

The four basic ways of creating dark matter through a portal

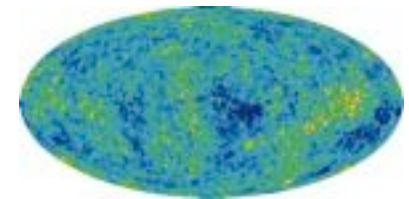
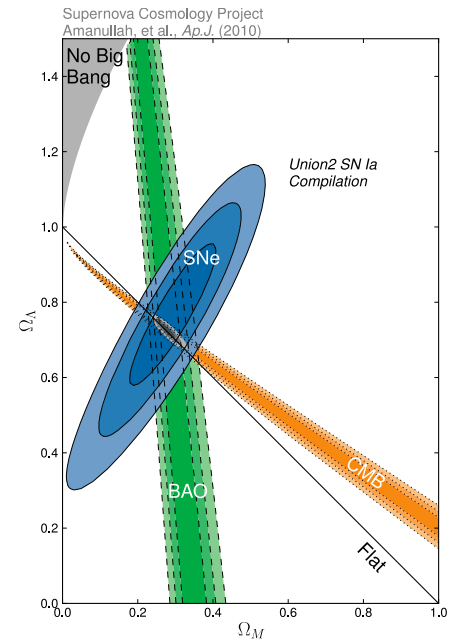
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Gravitational evidences of dark matter

- At galactic scale: velocity distribution of stars
- At galaxy cluster scale: -velocity distribution of galaxies
-bullet cluster
- At cosmological scales: CMB data (WMAP),
supernovae,....

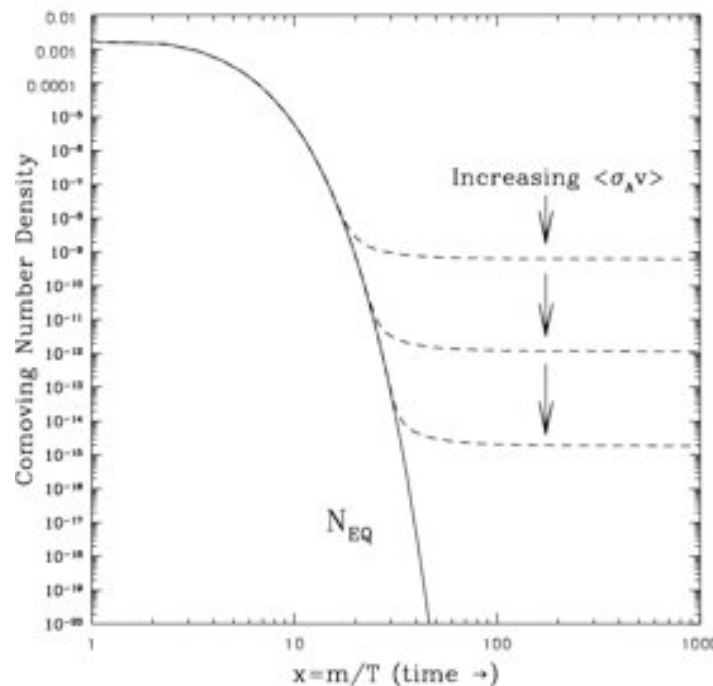
lead consistently to: $\Omega_{DM} \simeq 0.229 \pm 0.015\%$



- DM is neutral, stable ($\tau_{DM} > 10^{26}$ 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:



with SM from $DMDM \leftrightarrow SMSM$

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

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

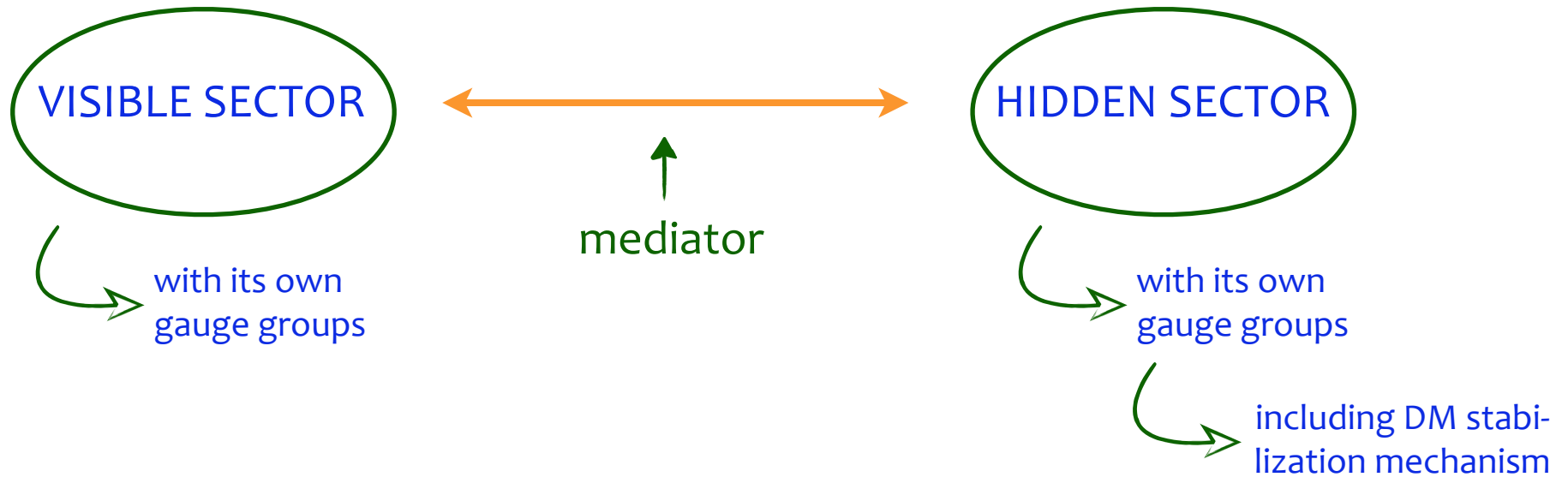
freeze-out of annihilation

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

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

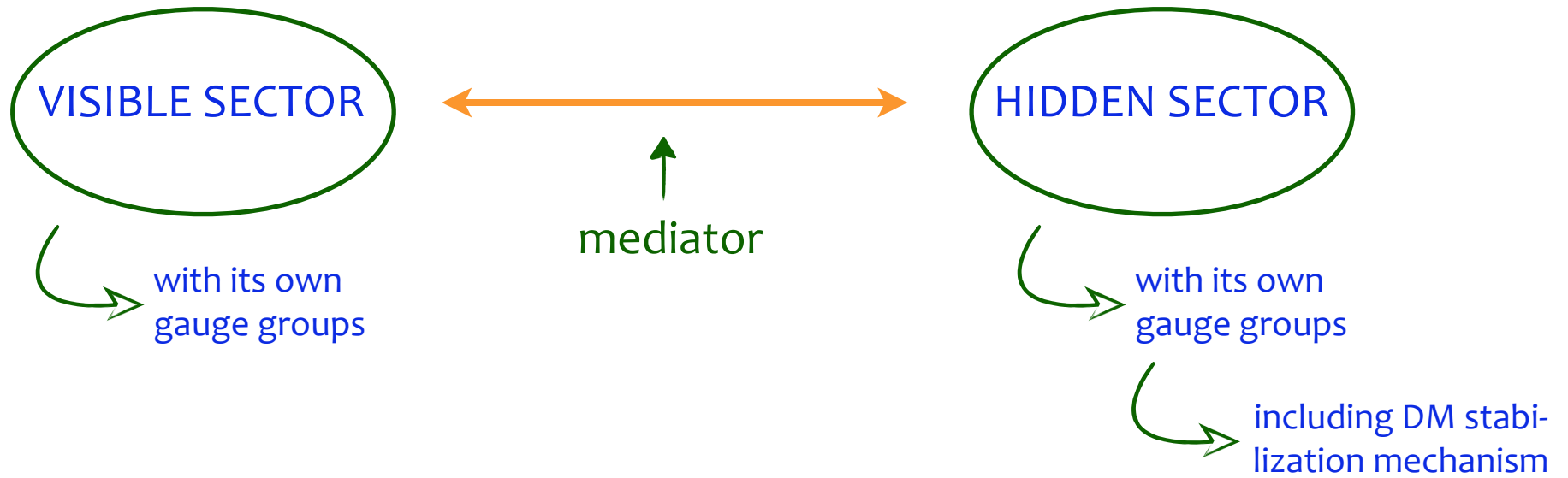
\Rightarrow most straightforward/natural mechanism but not at all the only possible/simple one

