Composite Dark Matter

and insights from the Lattice

Enrico Rinaldi

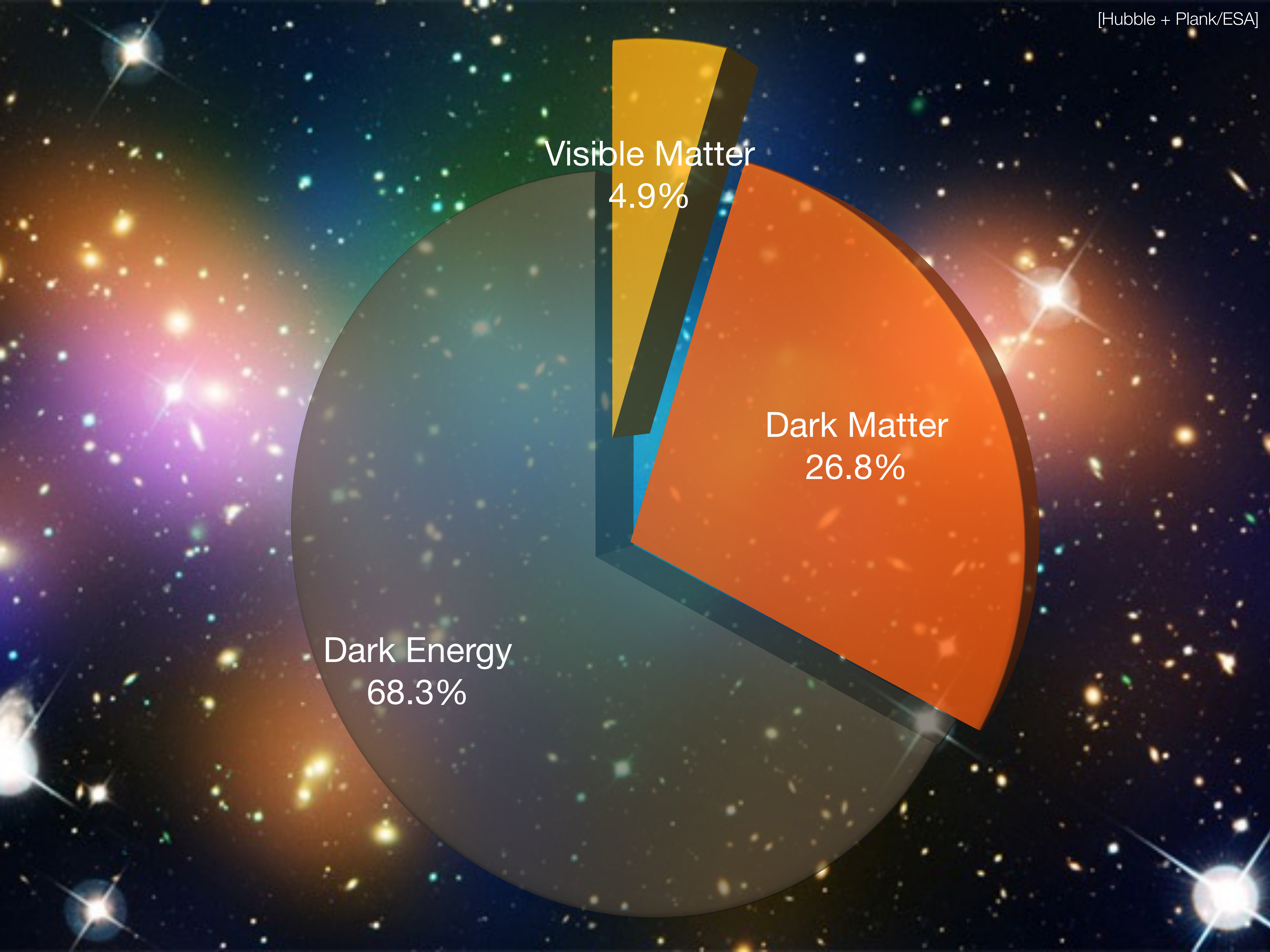
Lawrence Livermore National Laboratory

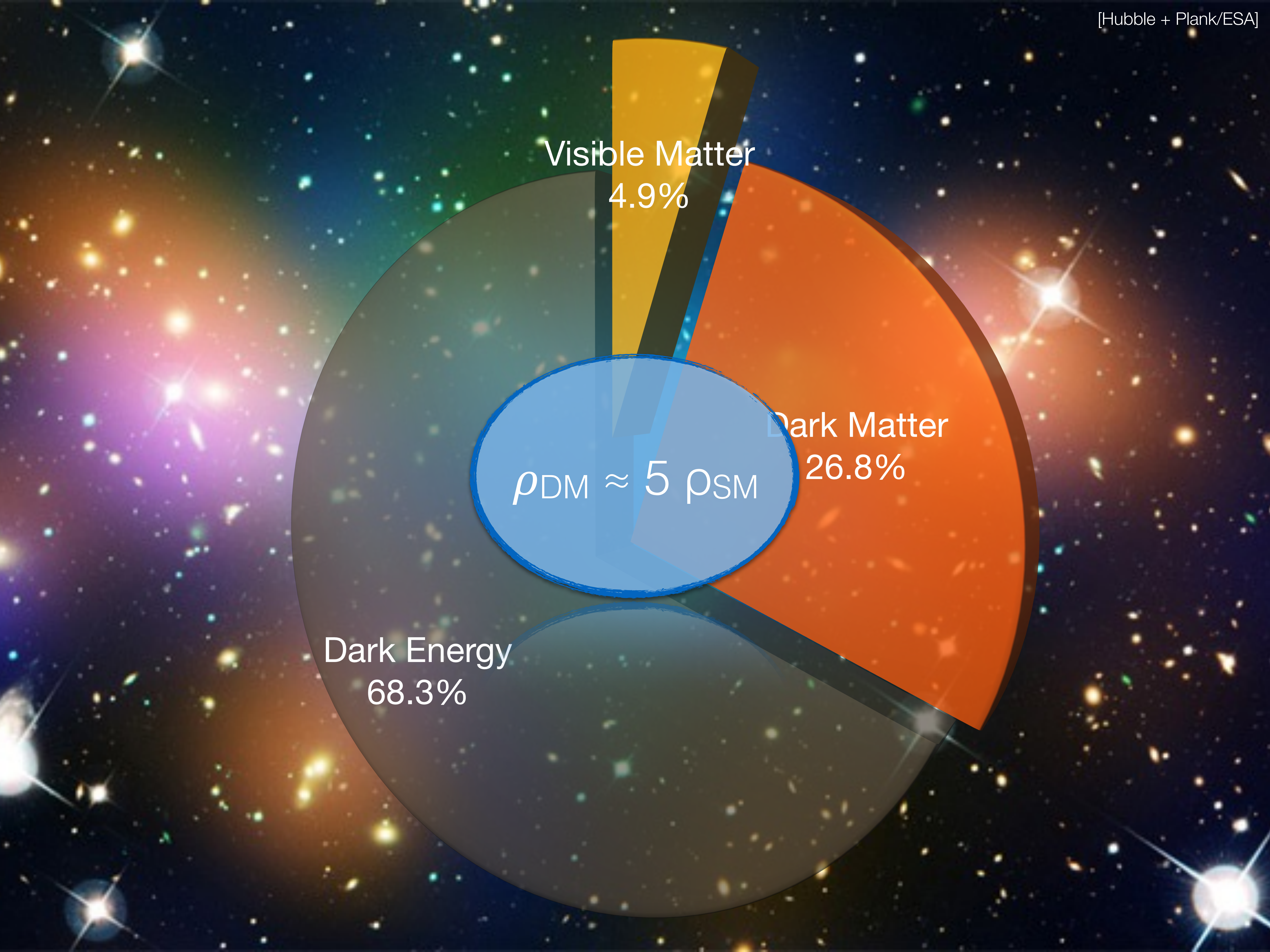
This research was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344 and supported by the LLNL LDRD "Illuminating the Dark Universe with PetaFlops Supercomputing" 13-ERD-023.

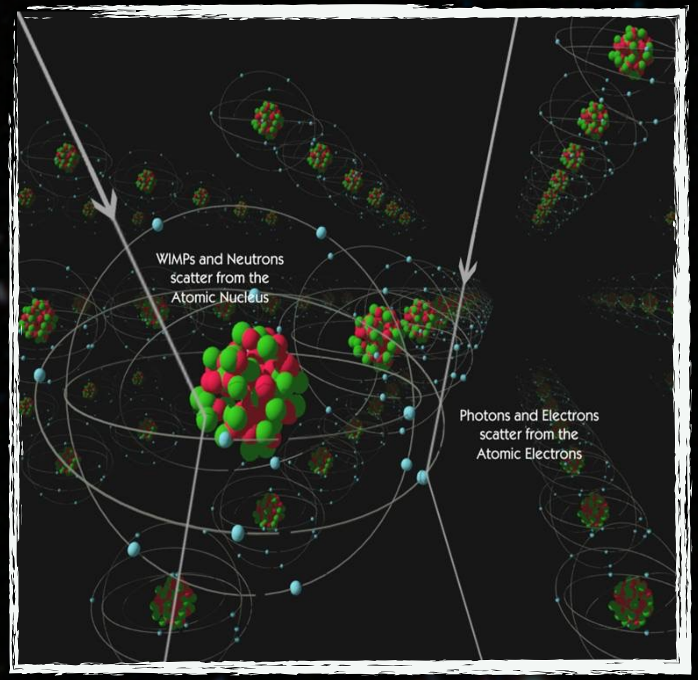
Computing support comes from the LLNL Institutional Computing Grand Challenge program. *LLNL-PRES-669543*

[Hubble + Plank/ESA]

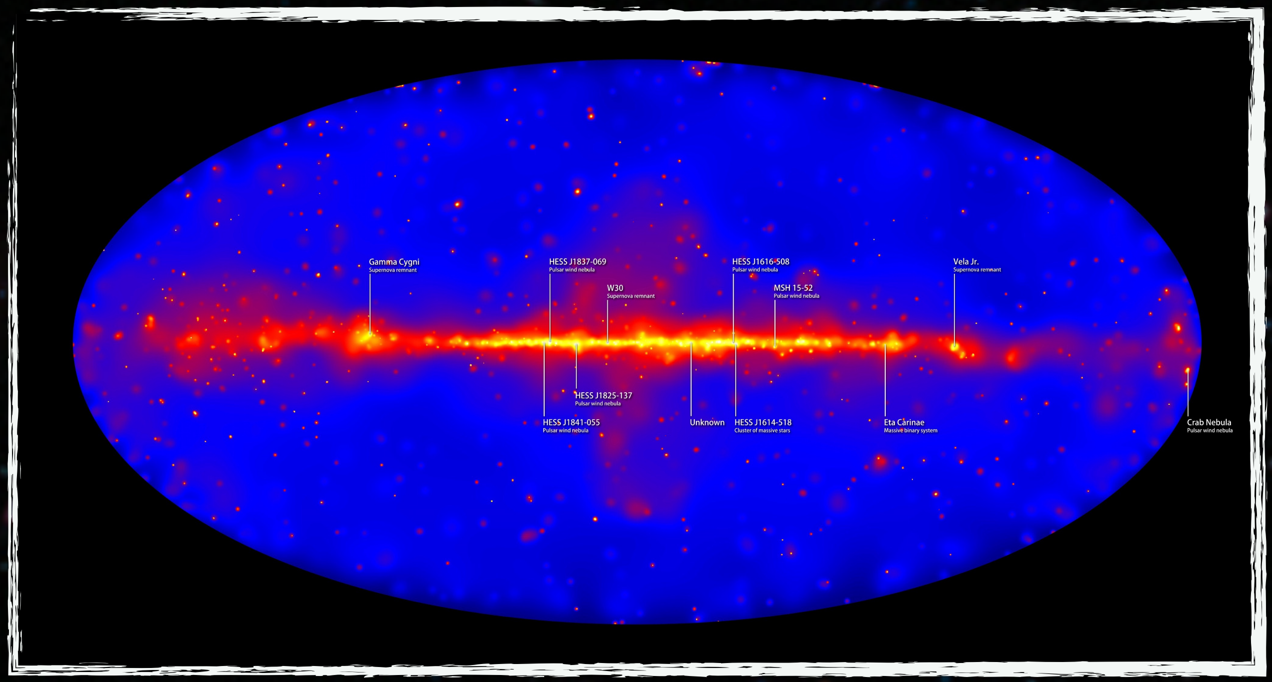

[Hubble + Plank/ESA]
Visible Matter
4.9%


[Hubble + Plank/ESA]
Visible Matter
4.9%
Dark Matter
26.8%
Dark Energy
68.3%

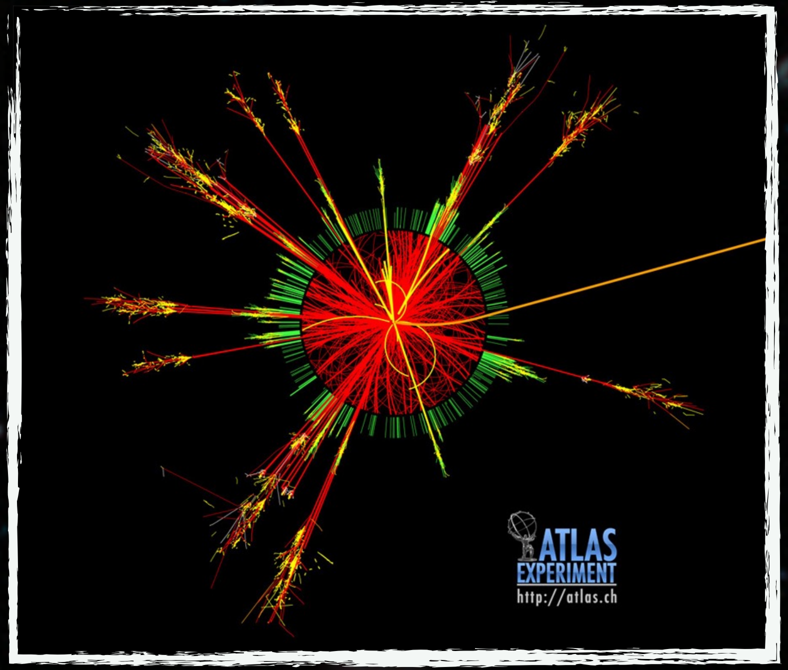

[Hubble + Plank/ESA]
Visible Matter
4.9%
Dark Matter
26.8%
Dark Energy
68.3%
$\rho_{DM} \approx 5\ \rho_{SM}$



