The Dark Matter Phase Diagram: Thermal Relics between keV and TeV

Raffaele Tito D'Agnolo - IPhT Saclay

10^{-22} eV m_χ 10^{48} GeV

$\mathcal{O}(10^{-50})$ $\mathcal{O}(10^{-50})$

$\alpha_{\rm self}$ $\alpha_{\rm SM}$

$\mathcal{O}(1)$ $\mathcal{O}(1)$

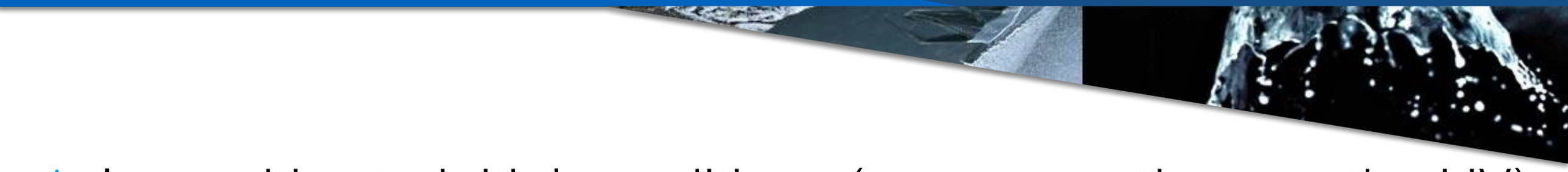
LDM INTRO FROM 6 YEARS AGO

We have looked for WIMPs for decades…
We have looked for SUSY for decades…

We have not found anything (yet)

Here is something new (and motivated?)

THE UNUSUAL APPEAL OF THE WIMP

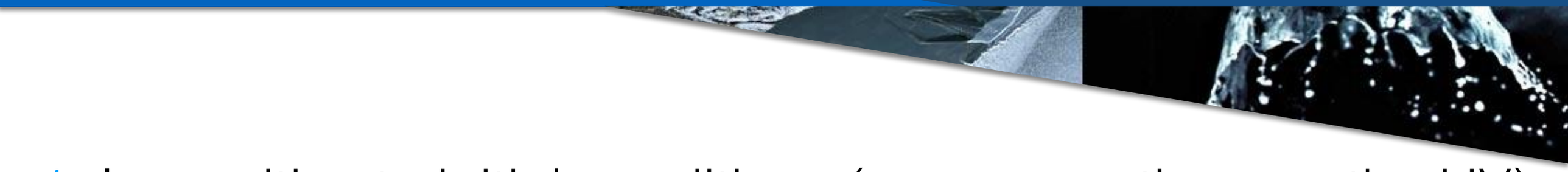


1. Insensitive to initial conditions (no assumptions on the UV)

$$T > m_{\rm DM}$$

DM in Kinetic and Chemical Eq. with a bath at $T=T_{SM}$

THE UNUSUAL APPEAL OF THE WIMP



1. Insensitive to initial conditions (no assumptions on the UV)

$$T > m_{\rm DM}$$

DM in Kinetic and Chemical Eq. with a bath at $T=T_{SM}$

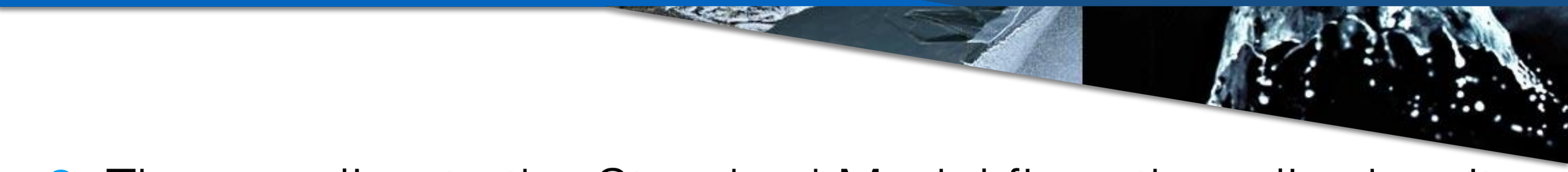
A coupling in the dark sector [or non-standard cosmology] is needed to remove excess DM abundance

Cannibal, Secluded, Forbidden v1, ELDER, Co-decaying, sub-MeV, Inflatable, asymmetric, WIMPs with GUTs, …

Potential Experimental Target: Decay to SM radiation

$$\alpha_{\rm eff} \gtrsim 10^{-20}$$

THE UNUSUAL APPEAL OF THE WIMP



2. The coupling to the Standard Model fixes the relic density

$$T > m_{\rm DM}$$

DM in Kinetic and Chemical Eq. with a bath at $T=T_{SM}$

A coupling in the dark sector is needed to remove excess DM abundance

Cannibal, Secluded, Forbidden v1, ELDER, Co-decaying, sub-MeV, Inflatable, asymmetric, WIMPs with GUTs, …

$$\alpha_{\rm eff} \gtrsim 10^{-20}$$

A coupling to the SM removes excess DM abundance

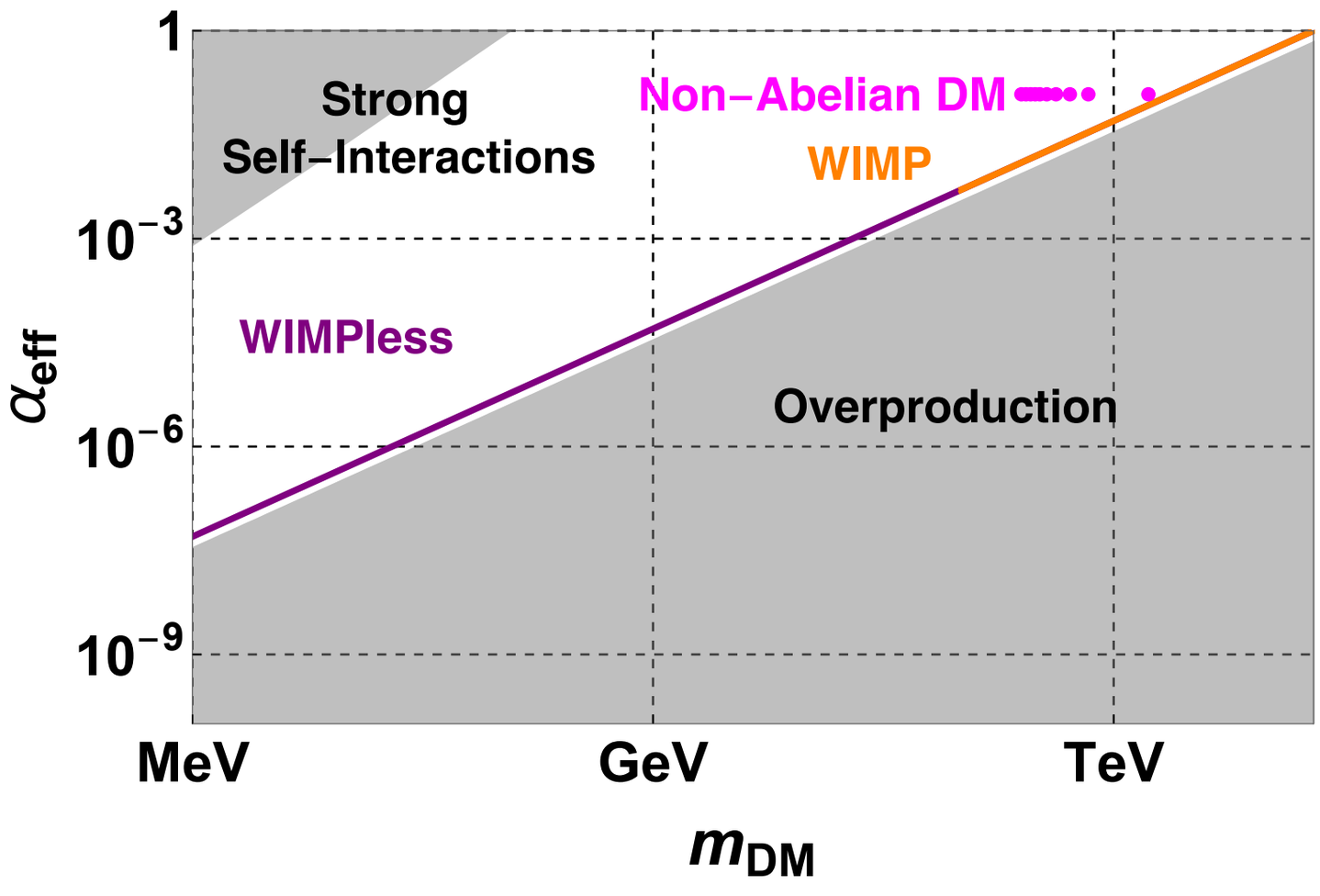
WIMP [=WIMPless, Semi-Annihilation, Inelastic, non-Abelian] + ?

