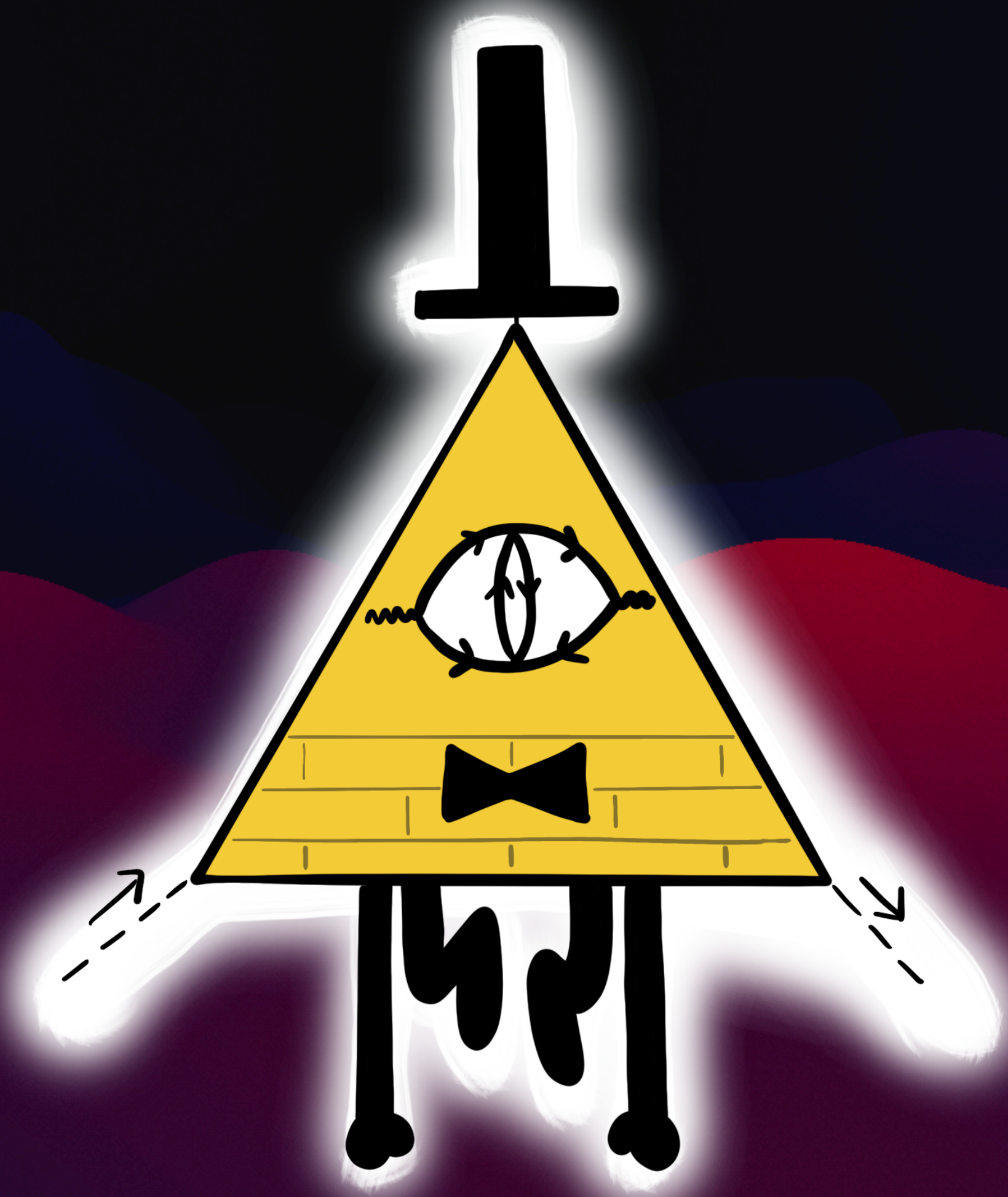


# DARK MATTER @ FINITE TEMPERATURE

SANIYA HEEBA,  
IPP FELLOW,  
CARLETON U.



**SECRET  
MOTIVATION**



**LET'S ALL DO FINITE  
TEMPERATURE DM PHENO**

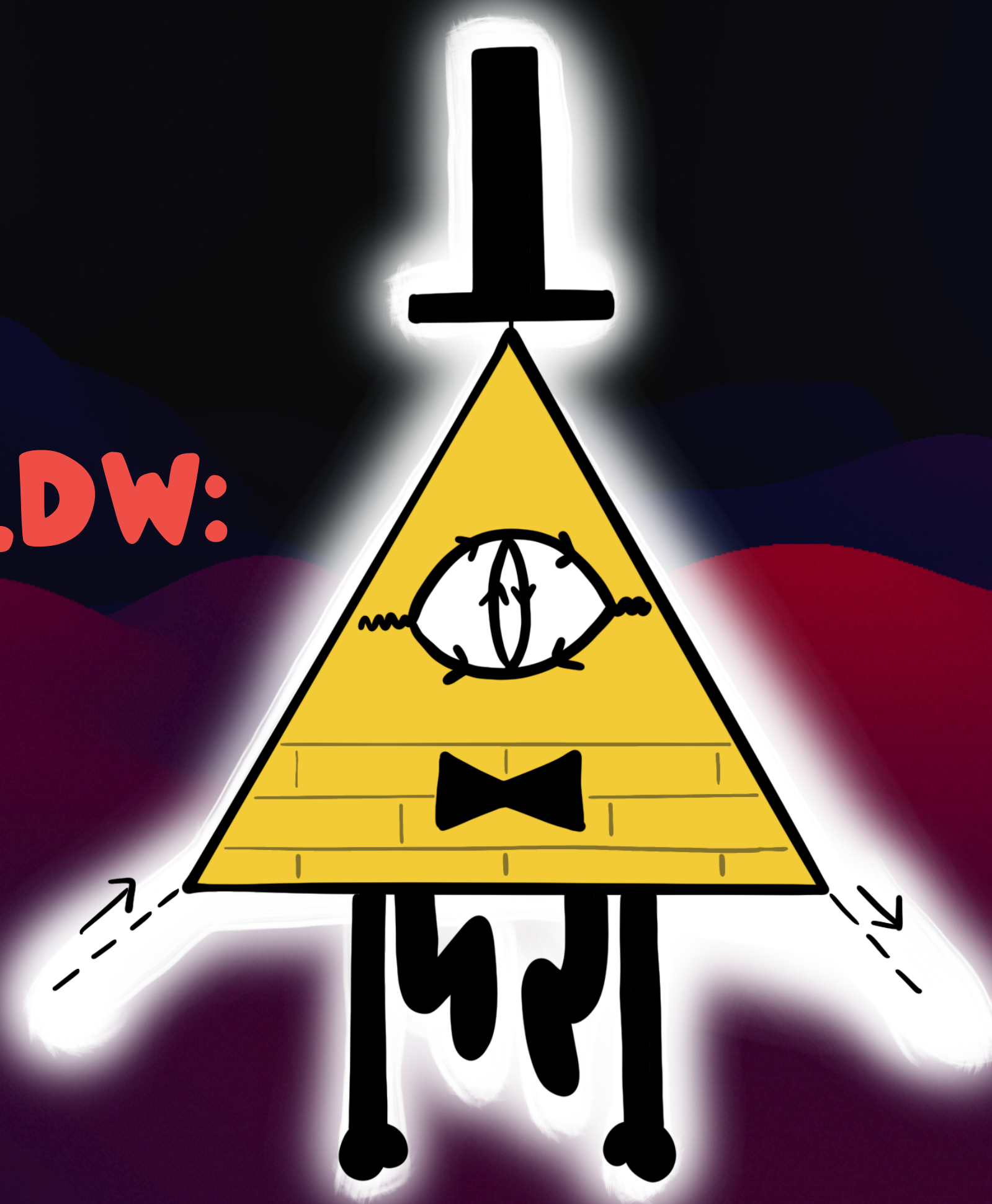


SECRET  
MOTIVATION

2

## FINITE TEMPERATURE AT LDW:

- ▶ GOPOLANG MOHLABENG
- ▶ NATNAEL DEBRU
- ▶ NIRMALYA BRAHMA
- ▶ MAXIM PERELSTEIN
- ▶ LEONARDO BADURINA
- ▶ HUGO SCHERER
- + ...



LET'S ALL DO FINITE  
TEMPERATURE DM PHENO



# FINITE TEMPERATURE AND DENSITY EFFECTS...



...ARE **RELEVANT**  
TO LIGHT BSM  
PHYSICS



...ARE **Non**  
**TRIVIAL** TO  
ESTIMATE



...REQUIRE  
**COLLABORATION AND**  
**CROSSTALK!**





PARTICLE  
PROPERTIES OF  
DARK MATTER  
ARE **POORLY**  
**CONSTRAINED**



TO BUILD A **DARK MATTER MODEL**, WE  
PROPOSE **PARTICLES AND INTERACTIONS**



TO BUILD A **DARK MATTER MODEL**, WE  
PROPOSE **PARTICLES AND INTERACTIONS**

5



WHAT IS THE  
**MASS SCALE?**



# TO BUILD A **DARK MATTER MODEL**, WE PROPOSE **PARTICLES** AND **INTERACTIONS**

5



WHAT IS THE  
**MASS SCALE?**



WHAT IS THE  
**INTERACTION TYPE?**  
**INTERACTION STRENGTH?**



# AND DETERMINE HOW THESE IMPACT **OBSERVABLES** AT DIFFERENT SCALES





ALL THESE CALCULATIONS ASSUME THAT EVERYTHING<sup>7</sup>  
HAPPENS IN A **VACUUM**



ALL THESE CALCULATIONS ASSUME THAT EVERYTHING<sup>7</sup>  
HAPPENS IN A **VACUUM**



BUT THE UNIVERSE IS A ~~HOT MESS~~  
FULL OF **PLASMAS**: FINITE DENSITY AND TEMPERATURE  
ENVIRONMENTS



DO PLASMAS **FUNDAMENTALLY**  
**ALTER THE BEHAVIOUR** OF  
PARTICLES?



IN THE **STANDARD MODEL:**



# IN THE STANDARD MODEL:



$$m_{\gamma}^{\text{vac}} = 0$$

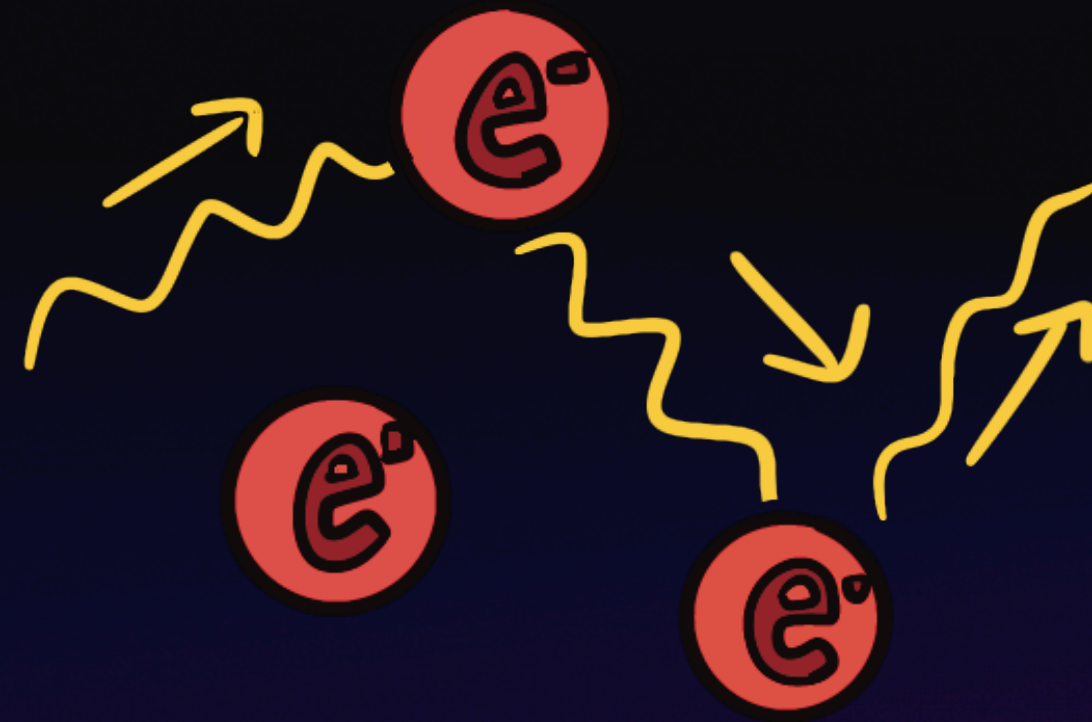


# IN THE STANDARD MODEL:

9



$$m_{\gamma}^{\text{vac}} = 0$$



DISPERSES LIKE  
A MASSIVE PARTICLE

$$\Pi_T = \omega_p^2 = \omega_e^2 - k^2$$

$$\Pi_L = \omega_p^2 = \omega_e^2$$

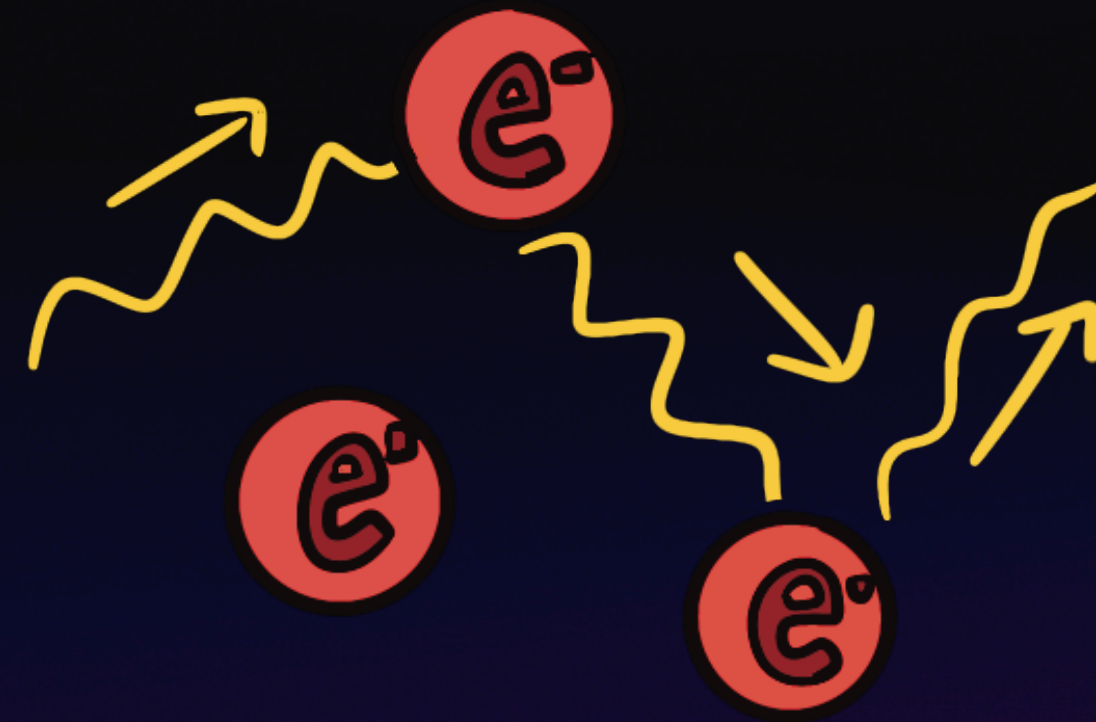


# IN THE STANDARD MODEL:

9



$$m_{\gamma}^{\text{vac}} = 0$$



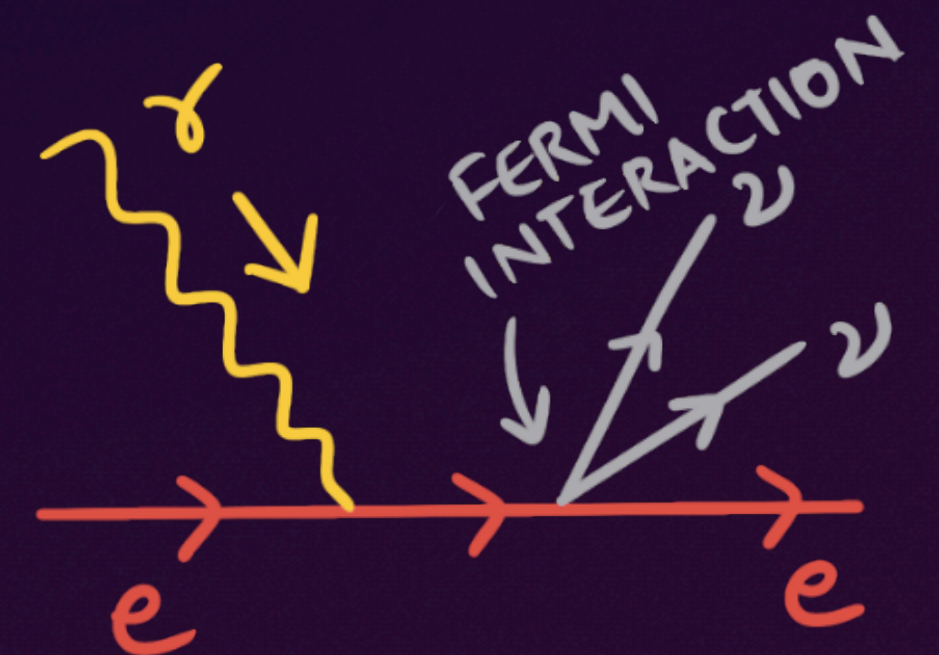
DISPERSES LIKE  
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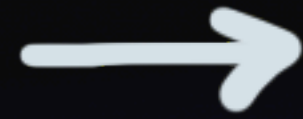
PLASMONS CAN  
DECAY!





# IN THE STANDARD MODEL:

10

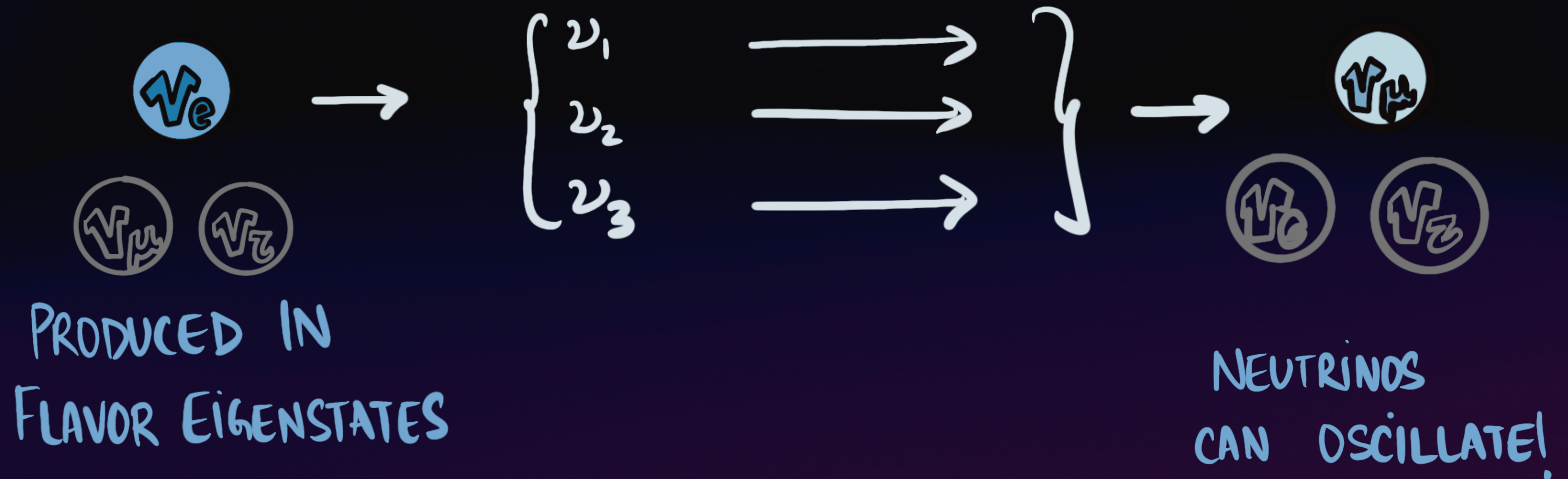


PRODUCED IN  
FLAVOR EIGENSTATES



# IN THE **STANDARD MODEL**:

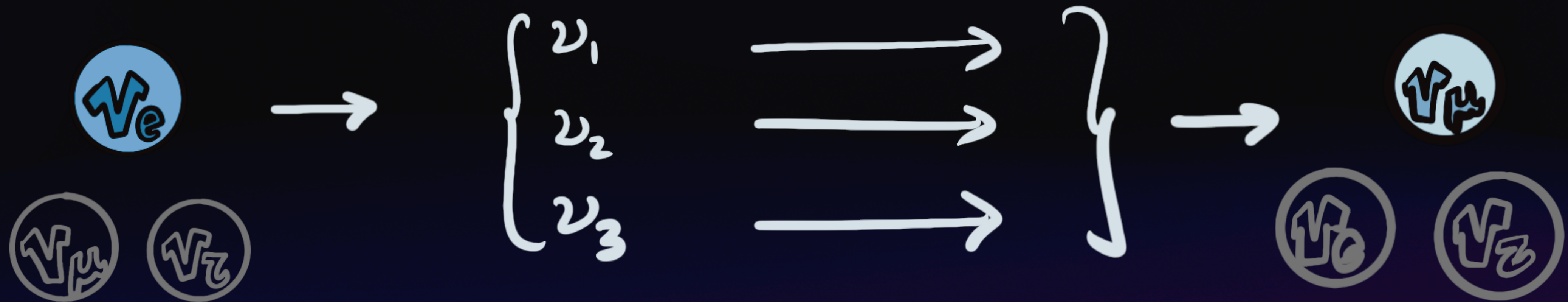
10



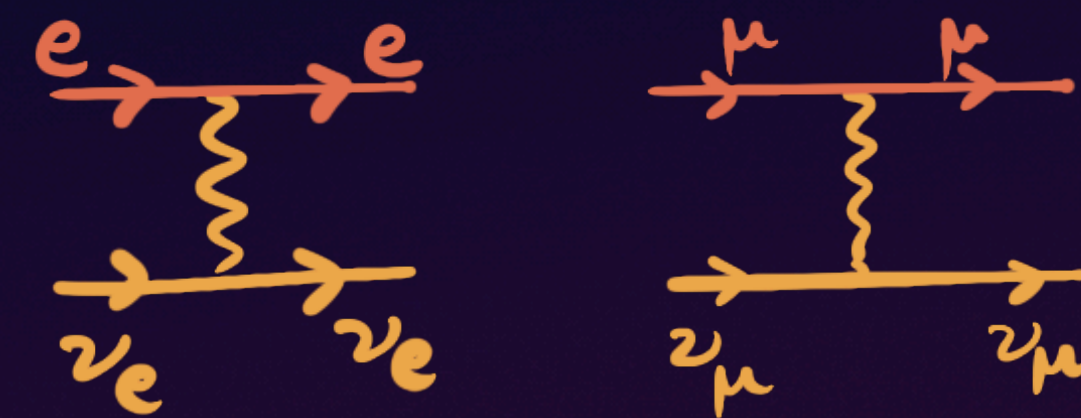


# IN THE STANDARD MODEL:

10



PRODUCED IN  
FLAVOR EIGENSTATES



MIXING ANGLE GETS  
MODIFIED IN THE MEDIUM

NEUTRINOS  
CAN OSCILLATE!

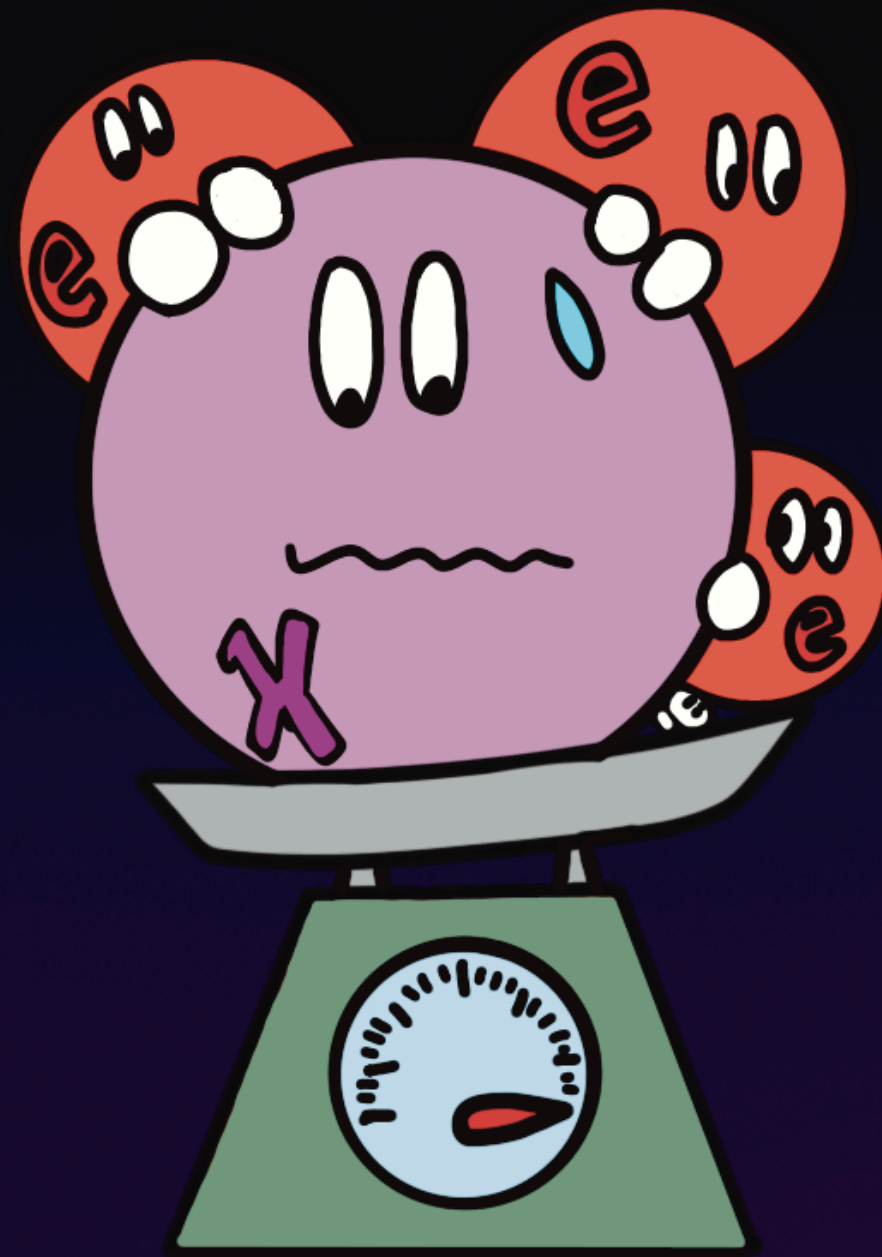
AT A DIFFERENT FREQUENCY!



