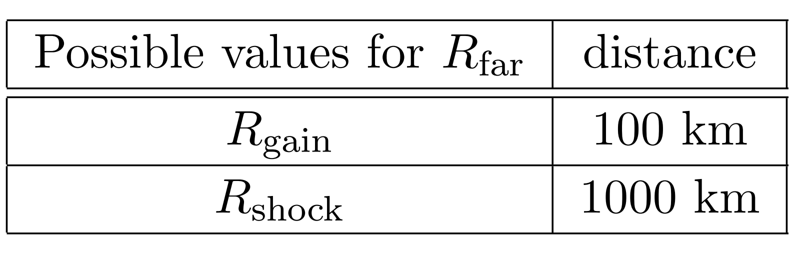
"fiducial model"
(Raffelt, 1995)

Uncertainties

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



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

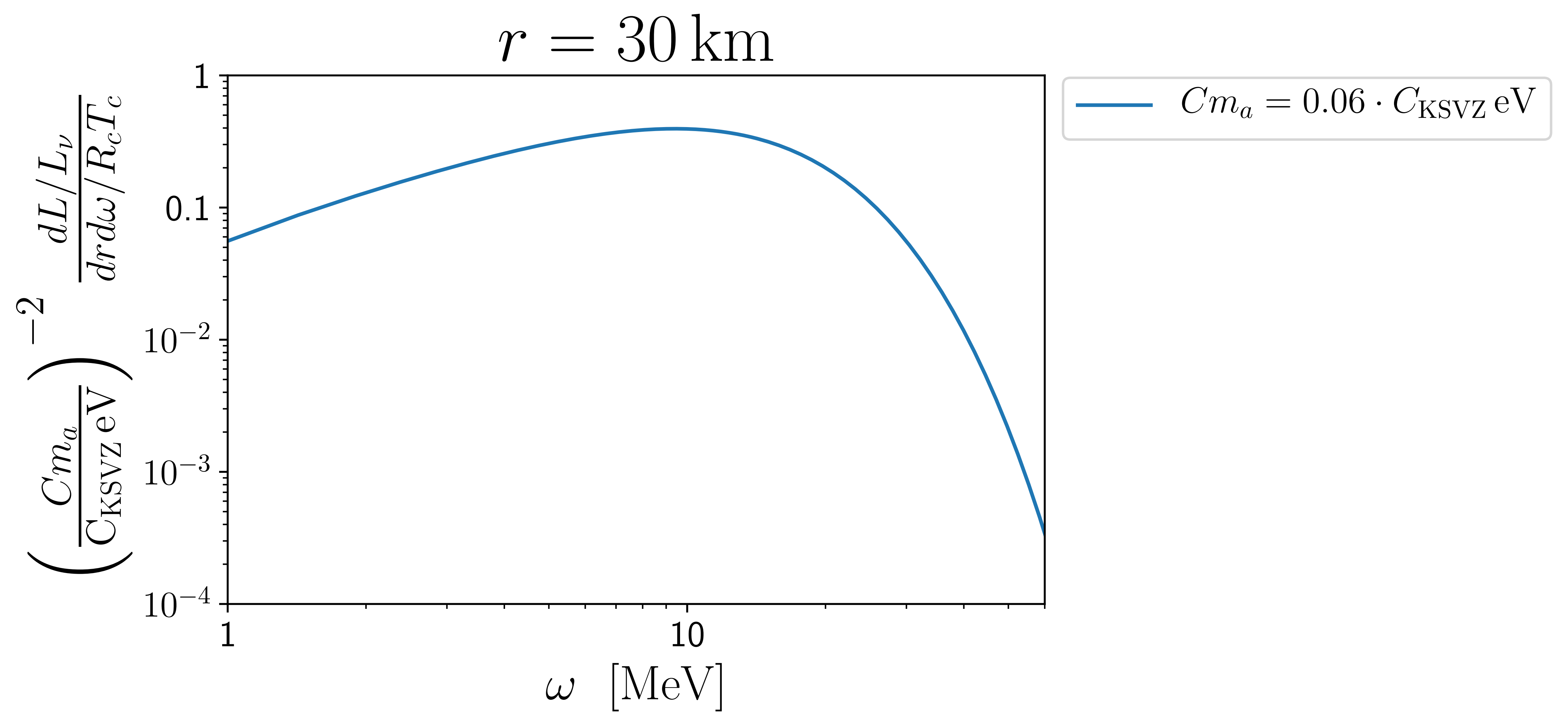


Possible values for $R_{\rm far}$	distance
$R_{\rm gain}$	100 km
$R_{\rm shock}$	1000 km

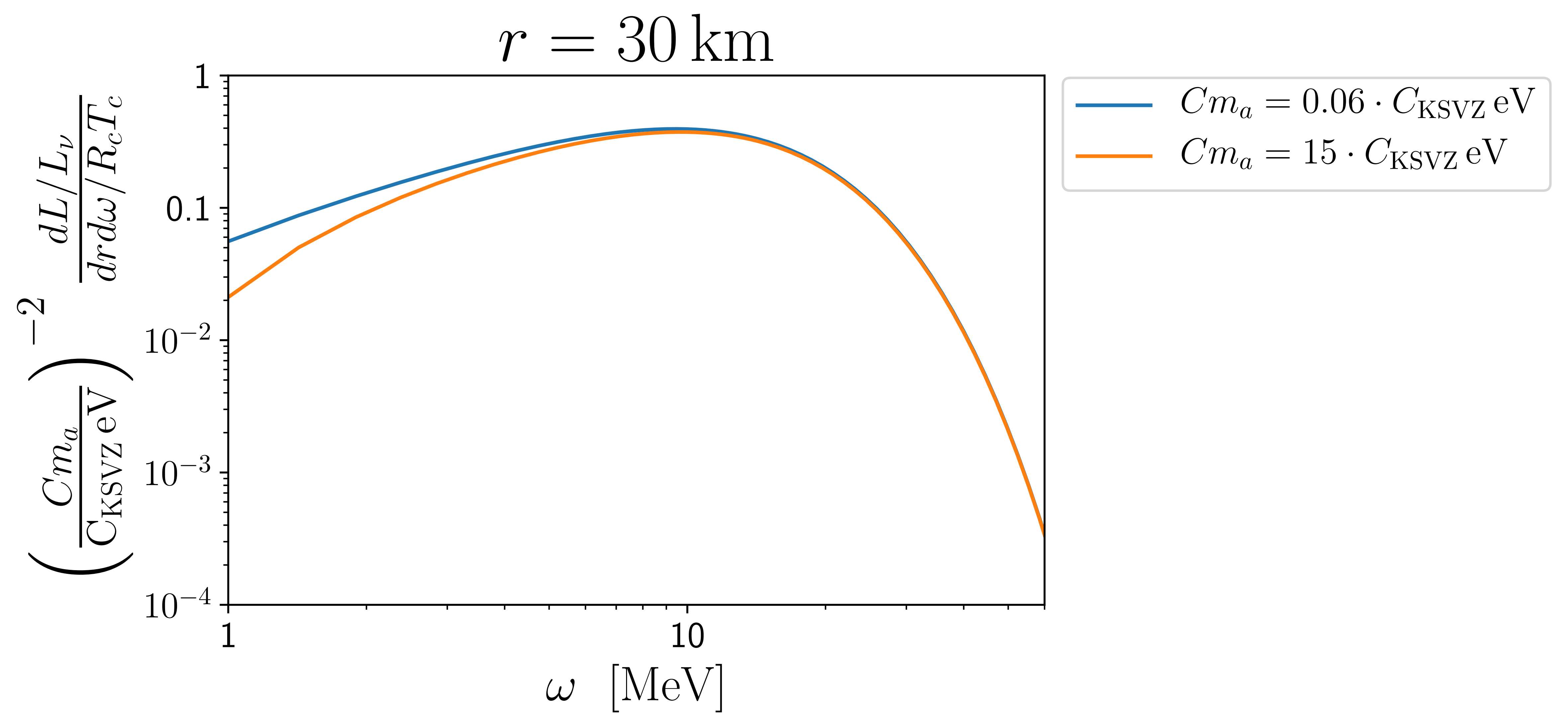
both τ and dP depend on ω and r, so the spectrum of dark photon emission is nontrivial

Let’s examine $dL/dV/d\omega$ vs ω (at e.g. core radius)

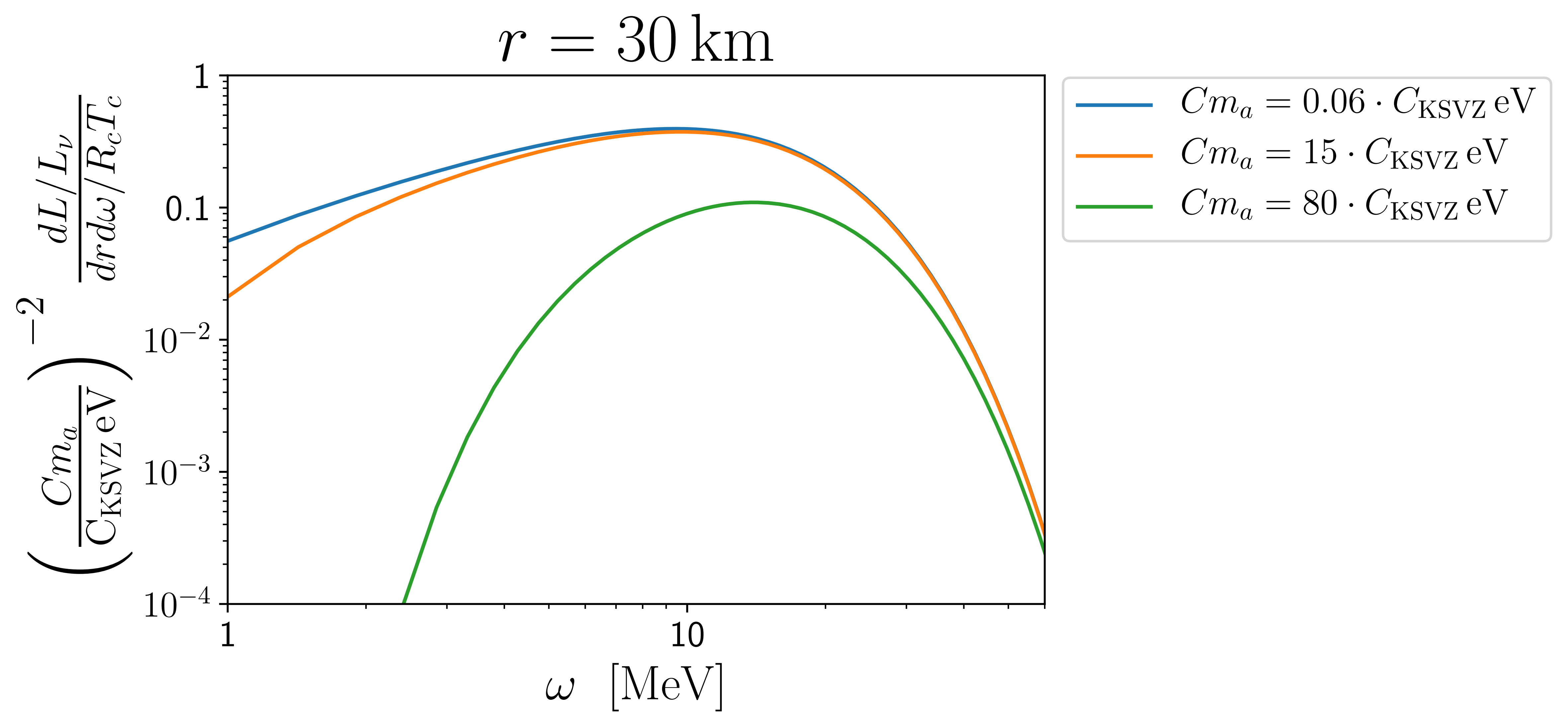
dL/dr/dω (rescaled)