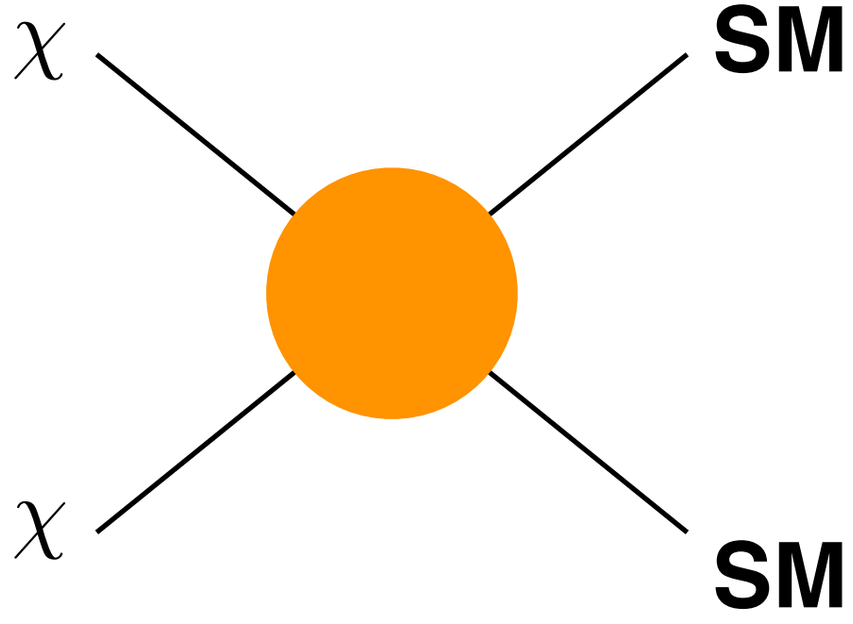
Irreducible Experimental Target: Relic Density

$$\alpha_{\rm eff} \gtrsim 10^{-7}$$

WIMPs AND TARGETS

χ = Dark Matter



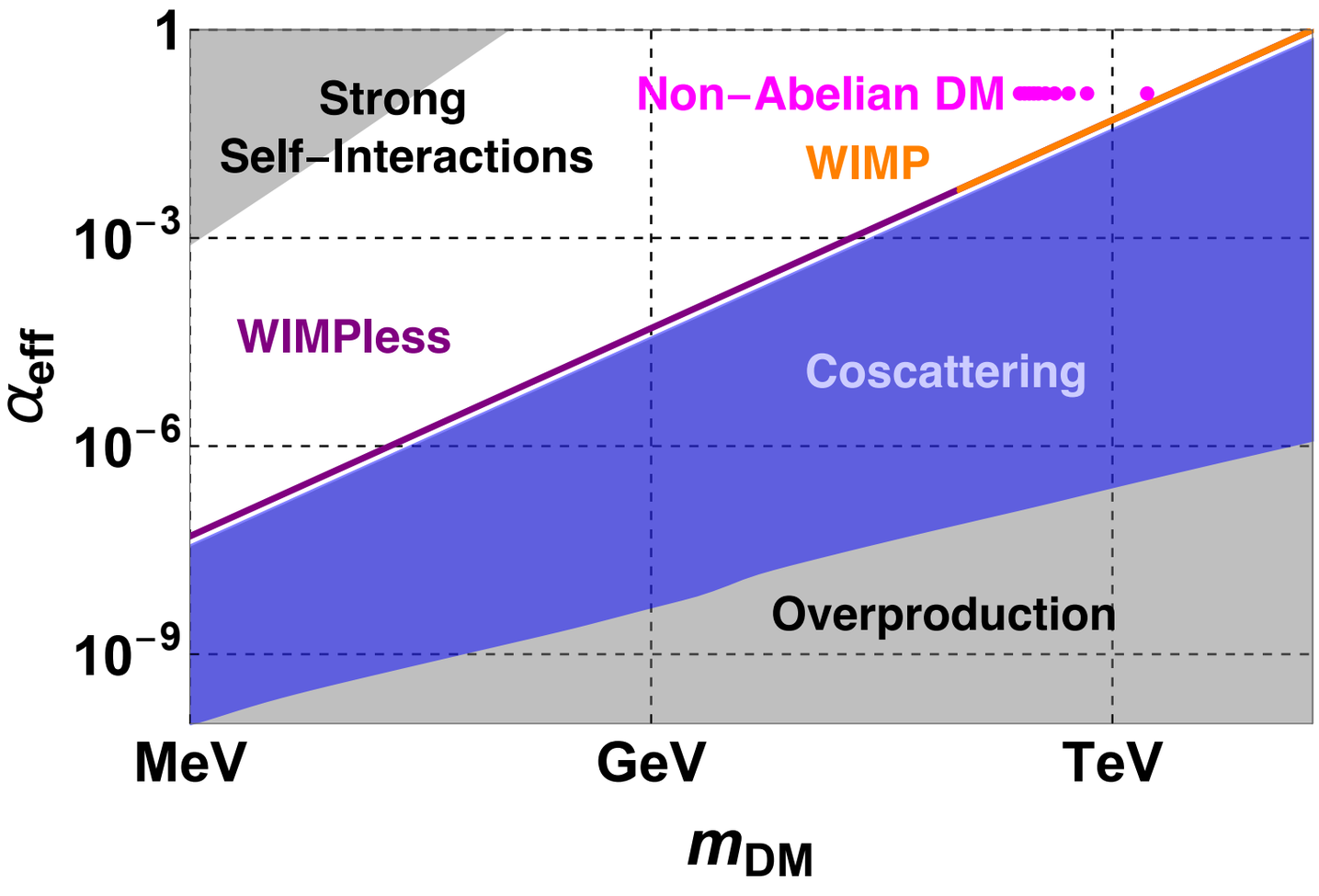


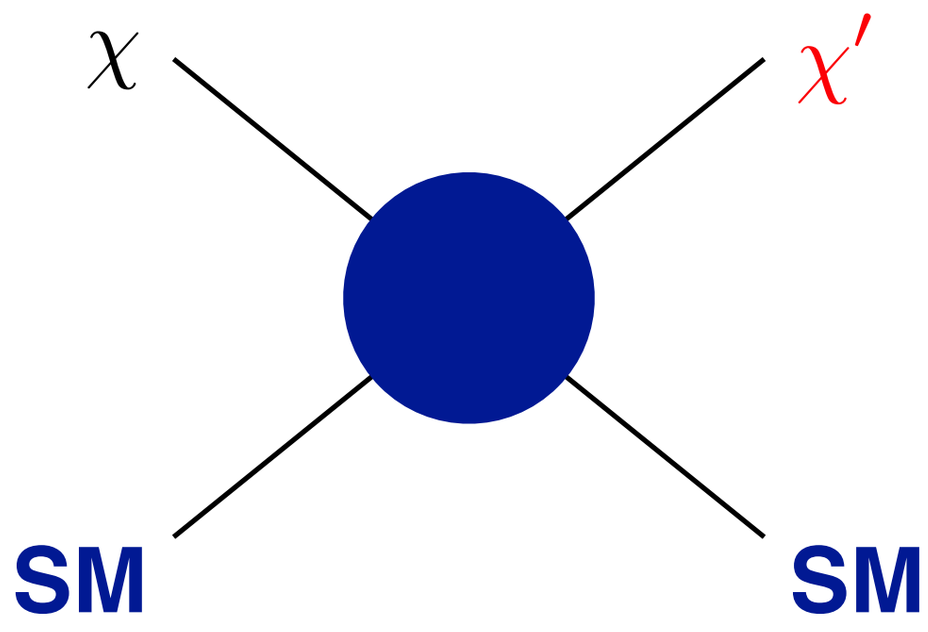
Semi-Annihilation [D'Eramo, Thaler '10], **Inelastic** [Smith, Weiner '01], **WIMPless Miracle** [Feng, Kumar '08], **Heavy Mediators** [Bohem, Fayet '07], **Non-Abelian DM** [Buen-Abad, Marques-Tavares, Schmaltz '15], and many more with similar parametrics

