

The Cosmic Landscape

Lake Louise Winter Institute

Jeff Dror



Outline

The Big Picture

Thermal Dark Matter

Non-Thermal Dark Matter

Conclusion

Outline

The Big Picture

Thermal Dark Matter

Non-Thermal Dark Matter

Conclusion

Outline

The Big Picture



Thermal Dark Matter

Non-Thermal Dark Matter

Conclusion

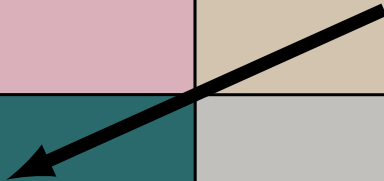
Outline

The Big Picture

Thermal Dark Matter

Non-Thermal Dark Matter

Conclusion



Outline

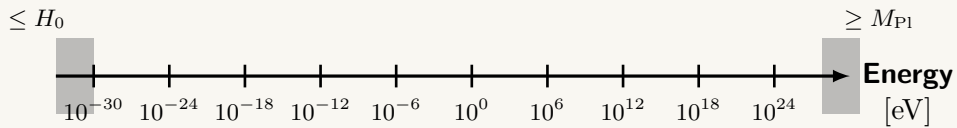
The Big Picture

Thermal Dark Matter

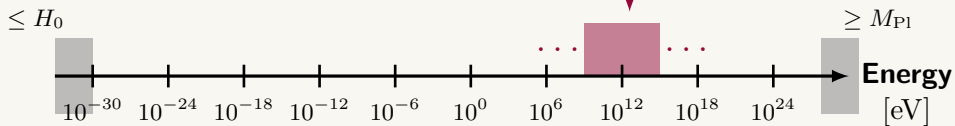
Non-Thermal Dark Matter

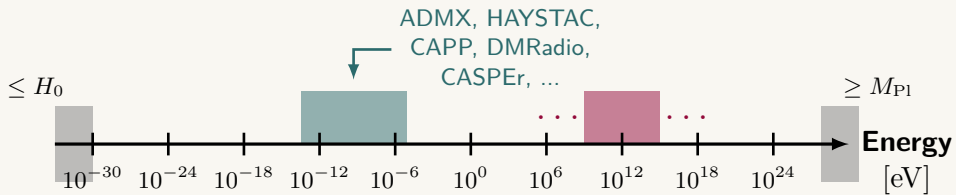


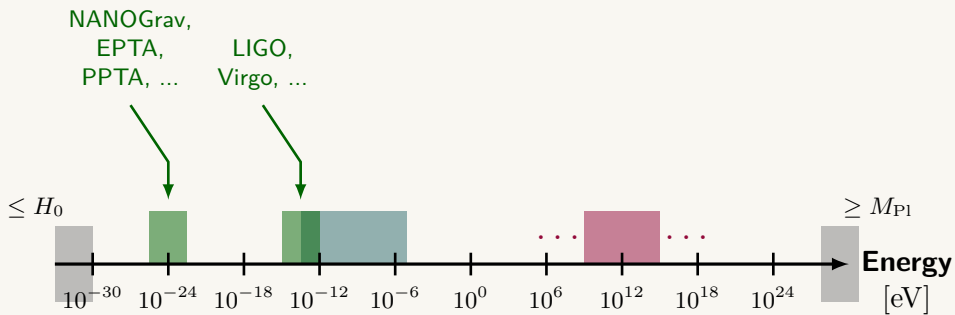
Conclusion

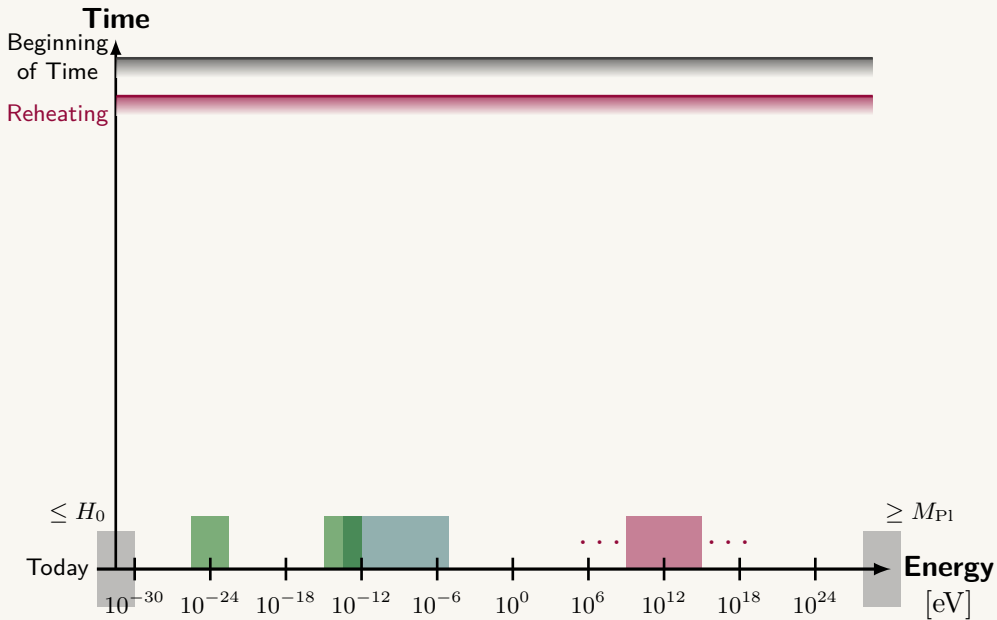


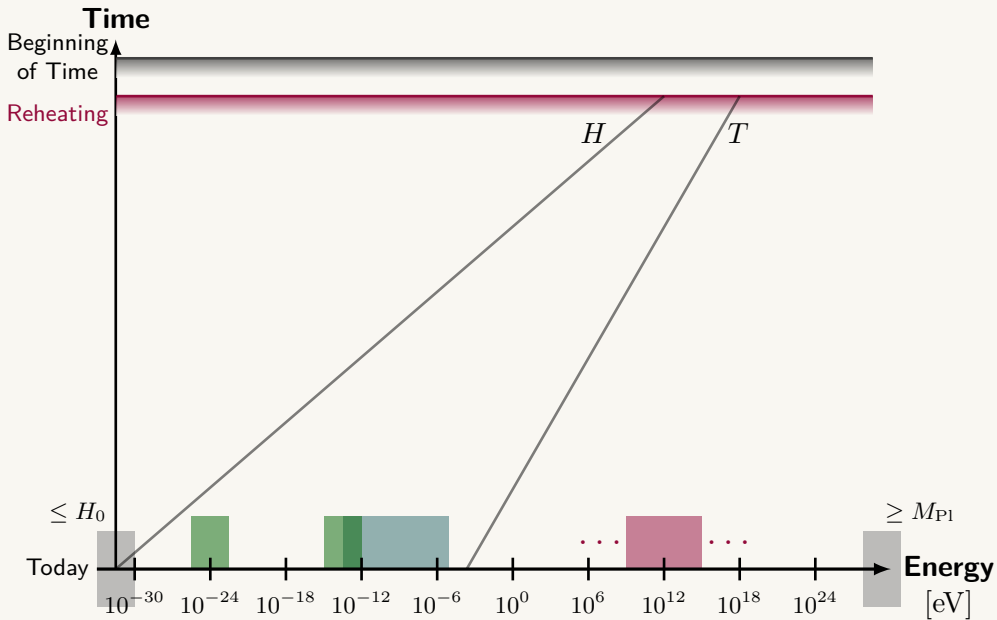
ARGO, DarkSide, DElight,
Lux-Zeppelin, ANAIS-112, NEWS-G,
XENON/DARWIN, PICO, DEAP-3600, ...

