Supernova Bounds on Dark Sectors

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1611.03864 (and ongoing)
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Big Picture

- We have passed through the electroweak scale, completing the Standard Model
- Many deep, as yet unanswered particle physics questions *(neutrino masses? nature of the dark matter/existence of a nonminimal dark sector? inflation? dark energy? baryogenesis?…)* that require new ideas *(hierarchy/CC problems?…)*, new methods *(new experiments to search for DM?…)*, new measurements *(neutrino masses, couplings, cosmological history?…)*, and new computational tools *(mechanism that drives supernova explosions?…)*

This Talk: “Supernova Constraints”

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

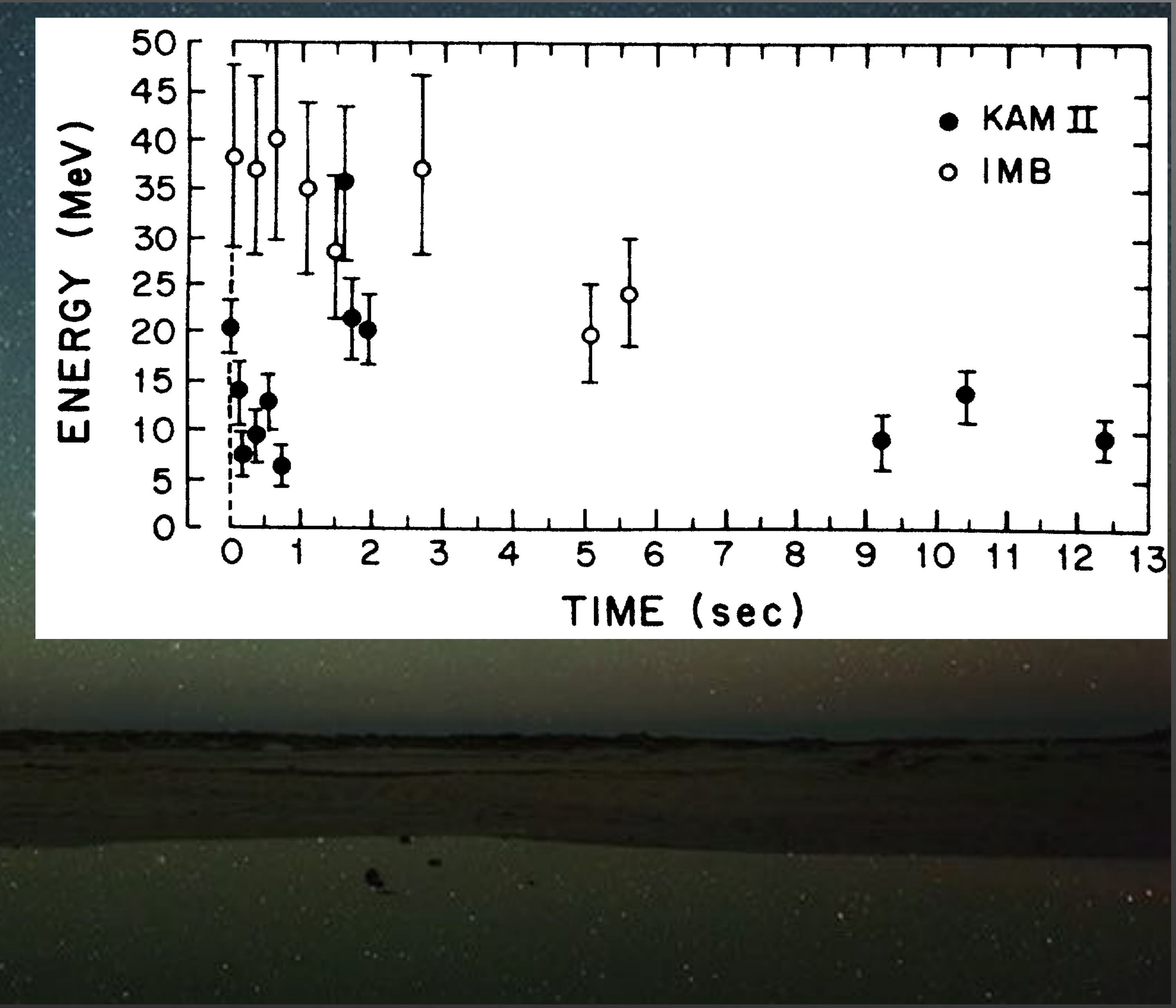
spacetelescope.org

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?



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Why Supernova 1987A?

“$L_{new} \leq L_{\nu}$”

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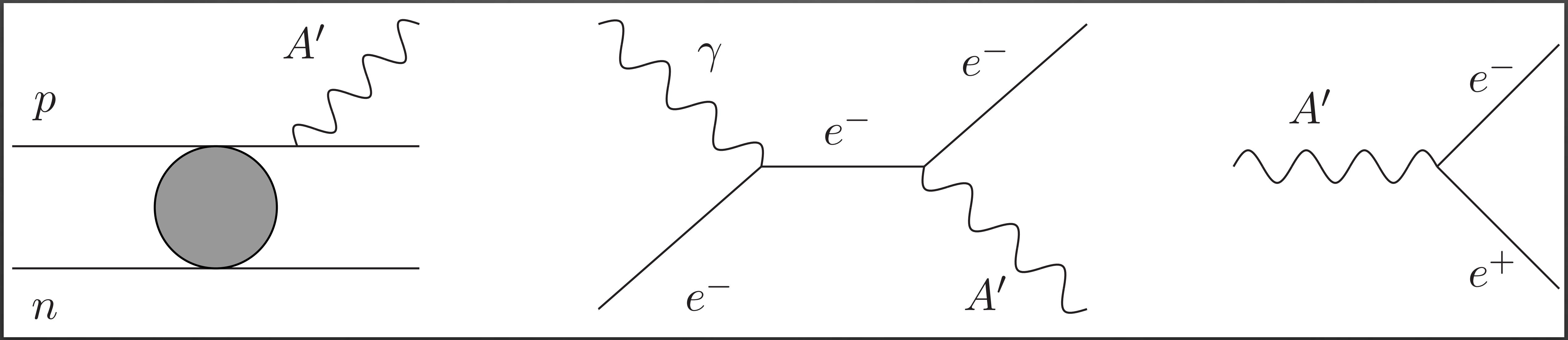
This Talk: Dark Photons

vector boson of a new U(1) gauge group, kinetically mixed with Standard Model photon



Dark photons get produced / absorbed in EM interactions (~ε^2 as often as photons)

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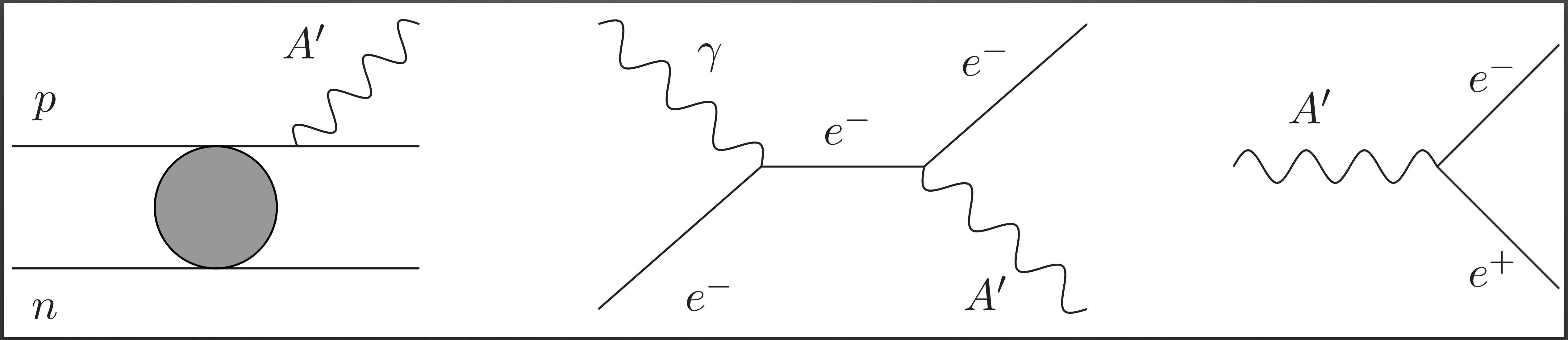


Dark photons get produced / absorbed in EM interactions (~ε^2 as often as photons)

Why Dark Photons?
“Top Down”

- The Standard Model contains three gauge groups with two interesting breaking mechanisms
- Maybe there is a similarly complex *dark sector*
- A massive dark photon appears in plausible, nontrivial extensions of the Standard Model

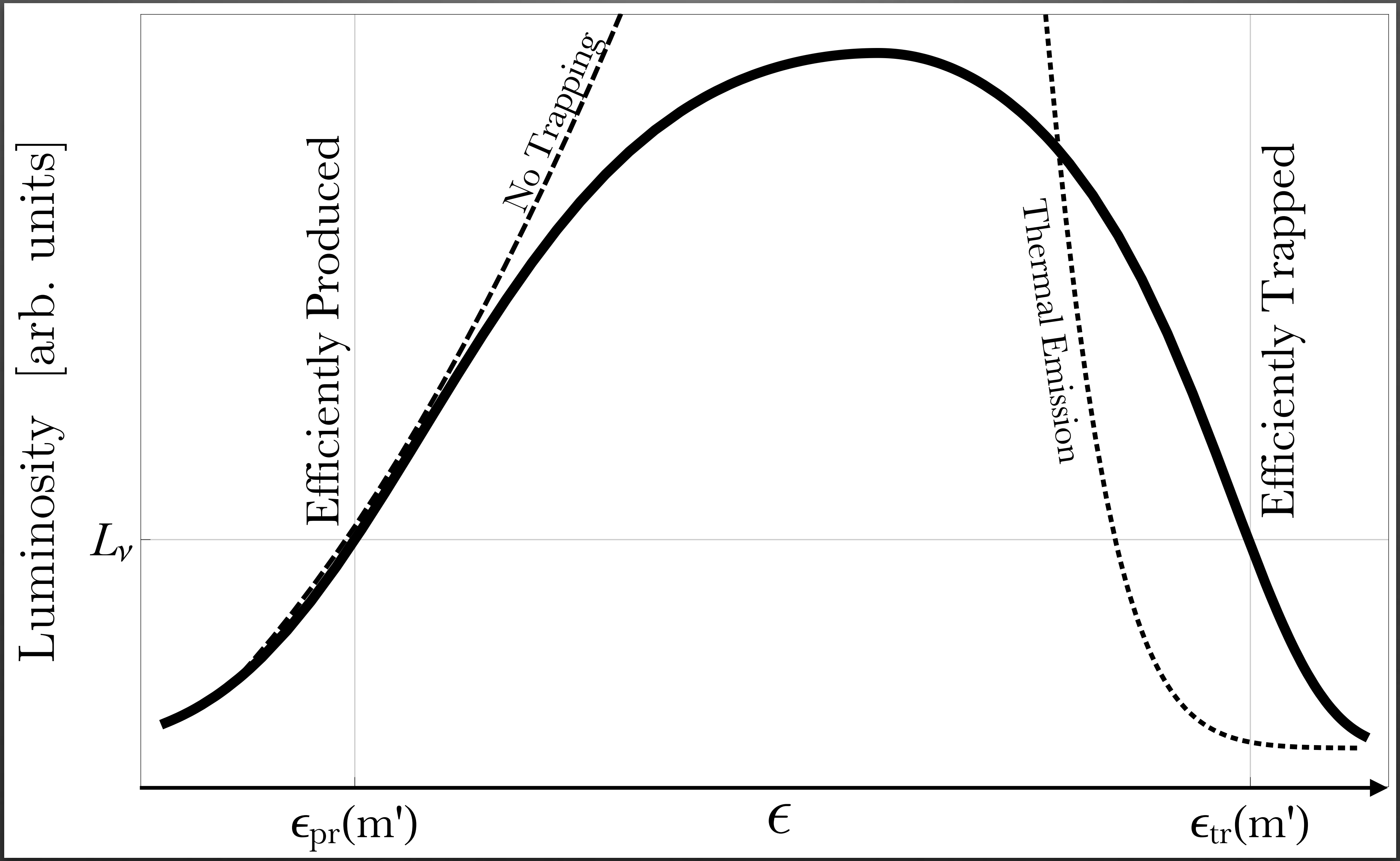
Why Dark Photons?
“Bottom Up”

- “Natural” energy scales aren’t furnishing evidence we hoped for; “energy frontiers” now seem far away
- Dark sectors can be light if weakly coupled (new lampposts?)
- How can we investigate their properties?
    - supernova = intense new particle source

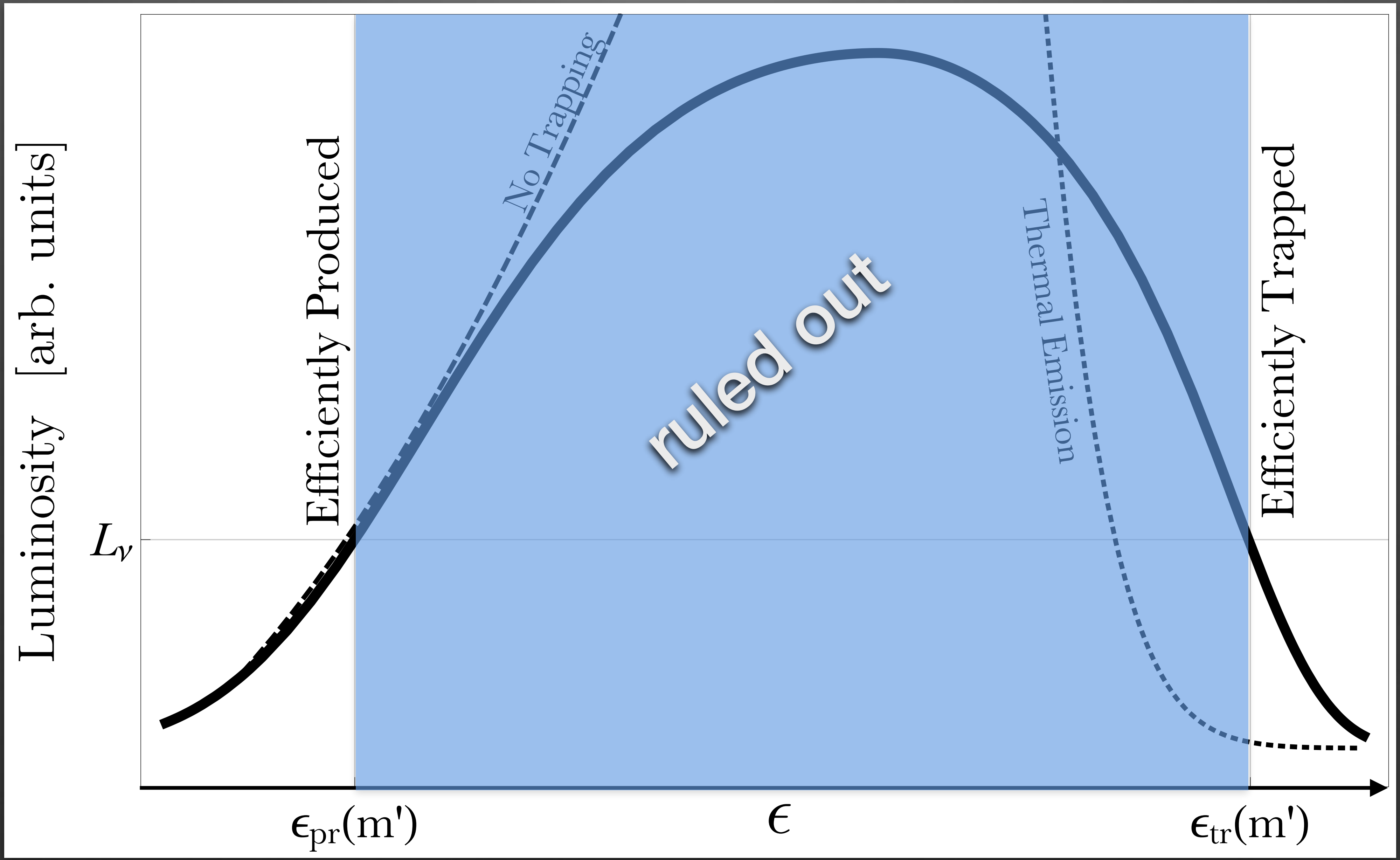
Novelties in this Work

- Finite temperature effects on dark photon mixing:
  - resonance emission at low mixing
  - decoupling behavior for low masses
- Thermal spectrum (blackbody emission) at large mixing angle underestimates the true emission
- First attempt to understand systematic uncertainties by varying progenitor profile

