The Future Is Flavourful, 4th June,2024

SN1987A Constraints to BSM Models with Extra Neutral Bosons Near the Trapping Regime

K.-C. Lai, C. S. Jason Leung and Guey-Lin Lin

under review in PRD [arXiV:2401.16023]

- **Introduction**
  - How does SN1987A constrain BSM physics?
  - Raffelt criterion
  - Unified luminosity formula (modified luminosity criterion)
  - The luminosity near the trapping regime
- **Discussion**
  - Comparison with previous studies
  - Conclusion

- **SN1987A observation and simulations**
  - **Neutrino Energy Release**: 99% of the difference in gravitational binding energy between the progenitor and the remnant is released as neutrinos*.
  - **Consistency with Predictions**: The observed neutrino burst from the explosion matches predictions from simulations based on the Standard Model (SM).

*G. Raffelt, "Stars as laboratories for fundamental physics", 1996

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- **Quantitative constraint: The Raffelt criterion**
  - If the instantaneous luminosity of the BSM particle were comparable to that of neutrinos, the duration of the neutrino burst from SN1987A could have been reduced by half, which is inconsistent with the observations.
  - Neutrino luminosity at $t_{\rm pb} = 1\,{\rm s} : L_\nu = 3 \times 10^{52}$ [erg/s]
  - Hence it is proposed by Raffelt that*

$$L_{Z'}(m_{Z'}, g_{Z'}) \ll L_\nu = 3 \times 10^{52}\ [\mathrm{erg/s}]\ \mathrm{at}\ t_{\rm pb} = 1\ \mathrm{s}$$

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- J. B. Dent, F. Ferrer, and L. M. Krauss, **arXiv:1201.2683**
  (calculate $N+N \to N+N+A'$ using one-pion exchange (OPE) approximation)

- E. Rrapaj and S. Reddy, **Phys. Rev. C 94, 045805 (2016)**
  (rely on low energy theorem to relate $N+N \to N+N+A'$ to $N+N \to N+N$)

- C. Mahoney, A. K. Leibovich, and A. R. Zentner, **Phys. Rev. D 96, 043018(2017)**
  (corrected the calculation by Dent et al., showing that OPE is not a bad approximation)

- J. H. Chang, R. Essig and S. D. McDermott, **JHEP01 (2017) 107**
  (unified treatment of free streaming and trapped scenarios in SN)

- D. Croon, G. Elor, R. K. Leane and S. D. McDermott, **JHEP 01 (2021) 107**
  (considering processes involving muons and testing axions, ALPs and Z' of $U(1)_{L_\mu - L_\tau}$)

- **SN simulation with muons:**
  R. Bollig, W. DeRocco, P. W. Graham, and H.-T. Janka, **Phys. Rev. Lett. 125, 051104 (2020)**

- **SFHo18.8:** A.W. Steiner, M. Hempel and T. Fischer, **Astrophys. J. 774 (2013) 17**

- **$U(1)_{L_\mu - L_\tau}$ model as an example***
  - Lagrangian:

*Xiao-Gang He et al., "Simplest Z' Model" Phys.Rev.D 44 (1991)

$$\mathscr{L}_{Z'} = \mathscr{L}_{\text{SM}} - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} - \frac{\varepsilon(m_{Z'}, g_{Z'})}{2}F'_{\mu\nu}F^{\mu\nu} + \frac{1}{2}m_{Z'}^2 Z'_\mu Z'^\mu$$
$$+ g_{Z'}Z'_\mu \left(\bar{l}_1\gamma^\mu l_1 - \bar{l}_2\gamma^\mu l_2 + \bar{\mu}_R\gamma^\mu\mu_R - \bar{\tau}_R\gamma^\mu\tau_R\right)$$

$l_1 = (\mu_L, \nu_{\mu,L})$, $l_2 = (\tau_L, \nu_{\tau,L})$

electroweak doublets for left-handed leptons

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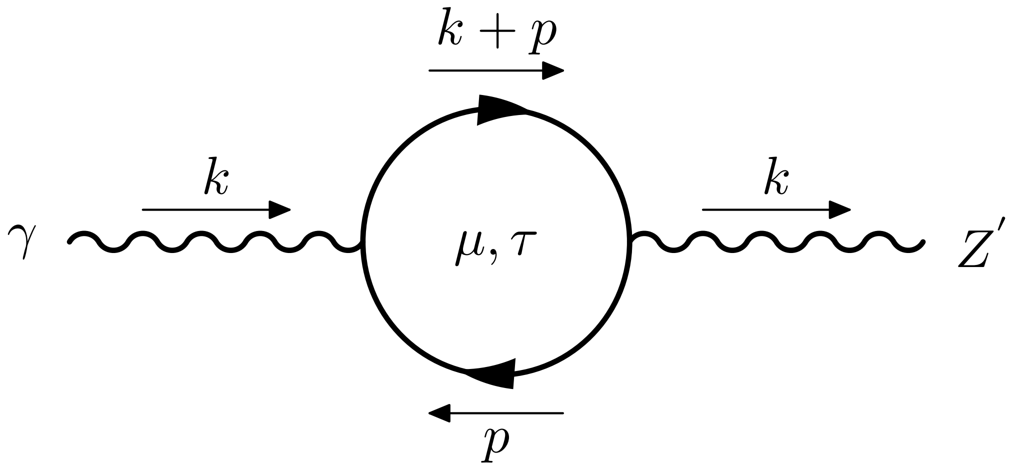
electroweak doublets for left-handed leptons

- **Non-reducible kinetic mixing parameter $\varepsilon(m_{Z'}, g_{Z'})$**



$$\varepsilon(m_{Z'}, g_{Z'}) \approx -\frac{e g_{Z'}}{2\pi^2}\int_0^1 x(1-x)\ln\left[\frac{m_\tau^2 - x(1-x)k^2}{m_\mu^2 - x(1-x)k^2}\right]dx$$

$$k^2 = m_{z'}^2$$

- $U(1)_{L_\mu - L_\tau}$ **model as an example***

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electroweak doublets for left-handed leptons

  - The luminosity calculation $L(m_{Z'}, g_{Z'})$ is non-trivial when the coupling $g_{Z'}$ is large. A salient feature of $L(m_{Z'}, g_{Z'})$ in this limit has not been noticed before.

  - Compare our results with earlier results of D. Croon* et al.

*D. Croon et al.,
JHEP 01 (2021) 107

- **The Luminosity of Z' in a SN**

* Chang et al., JHEP 1701 (2017) 107

$$L_{Z'}(m_{Z'}, g_{Z'}, R_\nu, R_{\text{att}}) = 4\pi \int_0^{R_\nu} \int_{m_{Z'}}^{\infty} r^2 \bar{\mathscr{A}}(\lambda_{\text{att}}(\omega, T), R_{\text{att}}) \sum_i \frac{d\dot{\epsilon}_i}{d\omega} d\omega dr$$

  - $d\dot{\epsilon}_i/d\omega$: the emissivity spectrum for the Z′ production channel i
    (Z′ luminosity per unit volume and unit energy of Z′ boson)
  - R_ν : radius of the neutrino sphere
    (the radius beyond which neutrinos decouple)
  - $\bar{\mathscr{A}}$: is the average attenuation factor along the propagation of the Z' boson
    (handle decays or absorptions of Z' boson)

$$\mathscr{A} = \exp\left(-\frac{\text{path of propagation}}{\lambda_{\text{att}}}\right)$$

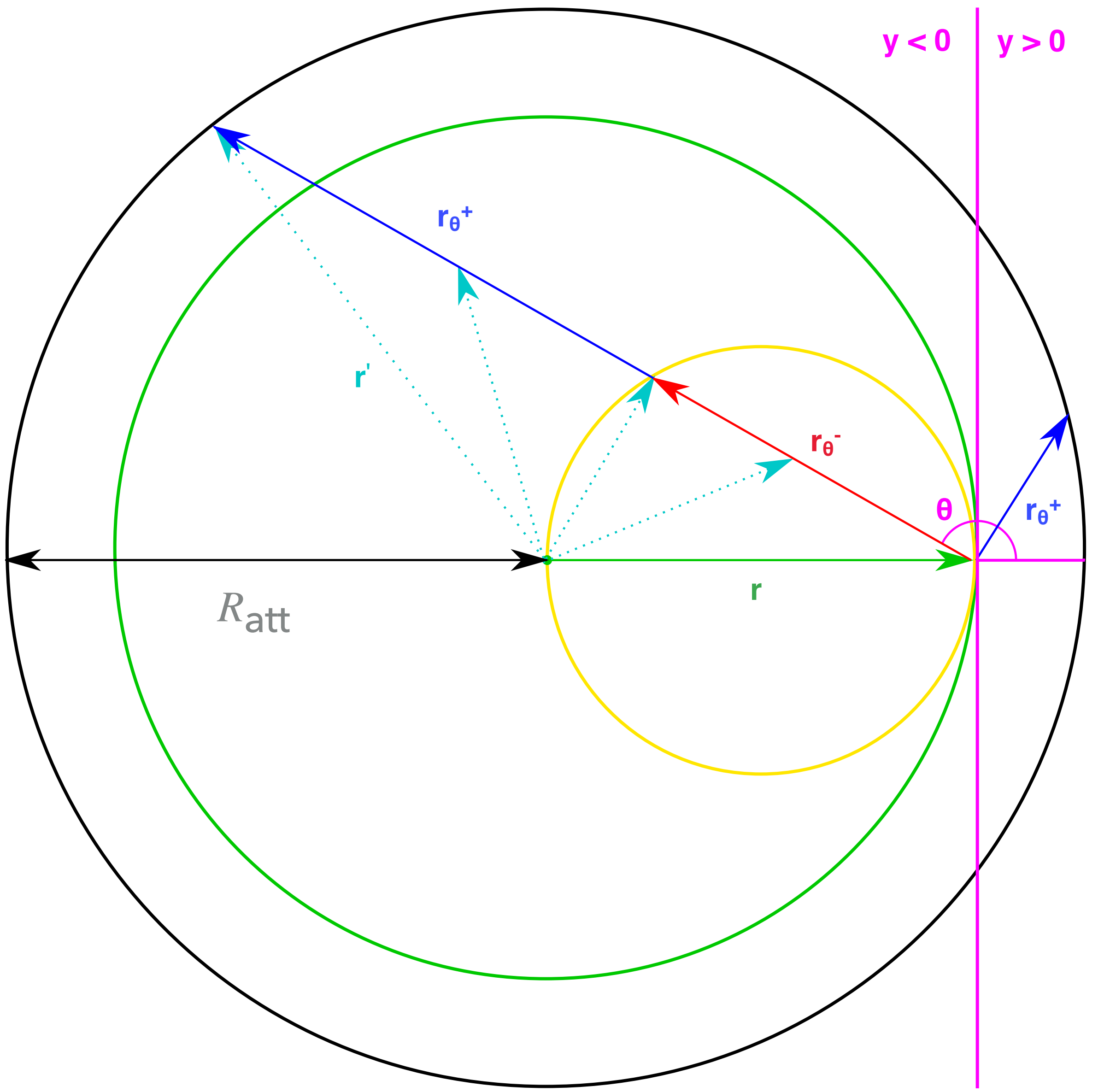
$$\frac{1}{\lambda_{\text{att}}} = \frac{1}{\lambda_{\text{decay}}} + \frac{1}{\lambda_{\text{reabs}}}$$

- **Average attenuation factor** $\bar{\mathscr{A}}(\lambda_{\text{att}}(\omega, T), R_{\text{far}})$

$$\mathscr{A} \equiv \exp\left(-\frac{\text{path of propagation}}{\lambda_{\text{att}}}\right)$$

$$\bar{\mathscr{A}} = \frac{1}{2}\int_{-1}^{1} \exp\left(-\int_{0}^{r_\theta^{\text{Max}}} \frac{1}{\lambda_{\text{att}}(\omega, T)} dr_\theta\right) dy$$

$y = \cos\theta$, $\vec{r}\,' = \vec{r} + \vec{r}_\theta$ and $r_\theta^2 + 2ryr_\theta + (r^2 - r'^2) = 0$



