Minimal Vector (Isotriplet) Dark Matter

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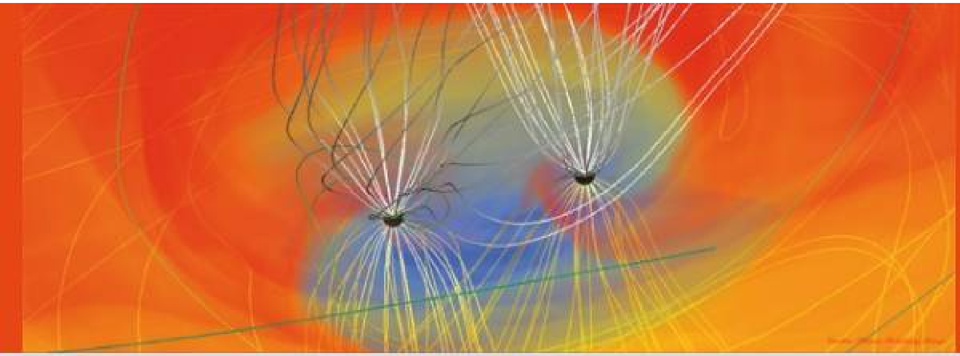
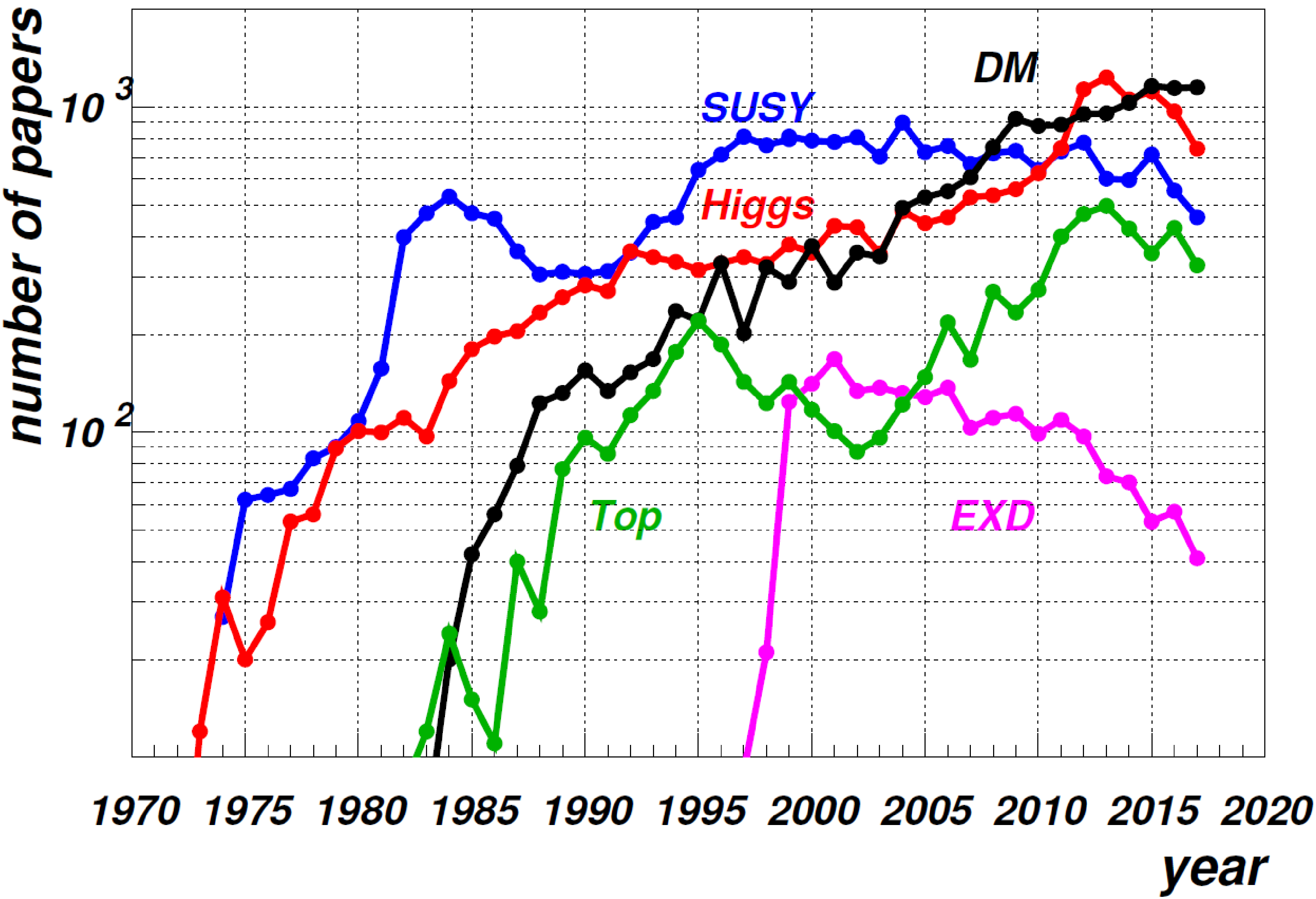
G.Cacciapaglia, J.McKay, D. Marin, A.Zerwekh, AB – arXiv:**1808.10464, PRD**



