The four basic ways of creating dark matter through a portal

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Work in collaboration with Xiaoyong Chu and Michel Tytgat

GGI, Firenze, 27/06/12

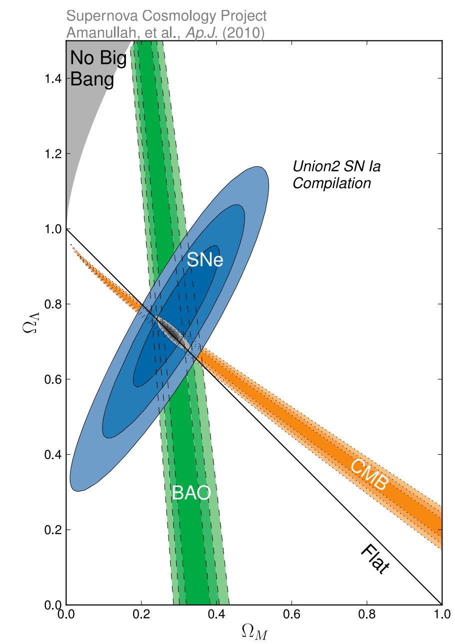
Gravitational evidences of dark matter

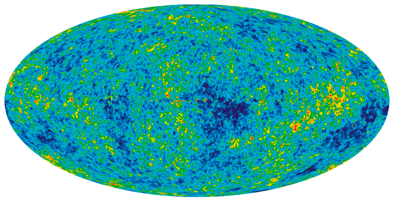
-At galactic scale: velocity distribution of stars

-At galaxy cluster scale: -velocity distribution of galaxies
-bullet cluster

-At cosmological scales: CMB data (WMAP),
supernovae,....

lead consistently to: $\Omega_{DM} \simeq 0.229 \pm 0.015\%$



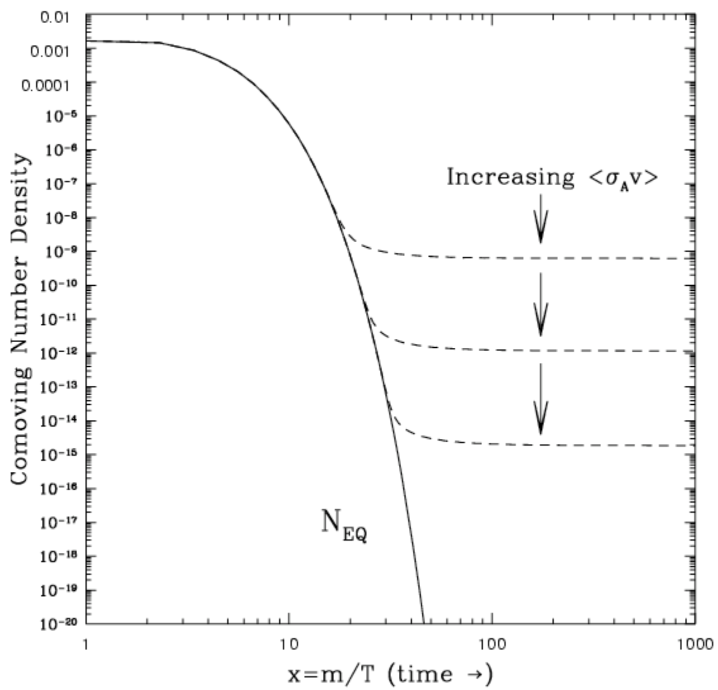


DM is neutral, stable ($\tau_{DM} > 10^{26}\,\mathrm{sec}$), cold, $\Omega_{DM} \simeq 23\%$, has constrained cross section on Nucleon, produces constrained fluxes of cosmic rays, BBN, ...

but this still leaves an enormous freedom for the DM particle (mass, spin, interactions, stabilization mechanism, ...)

The WIMP freeze-out mechanism

Relic density from annihilation freeze out:



down to $T \sim m_{DM}$ DM is thermal equilibrium

for $T \lesssim m_{DM}$ Boltzmann suppression of n_{DM}^{eq}

freeze-out of annihilation

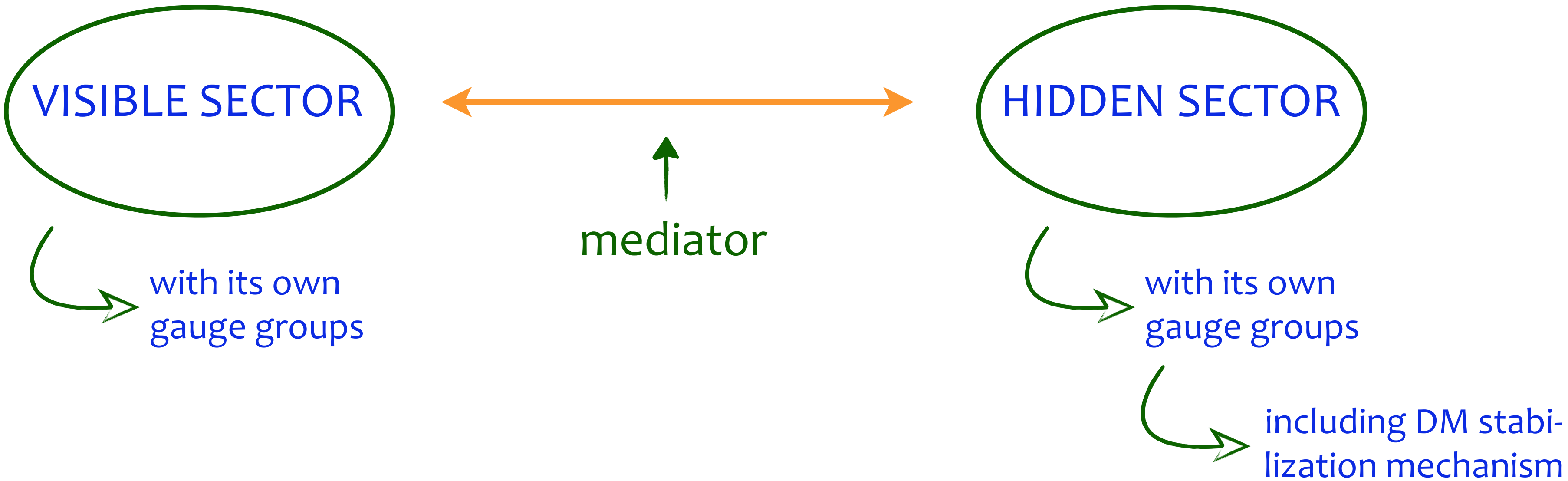
$\Downarrow$

$$\Omega_{DM} \propto 1/\langle\sigma_{annih} v\rangle$$

⇒ if $m_{DM} \sim 1\,\mathrm{GeV} - 10\,\mathrm{TeV}$ and $\lambda \sim 1$ ⇒ $\Omega_{DM} \sim 23\%$ ← $\sigma_{annih} v \simeq 10^{-26}\,\mathrm{cm}^3/\mathrm{sec}$

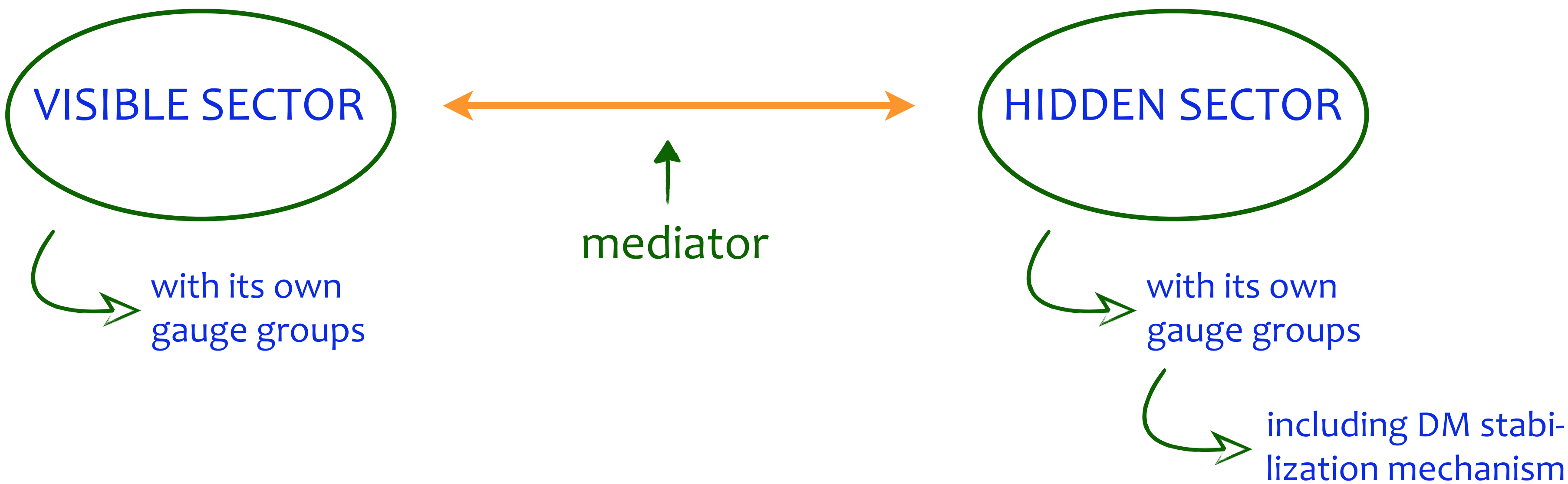
⇒ most straightforward/natural mechanism but not at all the only possible/simple one

A general visible sector/hidden sector/ mediator DM setup

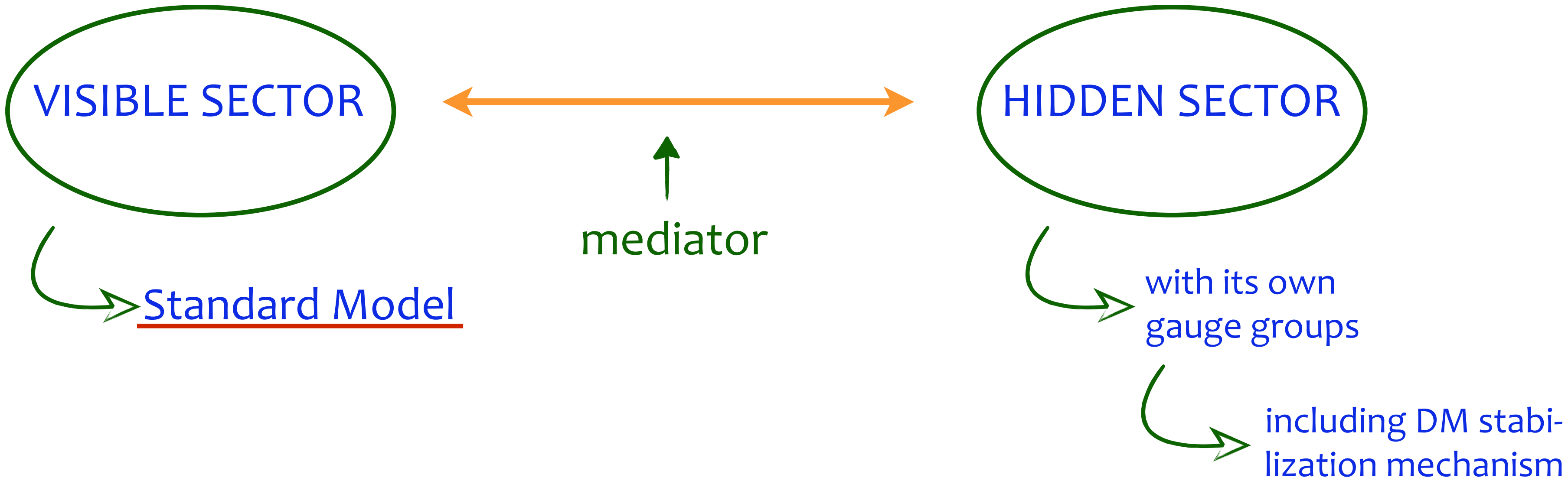


such a structure gives 4 regimes to get the observed relic density

A very simple light mediator model



A very simple light mediator model



A very simple light mediator model

VISIBLE SECTOR

HIDDEN SECTOR

mediator

Standard Model

a $U(1)'$ gauge symmetry and the lightest particle charged under it

a fermion: e'

$$\Uparrow$$

$$\mathcal{L} = \mathcal{L}_{SM} + \bar{\psi}'(i\not{D}' - m_\psi)\psi'$$

A very simple light mediator model

VISIBLE SECTOR

HIDDEN SECTOR

Standard Model

mediator

γ'

kinetic mixing

$$\mathcal{L} \ni -\frac{\varepsilon}{2} F_Y^{\mu\nu} F'_{\mu\nu}$$

a $U(1)'$ gauge symmetry and the lightest particle charged under it

a fermion: e'

$$\mathcal{L} = \mathcal{L}_{SM} + \bar{\psi}'(i\not{D}' - m_\psi)\psi'$$

Feldman, Kors, Nath 06'

Pospelov, Ritz, Voloshin 08'

for a massive Z'

A very simple light mediator model

VISIBLE SECTOR

HIDDEN SECTOR

mediator $\rightarrow \gamma'$

Standard Model

a $U(1)'$ gauge symmetry and the lightest particle charged under it

a fermion: e'

kinetic mixing

$$\mathcal{L} \ni -\frac{\varepsilon}{2} F_Y^{\mu\nu} F'_{\mu\nu}$$

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Feldman, Kors, Nath 06'

Pospelov, Ritz, Voloshin 08'

for a massive Z'

$\Longrightarrow$ a good DM candidate based on 3 parameters: $\underbrace{m_{DM}}_{= m_{e'}}$, α', ϵ

Motivations for such a Hidden sector gauge structure

- UV......

