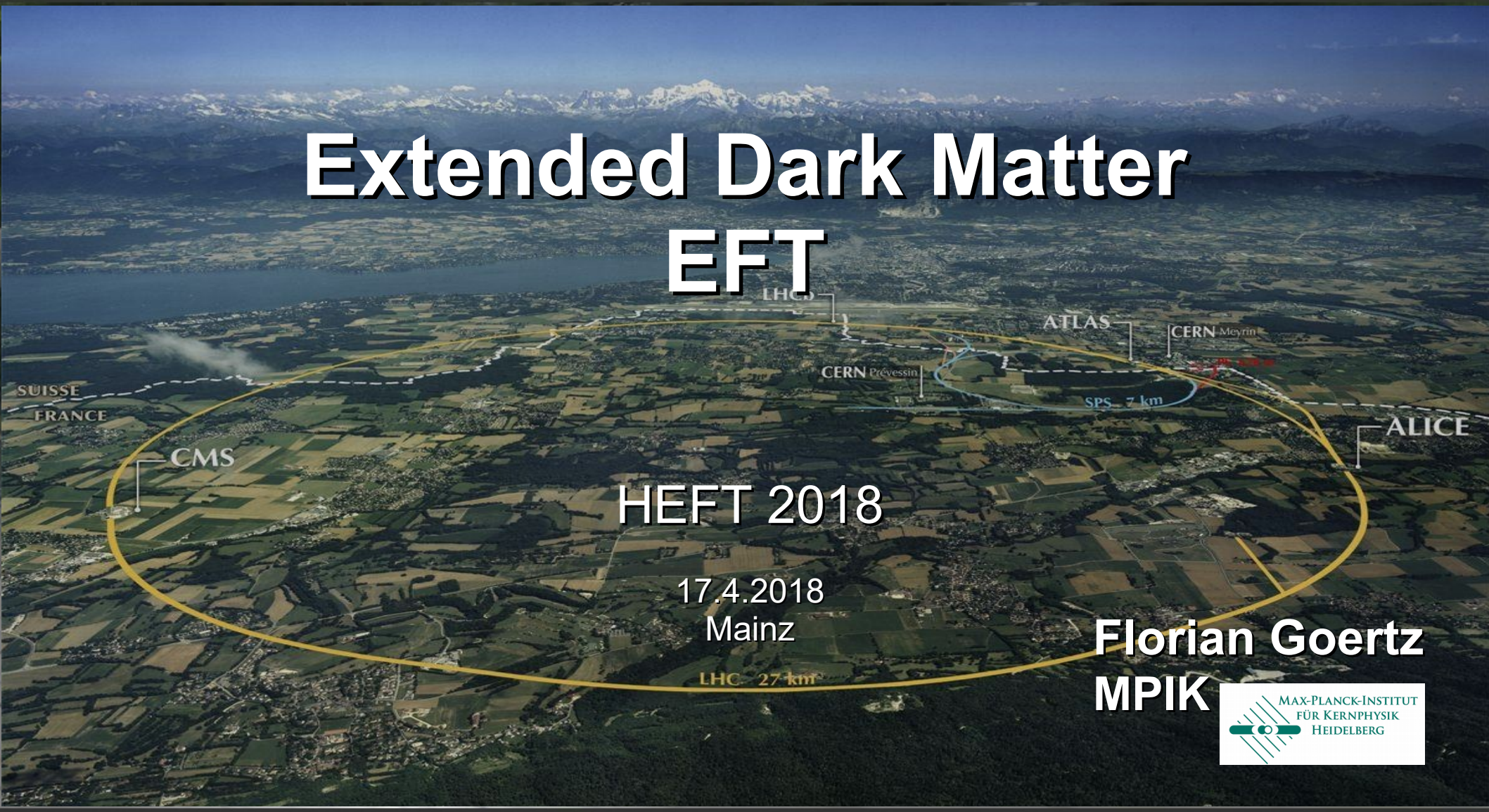


Extended Dark Matter EFT

HEFT 2018

17.4.2018
Mainz

Florian Goertz
MPIK

MAX-PLANCK-INSTITUT FÜR KERNPHYSIK HEIDELBERG

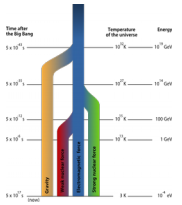
Alanne, FG, 1712.07626

and work in progress (Alanne, Arcadi, FG, Tenorth, Vogl)

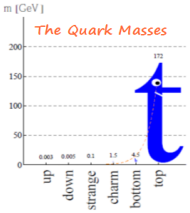
Physics Beyond the SM

SM does not explain everything!

- Gravity ∉ SM
- Hierarchy Problem: $m_h \ll M_{PL}$

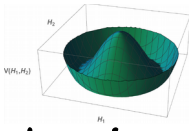


- Tiny Neutrino Masses
- Grand Unification of Forces?



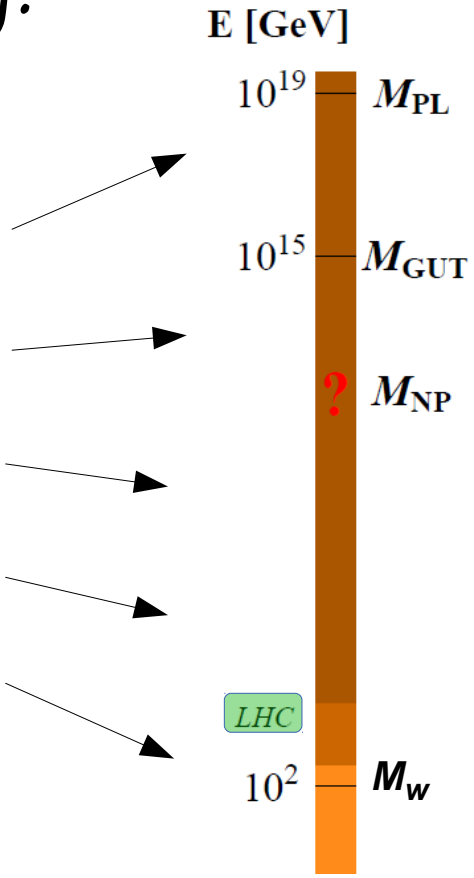
- Hierarchical Flavor Structure

- Baryogenesis → Existence of Universe
- Dark Matter ∉ SM
- Trigger for Symmetry-Breaking Potential?



- Strong CP Problem
- Some Hints in Flavor/Precision Physics

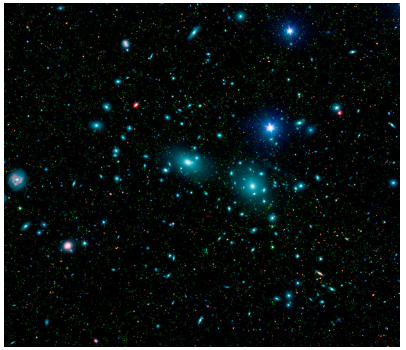
.....



Dark Matter

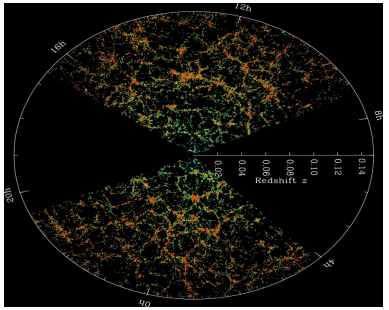
Luminous matter cannot explain many observations

- luminous matter not sufficient to keep clusters bound



Coma Cluster, NASA, Zwicky

- large-scale structure formation



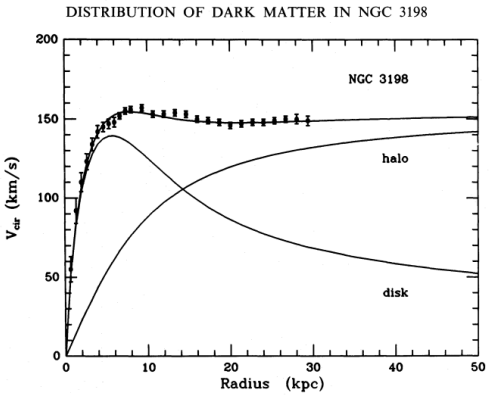
Sloan Digital Sky Survey

- Bullet Cluster: Optical observation (x-ray) vs. grav. lensing

NASA, ...

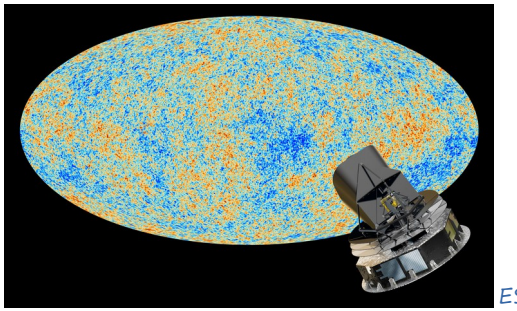
+ BBN, Lyman-α forest, ...

- rotation curves of galaxies



Albada, Bahcall, Begeman, Sanscisi, APJ, 295, 305-313 (1985)

- CMB



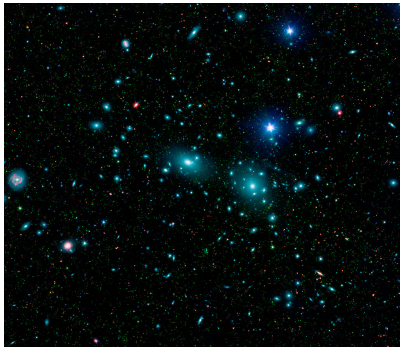
ESA

- All these observations can be explained by the presence of **Dark Matter**... What is its origin?

Dark Matter

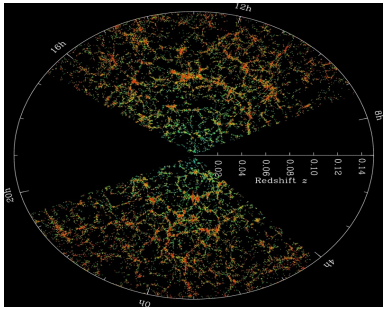
Luminous matter cannot explain many observations