A general visible sector/hidden sector/ mediator DM setup

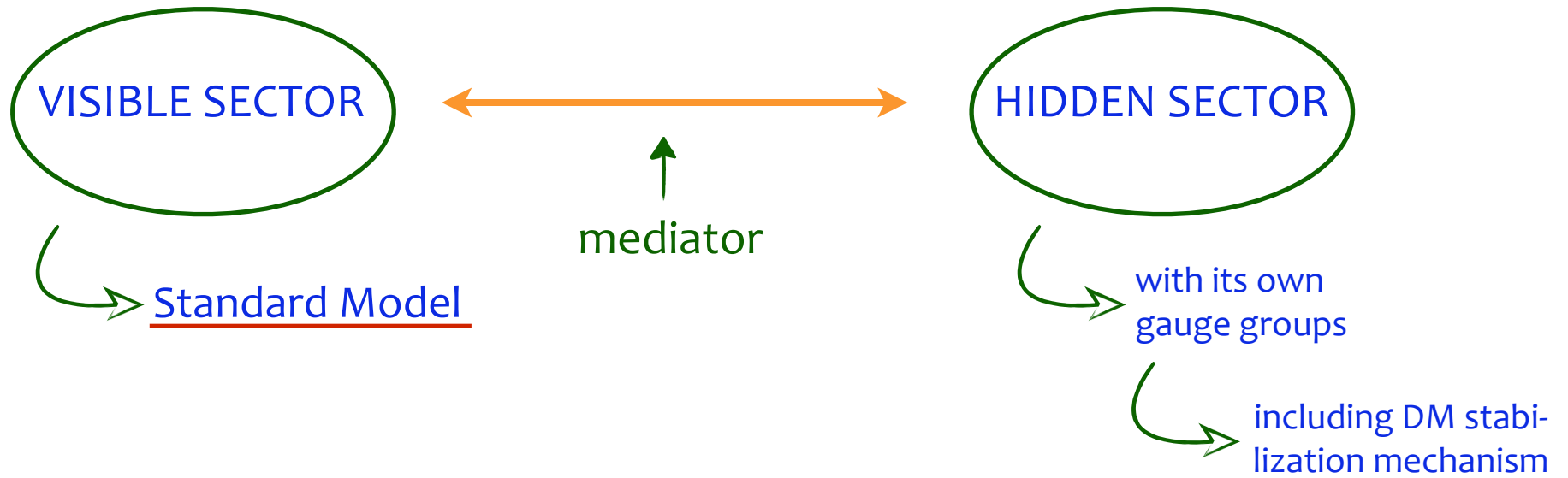


such a structure gives 4 regimes to get the observed relic density

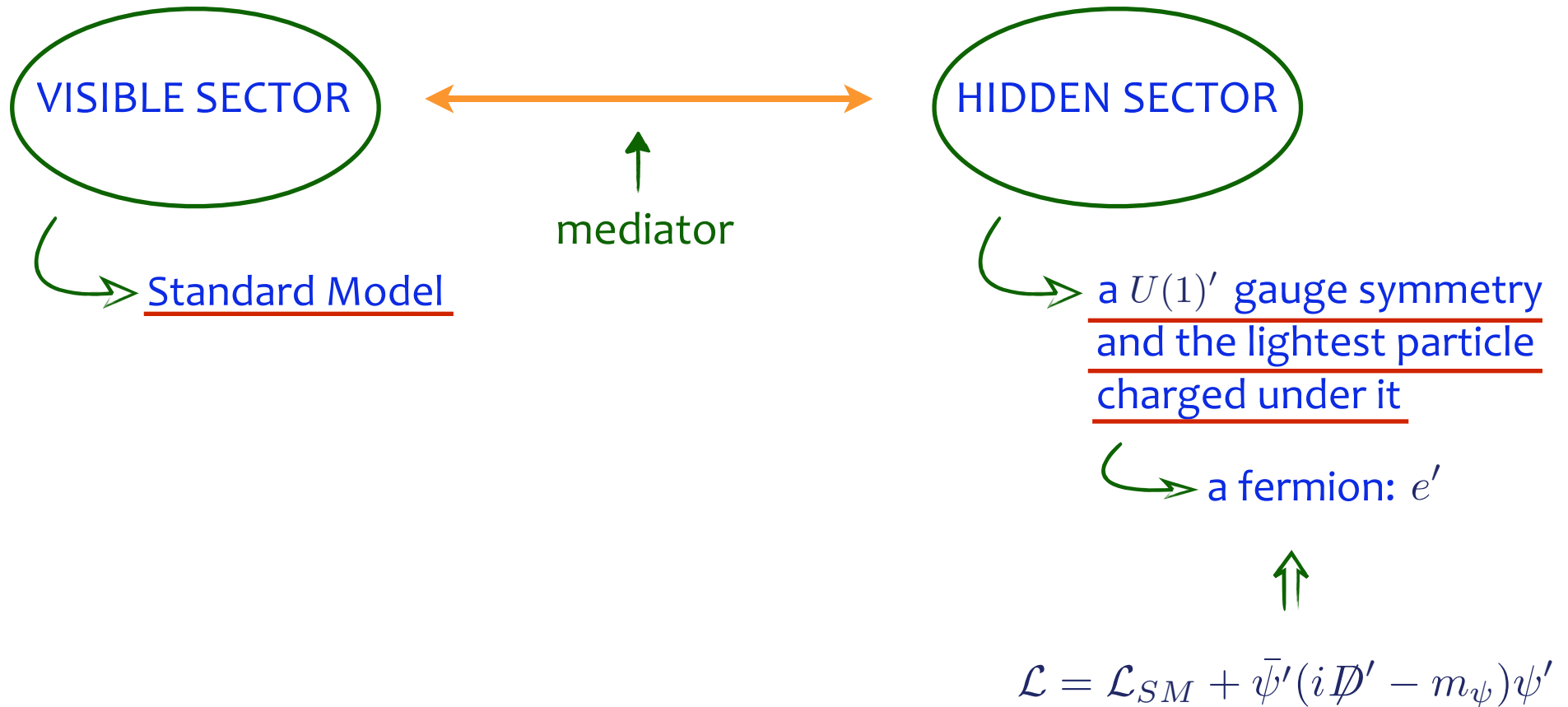
A very simple light mediator model



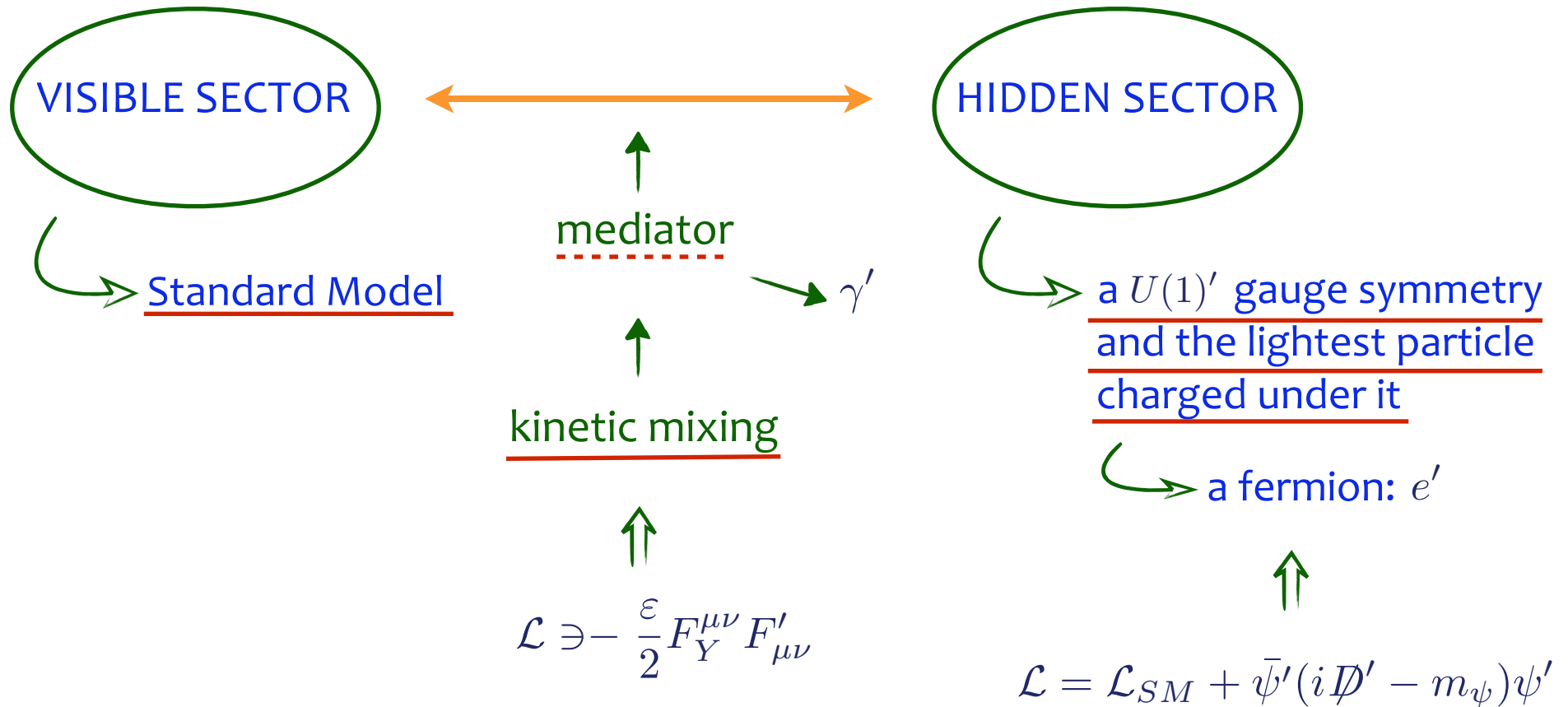
A very simple light mediator model



A very simple light mediator model



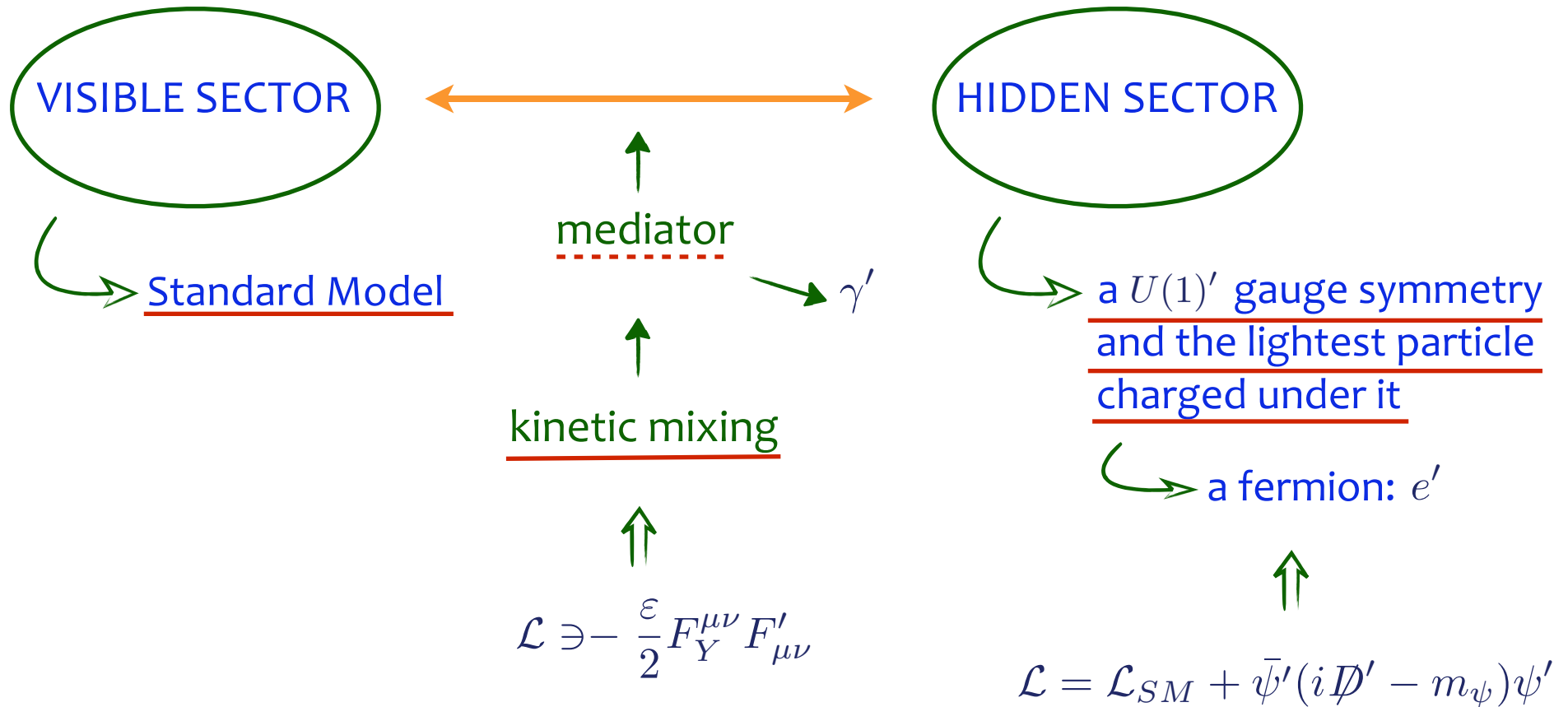
A very simple light mediator model



Feldman, Kors, Nath 06'
 Pospelov, Ritz, Voloshin 08'

↪ for a massive Z'

A very simple light mediator model



Feldman, Kors, Nath 06'
 Pospelov, Ritz, Voloshin 08'

↪ for a massive Z'

⇒ a good DM candidate based on 3 parameters: $m_{DM}, \alpha', \epsilon$
 ↪ = $m_{e'}$

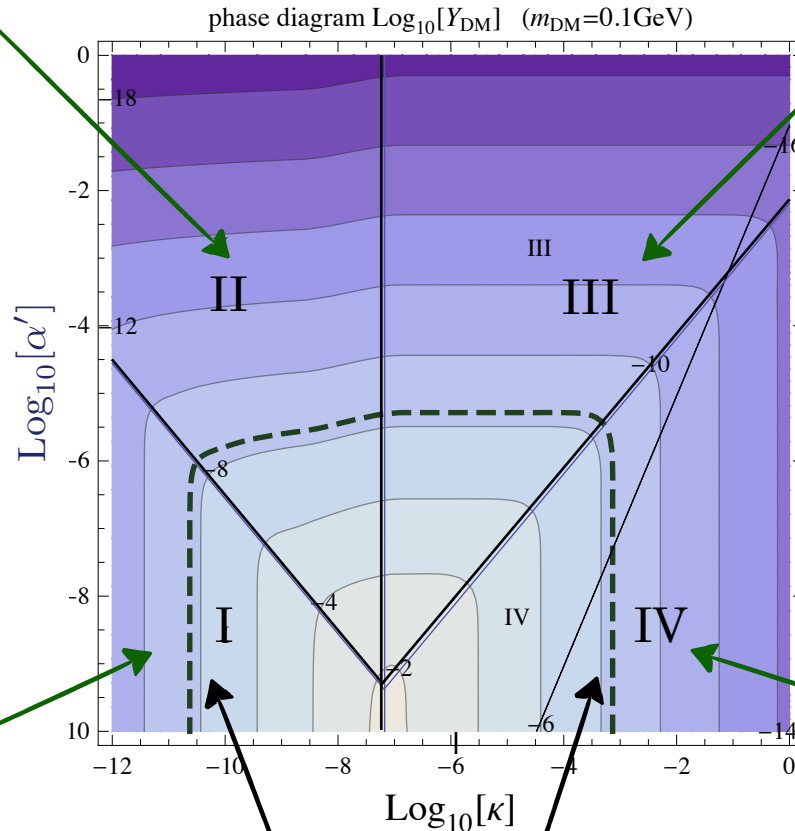
Motivations for such a Hidden sector gauge structure

- UV.....
- simplicity
- the stability of the DM particle is a fundamental issue! $\leftarrow \tau_{DM} > 10^{26} \text{ sec}$
 - \hookrightarrow not that many stabilization mechanisms
 - \hookrightarrow one of the simplest: the lightest charged particle under a new gauge group
- visible sector = Standard Model \Rightarrow mass and interactions of source particles are known
- new DM long range force from γ' \Rightarrow rich cosmological phenomenology
 - \hookrightarrow studied in details in: Ackerman, Buckley, Carroll, Kamionkowski 08', Feng Kaplinghat, Tu, Yu 09', Feng, Tu, Yu 08 see also Foot et al. 06'-10'
- prototype of visible sector/hidden sector/mediator structure
 - \hookrightarrow with such a structure: not only freeze-out but 4 DM production regimes

Relic density phase diagram

Reannihilation regime

Hidden sector freeze-out regime



Freeze-in regime

Connector freeze-out regime

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

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

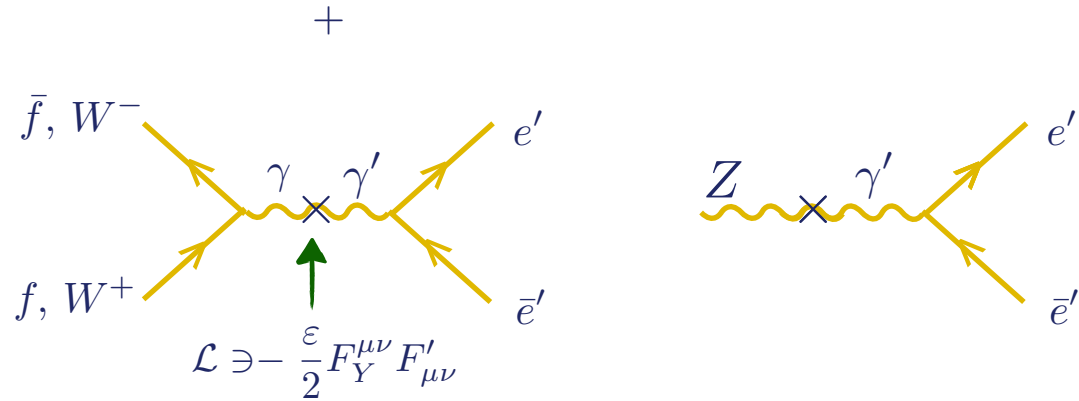
Observed relic density: "square" or "mesa" shape

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

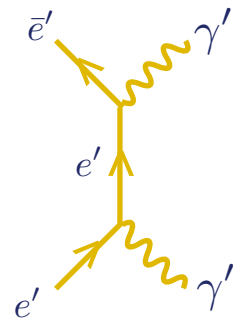
characteristic of the visible sector/hidden sector/mediator structure

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 e'
 γ couples to e' and f

Holdom 86'

⇒ $\sigma(SMSM \rightarrow e'\bar{e}') \propto \alpha^2 \kappa^2$ ← $\kappa \equiv \epsilon \sqrt{\alpha'/\alpha}$
 $\sigma(e'\bar{e}' \rightarrow \gamma'\gamma') \propto \alpha'^2$