- simplicity

- the stability of the DM particle is a fundamental issue! ← $\tau_{DM} > 10^{26}\,\mathrm{sec}$

  → not that many stabilization mechanisms

  → one of the simplest: the lightest charged particle under a new gauge group

- visible sector = Standard Model ⇒ mass and interactions of source particles are known

- new DM long range force from γ' ⇒ rich cosmological phenomenology

  → studied in details in: (without connector) Ackerman, Buckley, Carroll, Kamionkowski 08'
  Feng Kaplinghat, Tu, Yu 09'
  Feng, Tu , Yu 08
  see also Foot at al. 06'-10'

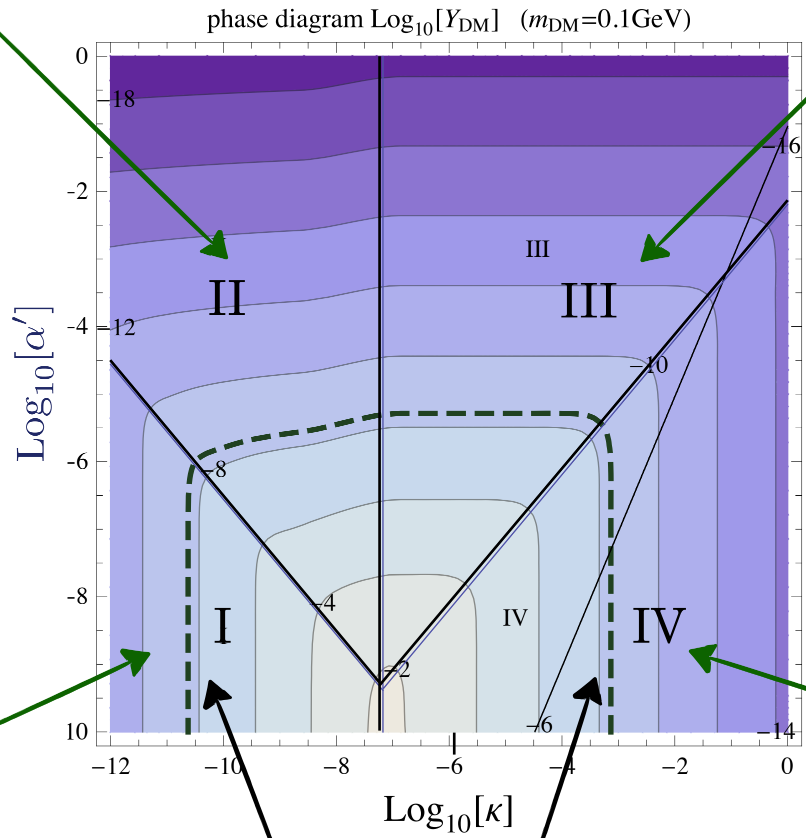
- prototype of visible sector/hidden sector/mediator structure

  → with such a structure: not only freeze-out and freeze-in but 4 DM production regimes

Relic density phase diagram

Reannihilation regime

Hidden sector freeze-out regime



$$\Omega_{DM} \sim 23\%$$

$$\kappa \equiv \epsilon\sqrt{\alpha'/\alpha}$$

Freeze-in regime

Connector freeze-out regime

Observed relic density: ”square” or “mesa” shape

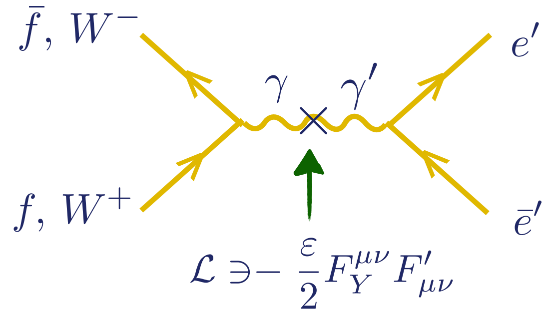
in each regime Ω_{DM} depends essentially on one coupling

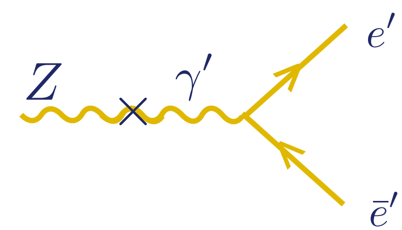
characteristic of the visible sector/hidden sector/mediator structure

Relevant processes

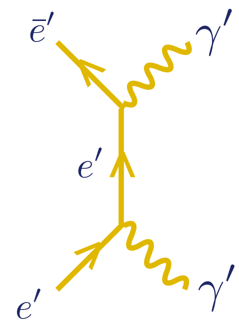
$+$

Connector processes:





Hidden sector process:



convenient to go in a $\gamma - \gamma'$ basis where kinetic terms are canonical (i.e. no $\gamma - \gamma'$mixing)

basis where γ' couples to f

γ couples to e' and f

Holdom 86'

$$\Longrightarrow \sigma(SMSM \to e'\bar{e}') \propto \alpha^2\kappa^2 \longleftarrow \kappa \equiv \epsilon\sqrt{\alpha'/\alpha}$$

$$\sigma(e'\bar{e}' \to \gamma'\gamma') \propto \alpha'^2$$

Boltzmann equation

in terms of the usual $\langle \sigma v \rangle$:

$$z \equiv m_{DM}/T$$

$$Y \equiv \frac{n_{e'}}{s} \quad (= Y_{DM}/2)$$

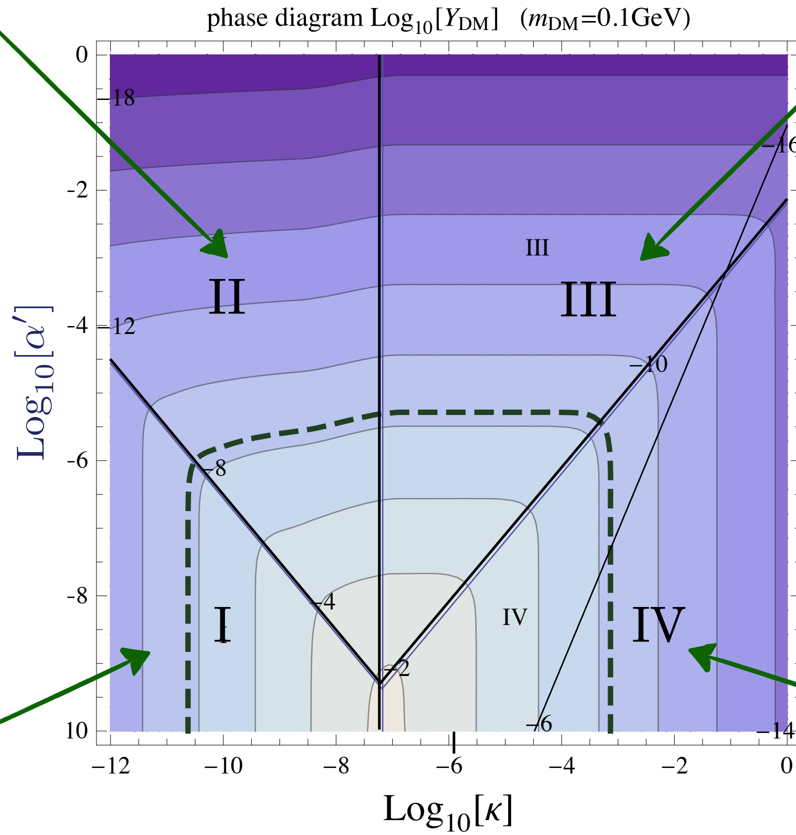
$$z\frac{H}{s}\frac{dY}{dz} = \sum_i \langle \sigma_{connect} v \rangle_i (Y_{eq}^2(T) - Y^2) + \langle \sigma_{HS} v \rangle (Y_{eq}^2(T') - Y^2)$$

$SM_i SM_i \to DMDM$ $\quad$ $DMDM \to SM_i SM_i$ $\quad$ $\gamma'\gamma' \to DMDM$ $\quad$ $DMDM \to \gamma'\gamma'$

Relic density phase diagram

Reannihilation regime

Hidden sector freeze-out regime



$$\Omega_{DM} \sim 23\%$$

$$\kappa \equiv \epsilon\sqrt{\alpha'/\alpha}$$

Freeze-in regime

Connector freeze-out regime

we consider a HS negligible at high temperature

$Y_{DM} \sim 0$

$\rho' \sim 0$

HS energy density

likely that DM production from inflaton decay negligible if reheating occurs mostly in one of the feebly coupled sectors

can be tested if the DM mass and coupling measured are the ones which give the right relic density

κ and α' are small $\Longrightarrow$ freeze-in regime

if κ and α' small: $SMSM \leftrightarrow DMDM$ does not thermalize

$DMDM \leftrightarrow \gamma'\gamma'$ does not thermalize

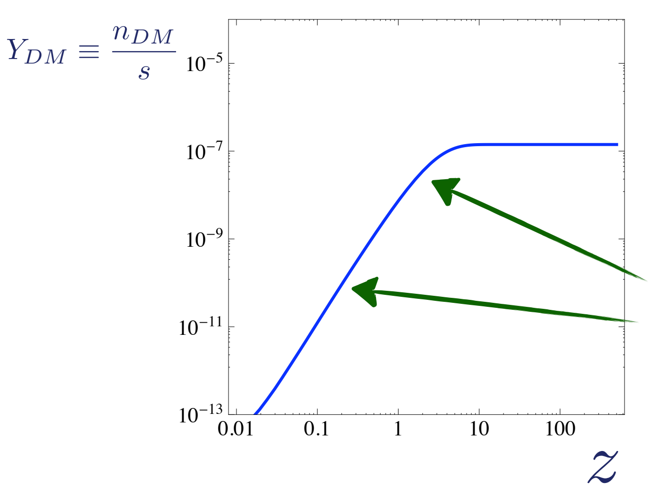
$$z\frac{H}{s}\frac{dY}{dz} = \sum_i \langle\sigma_{connect}v\rangle_i (Y^2_{eq}(T) - \cancel{Y^2}) + \langle\sigma_{HS}v\rangle(\cancel{Y^2_{eq}}(T') - \cancel{Y^2})$$

$SM_iSM_i \to DMDM$ $\quad$ $DMDM \to SM_iSM_i$ $\quad$ $\gamma'\gamma' \to DMDM$ $\quad$ $DMDM \to \gamma'\gamma'$

only $SMSM \to DMDM$ is relevant because only Y^{eq}_{SM} is large

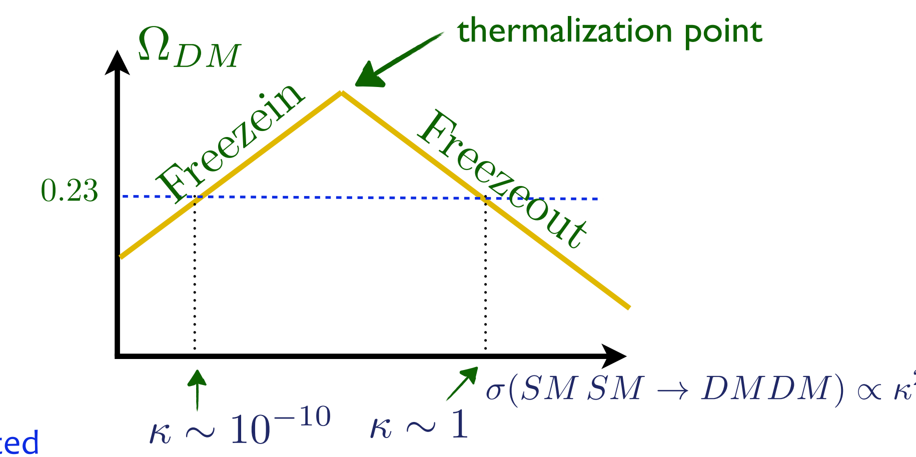
$\Longrightarrow$ freeze-in regime:

Mc Donald 02'
Hall, Jedamzik, March-Russell, West 09'



$Y_{DM} \propto 1/T$ down to $T \sim m_{DM}$ where n^{eq}_A becomes Boltz. suppressed

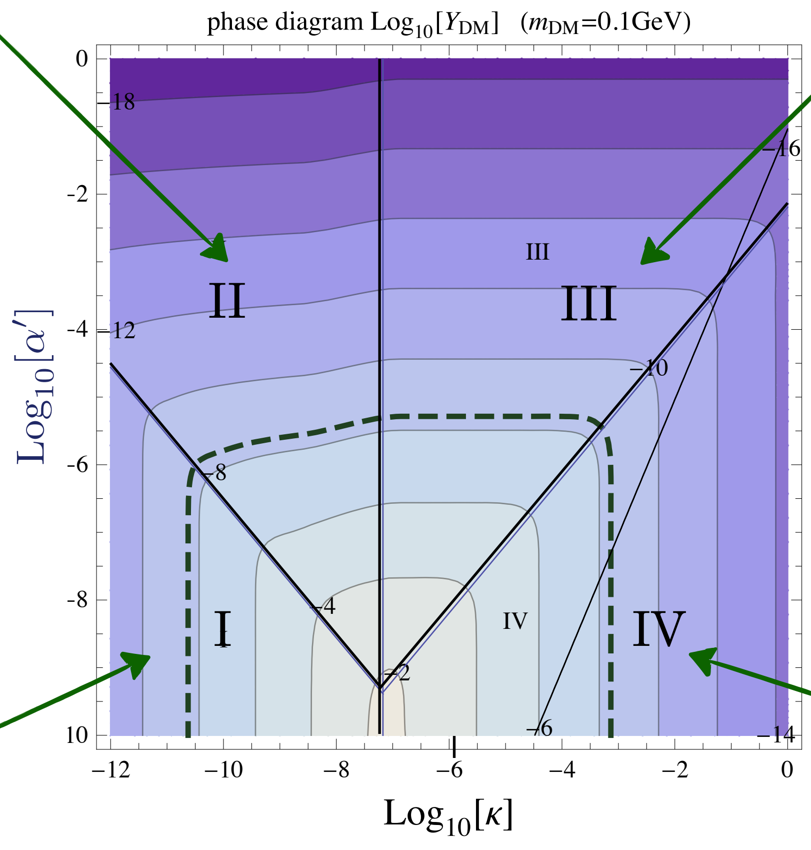
DM production IR dominated



Relic density phase diagram

Reannihilation regime

Hidden sector freeze-out regime



$\Omega_{DM} \sim 23\%$

Freeze-in regime

Connector freeze-out regime

Reannihilation regime

if one increases κ $\Rightarrow$ more DM created
if one increases α' $\Rightarrow$ $\langle\sigma_{HS}v\rangle$ increases
} both favor thermalization of $\langle\sigma_{HS}v\rangle$

