Dark Matter & Particle Cosmology

A personal selection of recent developments in the field.

Julia Harz

7. Oktober 2020

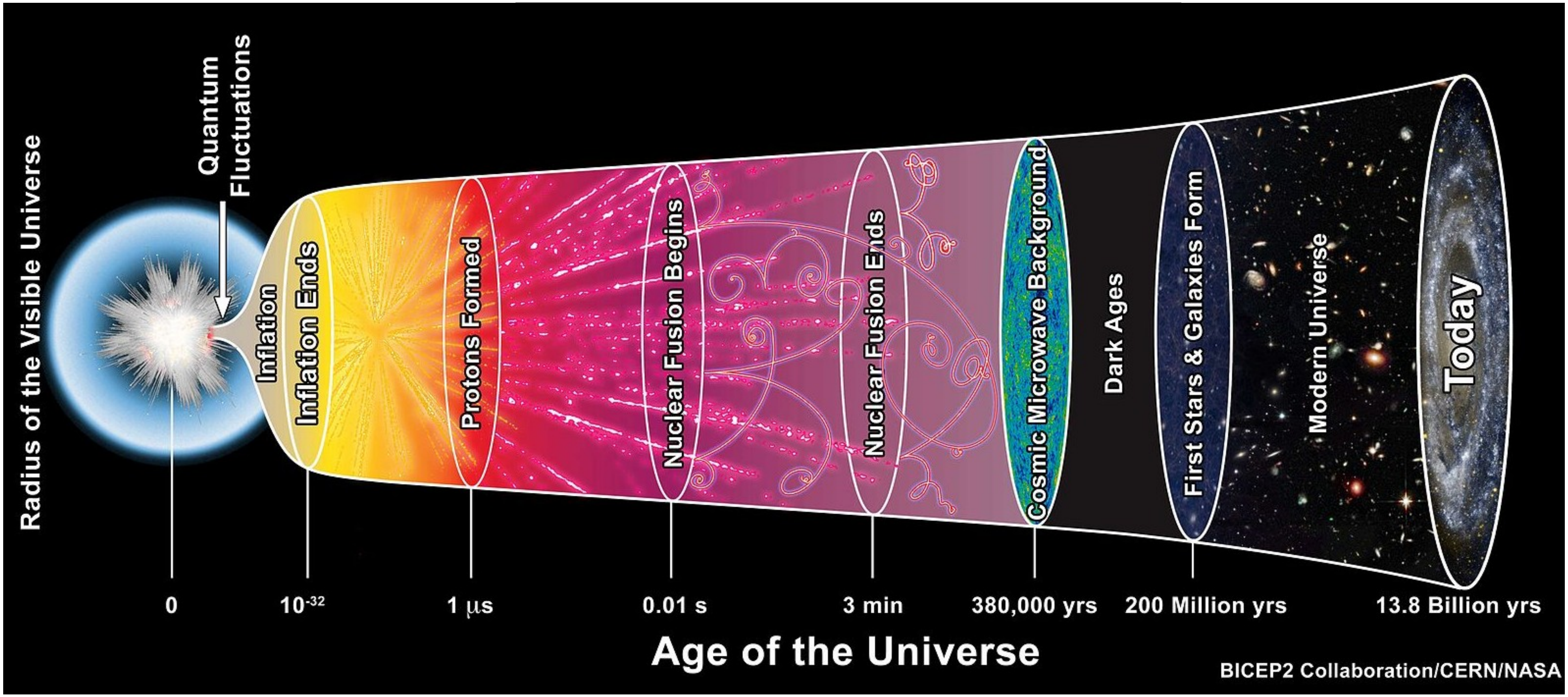
Annual CRC TRR 257 meeting, Siegen

Technische Universität München

Emmy Noether-Programm

DFG Deutsche Forschungsgemeinschaft

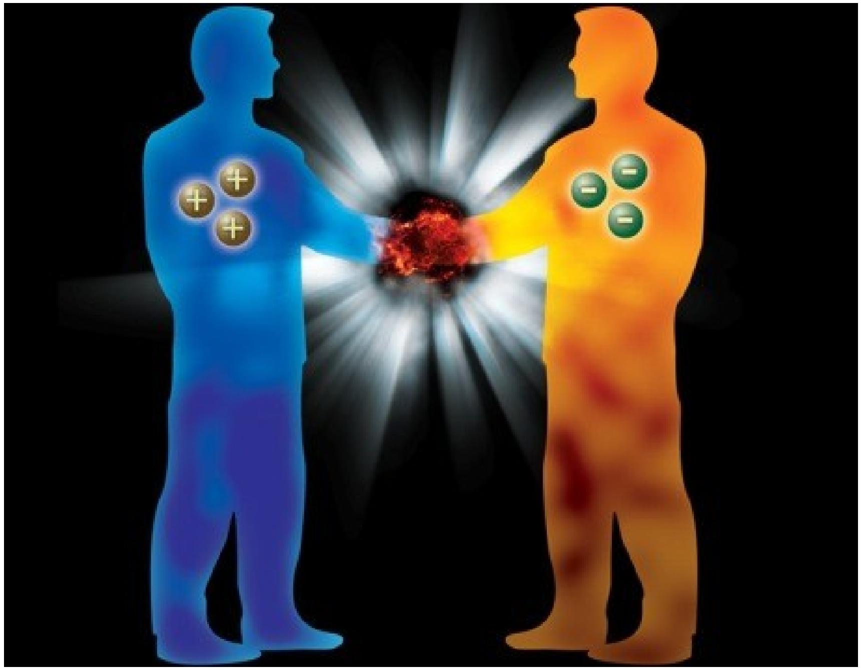
From the Big Bang to Today...



How big is the baryon asymmetry?

Our Universe consists mainly out of baryonic matter, quantified by the baryon-to-photon ratio:

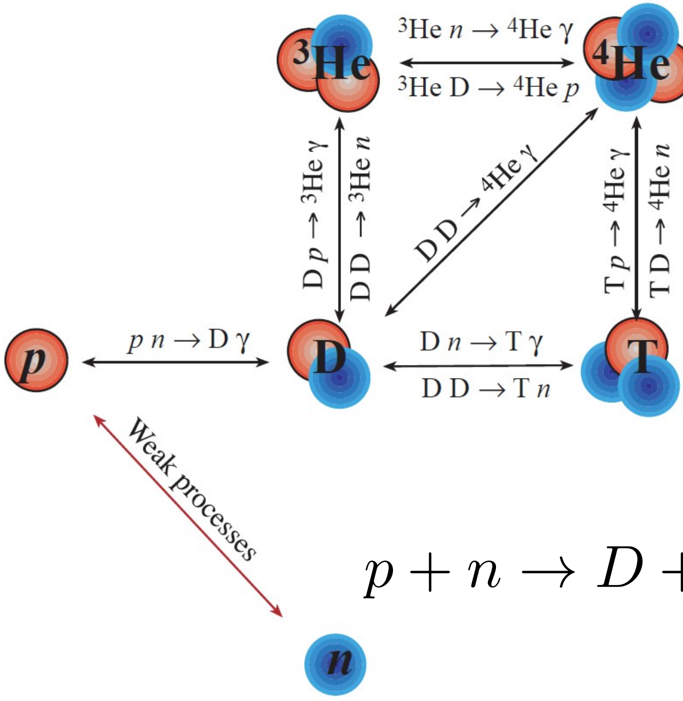
$$\eta_B = \frac{n_B}{n_\gamma} = \frac{n_b - n_{\bar{b}}}{n_\gamma}$$



$$\boxed{\eta_B^{\text{obs}} = (6.09 \pm 0.06) \times 10^{-10}}$$

What created the asymmetry?

Big Bang Nucleosynthesis

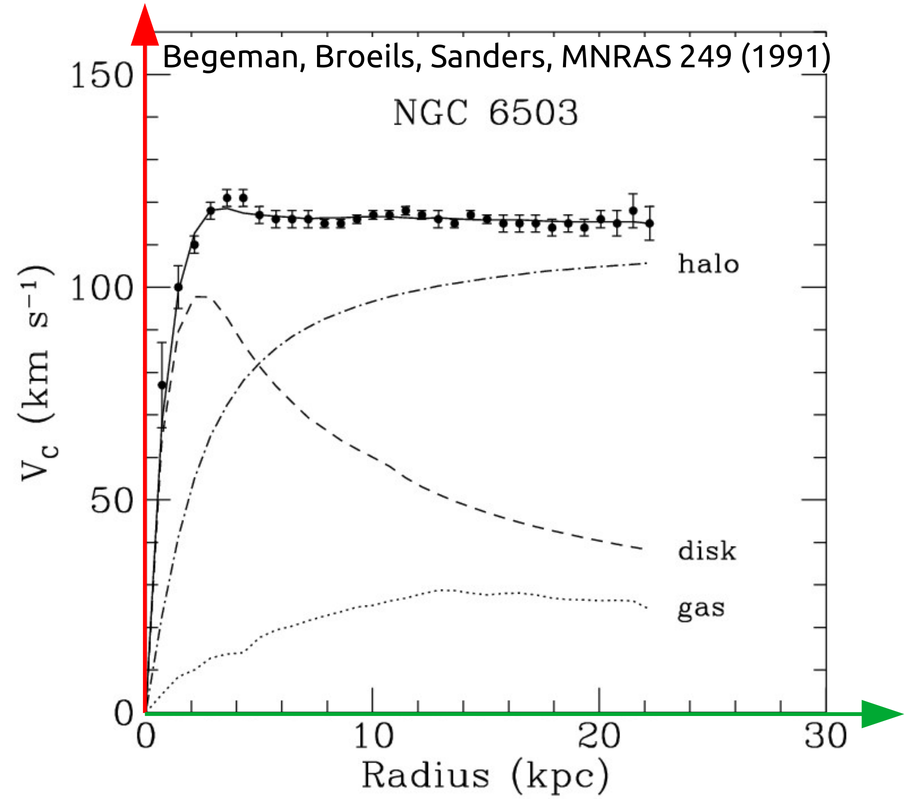


$$p + n \to D + \gamma$$

$$T_{\text{nuc}}^D \approx \frac{B_D}{\log \eta_B^{-1}}$$

How do we know that there is dark matter?

Rotation Curves of Spiral Galaxies



circular velocity from Newtonian gravity:

$$v_c(r) = \sqrt{\frac{GM(r)}{r}}$$

expectation for r>R: $v_c(r) \approx 1/\sqrt{r}$

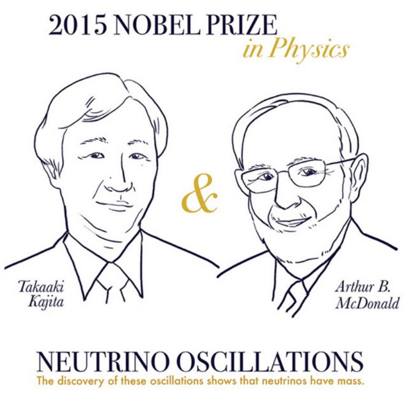
observation: $v_c(r) \approx \text{const}$

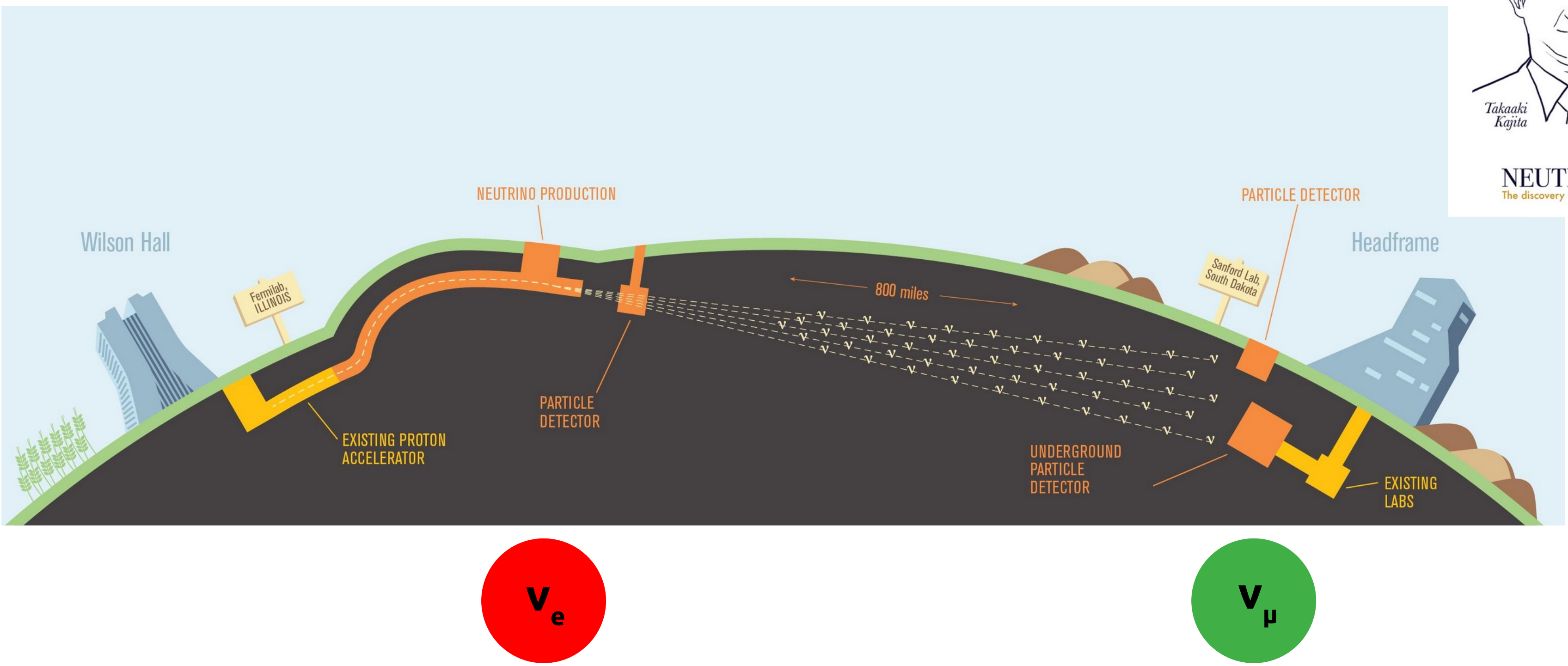
Different qualitative and quantitative evidence for the existence of Dark Matter!

$$\boxed{\Omega_{\mathrm{CDM}} h^2 = 0.120 \pm 0.001}$$

PLANCK 2018

What is the nature of neutrinos?





$$\boxed{P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta \sin^2\left(\frac{\Delta m^2}{4E} L\right)}$$

Neutrino **oscillations** require **massive** neutrinos, forbidden in the Standard Model.

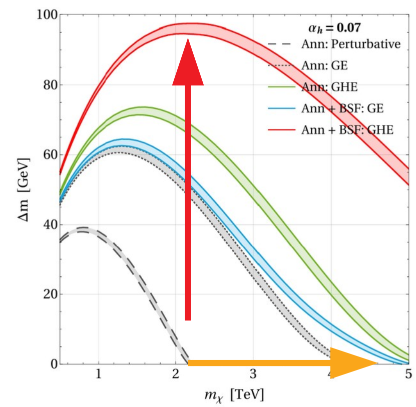
How do neutrinos get their masses?

What nature do neutrinos have? Are they their own anti-particles?

Outline

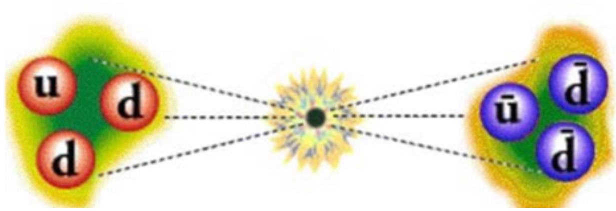
Dark Matter.

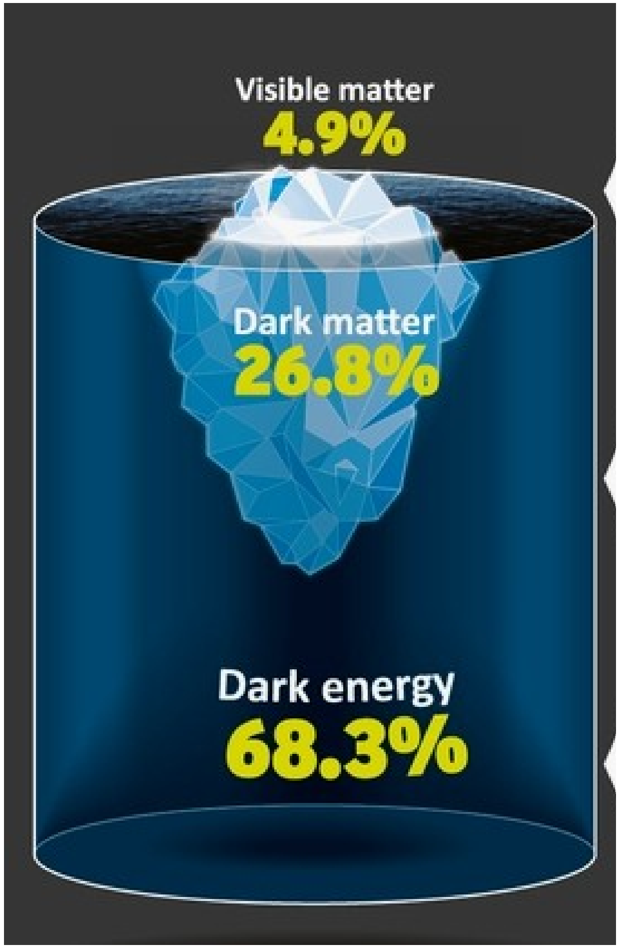
- Is the **WIMP** dead?
- Recent developments in the DM **abundance calculation**
- **Feebly** Interacting Massive Particles (FIMPs)
- **Super heavy** dark matter



Baryogenesis.

- Recent developments in **low and high scale baryogenesis**
- Testing baryogenesis with **lepton number violating** interactions
- Leptogenesis and **gravitational waves**





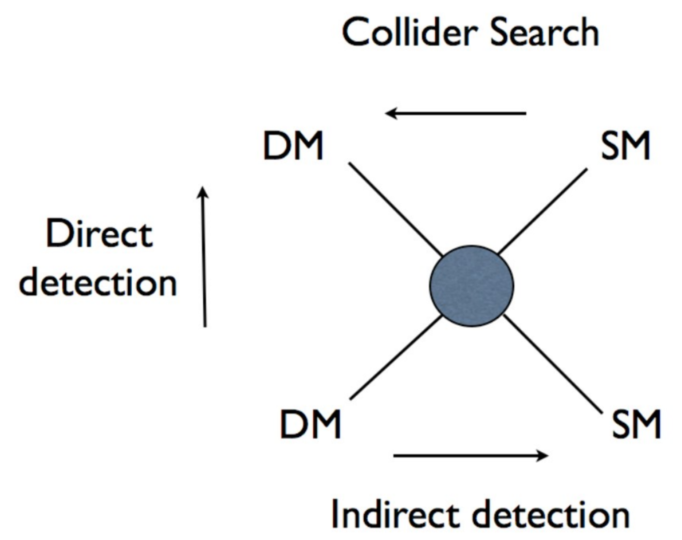
What is dark matter?

What is dark matter?

WIMP miracle?

$$\Omega h^2 \sim \frac{10^{-10}\mathrm{GeV}^{-2}}{\langle\sigma v\rangle} \sim 0.1$$

$$\Rightarrow \quad \langle\sigma v\rangle \sim \frac{g^4}{m_\chi^2} \sim 10^{-9}\mathrm{GeV}^{-2}$$



- **no observations** at the LHC, direct or indirect detection so far that supports the *minimal* WIMP model

- **Reasons** could be manifold

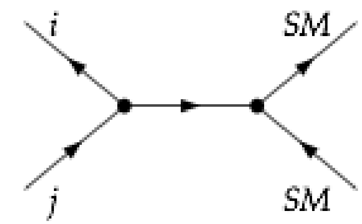
  (1) more **complex WIMP** models can evade bounds

  (2) "exceptions" in the **DM abundance calculation** that were previously not considered

  (3) **another DM generation mechanism**, e.g. freeze-in instead of freeze-out

  (4) a much **lighter** or **heavier** DM candidate

Dark Matter Freeze-out

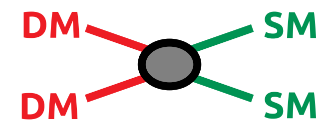


Thermal equilibrium regime (T >> m)

annihilation and production of DM in thermal equilibrium $Y \approx \text{const.}$

(2) Annihilation regime (T ~ m/10)

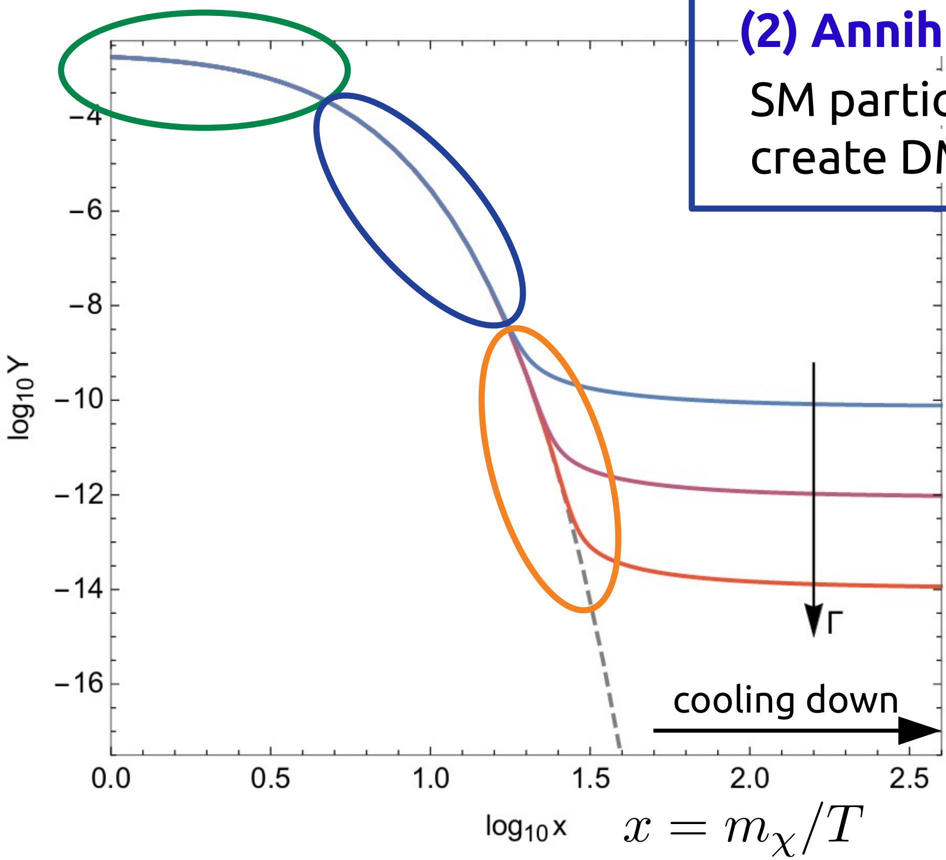
SM particles not energetic enough to create DM particles $Y \approx \exp(-m_{DM}/T)$



(3) Freeze-out (T ~ m/30)

Annihilation rate falls behind expansion rate

$$\frac{\Gamma}{H} < 1$$



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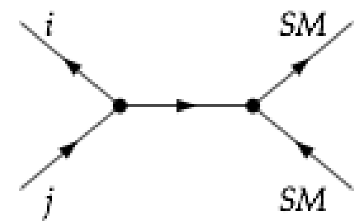

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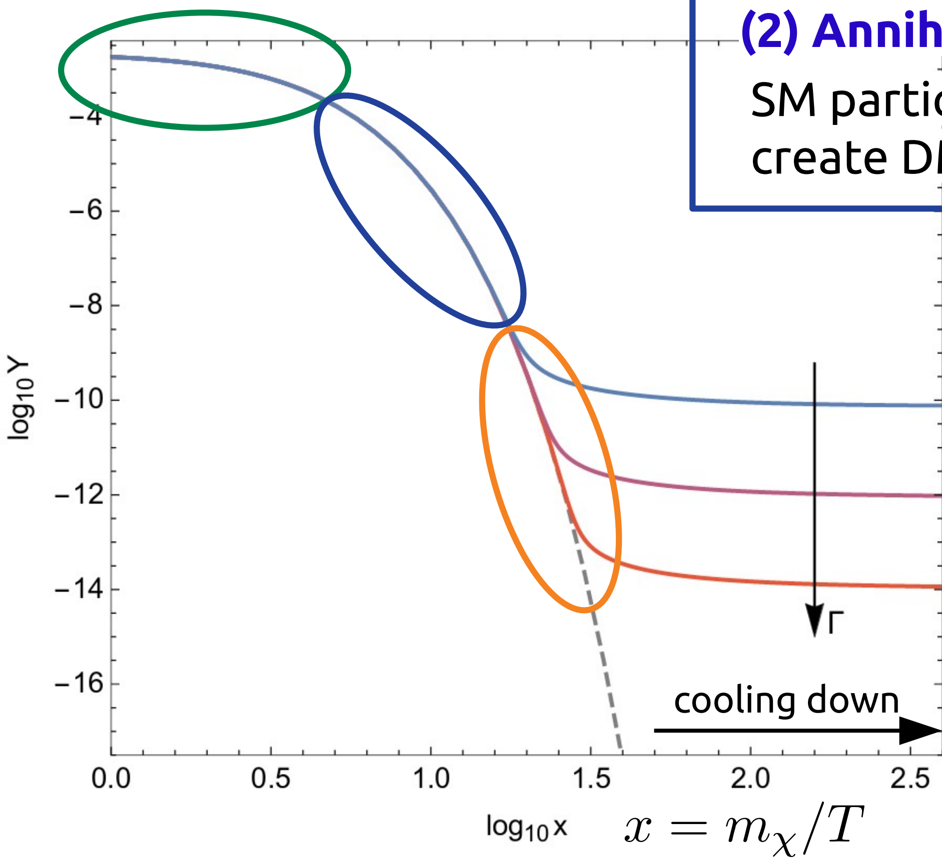

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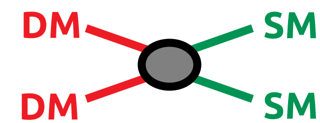

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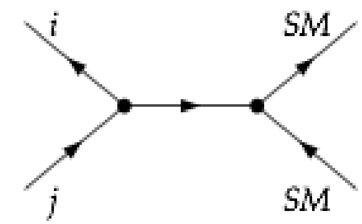
$$\Omega_\chi h^2 \propto \frac{1}{\langle \sigma_{\rm eff} v \rangle}$$

Dark Matter Freeze-out



Thermal equilibrium regime (T >> m)
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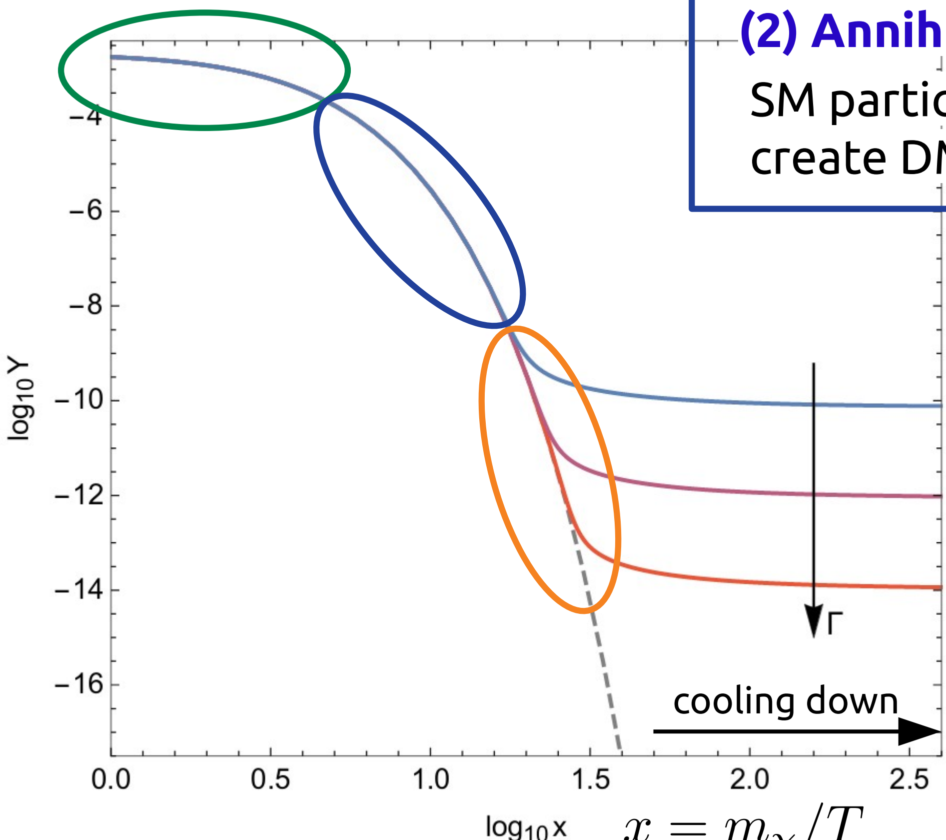

$$x = m_\chi / T$$

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SM particles not energetic enough to
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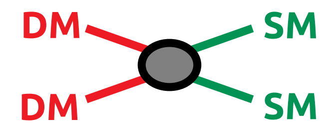

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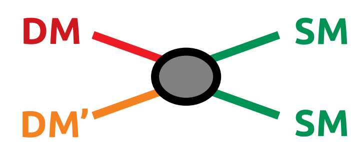


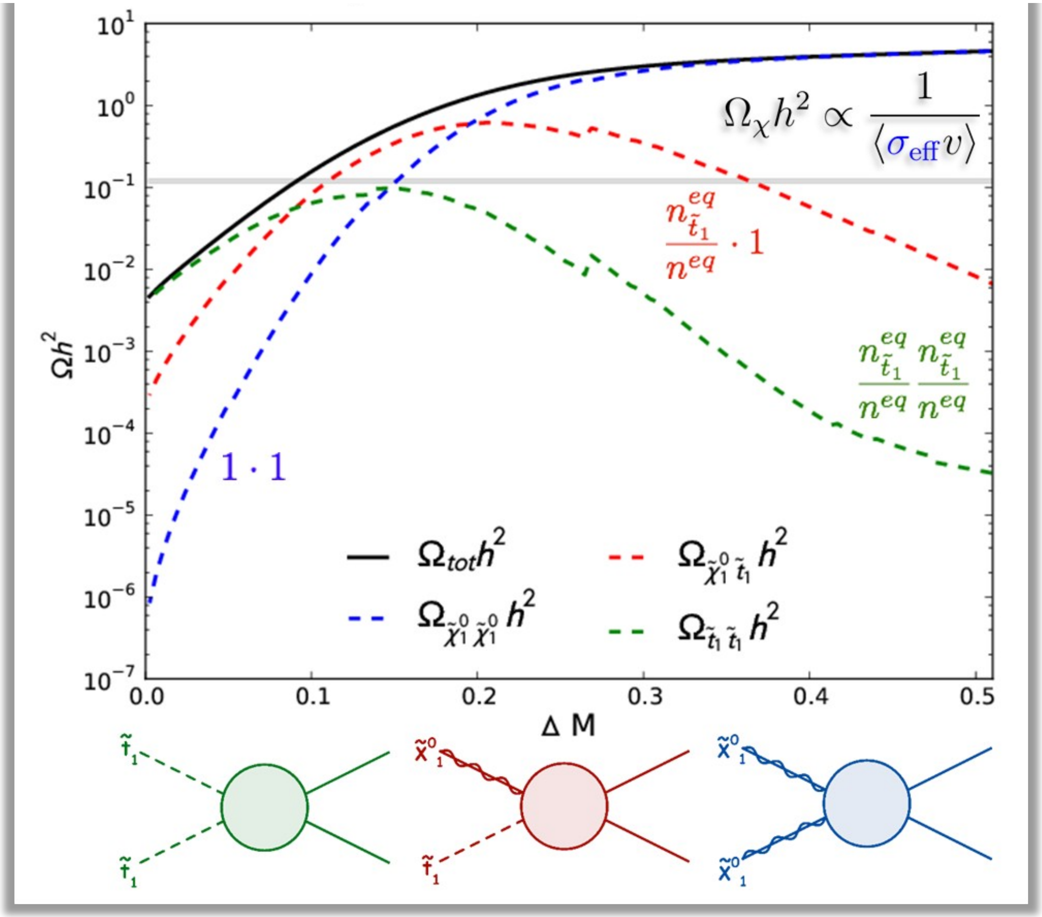
$$\langle \sigma_{\text{eff}} v \rangle = \sum_{ij} \langle \sigma_{ij} v_{ij} \rangle \frac{n_i^{eq}}{n^{eq}} \frac{n_j^{eq}}{n^{eq}}$$

$$\frac{n_i^{eq}}{n^{eq}} \propto \exp^{\frac{-(m_i - m_\chi)}{T}}$$

co-annihilation

More complex WIMP model: Coannihilation

- Standard WIMP is limited to around few TeV
- Coannihilation can open up window up to O(10 TeV) by accelerating DM depletion



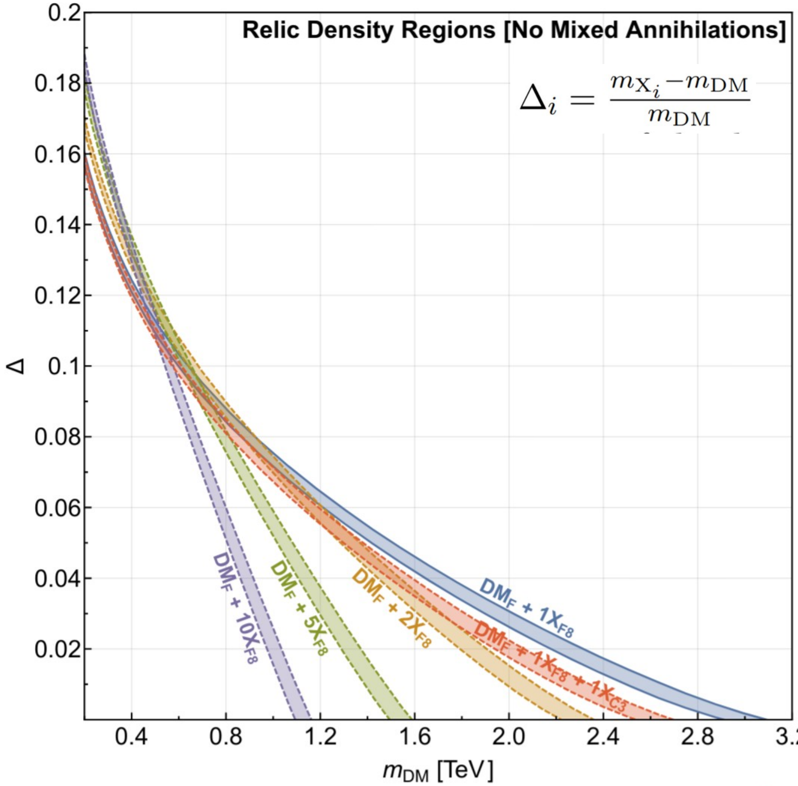
$$\Delta M = \frac{m_{\tilde{t}_1} - m_{\tilde{\chi}_1}}{m_{\tilde{\chi}_1}}$$

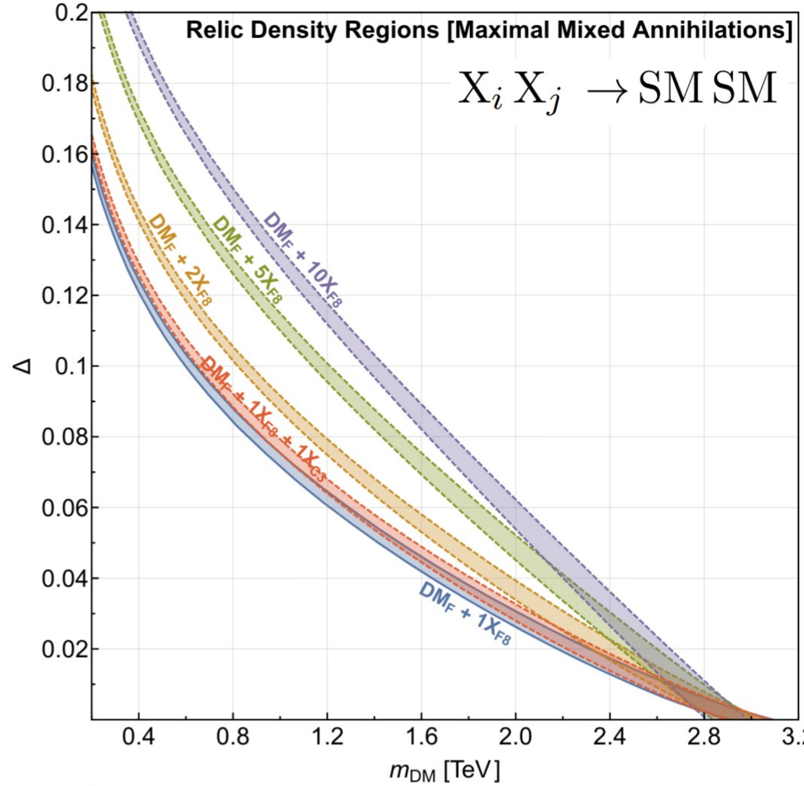
Can we simply push maximal DM mass by adding N copies of coannihilating particle X?