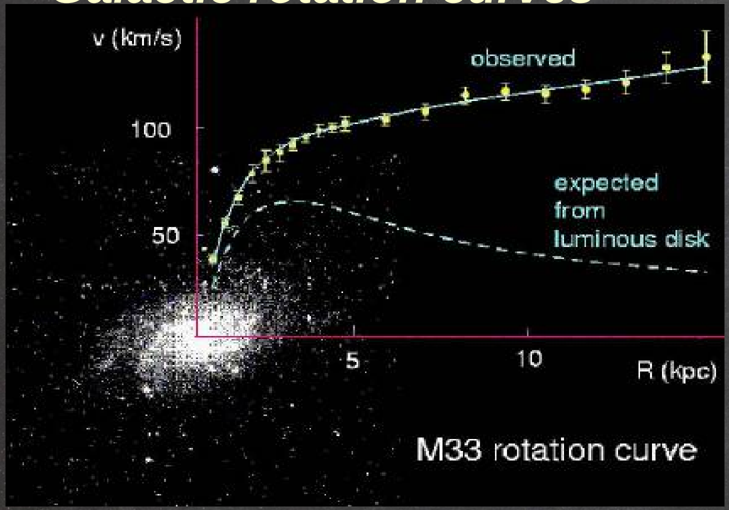
PASCOS 2019
XXV International Symposium

Why we are so keen to study DM?

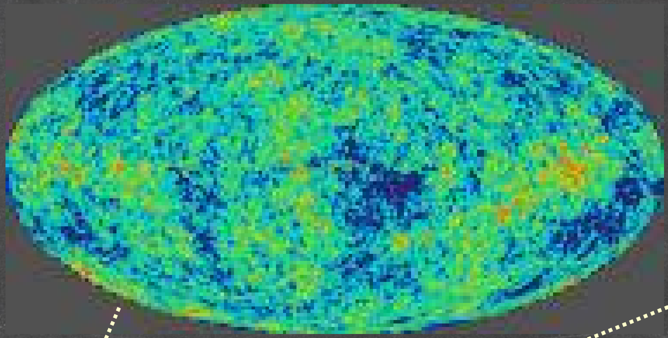


Because the existence of DM is the strongest evidence for BSM!