**PLASMAS DO FUNDAMENTALLY ALTER THE  
PROPERTIES OF PARTICLES**



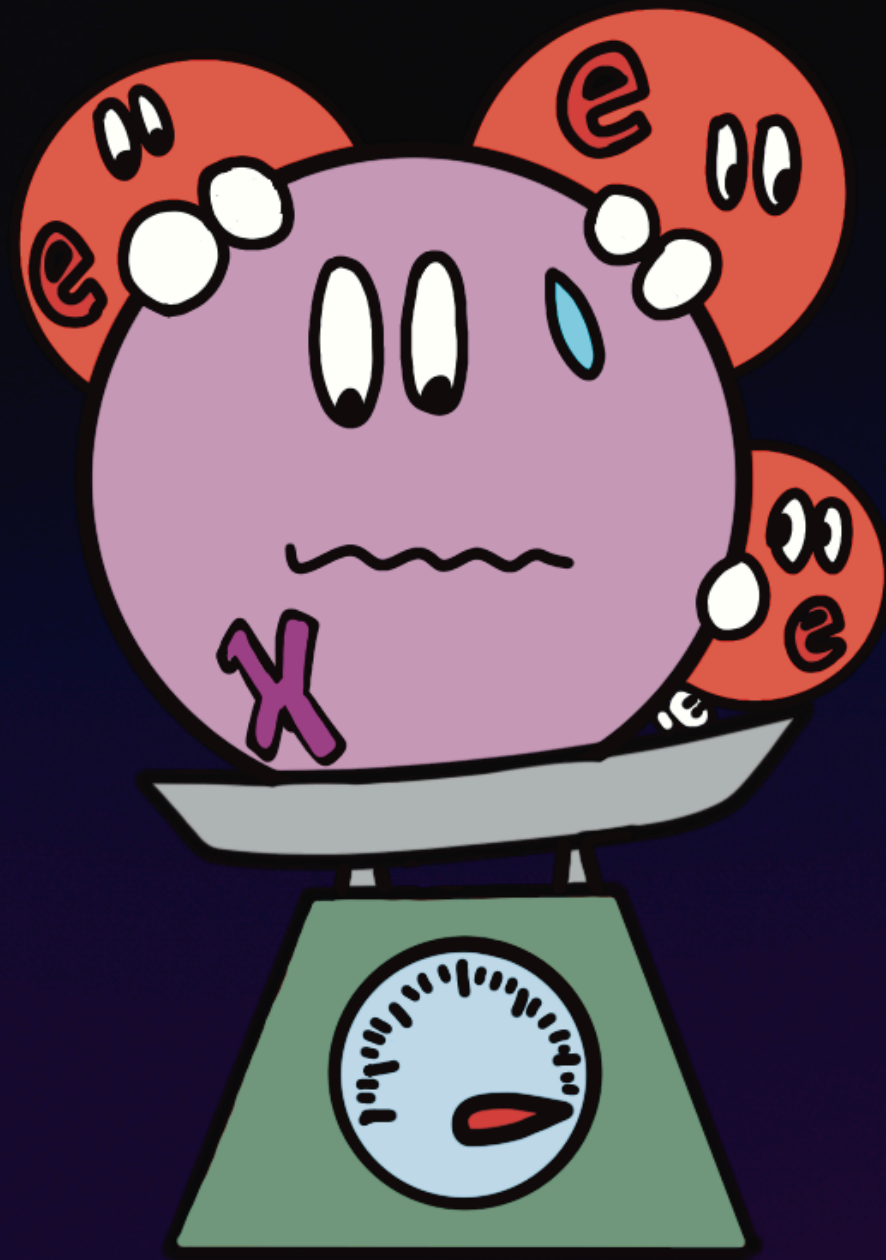
# PLASMAS DO **FUNDAMENTALLY ALTER THE** **PROPERTIES** OF PARTICLES



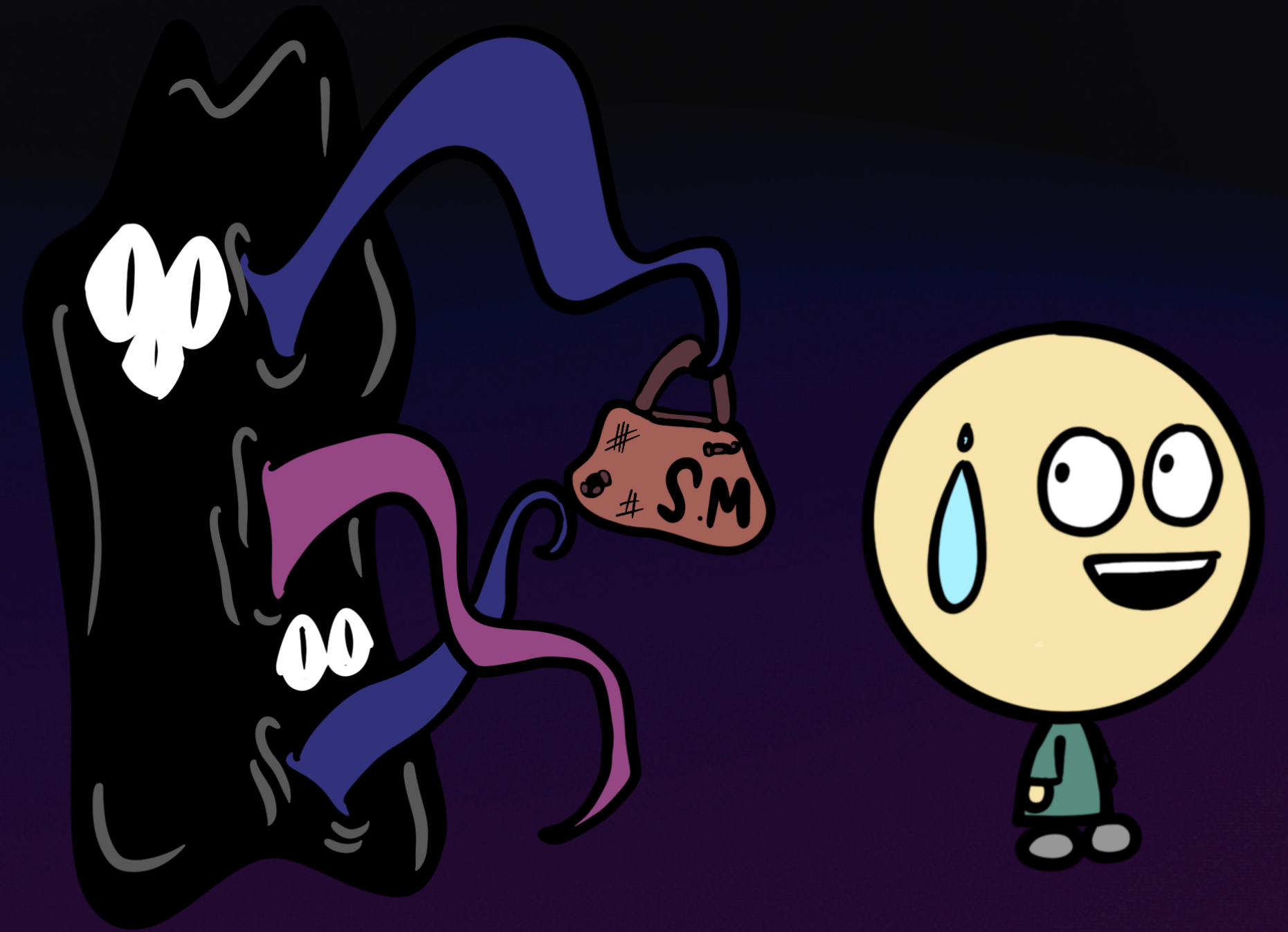
A MEDIUM DEPENDENT  
**EFFECTIVE MASS**



# PLASMAS DO **FUNDAMENTALLY** ALTER THE **PROPERTIES** OF PARTICLES



A MEDIUM DEPENDENT  
**EFFECTIVE MASS**



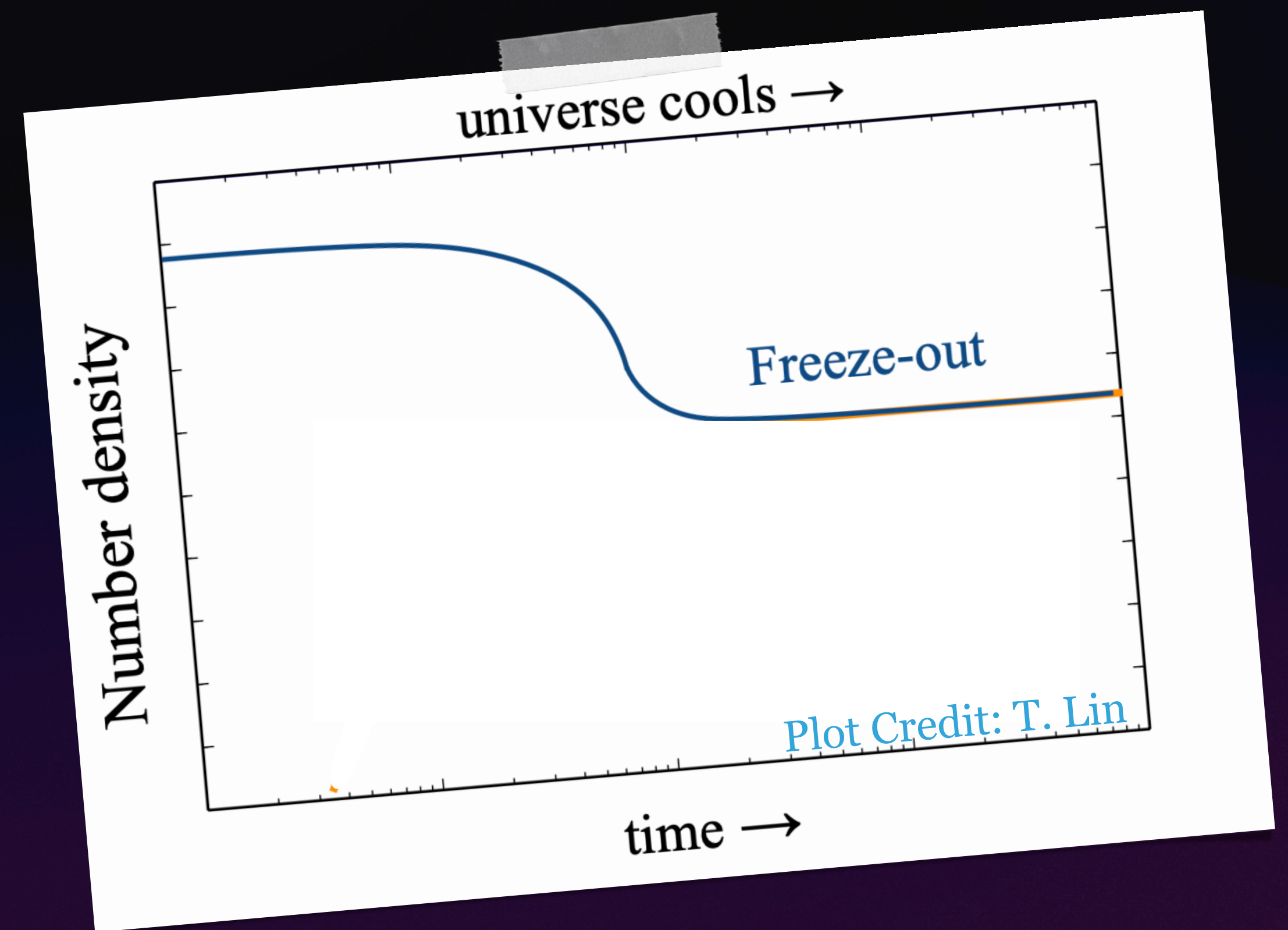
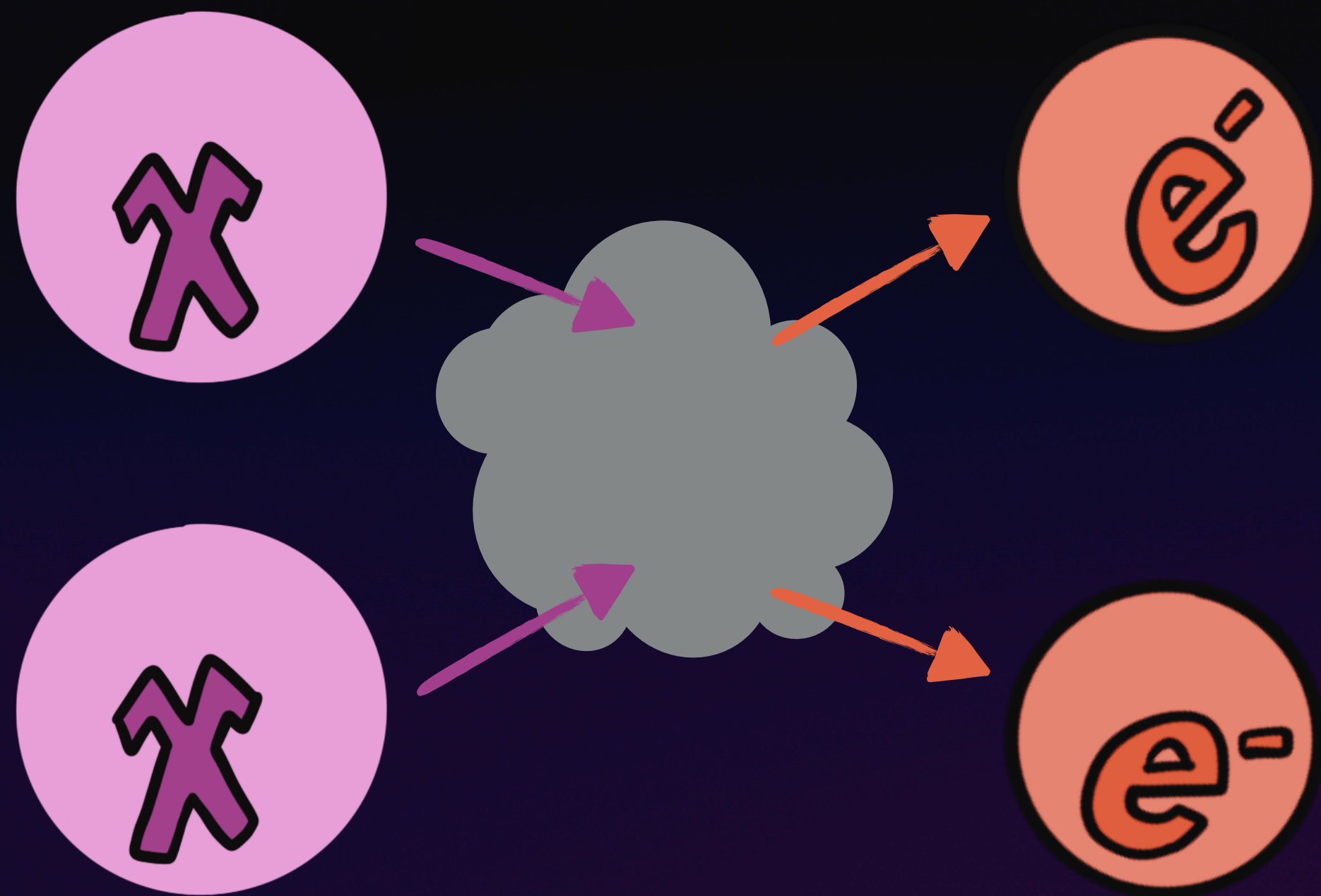
NEW **PROCESSES**  
DIFFERENT **COUPLINGS**



**WHAT DOES THIS MEAN  
FOR DARK MATTER?**



# DARK MATTER PRODUCTION IN THE EARLY UNIVERSE<sup>13</sup>

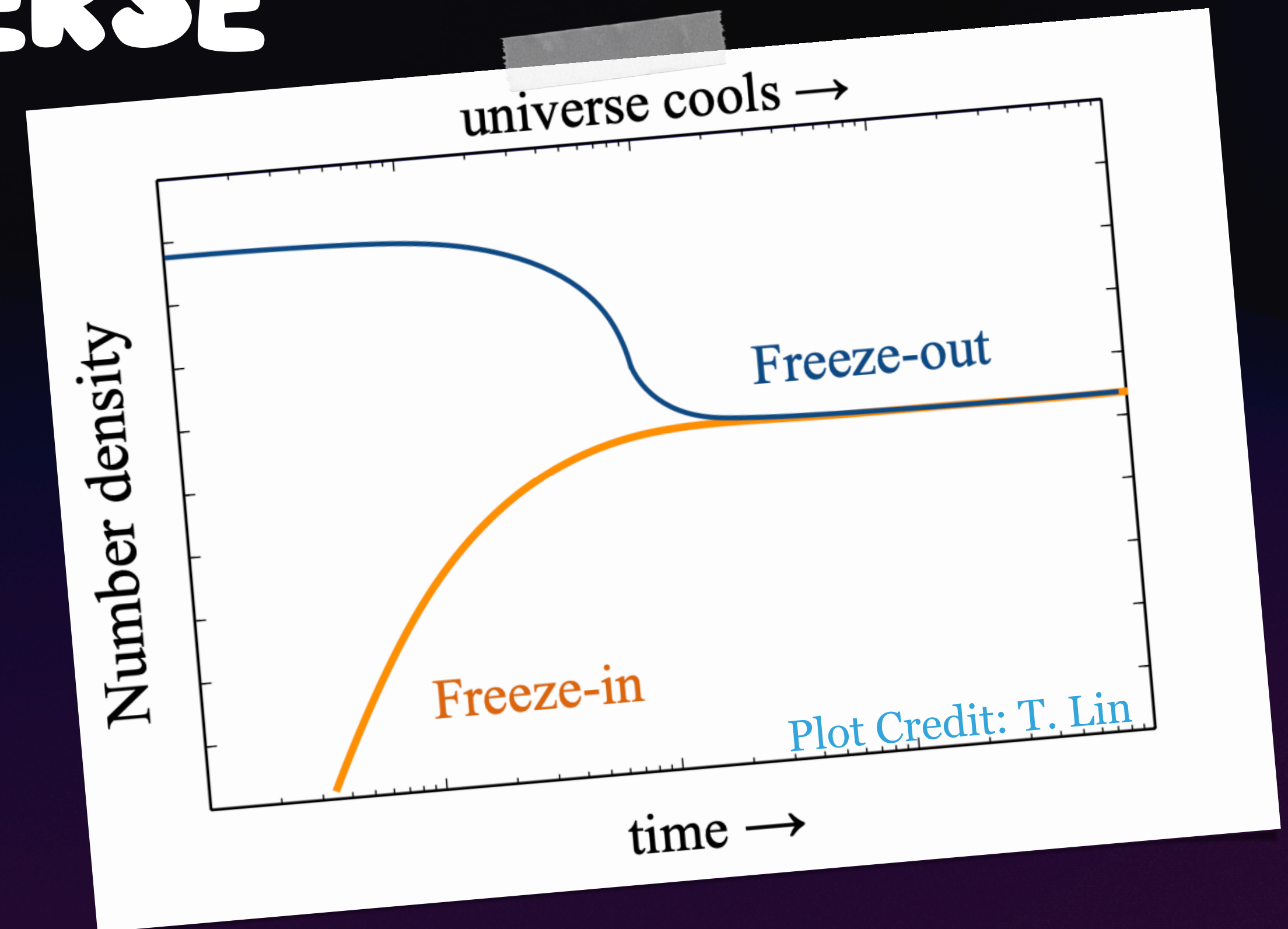
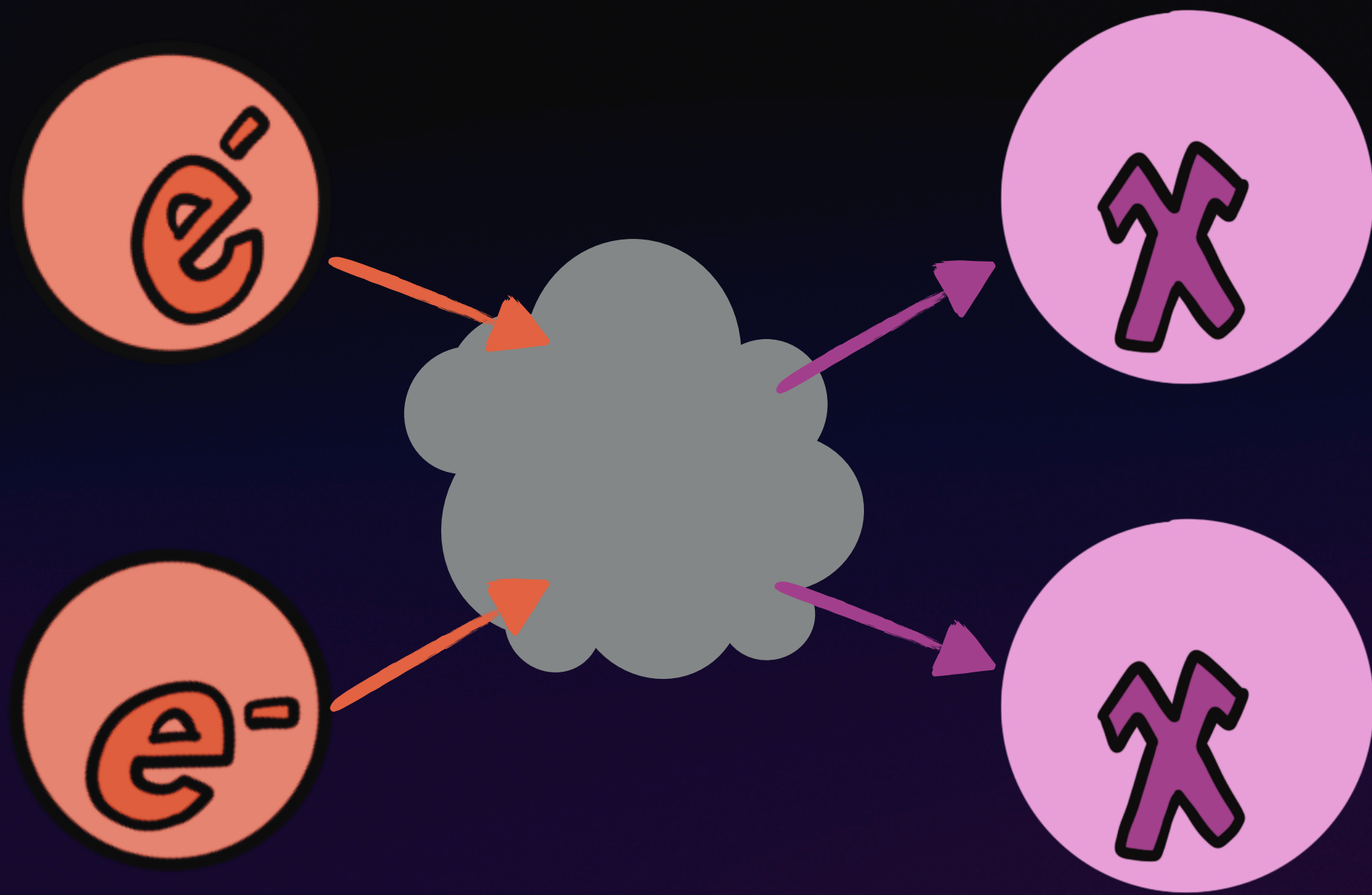


IF DARK MATTER IS **THERMALLY COUPLED**

SEE GORDON'S TALK FOR MODELS!



# DARK MATTER PRODUCTION IN THE EARLY UNIVERSE



IF DARK MATTER IS **THERMALLY DECOUPLED**

SEE GORDON'S TALK FOR MODELS!



FREEZE IN PRODUCTION CAN BE SIGNIFICANTLY **THERMALLY CORRECTED**

15



# FREEZE IN PRODUCTION CAN BE SIGNIFICANTLY **THERMALLY CORRECTED**

15

EG. MILLICHARGED DARK MATTER

$$\mathcal{L} \supset qe\bar{\chi}\gamma_{\mu}\chi A^{\mu} + \bar{\chi}(i\partial^{\mu}\gamma_{\mu} - m)\chi$$

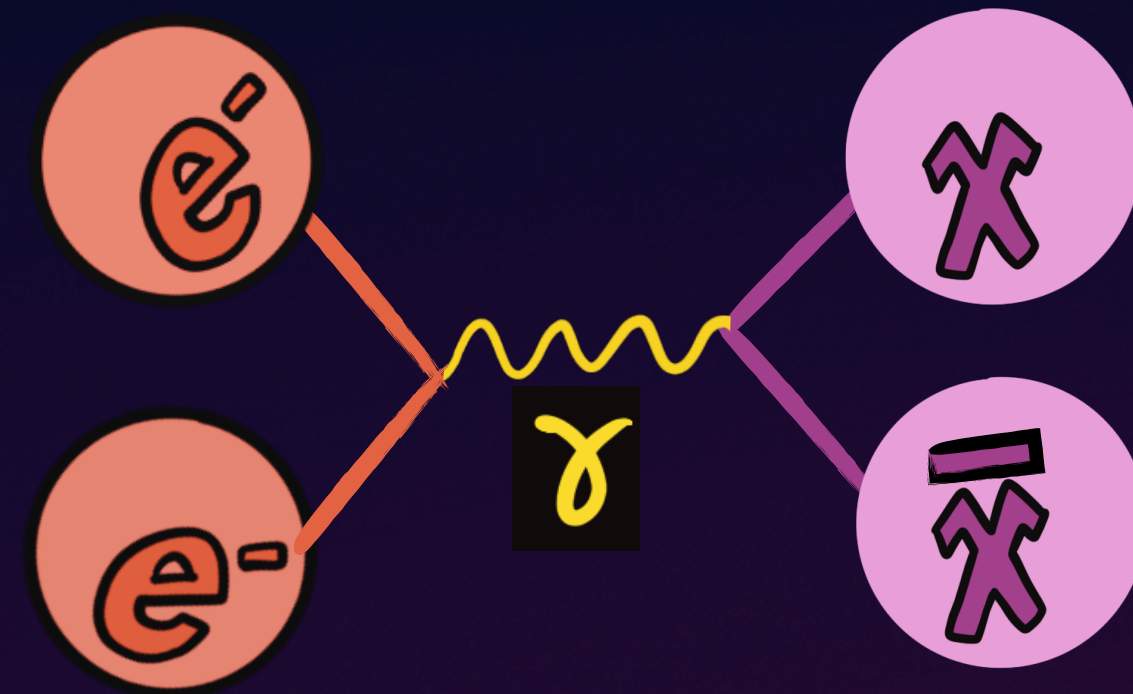


# FREEZE IN PRODUCTION CAN BE SIGNIFICANTLY **THERMALLY CORRECTED**

15

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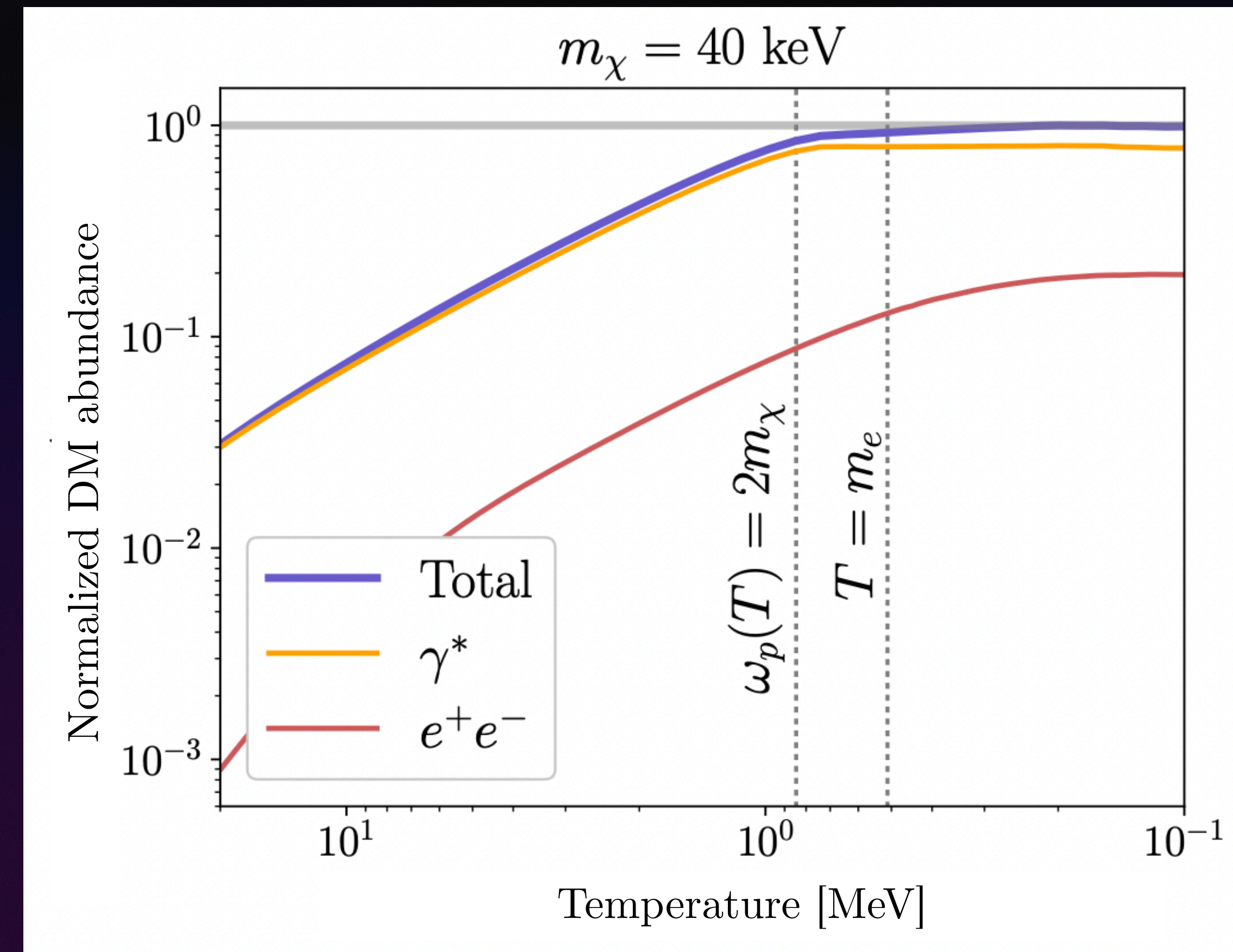
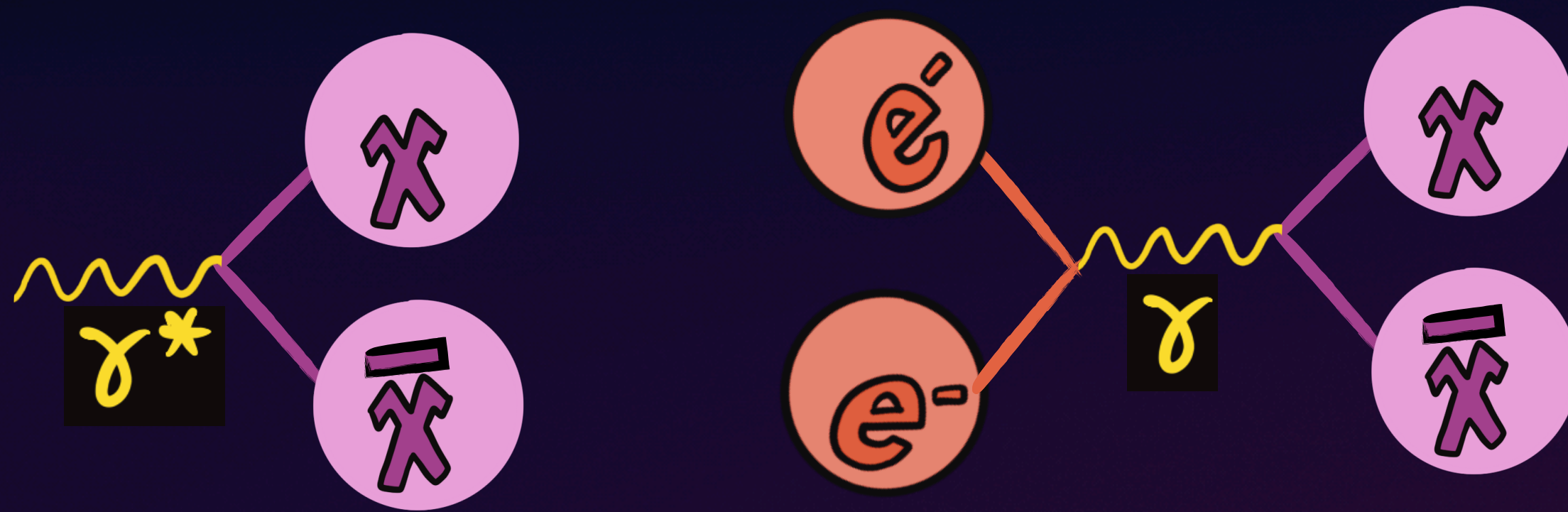


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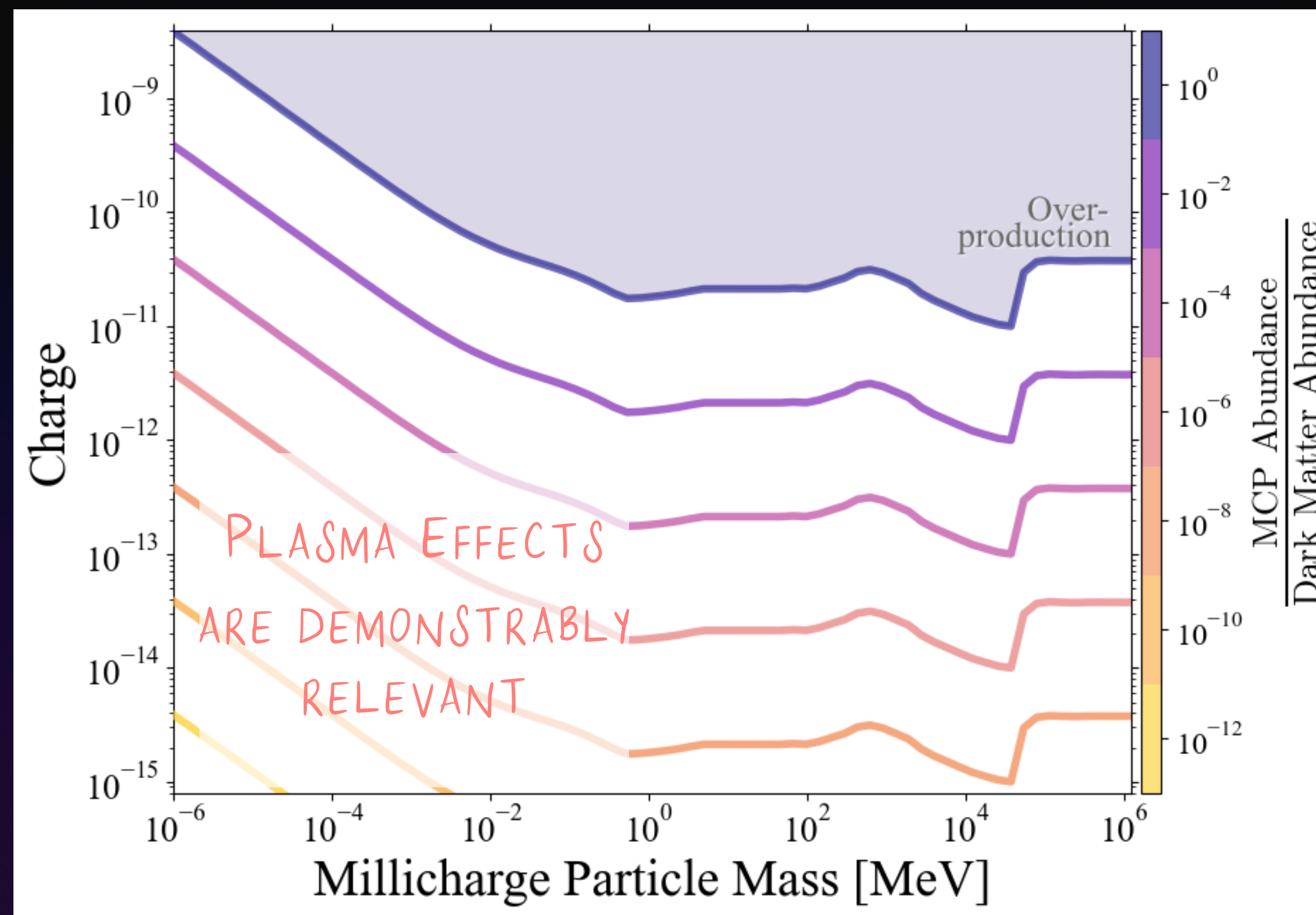




ASIDE...