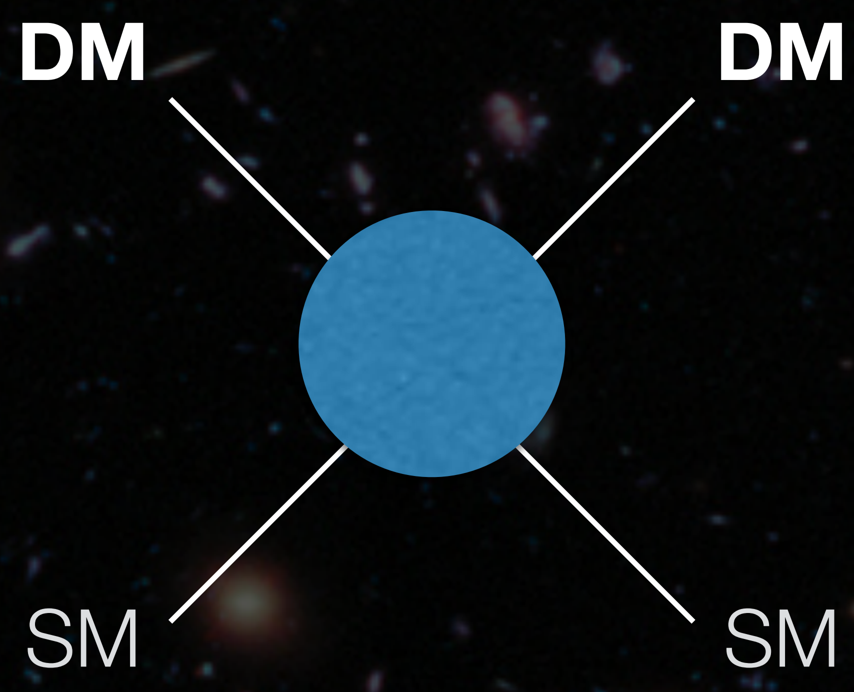
Direct Detection

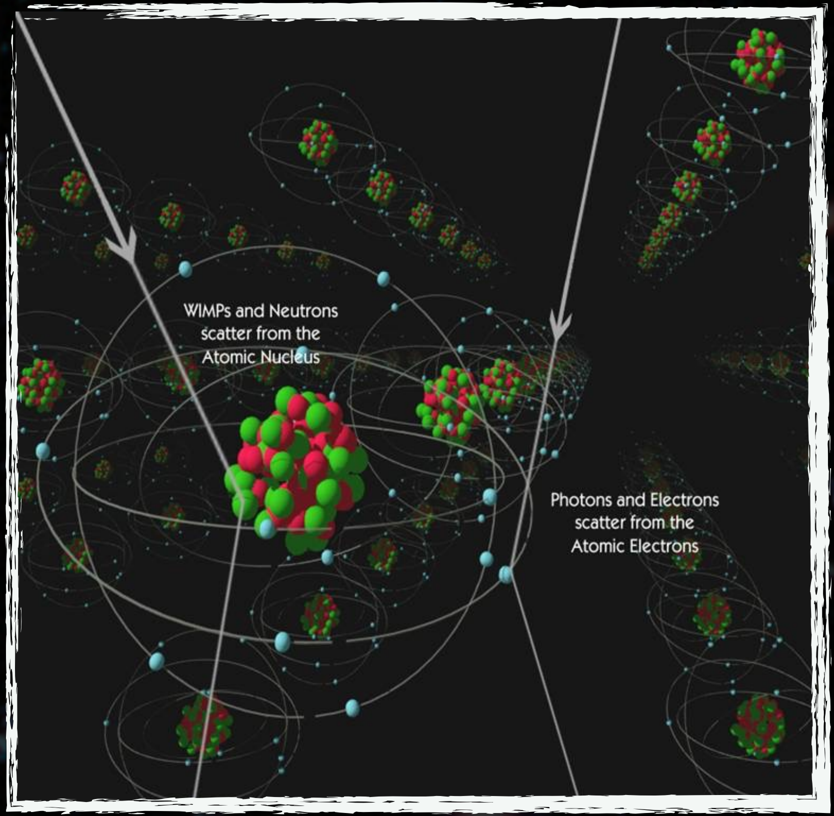


Indirect Detection

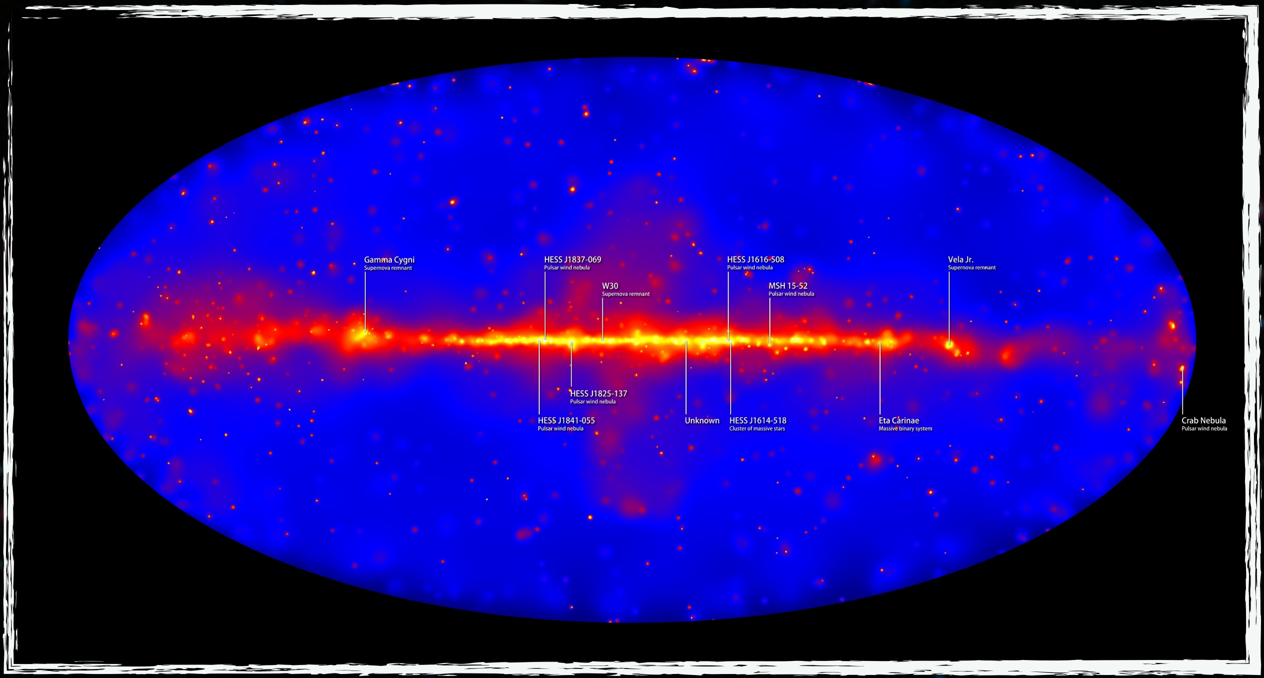


Production at Colliders

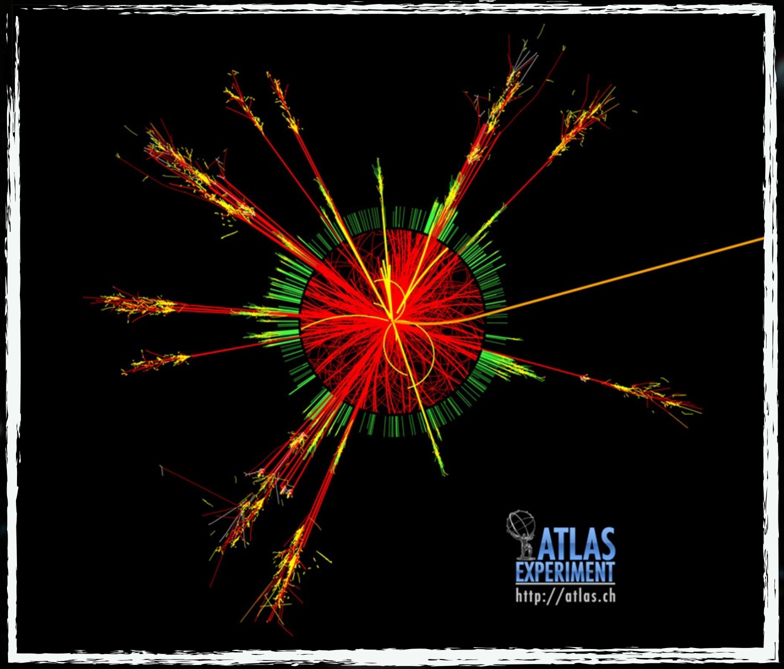




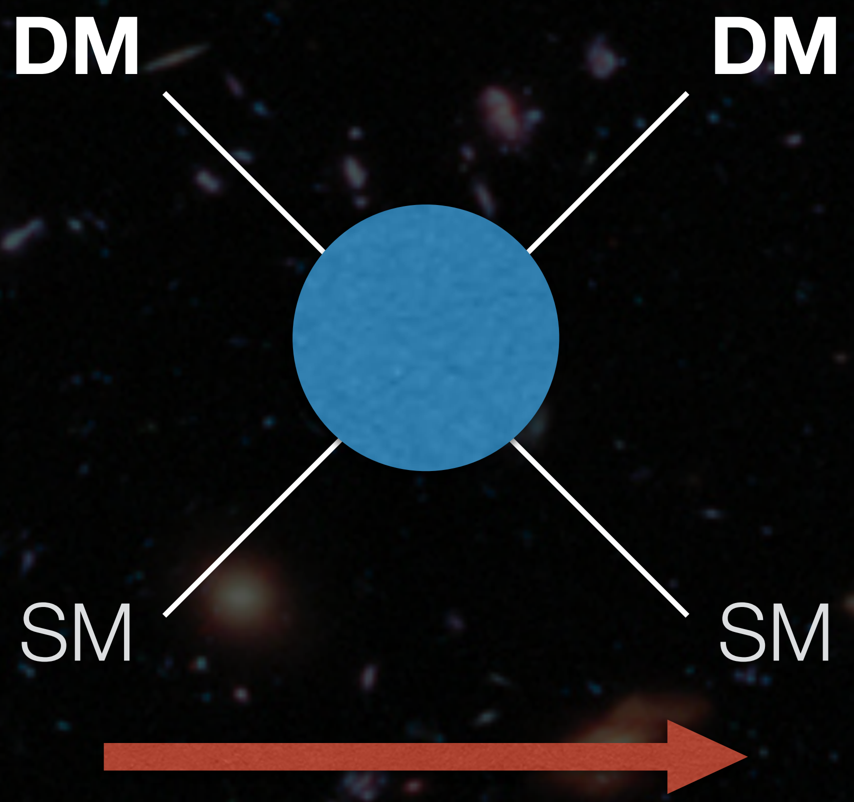
Direct Detection

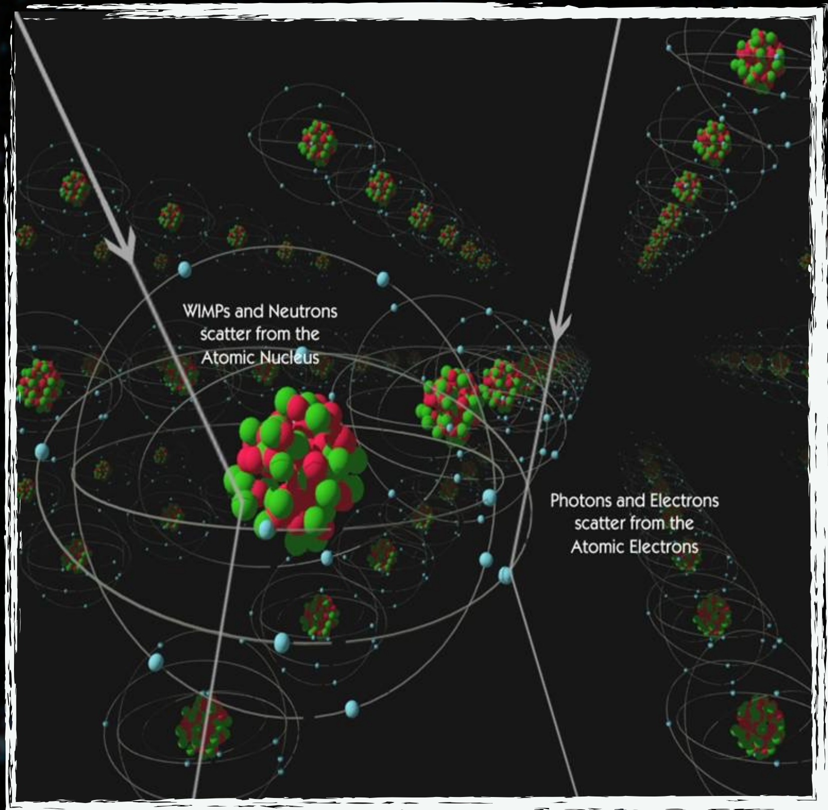


Indirect Detection

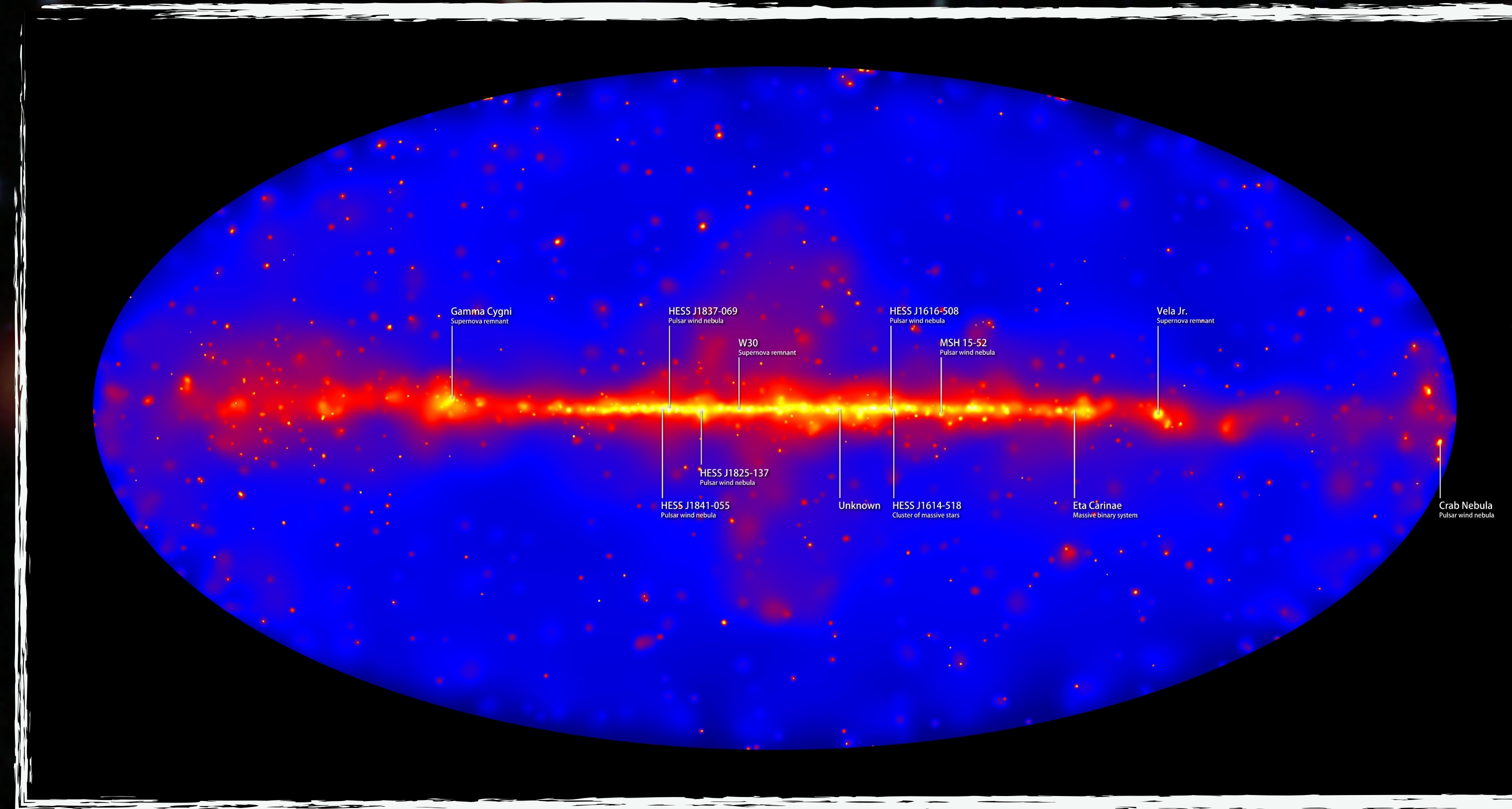


Production at Colliders

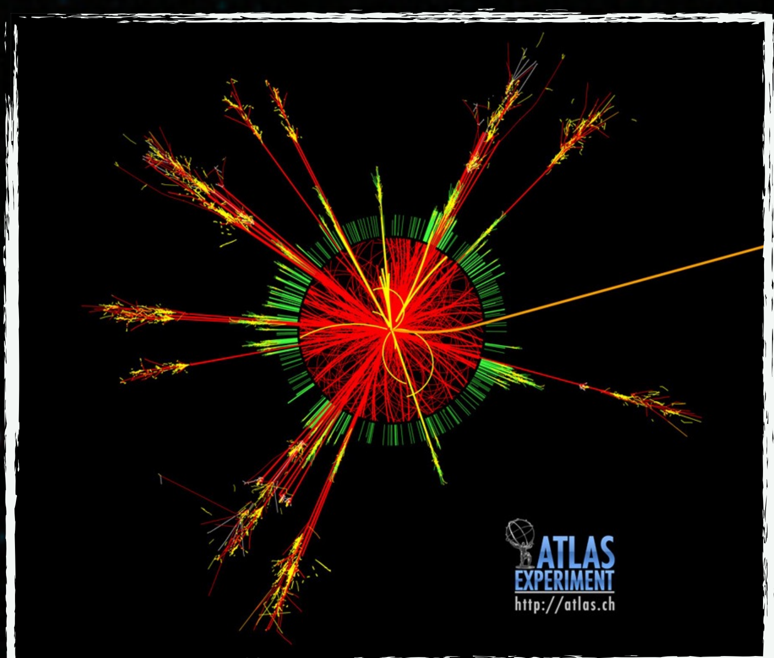




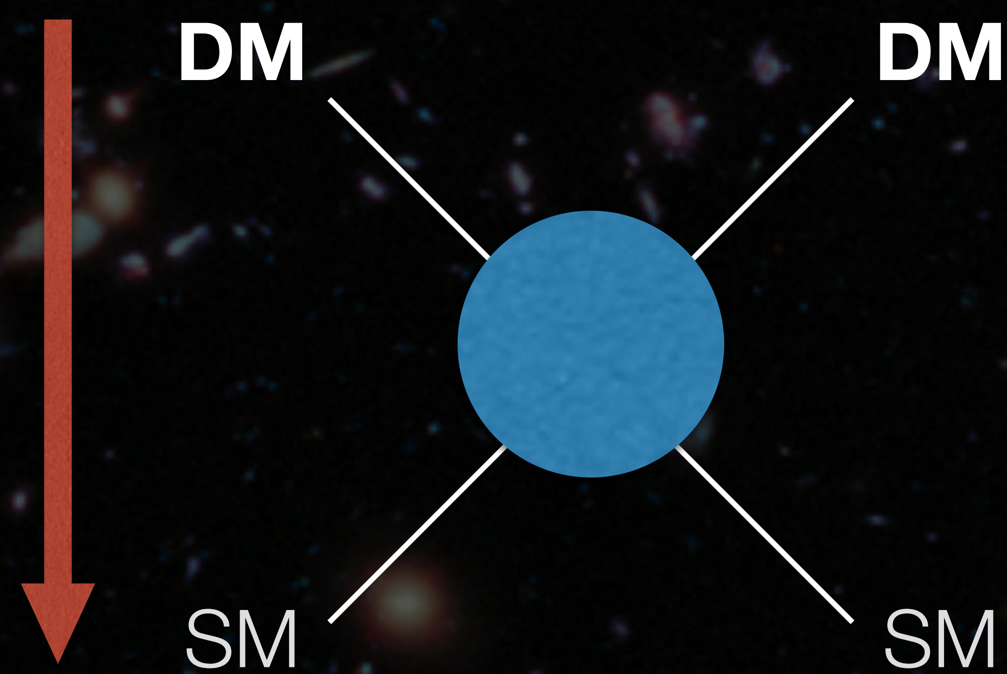
Direct Detection

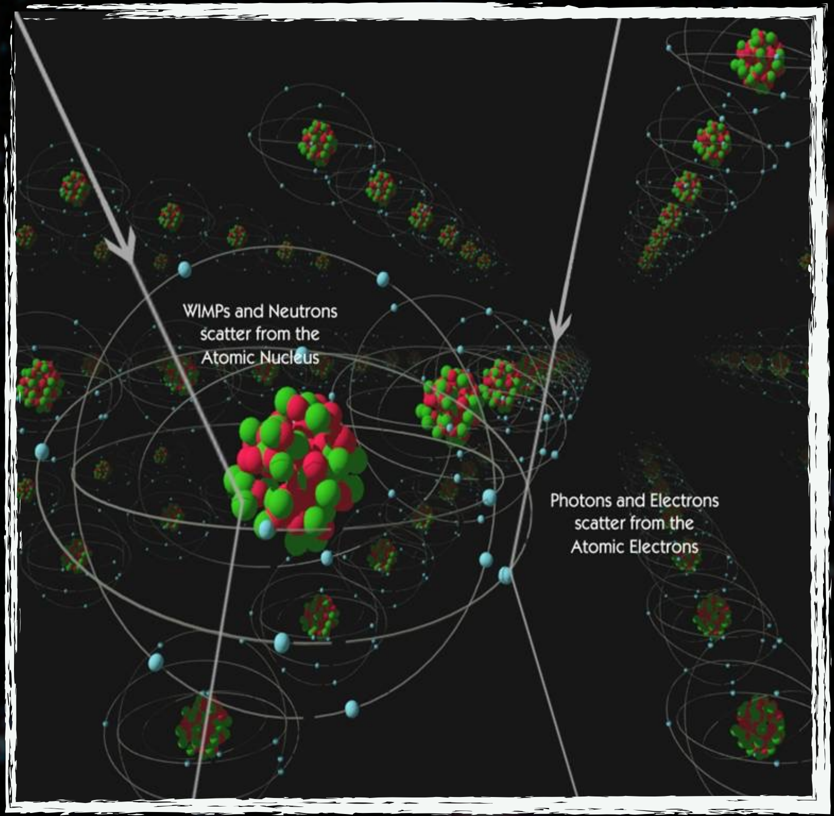


Indirect Detection

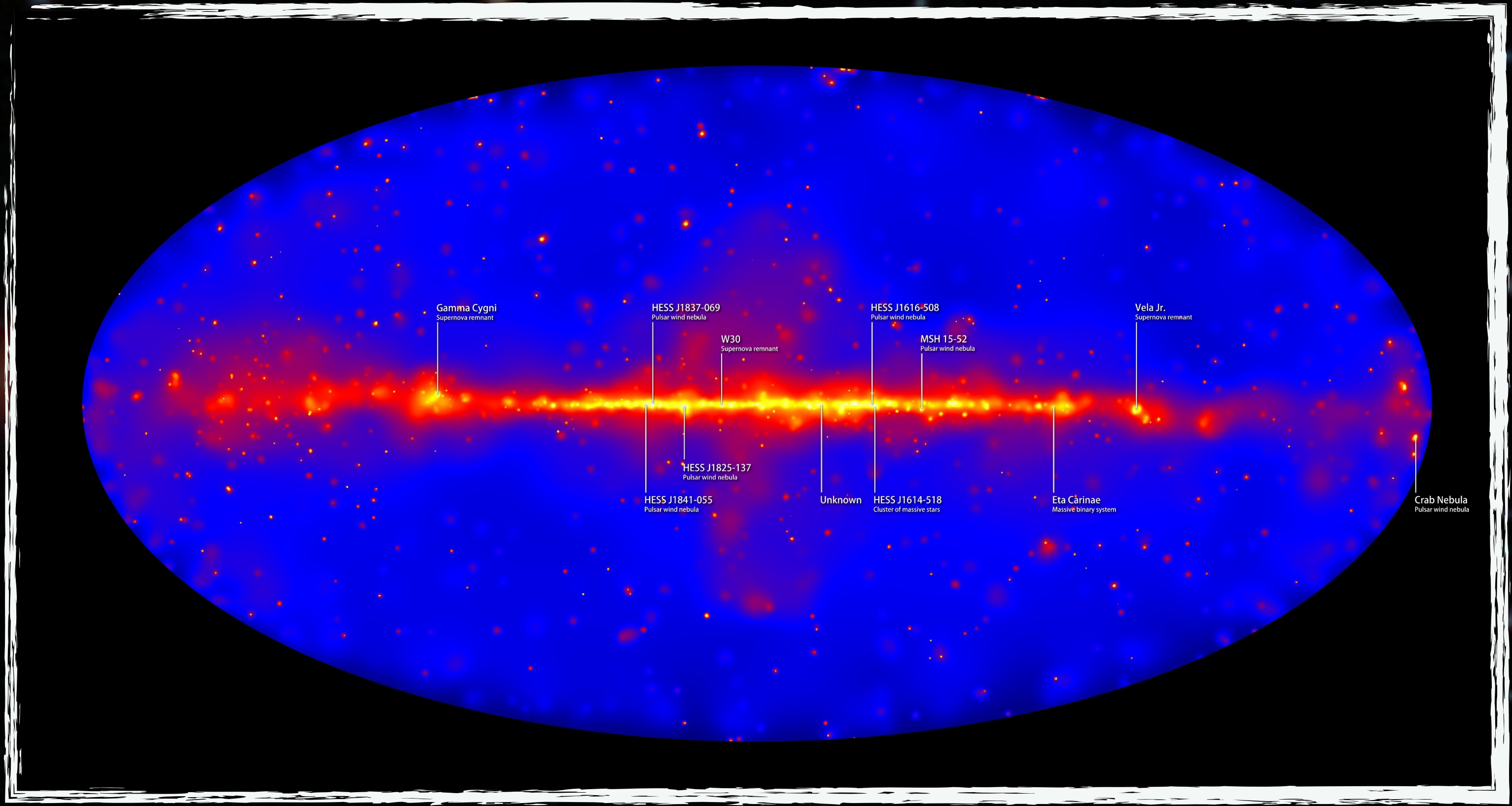


Production at Colliders

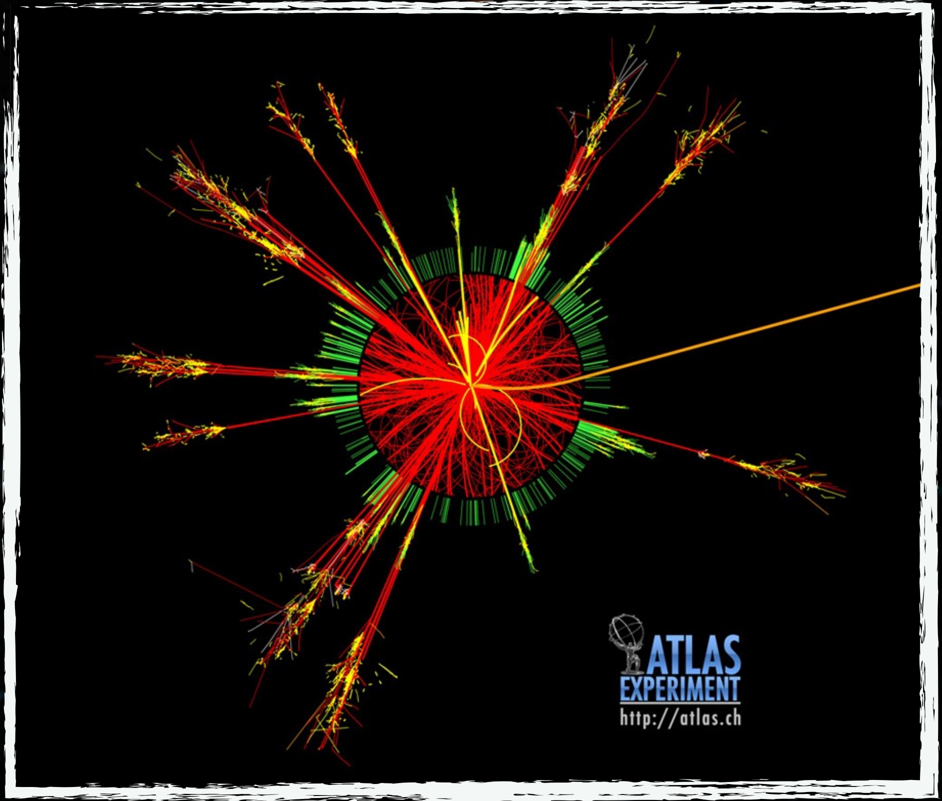




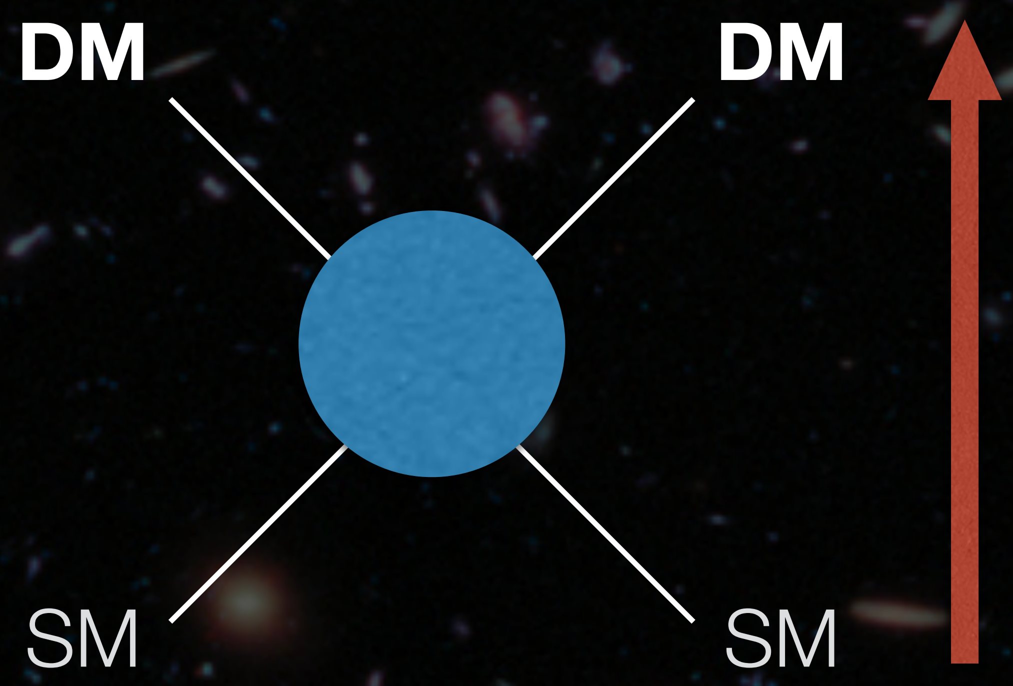
Direct Detection



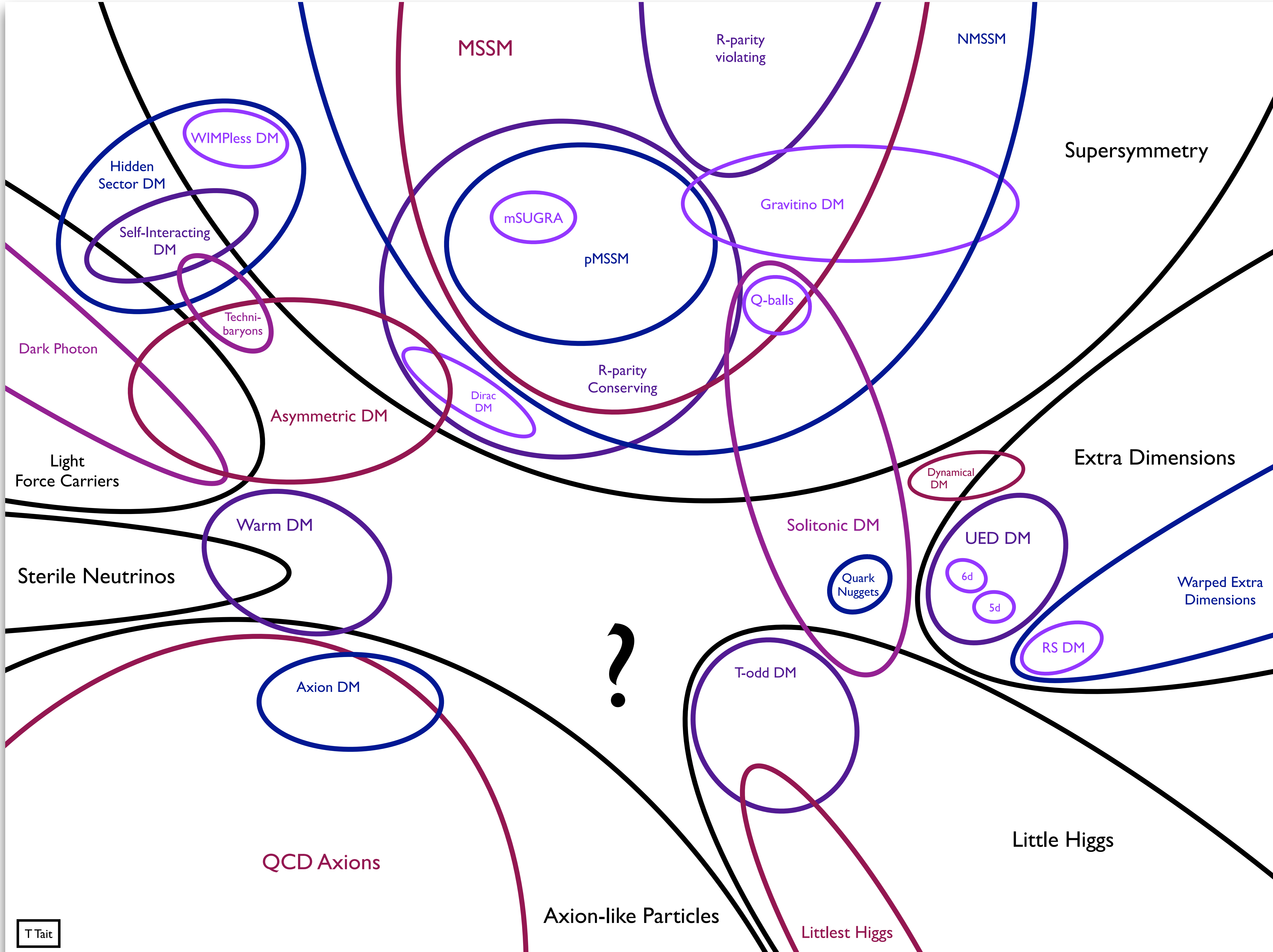
Indirect Detection



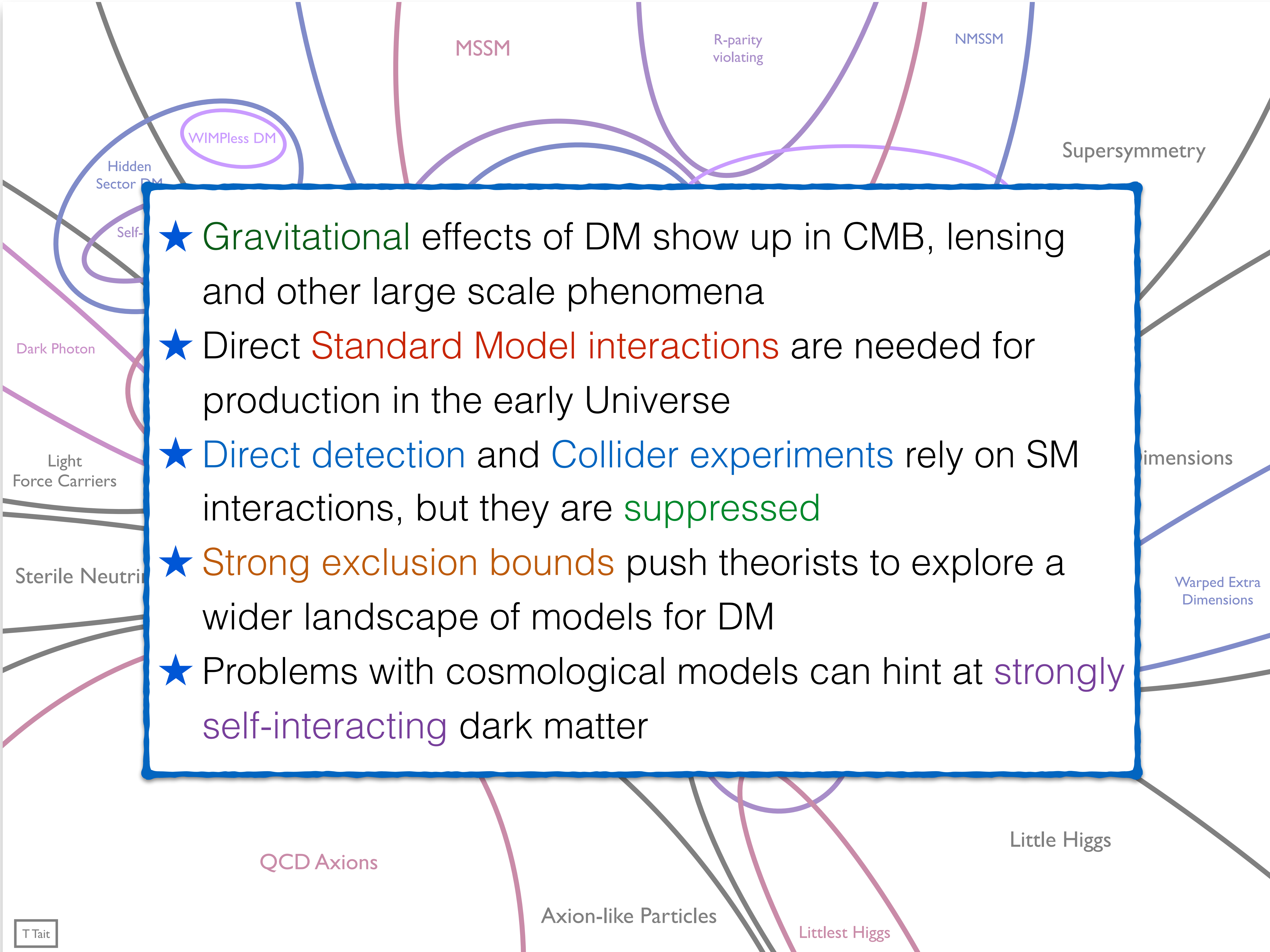
Production at Colliders



What is Dark Matter?



[Planning the Future of U.S. Particle Physics (Snowmass 2013), 1401.6085]



★ Gravitational effects of DM show up in CMB, lensing and other large scale phenomena

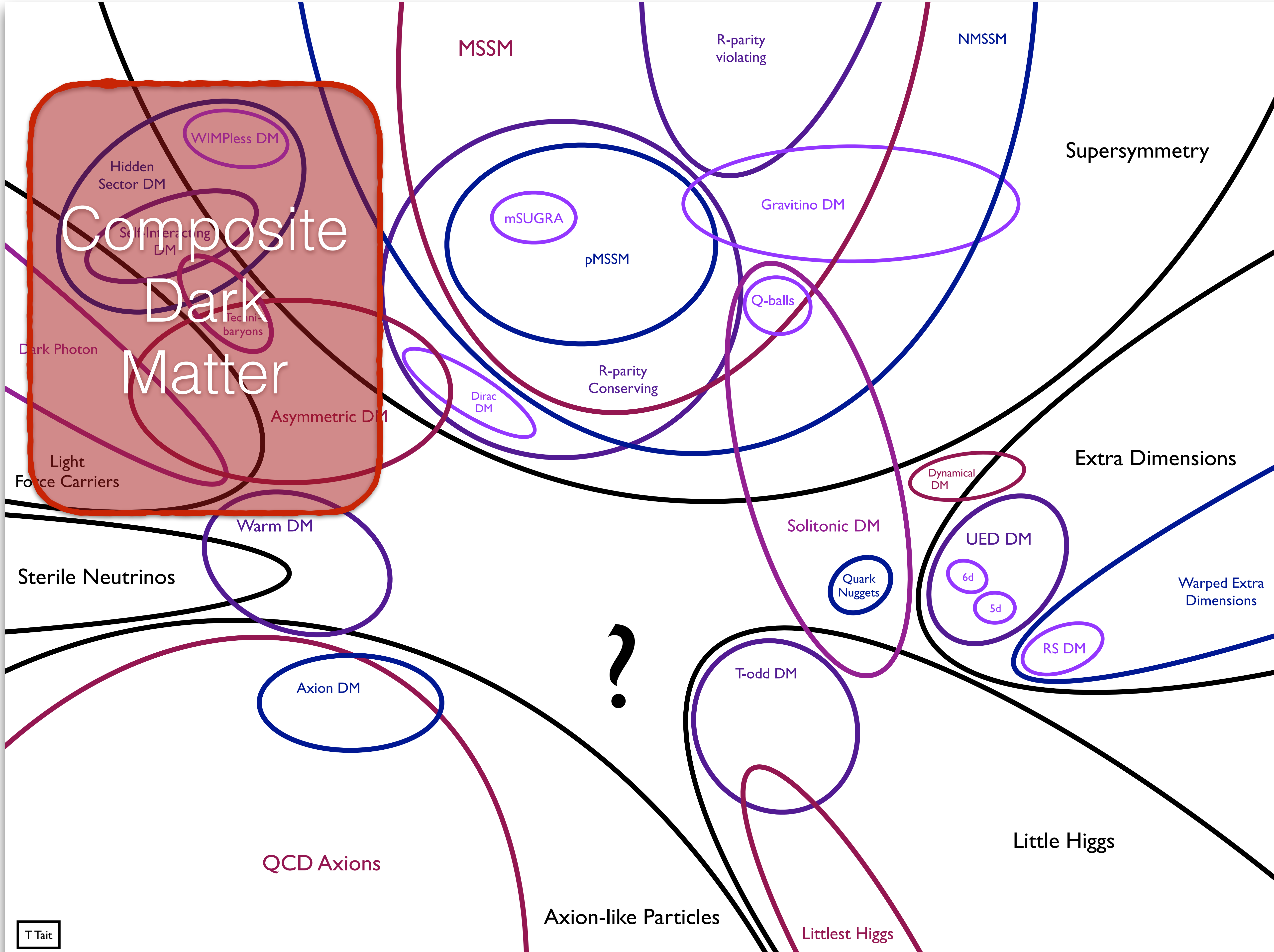
★ Direct Standard Model interactions are needed for production in the early Universe

★ Direct detection and Collider experiments rely on SM interactions, but they are suppressed

★ Strong exclusion bounds push theorists to explore a wider landscape of models for DM

★ Problems with cosmological models can hint at strongly self-interacting dark matter

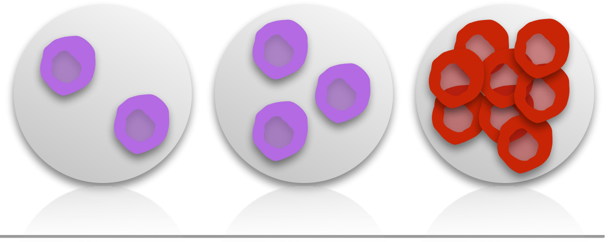
[Planning the Future of U.S. Particle Physics (Snowmass 2013), 1401.6085]



[Planning the Future of U.S. Particle Physics (Snowmass 2013), 1401.6085]