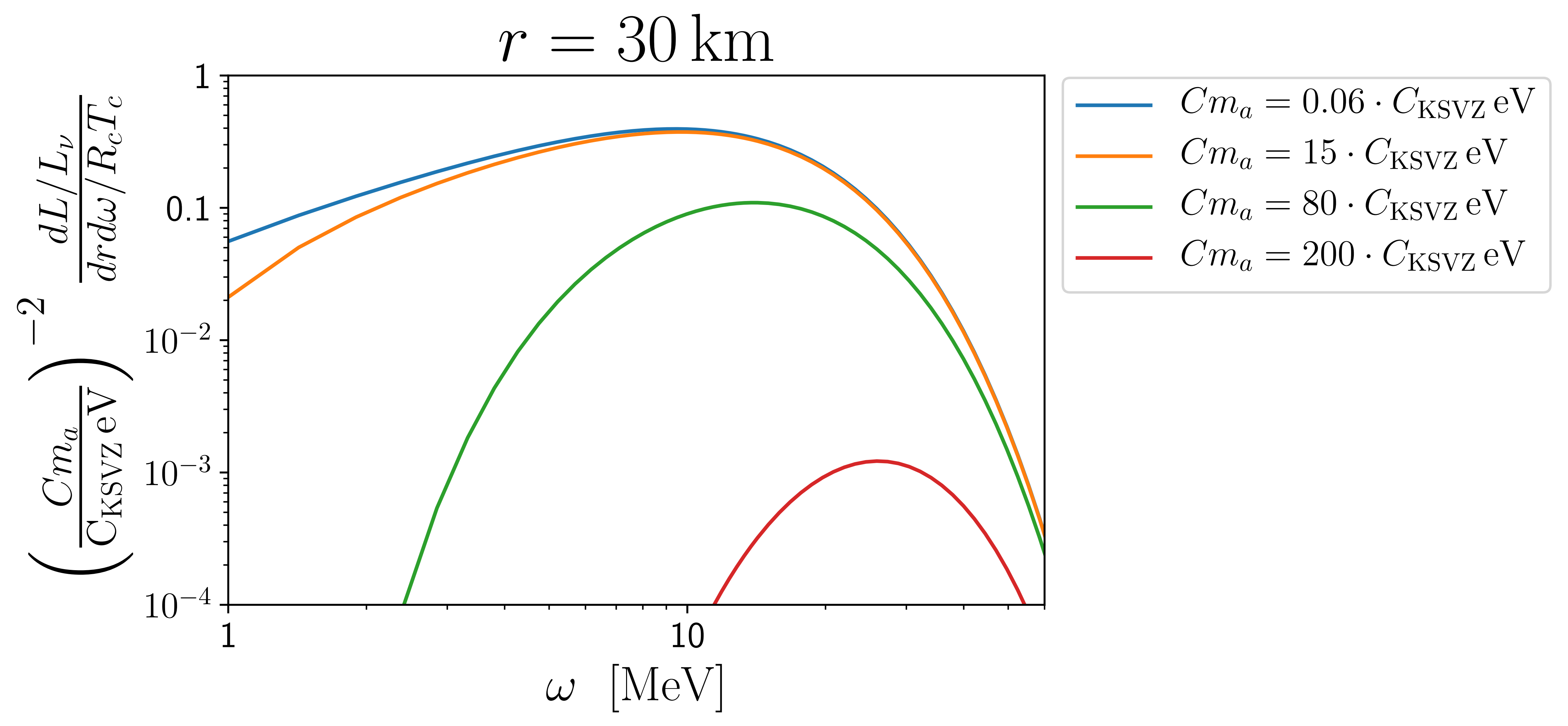
dL/dr/dω (rescaled)



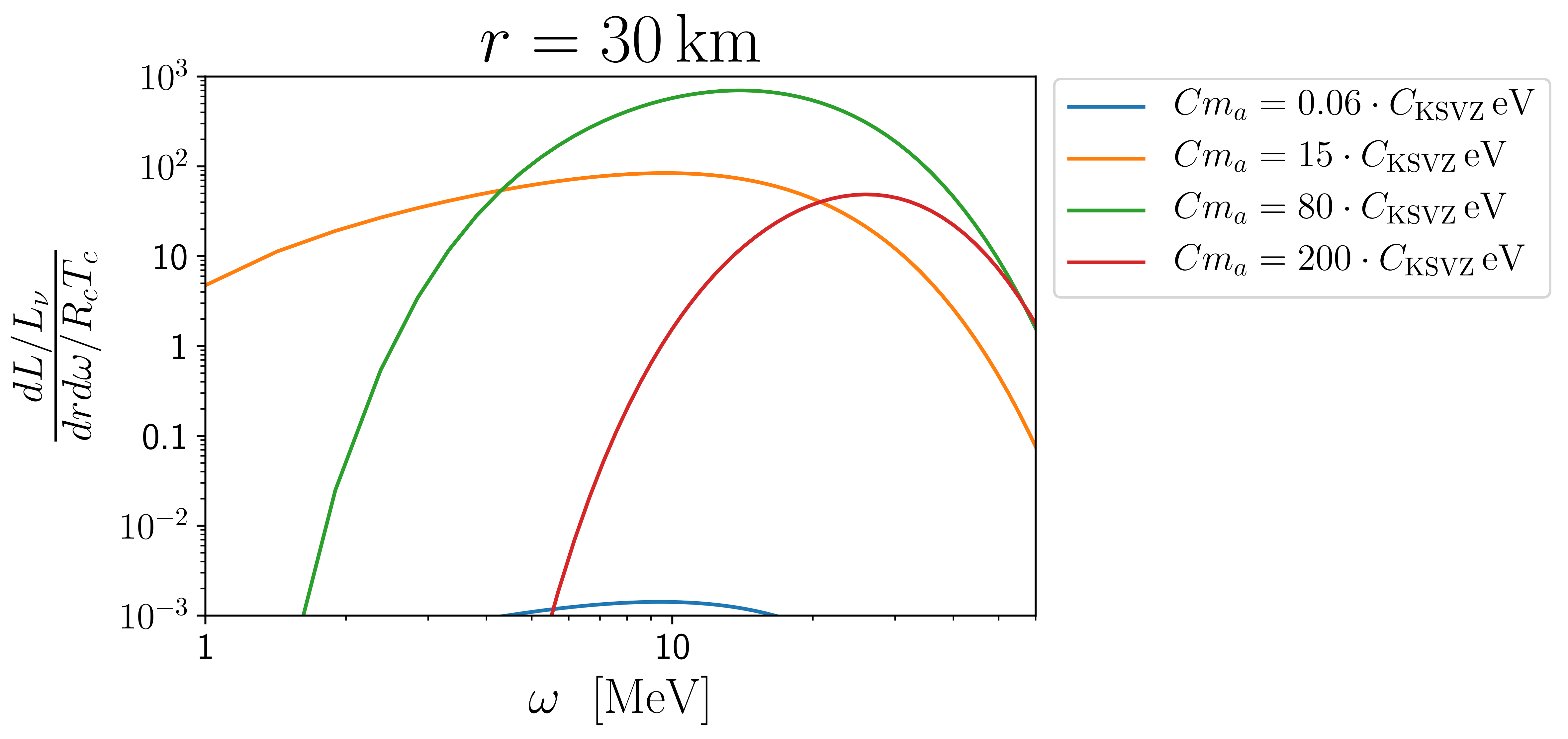
dL/dr/dω (rescaled)



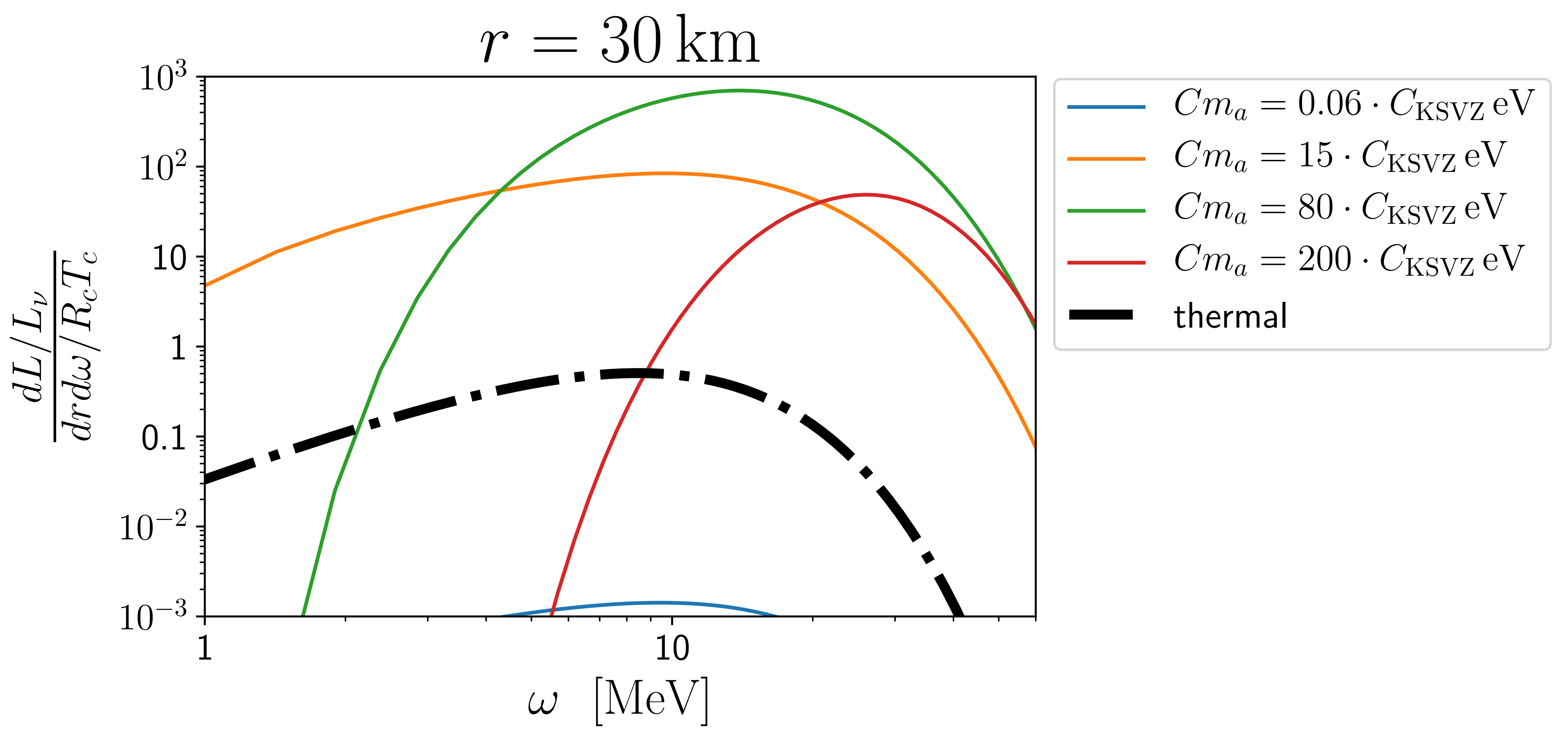
dL/dr/dω (rescaled)