16

IF **MILLICHARGES EXIST**, AN **IRREDUCIBLE ABUNDANCE** OF THEM WOULD BE PRODUCED THROUGH FREEZE IN



Iles, SH, & Schutz (2024)

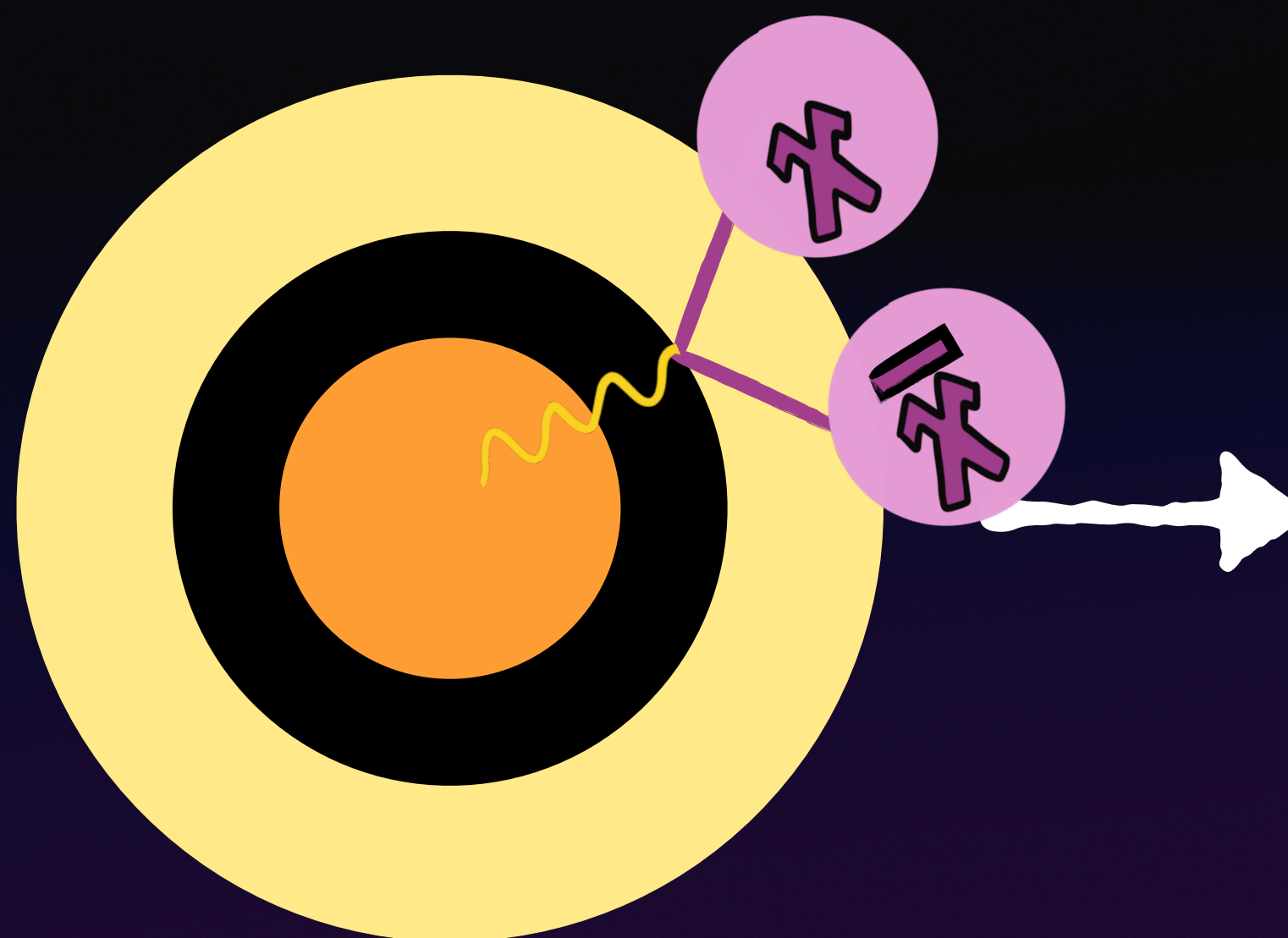


ASIDE...

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# ENERGY LOSS THROUGH MCPs **COOLS** STARS AND **DELAYS** HELIUM FLASH

HYDROGEN  
BURNING  
ENVELOP



STAR BECOMES  
**BRIGHTER** AND  
**REDDER**



HELIUM FLASH  
(TIP OF THE RED GIANT  
BRANCH)

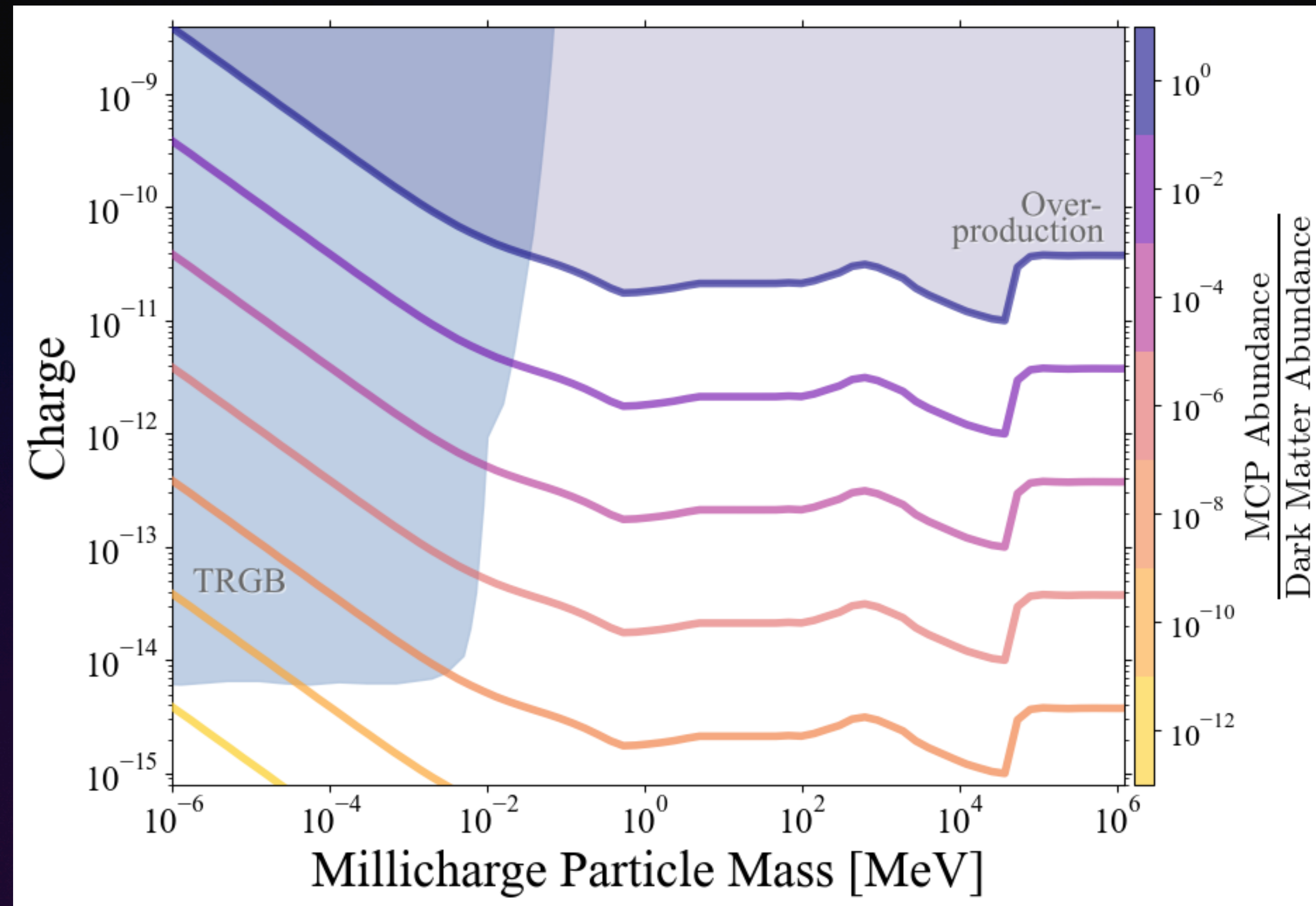
**RED GIANT BRANCH**

SEE NATNAEL'S TALK FOR ANOTHER MODEL!

Fung, SH, Liu, Schutz, Vincent & Muralidharan (2023)



IF **MILLICHARGES EXIST**, THEIR **PRODUCTION IN STELLAR PLASMAS** CAN BE USED TO HUNT FOR THEM



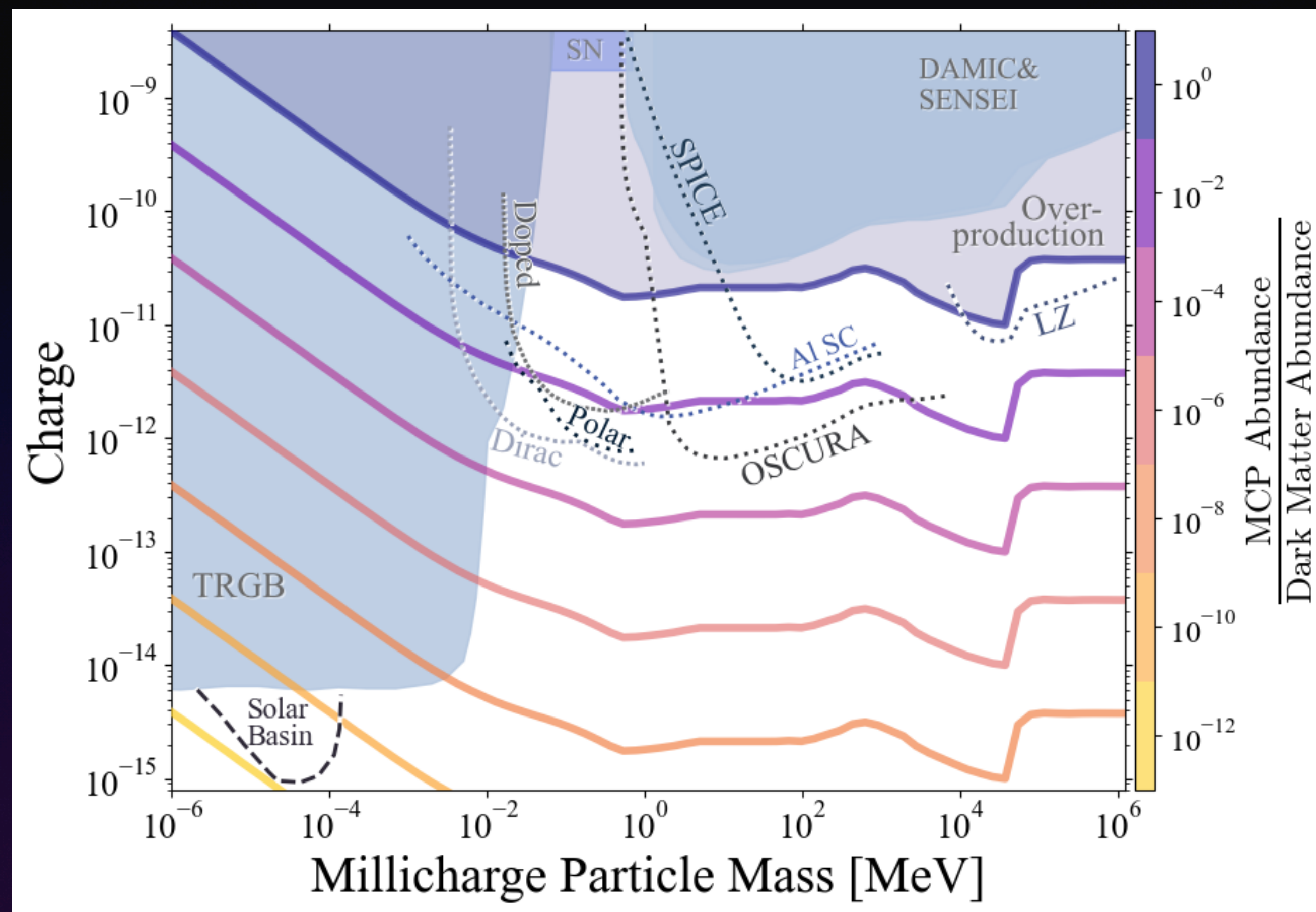
Iles, SH, & Schutz (2024)



ASIDE...

19

IF **MILLICHARGES EXIST**, A **DIVERSITY OF EXPERIMENTAL PROBES** CAN BE USED TO HUNT FOR THEM



Iles, SH, & Schutz (2024)



OTHER FREEZE IN MODELS ARE ALSO SIGNIFICANTLY<sup>20</sup>  
**THERMALLY CORRECTED**

EG. SCALAR DARK MATTER

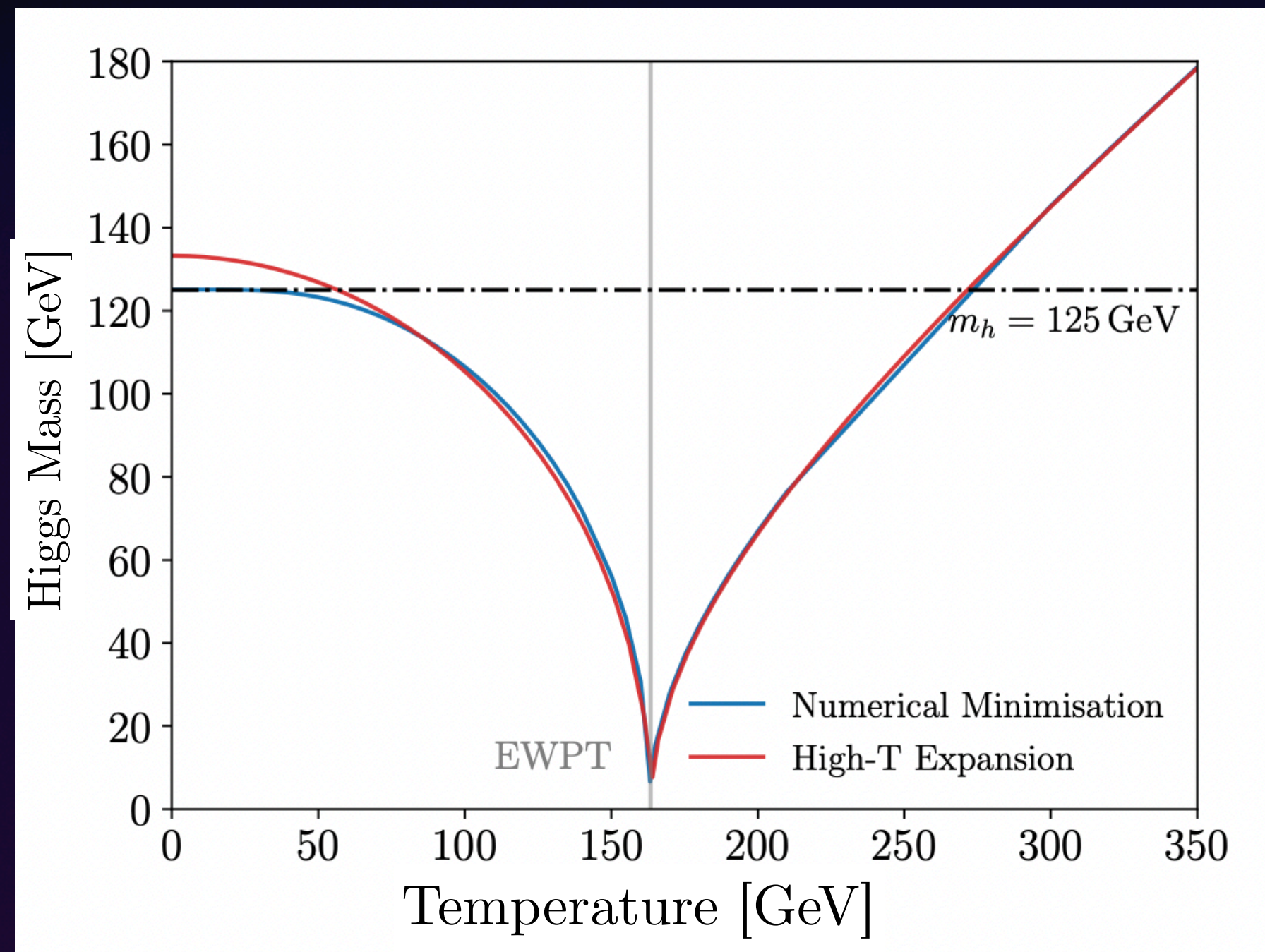
$$\mathcal{L} \supset \frac{\lambda_{hs}}{2} H^\dagger H s^2$$



# OTHER FREEZE IN MODELS ARE ALSO SIGNIFICANTLY<sup>20</sup> **THERMALLY CORRECTED**

EG. SCALAR DARK MATTER

$$\mathcal{L} \supset \frac{\lambda_{hs}}{2} H^\dagger H s^2$$



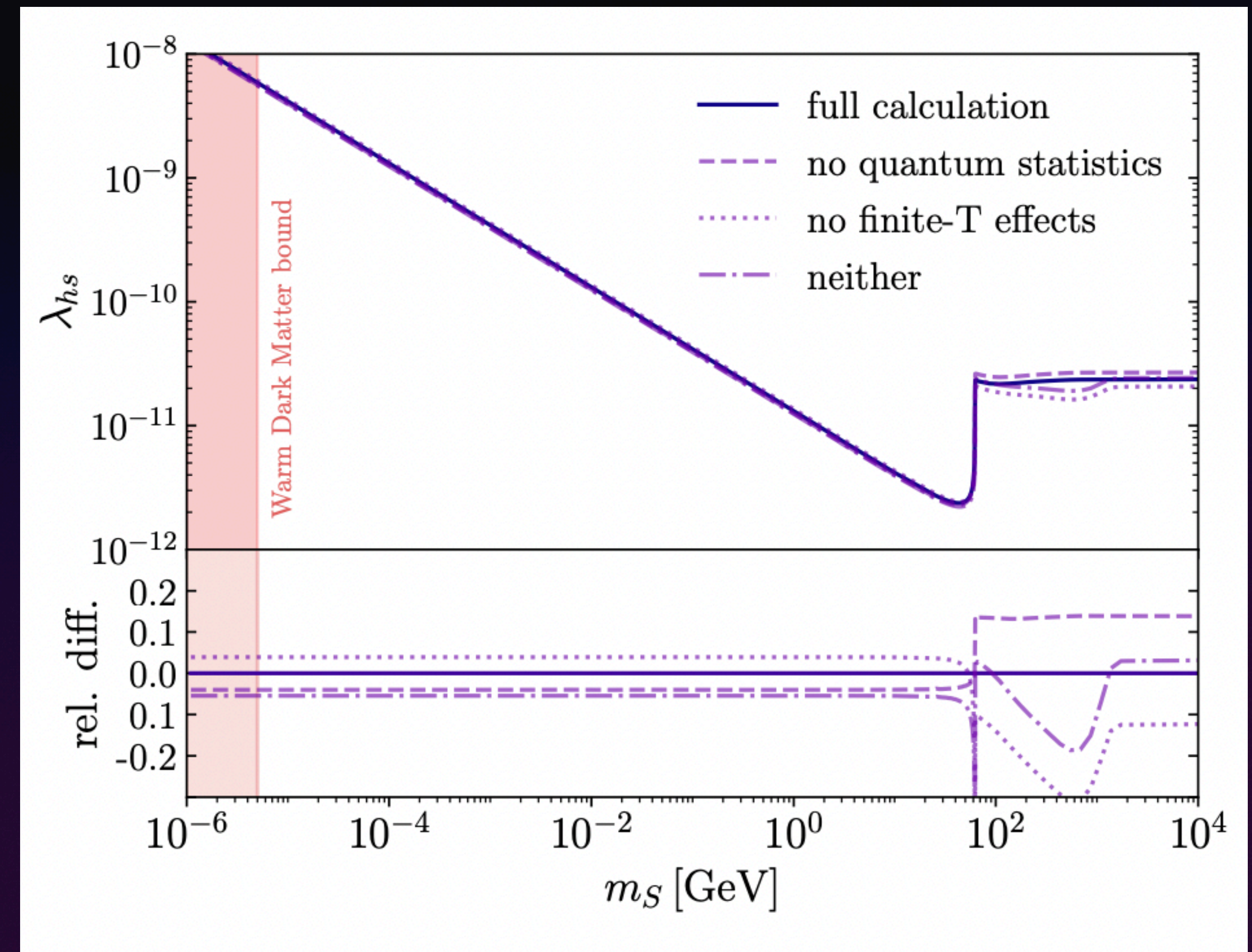
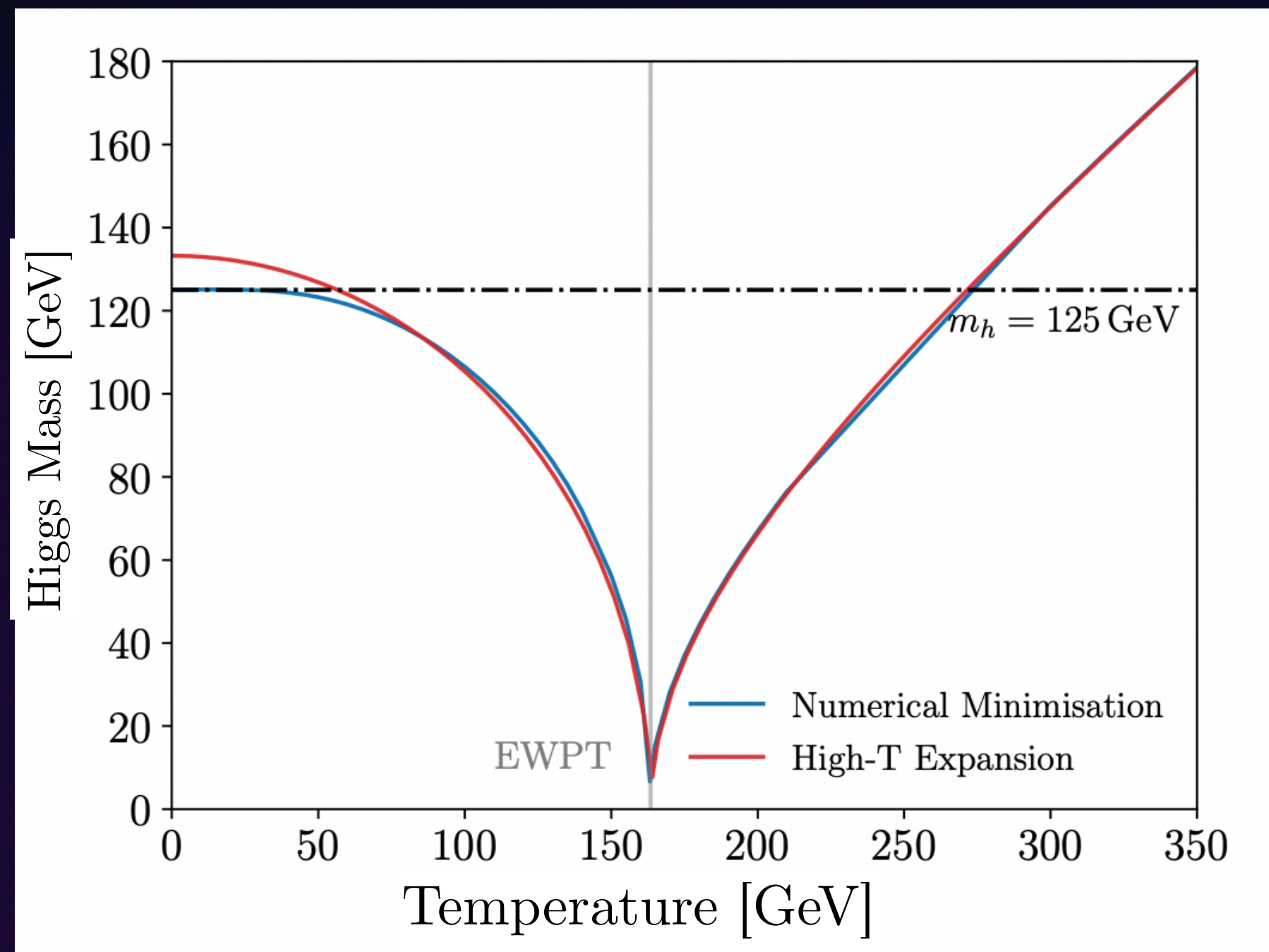
Bringmann, SH, et al (2021)



# OTHER FREEZE IN MODELS ARE ALSO SIGNIFICANTLY<sup>20</sup> **THERMALLY CORRECTED**

EG. SCALAR DARK MATTER

$$\mathcal{L} \supset \frac{\lambda_{hs}}{2} H^\dagger H s^2$$



Bringmann, SH, et al (2021)