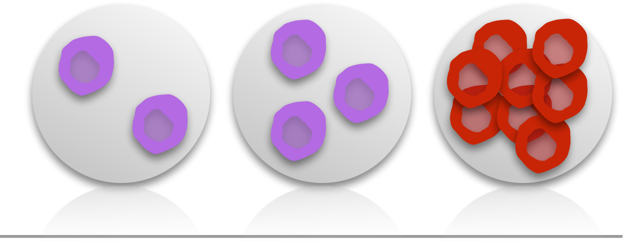
Composite Dark Matter

Composite Dark Matter



- Dark Matter is a composite object

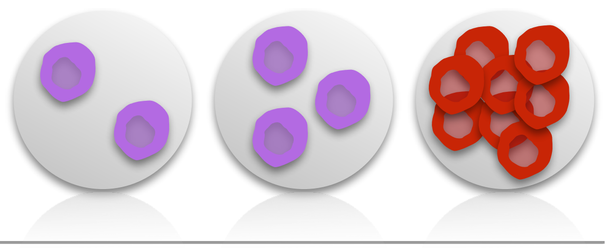
Composite Dark Matter



- Dark Matter is a composite object

e.g. technibaryon or hidden glueball

Composite Dark Matter



- Dark Matter is a composite object

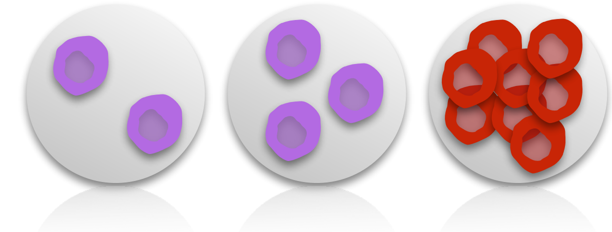
e.g. technibaryon or hidden glueball

- Interesting and complicated internal structure

- Properties dictated by strong dynamics

- Self-interactions are natural

Composite Dark Matter

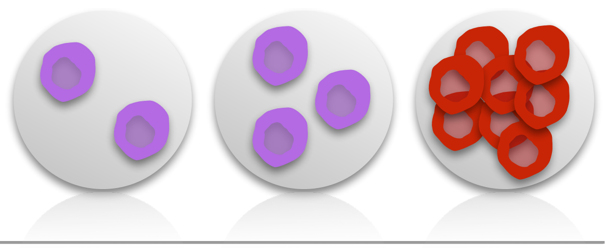


- Dark Matter is a composite object
- Interesting and complicated internal structure
- Properties dictated by strong dynamics
- Self-interactions are natural

e.g. technibaryon or hidden glueball

Similar to QCD

Composite Dark Matter

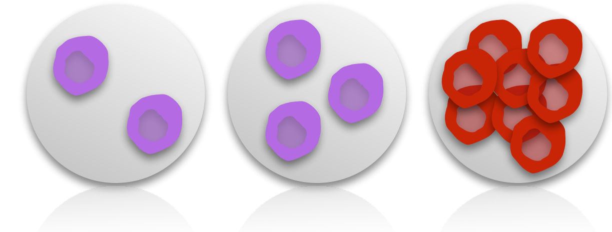


- Dark Matter is a composite object
- Interesting and complicated internal structure
- Properties dictated by strong dynamics
- Self-interactions are natural
- Composite object is neutral
- Constituents may interact with Standard Model particles

e.g. technibaryon or hidden glueball

Similar to QCD

Composite Dark Matter



- Dark Matter is a composite object

e.g. technibaryon or hidden glueball

- Interesting and complicated internal structure

- Properties dictated by strong dynamics

Similar to QCD

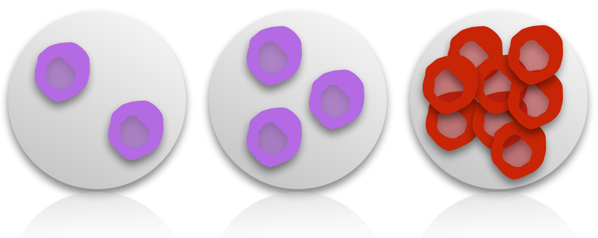
- Self-interactions are natural

- Composite object is neutral

Chance to observe them in experiments and give the correct relic abundance

- Constituents may interact with Standard Model particles

Composite Dark Matter



- ✦ Dark Matter is a composite object
- ✦ Interesting and complicated internal structure
- ✦ Properties dictated by strong dynamics
- ✦ Self-interactions are natural
- ✦ Composite object is neutral
- ✦ Constituents may interact with Standard Model particles

e.g. technibaryon or hidden glueball

Lattice Field Theory methods

Similar to QCD

Chance to observe them in experiments and give the correct relic abundance

[review by Kribs & Neil, 1604.04627]

Natural features of Composite Dark Matter

[review by Kribs & Neil, 1604.04627]

Natural features of Composite Dark Matter

Stability is a direct consequence of accidental **symmetries**

[review by Kribs & Neil, 1604.04627]

Natural features of Composite Dark Matter

Stability is a direct consequence of accidental **symmetries**

Neutrality follows naturally from **confinement** into singlet objects wrt. SM charges

[review by Kribs & Neil, 1604.04627]

Natural features of Composite Dark Matter

Stability is a direct consequence of accidental **symmetries**

Neutrality follows naturally from **confinement** into singlet objects wrt. SM charges

Small **interactions** with SM particles arise from form factor **suppression** (higher dim. operators)

[review by Kribs & Neil, 1604.04627]

Natural features of Composite Dark Matter

Stability is a direct consequence of accidental **symmetries**

Neutrality follows naturally from **confinement** into singlet objects wrt. SM charges

Small **interactions** with SM particles arise from form factor **suppression** (higher dim. operators)

Self-interactions are included due to **strongly coupled** dynamics

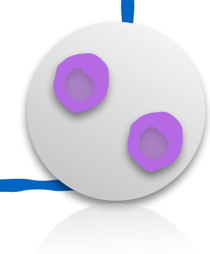
[list of references focused on lattice results when possible]

[review by Kribs & Neil, 1604.04627]

Models for Composite Dark Matter

★ Pion-like (dark quark-antiquark)

- ✦ pNGB DM *[Hietanen et al.,1308.4130]*
- ✦ Quirky DM *[Kribs et al.,0909.2034]*
- ✦ Ectocolor DM *[Buckley&Neil,1209.6054]*
- ✦ SIMP *[Hochberg et al.,1411.3727]*
- ✦ Minimal SU(2) *[Lewis, Wed.@11:50]*



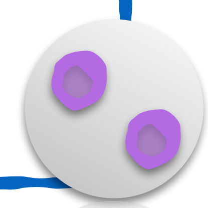
[list of references focused on lattice results when possible]

[review by Kribs & Neil, 1604.04627]

Models for Composite Dark Matter

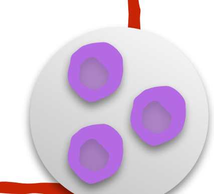
★ Pion-like (dark quark-antiquark)

- ✦ pNGB DM *[Hietanen et al., 1308.4130]*
- ✦ Quirky DM *[Kribs et al., 0909.2034]*
- ✦ Ectocolor DM *[Buckley&Neil, 1209.6054]*
- ✦ SIMP *[Hochberg et al., 1411.3727]*
- ✦ Minimal SU(2) *[Lewis, Wed.@11:50]*



★ Baryon-like (multiple quarks)

- ✦ "Technibaryons" *[LSD, 1301.1693]*
- ✦ Stealth DM *[LSD, 1503.04203-1503.04205]*
- ✦ One-family TC *[LatKMI, 1510.07373]*
- ✦ Sextet CH *[LatHC, 1601.03302][Kuti, Mon.@15:15]*



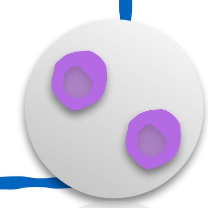
[list of references focused on lattice results when possible]

[review by Kribs & Neil, 1604.04627]

Models for Composite Dark Matter

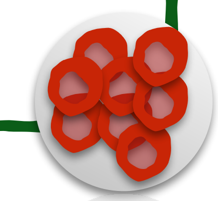
★ Pion-like (dark quark-antiquark)

- ✦ pNGB DM *[Hietanen et al.,1308.4130]*
- ✦ Quirky DM *[Kribs et al.,0909.2034]*
- ✦ Ectocolor DM *[Buckley&Neil,1209.6054]*
- ✦ SIMP *[Hochberg et al.,1411.3727]*
- ✦ Minimal SU(2) *[Lewis, Wed.@11:50]*



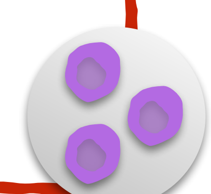
★ Glueball-like (only gluons)

- ✦ SUNonia *[Boddy et al.,1402.3629]* *[Soni, Wed.@11:30]*



★ Baryon-like (multiple quarks)

- ✦ “Technibaryons” *[LSD,1301.1693]*
- ✦ Stealth DM *[LSD,1503.04203-1503.04205]*
- ✦ One-family TC *[LatKMI,1510.07373]*
- ✦ Sextet CH *[LatHC,1601.03302][Kuti, Mon.@15:15]*



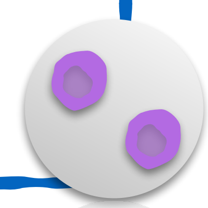
[list of references focused on lattice results when possible]

[review by Kribs & Neil, 1604.04627]

Models for Composite Dark Matter

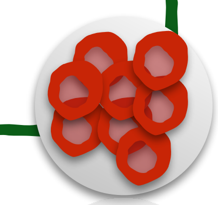
★ Pion-like (dark quark-antiquark)

- ✦ pNGB DM *[Hietanen et al.,1308.4130]*
- ✦ Quirky DM *[Kribs et al.,0909.2034]*
- ✦ Ectocolor DM *[Buckley&Neil,1209.6054]*
- ✦ SIMP *[Hochberg et al.,1411.3727]*
- ✦ Minimal SU(2) *[Lewis, Wed.@11:50]*



★ Glueball-like (only gluons)

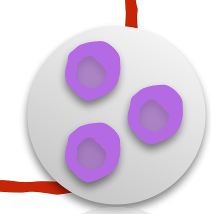
- ✦ SUNonia *[Boddy et al.,1402.3629]* *[Soni, Wed.@11:30]*



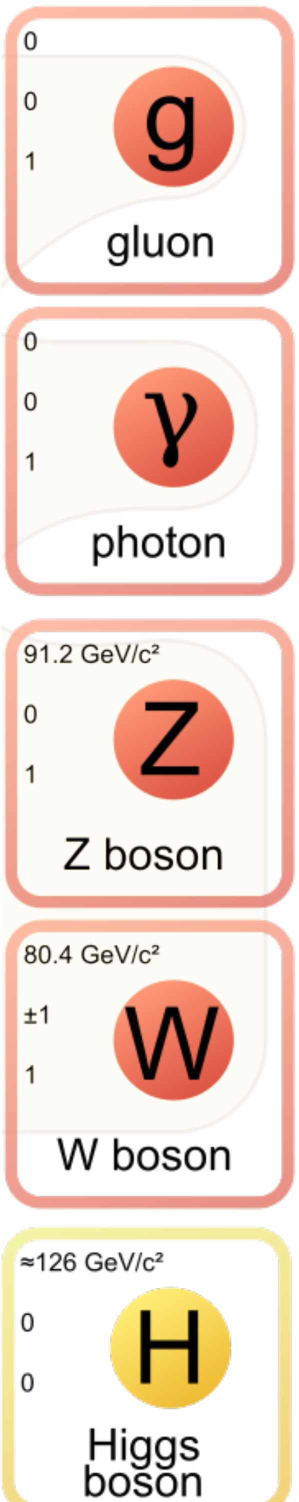
★ Dark Nuclei *[Detmold et al.,1406.2276-1406.4116]*

★ Baryon-like (multiple quarks)

- ✦ “Technibaryons” *[LSD,1301.1693]*
- ✦ Stealth DM *[LSD,1503.04203-1503.04205]*
- ✦ One-family TC *[LatKMI,1510.07373]*
- ✦ Sextet CH *[LatHC,1601.03302][Kuti, Mon.@15:15]*



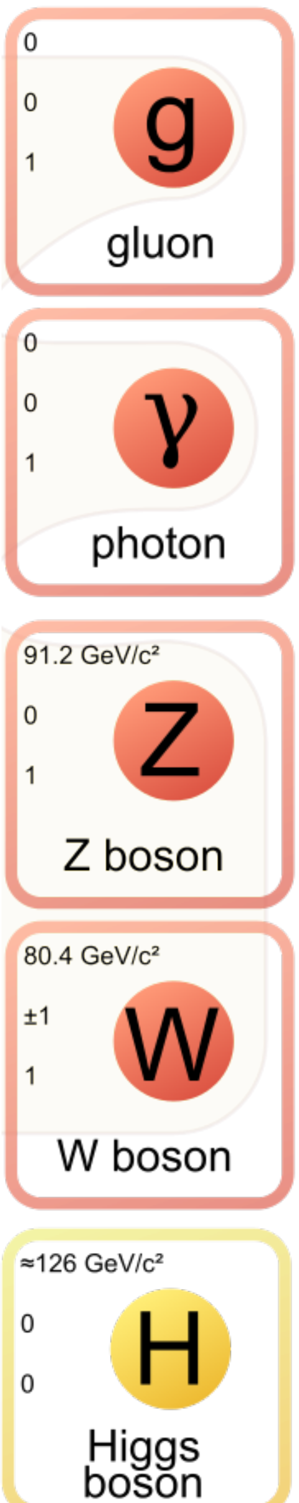
The darkness of Composite Dark Matter



[Wikipedia]

[Bagnasco et al., hep-ph/9310290]

The darkness of Composite Dark Matter



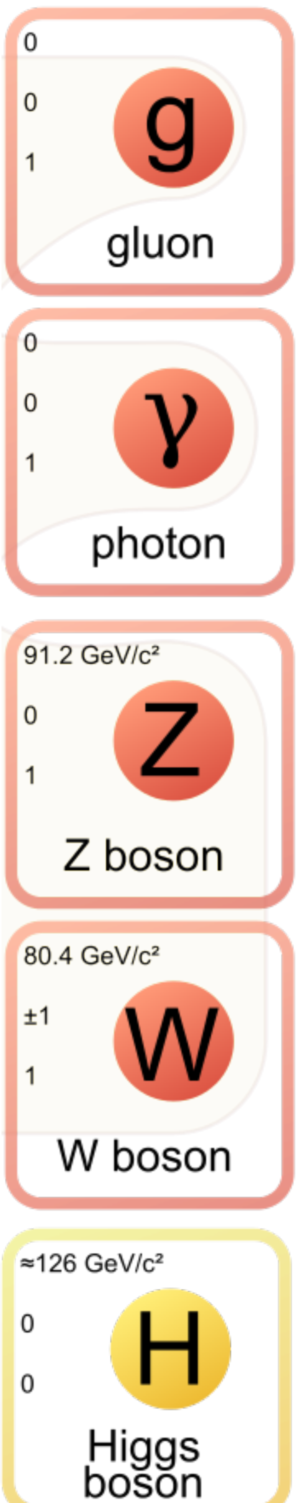
[Wikipedia]

Relevant if the constituents have SM color charges

[Chivukula et al.,hep-ph/9210274] [Godbole et al.,1506.01408] [Bay&Osborne,1506.07110]

[Bagnasco et al., hep-ph/9310290]

The darkness of Composite Dark Matter



[Wikipedia]

Relevant if the constituents have SM color charges

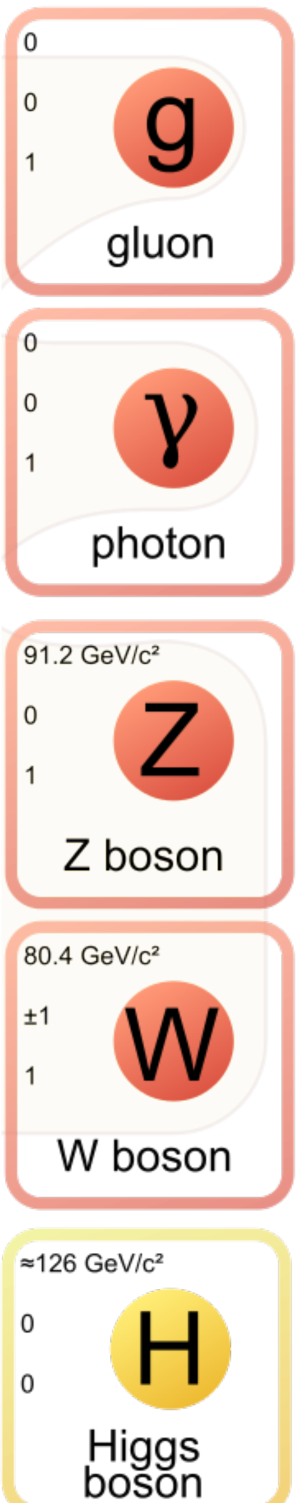
[Chivukula et al.,hep-ph/9210274] [Godbole et al.,1506.01408] [Bay&Osborne,1506.07110]

Lowest dimensional operators:

★ magnetic dipole (5)
★ charge radius (6)
★ polarizability (7)

[Bagnasco et al., hep-ph/9310290]

The darkness of Composite Dark Matter



[Wikipedia]

Relevant if the constituents have SM color charges

[Chivukula et al.,hep-ph/9210274] [Godbole et al.,1506.01408] [Bay&Osborne,1506.07110]

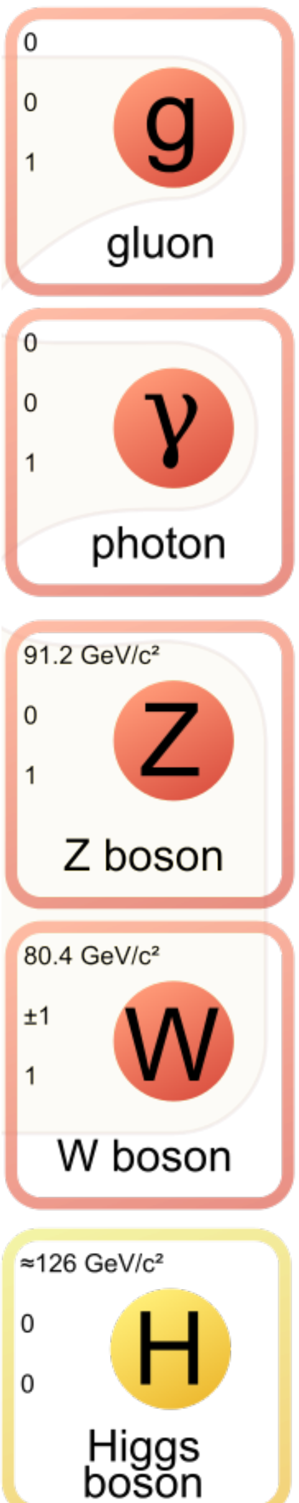
Lowest dimensional operators:

★ magnetic dipole (5)
★ charge radius (6)
★ polarizability (7)

Same as γ but suppressed due to heavy mass

[Bagnasco et al., hep-ph/9310290]

The darkness of Composite Dark Matter



[Wikipedia]

Relevant if the constituents have SM color charges

[Chivukula et al.,hep-ph/9210274] [Godbole et al.,1506.01408] [Bay&Osborne,1506.07110]

Lowest dimensional operators:

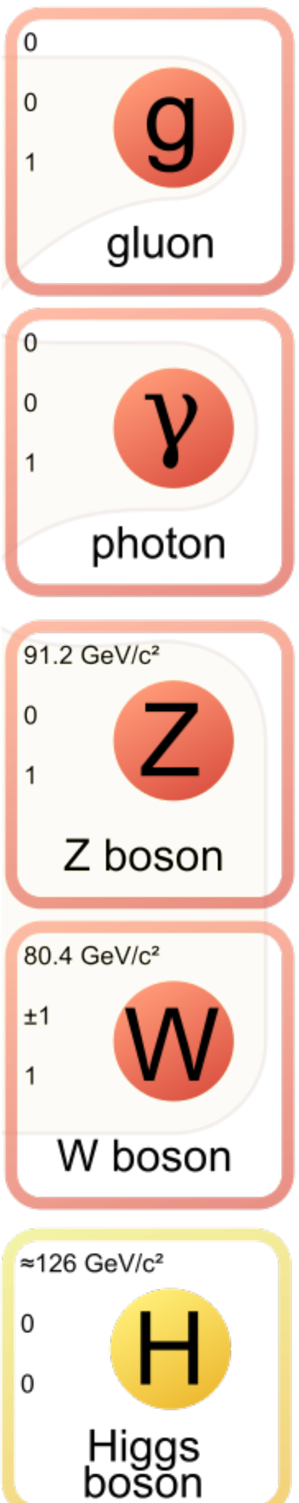
- ★ magnetic dipole (5)
- ★ charge radius (6)
- ★ polarizability (7)

Same as γ but suppressed due to heavy mass

Most relevant interaction if constituents have Yukawa couplings!

[Bagnasco et al., hep-ph/9310290]

The darkness of Composite Dark Matter



[Wikipedia]

Relevant if the constituents have SM color charges

[Chivukula et al.,hep-ph/9210274] [Godbole et al.,1506.01408] [Bay&Osborne,1506.07110]

Lowest dimensional operators:

- ★ magnetic dipole (5)
- ★ charge radius (6)
- ★ polarizability (7)

Same as γ but suppressed due to heavy mass

Most relevant interaction if constituents have Yukawa couplings!

[references in Kribs & Neil, 1604.04627]

★ lattice
★ estimate
■ forbidden

Lattice results for Composite Dark Matter

Template Models	Spectrum	Higgs	Mag. Dip.	Charge r.	Polariz.
SU(2) N_f=1	★		[Talk by Lewis, Wed.@11.50, new simulations are in progress]		
SU(2) N_f=2	★	★		★	★
SU(3) N_f=2,6	★		★	★	
SU(3) N_f=8	★	★			
SU(3) N_f=2 (S)	★	[Talk by Kuti, Mon.@15.15, small component of DM and tree-level interaction with Z boson]			
SU(4) N_f=4	★	★			★
SO(4) N_f=2 (V)	★				
SU(N) N_f=0	★	[Talk by Soni, Wed.@11.30, interested in calculating self-interactions on the lattice]			

[references in Kribs & Neil, 1604.04627]

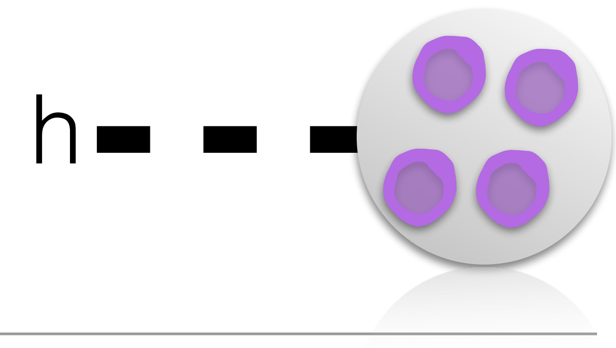
★ lattice
★ estimate
■ forbidden

Lattice results for Composite Dark Matter

Template Models	Spectrum	Higgs	Mag. Dip.	Charge r.	Polariz.
SU(2) N_f=1	lattice	[Talk by Lewis, Wed.@11.50, new simulations are in progress]			
SU(2) N_f=2	lattice	estimate	forbidden **forbidden in pNGB DM**	estimate	lattice
SU(3) N_f=2,6	lattice		lattice	lattice	
SU(3) N_f=8	lattice	estimate			
SU(3) N_f=2 (S)	lattice	[Talk by Kuti, Mon.@15.15, small component of DM and tree-level interaction with Z boson]			
SU(4) N_f=4	lattice	lattice	forbidden	forbidden **forbidden in Stealth DM**	lattice
SO(4) N_f=2 (V)	lattice				
SU(N) N_f=0	lattice	forbidden	forbidden	forbidden **forbidden in SUNonia**	forbidden

[LSD, 1402.6656-1503.04203]
[LatKMI, 1510.07373]
[DeGrand et al., 1501.05665]

Computing Higgs exchange

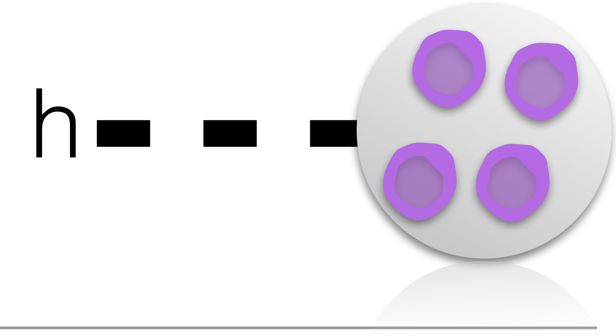


- Need to non-perturbatively evaluate the dark σ-term

$$\mathcal{M}_a = \frac{y_f y_q}{2m_h^2} \sum_f \langle B|\bar{f} f|B\rangle \sum_q \langle a|\bar{q} q|a\rangle$$

[LSD, 1402.6656-1503.04203]
[LatKMI, 1510.07373]
[DeGrand et al., 1501.05665]

Computing Higgs exchange



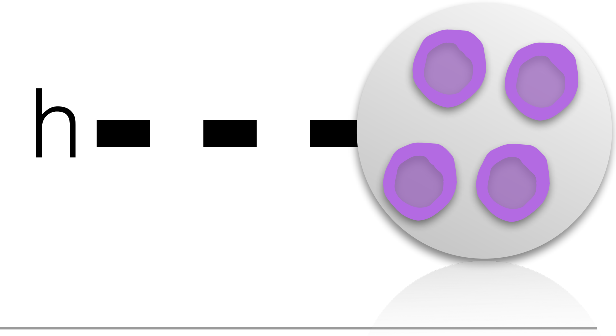
✦ Need to non-perturbatively evaluate the dark σ-term

$$\mathcal{M}_a = \boxed{\frac{y_f y_q}{2m_h^2}} \sum_f \boxed{\langle B|\bar{f} f|B\rangle} \sum_q \boxed{\langle a|\bar{q} q|a\rangle}$$

1. effective Higgs coupling with dark fermions and quark Yukawa coupling
2. dark baryon scalar form factor: need lattice input for generic DM models!
3. nucleon scalar form factor: ChPT and lattice input [Plenary talk by Collins, Tue@10:15]

[LSD, 1402.6656-1503.04203]
[LatKMI, 1510.07373]
[DeGrand et al., 1501.05665]

Computing Higgs exchange



- Need to non-perturbatively evaluate the dark σ-term
- Effective Higgs coupling non-trivial with mixed chiral and vector-like masses

$$\mathcal{M}_a = \boxed{\frac{y_f y_q}{2m_h^2}} \sum_f \boxed{\langle B|\bar{f}f|B\rangle} \sum_q \boxed{\langle a|\bar{q}q|a\rangle}$$

1. effective Higgs coupling with dark fermions and quark Yukawa coupling
2. dark baryon scalar form factor: need lattice input for generic DM models!
3. nucleon scalar form factor: ChPT and lattice input [Plenary talk by Collins, Tue@10:15]

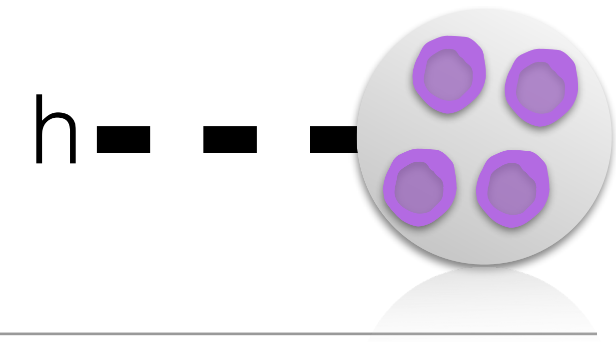
$$\boxed{y_f}\boxed{\langle B|\bar{f}f|B\rangle} = \frac{m_B}{v} \sum_f \frac{v}{m_f} \frac{\partial m_f(h)}{\partial h}\bigg|_{h=v} f_f^{(B)}$$

$$m_f(h) = m + \frac{y_f h}{\sqrt{2}}$$

$$\alpha \equiv \frac{v}{m_f} \frac{\partial m_f(h)}{\partial h}\bigg|_{h=v} = \frac{yv}{\sqrt{2}m + yv}$$

[LSD, 1402.6656-1503.04203]
[LatKMI, 1510.07373]
[DeGrand et al., 1501.05665]

Computing Higgs exchange



- Need to non-perturbatively evaluate the dark σ-term
- Effective Higgs coupling non-trivial with mixed chiral and vector-like masses
- Model-dependent answer for the cross-section

$$\mathcal{M}_a = \boxed{\frac{y_f y_q}{2m_h^2}} \sum_f \boxed{\langle B|\bar{f}f|B\rangle} \sum_q \boxed{\langle a|\bar{q}q|a\rangle}$$

1. effective Higgs coupling with dark fermions and quark Yukawa coupling
2. dark baryon scalar form factor: need lattice input for generic DM models!
3. nucleon scalar form factor: ChPT and lattice input [Plenary talk by Collins, Tue@10:15]

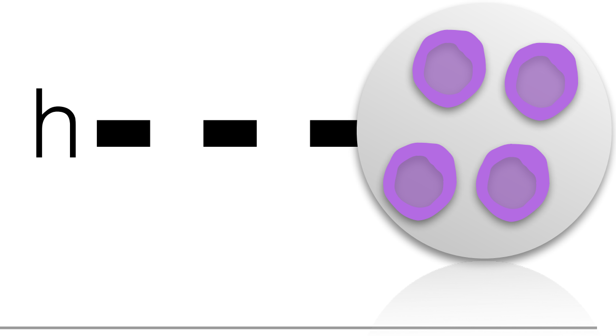
$$\boxed{y_f}\boxed{\langle B|\bar{f}f|B\rangle} = \frac{m_B}{v} \sum_f \boxed{\frac{v}{m_f} \frac{\partial m_f(h)}{\partial h}\bigg|_{h=v}} f_f^{(B)}$$

$$m_f(h) = m + \frac{y_f h}{\sqrt{2}}$$

$$\alpha \equiv \frac{v}{m_f} \frac{\partial m_f(h)}{\partial h}\bigg|_{h=v} = \frac{yv}{\sqrt{2}m + yv}$$

[LSD, 1402.6656-1503.04203]
[LatKMI, 1510.07373]
[DeGrand et al., 1501.05665]

Computing Higgs exchange



- Need to non-perturbatively evaluate the dark σ-term
- Effective Higgs coupling non-trivial with mixed chiral and vector-like masses
- Model-dependent answer for the cross-section
- **Lattice input** is necessary: compute mass and form factor

$$\mathcal{M}_a = \frac{y_f y_q}{2m_h^2} \sum_f \langle B|\bar{f} f|B\rangle \sum_q \langle a|\bar{q} q|a\rangle$$