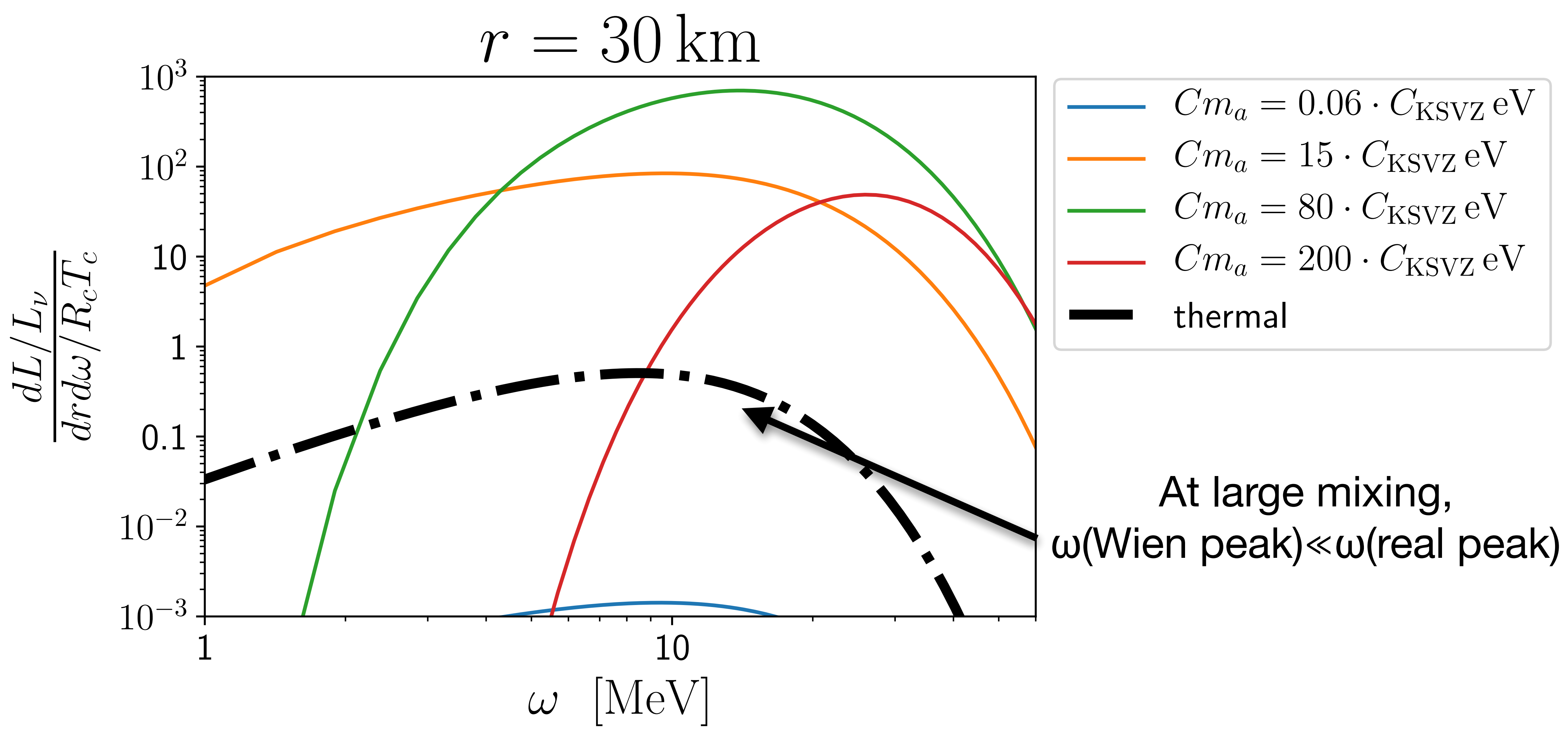
dL/dr/dω


$r = 30\,\mathrm{km}$
$\frac{dL/L_\nu}{dr d\omega/R_c T_c}$
10^3
10^2
10
1
0.1
10^{-2}
10^{-3}
1
10
ω [MeV]
$Cm_a = 0.06 \cdot C_{\mathrm{KSVZ}}\,\mathrm{eV}$
$Cm_a = 15 \cdot C_{\mathrm{KSVZ}}\,\mathrm{eV}$
$Cm_a = 80 \cdot C_{\mathrm{KSVZ}}\,\mathrm{eV}$
$Cm_a = 200 \cdot C_{\mathrm{KSVZ}}\,\mathrm{eV}$

dL/dr/dω

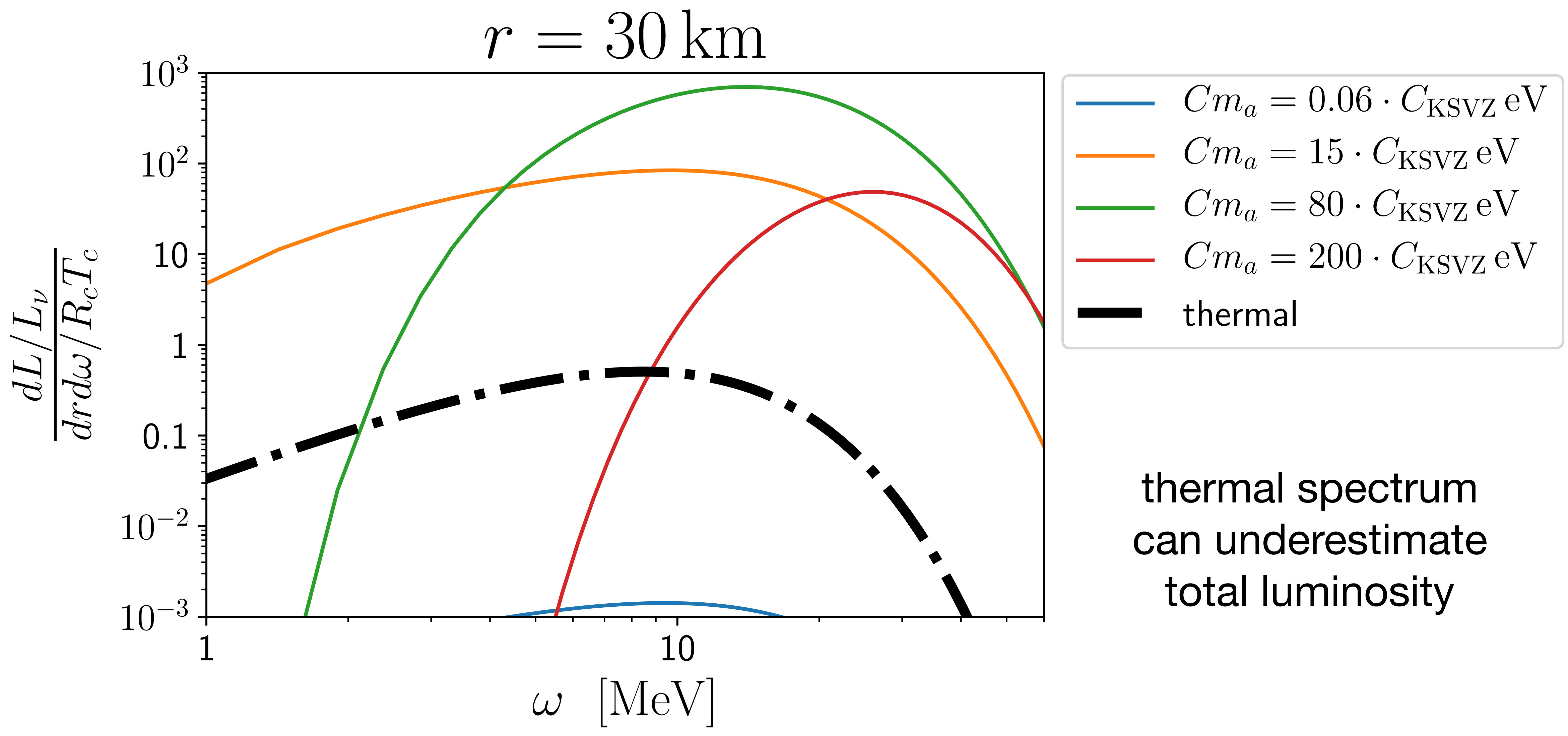

$r = 30\,\mathrm{km}$
10^3
10^2
10
1
0.1
10^{-2}
10^{-3}
$\frac{dL/L_\nu}{dr\,d\omega/R_cT_c}$
1
10
ω [MeV]
$Cm_a = 0.06 \cdot C_{\mathrm{KSVZ}}\,\mathrm{eV}$
$Cm_a = 15 \cdot C_{\mathrm{KSVZ}}\,\mathrm{eV}$
$Cm_a = 80 \cdot C_{\mathrm{KSVZ}}\,\mathrm{eV}$
$Cm_a = 200 \cdot C_{\mathrm{KSVZ}}\,\mathrm{eV}$
thermal