OTHER FREEZE IN MODELS ARE ALSO SIGNIFICANTLY<sup>21</sup>  
**THERMALLY CORRECTED**

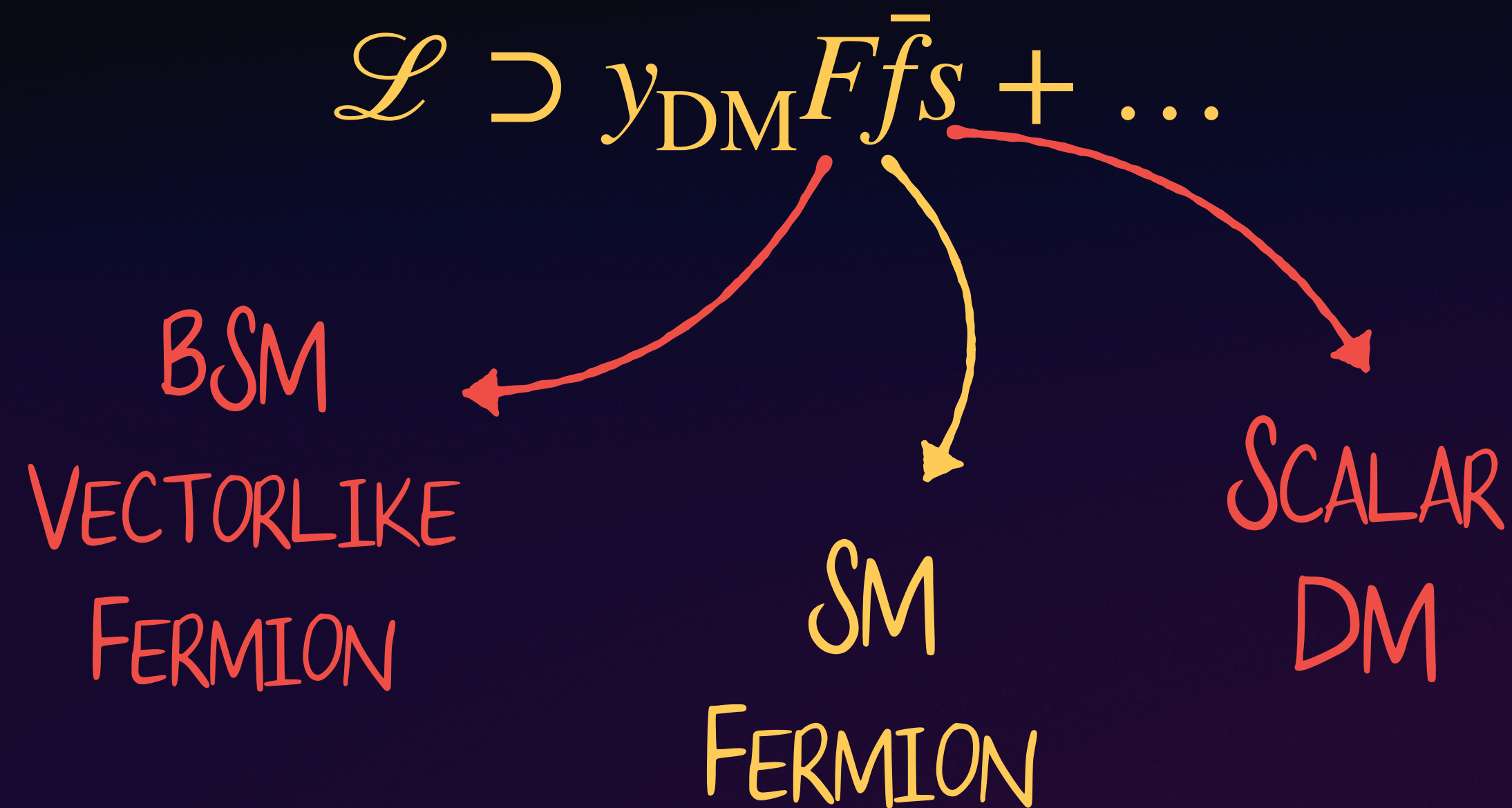
EG. VECTORLIKE PORTAL DARK MATTER

$$\mathcal{L} \supset y_{\text{DM}} F \bar{f} s + \dots$$



# OTHER FREEZE IN MODELS ARE ALSO SIGNIFICANTLY<sup>21</sup> **THERMALLY CORRECTED**

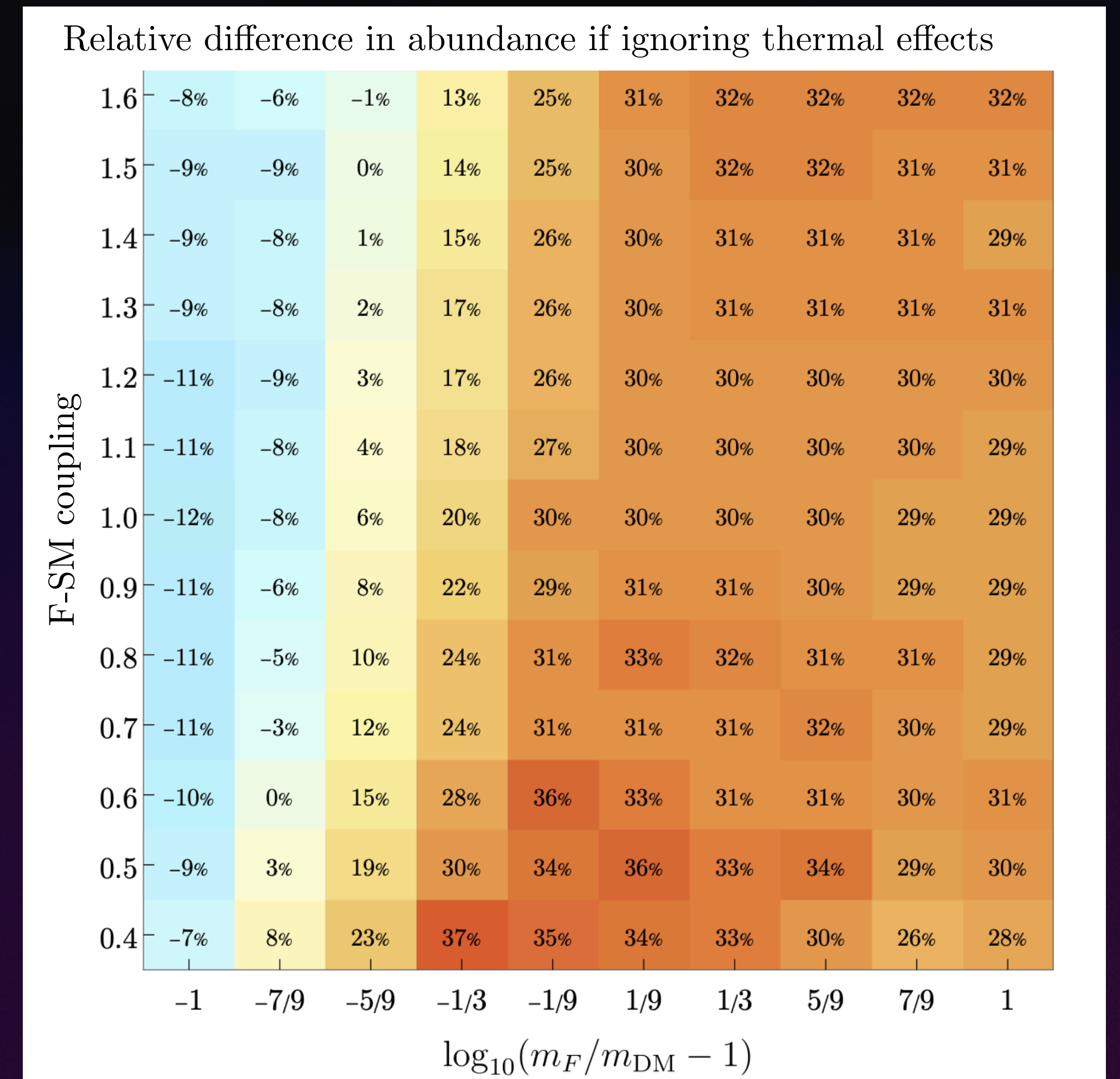
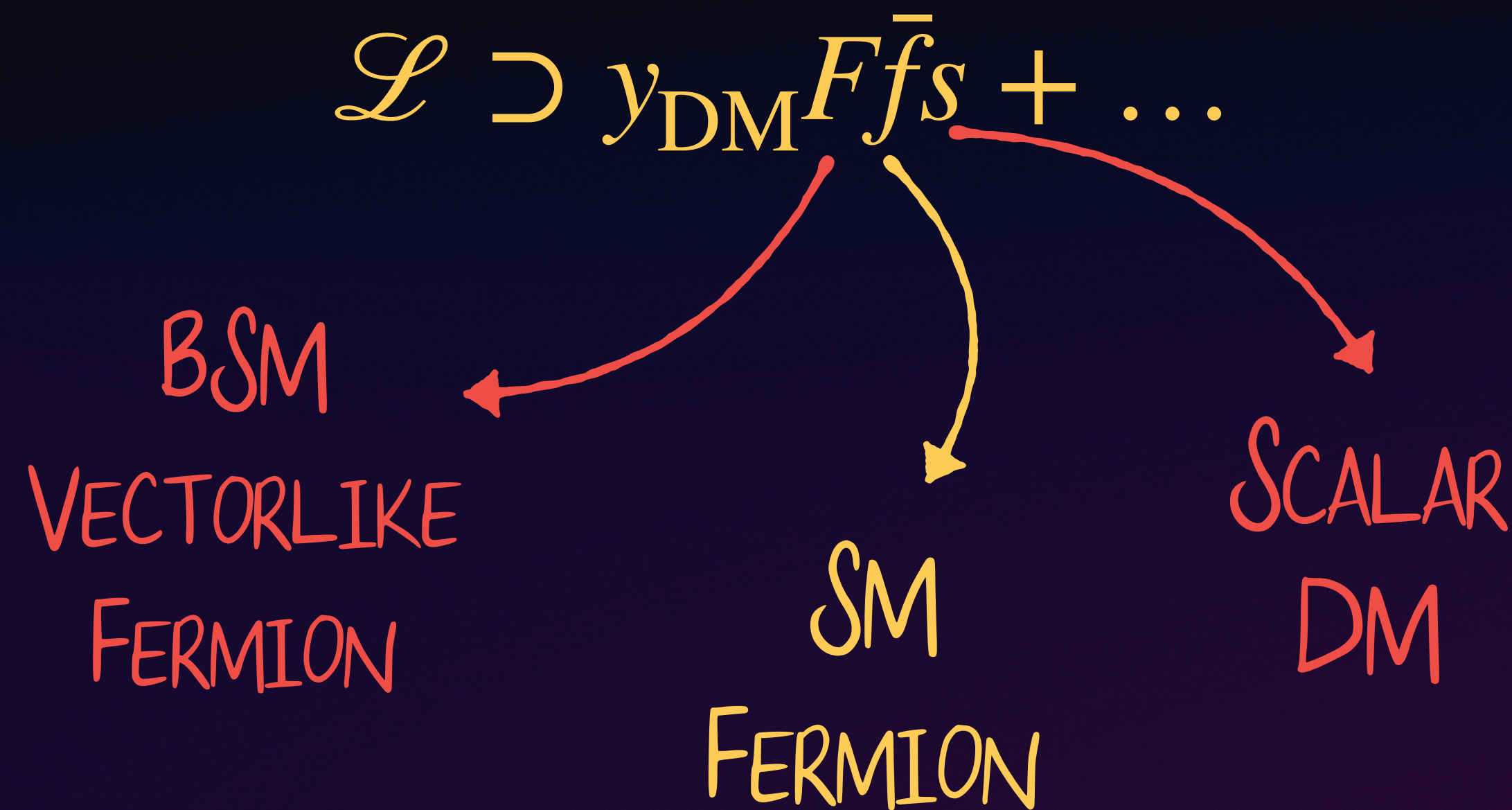
EG. VECTORLIKE PORTAL DARK MATTER





# OTHER FREEZE IN MODELS ARE ALSO SIGNIFICANTLY<sup>21</sup> THERMALLY CORRECTED

EG. VECTORLIKE PORTAL DARK MATTER





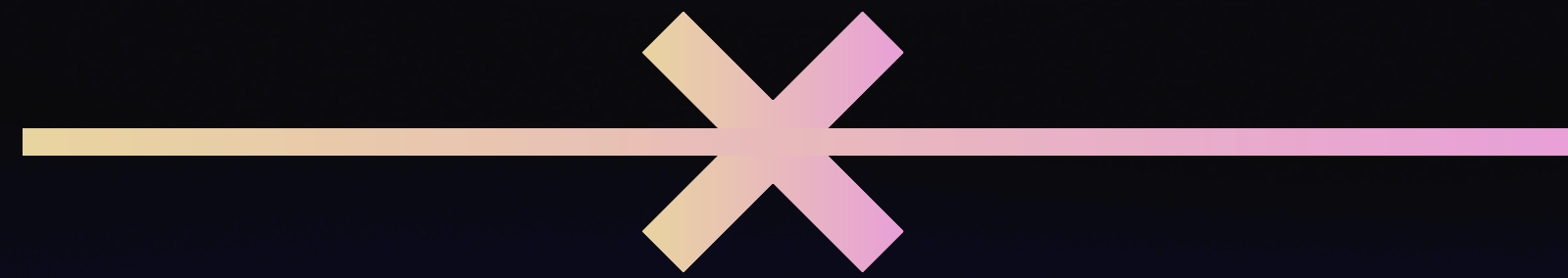
# WHAT ABOUT OTHER DARK MATTER **ORIGIN STORIES?**

...YET ANOTHER DARK MATTER PRODUCTION MECHANISM



IF DARK MATTER IS **THERMALLY DECOUPLED**, BUT **MIXES**<sup>23</sup>  
WITH ANOTHER PARTICLE

**BSM OR  
SM STATE**

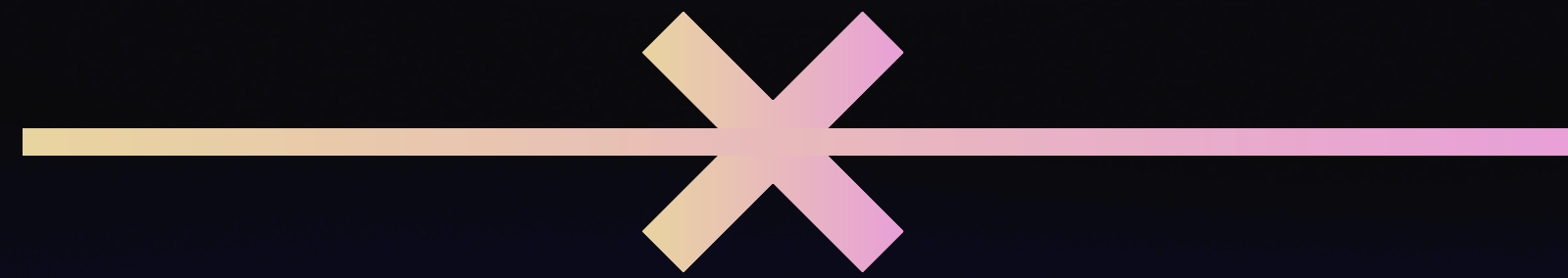


**STERILE OR  
NON-  
INTERACTING  
STATE: DARK  
MATTER**



IF DARK MATTER IS **THERMALLY DECOUPLED**, BUT **MIXES**<sup>23</sup>  
WITH ANOTHER PARTICLE

**BSM OR  
SM STATE**



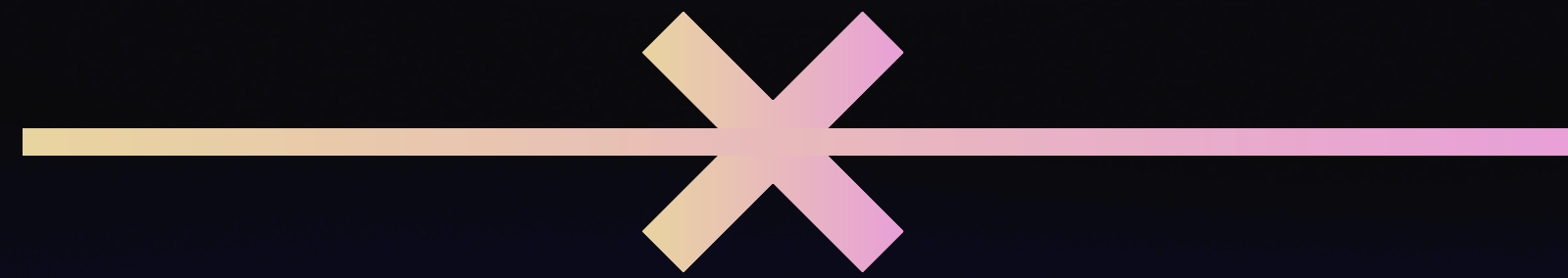
**STERILE OR  
NON-  
INTERACTING  
STATE: DARK  
MATTER**

START OFF WITH  $\psi$  IN THE EARLY UNIVERSE,  
GENERATE A  $\chi$  DENSITY THROUGH **OSCILLATIONS**



IF DARK MATTER IS **THERMALLY DECOUPLED**, BUT **MIXES**<sup>23</sup>  
WITH ANOTHER PARTICLE

**BSM OR  
SM STATE**



**STERILE OR  
NON-  
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STATE: DARK  
MATTER**

START OFF WITH  $\psi$  IN THE EARLY UNIVERSE,  
GENERATE A  $\chi$  DENSITY THROUGH **OSCILLATIONS**

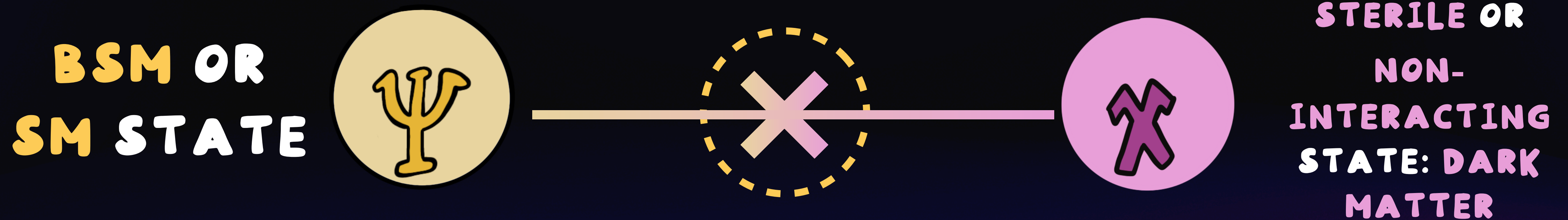
**ROMPS!**

**RAPIDLY OSCILLATING MASSIVE PARTICLES**

(ONGOING WORK WITH D. DUNSKY AND J. RUDERMAN)



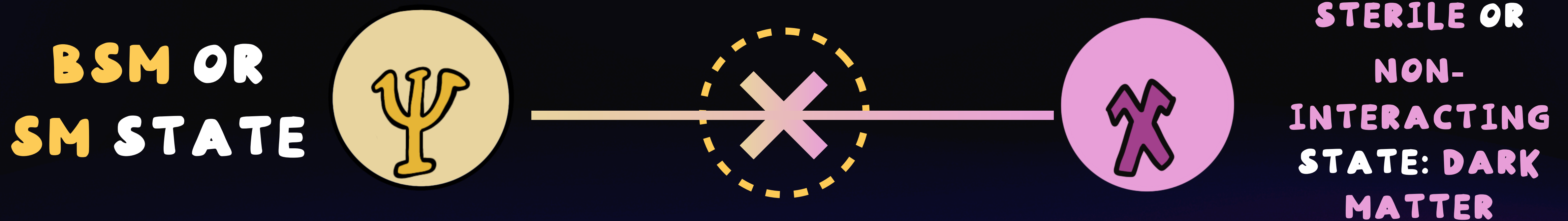
PROBABILITY OF CONVERSION FROM  $\psi \rightarrow \chi$  DEPENDS ON THE  
AMOUNT OF **MIXING**



$$\mathcal{L}_{\psi-\chi} \supset m_{\psi\chi} (\bar{\psi}\chi + \text{h.c.})$$



# PROBABILITY OF CONVERSION FROM $\psi \rightarrow \chi$ DEPENDS ON THE AMOUNT OF **MIXING**



$$\mathcal{L}_{\psi-\chi} \supset m_{\psi\chi} (\bar{\psi}\chi + \text{h.c.})$$

PARAMETERIZE IN TERMS  
OF AN ANGLE

$$\begin{pmatrix} \psi \\ \chi \end{pmatrix}_{\text{flavor}} = \begin{pmatrix} \cos \theta_0 & -\sin \theta_0 \\ \sin \theta_0 & \cos \theta_0 \end{pmatrix} \begin{pmatrix} \psi \\ \chi \end{pmatrix}_{\text{mass}},$$

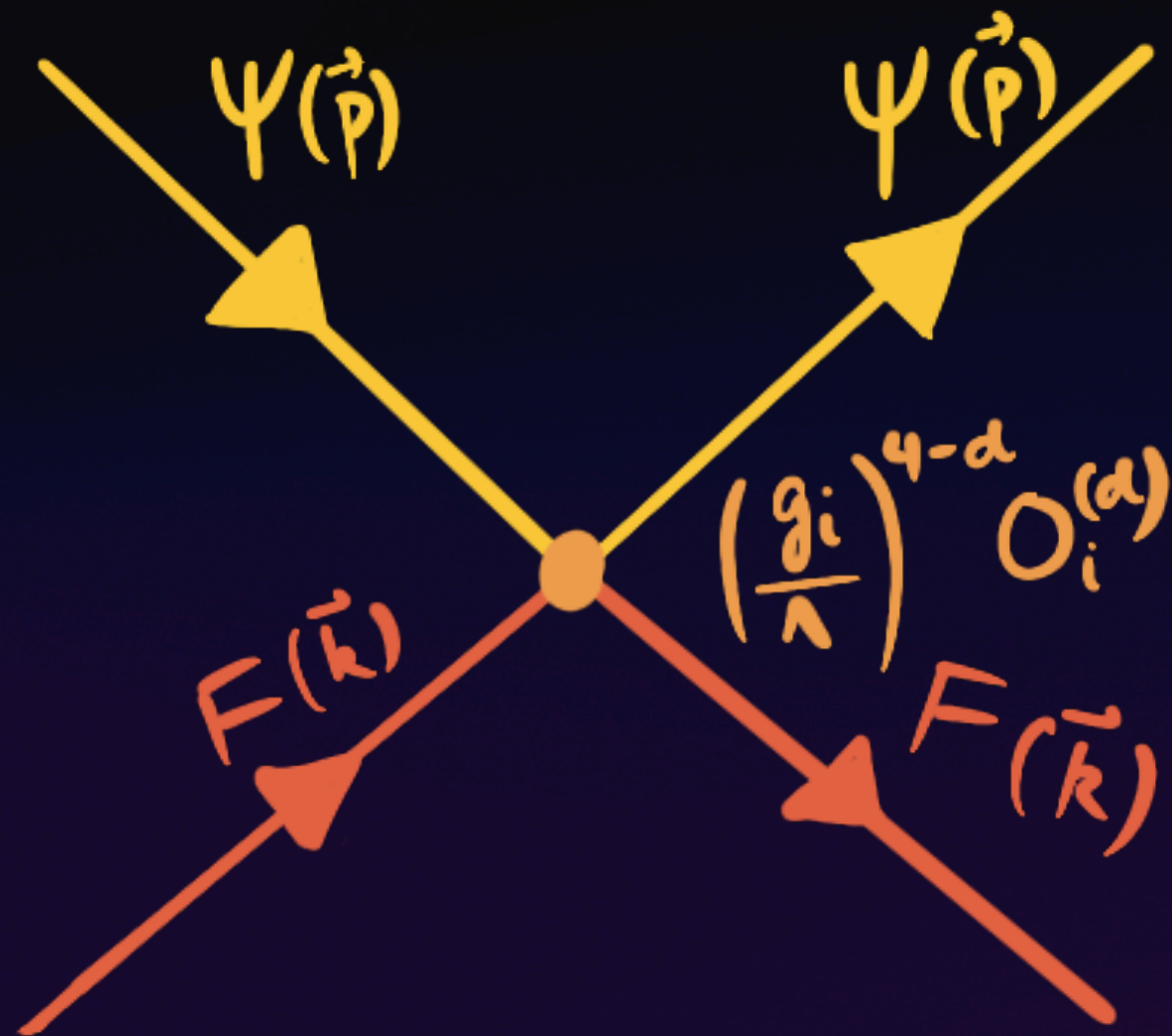
$$\tan 2\theta_0 = \frac{2m_{\psi\chi}^2}{m_{\psi}^2 - m_{\chi}^2}$$



# THERMAL EFFECTS CHANGES THE DISPERSION OF $\psi$

$\psi$  PICKS UP AN **IN MEDIUM MASS**

$$m_{\psi, \text{medium}}^2 = m_{\psi}^2 + \Delta m_T^2$$



"FORWARD SCATTERING"  
( $\psi$  MAINTAINS ITS MOMENTUM)



# THERMAL EFFECTS CHANGES THE DISPERSION OF $\psi$

$\psi$  PICKS UP AN **IN MEDIUM MASS**

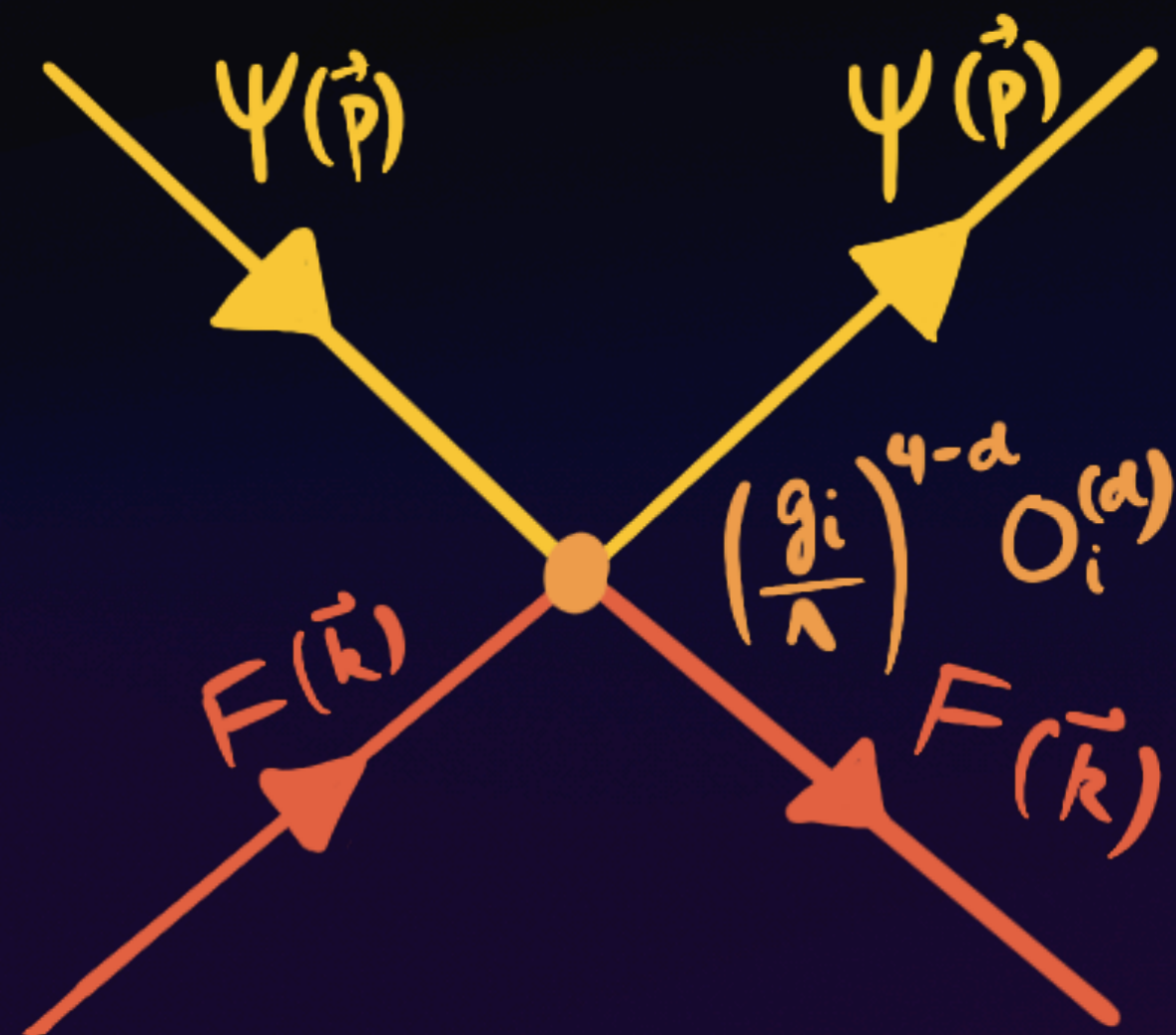
$$m_{\psi, \text{medium}}^2 = m_{\psi}^2 + \Delta m_T^2$$

IN MEDIUM MIXING ANGLE **MODIFIED!**

$$\tan 2\theta_m = \frac{2m_{\psi\chi}^2}{m_{\psi}^2 + \Delta m_T^2 - m_{\chi}^2}$$



FUNCTION OF **TEMPERATURE!**



"FORWARD SCATTERING"  
( $\psi$  MAINTAINS ITS MOMENTUM)



# THERMAL EFFECTS **CHANGES** THE **DISPERSION** OF $\psi$

**ROMP PRODUCTION IS ESPECIALLY  
SENSITIVE TO THE PROPERTIES OF THE  
BACKGROUND!**

"FORWARD SCATTERING"  
( $\psi$  MAINTAINS ITS MOMENTUM)

$$\tan 2\theta_m = \frac{2m_{\psi\chi}^2}{m_{\psi}^2 + \Delta m_T^2 - m_{\chi}^2}$$

FUNCTION OF **TEMPERATURE!**



THE PRODUCTION OF FEEBLY COUPLED  
PARTICLES IN THE **EARLY**  
**UNIVERSE** AS WELL AS IN  
**ASTROPHYSICAL SYSTEMS** IS  
SENSITIVE TO THE PROPERTIES OF  
THE AMBIENT PLASMA



SETS THE ABUNDANCE WHICH IS THE TARGET FOR  
TERRESTRIAL SEARCHES FOR DARK MATTER

26

THE PRODUCTION OF FEEBLY COUPLED  
PARTICLES IN THE **EARLY**  
**UNIVERSE** AS WELL AS IN  
**ASTROPHYSICAL SYSTEMS** IS  
SENSITIVE TO THE PROPERTIES OF  
THE AMBIENT PLASMA





SETS THE ABUNDANCE WHICH IS THE TARGET FOR 26  
TERRESTRIAL SEARCHES FOR DARK MATTER

THE PRODUCTION OF FEEBLY COUPLED  
PARTICLES IN THE **EARLY**  
**UNIVERSE** AS WELL AS IN  
**ASTROPHYSICAL SYSTEMS** IS  
SENSITIVE TO THE PROPERTIES OF  
THE AMBIENT PLASMA

NEW PROBES OF DARK MATTER



**HOW DO WE CALCULATE  
OBSERVABLES AT  
FINITE TEMPERATURE?**

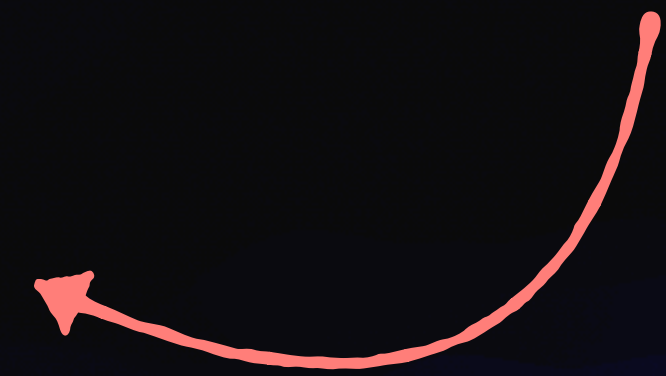


WE'RE INTERESTED IN  
**PARTICLE  
DISPERSION**  
AND  
**PARTICLE  
INTERACTIONS** IN A  
MEDIUM



WE'RE INTERESTED IN  
**PARTICLE  
DISPERSION**  
AND  
**PARTICLE  
INTERACTIONS** IN A  
MEDIUM

EFFECTIVE MASS





WE'RE INTERESTED IN  
**PARTICLE  
DISPERSION**  
AND  
**PARTICLE  
INTERACTIONS** IN A  
MEDIUM

EFFECTIVE MASS



PRODUCTION  
RATE





# EFFECTS CAPTURED BY THERMAL SELF ENERGY

$$\Pi^{\mu\nu}(K) = \text{diagram 1} + \text{diagram 2} + \dots$$

The diagrammatic equation for the polarization function  $\Pi^{\mu\nu}(K)$  is shown. The first term consists of a wavy line with momentum  $\vec{K}$  entering a red loop. Inside the loop, the top arc is labeled  $P+K$  and the bottom arc is labeled  $P$ . A wavy line with momentum  $\vec{K}$  exits the loop. The second term consists of a wavy line with momentum  $K$  entering a red loop. Inside the loop, the top arc is labeled  $P+K+Q$  and the bottom arc is labeled  $P$ . A wavy line with momentum  $K$  exits the loop. The equation ends with a plus sign and an ellipsis.