SCATTERING WITH A PARTNER

[**RTD**, Ruderman, Pappadopulo '17]

[**RTD**, Ruderman, Pappadopulo ,Wang, '19]

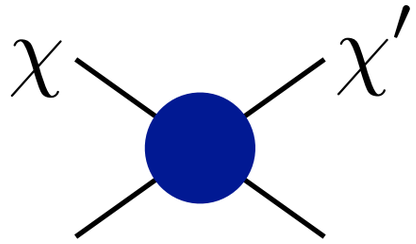




Resonant [Feng, Smolinsky '17]
Similar in this plane

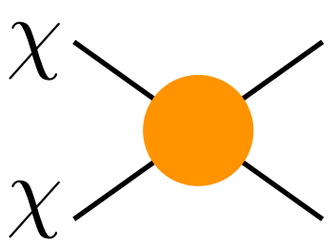
HOW IT WORKS: COSCATTERING

χ = Dark Matter

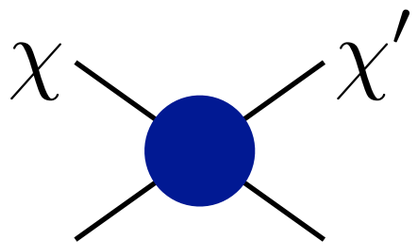


$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle\sigma v\rangle \left[n_\chi - n_\chi^{eq}\right] n^{eq}$$

WIMP



COSCATTERING

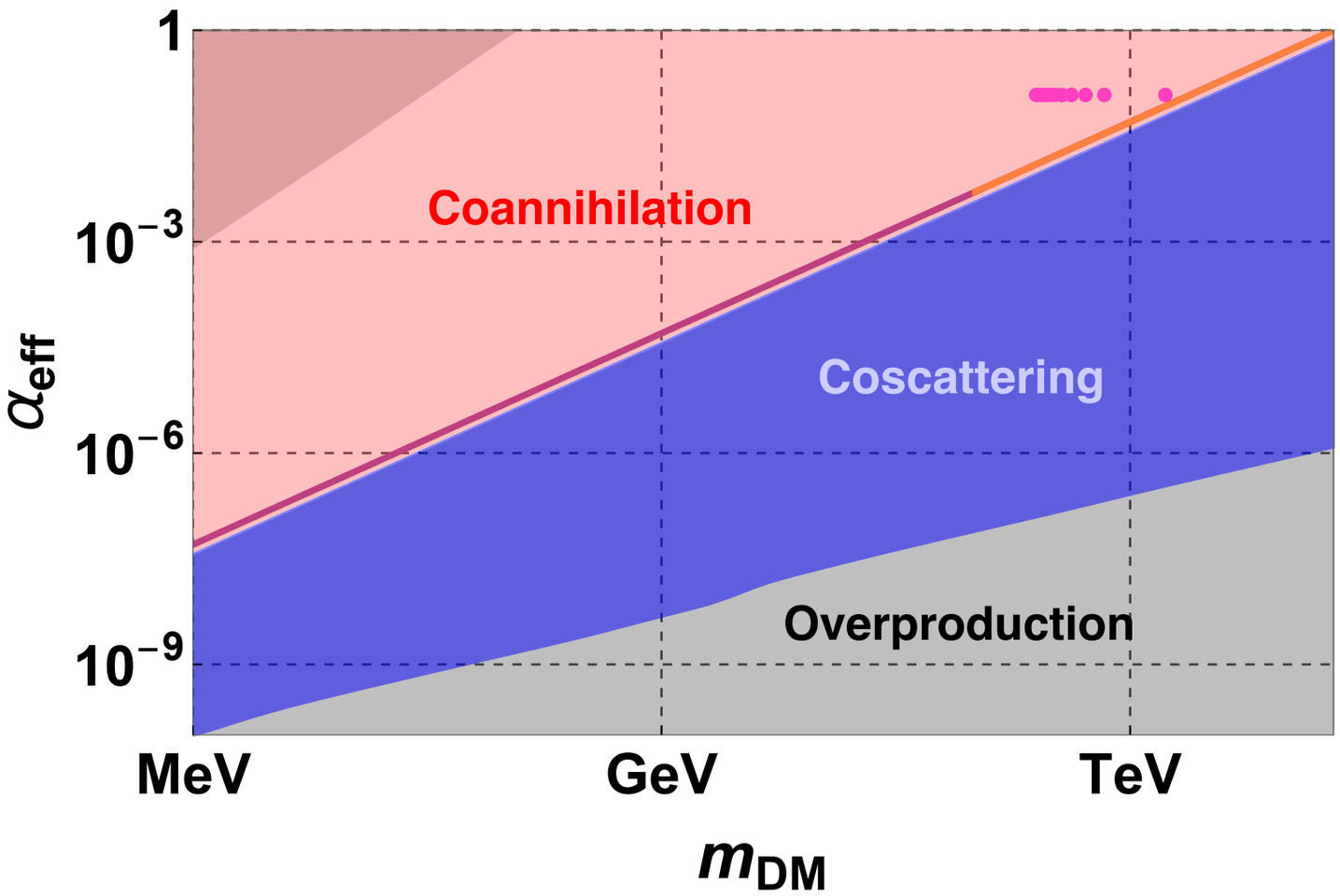


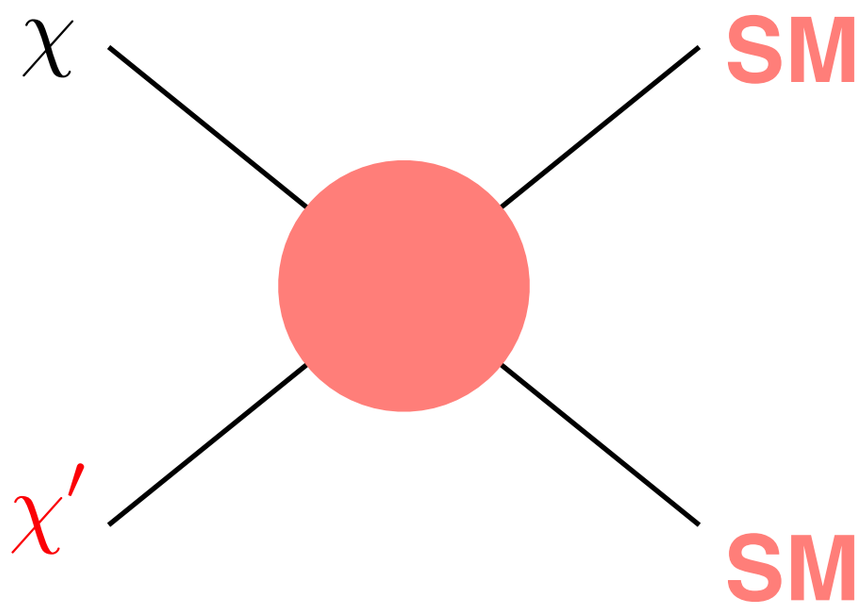
$$\sim e^{-m_\chi/T_F}$$

[**RTD**, Ruderman, Pappadopulo '17], [**RTD**, Pappadopulo ,Ruderman, Wang, '19]

ANNIHILATIONS WITH A PARTNER

[Griest, Seckel '89]
[**RTD**, Mondino, Ruderman, Wang '18]