dL/dr/dω



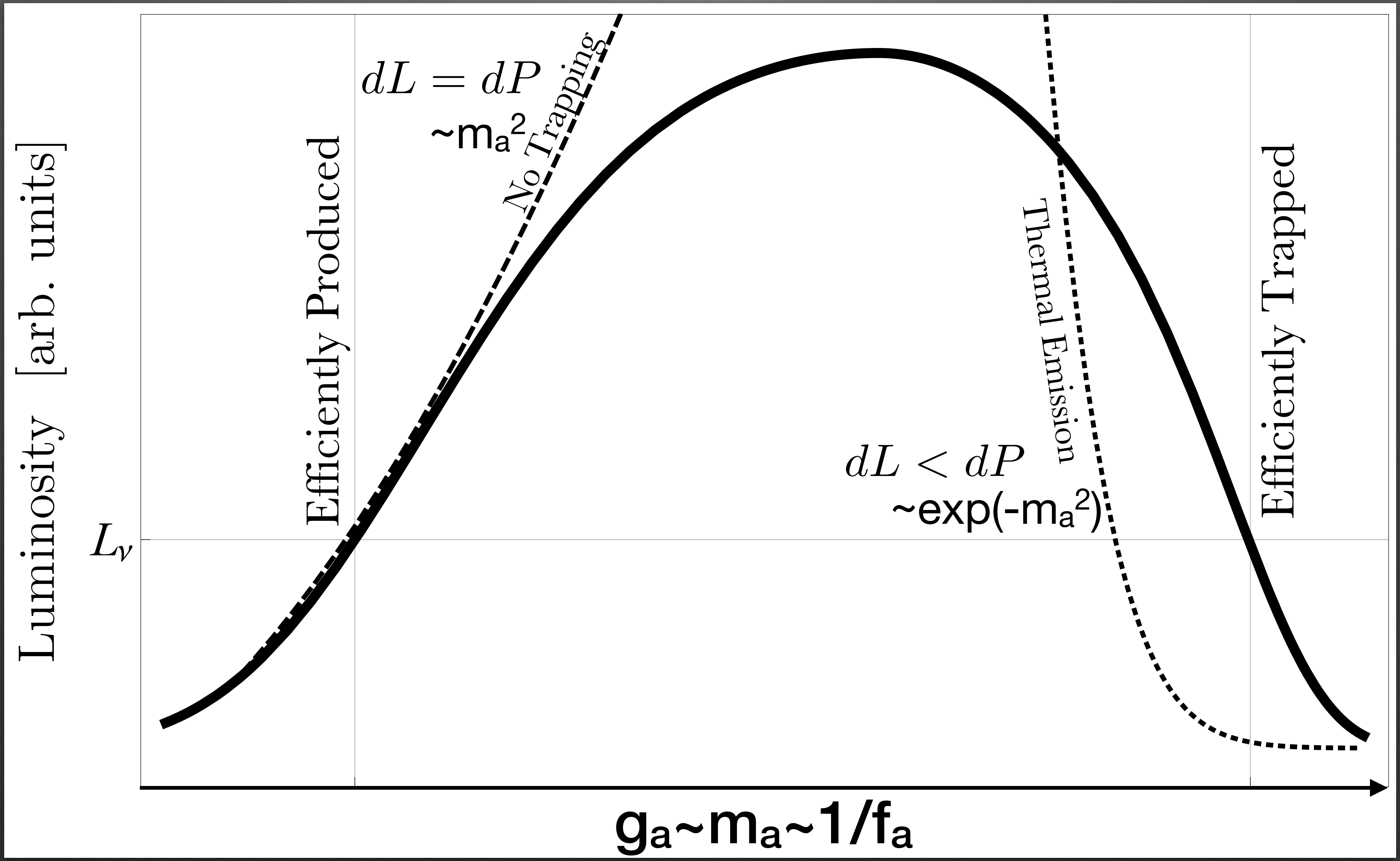
At large mixing,
ω(Wien peak)≪ω(real peak)

dL/dr/dω



thermal spectrum
can underestimate
total luminosity

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


Luminosity [arb. units]
L_ν
Efficiently Produced
$dL = dP$
~m_a^2
No Trapping
$dL < dP$
~exp(-m_a^2)
Thermal Emission
Efficiently Trapped
g_a~m_a~$1/f_a$

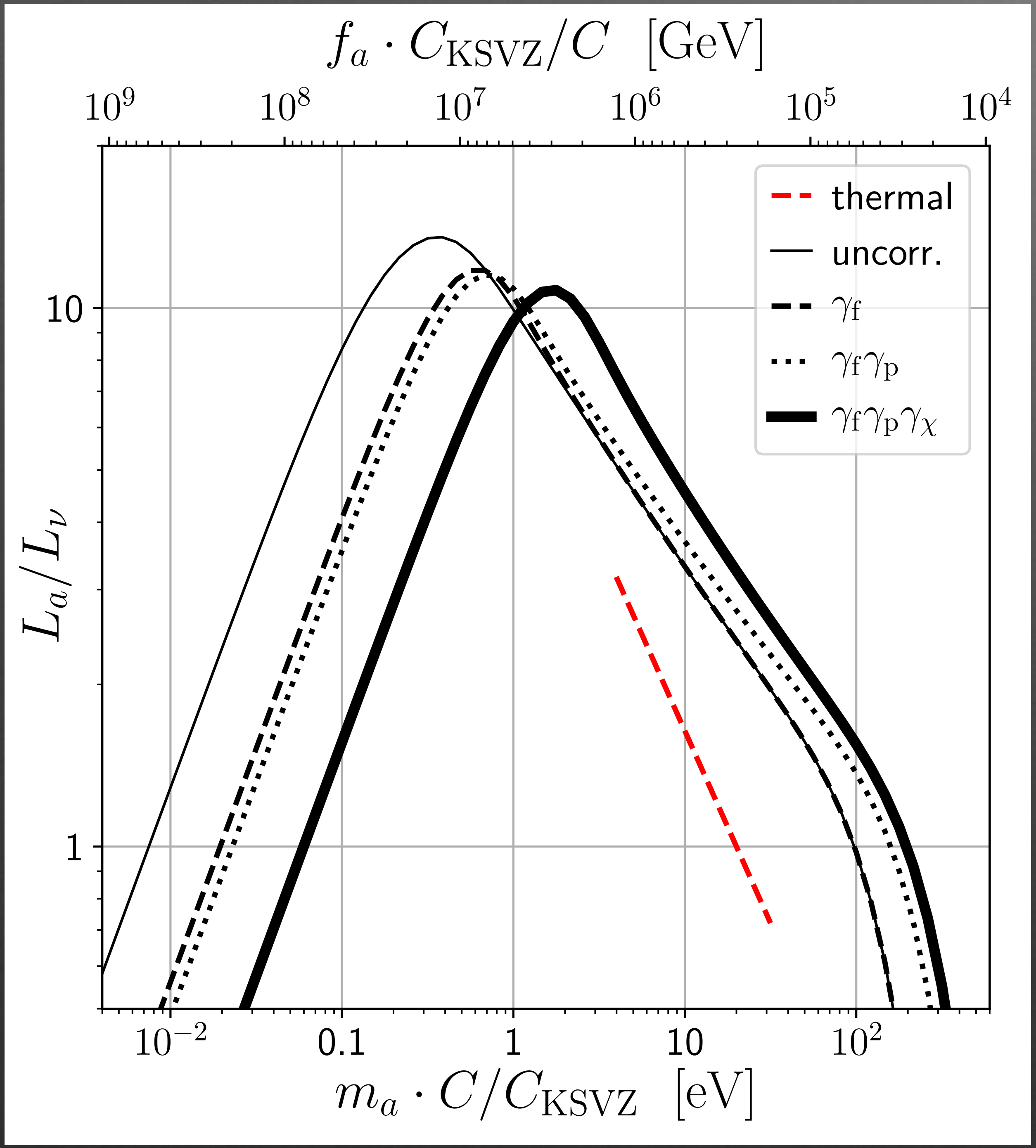
Outline

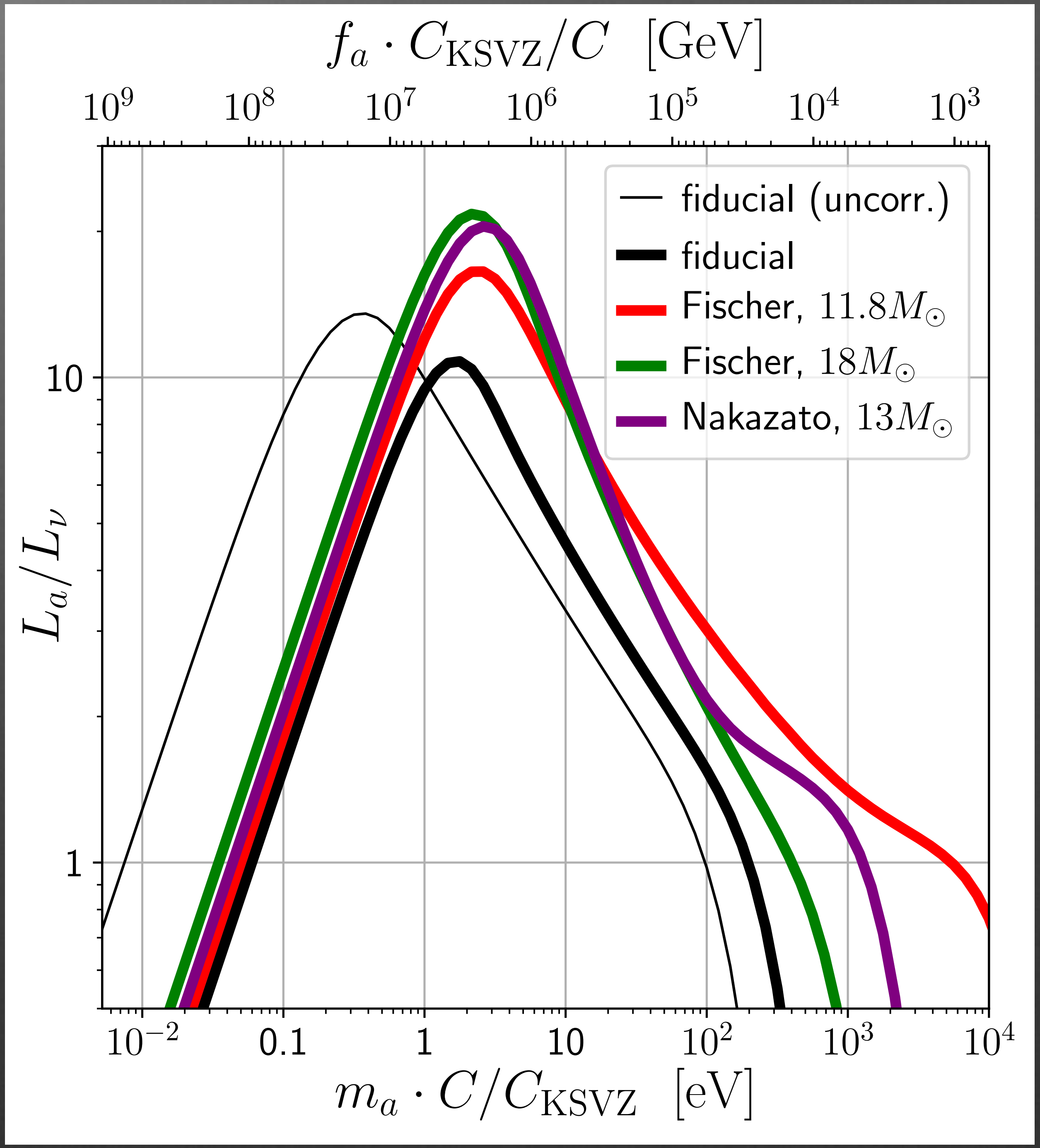
I. Kinetic Mixing and Finite Temperature