More complex WIMP model: Coannihilation

Unfortunately, adding more copies of coannihilating particle does not increase maximal DM mass!

$$\Omega_\chi h^2 \propto \frac{1}{\langle \sigma_{\rm eff} v \rangle}$$





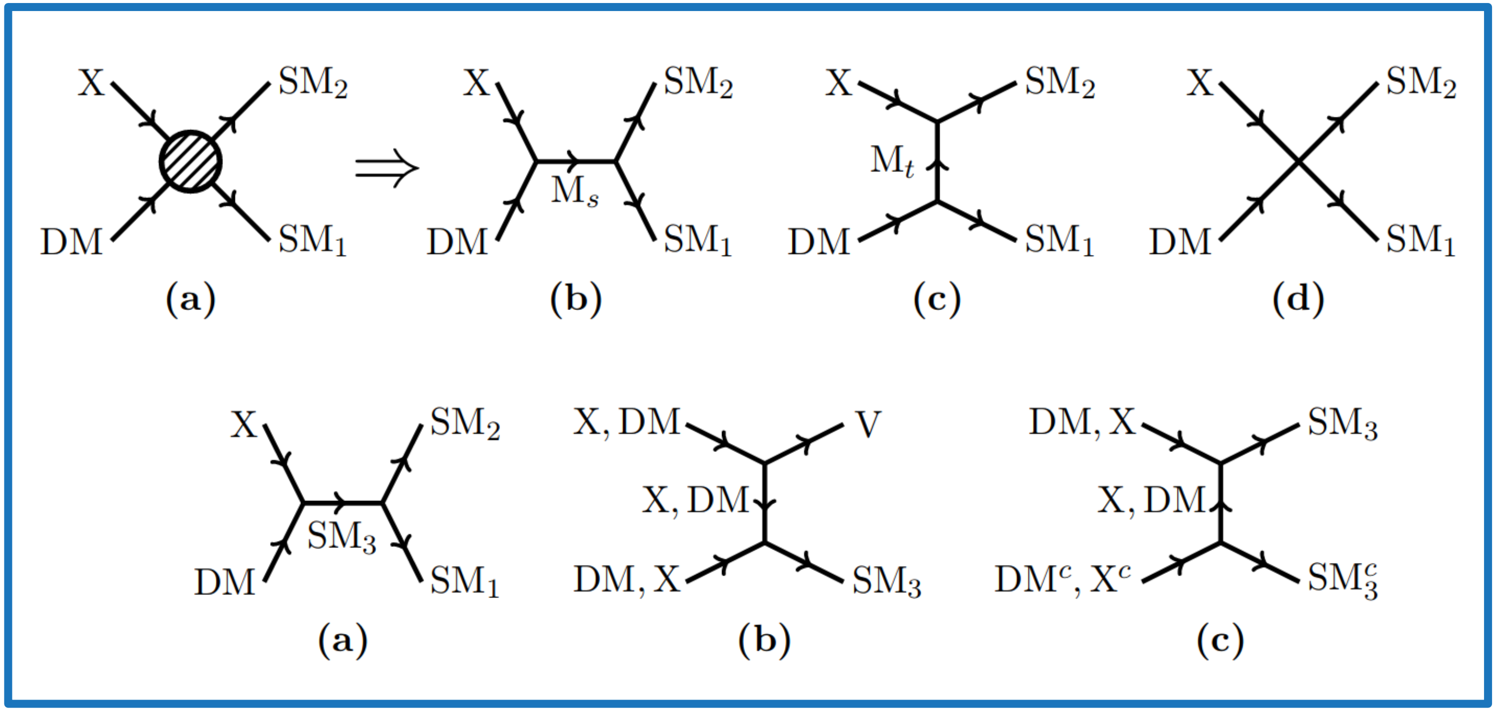
$$\sigma_{\rm eff} = \frac{N g_X^2 (1+\Delta)^3 e^{-2x\Delta}}{(g_{DM} + N g_X (1+\Delta)^{3/2} e^{-x\Delta})^2} \sigma_{XX}$$

Small Δ: $\sigma_{\rm eff} = \frac{N g_X^2}{(g_{DM} + N g_X)^2} \sigma_{XX} \quad \propto \frac{1}{N}$

Large Δ: $\sigma_{\rm eff} = N \frac{g_X^2 (1+\Delta)^3 e^{-2x\Delta}}{g_{DM}^2} \sigma_{XX} \quad \propto N$

El Hedri, de Vries (2018)

Recent specific focus on (colored) Coannihilation



Recent activities in the LHC t-channel working group (ongoing, white paper!)

Coloured coannihilations: Dark matter phenomenology meets non-relativistic EFTs, Biondini et al (2018)

Cornering Colored Coannihilation, El Hedri et al (2018)

Stop Coannihilation in the CMSSM and SubGUT Models, Ellis et al (2018)

Simplified Phenomenology for Colored Dark Sector, El Hedri et al (2017)

The Coannihilation Codex, Baker et al (2016)

To name only few examples…

Exceptions in the calculation of the relic density

1990

October 1990

CfPA-TH-90-001
BA-90-79

UNIVERSITY OF CALIFORNIA, BERKELEY

CENTER FOR PARTICLE ASTROPHYSICS

Three Exceptions in the Calculation of Relic Abundances

KIM GRIEST

Center for Particle Astrophysics and Astronomy Department, University of California, Berkeley, CA 94720

and

DAVID SECKEL

Bartol Research Institute, University of Delaware, Newark, DE 19716

Famous three exceptions:

(1) particles degenerate in mass to DM (*coannihilation*)

(2) annihilation in heavier states (*forbidden channels*)

(3) resonant enhancement

Everything settled and straightforward?

“Exceptions” in the relic calculation in 2020

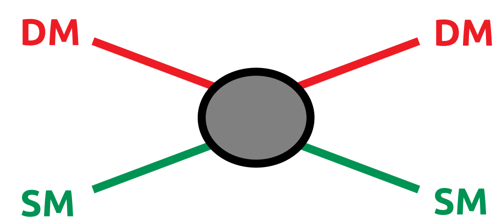
modified Hubble expansion

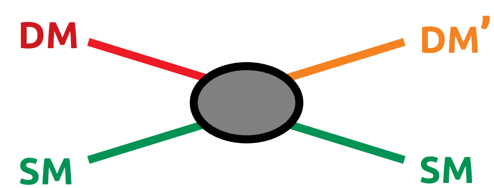
e.g. **Relentless Dark Matter**, D’Eramo, Fernandez, Profumo (2017)
see also Arbey, Mahmoudi (2008)

$$\boxed{\dot{n} + 3Hn = -\langle \sigma_{\rm eff} v \rangle (n^2 - n_{\rm eq}^2)}$$

Breakdown of assumptions:

Kinetic equilibrium maintained by





modification of particle physics cross section

- NLO
- theoretical uncertainties
- Sommerfeld enhancement
- Boundstate formation

finite temperature effects

Breakdown of assumptions

Early kinetic decoupling

In the usual Dark Matter calculation it is assumed that DM stays in thermal equilibrium at least until freeze-out

$$\dot{n} + 3Hn = -\langle \sigma_{\rm eff} v \rangle (n^2 - n_{\rm eq}^2)$$

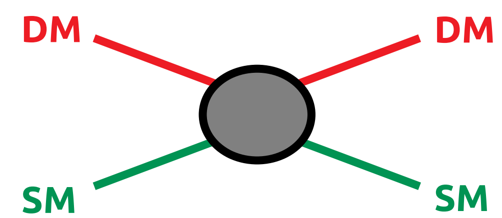
$$\frac{dn_\chi}{dt} + 3Hn_\chi = g_\chi \int \frac{d^3p}{(2\pi)^3 E} C_{\rm ann}[f_\chi]$$

$$C_{\rm ann} = g_\chi E \int \frac{d^3\tilde{p}}{(2\pi)^3} v\sigma_{\bar\chi\chi\to\bar f f} \times \left[f_{\chi,\rm eq}(E) f_{\chi,\rm eq}(\tilde{E}) - \boxed{f_\chi(E) f_\chi(\tilde{E})} \right]$$

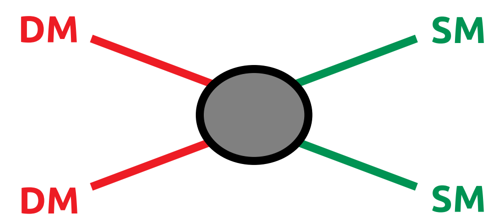
$$\boxed{f_\chi = A(T) f_{\chi,\rm eq} = \frac{n_\chi}{n_{\chi,\rm eq}} f_{\chi,\rm eq}}$$

$$\langle \sigma v \rangle \equiv \frac{g_\chi^2}{n_{\chi,\rm eq}^2} \int \frac{d^3p}{(2\pi)^3} \frac{d^3\tilde{p}}{(2\pi)^3} \sigma v_{\bar\chi\chi\to\bar f f} f_{\chi,\rm eq}(\mathbf{p}) f_{\chi,\rm eq}(\tilde{\mathbf{p}})$$

Hard-coded in common DM codes!



$$\gg$$



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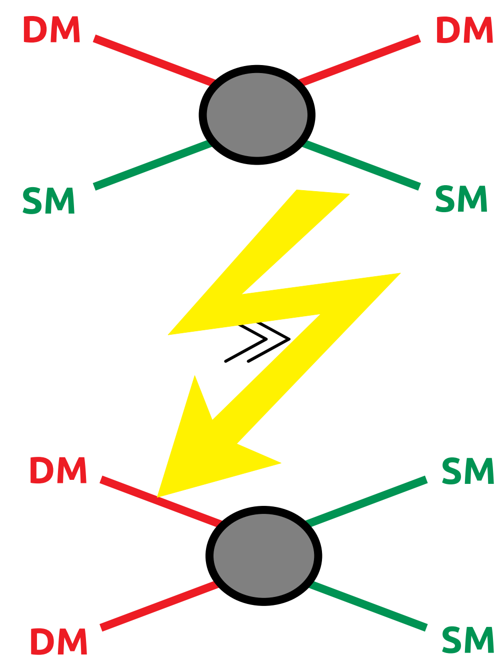


In case of enhancement of the annihilation cross section this is not necessarily fullfilled!

→ Development of a rigorous numerical treatment + code:

Binder, Bringmann, Gustafsson, Hryczuk (2017)

→ phenomenologcial studies:

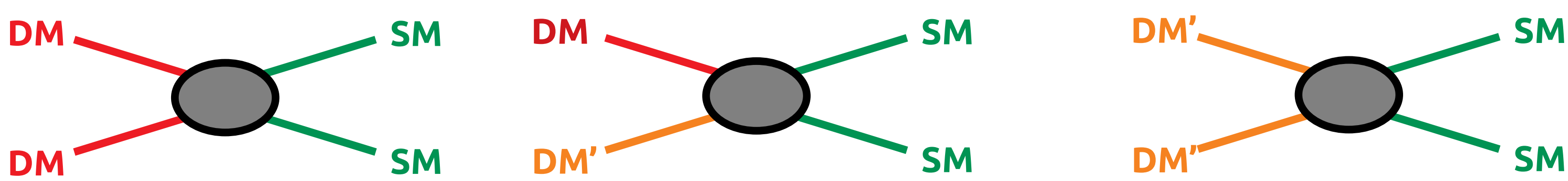
Duch, Grzadkowski (2017)
Feng, Kaplinghat, Yu (2010)
Dent, Dutta, Scherrer (2010)

Conversion driven freeze-out

Based on Gondolo & Gelmini's exception "coannihilation"

$$\dot{n} + 3Hn = -\langle \sigma_{\rm eff} v \rangle (n^2 - n_{\rm eq}^2)$$

In **coannihilation** scenarios the following processes are present:



Kinetic equilibrium maintained by

justifies the usage of **one** BEQ

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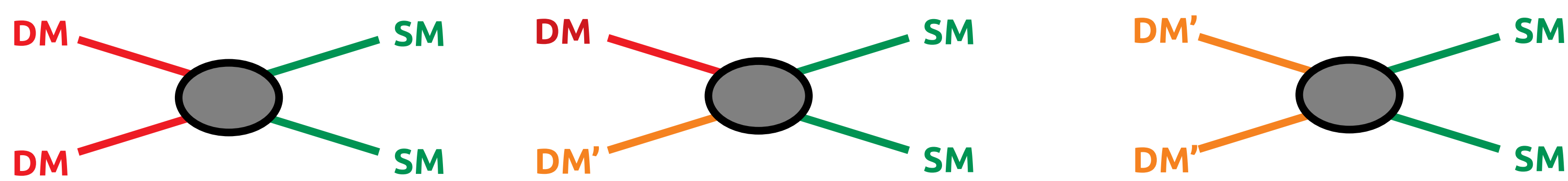

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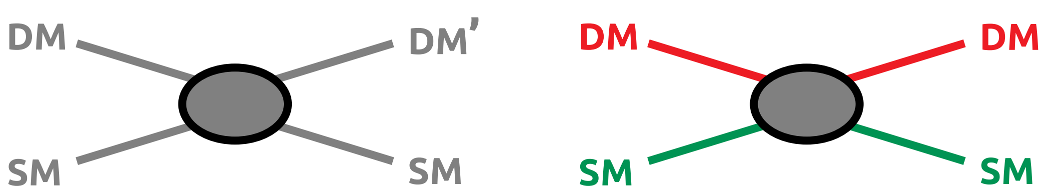


~~justifies the usage of **one** BEQ~~

If it falls out of equilibrium,
coupled BEQ are needed

"Coannihilation without chemical equilibrium",
Garny, Heisig, Lülf, Vogl (2017)

And more…

$$\dot{n} + 3Hn = -\langle\sigma_{\rm eff} v\rangle(n^2 - n_{\rm eq}^2)$$

Coscattering

D'Agnolo, Pappadopulo, Rudermann (2017)

Forbidden Dark Matter

D'Angelo, Rudermann (2015)

Re-annihilation

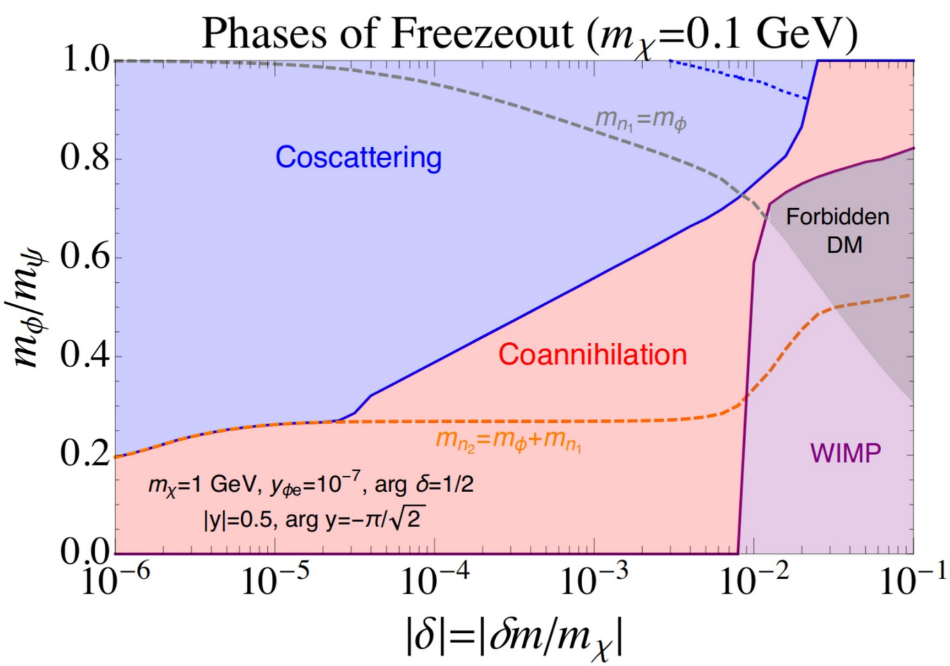
Binder, Gustafsson, Kamada (2018)

Cannibal Dark Matter

Pappadopulo, Rudermann, Trevisan (2016)

Semi-annihilation

D'Eramo, Thaler (2010)

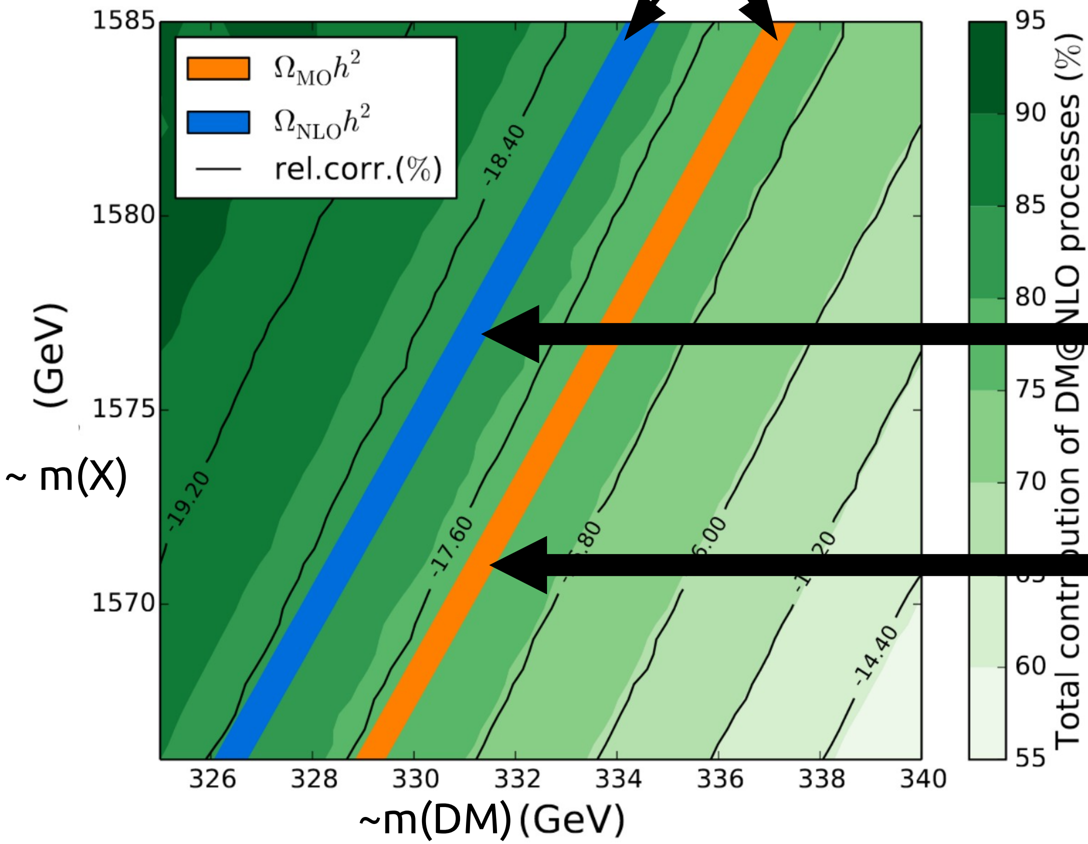


… and more …

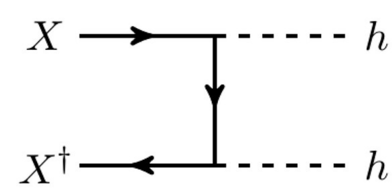
Effects impacting the particle cross section

Impact of higher order corrections

$$\Omega_{\mathrm{CDM}}h^2 = 0.120 \pm 0.001$$



Born level calculation



$$\sigma_{\mathrm{eff}}v_{\mathrm{rel}} = \sigma^{\mathrm{tree}}v_{\mathrm{rel}}$$

Our calculation that includes higher order corrections

Conventional dark matter tool at lowest order only

→ 20 % correction on the theoretical relic density prediction

$$\Omega_\chi h^2 \propto \frac{1}{\langle \sigma_{\mathrm{eff}} v \rangle}$$

JH et al., (2013 - 2019)

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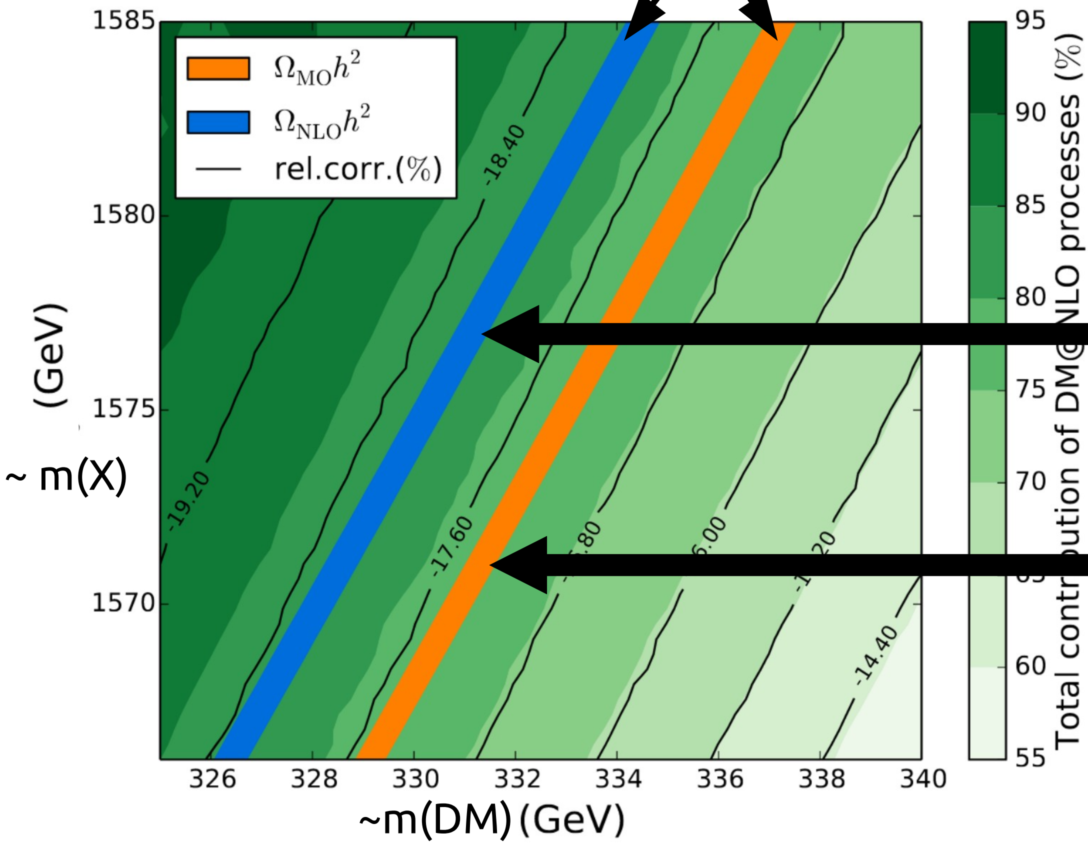

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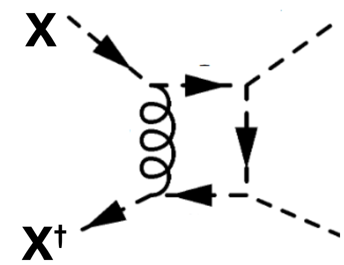
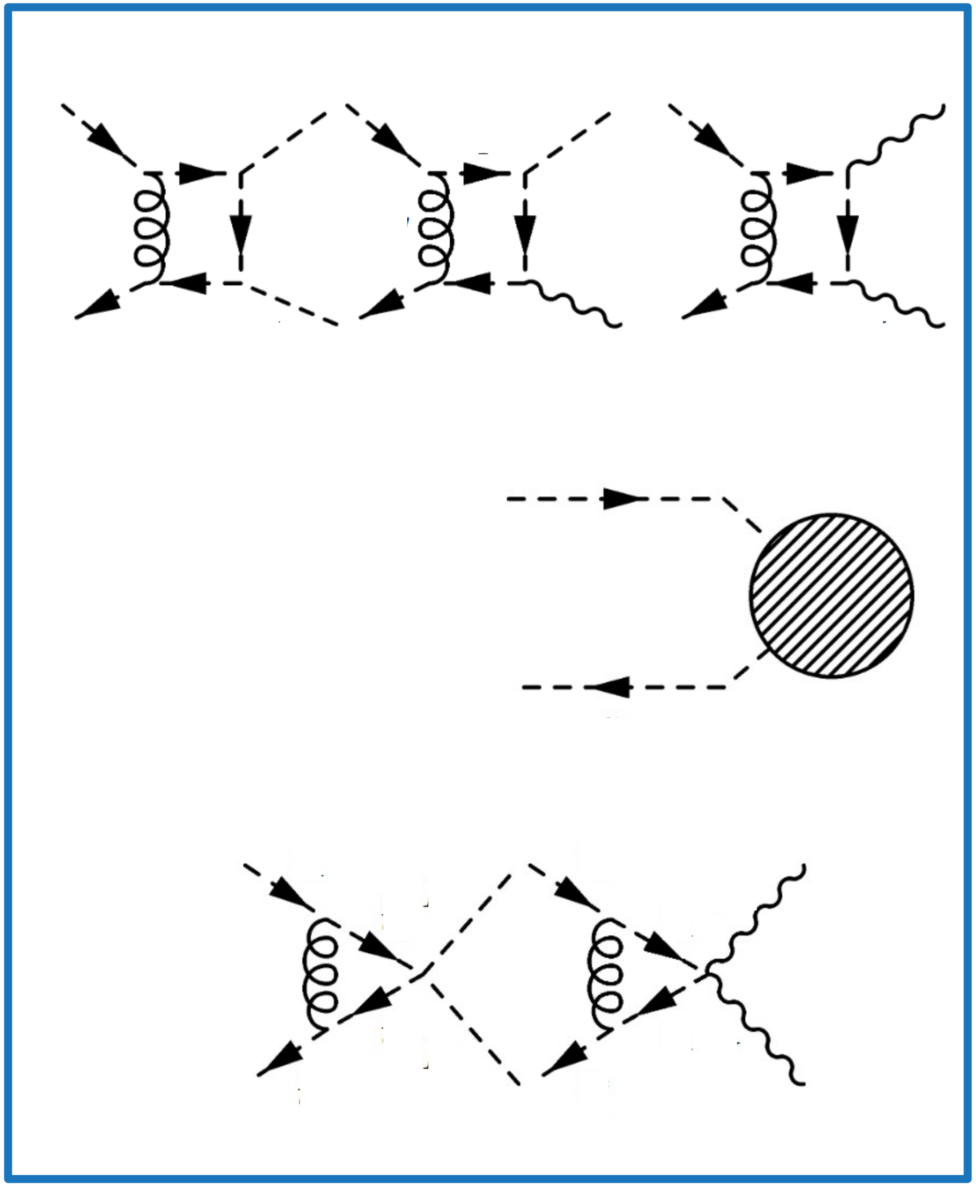


$$\sigma_{\rm eff}v_{\rm rel} = \sigma^{\rm NLO}v_{\rm rel}$$

$$\Omega_\chi h^2 \propto \frac{1}{\langle\sigma_{\rm eff}v\rangle}$$

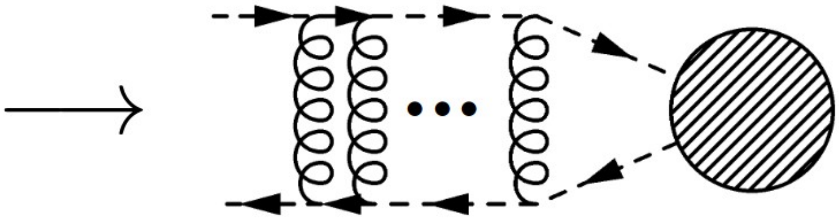
JH et al., (2013 - 2019)

Sommerfeld effect



Important in the regime:

$$\alpha \sim v_{\mathrm{rel}}$$

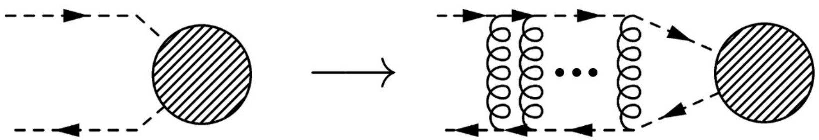


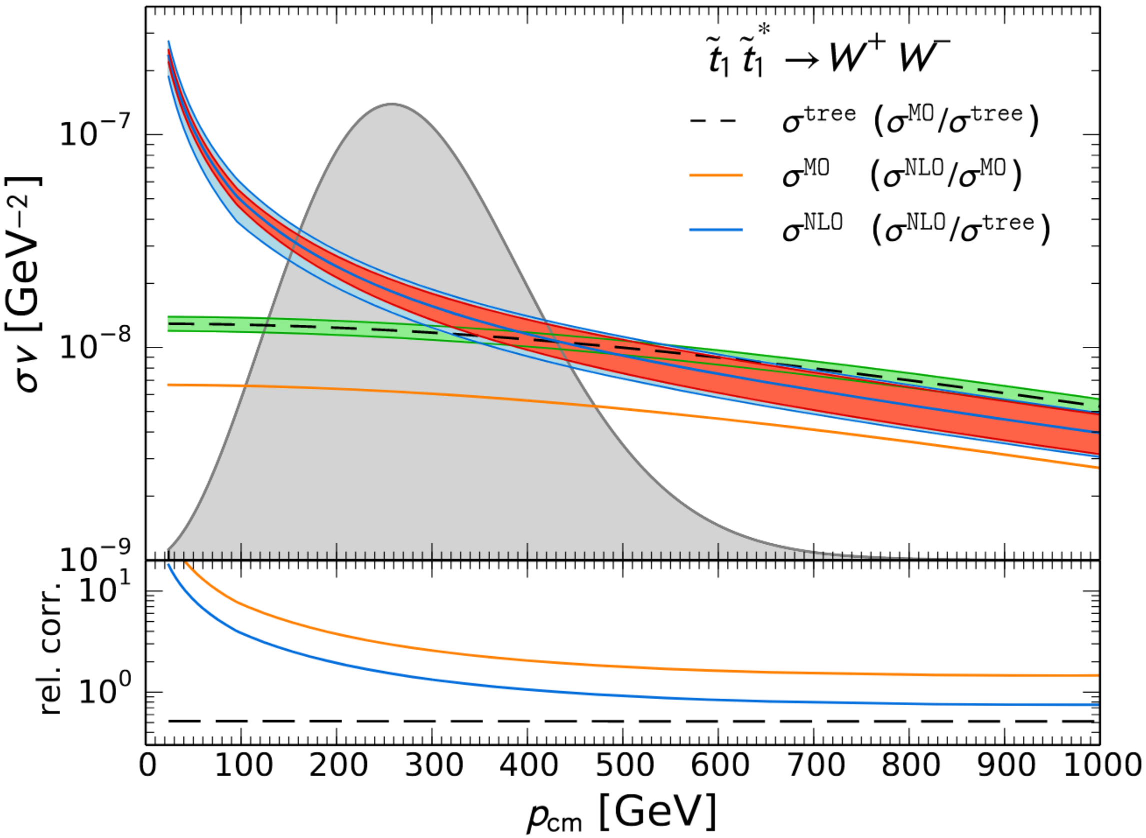
Exchange of n gluons contains a correction proportional to

$$\left(\frac{\alpha}{v_{\mathrm{rel}}}\right)^n \sim 1$$

Sommerfeld effect

Non-perturbative effects for small velocities





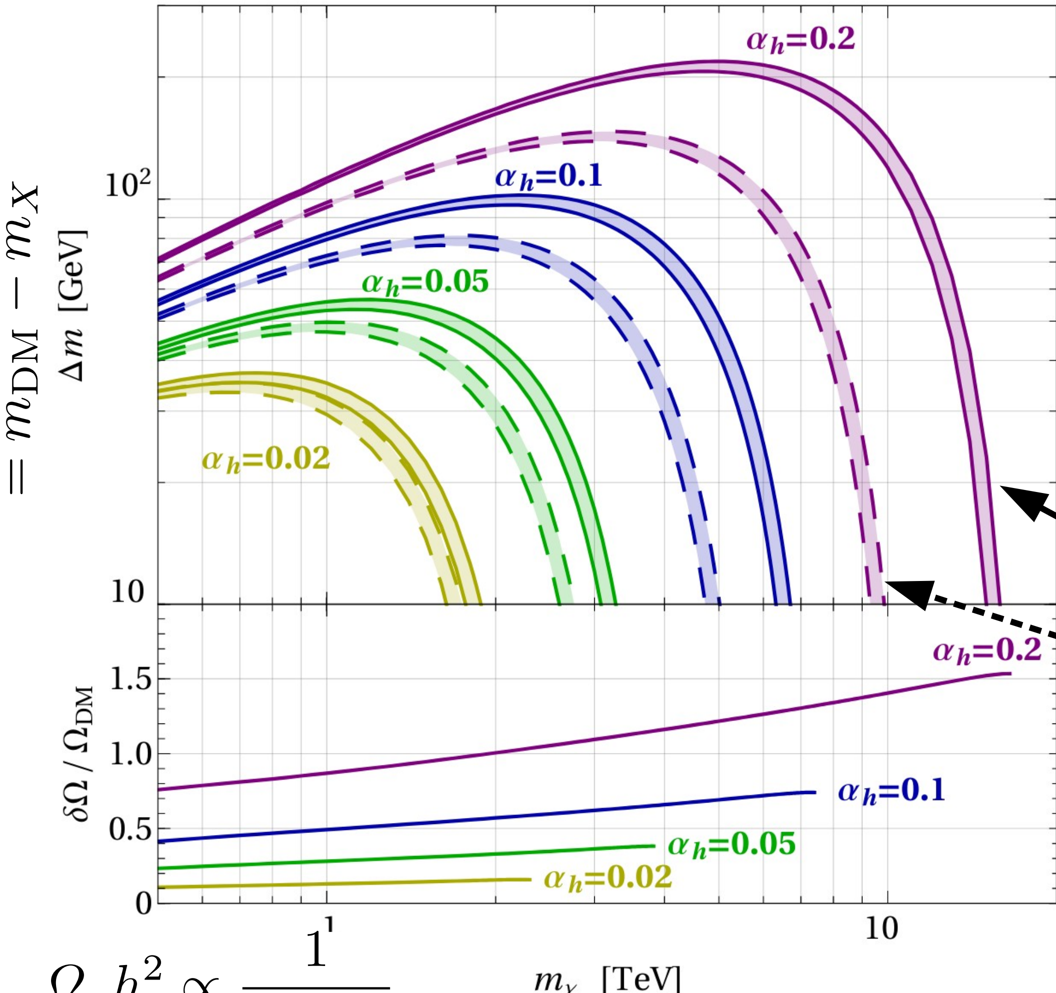
$$\Omega_\chi h^2 \propto \frac{1}{\langle \sigma_{\rm eff} v_{\rm rel} \rangle}$$