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HOW IT WORKS: COANNIHILATION

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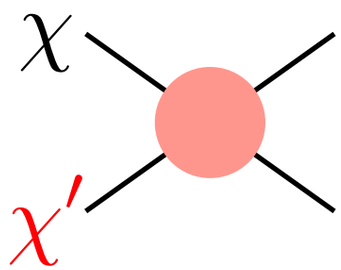

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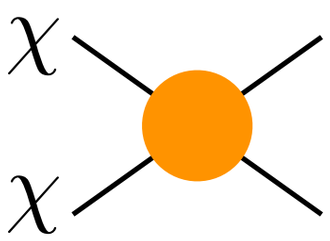
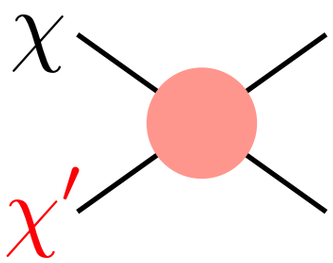
WIMP



COANNIHILATION

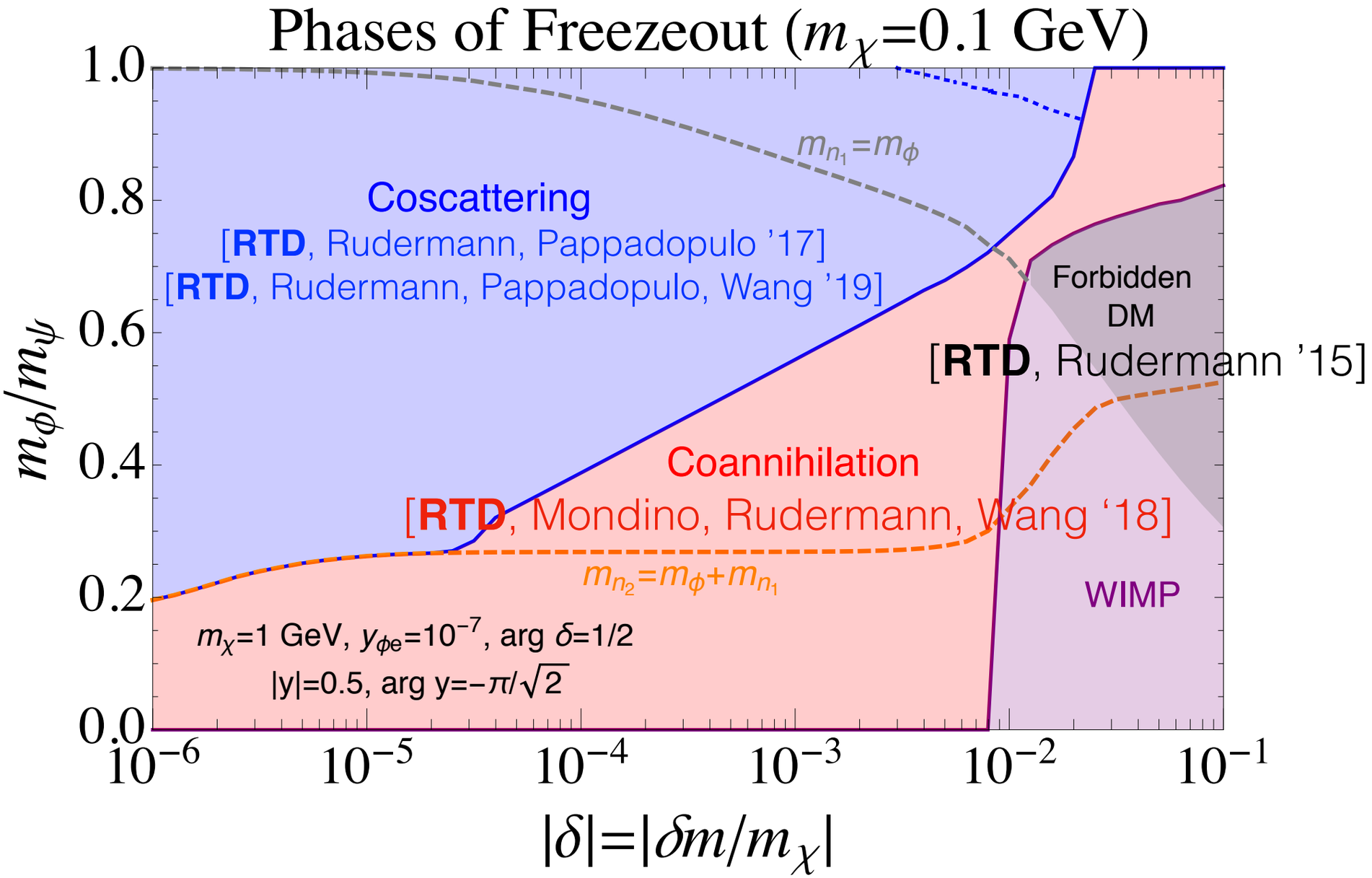


$$\sim e^{\frac{m_{\chi'} - m_\chi}{T_F}}$$

[Griest, Seckel ’89], [**RTD**, Mondino, Ruderman, Wang ’18]

TOWARDS A PHASE DIAGRAM OF DARK MATTER

Coscattering, Coannihilation and WIMP phases are all continuously connected and there is more…



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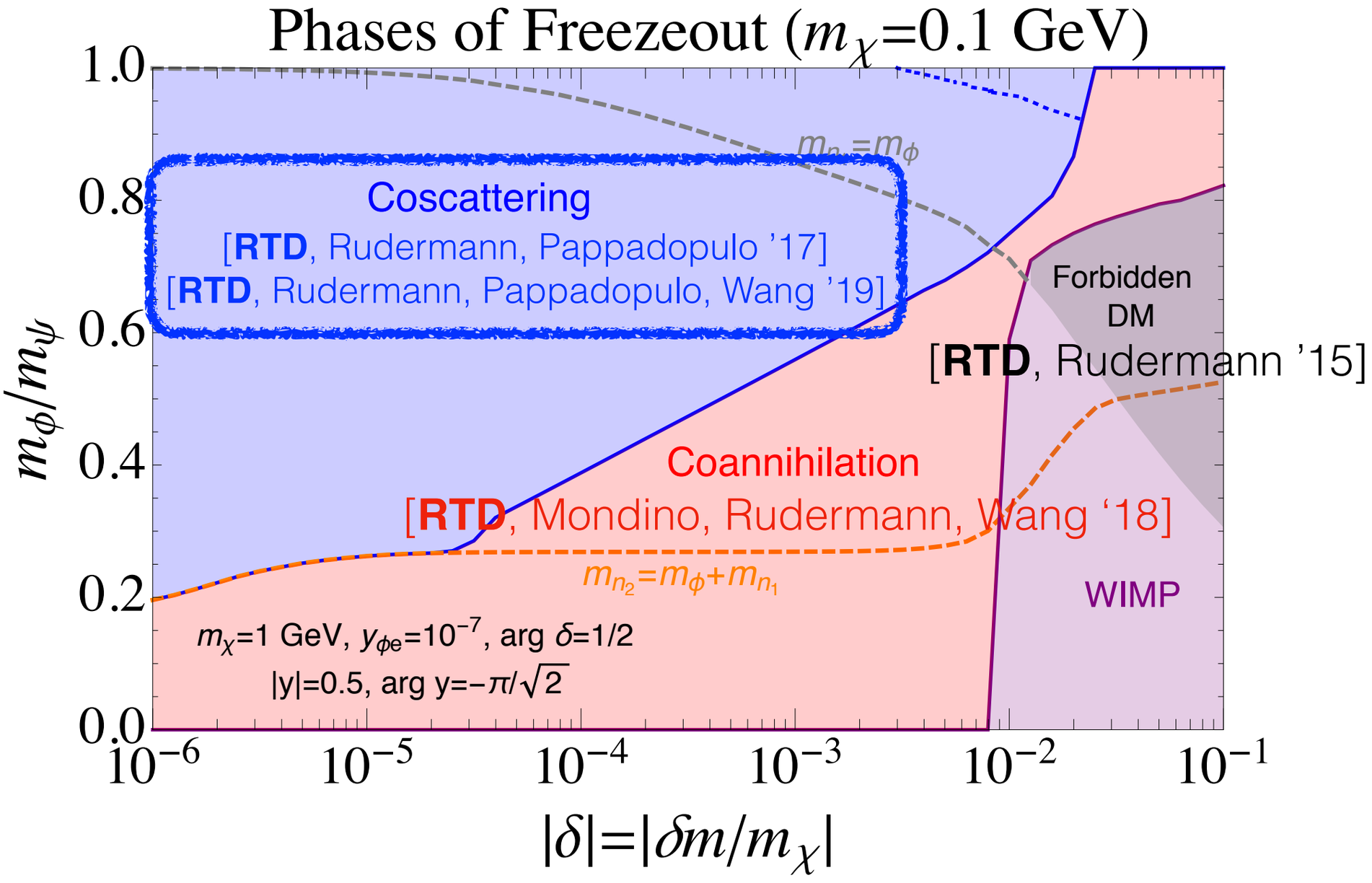