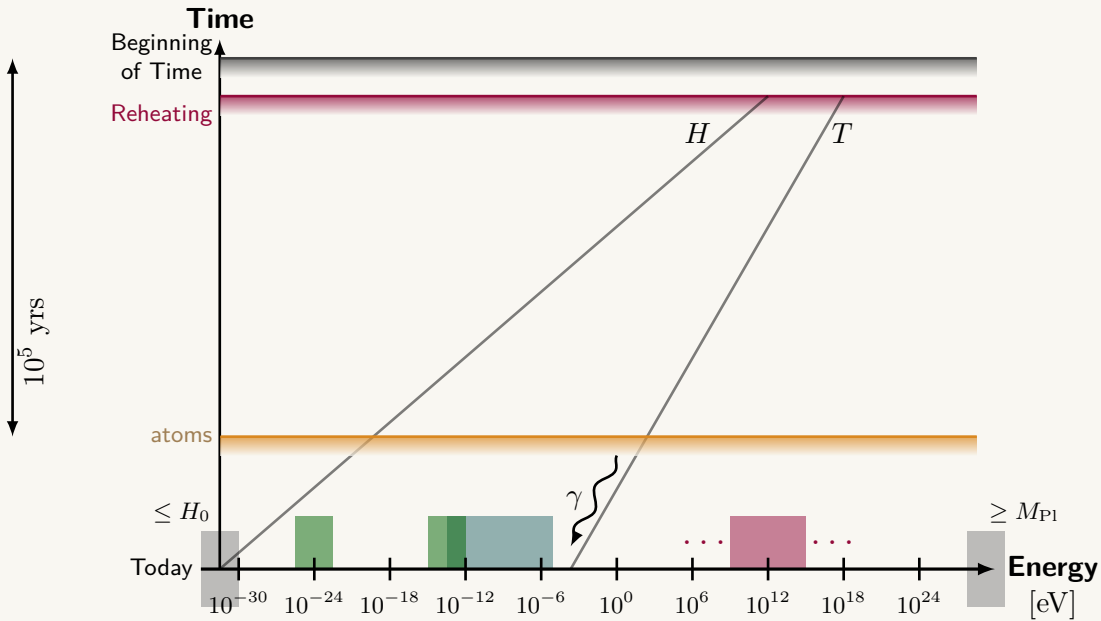


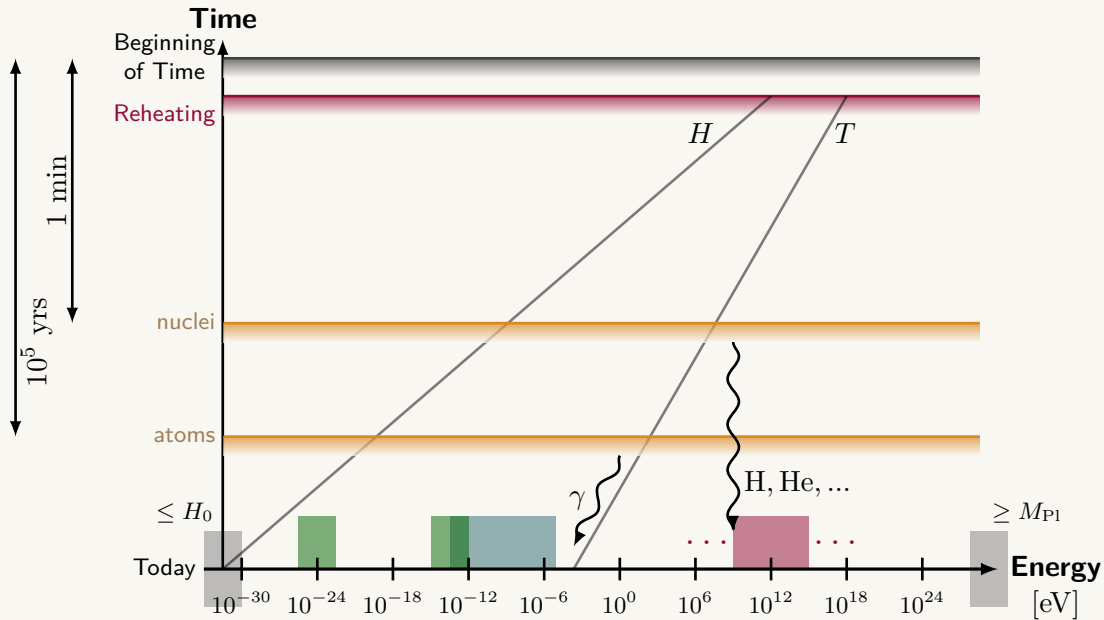


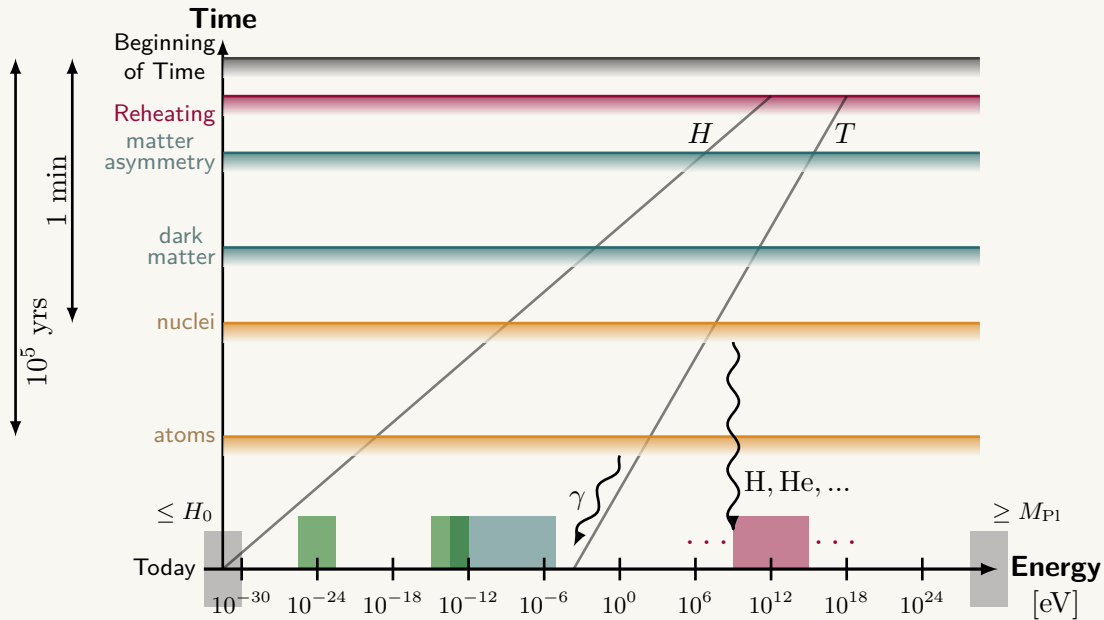


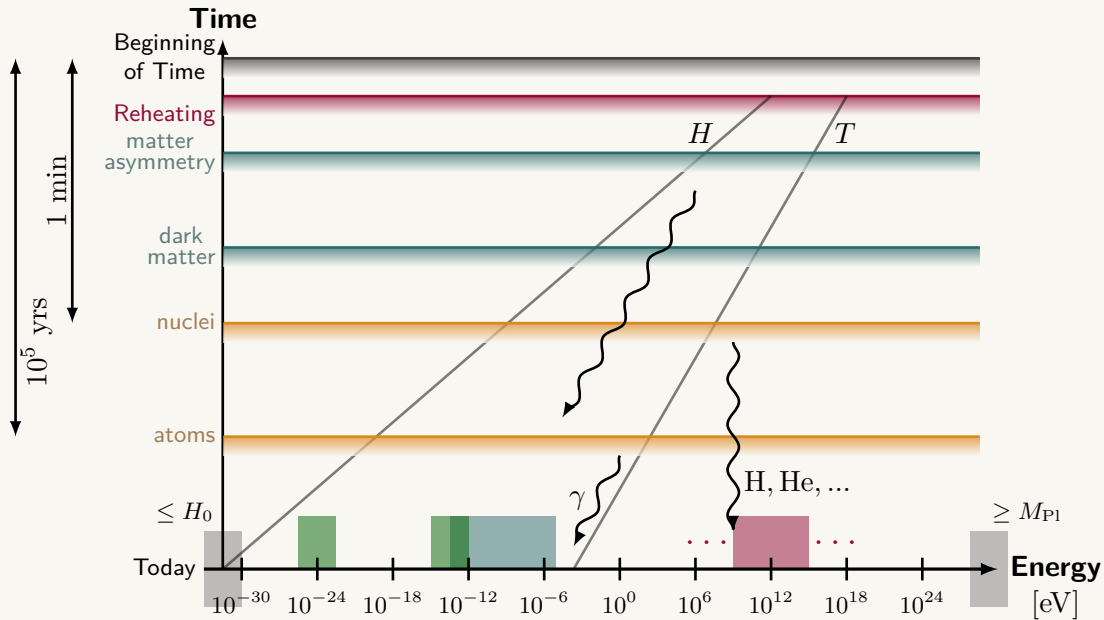


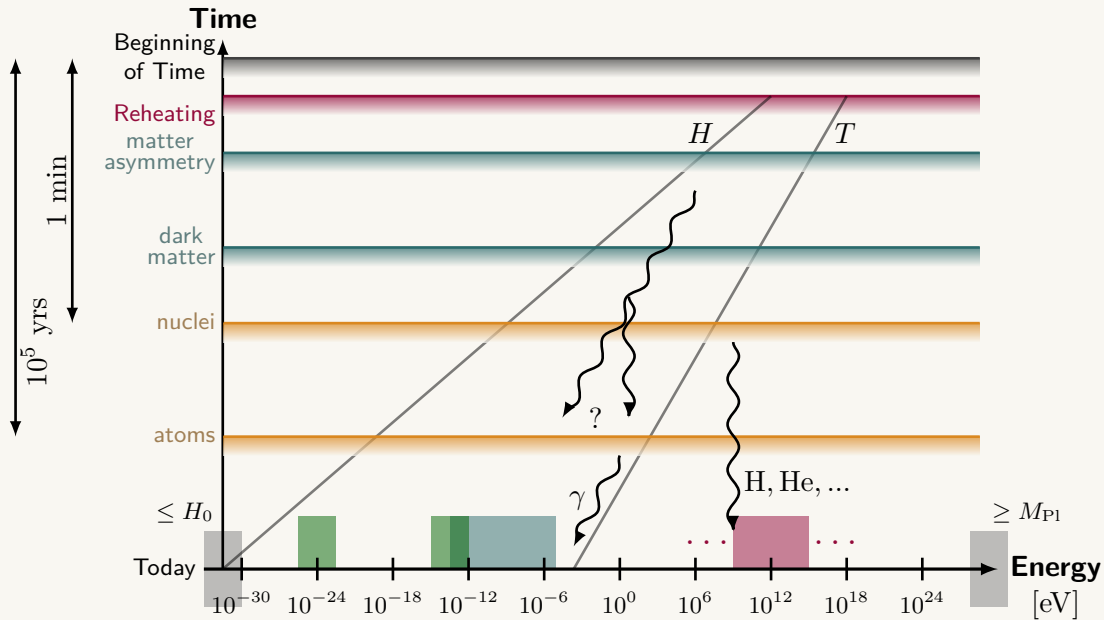


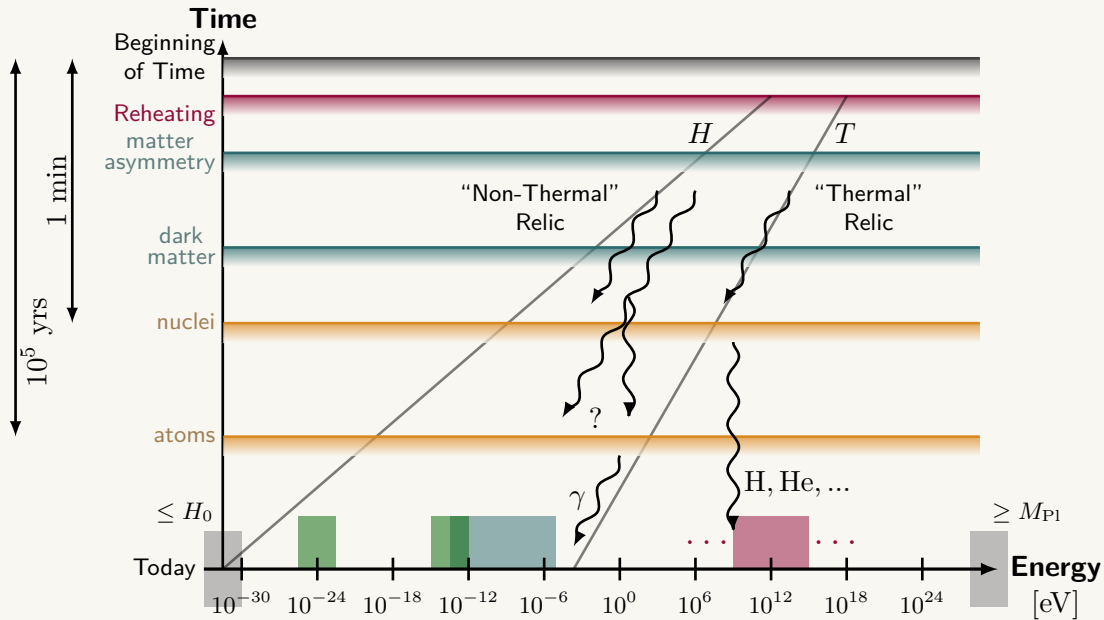


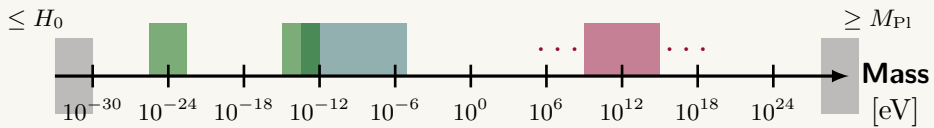


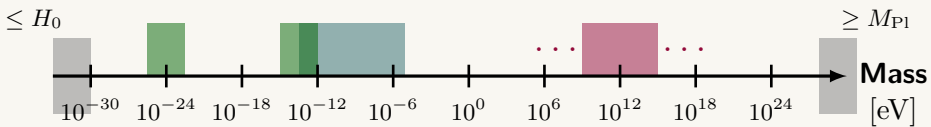
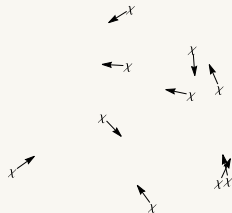
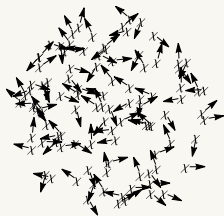
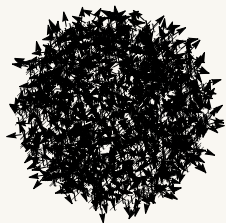


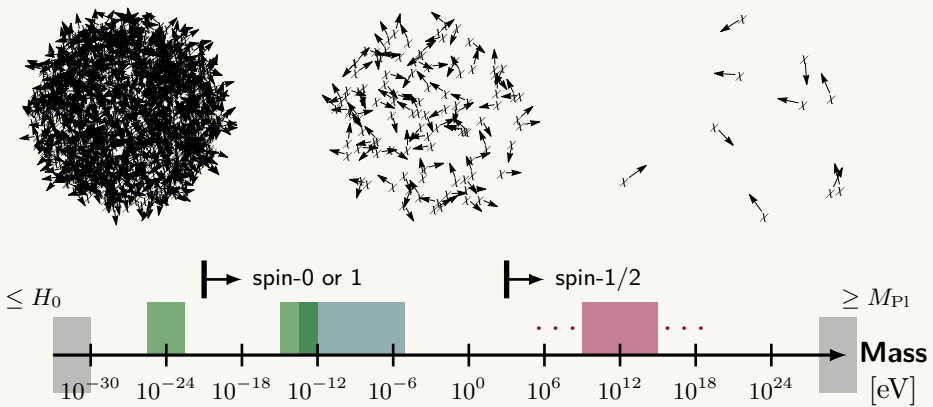


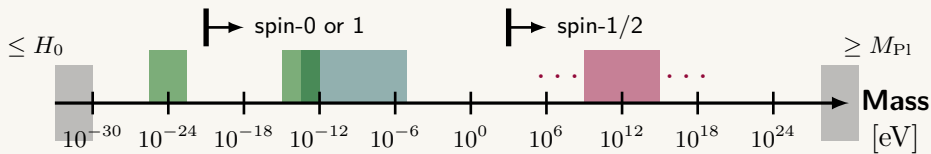


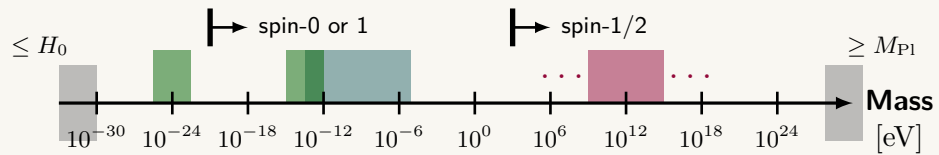
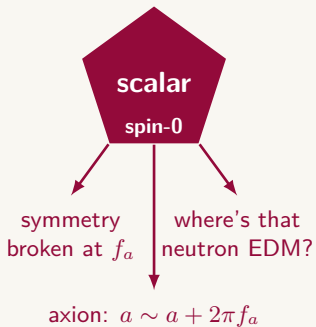


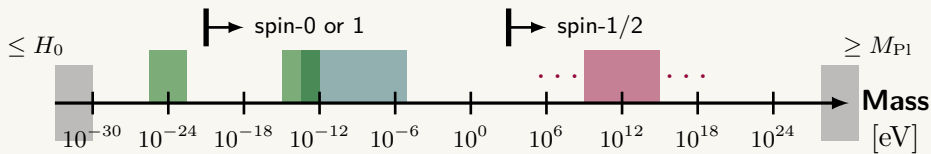
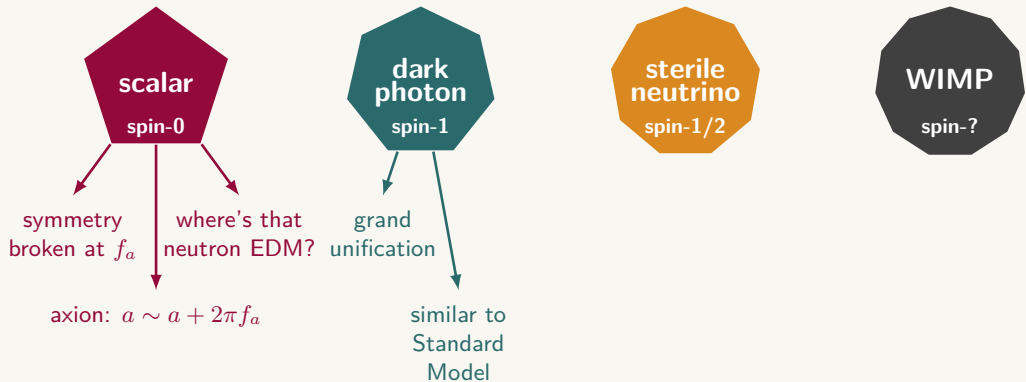