- luminous matter not sufficient to keep clusters bound

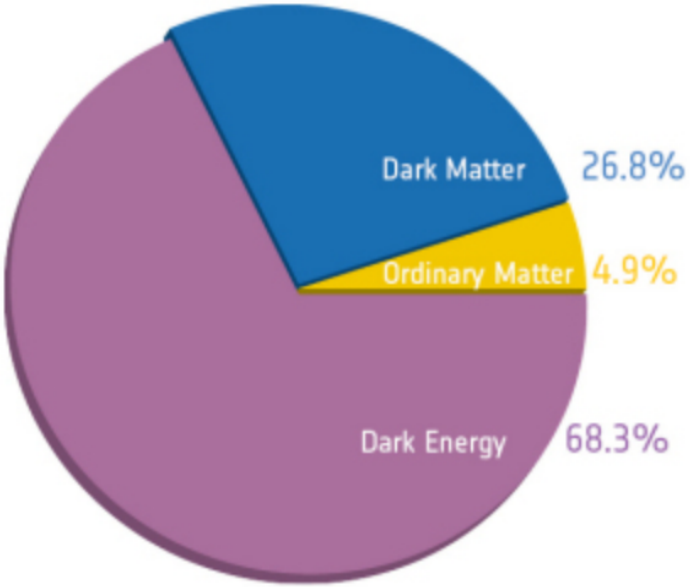


Coma Cluster, NASA, Zwicky

- large-scale structure formation

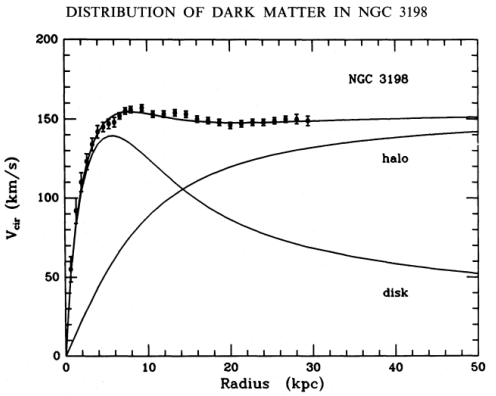


Sloan Digital Sky Survey



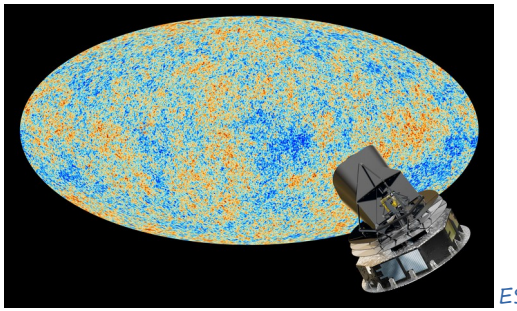
After Planck

- rotation curves of galaxies



Albada, Bahcall, Begeman, Sanscisi, APJ, 295, 305-313 (1985)

- CMB



ESA

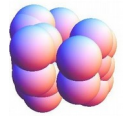
- All these observations can be explained by the presence of **Dark Matter**... What is its origin?

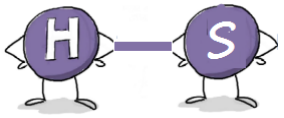
Dark Matter

DM Candidates in 'UV complete' models

- Lightest SUSY partner (Neutralino ...)
- Lightest Kaluza-Klein excitation (KK parity)

- Composite scalar
- Sterile neutrino
- Higgs-Portal DM
- Extended Higgs sectors
- Axions, ALPs
- ...





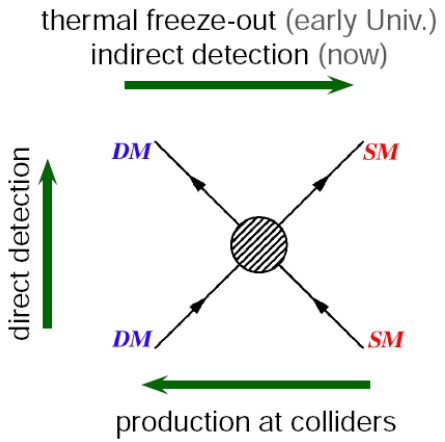
Dark Matter

DM Candidates in 'UV complete' models

- Lightest SUSY partner (Neutralino ...)
- Lightest Kaluza-Klein excitation (KK parity)
- Composite scalar
- Sterile neutrino
- Higgs-Portal DM
- Extended Higgs sectors
- Axions, ALPs
- ...

→ DM searches:

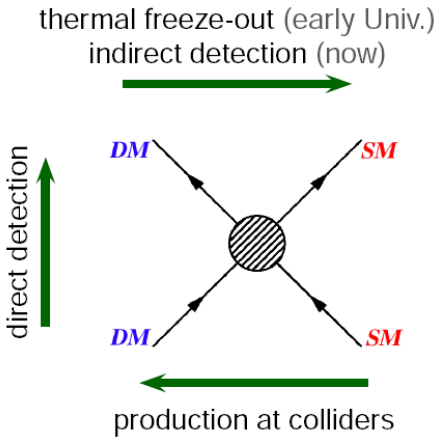
- indirect detection
- direct detection
- collider



Dark Matter

→ DM searches:

- indirect detection
- direct detection
- collider

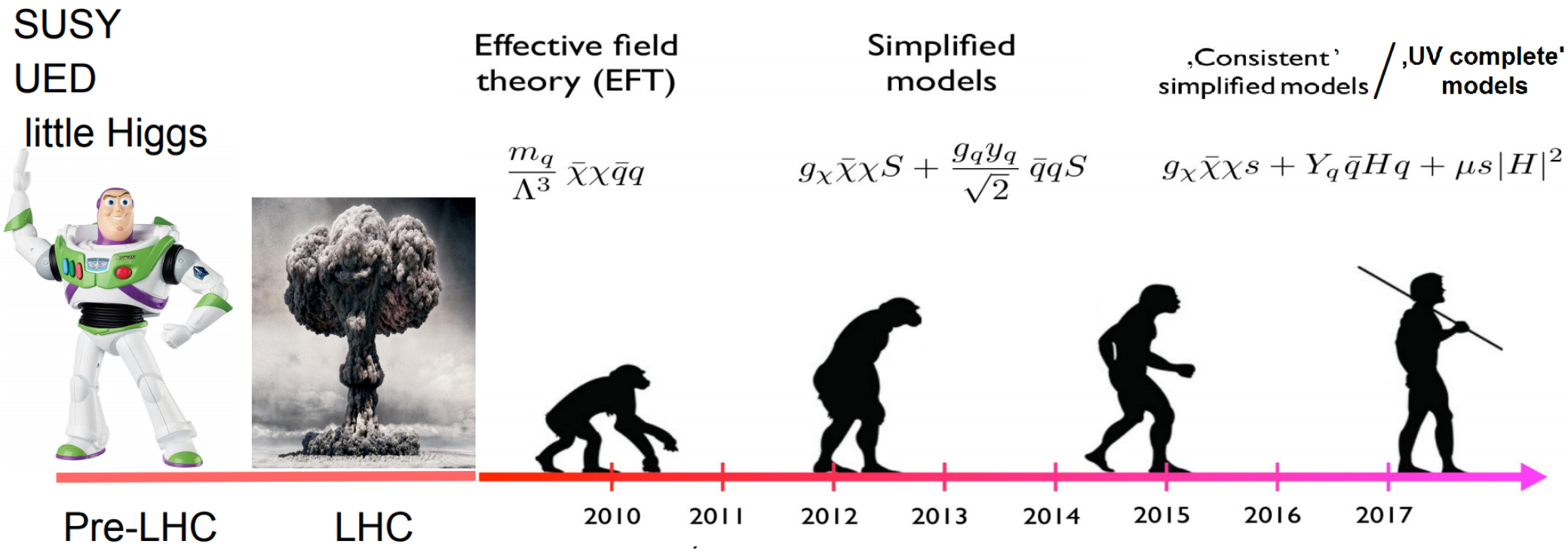


→ Combined effort to understand the nature of DM!

Generic ('Model-independent') framework?

Theoretical Description

From full theories to EFT and back



G. Polesello, U. Haisch

Theoretical Description

From full theories to EFT (and back)

SUSY
UED
little Higgs

Effective field theory (EFT)

$$\frac{m_q}{\Lambda^3}\,\bar{\chi}\chi\bar{q}q$$

Simplified models

$$g_\chi\bar{\chi}\chi S + \frac{g_q y_q}{\sqrt{2}}\,\bar{q}qS$$

„Consistent" simplified models

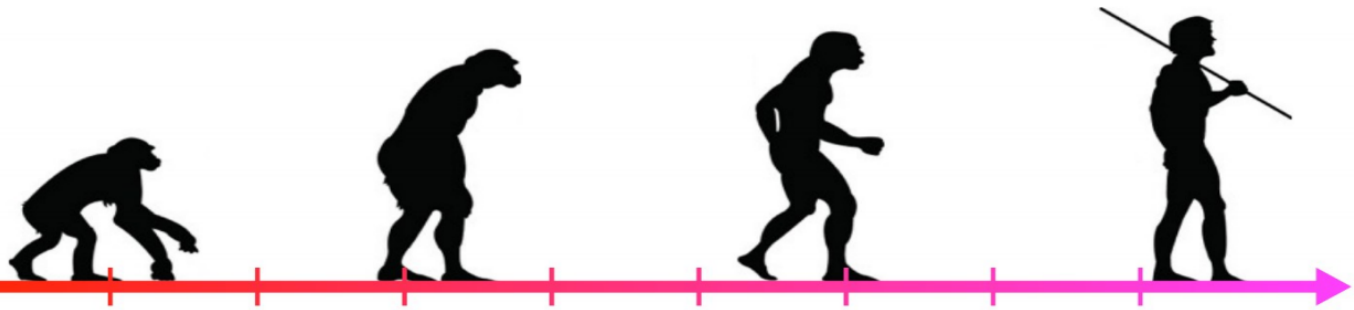
„UV complete" models

$$g_\chi\bar{\chi}\chi s + Y_q\bar{q}Hq + \mu s|H|^2$$

eDMEFT

$$-y_S\mathcal{S}\bar{\chi}_L\chi_R - \frac{\mathcal{S}}{\Lambda}(y_d^S)^{ij}\bar{Q}^i_{\rm L}Hd^j_{\rm R}$$

$$-\frac{\mathcal{S}}{\Lambda}c_G^S G^{a\mu\nu}G^a_{\mu\nu} + \ldots$$



Pre-LHC LHC 2010 2011 2012 2013 2014 2015 2016 2017

DM EFT vs. Simplified Models

DM EFT	Simpl. Models
'model independent'	rather specific
'proper' QFT	gauge inv./unitarity?
LHC validity questionable	valid for LHC searches

$$\frac{m_q}{\Lambda^3}\,\bar{\chi}\chi\bar{q}q$$

DM

$$g_\chi \bar{\chi}\chi S + \frac{g_q y_q}{\sqrt{2}}\,\bar{q}qS$$

DM mediator

Shepherd, Tait, Zaharijas, 0901.2125
Beltran, Hooper, Kolb, Krusberg, Tait, 1002.4137
Goodman, Ibe, Rajaraman, Shepherd, Tait, Yu, 1005.1286, 1008.1783
Bai, Fox, Harnik, 1005.3797
Busoni, De Simone, (Gramling), Morgante, Riotto, 1307.2253, 1402.1275
Bruggisser, Riva, Urbano, 1607.02475

Alwall, Schuster, Toro, 0810.3921
De Simone, Giudice, Strumia, 1402.6287
Abdallah et al, 1506.03116
Kahlhoefer, S-Hoberg, Schwetz, Vogl, 1510.02110
Boveia et al, 1603.04156
De Simone, Jacques, 1603.08002
Englert, McCullough, Spannowsky, 1604.07975

Extended Dark Matter EFT

eDMEFT
'minimal' assumptions
'proper' QFT
valid for LHC searches

Alanne, FG, 1712.07626

$$-y_S \mathcal{S} \bar{\chi}_L \chi_R - \frac{\mathcal{S}}{\Lambda} (y_d^S)^{ij} \bar{Q}_{\rm L}^i H d_{\rm R}^j$$

$$- \frac{\mathcal{S}}{\Lambda} c_G^S G^{a\mu\nu} G^a_{\mu\nu} + \ldots$$

Extended Dark Matter EFT

- Keep mediator:
  LHC Applicability → Exploit synergies in combining DD + ID + LHC
- Construct all *gauge invariant* ops of SM + DM + med.:
  Correlations induced by gauge symmetry
- Allow for D > 4 operators:
  New sector likely richer than just DM + mediator