→ Large K-factor in relevant region K=1-9

JH et al. (2015-2019)

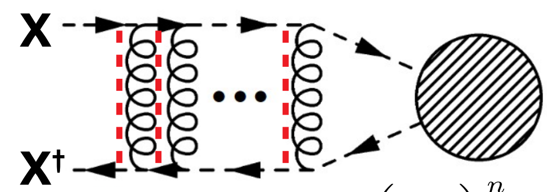
Sommerfeld effect

Higgs enhancement



$$\Omega_\chi h^2 \propto \frac{1}{\langle \sigma_{\rm eff} v \rangle}$$

Sommerfeld enhancement



$$\left(\frac{\alpha}{v_{\rm rel}}\right)^n \sim 1$$

$$\sigma_{\rm eff} v_{\rm rel} = \sigma^{\rm tree} v_{\rm rel} \times S_0$$

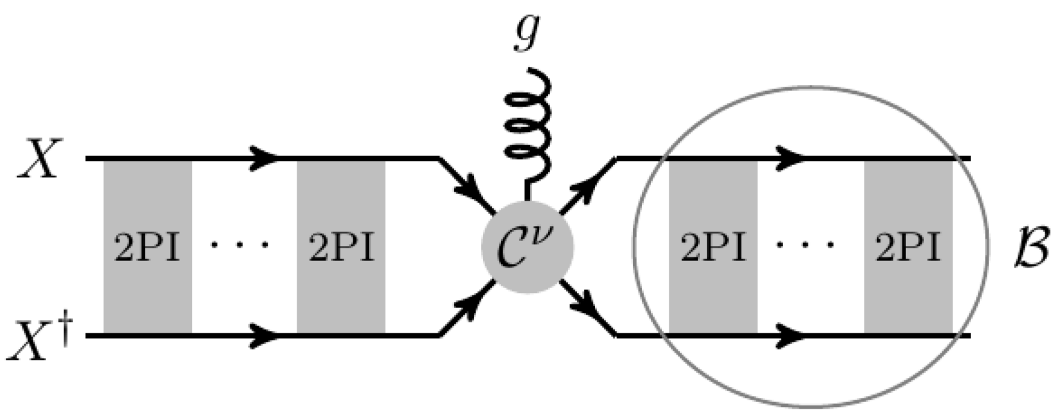
including Higgs exchange

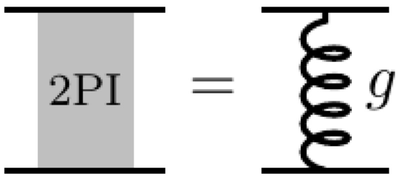
without Higgs exchange

→ first study of Higgs enhancement in colored coannihilation scenarios

JH, Petraki (2018)

Bound state formation





$(X + X^\dagger)_{[\mathbf{8}]} \to \mathcal{B}(XX^\dagger)_{[\mathbf{1}]} + g_{[\mathbf{8}]}$ **bound state formation**

$(\mathrm{XX}^\dagger)_{[\mathbf{1}]} + g_{[\mathbf{8}]} \to (X + X^\dagger)_{[\mathbf{8}]}$ **bound state ionisation**

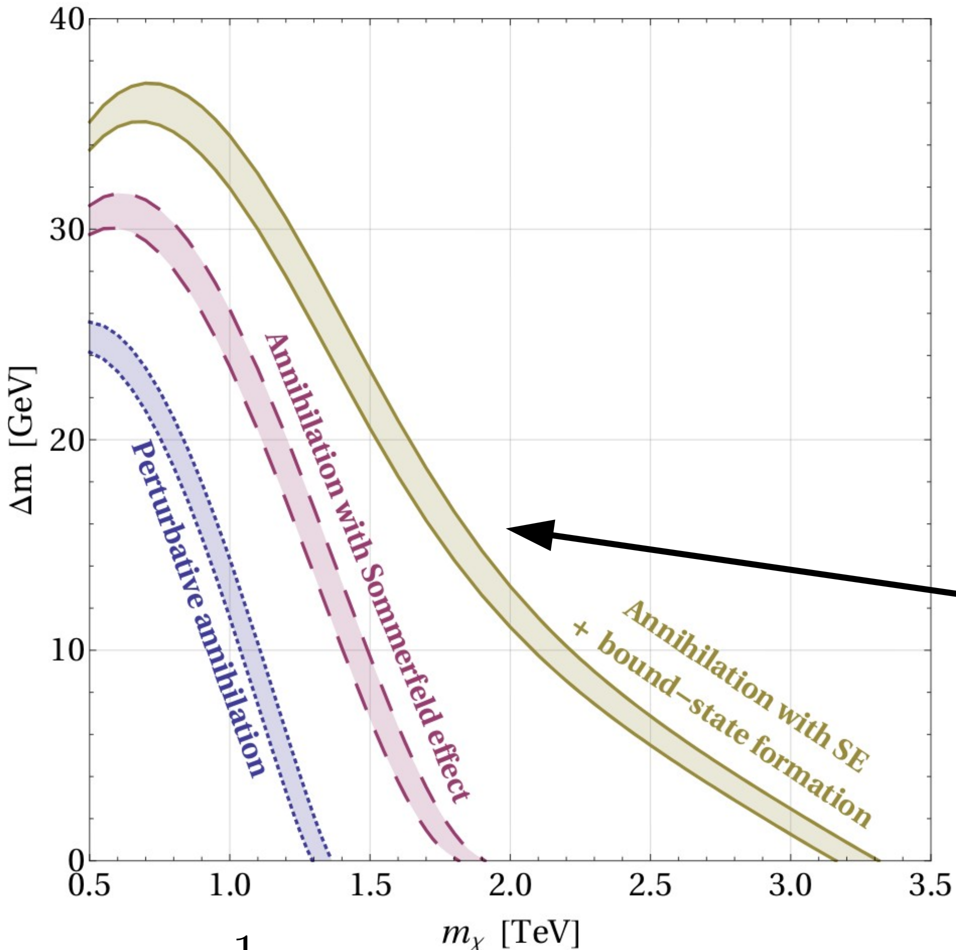
$\mathcal{B}(XX^\dagger)_{[\mathbf{1}]} \to g_{[\mathbf{8}]}\ g_{[\mathbf{8}]}$ **bound state decay**

$$\boxed{\langle \sigma_{\rm BSF} v_{\rm rel} \rangle_{\rm eff} = \langle \sigma_{\rm BSF} v_{\rm rel} \rangle \times \left(\frac{\Gamma_{\rm dec}}{\Gamma_{\rm dec} + \Gamma_{\rm ion}} \right)}$$

→ additional "annihilation" channel alters the relic density prediction

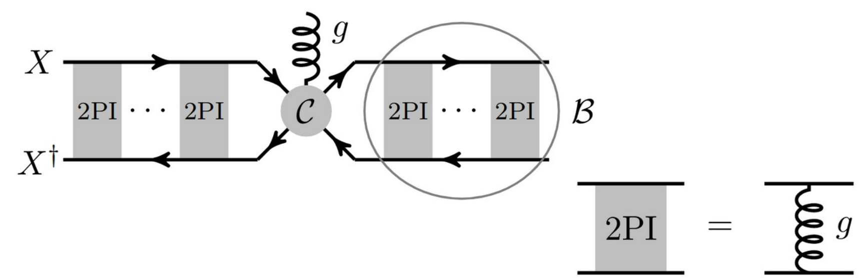
Bound state formation

Bound state formation in non-abelian theories



$$\Omega_\chi h^2 \propto \frac{1}{\langle \sigma_{\rm eff} v \rangle}$$

bound state formation and decay



$$\langle \sigma_{\rm eff} v_{\rm rel} \rangle = \langle \sigma_{\rm ann} v_{\rm rel} \rangle + \langle \sigma_{\rm BSF} v_{\rm rel} \rangle_{\rm eff}$$

Bound states and their consecutive decays provide an additional annihilation channel.

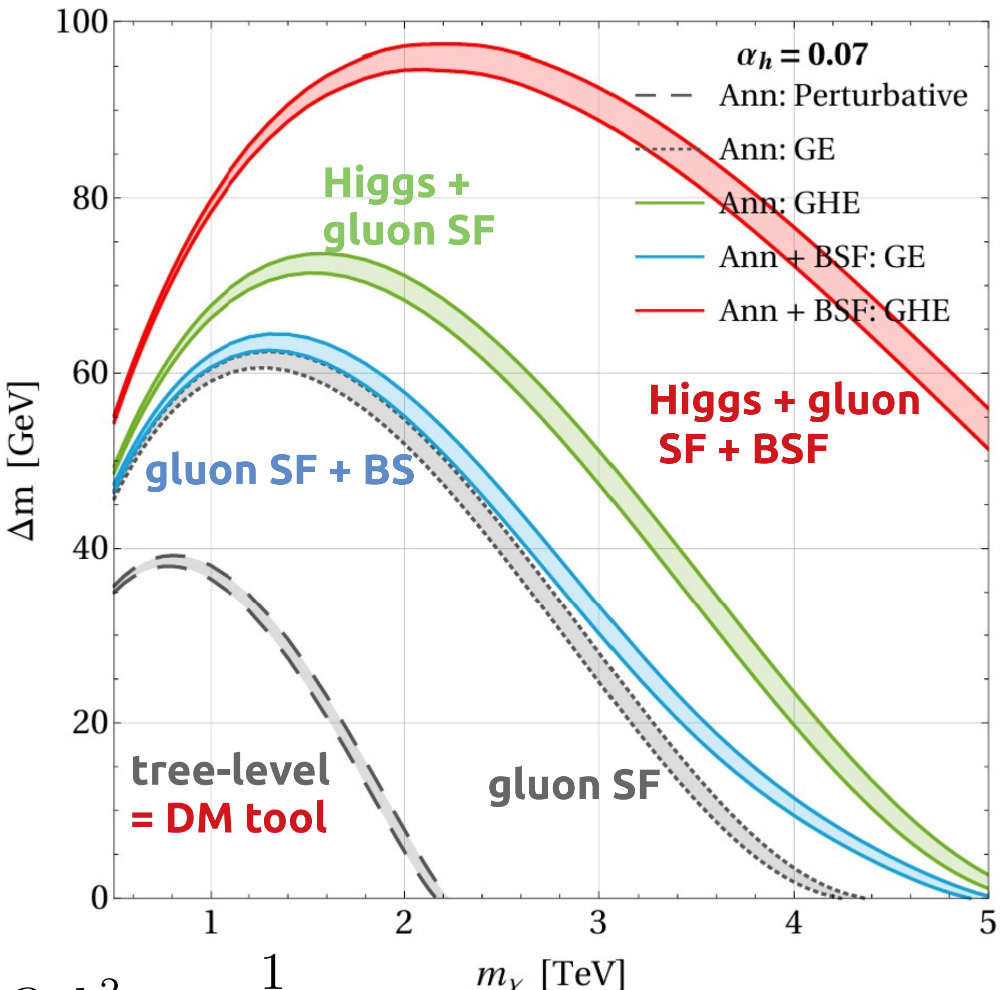
including bound state formation

→ bound state formation can have significant effect on relic abundance

JH, Petraki (2018)

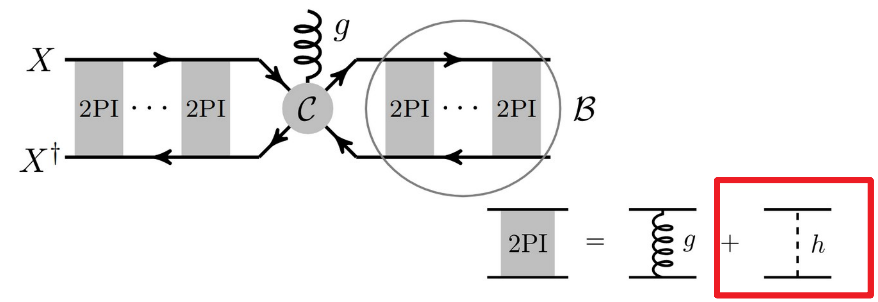
Bound state formation

Bound state formation including the Higgs boson



$$\Omega_\chi h^2 \propto \frac{1}{\langle \sigma_{\rm eff} v \rangle}$$

bound state formation and decay



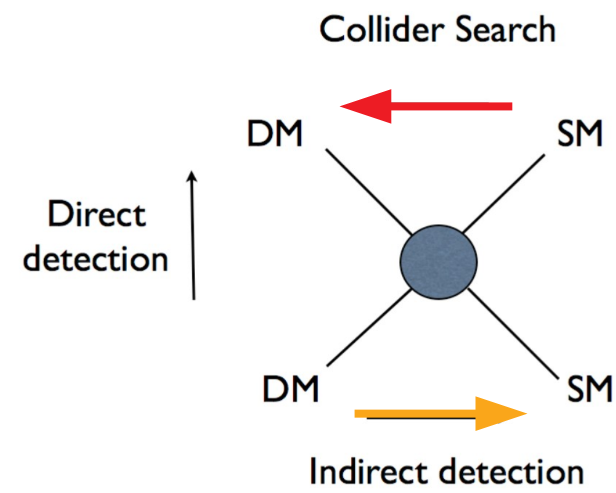
$$\langle \sigma_{\rm eff} v_{\rm rel} \rangle = \langle \sigma_{\rm ann} v_{\rm rel} \rangle + \langle \sigma_{\rm BSF} v_{\rm rel} \rangle_{\rm eff}$$

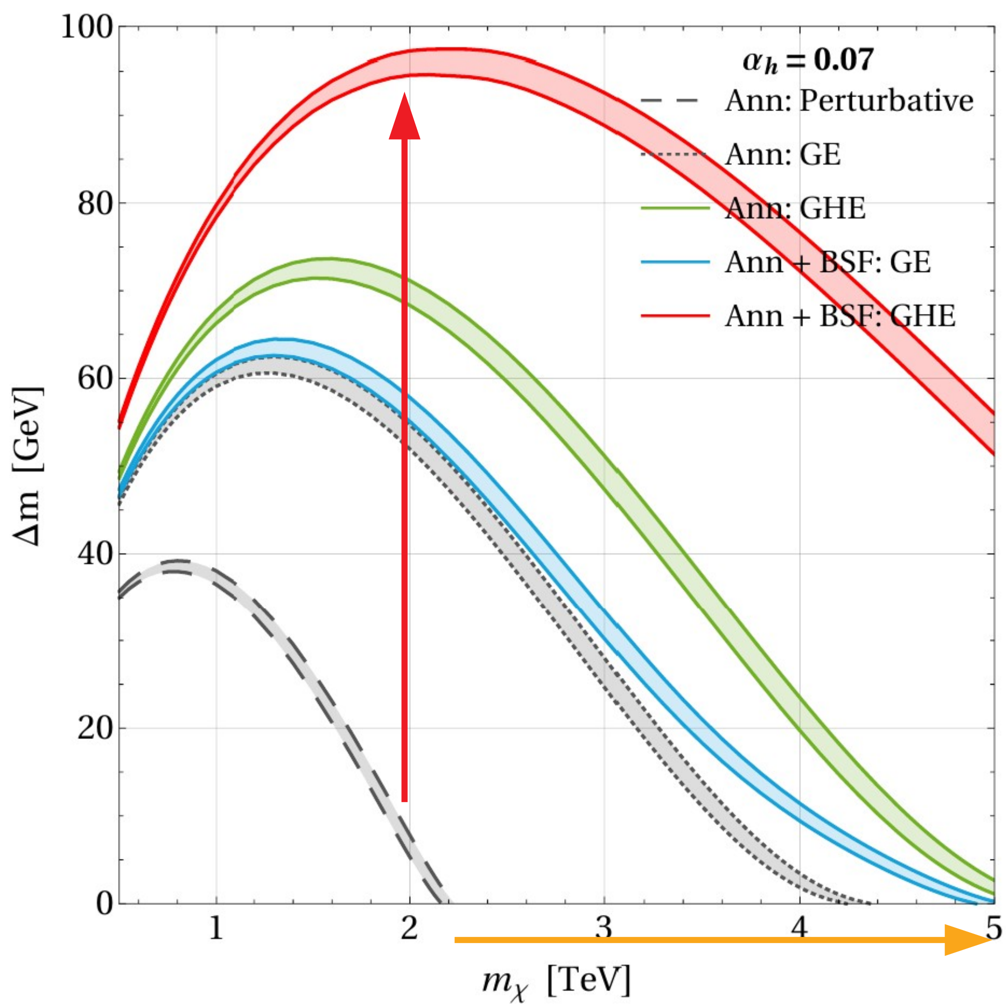
Bound states and their consecutive decays provide an additional annihilation channel.

→ **Higgs can alter the result significantly, but was previously neglected!**

JH, Petraki (2019)

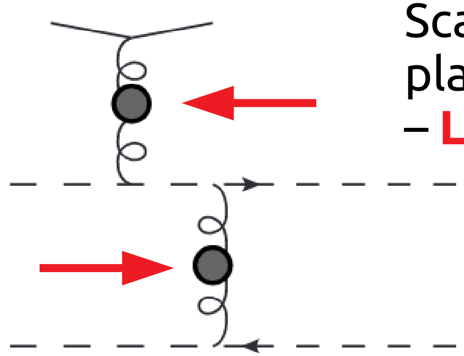
Why relevant?





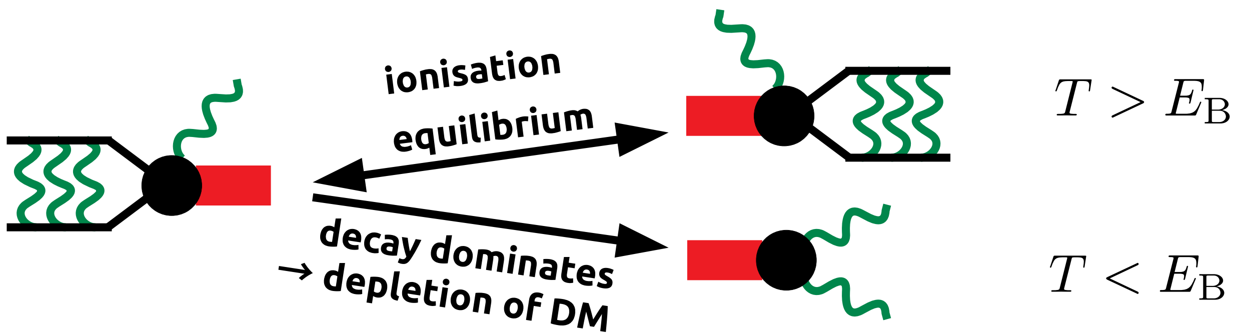
- More precise theoretical predictions
- Increased predicted mass splitting
  → **improved detection prospects with respect to multi-/mono-jet searches**
- DM can be heavier than anticipated
  → **interesting multi-TeV regime to be probed with indirect detection**

Thermal effects & BSF at NLO



Scattering with light plasma constituents – **Landau damping**

Thermal masses – **Deybe screening**



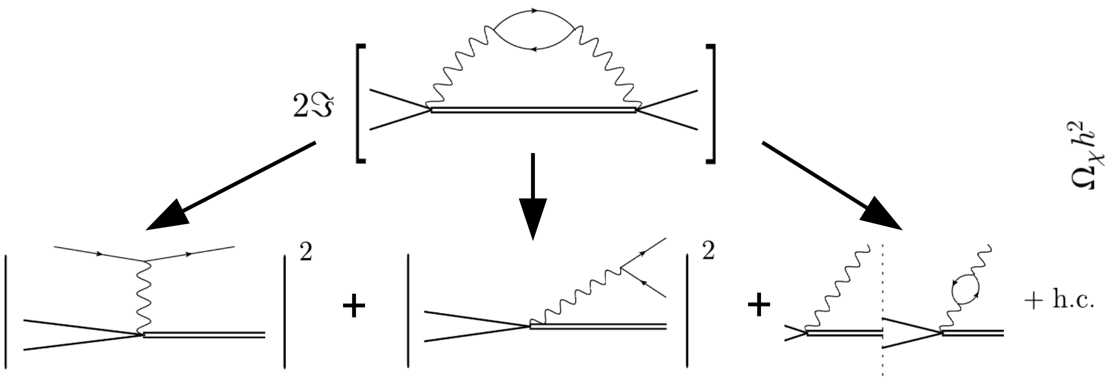
Description so far [Laine et al. (2017), Biondini et al. (2018), Covi et al. (2018)] **was only valid in ionisation equilibrium!**

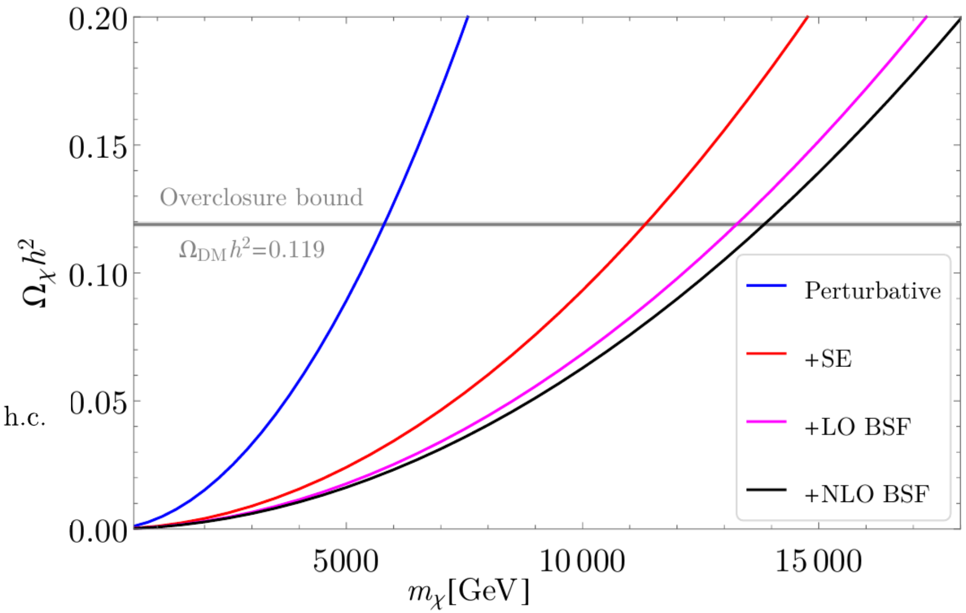
Thermal effects & BSF at NLO

$$\dot{n}_\chi + 3Hn_\chi = -\sum_{\mathcal{B}} \langle \sigma_{\mathcal{B}}^{\mathrm{bsf}} v_{\mathrm{rel}} \rangle \left[n_\chi n_{\bar{\chi}} - n_{\mathcal{B}} \frac{n_\chi^{\mathrm{eq}} n_{\bar{\chi}}^{\mathrm{eq}}}{n_{\mathcal{B}}^{\mathrm{eq}}} \right] - \langle \sigma^{\mathrm{an}} v_{\mathrm{rel}} \rangle \left[n_\chi n_{\bar{\chi}} - n_\chi^{\mathrm{eq}} n_{\bar{\chi}}^{\mathrm{eq}} \right]$$

$$\sigma_{\mathcal{B}}^{\mathrm{bsf}} v_{\mathrm{rel}} \equiv \int \frac{\mathrm{d}^3 p}{(2\pi)^3} \left[1 + f_\gamma^{\mathrm{eq}}(\Delta E) \right] D^\rho_{\mu\nu}(\Delta E, \mathbf{p}) \sum_{\mathrm{Spin}} \mathcal{T}^\mu_{\mathbf{k},\mathcal{B}}(\Delta E, \mathbf{p}) \mathcal{T}^{\nu\star}_{\mathbf{k},\mathcal{B}}(\Delta E, \mathbf{p})$$

$$D^\rho_{\mu\nu} = 2\Im \left[i D^R_{\mu\nu} \right] = 2\Im \left[D^{R,0}_{\mu\nu} + D^{R,0}_{\mu\alpha} \Pi^{\alpha\beta}_R D^{R,0}_{\beta\nu} + \ldots \right]$$



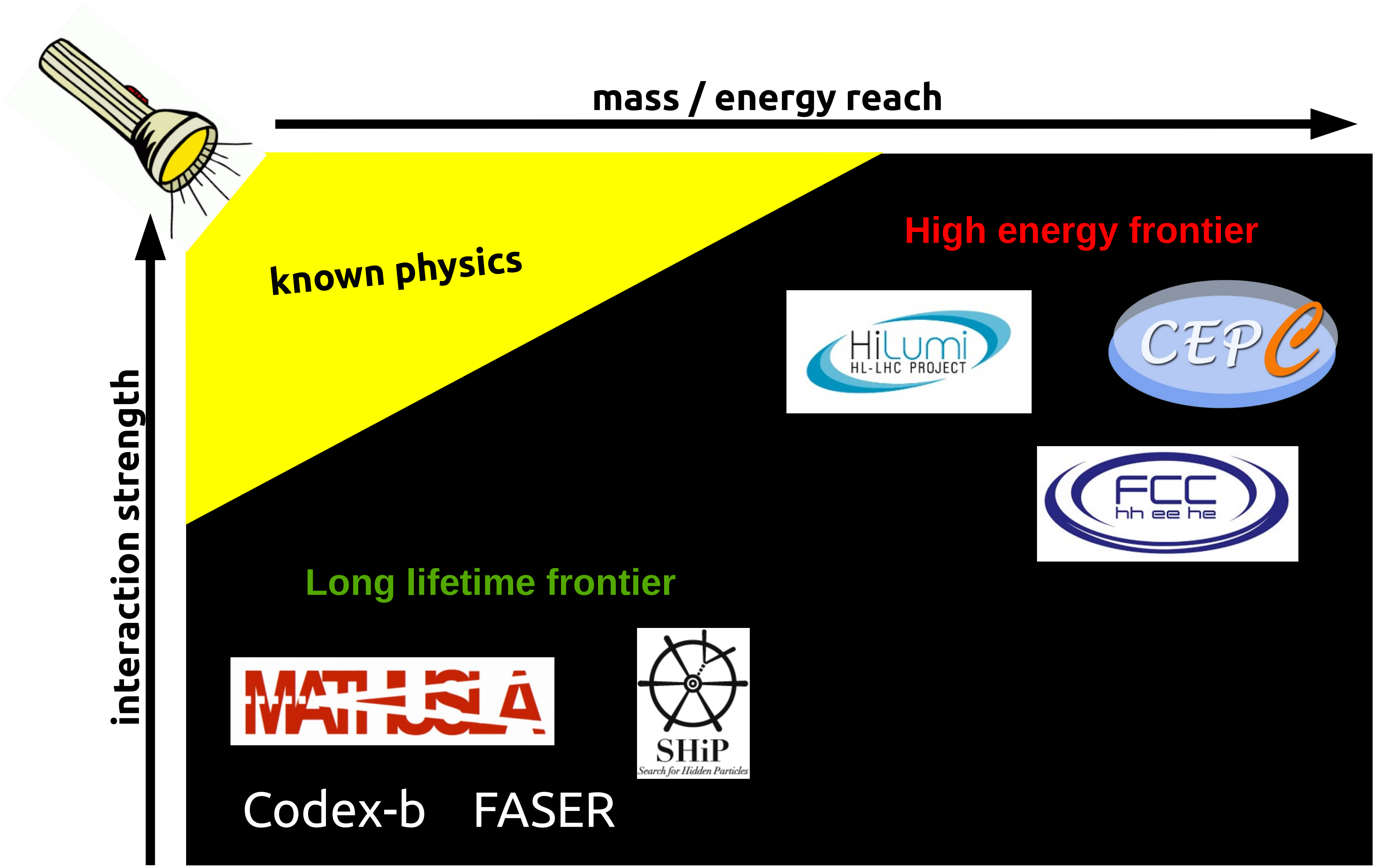


→ **first thermal description at NLO** of bound state formation beyond ionisation equilibrium

→ close links to **heavy quarkonium** literature

Binder, Mukaida, Petraki (2019), Binder, Blobel, JH, Mukaida (2020)

Why have we not seen DM yet?



Is DM feebly interacting?