II. Luminosity: Resonance and “Trapping”

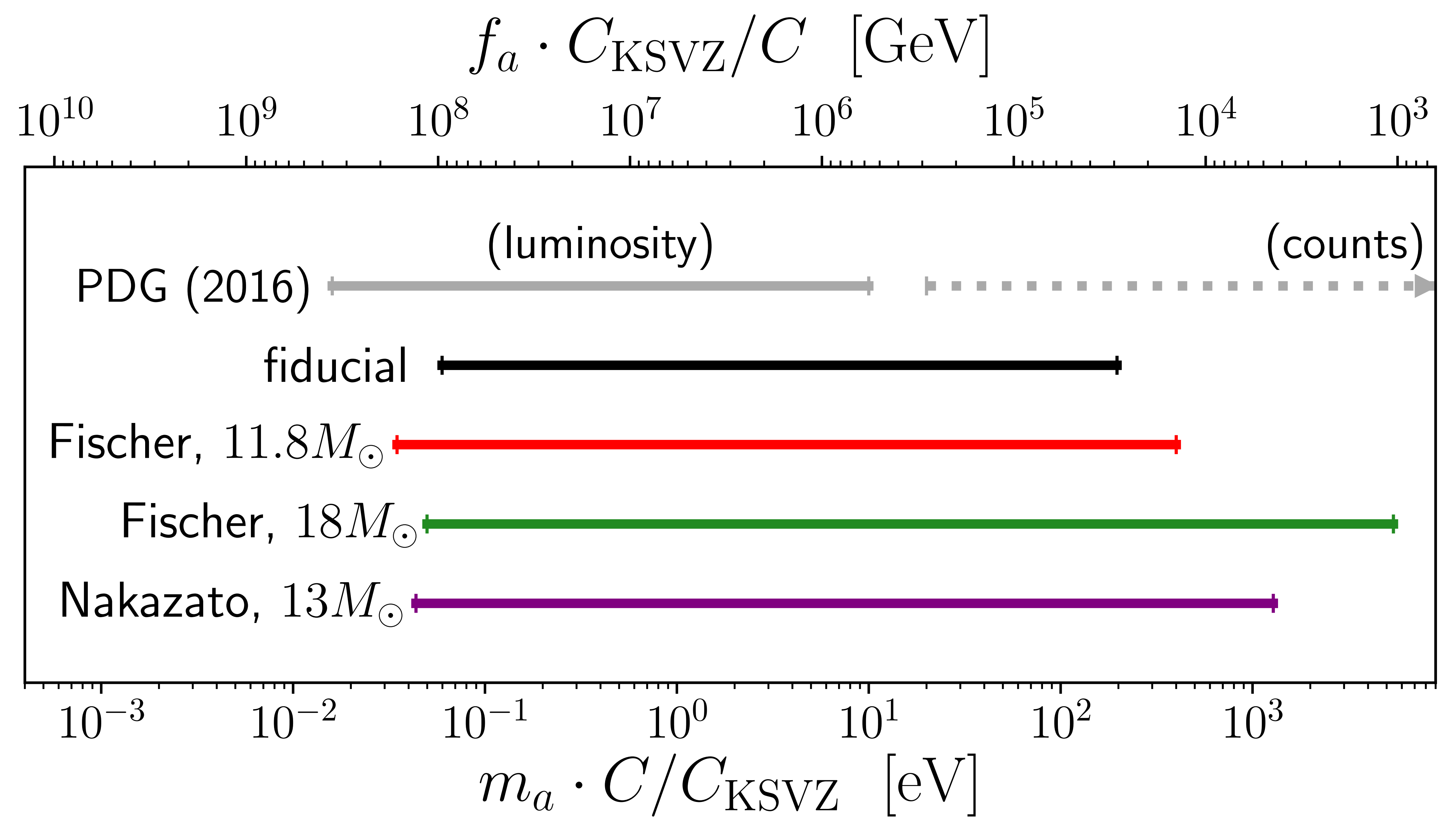
III. Results and future directions

Luminosity vs. Coupling

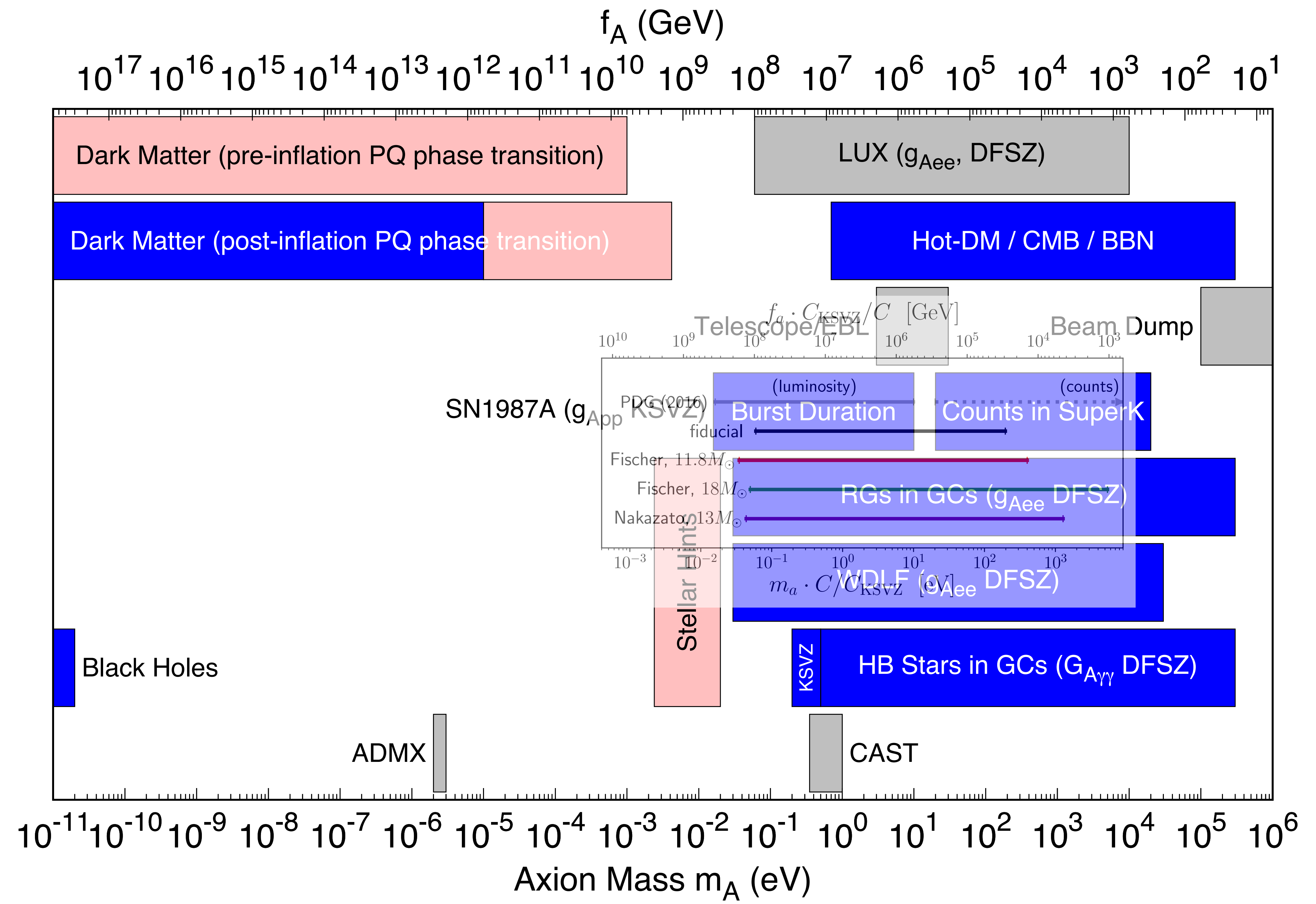




Constraints



Hadronic Axion



“hadronic axion window” seems to be ruled out

Thanks!

Outline

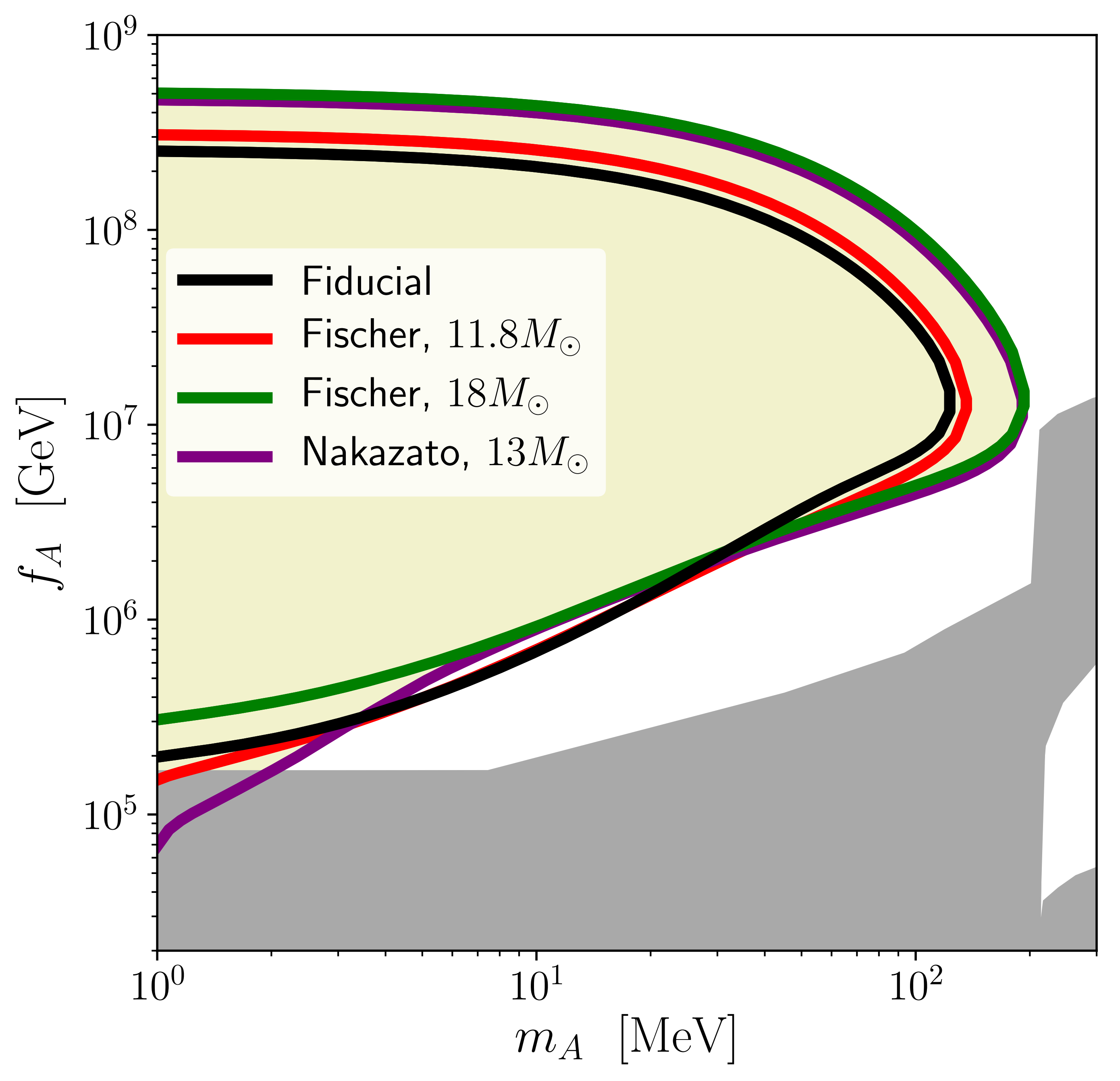
I. Kinetic Mixing and Finite Temperature