Luminosity vs. mixing angle



Luminosity vs. mixing angle



Outline

I. Kinetic Mixing and Finite Temperature

II. Luminosity: Resonance and “Trapping”

III. Results and future directions

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II. Luminosity: Resonance and “Trapping”

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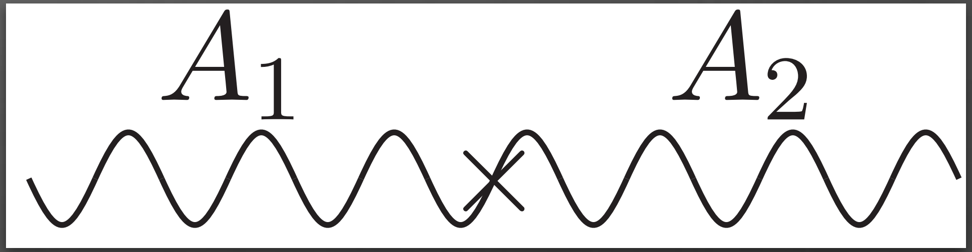
Kinetic Mixing

gauge invariant product of field strengths

$$\mathcal{L} \supset \epsilon F_{1\mu\nu} F_2^{\mu\nu}/2 \Longleftrightarrow$$



becomes $\mathcal{L} \supset \epsilon J_\mu^{\mathrm{SM}} A'^{\mu}$

after diagonalizing gauge kinetic terms

“Plasmas Give Photon a Mass”

high density of charge carriers modifies the SM photon dispersion relation:

$$\omega^2 = k^2 + \mathrm{Re}\Pi(k^2, \omega^2, n_e) \quad K^\mu = (\omega, k)$$

at low k, Π equals the “plasma mass” ω_p

$$\lim_{k \to 0} \Pi = \omega_p^2(n_e) \simeq \frac{4\pi\alpha n_e}{E_F}$$

$$\omega_p^2(n_e) = \int \frac{4\pi\alpha\, d^3p}{(2\pi)^3 2E} \left(1 - \frac{p^2}{3E^2}\right) [f_{e^-}(E) + f_{e^+}(E)]$$

Coupling to Dark Photon

in vacuum:

$$\mathcal{L} \supset \epsilon J_\mu^{\rm SM} A'^\mu$$

Coupling to Dark Photon

in vacuum:

$$\mathcal{L} \supset \epsilon J_\mu^{\mathrm{SM}} A'^\mu$$

in plasma:

$$\mathcal{L} \supset \frac{\epsilon}{1 - \Pi/m'^2} J_\mu^{\mathrm{SM}} A'^\mu$$

Rates for A’s

dark photon rates $\propto$ SM photon rates:

$$\begin{aligned}\Gamma'_p &= \left|\frac{\epsilon}{1-\Pi/m'^2}\right|^2 \Gamma_p \\ &= \frac{\epsilon^2\Gamma_p}{(1-\mathrm{Re}\Pi/m'^2)^2+(\mathrm{Im}\Pi/m'^2)^2}\end{aligned}$$

Rates for A's

dark photon rates ∝ SM photon rates:

$$\Gamma'_p = \left|\frac{\epsilon}{1-\Pi/m'^2}\right|^2 \Gamma_p$$

$$= \frac{\epsilon^2\Gamma_p}{(1-\mathrm{Re}\Pi/m'^2)^2 + (\mathrm{Im}\Pi/m'^2)^2}$$

[*resonance if $m'^2 \gg \mathrm{Im}\Pi$ and $\exists\ \omega_{res}$ with $\mathrm{Re}\Pi(\omega_{res})=m'^2$]

Photon Self-Energy

$$\mathrm{Re}\Pi = \begin{cases} \frac{3\omega_p^2}{v^2}(1-v^2)\left[\frac{1}{2v}\ln\left(\frac{1+v}{1-v}\right)-1\right] & L \\ \frac{3\omega_p^2}{2v^2}\left[1-\frac{1-v^2}{2v}\ln\left(\frac{1+v}{1-v}\right)\right] & T \end{cases}$$

($v=|k|/\omega$)

different dispersion relations for *L* and *T* modes

Photon Self-Energy

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(v=|k|/ω)

different dispersion relations for *L* and *T* modes

ImΠ ~ rate at which photon thermalizes:

$$\mathrm{Im}\Pi = \omega\left(\Gamma_{\mathrm{prod}} - \Gamma_{\mathrm{abs}}\right)$$

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I. Kinetic Mixing and Finite Temperature

II. Luminosity: Resonance and “Trapping”
(low mixing) (high mixing)

III. Results and future directions

Particle Luminosity

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

Particle Luminosity

energy lost
in A’s per
unit time

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

Particle Luminosity

energy lost
in A's per
unit time

rate at which
A's are
produced

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

Particle Luminosity

energy lost
in A’s per
unit time

rate at which
A’s are
produced

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

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

Differential Luminosity

$$\frac{dL}{dV} \simeq \int d\omega \, \frac{\epsilon^2 \omega^3 v e^{-\omega/T} \Gamma_{\rm abs}(\omega, r) \, e^{-\epsilon^2 \int dr \Gamma_{\rm abs}(\omega, r)}}{\left[1 - \frac{{\rm Re}\Pi(\omega,r)}{m'^2}\right]^2 + \left[\frac{{\rm Im}\Pi(\omega,r)}{m'^2}\right]^2}$$

Differential Luminosity

(for small ε)

$$\frac{dL}{dV} \simeq \int d\omega \frac{\epsilon^2 \omega^3 v e^{-\omega/T} \Gamma_{\mathrm{abs}}(\omega, r) \overset{\sim 1}{\cancel{e^{-\epsilon^2 \int dr \Gamma_{\mathrm{abs}}(\omega,r)}}}}{\left[1 - \frac{\mathrm{Re}\Pi(\omega,r)}{m'^2}\right]^2 + \left[\frac{\mathrm{Im}\Pi(\omega,r)}{m'^2}\right]^2}$$

Differential Luminosity

(for $\mathrm{Im}\Pi_{\mathrm{res}} \ll m'^2$)

(for small ε)

$$\frac{dL}{dV} \simeq \Delta\omega_{\mathrm{res}} \frac{\epsilon^2 \omega^3 v e^{-\omega/T} \Gamma_{\mathrm{abs}}(\omega, r)}{0 + [\mathrm{Im}\Pi(\omega, r)/m'^2]^2} \cancelto{\sim 1}{e^{-\epsilon^2 \cdots}}$$

Differential Luminosity

(for $\mathrm{Im}\Pi_{\mathrm{res}} << m'^2$) (for small ε)

~1

$$\frac{dL}{dV} \simeq \Delta\omega_{\mathrm{res}} \frac{\epsilon^2 \omega^3 v e^{-\omega/T} \Gamma_{\mathrm{abs}}(\omega, r)}{0 + [\mathrm{Im}\Pi(\omega, r)/m'^2]^2} \cancel{e^{-\epsilon^2 \cdots}}$$

rates cancel since ImΠ~Γ, $\Delta\omega_{\mathrm{res}}$~Γ

Differential Luminosity

(for $\mathrm{Im}\Pi_{\mathrm{res}} << m'^2$)

(for small ε)

~1

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rates cancel since $\mathrm{Im}\Pi \sim \Gamma$, $\Delta\omega_{\mathrm{res}} \sim \Gamma$

at low mixing, resonant luminosity is

$$\frac{dL_{\mathrm{res}}}{dV} \simeq \frac{\epsilon^2 m'^2 \omega_{\mathrm{res}}^3 v^3}{2\pi \left(e^{\omega/T} - 1\right)}$$

~10^{69} erg/s $(\varepsilon m'/\mathrm{MeV})^2$

~L_ν $(\varepsilon/5\times10^{-9})^2$ $(m'/\mathrm{MeV})^2$

Differential Luminosity

(for $\mathrm{Im}\Pi_{\mathrm{res}} \ll m'^2$)

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rates cancel since ImΠ~Γ, $\Delta\omega_{\mathrm{res}} \sim \Gamma$

at low mixing, resonant luminosity is

bounds not flat in ε-m' plane

$$\frac{dL_{\mathrm{res}}}{dV} \simeq \frac{\epsilon^2 m'^2 \omega_{\mathrm{res}}^3 v^3}{2\pi \left(e^{\omega/T} - 1\right)}$$

~10^{69} erg/s $(\epsilon m'/\mathrm{MeV})^2$

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Higher Mixing

at large mixing: τ is large, dP_{res} is suppressed

differential luminosity $dL = e^{-\tau}\, dP \neq dP$

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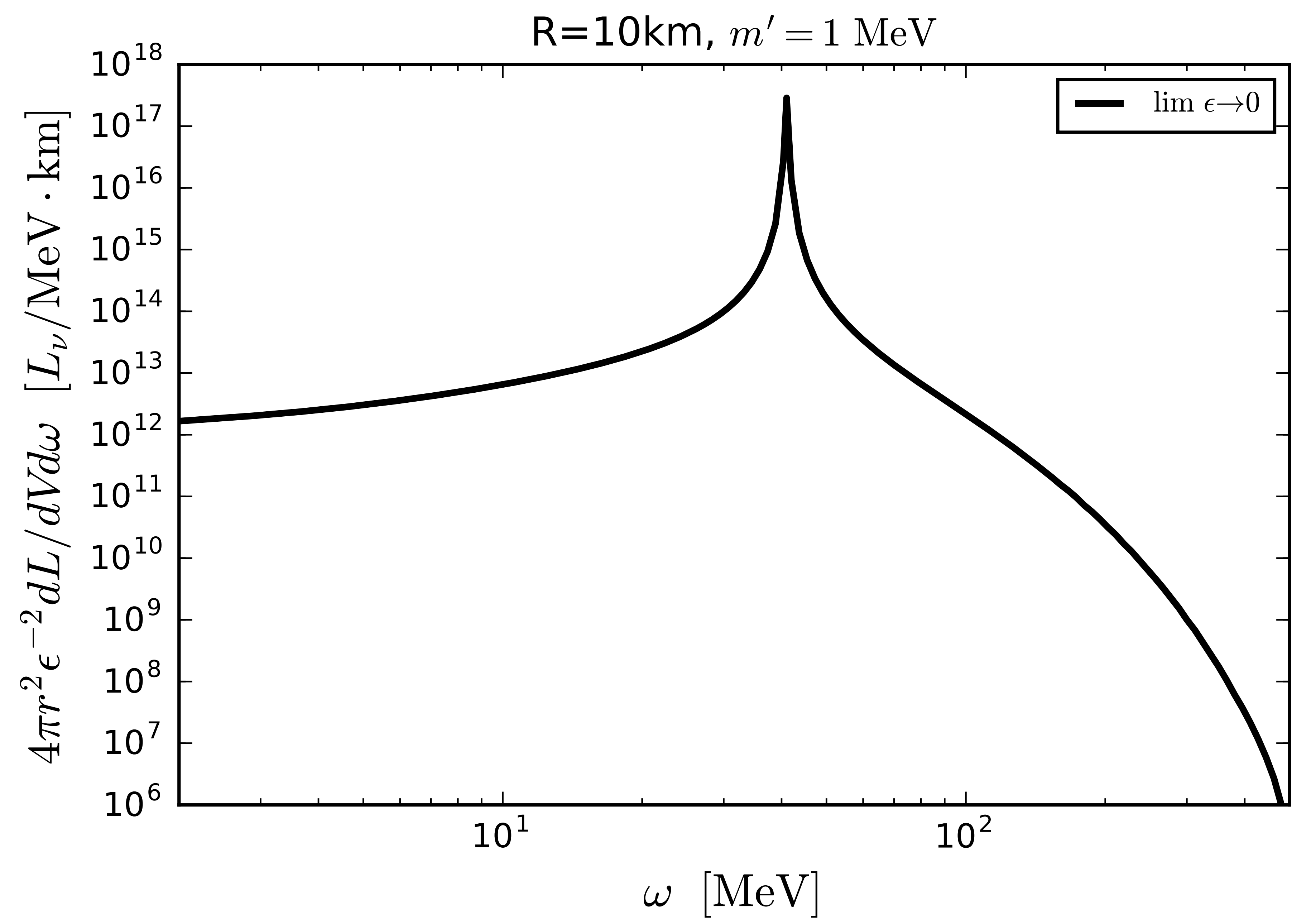
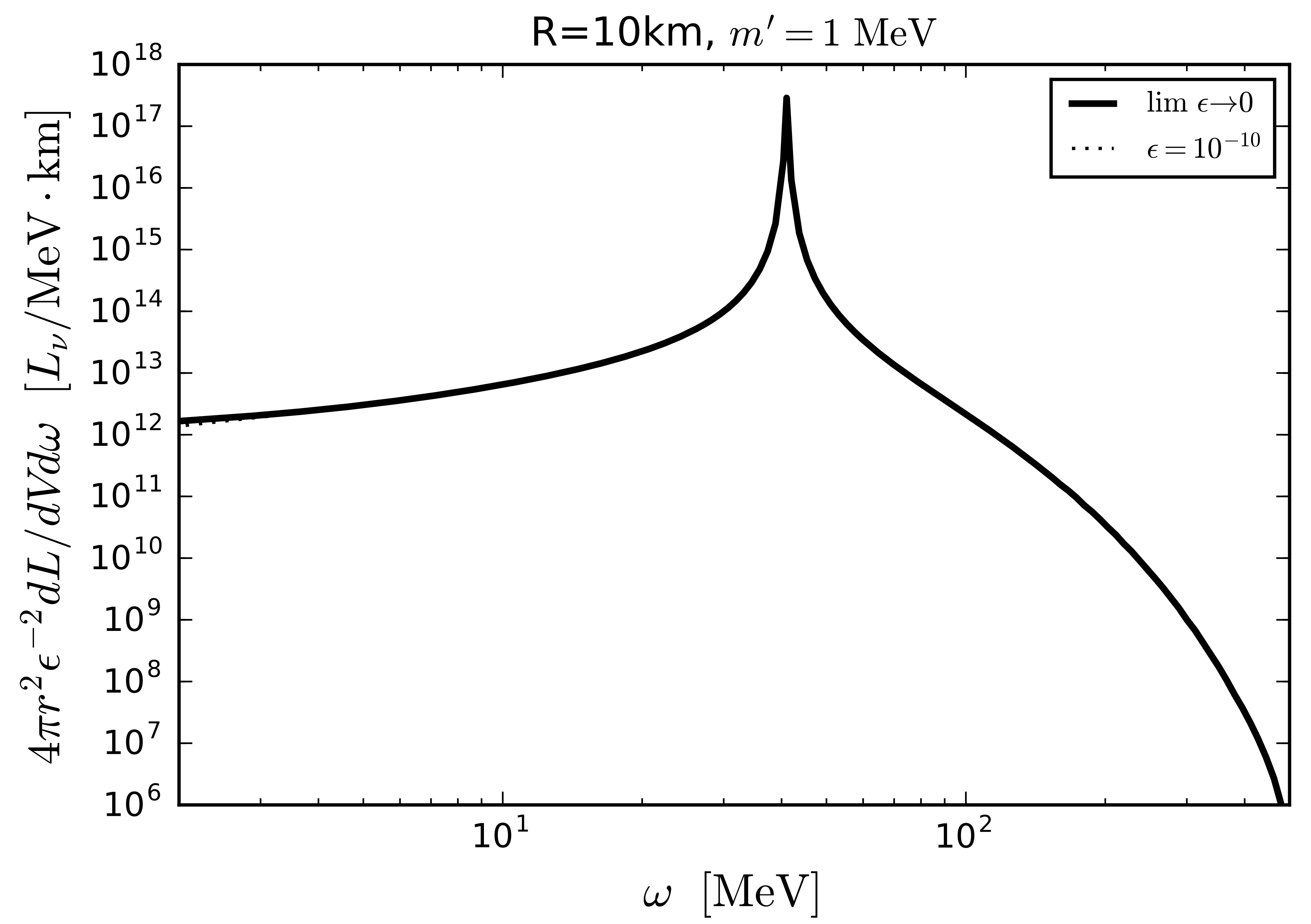
differential luminosity $dL = e^{-\tau}\, dP \neq dP$

need to know Γ for all r and ω

dL/dV/dω/ε^2


R=10km, $m' = 1$ MeV
$\lim \epsilon \to 0$
$4\pi r^2 \epsilon^{-2} dL/dVd\omega$ $[L_\nu/\mathrm{MeV}\cdot\mathrm{km}]$
10^{18}
10^{17}
10^{16}
10^{15}
10^{14}
10^{13}
10^{12}
10^{11}
10^{10}
10^{9}
10^{8}
10^{7}
10^{6}
10^{1}
10^{2}
ω [MeV]