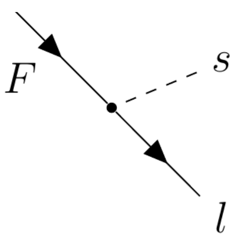
The freeze-in mechanism

Freeze-in
DM = FIMP

(1) DM *not* in thermal equilibrium with SM bath

DM is feebly interacting with the SM bath; abundance negligible

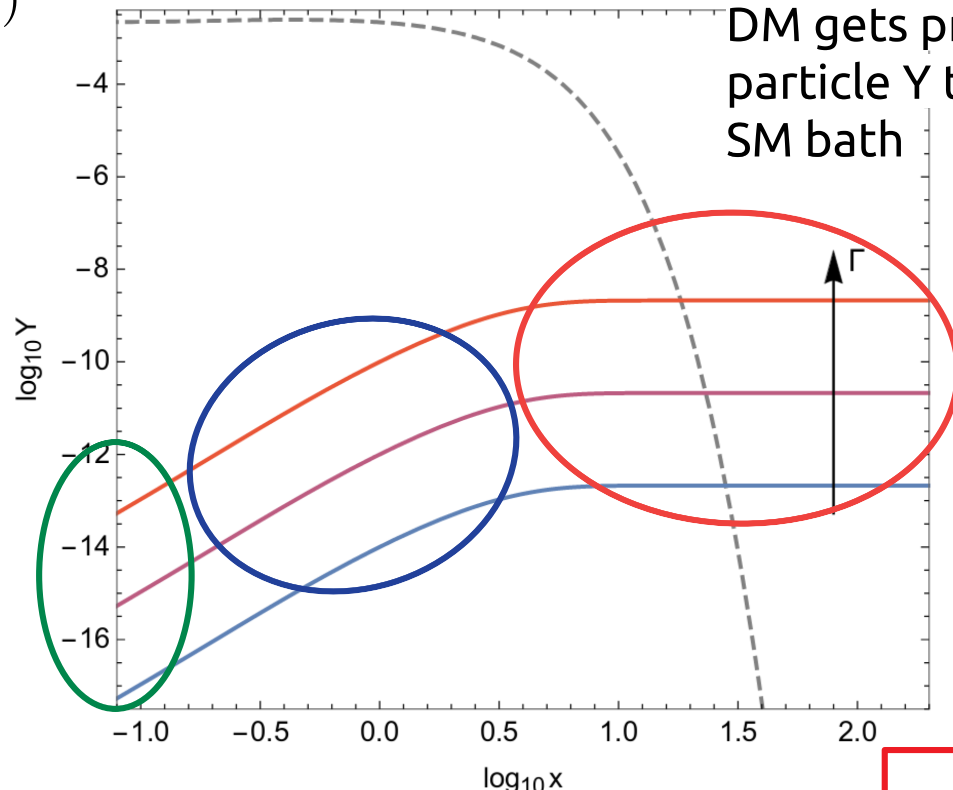
$$\lambda \sim \mathcal{O}(10^{-7})$$



(2) DM production

DM gets produced via decay of a heavier particle Y that is in equilibrium with the SM bath

$$Y \to \mathrm{SM}\ \chi$$



$$x = m_Y/T$$

cooling down

(3) Freeze-in

when T falls below mass of parent particle Y, production gets Boltzmann suppressed

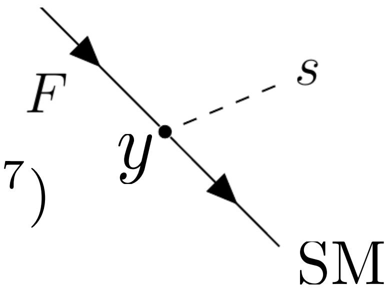
$$n_Y \approx \exp(-m_Y/T)$$

$$\boxed{\Omega_\chi h^2 \sim 4.48 \times 10^8 \frac{g_Y}{g_*^S\sqrt{g_*}} \frac{m_\chi}{\mathrm{GeV}} \frac{M_{\mathrm{Pl}}\Gamma_Y}{m_Y^2}}$$

Feebly Interacting Dark Matter (FIMPs)

$$y_\chi Y_F X_{SM} \chi_s$$

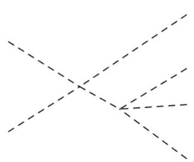
$y \sim \mathcal{O}(10^{-7})$

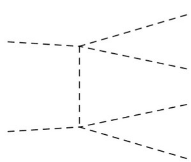


Review Article: The Dawn of FIMP Dark Matter: A Review of Models and Constraints, Bernal, Heikinheimo, Tenkanen, Tuominen, Vaskonen (2017)

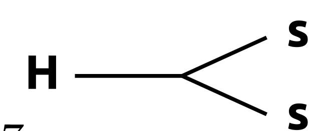
Higgs portal:

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \partial_\mu s\, \partial^\mu s - \frac{\mu_s^2}{2} s^2 + \frac{\lambda_s}{4} s^4 + \lambda_{sh} s^2 \left(H^\dagger H\right)$$





self interacting DM



if $\lambda_{sh} \lesssim 10^{-7}$

many variants of SIDM
$\to$ different production mechanisms:
freeze-in, reannihilation, dark freeze-out

scalar singlet not in thermal equilibrium

$$\frac{\Omega_s h^2}{0.12} \simeq 5.3 \times 10^{21}\, \lambda_{\rm hs}^2 \left(\frac{m_s}{\rm GeV}\right)$$

Yaguna (2011)

Production regimes for SIDM, Bernal et al. (2016)
SIMP miracle, Hochberg et al. (2014)
Cannibal Dark Matter, Farina et al. (2016)

LHC friendly freeze-in models

We consider an extension of the SM by a Z_2-odd real scalar singlet s (DM) and a Z_2-odd vector-like SU(2) singlet fermion F (parent)

$$\boxed{\begin{aligned}\mathcal{L} = \mathcal{L}_{\rm SM} + \partial_\mu s\, \partial^\mu s - \frac{\mu_s^2}{2} s^2 + \cancel{\frac{\lambda_s}{4}} s^4 + \cancel{\lambda_{sh}} s^2 \left(H^\dagger H\right) \\ + \bar{F}\,(iD)\,F - m_F \bar{F} F - \sum_f y_s^f \left(s\bar{F} \left(\frac{1+\gamma^5}{2}\right) f + \text{h.c.}\right)\end{aligned}}$$

$$y_\chi Y_F X_{SM} \chi_s$$

with $F = \{e, \mu, \tau\}$ **(1,1,-1)** heavy lepton

$\{u, c, t\}$ **(3,1,-2/3)** heavy up-type quark

$\{d, s, b\}$ **(3,1,1/3)** heavy down-type quark

with $\mu_s^2 = m_s^2 + \lambda_{sh} v^2$

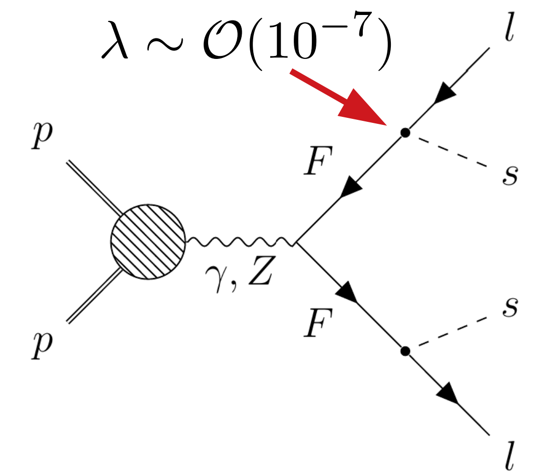
two separate studies:

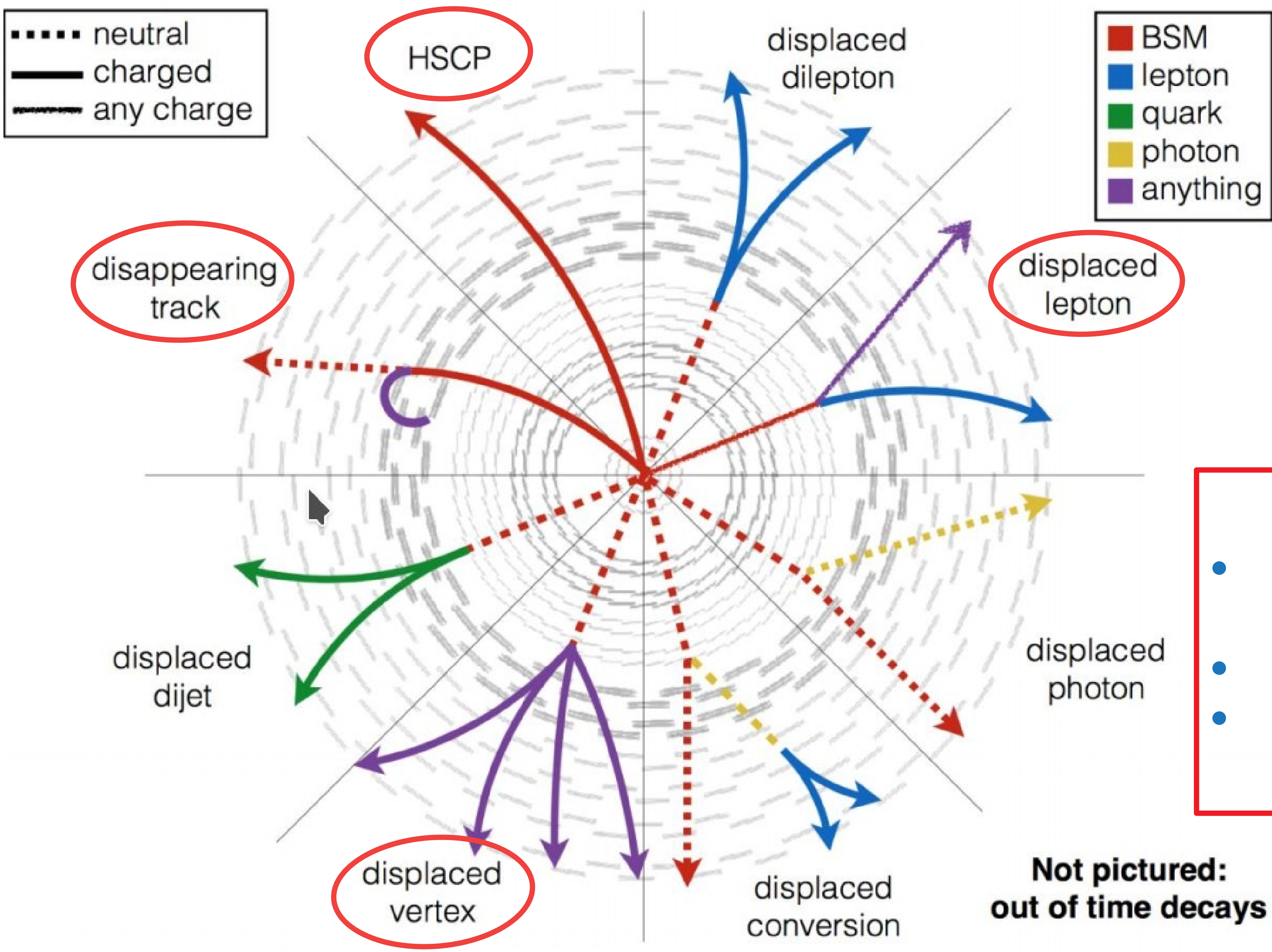
- heavy lepton & heavy up-type quark
- only 1[st] and 2[nd] generation

Free parameters: $m_s, m_F, \{y_s^f\}$

Belanger, JH et al. (2018)

Collider constraints



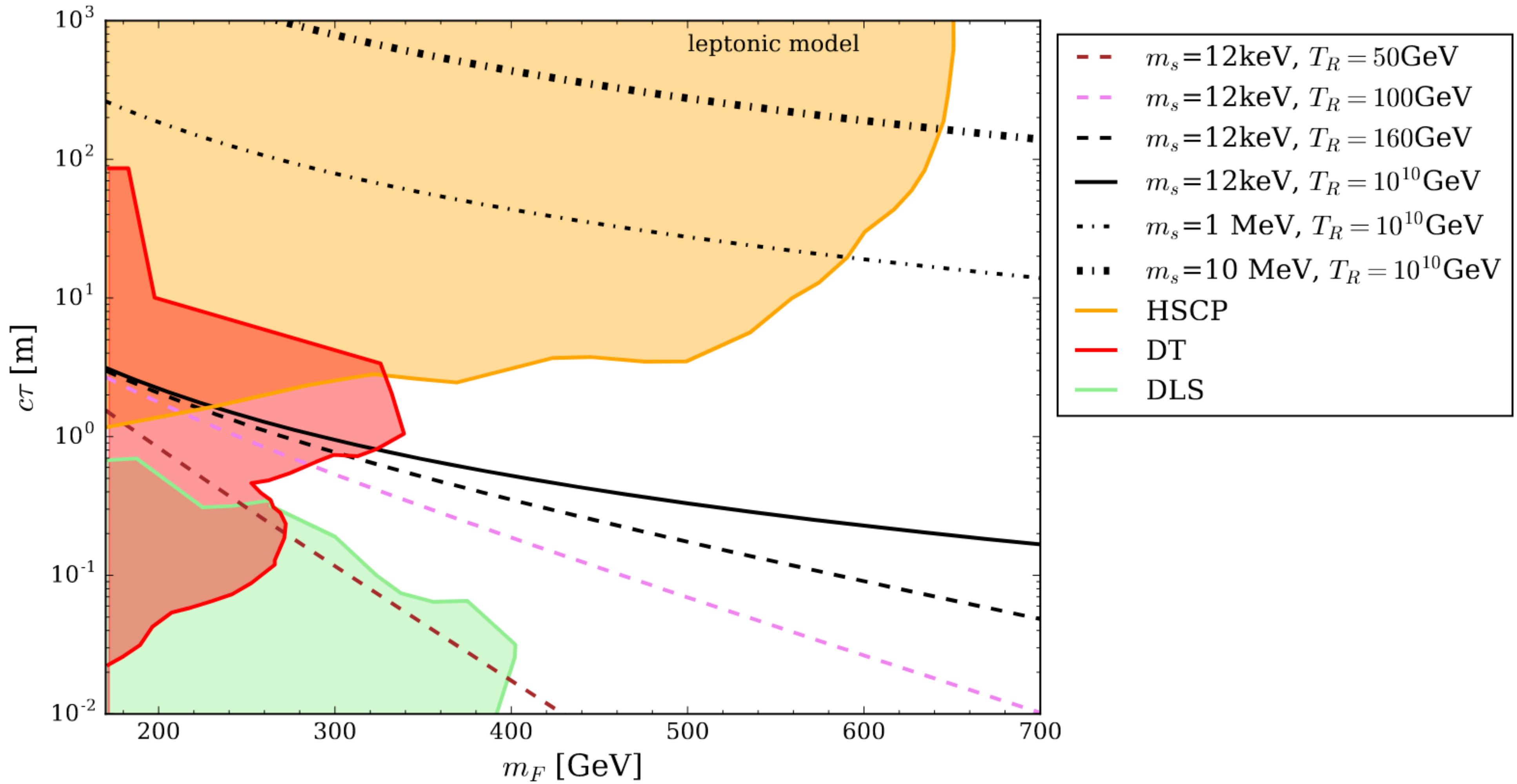


Long-lived particles (LLPs)

- Large mass hierarchies / off-shell mediator
- Compressed spectra
- *Small couplings / small rates*

Review: "*Searching for long-lived particles beyond the Standard Model at the Large Hadron Collider*"

Results for the leptonic model



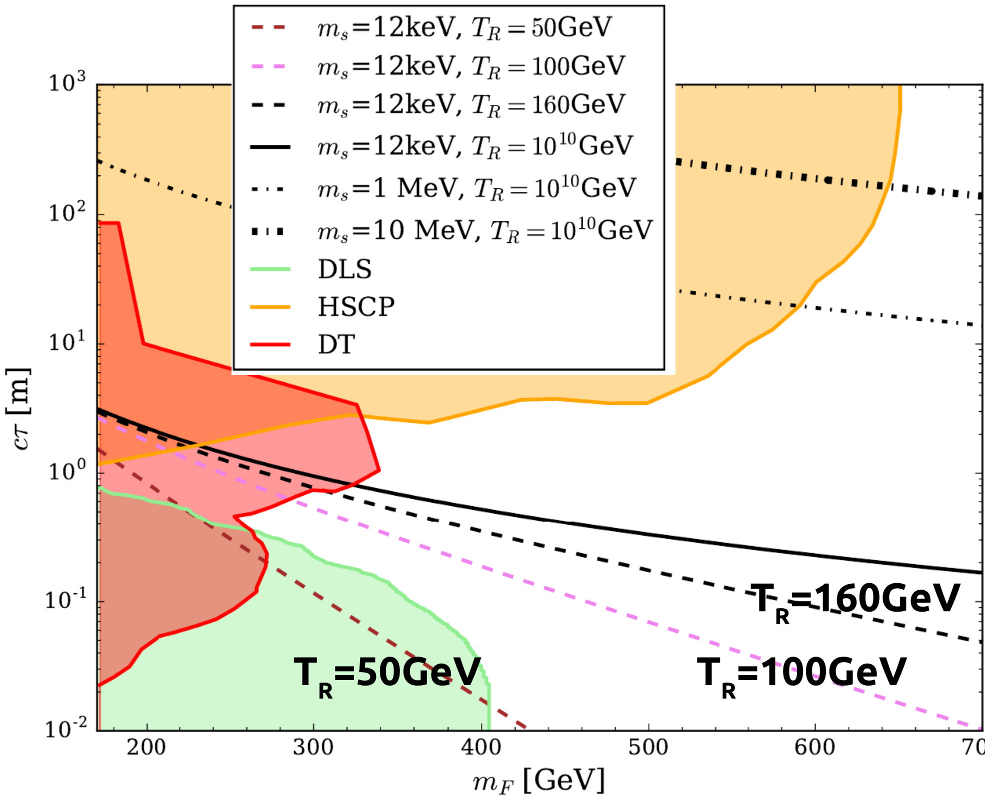
$$c\tau \approx 4.5\ \mathrm{m}\ \xi g_F \left(\frac{0.12}{\Omega_s h^2}\right)\left(\frac{m_s}{100\mathrm{keV}}\right)\left(\frac{200\mathrm{GeV}}{m_F}\right)^2\left(\frac{102}{g_*(m_F/3)}\right)^{3/2}\left[\frac{\int_{m_F/T_R}^{m_F/T_0} dx\ x^3 K_1(x)}{3\pi/2}\right]$$

Belanger, JH et al. (2018)

Probing freeze-in dark matter and baryogenesis

Assuming that DM is mostly generated by decays of the parent F, we can relate the **relic abundance** with the parent particle life time

$$c\tau \approx 4.5\ \mathrm{m}\ \xi g_F \left(\frac{0.12}{\Omega_s h^2}\right)\left(\frac{m_s}{100\mathrm{keV}}\right)\left(\frac{200\mathrm{GeV}}{m_F}\right)^2\left(\frac{102}{g_*(m_F/3)}\right)^{3/2}\left[\frac{\int_{m_F/T_R}^{m_F/T_0} dx\ x^3 K_1(x)}{3\pi/2}\right]$$



- m_s=12keV is the **smallest possible mass** from Lyman-α constraints
  m_s > 12 keV would imply even smaller T_R
- If s made up **not all of the DM**, a smaller T_R would be implied

→ **most conservative choice**

Possibility to falsify baryogenesis / leptogenesis models that rely on effective sphaleron interactions.

Belanger, JH et al. (2018)

Freeze-in extensions

Neutrino portal:

Light sterile neutrino production via Dodelson-Widrow mechanism ruled out by x-ray and Lyman-α
→ sterile neutrino freeze-in

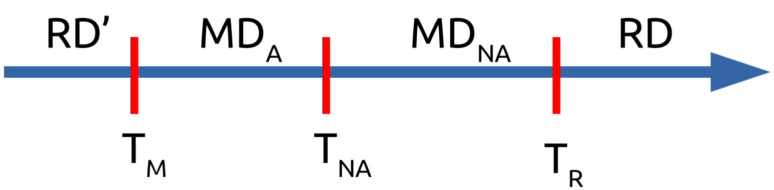
$$\mathcal{L} \supset y\,\bar{L}\,\tilde{\Phi}^\dagger\,\nu_{\rm R} + m\,\bar{\nu}_{\rm R}^c\,\nu_{\rm R} + s\,\bar{\nu}_{\rm R}^c\,(y_S + i\,y_P)\,\nu_{\rm R} + {\rm h.c.} + V(\Phi, s)$$

$$\frac{\Omega_{\nu_{\rm R}} h^2}{0.12} \simeq \left(\frac{y}{10^{-8}}\right)^3 \frac{\langle s\rangle}{m_{\rm s}}$$

Kusenko (2006)
Petraki, Kusenko (2007)

Sterile Neutrino DM from freeze-in, Shakya (2015)
Dark Matter from Freeze-In via the Neutrino Portal, Becker (2018)
The Dark Side of the Littlest Seesaw, Chianese, King (2018)

Probing an altered cosmological history:

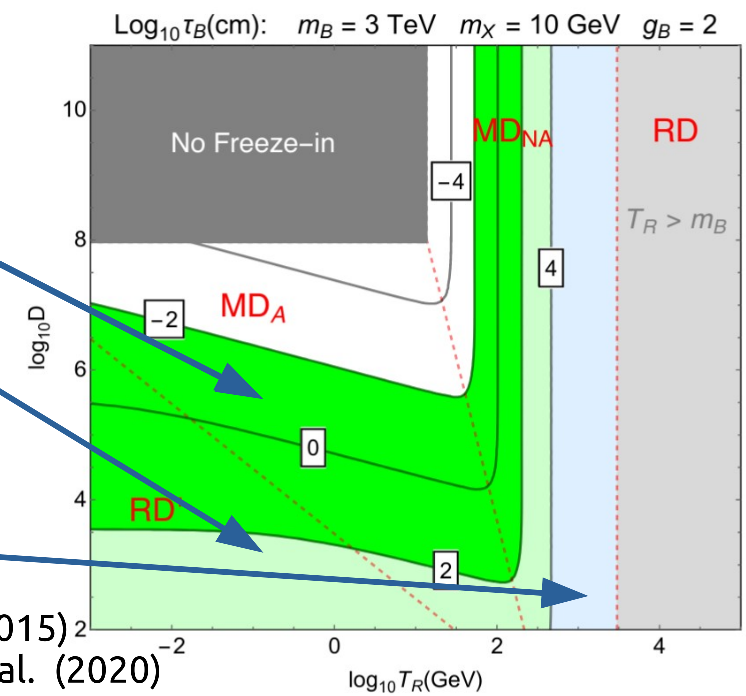


$$D \approx \frac{T_M}{T_R}$$

displaced vertices
$10^{-2}\text{cm} < \tau < 10^{2}\text{cm}$

displaced jets / leptons
$10^{2}\text{cm} < \tau < 10^{4}\text{cm}$

stopped particle decay
$\tau > 10^{4}\text{cm}$



Freeze-In Dark Matter with Displaced Signatures at Colliders, Co et al. (2015)
Neutrino Portal to FIMP Dark Matter with an Early Matter Era, Cosme et al. (2020)

More and more new ideas…

Unitary bound sets a limit on the maximal DM mass… ways out?

Composite DM – QCD-like dark sector

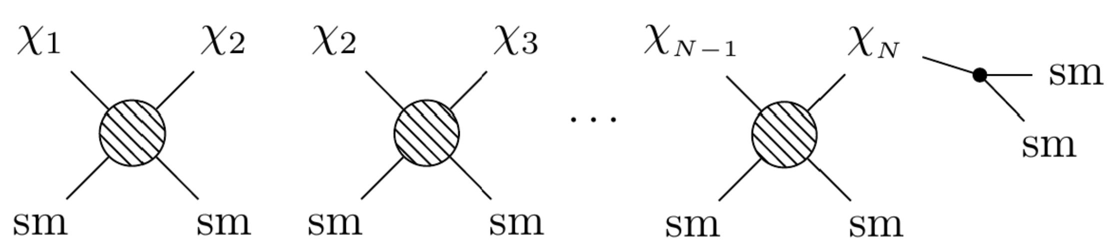
- Could we have a rich strongly interacting dark sector similarly to the SM?
- Depending on Λ_{QCD} and the constituent masses, we could get darkonium, dark mesons or quirks

–> Rich new signals: emerging jets, oscillating quirk signals, dark showers, etc.…

Schwaller et al. (2015), Cohen et al. (2017), Cohen et al. (2020)
Kribs et al. (2010), Knapen et al. (2017), Evans et al. (2019)
Geller et al. (2018), Smirnov, Beacom (2019), Contino et al. (2019), Gross et al. (2019)

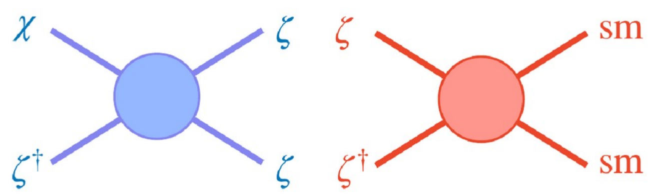
Chain Dark Matter

Kim, Kuflik (2019)

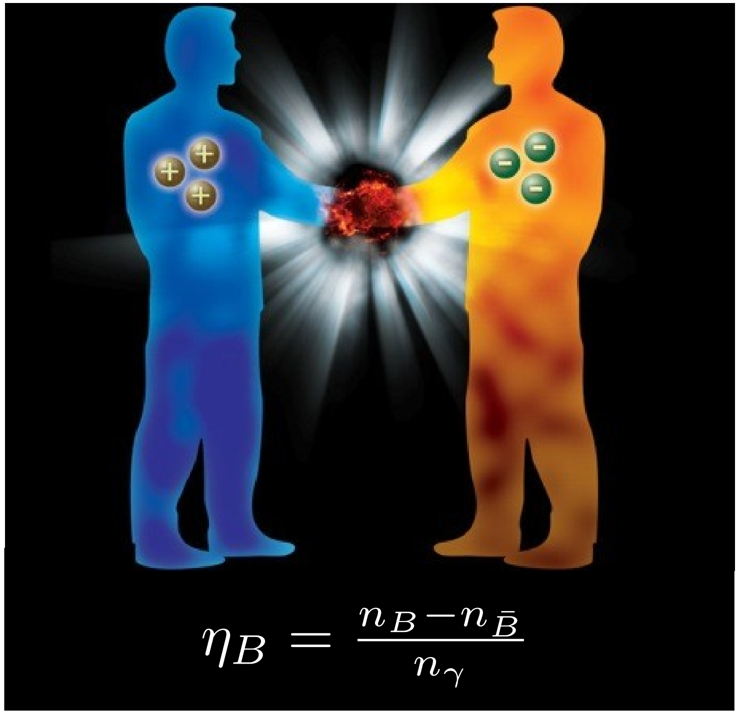


Zombies

Kramer, Kuflik, Levi, Outmezguine, Ruderman (2020)



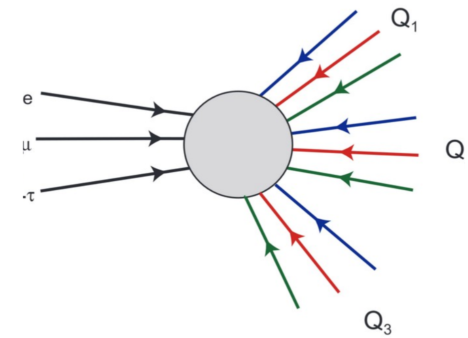
and… and … and …



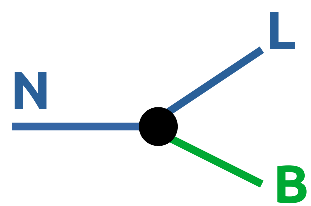
Baryon Asymmetry.

Why do we need new physics?

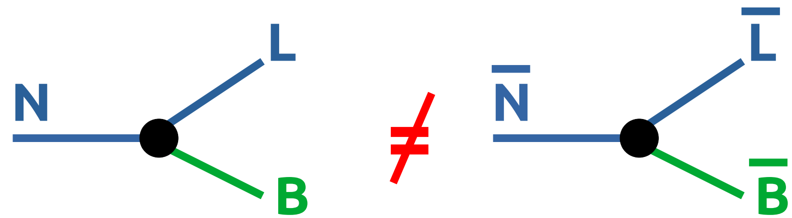
Theoretically, we know the conditions on interactions that have to be fulfilled (Sakharov conditions).



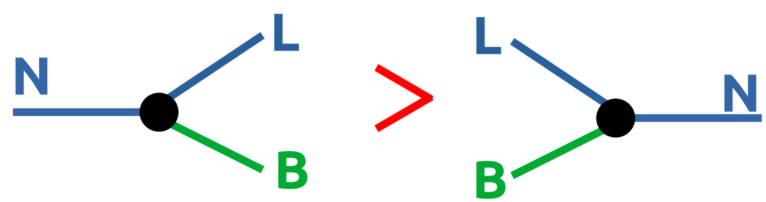
- ☐ baryon number violation



- ☐ C and CP violation



- ☐ departure from thermal equilibrium



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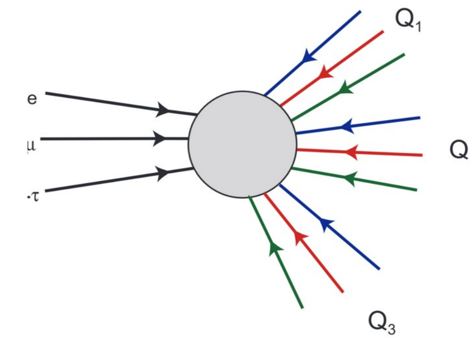
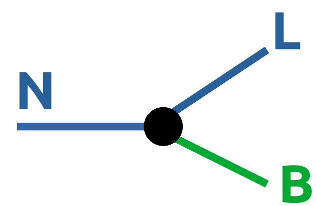
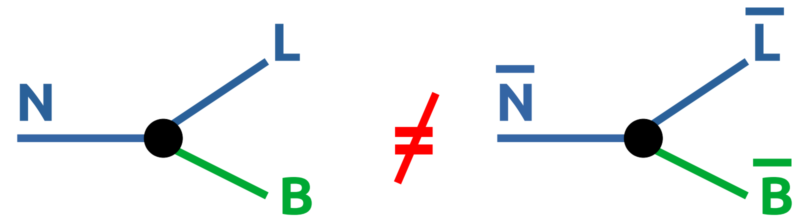


Standard Model?

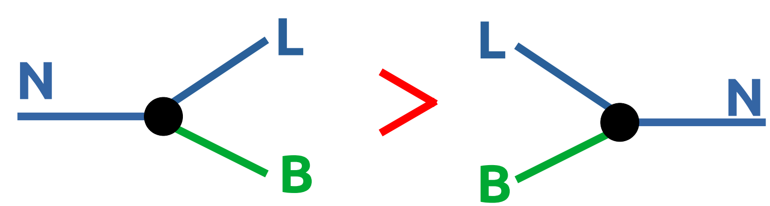
baryon number violation



C and CP violation



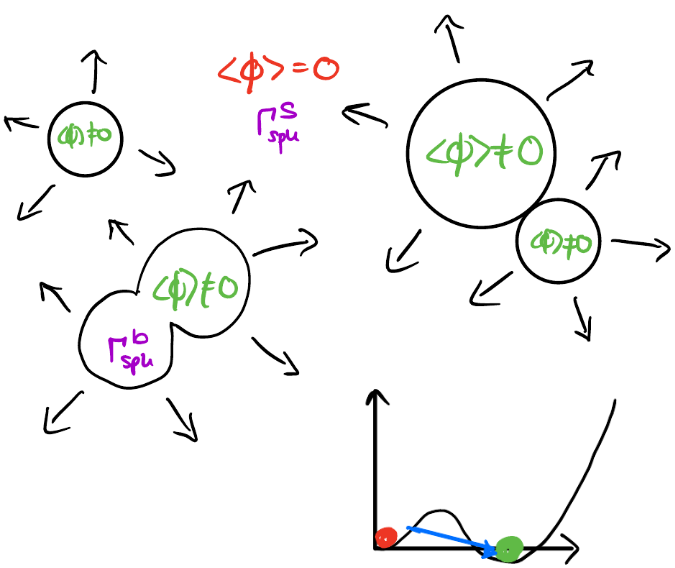
departure from thermal equilibrium



There has to be new physics in order to explain our own existence!

Many theoretical models and ideas…

- **Electroweak Baryogenesis** Kuzmin, Rubakov, Shasposhnikov (1985)
- **Affleck-Dine Baryogenesis** Affleck, Dine (1985)
- **Spontanous Baryogenesis** Kohen, Kaplan (1987)
- **GUT Baryogenesis** Youshimura (1978), Barr (1979), Toussaint et al. (1979), Dimopoulos, Susskind (1978)
- **Leptogenesis** Fukugita-Yanagida (1986)
- **and many new ones!**



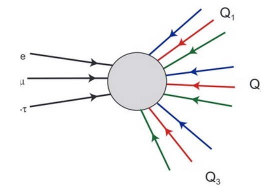
baryon asymmetry

SM processes

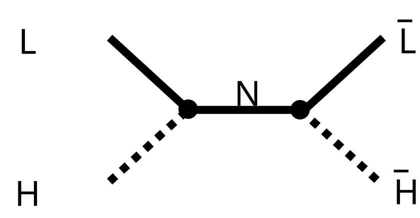
lepton asymmetry

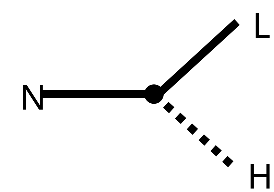
lepton asymmetry washout (LNV)

lepton asymmetry generation (CPV and LNV)



$$\Delta B = \Delta L = 3$$





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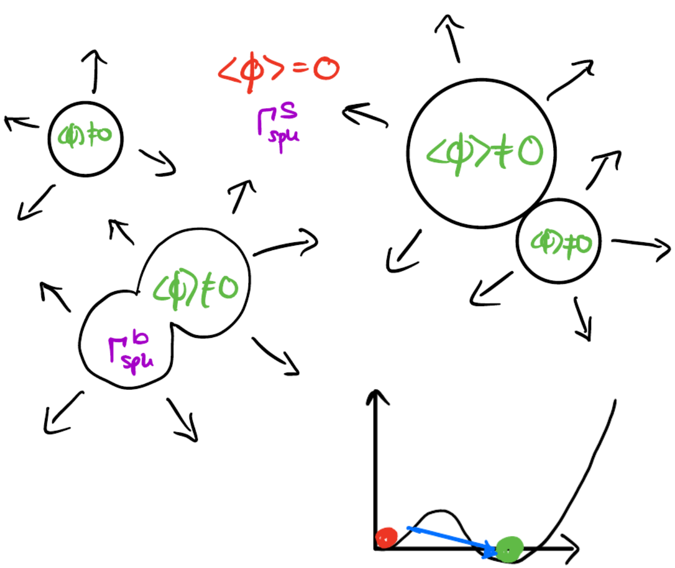
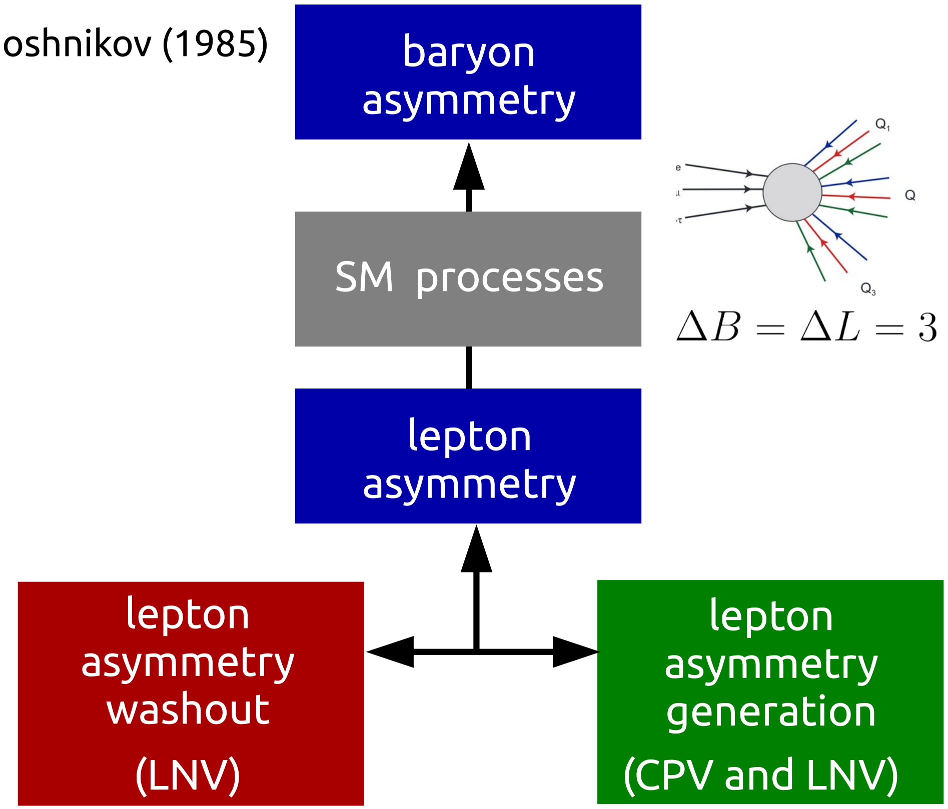
- **Leptogenesis** Fukugita-Yanagida (1986)
- **and many new ones!**

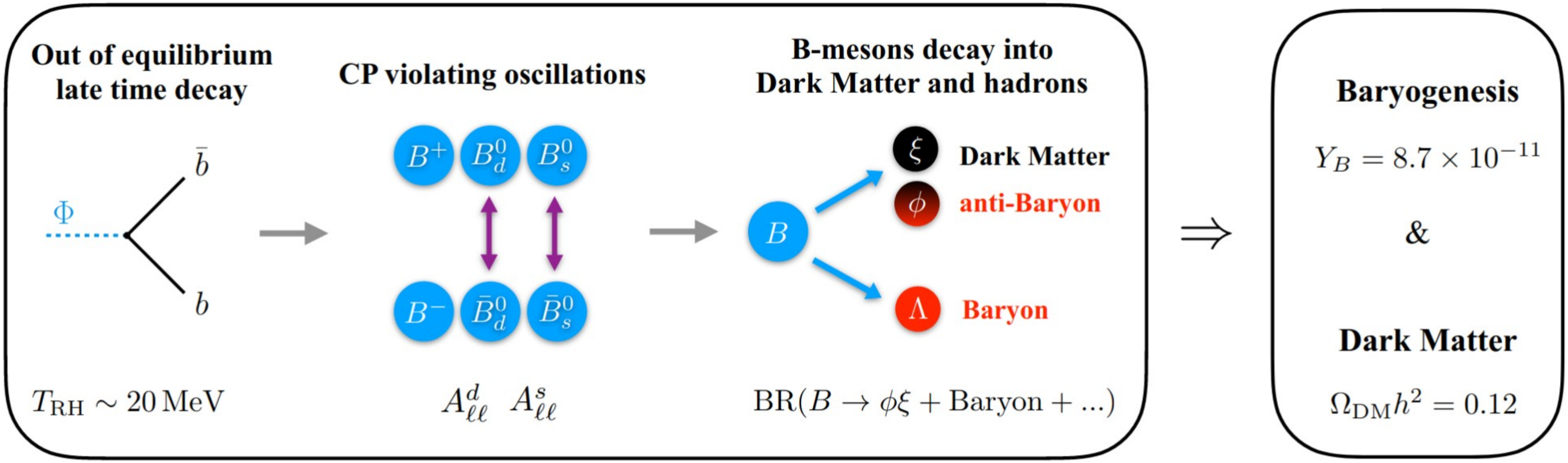




$$\Delta B = \Delta L = 3$$

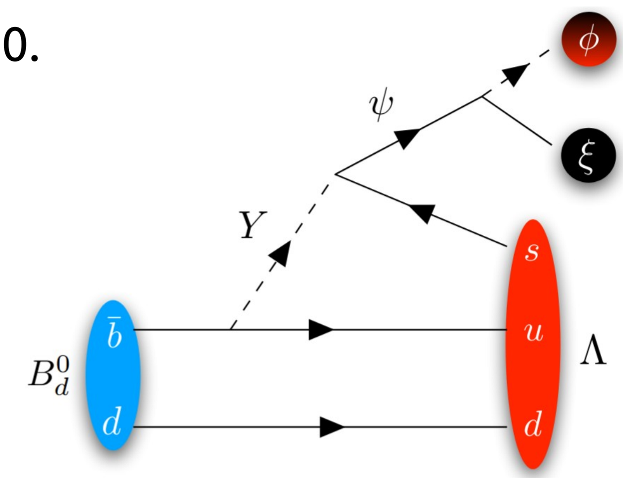
Which mechanism is realised in nature?