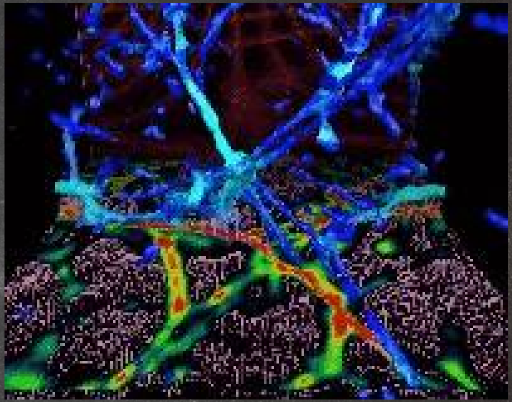
Galactic rotation curves

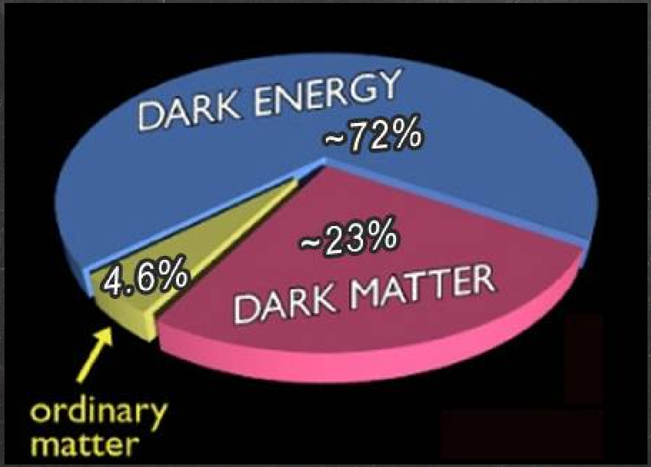