Extended Dark Matter EFT

eDMEFT

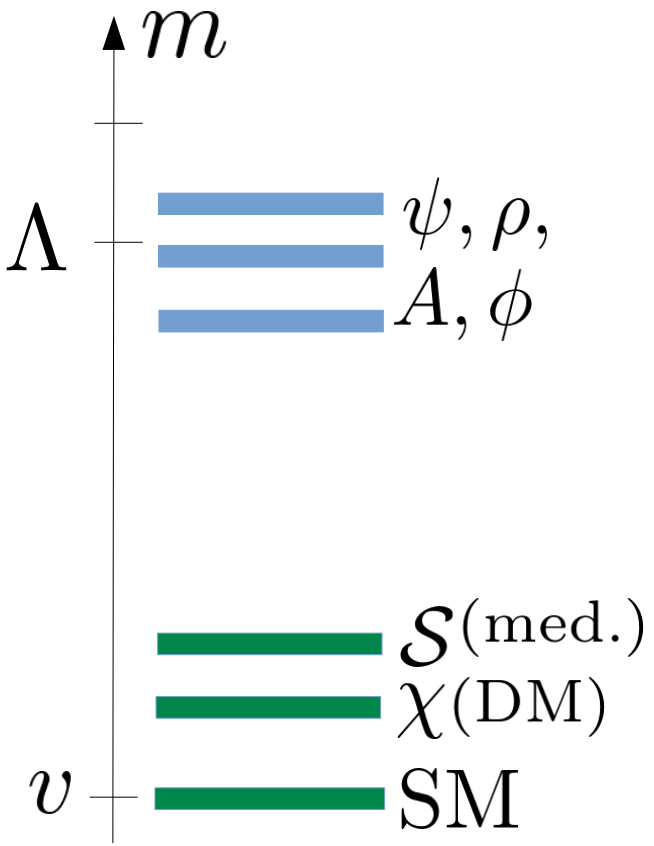
'minimal' assumptions

'proper' QFT

valid for LHC searches

$$-y_S \mathcal{S} \bar{\chi}_L \chi_R - \frac{\mathcal{S}}{\Lambda} (y_d^S)^{ij} \bar{Q}_{\mathrm{L}}^i H d_{\mathrm{R}}^j$$

$$- \frac{\mathcal{S}}{\Lambda} c_G^S G^{a\mu\nu} G_{\mu\nu}^a + \ldots$$



Extended Dark Matter EFT

- Fermionic or scalar DM with (pseudo-)scalar mediator:

Leading effects at D=5

→ *limited number of free couplings*

Extended Dark Matter EFT

Fermionic DM with scalar mediator:

$$
\begin{aligned}
\mathcal{L}_{\text{eff}}^{\mathcal{S}\chi} &= \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{kin+mass}} - V(\mathcal{S}) \\
&- \lambda'_{HS} v |H|^2 \mathcal{S} - \lambda_{HS} |H|^2 \mathcal{S}^2 - y_S \mathcal{S} \bar{\chi}_L \chi_R + \text{h.c.} \\
&- \frac{\mathcal{S}}{\Lambda} \left[c_{\lambda S} \mathcal{S}^4 + c_{HS} |H|^2 \mathcal{S}^2 + c_{\lambda H} |H|^4 \right] \\
&- \frac{\mathcal{S}}{\Lambda} (y_f^S)^{ij} \bar{F}_{\text{L}}^i H f_{\text{R}}^j - \frac{y_S^{(2)} \mathcal{S}^2 + y_H^{(2)} |H|^2}{\Lambda} \bar{\chi}_L \chi_R + \text{h.c.} \\
&- \frac{\mathcal{S}}{\Lambda} \frac{1}{16\pi^2} \sum_{V=G,B,W} C_V^S V_{\mu\nu} V^{\mu\nu}
\end{aligned}
$$

Extended Dark Matter EFT

Fermionic DM with scalar mediator:

$$
\begin{aligned}
\mathcal{L}_{\text{eff}}^{\mathcal{S}\chi} &= \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{kin+mass}} - V(\mathcal{S}) \\
&- \lambda'_{HS} v |H|^2 \mathcal{S} - \lambda_{HS} |H|^2 \mathcal{S}^2 - y_S \mathcal{S} \bar{\chi}_L \chi_R + \text{h.c.} \\
&- \frac{\mathcal{S}}{\Lambda} \left[c_{\lambda S} \mathcal{S}^4 + c_{HS} |H|^2 \mathcal{S}^2 + c_{\lambda H} |H|^4 \right] \\
&- \frac{\mathcal{S}}{\Lambda} (y_f^S)^{ij} \bar{F}_{\text{L}}^i H f_{\text{R}}^j - \frac{y_S^{(2)} \mathcal{S}^2 + y_H^{(2)} |H|^2}{\Lambda} \bar{\chi}_L \chi_R + \text{h.c.} \\
&- \frac{\mathcal{S}}{\Lambda} \frac{1}{16\pi^2} \sum_{V=G,B,W} C_V^S V_{\mu\nu} V^{\mu\nu}
\end{aligned}
$$

Higgs-mediator portal

Extended Dark Matter EFT

Fermionic DM with scalar mediator:

$$
\begin{aligned}
\mathcal{L}_{\rm eff}^{\mathcal{S}\chi} &= \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm kin+mass} - V(\mathcal{S}) \\
&- \lambda'_{HS} v |H|^2 \mathcal{S} - \lambda_{HS} |H|^2 \mathcal{S}^2 - y_S \mathcal{S} \bar{\chi}_L \chi_R + \text{h.c.} \\
&- \frac{\mathcal{S}}{\Lambda} \left[c_{\lambda S} \mathcal{S}^4 + c_{HS} |H|^2 \mathcal{S}^2 + c_{\lambda H} |H|^4 \right] \\
&- \frac{\mathcal{S}}{\Lambda} (y_f^S)^{ij} \bar{F}_{\rm L}^i H f_{\rm R}^j - \frac{y_S^{(2)} \mathcal{S}^2 + y_H^{(2)} |H|^2}{\Lambda} \bar{\chi}_L \chi_R + \text{h.c.} \\
&- \frac{\mathcal{S}}{\Lambda} \frac{1}{16\pi^2} \sum_{V=G,B,W} C_V^S V_{\mu\nu} V^{\mu\nu}
\end{aligned}
$$

mediator-DM int.

Extended Dark Matter EFT

Fermionic DM with scalar mediator:

$$
\begin{aligned}
\mathcal{L}_{\text{eff}}^{\mathcal{S}\chi} &= \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{kin+mass}} - V(\mathcal{S}) \\
&- \lambda'_{HS} v |H|^2 \mathcal{S} - \lambda_{HS} |H|^2 \mathcal{S}^2 - y_S \mathcal{S} \bar{\chi}_L \chi_R + \text{h.c.} \\
&- \frac{\mathcal{S}}{\Lambda} \left[c_{\lambda S} \mathcal{S}^4 + c_{HS} |H|^2 \mathcal{S}^2 + c_{\lambda H} |H|^4 \right] \\
&- \frac{\mathcal{S}}{\Lambda} (y_f^S)^{ij} \bar{F}_{\text{L}}^i H f_{\text{R}}^j - \frac{y_S^{(2)} \mathcal{S}^2 + y_H^{(2)} |H|^2}{\Lambda} \bar{\chi}_L \chi_R + \text{h.c.} \\
&- \frac{\mathcal{S}}{\Lambda} \frac{1}{16\pi^2} \sum_{V=G,B,W} C_V^S V_{\mu\nu} V^{\mu\nu}
\end{aligned}
$$

portal-like
D=5 terms

Extended Dark Matter EFT

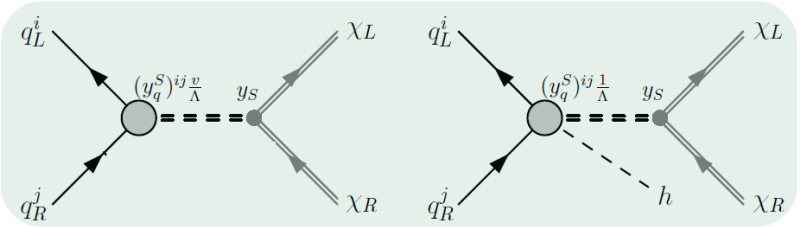
Fermionic DM with scalar mediator:

$$
\begin{aligned}
\mathcal{L}_{\text{eff}}^{\mathcal{S}\chi} &= \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{kin+mass}} - V(\mathcal{S}) \\
&- \lambda'_{HS} v |H|^2 \mathcal{S} - \lambda_{HS} |H|^2 \mathcal{S}^2 - y_S \mathcal{S} \bar{\chi}_L \chi_R + \text{h.c.} \\
&- \frac{\mathcal{S}}{\Lambda} \left[c_{\lambda S} \mathcal{S}^4 + c_{HS} |H|^2 \mathcal{S}^2 + c_{\lambda H} |H|^4 \right] \\
&- \frac{\mathcal{S}}{\Lambda} (y_f^S)^{ij} \bar{F}_{\text{L}}^i H f_{\text{R}}^j - \frac{y_S^{(2)} \mathcal{S}^2 + y_H^{(2)} |H|^2}{\Lambda} \bar{\chi}_L \chi_R + \text{h.c.} \\
&- \frac{\mathcal{S}}{\Lambda} \frac{1}{16\pi^2} \sum_{V=G,B,W} C_V^S V_{\mu\nu} V^{\mu\nu}
\end{aligned}
$$

Gauge inv. couplings to SM!

Inevitably links DM to DM+H production!

Correlates different LHC observables → test nature of dark sector!



Extended Dark Matter EFT

Fermionic DM with scalar mediator:

$$
\begin{aligned}
\mathcal{L}_{\text{eff}}^{\mathcal{S}\chi} &= \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{kin+mass}} - V(\mathcal{S}) \\
&- \lambda'_{HS} v |H|^2 \mathcal{S} - \lambda_{HS} |H|^2 \mathcal{S}^2 - y_S \mathcal{S} \bar{\chi}_L \chi_R + \text{h.c.} \\
&- \frac{\mathcal{S}}{\Lambda} \left[c_{\lambda S} \mathcal{S}^4 + c_{HS} |H|^2 \mathcal{S}^2 + c_{\lambda H} |H|^4 \right] \\
&- \frac{\mathcal{S}}{\Lambda} (y_f^S)^{ij} \bar{F}_{\text{L}}^i H f_{\text{R}}^j - \frac{y_S^{(2)} \mathcal{S}^2 + y_H^{(2)} |H|^2}{\Lambda} \bar{\chi}_L \chi_R + \text{h.c.} \\
&- \frac{\mathcal{S}}{\Lambda} \frac{1}{16\pi^2} \sum_{V=G,B,W} C_V^S V_{\mu\nu} V^{\mu\nu}
\end{aligned}
$$

Higgs-DM portal and (med.)^2-DM^2 → assoc. prod.?