Low scale baryogenesis



Globally, Δ B = 0.

$$Y_B \propto \sum_{q=s,d} A_{\ell\ell}^q \times {\rm Br}(B_q^0 \to \phi\,\xi + {\rm Baryon} + X)$$



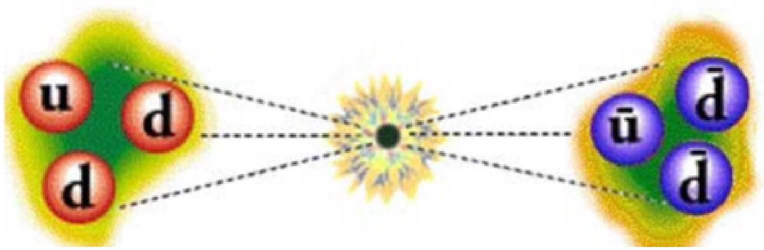
Testable scenario at Belle, Belle-II and BarBar!

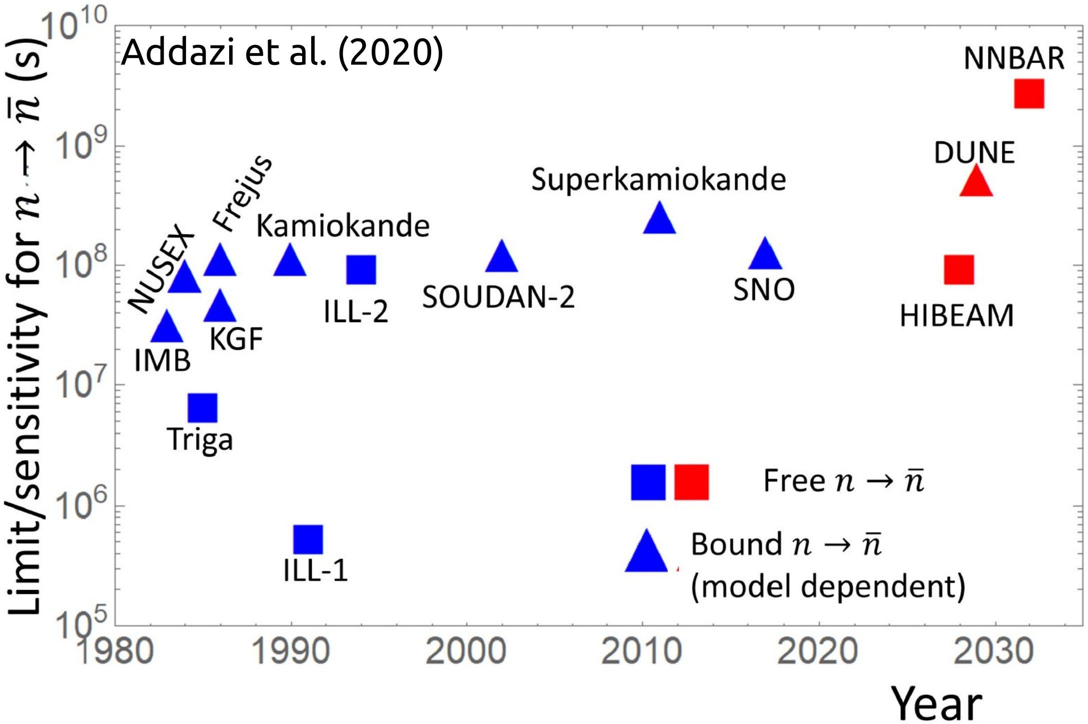
A Supersymmetric Theory of Baryogenesis and Sterile Sneutrino Dark Matter from B Mesons, Alonso-Alvarez, Elor, Nelson, Xiao (2019)
Baryogenesis and Dark Matter from B Mesons, Elor, Escudero, Nelson (2019)

High scale baryogenesis

Testable B violation scenarios:

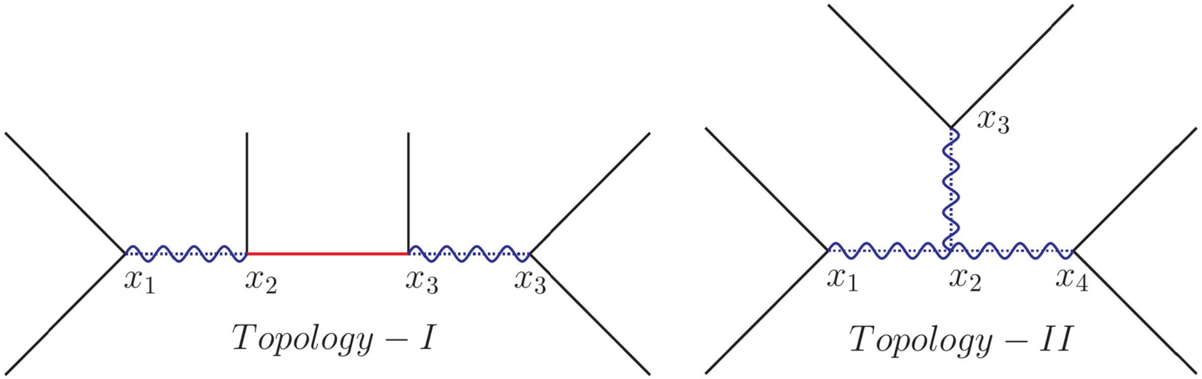
- Δ B = 1: proton decay
- Δ B = 2: n-nbar oscillations





Future sensitivity at ESS: $\tau_{n\overline{n}} \geq 10^{10} s$

New high-sensitivity searches for neutrons converting into antineutrons and/or sterile neutrons at the European Spallation Source, Addazi et al. (2020)



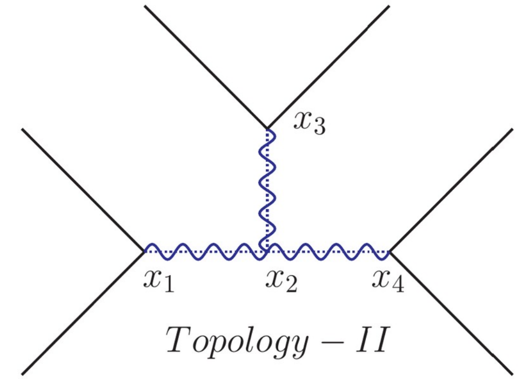
Grojean et al. (2019)

Mohapatra, Marshak (1980)
Babu, Mohapatra (2012)

High scale baryogenesis

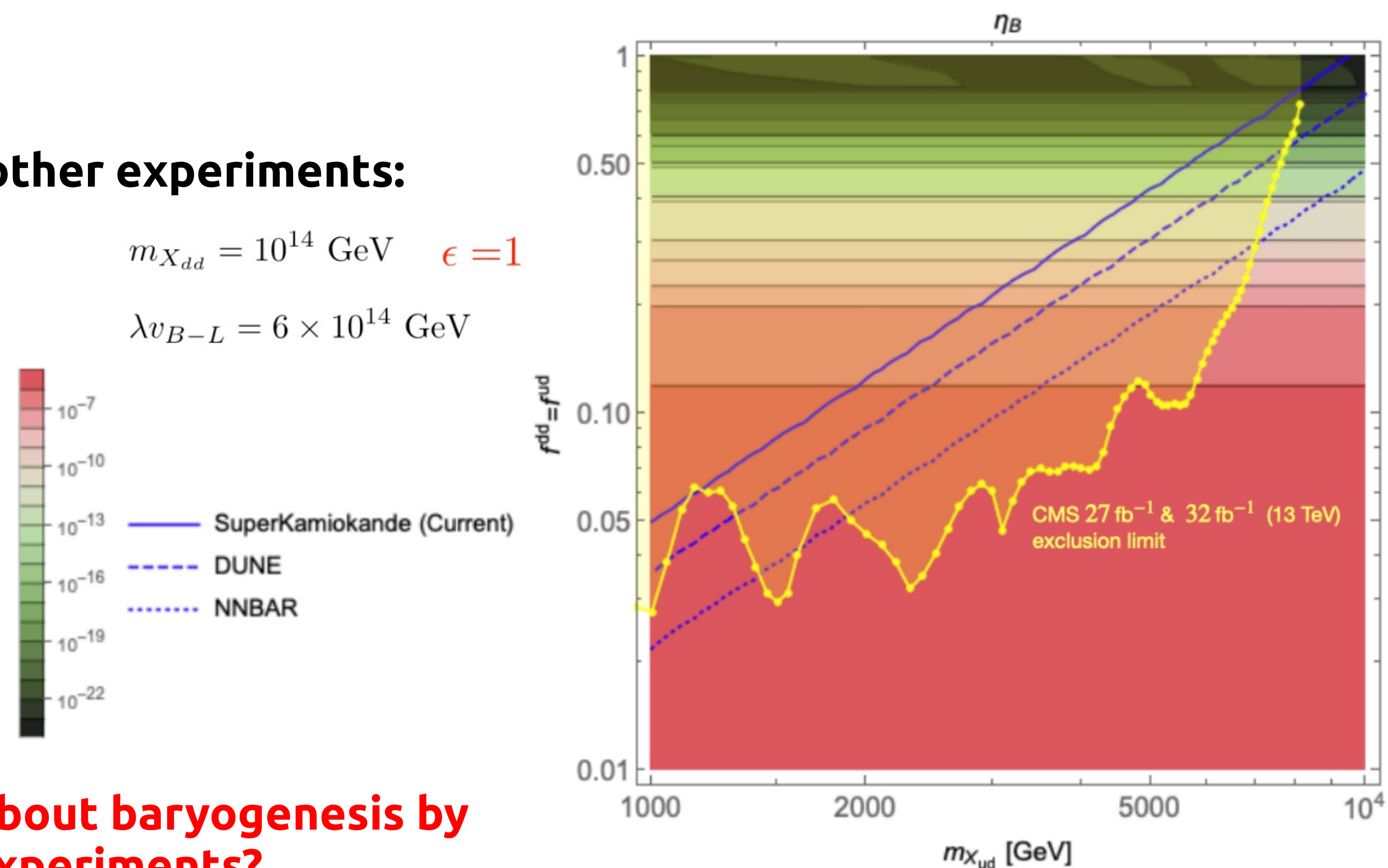
Simplified model:

$$\mathcal{L}_{II} = f_{ij}^{dd} X_{dd} d_{iR} d_{jR} + \frac{f_{ij}^{ud}}{\sqrt{2}} X_{ud}(u_{iR} d_{jR} + u_{jR} d_{iR})$$
$$+ \lambda \xi X_{dd} X_{ud} X_{ud} + \text{h.c.}$$



Interesting interplay with other experiments:

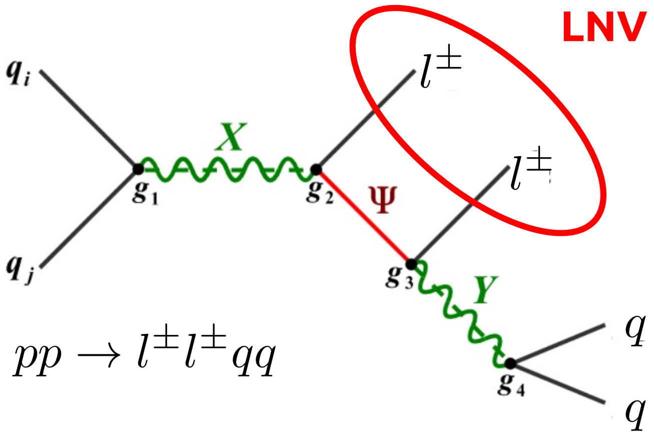
- N-nbar oscillations
- Di-nucleon decay
- LHC
- meson oscillations



Fridell, JH, Hati, in preparation

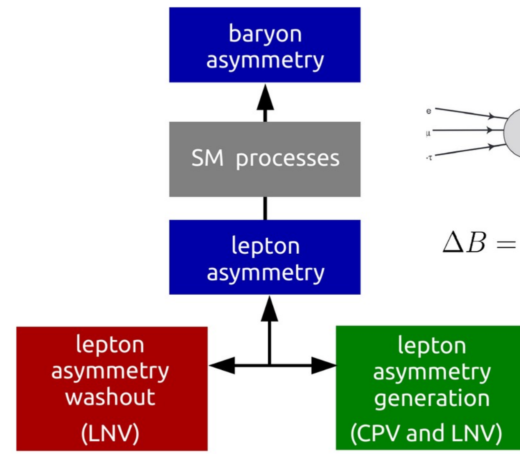
Can we learn something about baryogenesis by the complementarity of experiments?

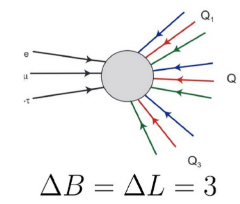
Falsifying Baryogenesis with LNV @ LHC



$pp \to l^\pm l^\pm qq$

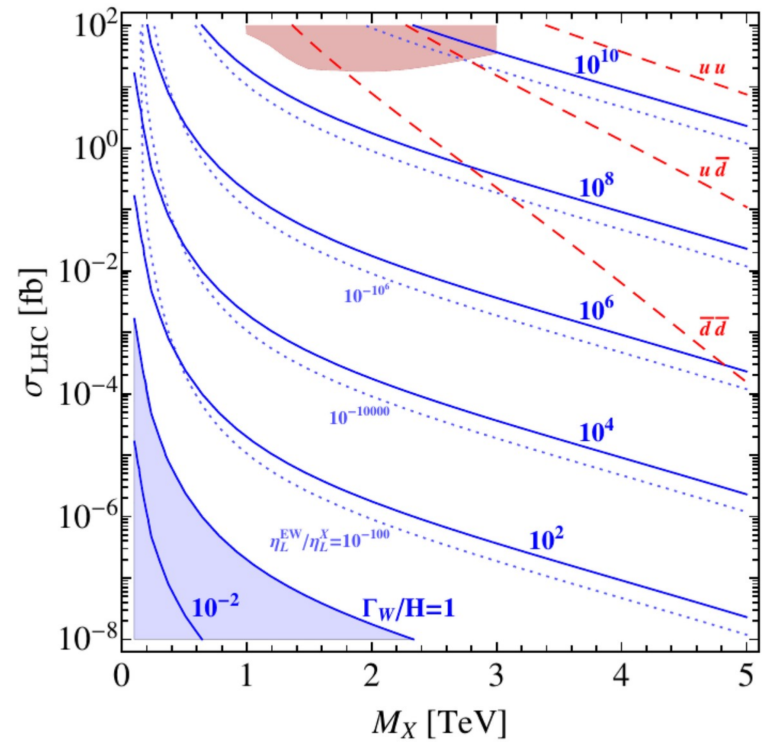
$$\Delta L = 2$$





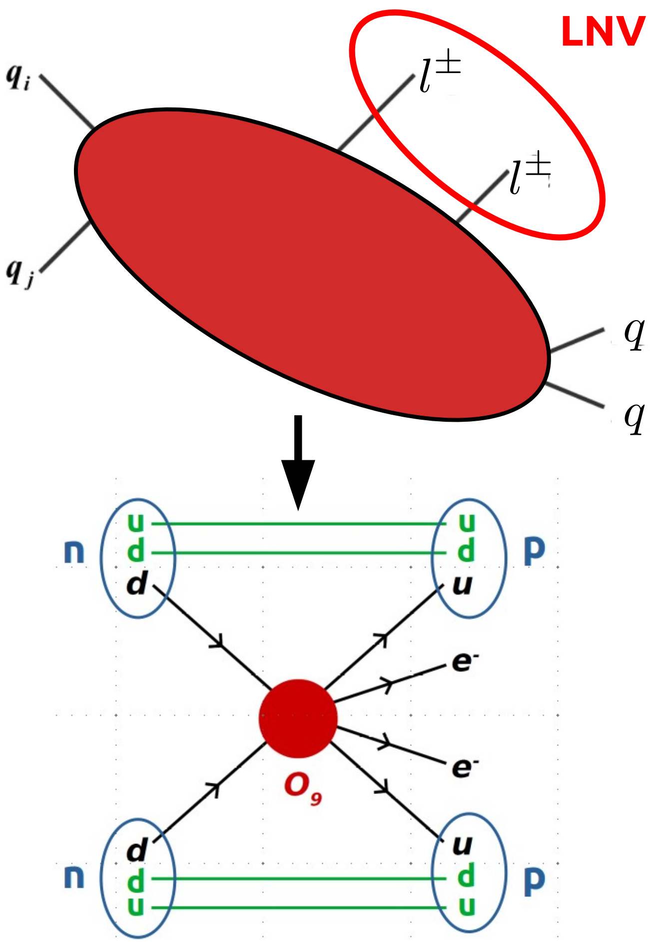
Large washout, if $\dfrac{\Gamma_W}{H} > 1$.

Observation of any washout process at the LHC would falsify high scale baryogenesis!

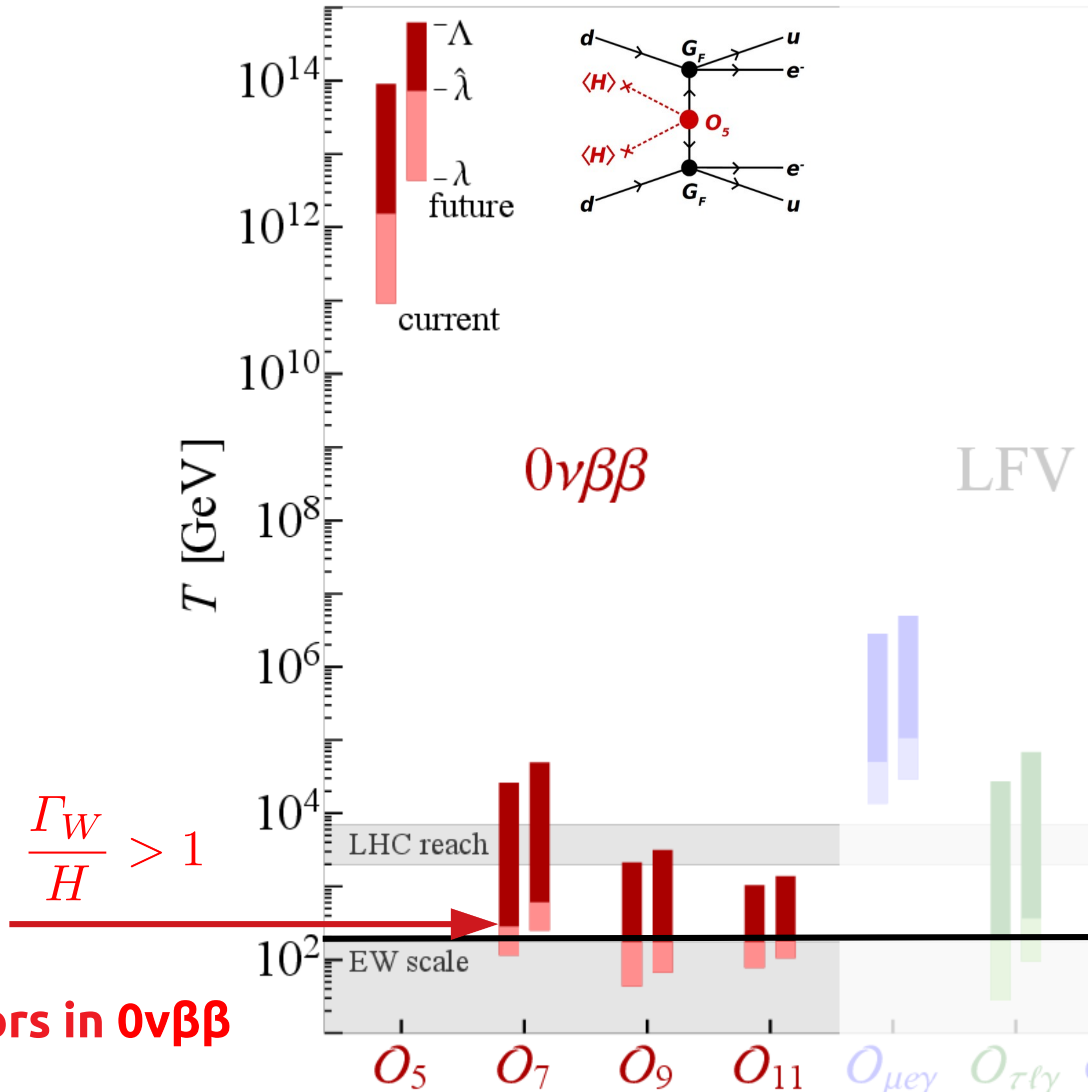


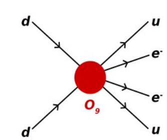
Deppisch, JH, Hirsch (2014)
Deppisch, JH, Hirsch, Päs (2015)

Falsifying Baryogenesis with LNV @ 0νββ



$\Delta L = 2$



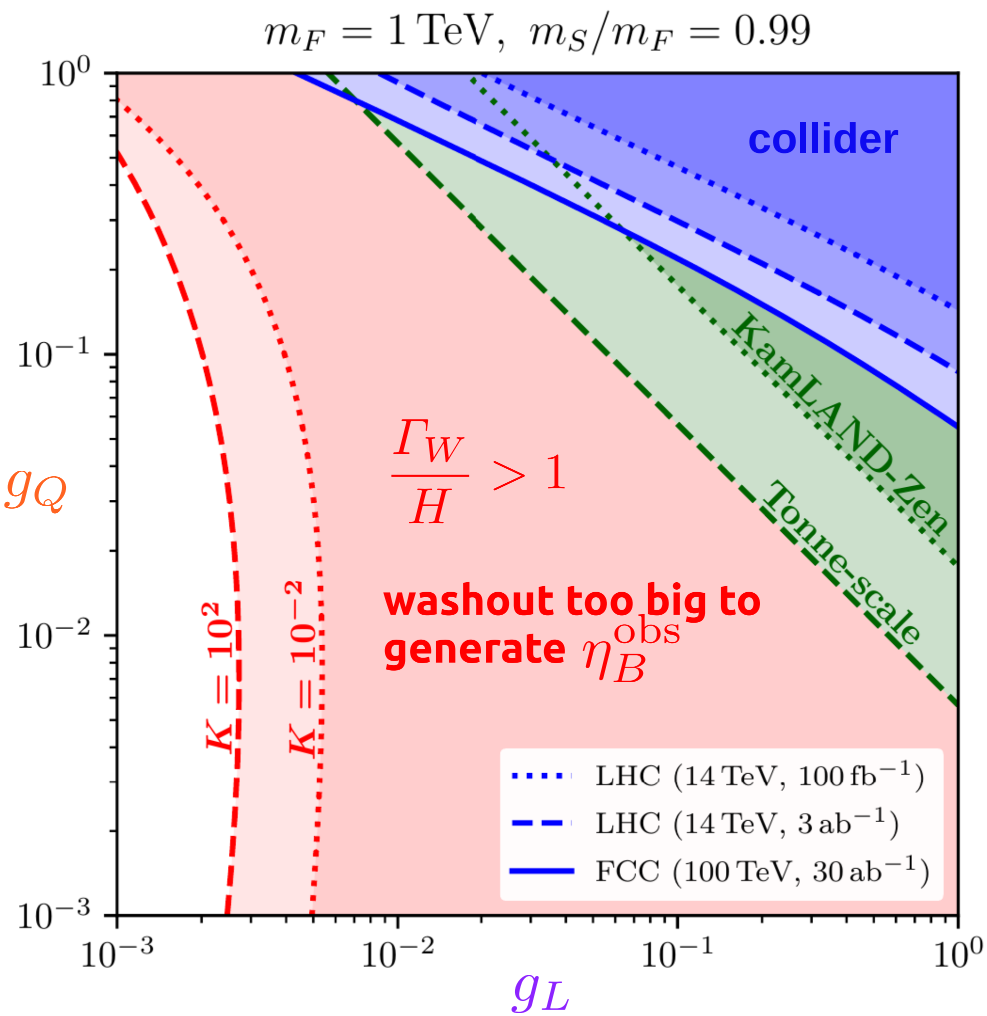


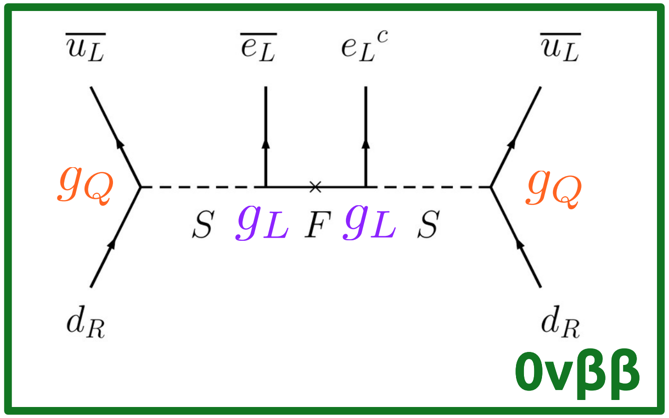
Observation of higher dimensional operators in 0νββ decay excludes high-scale baryogenesis!

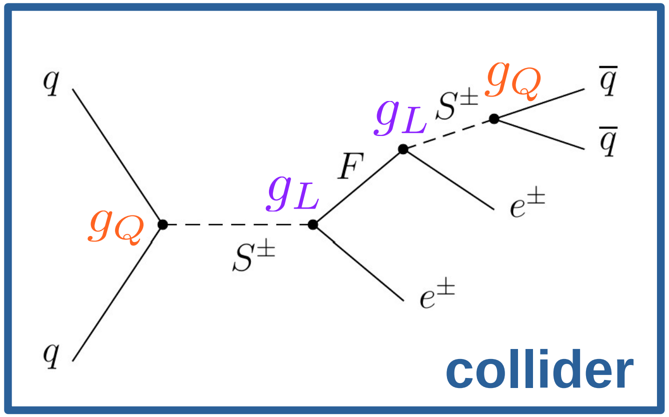
Deppisch, Graf, JH, Huang (2018)
Deppisch, JH, Huang, Hirsch, Päs (2015)

Falsifying Baryogenesis – Combining LHC & 0νββ

$$\mathcal{L} = g_Q \overline{Q} S d_R + g_L \overline{L}(i\tau^2) S^* F - m_S^2 S^\dagger S - \frac{m_F}{2}\overline{F^c}F + g_S(S^\dagger S)^2 + \lambda_{HS}(S^\dagger H)^2 + \text{h.c.}$$







Comprehensive analysis confirms EFT results and shows interesting interplay between collider and 0νββ reach.

JH, Ramsey-Musolf, Shen, Urrutia, in preparation

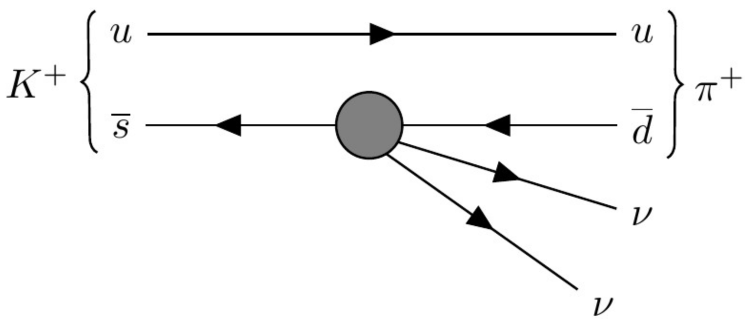
Probing LNV at rare kaon decays

$$K^+ \to \pi^+ \nu \bar{\nu}$$

- **NA62 will measure decay to SM precision**

$$\mathrm{BR}(K^+ \to \pi^+ \nu\bar{\nu})_{\mathrm{SM}} = (8.4 \pm 1.0) \times 10^{-11}$$

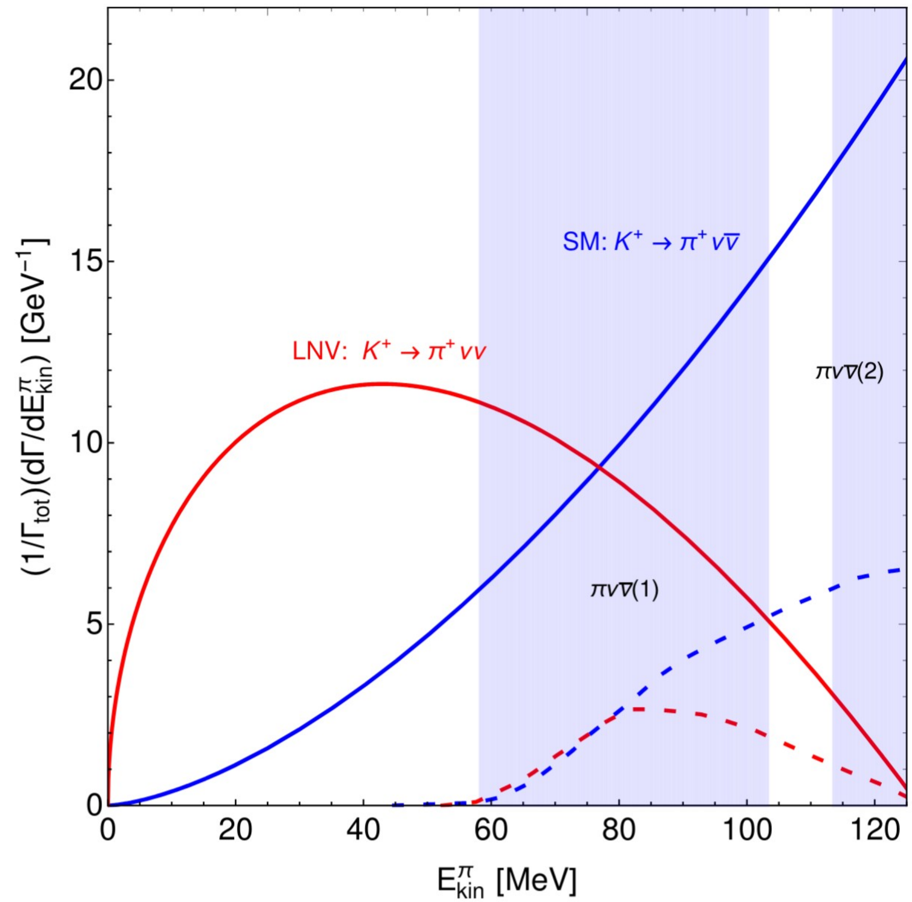
- **possible contribution of LNV interaction**



$$i\mathcal{M} = \frac{v}{\Lambda^3_{ijab}} \langle \pi \nu_i \bar{\nu}^c_j | \, \bar{d} d \nu \nu \, | K \rangle$$

- **limit on scale of new LNV interactions**

$$\mathrm{BR}_{\mathrm{LNV}}(K^+ \to \pi^+ \nu_i \nu_j) = 10^{-10} \left(\frac{19.2 \text{ TeV}}{\Lambda_{ij}} \right)^6$$



Sensitivity to different flavors than most constraining 0νββ !

$$\Lambda^{\mathrm{E949}}_{\nu\nu sd} > 11.5 \mathrm{TeV}$$

Deppisch, Fridell, JH (2020)

Leptogenesis & Gravitational waves?

NanoGrav: Sign of cosmic strings?