# EFFECTS CAPTURED BY THERMAL SELF ENERGY

$$\Pi^{\mu\nu}(K) = \text{diagram 1} + \text{diagram 2} + \dots$$

The equation shows the expansion of the photon polarization tensor  $\Pi^{\mu\nu}(K)$  into a series of diagrams. The first diagram consists of a wavy line with momentum  $\vec{K}$  entering from the left and exiting to the right, with a red circular loop in the middle. The top of the loop is labeled  $P+K$  and the bottom is labeled  $P$ . The second diagram is similar, but the wavy line has momentum  $K$  and the red loop contains a wavy line with momentum  $Q$  and a fermion line with momentum  $P$ . The top of the loop is labeled  $P+K+Q$ . The series continues with an ellipsis.

$$\text{Re}(\Pi) = \omega^2 - k^2$$

DISPERSION RELATION



# EFFECTS CAPTURED BY THERMAL SELF ENERGY

$$\Pi^{\mu\nu}(K) = \text{diagram 1} + \text{diagram 2} + \dots$$

$$\text{Re}(\Pi) = \omega^2 - k^2$$

DISPERSION RELATION

$$\text{Im}(\Pi) = \omega \Gamma$$

INTERACTION RATE



FINITE TEMPERATURE FIELD THEORY

30

IS HARD\*

:(



# FINITE TEMPERATURE FIELD THEORY

30

IS HARD\*

:(





# FINITE TEMPERATURE FIELD THEORY

30

IS HARD\*

∴



$$= i T \sum_{n=-\infty}^{\infty} i T \sum_{m=-\infty}^{\infty} N \int d^3 p \int d^3 q (-i g)^2 (-i \lambda)^2$$

$$\times [i D(\omega_e + \omega_n, \vec{k} + \vec{p})]^2 i D(\omega_e + \omega_n + \omega_m, \vec{k} + \vec{p} + \vec{q})$$

$$i D(\omega_m, \vec{q}) i D(\omega_n, \vec{p})]$$

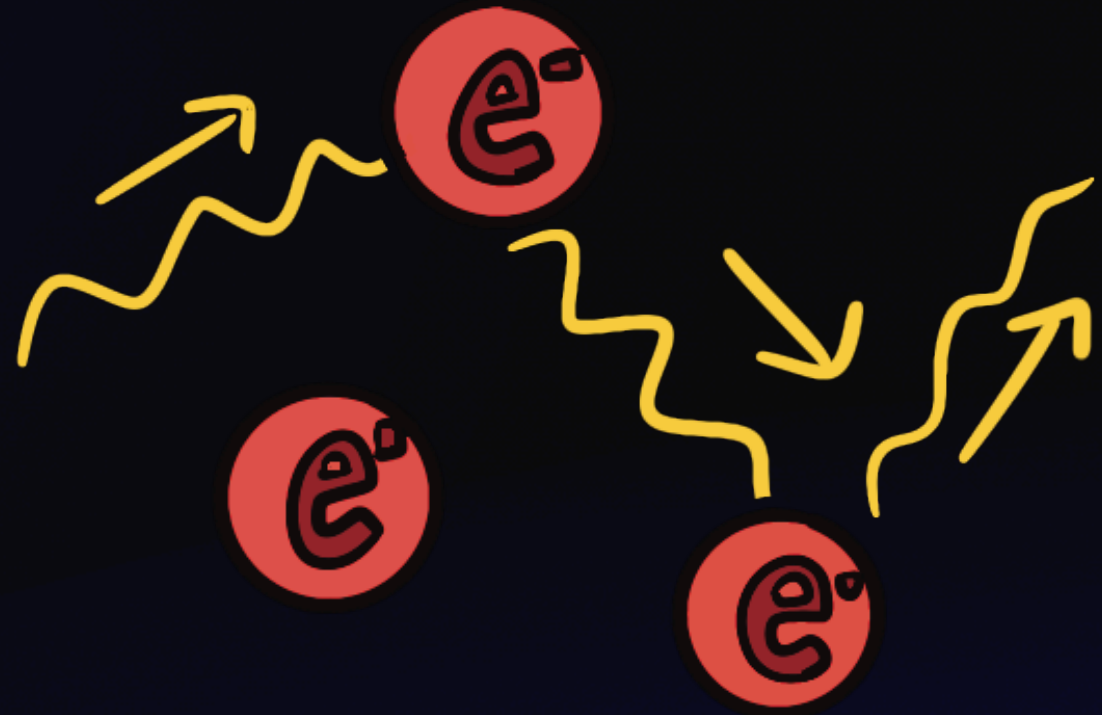


IS THERE A WAY TO RELATE  
FINITE TEMPERATURE SELF ENERGY  
LOOPS TO TREE LEVEL DIAGRAMS?





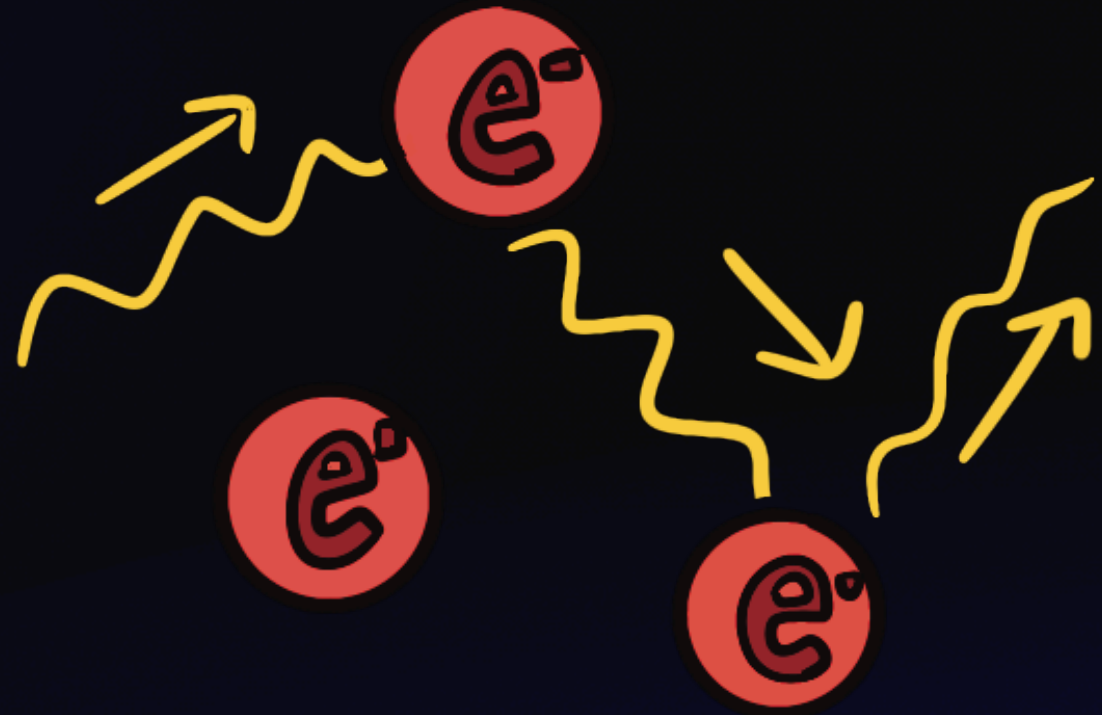
# THE REAL PART, OR PARTICLE DISPERSION



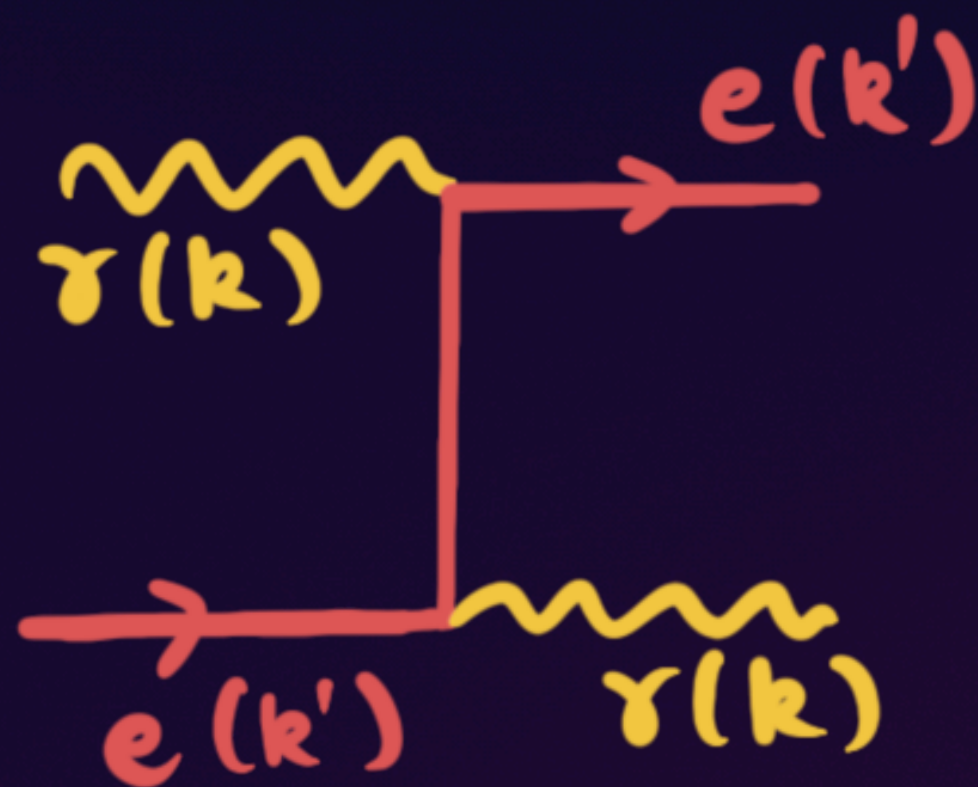
WE CAN IMAGINE DISPERSION IN TERMS OF FORWARD  
SCATTERING



# THE REAL PART, OR PARTICLE DISPERSION



WE CAN IMAGINE DISPERSION IN TERMS OF **FORWARD SCATTERING**



$\overline{\uparrow}$   
AVERAGE  
OVER  
 $n_e, n_{e^+}$

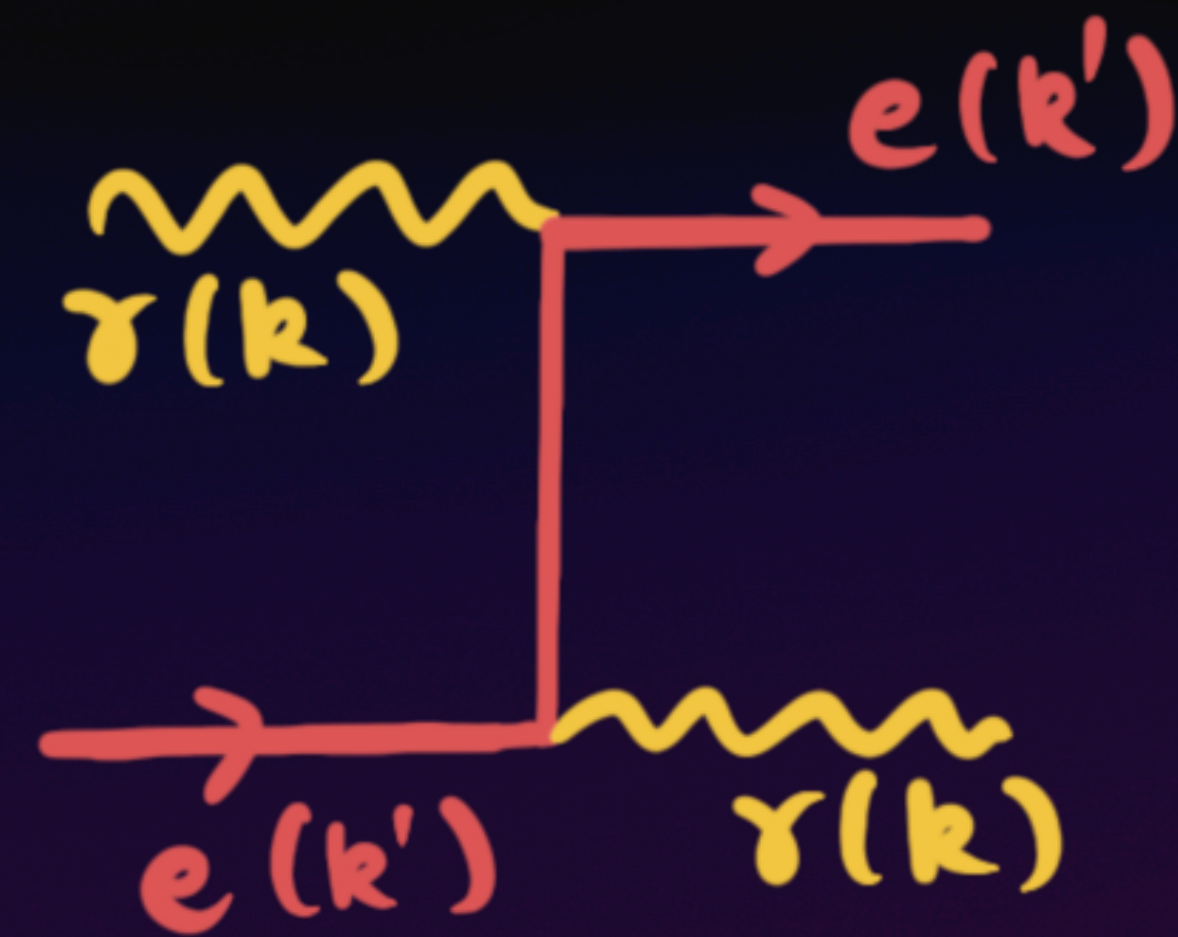
$$\int \frac{d^3 k'}{(2\pi)^3} \frac{M_{e\gamma \rightarrow e\gamma}}{2E_{k'}} \{f_e(k') + f_{e^+}(k')\} = \Delta m_\gamma^2(T)$$

EQUIVALENT TO CALCULATING THE

**REFRACTIVE INDEX** OF THE PARTICLE

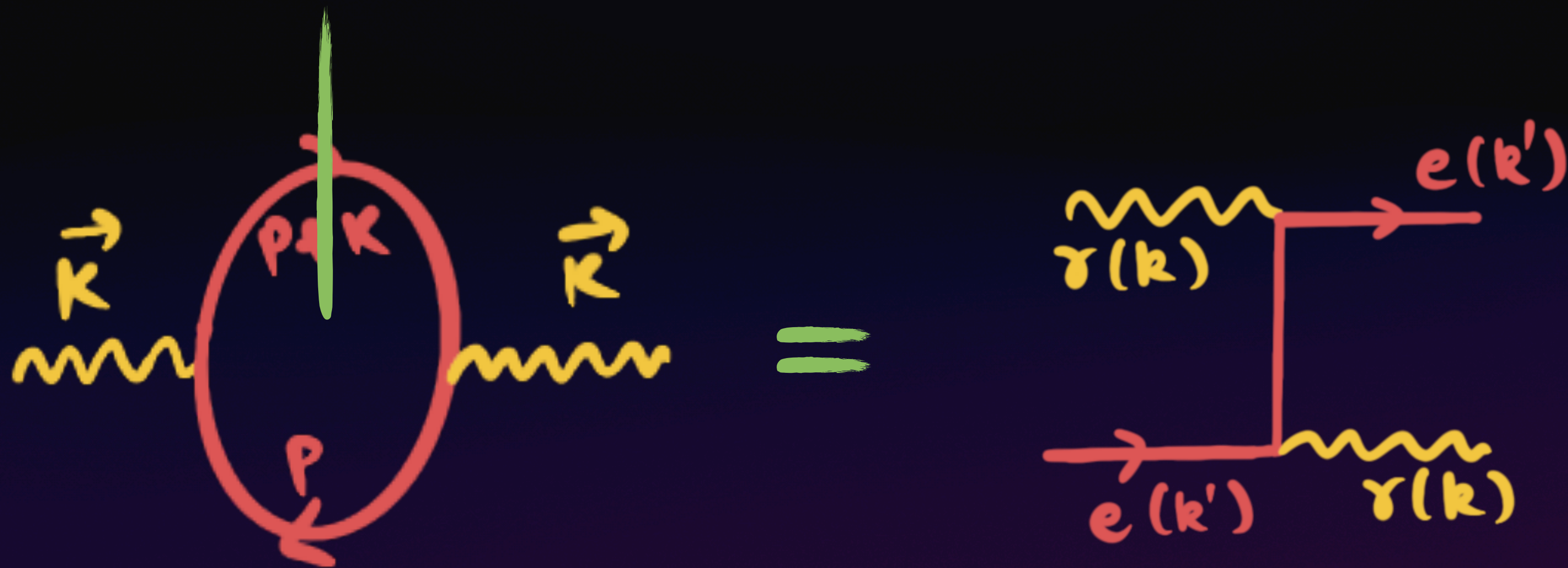


THE **REAL PART OF THE SELF ENERGY** IS  
 BASICALLY **TREE-LEVEL FORWARD SCATTERING**



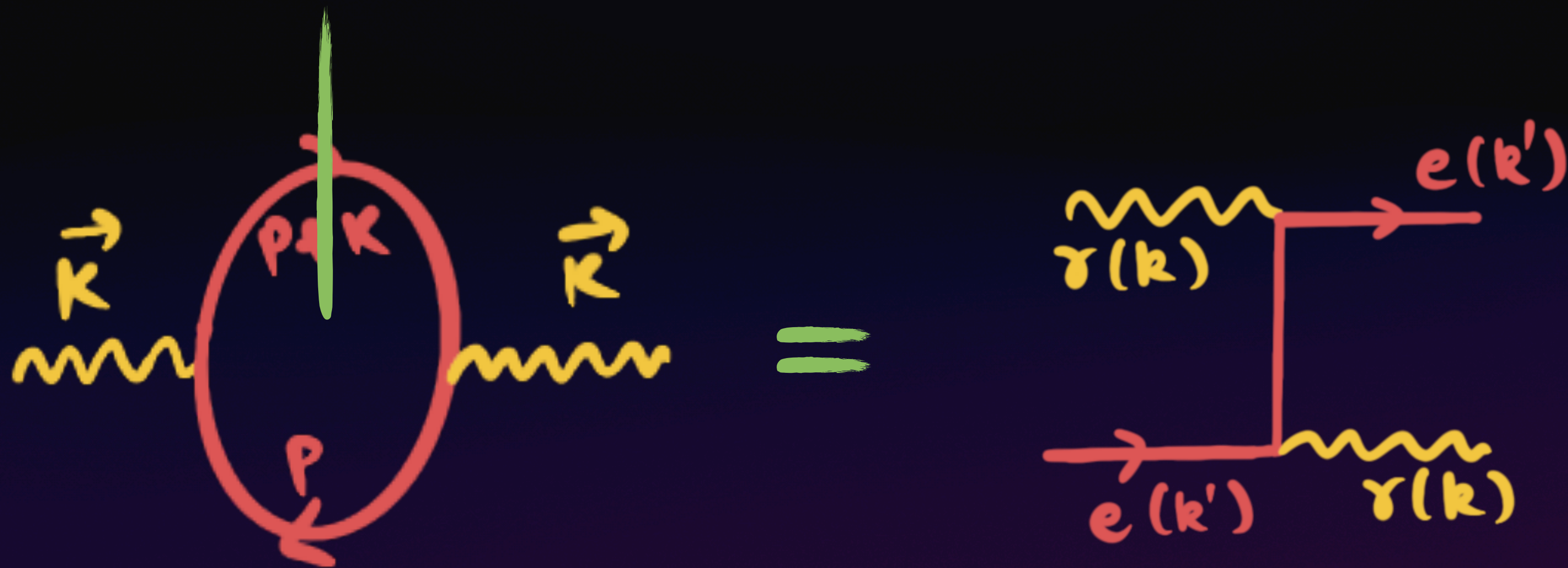


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WHAT ABOUT THE IMAGINARY PART?



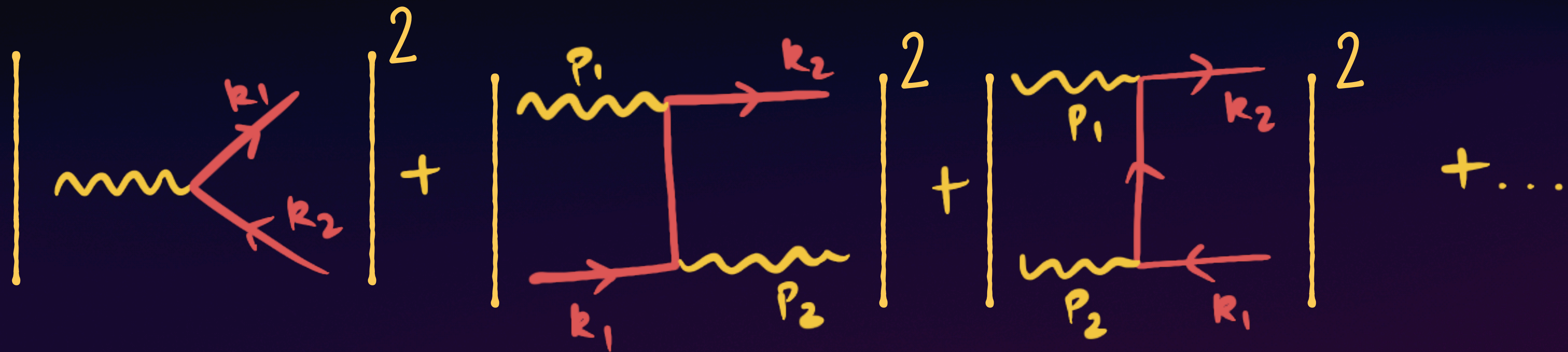
# IMAGINARY PART = PRODUCTION RATE

**ANSATZ:** WRITE DOWN ALL POSSIBLE PROCESSES, SUM OVER THEIR CROSS SECTIONS, AND WEIGH BY THERMAL PHASE SPACE



# IMAGINARY PART = PRODUCTION RATE

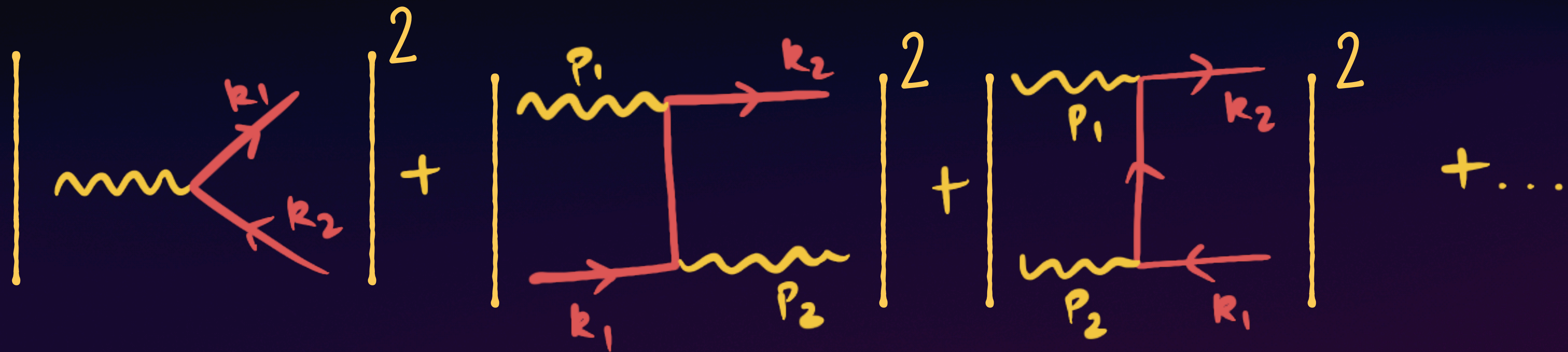
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# IMAGINARY PART = PRODUCTION RATE

**ANSATZ:** WRITE DOWN ALL POSSIBLE PROCESSES, SUM OVER THEIR CROSS SECTIONS, AND WEIGH BY THERMAL PHASE SPACE



$$\Gamma = n \sigma_{\text{vac}} v$$

$$\Gamma = n \sigma_{\text{med}}(m_{\text{bg}}(T), n_{\text{bg}}(T)) v$$

REPLACE MASSES BY THERMAL MASSES



AS BEFORE:

$$\Pi^{\mu\nu}(K) = \text{wavy line } \vec{K} \text{ } \circlearrowleft \text{ } \vec{K} \text{ wavy line} + \text{wavy line } K \text{ } \circlearrowleft \text{ } K \text{ wavy line} + \dots$$

The first loop has momentum  $P+K$  on the top arc and  $P$  on the bottom arc. The second loop has momentum  $P+K+Q$  on the top arc,  $Q$  on the top wavy line, and  $P$  on the bottom arc.



$$\left| \text{wavy line} \begin{array}{l} \nearrow k_1 \\ \searrow k_2 \end{array} \right|^2 + \left| \begin{array}{c} \text{wavy line } P_1 \text{ } \rightarrow k_2 \\ \leftarrow k_1 \text{ wavy line } P_2 \end{array} \right|^2 + \left| \begin{array}{c} \text{wavy line } P_1 \text{ } \rightarrow k_2 \\ \leftarrow k_1 \text{ wavy line } P_2 \end{array} \right|^2 + \dots$$

The first diagram shows a wavy line splitting into two straight lines with momenta  $k_1$  and  $k_2$ . The second and third diagrams show a square loop with wavy lines on the left and right sides (momenta  $P_1$  and  $P_2$ ) and straight lines on the top and bottom sides (momenta  $k_2$  and  $k_1$ ).



AS BEFORE:

$$\Pi^{\mu\nu}(K) = \text{wavy line} \xrightarrow{\vec{K}} \text{red circle} \xrightarrow{\vec{K}} \text{wavy line} + \text{wavy line} \xrightarrow{K} \text{red circle} \xrightarrow{K} \text{wavy line} + \dots$$

The first red circle contains a vertical line with momentum  $P$  and  $P+K$  at the vertices. The second red circle contains a vertical line with momentum  $P$  and  $P+K+Q$  at the vertices, with a wavy line connecting them.

OPTICAL THEOREM?

$$\left| \text{wavy line} \rightarrow \begin{matrix} \nearrow k_1 \\ \searrow k_2 \end{matrix} \right|^2 + \left| \begin{matrix} \text{wavy line } P_1 \rightarrow k_2 \\ \leftarrow k_1 \text{ wavy line } P_2 \end{matrix} \right|^2 + \left| \begin{matrix} \text{wavy line } P_1 \rightarrow k_2 \\ \leftarrow k_1 \text{ wavy line } P_2 \end{matrix} \right|^2 + \dots$$

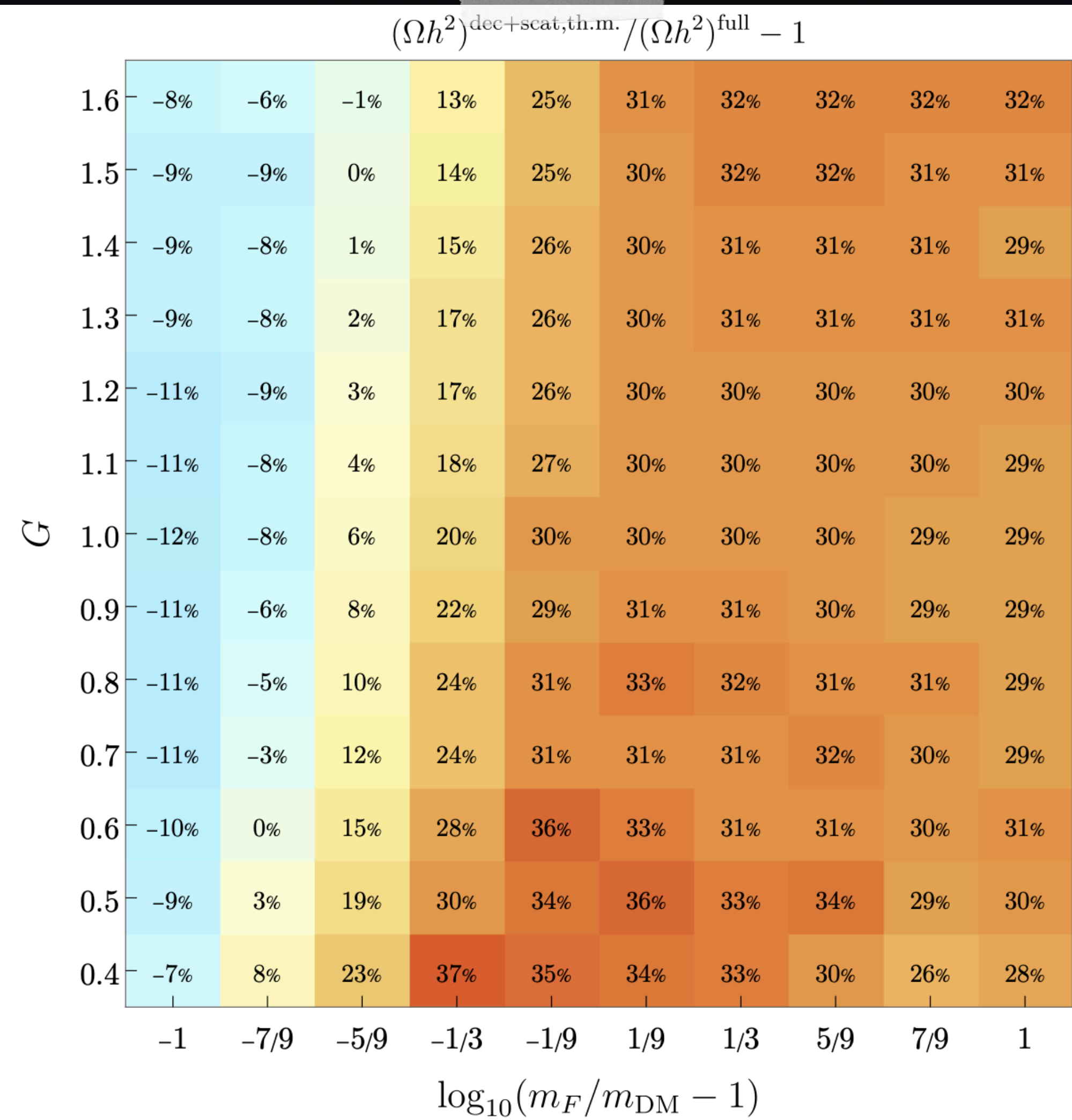
The diagrams are enclosed in vertical yellow lines. The first diagram shows a wavy line entering from the left and splitting into two outgoing lines with momenta  $k_1$  and  $k_2$ . The second and third diagrams show a box with wavy lines on the left and right sides, and straight lines on the top and bottom sides. The second diagram has incoming momenta  $k_1$  and  $k_2$  on the bottom and top respectively, and outgoing wavy lines  $P_1$  and  $P_2$  on the left. The third diagram has incoming wavy lines  $P_1$  and  $P_2$  on the left, and outgoing momenta  $k_2$  and  $k_1$  on the top and bottom respectively.