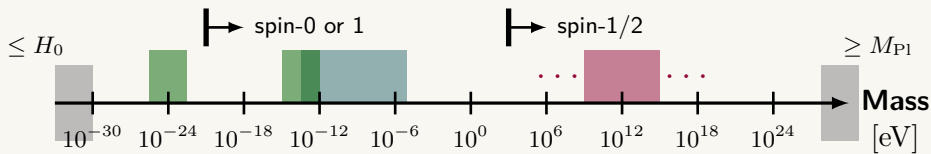
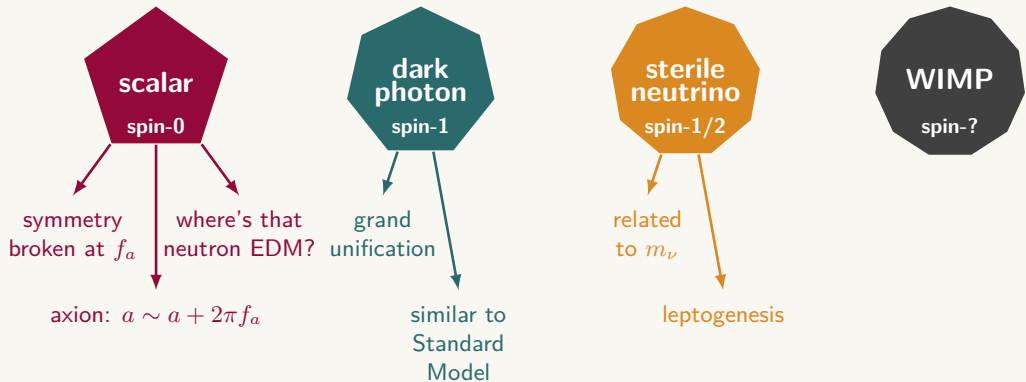


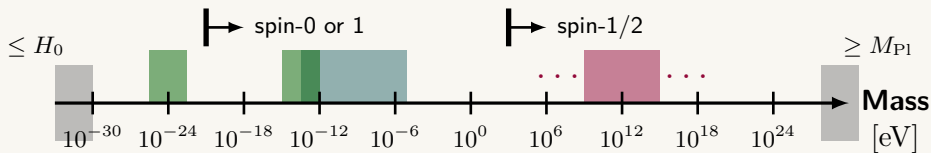
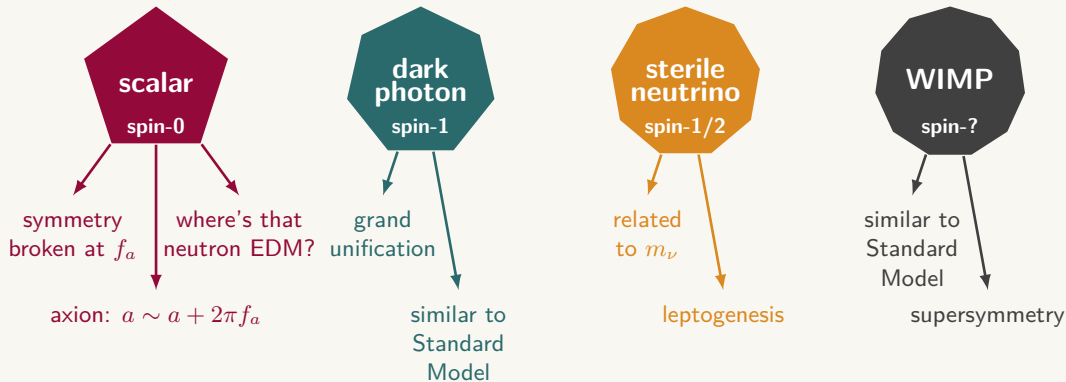






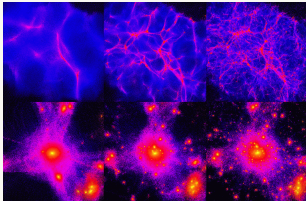




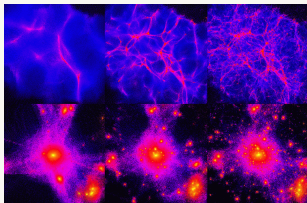


KNOW THE
RULES

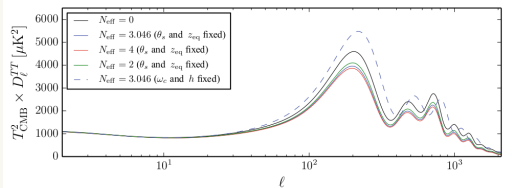
dark matter is
"cold" by $T \sim \text{keV}$



dark matter is
"cold" by $T \sim \text{keV}$

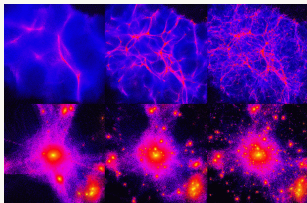


less dark radiation
then CMB photons

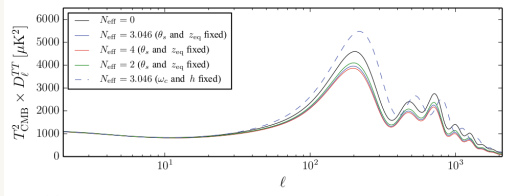




dark matter is
"cold" by $T \sim \text{keV}$



less dark radiation
than CMB photons

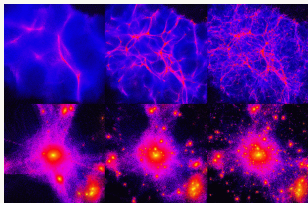


must be \sim
cosmically stable

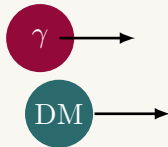




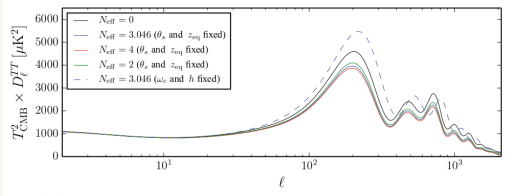
dark matter is
"cold" by $T \sim \text{keV}$



density perturbations
must be adiabatic



less dark radiation
than CMB photons

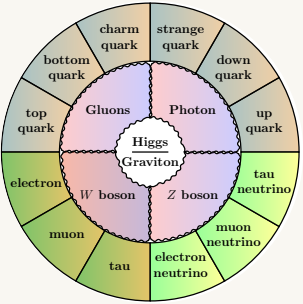


must be \sim
cosmically stable



axion

dark photon

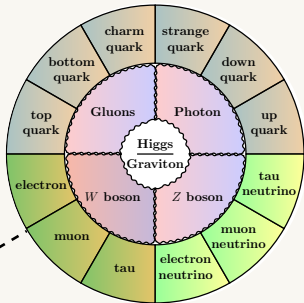


WIMP

sterile neutrino

axion

dark photon



Thermal:
Freeze-out

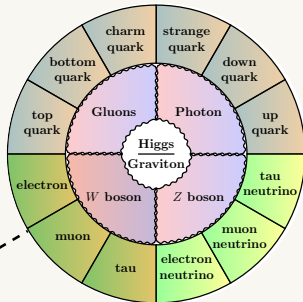
Thermal:
Freeze-in

WIMP

sterile neutrino

axion

dark photon



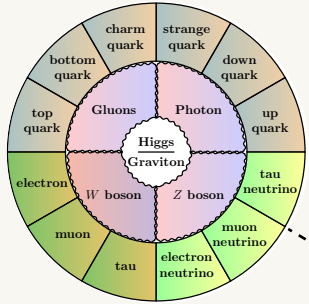
Thermal:
multi-particles

WIMP

sterile neutrino

axion

dark photon



WIMP

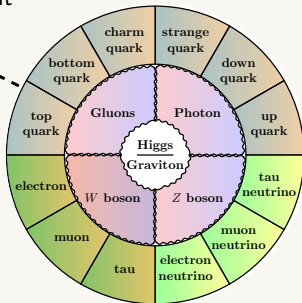
Thermal: mixing
Thermal: dilution

sterile neutrino

axion

Non-thermal:
misalignment

Non-thermal:
cosmic strings



dark photon

WIMP

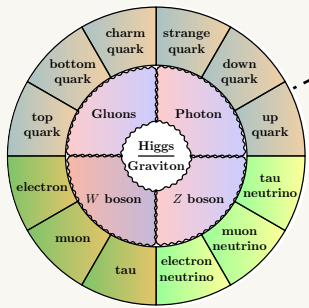
sterile neutrino

axion

dark photon

Non-thermal:
inflation fluctuations

Non-thermal:
parametric resonance



WIMP

sterile neutrino

Outline

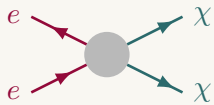
The Big Picture

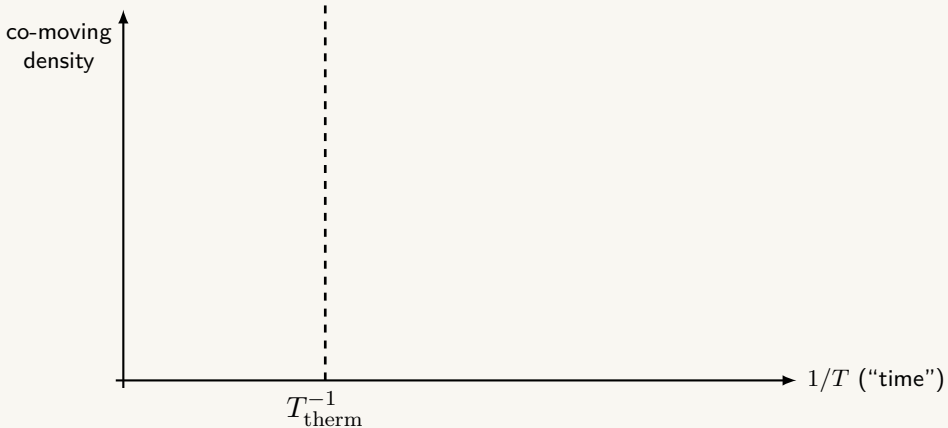
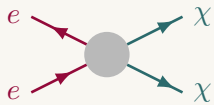


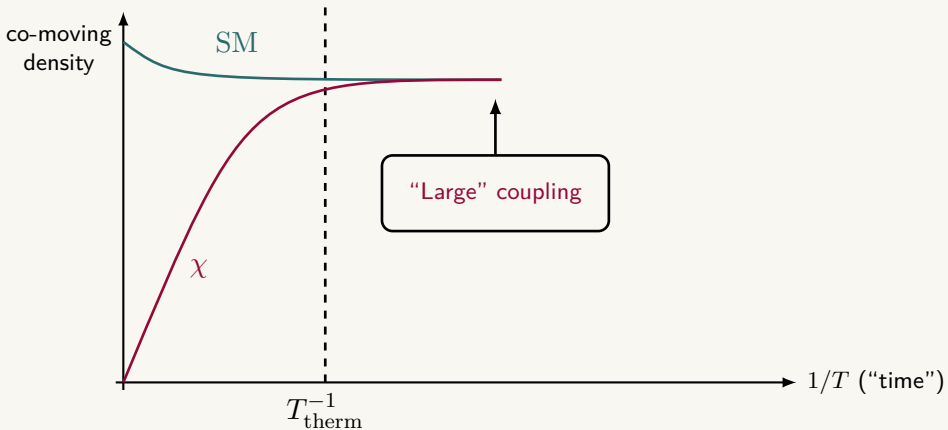
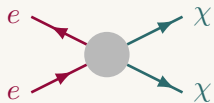
Thermal Dark Matter

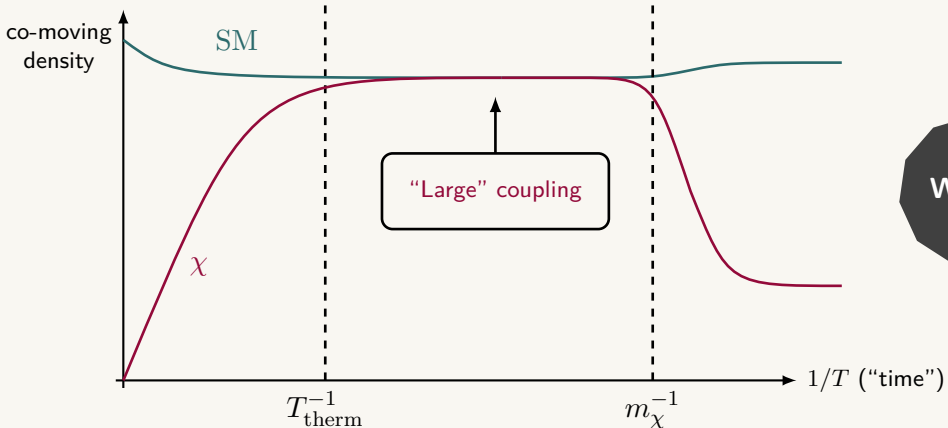
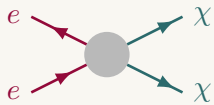
Non-Thermal Dark Matter