1. effective Higgs coupling with dark fermions and quark Yukawa coupling
2. dark baryon scalar form factor: need lattice input for generic DM models!
3. nucleon scalar form factor: ChPT and lattice input [Plenary talk by Collins, Tue@10:15]

$$y_f \langle B|\bar{f} f|B\rangle = \frac{m_B}{v} \sum_f \frac{v}{m_f} \frac{\partial m_f(h)}{\partial h}\Big|_{h=v} f_f^{(B)}$$

Lattice!

$$m_f(h) = m + \frac{y_f h}{\sqrt{2}}$$

$$\alpha \equiv \frac{v}{m_f} \frac{\partial m_f(h)}{\partial h}\Big|_{h=v} = \frac{yv}{\sqrt{2}m + yv}$$

Bounds from Higgs exchange

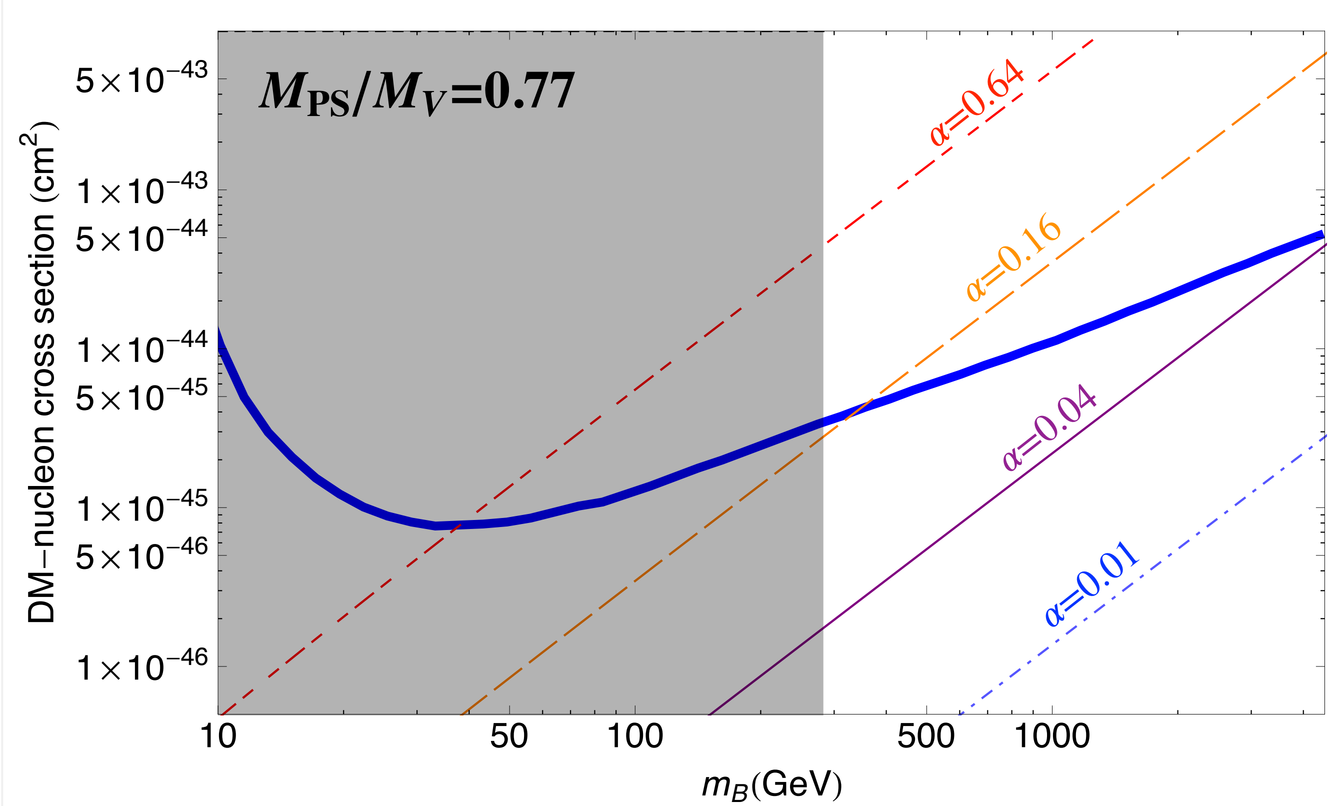
h

✦Lattice results for the cross-section are compared to **experimental** bounds

✦Coupling space in specific models can be vastly constrained

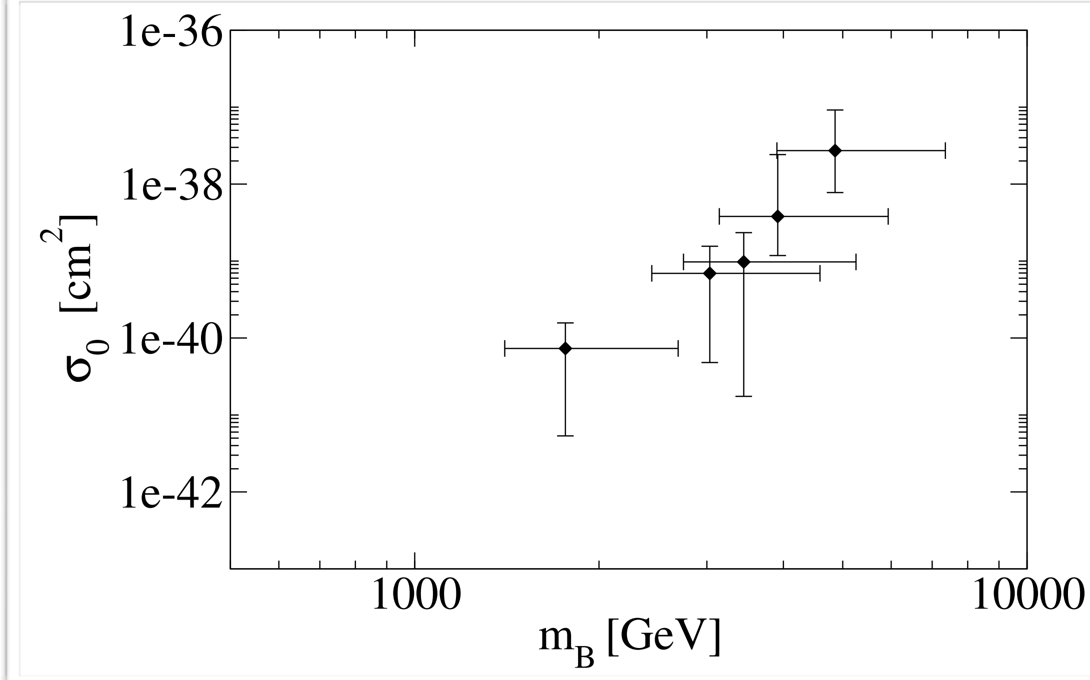
SU(4) N_f=4 Stealth DM

[LSD, 1402.6656-1503.04203]



SU(3) N_f=8 "technibaryon"

[LatKMI, 1510.07373]

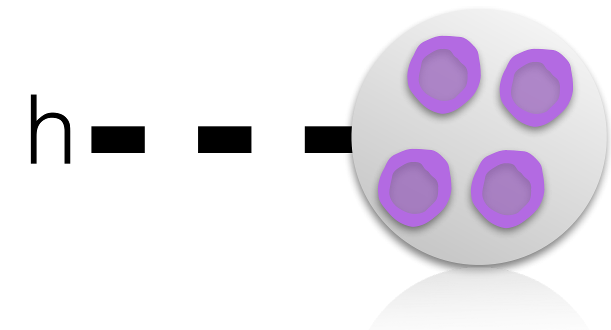


✦Some candidates can be excluded as dominant sources of dark matter

✦There is lattice evidence for universality of dark scalar form factors

[DeGrand et al., 1501.05665]

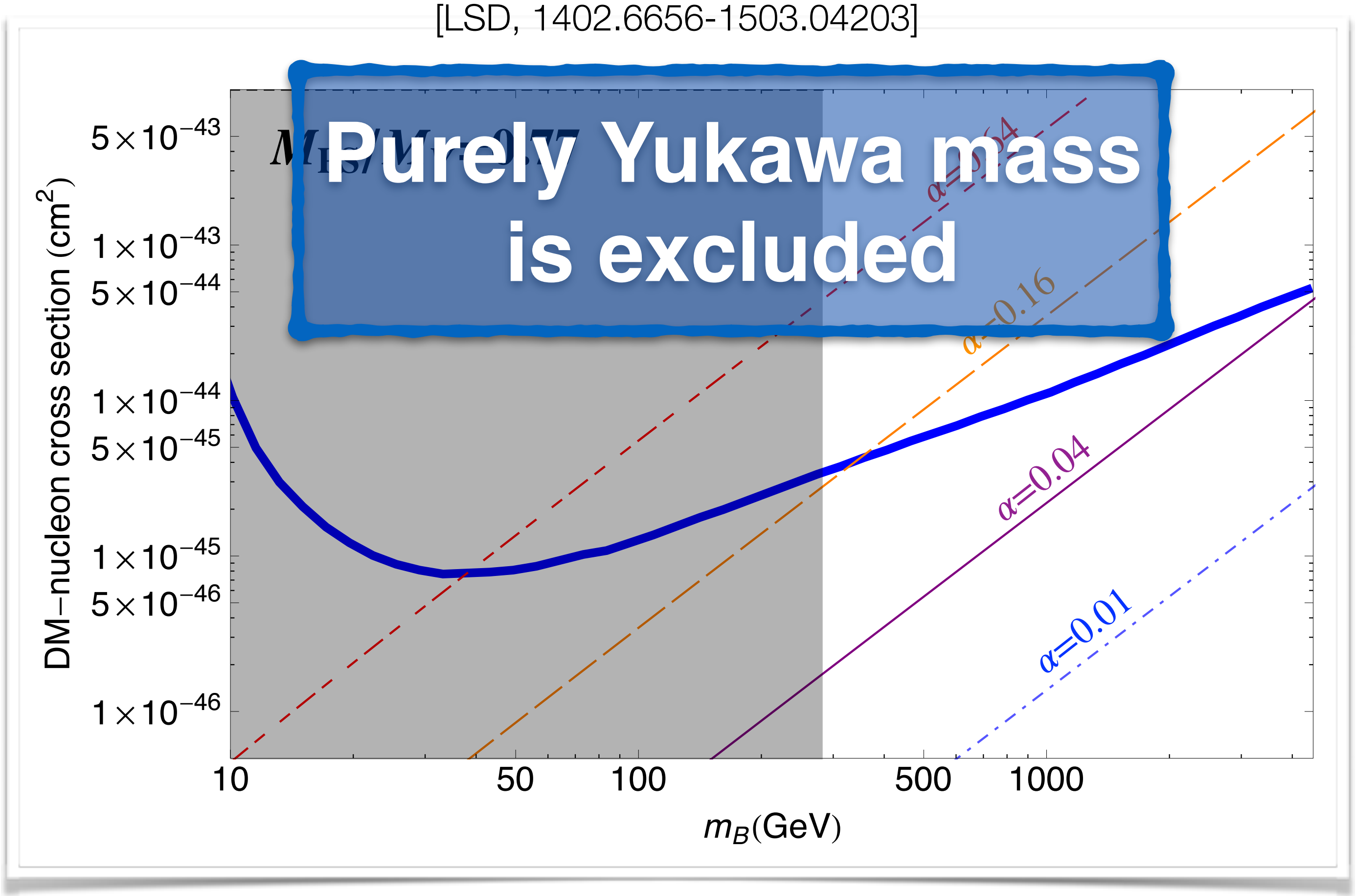
Bounds from Higgs exchange



- ✦Lattice results for the cross-section are compared to **experimental** bounds
- ✦Coupling space in specific models can be vastly constrained

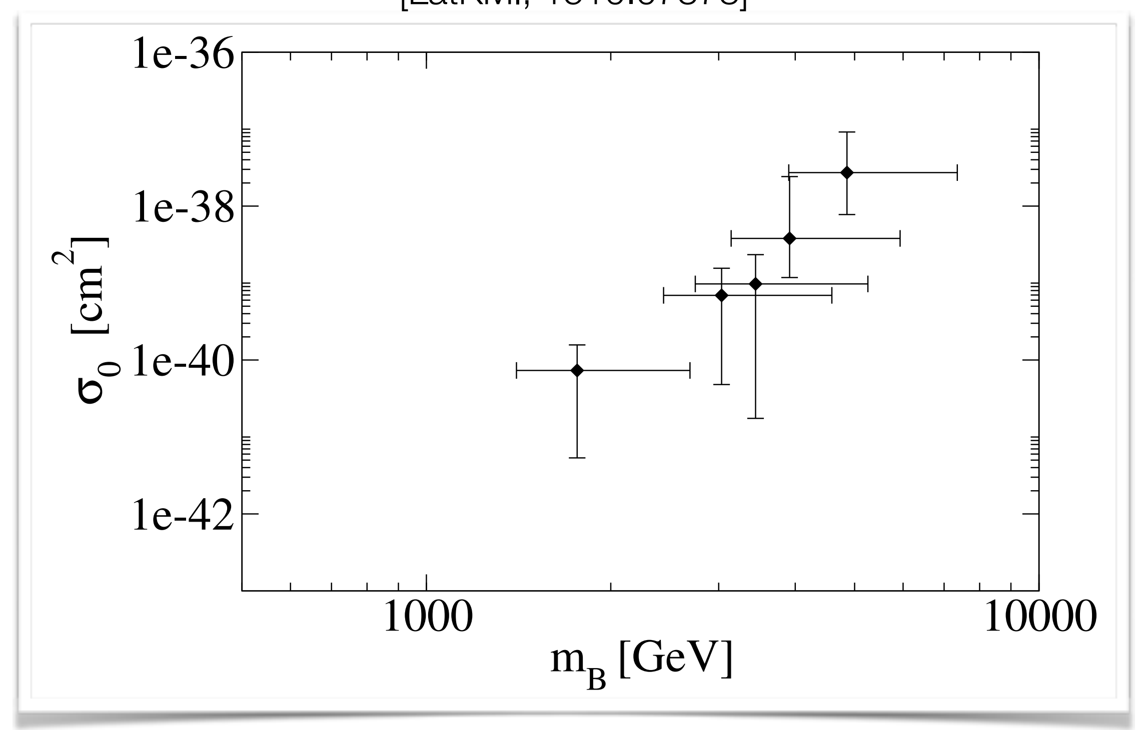
SU(4) N_f=4 Stealth DM

[LSD, 1402.6656-1503.04203]



SU(3) N_f=8 “technibaryon”

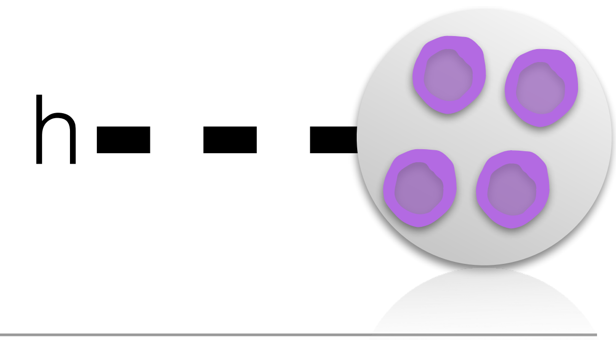
[LatKMI, 1510.07373]



- ✦Some candidates can be excluded as dominant sources of dark matter
- ✦There is lattice evidence for universality of dark scalar form factors

[DeGrand et al., 1501.05665]

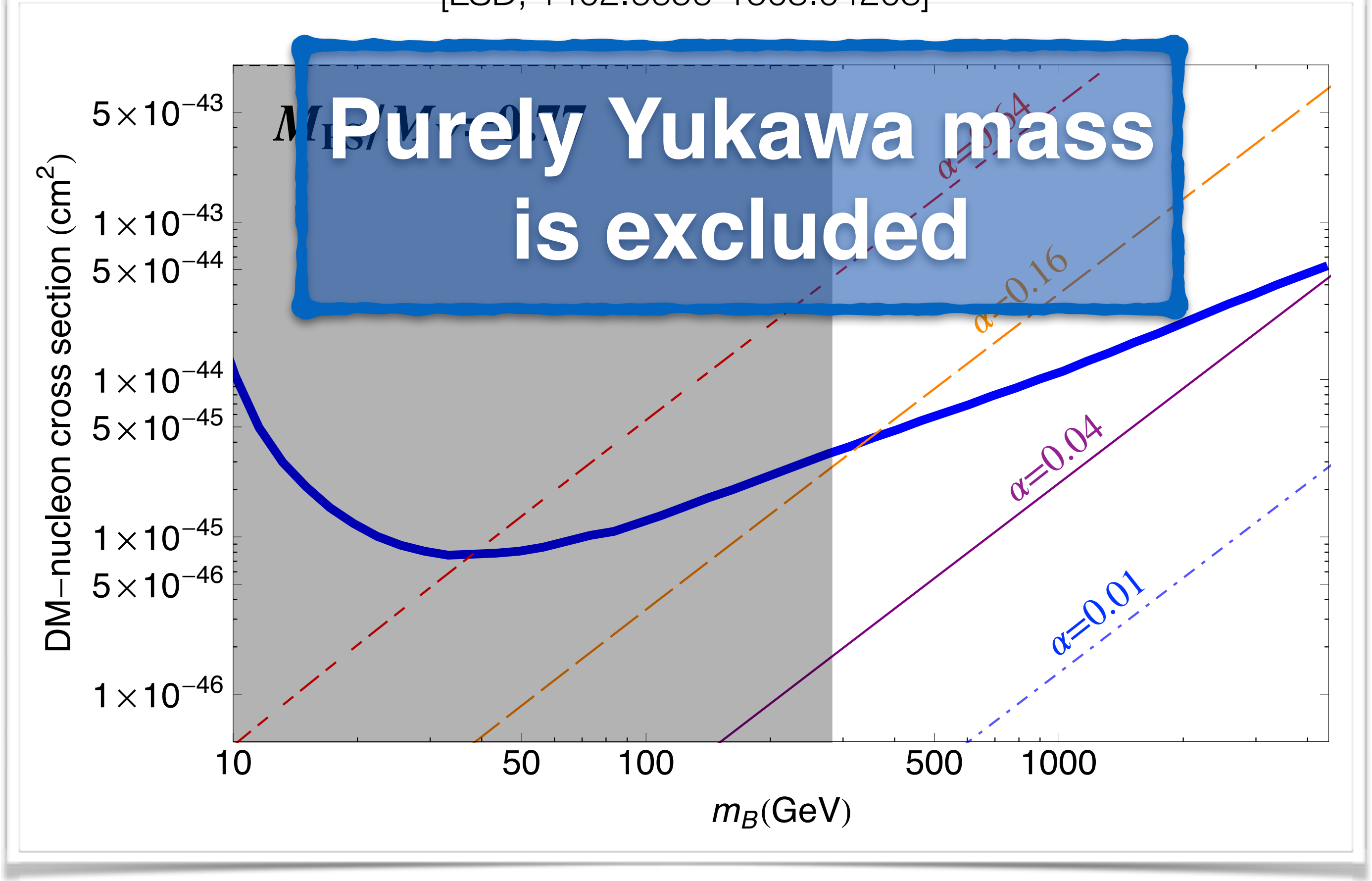
Bounds from Higgs exchange



- ✦Lattice results for the cross-section are compared to **experimental** bounds
- ✦Coupling space in specific models can be vastly constrained

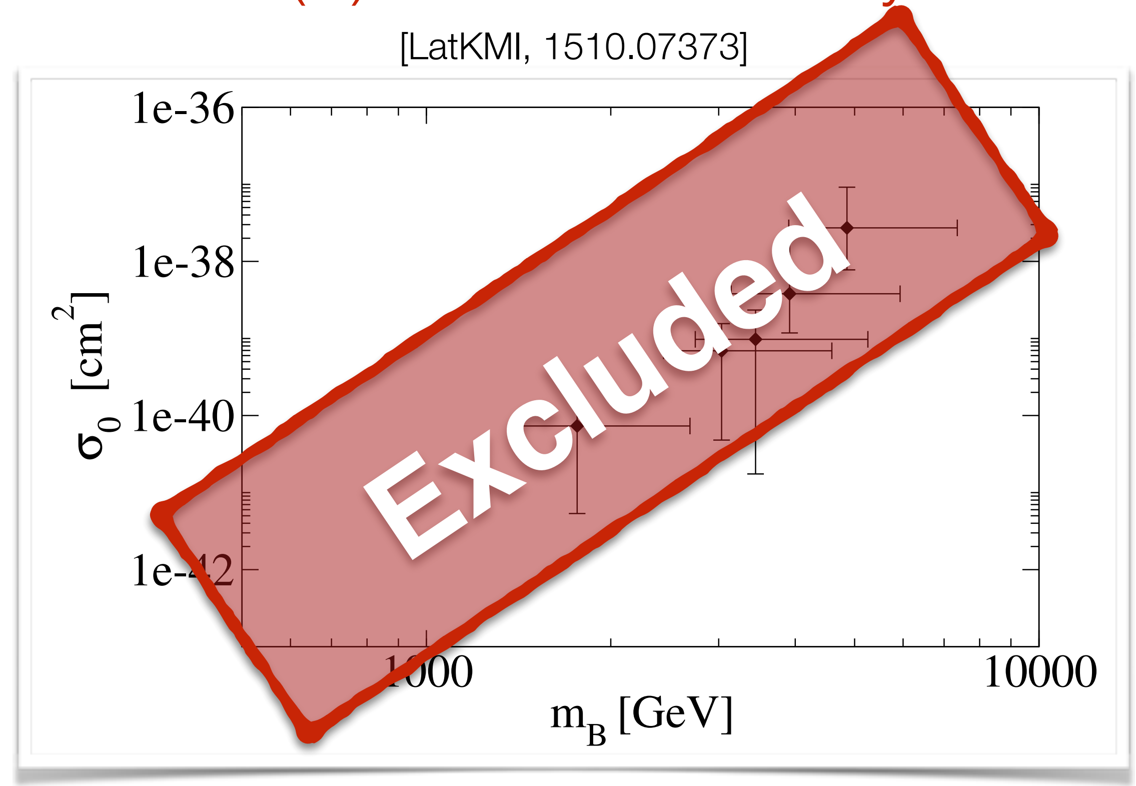
SU(4) N_f=4 Stealth DM

[LSD, 1402.6656-1503.04203]



SU(3) N_f=8 “technibaryon”

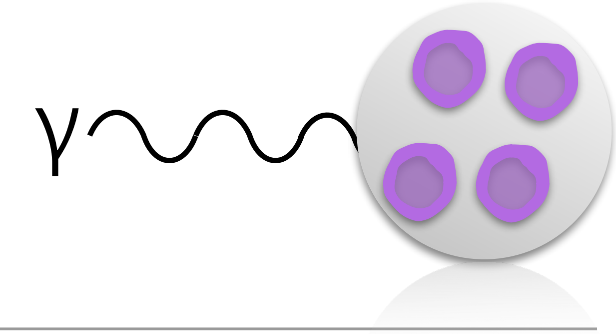
[LatKMI, 1510.07373]



- ✦Some candidates can be excluded as dominant sources of dark matter
- ✦There is lattice evidence for universality of dark scalar form factors

[DeGrand et al., 1501.05665]

[Plenary talk by Collins, Tue@10:15]

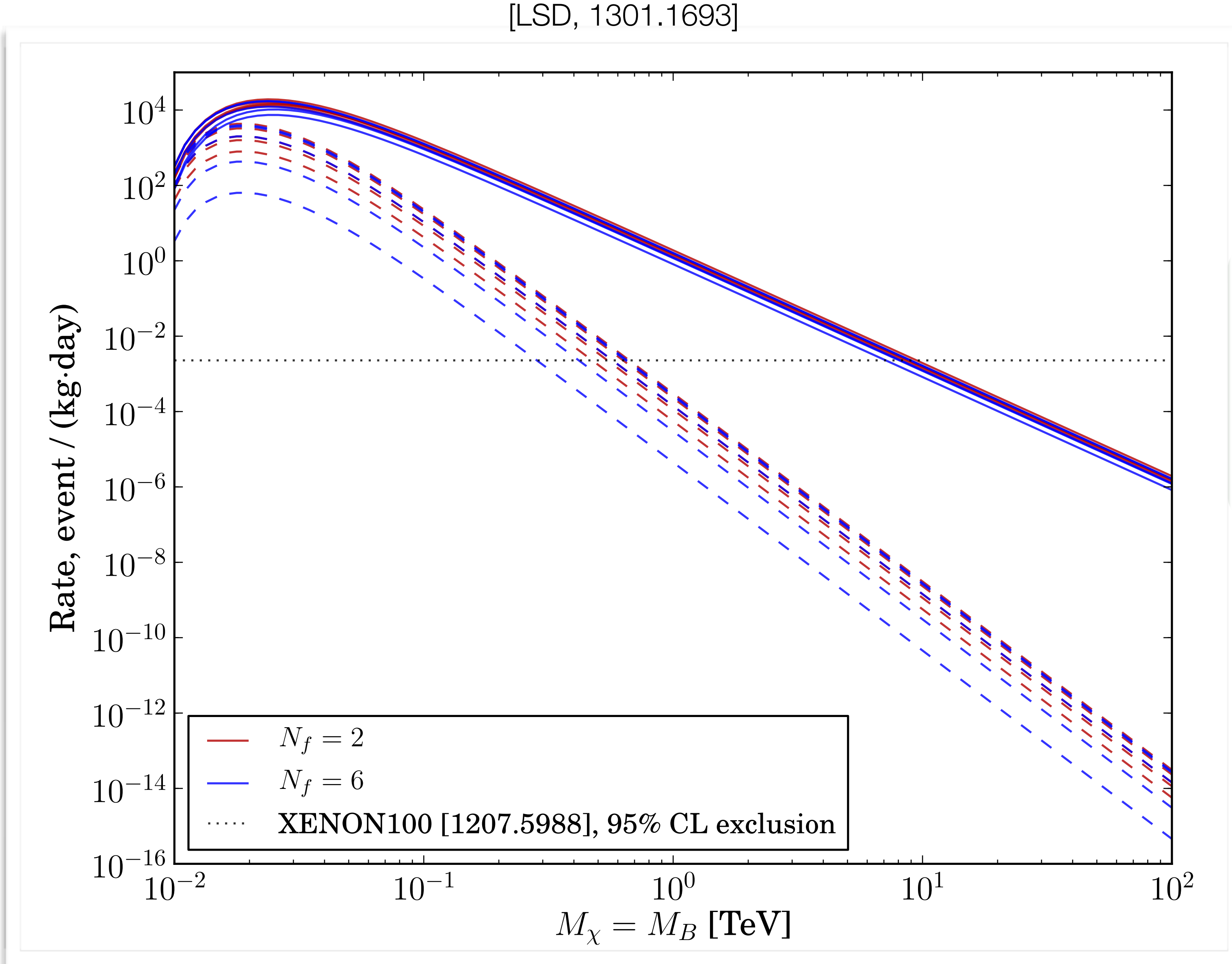


Bounds from EM moments

Mesonic and Baryonic EM form factors directly from lattice simulations

SU(3) N_f=2,6 dark fermionic baryon

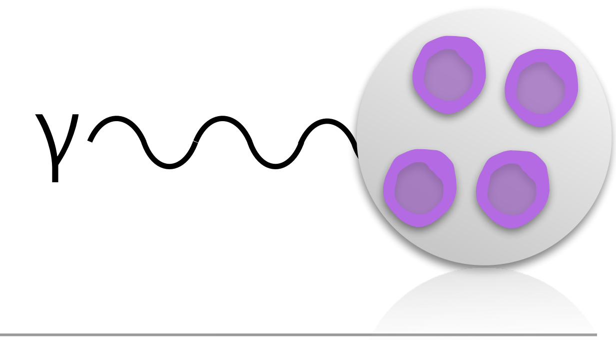
[LSD, 1301.1693]



- ★ baryon similar to QCD neutron
- ★ dark quarks with Q=Y
- ★ calculate connected 3pt
- ★ scale set by DM mass
- ★ magnetic moment dominates
- ★ results independent of N_f

[Plenary talk by Collins, Tue@10:15]