COSCATTERING

INGREDIENTS BEYOND WIMPs

χ = Dark Matter

ψ = Strongly interacting Dark Matter partner

INGREDIENTS BEYOND WIMPs

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Examples: Gluino-Bino, Wino-Bino, …

INGREDIENTS BEYOND WIMPs

χ = Dark Matter

ψ = Strongly interacting Dark Matter partner

$$m_\psi \gtrsim m_\chi$$

$$\Delta \equiv \frac{m_\psi - m_\chi}{m_\chi}$$

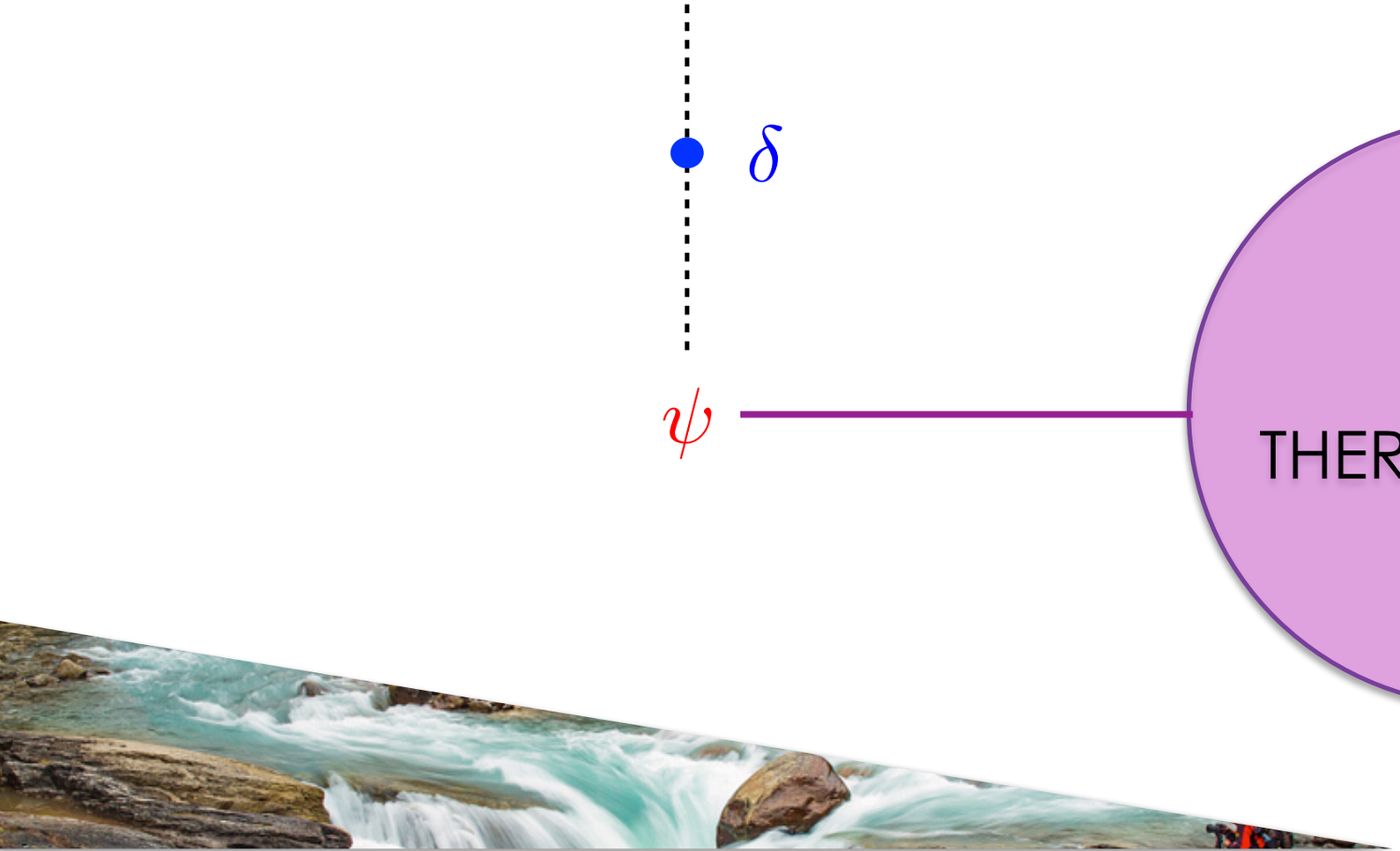
A GENERAL REALIZATION OF THE MECHANISM

χ

ψ

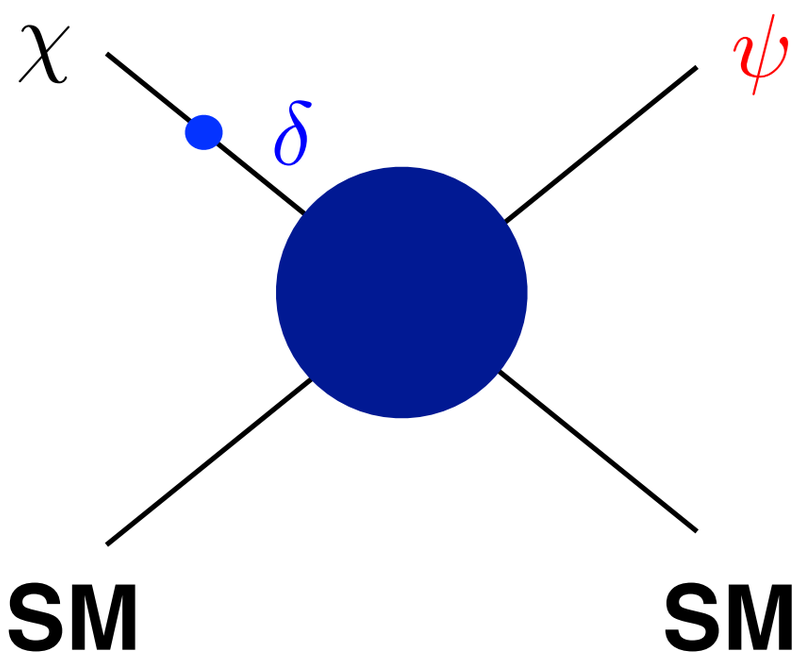