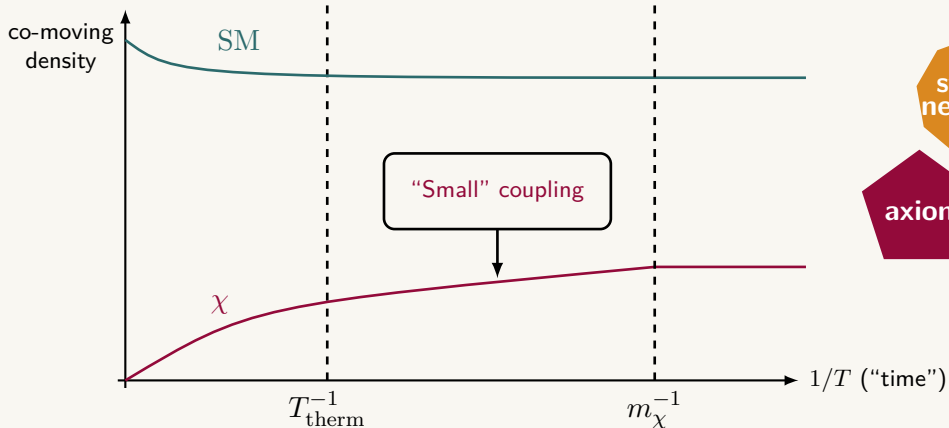
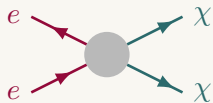
Conclusion

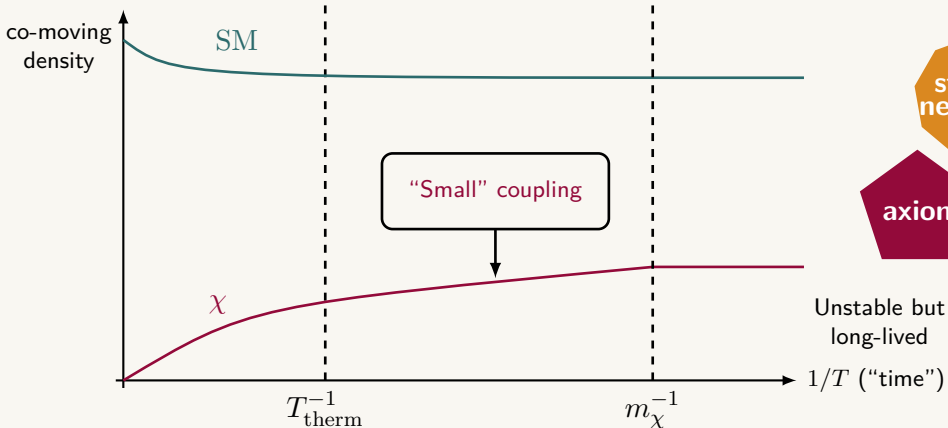
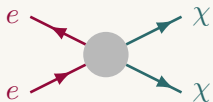












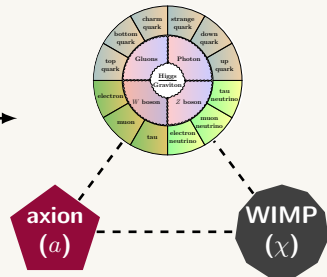
Unstable but long-lived



Simple picture radically
modified if with
additional fields

Simple picture radically
modified if with
additional fields

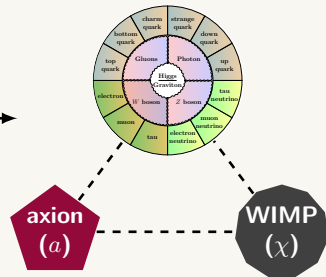
concrete
example*



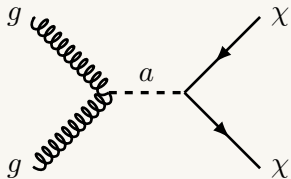
*[JD, Gori, Munbodh - '23]

Simple picture radically modified if with additional fields

concrete example*



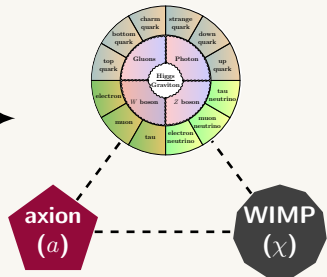
χ -SM scattering



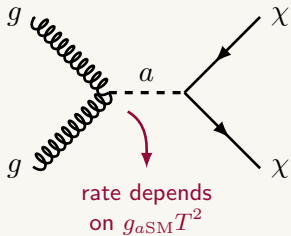
*[JD, Gori, Munbodh - '23]

Simple picture radically modified if with additional fields

concrete example*



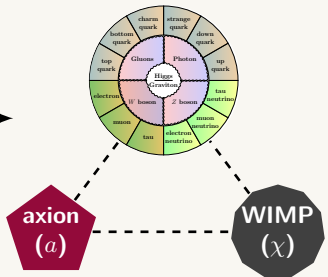
χ -SM scattering



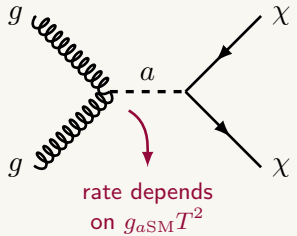
*[JD, Gori, Munbodh - '23]

Simple picture radically modified if with additional fields

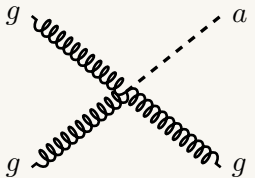
concrete example*



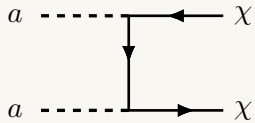
χ -SM scattering



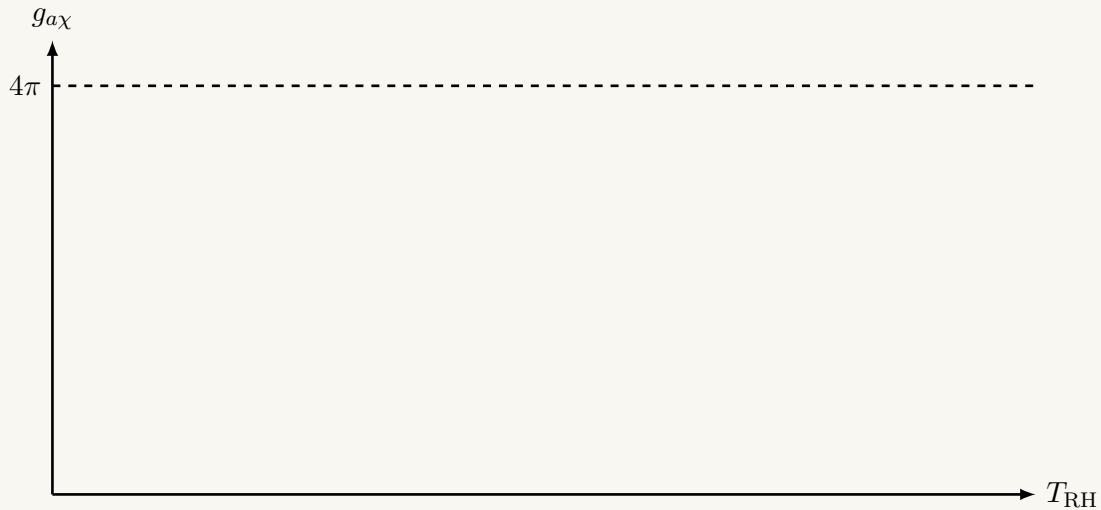
a -SM scattering



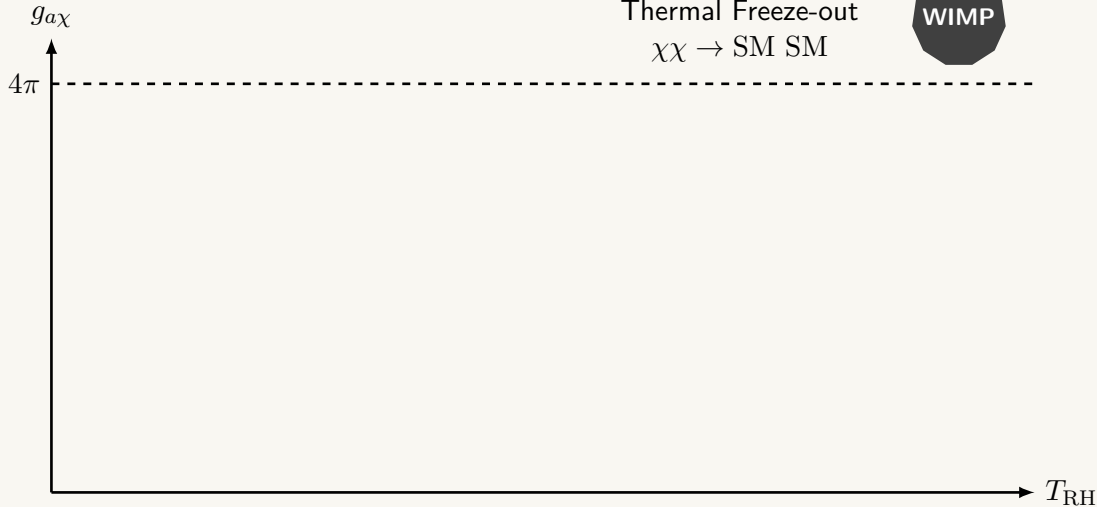
a - χ scattering



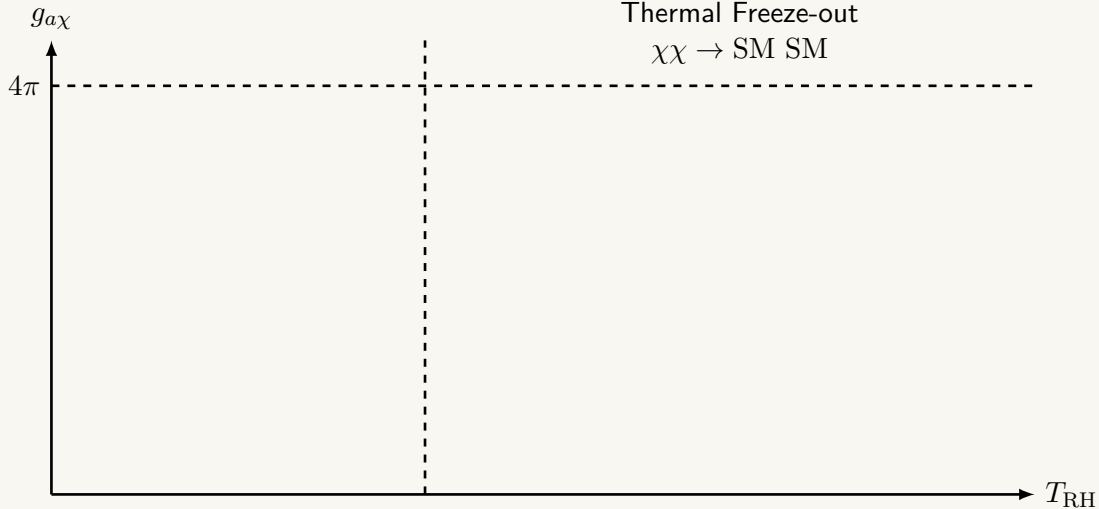
*[JD, Gori, Munbodh - '23]



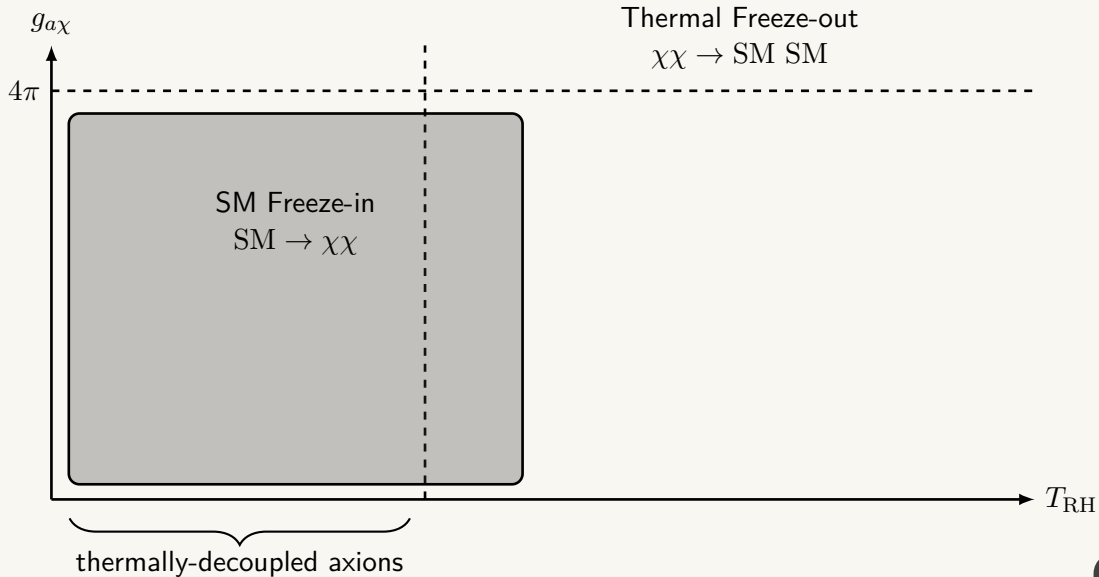
Thermal Freeze-out
 $\chi\chi \rightarrow \text{SM SM}$