$\Downarrow$

at some point the γ' thermalize with the e':

$$\Gamma_{annih} > H \qquad \Gamma_{annih} = \underbrace{n_{e'}}_{n^2_{eq}(T)\langle\sigma_{connect}v\rangle/H}\langle\sigma_{HS}v\rangle$$

$\Updownarrow$

$$n_{eq}(T)\underbrace{\langle\sigma_{eff}v\rangle}_{\langle\sigma_{eff}v\rangle \equiv \sqrt{\langle\sigma_{HS}v\rangle\langle\sigma_{connect}v\rangle}} > H$$

$\Longrightarrow$ we can define a HS temperature T' $\leftarrow$ $n_{\gamma'} = n_{eq}(T') \sim g_{\gamma'}T'^3$, $\rho' \sim g_*^{HS}T'^4$

$\Downarrow$

necessary to know the number of γ', i.e. the $\gamma'\gamma' \to DMDM$ rate

$$z\frac{H}{s}\frac{dY}{dz} = \sum_i \langle\sigma_{connect}v\rangle_i (Y^2_{eq}(T) - Y^2) + \langle\sigma_{HS}v\rangle(Y^2_{eq}(T') - Y^2)$$

$\Longrightarrow$ we need to calculate the HS energy density ρ' in order to determine T'

Calculation of the energy transfer from the SM to the HS

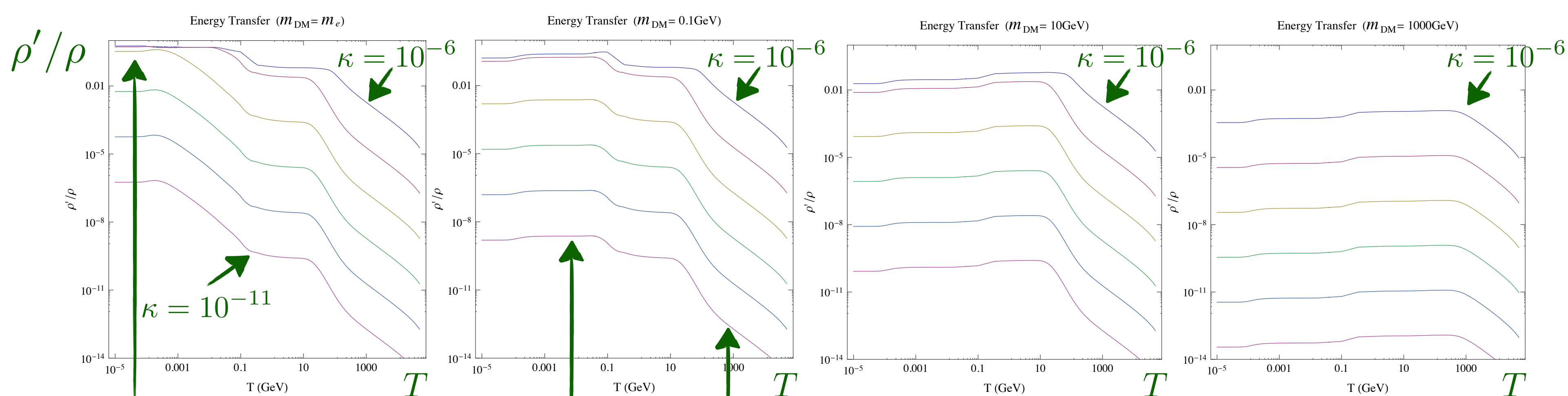
energy transfer Boltzmann equation

$$\frac{d\rho'}{dt} + 3H(\rho' + p') = \int \prod_{i=1}^{4} d^3\bar{p}_i \cdot g_i f_1(\vec{p}_1) f_2(\vec{p}_2) |i\mathcal{M}_{1\,2\leftrightarrow 3\,4}|^2 (2\pi)^4 \delta^{(4)}(p_1 + p_2 - p_3 - p_4)\Delta E_{tr}$$

$$\frac{d(\rho'/\rho)}{dT} = -\frac{1}{H(T)T\rho}\frac{g_1 g_2}{32\pi^4}\int ds \cdot \sigma_{connect}(s)(s-4m^2)sTK_2(\frac{\sqrt{s}}{T})$$

$SM_i SM_i \to DM DM$

$m_{DM} = m_e$ $\quad$ $m_{DM} = 0.1\,\mathrm{GeV}$ $\quad$ $m_{DM} = 10\,\mathrm{GeV}$ $\quad$ $m_{DM} = 1\,\mathrm{TeV}$



ρ'/ρ saturates when T' reaches T

$\rho'/\rho \sim 1/T$ for $T > m_{DM}$

$\rho'/\rho \sim$ const for $T < m_{DM}$

Reannihilation regime: Boltzmann equation

HS process in thermal equilibrium but not the connector: $T'/T << 1$

$$z\frac{H}{s}\frac{dY}{dz} = \sum_i \langle\sigma_{connect}v\rangle_i(Y_{eq}^2(T) - \cancel{Y^2}) + \langle\sigma_{HS}v\rangle(Y_{eq}^2(T') - Y^2)$$

$SM_iSM_i \to DMDM$

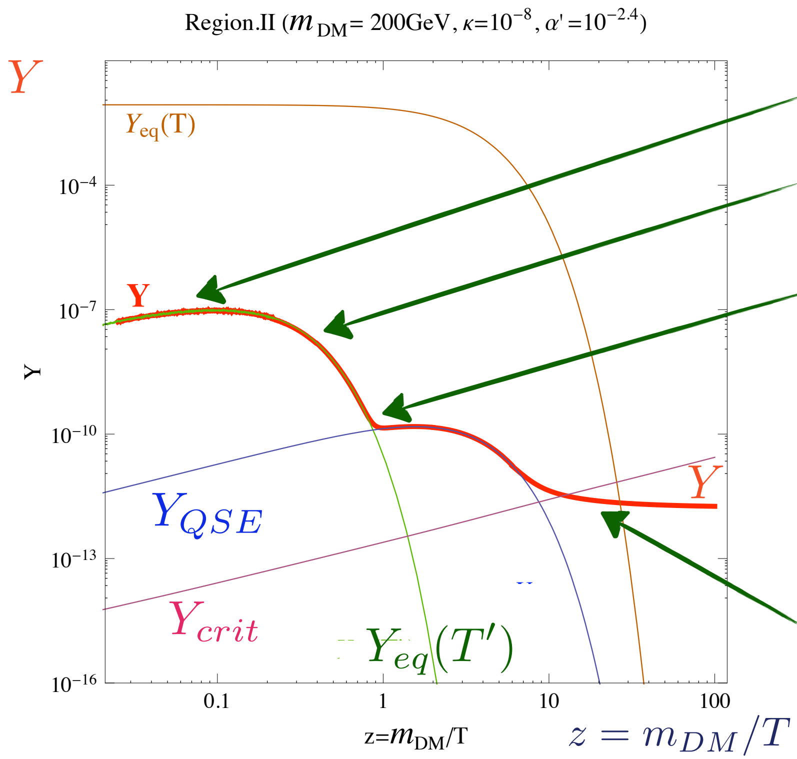
$DMDM \to SM_iSM_i$

$\gamma'\gamma' \to DMDM$

$DMDM \to \gamma'\gamma'$

Cheung, Elor, Hall, Kumar 10'

in $A \to DMB$ decay context



$\Gamma_{annih} = H \leftrightarrow Y = Y_{crit} \equiv H/\langle\sigma_{HS}v\rangle$

after thermalization Y follows $Y_{eq}(T')$

at $T' \lesssim m_{DM}$: $Y_{eq}(T')$ becomes Boltzmann suppressed

$SMSM \to DMDM$ rate (which decouples only at $T \lesssim m_{DM}$) gets larger than the $\gamma'\gamma' \to DMDM$ rate (which decouples already at $T' \lesssim m_{DM}$) $\Rightarrow$ reannihilation

at $T \lesssim m_{DM}$ the $SMSM \to DMDM$ source term gets Boltzmann suppressed $\Rightarrow$ freezes

Reannihilation regime: Boltzmann equation

when the $\gamma'\gamma' \to DMDM \propto Y_{eq}^2(T')$ rate goes below the $SMSM \to DMDM \propto Y_{eq}^2(T)$ rate:

in thermal equilibrium

out of thermal equilibrium

$$z\frac{H}{s}\frac{dY}{dz} = \sum_i \langle\sigma_{connect} v\rangle_i \Big(\underbrace{Y_{eq}^2(T)}_{SM_iSM_i \to DMDM} - \underbrace{\cancel{Y^2}}_{DMDM \to SM_iSM_i}\Big) + \langle\sigma_{HS} v\rangle \Big(\underbrace{\cancel{Y_{eq}^2(T')}}_{\gamma'\gamma' \to DMDM} - \underbrace{Y^2}_{DMDM \to \gamma'\gamma'}\Big)$$

$$z\frac{dY}{dz} = \frac{\langle\sigma_{connect} v\rangle s}{H} Y_{eq}^2(T) - \frac{Y^2}{Y_{crit}}$$

period of Quasi Static Equilibrium where both terms compensates each other

$$\Rightarrow\quad Y = Y_{QSE} \equiv \sqrt{Y_{crit}\frac{\langle\sigma_{connect} v\rangle s}{H} Y_{eq}^2(T)}$$

until $Y = Y_{QSE} = Y_{crit}$ where Y freeze $\leftarrow$ at $T \equiv T_f$

$\Rightarrow$ simultaneous freezing of both connector source term and HS reannihilation term

Reannihilation regime: analytical result

in practice: if the HS thermalize but the connector does not one has always a period of reannihilation

(except through Z decay for $m_{DM} \lesssim m_Z/2$)

Freeze-out equation to determine T_f :

$$n_{eq}(T_f)\langle\sigma_{eff}v\rangle = H(T_f)$$

$$\langle\sigma_{eff}v\rangle \equiv \sqrt{\langle\sigma_{connect}v\rangle\langle\sigma_{HS}v\rangle}$$

ordinary freeze-out equation but with another cross section: $\langle\sigma_{eff}v\rangle$

$$\Rightarrow \quad x_f = \log[0.038\frac{g_{e'}}{\sqrt{g_*^{eff}}}m_{Pl}m_{DM}\langle\sigma_{eff}v\rangle c(c+2)] - \frac{1}{2}\log[\log[0.038\frac{g_{e'}}{\sqrt{g_*^{eff}}}m_{Pl}m_{DM}\langle\sigma_{eff}v\rangle c(c+2)]]$$

$$x_f \equiv m_{DM}/T_f$$

$$\Rightarrow \quad Y(T_f) \equiv Y_{QSE}(T_f) = \frac{1}{\langle\sigma_{HS}v\rangle}\frac{3.79x_f}{(g_{\star s}/\sqrt{g_*^{eff}})}m_{Pl}m_{DM}.$$

$\Rightarrow \Omega_{DM} \propto \frac{x_f}{\langle\sigma_{HS}v\rangle}$ as in usual freeze-out but with a x_f determined by another cross section

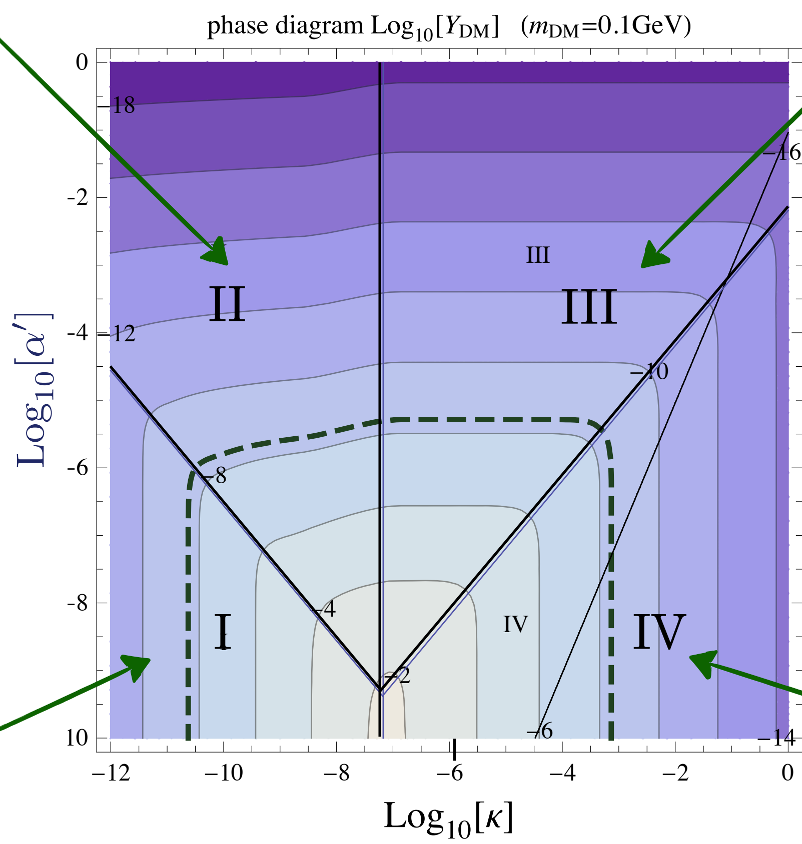
$\propto \log(\alpha'\kappa)/\alpha'^2$

$\langle\sigma_{eff}v\rangle$

Relic density phase diagram

Reannihilation regime

Hidden sector freeze-out regime



$\Omega_{DM} \sim 23\%$

Freeze-in regime

Connector freeze-out regime

Hidden sector freeze-out regime

starting from a reannihilation situation

if one increases κ further $\Rightarrow$ the connector interaction thermalizes: $T' = T$