AS BEFORE:

THIS SEEMS TO MISS THE FULL PICTURE

SEE FOR EG BECKER ET AL (2023)





THE IMAGINARY PART OF THE SELF ENERGY IS GIVEN BY THE **DISCONTINUITY** OF THESE DIAGRAMS

$$\Pi^{\mu\nu}(K) = \text{diagram 1} + \text{diagram 2} + \dots$$

The first diagram shows a horizontal wavy line with momentum  $\vec{K}$  entering from the left and exiting to the right. In the middle, there is a red circle representing a loop. A vertical yellow line passes through the center of the circle. The top half of the circle is labeled  $P+K$  and the bottom half is labeled  $P$ .

The second diagram is similar, but the wavy lines are yellow. The loop is a red circle with a vertical yellow line through its center. The top half is labeled  $P+K+Q$  and the bottom half is labeled  $P$ .



# OTHER CUTS ARE POSSIBLE THAT DON'T DIRECTLY TRANSLATE TO SIMPLE PROCESSES

37

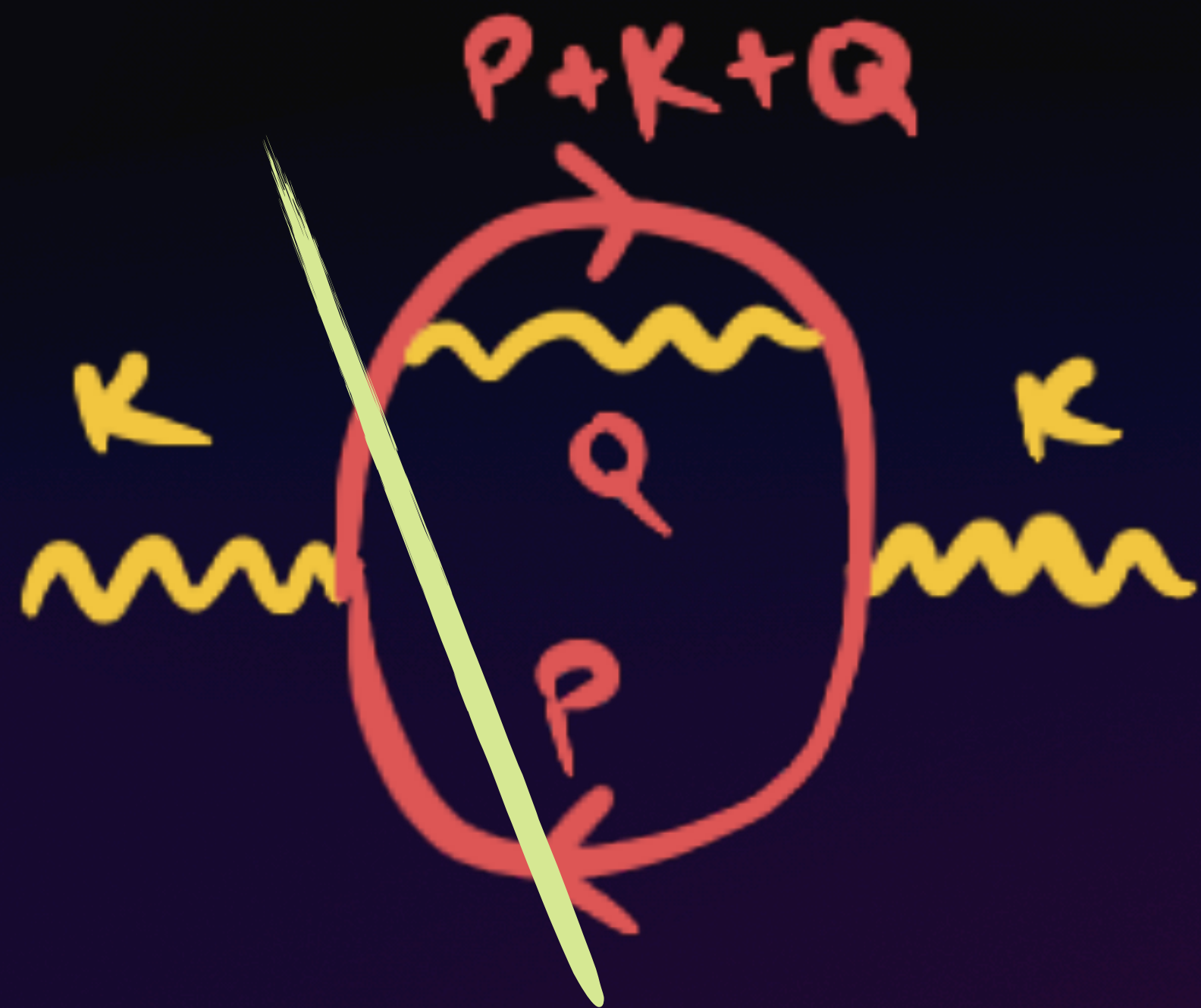


WONG (2001)

MAJUMDAR AND GALE (2002)



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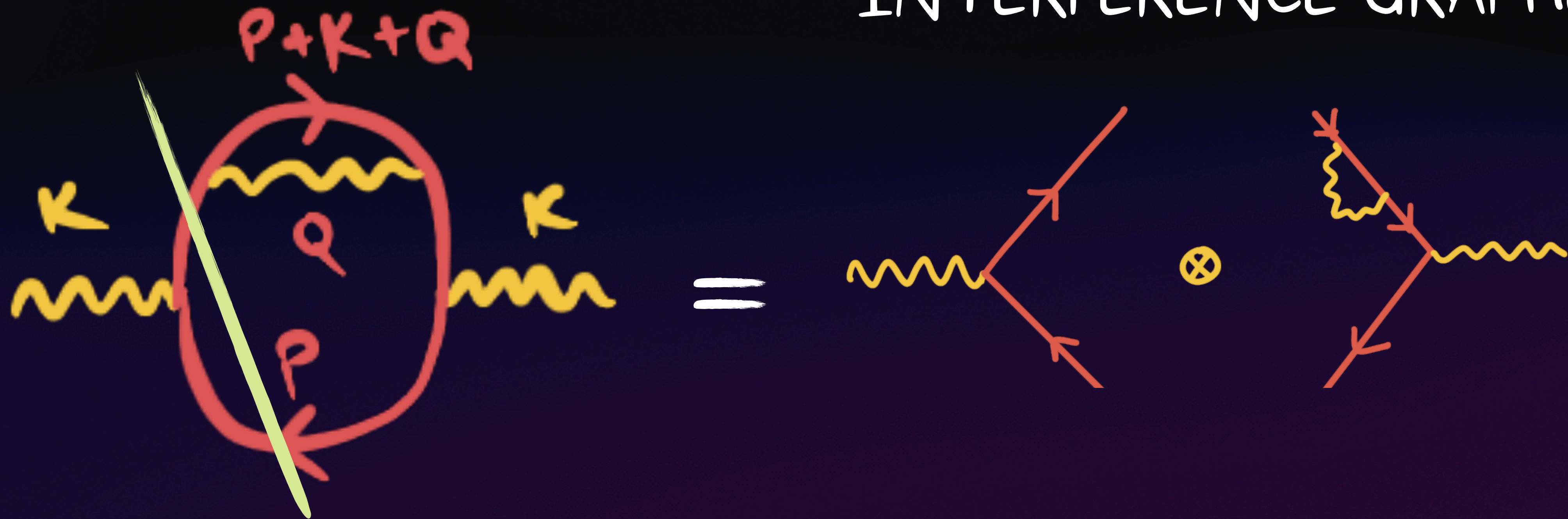
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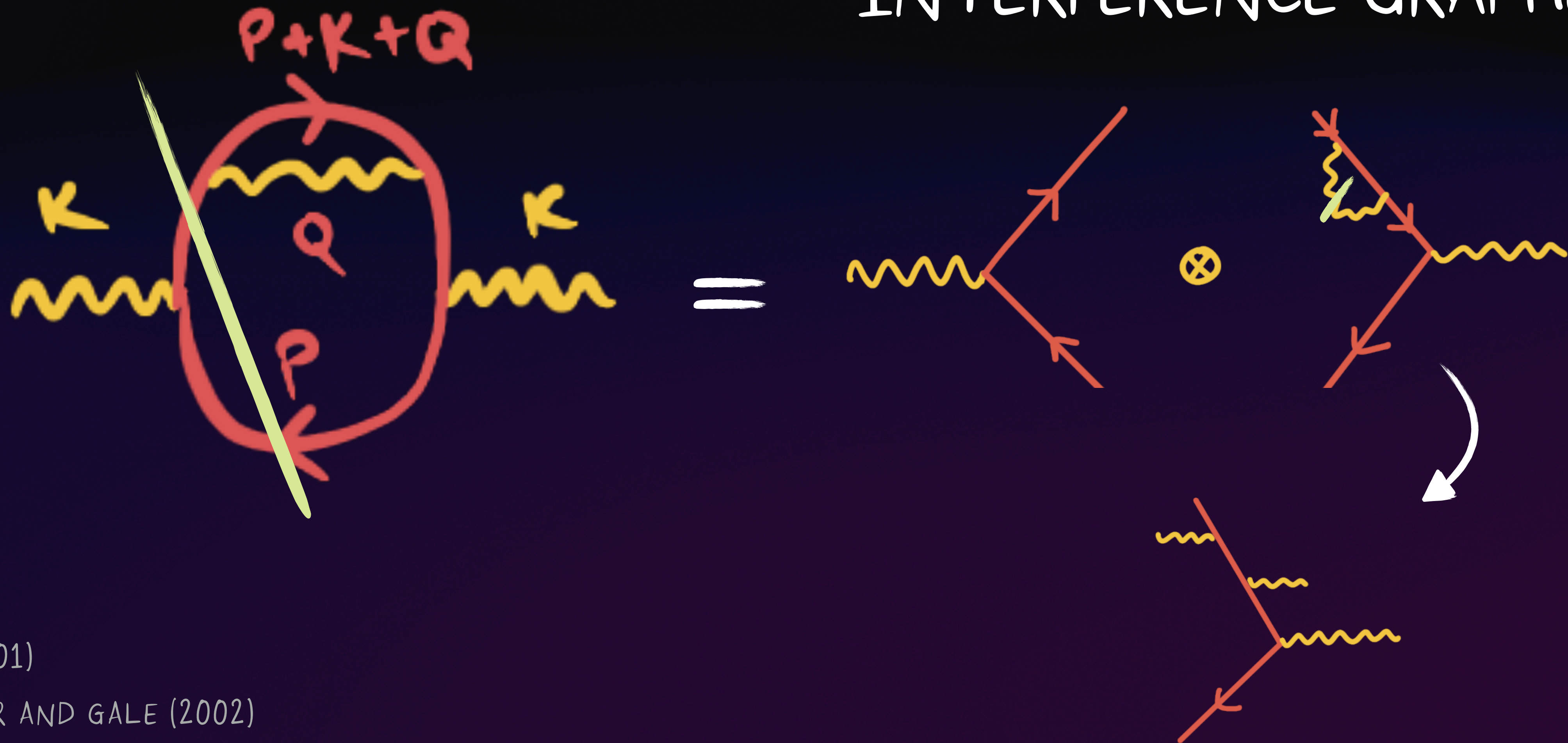
"INTERFERENCE GRAPHS"





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"INTERFERENCE GRAPHS"



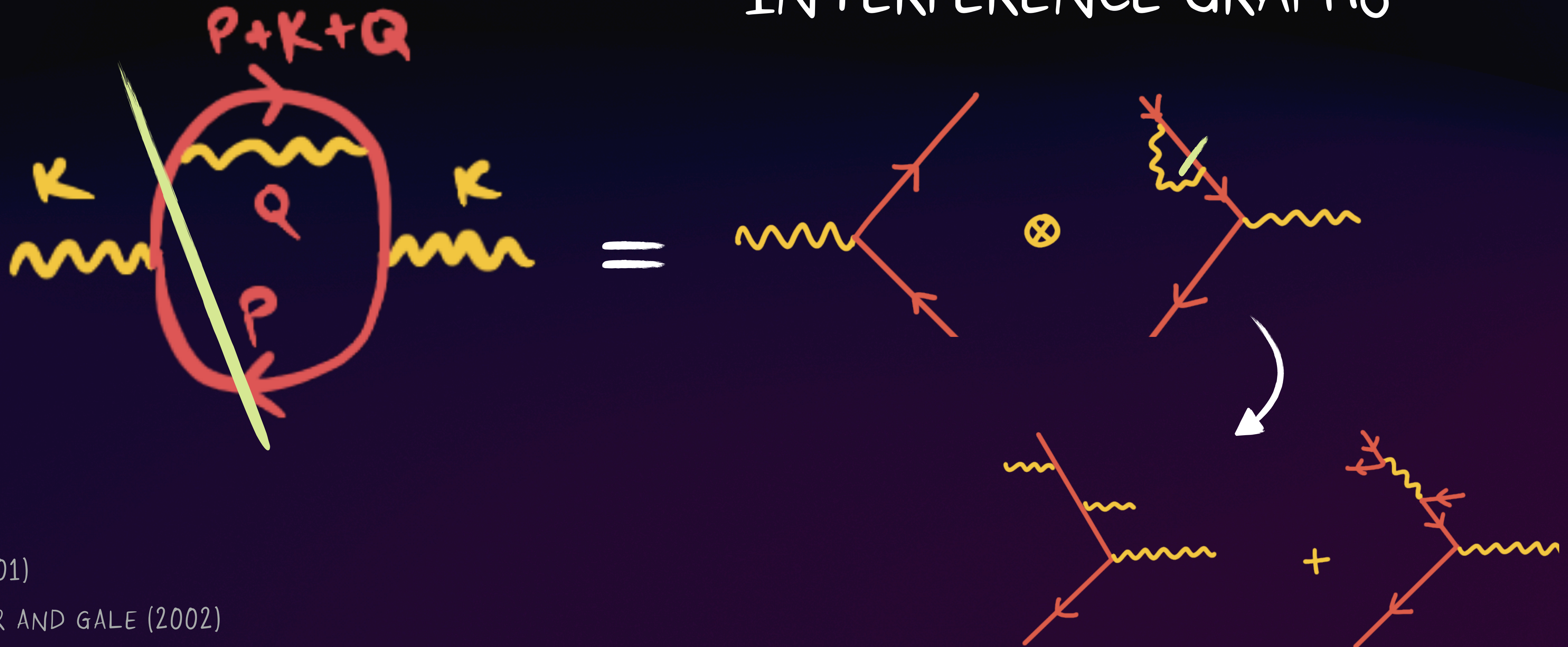
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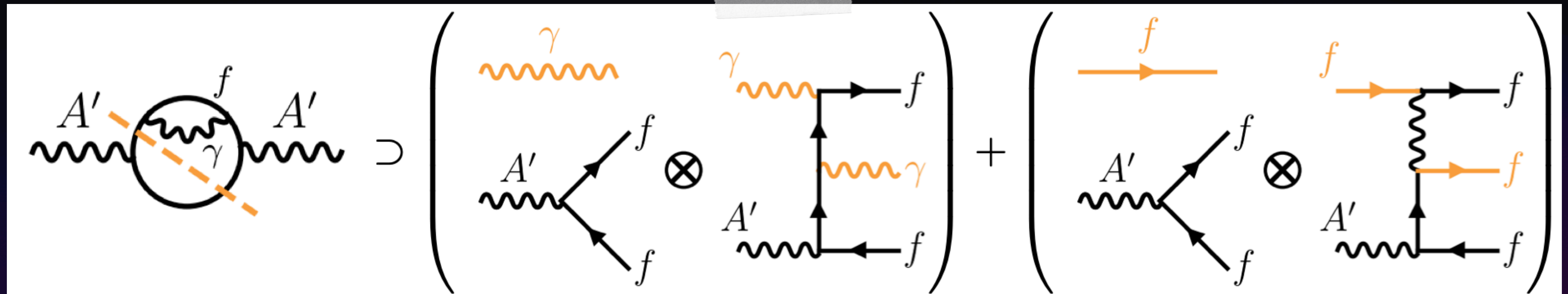


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# INTERFERENCE GRAPHS CAN BE UNDERSTOOD AS "SPECTATORS" FORWARD SCATTERING



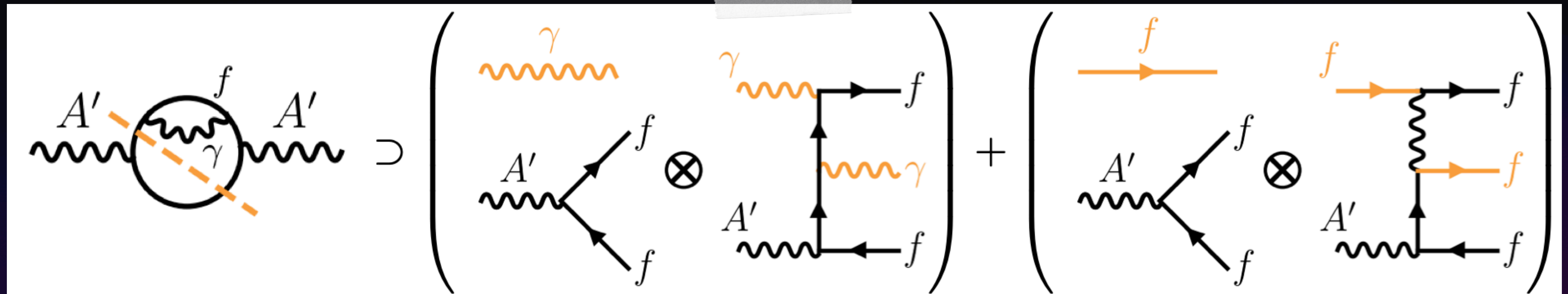
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BRAHMA, **SH**, SCHERER AND SCHUTZ (2025)



# INTERFERENCE GRAPHS CAN BE UNDERSTOOD AS "SPECTATORS" FORWARD SCATTERING



THESE DIAGRAMS ARE REQUIRED TO CANCEL THE IR AND  
COLLINEAR DIVERGENCES IN THE THEORY!

WONG (2001)

MAJUMDAR AND GALE (2002)

BRAHMA, **SH**, SCHERER AND SCHUTZ (2025)



INTERACTION RATE IN A MEDIUM:

**USUAL PROCESSES IN A VACUUM**

APPROPRIATELY WEIGHTED

+

**INTERFERENCE PROCESS** WITH NO

VACUUM ANALOG



**OKAY BUT HOW?**



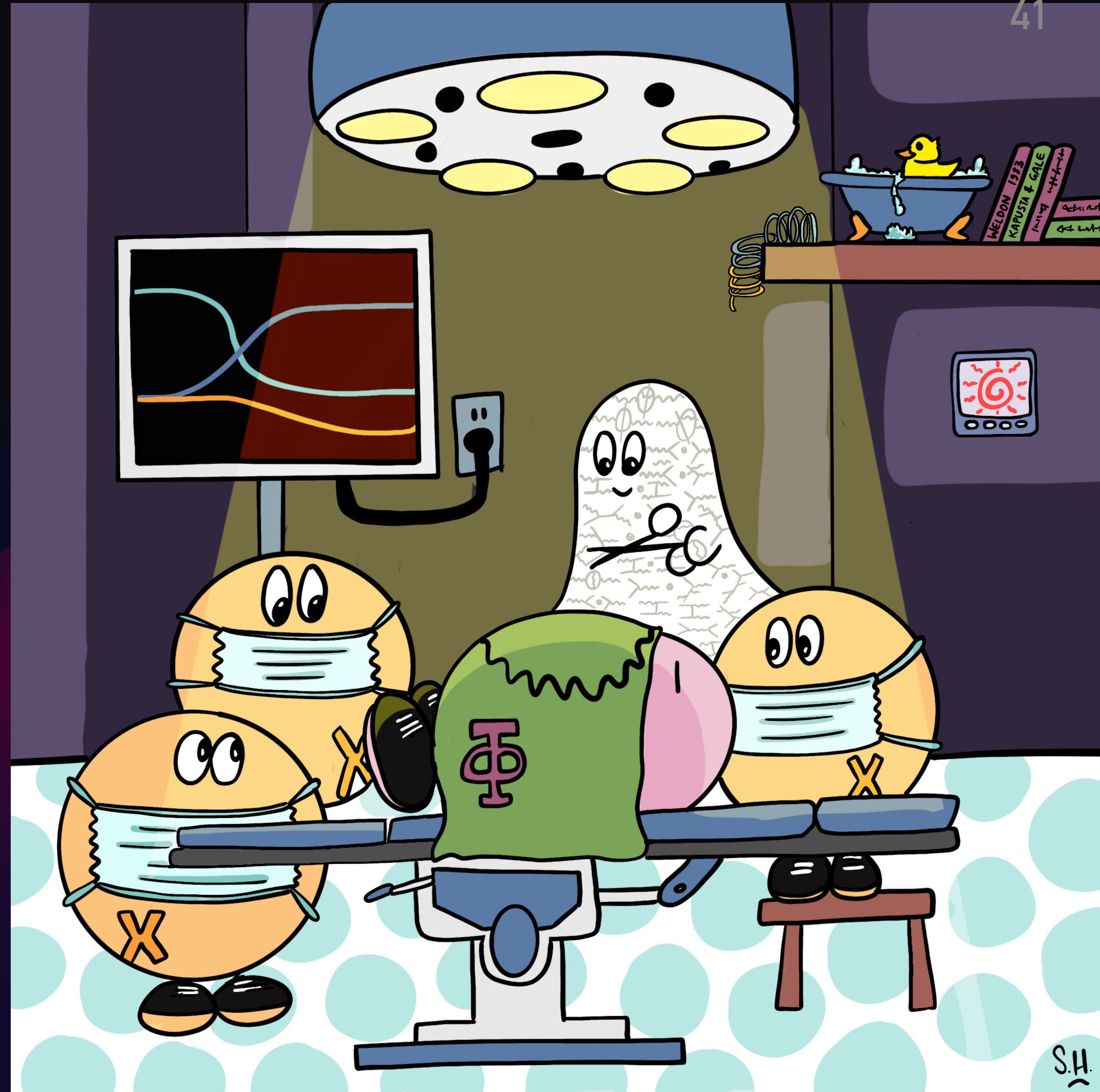
# SPECTRAL SURGERY IN A HEAT BATH

(SSHb)

SYSTEMATICALLY LINK FINITE  
TEMPERATURE SELF ENERGIES TO TREE  
LEVEL SCATTERING PROCESSES

JHEP 05 (2026) 131

(WITH N. BRAHMA, H. SCHERER AND K. SCHUTZ)  
SEE HUGO'S TALK!





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(WITH N. BRAHMA, H. SCHERER AND K. SCHUTZ)

SEE HUGO'S TALK!

PROVIDES STEP BY STEP  
INSTRUCTIONS TO GO FROM  
LOOPS TO TREES!



$$= \left| \text{---} \text{---} \right|^2$$

The diagram shows a horizontal line on the left connected to a vertex, which then splits into two lines: a solid red line going up and to the right, and a dashed red line going down and to the right. The entire expression is enclosed in vertical bars with a superscript 2.

$$+ \left| \text{---} \text{---} \right|^2 + \left| \text{---} \text{---} \right|^2 + \left| \text{---} \text{---} \right|^2$$

The first row shows three terms, each enclosed in vertical bars with a superscript 2. The first term has a solid red line on the left and a dashed red line on the right. The second term has a solid red line on the left and a solid red line on the right. The third term has a dashed red line on the left and a solid red line on the right.

$$+ \left| \text{---} \text{---} \right| \otimes \left( \text{---} \text{---} + \text{---} \text{---} \right)$$

The second row shows a term enclosed in vertical bars with a superscript 2, followed by a tensor product symbol  $\otimes$  and a sum of two terms in parentheses. The first term in the parentheses has a solid red line on the left and a dashed red line on the right. The second term has a dashed red line on the left and a solid red line on the right.

$$+ \left| \text{---} \text{---} \right| \otimes \left( \text{---} \text{---} + \text{---} \text{---} \right)$$

The third row shows a similar structure to the second row, with a term enclosed in vertical bars with a superscript 2, followed by a tensor product symbol  $\otimes$  and a sum of two terms in parentheses. The first term in the parentheses has a solid red line on the left and a solid red line on the right. The second term has a dashed red line on the left and a dashed red line on the right.



# SPECTRAL SURGERY IN A HEAT BATH

(SSHb)

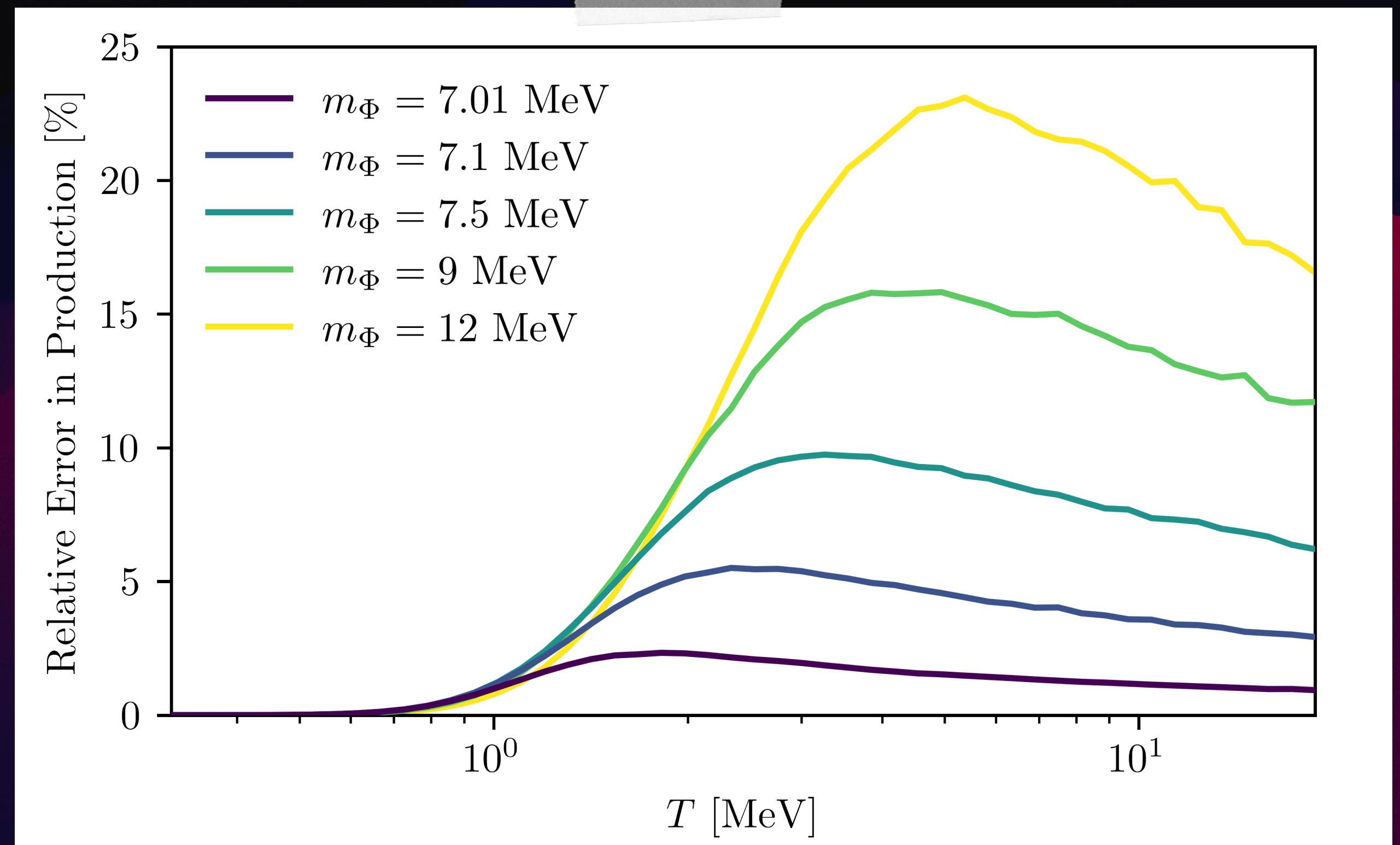
SYSTEMATICALLY LINK FINITE  
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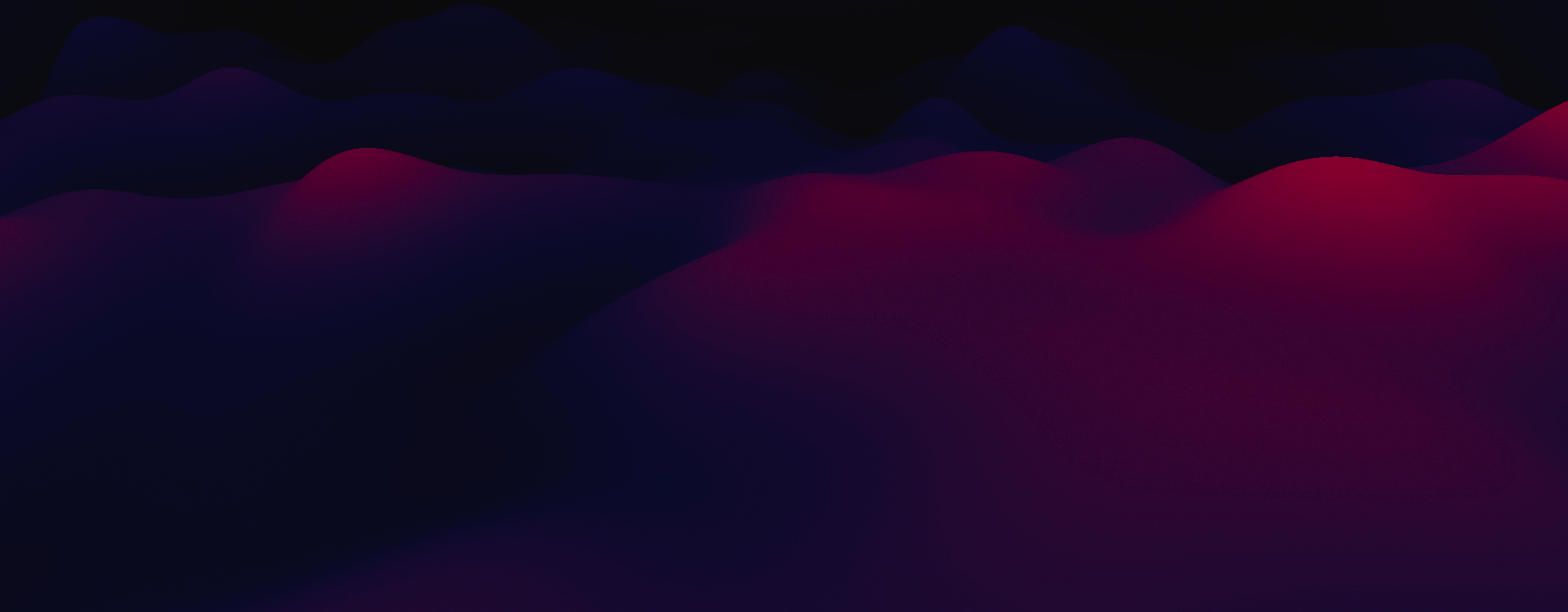
SEE HUGO'S TALK!