dL/dV/dω/ε^2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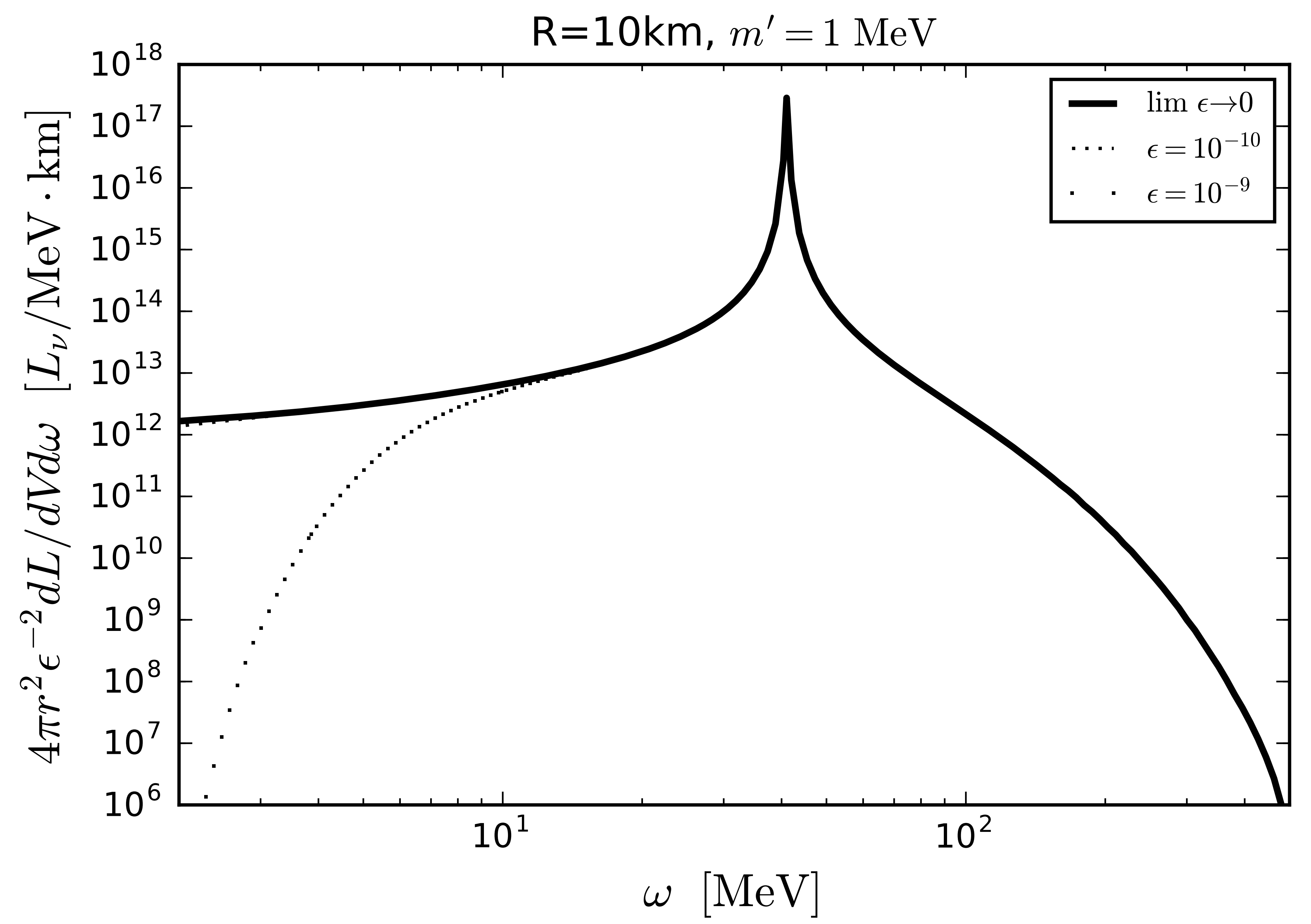
10^{9}
10^{8}
10^{7}
10^{6}
$4\pi r^2 \epsilon^{-2} dL/dVd\omega \ \ [L_\nu/\mathrm{MeV}\cdot\mathrm{km}]$
10^{1}
10^{2}
$\omega \ \ [\mathrm{MeV}]$
$\lim\ \epsilon\to 0$
$\epsilon = 10^{-10}$

dL/dV/dω/ε²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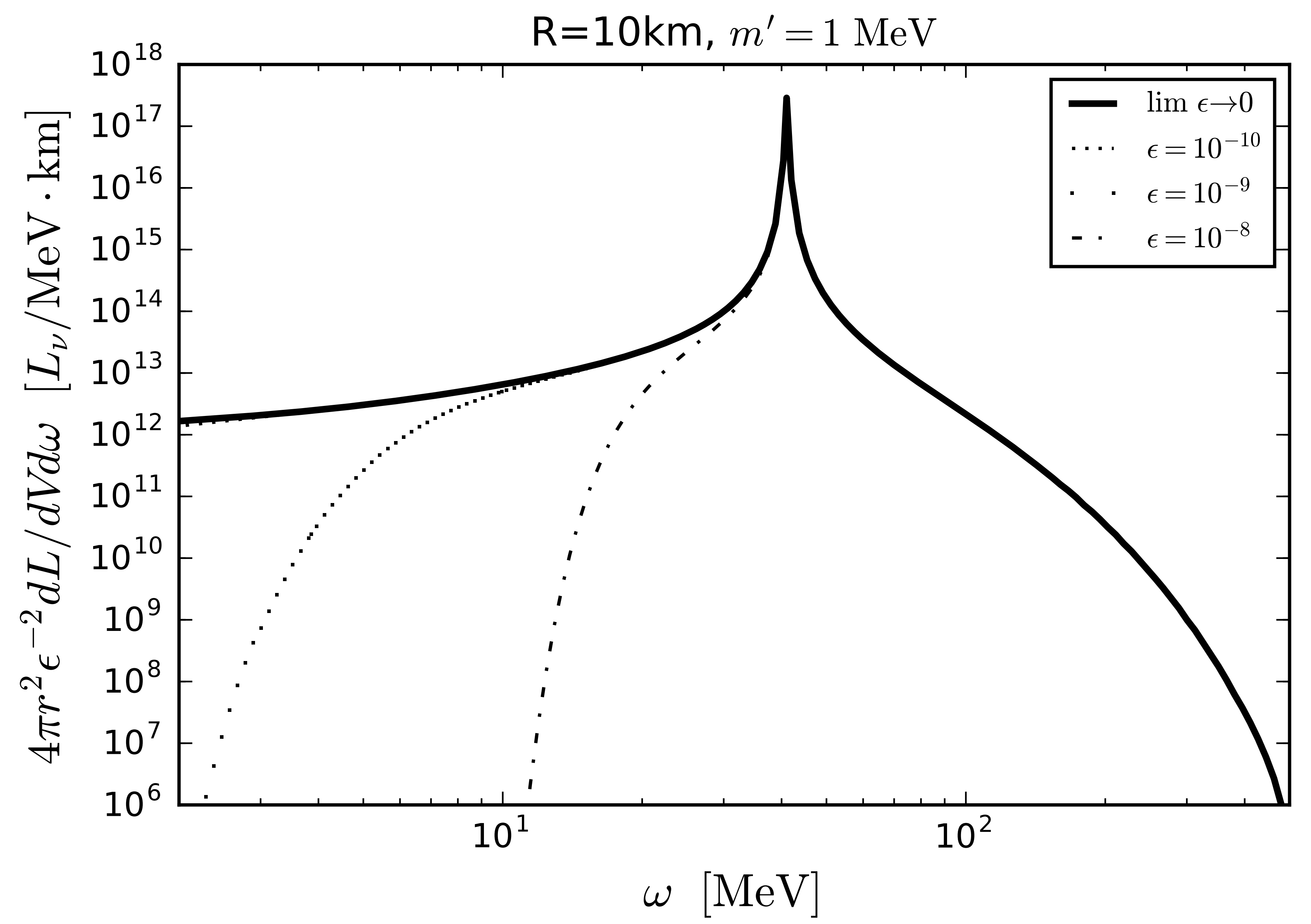
10^{7}
10^{8}
10^{9}
10^{10}
10^{11}
10^{12}
10^{13}
10^{14}
10^{15}
10^{16}
10^{17}
10^{18}
10^{1}
10^{2}
$\omega \ [\mathrm{MeV}]$
lim $\epsilon \to 0$
$\epsilon = 10^{-10}$
$\epsilon = 10^{-9}$

dL/dV/dω/ε^2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$\omega \quad [\mathrm{MeV}]$
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10^{16}
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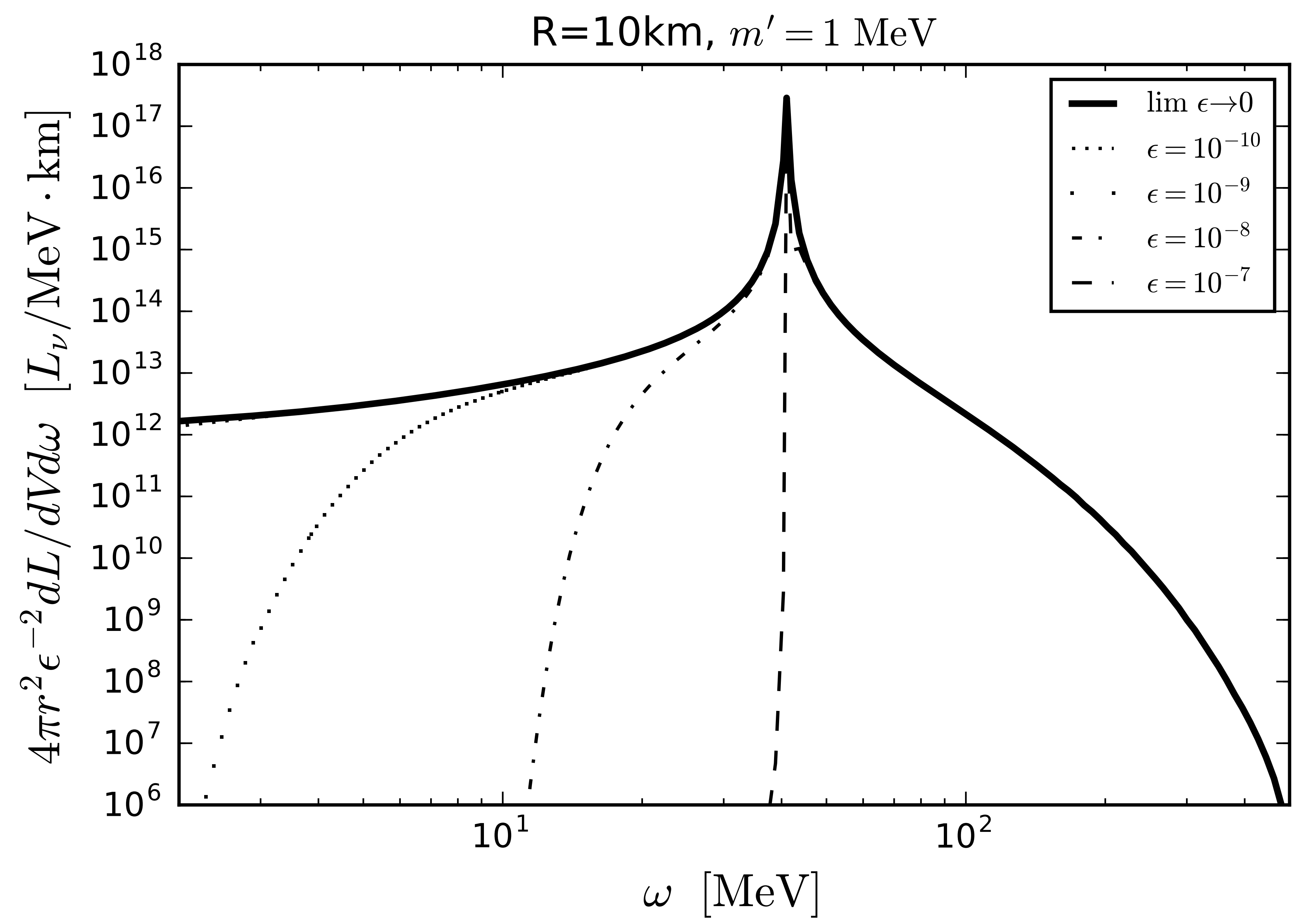
10^{8}
10^{7}
10^{6}
10^{1}
10^{2}
$\lim\ \epsilon \to 0$
$\epsilon = 10^{-10}$
$\epsilon = 10^{-9}$
$\epsilon = 10^{-8}$