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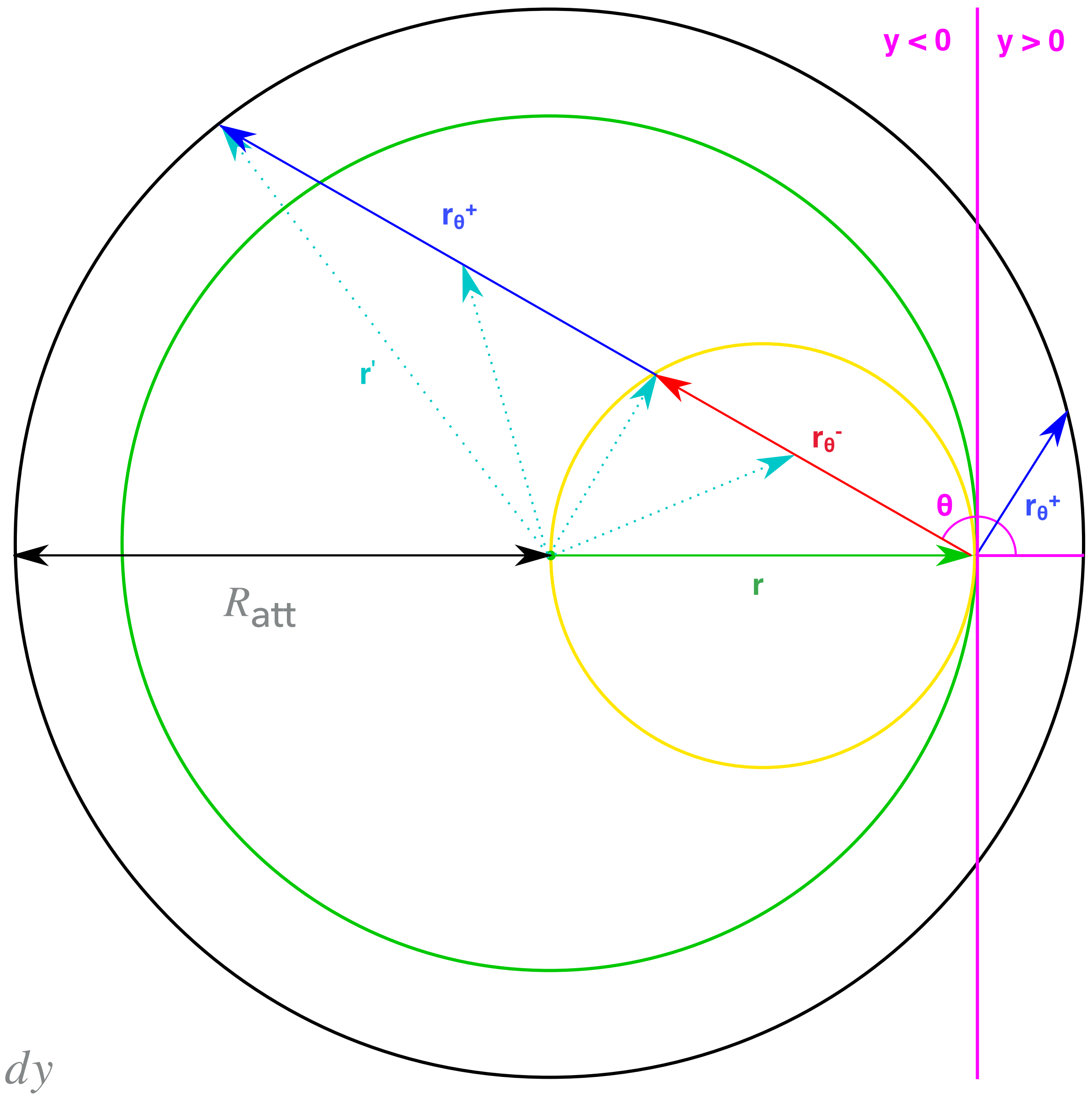
$$\bar{\mathscr{A}} = \frac{1}{2}\int_0^1 \exp\left(-\int_r^{R_{\text{att}}} \frac{1}{\lambda_{\text{att}}} \frac{r'}{\sqrt{r^2(y^2-1) + r'^2}} dr'\right) dy$$
$$+\frac{1}{2}\int_{-1}^{0} \exp\left(-\int_{r\sqrt{1-y^2}}^{r} \frac{1}{\lambda_{\text{att}}} \frac{r'}{\sqrt{r^2(y^2-1) + r'^2}} dr'\right.$$
$$\left. - \int_{r\sqrt{1-y^2}}^{R_{\text{att}}} \frac{1}{\lambda_{\text{att}}} \frac{r'}{\sqrt{r^2(y^2-1) + r'^2}} dr'\right) dy$$



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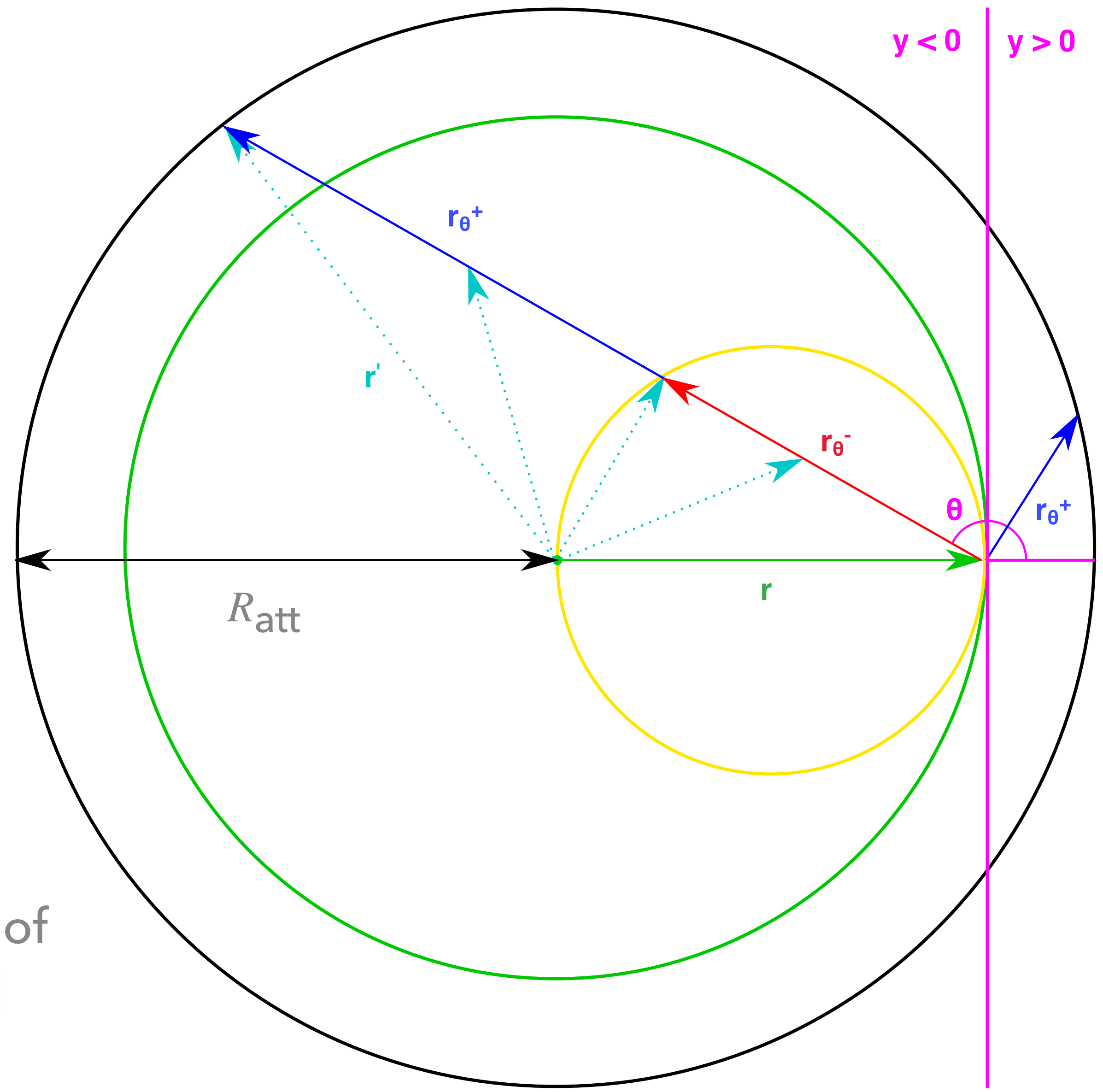


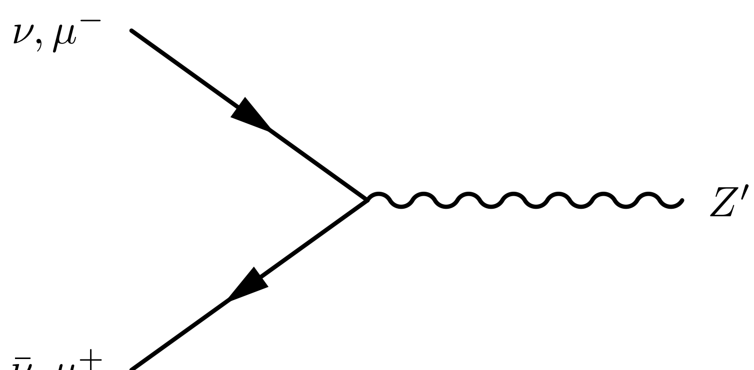
- In Chang *et al.* and D. Croon *et al.*, the attenuation region is taken to be larger than the neutrino sphere, i.e., $R_{\text{att}} > R_\nu$. However, we take $R_{\text{att}} = R_\nu$
- We consider the production and attenuation regions of the Z' boson to be identical. Both regions are located within the neutrino sphere with radius of R_ν.
- We consider all propagation directions of Z' boson once it is produced.

*Chang et al., JHEP 1701 (2017) 107

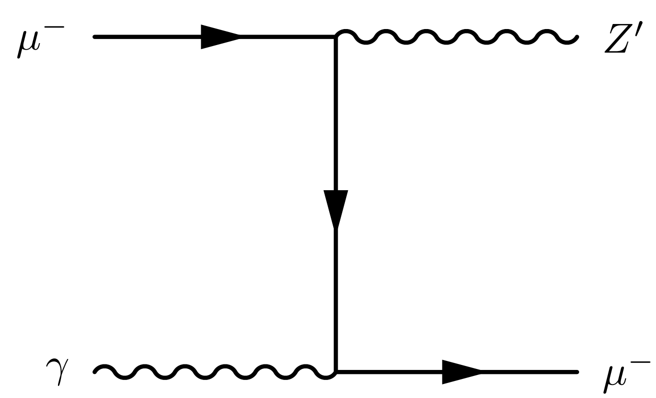
- **The Luminosity of Z' in a SN**

$$L_{Z'}(m_{Z'}, g_{Z'}, R_\nu, R_{\text{far}}) = 4\pi \int_0^{R_\nu} \int_{m_{Z'}}^{\infty} r^2 \bar{\mathscr{A}}(\lambda_{\text{att}}(\omega, T), R_{\text{far}}) \sum_i \frac{d\dot{\epsilon}_i}{d\omega} d\omega dr$$