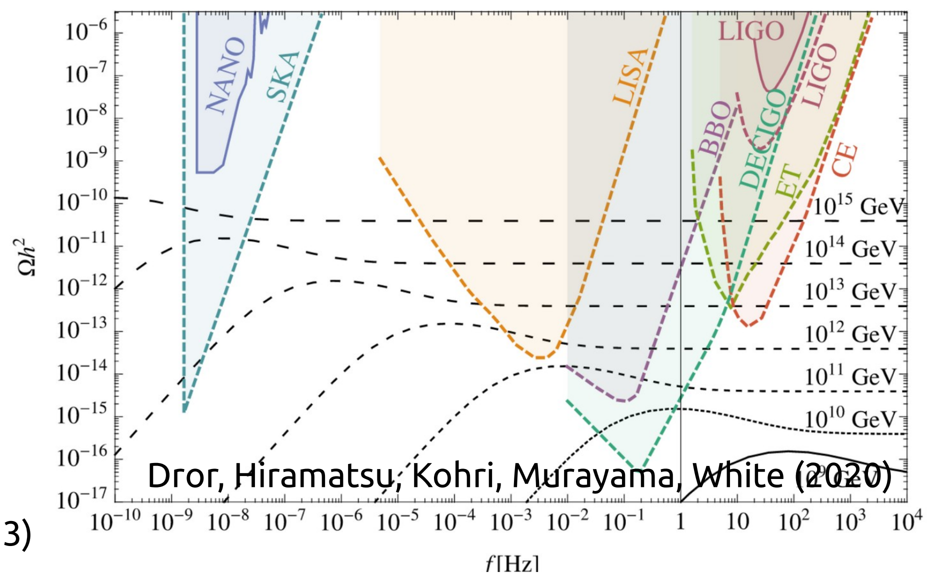
If particle production dominates, stochastic gravitational wave spectrum depends on

$$\Omega_{\rm GW} h^2 \propto G\mu^2$$

$$\mu \sim v^2$$

cosmic string tension　　　breaking scale

Hindmarsh (2011)
Buchmueller, Domcke, Kamada, Schmitz (2013)

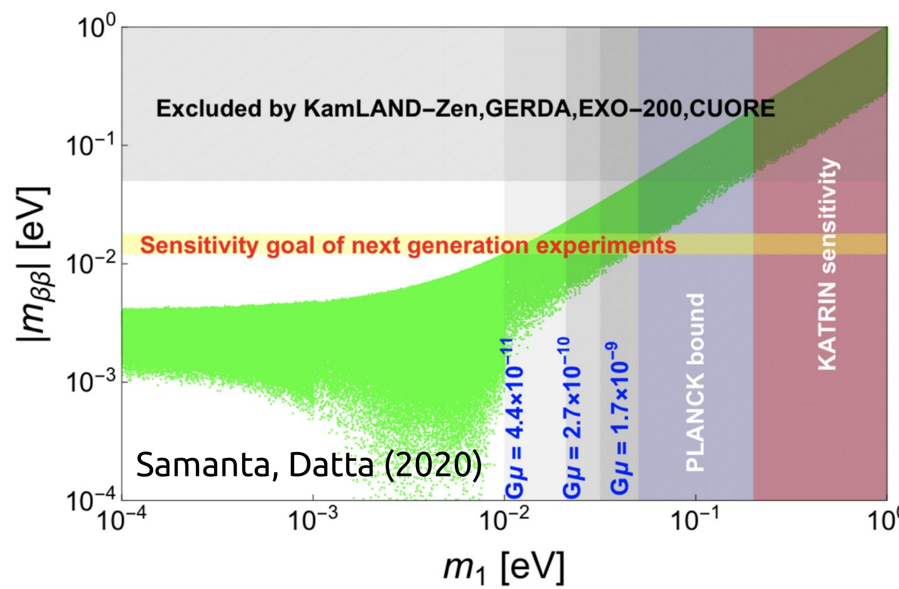


Dror, Hiramatsu, Kohri, Murayama, White (2020)

Direct and indirect links:

- cosmic string network is a generic prediction of the seesaw mechanism when B-L is broken spontaneously
- RH neutrino induced gravitational leptogenesis mechanism (RIGL)

McDonald, Shore (2015)



Samanta, Datta (2020)

Conclusions

Conclusions

We live in a world full of interesting mysteries!

Together we can try to put the pieces of the puzzle together.

Thank you for your attention!

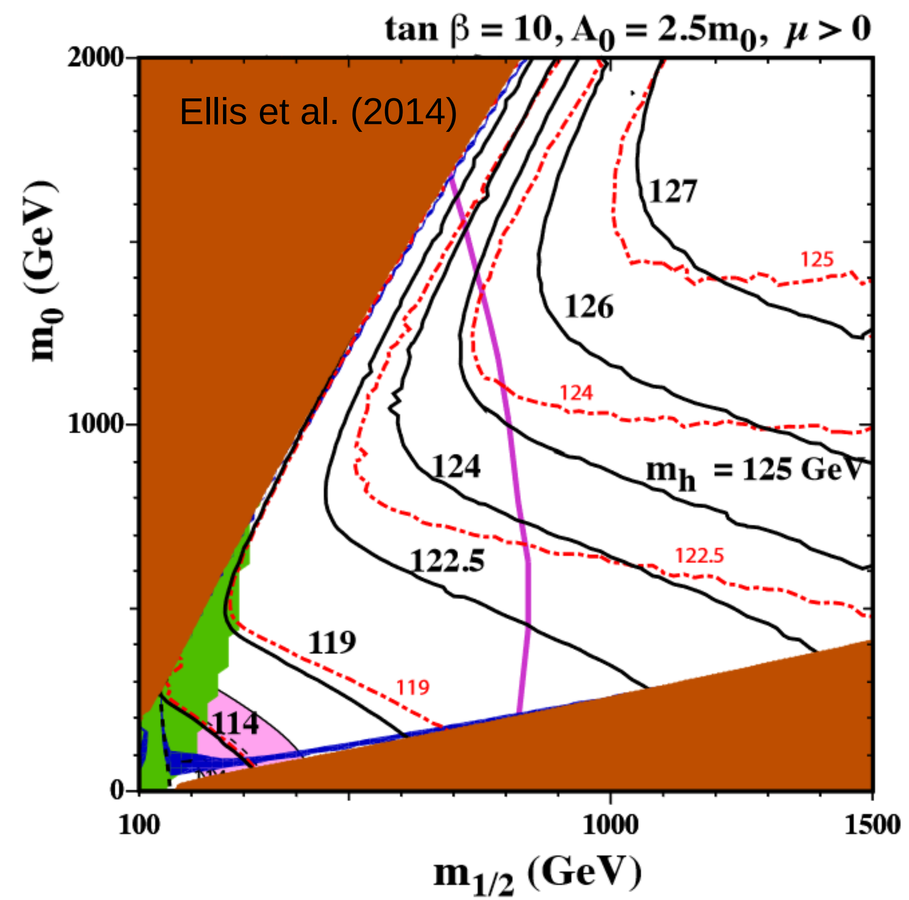
Test your favorite model in agreement with DM

Software tools are publicly available to constrain the parameter space, e.g.:

MicrOMEGAs, Belanger, Boudjema, Pukhov, Semenov et al. [2002-2020]

DarkSUSY, Bringmann, Edsjo, Gondolo, Ullio, Bergstrom [2002-2018]

MadDM, Ambrogio, Arina, Backovic, Heisig, Maltoni, Mantani, Mattelaer, Mohlabeng [2014-2019]



Everything settled and straightforward?

Modified Hubble expansion

$$\dot{n} + 3Hn = -\langle \sigma_{\rm eff} v \rangle (n^2 - n_{\rm eq}^2)$$

Existence of another species Φ whose energy density red shifts according to

$$\rho_\phi \propto a^{-(4+n)}$$

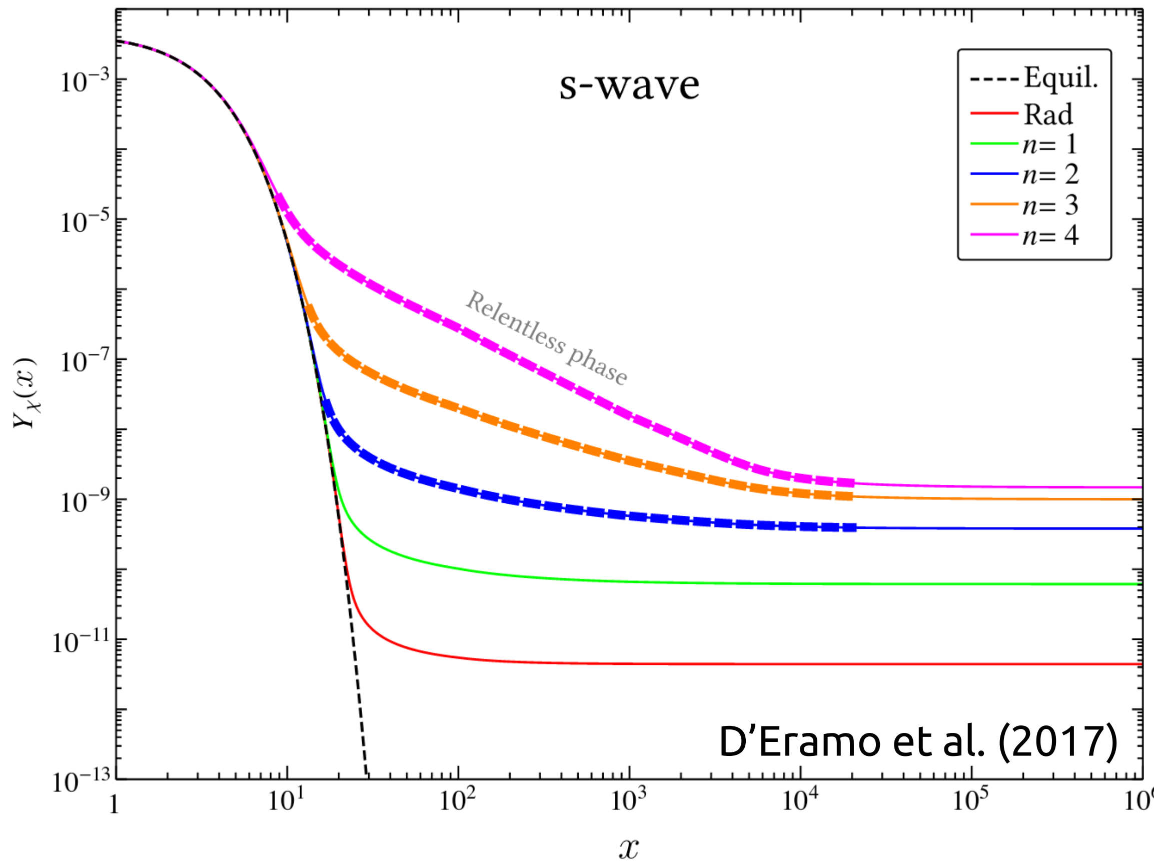
n = 0 radiation
n > 0 energy density dominates over radiation

Which leads to **modified Hubble expansion**

$$H(T) \simeq \frac{\pi \bar{g}_\star^{1/2}}{3\sqrt{10}} \frac{T^2}{M_{\rm Pl}} \left(\frac{T}{T_r}\right)^{n/2}$$

$$T_r = T\Big|_{\rho_\phi = \rho_r}$$

$$T_r > T_{\rm BBN}$$



"Relentless Dark Matter",
D'Eramo, Fernandez, Profumo (2017)

see also Arbey, Mahmoudi (2008)

Early kinetic decoupling

In the usual Dark Matter calculation it is assumed that DM stays in thermal equilibrium at least until freeze-out

$$\dot{n} + 3Hn = -\langle\sigma_{\rm eff} v\rangle(n^2 - n_{\rm eq}^2)$$

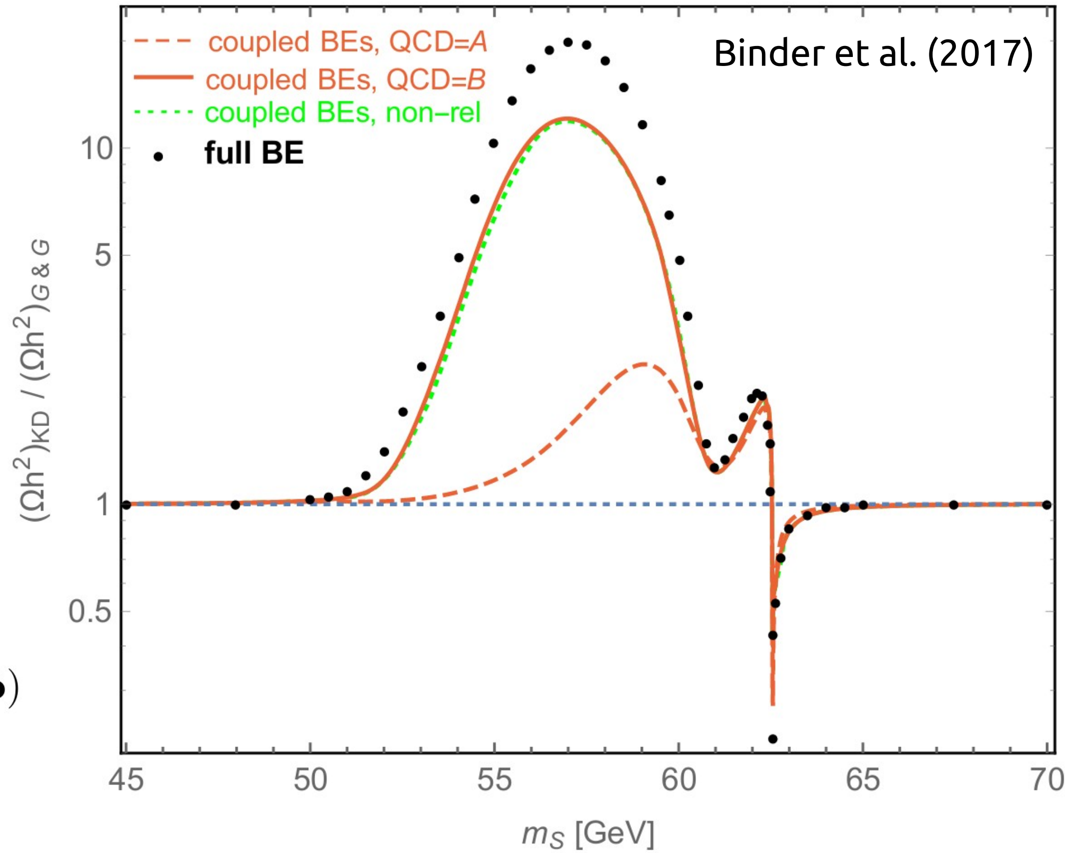
$$\frac{dn_\chi}{dt} + 3Hn_\chi = g_\chi \int \frac{d^3p}{(2\pi)^3 E} C_{\rm ann}[f_\chi]$$

$$C_{\rm ann} = g_\chi E \int \frac{d^3\tilde{p}}{(2\pi)^3} v\sigma_{\bar\chi\chi\to\bar f f} \times \left[f_{\chi,\rm eq}(E) f_{\chi,\rm eq}(\tilde{E}) - \boxed{f_\chi(E) f_\chi(\tilde{E})}\right]$$

$$\boxed{f_\chi = A(T) f_{\chi,\rm eq} = \frac{n_\chi}{n_{\chi,\rm eq}} f_{\chi,\rm eq}}$$

$$\langle\sigma v\rangle \equiv \frac{g_\chi^2}{n_{\chi,\rm eq}^2} \int \frac{d^3p}{(2\pi)^3} \frac{d^3\tilde{p}}{(2\pi)^3} \sigma v_{\bar\chi\chi\to\bar f f} f_{\chi,\rm eq}(\mathbf{p}) f_{\chi,\rm eq}(\tilde{\mathbf{p}})$$

Hard-coded in common DM codes!



→ Development of a rigorous numerical treatment + code:

Binder, Bringmann, Gustafsson, Hryczuk (2017)

→ phenomenologcial studies:

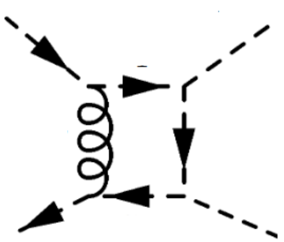
Duch, Grzadkowski (2017)
Feng, Kaplinghat, Yu (2010)
Dent, Dutta, Scherrer (2010)

Effects impacting the particle cross section

$$\dot{n} + 3Hn = -\langle \sigma_{\text{eff}} v \rangle (n^2 - n_{\text{eq}}^2)$$

$$\Omega_\chi h^2 \propto \frac{1}{\langle \sigma_{\text{eff}} v \rangle}$$

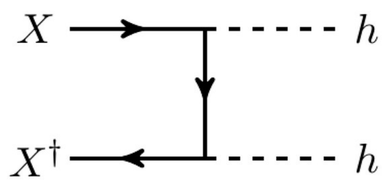
Higher order corrections



$$\sigma_{\text{eff}} v_{\text{rel}} = \sigma^{\text{NLO}} v_{\text{rel}}$$

can lead to sizeable corrections to the DM abundance

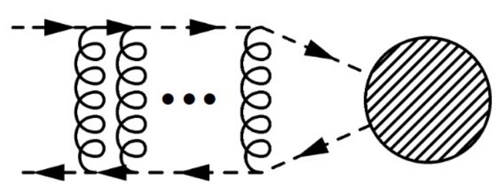
Born level annihilation



$$\sigma_{\text{eff}} v_{\text{rel}} = \sigma^{\text{tree}} v_{\text{rel}}$$

usually DM codes include *only* born level calculation

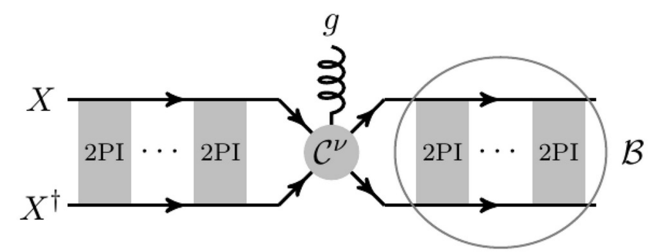
Sommerfeld enhancement



$$\left(\frac{\alpha}{v_{\text{rel}}}\right)^n \sim 1$$

$$\sigma_{\text{eff}} v_{\text{rel}} = \sigma^{\text{tree}} v_{\text{rel}} \times S_0$$

Bound state formation



$$\langle \sigma_{\text{eff}} v_{\text{rel}} \rangle = \langle \sigma_{\text{ann}} v_{\text{rel}} \rangle + \langle \sigma_{\text{BSF}} v_{\text{rel}} \rangle_{\text{eff}}$$

bound state formation and subsequent decay open up a new effective DM annihilation channel

Impact of higher order corrections

non-exhaustive list!

QED:

- **Relic density calculations beyond tree-level, exact calculations versus effective couplings: the ZZ final state,** Boudjema, Drieu La Rochelle, Mariano (2014)
- **Radiative Corrections to the Neutralino Dark Matter Relic Density - an Effective Coupling Approach,** Chatterjee, Drees, Kulkarni (2012)
- **One-loop corrections, uncertainties and approximations in neutralino annihilations: Examples,** Boudjema, Drieu La Rochelle, Kulkarni (2011)
- **Relic density at one-loop with gauge boson pair production,** Baro, Boudjema, Chalons, Hao (2010)
- **Full one-loop corrections to the relic density in the MSSM: A Few examples,** Baro, Boudjema, Semenov (2008)
- **SUSY dark matter: Loops and precision from particle physics,** Boudjema, Semenov , Temes (2006)

QCD:

- **Theoretical uncertainty of the supersymmetric dark matter relic density from scheme and scale variations,** JH, Herrmann, Klasen, Kovarik, Steppeler (2016)
- **SUSY-QCD corrections to stop annihilation into electroweak final states including Coulomb enhancement effects,** JH, Herrmann, Klasen, Kovařík, Meinecke (2015)
- **One-loop corrections to neutralino-stop coannihilation revisited,** JH, Herrmann, Klasen, Kovarik (2015)
- **One-loop corrections to gaugino (co)annihilation into quarks in the MSSM,** Herrmann, Klasen, Kovarik, Meinecke, Steppeler (2014)
- **Neutralino-stop coannihilation into electroweak gauge and Higgs bosons at one loop,** JH, Herrmann, Klasen, Kovarik, Le Boulc'h (2013)
- **SUSY-QCD effects on neutralino dark matter annihilation beyond scalar or gaugino mass unification,** Herrmann, Klasen, Kovarik (2009)
- **Neutralino Annihilation into Massive Quarks with SUSY-QCD Corrections**, Herrmann, Klasen, Kovarik (2009)

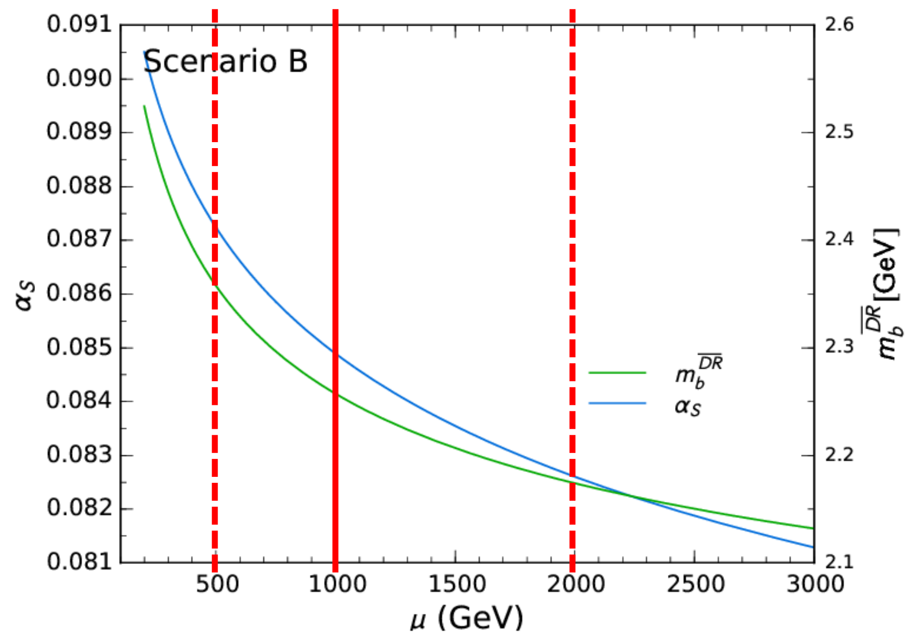
other obser-vables:

- **Leading QCD Corrections for Indirect Dark Matter Searches: a Fresh Look,** Bringmann, Galea, Walia (2016)
- **SUSY-QCD corrections for direct detection of neutralino dark matter and correlations with relic density,** Klasen, Kovarik, Steppeler (2016)

Theoretical uncertainties

There was no estimation of the theoretical uncertainty in the literature before!

→ scale variation $\mu_R/2 < \mu < 2\mu_R$ gives an estimate

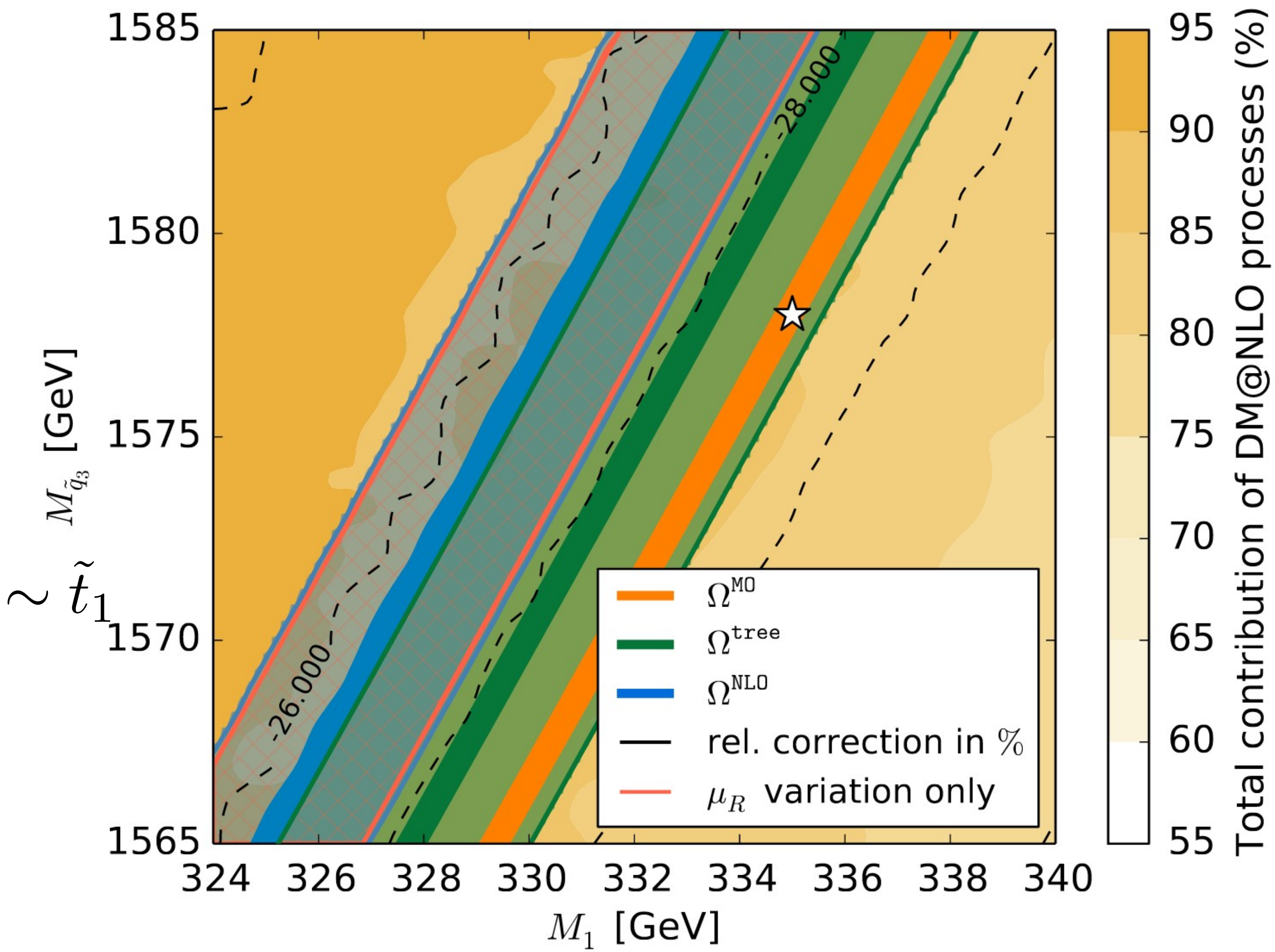


- Calculation contains explicit uncancelled logs of the renormalisation scale
- Depends implicitly on scale dependent parameters, such as $\alpha_s, \theta_{\tilde{t}}, \theta_{\tilde{b}} A_t, A_b, m_b, m_{\tilde{t}_2}$

→ first study of this kind in the context of DM

JH, B. Herrmann, M. Klasen, K. Kovařík, and P. Steppeler, Phys. Rev. D93, 114023 (2016)

NLO corrections and theoretical uncertainties



$\sim \tilde{\chi}_1^0$

		C
$\tilde{\chi}_1^0\tilde{\chi}_1^0 \rightarrow$	$t\bar{t}$	16%
$\tilde{\chi}_1^0\tilde{t}_1 \rightarrow$	th^0	23%
	tg	23%
	tZ^0	5%
	bW^+	11%
$\tilde{t}_1\tilde{t}_1^* \rightarrow$	h^0h^0	5%
	Z^0Z^0	2%
	W^+W^-	3%
Total		88%

JH, B. Herrmann, M. Klasen, K. Kovařík, and P. Steppeler, Phys. Rev. D93, 114023 (2016)
JH, B. Herrmann, M. Klasen, and K. Kovařík, Phys. Rev. D 91, 034028 (2015)
JH, B. Herrmann, M. Klasen, K. Kovařík, and M. Meinecke, Phys. Rev. D 91, 034012 (2015)
JH, B. Herrmann, M. Klasen, K. Kovařík, and Q. Le Boulc'h, Phys. Rev. D 87, 054031 (2013)

Sommerfeld effect

MSSM:

non-exhaustive list!

- **Relic density of wino-like dark matter in the MSSM**, Beneke, Bharucha, Dighera, Hellmann, Hryczuk, Recksiegel, Ruiz-Femenia (2016)
- **Heavy neutralino relic abundance with Sommerfeld enhancements - a study of pMSSM scenarios**, Beneke, Hellmann, Ruiz-Femenia (2015)
- **SUSY-QCD corrections to stop annihilation into electroweak final states including Coulomb enhancement effects,** JH, B. Herrmann, M. Klasen, K. Kovařík, and M. Meinecke, Phys. Rev. D 91, 034012 (2015)
- **Non-relativistic pair annihilation of nearly mass degenerate neutralinos and charginos III. Computation of the Sommerfeld enhancements**, Beneke, Hellmann, Ruiz-Femenia (2015)
- **Non-relativistic pair annihilation of nearly mass degenerate neutralinos and charginos II. P-wave and next-to-next-to-leading order S-wave coefficients**, Hellmann, Ruiz-Femenía (2013)
- **Non-relativistic pair annihilation of nearly mass degenerate neutralinos and charginos I. General framework and S-wave annihilation,** Beneke, Hellmann, Ruiz-Femenia (2013)
- **Enhanced One-Loop Corrections to WIMP Annihilation and their Thermal Relic Density in the Coannihilation Region**, Drees, Gu (2013)

Other Models:

- **Higgs Enhancement for the Dark Matter Relic Density**, JH, Petraki, (2018)
- **A Sommerfeld Toolbox for Colored Dark Sectors**, El Hedri, Kaminska, Vries (2017)
- **Asymmetric thermal-relic dark matter: Sommerfeld-enhanced freeze-out, annihilation signals and unitarity bounds**, Baldes, Petraki (2017)
- **The Sommerfeld Enhancement in the Scotogenic Model with Large Electroweak Scalar Multiplets,** Chowdhury, Nasri (2017)
- **Self-consistent Calculation of the Sommerfeld Enhancement**, Blum, Sato, Slatyer (2016)

Sommerfeld effect via massive scalar exchange

non-exhaustive list!

First conceptional studies before the Higgs discovery:

- **The Sommerfeld enhancement for scalar particles and application to sfermion co-annihilation regions**, Hryczuk (2011)
- **Sommerfeld Enhancements for Thermal Relic Dark Matter**, Feng, Kapling, Yu (2010)
- **Potentially Large One-loop Corrections to WIMP Annihilation**, Drees, Kim, Nagao (2009)

More specific studies after the Higgs discovery:

- **Relic density of wino-like dark matter in the MSSM**, Beneke, Bharucha, Dighera, Hellmann, Hryczuk, Recksiegel, Ruiz-Femenia (2016)
- **Non-relativistic pair annihilation of nearly mass degenerate neutralinos and charginos III. Computation of the Sommerfeld enhancements**, Beneke, Hellmann, Ruiz-Femenia (2015)
- **Heavy neutralino relic abundance with Sommerfeld enhancements - a study of pMSSM scenarios**, Beneke, Hellmann, Ruiz-Femenia (2015)
- **Higgs portal, fermionic dark matter, and a Standard Model like Higgs at 125 GeV**, Lopez-Honorez, Schwetz, Zupan (2012)

However, Higgs boson exchange has been neglected in recent studies of generic, (colored) coannihilation scenarios!