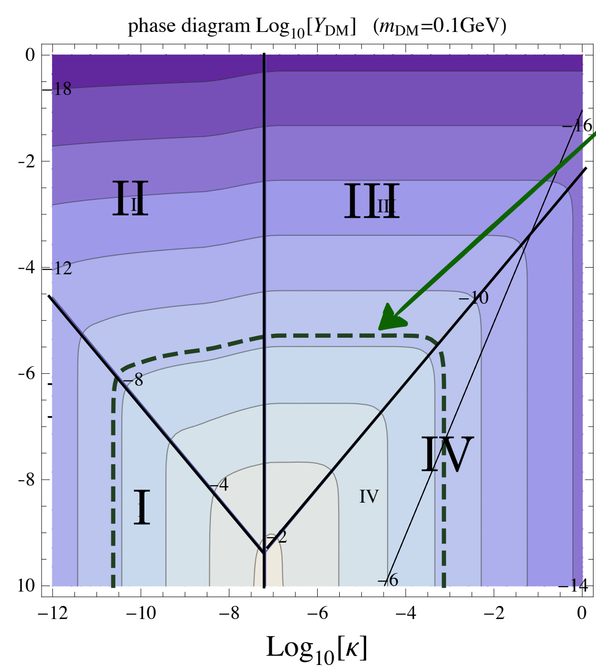
$SMSM \leftrightarrow DMDM$

one enters a regime where even if the connector thermalizes

the HS interaction thermalizes much more $\langle \sigma_{HS} v \rangle > \langle \sigma_{connect} v \rangle$

standard freeze-out (only one temperature) dominated by the HS interaction

$$\Rightarrow \Omega_{DM} \propto \frac{1}{\langle \sigma_{HS} v \rangle} \propto \frac{1}{\alpha'^2}$$

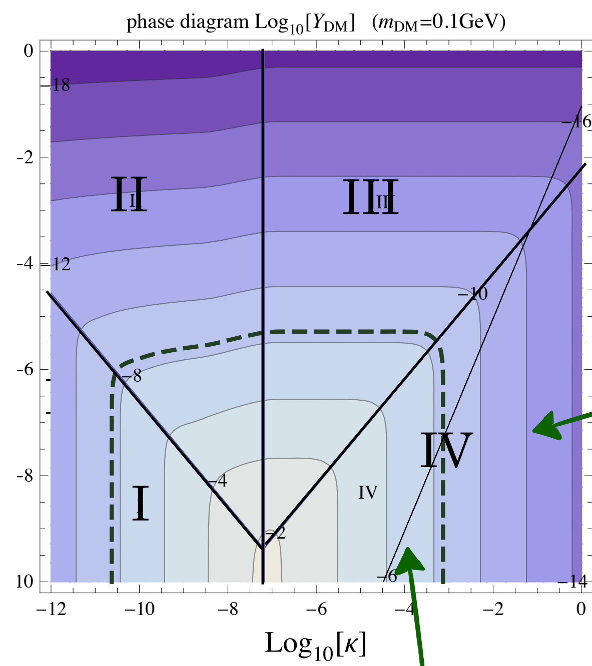


Hidden sector freeze-out regime

Connector freeze-out regime

if one increases κ further $\Rightarrow$ the connector not only thermalizes but dominates the freeze-out process $\langle \sigma_{connect} v \rangle > \langle \sigma_{HS} v \rangle$

$$\Omega_{DM} \propto \frac{1}{\langle \sigma_{connect} v \rangle} \propto \frac{1}{\kappa^2}$$



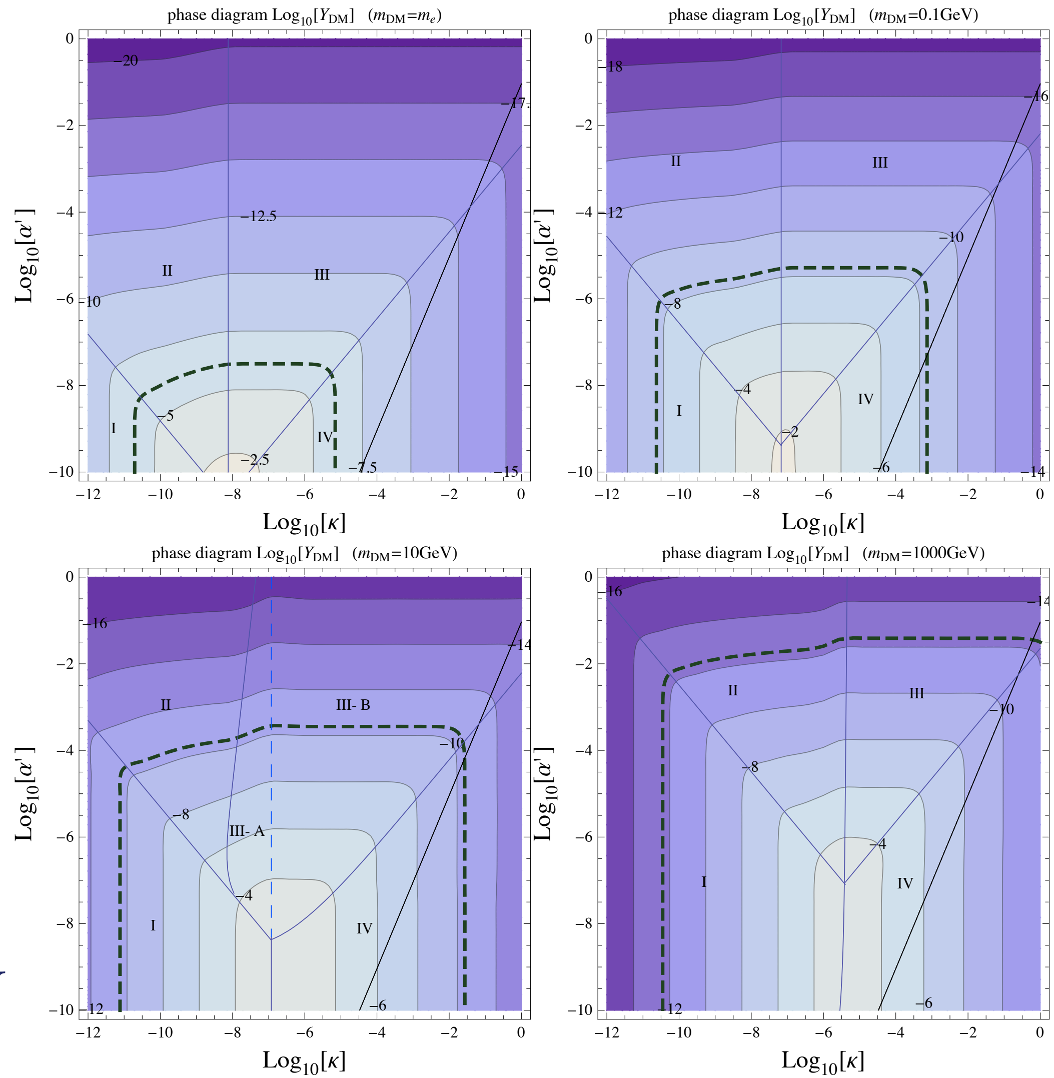
Connector freeze-out regime

$\kappa \equiv \epsilon \sqrt{\alpha'/\alpha} \Rightarrow$ if κ big, α' small $\Rightarrow$ ϵ non perturbative

Relic density phase diagram

$m_{DM} = m_e$

$m_{DM} = 0.1\,\mathrm{GeV}$



$m_{DM} = 10\,\mathrm{GeV}$

$m_{DM} = 1\,\mathrm{TeV}$

Generality of the “mesa” phase diagram: the Higgs portal example

VISIBLE SECTOR

HIDDEN SECTOR

Standard Model

coupled through the Higgs portal

$$\mathcal{L} \ni -\lambda_m \phi\phi^\dagger H H^\dagger$$

a $U(1)'$ gauge symmetry and the lightest particle charged under it

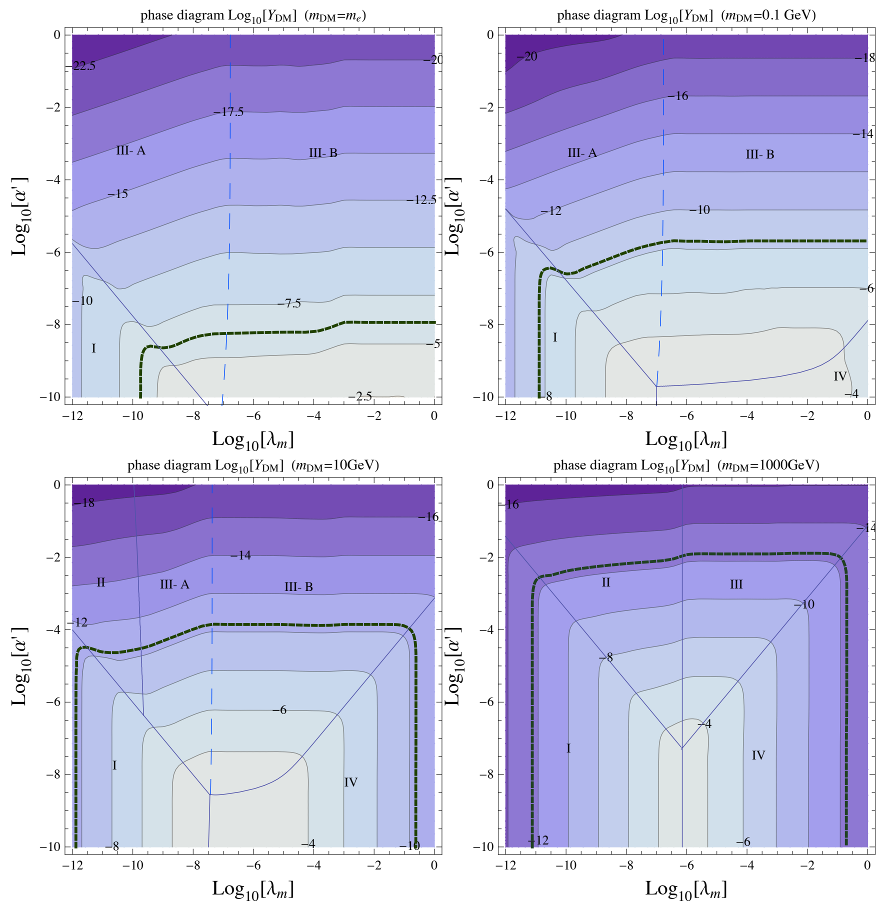
a scalar: ϕ

$$\mathcal{L} \ni \mathcal{L}_{SM} + D'_\mu \phi^\dagger D'^\mu \phi - \mu_\phi^2 \phi\phi^\dagger - \lambda_\phi (\phi\phi^\dagger)^2$$

Generality of the “mesa” phase diagram: the Higgs portal example

$m_{DM} = m_e$

$m_{DM} = 0.1\,\mathrm{GeV}$



$m_{DM} = 10\,\mathrm{GeV}$

$m_{DM} = 1\,\mathrm{TeV}$

same general structure despite of important differences: the mediator is massive

$m_h \simeq 120\,\mathrm{GeV}$

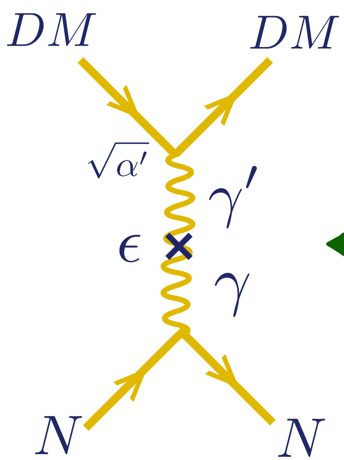
production through $m_h \to \phi\phi^\dagger$ decay if $m_{DM} < m_h/2$

visible/hidden sector communication cut-off at $T \sim \mathrm{Max}[m_h, m_{DM}]$

if the HS thermalizes but not the connector: both reannihilation and HS freeze-out possible

Test of mesa phase diagrams for kinetic mixing: direct detection

DM elastic cross section on Nucleon



$$\frac{1}{q^2} \to \frac{1}{E_r^2}$$

$$\frac{d\sigma}{dE_r} = \frac{1}{E_r^2}\frac{1}{v^2}\frac{2\pi\kappa^2 Z^2\alpha^2}{m_A}F_A^2(qr_A)$$