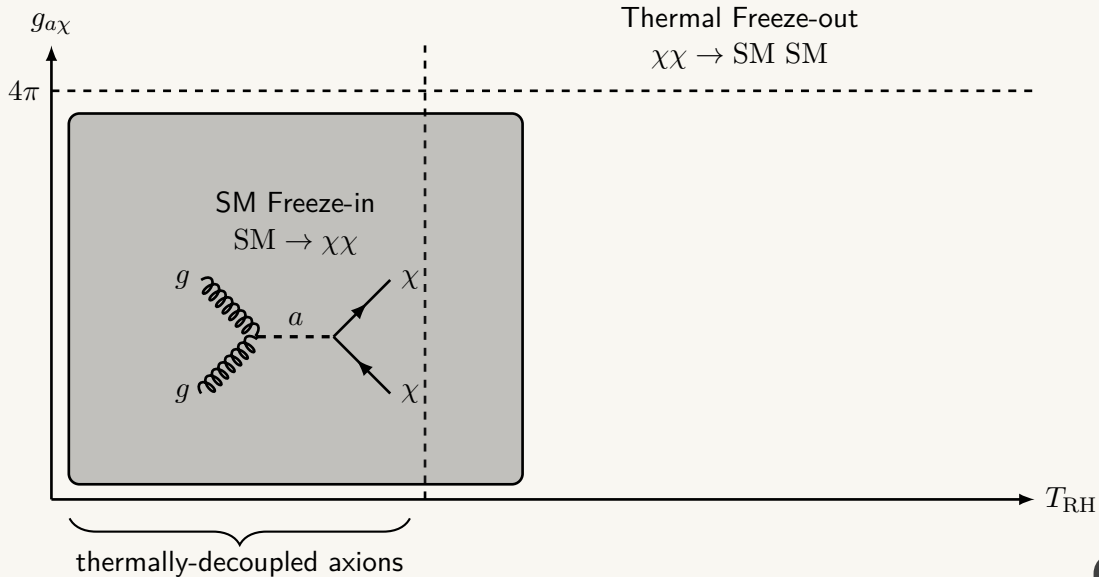


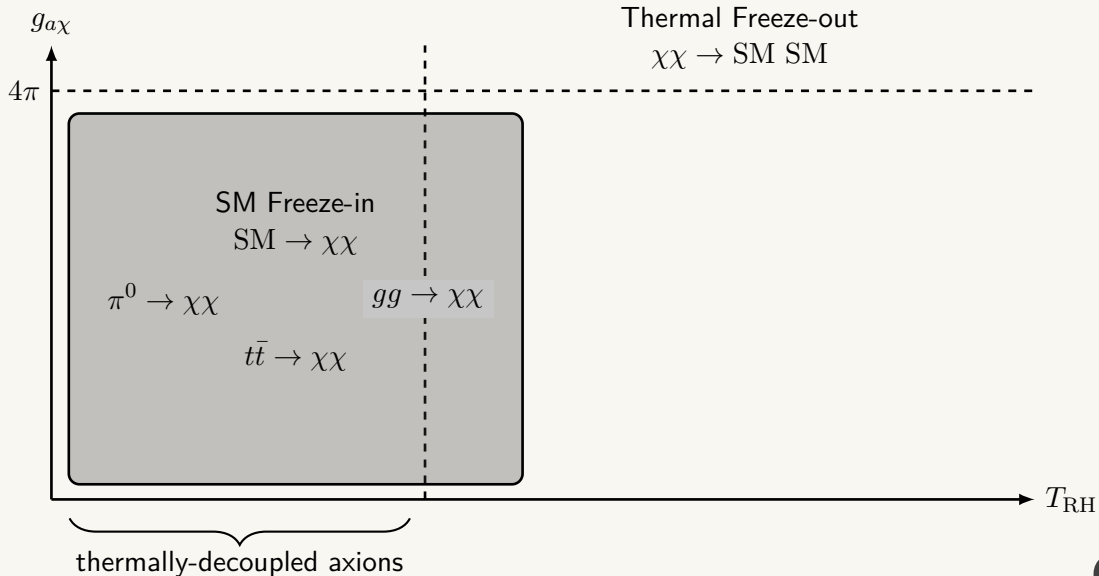
Thermal Freeze-out



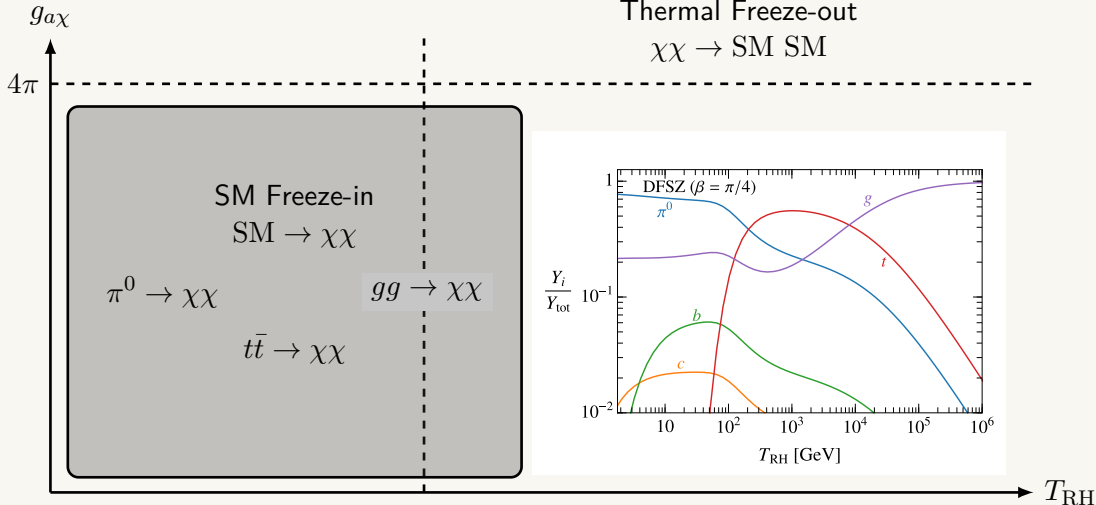
thermally-decoupled axions



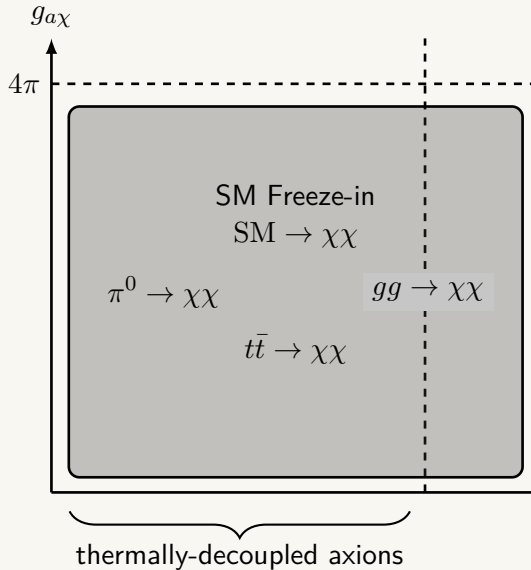




Thermal Freeze-out

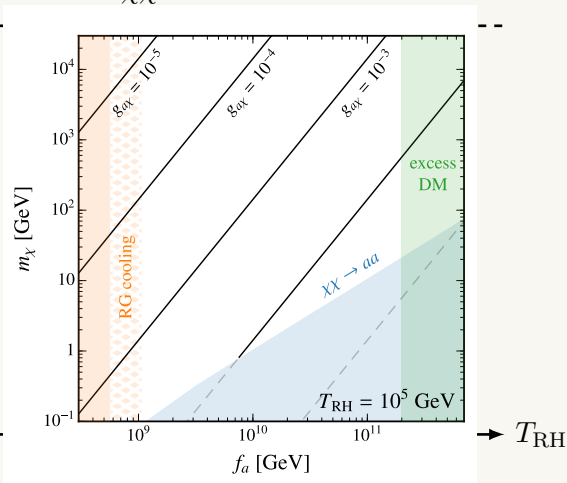


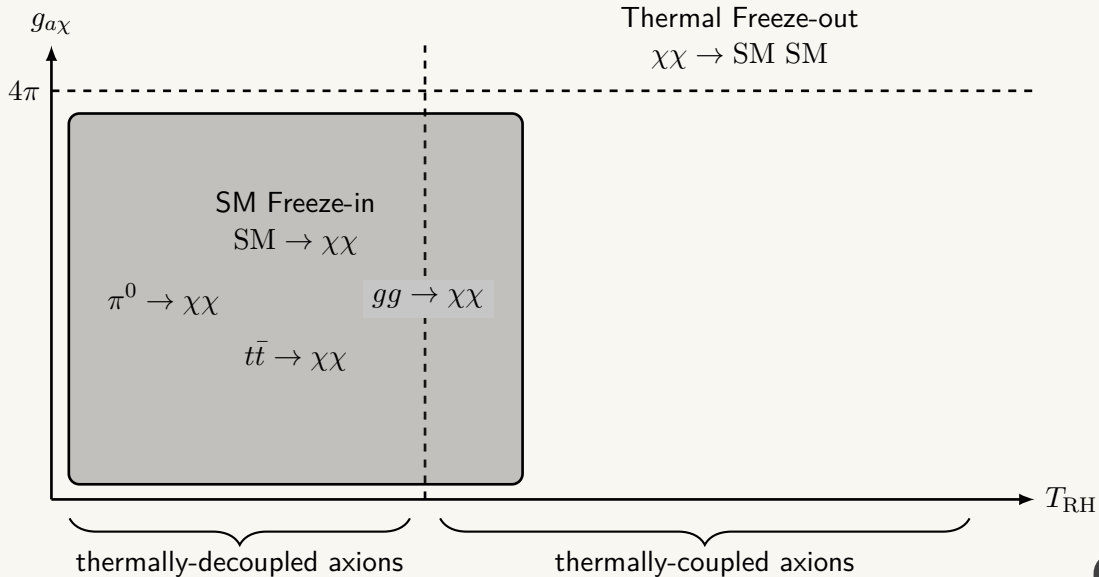
thermally-decoupled axions

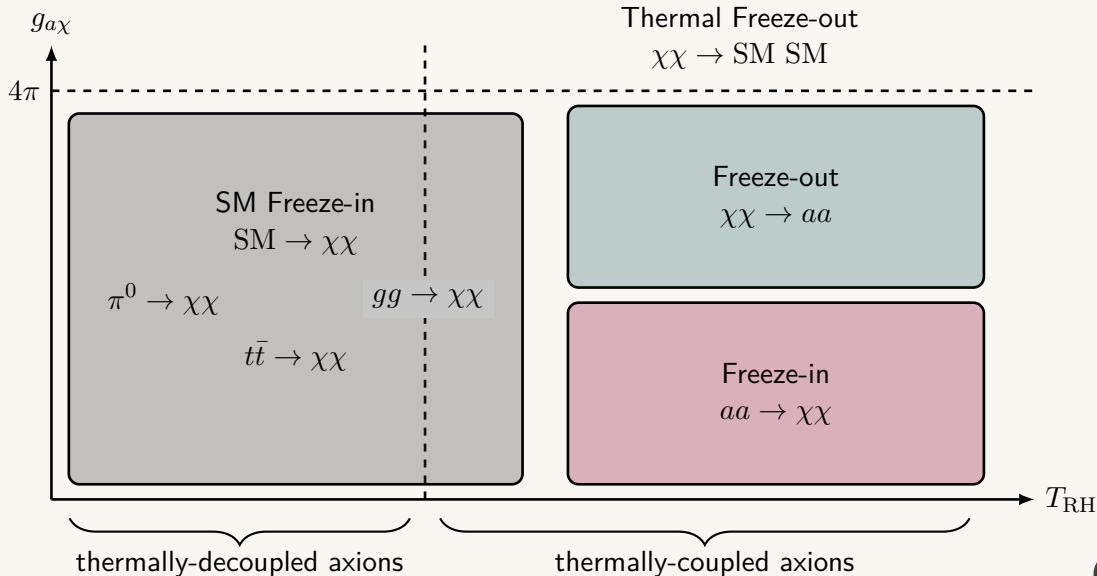


Thermal Freeze-out

$$\chi\chi \rightarrow \text{SM SM}$$

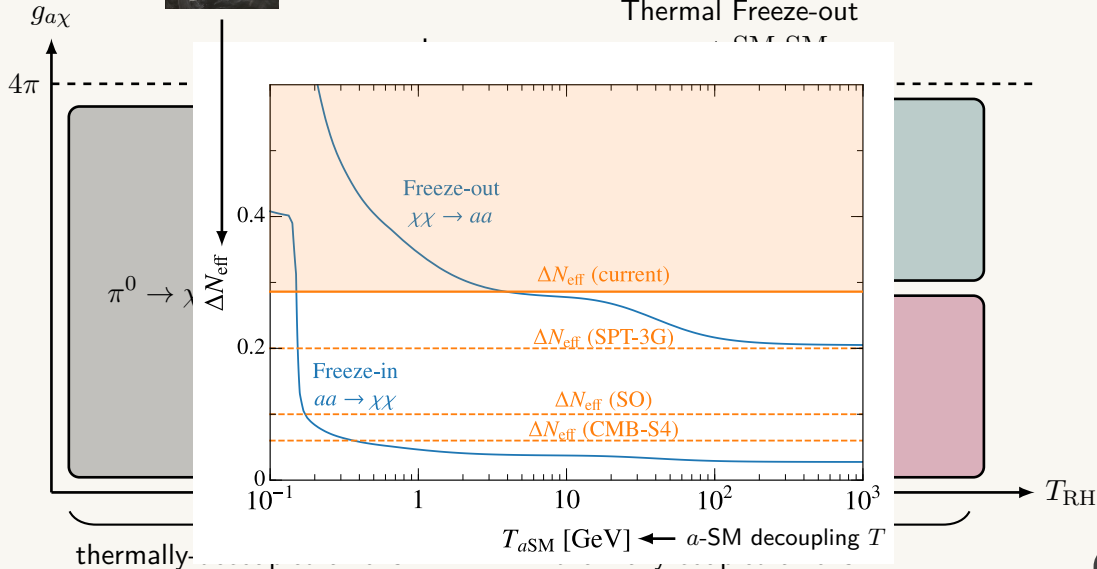




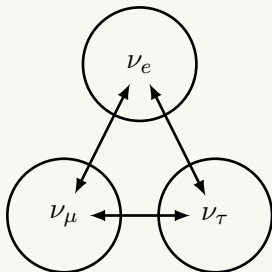


Thermal Freeze-out

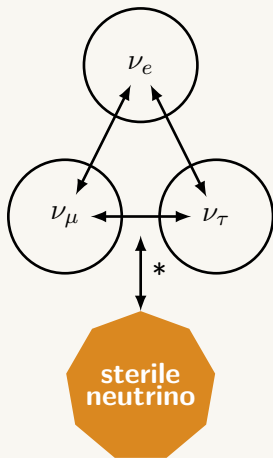
KNOW THE RULES



Sterile Neutrino Production

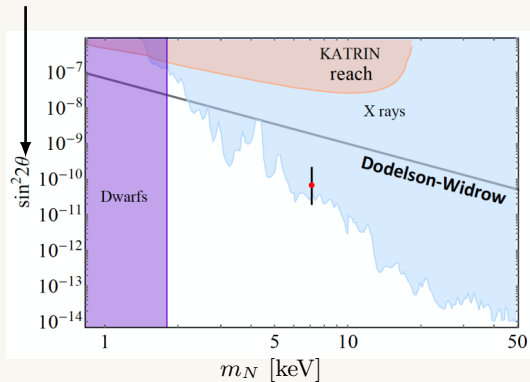
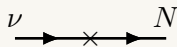
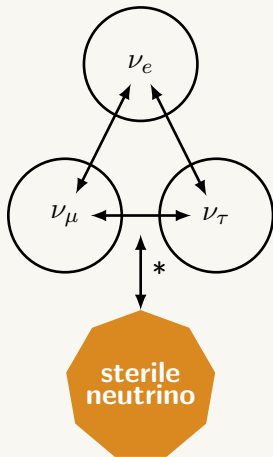