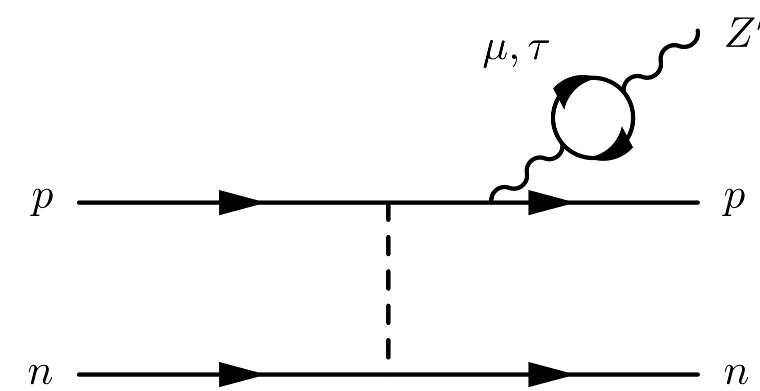
- **Z' Production Channels**



ν and μ pair coalescence



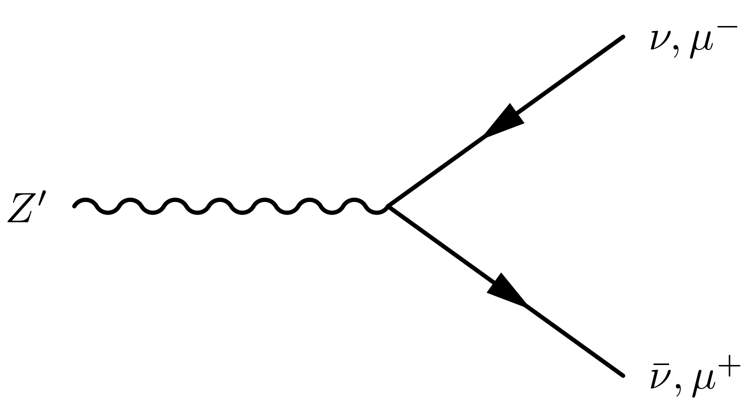
semi-Compton



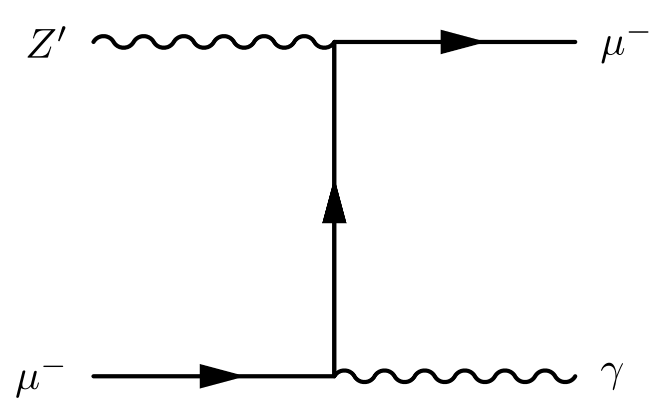
loop Bremsstrahlung

*D. Croon *et al.*, JHEP 01 (2021) 107

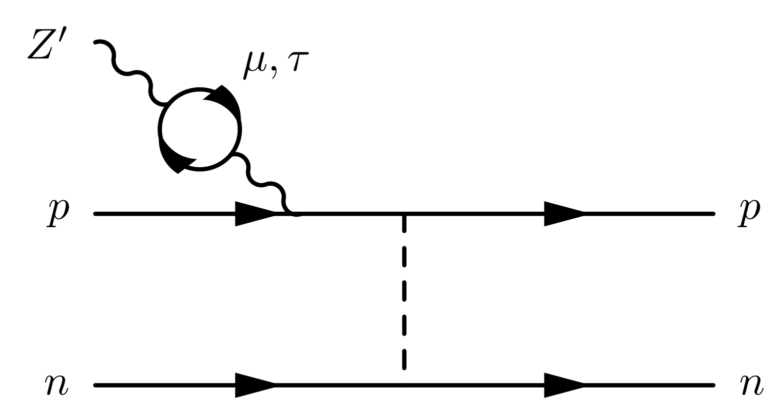
- **Z' Absorption/Decay Channels**



Z' decay to ν and μ

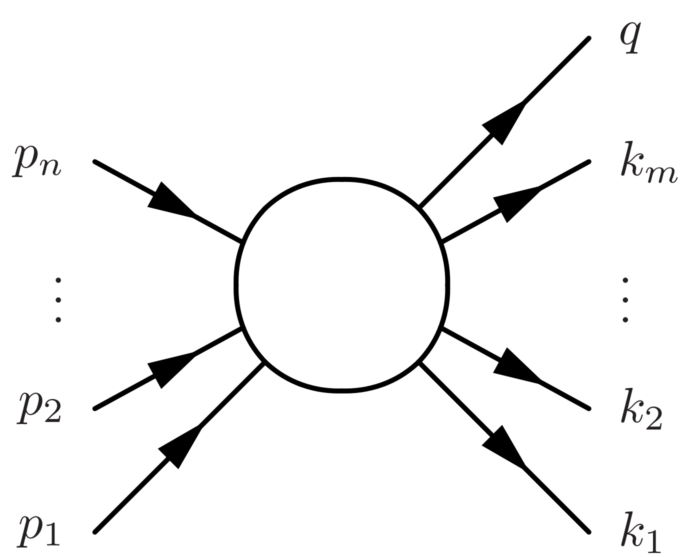


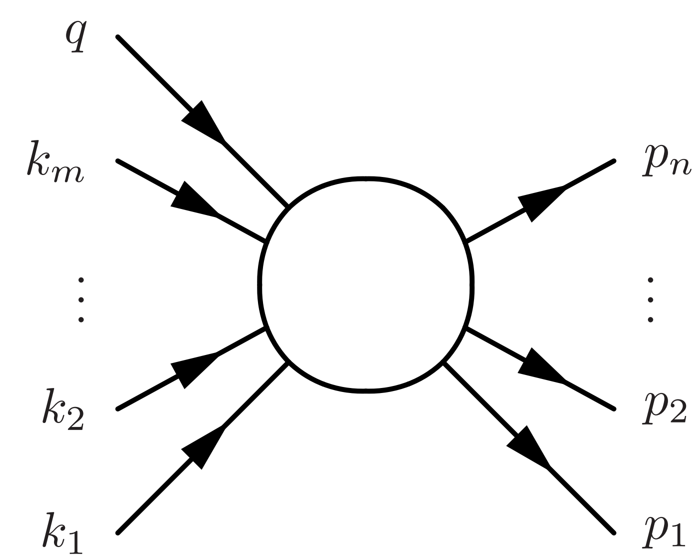
inverse semi-Compton



inverse loop Bremsstrahlung

- **The principle of detailed balance**





$$d\Gamma_{\text{prod}} = \frac{1}{2\omega}|\mathcal{M}(n \to m+1)|^2(2\pi)^4\delta^4(q - \sum_{i=1}^{n} p_i + \sum_{j=1}^{m} k_j)$$
$$\times \prod_{i=1}^{n}\frac{d^3p_i}{2E_i(2\pi)^3}f_i(E_i)\prod_{j=1}^{m}\frac{d^3k_j}{2E_j(2\pi)^3}(1 \pm f_j(E_j))$$

$$d\Gamma_{\text{rabs}} = \frac{1}{2\omega}|\mathcal{M}(m+1 \to n)|^2(2\pi)^4\delta^4(q - \sum_{i=1}^{n} p_i + \sum_{j=1}^{m} k_j)$$
$$\times \prod_{j=1}^{m}\frac{d^3k_j}{2E_j(2\pi)^3}f_j(E_j)\prod_{i=1}^{n}\frac{d^3p_i}{2E_i(2\pi)^3}(1 \pm f_i(E_i))$$

$$\text{Bose-Einstein distribution}: f(E) = \frac{1}{e^{E/T} - 1},$$
$$\text{Fermi-Dirac distribution}: f(E) = \frac{1}{e^{E/T} + 1}.$$

$$\text{Bosons}: (1 + f(E))/f(E) = e^{E/T},$$
$$\text{Fermions}: (1 - f(E))/f(E) = e^{E/T}.$$

$$\prod_{i=1}^{n}\prod_{j=1}^{m} f_i(1 \pm f_j) = e^{-\omega/T}\prod_{i=1}^{n}\prod_{j=1}^{m}(1 \pm f_i)f_j$$

$$d\Gamma_{\text{prod}} = e^{-\omega/T}d\Gamma_{\text{rabs}}$$

- **The Luminosity of Z' in a SN (full calculation)**

$$L_{Z'}(m_{Z'}, g_{Z'}, R_\nu, R_{\text{att}}) = 4\pi \int_0^{R_\nu} \int_{m_{Z'}}^{\infty} r^2 \bar{\mathscr{A}}(\lambda_{\text{att}}(\omega, T), R_{\text{att}}) \sum_i \frac{d\dot{\epsilon}_i}{d\omega} d\omega dr$$

- **Free streaming limit (small $g_{Z'}$)**

$$\lambda_{\text{att}} \gg R_\nu$$

so that $\bar{\mathscr{A}} = 1$

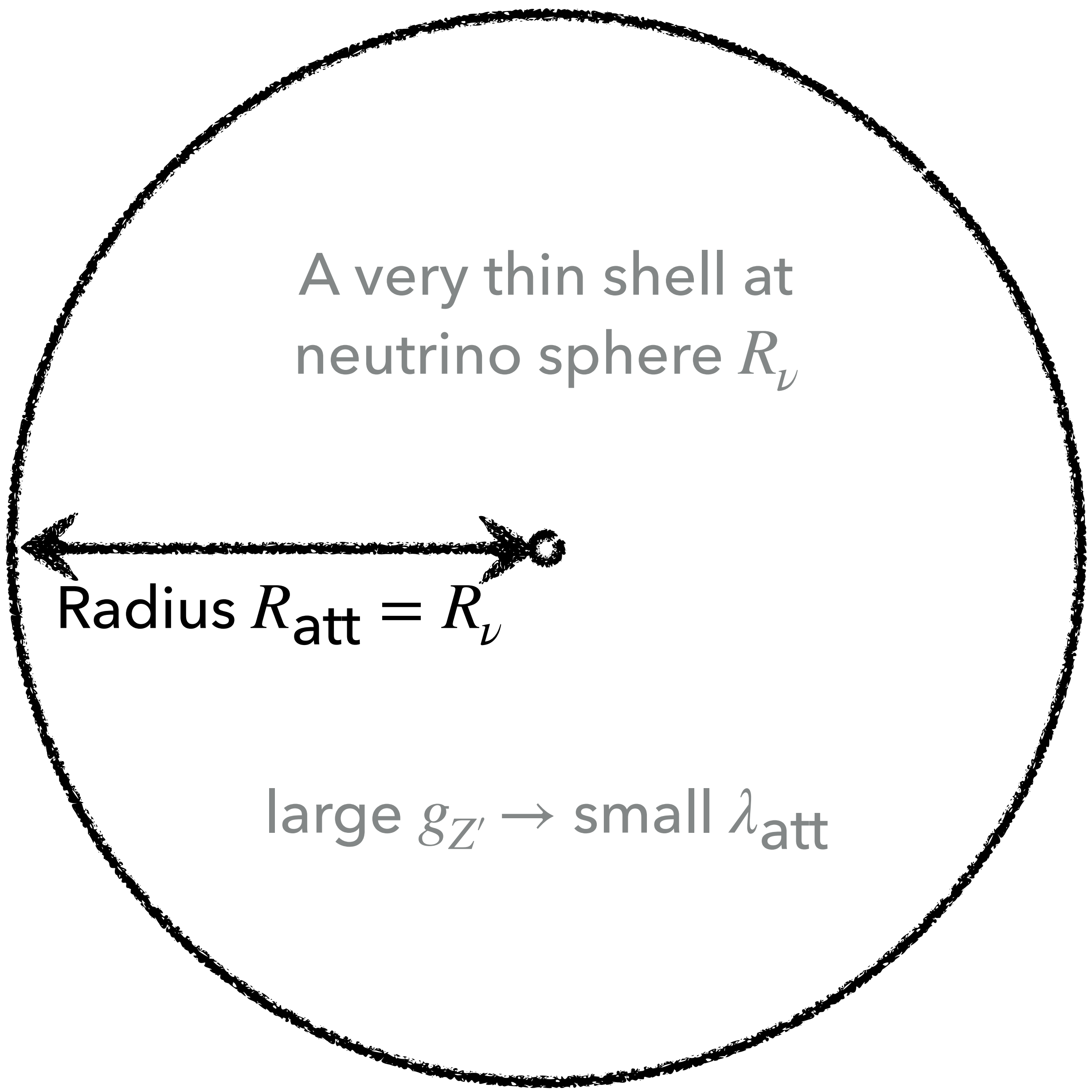
$$L_{Z'}(m_{Z'}, g_{Z'}, R_\nu) = 4\pi \int_0^{R_\nu} \int_{m_{Z'}}^{\infty} r^2 \sum_i \frac{d\dot{\epsilon}_i}{d\omega} d\omega dr$$

- **Trapping limit (large $g_{Z'}$)**

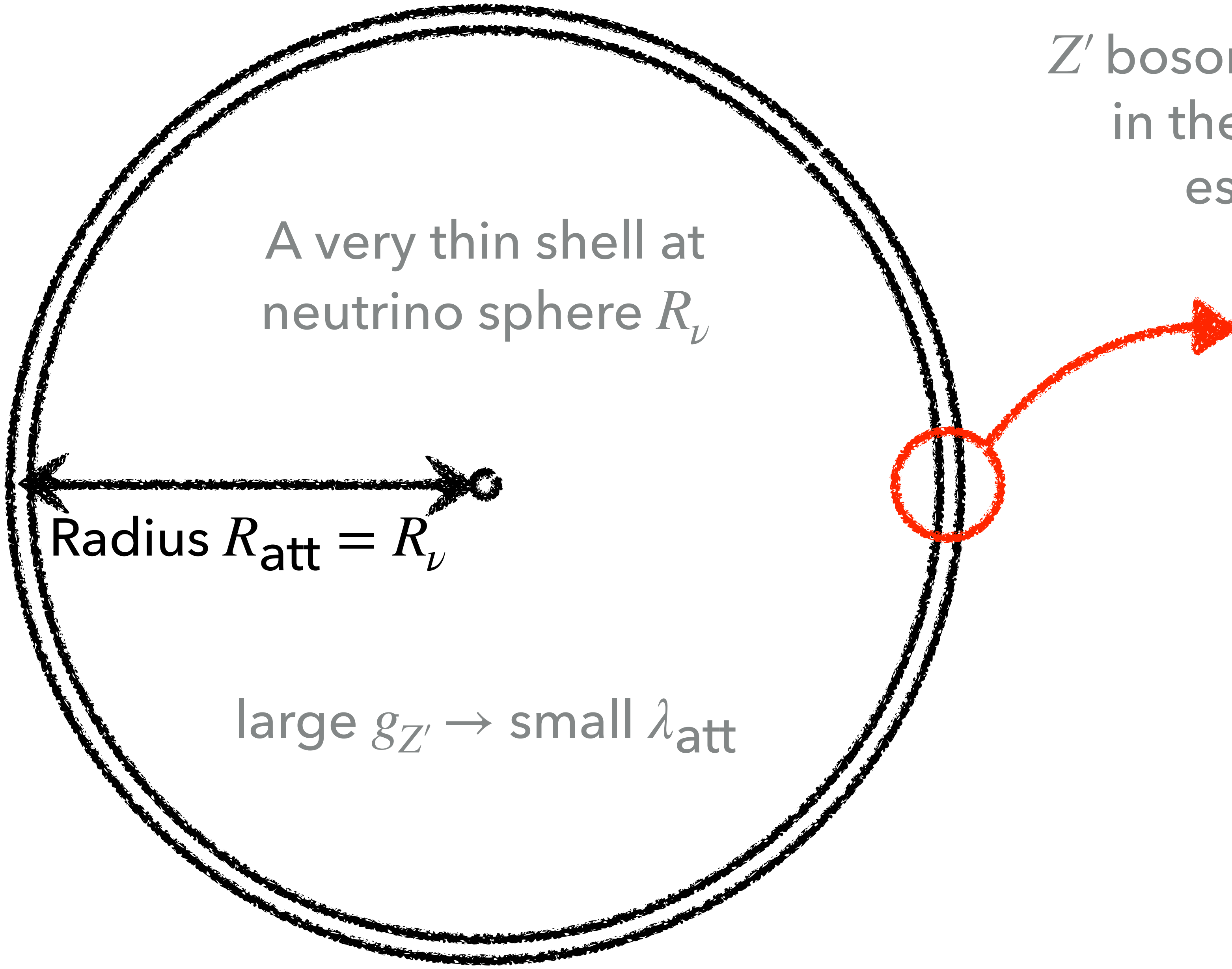
$$\lambda_{\text{att}} \ll R_\nu$$

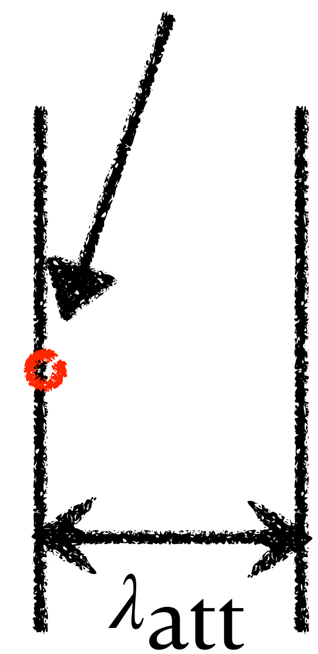
$$L_\infty(m_{Z'}) = \pi R_\nu^2 \int_{m_{Z'}}^{\infty} \lambda_{\text{att}}(m_{Z'}, R_\nu, \omega) \frac{d\dot{\epsilon}}{d\omega}(m_{Z'}, R, \omega) d\omega$$