$E_r \sim$ few KeV

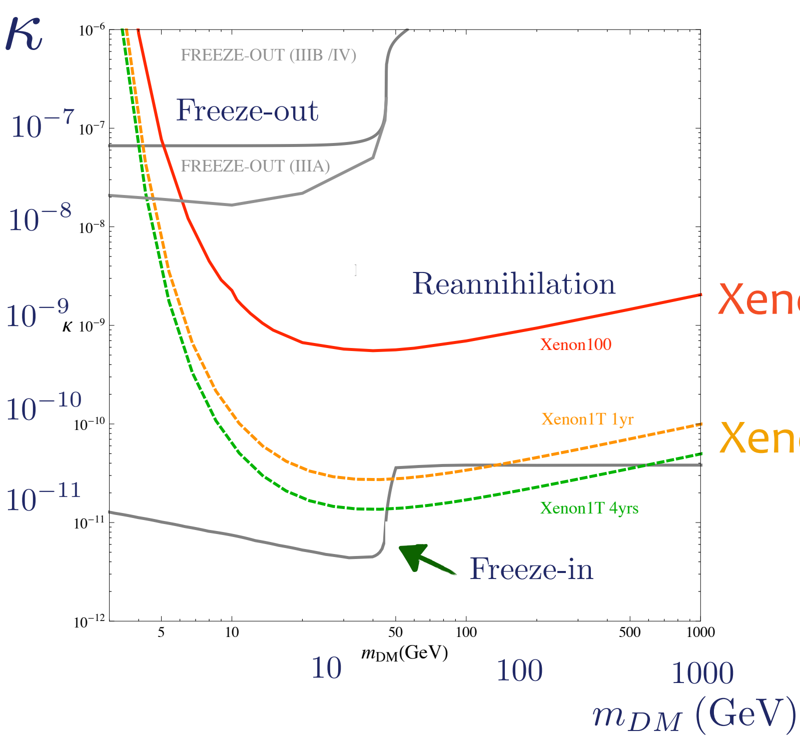
$\Downarrow$

huge enhancement

$\Downarrow$

direct detection sensitive to very small κ values

Test of mesa phase diagrams for kinetic mixing: direct detection



Xenon-100kg: excludes all regimes for $m_{DM} > \text{few GeV}$ except freeze-in and part of reannihilation

Xenon-1T: will test freeze-in for

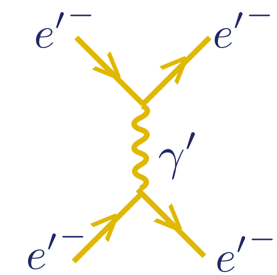
$50\,\text{GeV} < m_{DM} < 140\,\text{GeV}$ ← 1 T/year

$40\,\text{GeV} < m_{DM} < 600\,\text{GeV}$ ← 4 T/year

characteristic $\sim \dfrac{1}{E_r^2}$ spectrum to be observed!!

Cosmological constraints

associated to new long range $U(1)'$ force



- BBN
- bullet cluster
- galactic dynamics
- ...

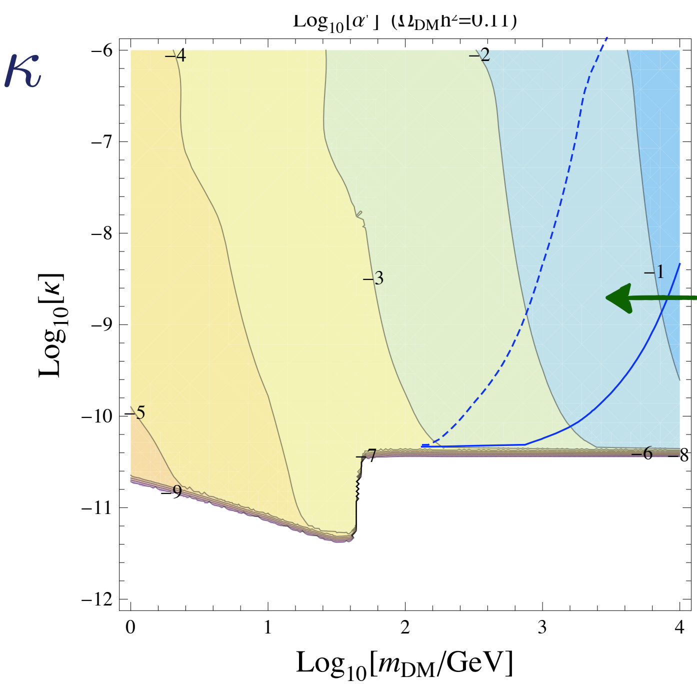
DM Rutherford scattering may affect formation of DM halo

ellipticity of galaxies: $\alpha' \lesssim 10^{-7}\,(m_{DM}/\mathrm{GeV})^{3/2}$

Ackerman, Buckley,
Carroll, Kamionkowski 08'
Feng Kaplinghat, Tu, Yu 09'
Feng, Tu , Yu 08

Ellipticity and relic density constraints combined

κ



reannihilation allowed for:

$m_{DM} > \sim$ few 100 GeV

freeze-in always allowed

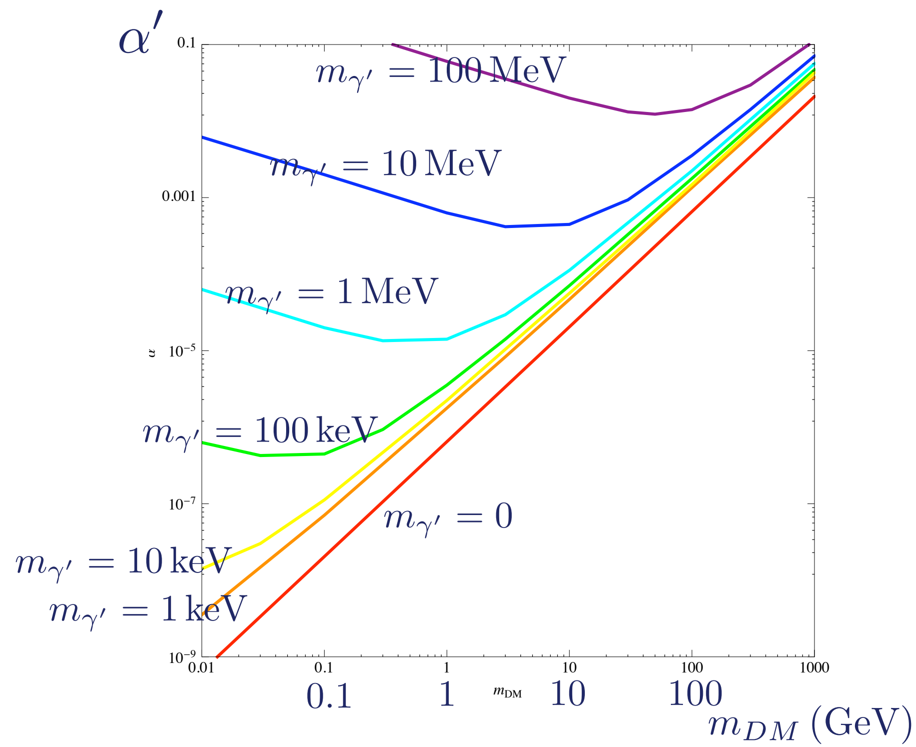
Ellipticity constraint for the case of a slightly massive γ'

if we break the $U(1)'$ slightly with $m_{\gamma'} << m_{DM}$

the relic density plot doesn't change

the lightest charged fermion remains stable

but the cosmological constraints change a lot



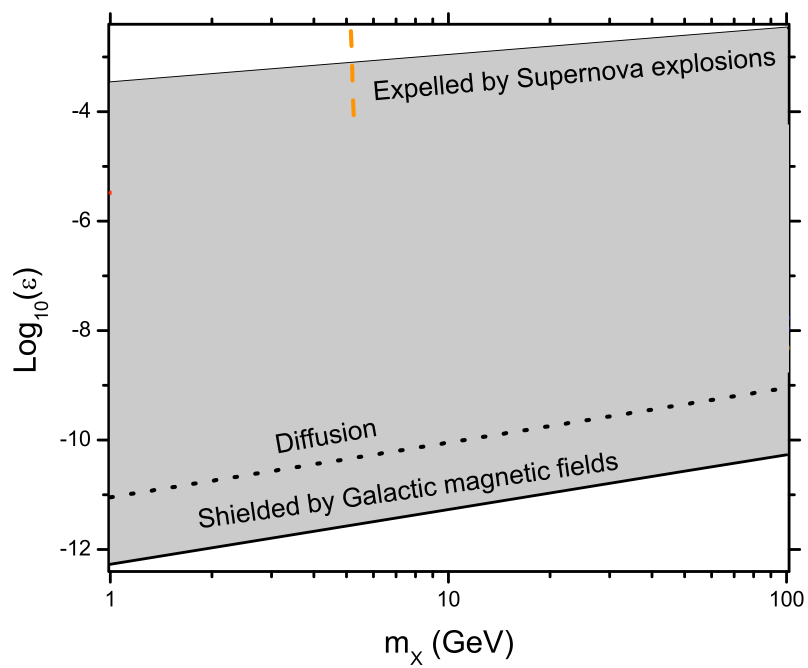
Depletion of DM in galactic disk

the DM feels the galactic magnetic field via κ

sufficient for a DM coming off the disk not to enter in the disk

Chuzhoy, Kolb 09'

Mc Dermott, Yu, Zurek 11'



Mc Dermott, Yu, Zurek 11'

shielding

only freeze-in regime is allowed for $m_{DM} \lesssim 100\,\mathrm{GeV}$ but the constraint vanishes as soon as the γ' becomes slightly massive

Summary

- Visible/hidden sectors/mediator structure:

  the observed relic density can be produced through characteristic 4 regimes

  "mesa" phase diagram...

  natural "analytic prolongation" of the usual freeze-out regime towards small coupling values

- Kinetic mixing portal:

  - all 4 regimes can be tested from direct detection, even the freeze-in one

  - rich cosmological phenomenology (which strongly depends on the mass of the γ')

Backup

Redondo, Ringvald 10'

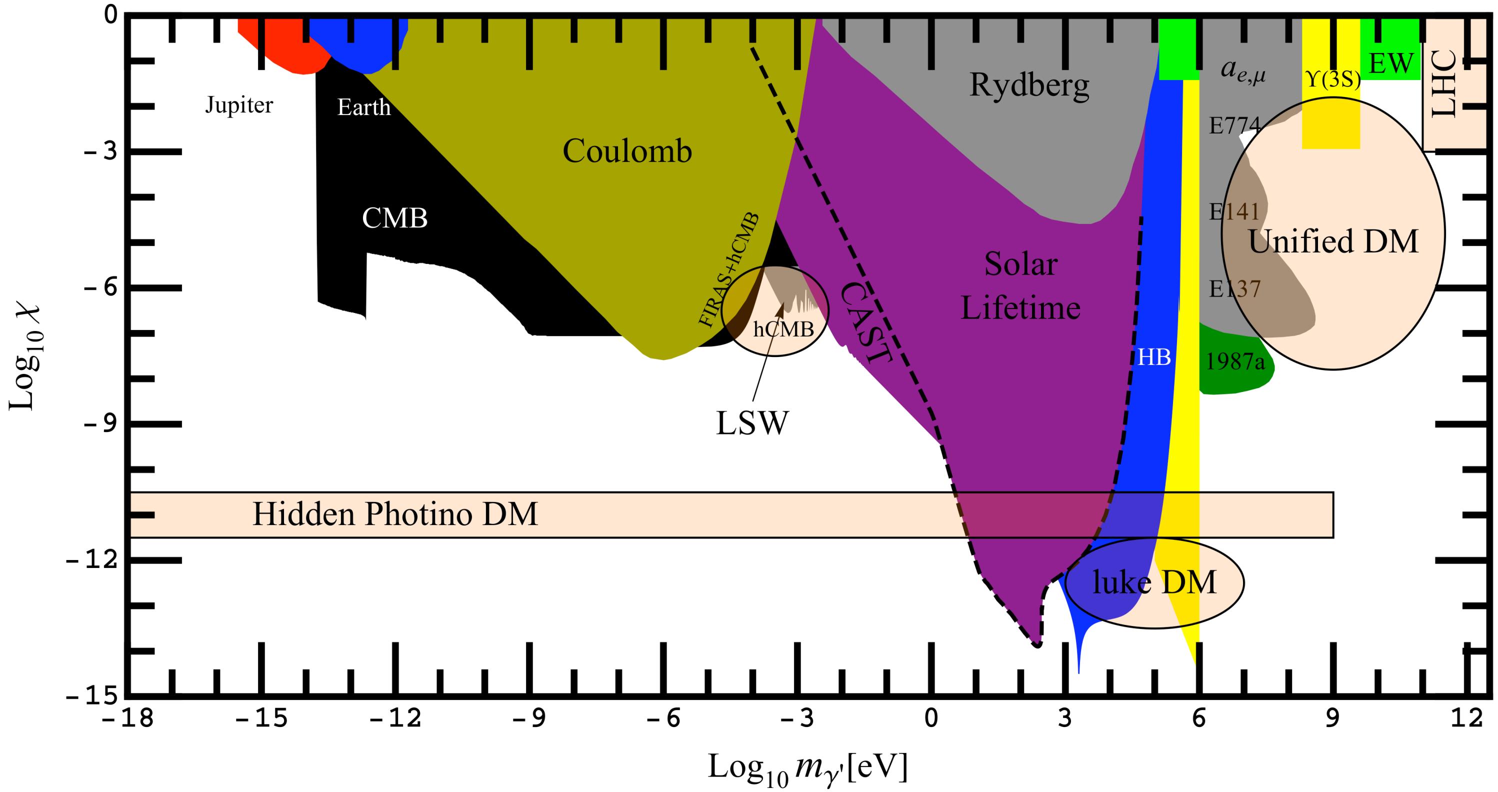


Figure 10. Summary of astrophysical, cosmological and laboratory constraints for hidden photons (kinetic mixing χ vs. mass $m_{\gamma'}$). At higher mass we have electroweak precision measurements (EW), bounds from upsilon decays (Υ_{3S}) and fixed target experiments (EXXX)). Areas that are especially interesting are marked in light orange. Compilation from Ref. [93].