dL/dV/dω/ε²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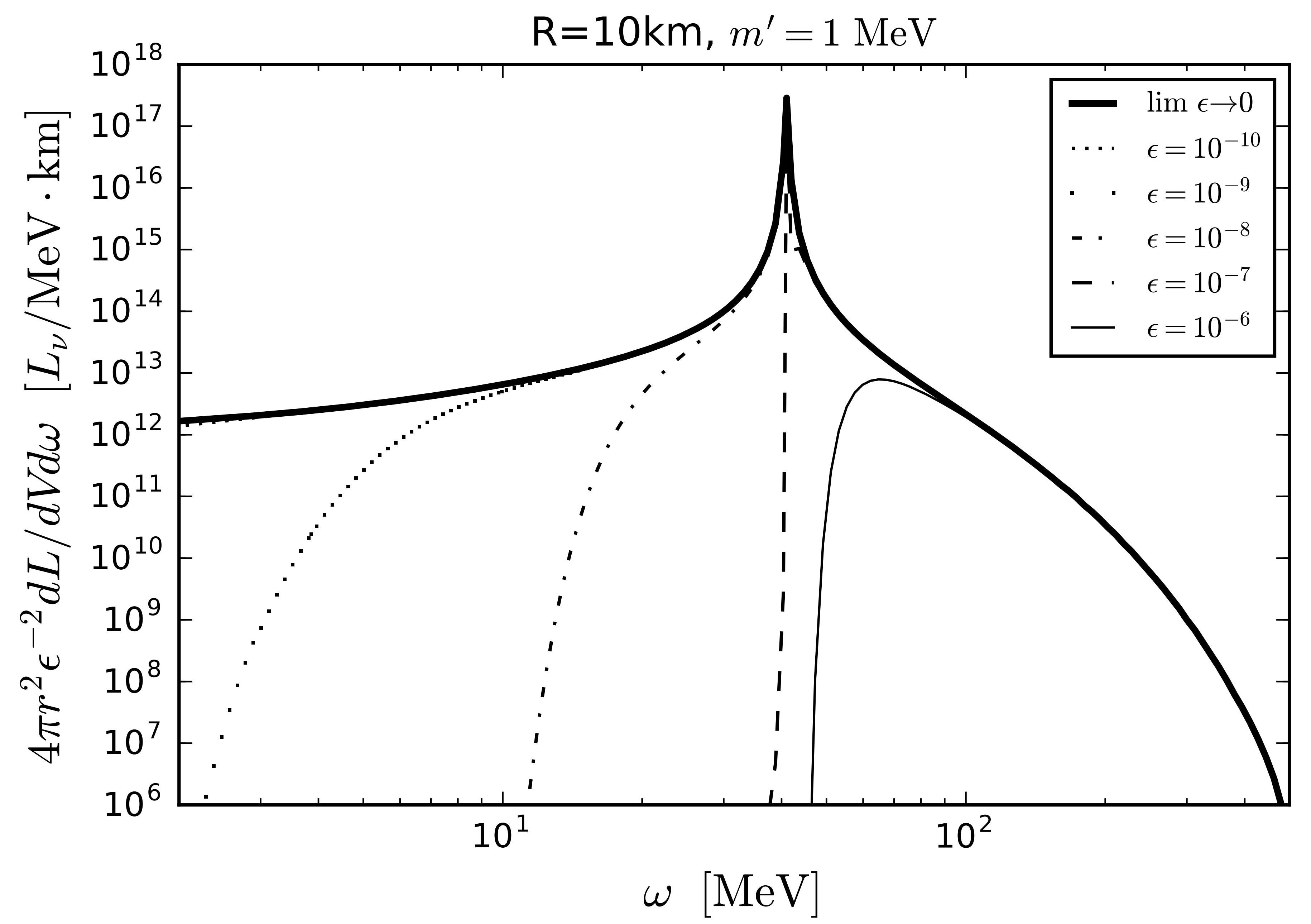
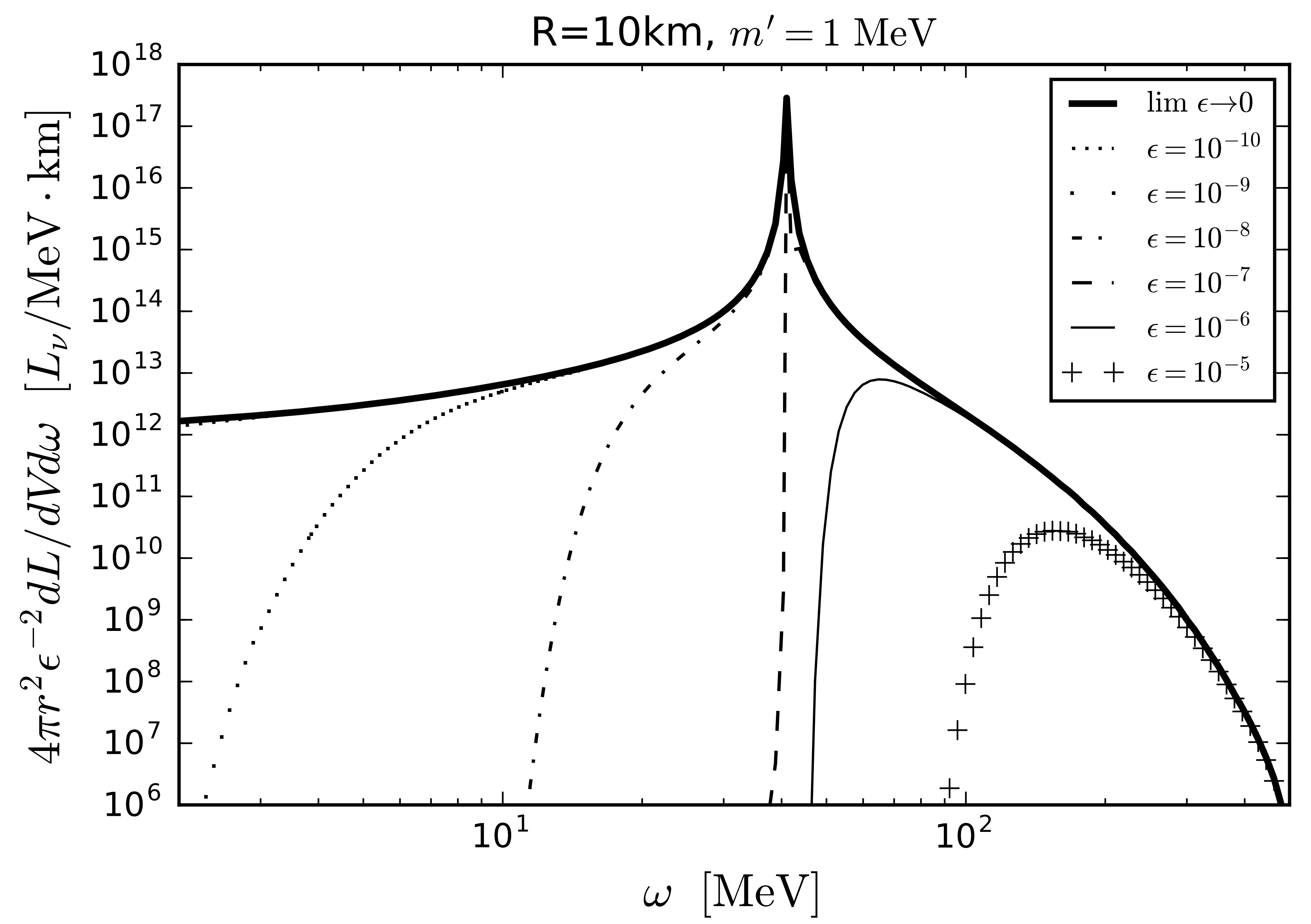
10^{6}
10^{1}
10^{2}
lim $\epsilon \to 0$
$\epsilon = 10^{-10}$
$\epsilon = 10^{-9}$
$\epsilon = 10^{-8}$
$\epsilon = 10^{-7}$

dL/dV/dω/ε^2


R=10km, $m'=1$ MeV
$4\pi r^2\epsilon^{-2}dL/dVd\omega$ $[L_\nu/\mathrm{MeV}\cdot\mathrm{km}]$
ω [MeV]
10^{6}
10^{7}
10^{8}
10^{9}
10^{10}
10^{11}
10^{12}
10^{13}
10^{14}
10^{15}
10^{16}
10^{17}
10^{18}
10^{1}
10^{2}
lim $\epsilon\to 0$
$\epsilon=10^{-10}$
$\epsilon=10^{-9}$
$\epsilon=10^{-8}$
$\epsilon=10^{-7}$
$\epsilon=10^{-6}$

dL/dV/dω/ε²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$\omega \;\; [\mathrm{MeV}]$
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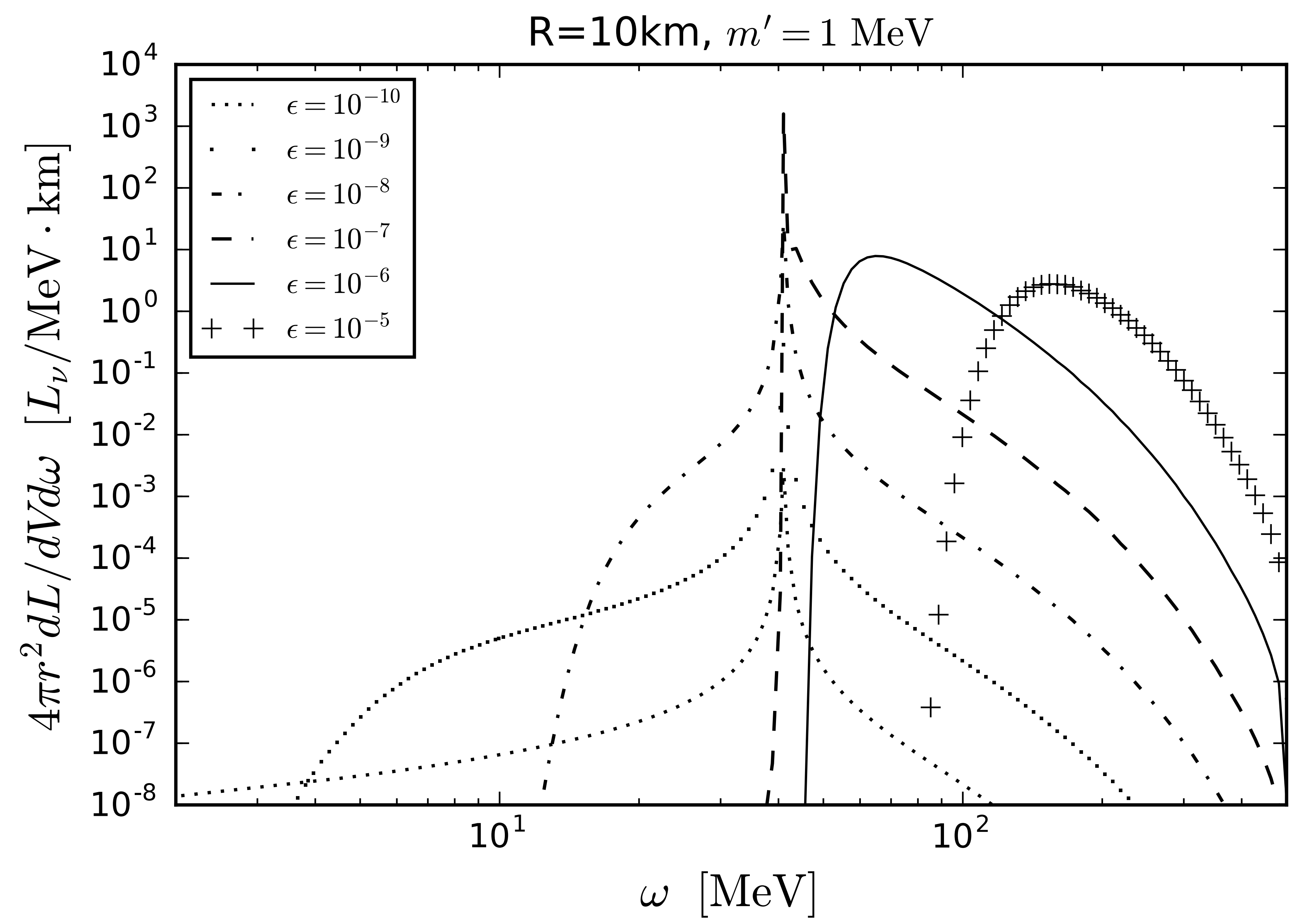
10^{7}
10^{8}
10^{9}
10^{10}
10^{11}
10^{12}
10^{13}
10^{14}
10^{15}
10^{16}
10^{17}
10^{18}
10^{1}
10^{2}
lim $\epsilon \to 0$
$\epsilon = 10^{-10}$
$\epsilon = 10^{-9}$
$\epsilon = 10^{-8}$
$\epsilon = 10^{-7}$
$\epsilon = 10^{-6}$
$\epsilon = 10^{-5}$

dL/dV/dω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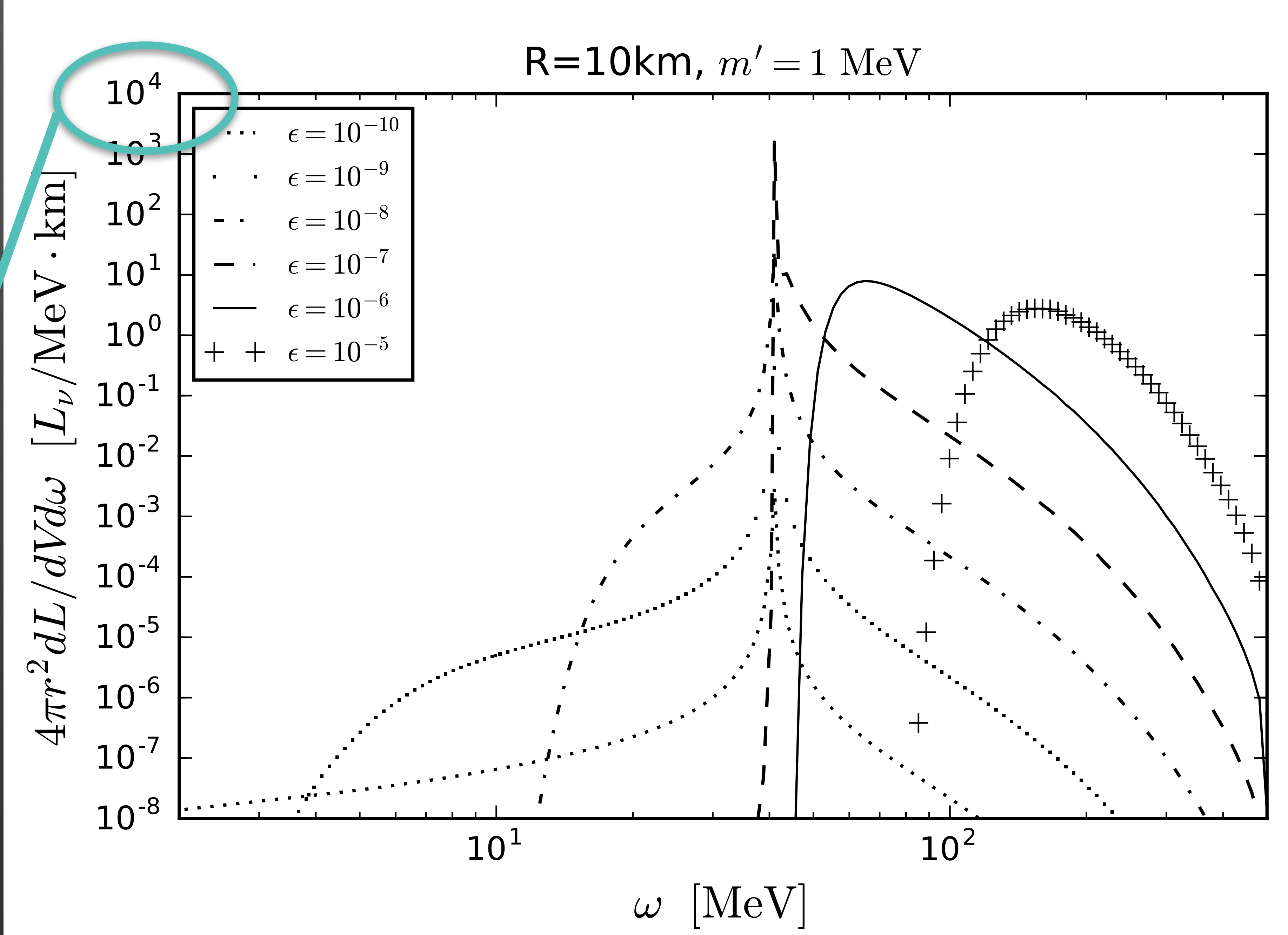
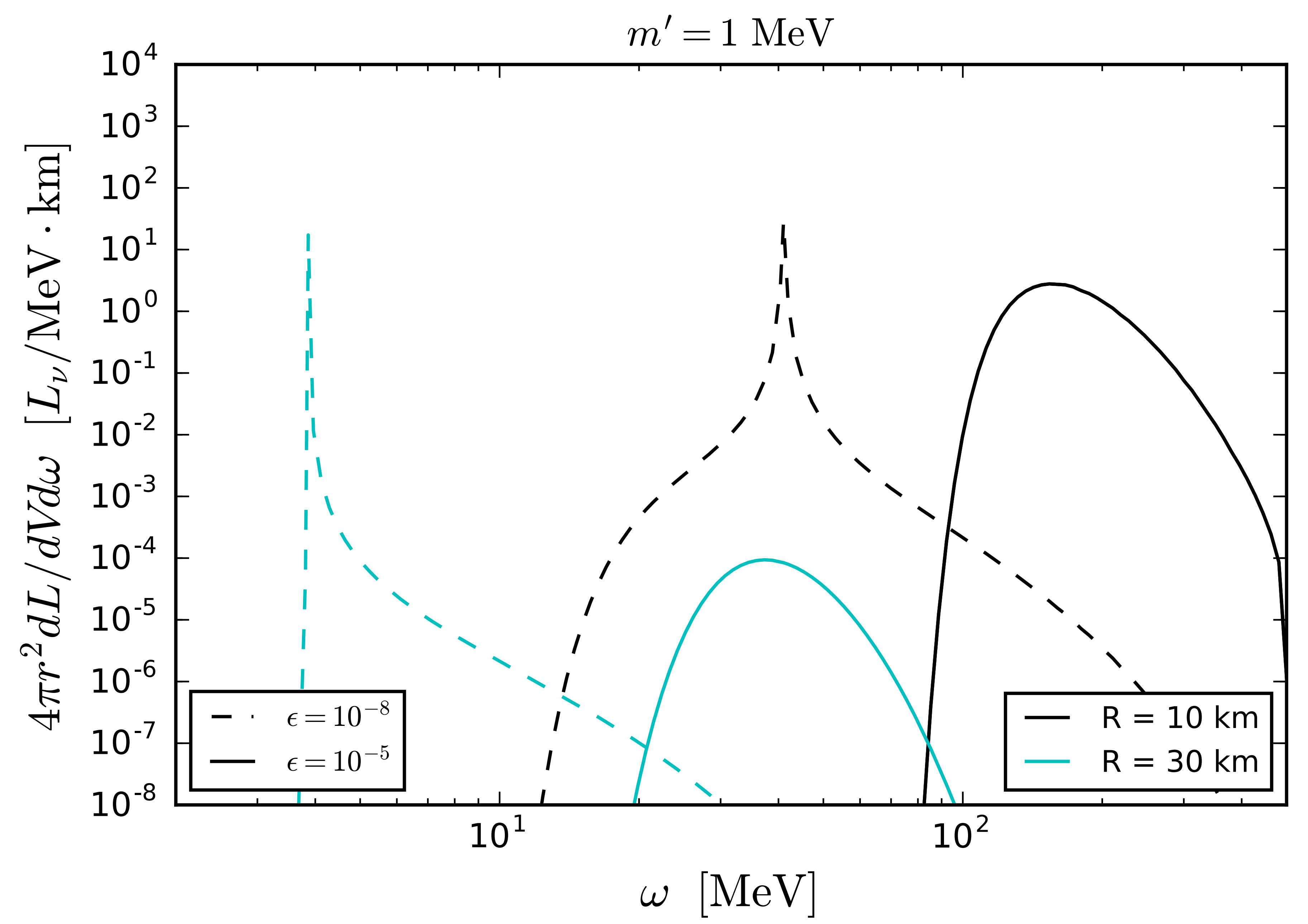
$\epsilon = 10^{-9}$
$\epsilon = 10^{-8}$
$\epsilon = 10^{-7}$
$\epsilon = 10^{-6}$
$\epsilon = 10^{-5}$
$4\pi r^2 dL/dVd\omega$ $[L_\nu/\mathrm{MeV}\cdot\mathrm{km}]$
10^4
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^1
10^2
ω [MeV]