SM
THERMAL BATH

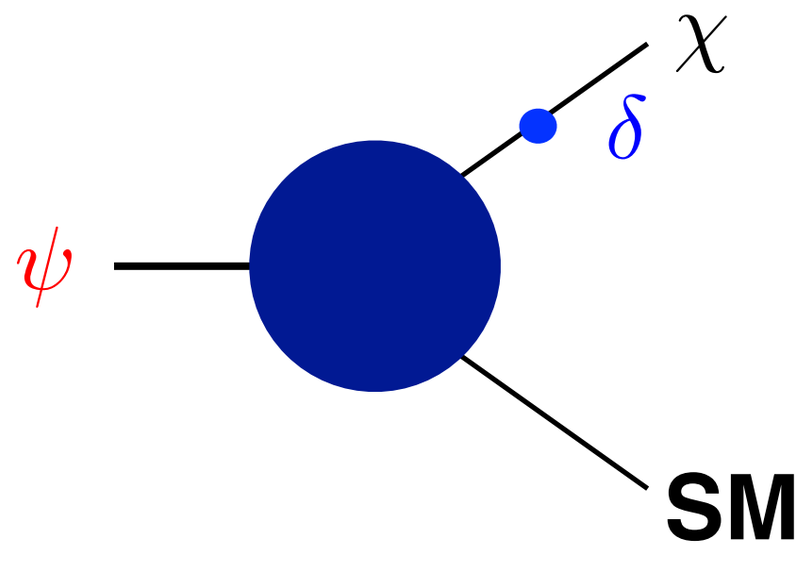
A GENERAL REALIZATION OF THE MECHANISM



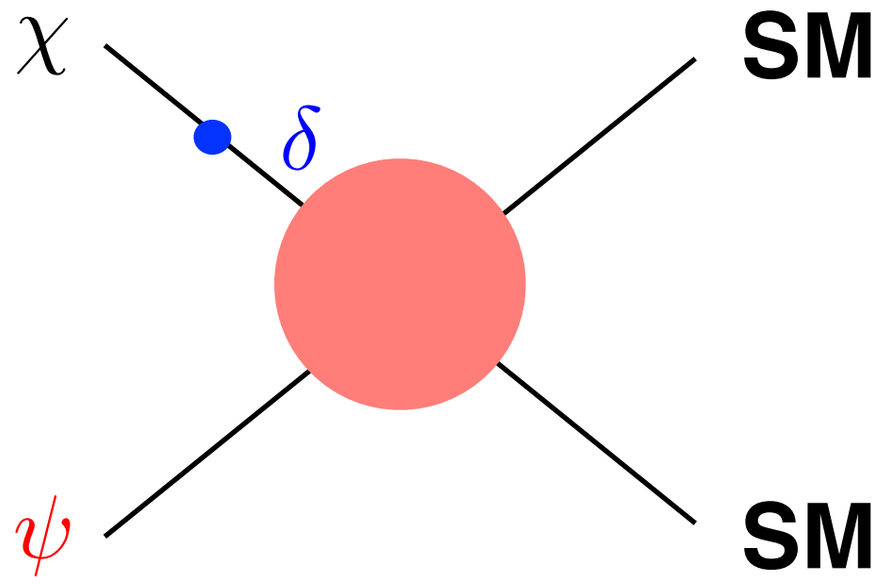
A GENERAL REALIZATION OF THE MECHANISM

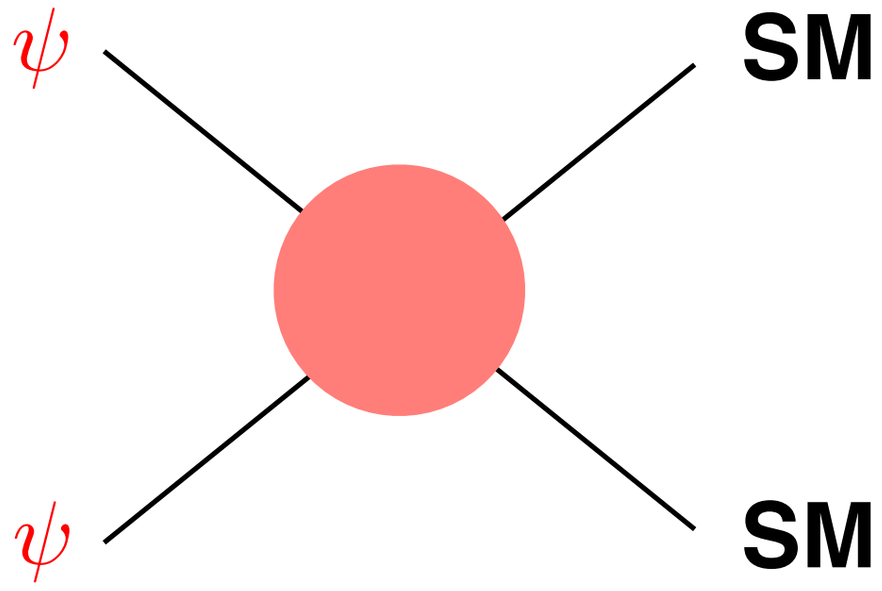
$\chi \leftrightarrow \psi$





$\chi,\ \psi \leftrightarrow$ **SM**

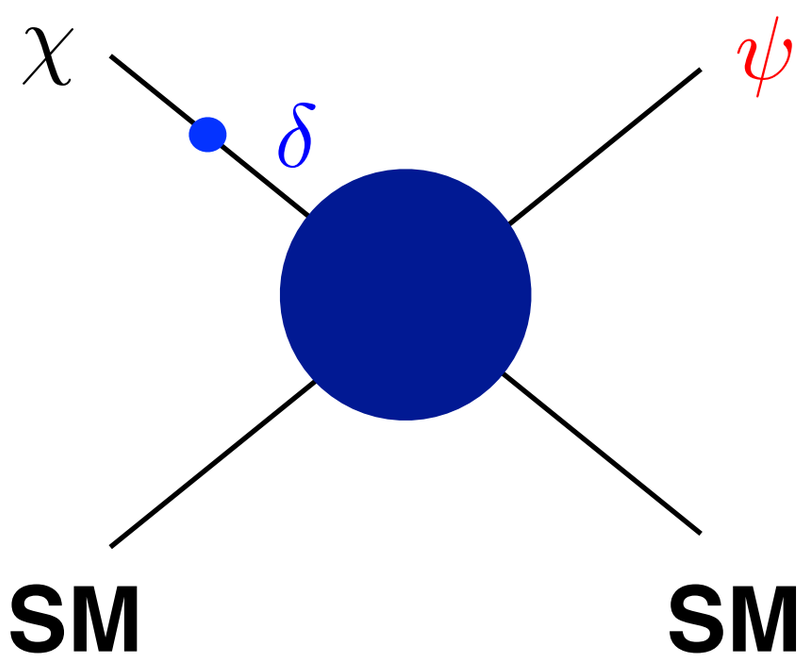




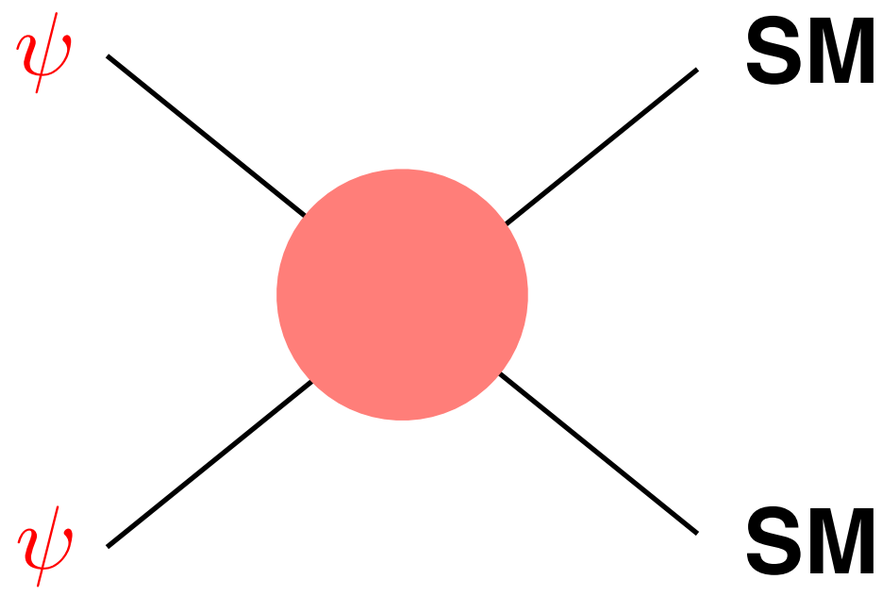
BOLTZMANN "NDA"

Relevant timescale

$$n_\chi \langle \sigma v \rangle_F \approx H_F \qquad\qquad n_\chi(T_F) \sim e^{-m_\chi/T_F}$$