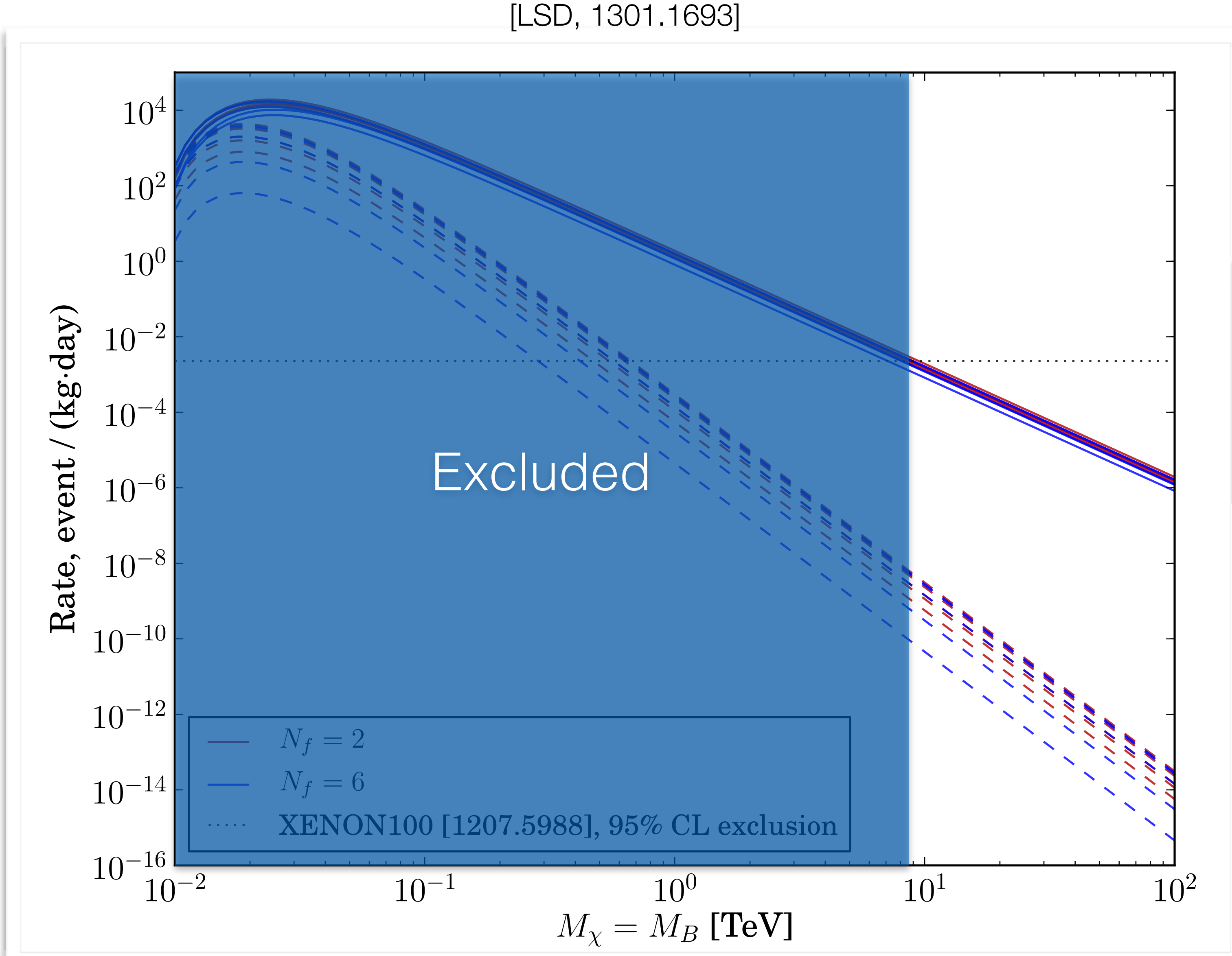
Bounds from EM moments



Mesonic and Baryonic EM form factors directly from lattice simulations

SU(3) N_f=2,6 dark fermionic baryon

[LSD, 1301.1693]

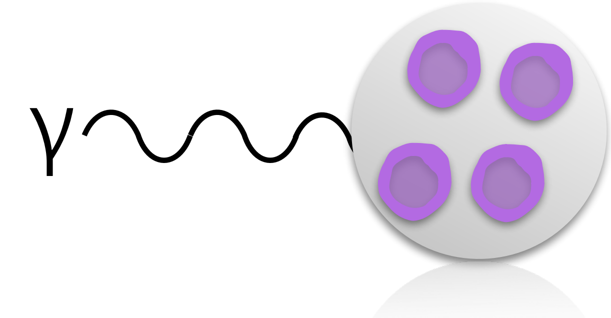


- ★ baryon similar to QCD neutron
- ★ dark quarks with Q=Y
- ★ calculate connected 3pt
- ★ scale set by DM mass
- ★ magnetic moment dominates
- ★ results independent of N_f

M_B >~ 10 TeV

[Plenary talk by Collins, Tue@10:15]

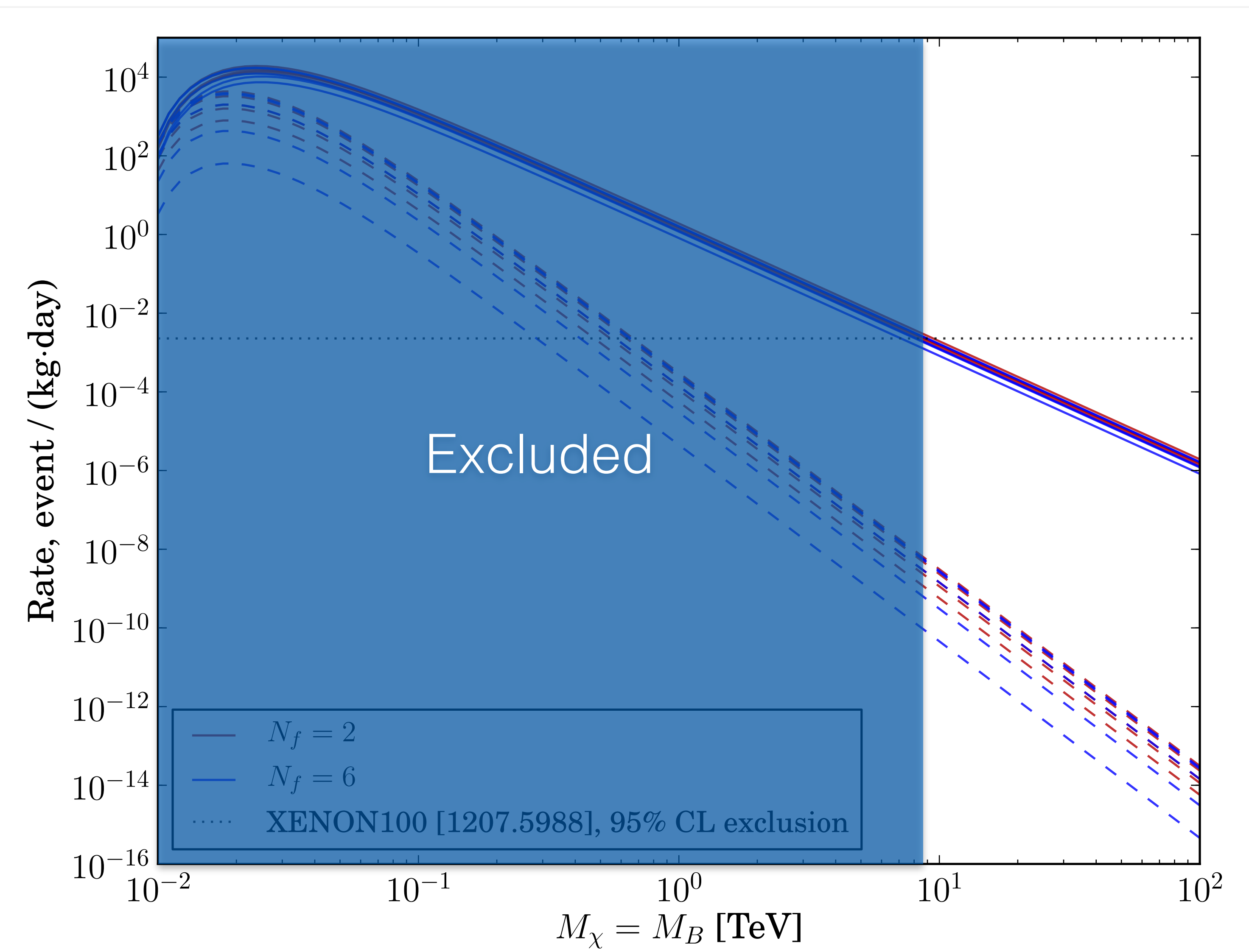
Bounds from EM moments



Mesonic and Baryonic EM form factors directly from lattice simulations

SU(3) N_f=2,6 dark fermionic baryon

[LSD, 1301.1693]



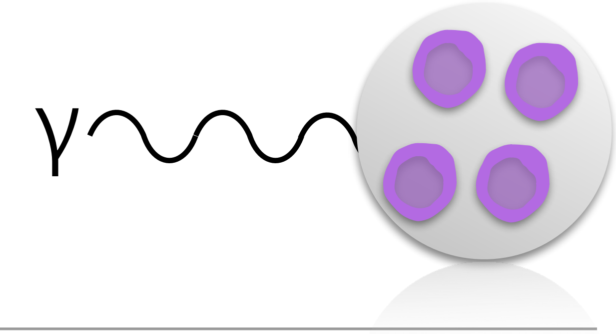
- ★ baryon similar to QCD neutron
- ★ dark quarks with Q=Y
- ★ calculate connected 3pt
- ★ scale set by DM mass
- ★ magnetic moment dominates
- ★ results independent of N_f

M_B >~ 10 TeV

pushed to ~100 TeV with new LUX

[Plenary talk by Collins, Tue@10:15]
[Plenary talk by Pica, Sat@09:00]

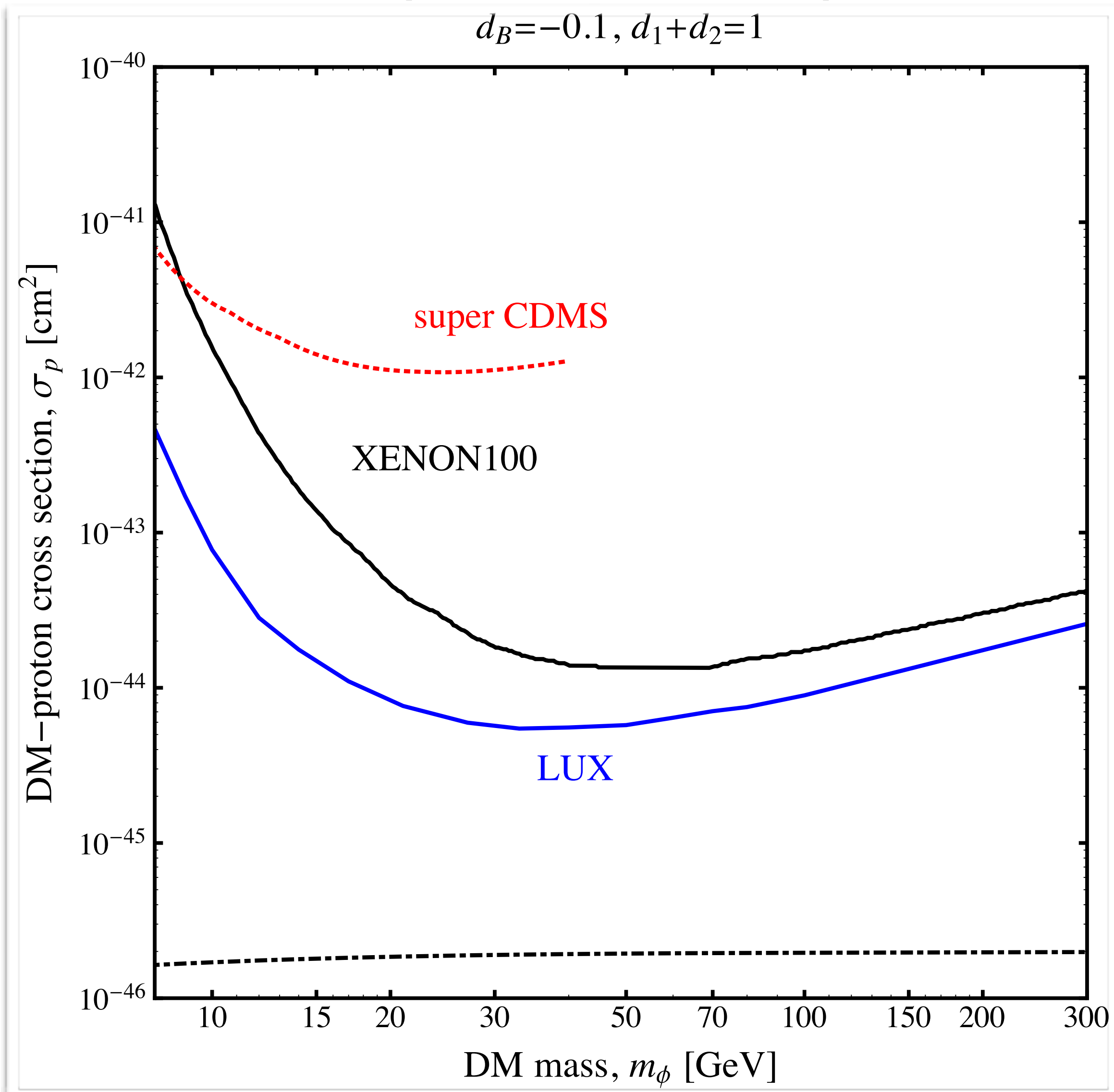
Bounds from EM moments



Mesonic and Baryonic EM form factors directly from lattice simulations

SU(2) N_f=2 pNGB DM

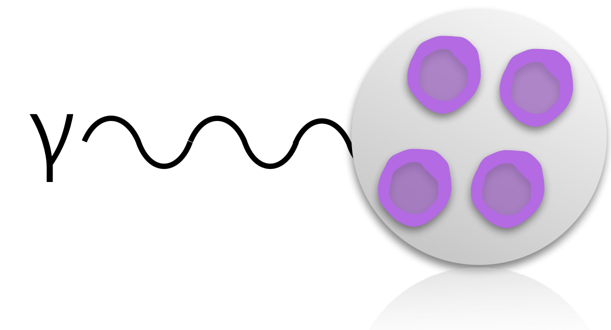
[Hietanen et al., 1308.4130]



- ★ dm is “mesonic” pNGB
- ★ calculate connected 3pt
- ★ use VMD with lattice ρ mass
- ★ scale set by F_π=256 GeV
- ★ depends on isospin breaking d_B
- ★ also couples to Higgs (d_1+d_2)

[Plenary talk by Collins, Tue@10:15]
[Plenary talk by Pica, Sat@09:00]

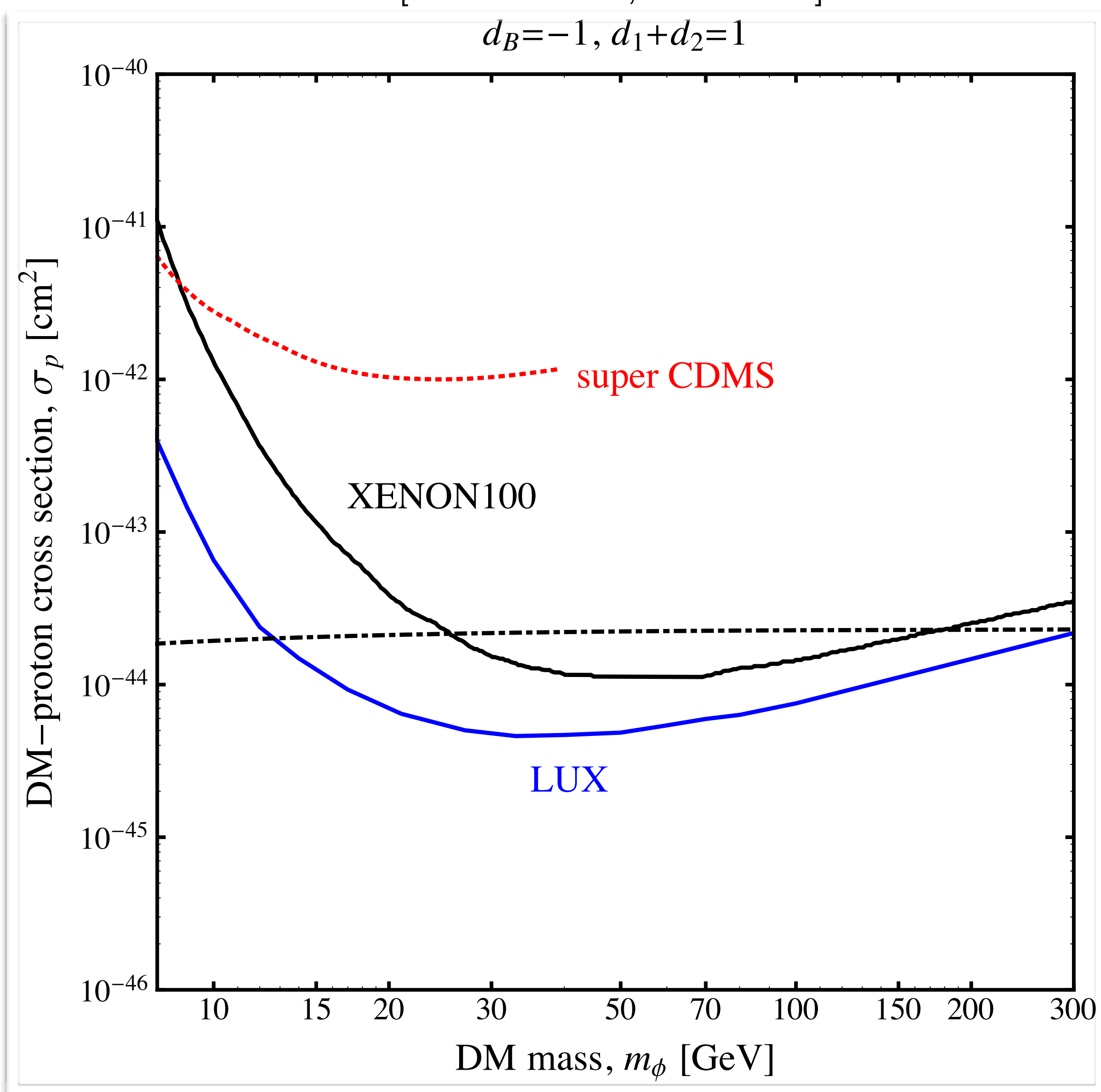
Bounds from EM moments



Mesonic and Baryonic EM form factors directly from lattice simulations

SU(2) N_f=2 pNGB DM

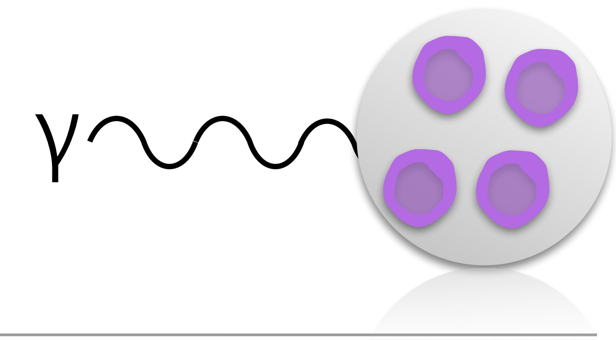
[Hietanen et al., 1308.4130]



- ★ dm is "mesonic" pNGB
- ★ calculate connected 3pt
- ★ use VMD with lattice ρ mass
- ★ scale set by F_π=256 GeV
- ★ depends on isospin breaking d_B
- ★ also couples to Higgs (d_1+d_2)

[Plenary talk by Collins, Tue@10:15]
[Plenary talk by Pica, Sat@09:00]

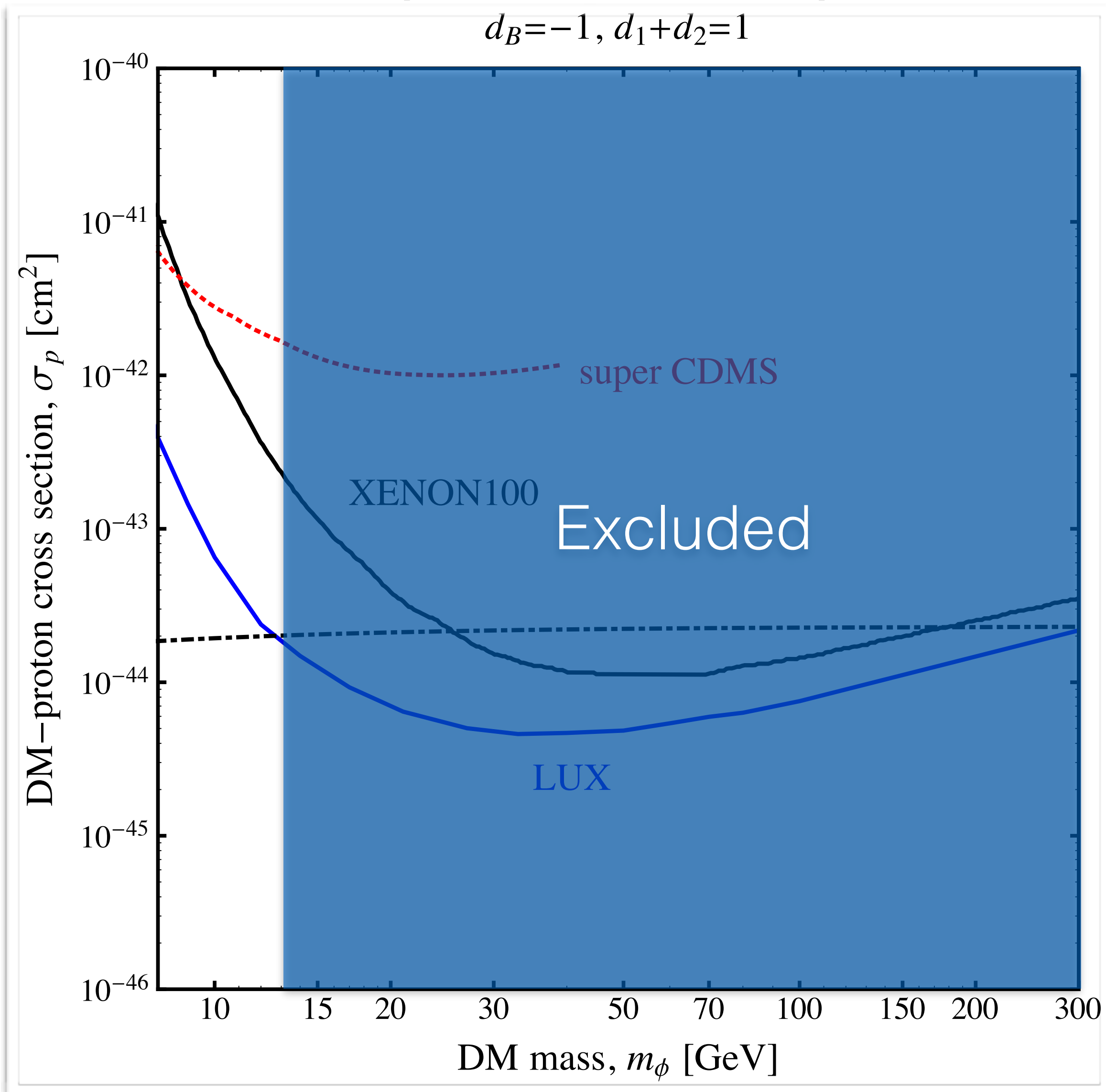
Bounds from EM moments



Mesonic and Baryonic EM form factors directly from lattice simulations

SU(2) N_f=2 pNGB DM

[Hietanen et al., 1308.4130]

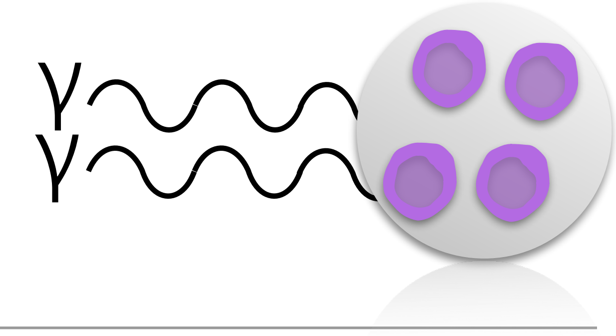


- ★ dm is "mesonic" pNGB
- ★ calculate connected 3pt
- ★ use VMD with lattice ρ mass
- ★ scale set by F_π=256 GeV
- ★ depends on isospin breaking d_B
- ★ also couples to Higgs (d_1+d_2)

M_B ~< 13 GeV
depends on d_B

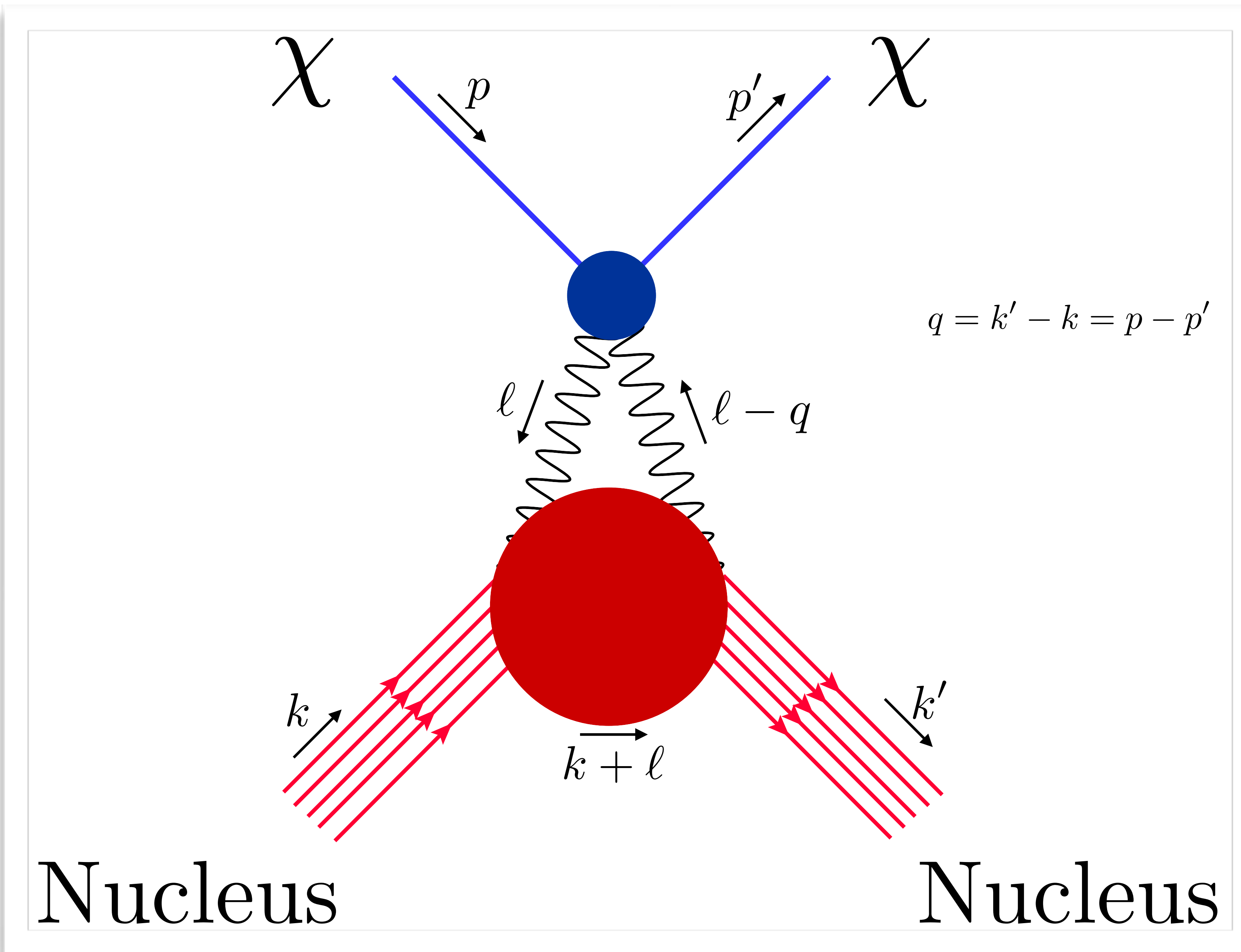
[Pospelov & Veldhuis, hep-ph/0003010] [Ovanesyan & Vecchi, 1410.0601] [Weiner & Yavin,1206.2910] [Frandsen et al., 1207.3971]

[Detmold et al., 0904.1586-1001.1131]



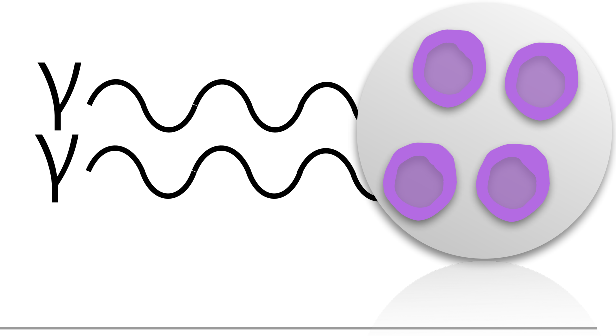
Computing polarizability

$$\boxed{\frac{c_F e^2}{m_\chi^3}\chi^\star\chi F^{\mu\alpha}F^{\nu}_{\alpha}v_\mu v_\nu}$$