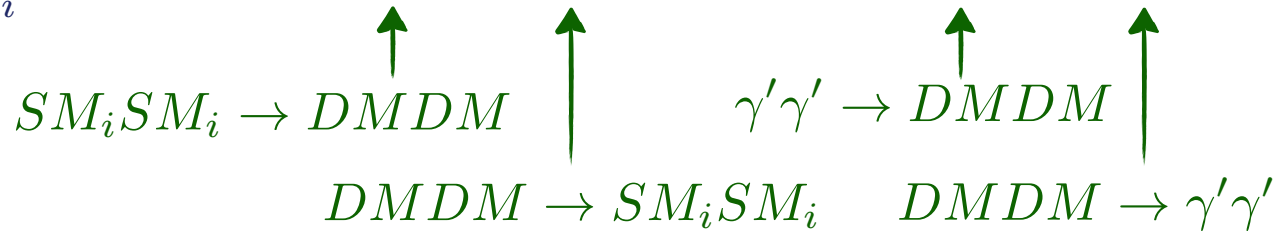
Boltzmann equation

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

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

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

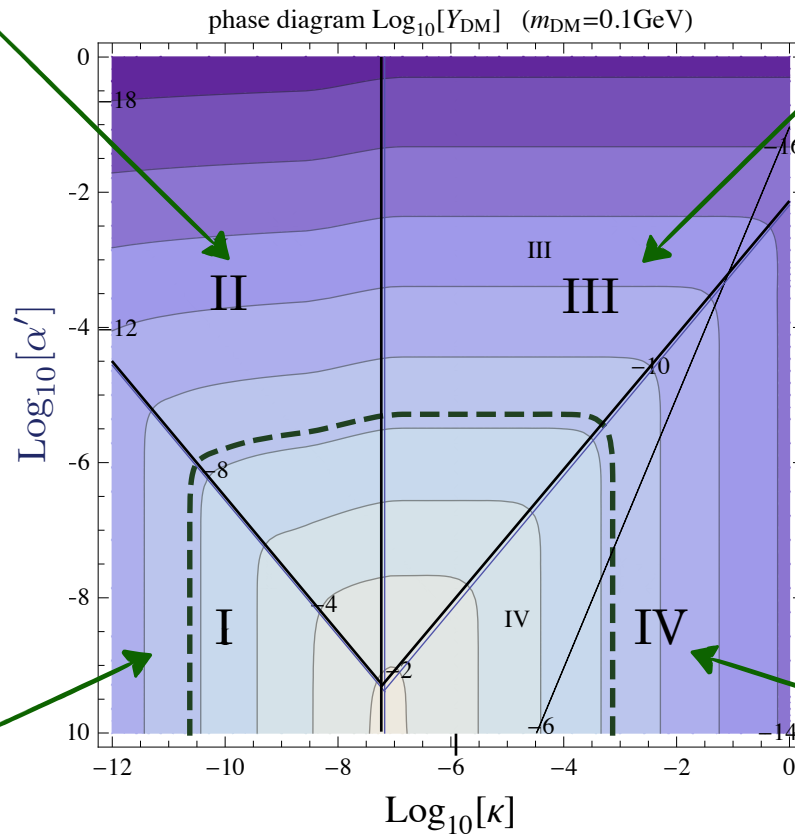
$$z \frac{H}{s} \frac{dY}{dz} = \sum_i \langle \sigma_{connect} v \rangle_i (Y_{eq}^2(T) - Y^2) + \langle \sigma_{HS} v \rangle (Y_{eq}^2(T') - Y^2)$$



Relic density phase diagram

Reannihilation regime

Hidden sector freeze-out regime



Freeze-in regime

Connector freeze-out regime

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

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

- we consider a HS negligible at high temperature $\begin{cases} Y_{DM} \sim 0 \\ \rho' \sim 0 \end{cases}$
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 \Rightarrow freeze-in regime

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

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

$\begin{matrix} \uparrow & & \uparrow & & \uparrow & & \uparrow \\ SM_i SM_i \rightarrow DMDM & & & & \gamma' \gamma' \rightarrow DMDM & & \\ \uparrow & & \uparrow & & \uparrow & & \\ DMDM \rightarrow SM_i SM_i & & & & DMDM \rightarrow \gamma' \gamma' & & \end{matrix}$

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

\Rightarrow freeze-in regime:

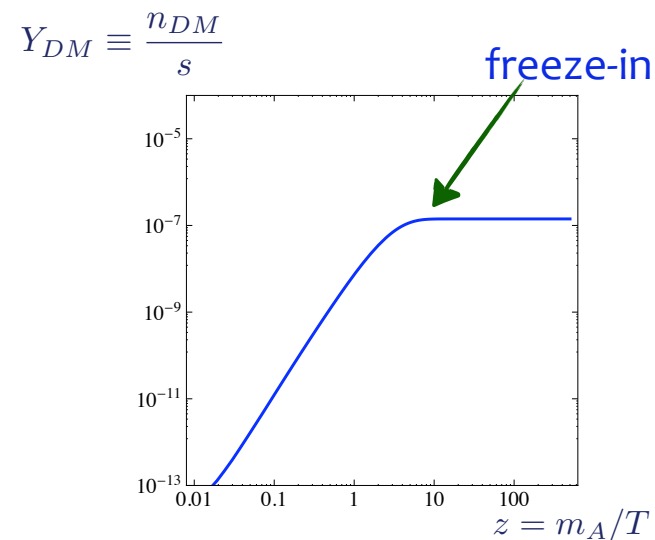
$$\frac{dn_{DM}}{dt} = n_{SM_i}^2(T) \langle \sigma_{SM_i SM_i \rightarrow DMDM} v \rangle$$

$$\frac{dY_{DM}}{dT} = \frac{n_{SM_i}^2(T) \langle \sigma_{SM_i SM_i \rightarrow DMDM} v \rangle}{TH(T)s(T)} \propto 1/T^2 \quad \leftarrow Y_{DM} \equiv \frac{n_{DM}}{s}$$

\Downarrow
 $Y_{DM} \propto 1/T$ down to $T \sim m_{DM}$ \leftarrow where $n_{SM_i}^{eq}$ becomes Boltzmann suppressed
 \uparrow
 $T > m_{DM}$

\hookrightarrow DM production IR dominated

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



κ and α' are small \Rightarrow freeze-in regime

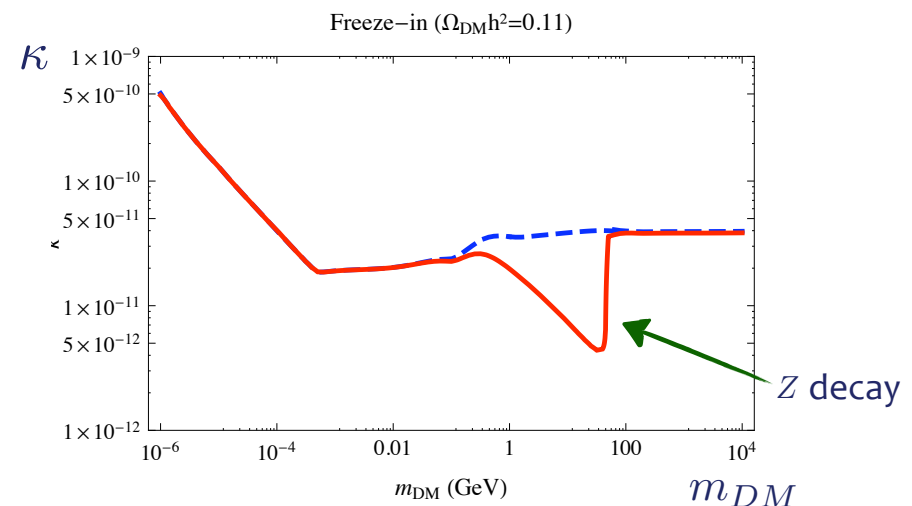
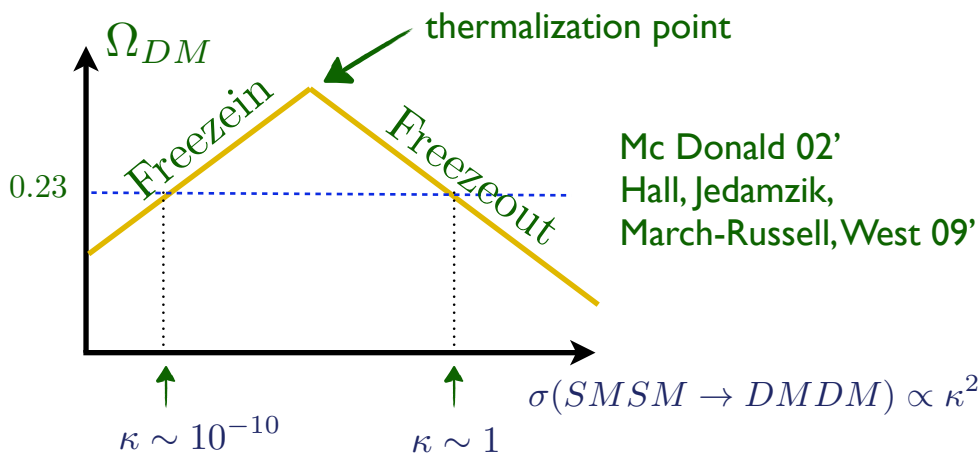
$$\Rightarrow Y \sim \frac{\langle \sigma_{connect} v \rangle n_{SM}^2}{sH} \Big|_{T=m_{DM}} \propto \kappa^2$$

\hookrightarrow freeze-in is “thermal” in the sense that DM is produced by a source particle in thermal equilibrium

$\hookrightarrow Y_{DM}$ produced depends only on mass and interactions of particles at freezing

$\hookrightarrow \Omega_{DM} \sim 23\%$ requires tiny coupling $\sim 10^{-10}$

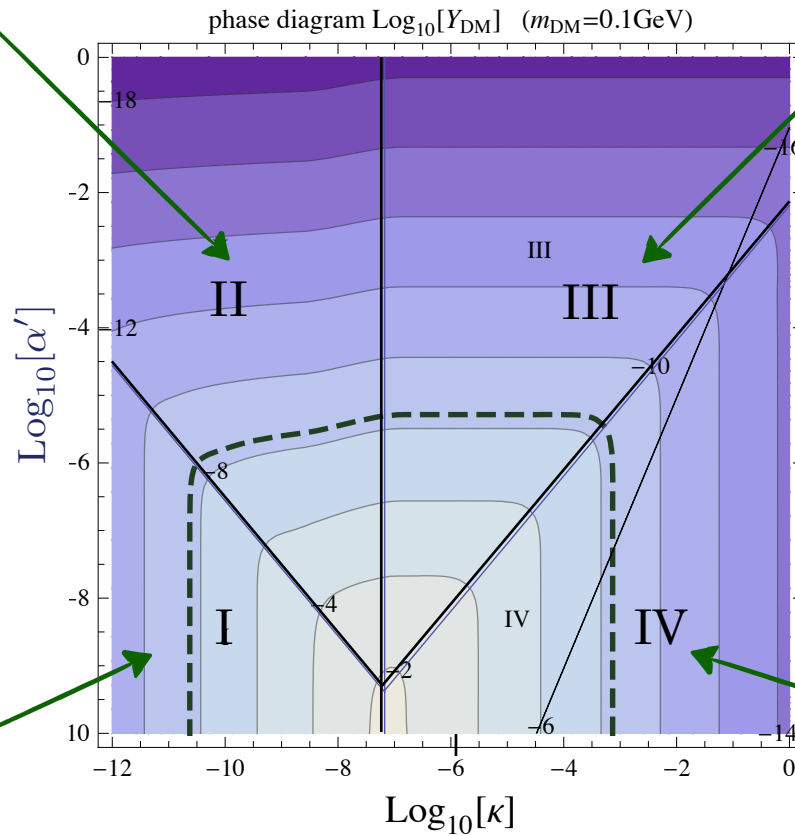
\Rightarrow for a $SMSM \rightarrow DMDM$ scattering production process:



Relic density phase diagram

Reannihilation regime

Hidden sector freeze-out regime



Freeze-in regime

Connector freeze-out regime

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

Reannihilation regime

 if one increases $\kappa \Rightarrow$ more DM created
 if one increases $\alpha' \Rightarrow \langle \sigma_{HSv} \rangle$ increases

} both favor thermalization of $\langle \sigma_{HSv} \rangle$



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

$$\Gamma_{annih} > H$$

$$\Gamma_{annih} = \underline{\underline{n_{e'}}} \langle \sigma_{HSv} \rangle$$



$$n_{eq}(T) \langle \underline{\underline{\sigma_{effv}}} \rangle > H$$

$$n_{eq}^2(T) \langle \sigma_{connectv} \rangle / H$$

$$\langle \sigma_{effv} \rangle \equiv \sqrt{\langle \sigma_{HSv} \rangle \langle \sigma_{connectv} \rangle}$$

 we can define a HS temperature T'

$$n_{\gamma'} = n_{eq}(T') \sim g_{\gamma'} T'^3$$

$$\rho' \sim g_*^{HS} T'^4$$



necessary to know the number of γ' , i.e. the $\underline{\underline{\gamma' \gamma' \rightarrow DM DM}}$ rate