dL/dV/dω

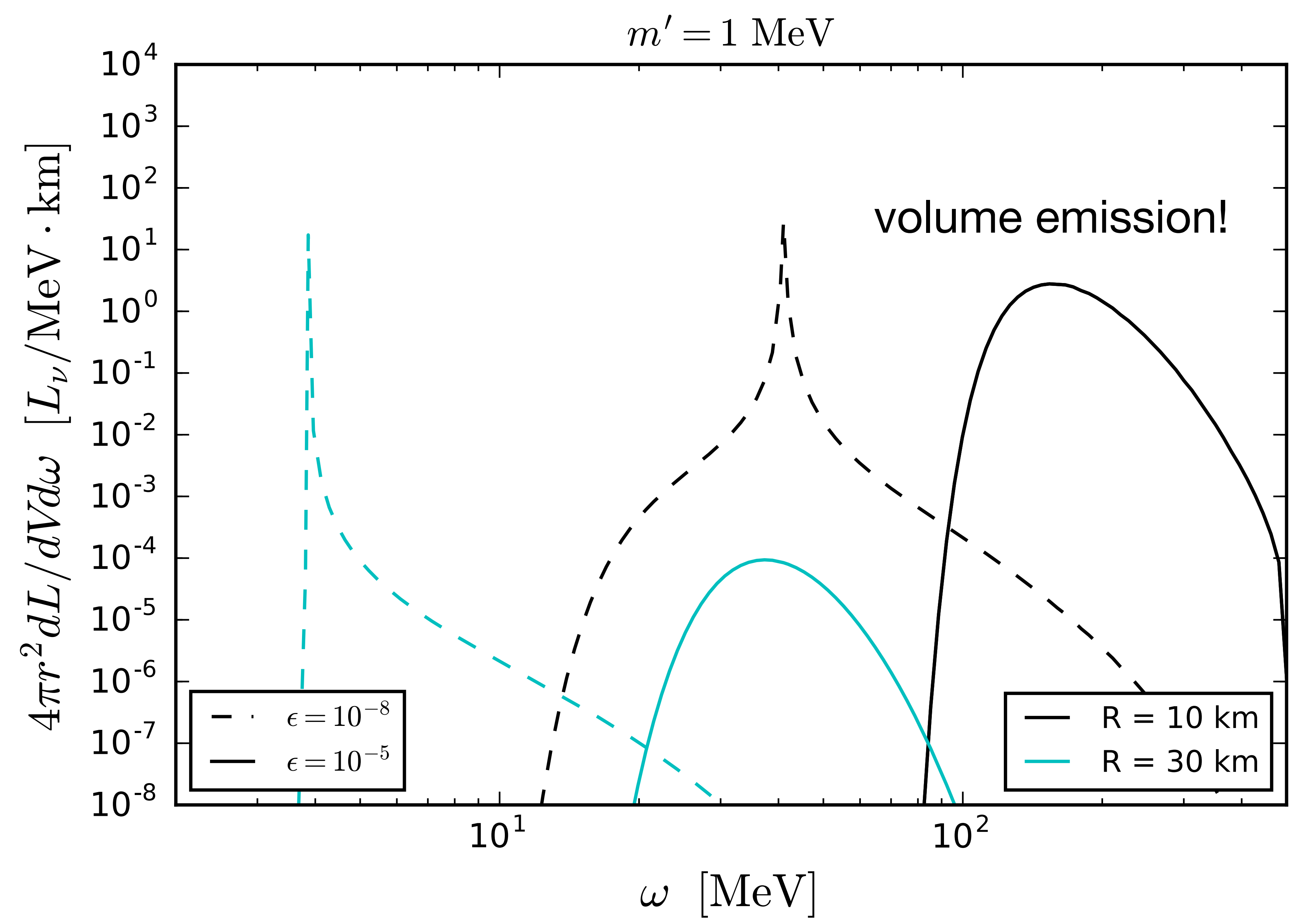


changed scale on y-axis

dL/dV/dω

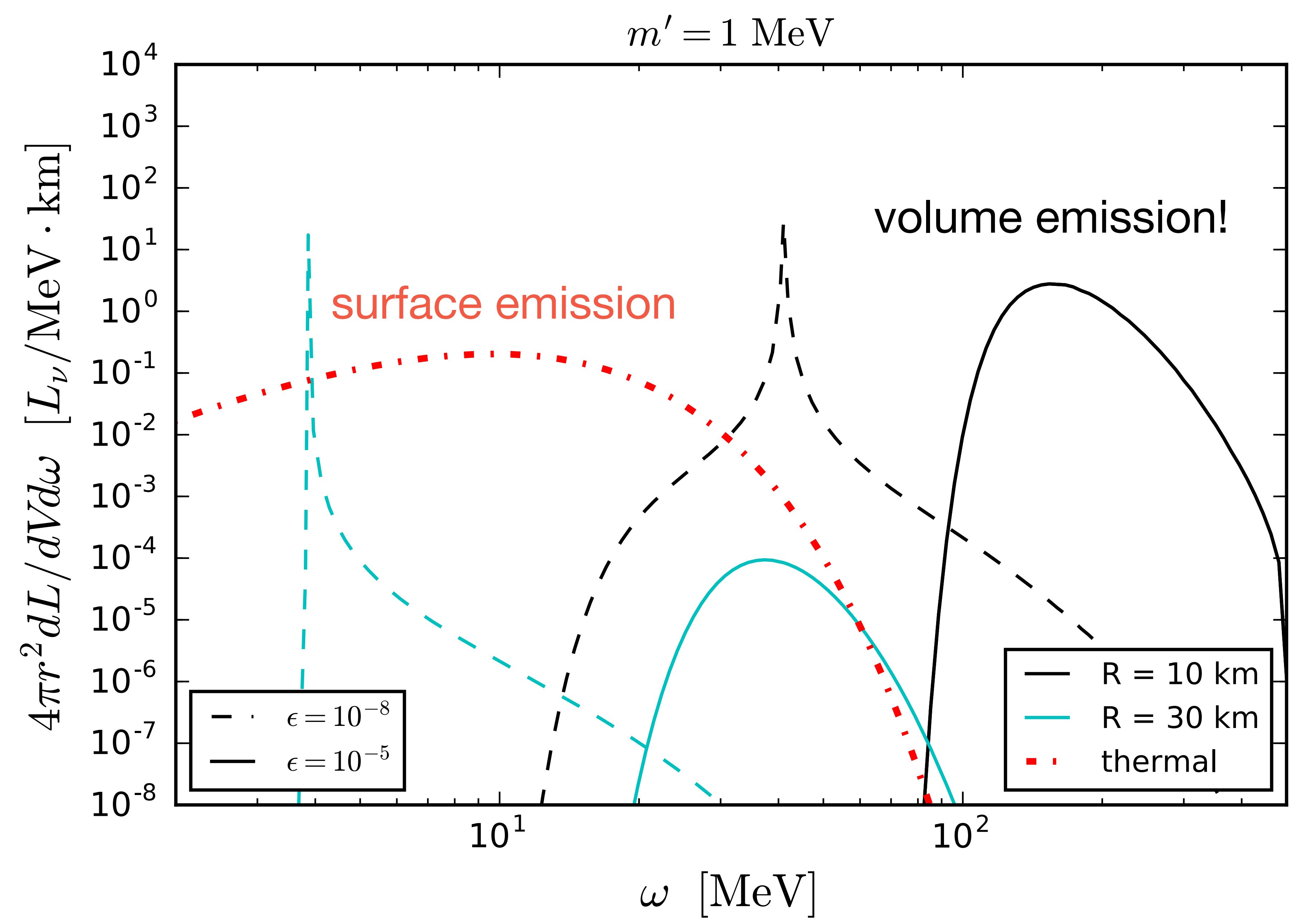

$m' = 1$ MeV
$4\pi r^2 dL/dVd\omega \quad [L_\nu/\mathrm{MeV}\cdot\mathrm{km}]$
10^{4}
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{1}
10^{2}
$\omega \quad [\mathrm{MeV}]$
$\epsilon = 10^{-8}$
$\epsilon = 10^{-5}$
R = 10 km
R = 30 km

dL/dV/dω

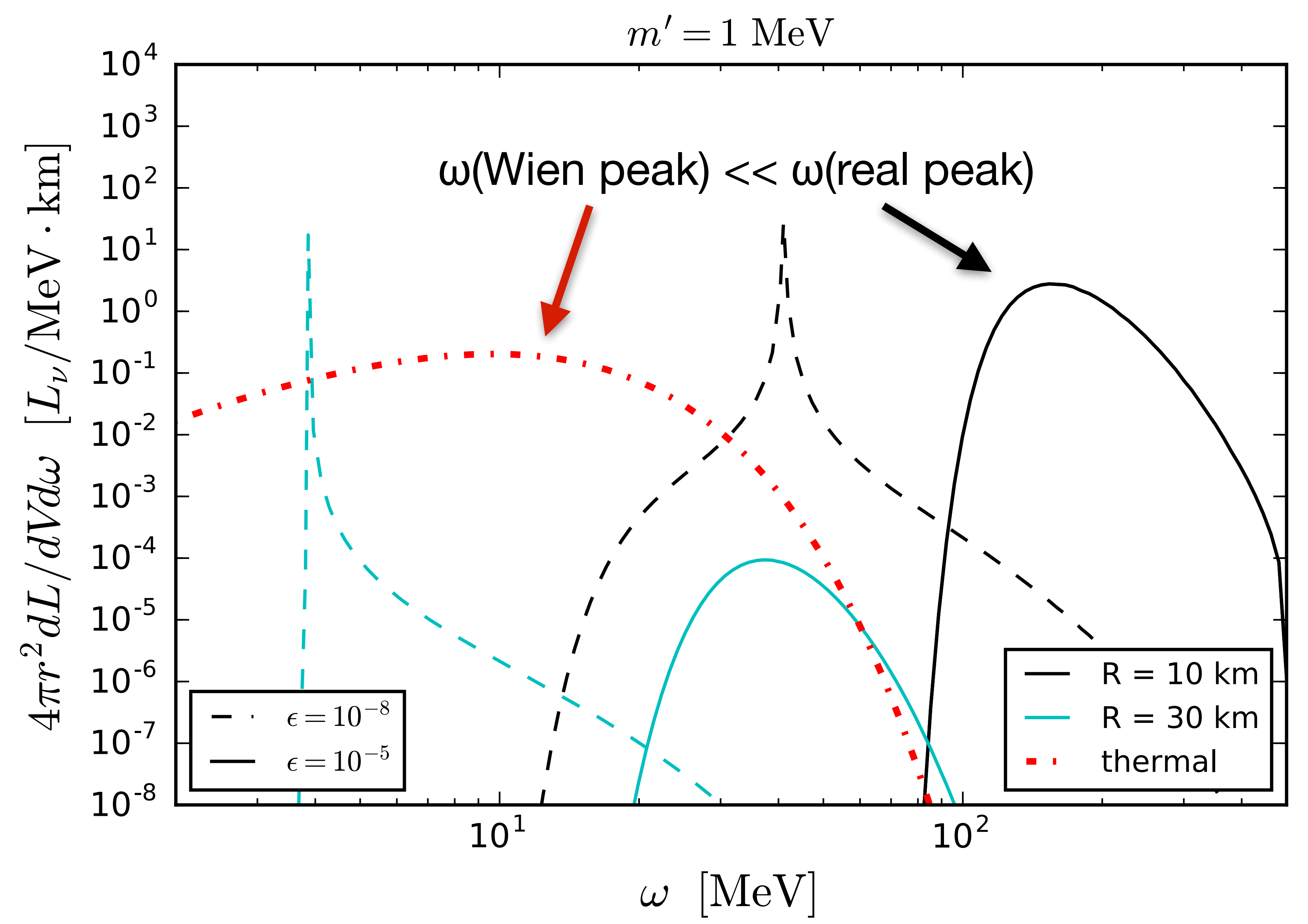


volume emission!

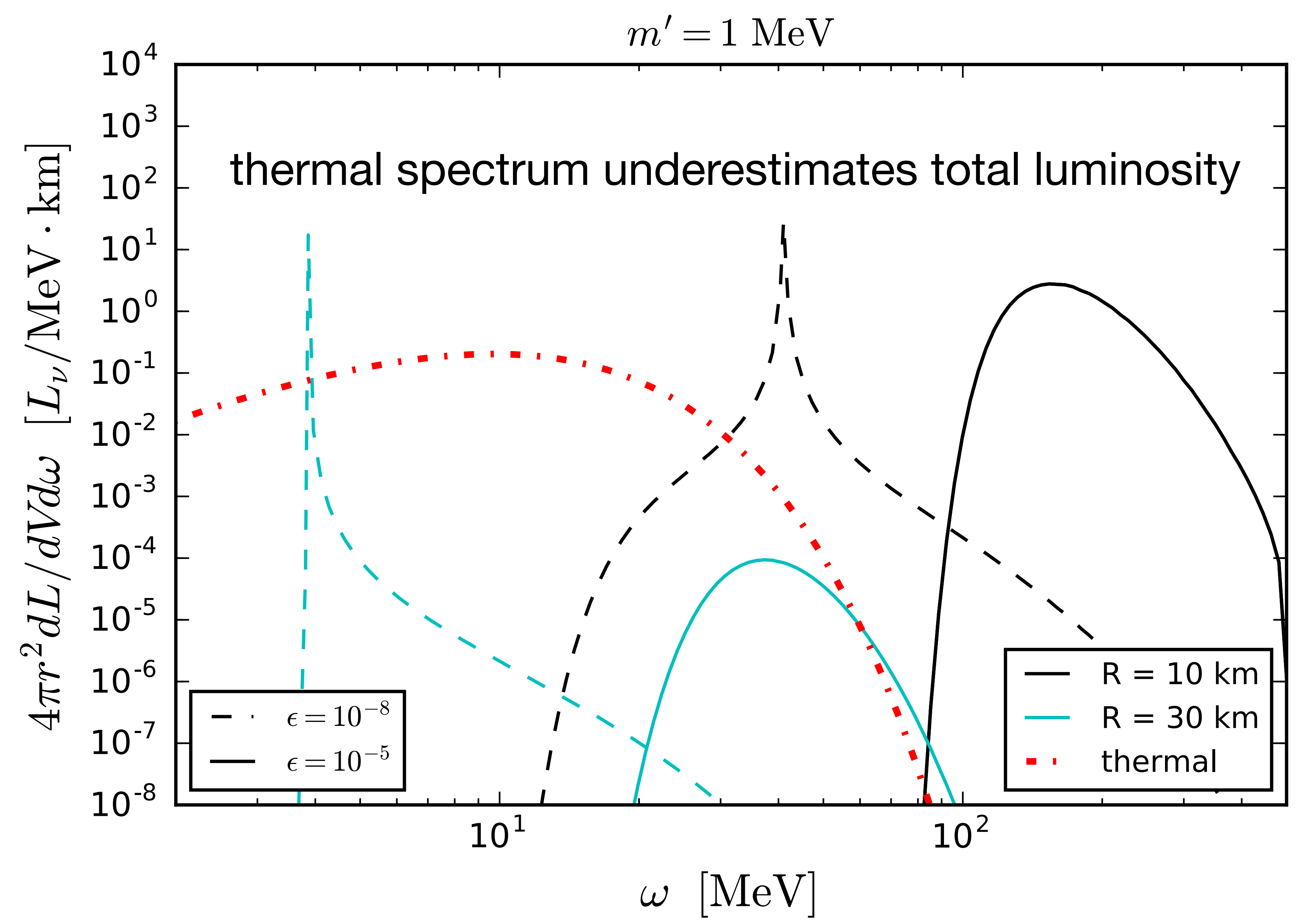
dL/dV/dω


$m' = 1$ MeV
$4\pi r^2 dL/dVd\omega \;\; [L_\nu/\mathrm{MeV}\cdot\mathrm{km}]$
10^4
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^1
10^2
$\omega \;\; [\mathrm{MeV}]$
surface emission
volume emission!
$\epsilon = 10^{-8}$
$\epsilon = 10^{-5}$
R = 10 km
R = 30 km
thermal