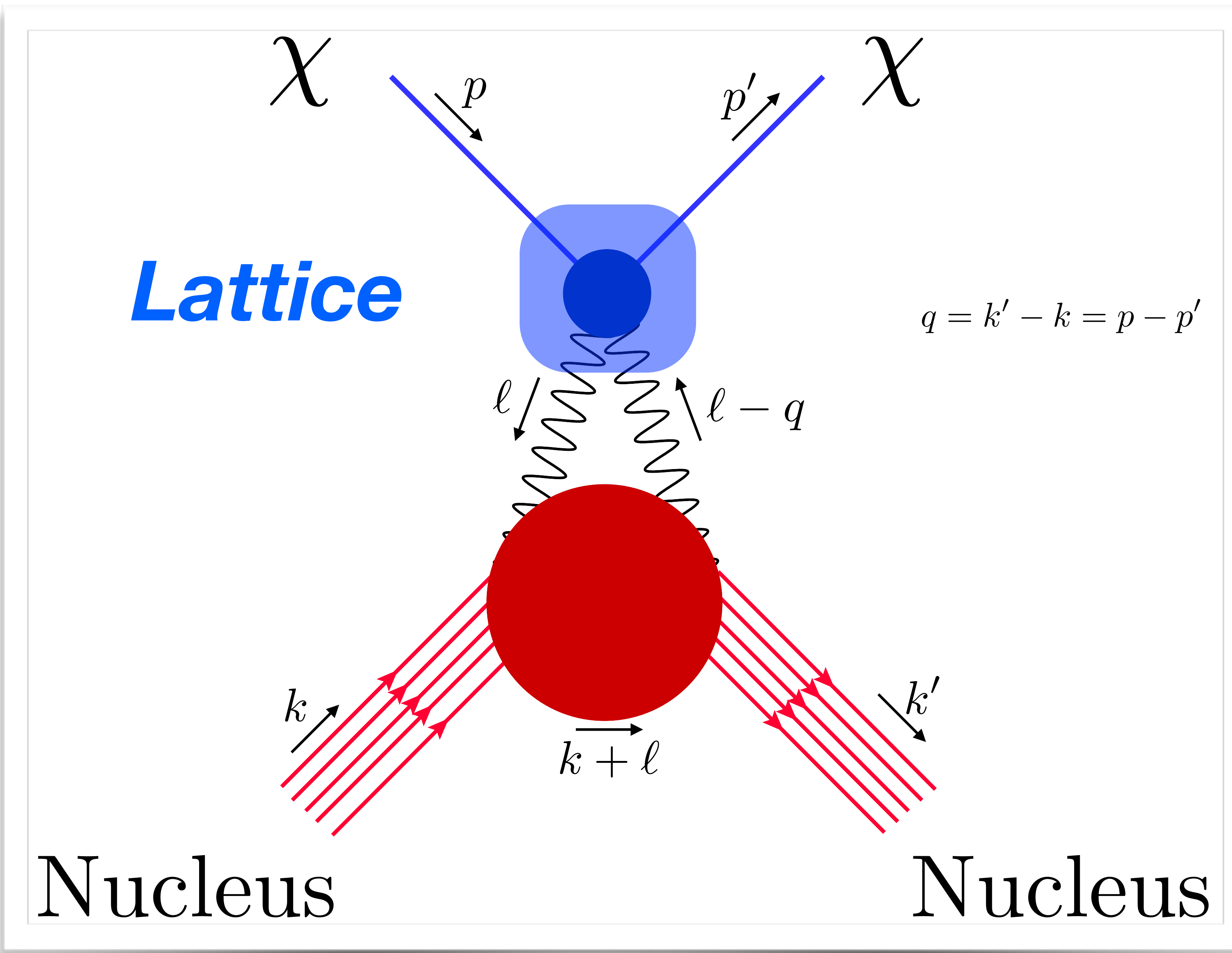
[Pospelov & Veldhuis, hep-ph/0003010] [Ovanesyan & Vecchi, 1410.0601] [Detmold et al., 0904.1586-1001.1131]

[Weiner & Yavin,1206.2910] [Frandsen et al., 1207.3971]



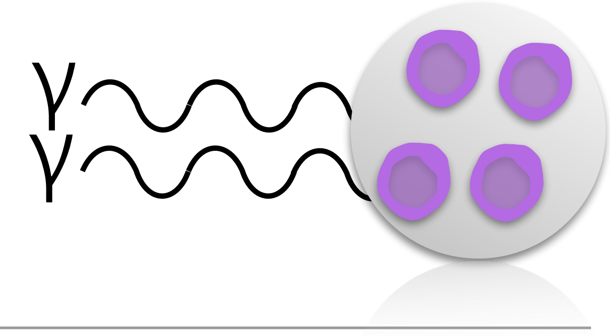
Computing polarizability

$$\boxed{\frac{c_F e^2}{m_\chi^3}\chi^\star\chi F^{\mu\alpha}F^{\nu}_{\alpha}v_\mu v_\nu}$$



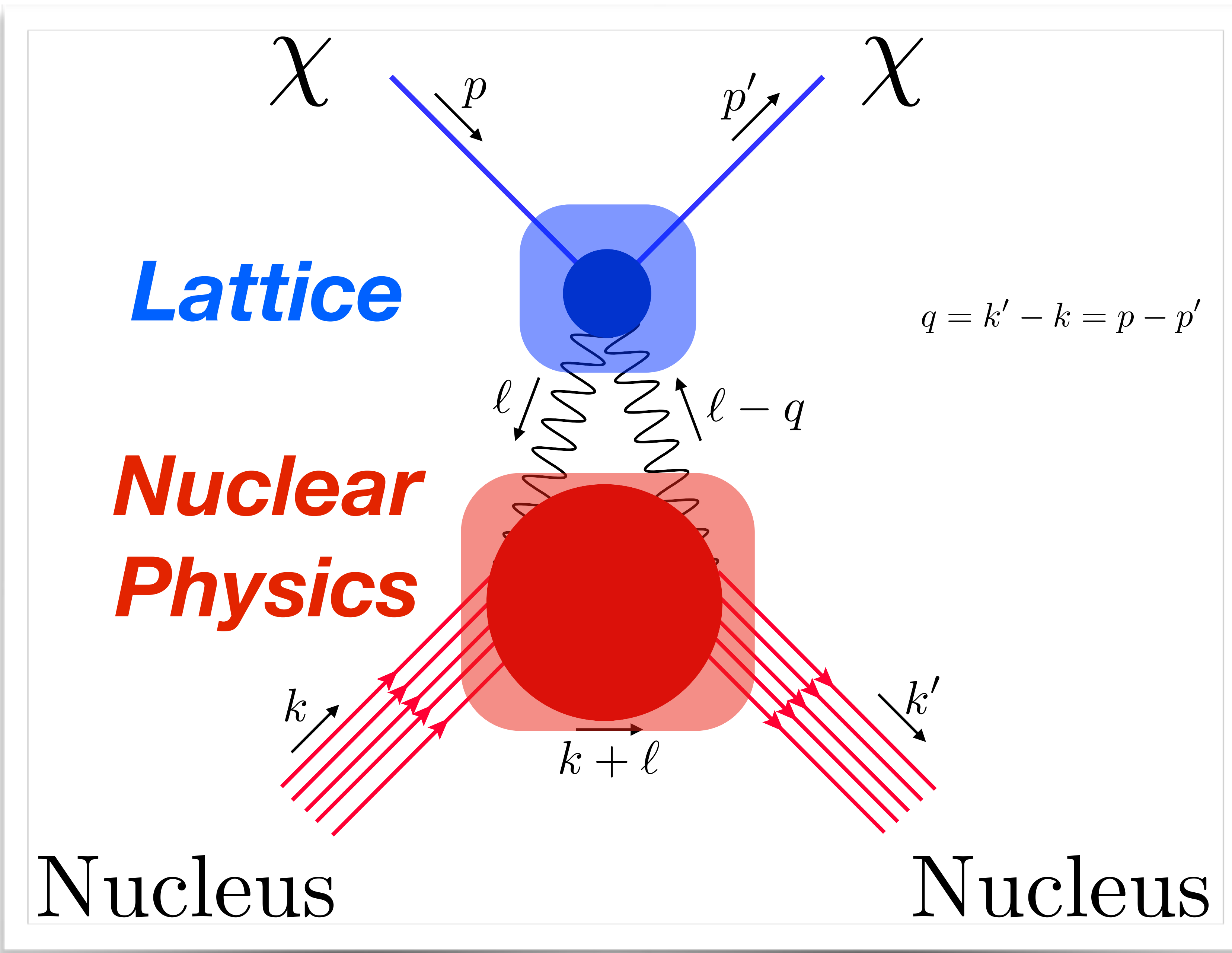
[Pospelov & Veldhuis, hep-ph/0003010] [Ovanesyan & Vecchi, 1410.0601] [Weiner & Yavin,1206.2910] [Frandsen et al., 1207.3971]

[Detmold et al., 0904.1586-1001.1131]

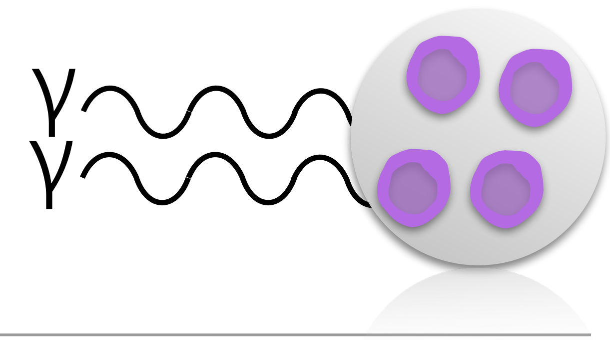


Computing polarizability

$$\frac{c_F e^2}{m_\chi^3}\chi^\star\chi F^{\mu\alpha}F^\nu_\alpha v_\mu v_\nu$$

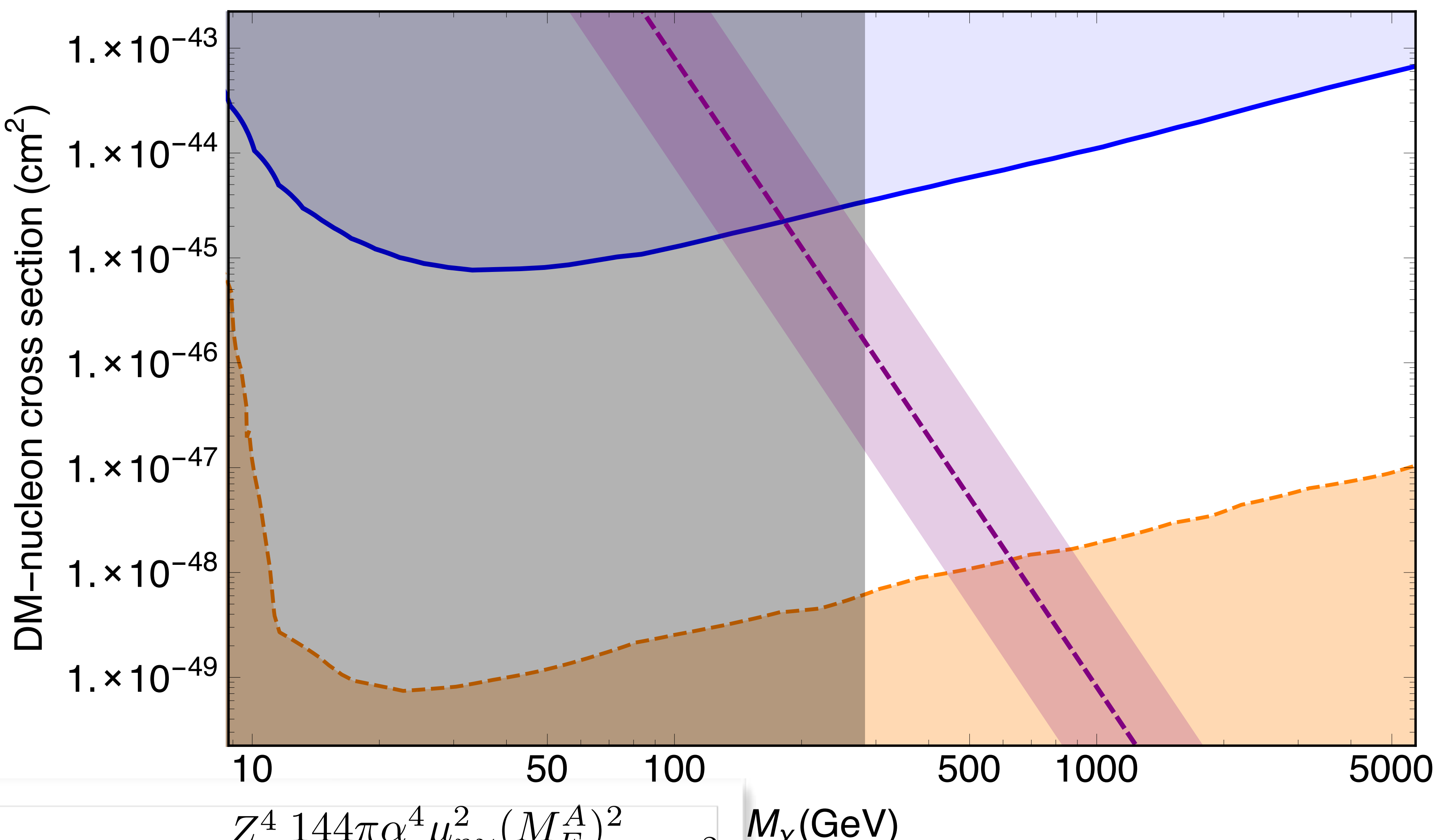


[see also Drach et al.,1511.04370 for SU(2) N_f=2]



Lowest bound from EM polarizability

Electric polarizability from lattice simulations with background fields



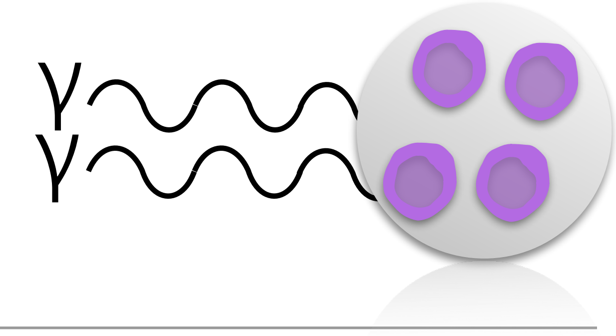
SU(4) N_f=4 Stealth DM

[LSD, 1503.04205]

$$\sigma_{\text{nucleon}}(Z,A) = \frac{Z^4}{A^2}\frac{144\pi\alpha^4\mu_{n\chi}^2(M_F^A)^2}{m_\chi^6 R^2}[c_F]^2$$

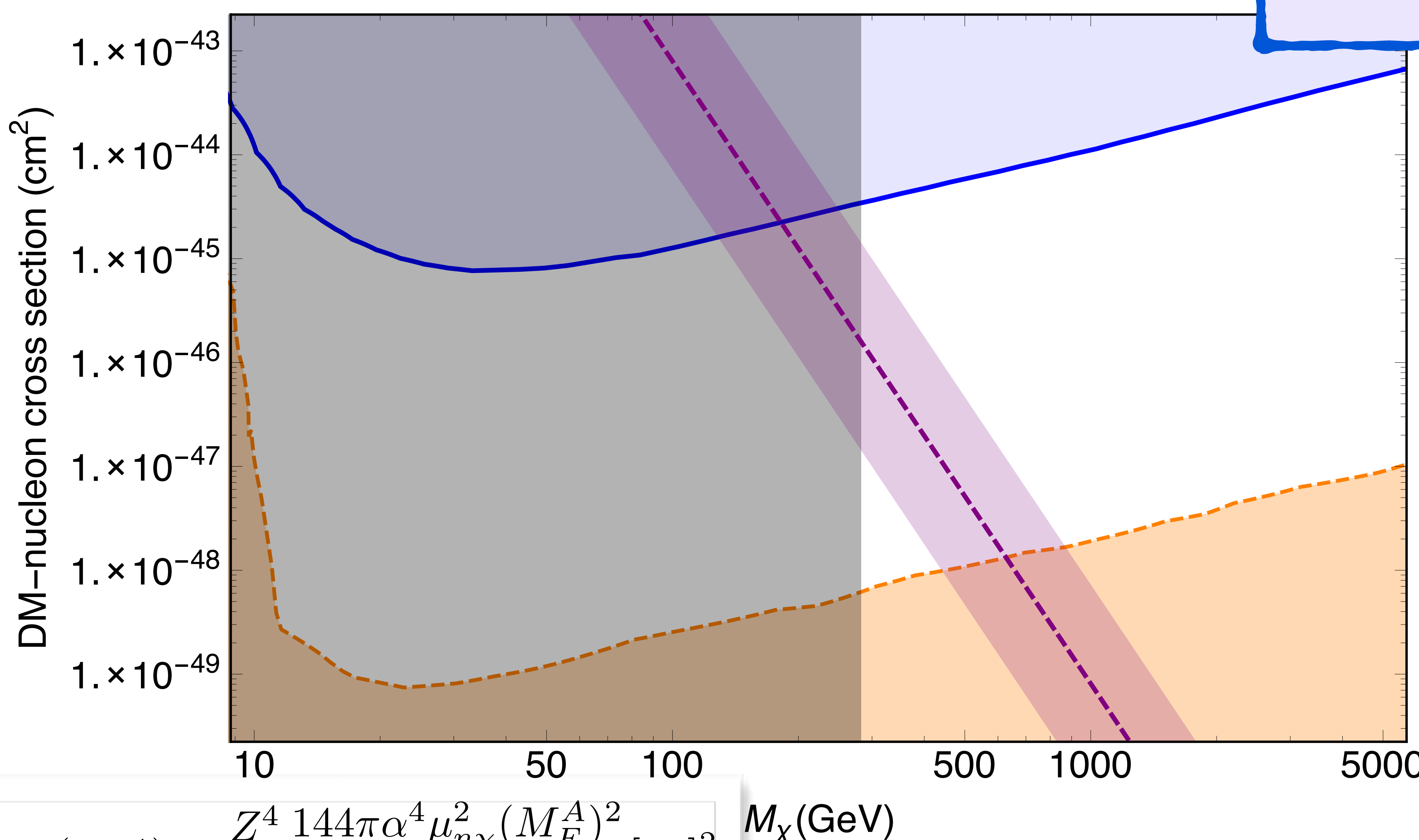
[see also Drach et al.,1511.04370 for SU(2) N_f=2]

Lowest bound from EM polarizability



Electric polarizability from lattice simulations with background fields

LUX exclusion bound for spin-independent cross section



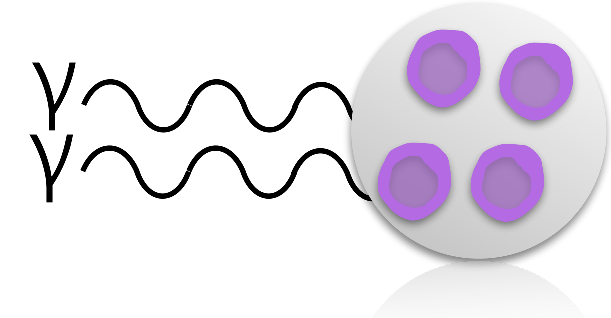
SU(4) N_f=4 Stealth DM

[LSD, 1503.04205]

$$\sigma_{\text{nucleon}}(Z,A) = \frac{Z^4}{A^2}\frac{144\pi\alpha^4\mu_{n\chi}^2(M_F^A)^2}{m_\chi^6 R^2}[c_F]^2$$

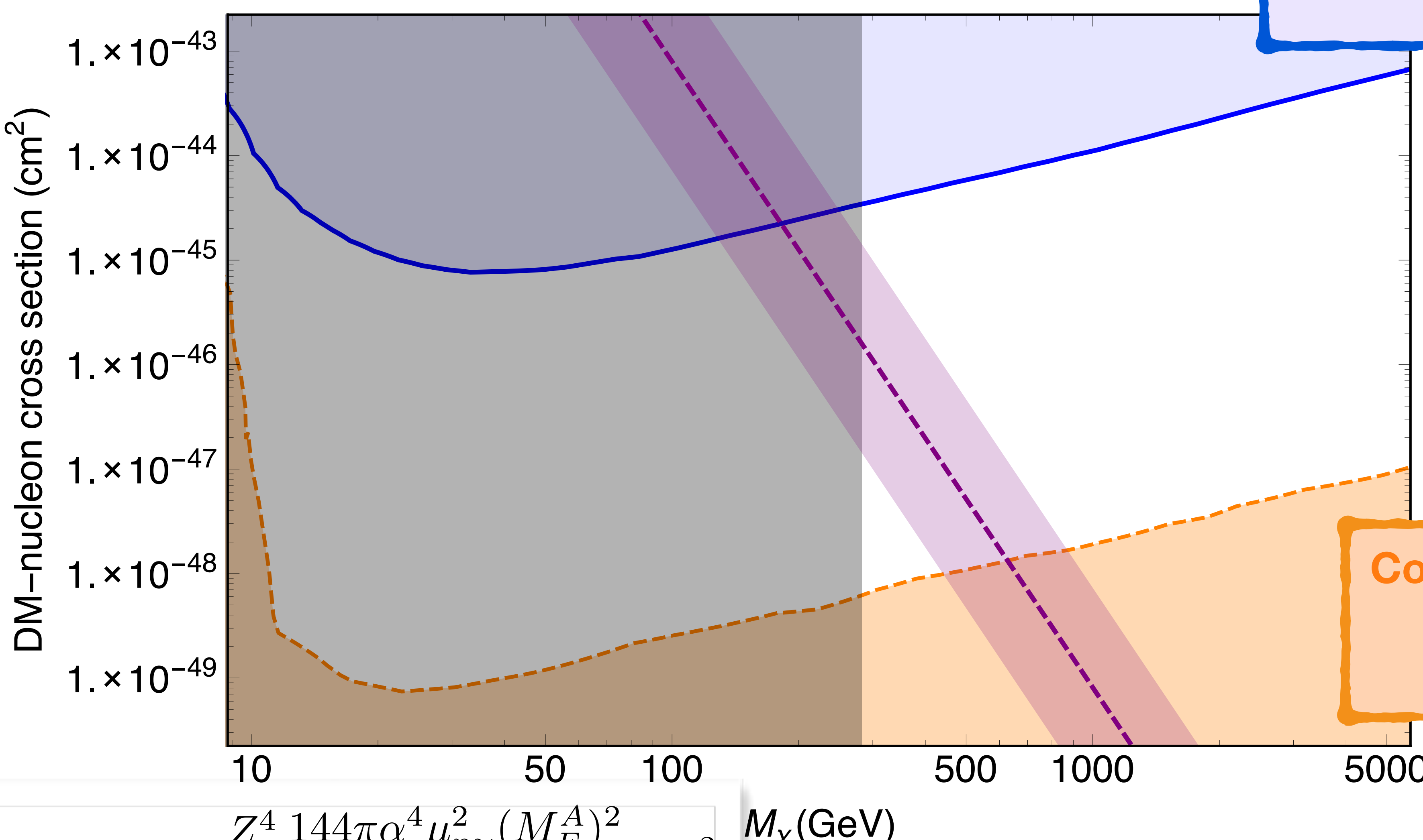
[see also Drach et al.,1511.04370 for SU(2) N_f=2]

Lowest bound from EM polarizability



Electric polarizability from lattice simulations with background fields

LUX exclusion bound for spin-independent cross section



SU(4) N_f=4 Stealth DM

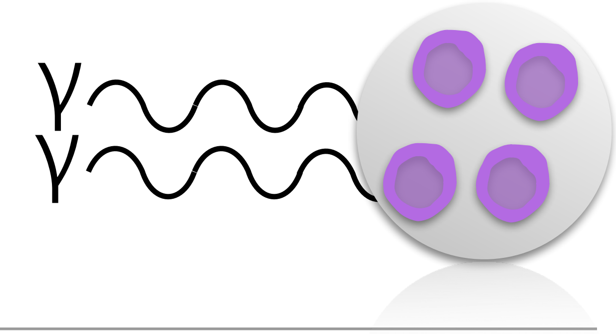
[LSD, 1503.04205]

Coherent neutrino scattering background

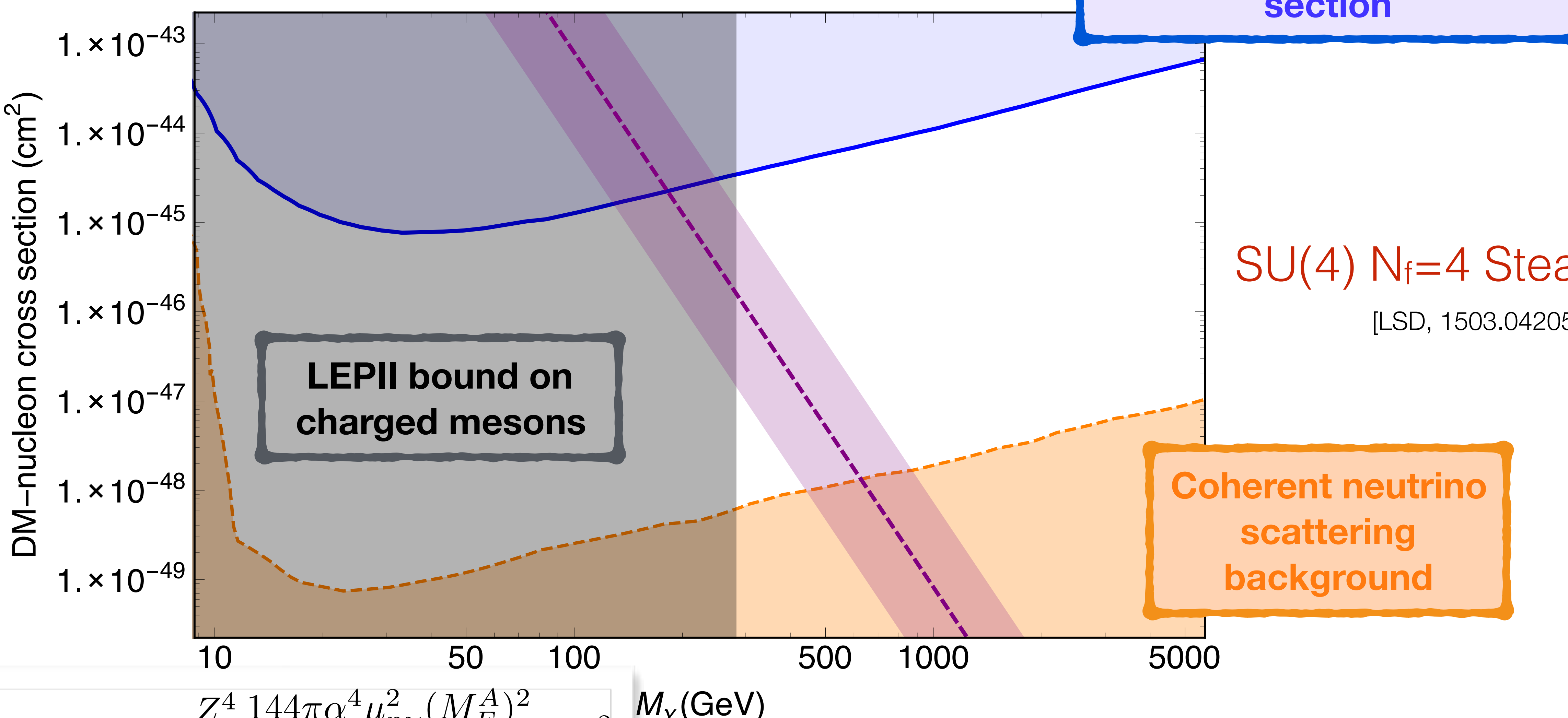
$$\sigma_{\text{nucleon}}(Z,A) = \frac{Z^4}{A^2}\frac{144\pi\alpha^4\mu_{n\chi}^2(M_F^A)^2}{m_\chi^6 R^2}[c_F]^2$$

[see also Drach et al.,1511.04370 for SU(2) N_f=2]

Lowest bound from EM polarizability



Electric polarizability from lattice simulations with background fields

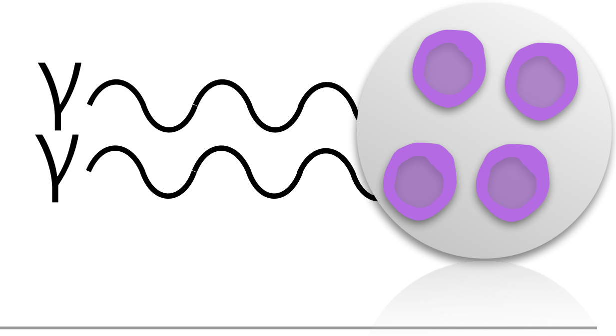


SU(4) N_f=4 Stealth DM

[LSD, 1503.04205]

$$\sigma_{\text{nucleon}}(Z,A) = \frac{Z^4}{A^2}\frac{144\pi\alpha^4\mu_{n\chi}^2(M_F^A)^2}{m_\chi^6 R^2}[c_F]^2$$

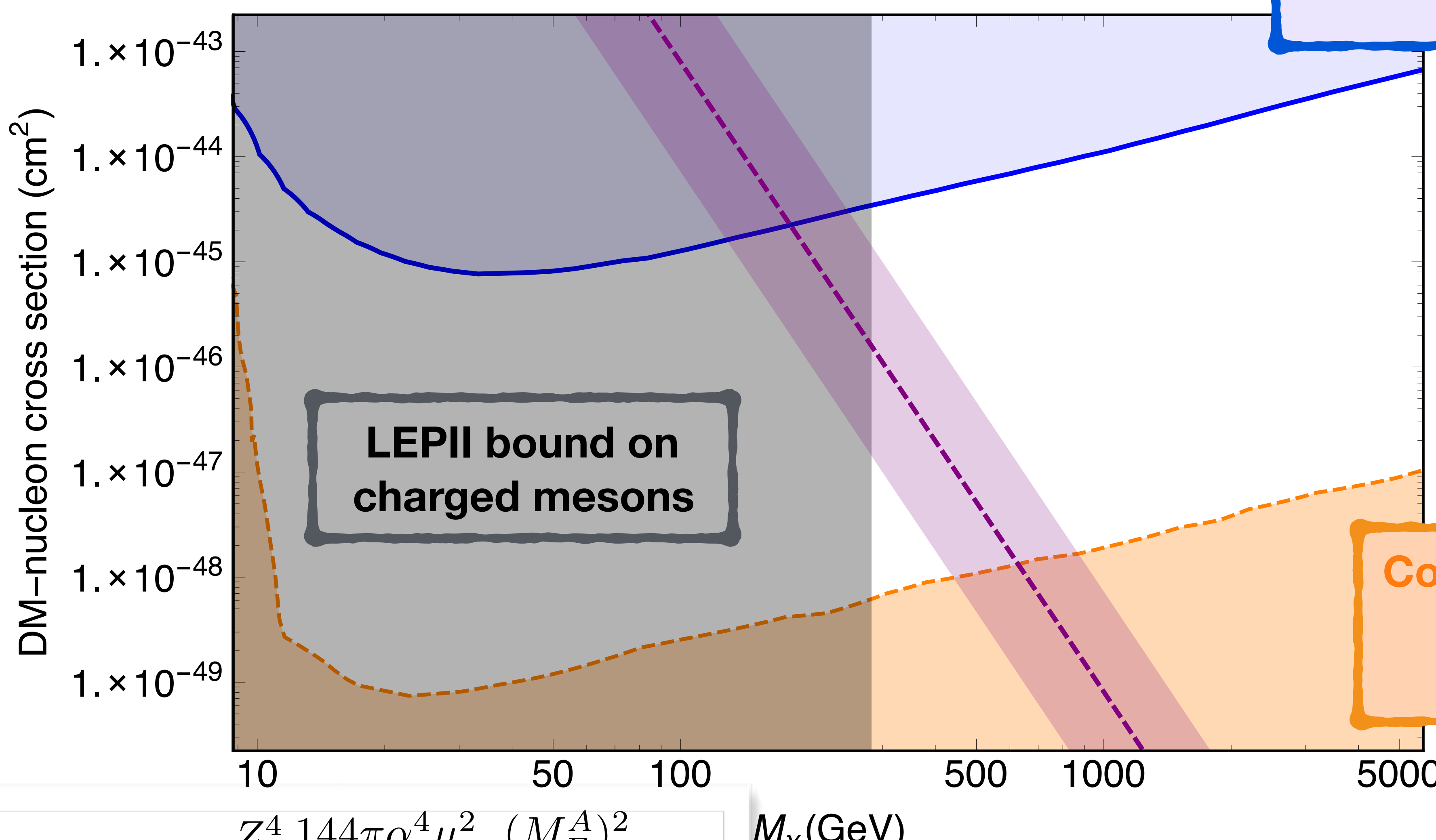
[see also Drach et al.,1511.04370 for SU(2) N_f=2]



Lowest bound from EM polarizability

Electric polarizability from lattice simulations with background fields

LUX exclusion bound for spin-independent cross section



SU(4) N_f=4 Stealth DM

[LSD, 1503.04205]

Coherent neutrino scattering background

$$\sigma_{\text{nucleon}}(Z,A) = \frac{Z^4}{A^2}\frac{144\pi\alpha^4\mu_{n\chi}^2(M_F^A)^2}{m_\chi^6 R^2}[c_F]^2$$

lowest allowed direct detection cross-section for composite dark matter theories with EW charged constituents

Concluding remarks

★QCD ideas and lattice QCD techniques can be borrowed when exploring the DM landscape (BSM)

★Composite dark matter is a viable interesting possibility with rich phenomenology

★Lattice methods can help in calculating direct detection cross sections, production rates at colliders, and self-interaction cross sections of phenomenological relevance.