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

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

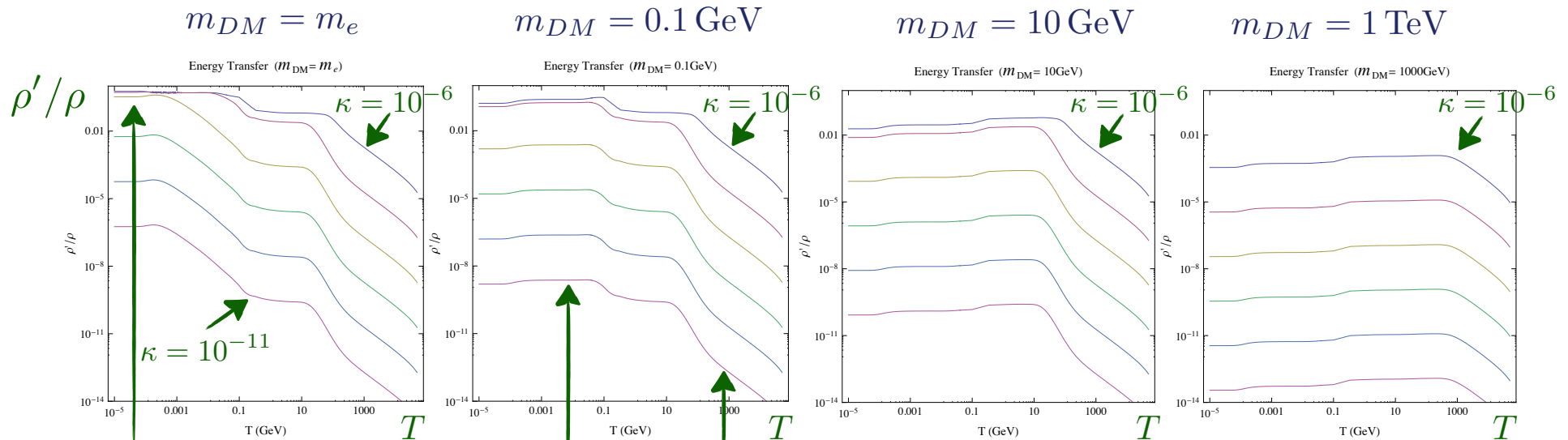
Calculation of the energy transfer from the SM to the HS

energy transfer Boltzmann equation

$$\frac{d\rho'}{dt} + 3H(\rho' + p') = \int \prod_{i=1}^4 d^3\vec{p}_i \cdot g_i f_1(\vec{p}_1) f_2(\vec{p}_2) |i\mathcal{M}_{12\leftrightarrow 34}|^2 (2\pi)^4 \delta^{(4)}(p_1 + p_2 - p_3 - p_4) \Delta E_{tr}$$

$$\frac{d(\rho'/\rho)}{dT} = -\frac{1}{H(T)T\rho} \frac{g_1 g_2}{32\pi^4} \int ds \cdot \sigma_{connect}(s) (s - 4m^2) s T K_2\left(\frac{\sqrt{s}}{T}\right)$$

$SM_i SM_i \rightarrow DMDM$



ρ'/ρ saturates when T' reaches T
 $\rho'/\rho \sim 1/T$ for $T > m_{DM}$
 $\rho'/\rho \sim \text{const}$ for $T < m_{DM}$

Reannihilation regime: Boltzmann equation

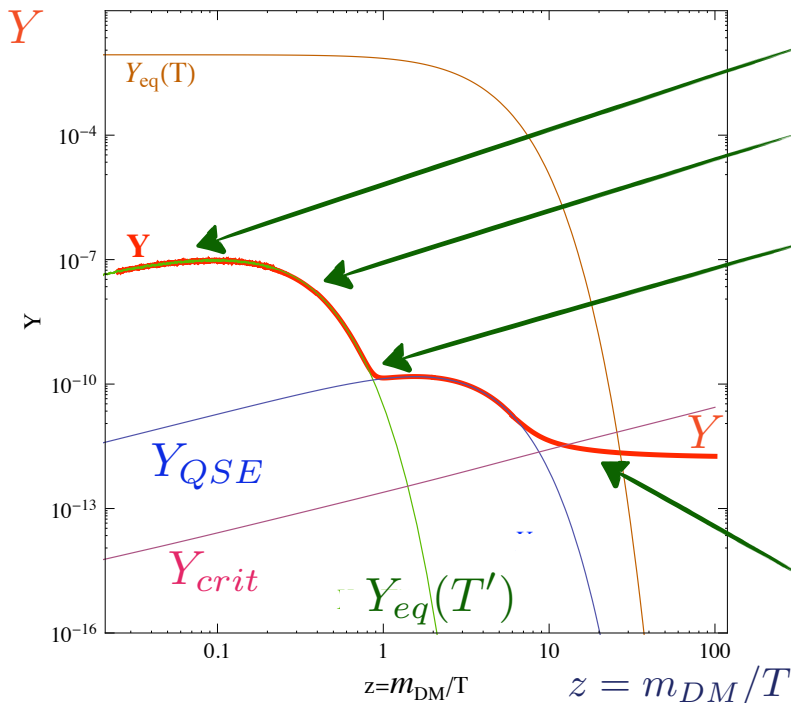
HS process in thermal equilibrium but not the connector: $T'/T \ll 1$

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

$SM_i SM_i \rightarrow DMDM$ $DMDM \rightarrow SM_i SM_i$ $\gamma' \gamma' \rightarrow DMDM$ $DMDM \rightarrow \gamma' \gamma'$

Cheung, Elor, Hall, Kumar 10'
 ↪ in $A \rightarrow DMB$ decay context

Region.II ($m_{DM} = 200\text{GeV}, \kappa = 10^{-8}, \alpha' = 10^{-2.4}$)



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

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

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

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





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

Reannihilation regime: Boltzmann equation

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

 in thermal equilibrium
  out of thermal equilibrium

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

 $SM_i SM_i \rightarrow DMDM$
 $DMDM \rightarrow SM_i SM_i$
 $\gamma'\gamma' \rightarrow DMDM$
 $DMDM \rightarrow \gamma'\gamma'$

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

 period of Quasi Static Equilibrium where both terms compensates each other

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

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

 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 :

$$n_{eq}(T_f) \langle \sigma_{eff} v \rangle = H(T_f) \quad \leftarrow \langle \sigma_{eff} v \rangle \equiv \sqrt{\langle \sigma_{connect} v \rangle \langle \sigma_{HS} v \rangle}$$

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

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

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

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

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

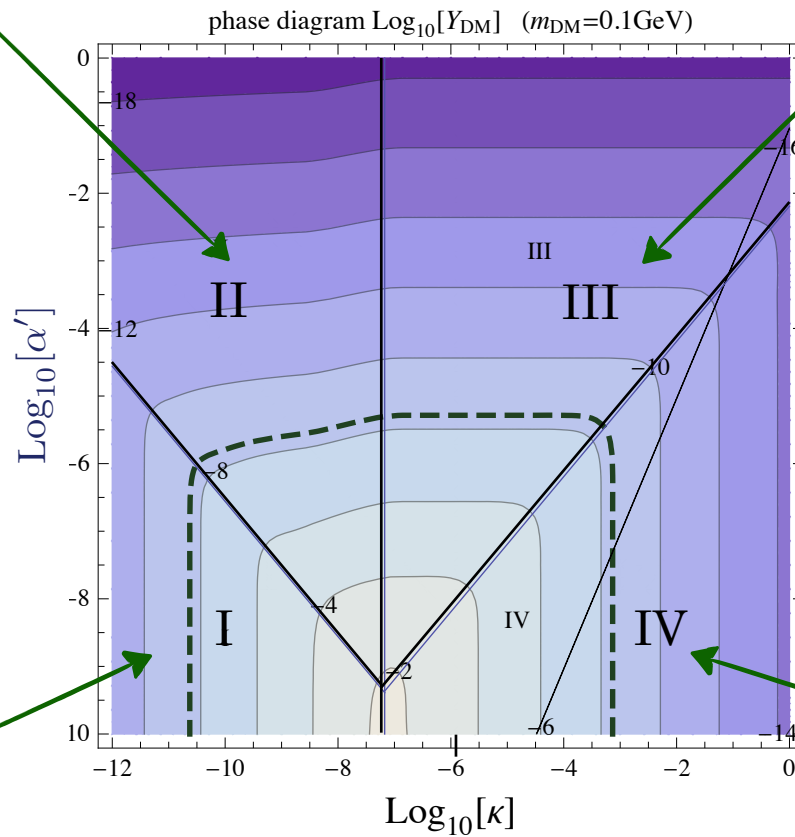
$$\hookrightarrow \propto \log(\alpha' \kappa) / \alpha'^2$$

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

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

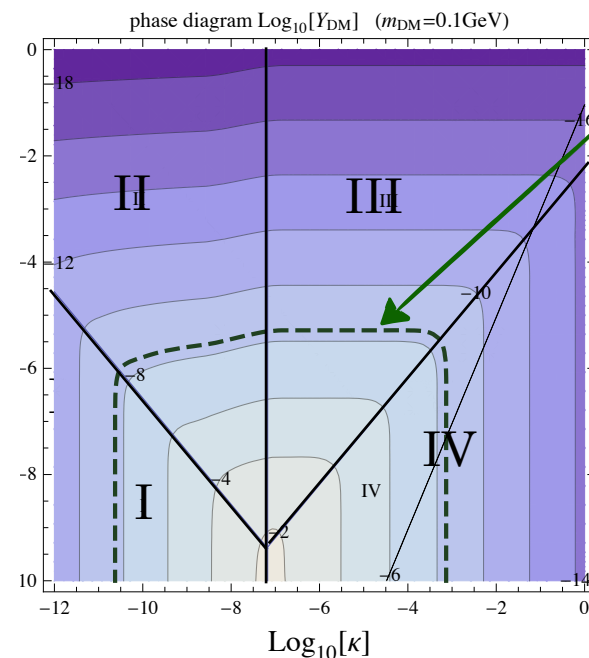
starting from a reannihilation situation
 if one increases κ further \Rightarrow the connector interaction thermalizes: $T' = T$

$SMSM \leftrightarrow DMDM$

one enters a regime where even if the connector thermalizes
 the HS interaction thermalizes much more $\langle \sigma_{HS\nu} \rangle > \langle \sigma_{connect\nu} \rangle$

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

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

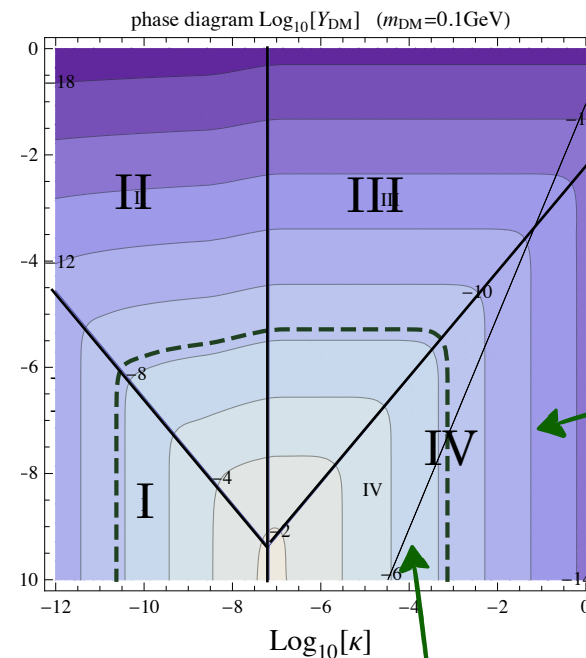


Hidden sector freeze-out regime

Connector freeze-out regime

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

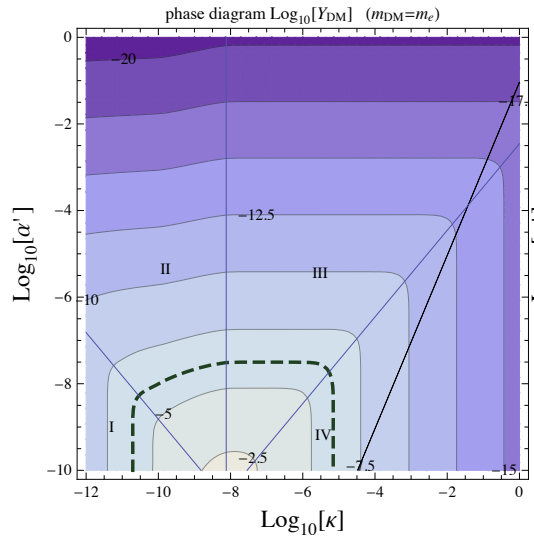
$$\Omega_{DM} \propto \frac{1}{\langle \sigma_{connect} v \rangle} \propto \frac{1}{\kappa^2}$$



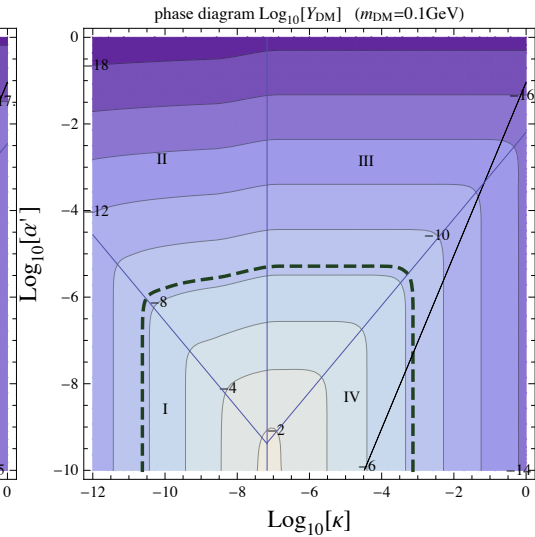
$\kappa \equiv \epsilon \sqrt{\alpha'/\alpha} \Rightarrow$ if κ big α' small $\Rightarrow \epsilon$ non perturbative