CMB: WMAP and PLANCK

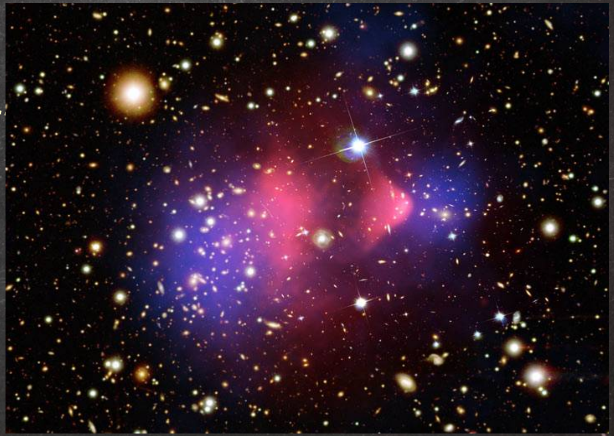


Large Scale Structures



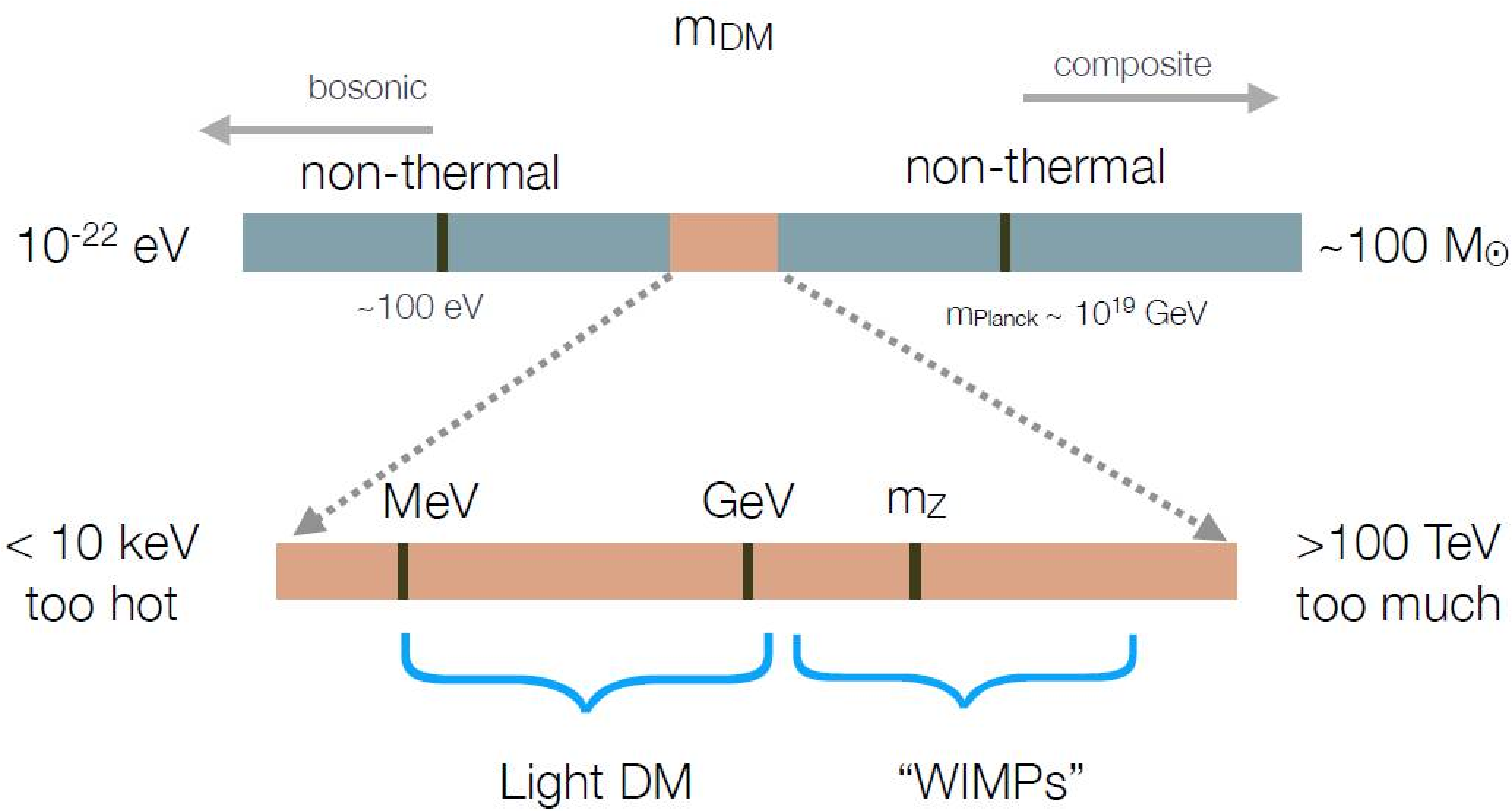


Bullet cluster

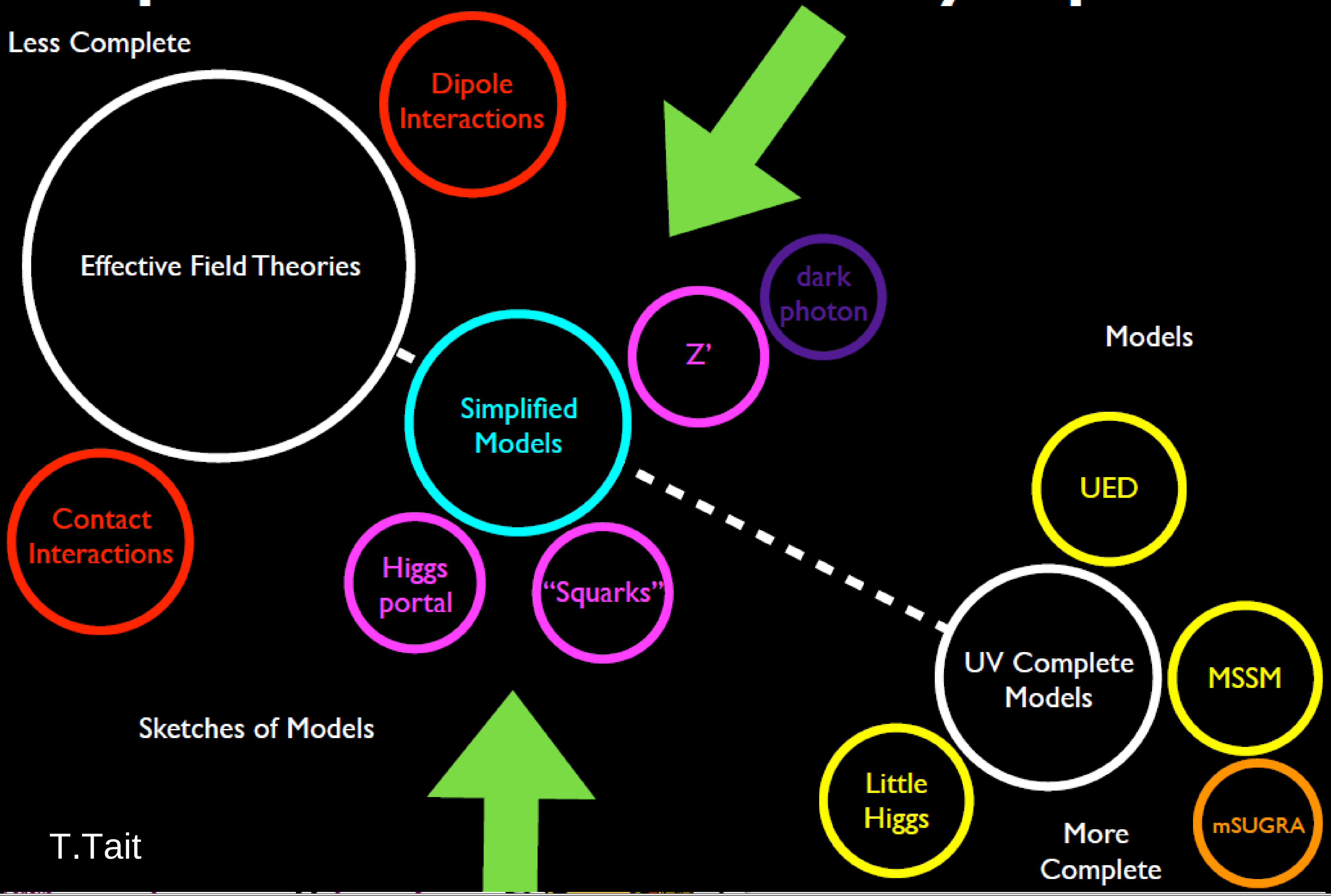