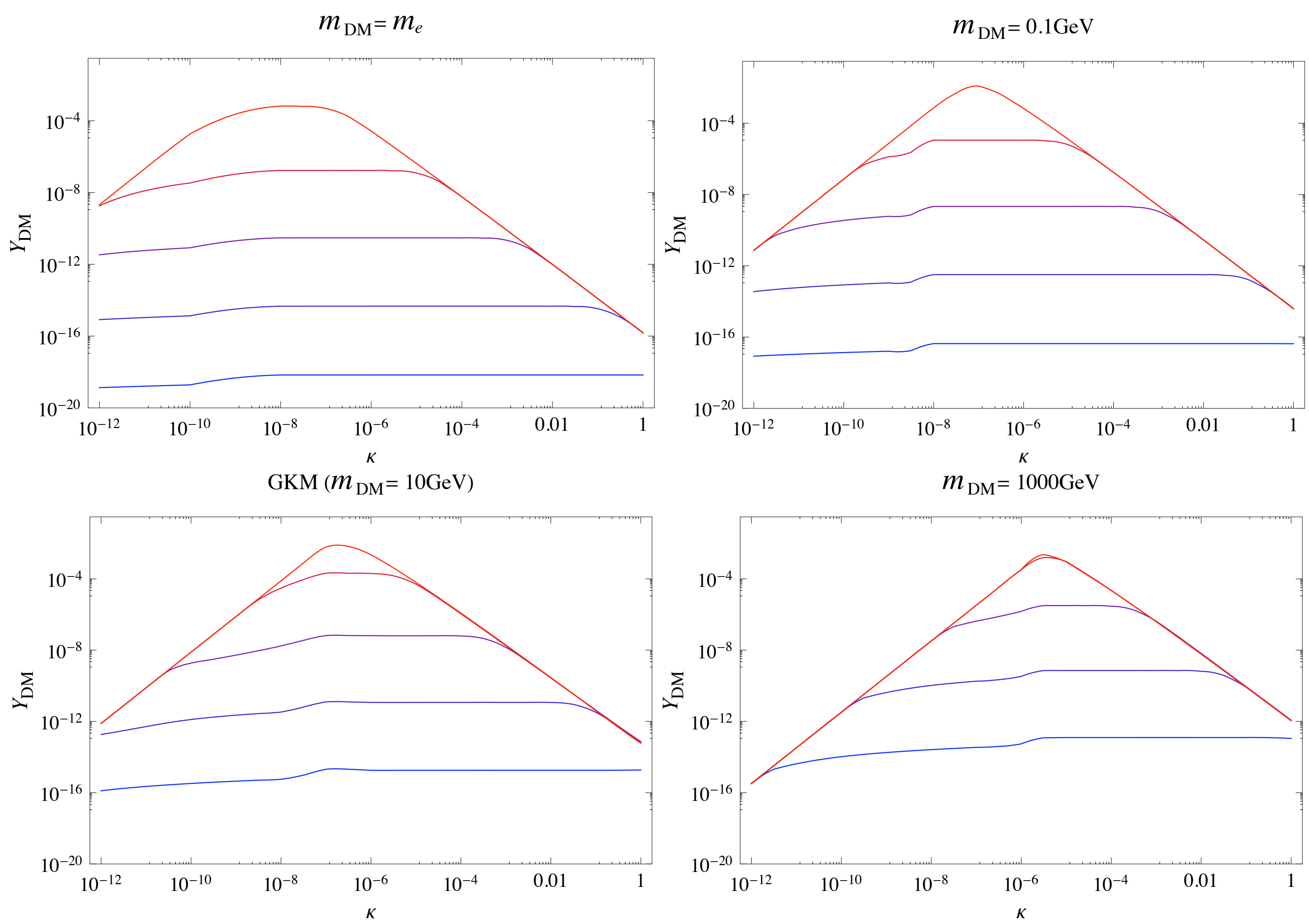
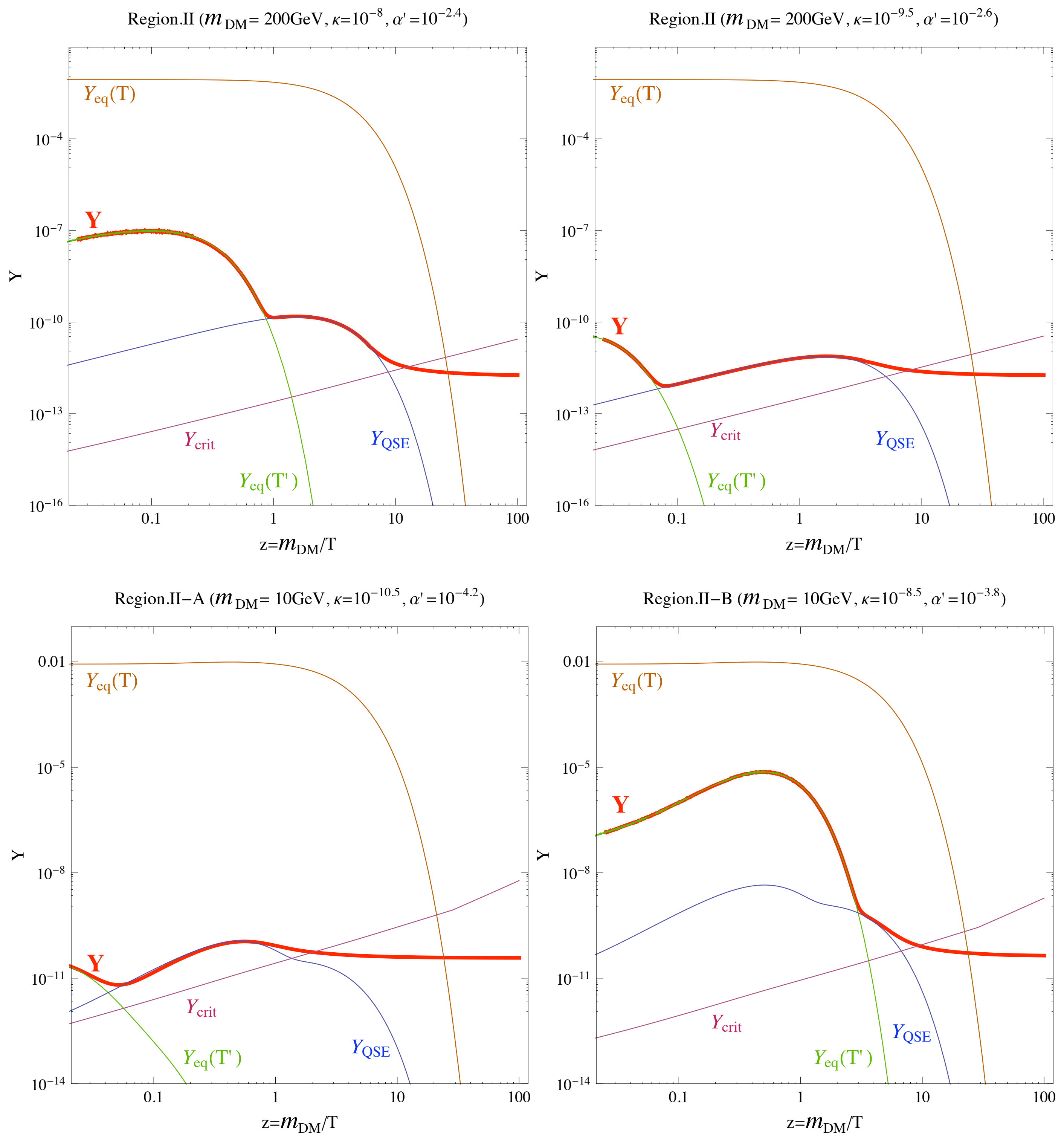


Figure 5: DM relic abundance Y_{DM} as a function of the connector parameter κ for different DM masses m_{DM} and values of the hidden sector interaction, $\log_{10}(\alpha'/\alpha) = 1, -1, -3, -5, -7$ (bottom-up).



Region.II (m_{DM}= 200GeV, $\kappa=10^{-8}$, $\alpha'=10^{-2.4}$)
Region.II (m_{DM}= 200GeV, $\kappa=10^{-9.5}$, $\alpha'=10^{-2.6}$)
Region.II−A (m_{DM}= 10GeV, $\kappa=10^{-10.5}$, $\alpha'=10^{-4.2}$)
Region.II−B (m_{DM}= 10GeV, $\kappa=10^{-8.5}$, $\alpha'=10^{-3.8}$)
Y_{eq}(T)
Y_{eq}(T')
Y_{crit}
Y_{QSE}
Y
$z=m_{DM}/T$

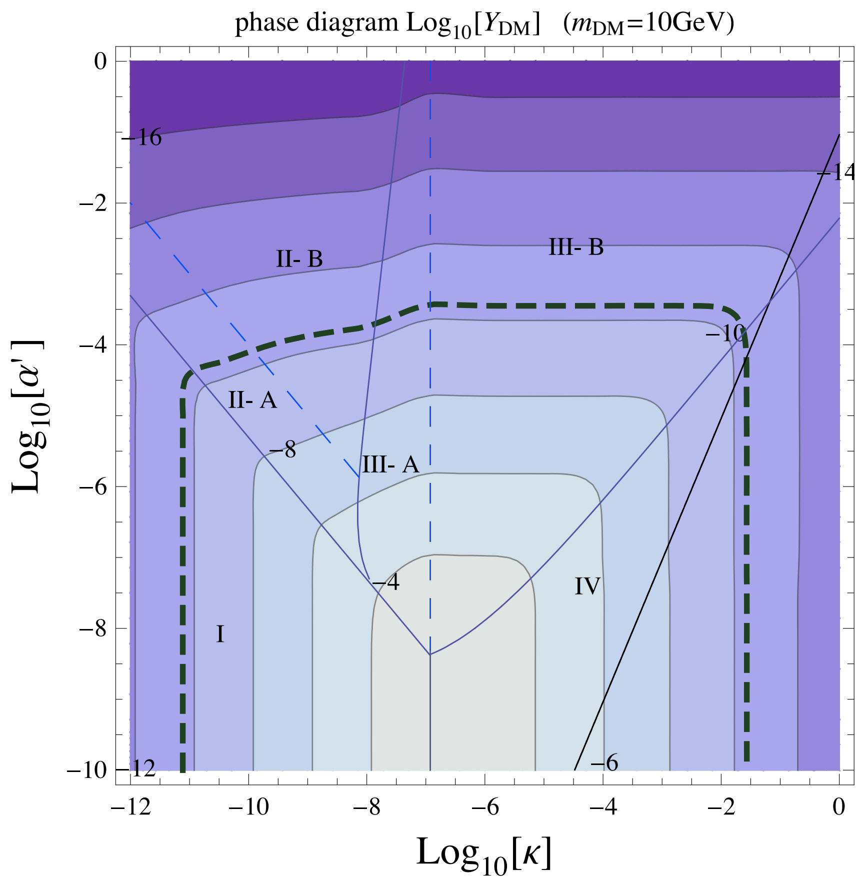


Figure 18: Phase diagram for the kinetic mixing portal and $m_{DM} = 10$ GeV separating explicitly the reannihilation regimes dominated by the decay (IIA) and by the γ mediated scattering (IIB).

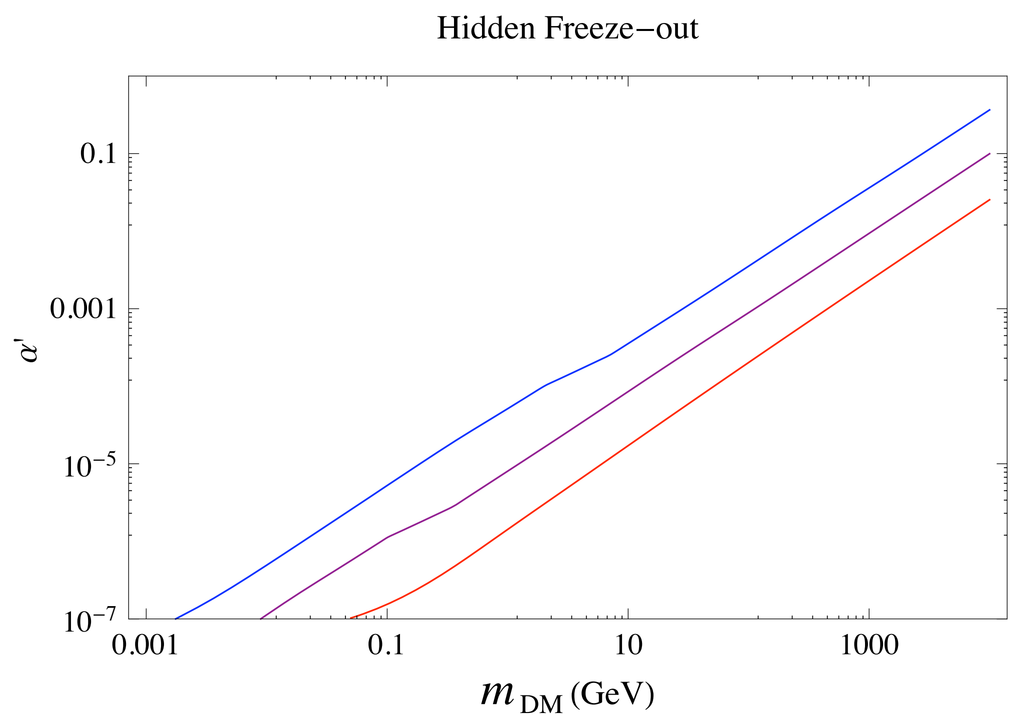


Figure 6: Values of α' required to get the WMAP relic density as a function of m_{DM} assuming no connector between the hidden sector and the SM sector, for different values of the temperature ratio $\xi \equiv T'/T = 0.01, 0.1, 1$ (bottom-up).