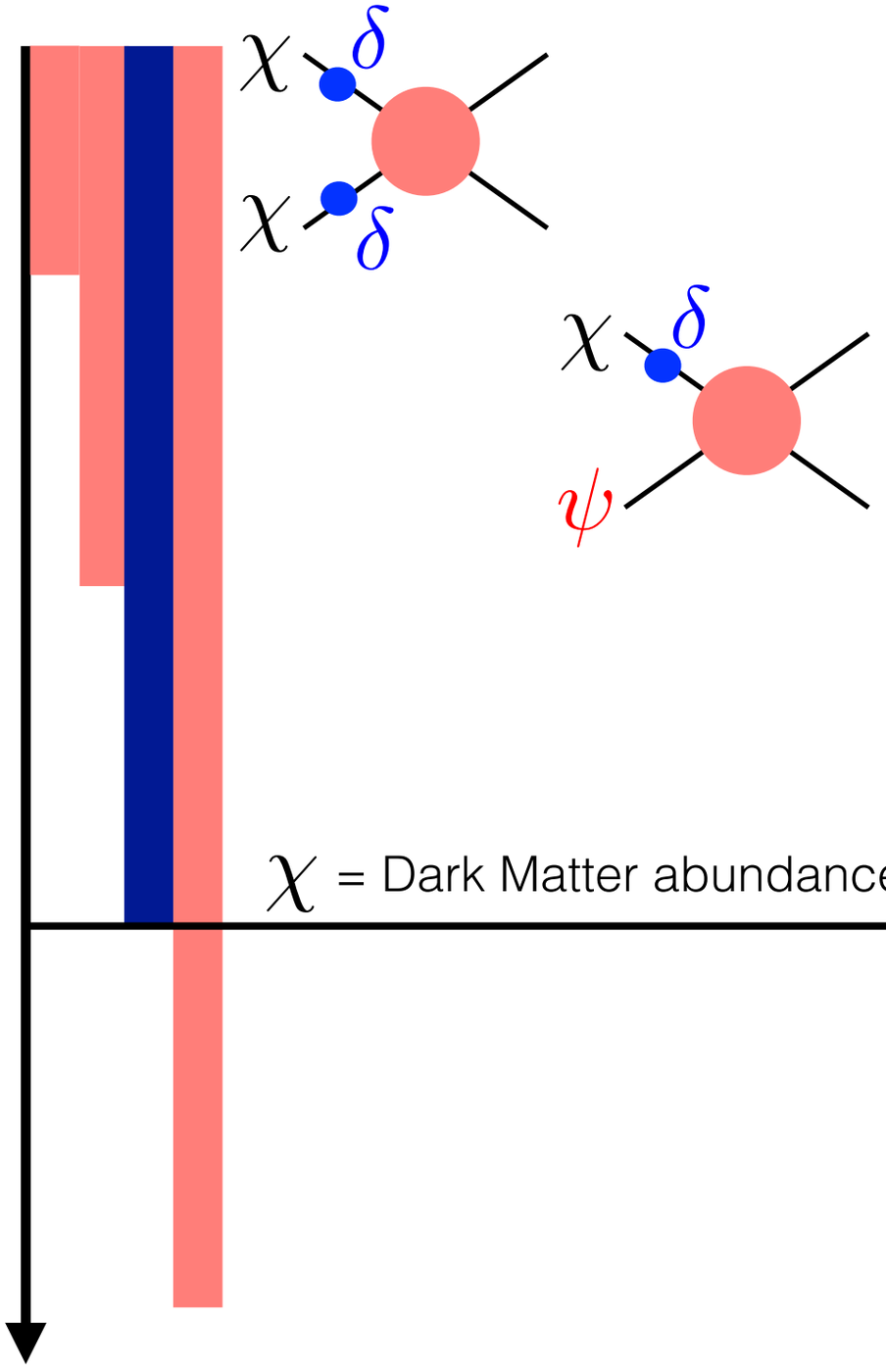
$$\sim \delta^2 T_F^3 \sigma_0$$



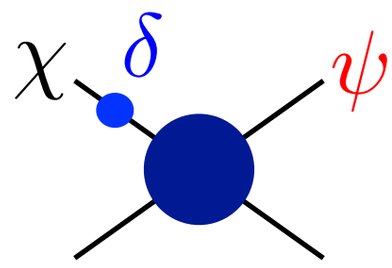
$$\sim (T_F m_\psi)^{3/2} e^{-m_\psi/T_F} \sigma_0$$

TIMESCALES OF FREEZE-OUT: COSCATTERING

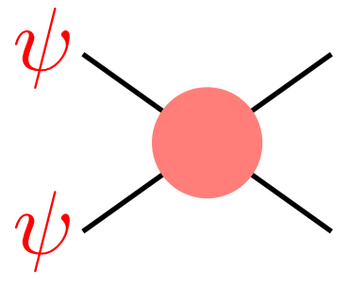
Time



$$\delta^2 \ll e^{-\Delta x_F}$$

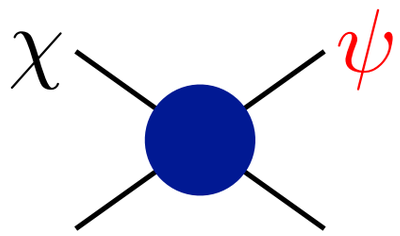


χ = Dark Matter abundance fixed



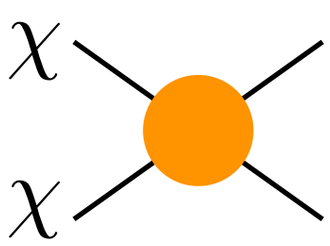
COSCATTERING: A REMINDER

χ = Dark Matter

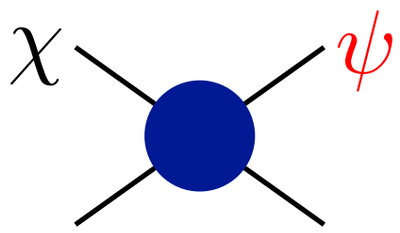


$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle\sigma v\rangle \left[n_\chi - n_\chi^{eq}\right] n^{eq}$$