Sterile Neutrino Production



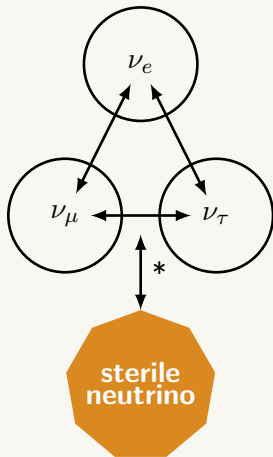
*[Dodelson, Widrow - '93]

Sterile Neutrino Production

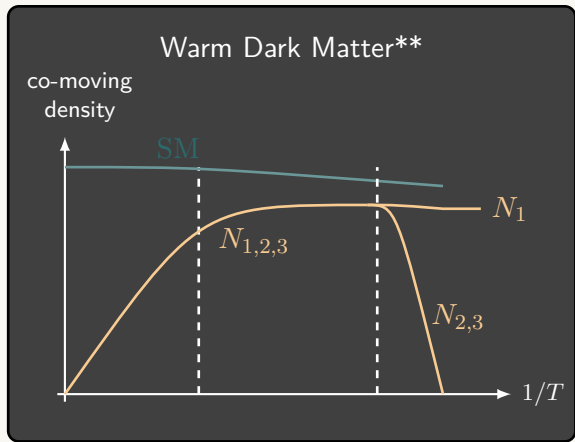


*[Dodelson, Widrow - '93]

Sterile Neutrino Production



*[Dodelson, Widrow - '93]



**[Bezrukov+, '09]

**[JD+, '20]

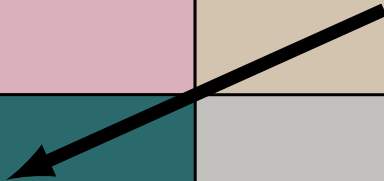
Outline


The Big Picture

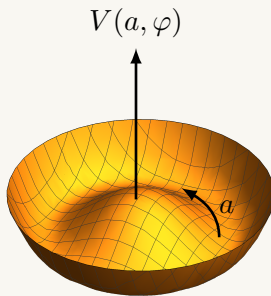
Thermal Dark Matter

Non-Thermal Dark Matter


Conclusion



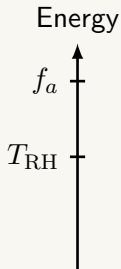
What is the
“initial” value of
an  ($a \equiv \theta f_a$)?



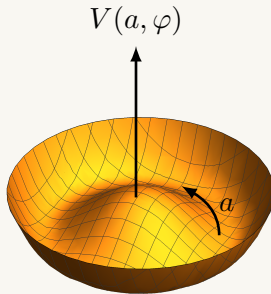
$$a \sim a + 2\pi f_a$$

What is the
“initial” value of
an  ($a \equiv \theta f_a$)?

phase transition
“before inflation”

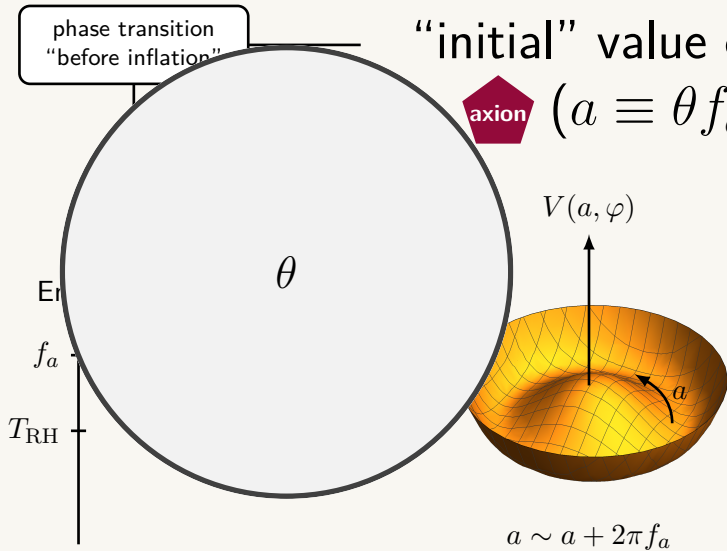



Field value is
identical everywhere
in space



$$a \sim a + 2\pi f_a$$

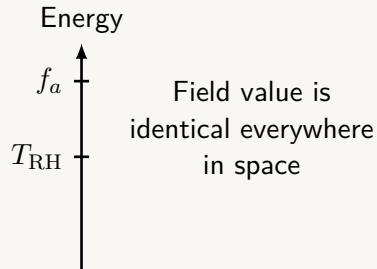
What is the
“initial” value of
axion ($a \equiv \theta f_a$)?



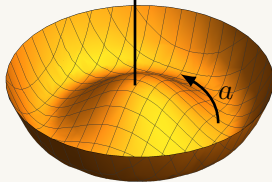
What is the
“initial” value of
an  ($a \equiv \theta f_a$)?

phase transition
“before inflation”

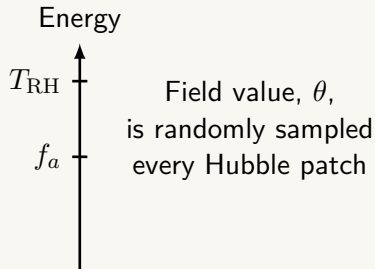
phase transition
“after inflation”



$V(a, \varphi)$



$$a \sim a + 2\pi f_a$$



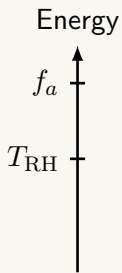
What is the

“initial” value of

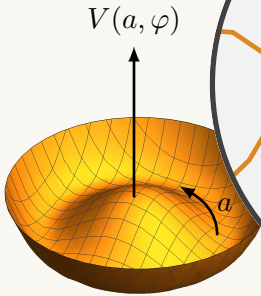
an **axion** ($a \equiv \theta f_a$)

phase transition
“before inflation”

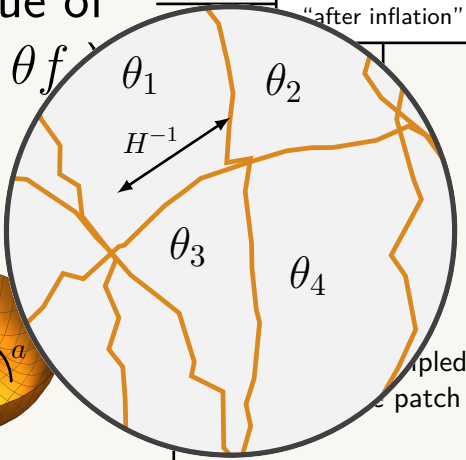
phase transition
“after inflation”



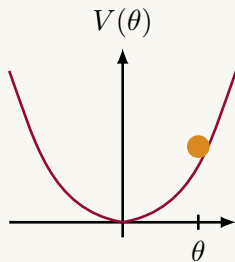
Field value is identical everywhere in space



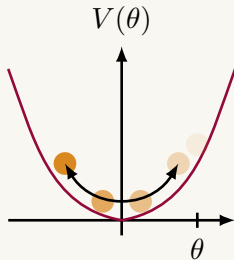
$a \sim a + 2\pi f_a$



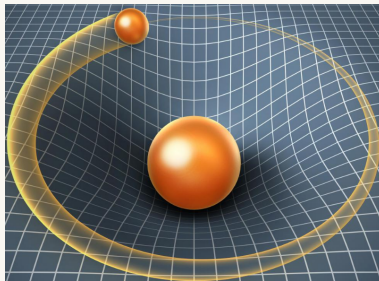
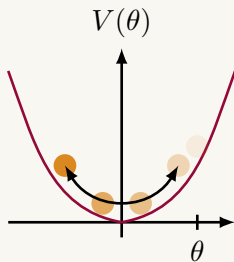
The Misalignment Mechanism



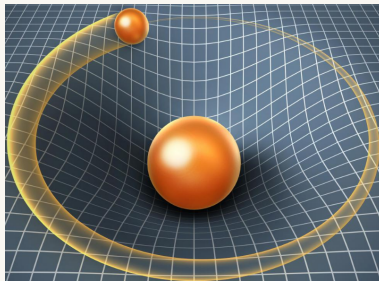
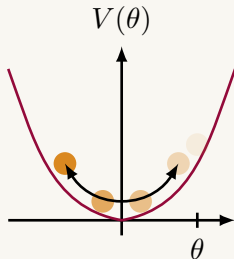
The Misalignment Mechanism



The Misalignment Mechanism



The Misalignment Mechanism



$$\rho_a \sim \theta^2 m_a^2 f_a^2$$

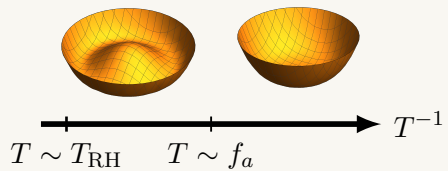
$$p_a \sim \theta^2 m_a^2 f_a^2 \cos(2mt)^*$$



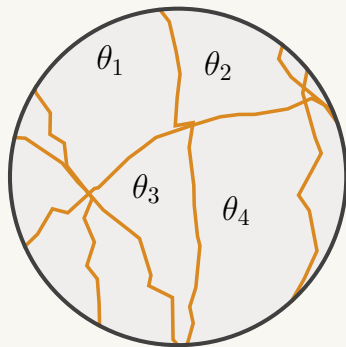
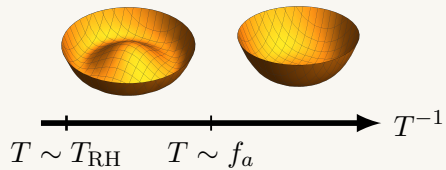
How do we know θ ?