RESULTS IN AN ORDER ONE  
EFFECT ON PRODUCTION!





# CAVEATS / OUTLOOK





# CAVEATS / OUTLOOK

1. PARTICLES IN THE SELF ENERGY LOOP SHOULD BE IN **EQUILIBRIUM**



# CAVEATS / OUTLOOK

1. PARTICLES IN THE SELF ENERGY LOOP SHOULD BE IN **EQUILIBRIUM**
2. THE '**THERMAL MASS**' OF THE PARTICLES IN THE LOOP SHOULD BE **INDEPENDENT** OF THEIR FOUR MOMENTA



# CAVEATS / OUTLOOK

**LOTS OF ROOM TO COLLABORATE  
TO BUILD THIS FURTHER!**

MOMENTA



# FINITE TEMPERATURE AND DENSITY EFFECTS...



...ARE **RELEVANT**  
TO LIGHT BSM  
PHYSICS



...ARE **NON**  
**TRIVIAL** TO  
ESTIMATE



...REQUIRE  
**COLLABORATION AND**  
**CROSSTALK!**





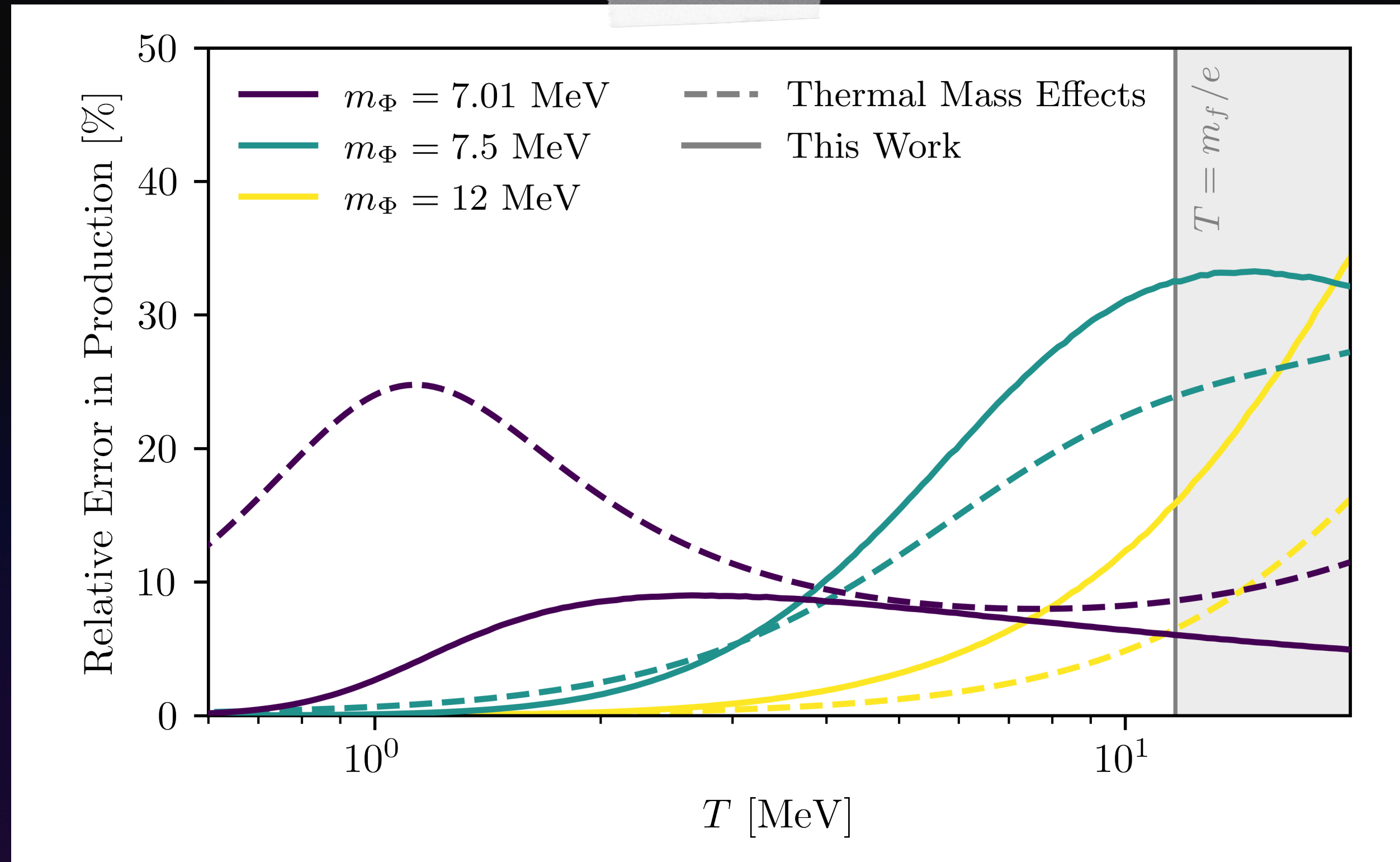
FIN.



# PHENOMENOLOGY:

$$\mathcal{L} \supset g\Phi\bar{f}f + eA'_\mu\bar{f}\gamma^\mu f$$

47

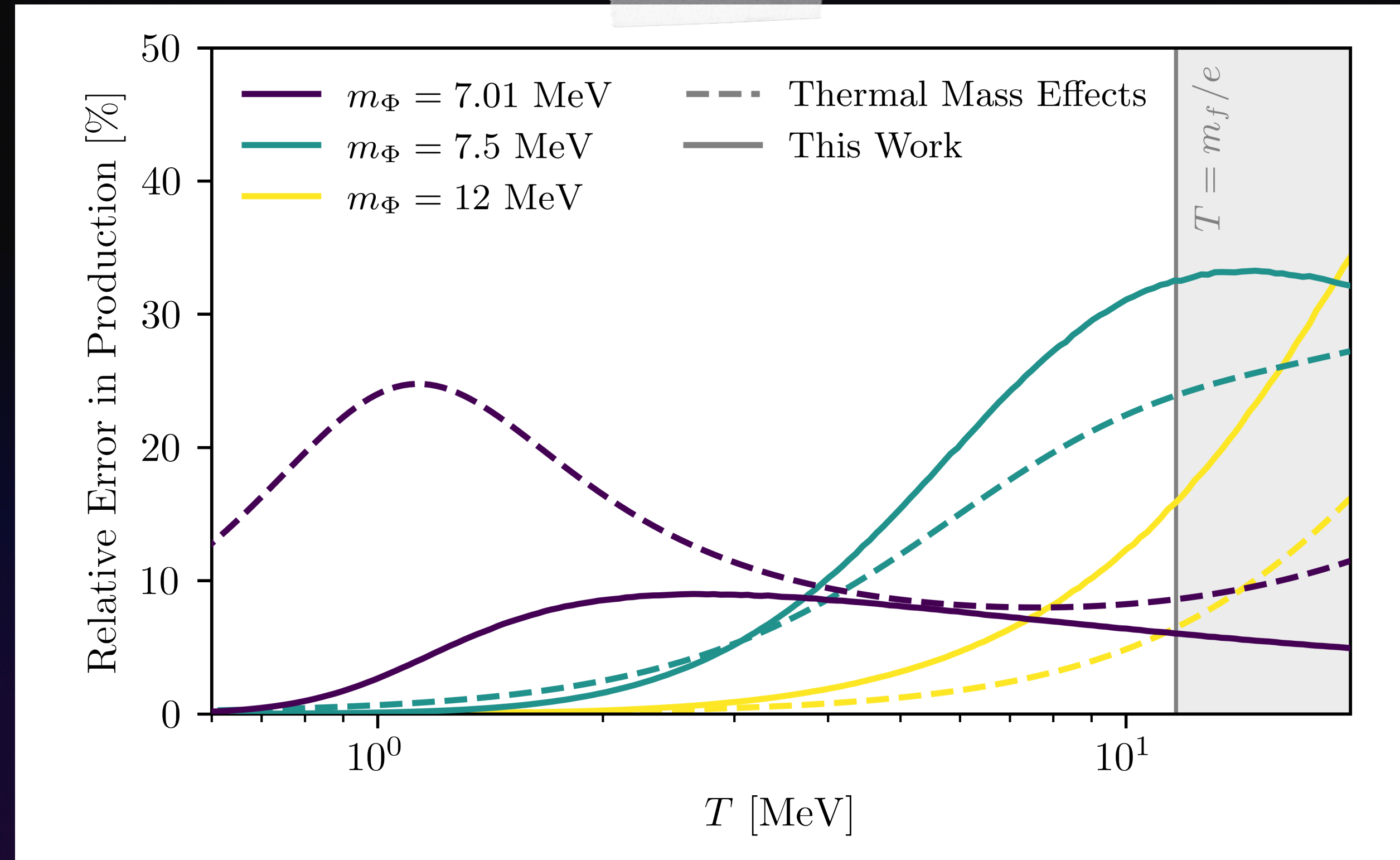




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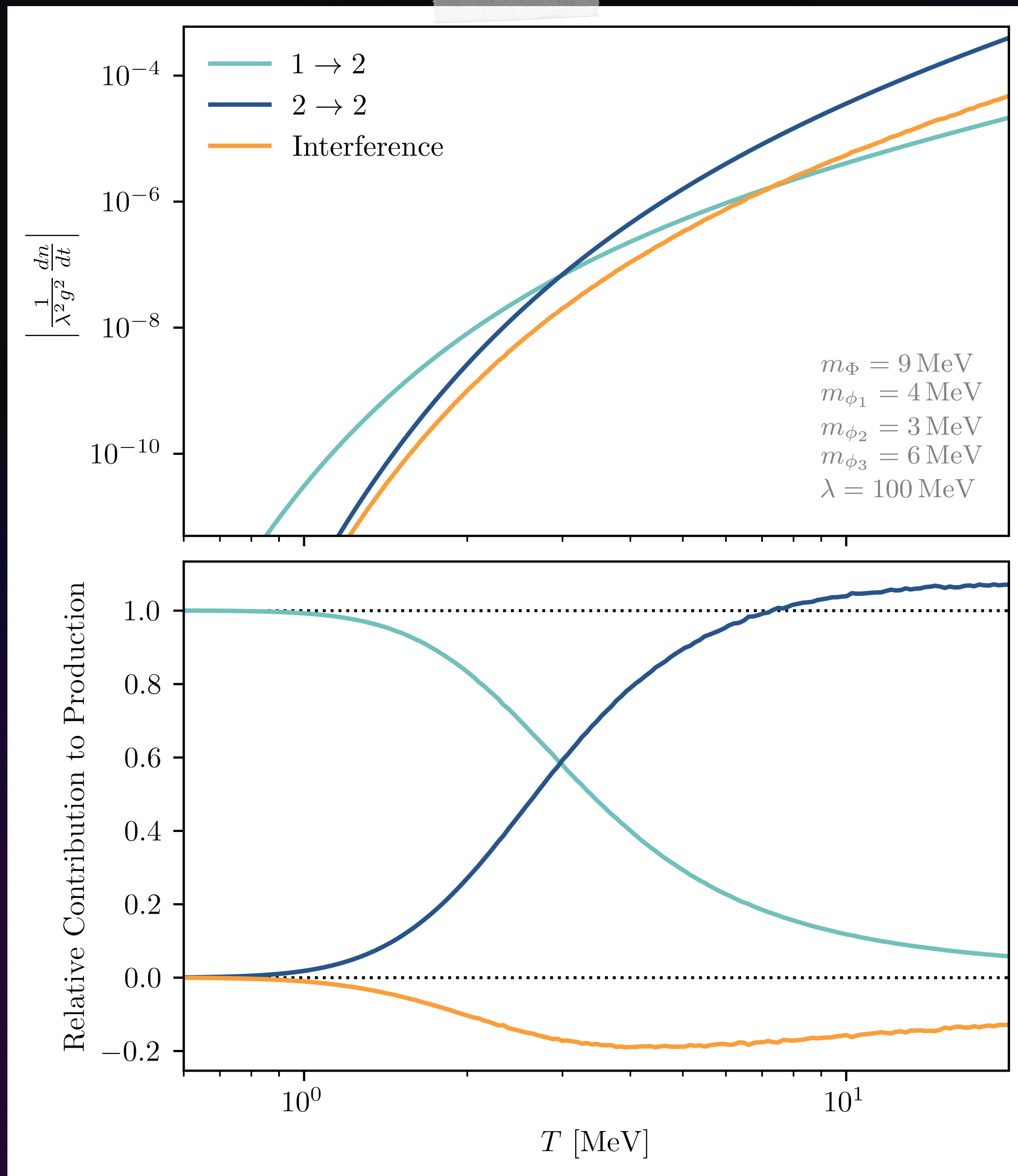
47



COMPARABLE TO THE "THERMAL MASS" EFFECT GENERALLY  
USED IN RATE CALCULATIONS

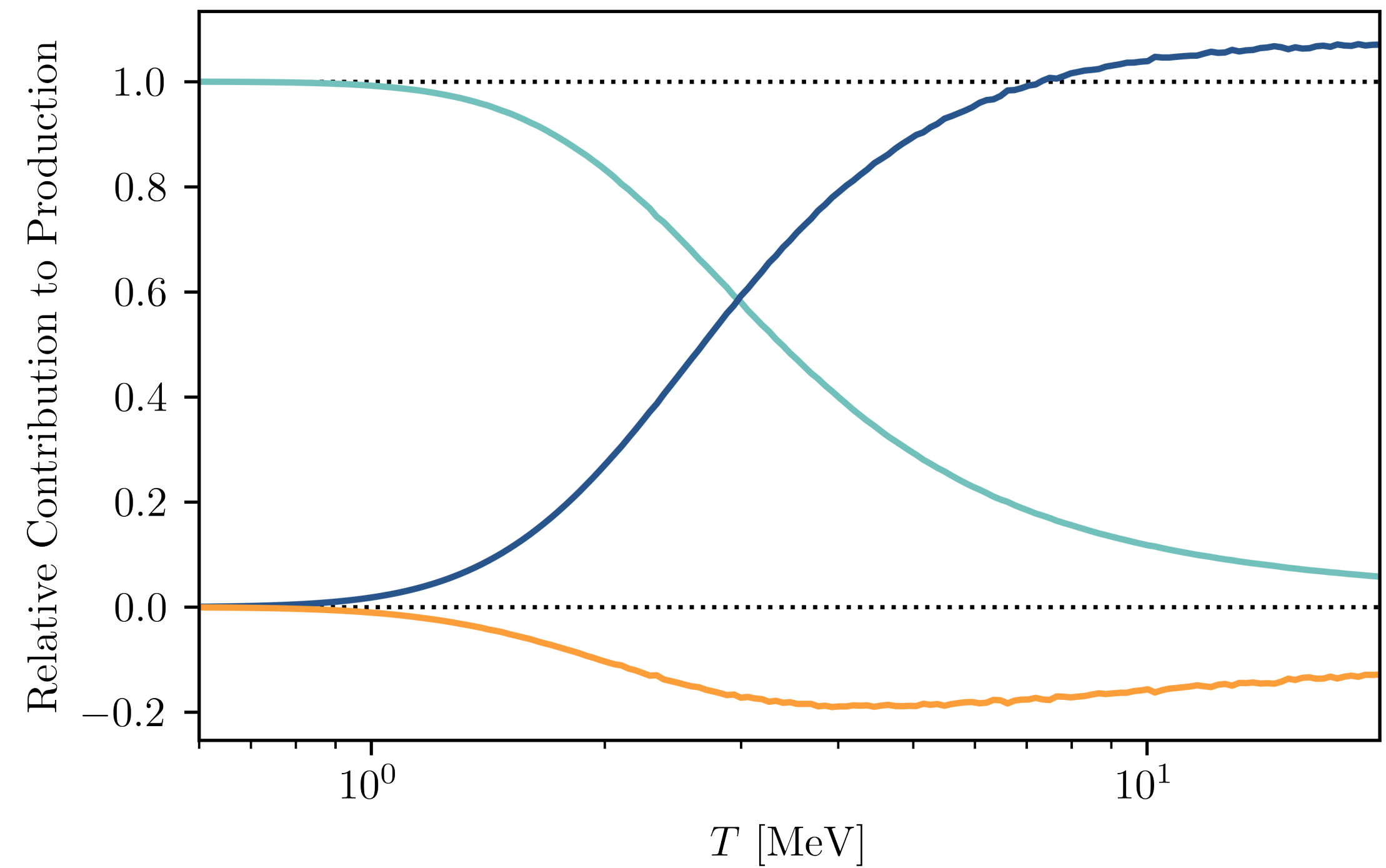
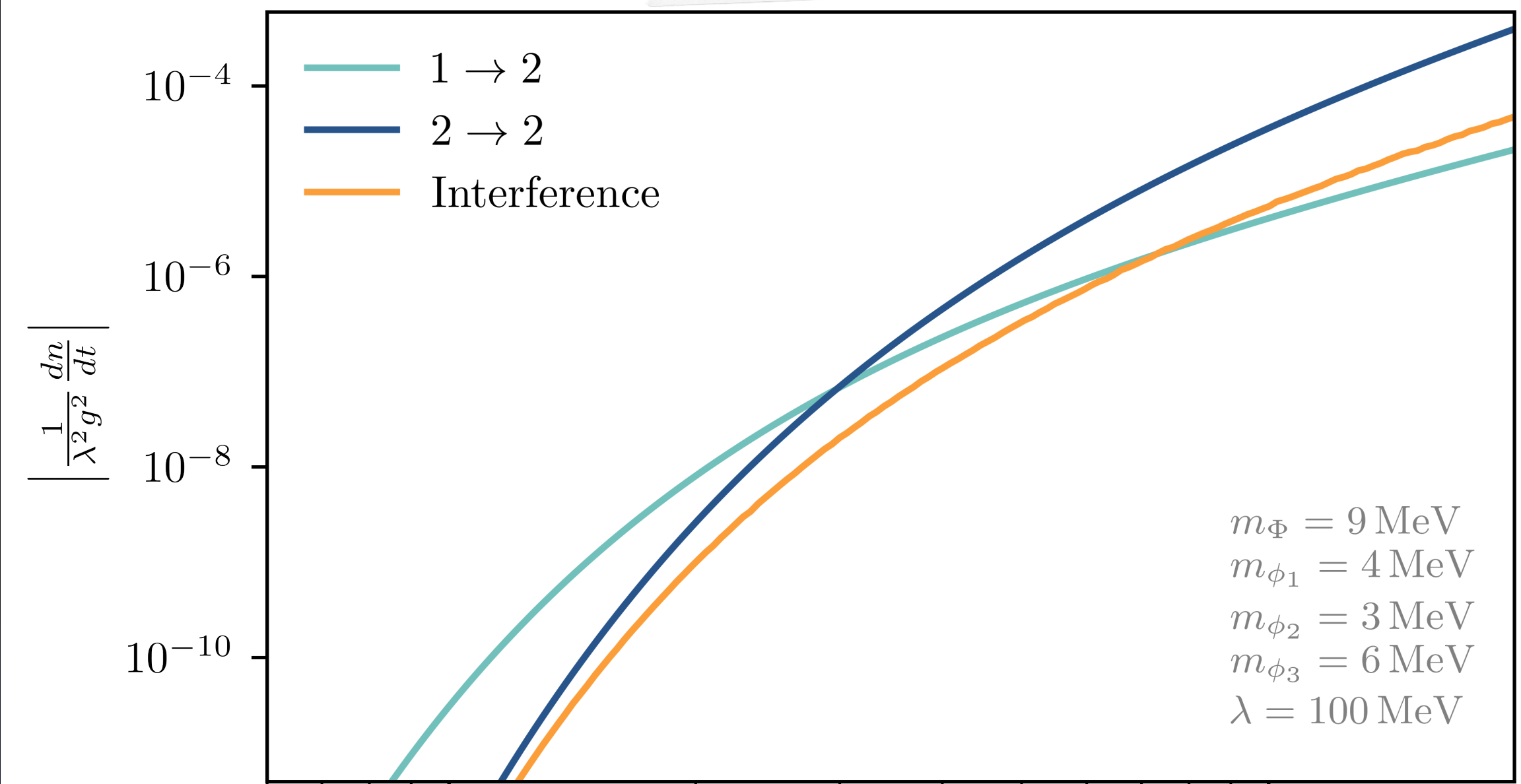
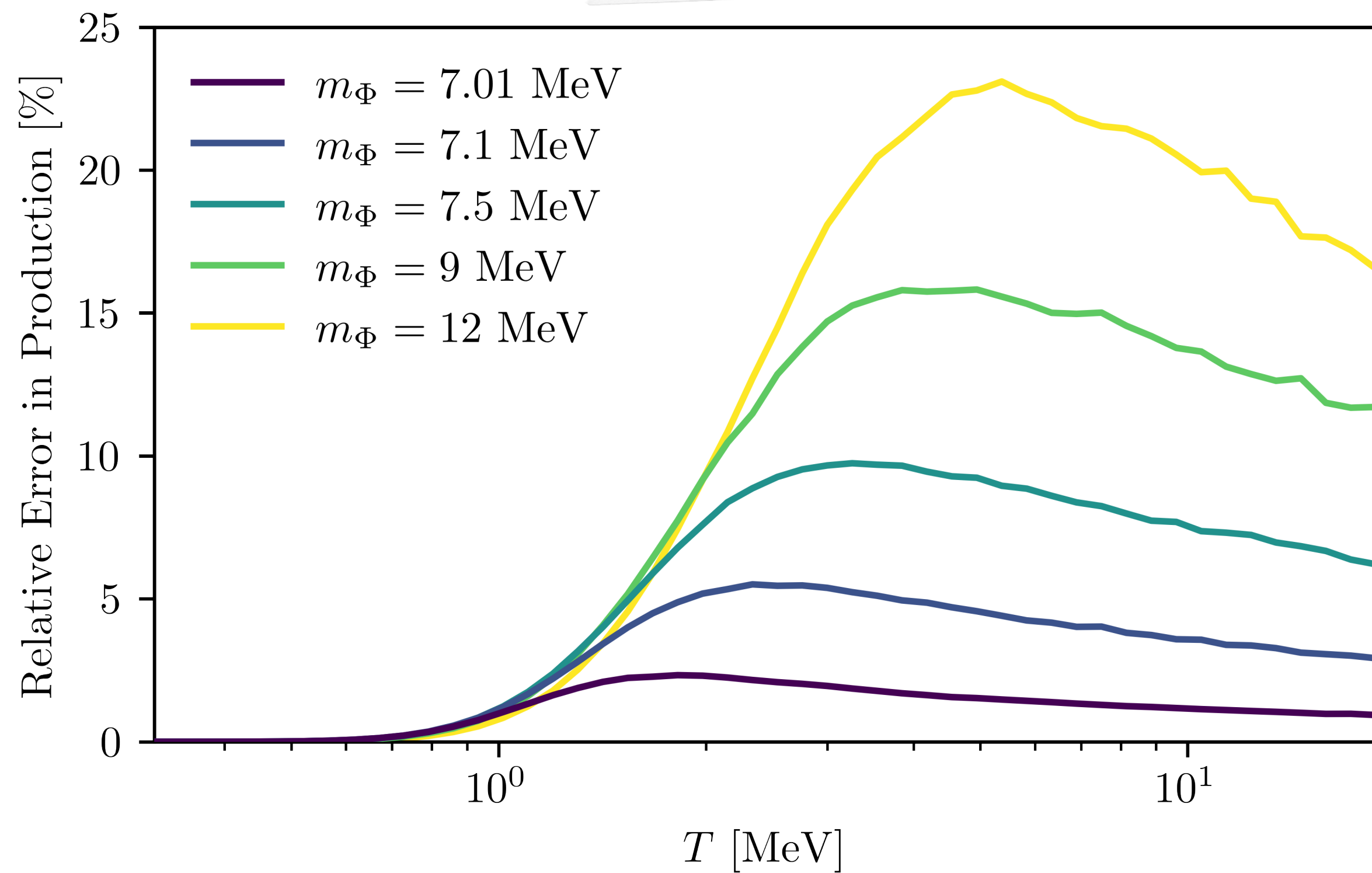