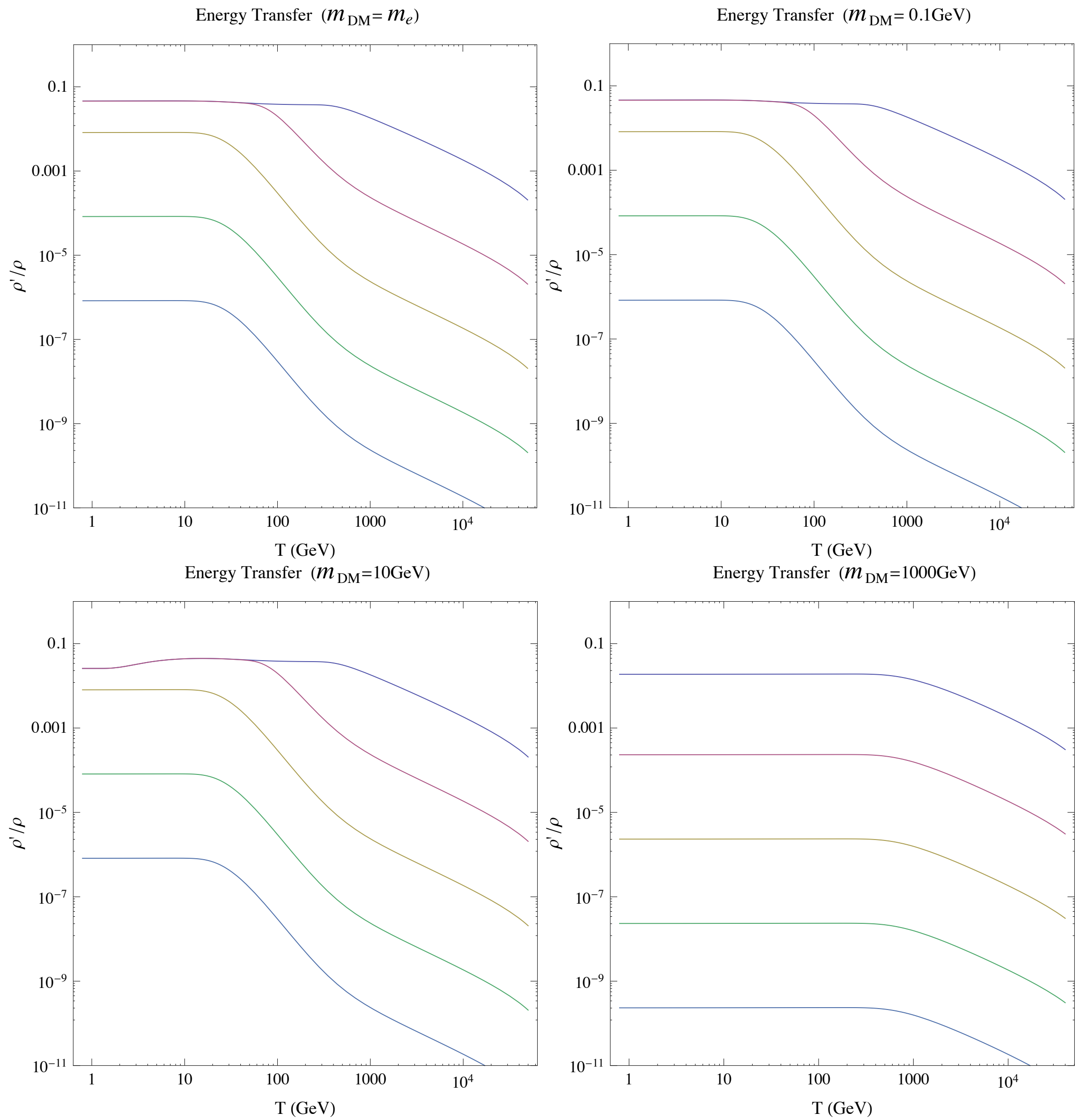


Figure 12: Evolution of the ratio of the visible and hidden sectors energy densities, for a range of connector parameter, $\lambda_m = 10^{-6,-7,-8,-9,-10}$ (from up to down), and for various DM masses.

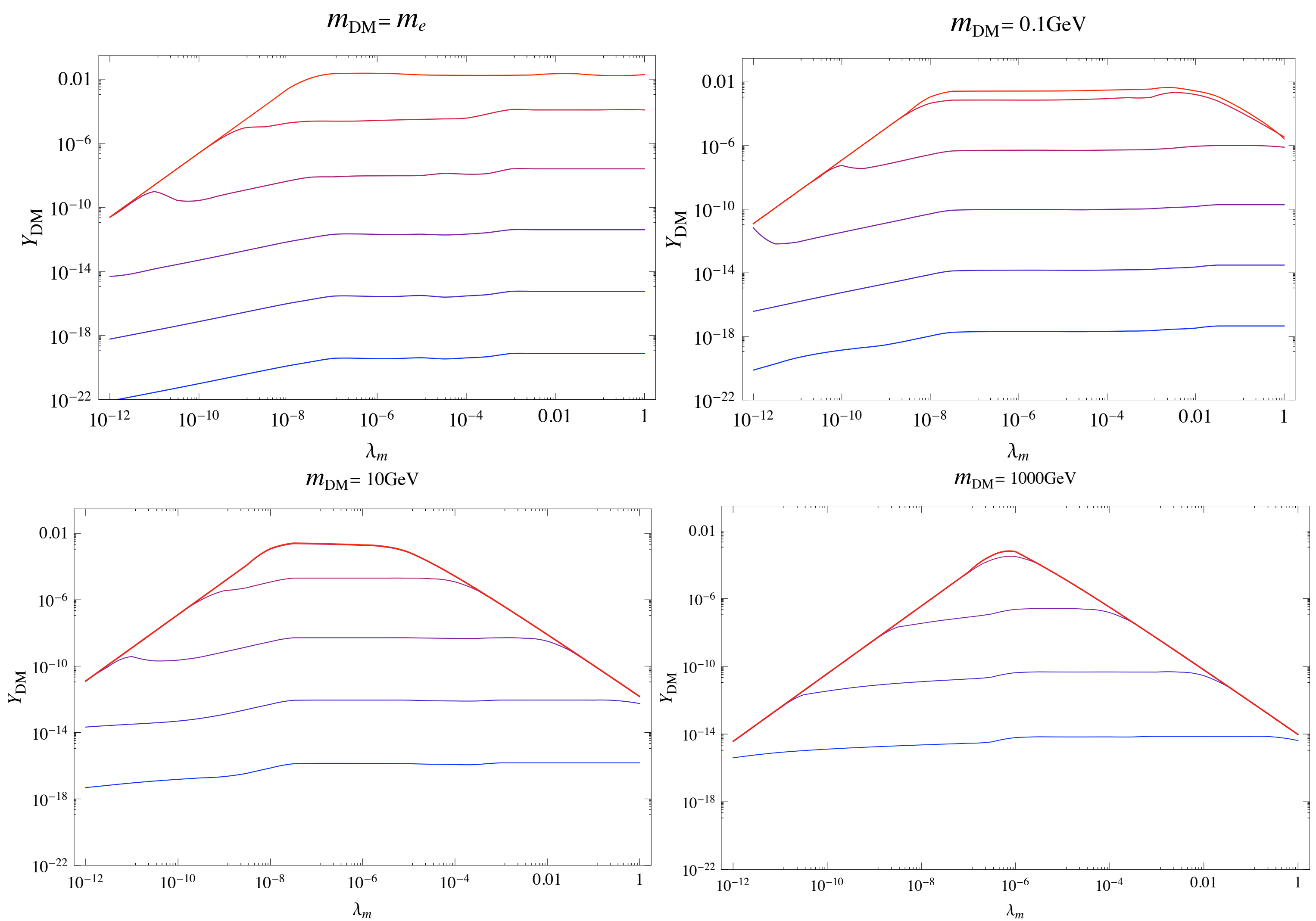


Figure 14: DM relic abundance Y_{DM} as a function of the connector parameter λ_m for different DM masses m_{DM} and values of the hidden sector interaction, $\log_{10}(\alpha'/\alpha) = 1, -1, -3, -5, -7, -9$, bottom-up (the last two lines are the same for $m_{DM} = 10$ GeV, as well as for $m_{DM} = 1$ TeV).

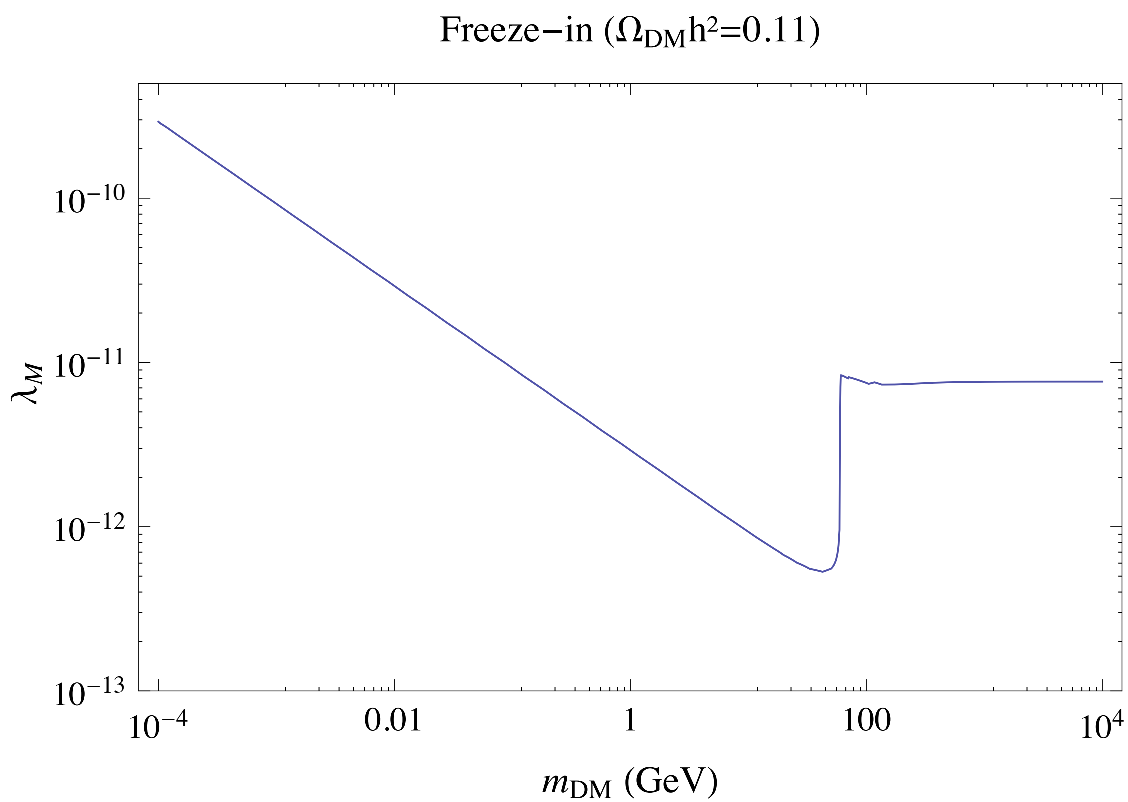
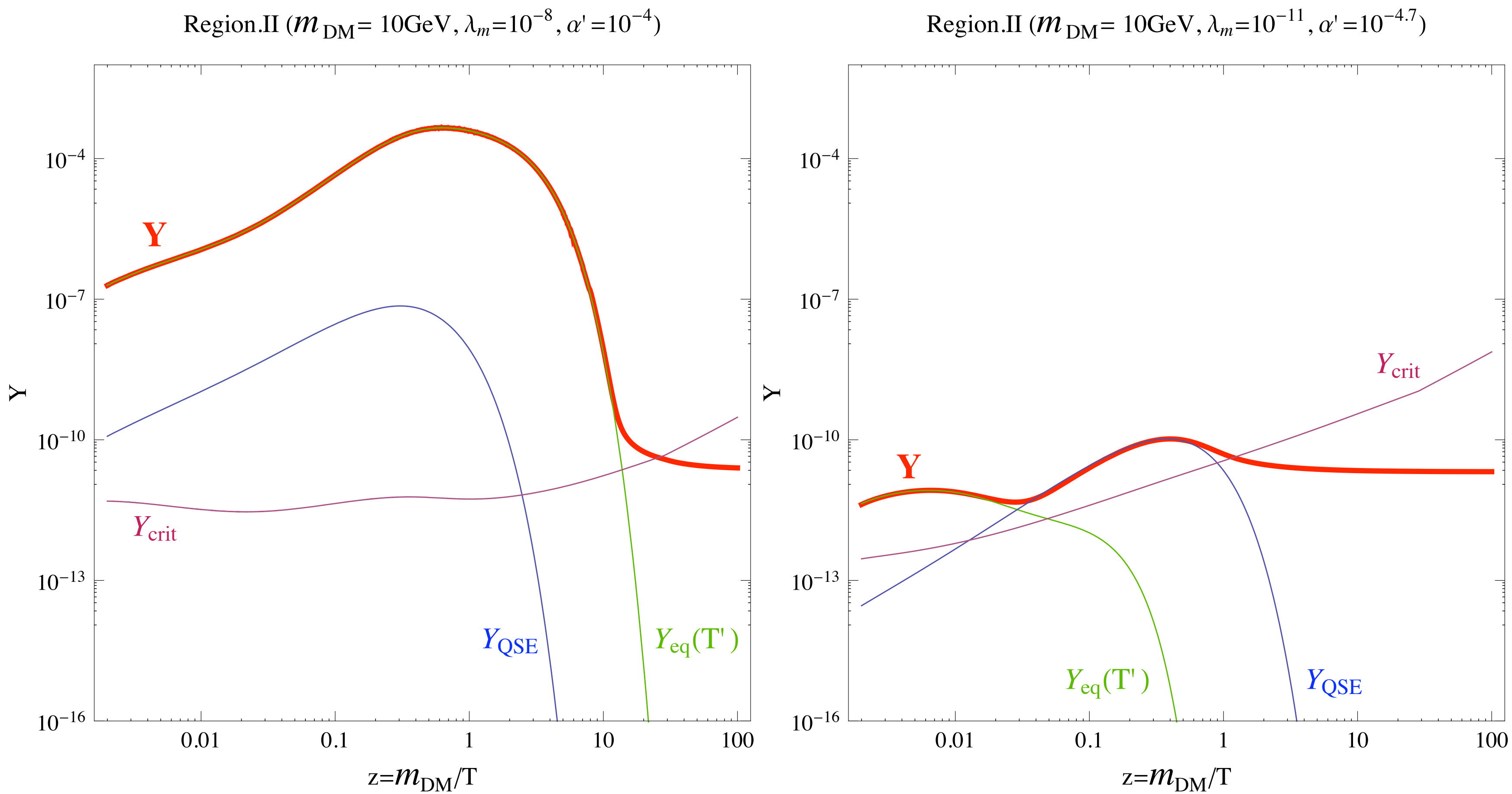


Figure 14: Higgs portal parameter required to get the observed DM relic density through freeze-in ($\alpha' = 0$).