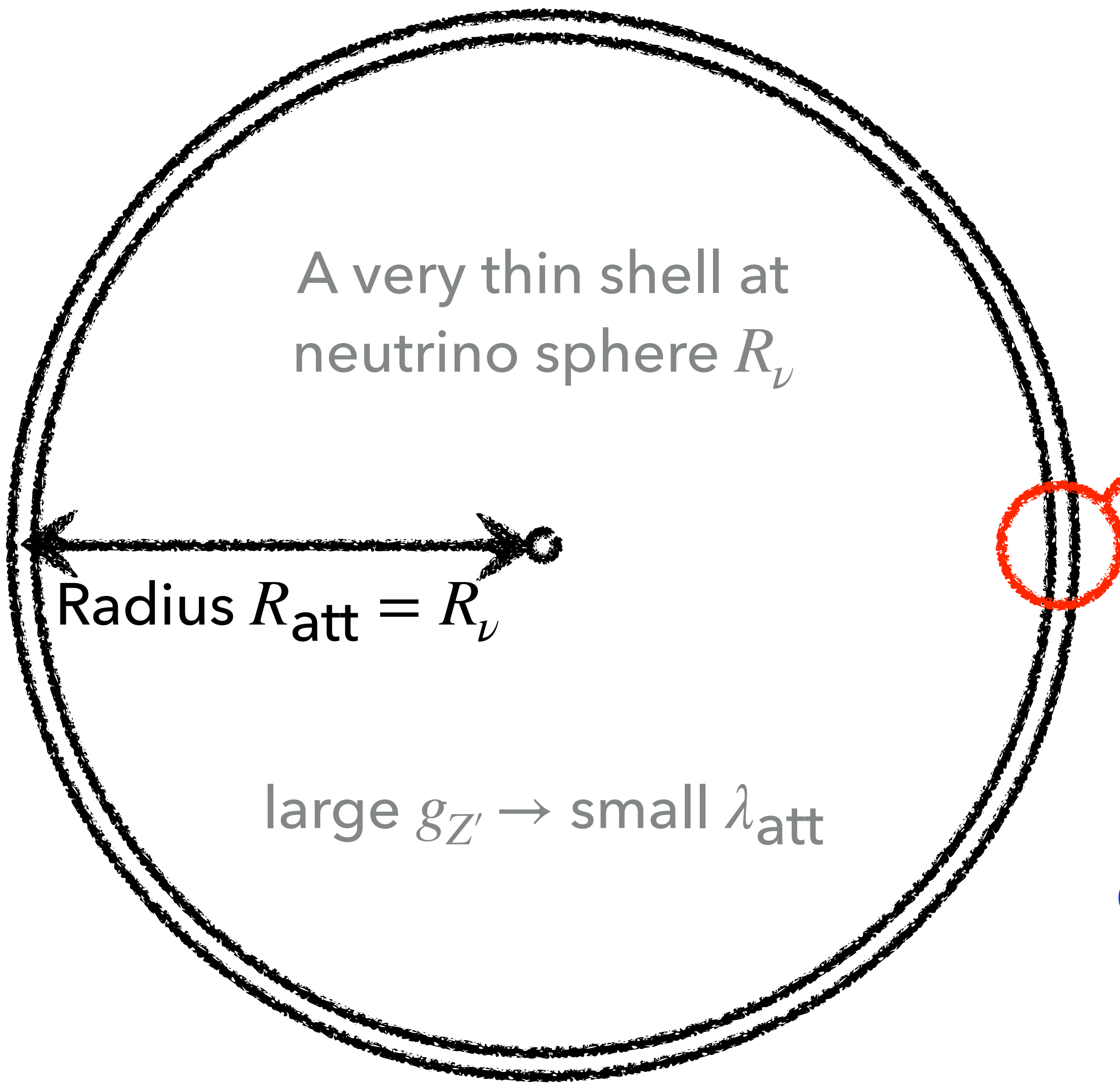
Only those Z′ produced within an attenuation length from the surface of the neutrino sphere could carry energies out of the PNS.


A very thin shell at
neutrino sphere R_ν
Radius $R_{\text{att}} = R_\nu$
large $g_{Z'}$ → small λ_{att}

Z' boson that is produced at any region in the gap might have a chance to escape the neutrino sphere.







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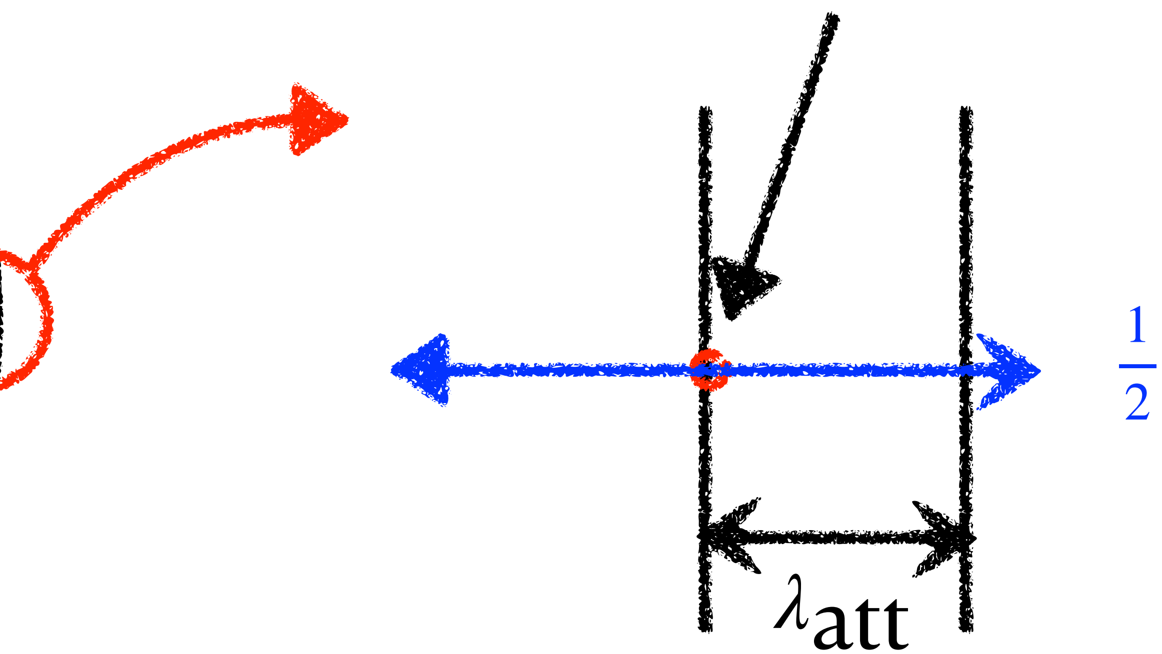

Only half of the produced Z' bosons propagate outward

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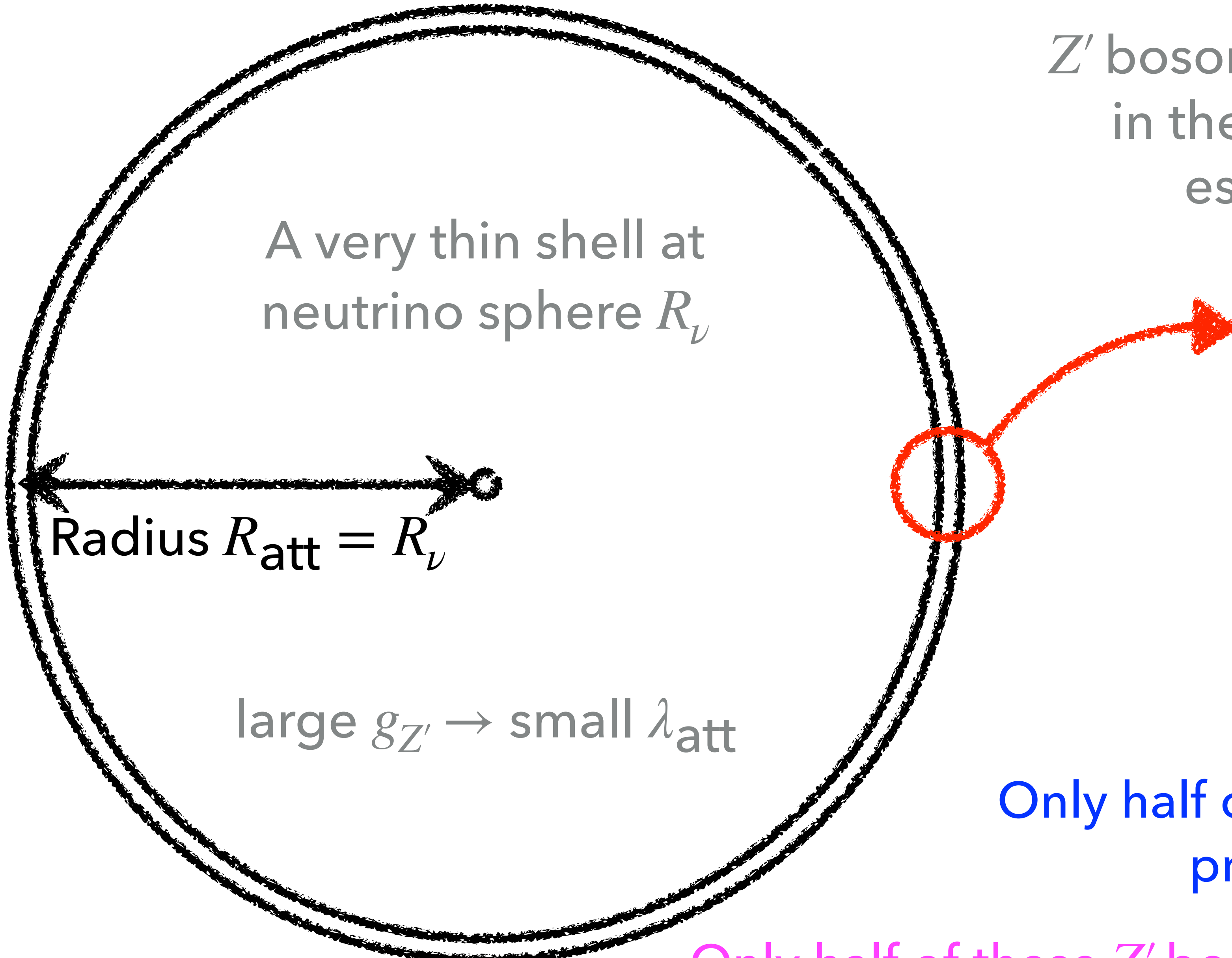
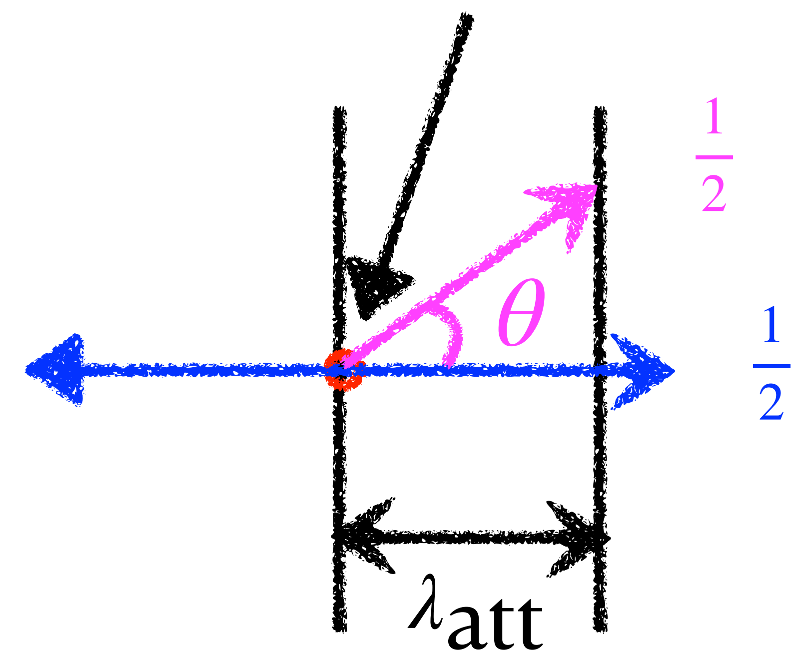
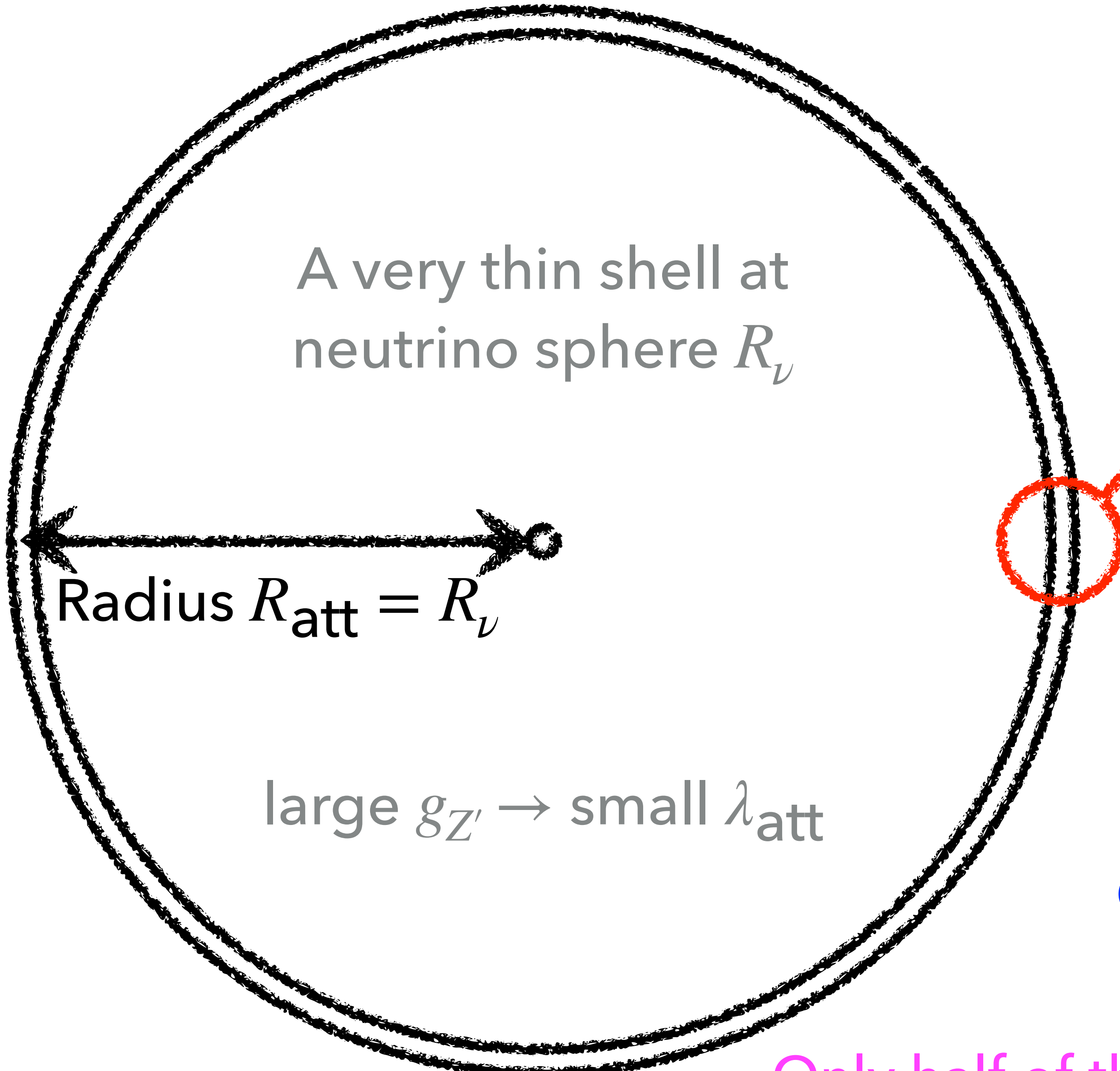