Gravitational lensing

Mass range for thermal DM

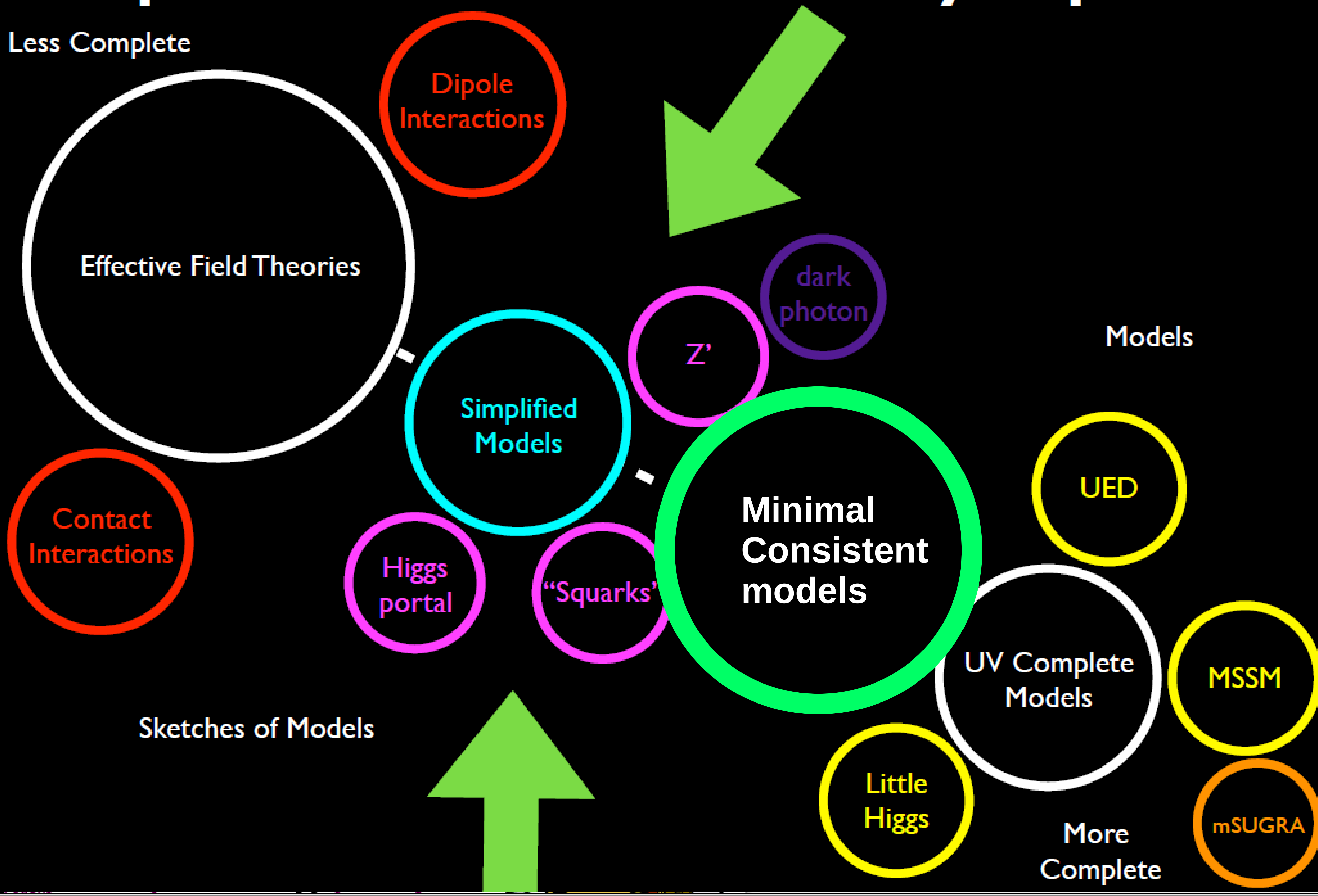