Relic density phase diagram

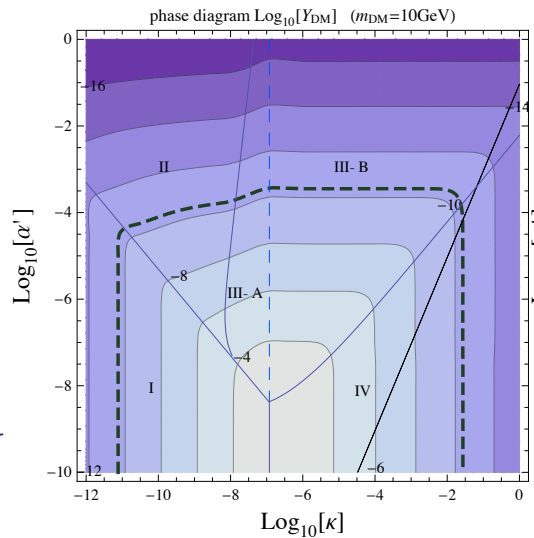
$$m_{DM} = m_e$$



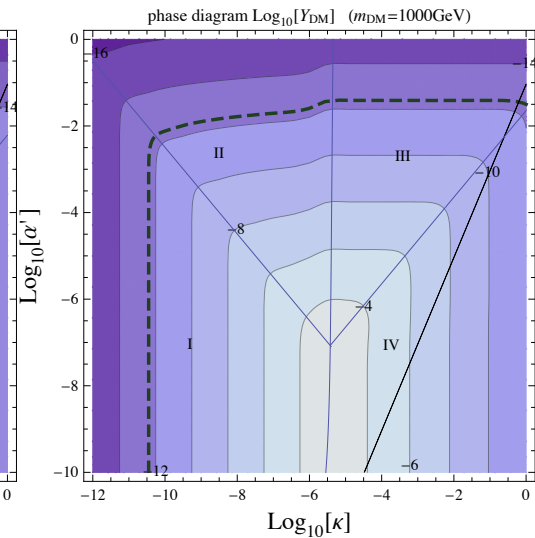
$$m_{DM} = 0.1 \text{ GeV}$$



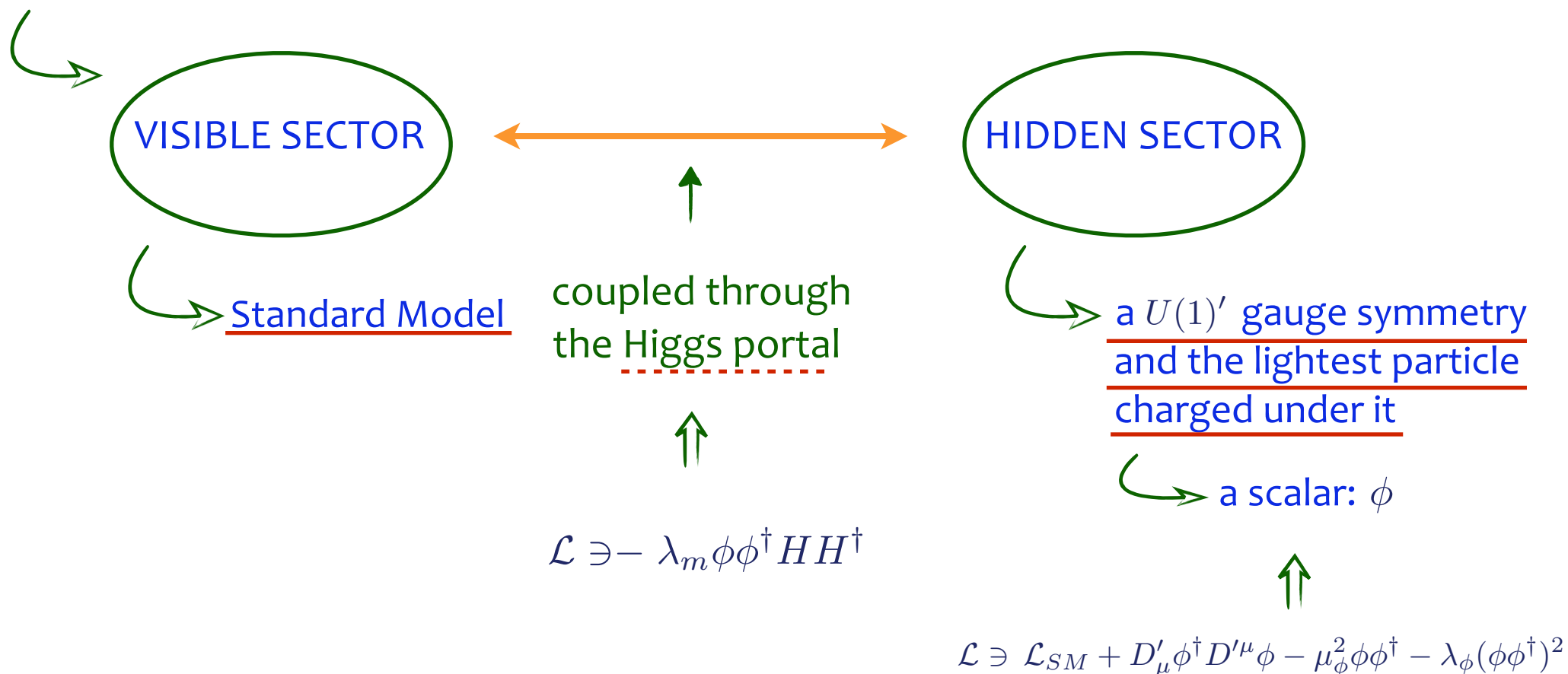
$$m_{DM} = 10 \text{ GeV}$$



$$m_{DM} = 1 \text{ TeV}$$

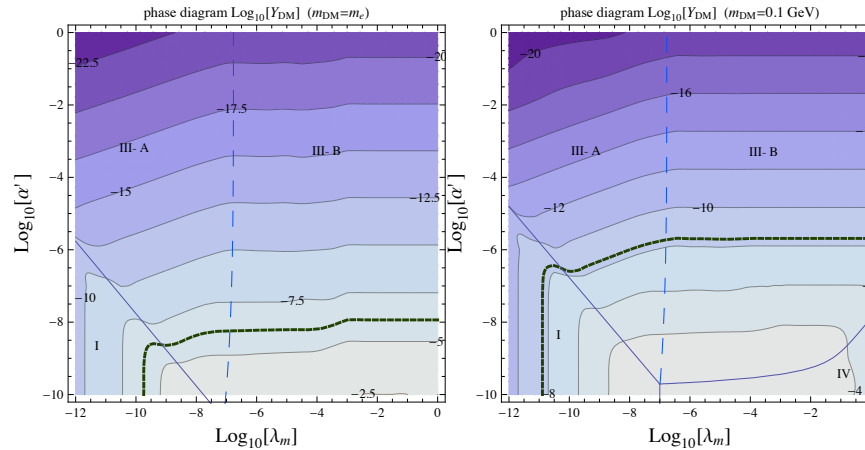


Generality of the “mesa” phase diagram: the Higgs portal example



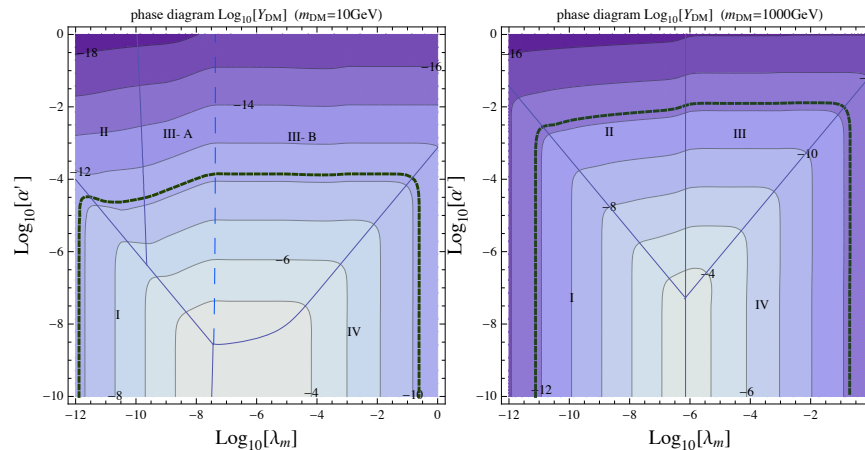
Generality of the “mesa” phase diagram: the Higgs portal example

$$m_{DM} = m_e$$



$$m_{DM} = 0.1 \text{ GeV}$$

$$m_{DM} = 10 \text{ GeV}$$



$$m_{DM} = 1 \text{ TeV}$$

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

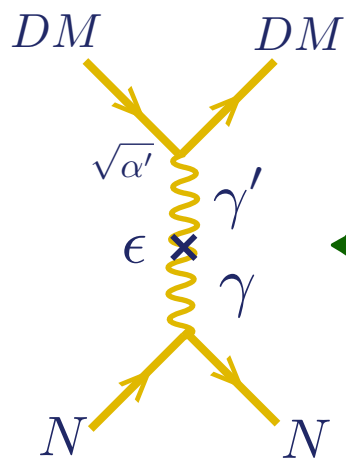
↪ production through $m_h \rightarrow \phi\phi^\dagger$ decay if $m_{DM} < m_h/2$ $m_h \simeq 120 \text{ GeV}$

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

⇒ 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



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

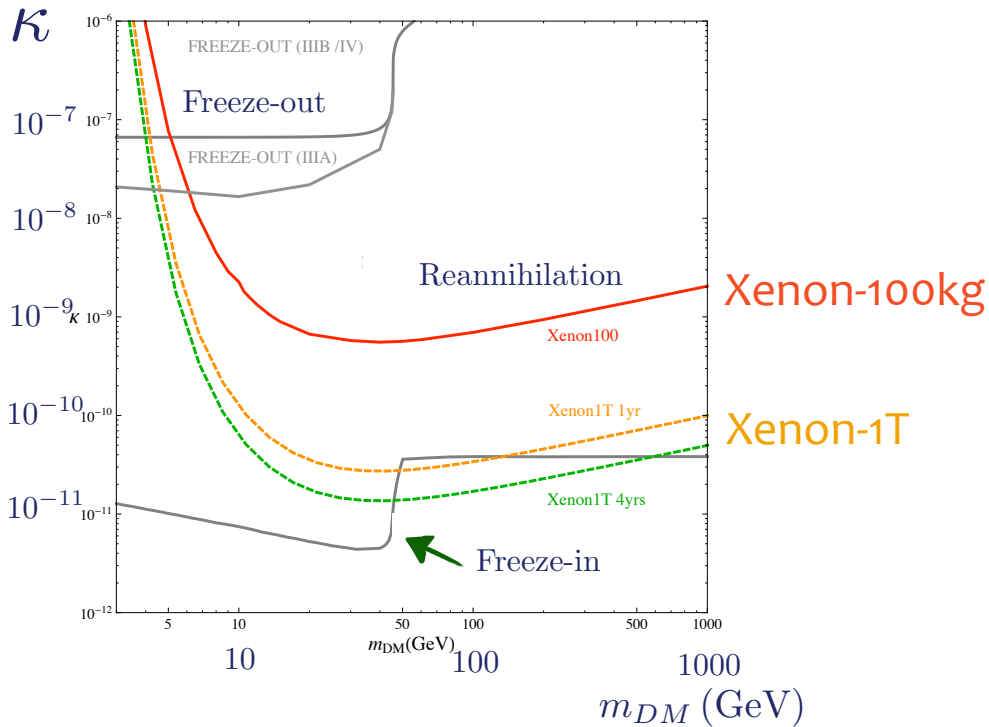
$$\frac{d\sigma}{dE_r} = \frac{1}{E_r^2} \frac{1}{v^2} \frac{2\pi\kappa^2 Z^2 \alpha^2}{m_A} F_A^2(qr_A)$$

$E_r \sim \text{few KeV}$

huge enhancement

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

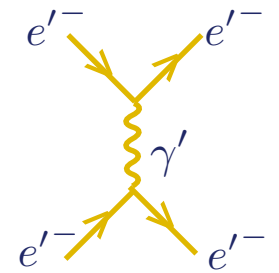
Cosmological constraints

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

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

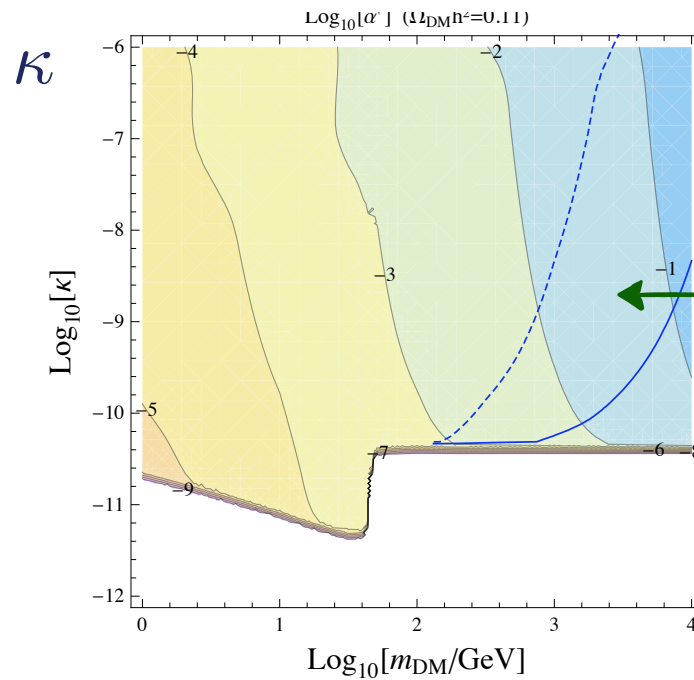
↪ DM Rutherford scattering may affect formation of DM halo

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



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

Ellipticity and relic density constraints combined



reannihilation allowed for:

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

freeze-in always allowed

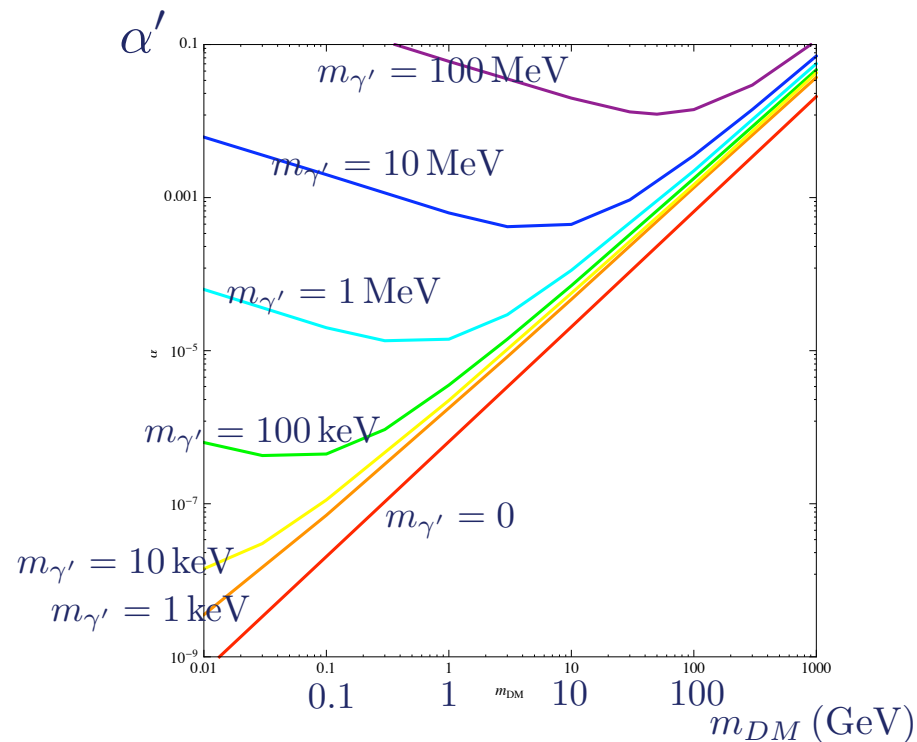
Ellipticity constraint for the case of a slightly massive γ'