Extended Dark Matter EFT

Fermionic DM with scalar mediator:

$$
\begin{aligned}
\mathcal{L}_{\text{eff}}^{\mathcal{S}\chi} &= \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{kin+mass}} - V(\mathcal{S}) \\
&- \lambda'_{HS} v |H|^2 \mathcal{S} - \lambda_{HS} |H|^2 \mathcal{S}^2 - y_S \mathcal{S} \bar{\chi}_L \chi_R + \text{h.c.} \\
&- \frac{\mathcal{S}}{\Lambda} \left[c_{\lambda S} \mathcal{S}^4 + c_{HS} |H|^2 \mathcal{S}^2 + c_{\lambda H} |H|^4 \right] \\
&- \frac{\mathcal{S}}{\Lambda} (y_f^S)^{ij} \bar{F}_{\text{L}}^i H f_{\text{R}}^j - \frac{y_S^{(2)} \mathcal{S}^2 + y_H^{(2)} |H|^2}{\Lambda} \bar{\chi}_L \chi_R + \text{h.c.} \\
&- \frac{\mathcal{S}}{\Lambda} \frac{1}{16\pi^2} \sum_{V=G,B,W} C_V^S V_{\mu\nu} V^{\mu\nu}
\end{aligned}
$$

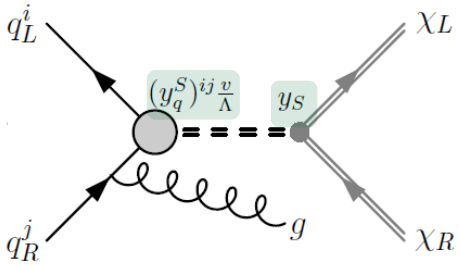
gluon-fusion, VBF prod., ...

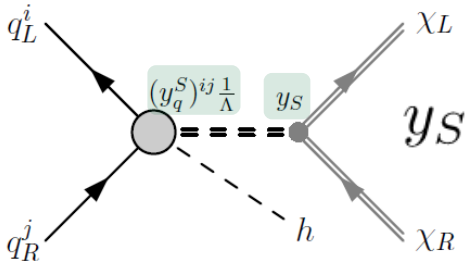
Phenomenology

Capture all kinds of production/scattering mechanisms of DM

- LHC Observables: mono-jet, mono-Higgs, ...

$$\frac{\mathcal{S}}{\Lambda}(y_f^S)^{ij}\bar{F}_{\mathrm{L}}^i H f_{\mathrm{R}}^j$$



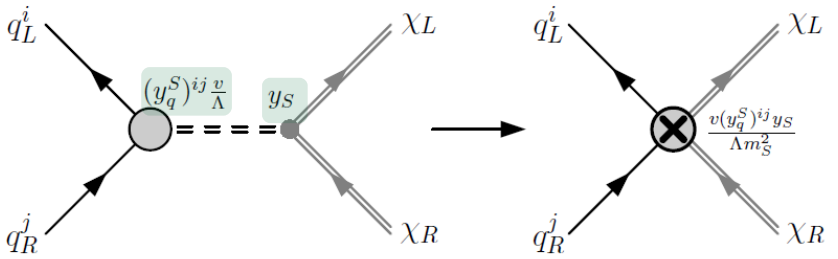


$$y_S\mathcal{S}\bar{\chi}_L\chi_R$$

$E \sim m_S$ (?!)

Explore correlations in proper EFT

- Direct Detection: DM-nucleon interaction



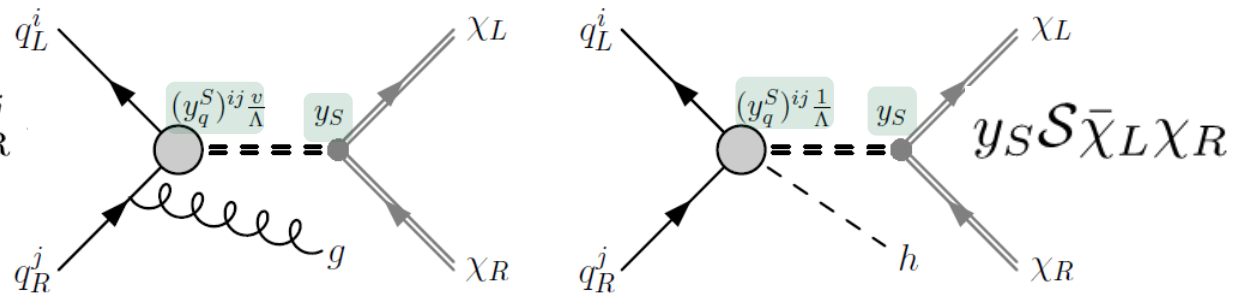
$E \ll m_S$

Phenomenology

$q\bar{q}$ induced production

LHC

$$\frac{\mathcal{S}}{\Lambda}(y_f^S)^{ij}\bar{F}_{\mathrm{L}}^i H f_{\mathrm{R}}^j$$

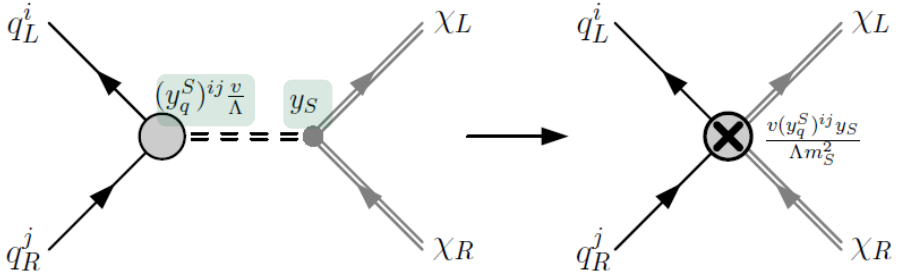


$y_S \mathcal{S} \bar{\chi}_L \chi_R$

[always turn on 2 couplings]