II. Luminosity: Resonance and “Trapping”

III. Results and future directions

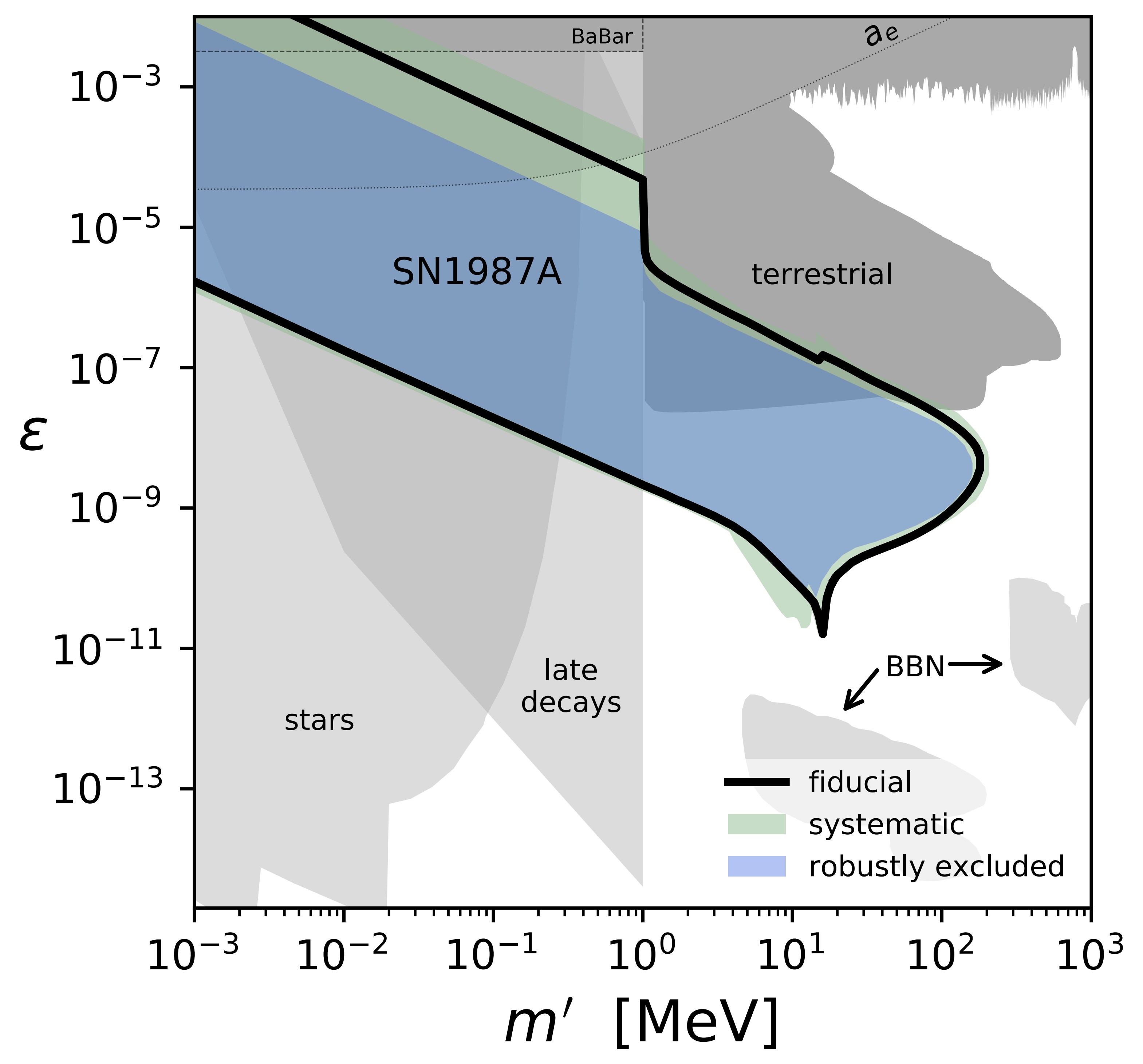
IV. Additional Results Lightning Round!