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

the relic density plot doesn't change

the lightest charged fermion remains stable

but the cosmological constraints change a lot



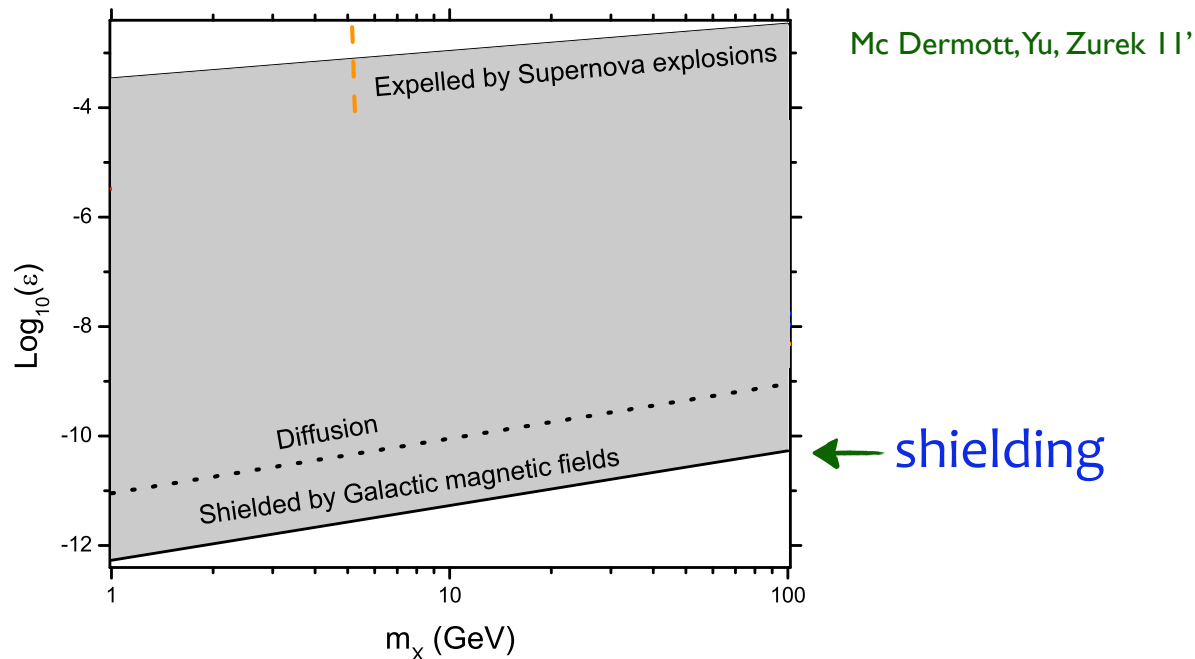
Depletion of DM in galactic disk

→ 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'



⇒ only freeze-in regime is allowed for $m_{DM} \lesssim 100 \text{ GeV}$ 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

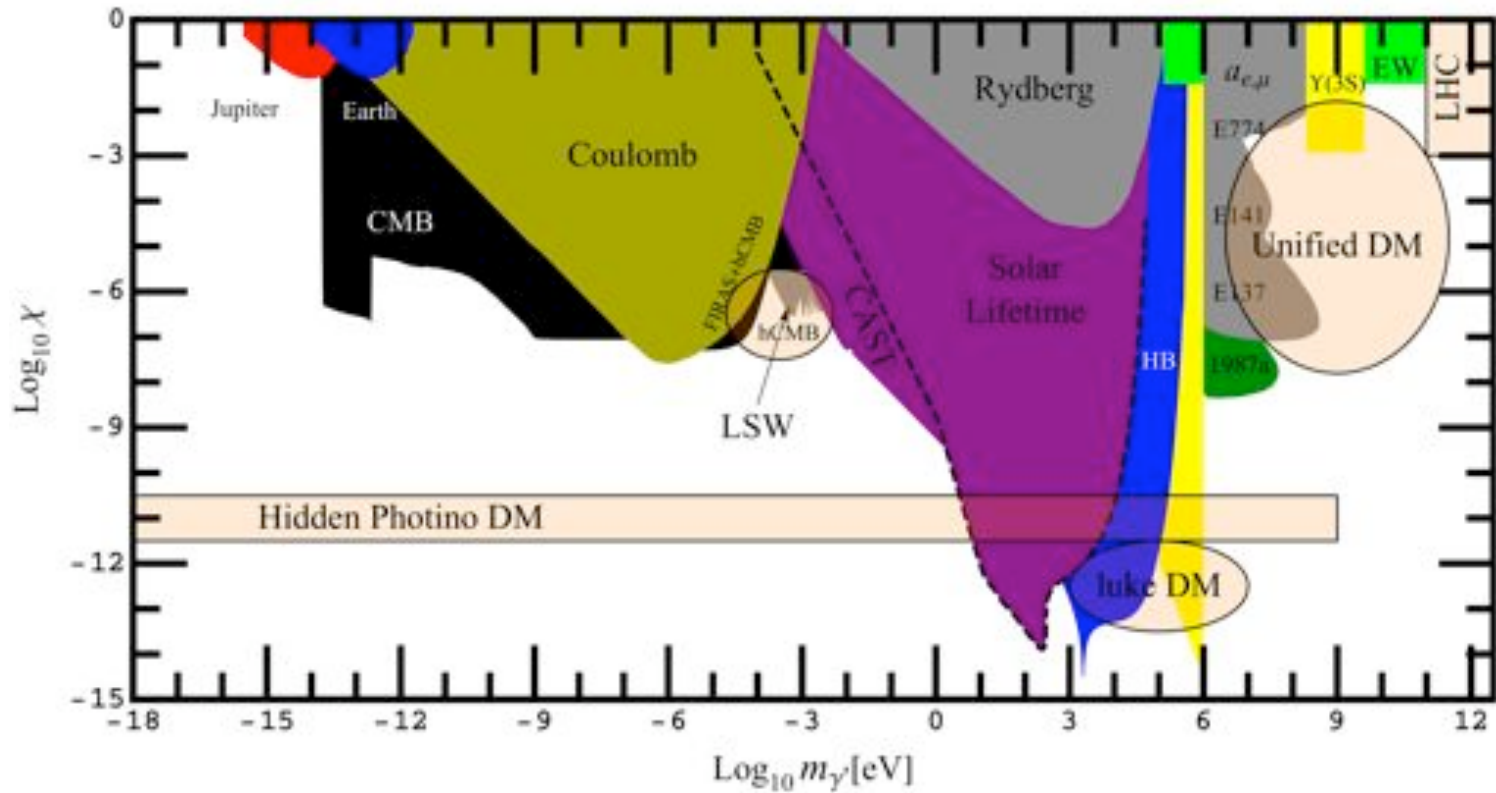


Figure 10. Summary of astrophysical, cosmological and laboratory constraints for hidden photons (kinetic mixing χ vs. mass m_γ). At higher mass we have electroweak precision measurements (EW), bounds from upsilon decays (Υ_{3S}) and fixed target experiments (EXXX). Areas that are especially interesting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

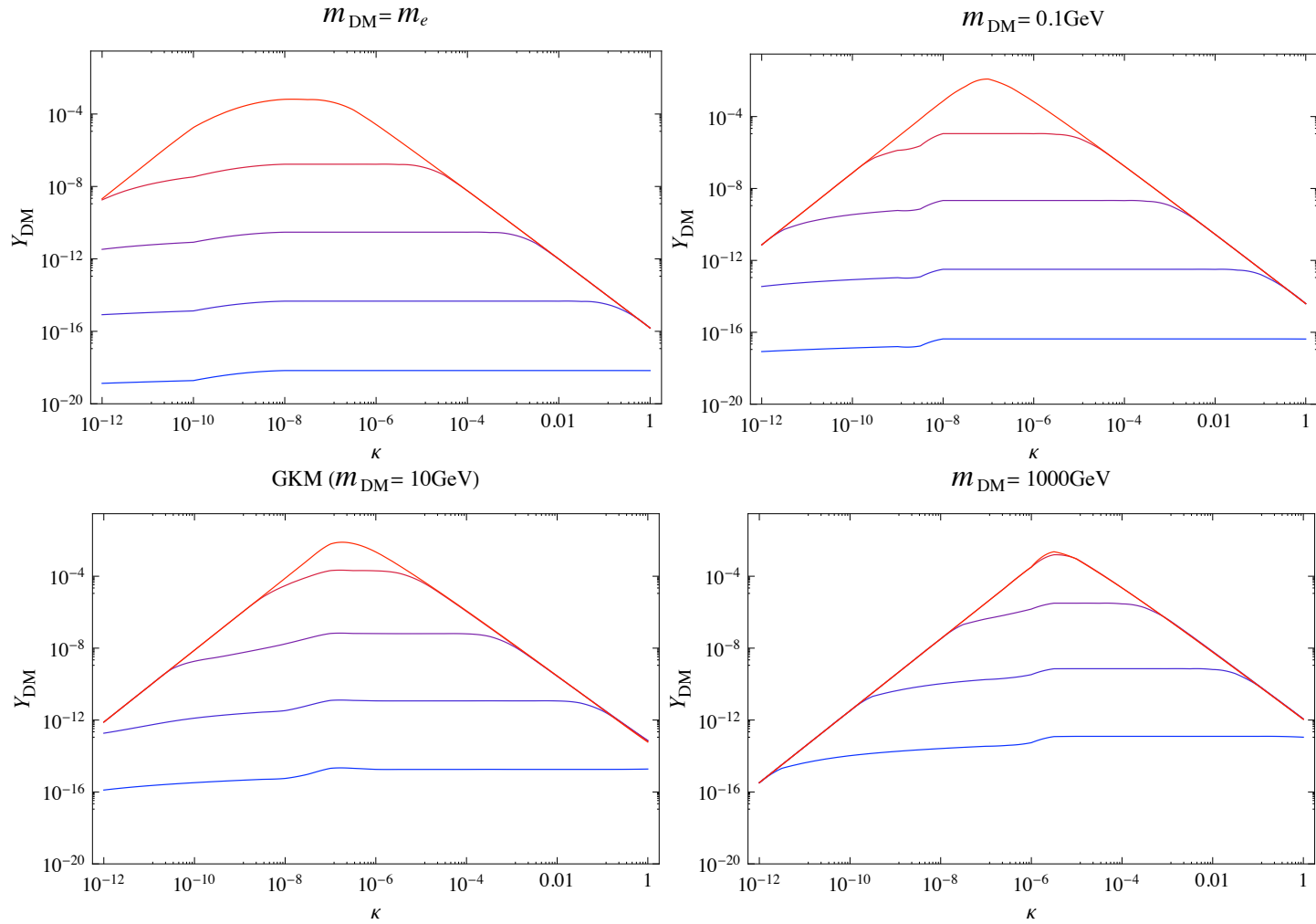
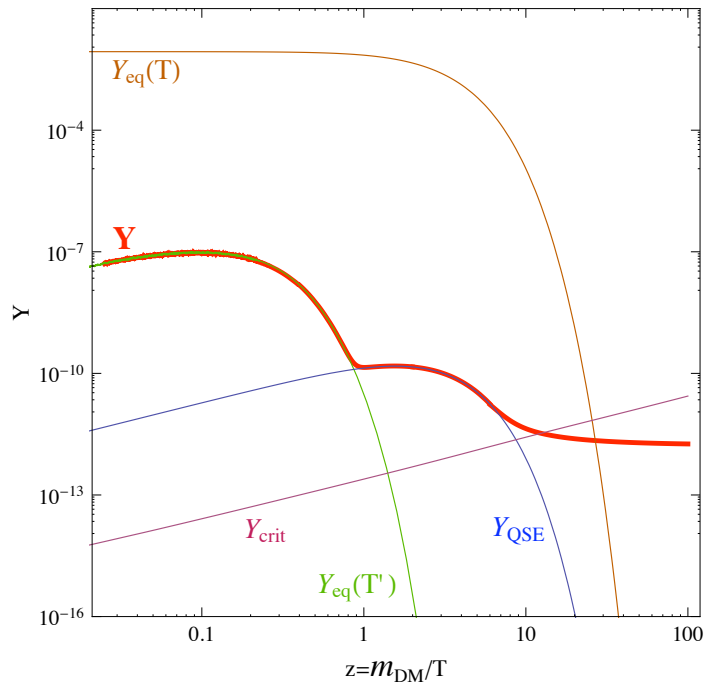
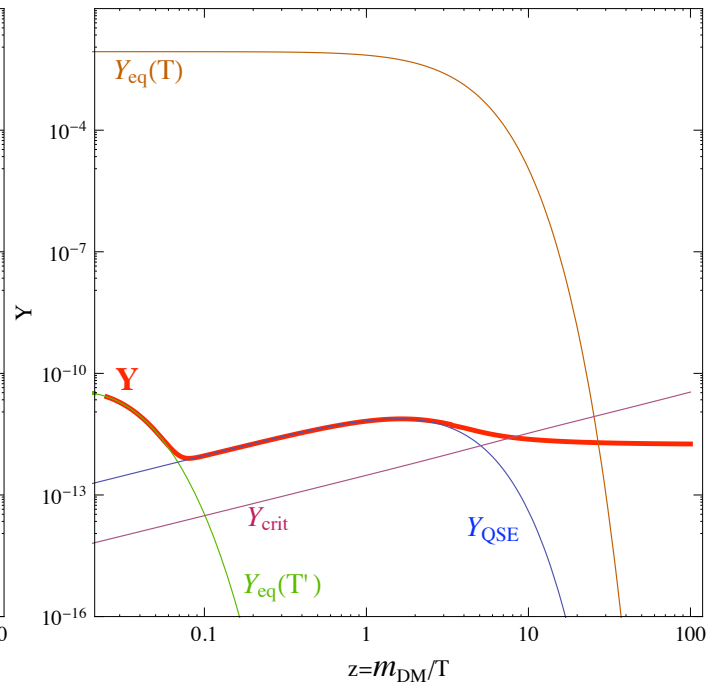


Figure 5: DM relic abundance Y_{DM} as a function of the connector parameter κ for different DM masses m_{DM} and values of the hidden sector interaction, $\log_{10}(\alpha'/\alpha) = 1, -1, -3, -5, -7$ (bottom-up).