WIMP



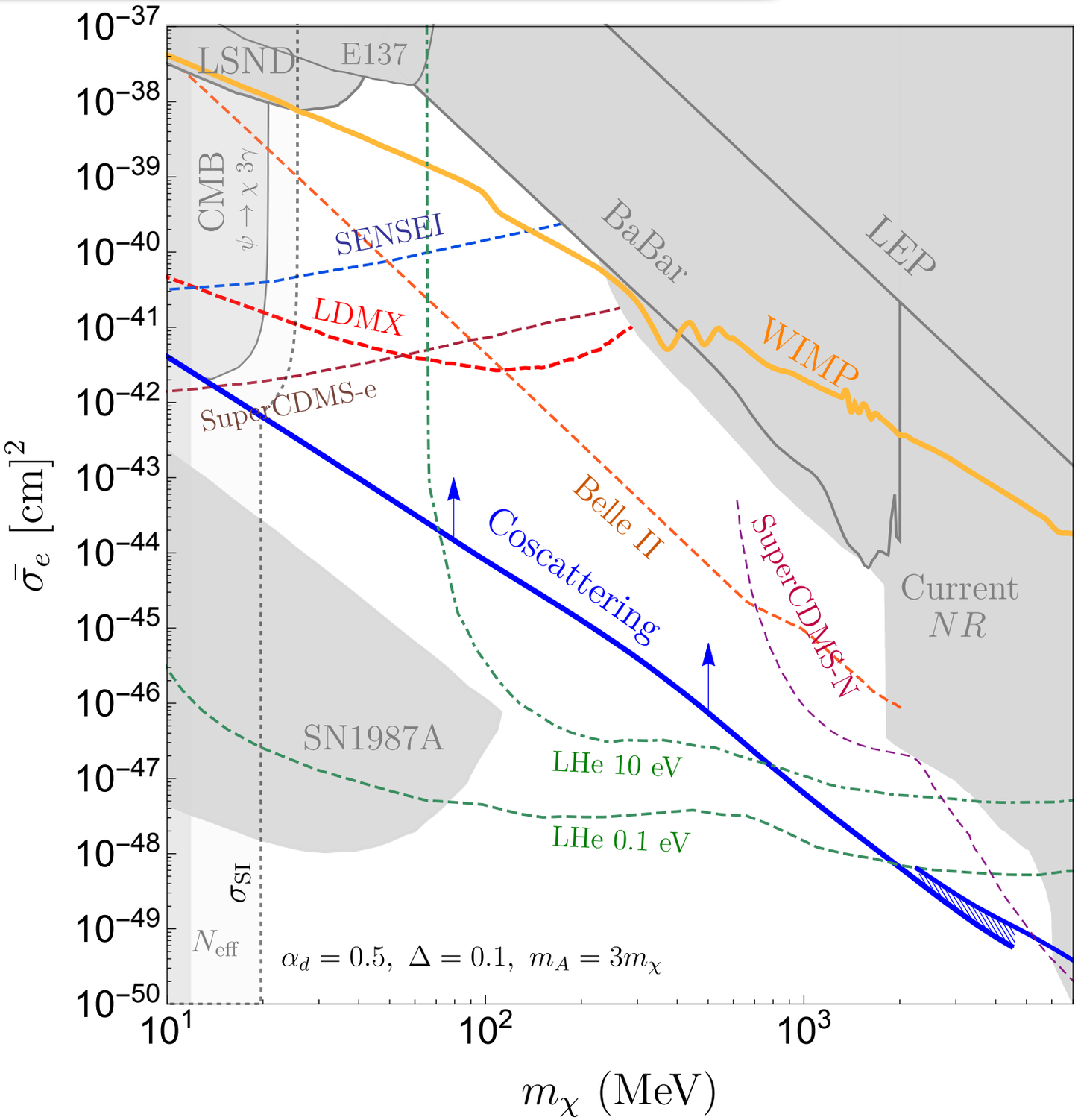
COSCATTERING



$$\sim e^{-m_\chi/T_F}$$

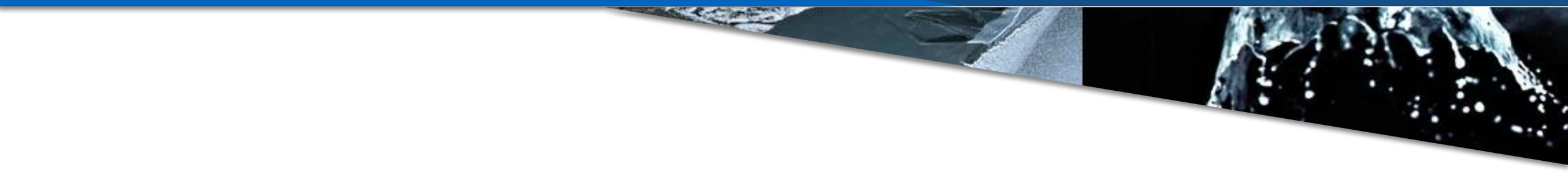
[**RTD**, Ruderman, Pappadopulo '17], [**RTD**, Pappadopulo ,Ruderman, Wang, '19]

PHENOMENOLOGY



[**RTD**, Ruderman, Pappadopulo, Wang, ’19]

CONCLUSION

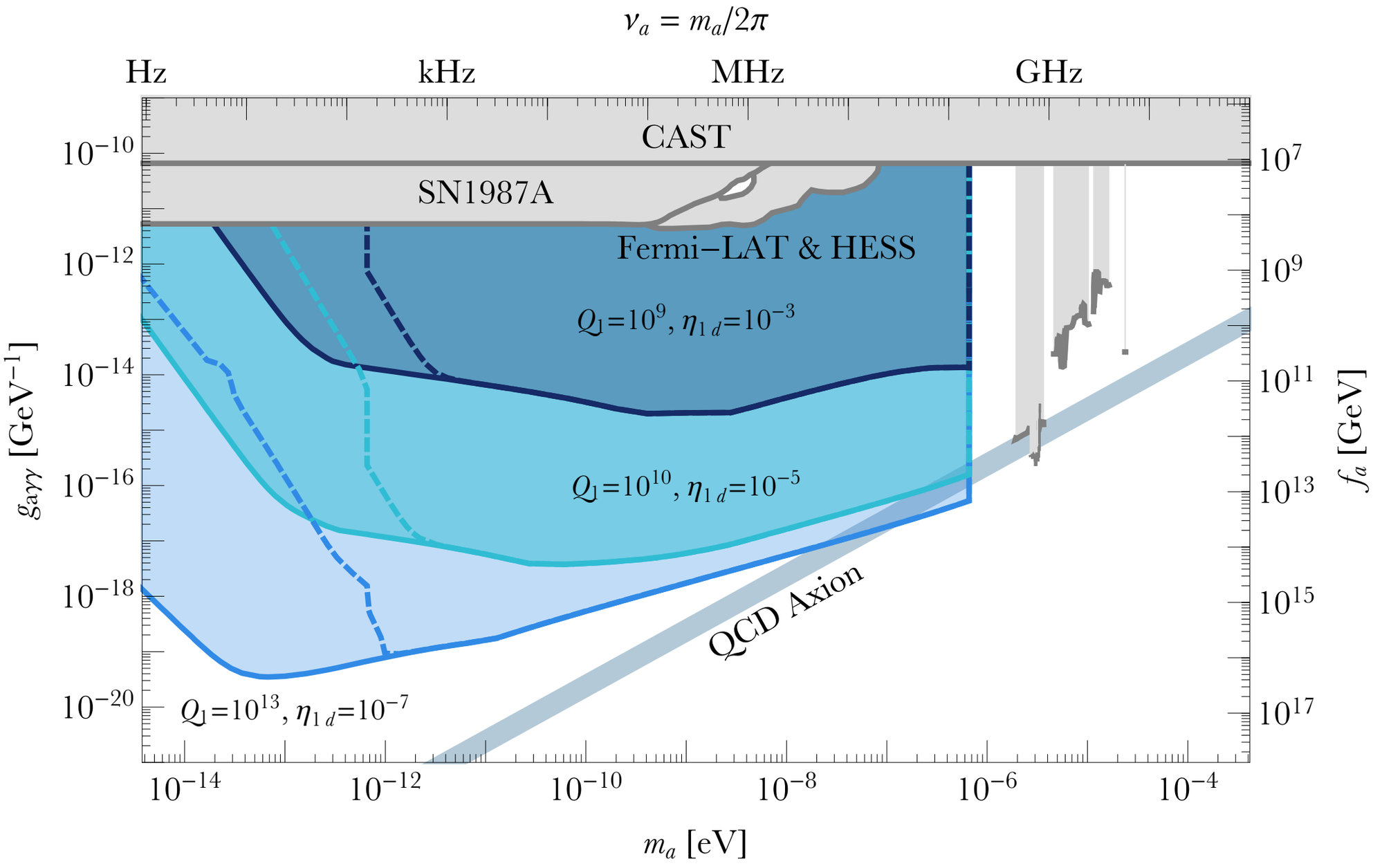


- Thermal Freeze-out has "built-in" exponential hierarchies that organize **DM phenomenology** in a rich **phase diagram**

- Take your favourite WIMP model and add a DM partner: the **couplings to SM** that give the right abundance are **exponentially reduced**

- Experimental lesson: **don't stop at thermal targets**!

SARA: Superconducting Apparatus for Resonant Axion detection



W/ A. Berlin, S. Ellis, P. Schuster, N. Toro, K. Zhou I C. Nantista, J. Nielson, S. Tantawi

TEASER: VERY PRELIMINARY

BEHIND THE WIMP

- Change the coupling
  - WIMPless, Heavy Mediators, Freeze-in, …
- Change the kinematics of freeze-out
  - Forbidden channel DM, Coannihilation, Coscattering, Impeded DM, …
- Change the thermal history of the DM sector
  - Cannibal DM, Inflatable DM, …
- Change the interaction relevant for freeze-out
  - SIMP, ELDER, Coscattering, …