Only half of the produced Z' bosons propagate outward

Only half of these Z' bosons are perpendicular to the surface of the sphere and contribute to the Z' luminosity

$$\int_0^{\pi/2} cos\theta \sin\theta d\theta = \frac{1}{2}$$



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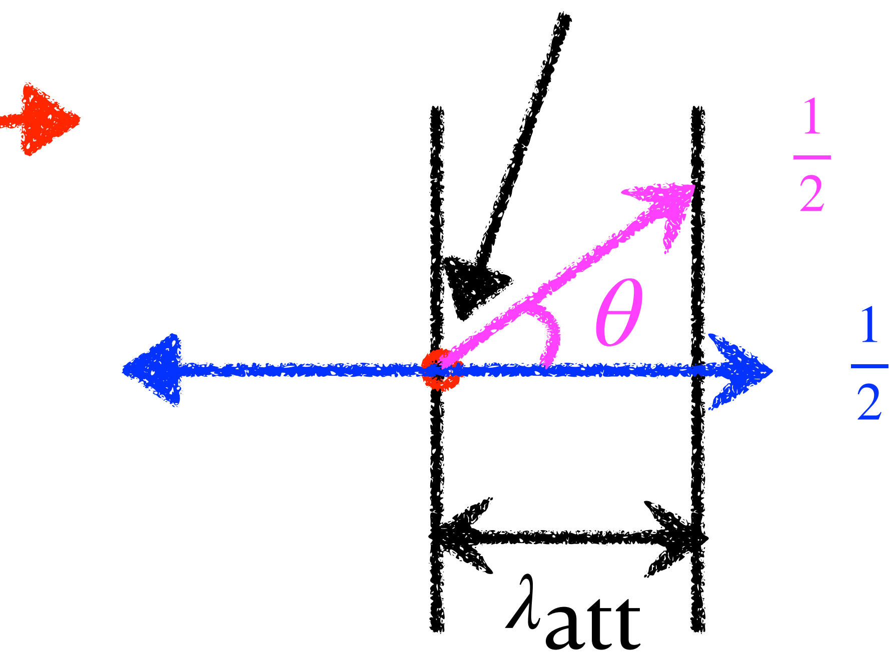

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$$L_\infty(m_{Z'}) = 4\pi R^2 \int_{m_{Z'}}^{\infty} \lambda_{\text{att}}(m_{Z'}, R_\nu, \omega) \frac{d\dot{\epsilon}}{d\omega}(m_{Z'}, R_\nu, \omega) d\omega \times \frac{1}{2} \times \frac{1}{2}$$

$$= \pi R_\nu^2 \int_{m_{Z'}}^{\infty} \lambda_{\text{att}}(m_{Z'}, R_\nu, \omega) \frac{d\dot{\epsilon}}{d\omega}(m_{Z'}, R, \omega) d\omega$$

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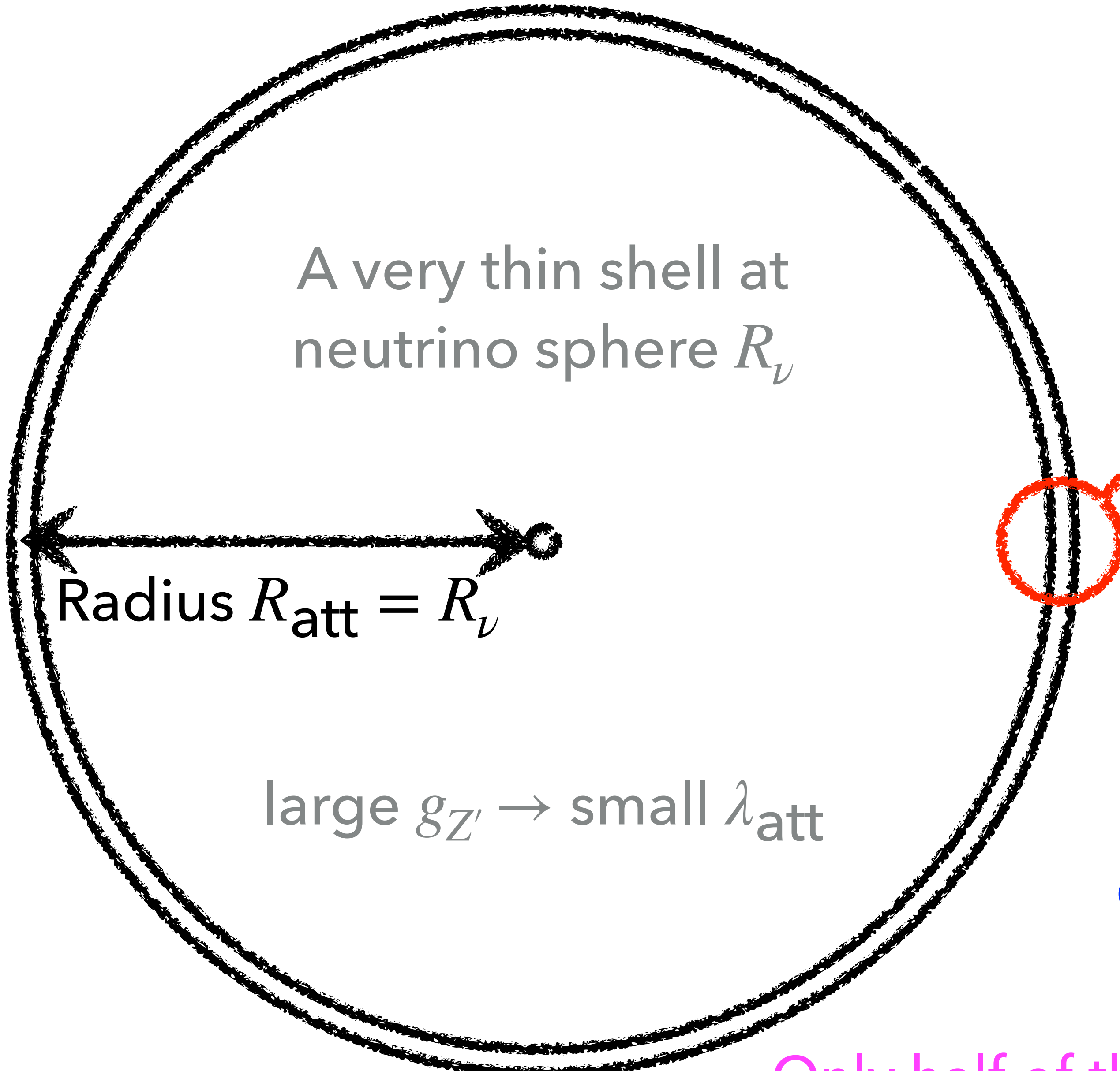

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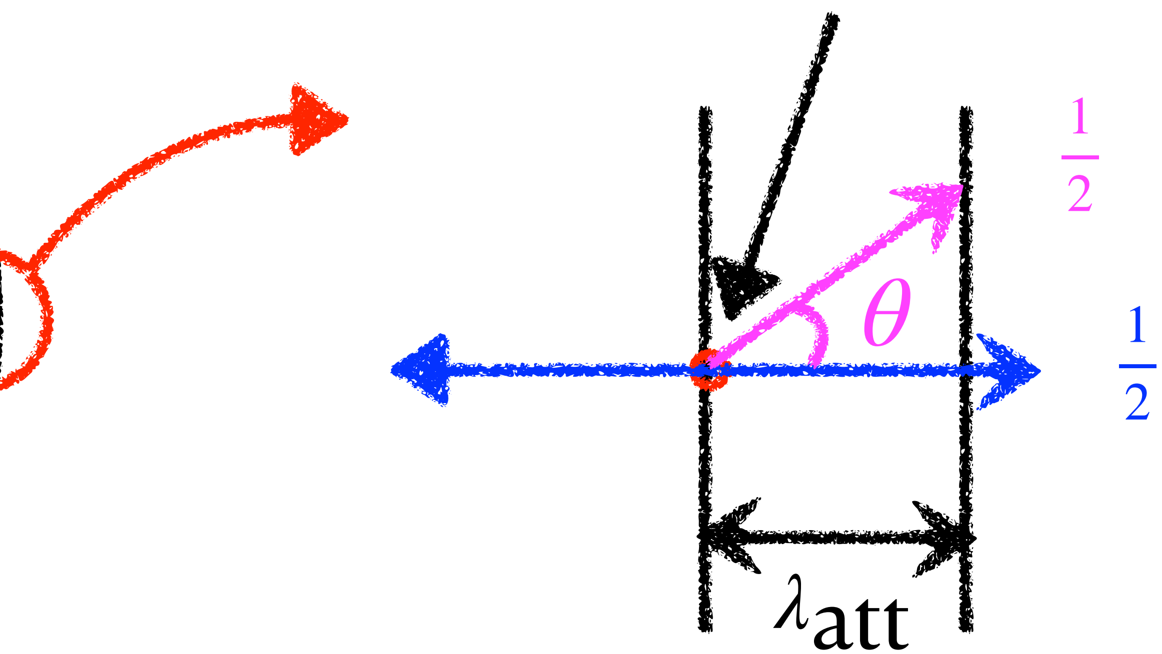