linked due to gauge invariance

Direct Detection

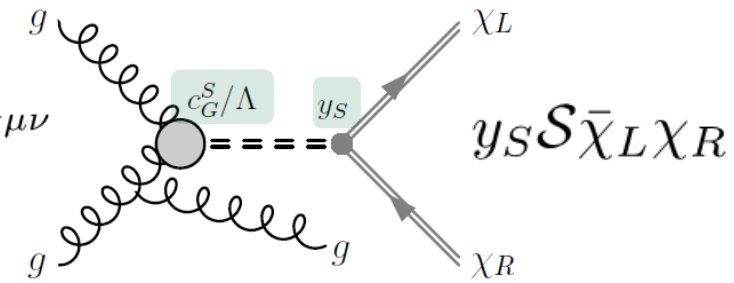


Phenomenology

gluon fusion

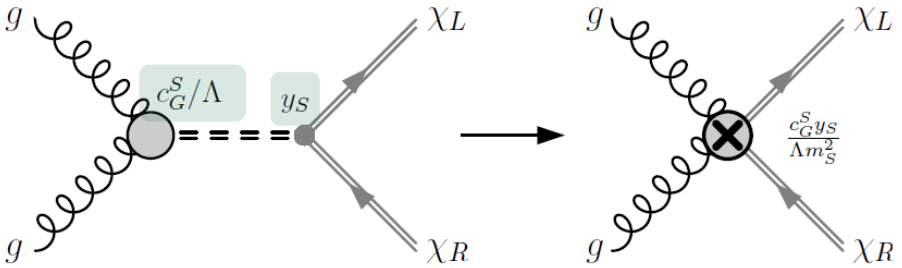
LHC

$$\frac{\mathcal{S}}{\Lambda}\frac{1}{16\pi^2}C_V^S V_{\mu\nu}V^{\mu\nu}$$



$$y_S \mathcal{S} \bar{\chi}_L \chi_R$$

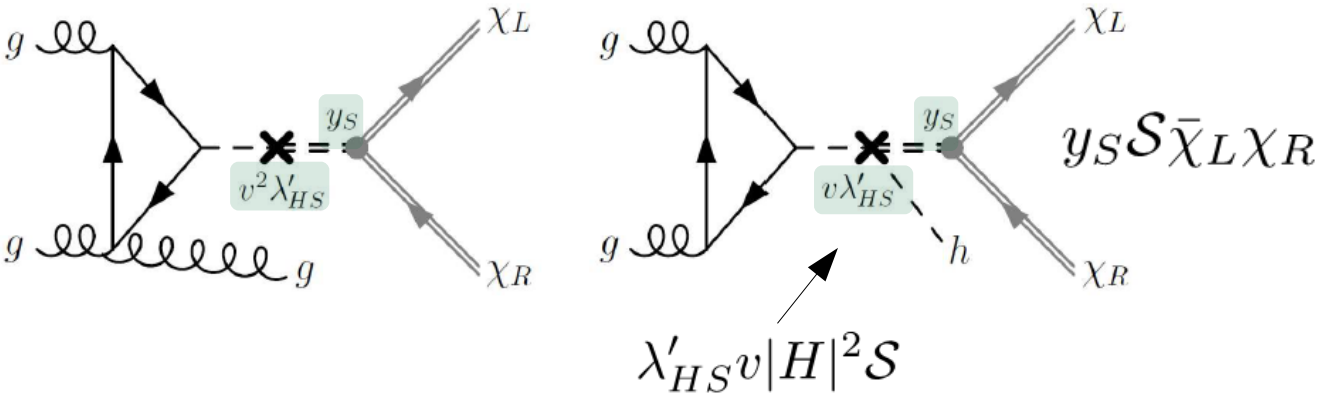
Direct Detection



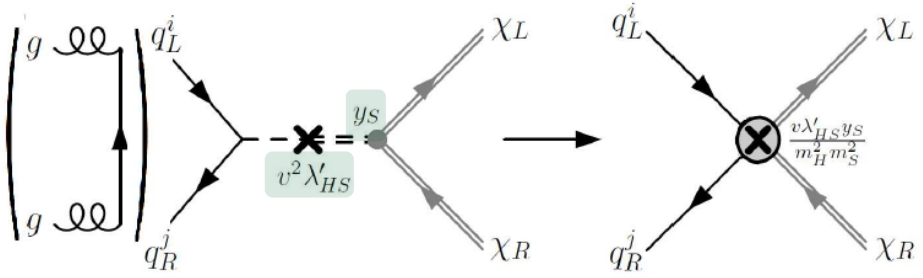
Phenomenology

Higgs - mediator portal

LHC



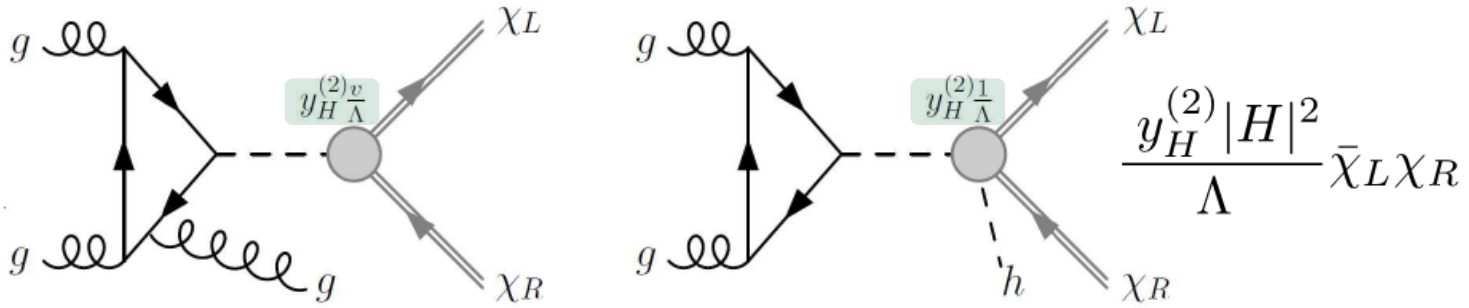
Direct Detection



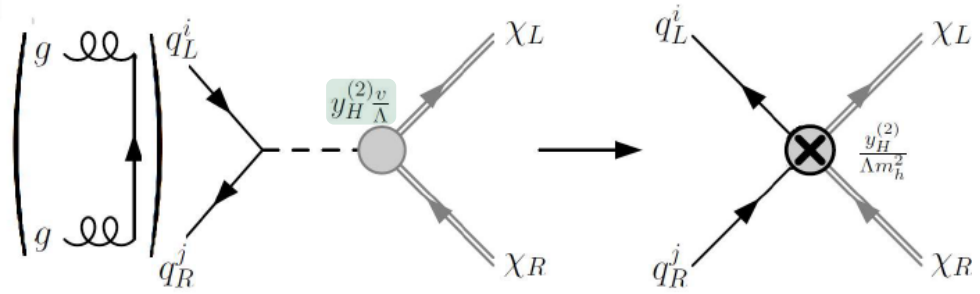
Phenomenology

Higgs - DM portal

LHC



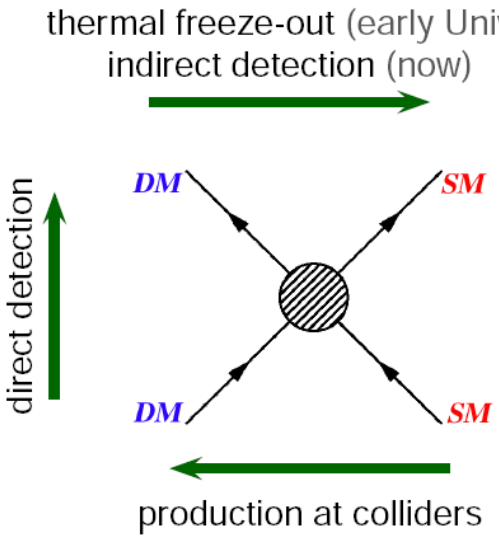
Direct Detection



Phenomenology

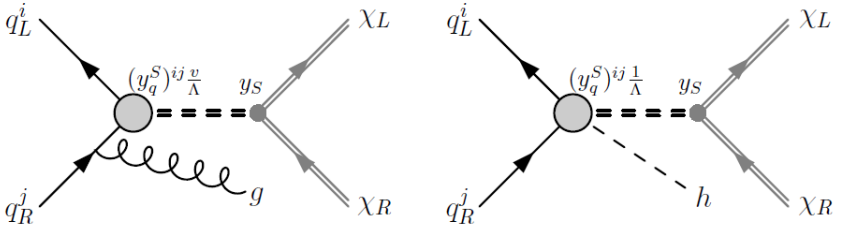
- Confront LHC with direct detection and relic abundance
- Can address the question:

Given constraints from relic density and direct detection, which mono-X cross sections can be expected at the LHC?

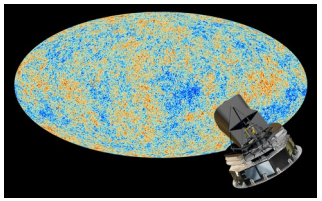


Phenomenology

$q\bar{q}$ induced



Relic abundance $(m_\chi > m_S)$

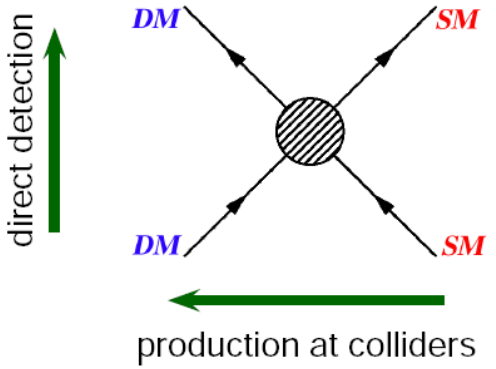


$$\langle \sigma v \rangle (\chi\chi \to SS) \approx 2.0 \times 10^{-26}\,\mathrm{cm}^3\mathrm{s}^{-1} y_S^4 \left(\frac{1\,\mathrm{TeV}}{m_\chi}\right)^2$$

thermal freeze-out (early Univ.)
indirect detection (now)

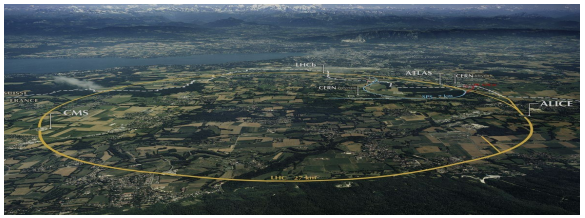
DD: scattering off nuclei

$$\sigma_N = \frac{y_S^2[(y_u^S)^{11})]^2 (f_N^u)^2 m_N^2 \mu_N^2 v^2}{2\pi\Lambda^2 m_S^4 m_u^2}$$



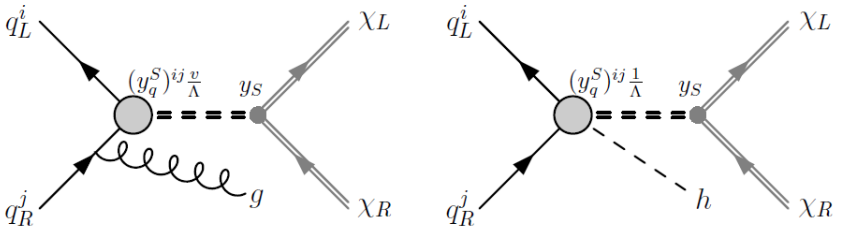
$$\langle N | m_q \bar{q} q | N \rangle \equiv m_N f_N^q$$

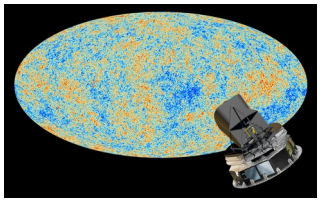
$$\mu_N \equiv \frac{m_\chi m_N}{m_\chi + m_N} \qquad m_N = (m_p + m_n)/2$$



Phenomenology

$q\bar{q}$ induced





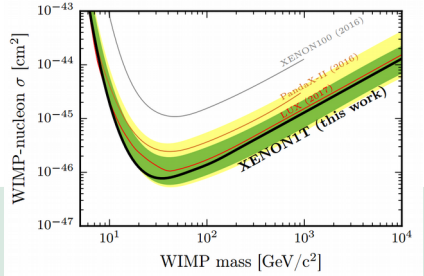
Relic abundance $(m_\chi > m_S)$

$$\langle \sigma v \rangle (\chi\chi \to SS) \approx 2.0 \times 10^{-26}\,\mathrm{cm}^3\mathrm{s}^{-1} y_S^4 \left(\frac{1\,\mathrm{TeV}}{m_\chi}\right)^2$$

fix y_S

DD: scattering off nuclei

$$\sigma_N = \frac{y_S^2[(y_u^S)^{11})]^2 (f_N^u)^2 m_N^2 \mu_N^2 v^2}{2\pi\Lambda^2 m_S^4 m_u^2}$$



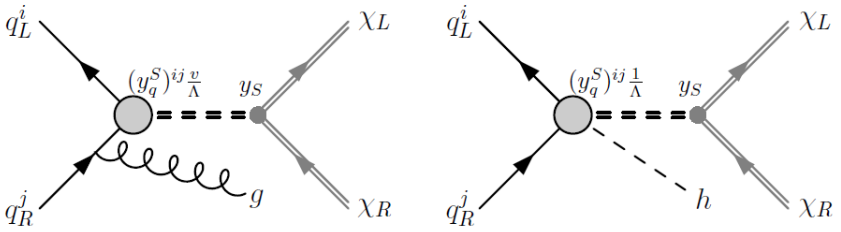
$$\frac{|(y_u^S)^{11}|}{\Lambda} \lesssim 2.9 \times 10^{-3} f_{\mathrm{rel}}^{-1/4} \left(\frac{m_S}{1\,\mathrm{TeV}}\right)^2 \mathrm{TeV}^{-1}$$

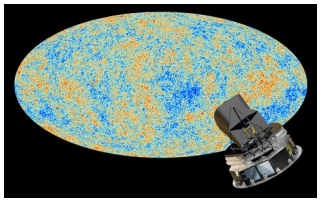
$$\langle N|m_q\bar{q}q|N\rangle \equiv m_N f_N^q$$

$$\mu_N \equiv \frac{m_\chi m_N}{m_\chi + m_N} \qquad m_N = (m_p + m_n)/2$$

Phenomenology

$q\bar{q}$ induced





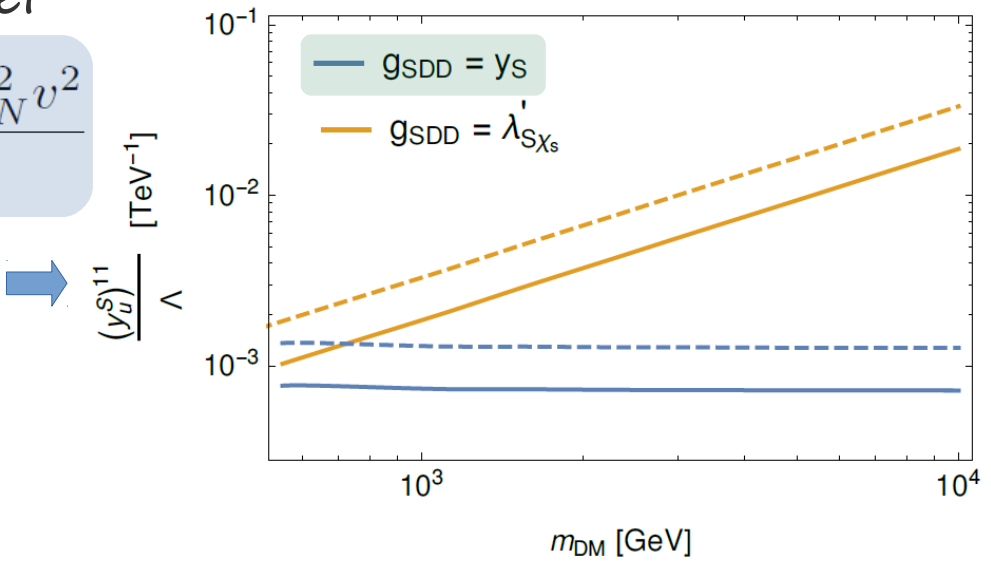
Relic abundance $(m_\chi > m_S)$

$$\langle \sigma v \rangle (\chi\chi \to SS) \approx 2.0 \times 10^{-26}\,\mathrm{cm^3 s^{-1}}\, y_S^4 \left(\frac{1\,\mathrm{TeV}}{m_\chi}\right)^2$$

fix y_S

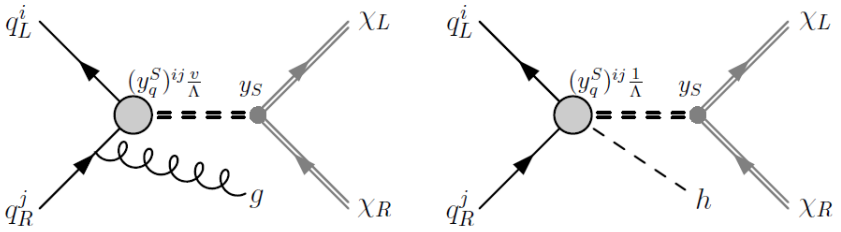
DD: scattering off nuclei

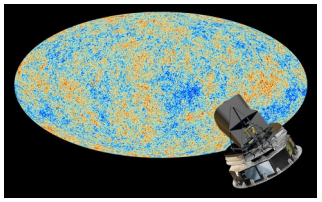
$$\sigma_N = \frac{y_S^2[(y_u^S)^{11})]^2 (f_N^u)^2 m_N^2 \mu_N^2 v^2}{2\pi\Lambda^2 m_S^4 m_u^2}$$