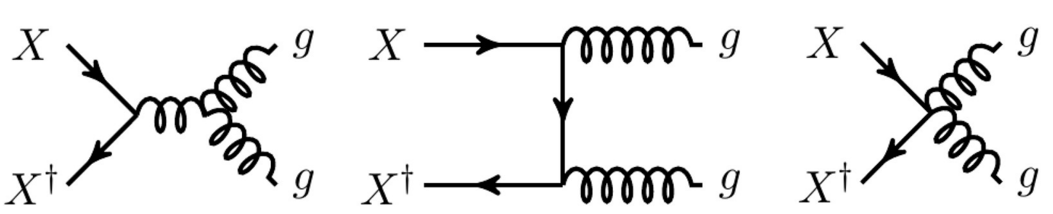
Higgs enhancement

- **Simplified model:**

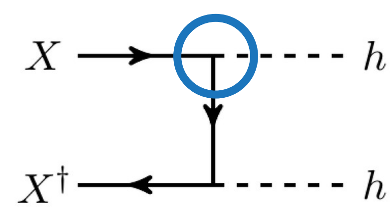
DM Majorana fermion χ; co-annihilating with complex scalar X charged under SU(3)$_c$

$$\delta\mathcal{L} = (D_{\mu,ij}X_j)^\dagger\,(D^\mu_{ij'}X_{j'}) - m_X^2\, X_j^\dagger X_j + \frac{1}{2}(\partial_\mu h)(\partial^\mu h) - \frac{1}{2}m_h^2 h^2 - g_h m_X\, h\, X_j^\dagger X_j$$

- **Annihilation processes:**



$$(\sigma v_{\mathrm{rel}})^{\mathrm{pert}}_{XX^\dagger\to gg} = \frac{14}{27}\frac{\pi\alpha_s^2}{m_X^2}$$

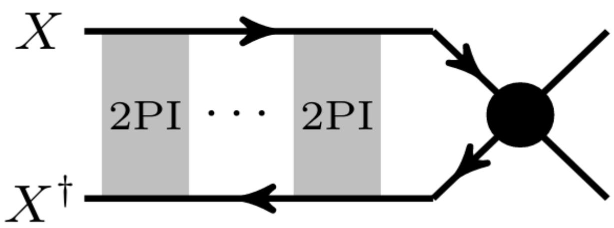


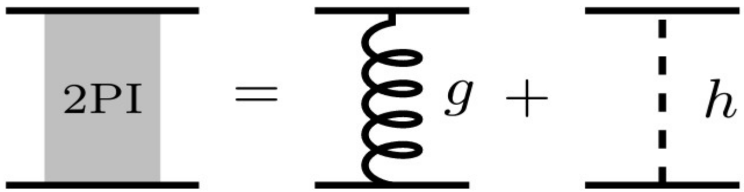
$$\alpha_h = \frac{g_h^2}{16\pi}$$

$$(\sigma v_{\mathrm{rel}})^{\mathrm{pert}}_{XX^\dagger\to hh} = \frac{4\pi\alpha_h^2}{3m_X^2}\frac{(1-m_h^2/m_X^2)^{1/2}}{[1-m_h^2/(2m_X^2)]^2}$$

we neglect p-wave suppressed contributions $X\bar{X}\to q\bar{q},\, X\bar{X}\to gh$

Higgs as mediator of long-range interactions





$$\left[-\frac{\nabla^2}{2\mu} + V_{\rm scatt}(\mathbf{r})\right]\phi_{\mathbf{k}}(\mathbf{r}) = \mathcal{E}_{\mathbf{k}}\,\phi_{\mathbf{k}}(\mathbf{r}) \quad \text{with} \quad \mathrm{V}_{\rm scatt}(r) = -\frac{\alpha_g^S}{r} - \frac{\alpha_h}{r}\,e^{-m_h r}$$

$$\boxed{S_0(\zeta_g, \zeta_h, d_h) \equiv |\phi_{\mathbf{k}}(0)|^2}$$

Color decomposition:

$$\mathbf{3} \otimes \bar{\mathbf{3}} = \mathbf{1} \oplus \mathbf{8} \qquad \alpha_g^S \equiv \alpha_s^S \times \begin{cases} C_{\mathbf{1}} = C_F = 4/3 \\ C_{\mathbf{8}} = C_F - C_A/2 = -1/6 \end{cases}$$

$$(\sigma v_{\rm rel})_{XX^\dagger \to gg} = (\sigma v_{\rm rel})^{\rm pert}_{XX^\dagger \to gg} \times \left(\frac{2}{7}S_0^{[\mathbf{1}]} + \frac{5}{7}S_0^{[\mathbf{8}]}\right)$$

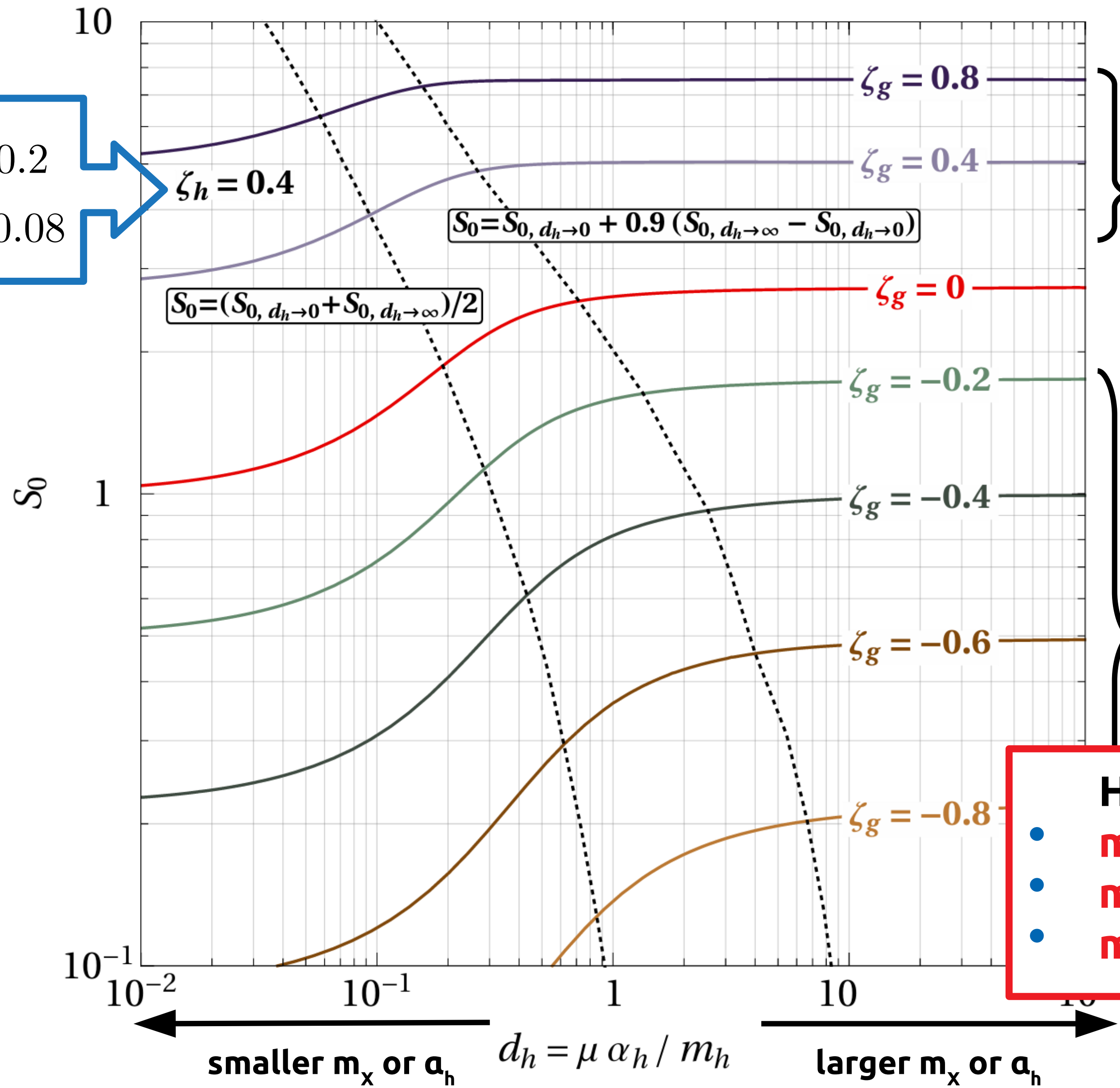
$$(\sigma v_{\rm rel})_{XX^\dagger \to hh} = (\sigma v_{\rm rel})^{\rm pert}_{XX^\dagger \to hh} \times S_0^{[\mathbf{1}]}$$

Higgs enhancement

$$\zeta_{g,h} \equiv \frac{\mu \alpha_{g,h}}{\mu v_{\rm rel}} = \frac{\alpha_{g,h}}{v_{\rm rel}}$$

$$d_h \equiv \frac{\mu \alpha_h}{m_h}$$

$v_{\rm rel} \approx 0.2$
$\alpha_h \approx 0.08$



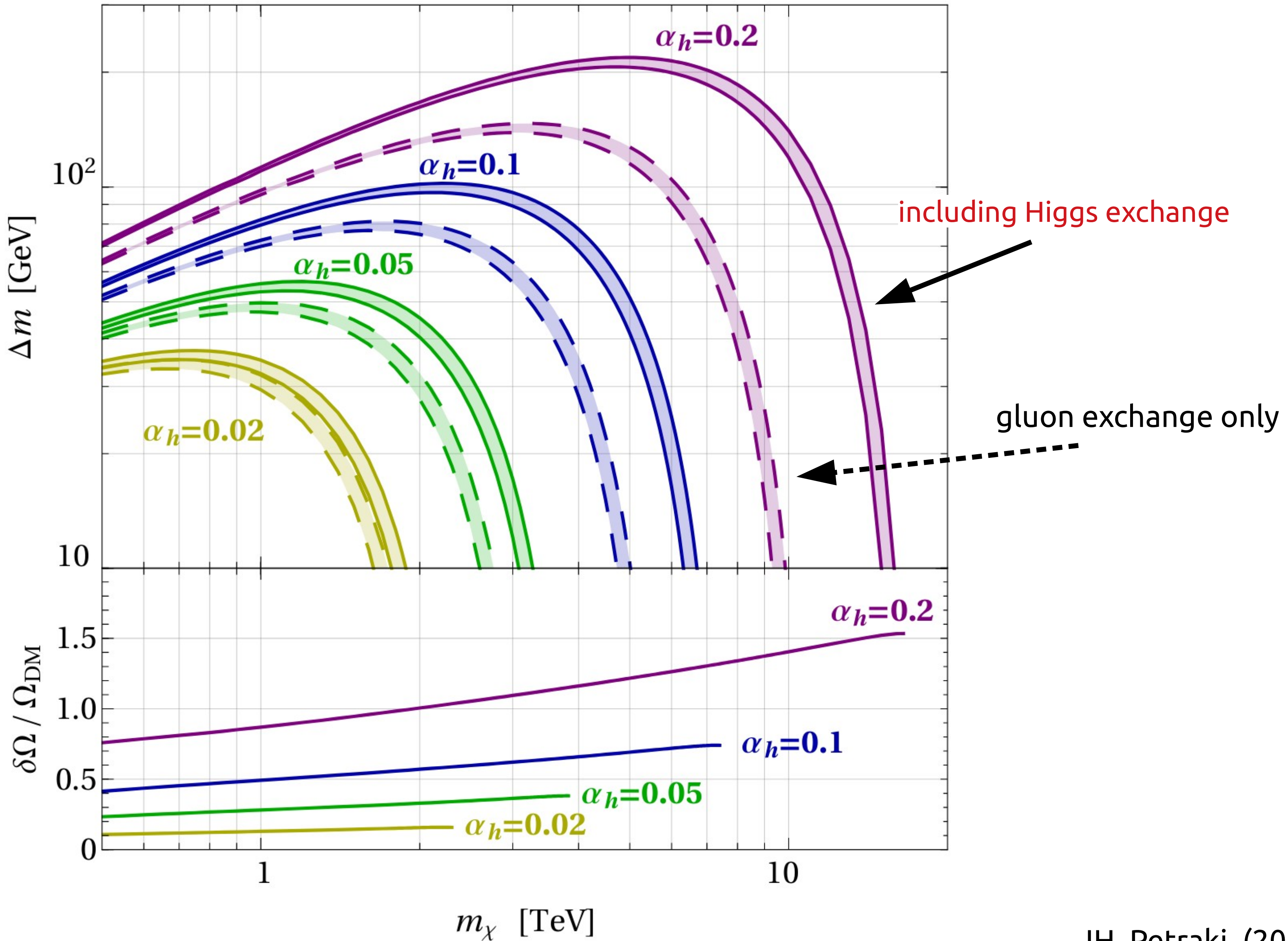
attractive gluon potential (singlet)

repulsive gluon potential (octet)

Higgs is able to
- **make singlet more attractive**
- **make octet less repulsive**
- **make octet attractive**

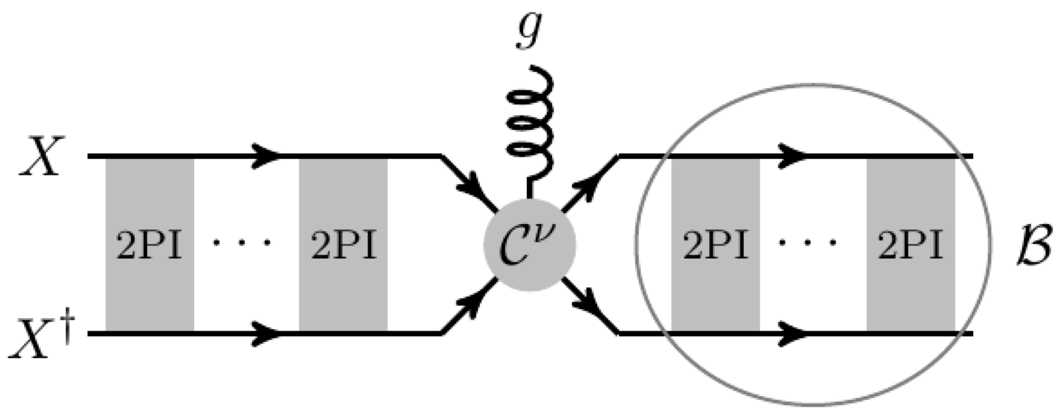
JH, Petraki, (2018)

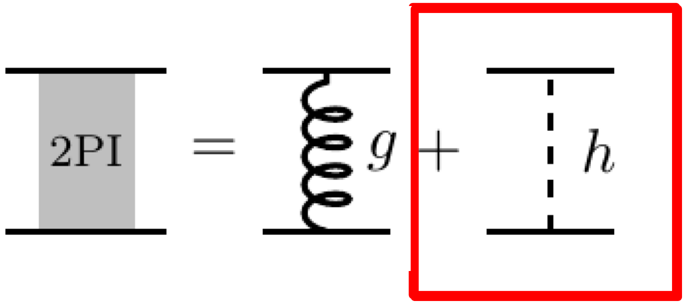
Impact of Higgs enhancement on the relic density



JH, Petraki, (2018)

Bound states with gluon and Higgs exchange





$$(X+X^\dagger)_{[\mathbf{8}]} \to \ \mathcal{B}(XX^\dagger)_{[\mathbf{1}]} + g_{[\mathbf{8}]}$$

bound state formation

$$(X+X^\dagger)_{[\mathbf{1}]} \to \ \{\mathcal{B}(XX^\dagger)_{[\mathbf{8}]} + g_{[\mathbf{8}]}\}_{\mathbf{1_S}}$$

$$(X+X^\dagger)_{[\mathbf{8}]} \to \ \{\mathcal{B}(XX^\dagger)_{[\mathbf{8}]} + g_{[\mathbf{8}]}\}_{\mathbf{8_S}\text{ or }\mathbf{8_A}}$$

Higgs may allow

(1) to form tighter bound states

(2) to form color octet bound states

$$\boxed{\langle \sigma_{\rm BSF} v_{\rm rel}\rangle_{\rm eff} = \langle \sigma_{\rm BSF} v_{\rm rel}\rangle \times \left(\frac{\Gamma_{\rm dec}}{\Gamma_{\rm dec}+\Gamma_{\rm ion}}\right)}$$

Contributions to the effective BSF cross section

$$\Omega_\chi h^2 \propto \frac{1}{\langle \sigma_{\rm eff} v \rangle}$$

$$\langle \sigma_{\rm eff} v_{\rm rel} \rangle = \langle \sigma_{\rm ann}\, v_{\rm rel} \rangle + \langle \sigma_{\rm BSF} v_{\rm rel} \rangle_{\rm eff}$$

$$\langle \sigma_{\rm BSF} v_{\rm rel} \rangle_{\rm eff} = \langle \sigma_{\rm BSF} v_{\rm rel} \rangle \times \left(\frac{\Gamma_{\rm dec}}{\Gamma_{\rm dec} + \Gamma_{\rm ion}} \right)$$

bound state ionisation

$$(\mathrm{XX}^\dagger)_{[\mathbf{1}]} + g_{[\mathbf{8}]} \to (X + X^\dagger)_{[\mathbf{8}]}$$

$$\Gamma_{\rm ion} = g_g \int_{\omega_{\rm min}}^{\infty} \frac{d\omega}{2\pi^2} \frac{\omega^2}{e^{\omega/T} - 1}\, \sigma_{ion}$$

$$\sigma_{ion} = \frac{g_X^2}{g_g g_{\mathcal{B}}} \frac{\mu^2 v_{rel}^2}{\omega^2}\, \sigma_{\rm BSF}$$

Milne relation

bound state decay

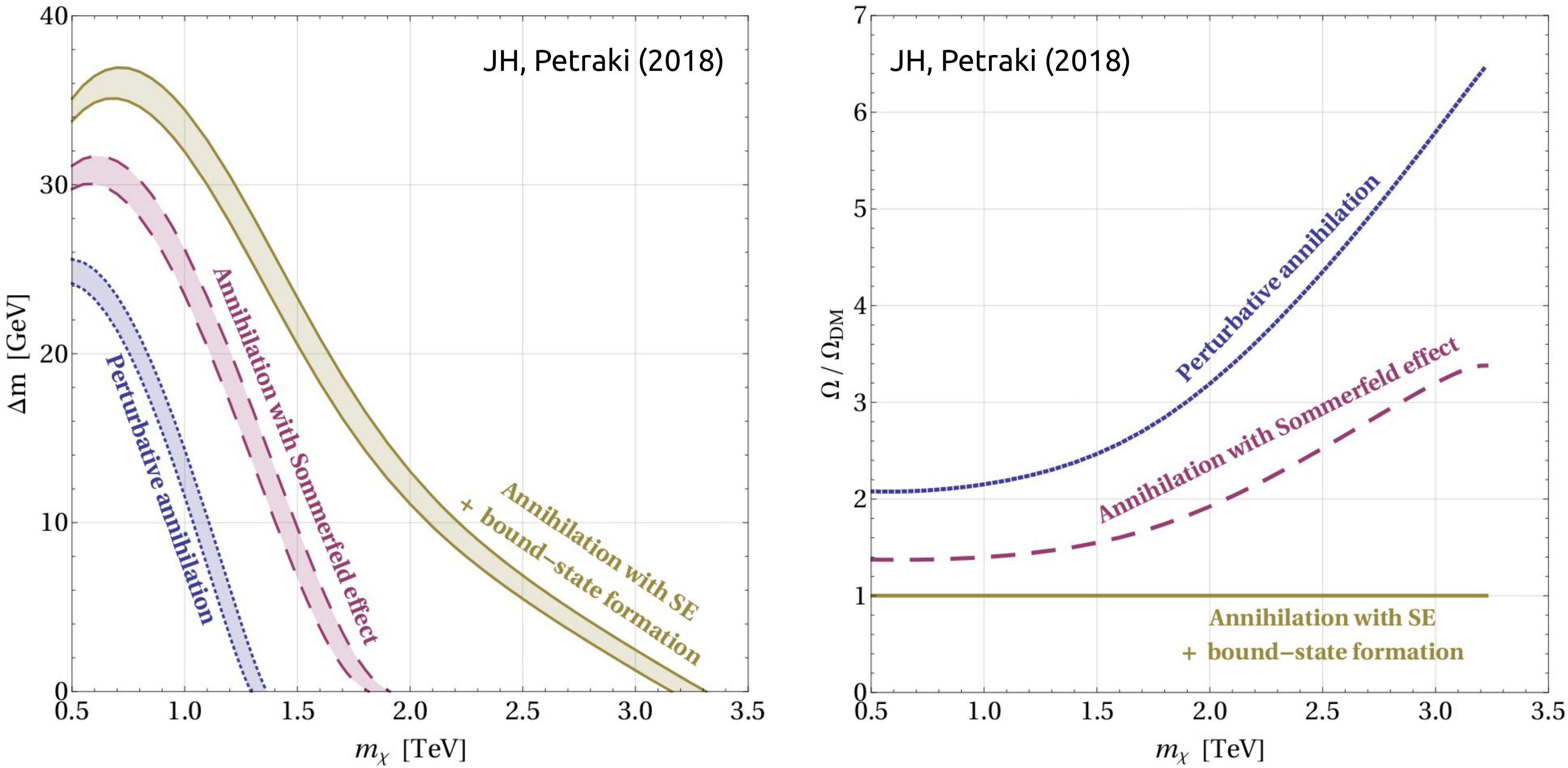
$$\mathcal{B}(XX^\dagger)_{[\mathbf{1}]} \to g_{[\mathbf{8}]}\ g_{[\mathbf{8}]}$$

$$\Gamma_{\rm dec} = (\sigma^{s-{\rm wave}}_{{\rm ann},[\mathbf{1},\mathbf{8}]} v_{\rm rel})\ |\psi^{[\mathbf{1},\mathbf{8}]}_{n\ell m}(0)|^2$$

$$|\psi^{[\mathbf{1},\mathbf{8}]}_{1,0,0}(0)|^2 = \frac{\mu^3(\alpha_h + \alpha^B_{g\ ,[\mathbf{1},\mathbf{8}]})^3}{\pi}$$

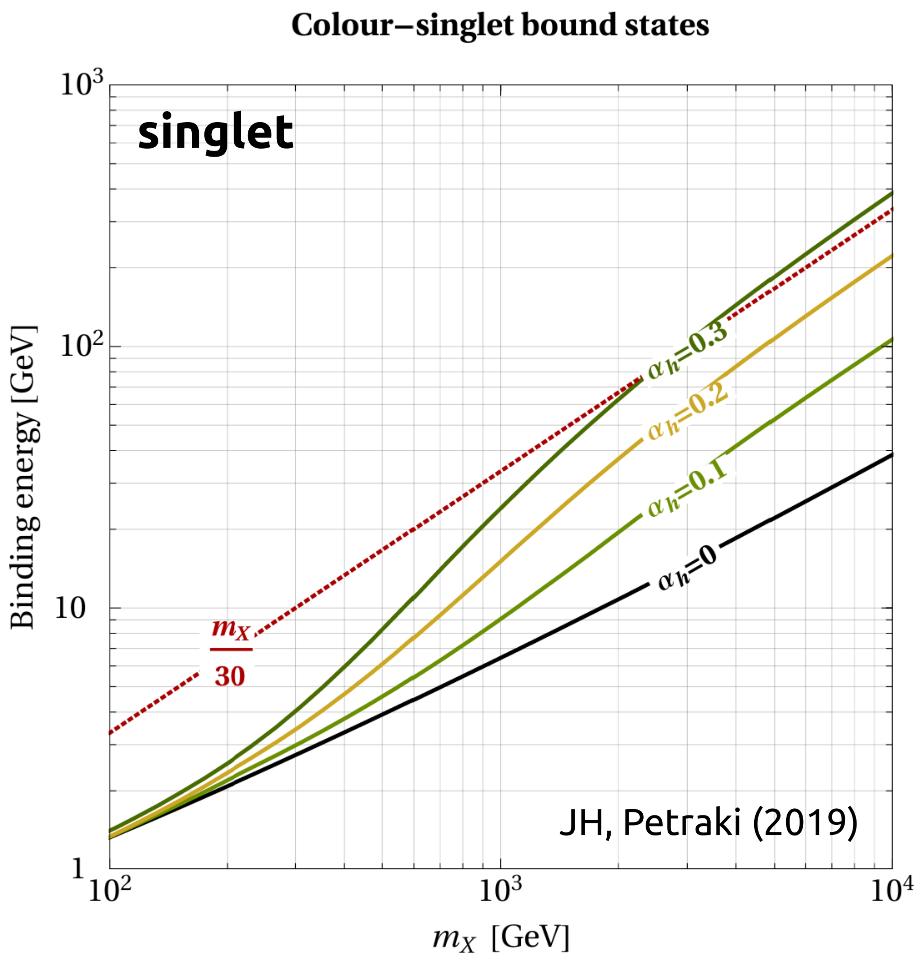
Impact on the relic density

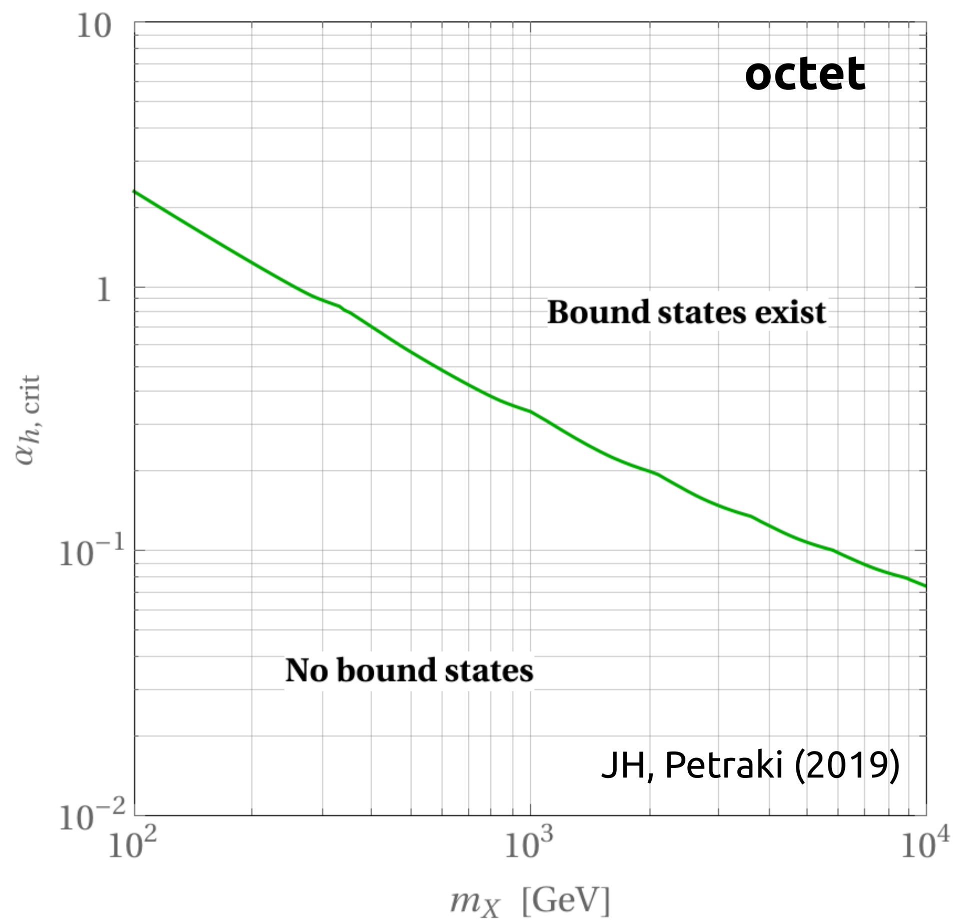
gluon exchange only



→ neglecting BSF and Sommerfeld enhancement would lead to a wrong relic density prediction by a factor 2 to 7

Impact of the Higgs on the formation of bound states

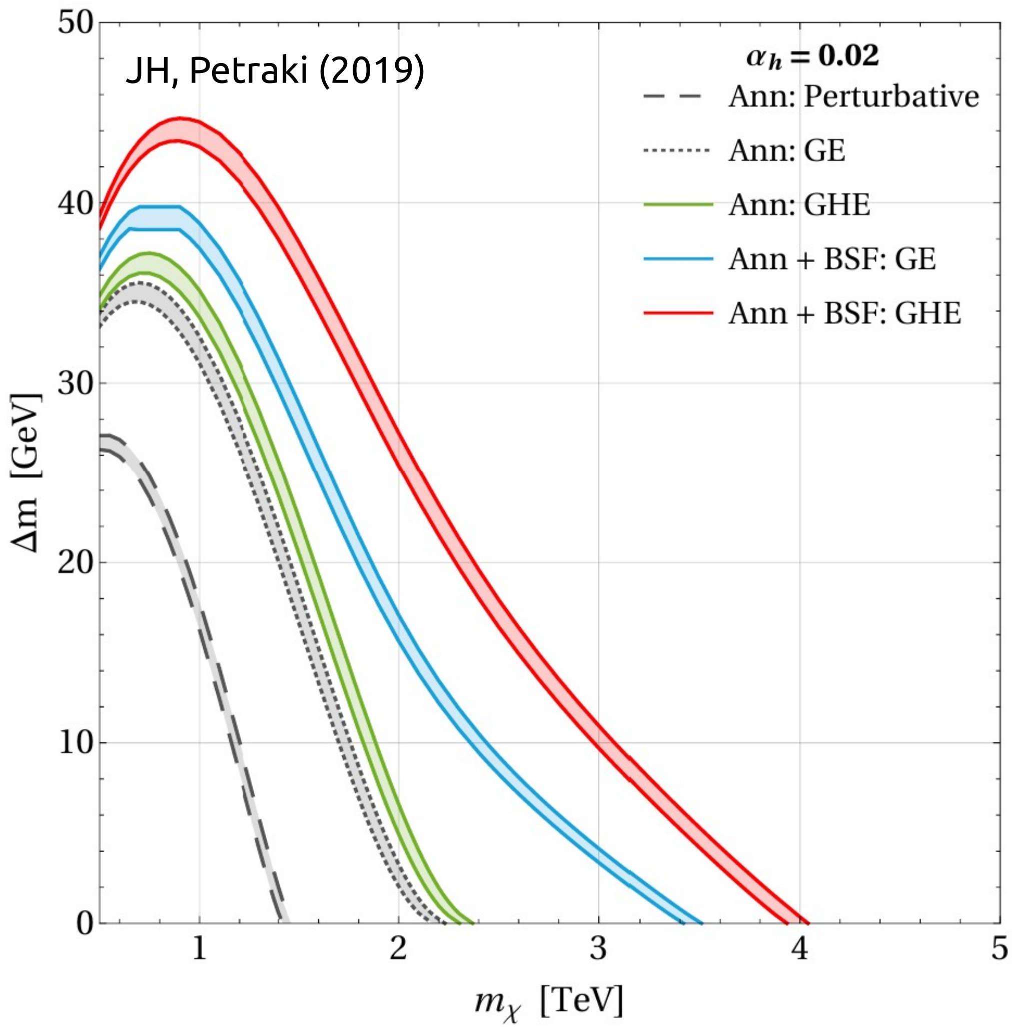


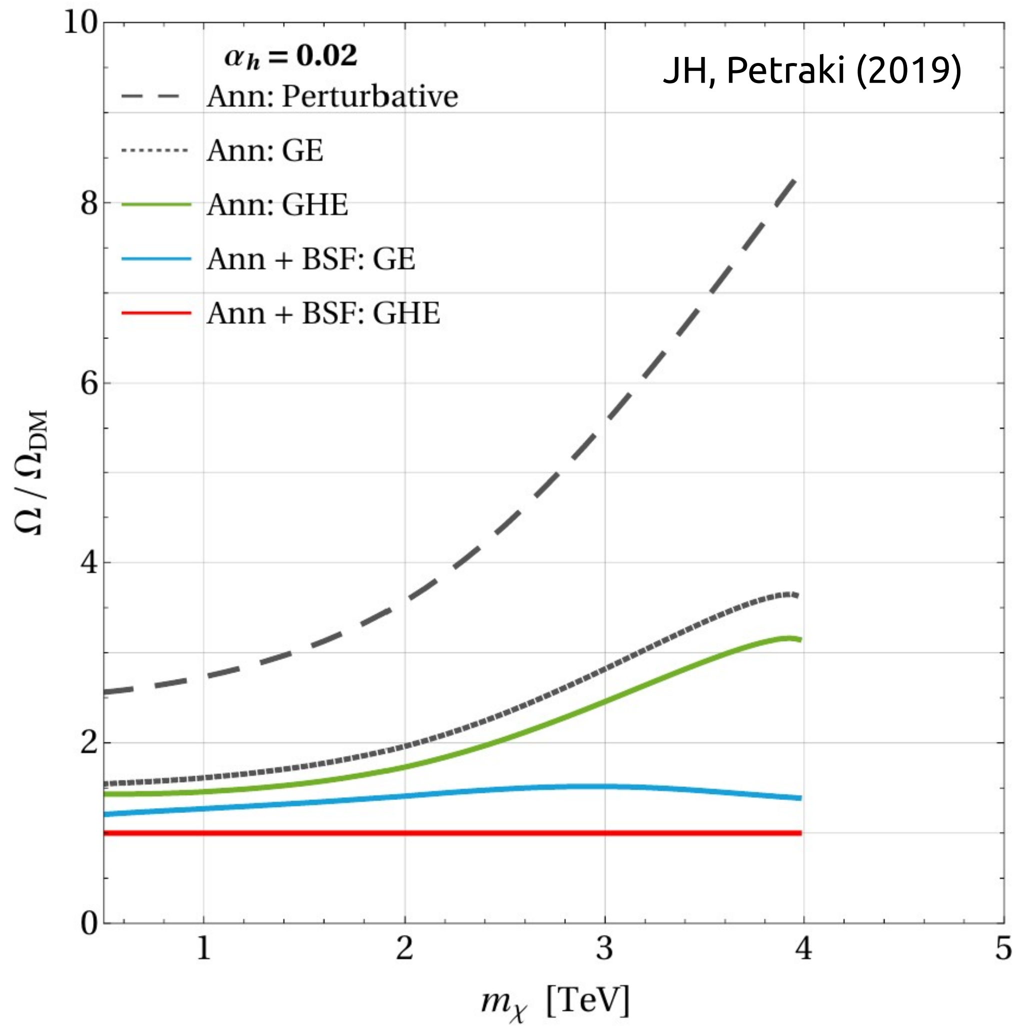


tighter bound states

additional bound states

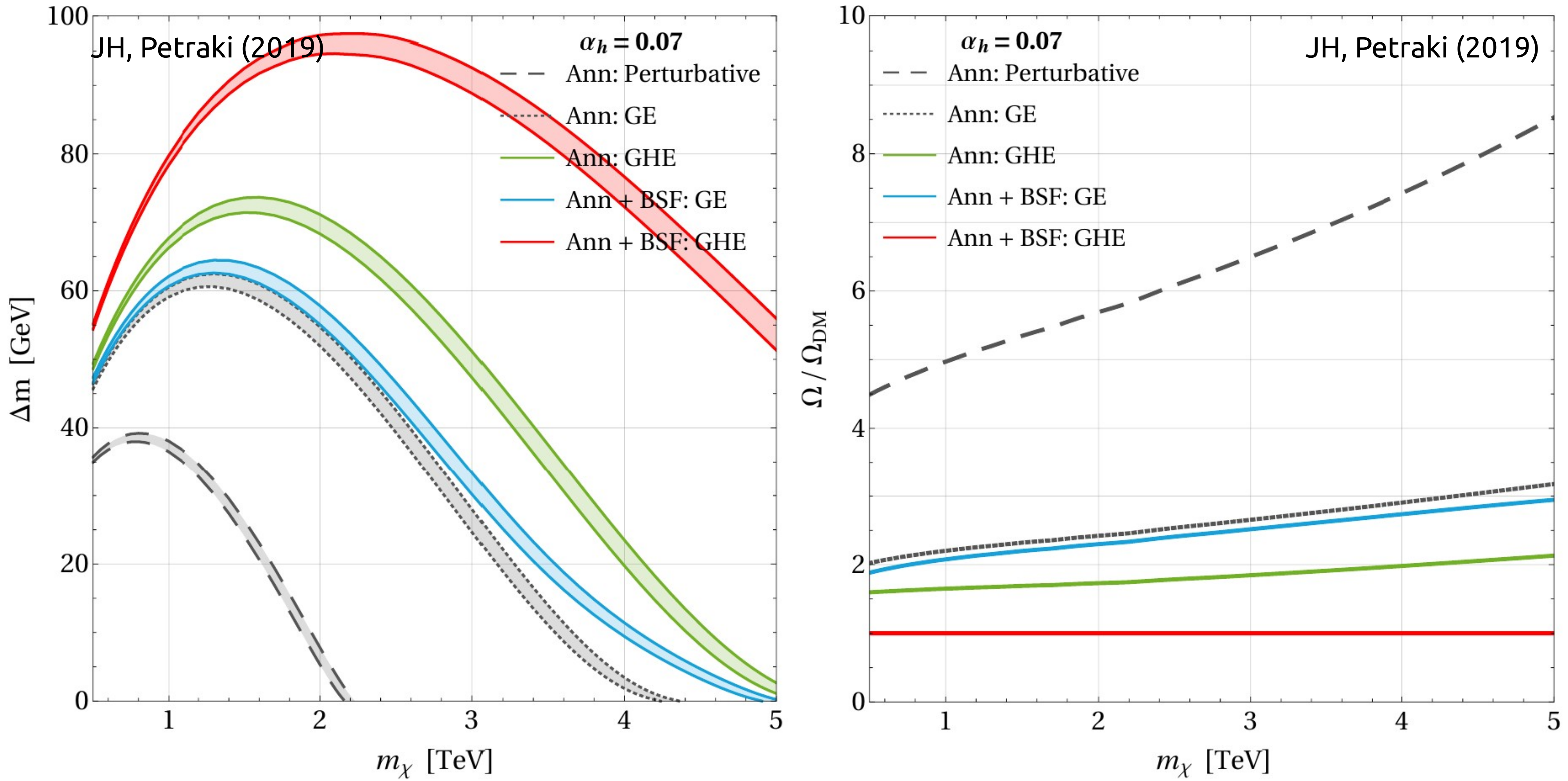
Impact on the relic density (with Higgs exchange)