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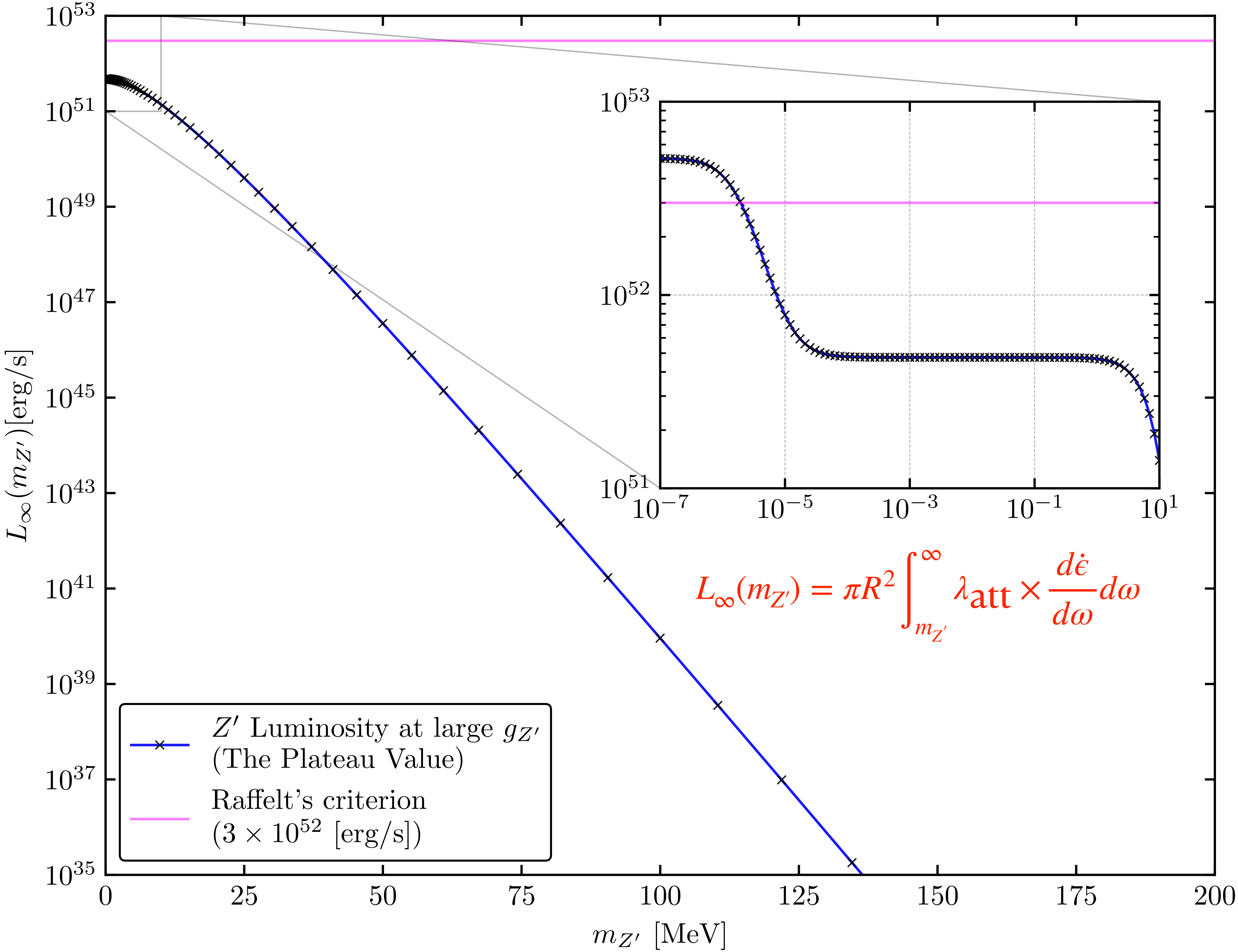
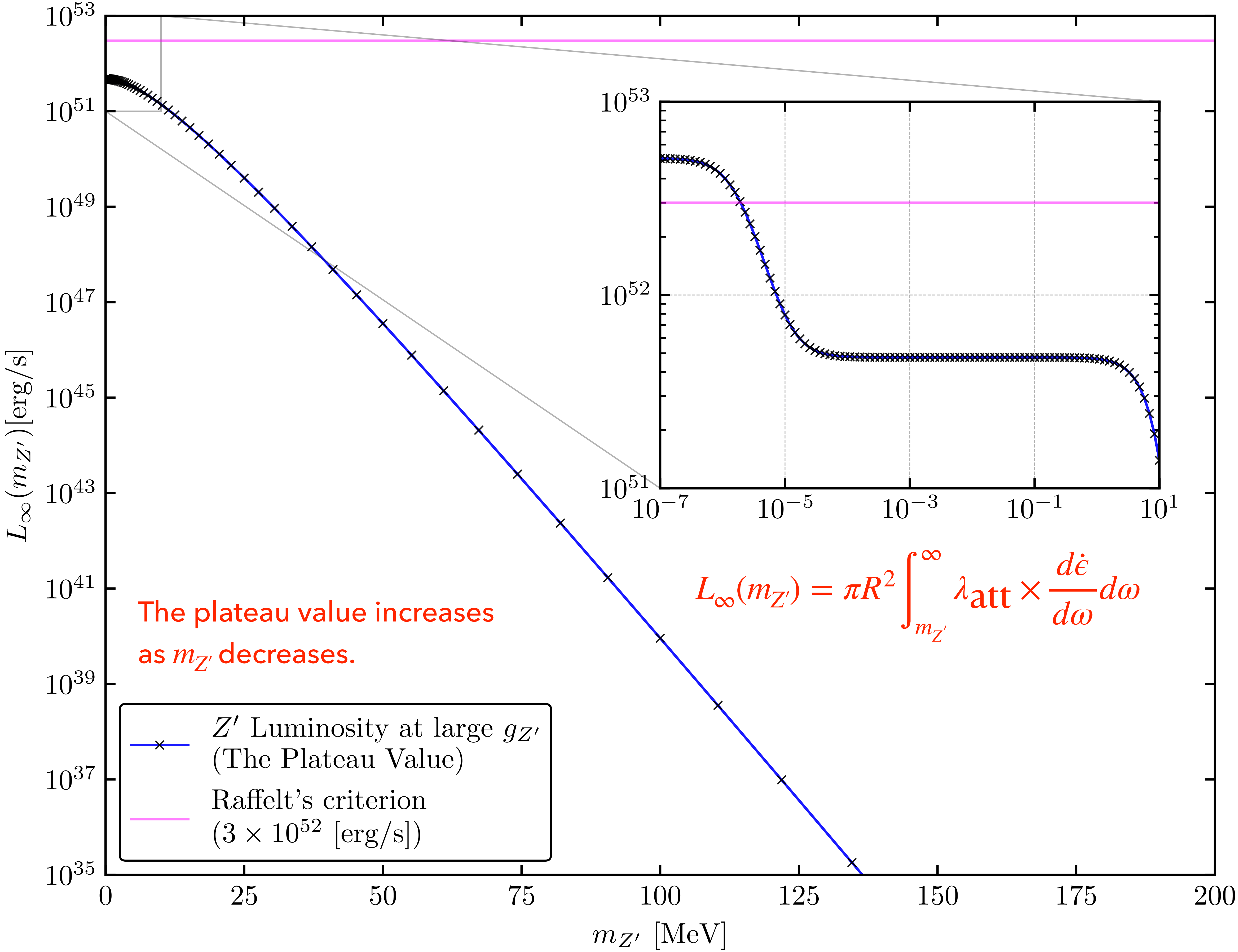
$$= \pi R_\nu^2 \int_{m_{Z'}}^{\infty} \underbrace{\lambda_{\text{att}}(m_{Z'}, R_\nu, \omega)}_{\propto g_{Z'}^{-2}} \underbrace{\frac{d\dot{\epsilon}}{d\omega}(m_{Z'}, R, \omega)}_{\propto g_{Z'}^{2}} d\omega$$

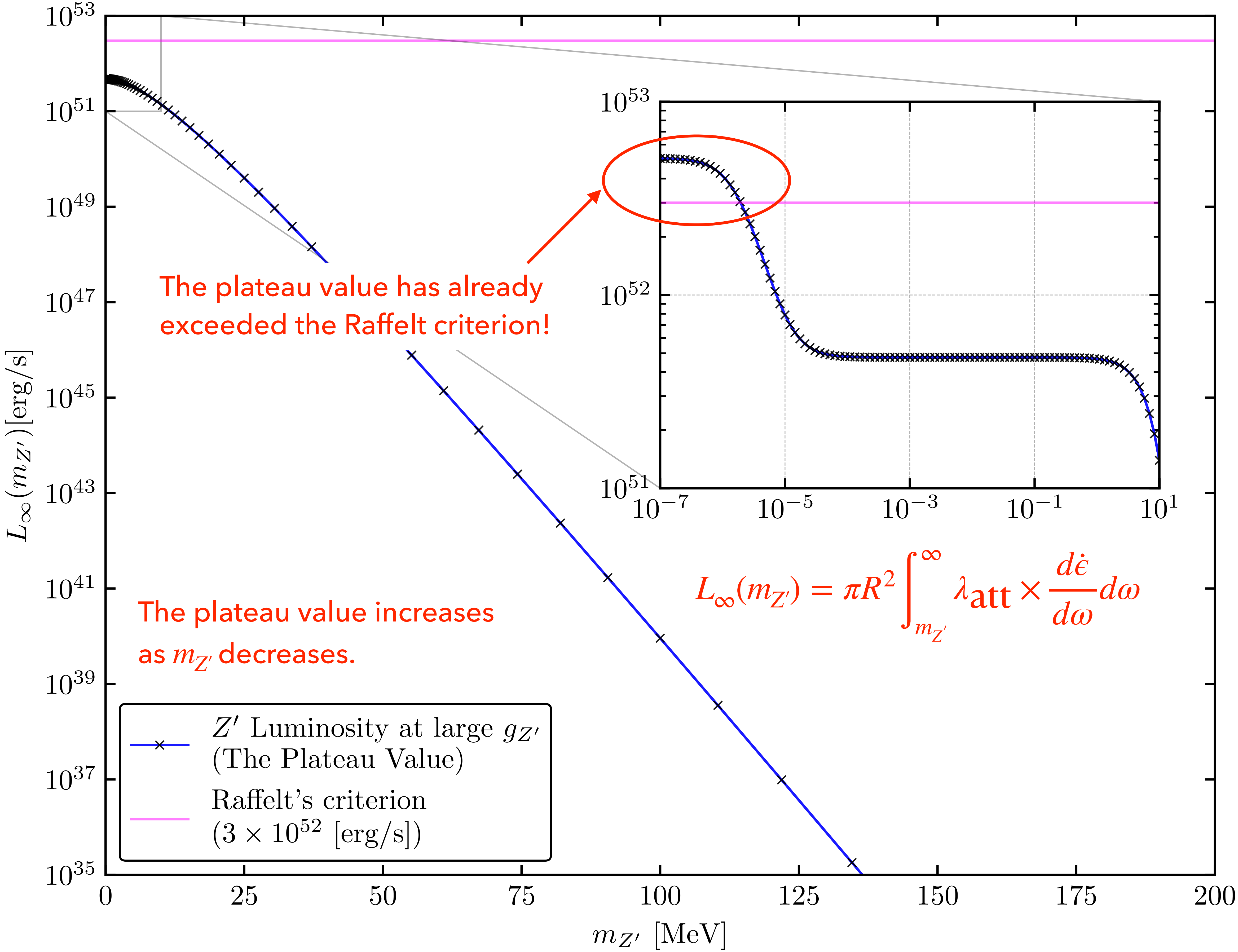
$$\int_0^{\pi/2} cos\theta \sin\theta d\theta = \frac{1}{2}$$

Independent of $g_{Z'}$!