Phenomenology

$q\bar{q}$ induced





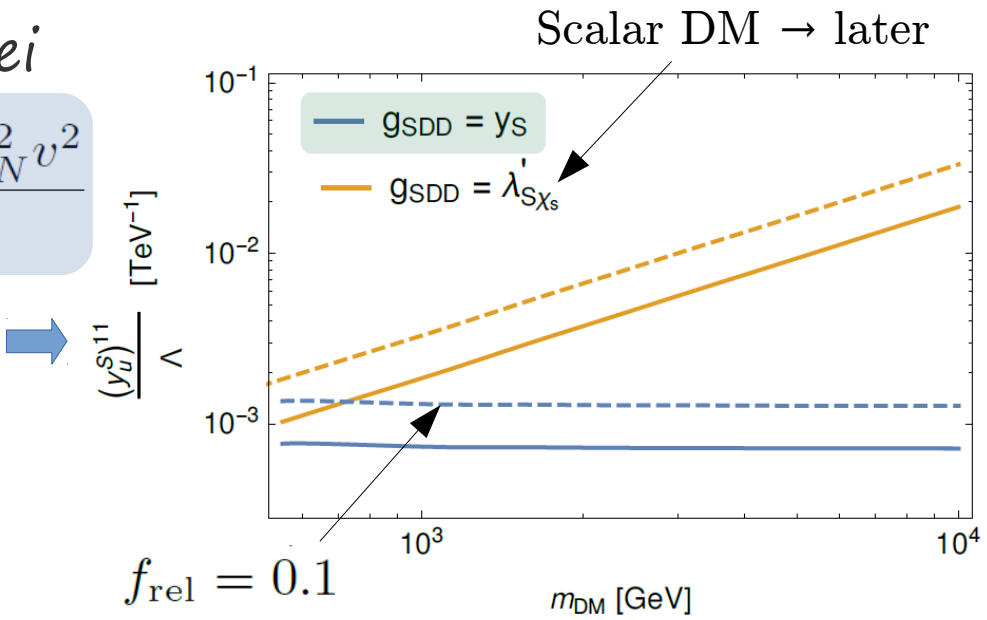
Relic abundance $(m_\chi > m_S)$

$$\langle \sigma v \rangle (\chi\chi \to SS) \approx 2.0 \times 10^{-26}\,\mathrm{cm^3 s^{-1}}\, y_S^4 \left(\frac{1\,\mathrm{TeV}}{m_\chi}\right)^2$$

fix y_S

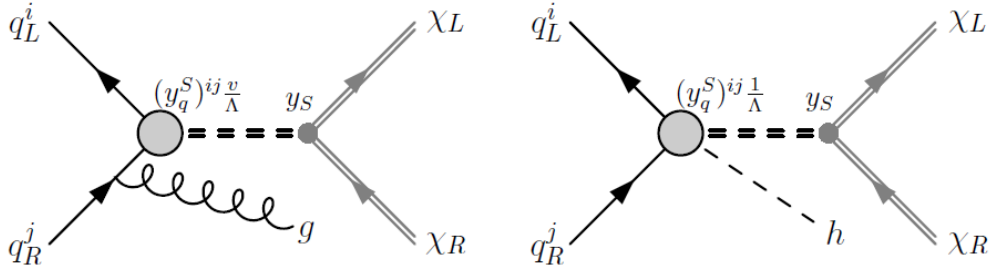
DD: scattering off nuclei

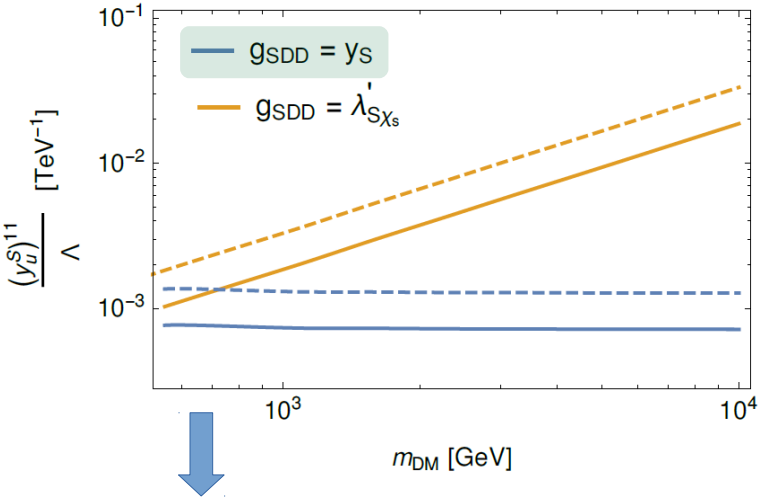
$$\sigma_N = \frac{y_S^2[(y_u^S)^{11})]^2 (f_N^u)^2 m_N^2 \mu_N^2 v^2}{2\pi\Lambda^2 m_S^4 m_u^2}$$



LHC cross sections

$u\bar{u}$ induced





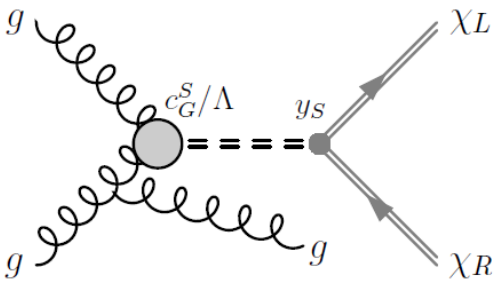
$$\sigma_j|_{m_\chi=500\,\mathrm{GeV}} \lesssim 3.0\cdot 10^{-7}\,\mathrm{fb},$$
$$\sigma_j|_{m_\chi=1\,\mathrm{TeV}} \lesssim 3.5\cdot 10^{-8}\,\mathrm{fb},$$
$$\sigma_{h+\not{E}_T}|_{m_\chi=500\,\mathrm{GeV}} \lesssim 2.0\cdot 10^{-8}\,\mathrm{fb},$$
$$\sigma_{h+\not{E}_T}|_{m_\chi=1\,\mathrm{TeV}} \lesssim 3.4\cdot 10^{-8}\,\mathrm{fb}$$

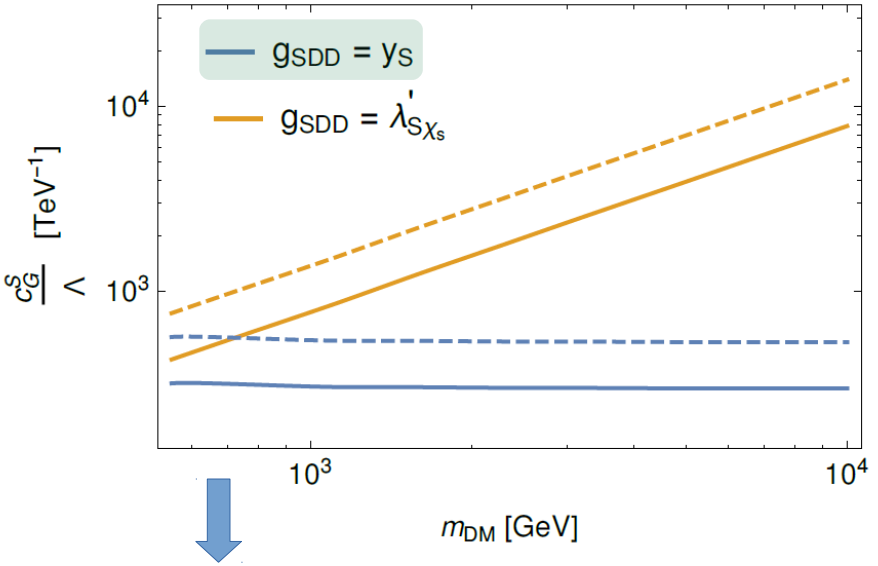
- Consider
  $(m_S = 400\,\mathrm{GeV}, m_{\chi_s} = 500\,\mathrm{GeV}),$
  $(m_S = 500\,\mathrm{GeV}, m_{\chi_s} = 1\,\mathrm{TeV})$

not visible (just for illustration)
→ more interesting (e.g.): $b\bar{b}$ induced

LHC cross sections

gg induced





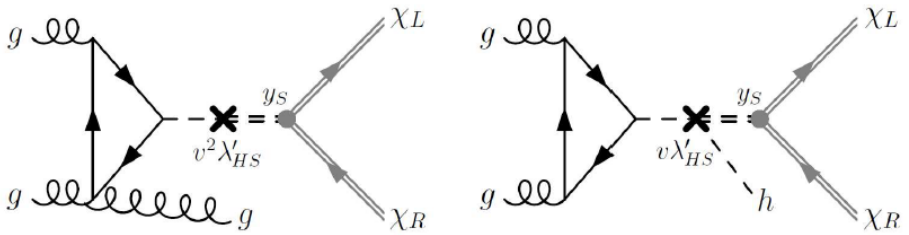
$$\sigma_j|_{m_\chi=500\,\mathrm{GeV}} \lesssim 1.9 \cdot 10^3\,\mathrm{fb},$$
$$\sigma_j|_{m_\chi=1\,\mathrm{TeV}} \lesssim 250\,\mathrm{fb}$$

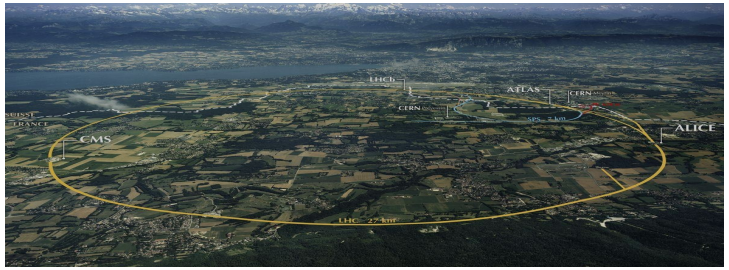
- Consider

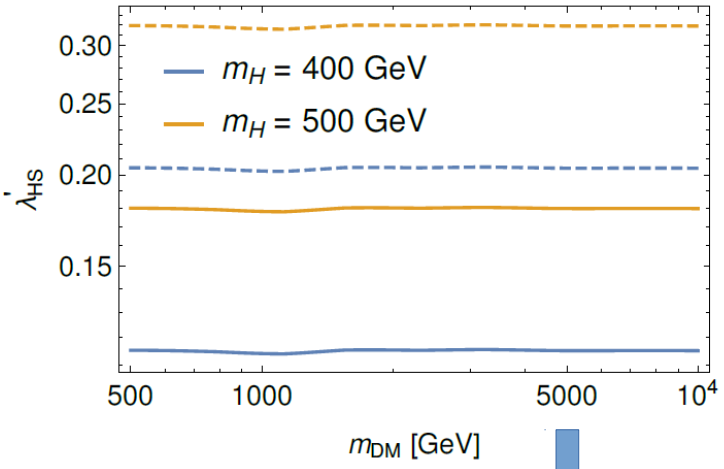
$$(m_S = 400\,\mathrm{GeV}, m_{\chi_s} = 500\,\mathrm{GeV}),$$
$$(m_S = 500\,\mathrm{GeV}, m_{\chi_s} = 1\,\mathrm{TeV})$$