Axion-Like Particle

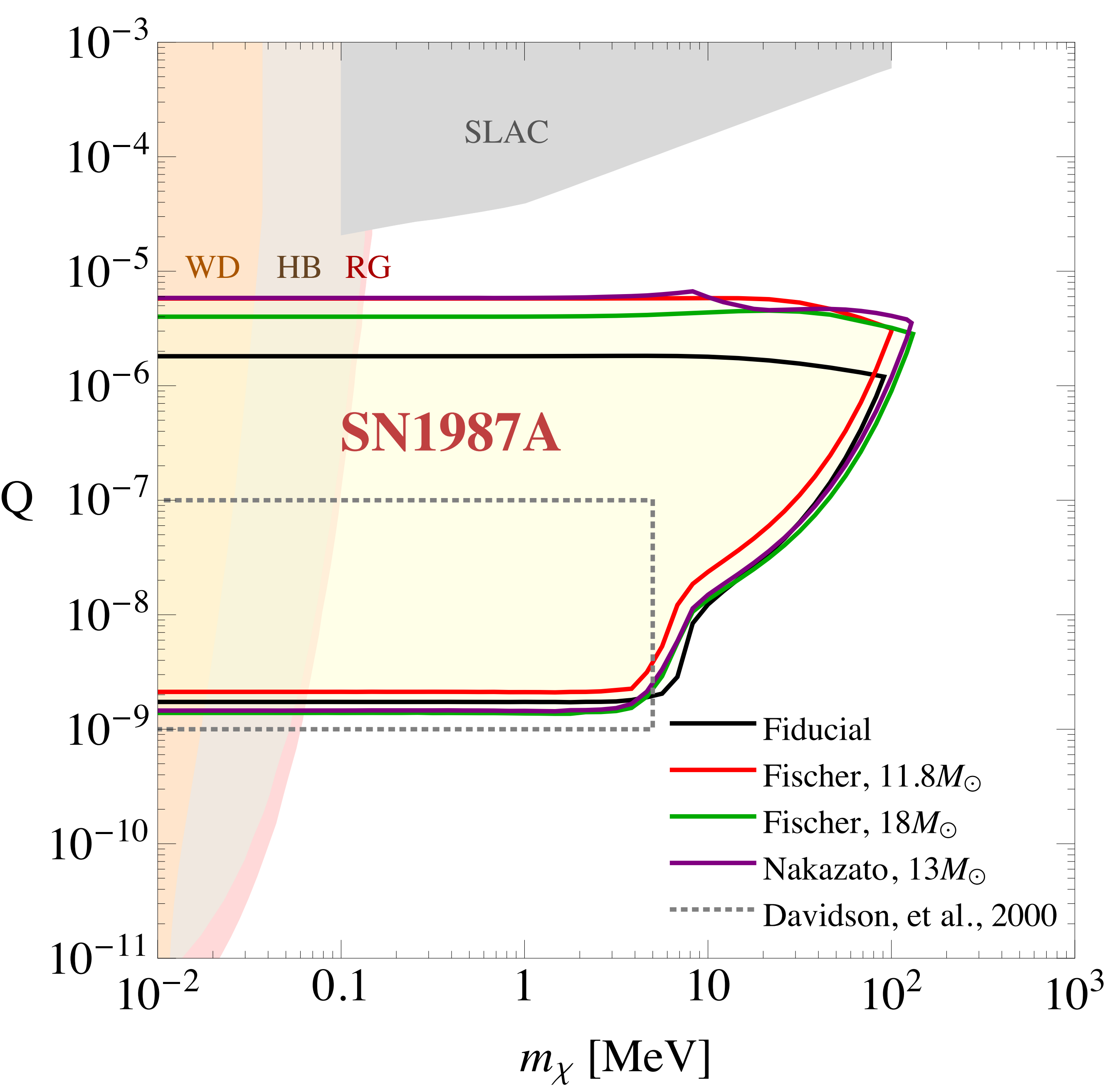


couples to all SM fermions ~ mass

Dark Photon

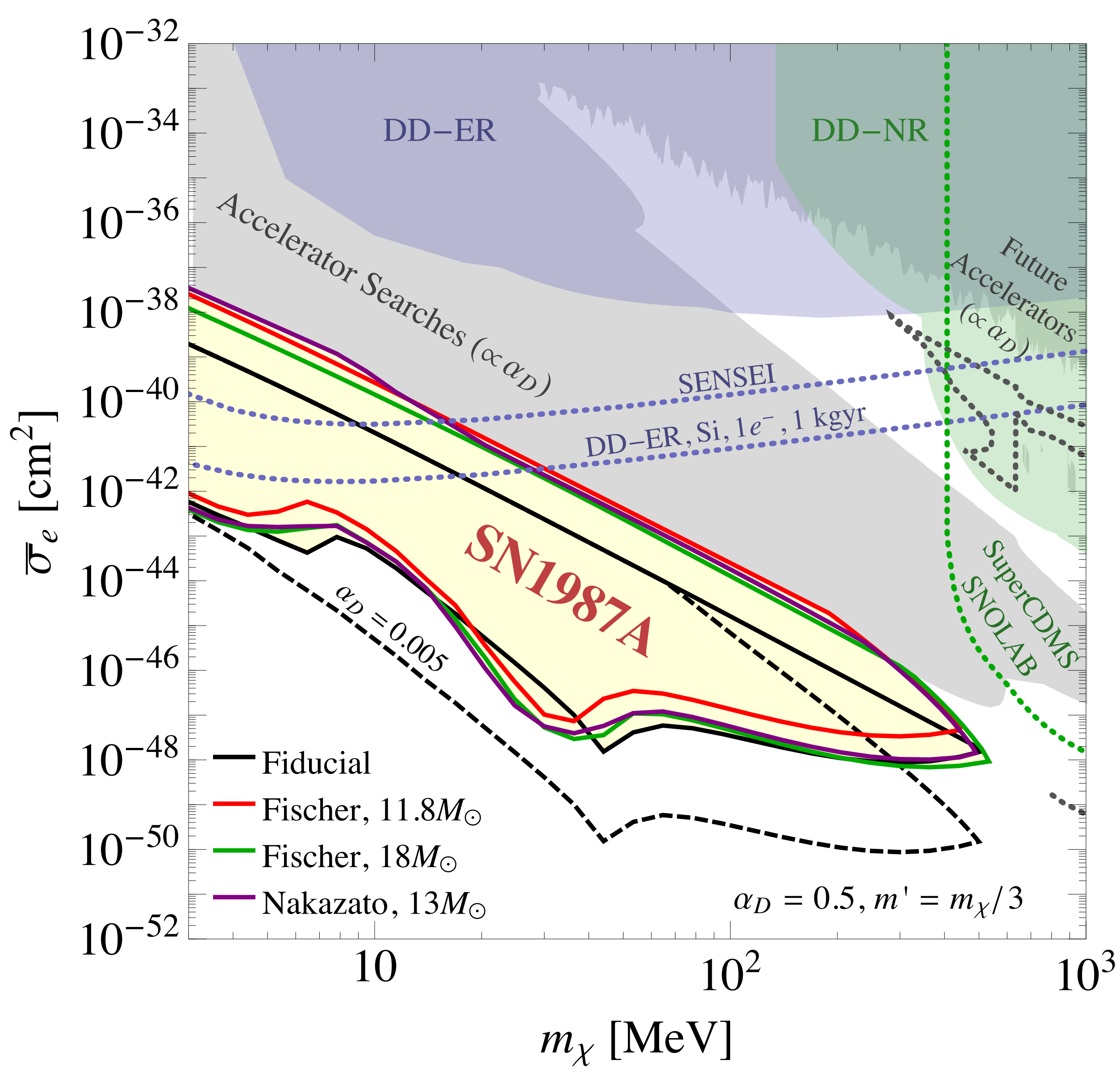

BaBar
a_e
10^{-3}
10^{-5}
10^{-7}
10^{-9}
10^{-11}
10^{-13}
ε
SN1987A
terrestrial
late decays
stars
BBN
fiducial
systematic
robustly excluded
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
m' [MeV]

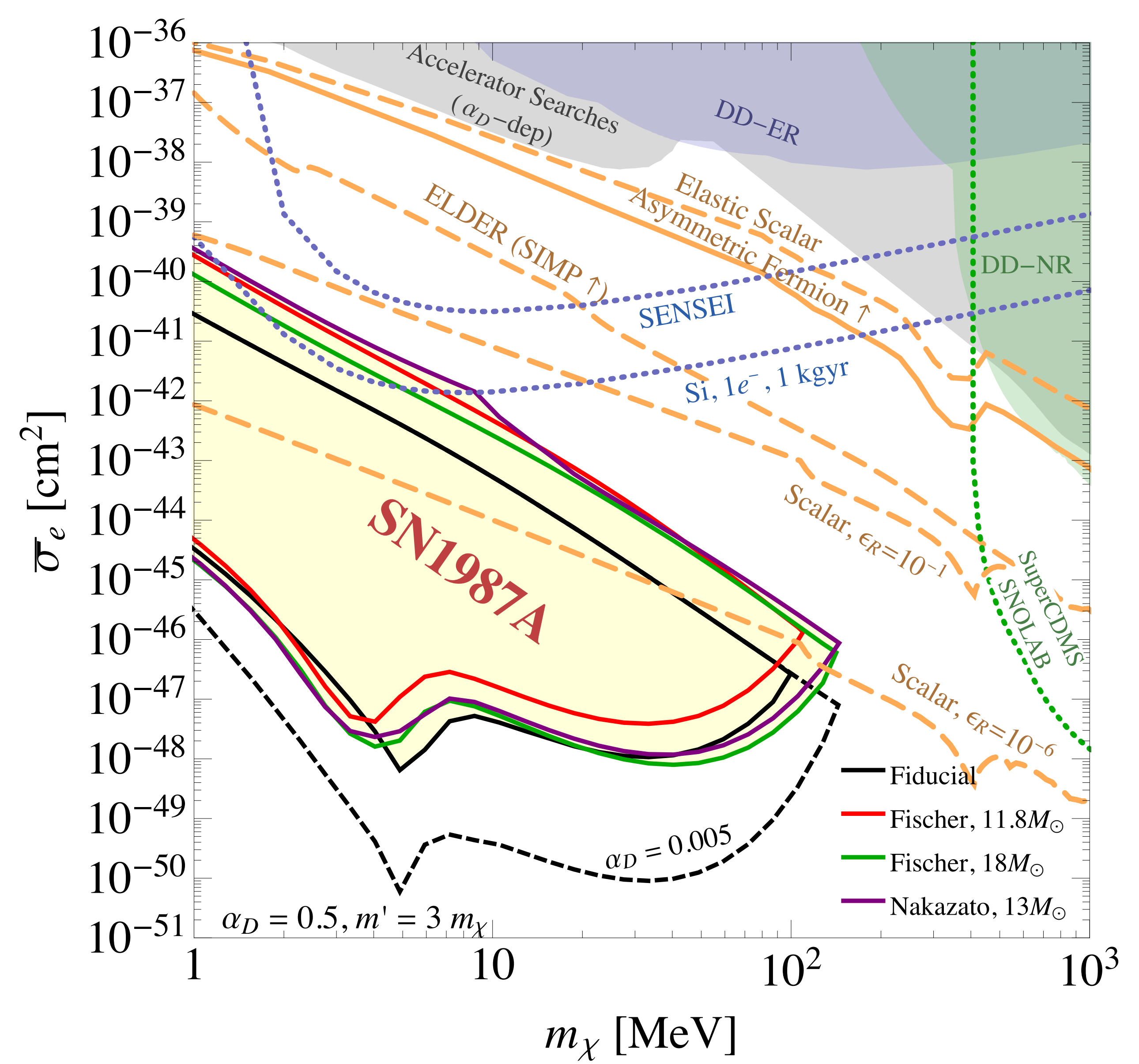
Millicharged Particle



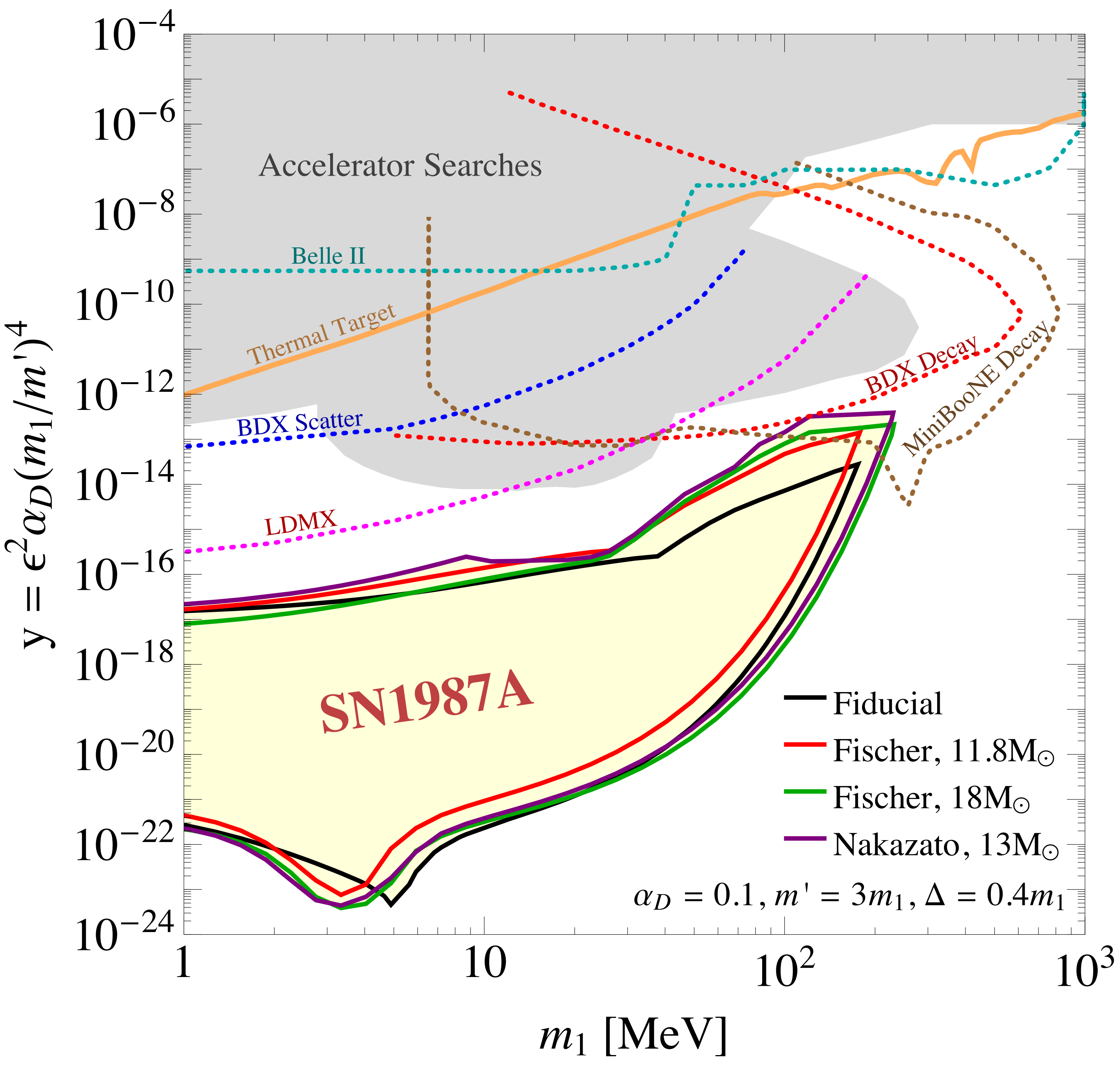
different bounds (or signals!) if it is the dark matter