→ **impact of gluon dominant for small Higgs couplings**

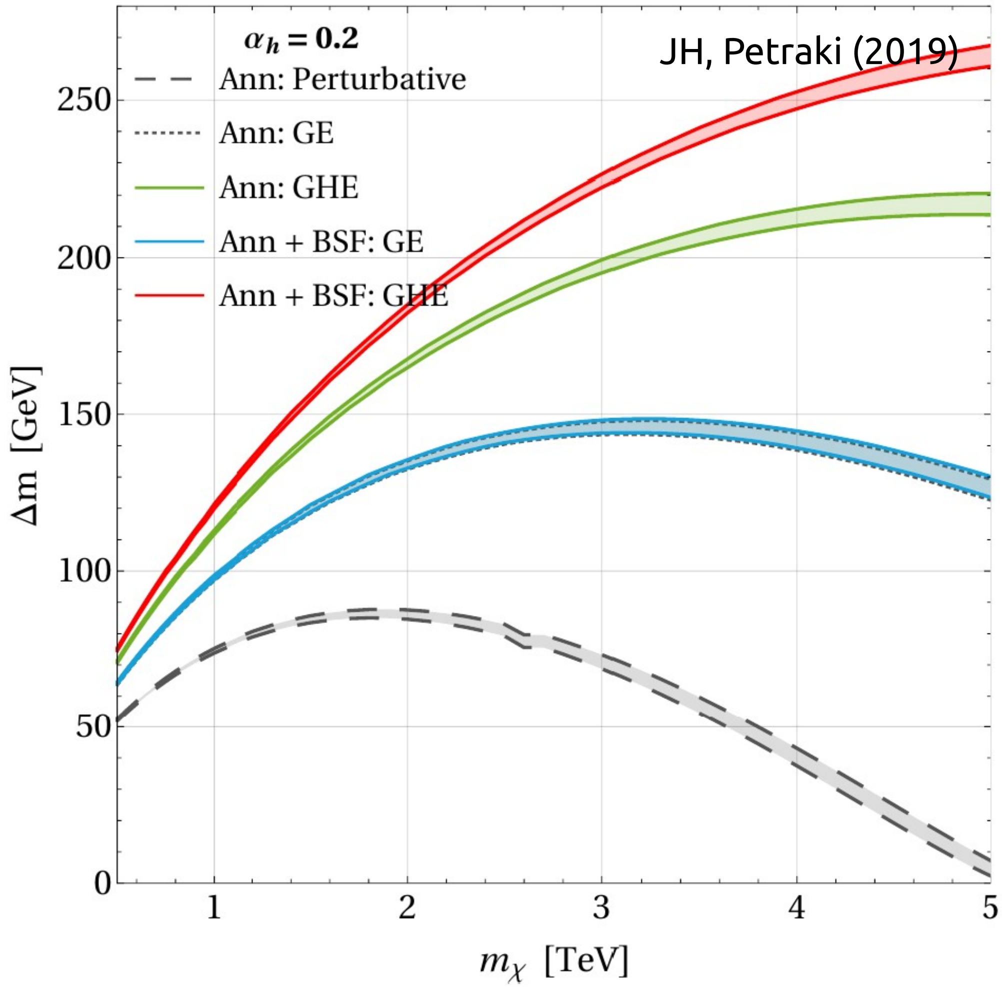
Impact on the relic density (with Higgs exchange)

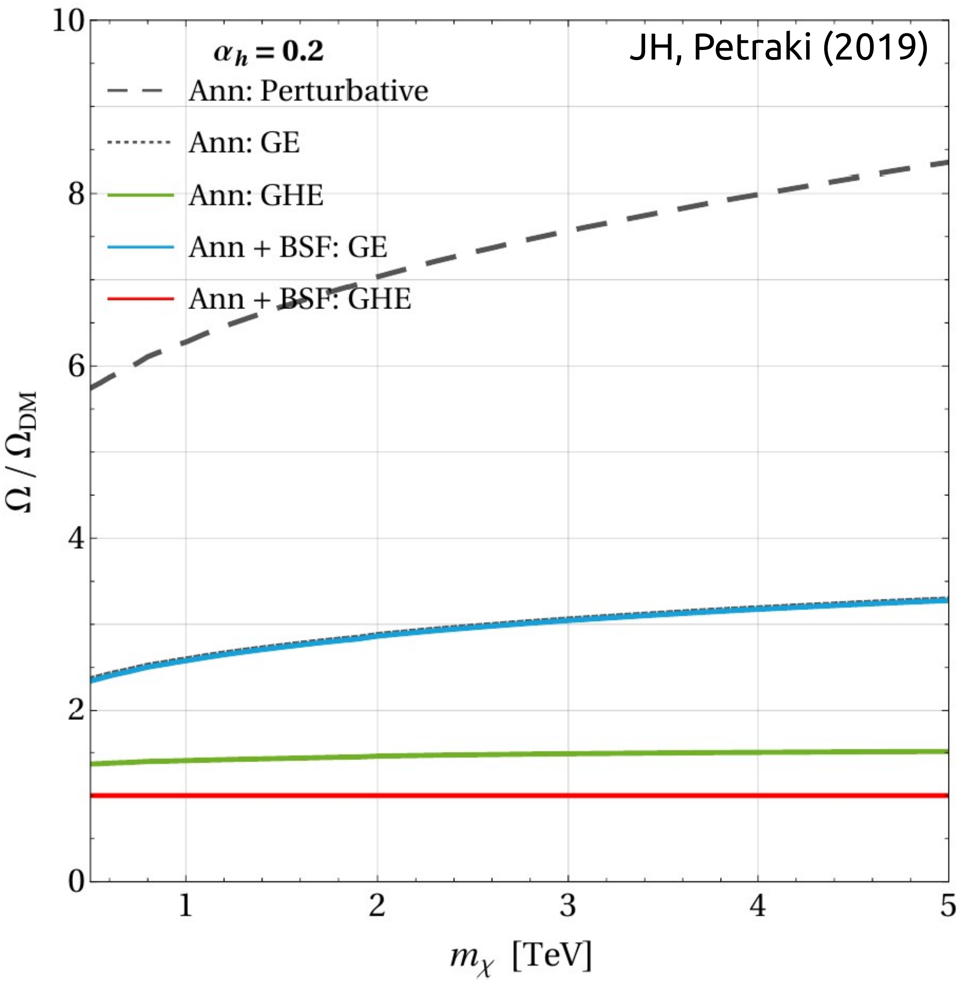


→ **effect of gluon relatively less prominent**

→ **main impact from Higgs enhancement and BSF**

Impact on the relic density (with Higgs exchange)



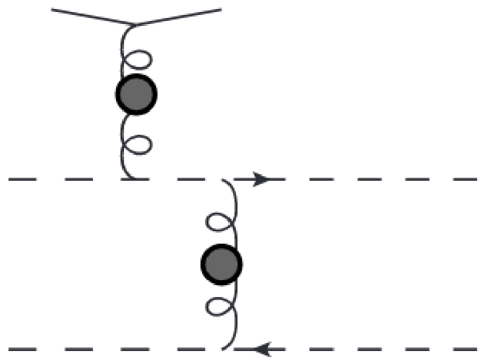


→ Higgs enhancement most prominent

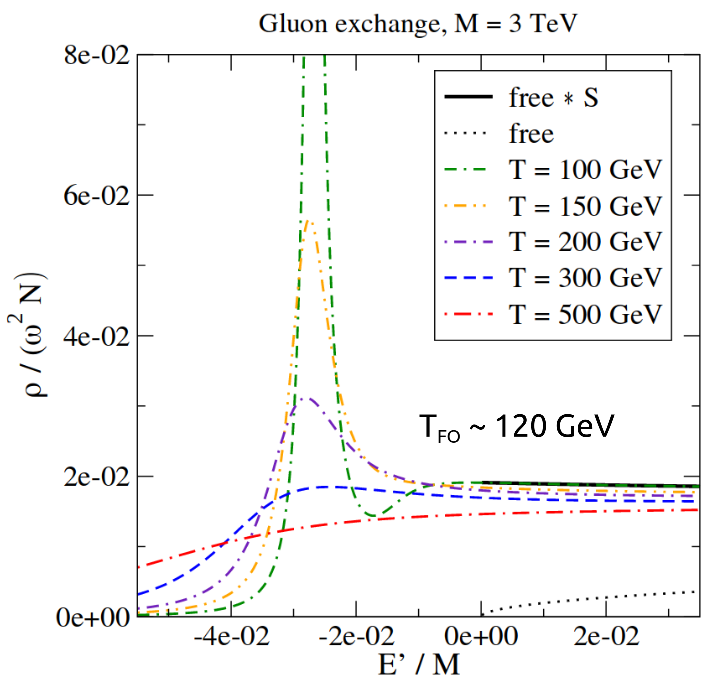
→ Higgs mediated BSF still sizable

Finite temperature effects

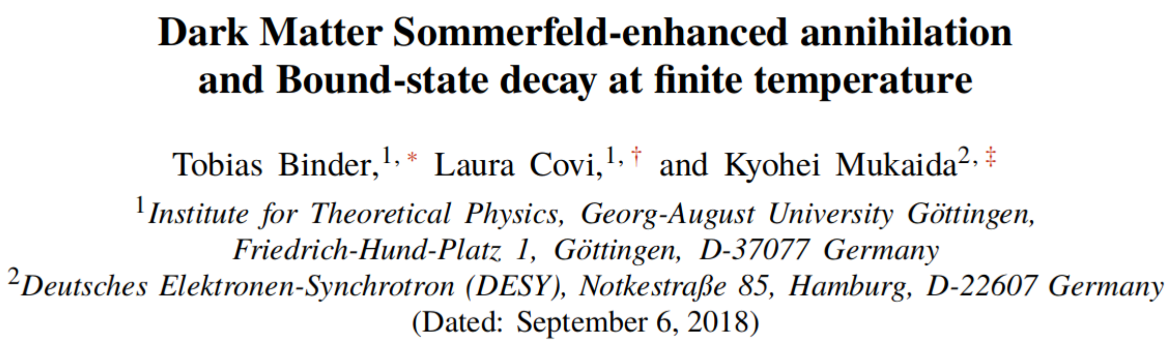
- Thermal masses – Deybe screening
- Scattering of heavy particles with light plasma constituents – Landau damping



Kim, Laine (2017)
Biondini, Laine (2018)
Biondini (2018)
Biondini, Vogl (2018)



Example: Gluino annihilation



Dark Matter Sommerfeld-enhanced annihilation and Bound-state decay at finite temperature

Tobias Binder,[1,*] Laura Covi,[1,†] and Kyohei Mukaida[2,‡]

[1]*Institute for Theoretical Physics, Georg-August University Göttingen, Friedrich-Hund-Platz 1, Göttingen, D-37077 Germany*

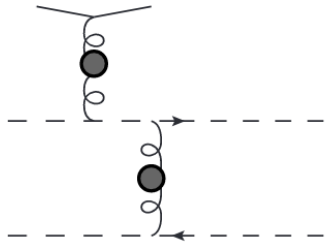
[2]*Deutsches Elektronen-Synchrotron (DESY), Notkestraße 85, Hamburg, D-22607 Germany*

(Dated: September 6, 2018)

Both approaches only valid in ionization equilibrium!

Finite temperature effects

Kim, Laine (2017)



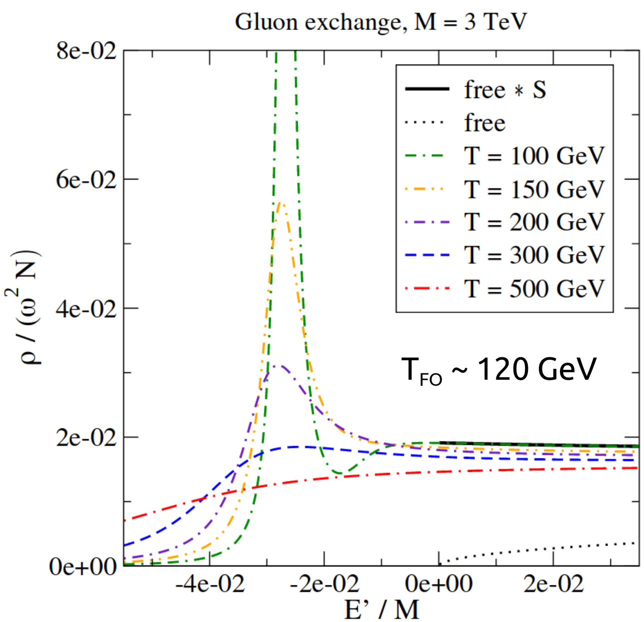
- Thermal masses – Deybe screening
- Scattering of heavy particles with light plasma constituents – Landau damping

Biondini, Laine (2018), Biondini (2018), Biondini, Vogl (2018)

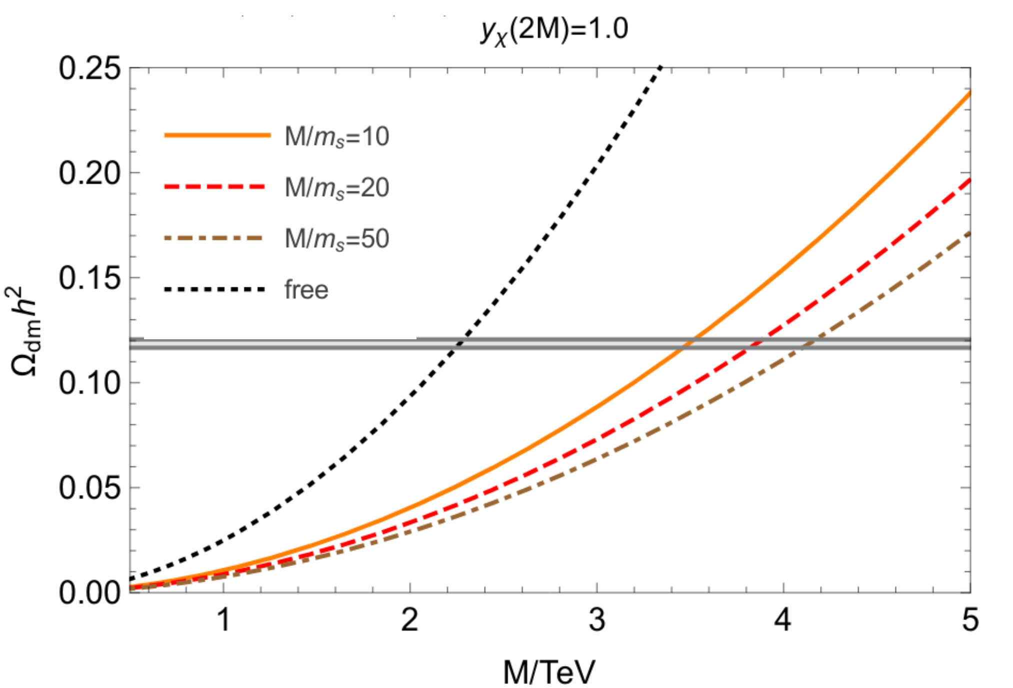
$$G(r,t) \overset{t\to+\infty}{\sim} G(r,0)\,\exp\{-i[V(r)-i\Gamma(r)]t\}\,,$$

$$V(r) = -\frac{g_s^2 C_F}{4\pi}\left[m_D + \frac{\exp(-m_D r)}{r}\right],$$

$$\Gamma(r) = \frac{g_s^2 C_F T}{2\pi}\int_0^\infty \frac{dz\, z}{(z^2+1)^2}\left[1-\frac{\sin(z m_D r)}{z m_D r}\right]$$



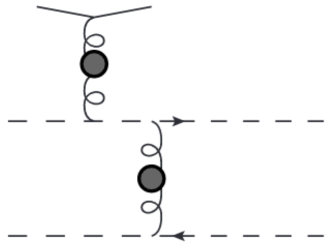
Example: Gluino annihilation



Dark Higgs as long-range force mediator, but no gluo-dissociation

Finite temperature effects

Kim, Laine (2017)



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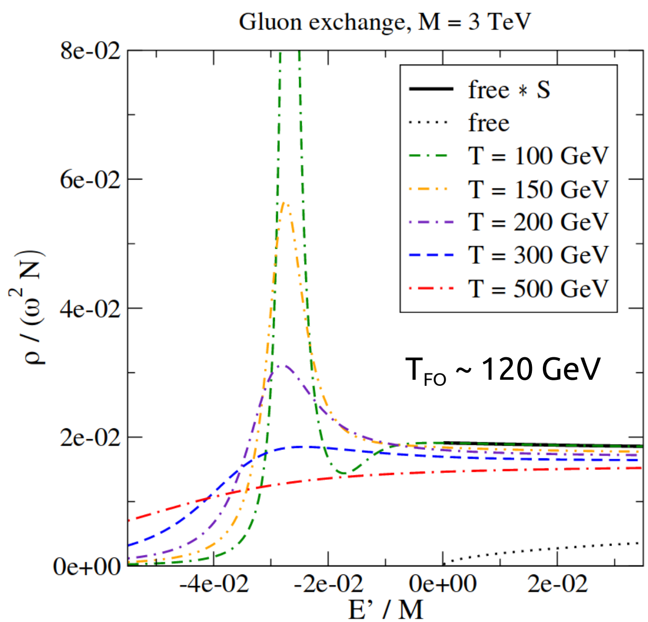
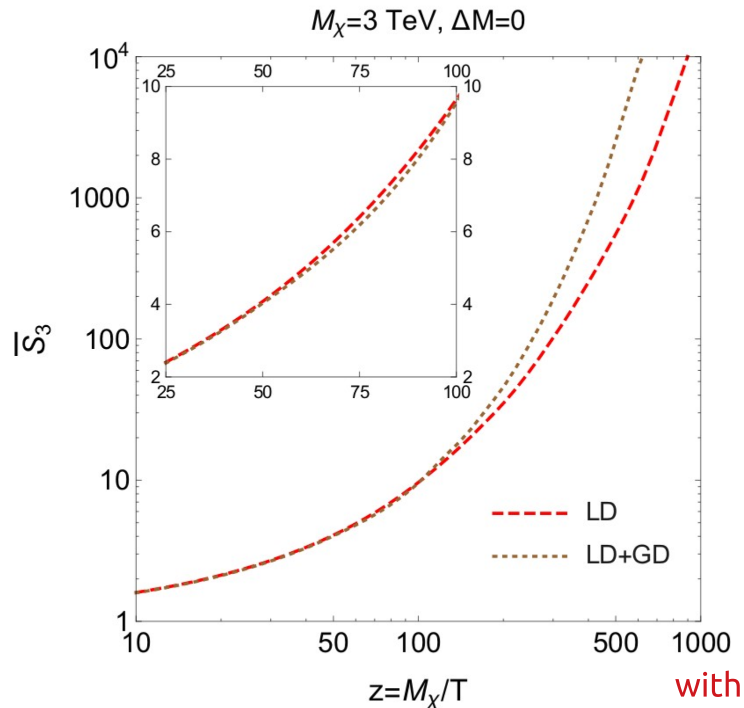
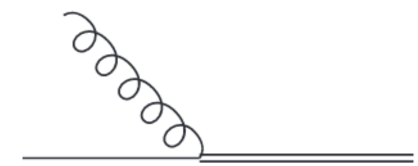


Example: Gluino annihilation





with gluo-dissociation, no Higgs as long-range force mediator

(In)direct constraints

Heavy lepton

- **Electroweak precision data**

  no mixing with SM fermions, SU(2)$_L$ singlets
  → no relevant contributions

  Ellis, Godbole, Gopalakrishna, Wells, 1404.4398

- **muon lifetime**

$$\mu \to ess$$

  below current experimental limits

- **Lepton-Flavour-Violation**

$$Br(\mu \to e\gamma) \sim \frac{2v^4 (y_s^e)^2 (y_s^\mu)^2}{3m_F^4 (16\pi)^2} \approx \mathcal{O}(10^{-46})$$

- **LEP**

$$m_F > 104 \text{ GeV}$$

  OPAL, hep-ex/0507048

Heavy quark

- **Running of the strong coupling**

$$m_F < \mathcal{O}(x \times 100\text{GeV})$$

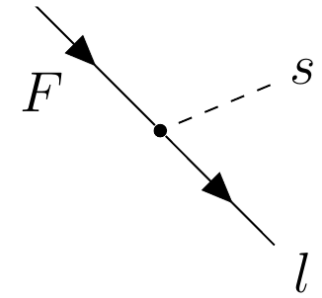
  Llorente, Nachman, 1807.00894

- **Meson mixing / $K^+ \to \pi^+ ss$**

  suppressed by small couplings y_s^f

- **LHC searches** for multi-jet plus missing energy subdominant

Cosmological constraints



- **Big-Bang Nucleosynthesis**

  we consider 1cm < $c\tau$ < 10^4m → T~150 MeV
  → heavy fermions decay well before onset of BBN

- **Lyman-α forest**

$$m_{\mathrm{DM}} \gtrsim 12\ \mathrm{keV} \left(\frac{\sum_i \mathrm{BR}_i \Delta_i^\eta}{\sum_i \mathrm{BR}_i} \right)^{1/\eta} \gtrsim 12\ \mathrm{keV}$$

$$\eta = 1.9$$

$$\Delta_i = 1 - m^2_{X^i_{\mathrm{SM}}} / m_Y^2$$

Boulebnane, Heeck, Nguyen, Teresi, 1709.07283

- **Relic density**

$$\mathrm{x} = \mathrm{m}_F / T$$

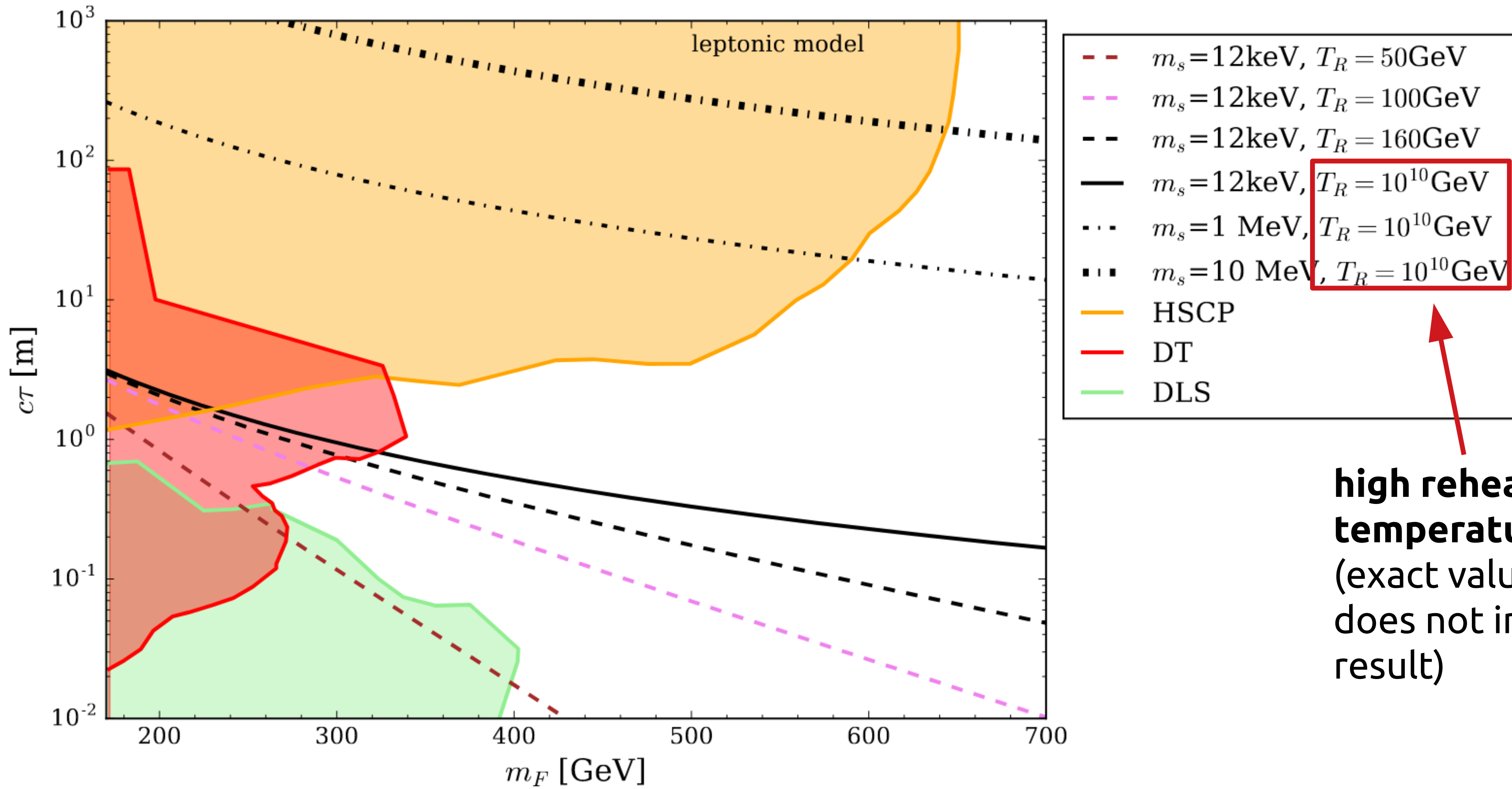
$$Y_s \approx \frac{45\, \xi\, M_{\mathrm{Pl}}}{8\pi^4 \cdot 1.66} \frac{g_F}{m_F^2} \Gamma \int_{m_F/T_R}^{m_F/T_0} dx\ x^3 \frac{K_1(x)}{g_*^s(m_F/x)\sqrt{g_*(m_F/x)}}$$

$$\Omega_s h^2 \approx \frac{m_s Y_s}{3.6 \times 10^{-9}\ \mathrm{GeV}}$$

$$\boxed{c\tau \approx 4.5\ \mathrm{m}\ \xi g_F \left(\frac{0.12}{\Omega_s h^2} \right) \left(\frac{m_s}{100\mathrm{keV}} \right) \left(\frac{200\mathrm{GeV}}{m_F} \right)^2 \left(\frac{102}{g_*(m_F/3)} \right)^{3/2} \left[\frac{\int_{m_F/T_R}^{m_F/T_0} dx\ x^3 K_1(x)}{3\pi/2} \right]}$$

relic density implies for a certain reheating temperature T_R a specific DM mass m_s

Combined results – leptonic model



high reheating temperature (exact value does not impact result)

Overlay with DM expectations:

$$c\tau \approx 4.5\ \mathrm{m}\ \xi g_F \left(\frac{0.12}{\Omega_s h^2}\right)\left(\frac{m_s}{100\mathrm{keV}}\right)\left(\frac{200\mathrm{GeV}}{m_F}\right)^2\left(\frac{102}{g_*(m_F/3)}\right)^{3/2}\left[\frac{\int_{m_F/T_R}^{m_F/T_0} dx\ x^3 K_1(x)}{3\pi/2}\right]$$

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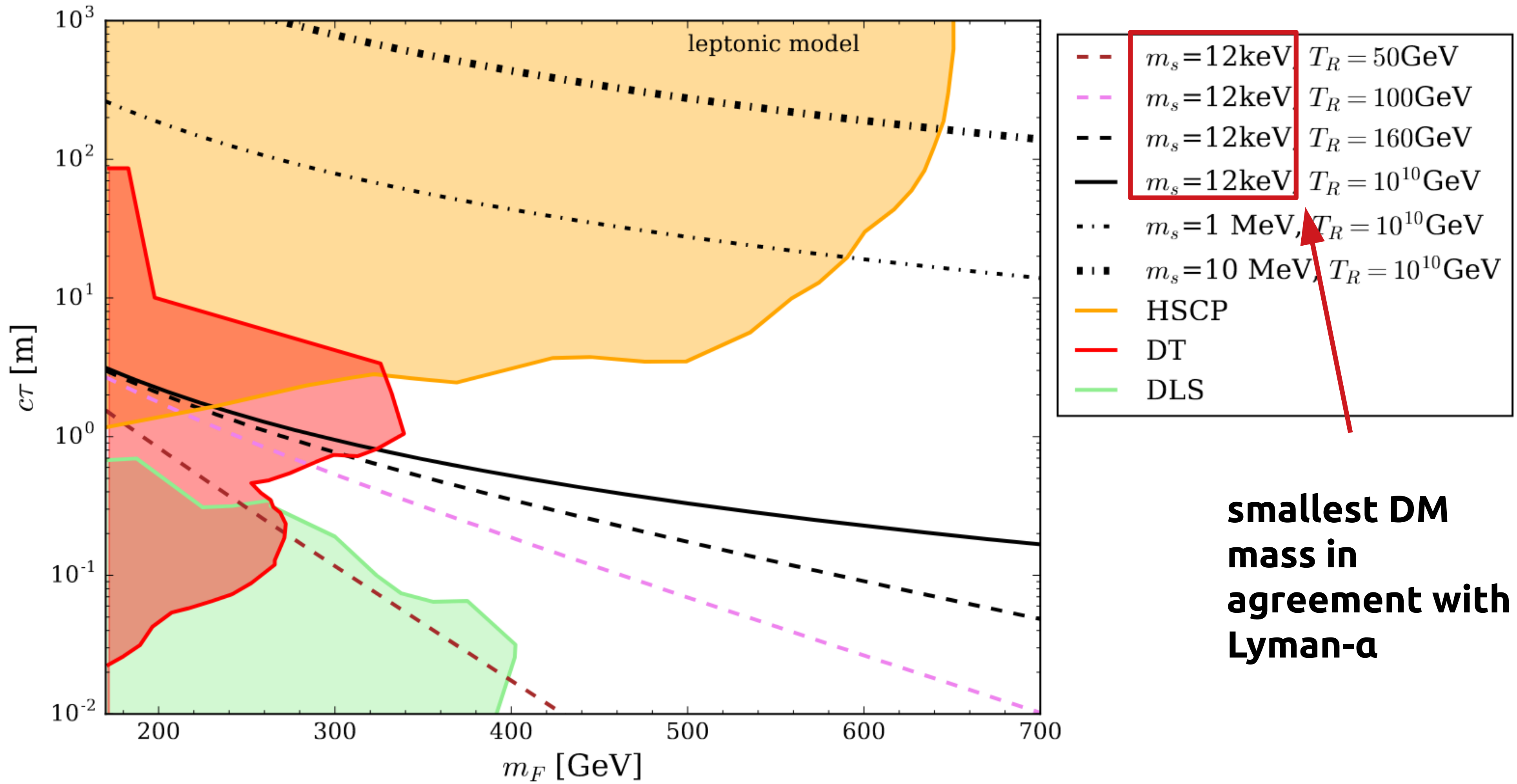
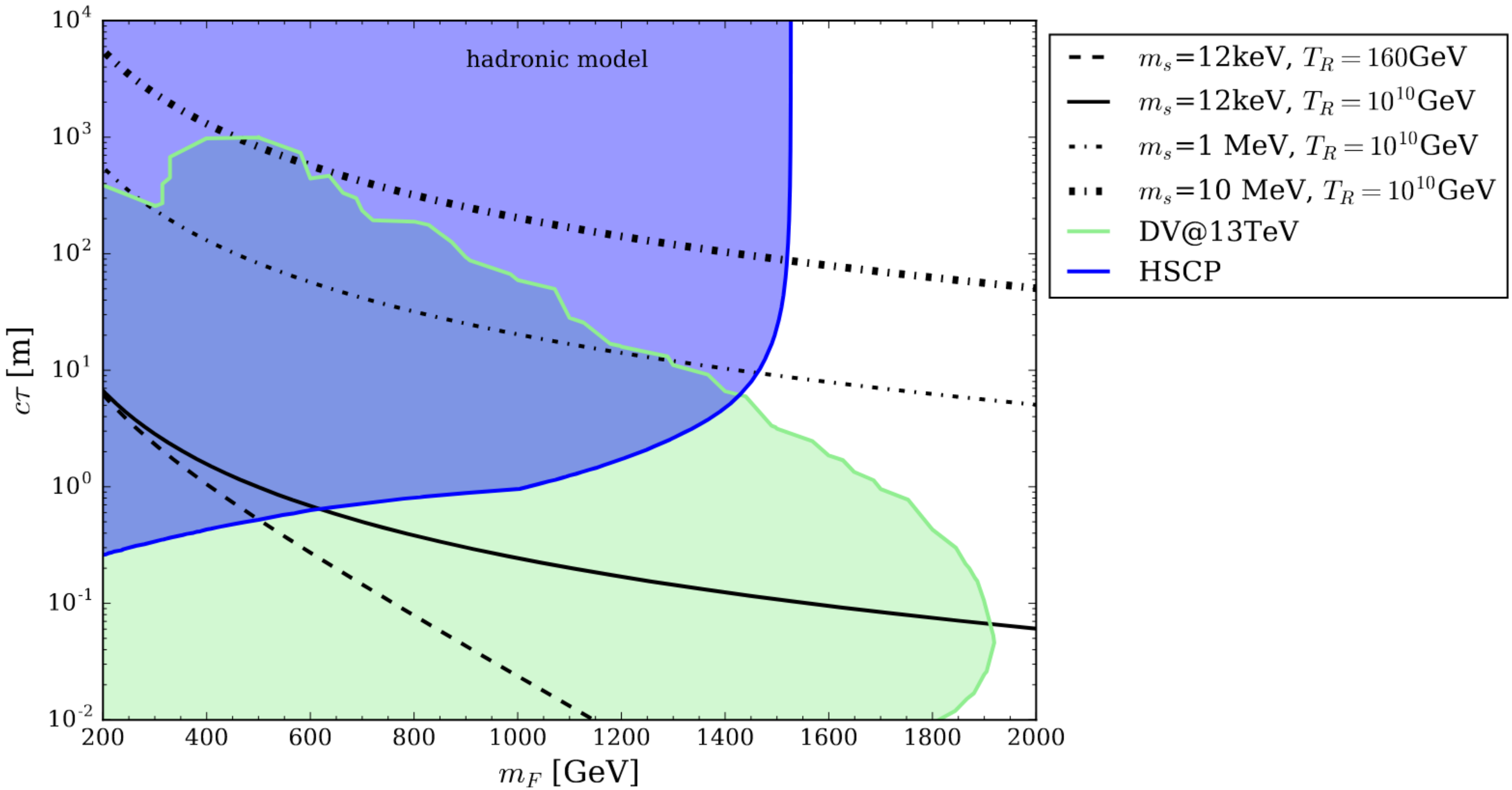


smallest DM mass in agreement with Lyman-α

Overlay with DM expectations:

$$c\tau \approx 4.5 \text{ m } \xi g_F \left(\frac{0.12}{\Omega_s h^2}\right) \left(\frac{m_s}{100\text{keV}}\right) \left(\frac{200\text{GeV}}{m_F}\right)^2 \left(\frac{102}{g_*(m_F/3)}\right)^{3/2} \left[\frac{\int_{m_F/T_R}^{m_F/T_0} dx\ x^3 K_1(x)}{3\pi/2}\right]$$

Combined results – hadronic model



Overlay with DM expectations:

$$\boxed{c\tau \approx 4.5\ \mathrm{m}\ \xi g_F \left(\frac{0.12}{\Omega_s h^2}\right)\left(\frac{m_s}{100\mathrm{keV}}\right)\left(\frac{200\mathrm{GeV}}{m_F}\right)^2\left(\frac{102}{g_*(m_F/3)}\right)^{3/2}\left[\frac{\int_{m_F/T_R}^{m_F/T_0} dx\ x^3 K_1(x)}{3\pi/2}\right]}$$