*[Rubakov, Khmel'nitsky-'13] [JD, in progress]

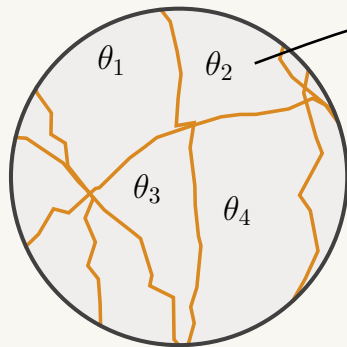
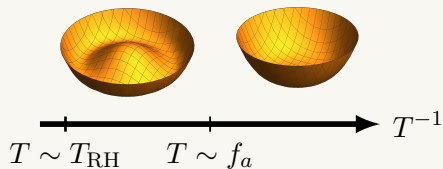
Post-inflationary
scenario



Post-inflationary
scenario



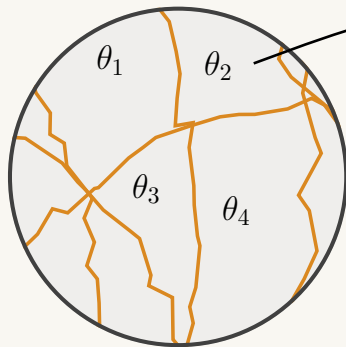
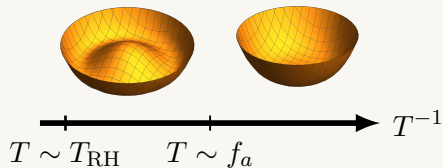
Post-inflationary
scenario



θ may reach
itself after going
around in a circle

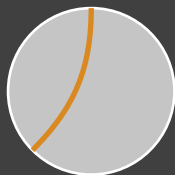
“cosmic string”
configuration carries
energy and is stable
for an infinite string

Post-inflationary scenario

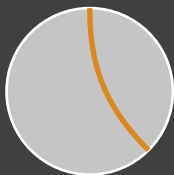


θ may reach itself after going around in a circle

“cosmic string” configuration carries energy and is stable for an infinite string



most of energy radiated in axions



large loop emission dominates



calculate axions semi-analytically

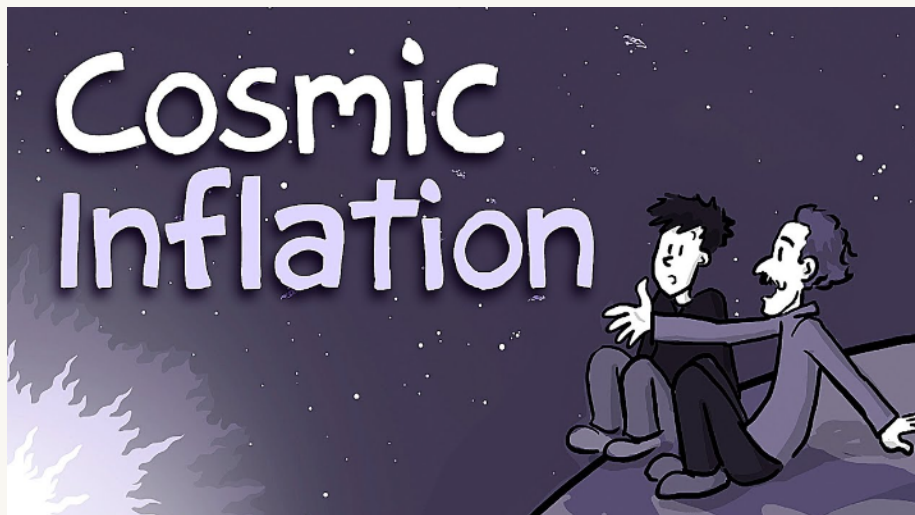
axion energy set by H^{-1}

[Gorghetto et al - '18,'20]

[Safdi et al - '21,'22]

[JD, Murayama, Rodd - '21]

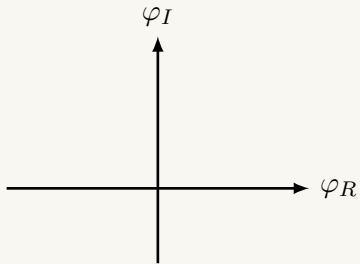
Inflationary Production



Inflationary Production

Complex scalar field
during inflation

$$\varphi = \varphi_R + i\varphi_I$$

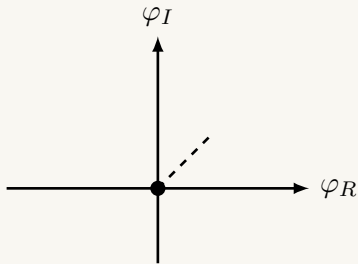


Inflationary Production

Complex scalar field
during inflation

$$\varphi = \varphi_R + i\varphi_I$$

$$\delta\varphi \sim \frac{H_{\text{inf}}}{2\pi}$$

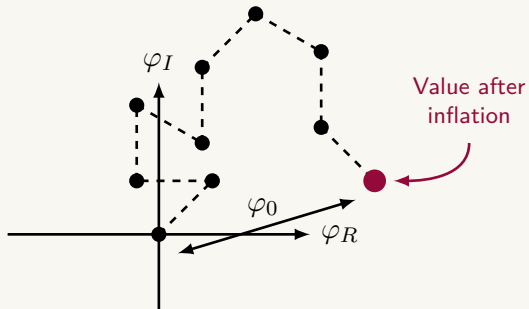


Inflationary Production

Complex scalar field
during inflation

$$\varphi = \varphi_R + i\varphi_I$$

$$\delta\varphi \sim \frac{H_{\text{inf}}}{2\pi}$$

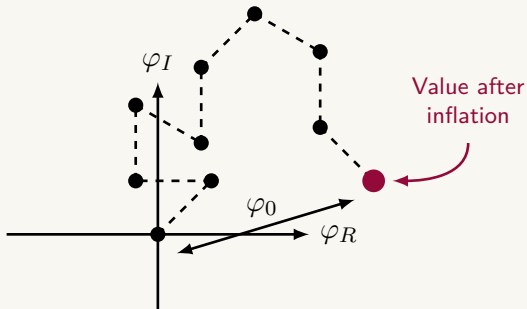


Inflationary Production

Complex scalar field
during inflation

$$\varphi = \varphi_R + i\varphi_I$$

$$\delta\varphi \sim \frac{H_{\text{inf}}}{2\pi}$$



φ as cold dark matter

$$\rho_\varphi \sim m_a^2 \varphi_0^2$$

non-adiabatic
 ρ_φ perturbations

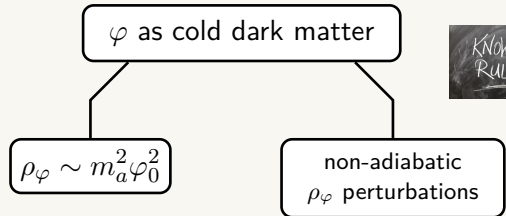
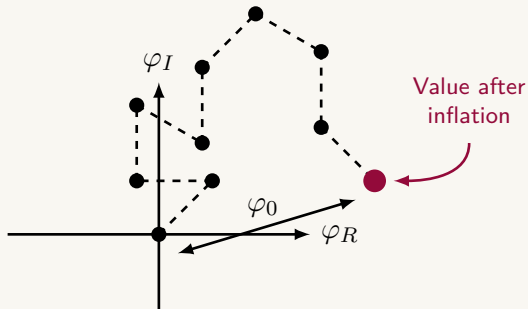


Inflationary Production

Complex scalar field during inflation

$$\varphi = \varphi_R + i\varphi_I$$

$$\delta\varphi \sim \frac{H_{\text{inf}}}{2\pi}$$



dark photon fluctuations*

Viable cosmology?

transfer energy to another species

Dark Photon Production

Dark Photon Production

What if another particle (“ χ ”) interacts with φ ?

E.g., equation of motion:

$$\ddot{\chi}_k + (k^2 + \varphi_0^2 \cos(2m_\varphi t))\chi_k = 0$$



oscillatory χ mass

Dark Photon Production

What if another particle (“ χ ”) interacts with φ ?

E.g., equation of motion:

$$\ddot{\chi}_k + (k^2 + \varphi_0^2 \cos(2m_\varphi t))\chi_k = 0$$



oscillatory χ mass

For certain k : $\chi_k \propto e^{\mu_k t}$

“Parametric Resonance”

Application: dark photons*



*[JD, Dror, Harigaya, Narayan - '19]

Dark Photon Production

What if another particle (“ χ ”) interacts with φ ?

E.g., equation of motion:

$$\ddot{\chi}_k + (k^2 + \varphi_0^2 \cos(2m_\varphi t))\chi_k = 0$$



oscillatory χ mass

For certain k : $\chi_k \propto e^{\mu_k t}$

“Parametric Resonance”

Application: dark photons*



*[JD, Dror, Harigaya, Narayan - '19]

Dark photon dark matter requires a mass mechanism

Higgs fluctuations during inflation

Dark Photon Production

What if another particle (“ χ ”) interacts with φ ?

E.g., equation of motion:
$$\ddot{\chi}_k + (k^2 + \varphi_0^2 \cos(2m_\varphi t))\chi_k = 0$$

↓
oscillatory χ mass

For certain k : $\chi_k \propto e^{\mu_k t}$

“Parametric Resonance”

Application: dark photons*

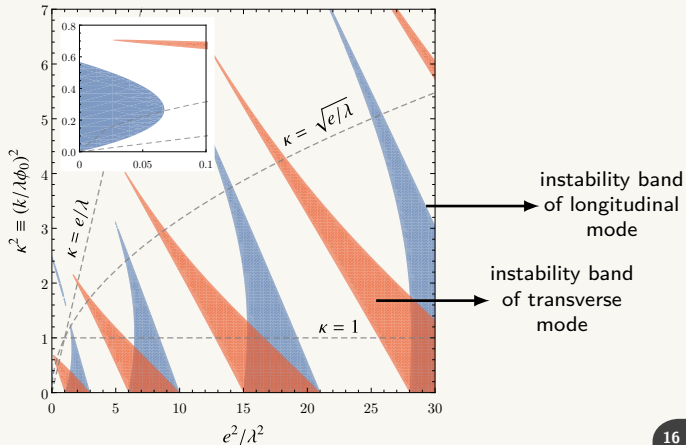


*[JD, Dror, Harigaya, Narayan - '19]

Dark photon dark matter requires a mass mechanism

Higgs fluctuations during inflation

Exponential dark photon production!



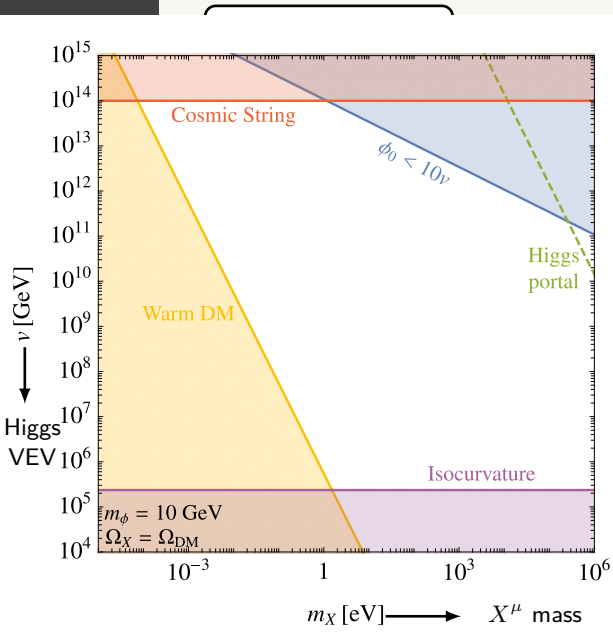
Dark Photon Pro

What if another part
interacts with

E.g., equation of m
 $\ddot{\chi}_k + (k^2 + \varphi_0^2 \cos(2m\varphi_0))\chi_k = 0$

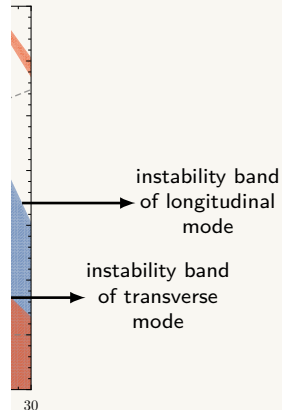
oscillatory

For certain k : χ_k
"Parametric Reso
Application: dark p



Higgs fluctuations
during inflation

on!



*[JD, Dror, Harigaya, Na

Dark Photon Pro

What if another part
interacts with

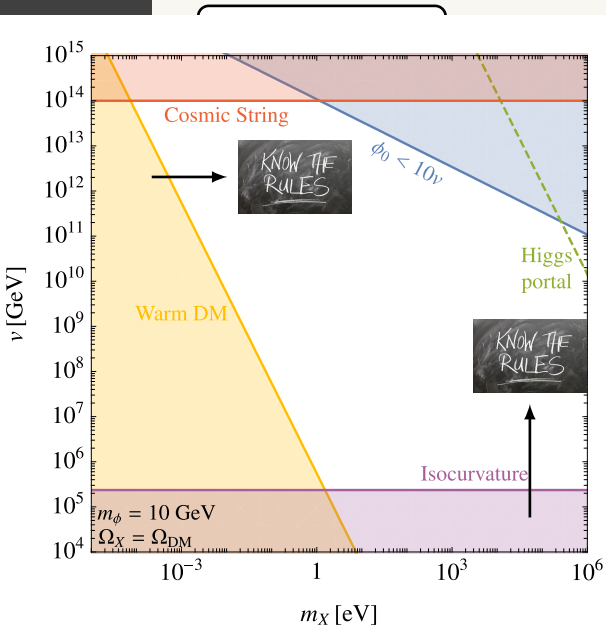
E.g., equation of r
 $\ddot{\chi}_k + (k^2 + \varphi_0^2 \cos(2m_\phi t)) \chi_k = 0$

oscillatory

For certain k : χ_k

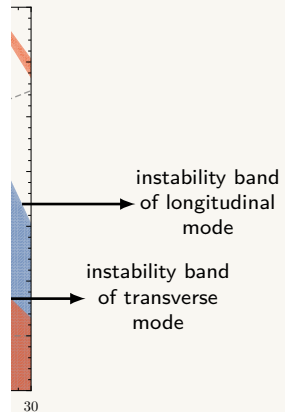
“Parametric Reso

Application: dark p

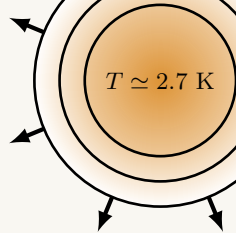
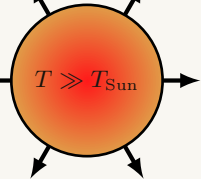


ggs fluctuations
during inflation

on!