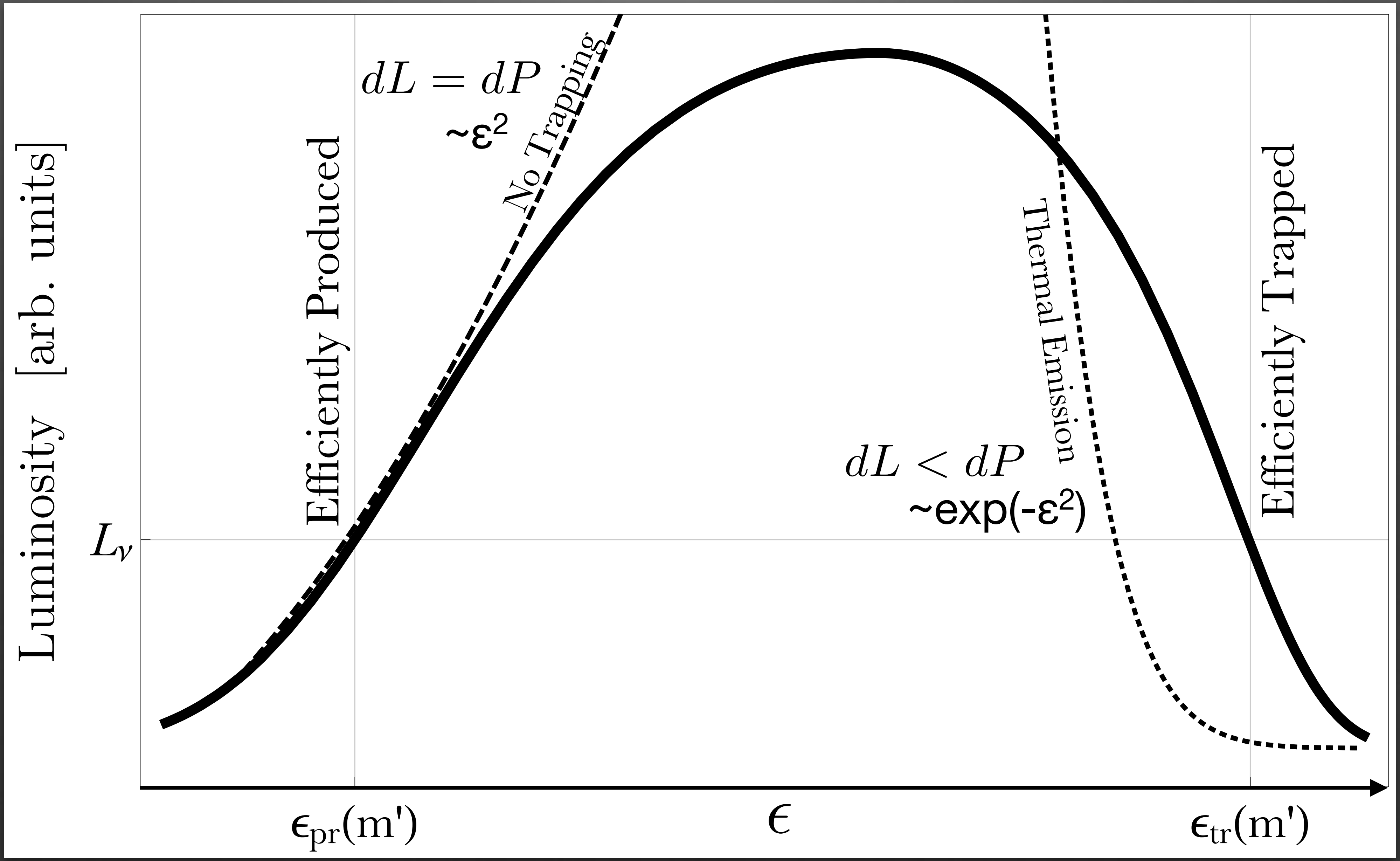
dL/dV/dω


$m' = 1$ MeV
ω(Wien peak) << ω(real peak)
$4\pi r^2 dL/dVd\omega$ $[L_\nu/\mathrm{MeV}\cdot\mathrm{km}]$
ω [MeV]
10^4
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^1
10^2
$\epsilon = 10^{-8}$
$\epsilon = 10^{-5}$
R = 10 km
R = 30 km
thermal

dL/dV/dω


$m' = 1$ MeV
thermal spectrum underestimates total luminosity
$4\pi r^2 dL/dVd\omega \ \ [L_\nu/\mathrm{MeV}\cdot\mathrm{km}]$
10^4
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^1
10^2
$\omega \ \ [\mathrm{MeV}]$
$\epsilon = 10^{-8}$
$\epsilon = 10^{-5}$
R = 10 km
R = 30 km
thermal

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


Luminosity [arb. units]
L_ν
$dL = dP$
~ε²
No Trapping
Efficiently Produced
Thermal Emission
$dL < dP$
~exp(-ε²)
Efficiently Trapped
ϵ_{pr}(m')
ϵ
ϵ_{tr}(m')

Outline

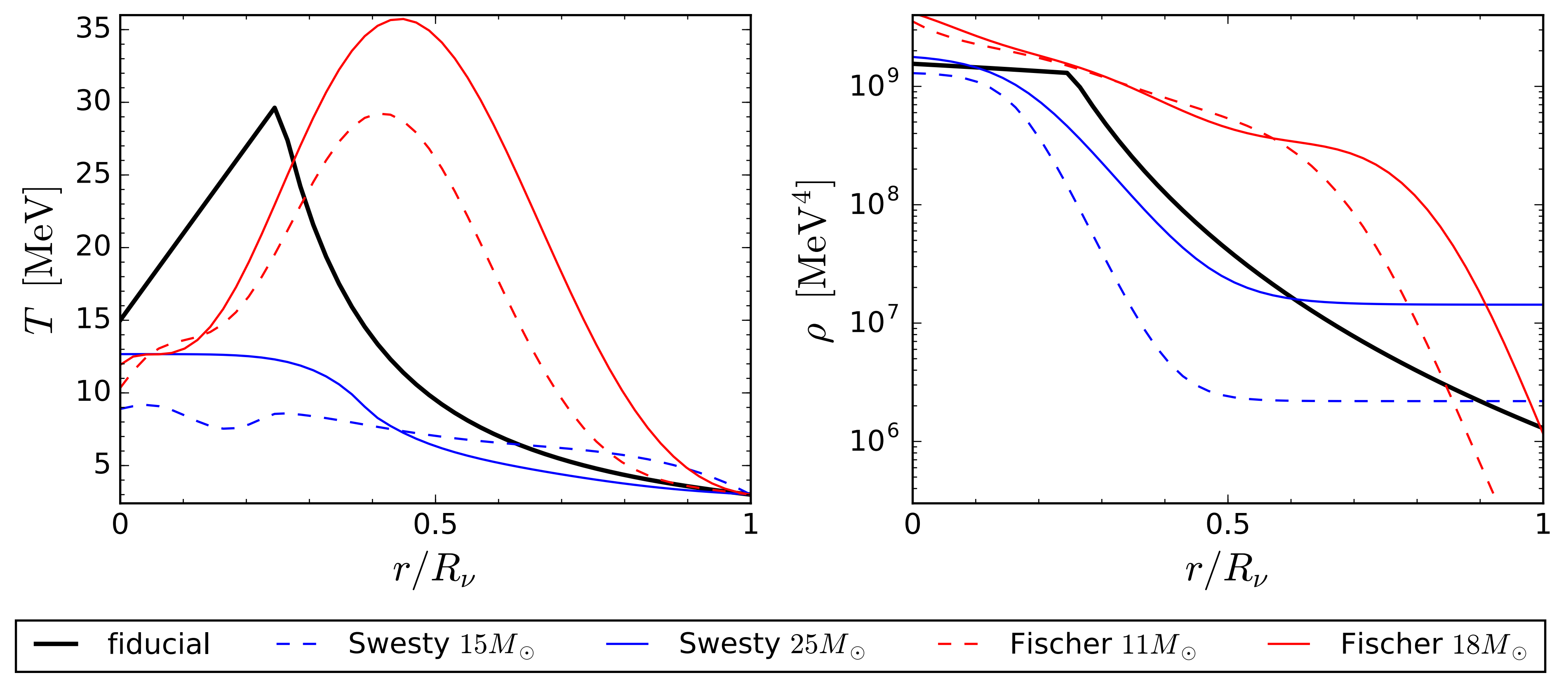
I. Kinetic Mixing and Finite Temperature

II. Luminosity: Resonance and “Trapping”

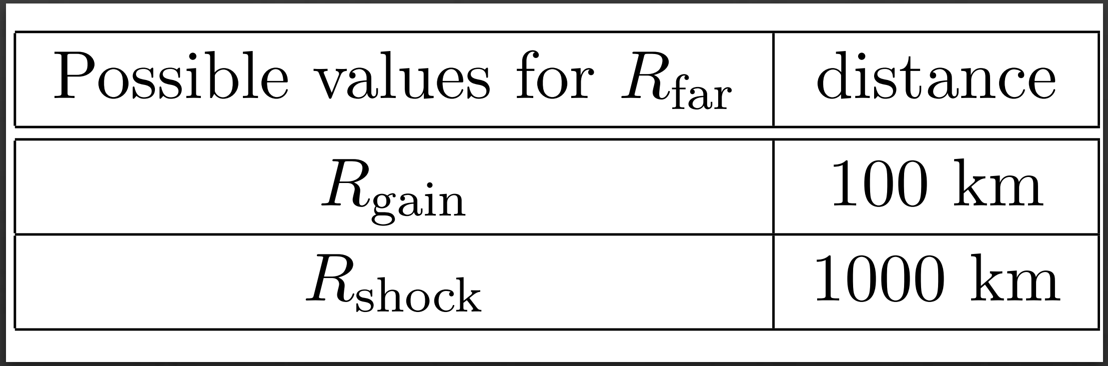
III. Results and future directions

Uncertainties

"fiducial model" differs from sims by ~O(10):

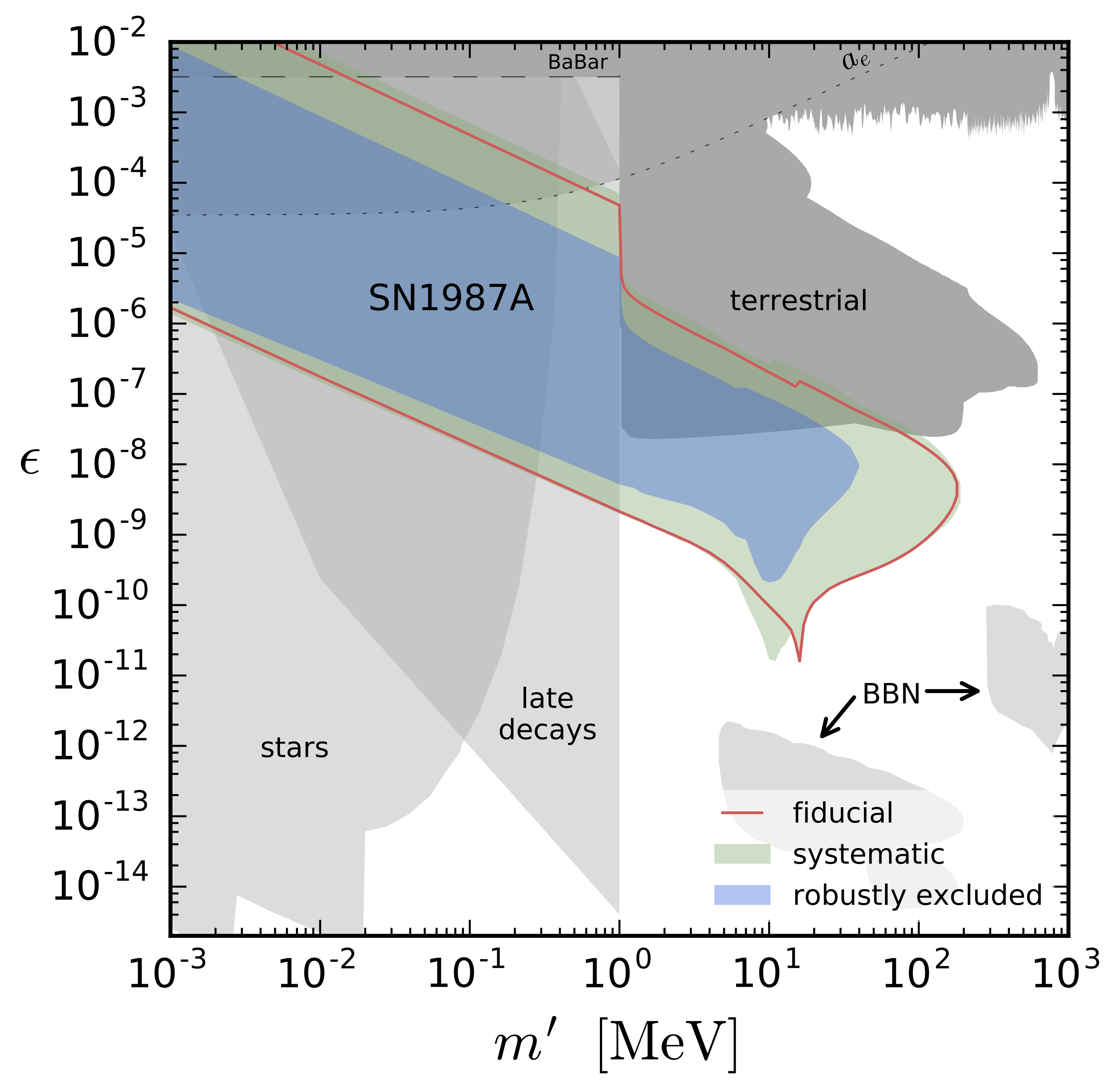


value of R_f (important for optical depth, $\tau(r)=\int_r^{R_f} \Gamma'(r')\, dr'$)



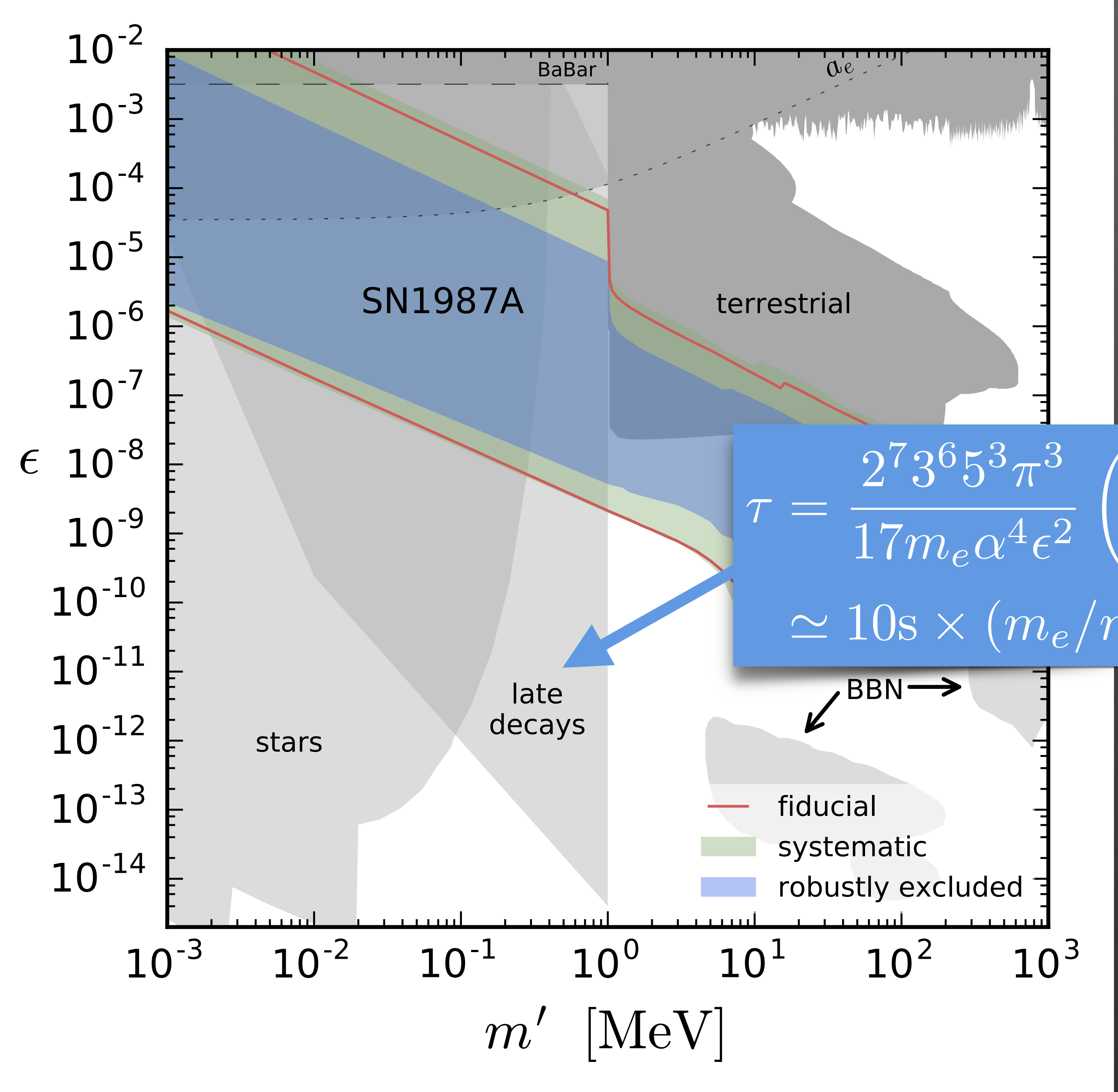
Possible values for $R_{\rm far}$	distance
$R_{\rm gain}$	100 km
$R_{\rm shock}$	1000 km