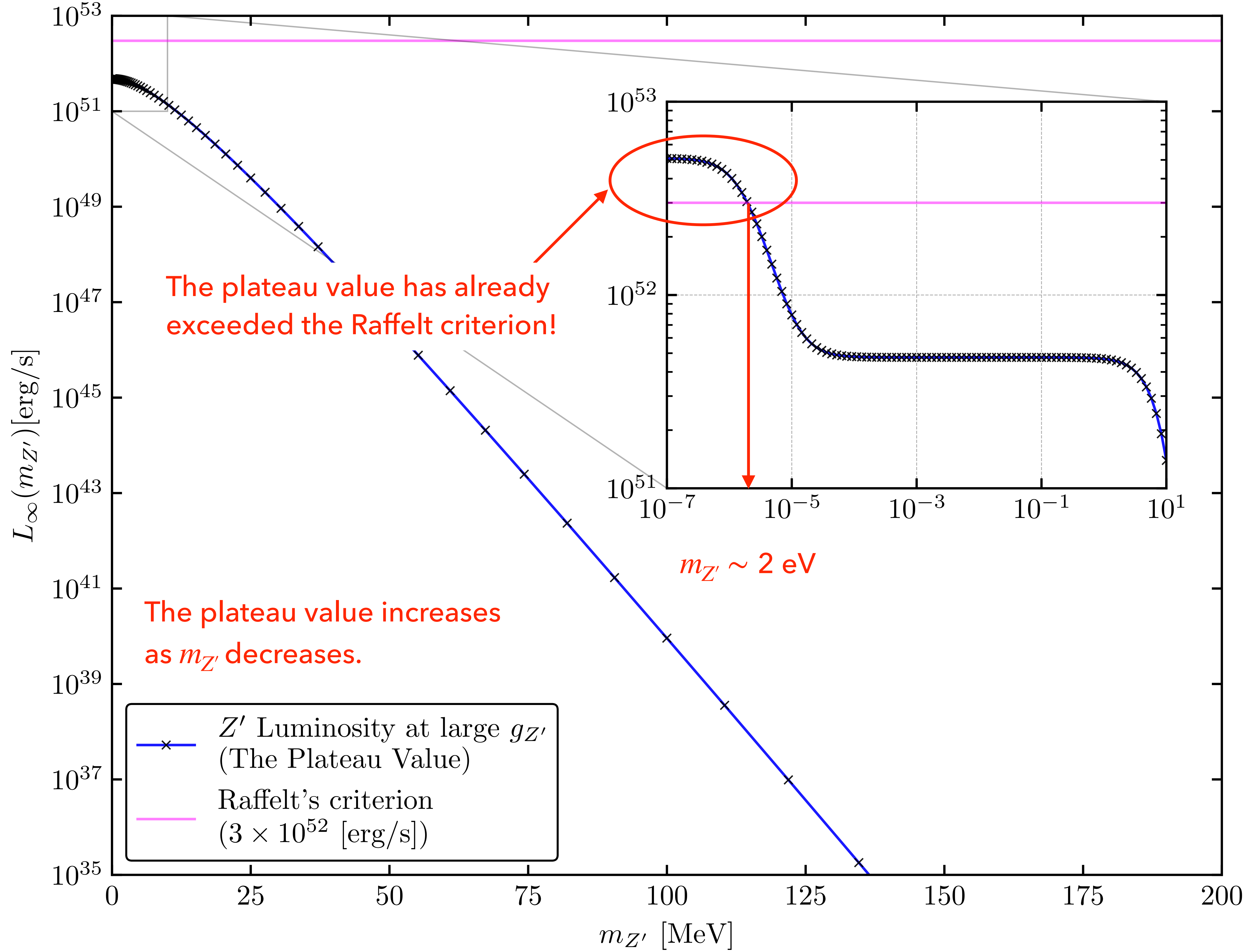

10^{53}
10^{51}
10^{49}
10^{47}
10^{45}
10^{43}
10^{41}
10^{39}
10^{37}
10^{35}
$L_\infty(m_{Z'})$[erg/s]
0 25 50 75 100 125 150 175 200
$m_{Z'}$ [MeV]
10^{53}
10^{52}
10^{51}
10^{-7} 10^{-5} 10^{-3} 10^{-1} 10^{1}
Z' Luminosity at large $g_{Z'}$
(The Plateau Value)
Raffelt's criterion
(3×10^{52} [erg/s])
$L_\infty(m_{Z'}) = \pi R^2 \int_{m_{Z'}}^{\infty} \lambda_{\text{att}} \times \frac{d\dot{\epsilon}}{d\omega} d\omega$

WHEN WILL THE PLATEAU BE HIGHER THAN THE RAFFELT CRITERION?

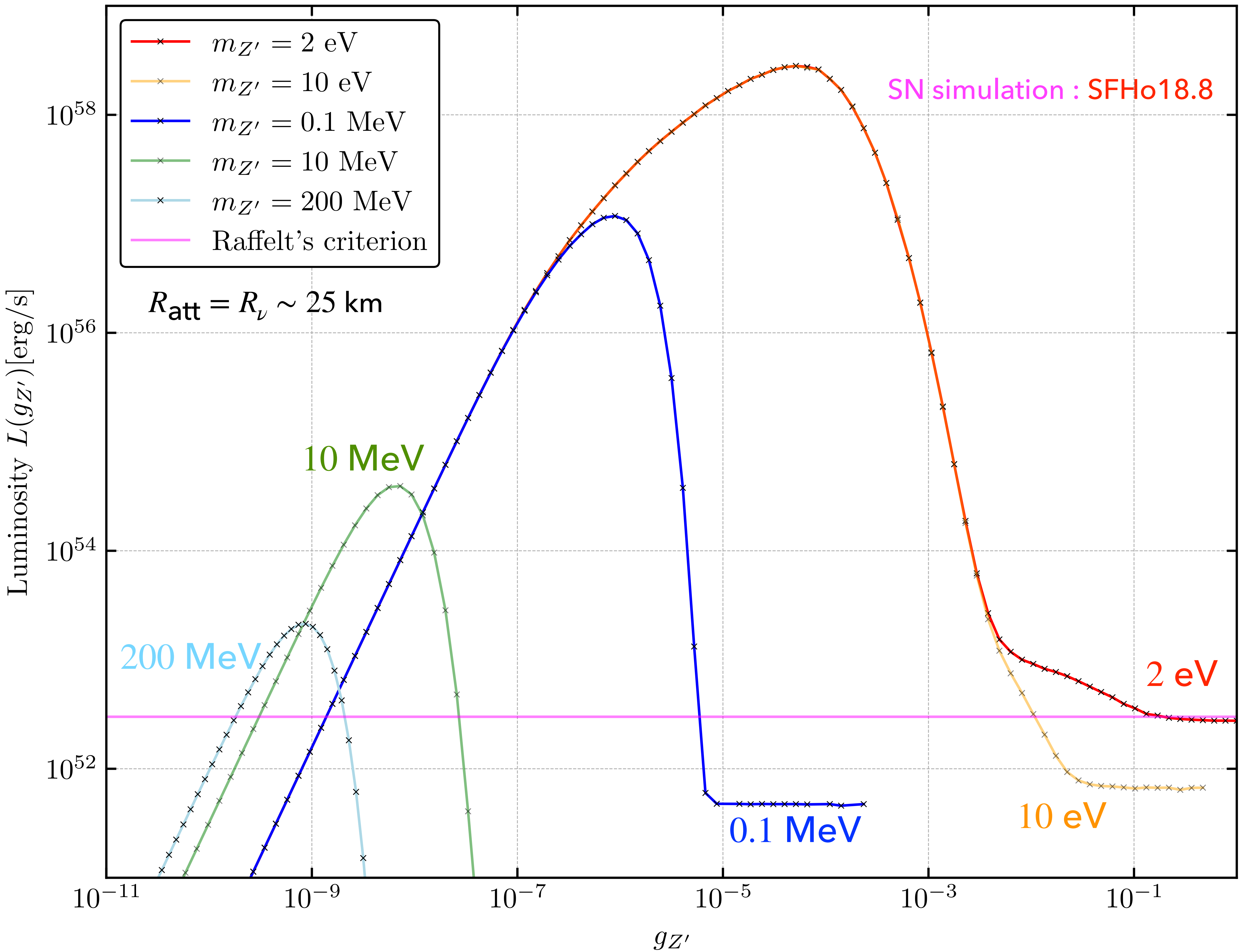


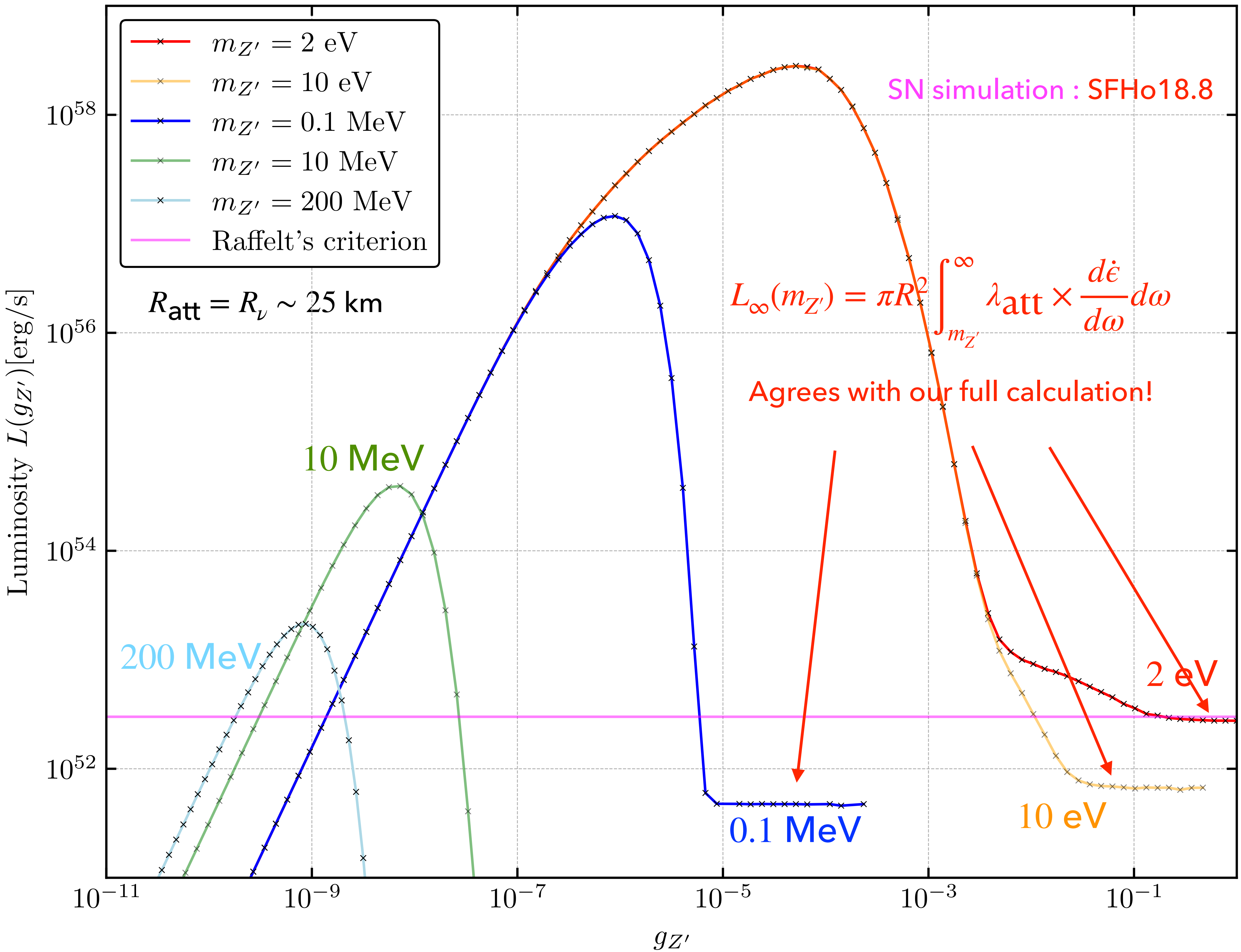


The plateau value has already exceeded the Raffelt criterion!
The plateau value increases as $m_{Z'}$ decreases.
$L_\infty(m_{Z'}) = \pi R^2 \int_{m_{Z'}}^{\infty} \lambda_{\text{att}} \times \frac{d\dot{\epsilon}}{d\omega} d\omega$
$L_\infty(m_{Z'})$[erg/s]
$m_{Z'}$ [MeV]
Z' Luminosity at large $g_{Z'}$ (The Plateau Value)
Raffelt's criterion (3×10^{52} [erg/s])