Region.II ($m_{\rm DM}$= 10GeV, λ_m=10^{-8}, α' =10^{-4})
Y
$Y_{\rm crit}$
$Y_{\rm QSE}$
$Y_{\rm eq}$(T')
z=$m_{\rm DM}$/T
Region.II ($m_{\rm DM}$= 10GeV, λ_m=10^{-11}, α' =$10^{-4.7}$)
Y
$Y_{\rm crit}$
$Y_{\rm eq}$(T')
$Y_{\rm QSE}$
z=$m_{\rm DM}$/T

The freeze-in mechanism

DM couples only feebly to the SM particles
production through out-of-equilibrium $AA \to DMDM$
or $A \to DMB$ processes

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March-Russell, West 09'

example: $A \to DMB$

at $T > m_A$: $\frac{dn_{DM}}{dt} = n_A^{eq}(T)\Gamma_{A\to DMB}(T)$

$\Downarrow$

in a comoving volume

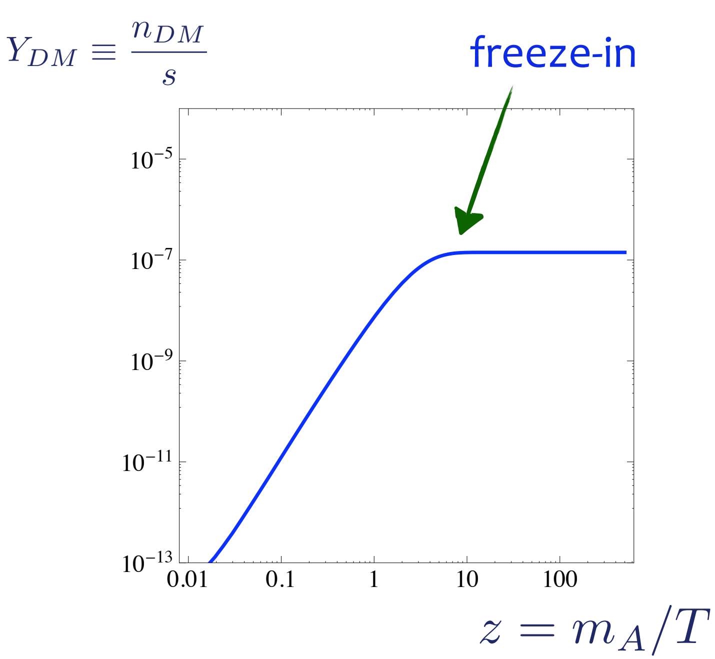
$$\frac{dY_{DM}}{dT} = \frac{n_A^{eq}(T)\Gamma_{A\to DMB}(T)}{TH(T)s(T)} \propto 1/T^2 \quad Y_{DM} \equiv \frac{n_{DM}}{s}$$

$\Downarrow$

$Y_{DM} \propto 1/T$ down to $T \sim m_A$

where n_A^{eq} becomes Boltzmann suppressed

DM production IR dominated

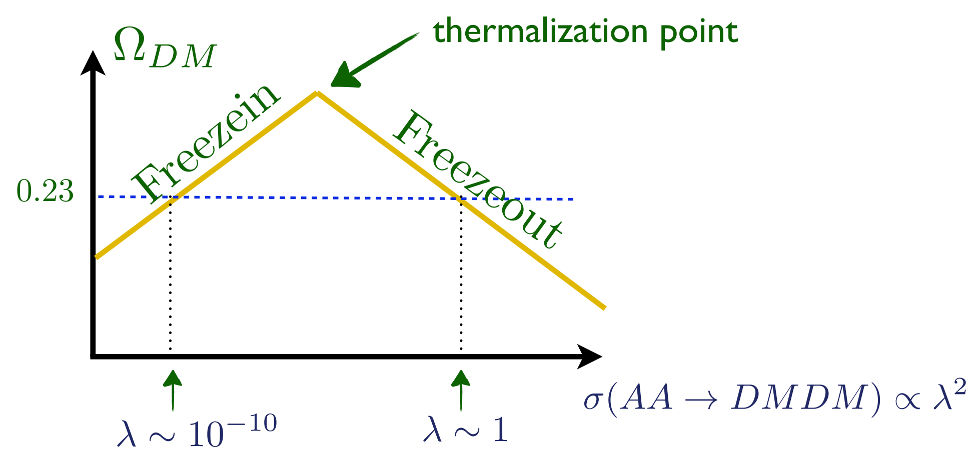


The freeze-in mechanism

$\Longrightarrow$ $$Y_{DM}(T << m_A) \simeq \frac{n_A^{eq}\Gamma_{A\to DMB}}{s}\frac{1}{H}\Big|_{T=m_A}$$

- freeze-in is “thermal” in the sense that DM is produced by a A particle in thermal equilibrium
- Y_{DM} produced depends only on mass and interactions of particles at freezing
- $\Omega_{DM} \sim 23\%$ requires tiny coupling $\sim 10^{-10}$

$\Longrightarrow$ for a $AA \to DMDM$ scattering production process:



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Freeze-in issues

- what about a primordial DM density?

↪ not washed-out by (out-of-equil.) DM production process

negligible if reheating occurs mostly in one of the feebly coupled sectors

↪ can be tested if the DM mass and coupling measured are the ones which give the right relic density

- what about testing the freeze-in mechanism? ← $\lambda \sim 10^{-10}$!!

↪ one possibility: $A \to DMB$ decay very slow ⇒ displaced vertex at colliders

⇓

requires:

Cheung, Elor, Hall, Kumar 10'

- A and B couple sizably to the SM

- sym. which stabilizes the DM particle also shared by visible sector

↪ $e.g.\ A$ and DM odd under a Z_2

⇒ rich phenomenology at LHC

κ and α' are small $\Longrightarrow$ freeze-in regime

we consider a HS negligible at high temperature $\to$ $Y_{DM} \sim 0$, $\rho' \sim 0$

HS energy density

if κ and α' small: $SMSM \leftrightarrow DMDM$ does not thermalize

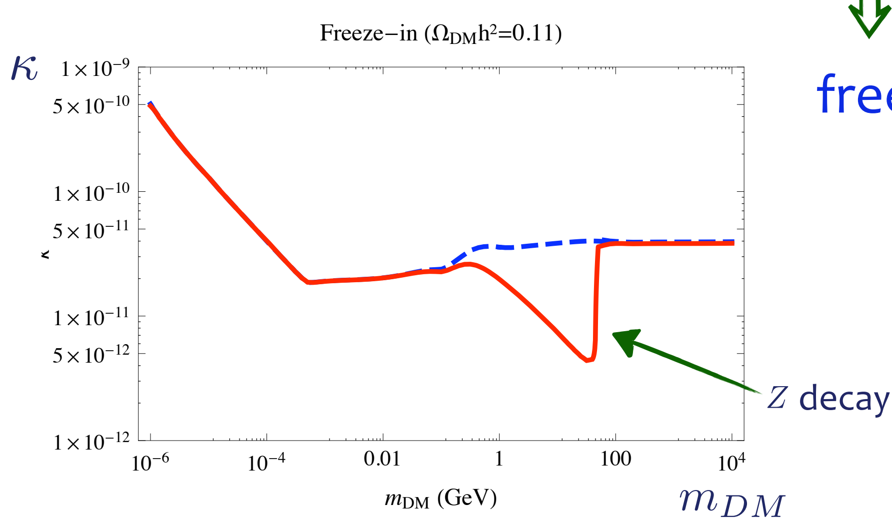
$DMDM \leftrightarrow \gamma'\gamma'$ does not thermalize

only $SMSM \to DMDM$ is relevant because only Y_{SM}^{eq} is large

$\Downarrow$

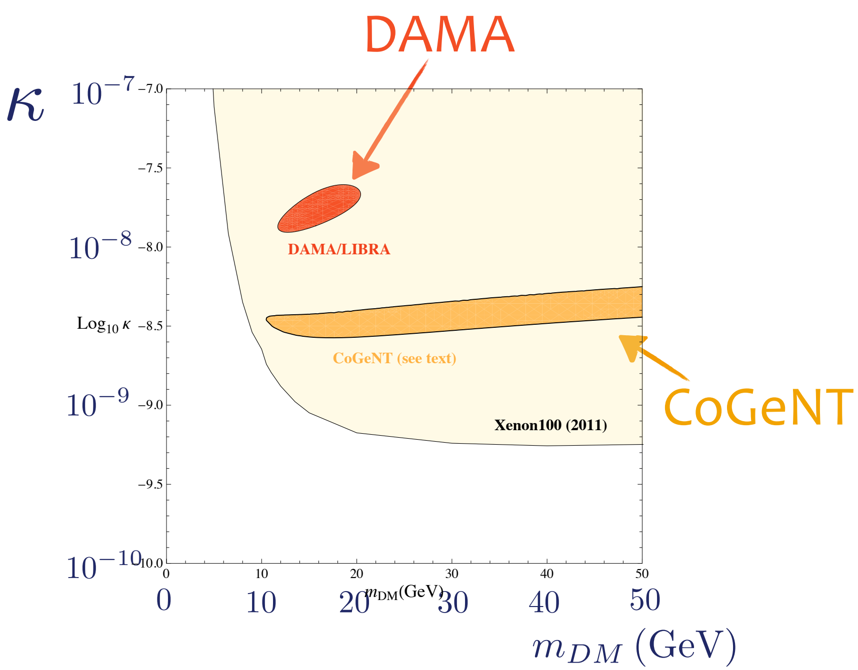
freeze-in: $$Y \sim \frac{\langle \sigma_{connect} v \rangle n_{SM}^2}{sH}\Big|_{T=m_{DM}} \propto \kappa^2$$

$$\kappa \sim 3 \cdot 10^{-11}$$



dominated by $m_{SM_i} < m_{DM}$ channels

Test of mesa phase diagrams for kinetic mixing: direct detection

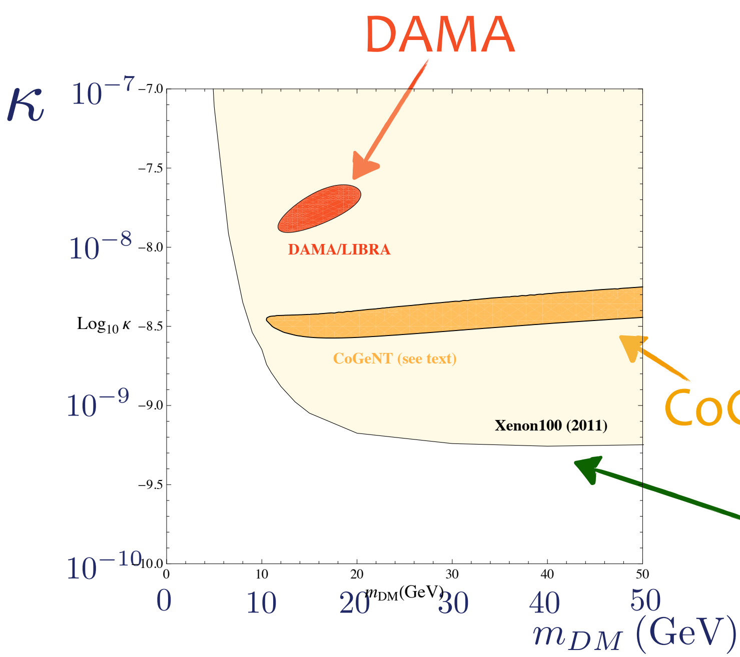


DAMA-CoGeNT: small threshold

Xenon: higher threshold

$\sim \frac{1}{E_r^2}$ gives much better agreement

Test of mesa phase diagrams for kinetic mixing: direct detection



DAMA-CoGeNT: small threshold

Xenon: higher threshold

$\sim \dfrac{1}{E_r^2}$ gives much better agreement

$\Downarrow$

but not compatible anymore

Xenon-100kg