Results



BaBar
α_e
SN1987A
terrestrial
late decays
stars
BBN
fiducial
systematic
robustly excluded
ϵ
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
m' [MeV]

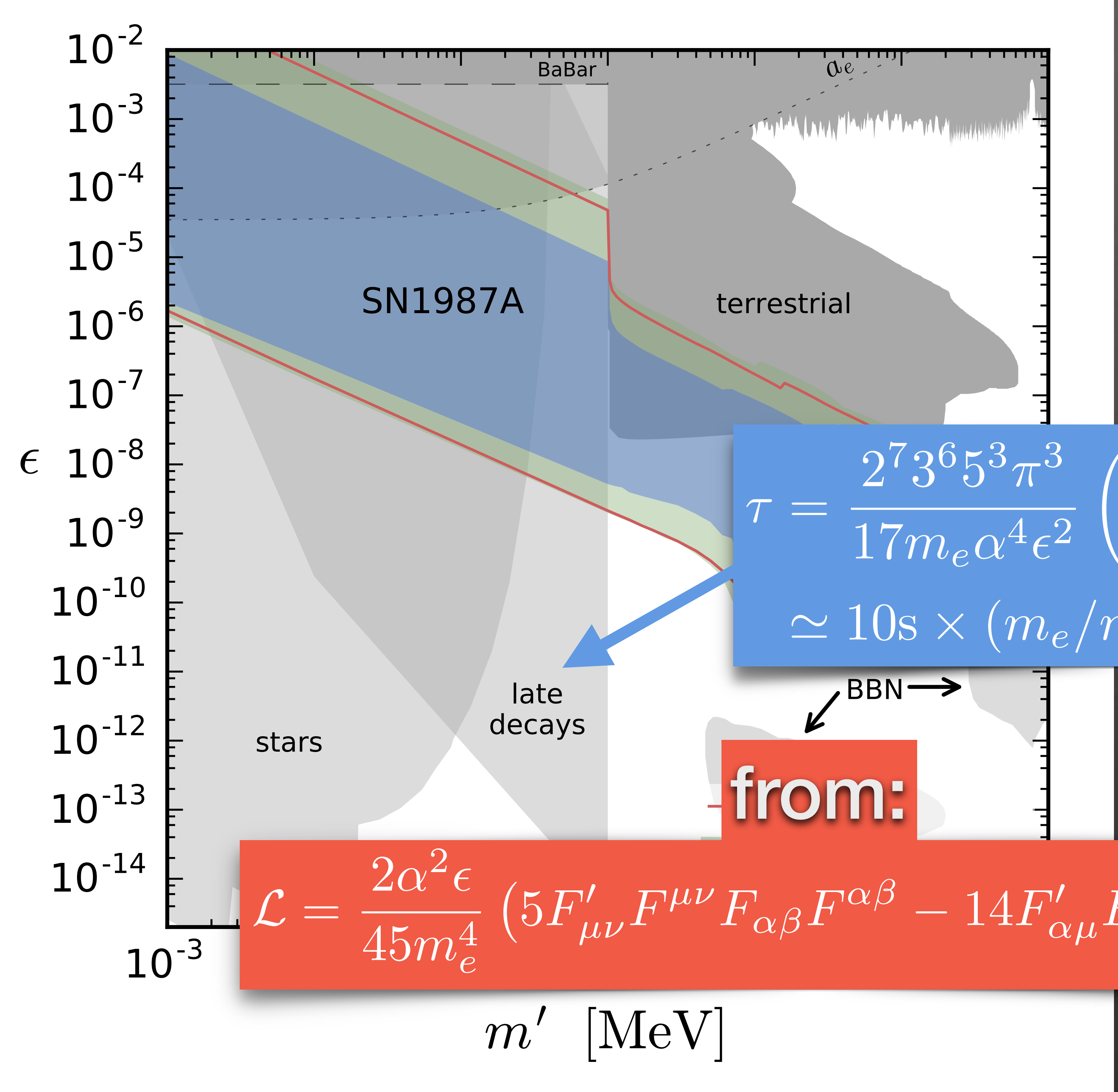
Results



$$\tau = \frac{2^7 3^6 5^3 \pi^3}{17 m_e \alpha^4 \epsilon^2} \left(\frac{m_e}{m_V} \right)^9$$

$$\simeq 10\mathrm{s} \times (m_e/m_V)^9 \times (10^{-3}/\epsilon)^2$$

Results



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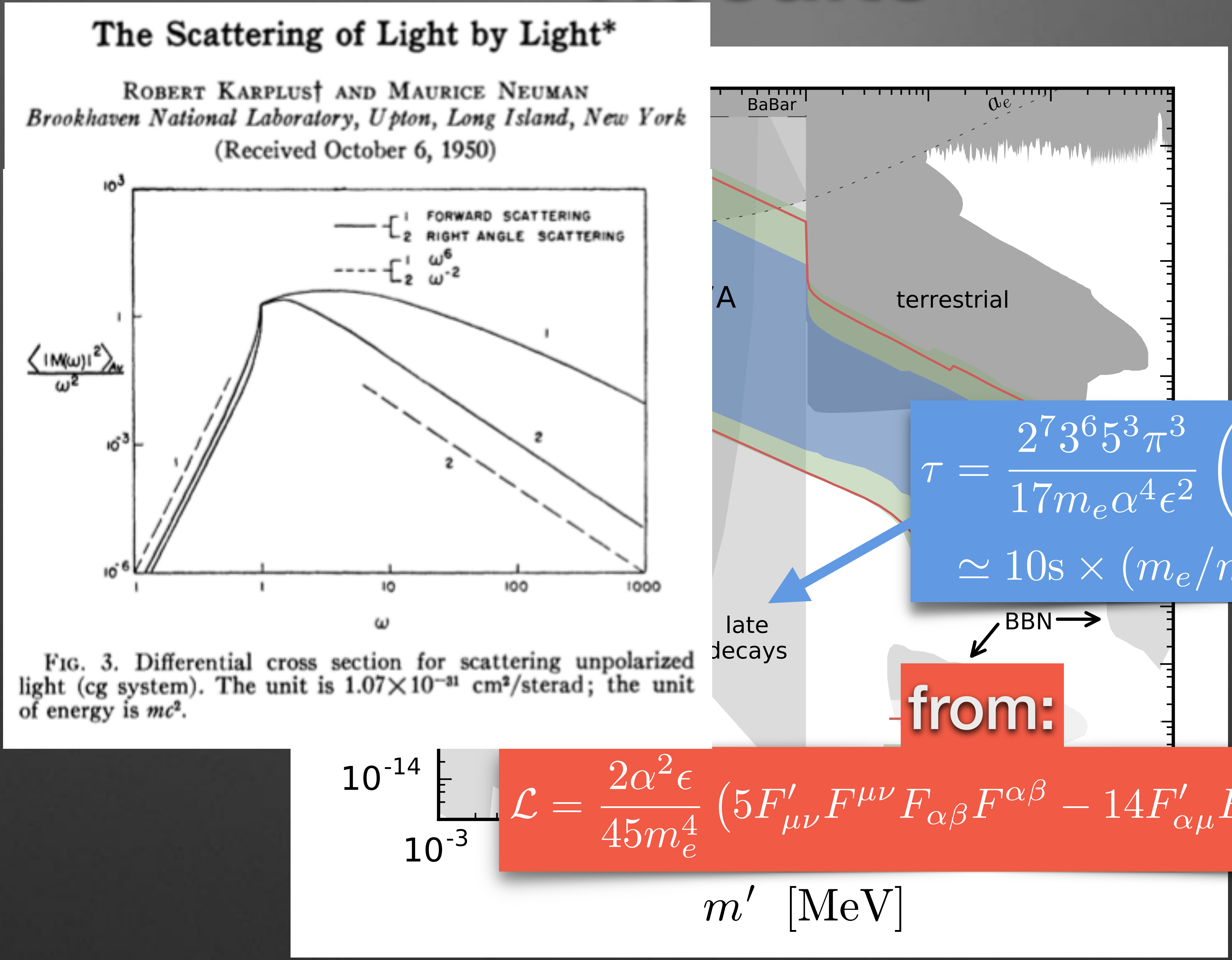
from:

$$\mathcal{L} = \frac{2\alpha^2\epsilon}{45 m_e^4}\left(5F'_{\mu\nu}F^{\mu\nu}F_{\alpha\beta}F^{\alpha\beta} - 14F'_{\alpha\mu}F^{\mu\nu}F_{\beta\nu}F^{\alpha\beta}\right)$$

Results



The Scattering of Light by Light*

Robert Karplus† and Maurice Neuman
Brookhaven National Laboratory, Upton, Long Island, New York
(Received October 6, 1950)

Fig. 3. Differential cross section for scattering unpolarized light (cg system). The unit is 1.07×10^{-31} cm²/sterad; the unit of energy is mc^2.

$$\tau = \frac{2^7 3^6 5^3 \pi^3}{17 m_e \alpha^4 \epsilon^2}\left(\frac{m_e}{m_V}\right)^9$$

$$\simeq 10\text{s} \times (m_e/m_V)^9 \times (10^{-3}/\epsilon)^2$$

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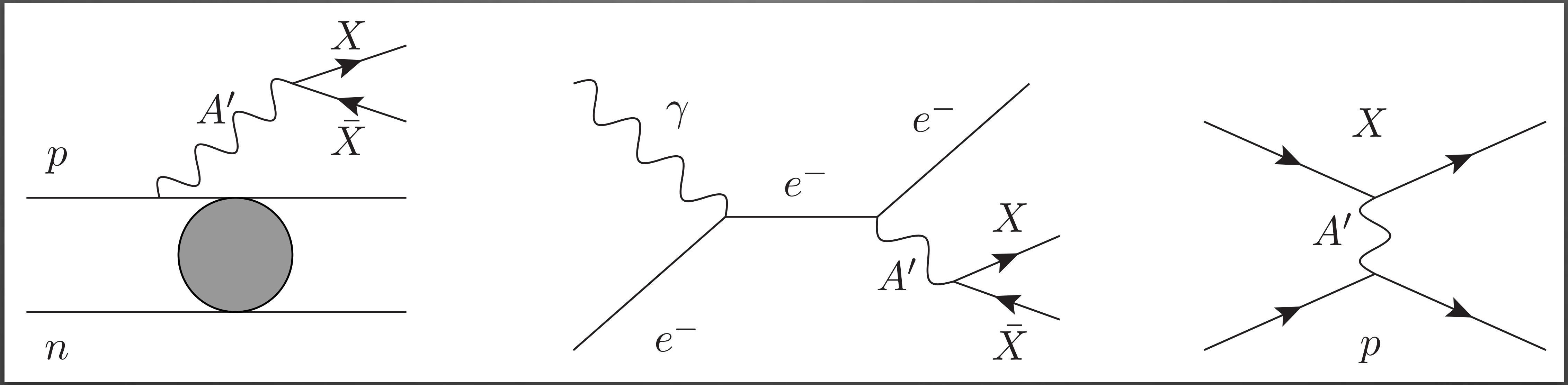
Further questions:

“How thermal” are axions at large mixing?

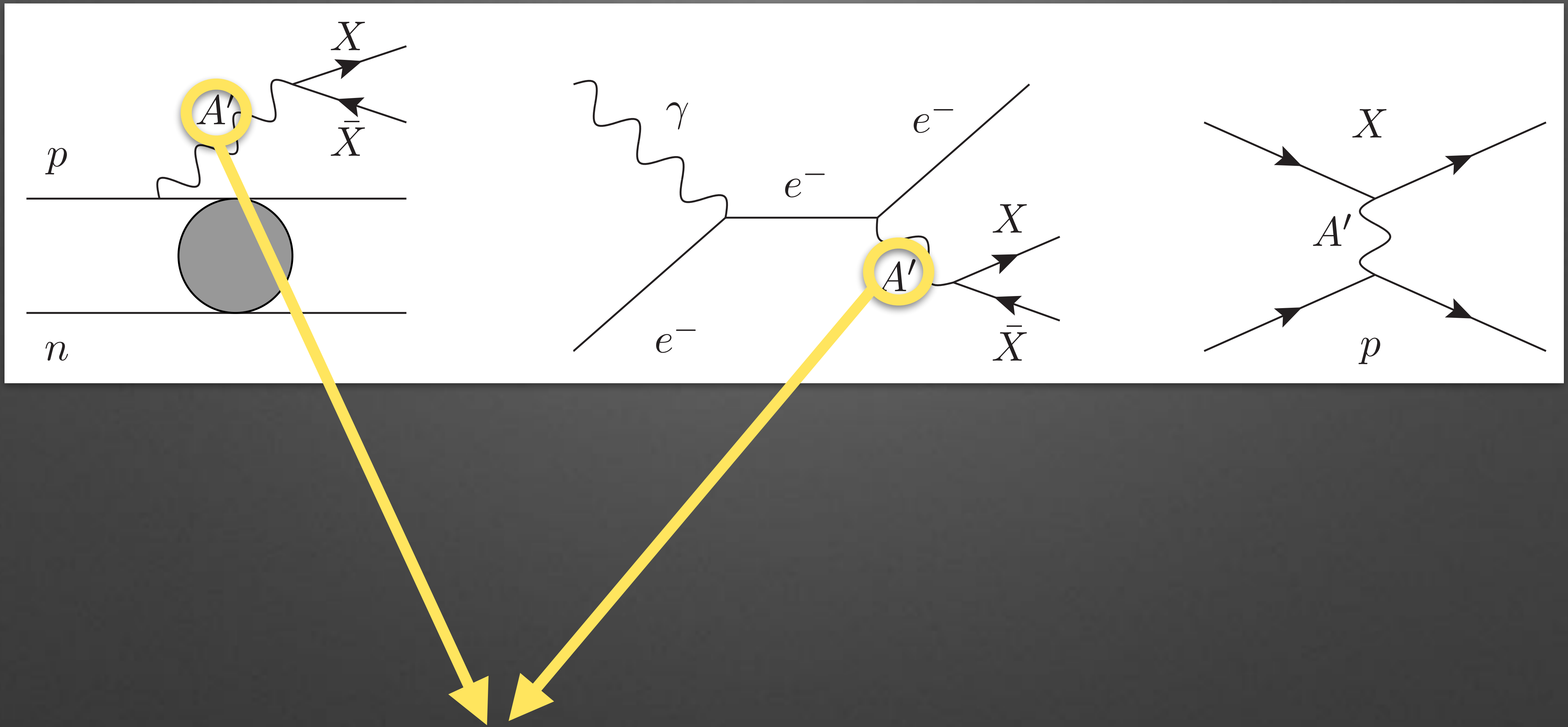
What if A’⇨$X\bar{X}$ is on shell?

What other DM varieties can be constrained?