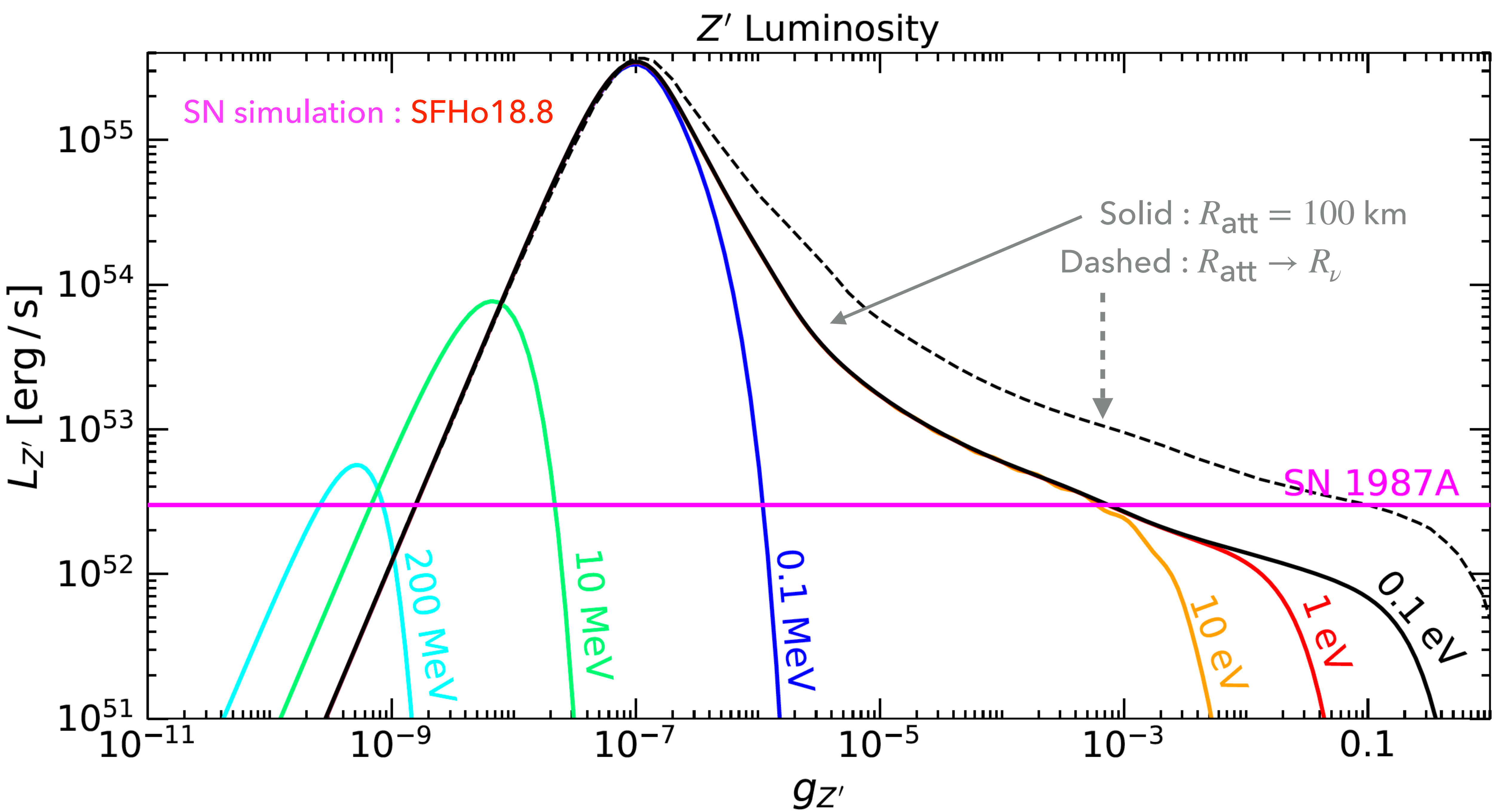


10^{53}
10^{51}
10^{49}
10^{47}
10^{45}
10^{43}
10^{41}
10^{39}
10^{37}
10^{35}
$L_\infty(m_{Z'})$[erg/s]
0 25 50 75 100 125 150 175 200
$m_{Z'}$ [MeV]
10^{53}
10^{52}
10^{51}
10^{-7} 10^{-5} 10^{-3} 10^{-1} 10^{1}
The plateau value has already exceeded the Raffelt criterion!
$m_{Z'} \sim$ 2 eV
The plateau value increases as $m_{Z'}$ decreases.
Z' Luminosity at large $g_{Z'}$ (The Plateau Value)
Raffelt's criterion (3×10^{52} [erg/s])

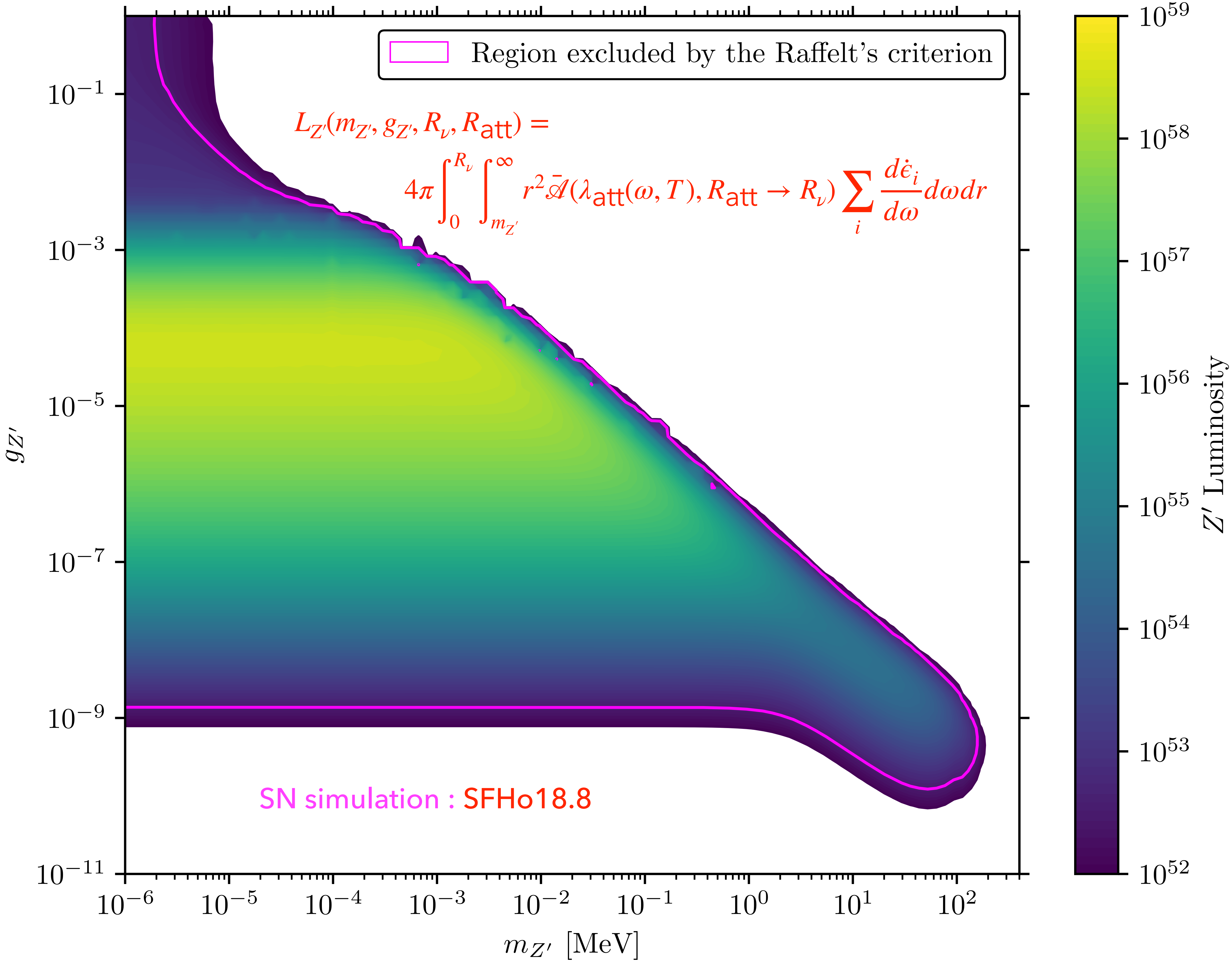

$m_{Z'} = 2$ eV
$m_{Z'} = 10$ eV
$m_{Z'} = 0.1$ MeV
$m_{Z'} = 10$ MeV
$m_{Z'} = 200$ MeV
Raffelt's criterion
$R_{\rm att} = R_\nu \sim 25$ km
SN simulation : SFHo18.8
10 MeV
200 MeV
0.1 MeV
10 eV
2 eV
Luminosity $L(g_{Z'})$[erg/s]
10^{58}
10^{56}
10^{54}
10^{52}
10^{-11}
10^{-9}
10^{-7}
10^{-5}
10^{-3}
10^{-1}
$g_{Z'}$


$m_{Z'} = 2$ eV
$m_{Z'} = 10$ eV
$m_{Z'} = 0.1$ MeV
$m_{Z'} = 10$ MeV
$m_{Z'} = 200$ MeV
Raffelt's criterion
$R_{\rm att} = R_\nu \sim 25$ km
SN simulation : SFHo18.8
$L_\infty(m_{Z'}) = \pi R^2 \int_{m_{Z'}}^{\infty} \lambda_{\rm att} \times \frac{d\dot{\epsilon}}{d\omega} d\omega$
Agrees with our full calculation!
10 MeV
200 MeV
0.1 MeV
10 eV
2 eV
Luminosity $L(g_{Z'})$[erg/s]
$g_{Z'}$
10^{58}
10^{56}
10^{54}
10^{52}
10^{-11}
10^{-9}
10^{-7}
10^{-5}
10^{-3}
10^{-1}

D. Croon *et al.*, JHEP. Phys. 2021, 107 (2021)

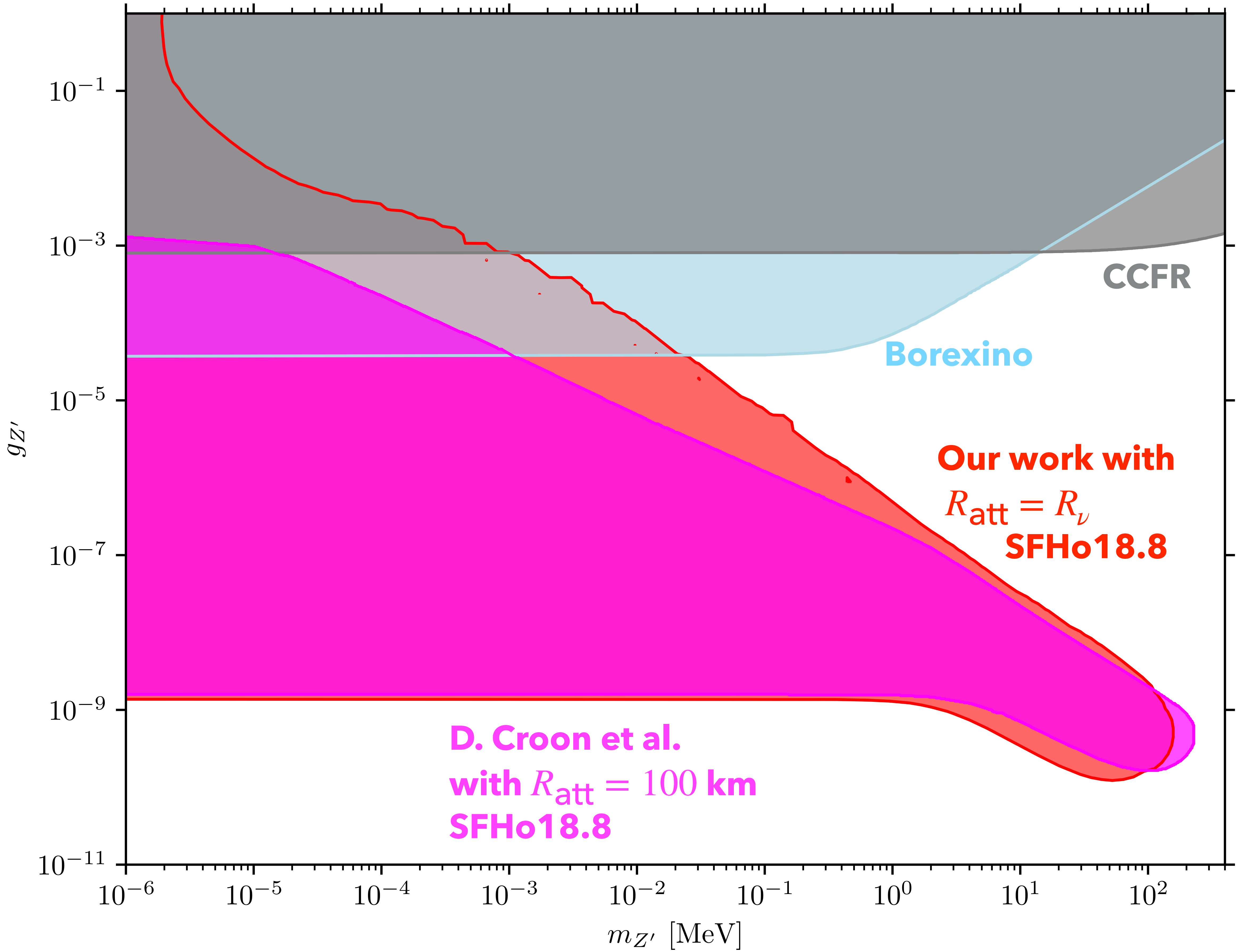


For $R_{\rm att} = R_\nu$, the Z′ luminosity does not approach the plateau value here!


Region excluded by the Raffelt's criterion
$L_{Z'}(m_{Z'}, g_{Z'}, R_\nu, R_{\rm att}) =$
$4\pi \int_0^{R_\nu} \int_{m_{Z'}}^{\infty} r^2 \bar{\mathscr{A}}(\lambda_{\rm att}(\omega, T), R_{\rm att} \to R_\nu) \sum_i \frac{d\dot{\epsilon}_i}{d\omega} d\omega dr$
SN simulation : SFHo18.8
$g_{Z'}$
$m_{Z'}$ [MeV]
Z' Luminosity
10^{-1}
10^{-3}
10^{-5}
10^{-7}
10^{-9}
10^{-11}
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{59}
10^{58}
10^{57}
10^{56}
10^{55}
10^{54}
10^{53}
10^{52}

d. Amaral *et al.*, JHEP 2020, 155 (2020)

W. Altmannshofer *et al.*,
JPhys. Rev. Lett. 113 (2014) 091801



SUMMARY

- We have explained how the observation of SN 1987A can be used to limit beyond-standard-model (BSM) physics.
- The constraint to the new physics is given by the condition $L(m_{Z'}, g_{Z'}) \ll L_\nu = 3 \times 10^{52}$ [erg/s] at $t_{\rm pb} = 1$ s (Raffelt criterion)
- Calculating $L(m_{Z'}, g_{Z'})$ is easy for a small $g_{Z'}$, but it gets complicated for a large $g_{Z'}$ because both the production and absorption of Z' become important and their interplays must be carefully considered.
- Previous works avoided this challenge by using $R_{\rm att} > R_\nu$, which we believe is inconsistent. We used $R_{\rm att} = R_\nu$ instead and found that the constrained parameter space is very different from what was previously found.