*[JD, Dror, Harigaya, Na

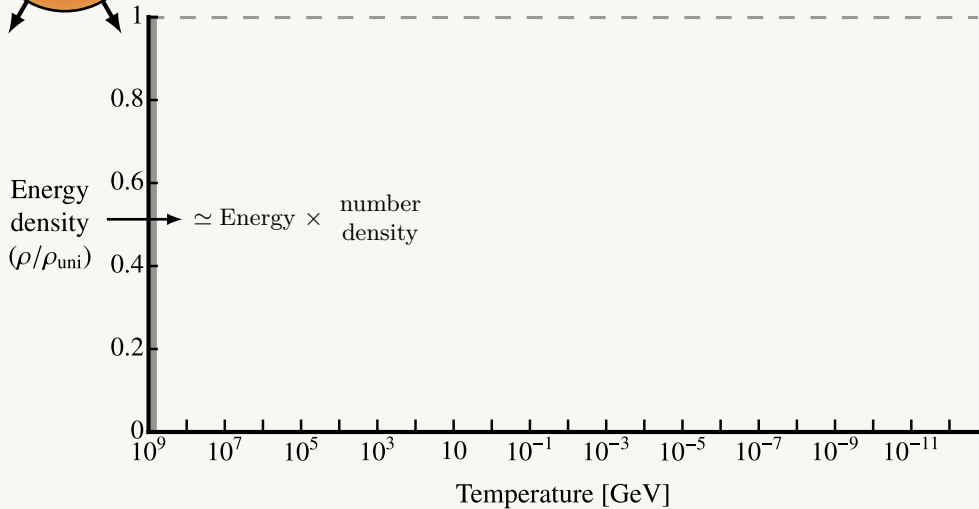
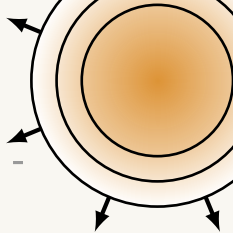
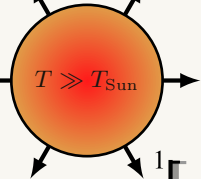


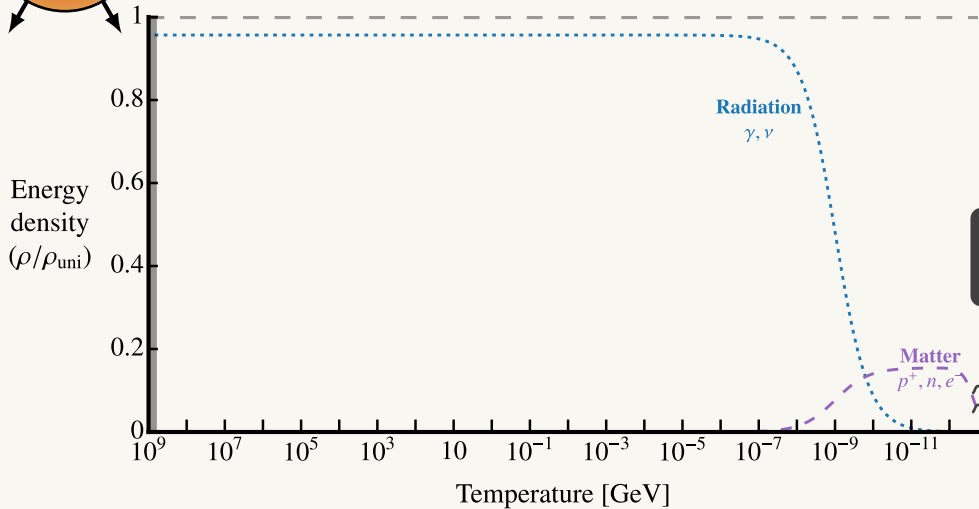
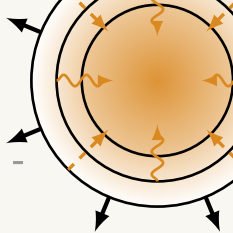
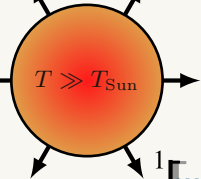
The beginning
of time

today

10^9 10^7 10^5 10^3 10 10^{-1} 10^{-3} 10^{-5} 10^{-7} 10^{-9} 10^{-11}

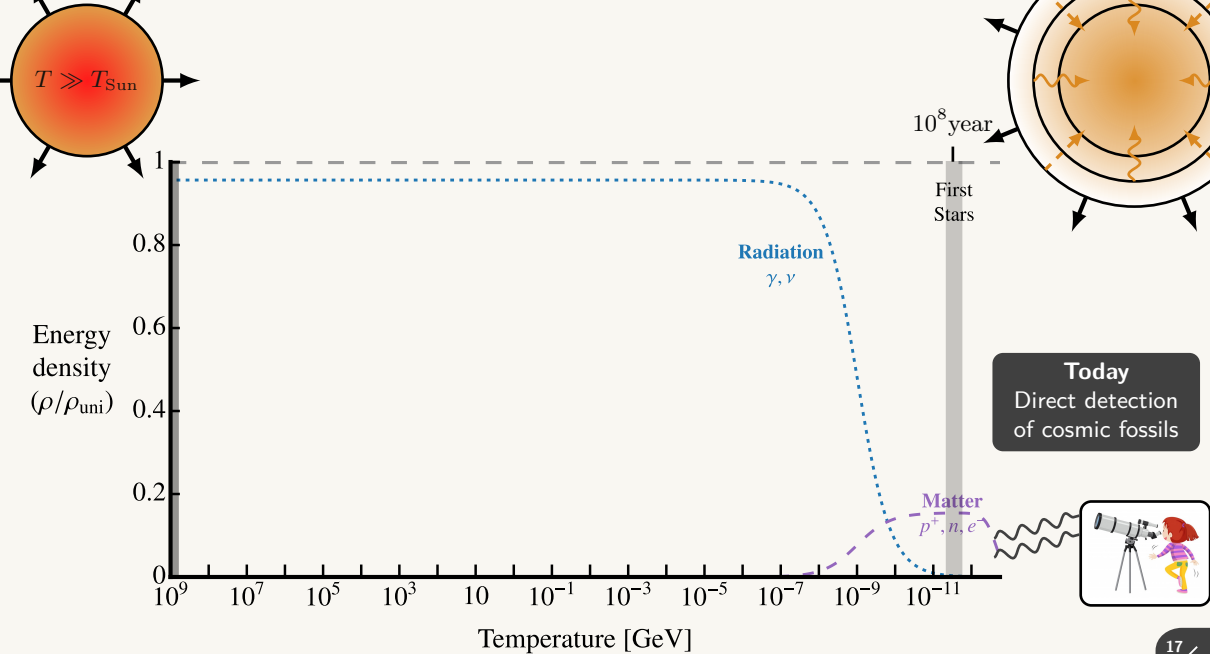
Temperature [GeV]

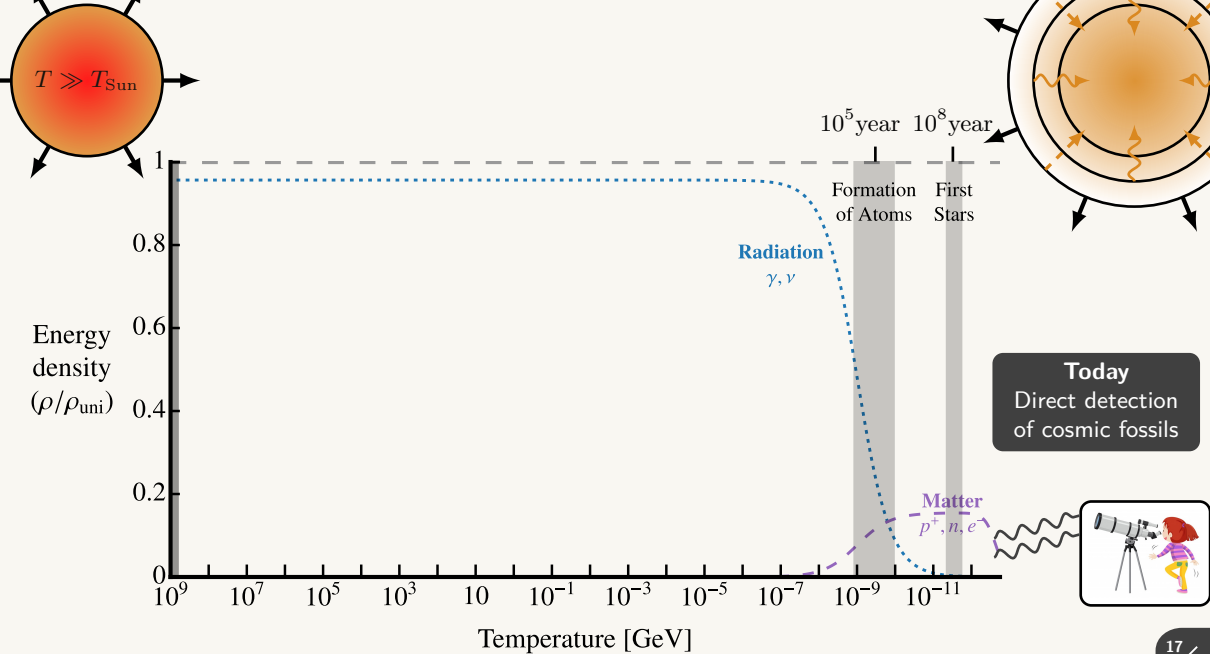


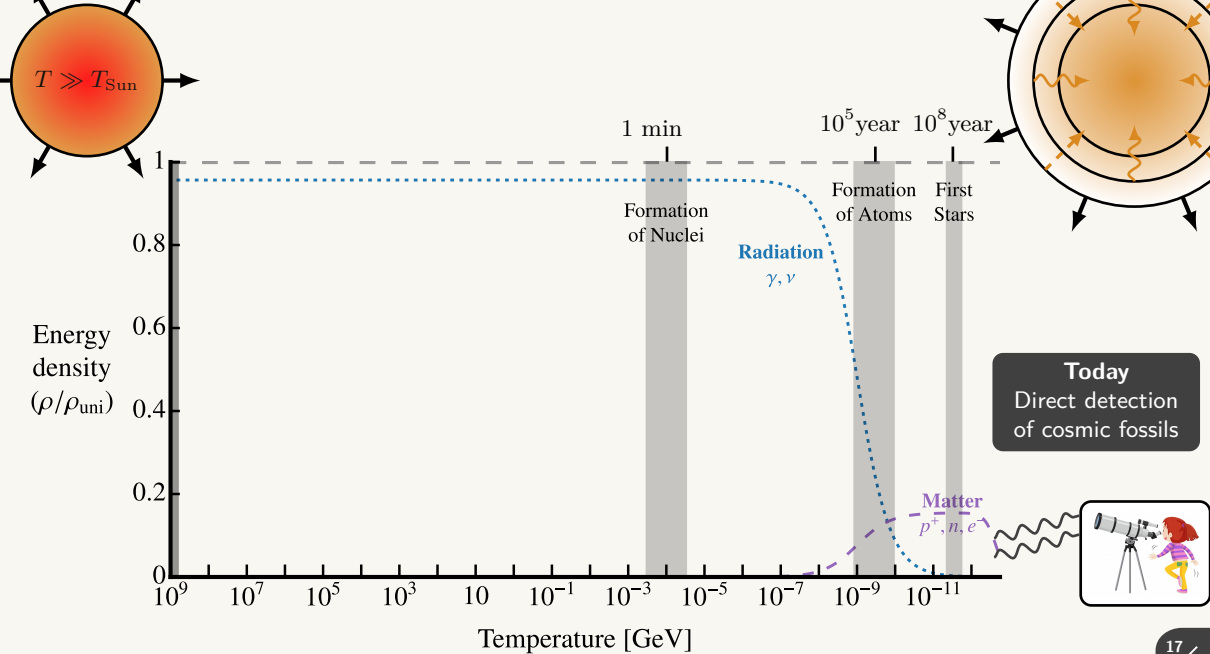


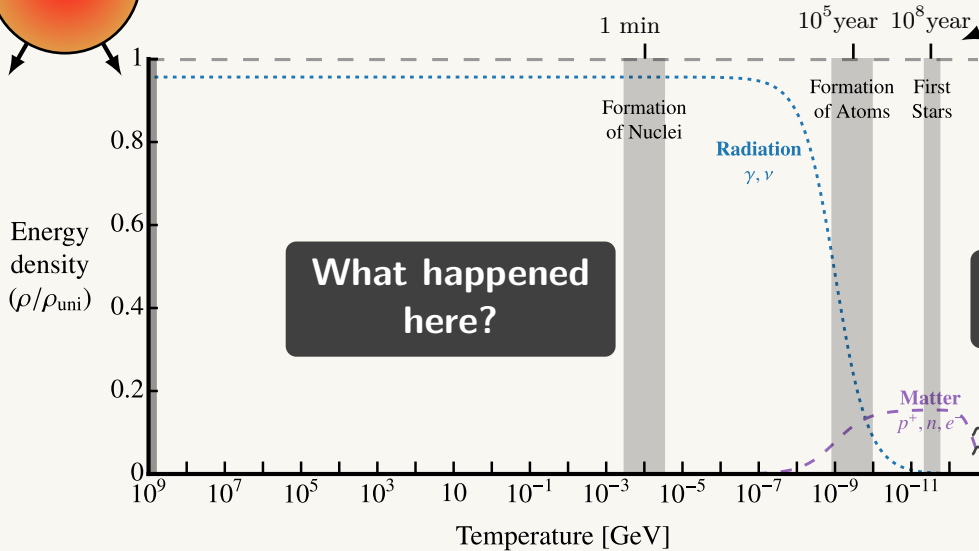
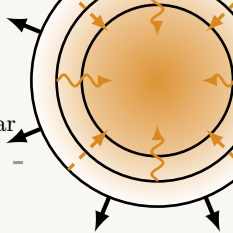
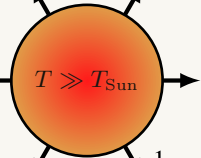
Today
Direct detection
of cosmic fossils











Today
Direct detection
of cosmic fossils