★Dark matter constituents can carry electroweak charges and still the stable composites are currently undetectable. Stealth cross section.

extra

Open questions and future projects

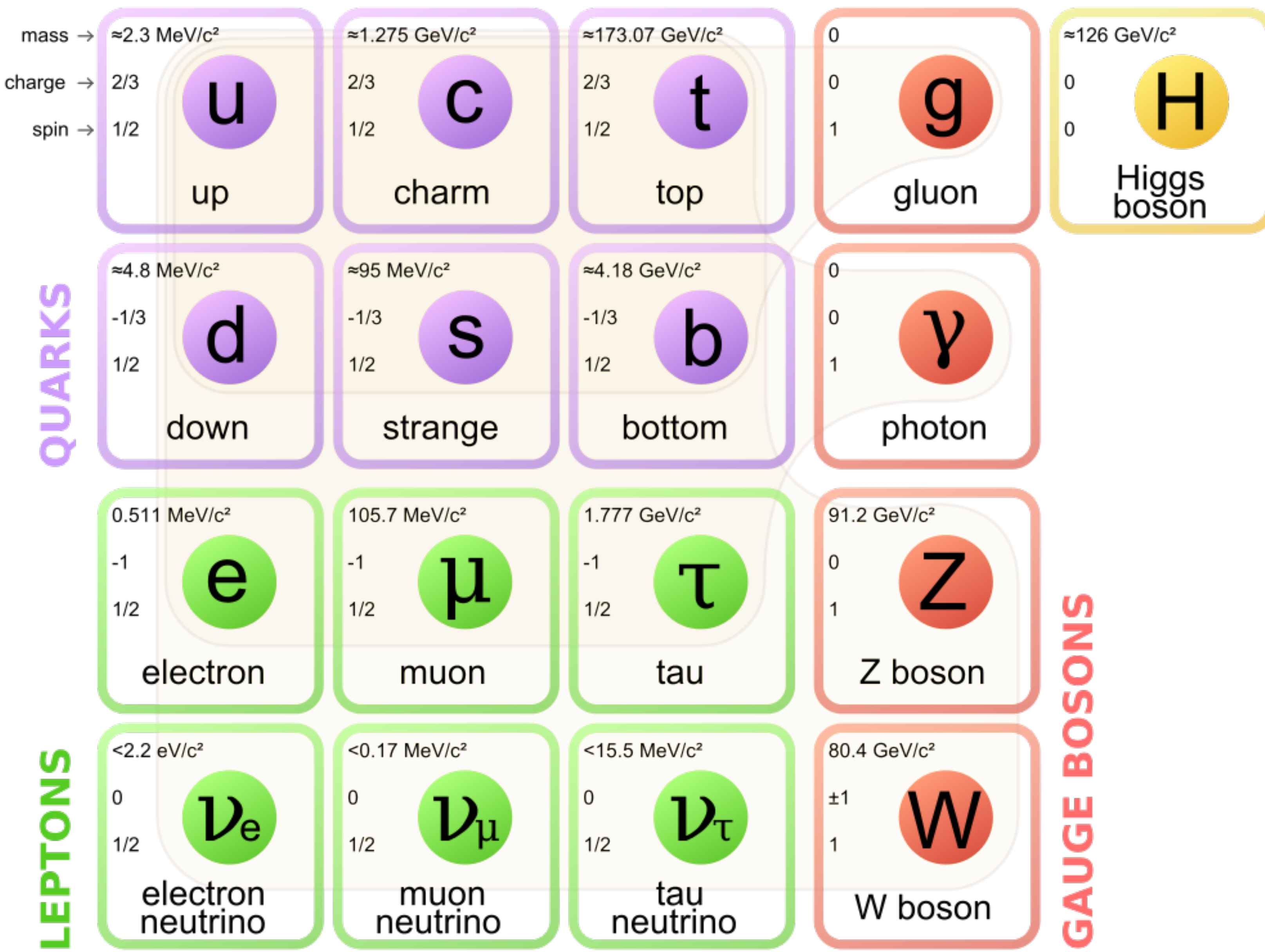
- Structure formation in galaxies ➜ influenced by DM scattering cross-section: hadron-hadron interactions are hard to model, but can be studied directly with lattice methods

- Colliders could produce the (lightest) dark mesons, but need to know their form factors: lattice methods can be used

- New dark sector ➜ deconfinement phase transition: if first order, gravitational wave signals could be soon observed
  [Schwaller, 1504.07263]

A very familiar picture

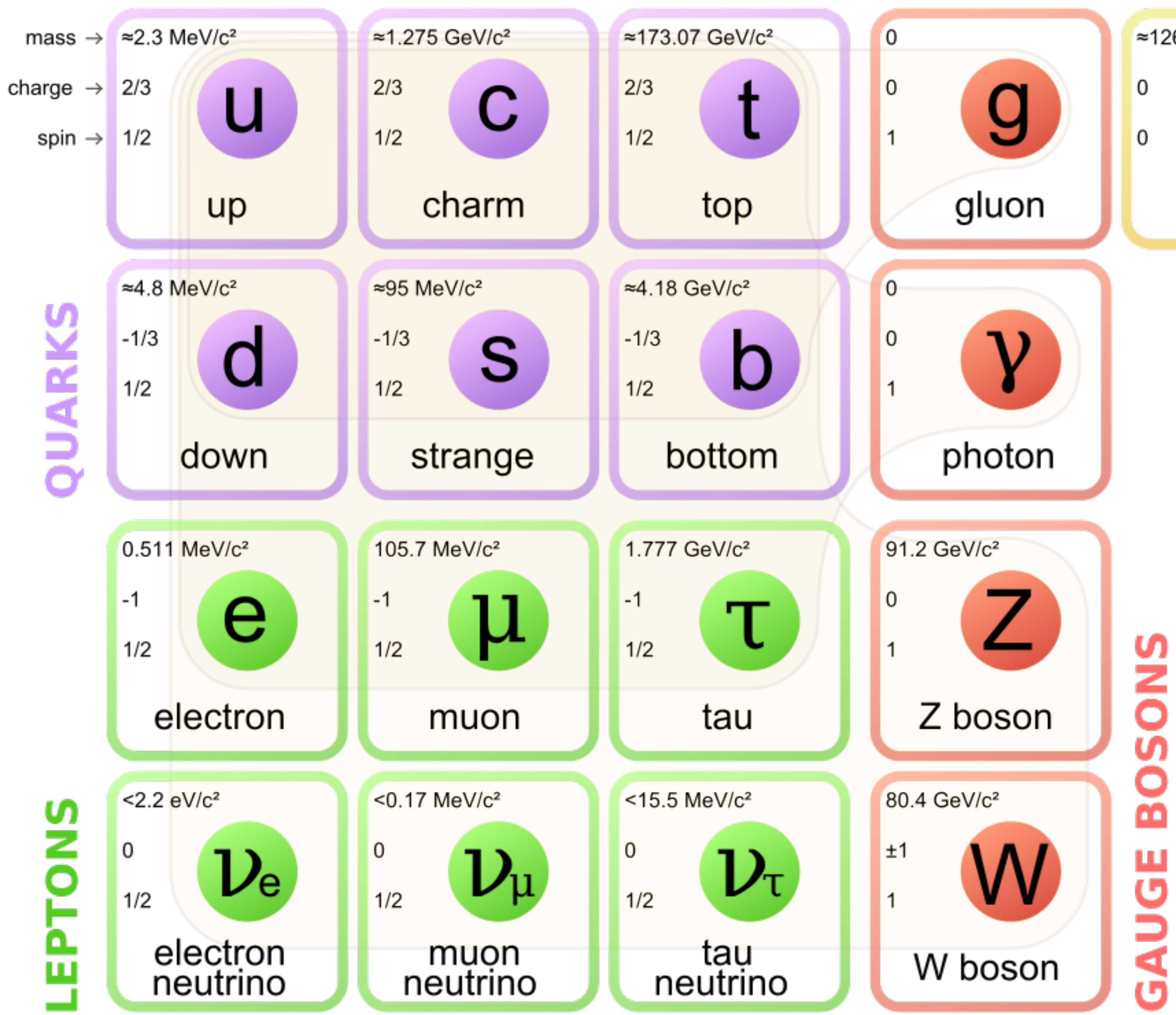
The Standard Model of particles



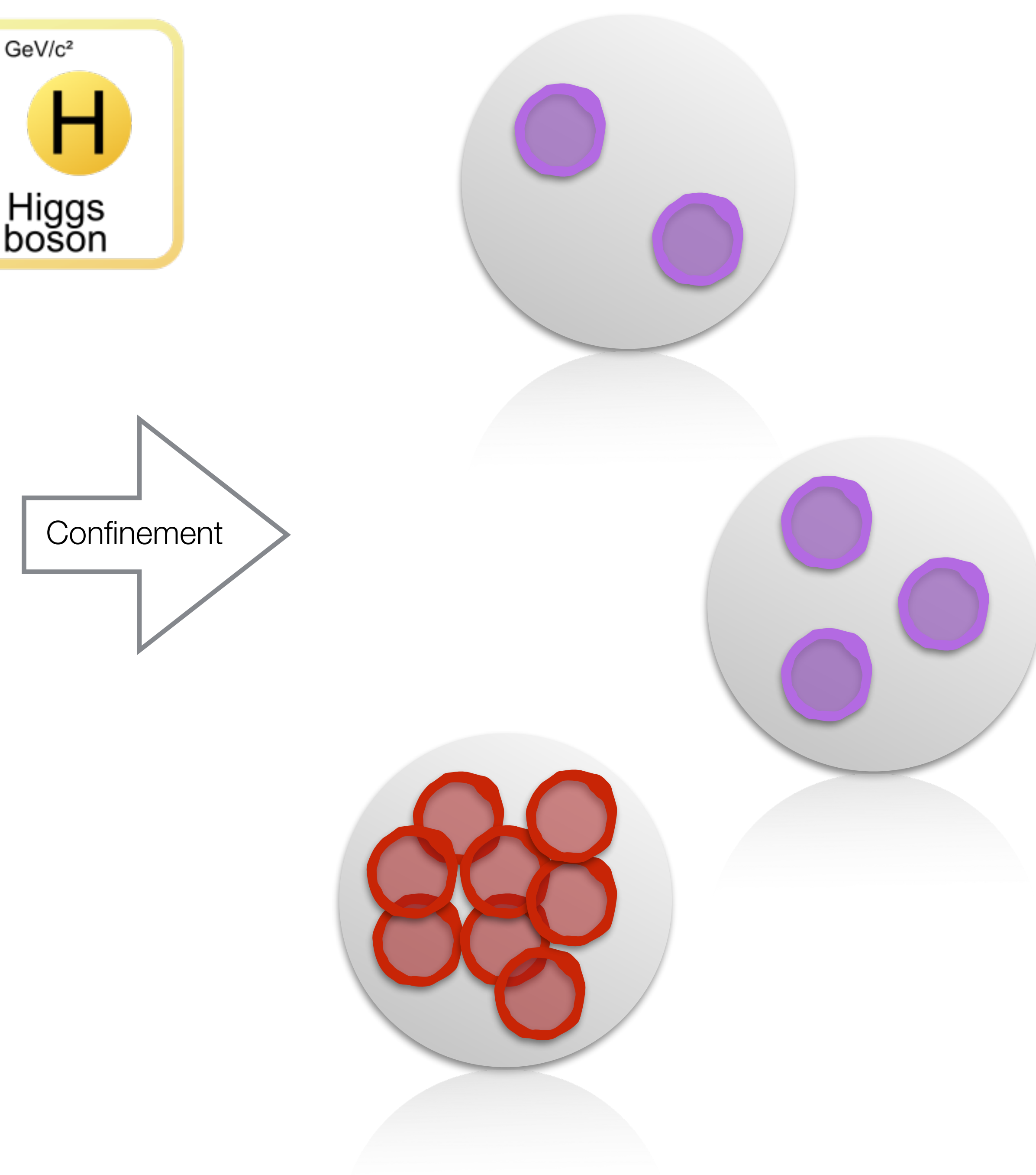
[Wikipedia]

A very familiar picture

The Standard Model of particles



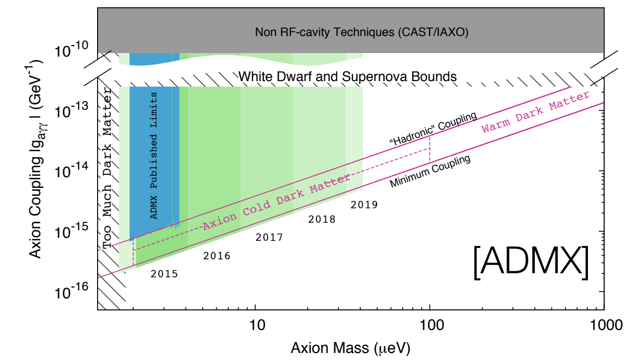
Mesons, Baryons and Glueballs



[Wikipedia]

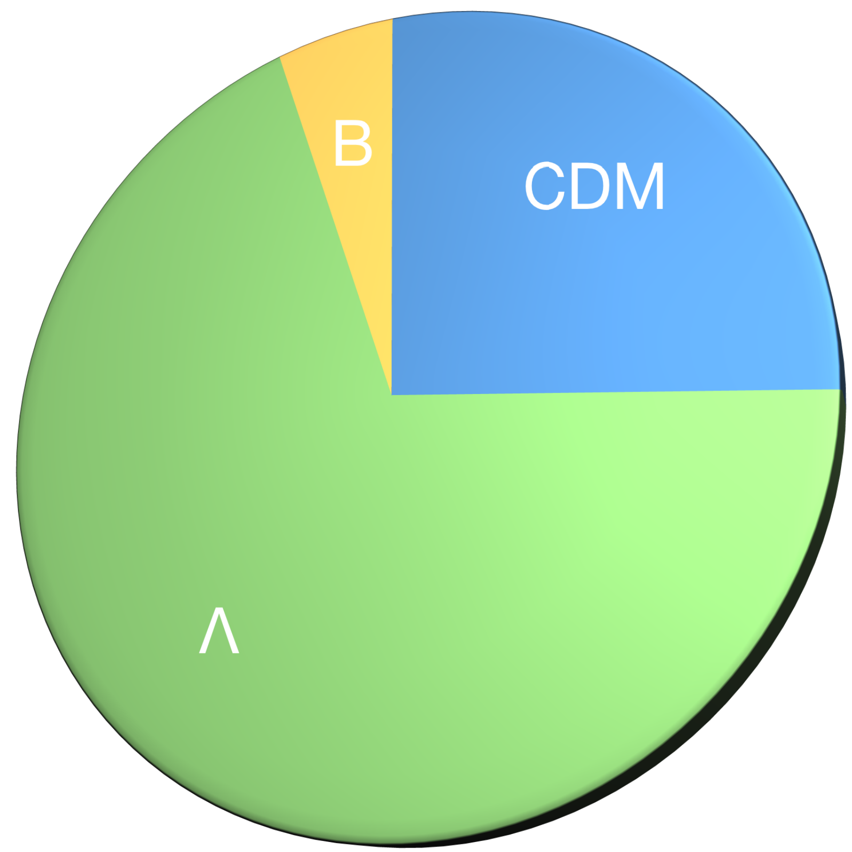
[Peccei & Quinn: PRL **38** (1977) 1440, PR **D16** (1977) 1791]

[Preskill, Wise & Wilczek, Phys. Lett. B **120** (1983) 127-132]



Axion dark matter

- Axions were originally proposed to deal with the Strong-CP problem
  - They also form a plausible DM candidate
  - The axion energy density requires non-perturbative QCD input
- Being sought in ADMX (LLNL, UW) & CAST-IAXO (CERN) with large discovery potential in the next few years
- Requiring $\Omega_a \leq \Omega_{CDM}$ yields a lower bound on the axion mass today

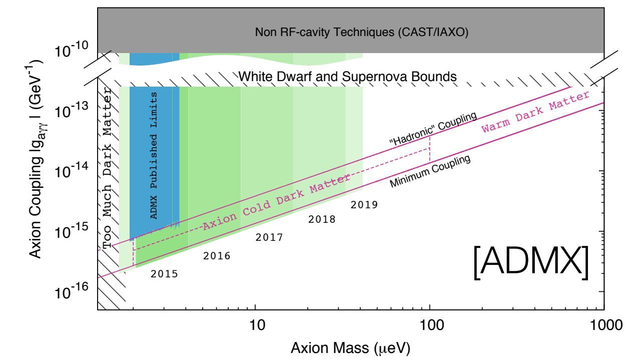


$\Omega_{tot} = 1.000(7)$
PDG 2014

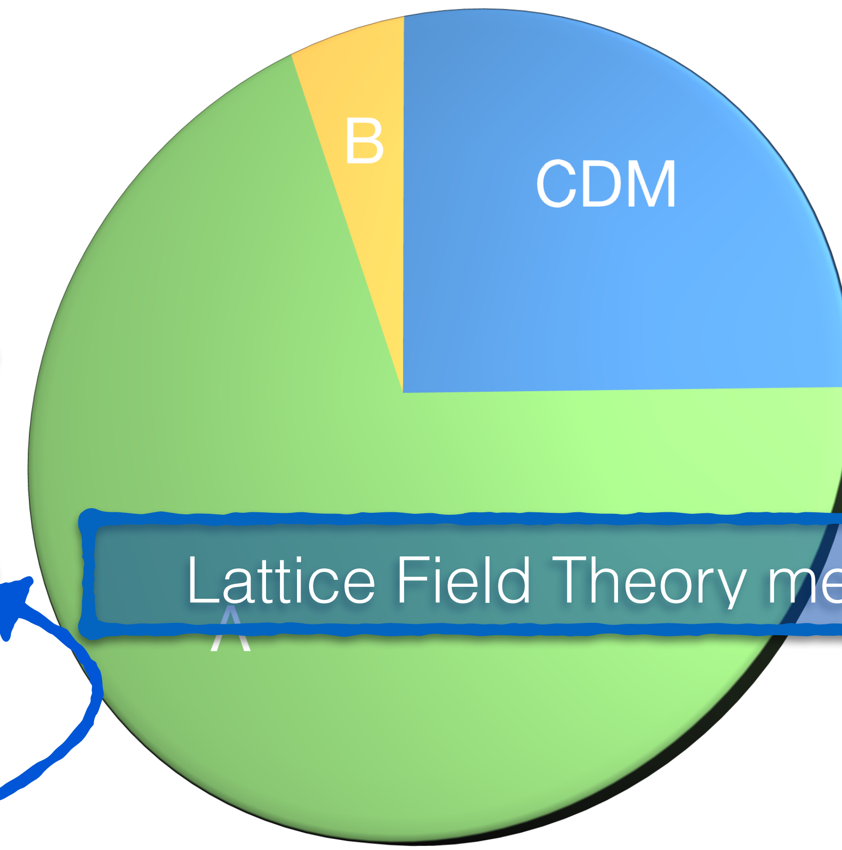
[Peccei & Quinn: PRL **38** (1977) 1440, PR **D16** (1977) 1791]

[Preskill, Wise & Wilczek, Phys. Lett. B **120** (1983) 127-132]

Axion dark matter



- Axions were originally proposed to deal with the Strong-CP problem
  - They also form a plausible DM candidate
  - The axion energy density requires non-perturbative QCD input
- Being sought in ADMX (LLNL, UW) & CAST-IAXO (CERN) with large discovery potential in the next few years
- Requiring $\Omega_a \leq \Omega_{CDM}$ yields a lower bound on the axion mass today



Lattice Field Theory methods

$\Omega_{tot} = 1.000(7)$
PDG 2014

[Talk by Martinelli, Fri@13:00][Talk by Katz, Mon.@14:35][Talk by Szabo, Mon.@13:15]
[Talk by Frison, Mon.@14:35][Talk by Taniguchi, Fri.@17:10]

$$m_a^2 f_a^2 = \left.\frac{\partial^2 F}{\partial \theta^2}\right|_{\theta=0}$$

Constraints from lattice simulations

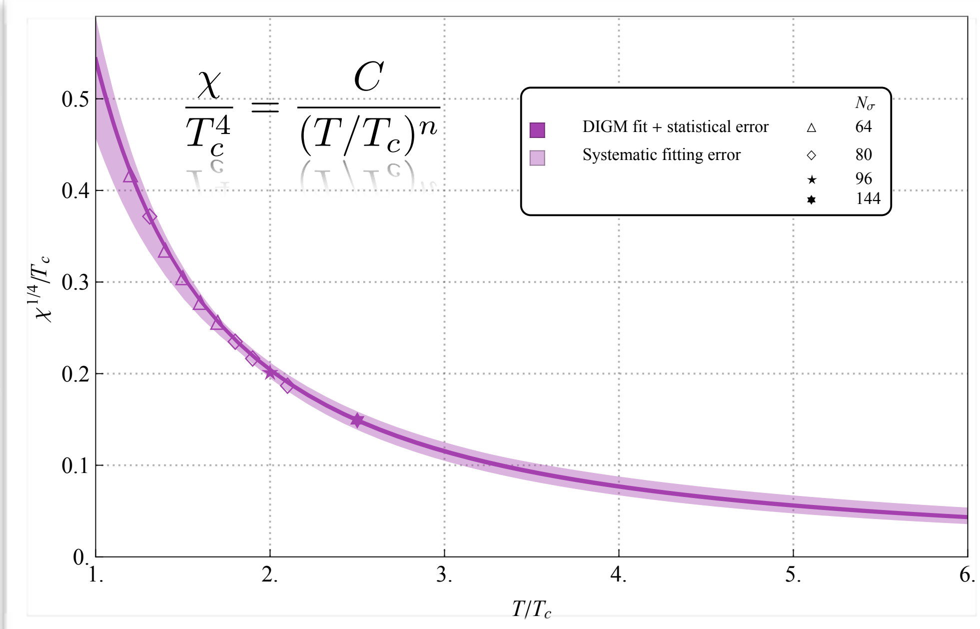
Non-perturbative calculation of QCD topology at finite temperature

- Pure gauge SU(3) topological susceptibility ➥ compatible with model predictions, but large non-perturbative effects

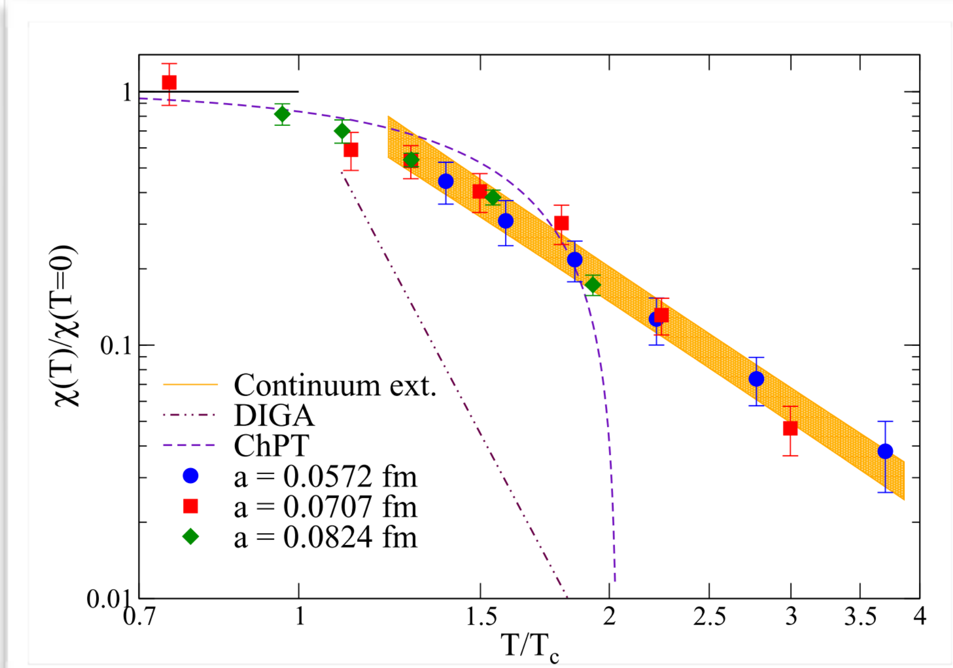
[Kitano&Yamada, 1506.00370][Borsanyi et al., 1508.06917][Frison et al.,1606.07175]

- is QCD topological susceptibility at high-T well described by models? ➥ light fermions importantly affect the vacuum

[Trunin et al., 1510.02265][Petreczky et al., 1606.03145][Borsanyi et al., 1606.07494]



[Berkowitz, Buchoff, ER., 1505.07455]



[Bonati et al., 1512.06746]

[Talk by Martinelli, Fri@13:00][Talk by Katz, Mon.@14:35][Talk by Szabo, Mon.@13:15]
[Talk by Frison, Mon.@14:35][Talk by Taniguchi, Fri.@17:10]

$$m_a^2 f_a^2 = \left.\frac{\partial^2 F}{\partial \theta^2}\right|_{\theta=0}$$

Constraints from lattice simulations

Non-perturbative calculation of QCD topology at finite temperature

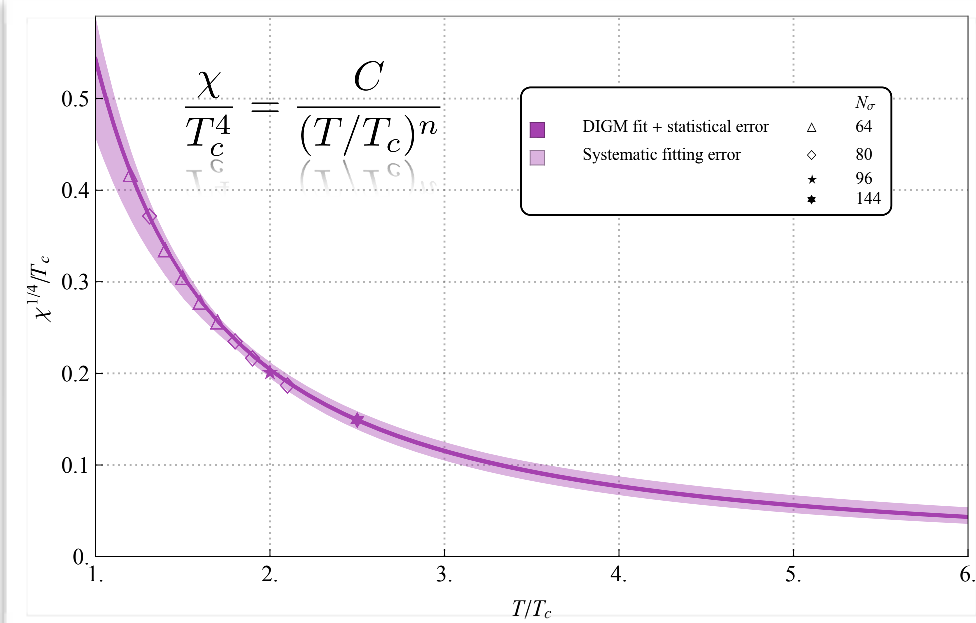
- Pure gauge SU(3) topological susceptibility ➡ compatible with model predictions, but large non-perturbative effects

[Kitano&Yamada, 1506.00370][Borsanyi et al., 1508.06917][Frison et al.,1606.07175]

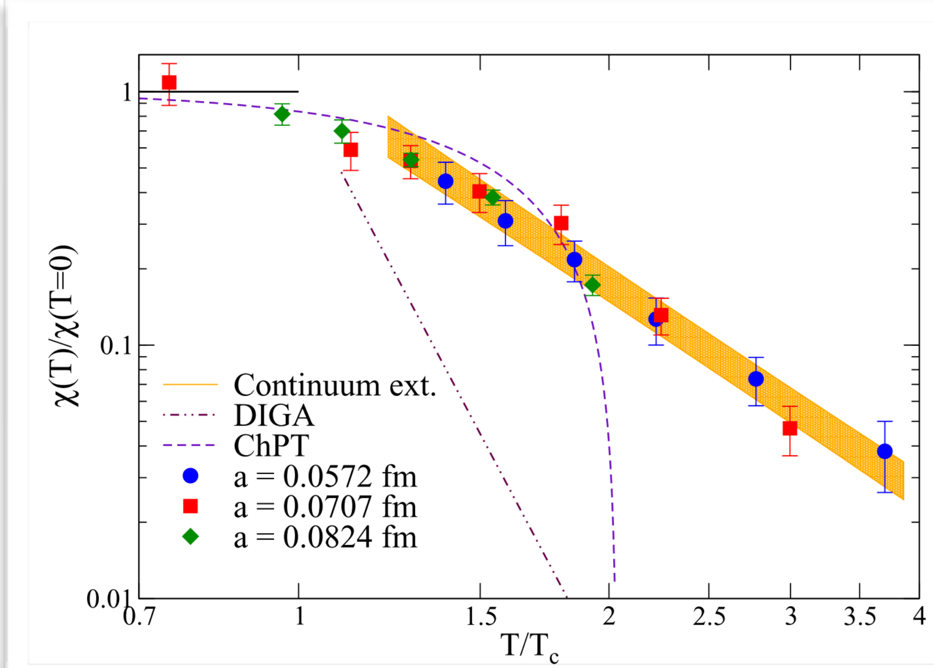
- is QCD topological susceptibility at high-T well described by models? ➡ light fermions importantly affect the vacuum

[Trunin et al., 1510.02265][Petreczky et al., 1606.03145][Borsanyi et al., 1606.07494]

Great effort to control all systematic lattice effects in order to impact experiments.
This direction has started only 1 year ago!