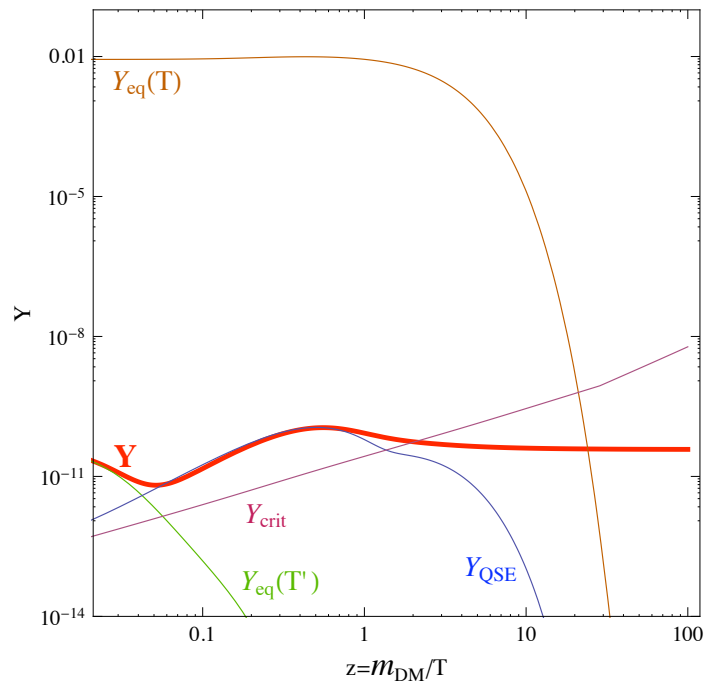
Region.II ($m_{\text{DM}}=200\text{GeV}$, $\kappa=10^{-8}$, $\alpha'=10^{-2.4}$)



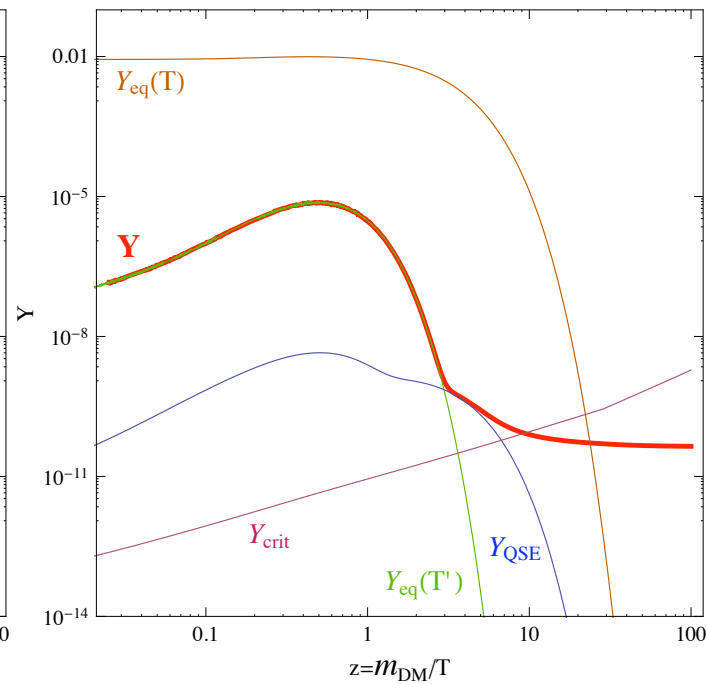
Region.II ($m_{\text{DM}}=200\text{GeV}$, $\kappa=10^{-9.5}$, $\alpha'=10^{-2.6}$)



Region.II-A ($m_{\text{DM}}=10\text{GeV}$, $\kappa=10^{-10.5}$, $\alpha'=10^{-4.2}$)



Region.II-B ($m_{\text{DM}}=10\text{GeV}$, $\kappa=10^{-8.5}$, $\alpha'=10^{-3.8}$)



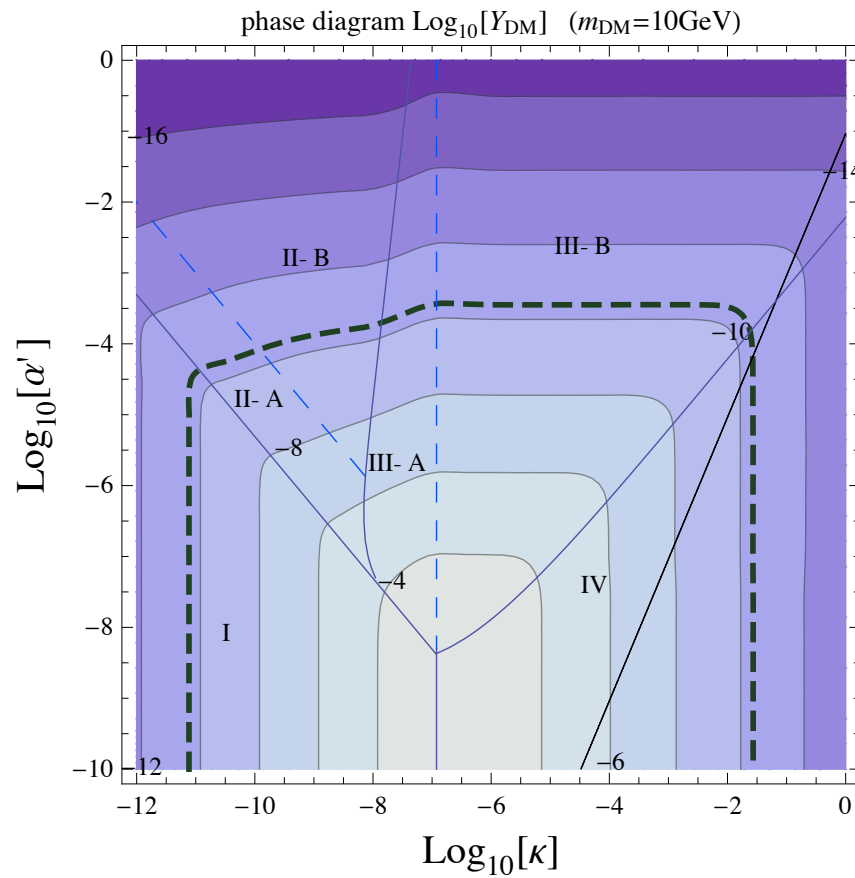


Figure 18: Phase diagram for the kinetic mixing portal and $m_{DM} = 10$ GeV separating explicitly the reannihilation regimes dominated by the decay (IIA) and by the γ mediated scattering (IIB).

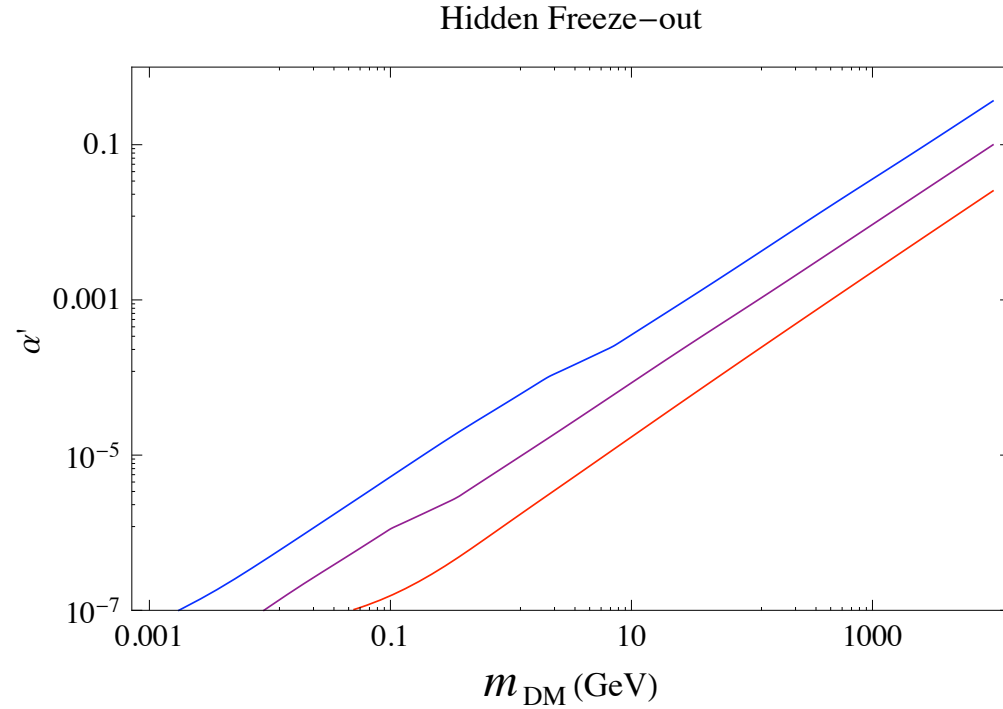


Figure 6: Values of α' required to get the WMAP relic density as a function of m_{DM} assuming no connector between the hidden sector and the SM sector, for different values of the temperature ratio $\xi \equiv T'/T = 0.01, 0.1, 1$ (bottom-up).

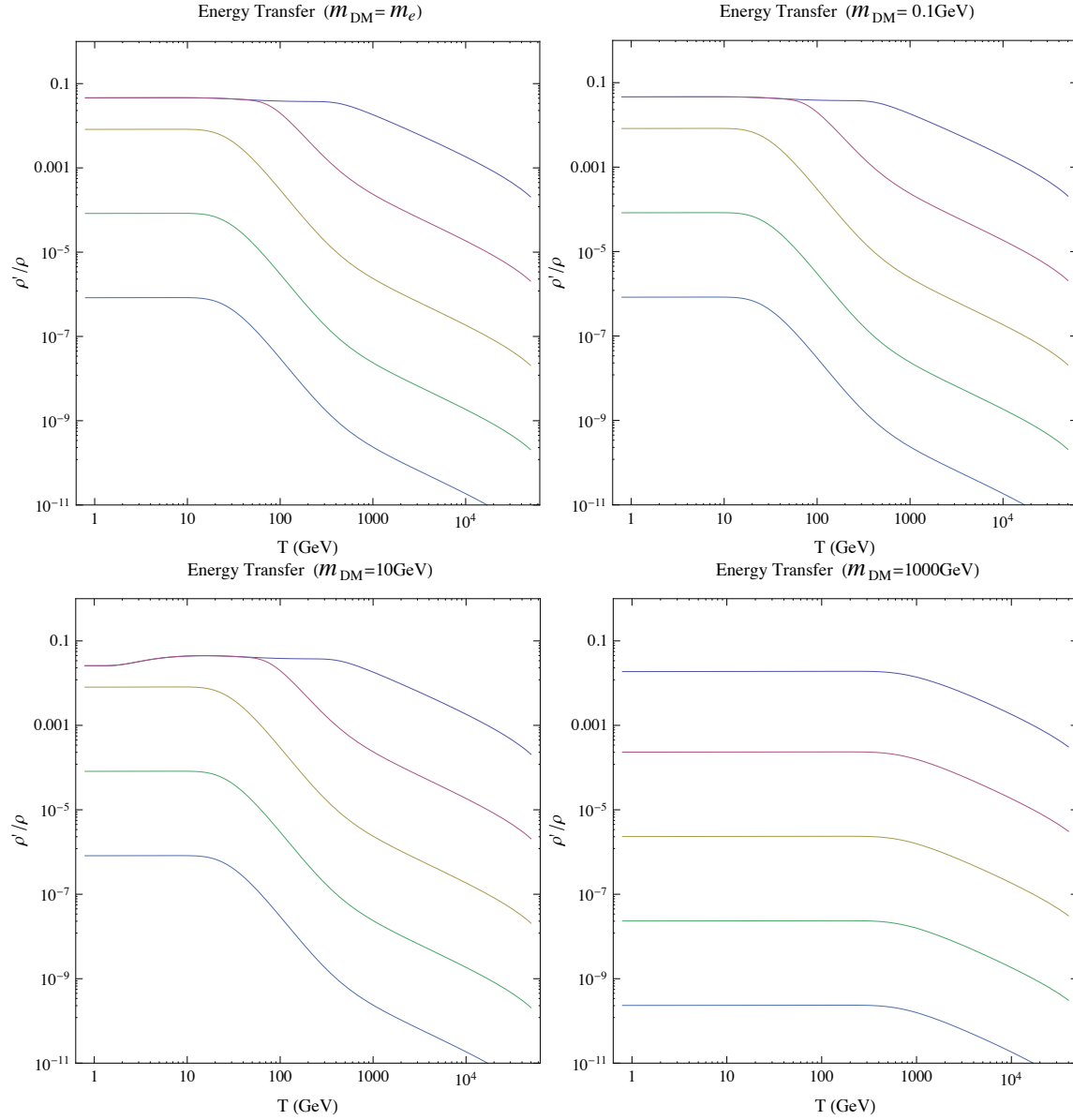


Figure 12: Evolution of the ratio of the visible and hidden sectors energy densities, for a range of connector parameter, $\lambda_m = 10^{-6, -7, -8, -9, -10}$ (from up to down), and for various DM masses.