Dark Photon + Dark Matter

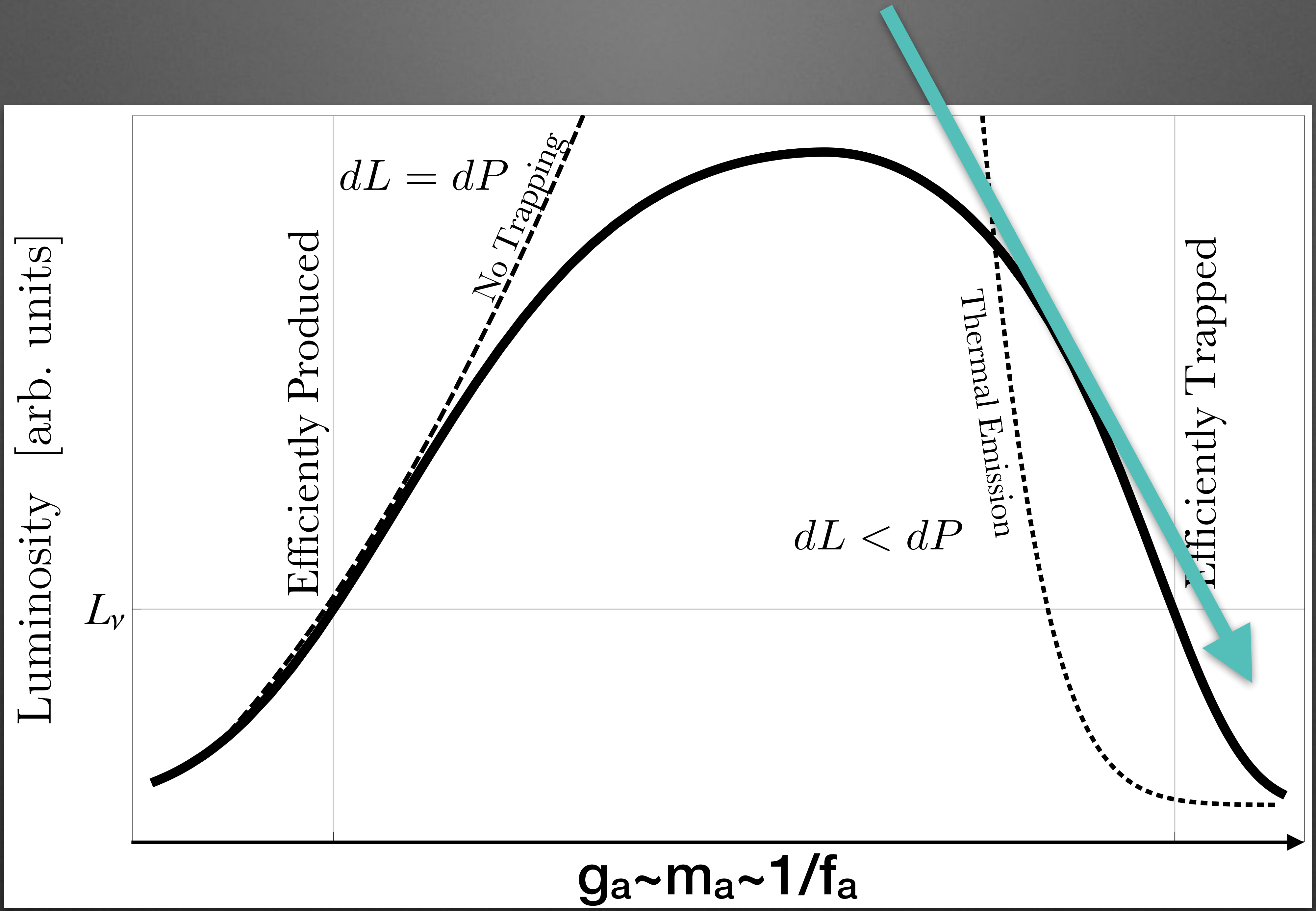




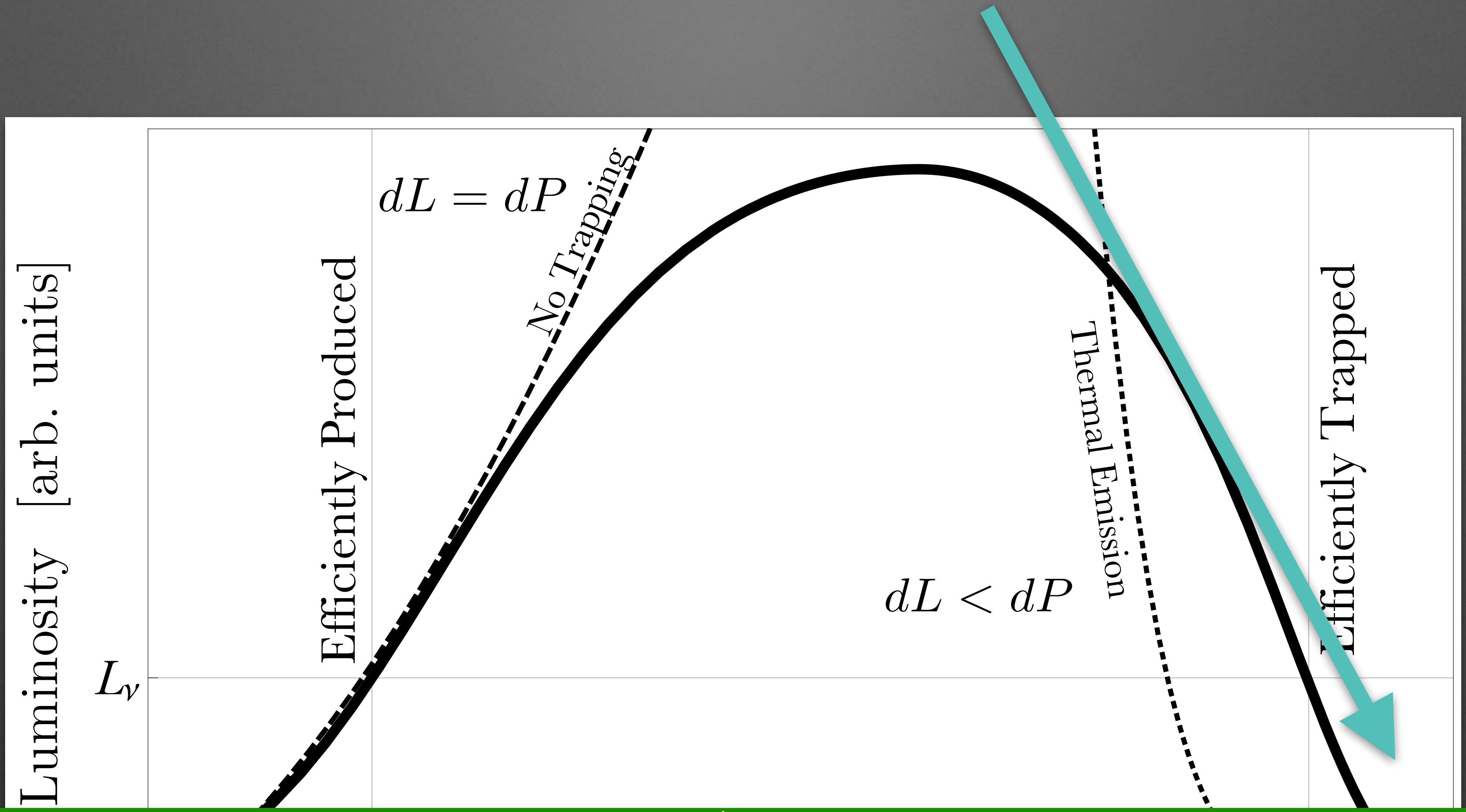
Inelastic Dark Matter



A note on (very) high mixing

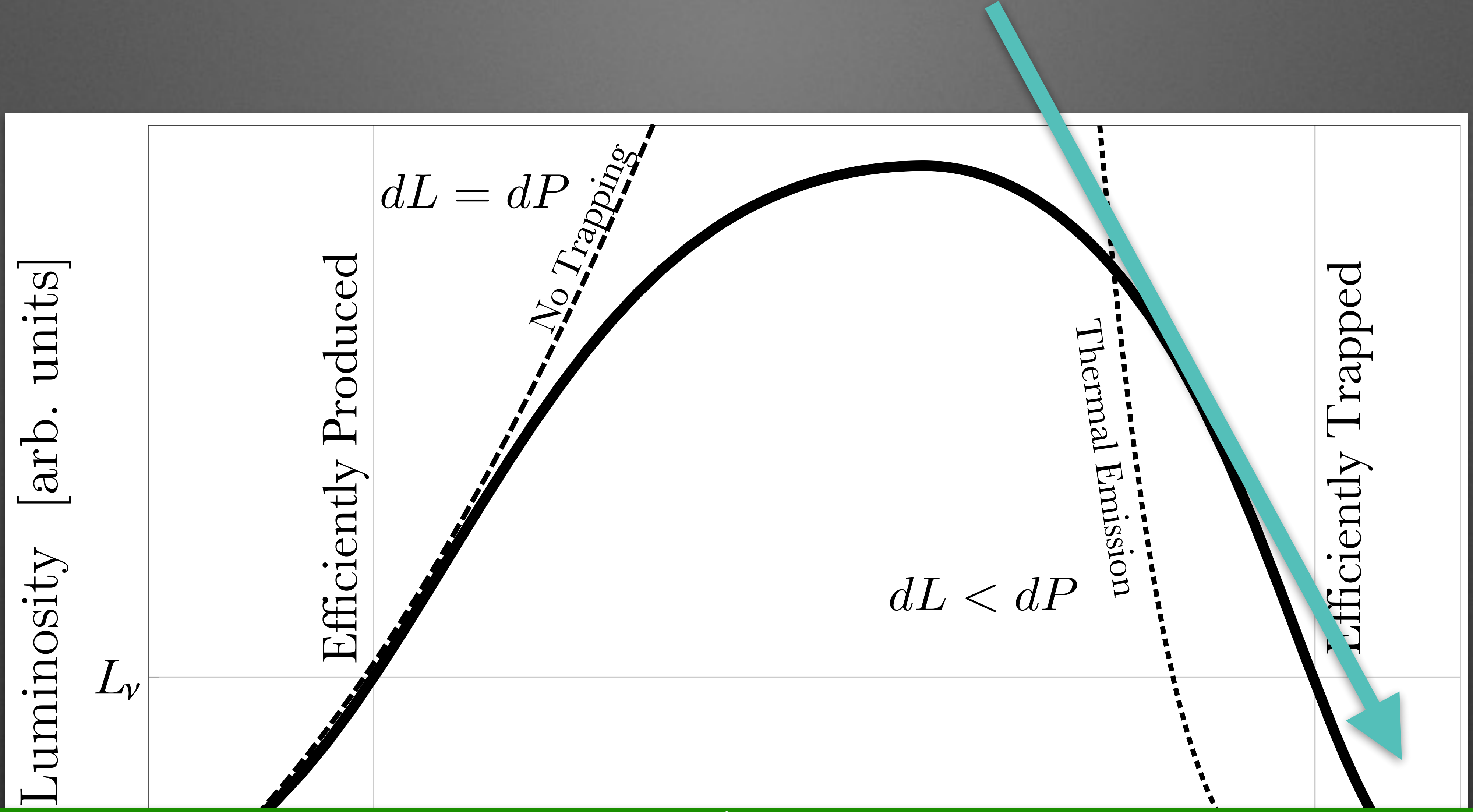


A note on (very) high mixing



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

A note on (very) high mixing



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