LHC cross sections

Higgs - mediator portal



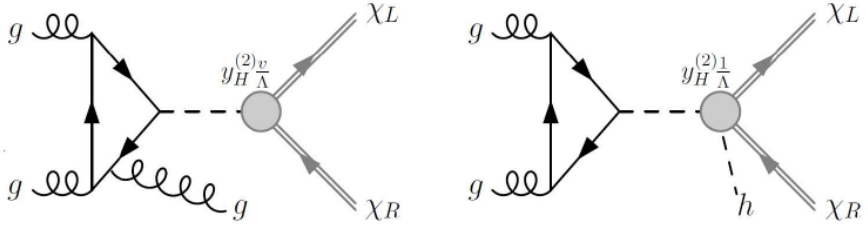


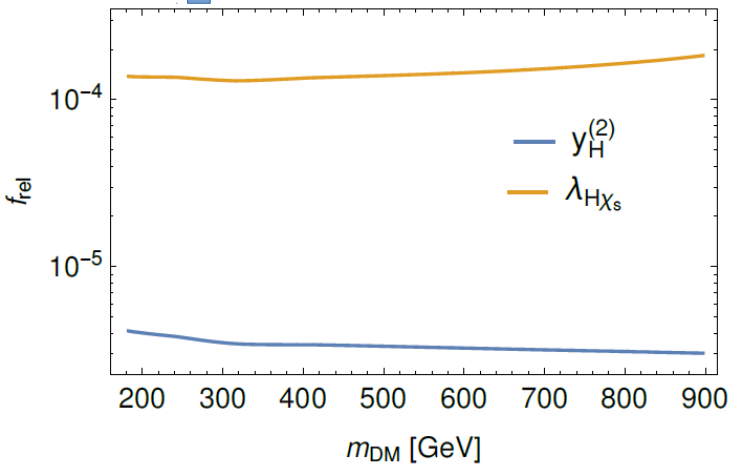


$$\sigma_j|_{m_\chi=500\,\mathrm{GeV}} \lesssim 1.1\cdot 10^{-3}\,\mathrm{fb},$$
$$\sigma_j|_{m_\chi=1\,\mathrm{TeV}} \lesssim 3.3\cdot 10^{-4}\,\mathrm{fb}$$

$$\sigma_j|_{m_\chi=500\,\mathrm{GeV}} \lesssim 49\,\mathrm{fb},$$
$$\sigma_j|_{m_\chi=1\,\mathrm{TeV}} \lesssim 3.3\,\mathrm{fb}$$

Higgs - DM portal





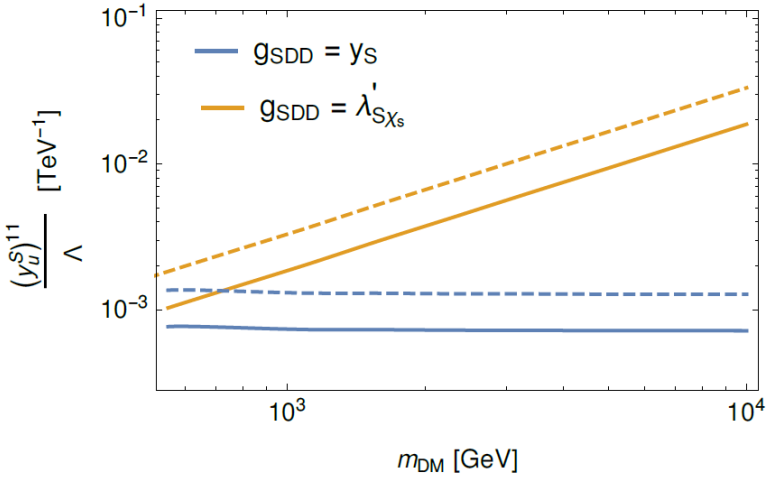
Scalar Dark Matter

$$\mathcal{L}_{\rm eff}^{\mathcal{S}\chi_s} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm kin} - V(\mathcal{S}) - V(\chi_s) - \lambda'_{HS} v |H|^2 \mathcal{S} - \lambda_{HS} |H|^2 \mathcal{S}^2$$

$$- \frac{\lambda'_{S\chi_s}}{2\sqrt{2}} v\, \mathcal{S}\chi_s^2 - \lambda_{S\chi_s} \mathcal{S}^2 \chi_s^2 - \lambda_{H\chi_s} |H|^2 \chi_s^2$$

$$- \frac{\mathcal{S}}{\Lambda} \left[c_{\lambda S} \mathcal{S}^4 + c_{HS} |H|^2 \mathcal{S}^2 + c_{\lambda H} |H|^4 \right.$$
$$\left. + c_{S\chi_s} \mathcal{S}^2 \chi_s^2 + c_{\lambda\chi_s} \chi_s^4 + c_{H\chi_s} |H|^2 \chi_s^2 \right]$$

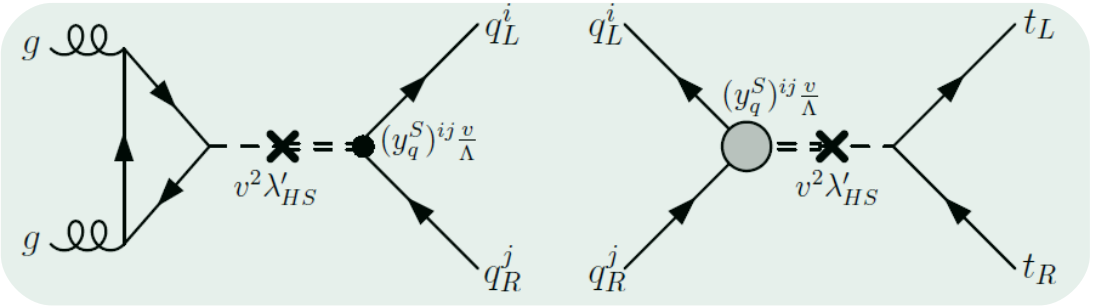
$$- \frac{\mathcal{S}}{\Lambda} (y_f^S)^{ij} \bar{F}_{\rm L}^i H f_{\rm R}^j - \frac{\mathcal{S}}{16\pi^2 \Lambda} \sum_{V=G,B,W} C_V^S V_{\mu\nu} V^{\mu\nu}$$



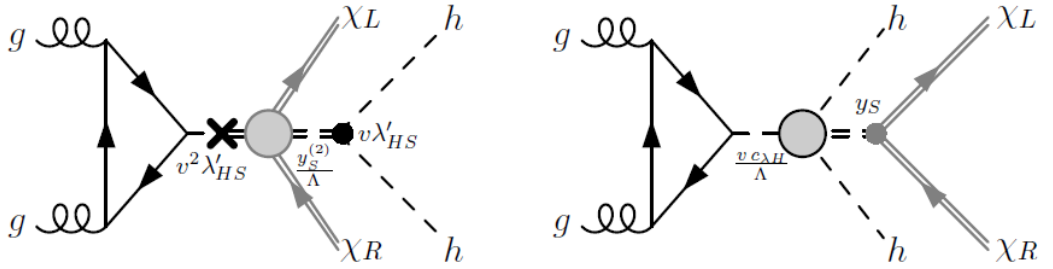
similar story...

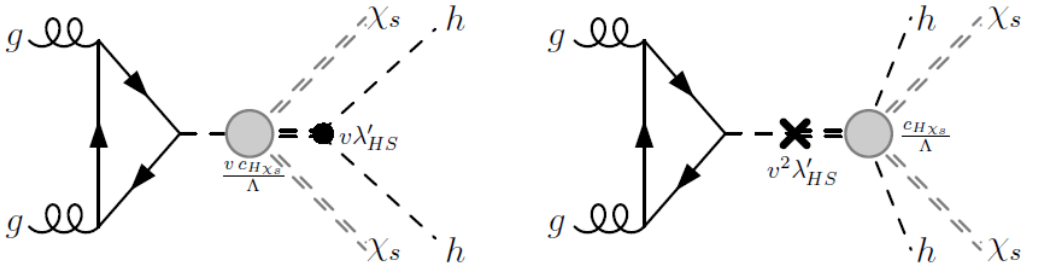
Further Processes

- Resonance Search for Mediator



- Higgs Pair + MET ?

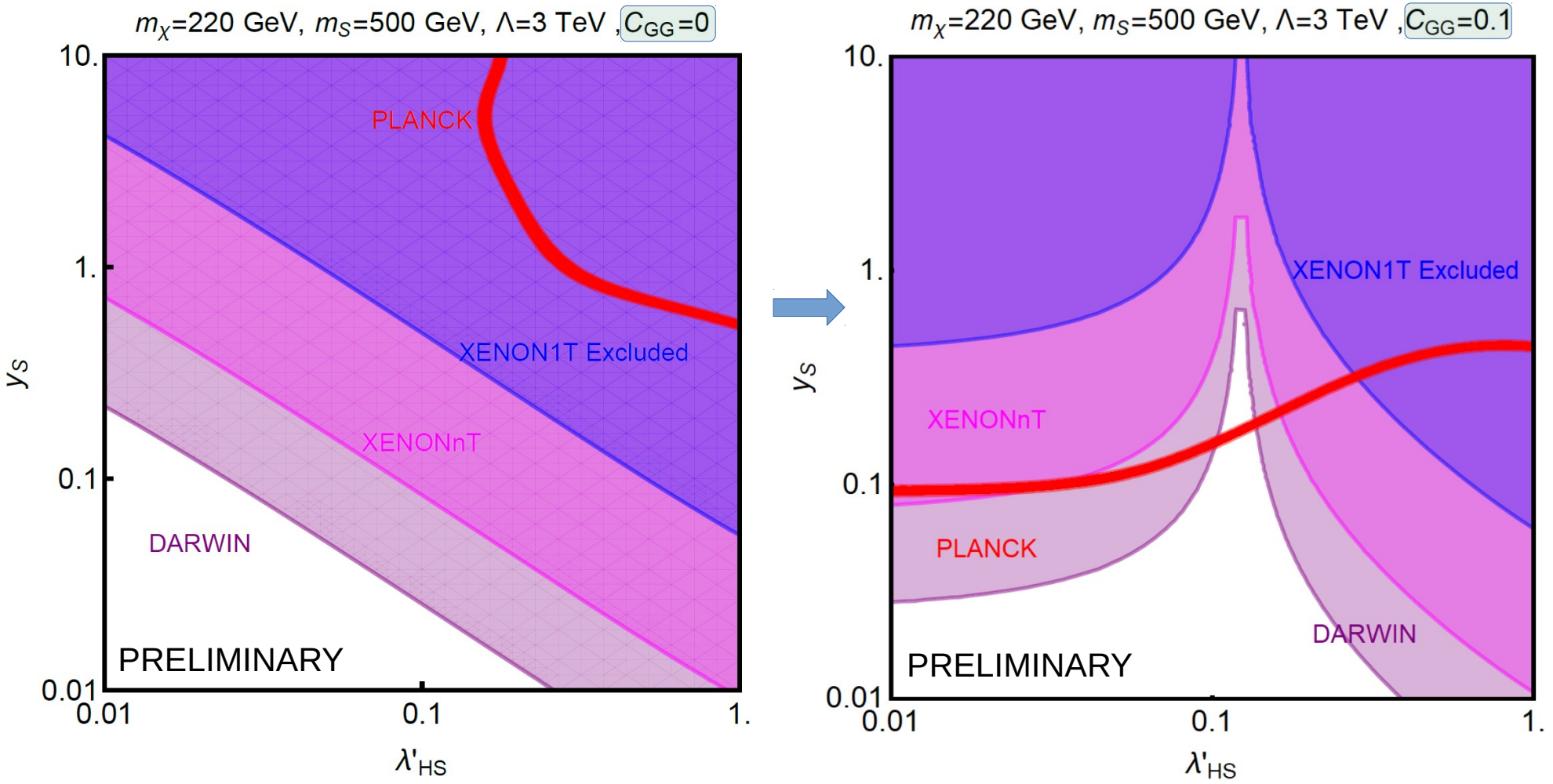




- ....