[Berkowitz, Buchoff, ER., 1505.07455]

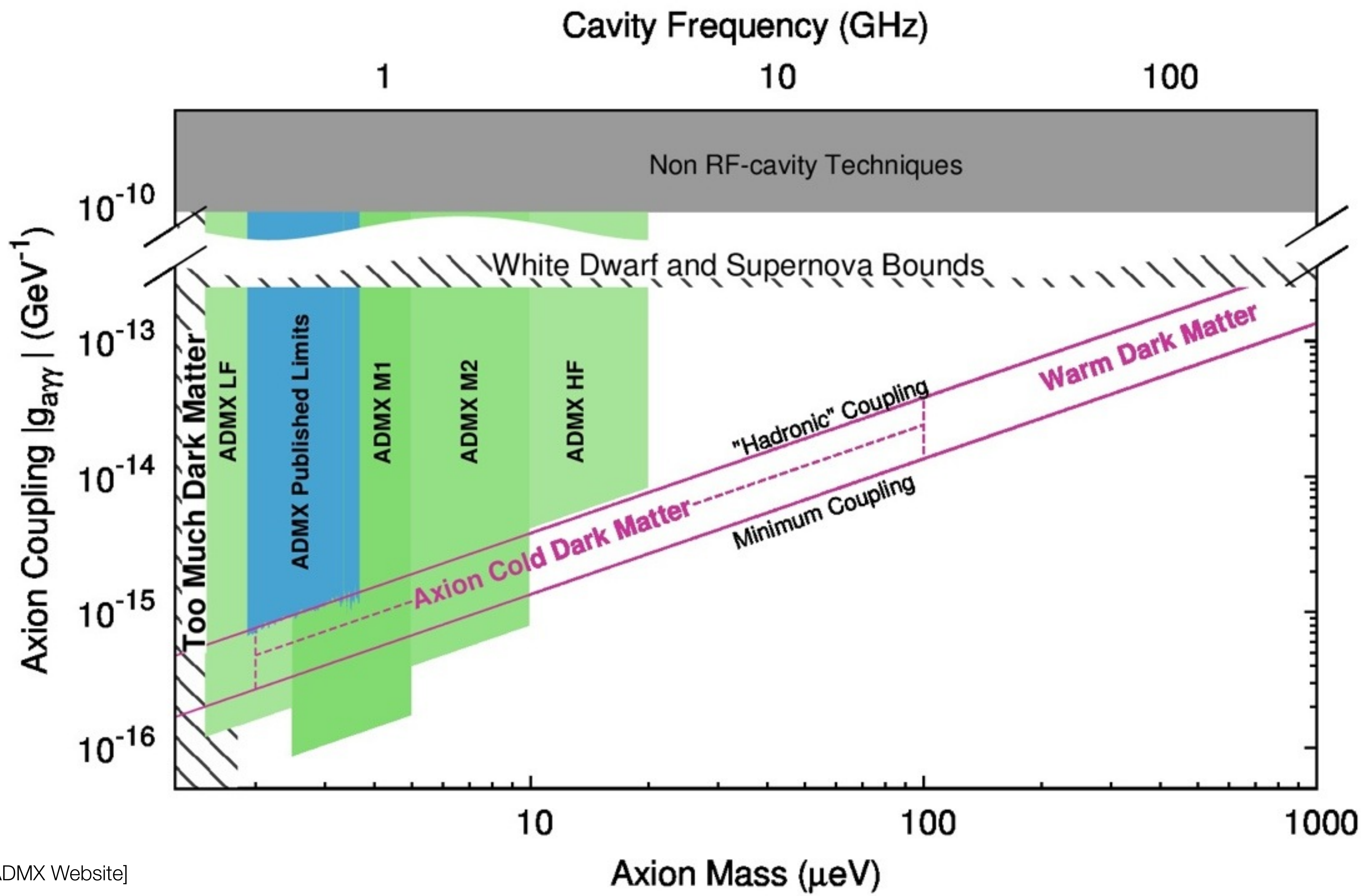


[Bonati et al., 1512.06746]

[Berkowitz, Buchoff, ER., 1505.07455]

$$m_a^2 f_a^2 = \left.\frac{\partial^2 F}{\partial \theta^2}\right|_{\theta=0}$$

Axion mass lower bound

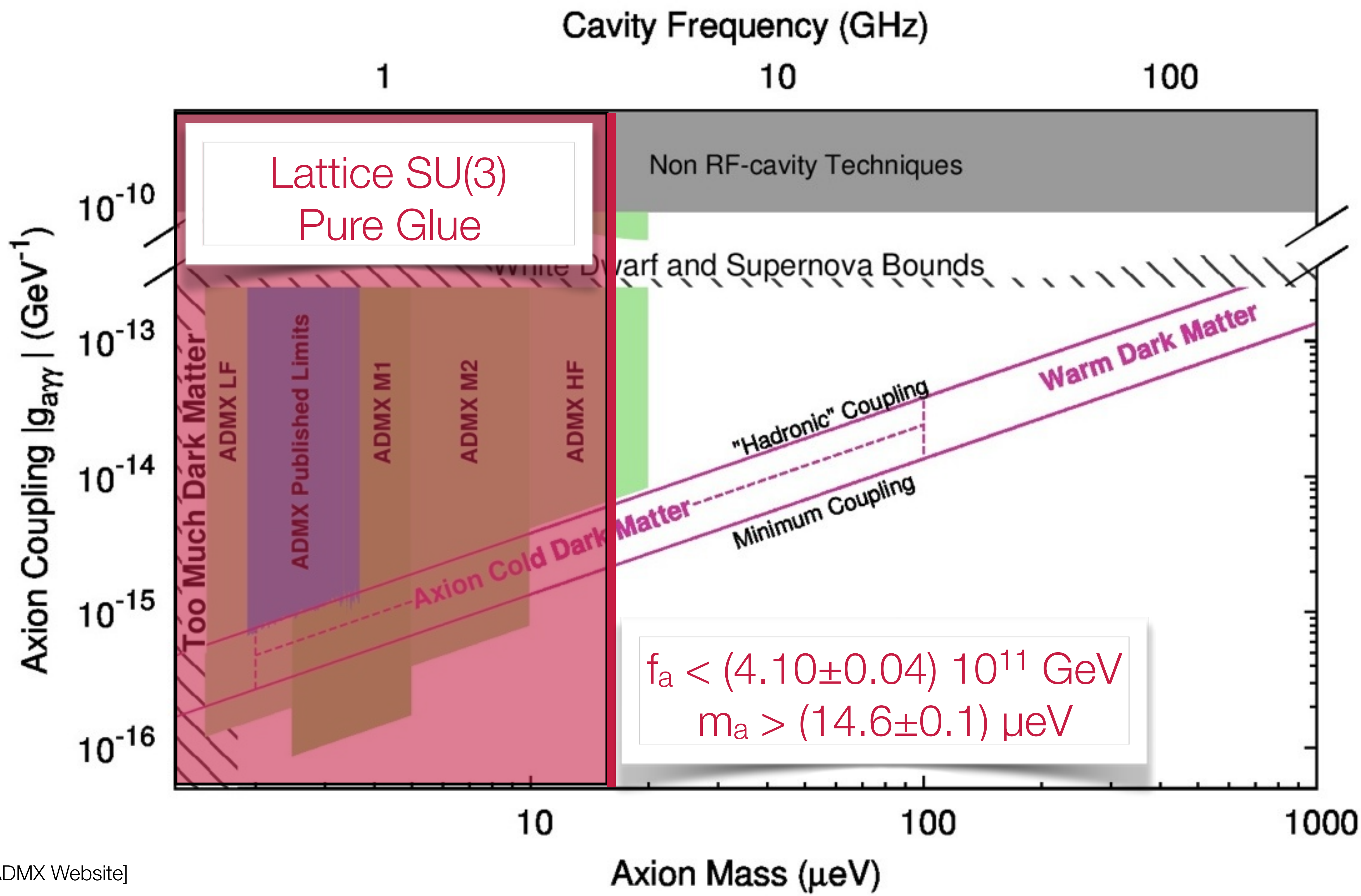


[ADMX Website]

[Berkowitz, Buchoff, ER., 1505.07455]

$$m_a^2 f_a^2 = \left.\frac{\partial^2 F}{\partial \theta^2}\right|_{\theta=0}$$

Axion mass lower bound

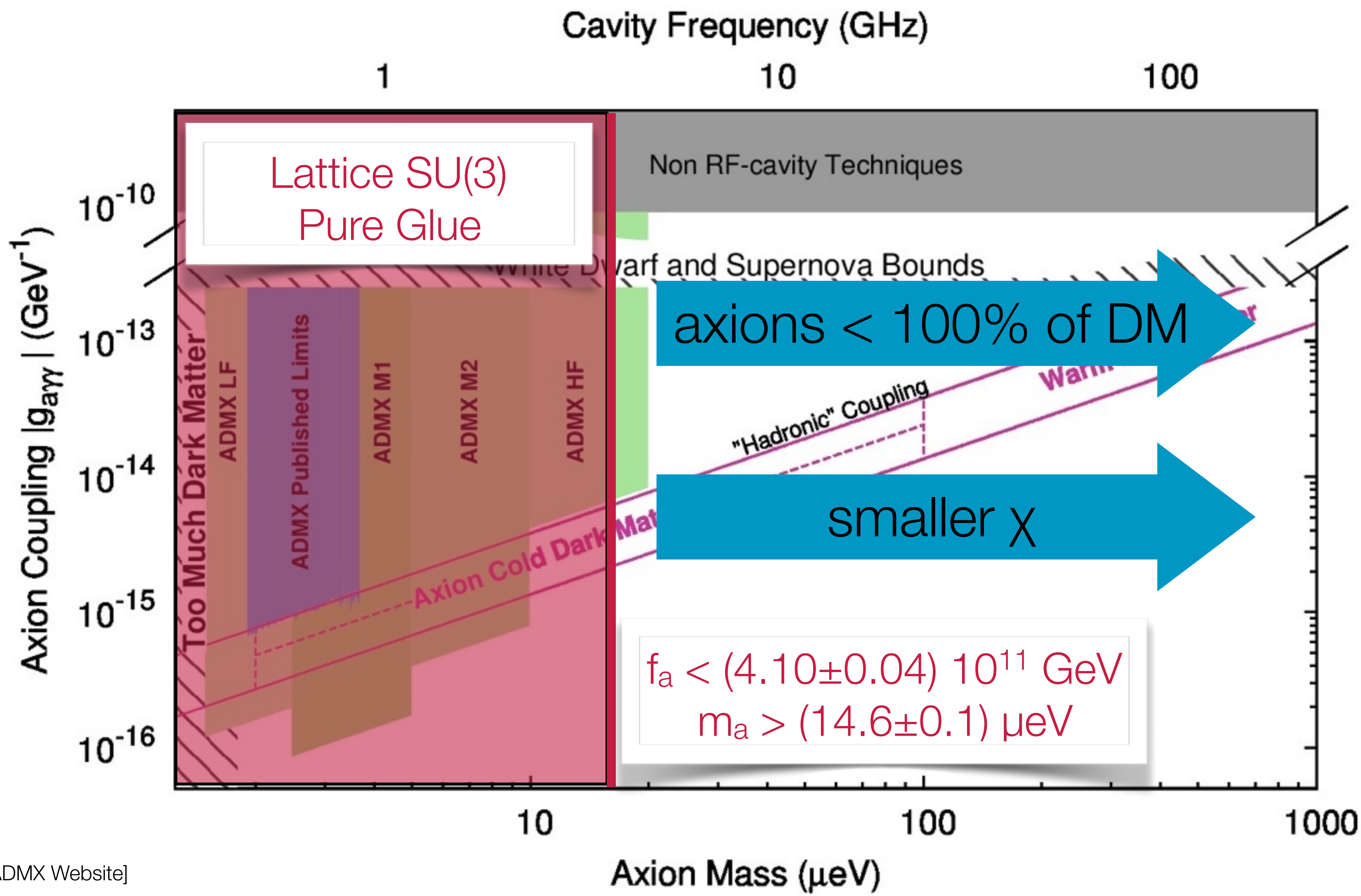


[ADMX Website]

[Berkowitz, Buchoff, ER., 1505.07455]

$$m_a^2 f_a^2 = \left.\frac{\partial^2 F}{\partial \theta^2}\right|_{\theta=0}$$

Axion mass lower bound

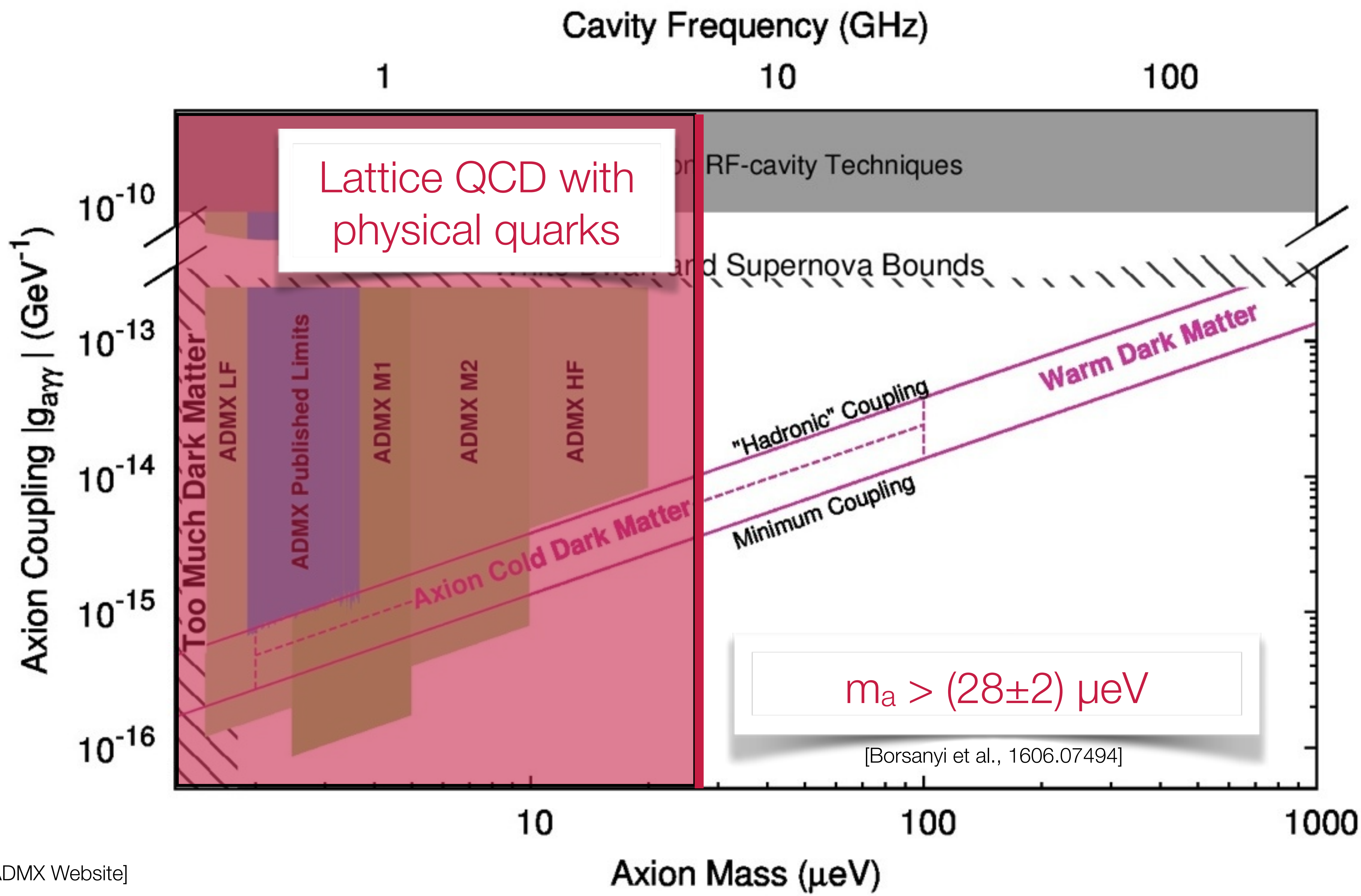


[ADMX Website]

[Talk by Martinelli, Fri@13:00][Talk by Katz, Mon.@14:35][Talk by Szabo, Mon.@13:15]
[Talk by Frison, Mon.@14:35][Talk by Taniguchi, Fri.@17:10]

$$m_a^2 f_a^2 = \left.\frac{\partial^2 F}{\partial \theta^2}\right|_{\theta=0}$$

Axion mass lower bound



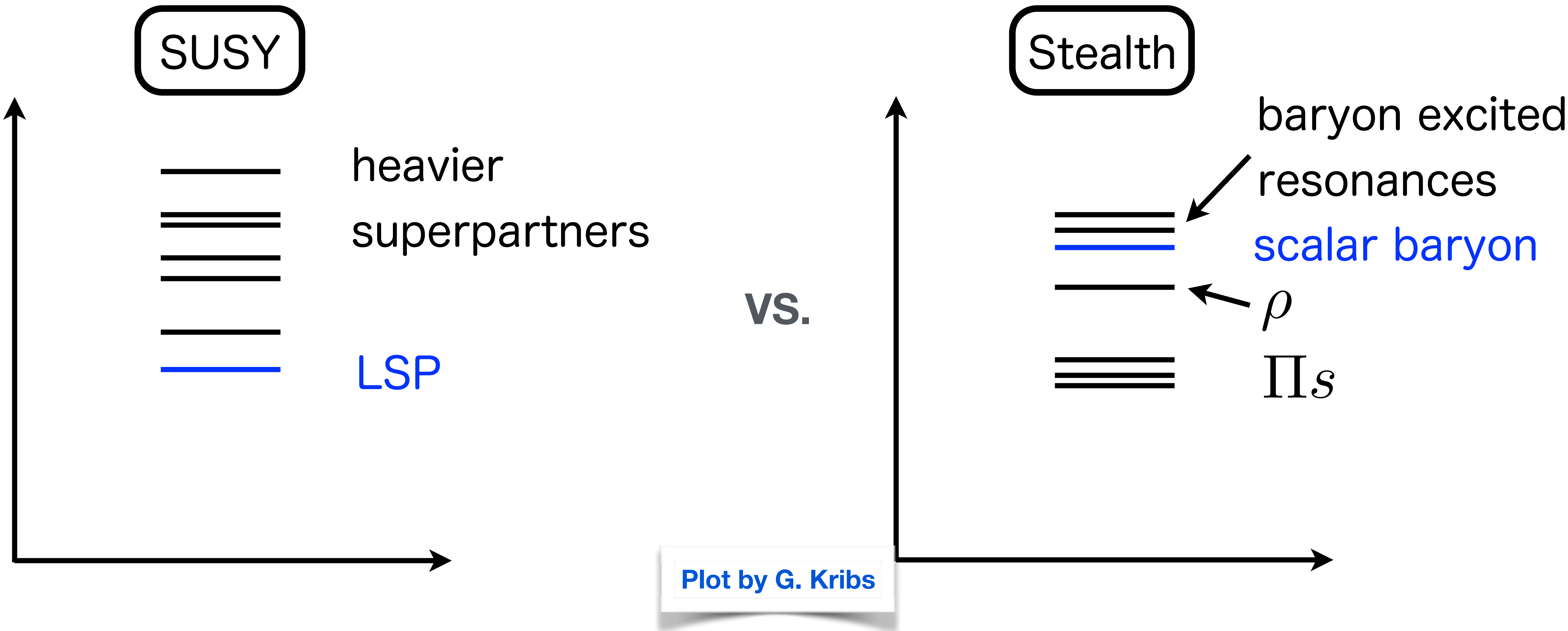
Lattice QCD with physical quarks

$m_a > (28 \pm 2)\ \mu\text{eV}$

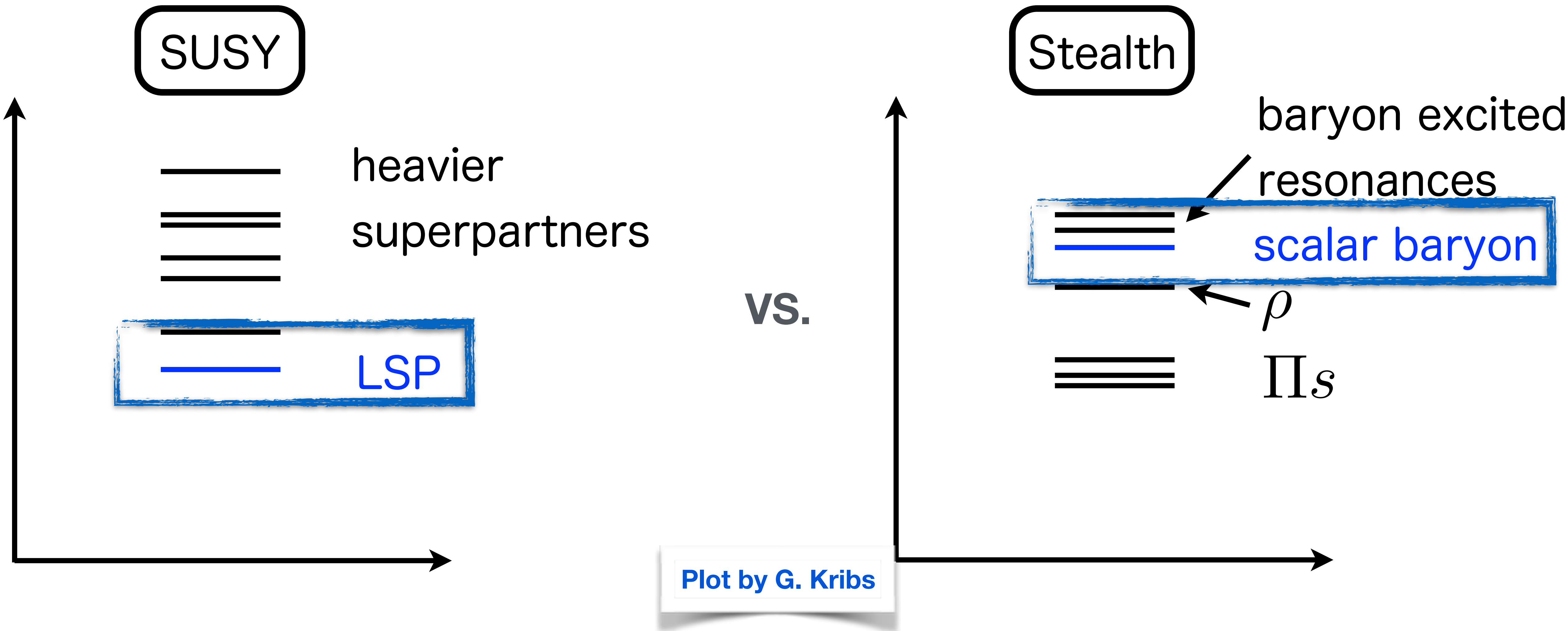
[Borsanyi et al., 1606.07494]

[ADMX Website]

Composite DM signatures at colliders

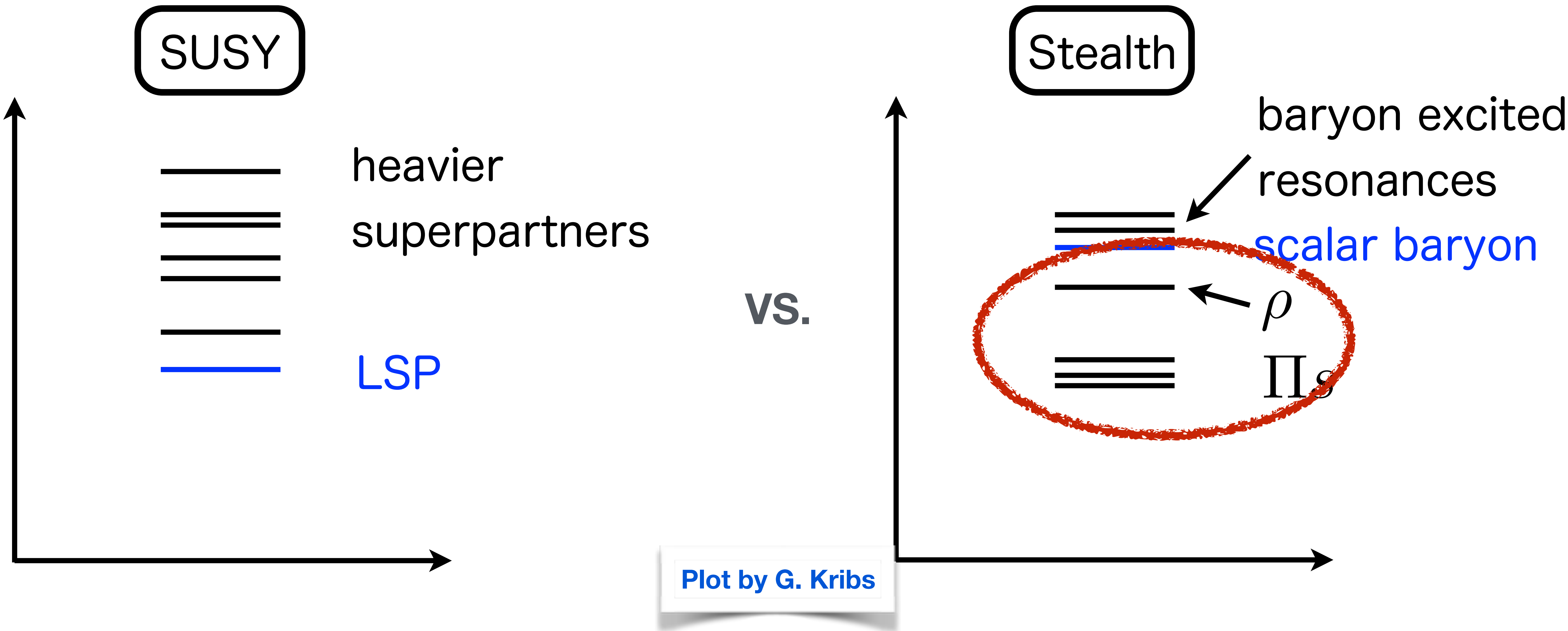


Composite DM signatures at colliders



★ Signatures are not dominated by missing energy: DM is not the lightest particle! The interactions are suppressed (form factors)

Composite DM signatures at colliders



- ★ Signatures are not dominated by missing energy: DM is not the lightest particle! The interactions are suppressed (form factors)
- ★ Light meson production and decay give interesting signatures: the model can be constrained by collider limits

[Bagnasco et al.,hep-ph/9310290]

Photon interactions

$$\langle \chi(p')|j^\mu_{\mathrm{EM}}|\chi(p)\rangle = F(q^2)q^\mu$$

Expansion at low momentum through effective operators

✦dimension 5 ➥ magnetic dipole

$$\frac{(\bar{\chi}\sigma^{\mu\nu}\chi)F_{\mu\nu}}{\Lambda_{\mathrm{dark}}}$$

✦dimension 6 ➥ charge radius

$$\frac{(\bar{\chi}\chi)v_\mu\partial_\nu F^{\mu\nu}}{\Lambda^2_{\mathrm{dark}}}$$

✦dimension 7 ➥ polarizability

$$\frac{(\bar{\chi}\chi)F_{\mu\nu}F^{\mu\nu}}{\Lambda^3_{\mathrm{dark}}}$$