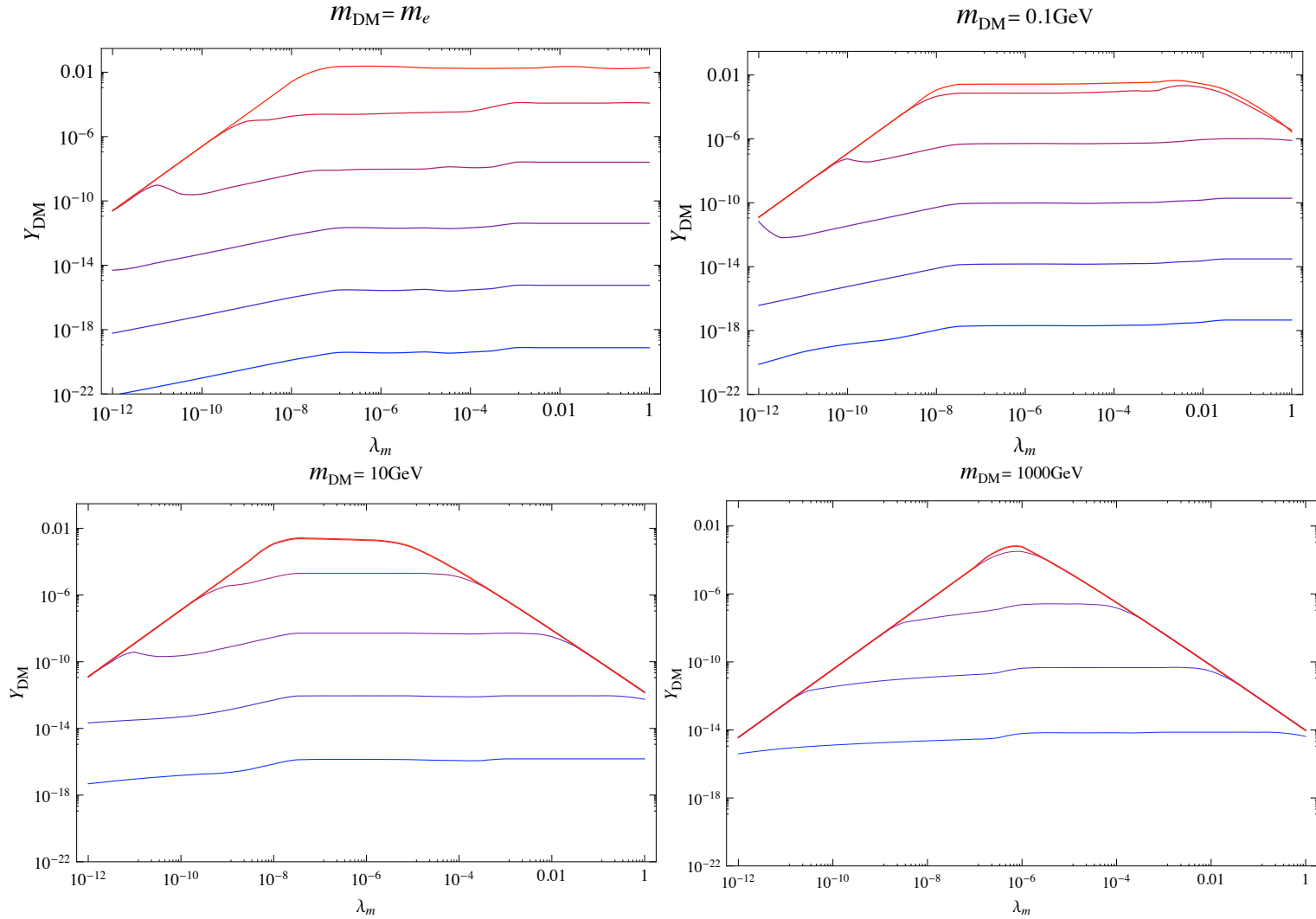


Figure 14: DM relic abundance Y_{DM} as a function of the connector parameter λ_m for different DM masses m_{DM} and values of the hidden sector interaction, $\log_{10}(\alpha'/\alpha) = 1, -1, -3, -5, -7, -9$, bottom-up (the last two lines are the same for $m_{DM} = 10$ GeV, as well as for $m_{DM} =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

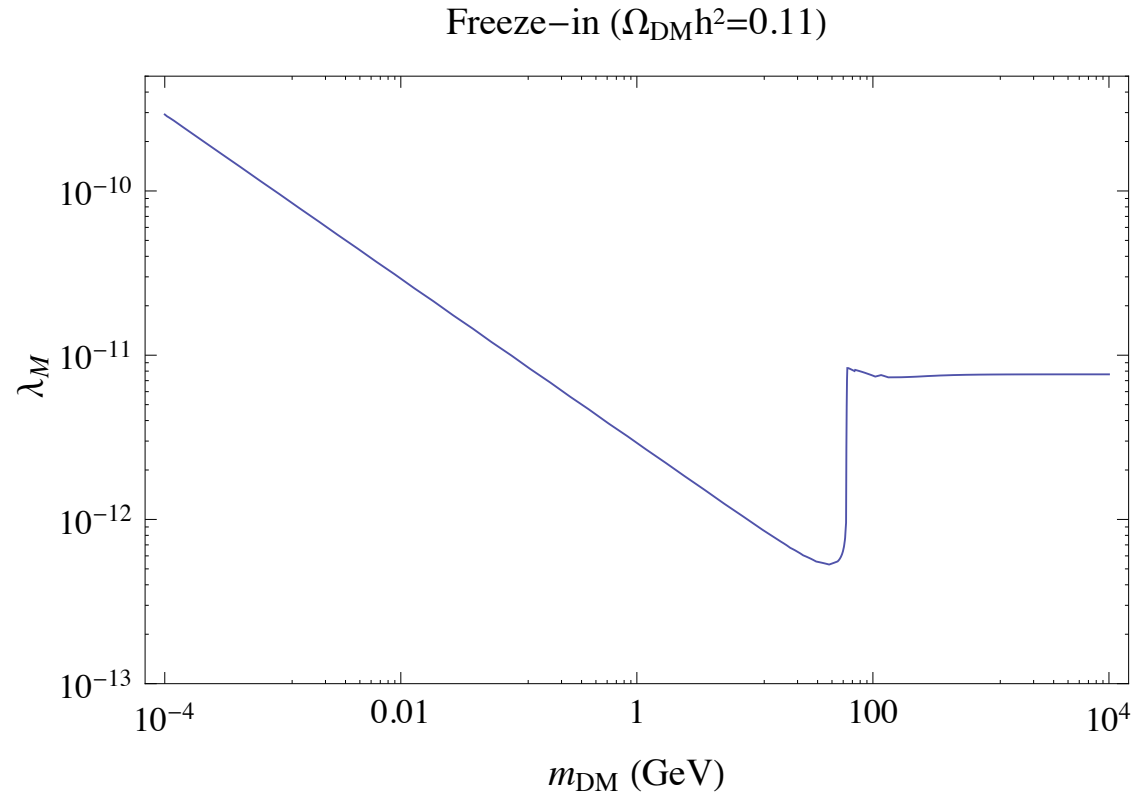
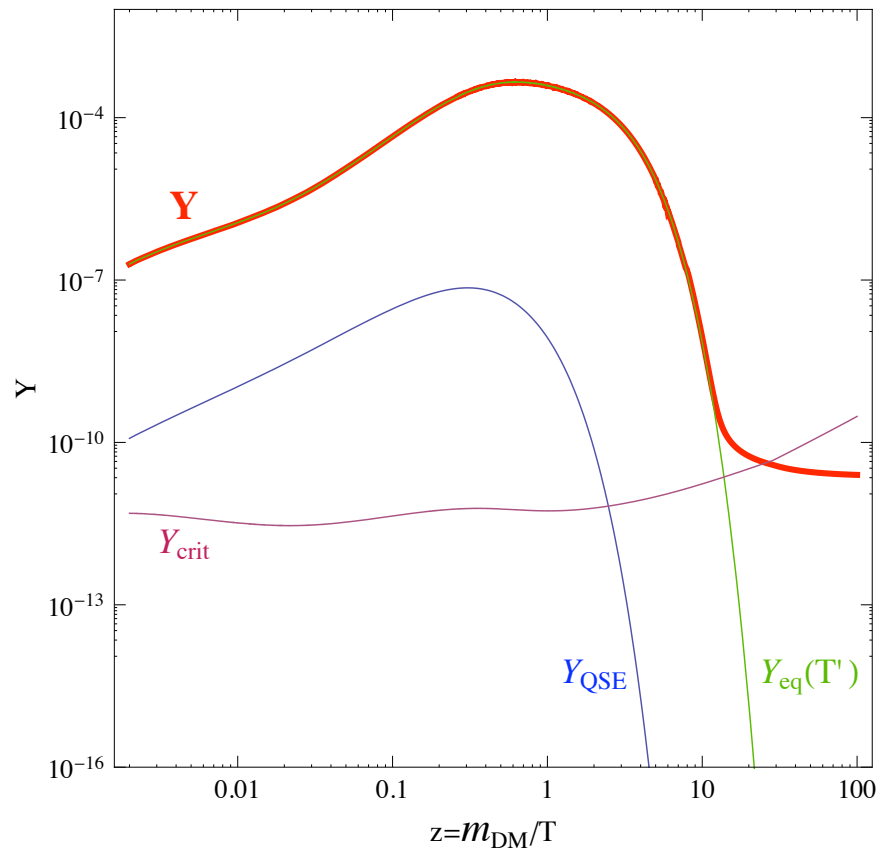
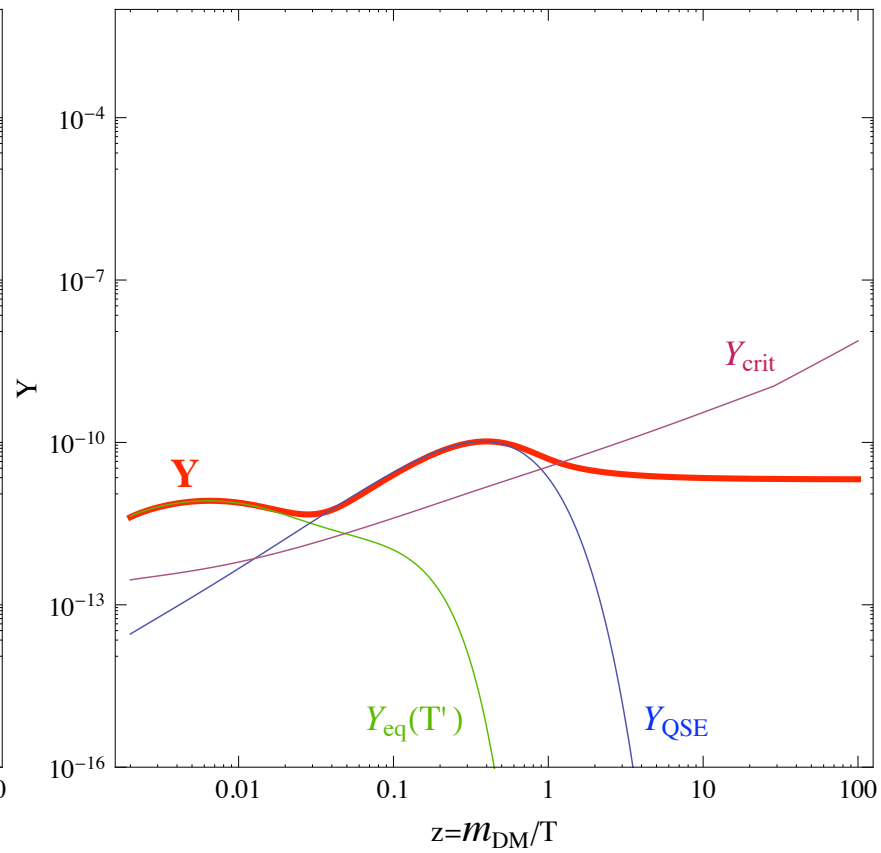


Figure 14: Higgs portal parameter required to get the observed DM relic density through freeze-in ($\alpha' = 0$).

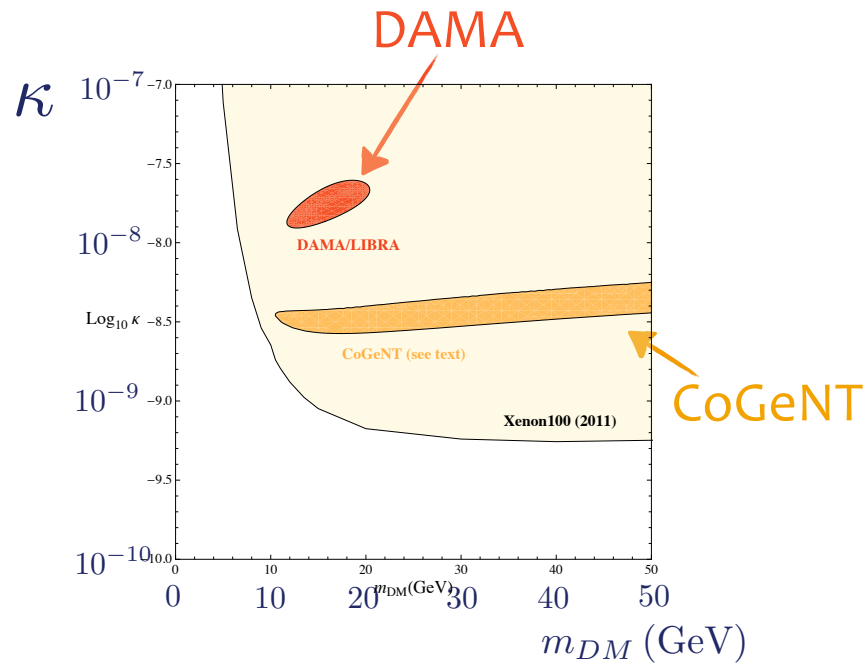
Region.II ($m_{\text{DM}}=10\text{GeV}, \lambda_m=10^{-8}, \alpha'=10^{-4}$)



Region.II ($m_{\text{DM}}=10\text{GeV}, \lambda_m=10^{-11}, \alpha'=10^{-4.7}$)



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