Global Picture

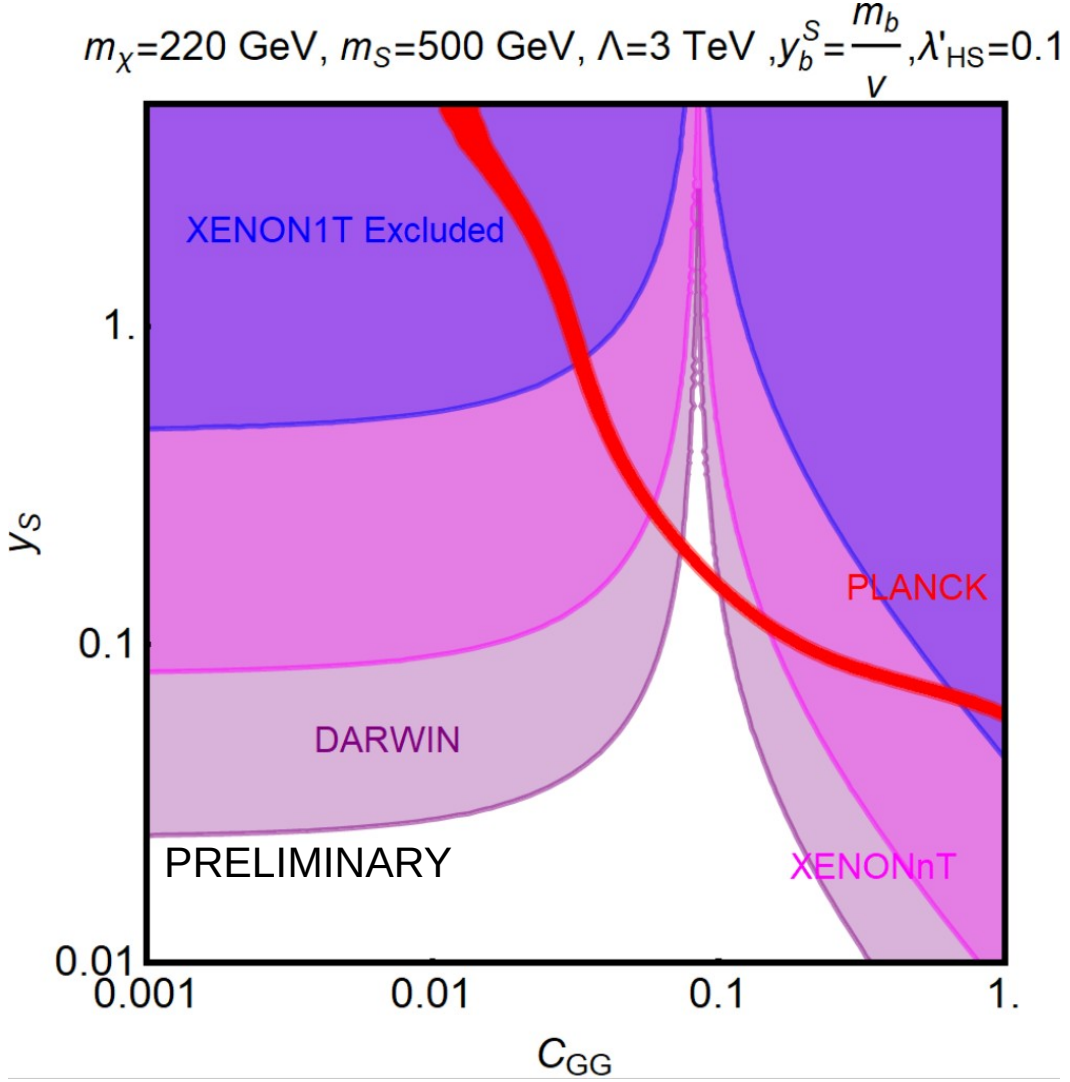
- Most interesting case: more than 2 couplings present



➡ open parameter space of Portal DM, ...

Global Picture

- *Most interesting case: more than 2 couplings present*



Matching to UV Theories

- 2HDM + scalar + DM

  integrate out H_2: $\quad c_{HS} = -2\lambda_{12}^{S}\lambda_{12}^{2S} v/M_{H_2}$

  $$c_{\lambda H} = 2Z_6\lambda_{12}^{S} v/M_{H_2}$$

  $$y_q^S = \lambda_{12}^{S}\eta_q/(\tan_\beta M_{H_2})$$

- Composite mediators $\quad y_q^{\tilde{S}} = y_q\,\Lambda/f$

  $$y_{\tilde{S}} = y_\chi$$

- NMSSM (singlino DM), VL fermions, ...

Matching to UV Theories

- 2HDM + scalar + DM

  integrate out H_2:

$$c_{HS} = -2\lambda_{12}^{S}\lambda_{12}^{2S} v/M_{H_2}$$
$$c_{\lambda H} = 2Z_6\lambda_{12}^{S} v/M_{H_2}$$
$$y_q^S = \lambda_{12}^{S}\eta_q/(\tan_\beta M_{H_2})$$

- Composite mediators $y_q^{\tilde{S}} = y_q\,\Lambda/f$

  $y_{\tilde{S}} = y_\chi$

Interpret exclusion in terms of models,

Scrutinize validity of EFT

- NMSSM (singlino DM), VL fermions, ...

Conclusions

eDMEFT:

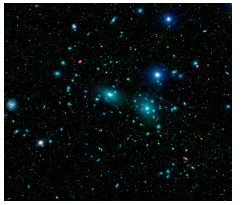
- Framework to study correlations between different DM observables (incl. LHC), maintaining gauge invariance and allowing for richer NP sector
- Potentially opening 'new' viable parameter regions for DM

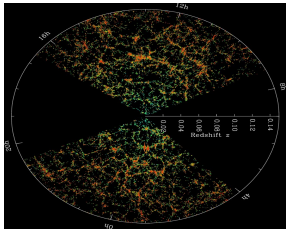
Backup

Dark Matter

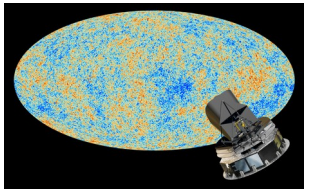
- *Viable candidate for DM:*

electrically neutral,
cosmologically stable,
colorless particle,
with abundance in agreement with Ω_{DM}



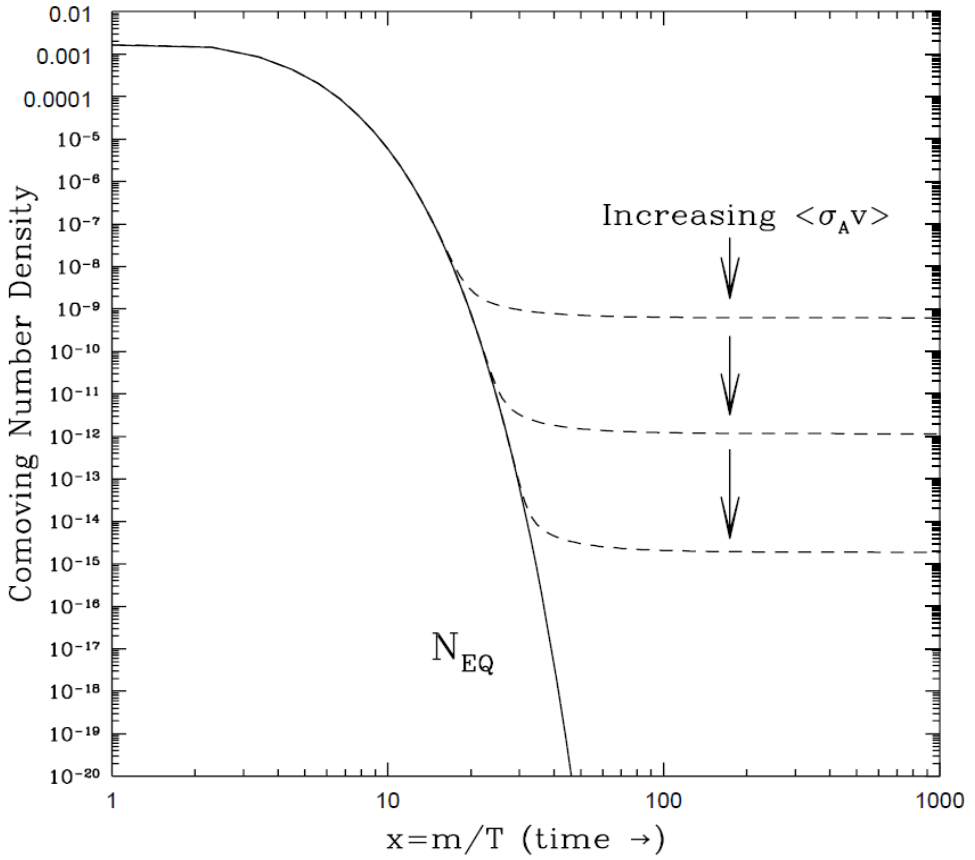


structure formation → cold (non-relativistic) dark matter preferred



weakly interacting massive particle (WIMP)

WIMP Miracle



$$< \sigma_{X\bar{X}}|v| >= a + b < v^2 > +\mathcal{O}(v^4)$$

$$x \equiv m_X/T$$

WIMP

$m_X \sim \mathrm{GeV} - \mathrm{TeV}$, weak scale $< \sigma_{X\bar{X}}|v| >$

$\downarrow$

$x_{FO} \sim 20 - 30$ (freeze-out temperature)

$$\rightarrow \text{Correct Relic Abundance } \Omega_X h^2 \approx 0.1 \overbrace{\left(\frac{x_{\rm FO}}{20}\right)\left(\frac{g_\star}{80}\right)^{-1/2}\left(\frac{a+3b/x_{\rm FO}}{3\times 10^{-26}{\rm cm}^3/{\rm s}}\right)^{-1}}^{\sim 1}$$

Hooper, 0901.4090

external dof ~80

$$\langle \sigma {\rm v} \rangle_0 \;=\; 3 \cdot 10^{-26}\ {\rm cm}^3{\rm s}^{-1} \qquad \Omega h^2 \;\propto\; \langle \sigma {\rm v} \rangle^{-1}$$