Dark Photon + Dark Fermions

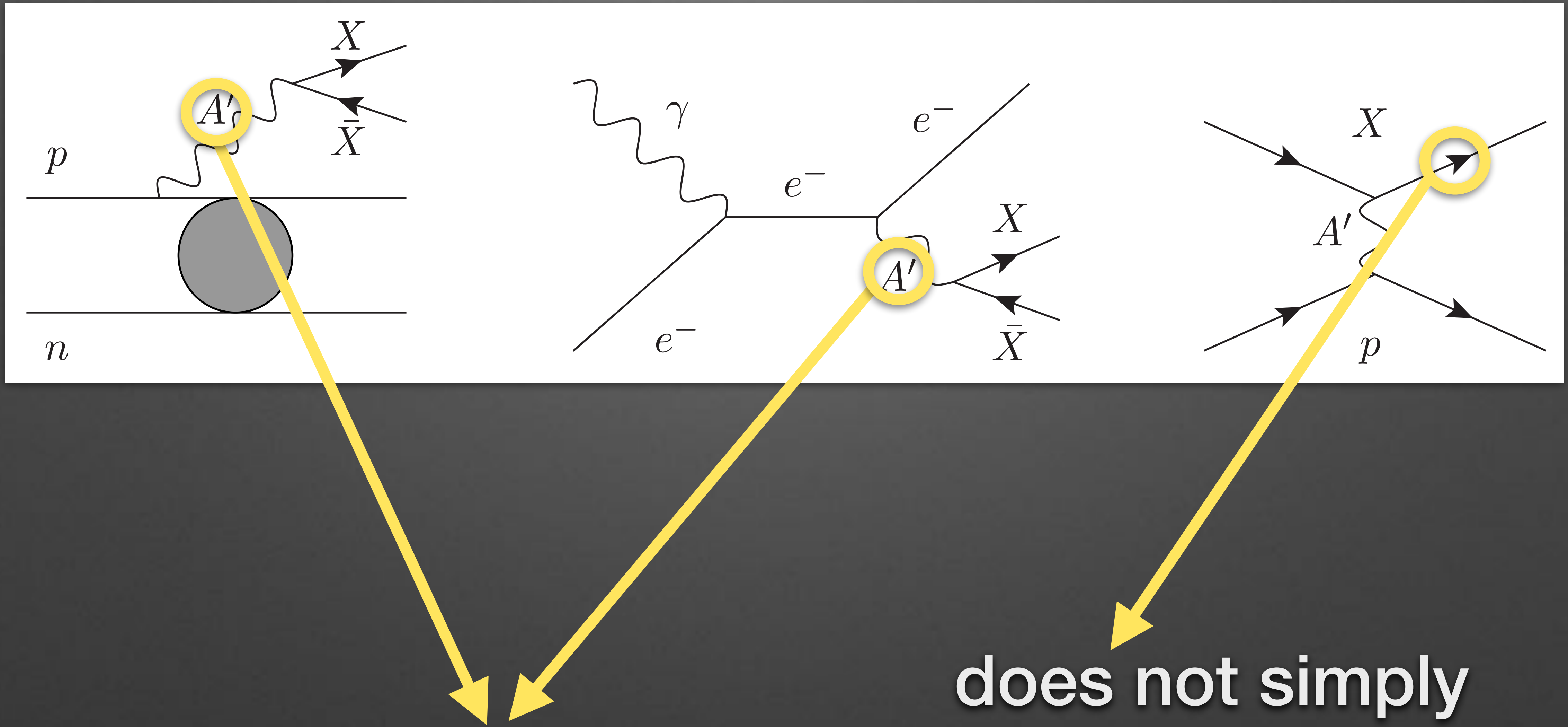


Dark Photon + Dark Fermions



can be on-shell or off

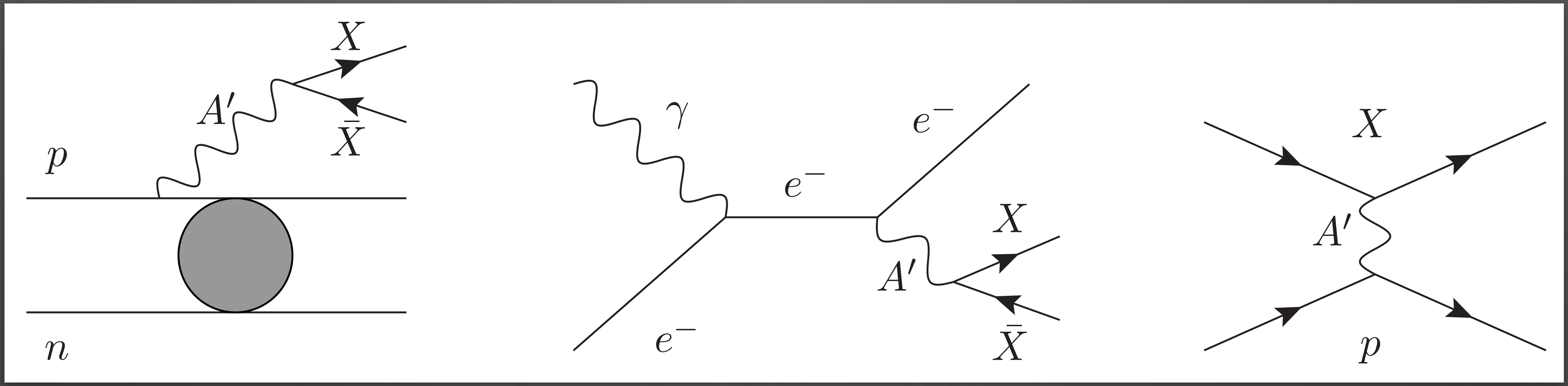
Dark Photon + Dark Fermions



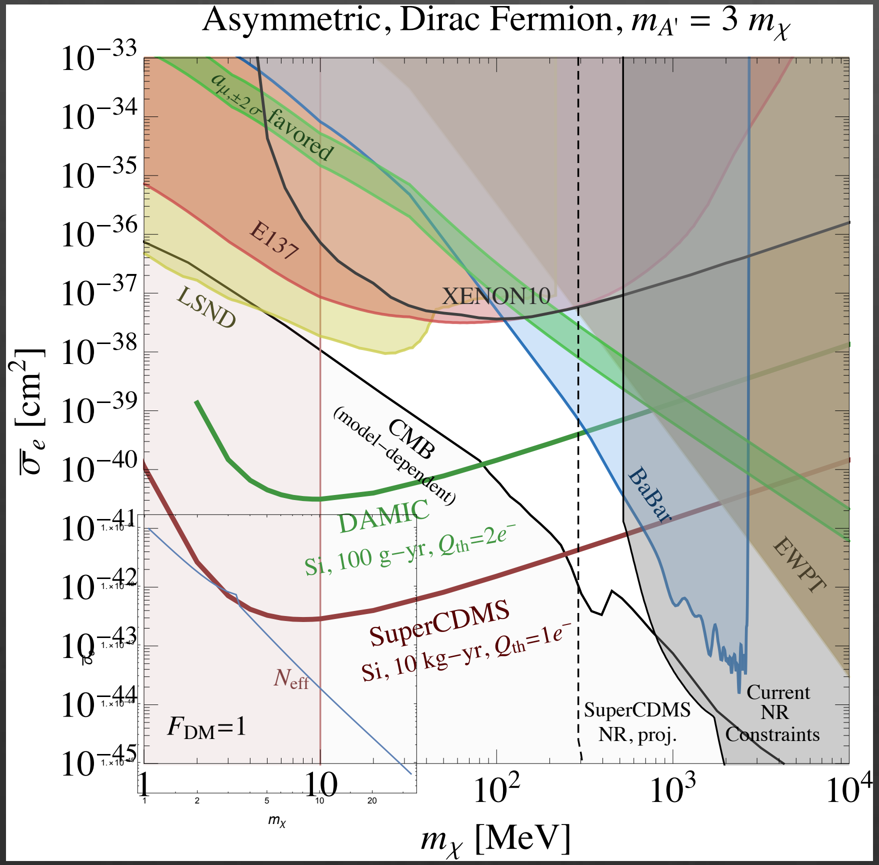
can be on-shell or off

does not simply get reabsorbed!

Dark Photon + Dark Fermions



very, very preliminary!

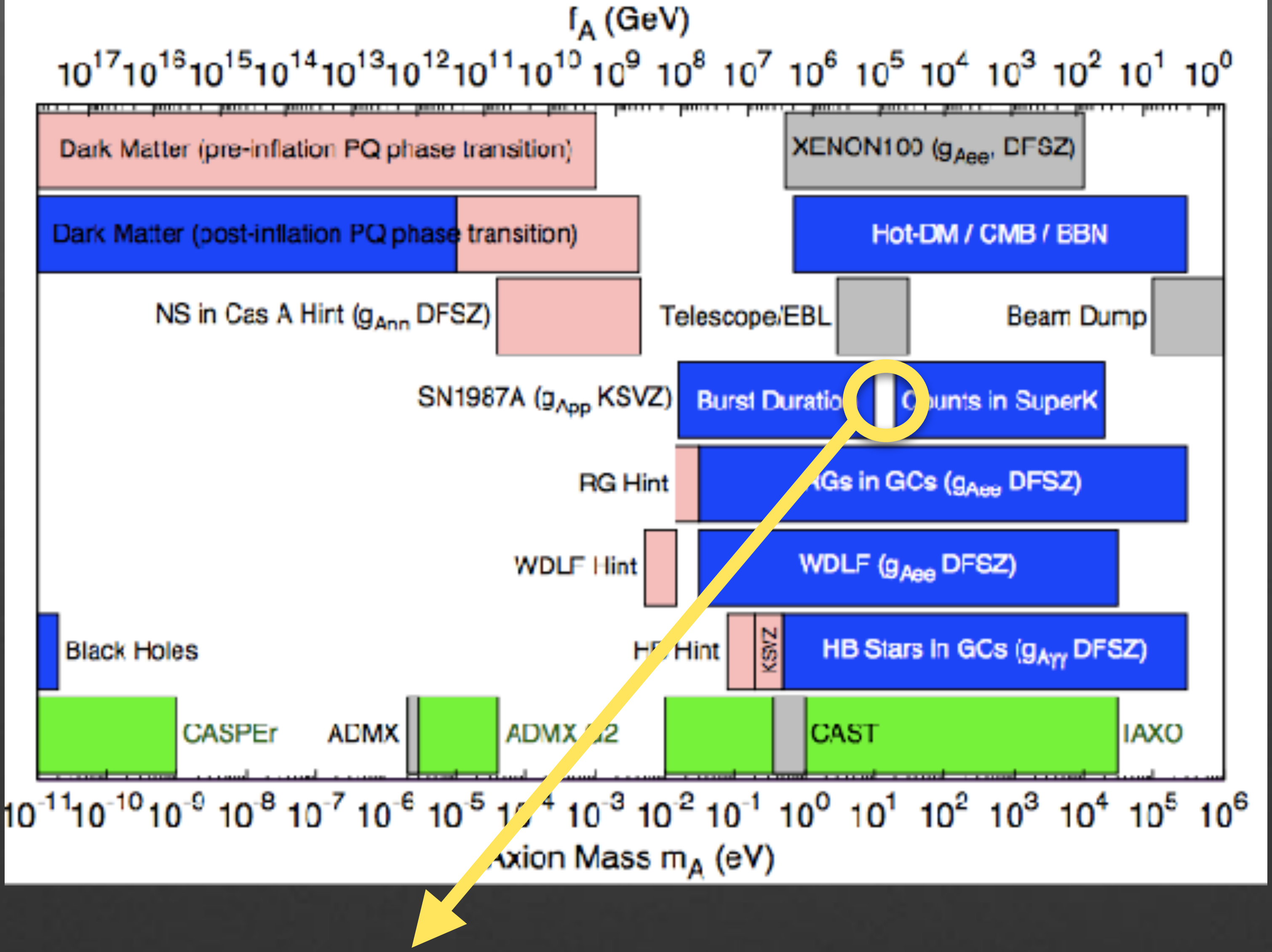


very, very preliminary!

$$\bar{\sigma}_e = \frac{16\pi\mu_{\chi e}^2\alpha\alpha_D\epsilon^2}{m_A'^4}$$

Hadronic Axion

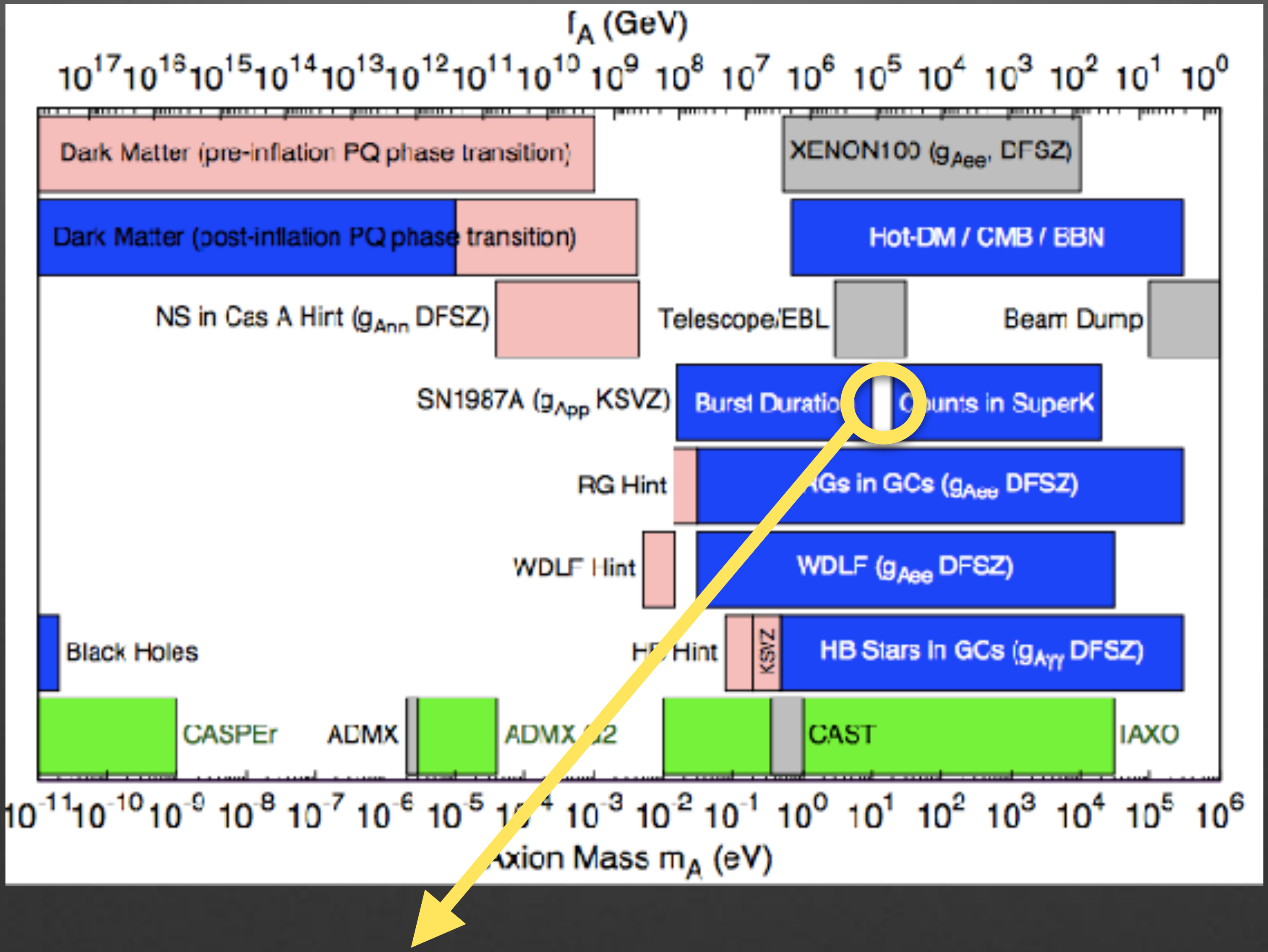
“How thermal” are axions at large mixing?



is this ruled out?

Hadronic Axion

"How thermal" are axions at large mixing?



…and are nuclear effects included here?

cf. Sigl, 1996; Hanhart, Phillips, Reddy, 2000

is this ruled out?

Different Dark Sectors?

What other dark sectors can be constrained?

- A'+DM (system could thermalize at high energy)
- millicharged DM (DM couples to photon)
- leptophilic gauge boson (A' only couples to e, μ, ν)
- light scalars (scalar portal? dark Higgs? A'h_D production doesn't decouple)
- diffuse background?

Conclusions

Supernovae provide a unique “laboratory” for weakly coupled physics

Kinetic mixing allows resonant production

Finite temperature effects are qualitatively important

Non-thermal spectrum in high-mixing regime — consequences for other particles?

Thanks!