# PHENOMENOLOGY:





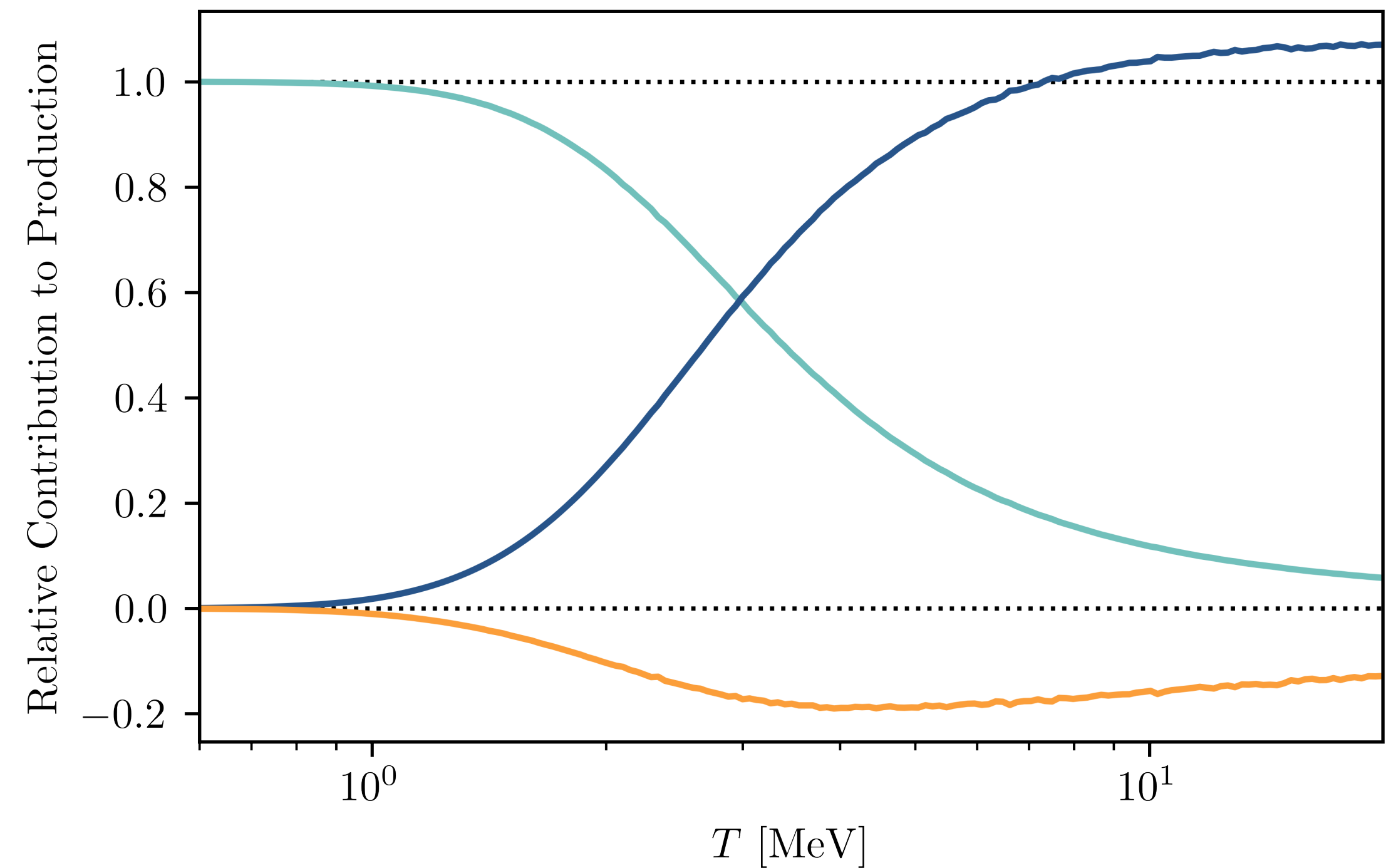
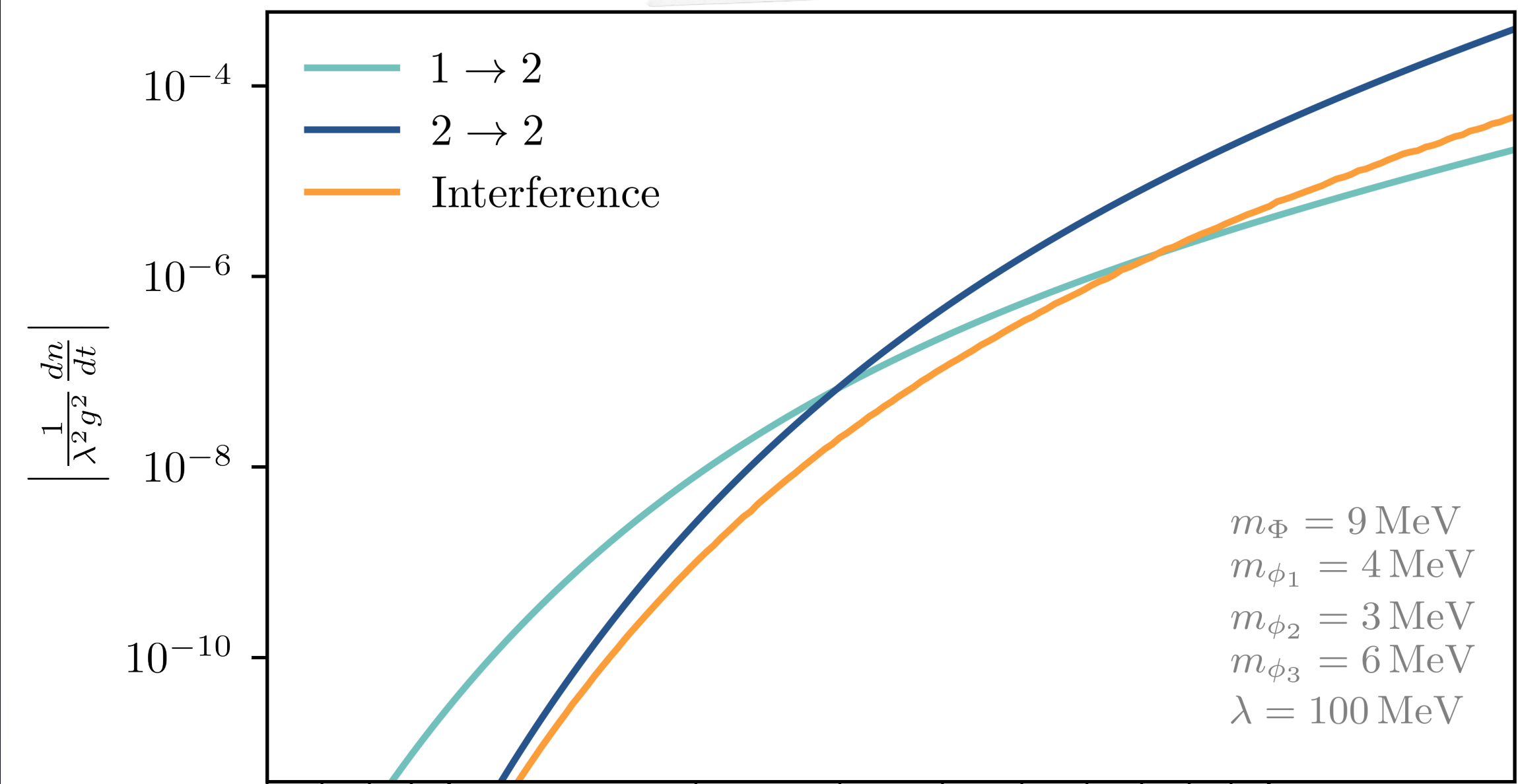
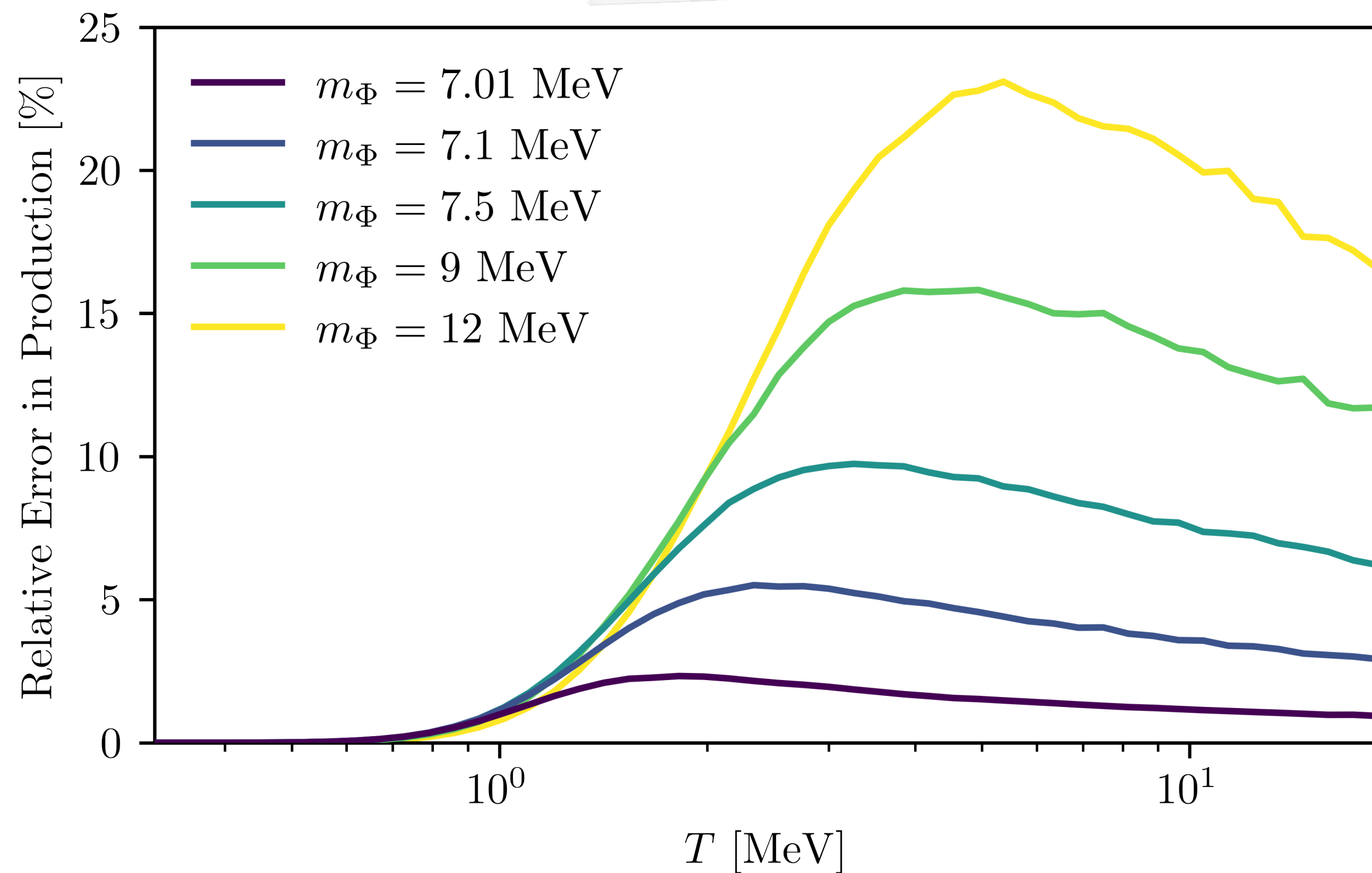
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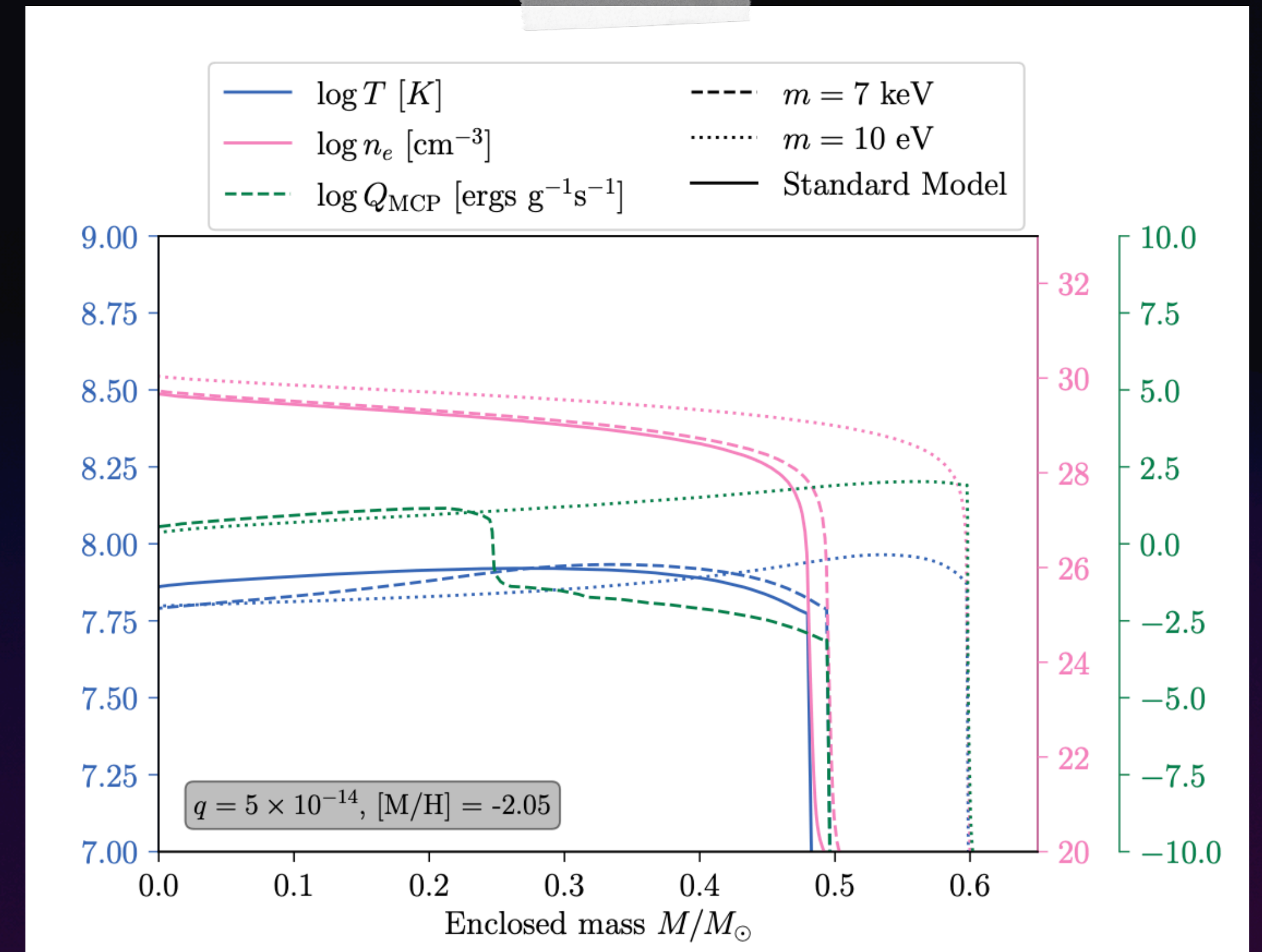
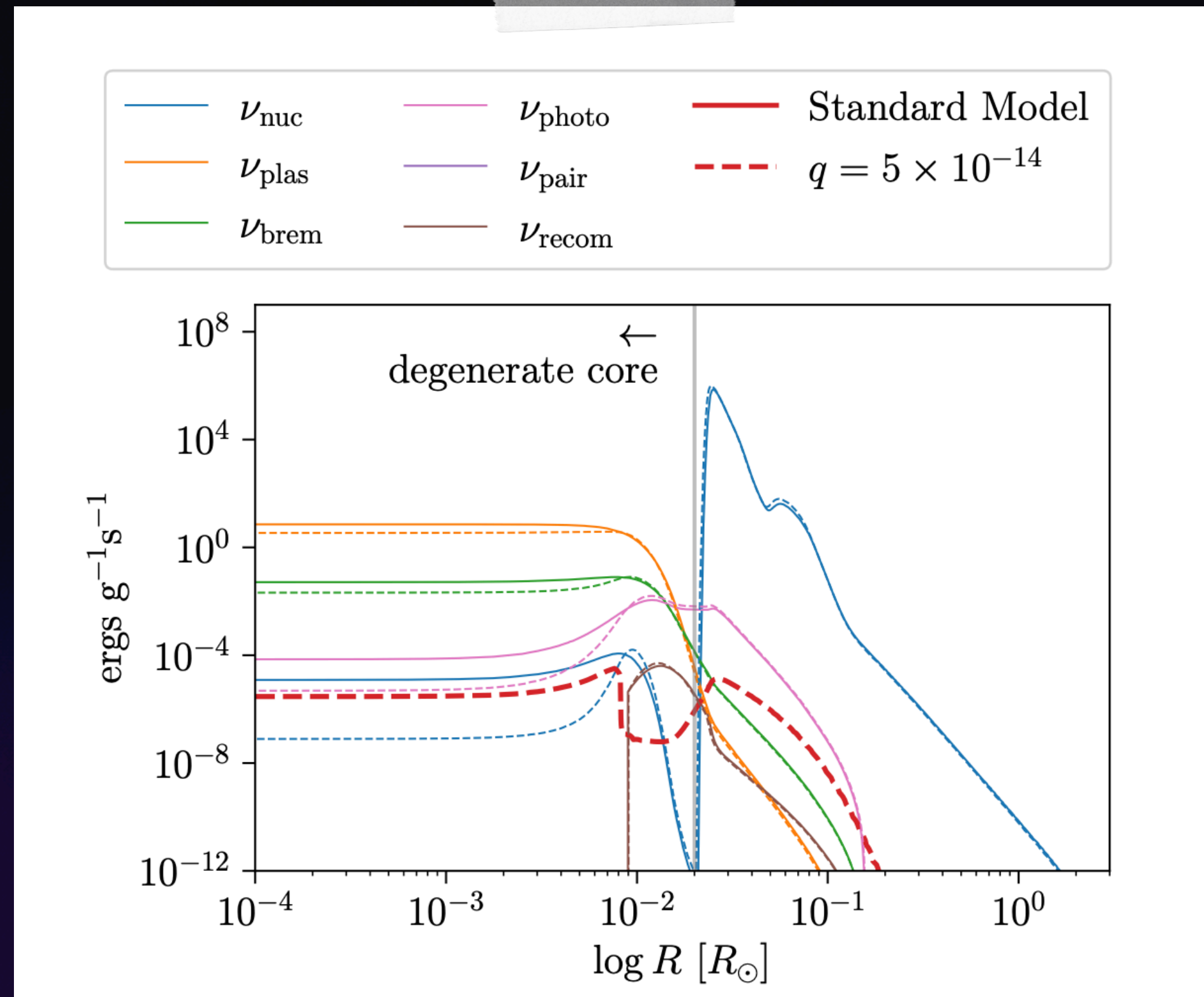
# PHENOMENOLOGY:

**AN ORDER ONE EFFECT ON PRODUCTION!**





# MCP BACKREACTION:

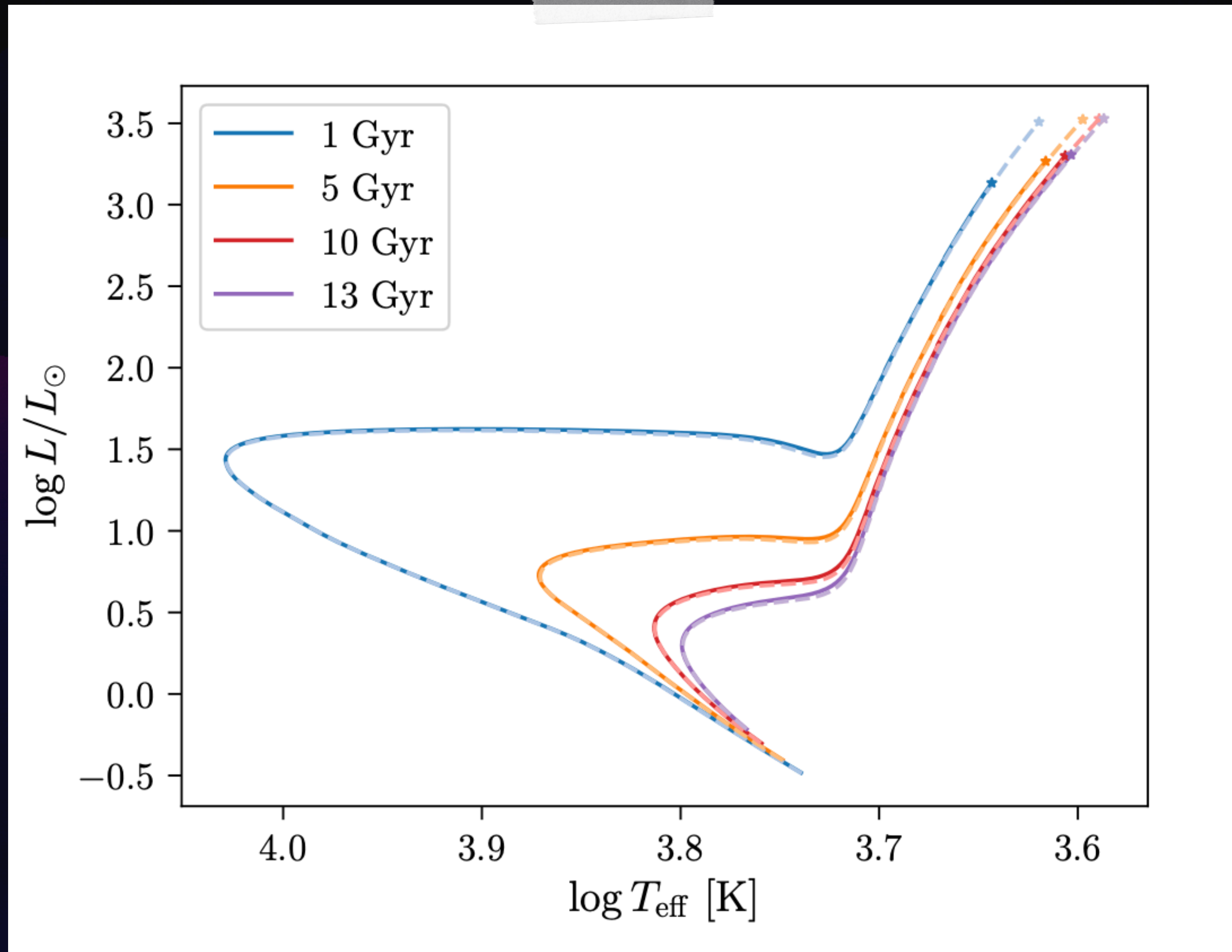


**THE INCLUSION OF THE MCP CHANNEL RESULTS IN A LOWER ENERGY LOSS RATES EVEN FROM THE SM CHANNELS**



# MCPS DELAY HELIUM FLASH

50

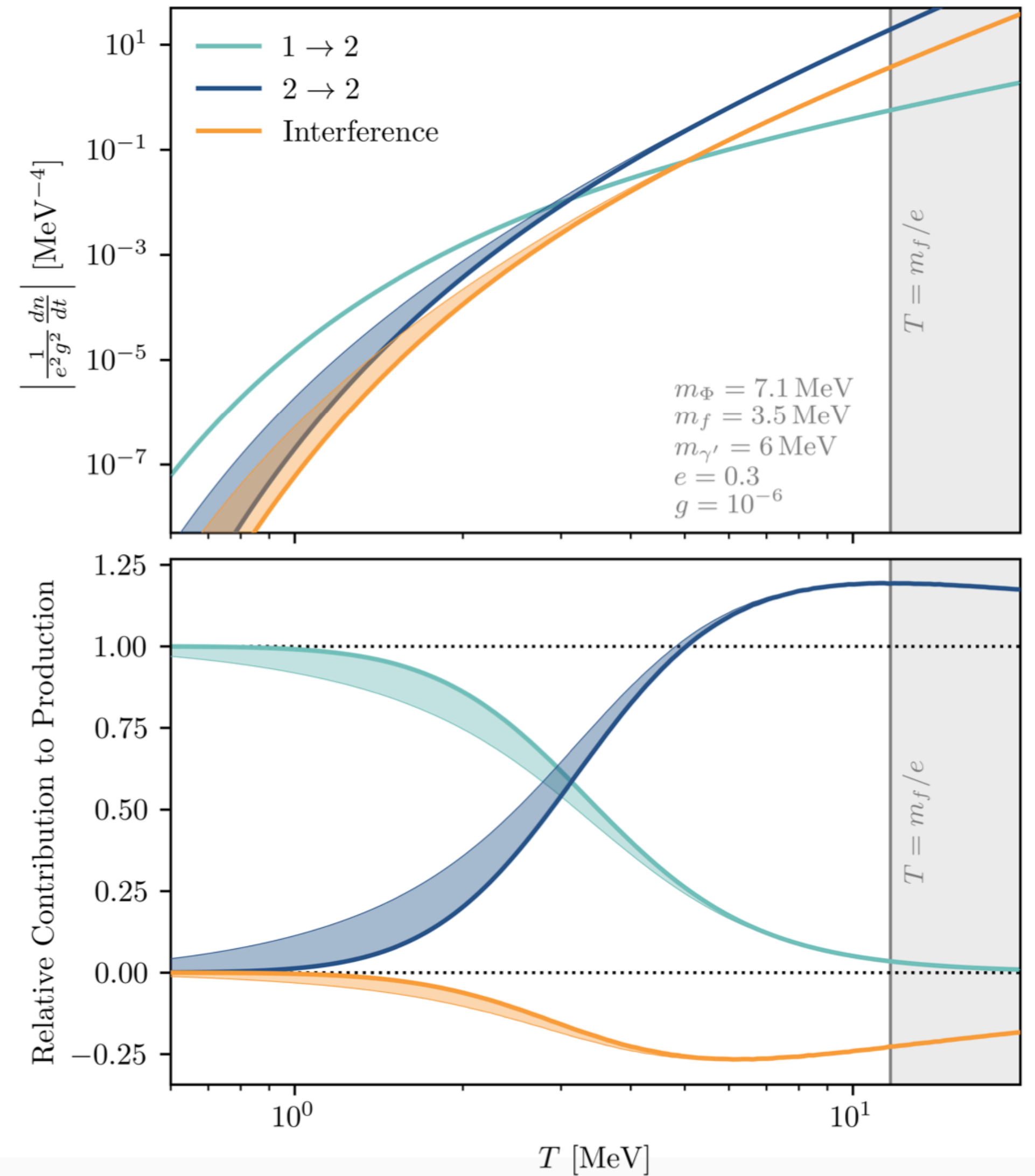
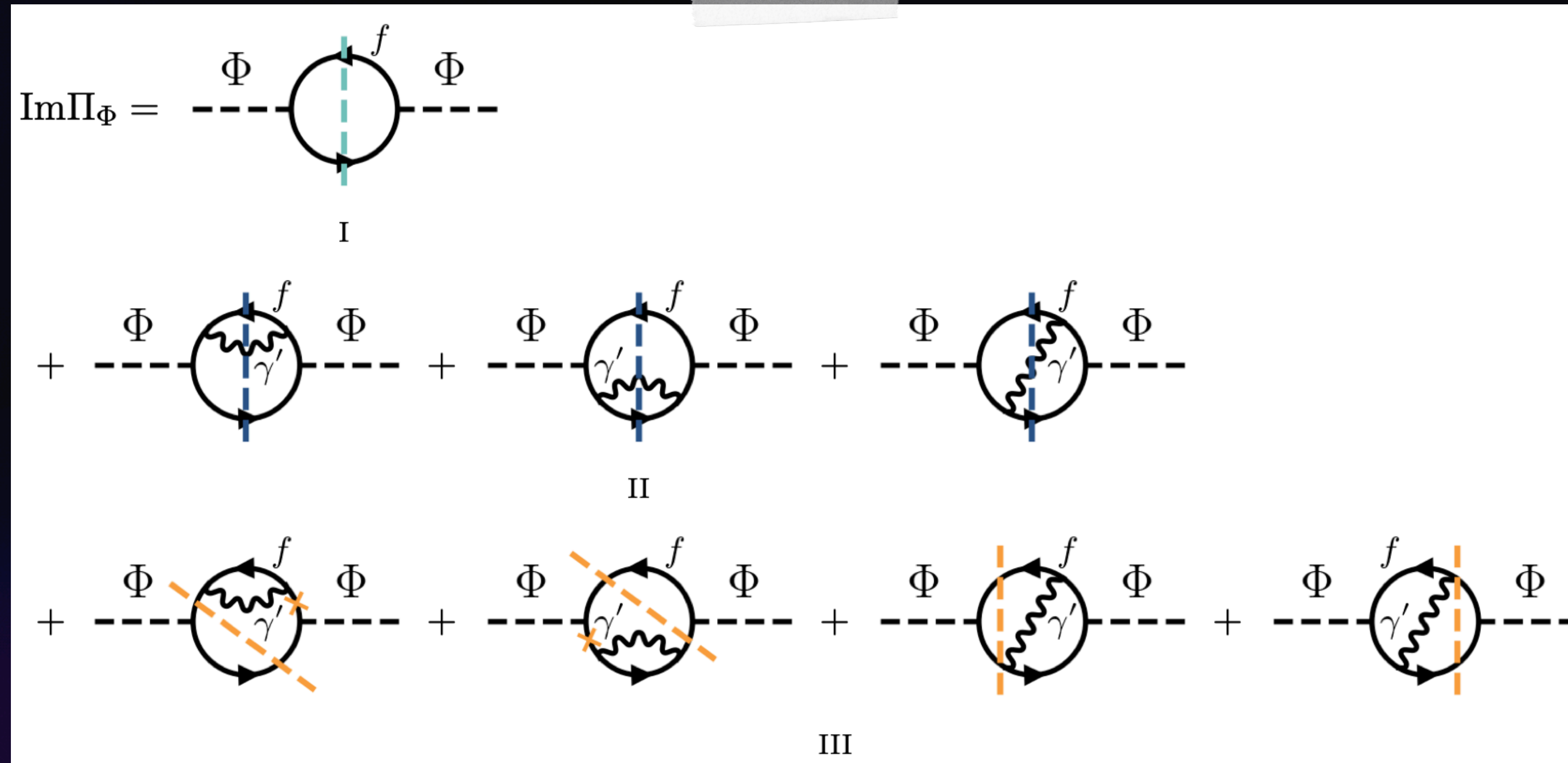




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51

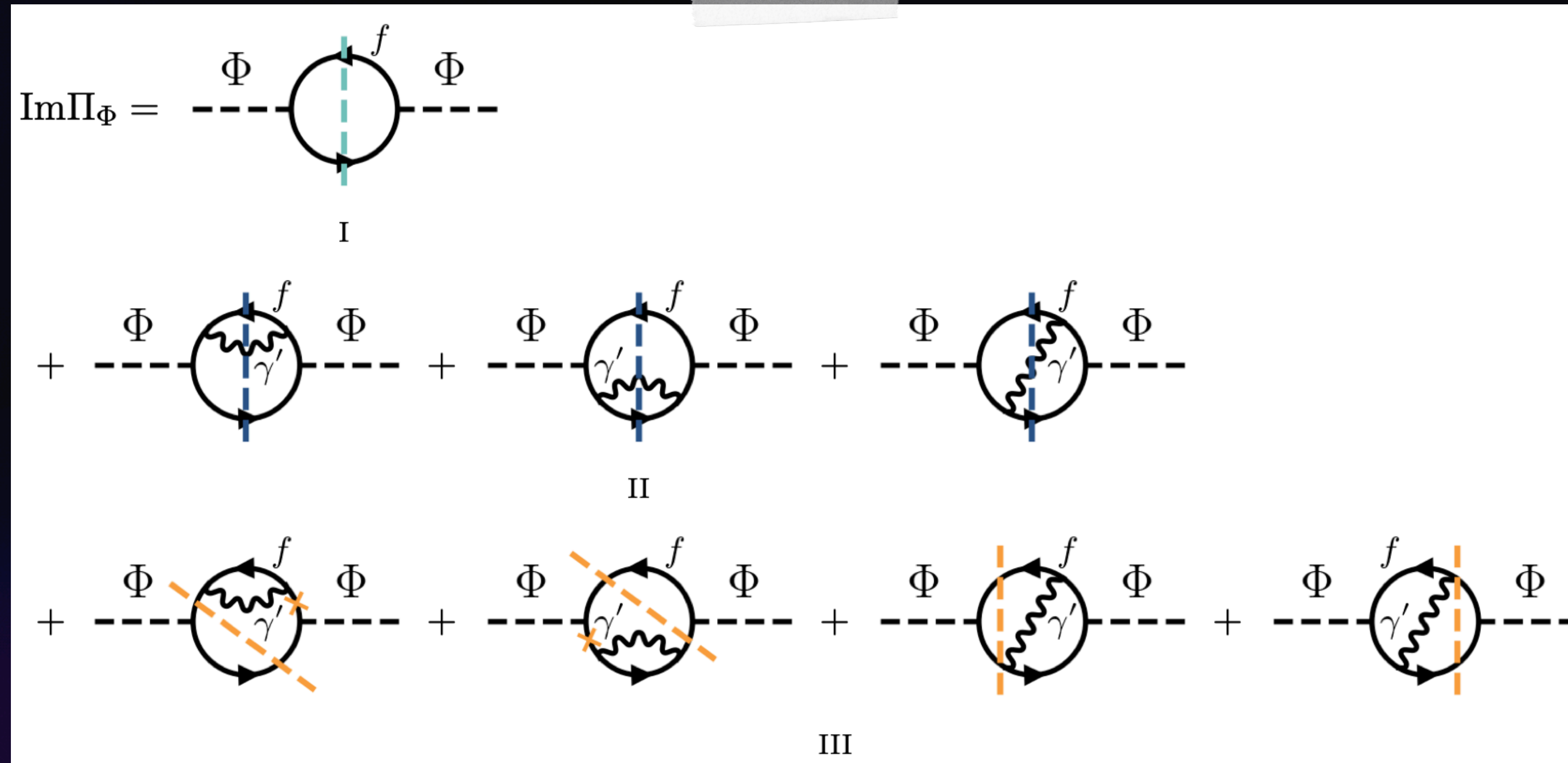




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51



VARYING THE CHEMICAL POTENTIAL  
IMPACTS PRODUCTION BY A FEW PERCENT