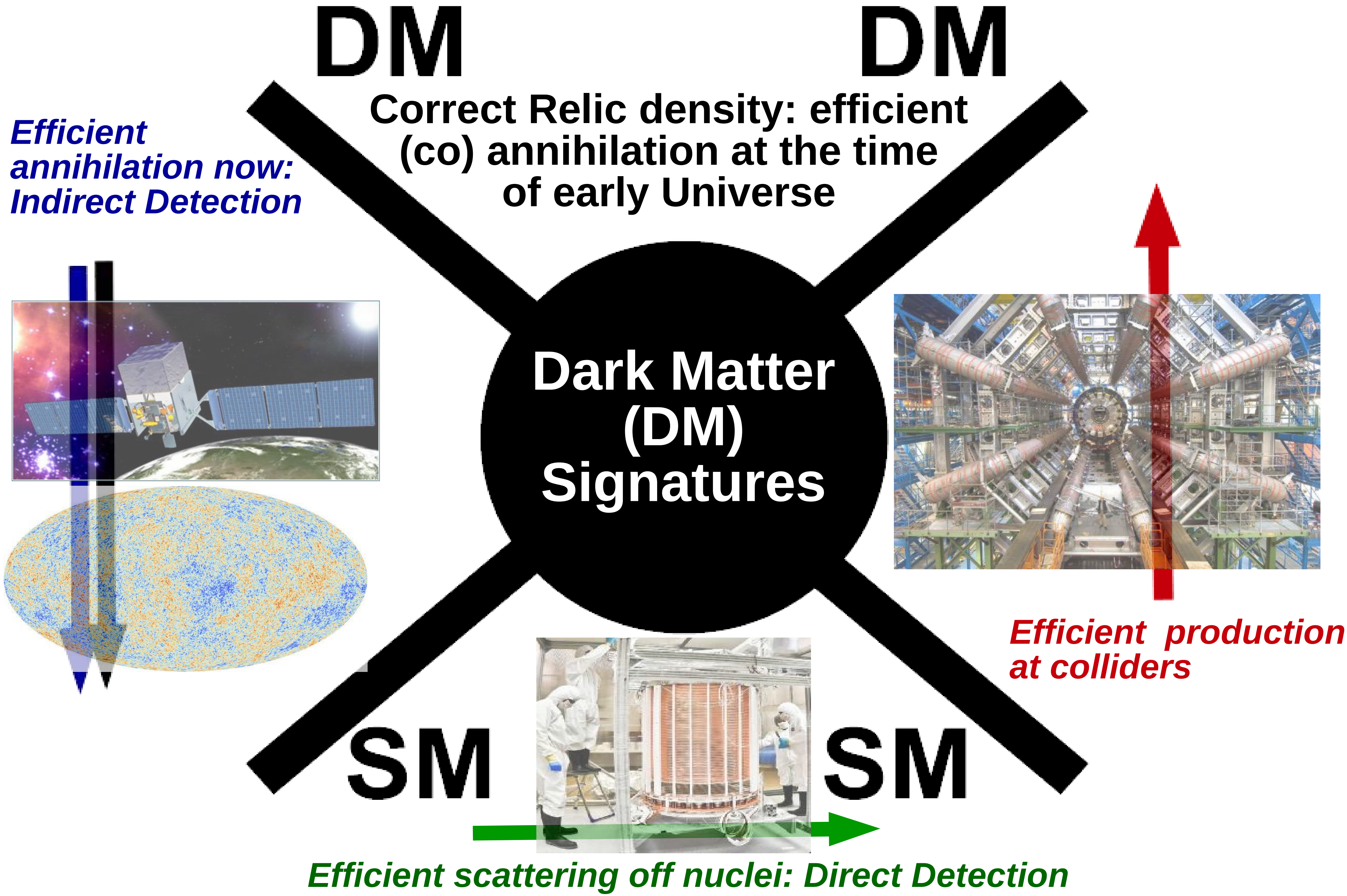
Spectrum of Theory Space



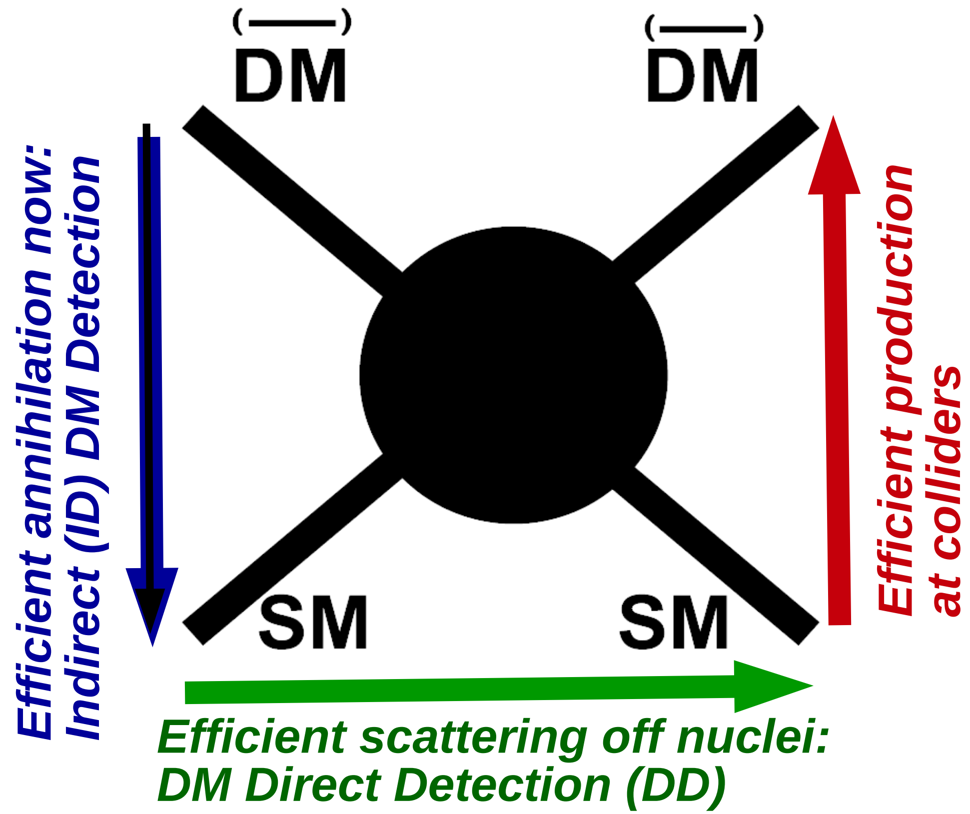
T.Tait

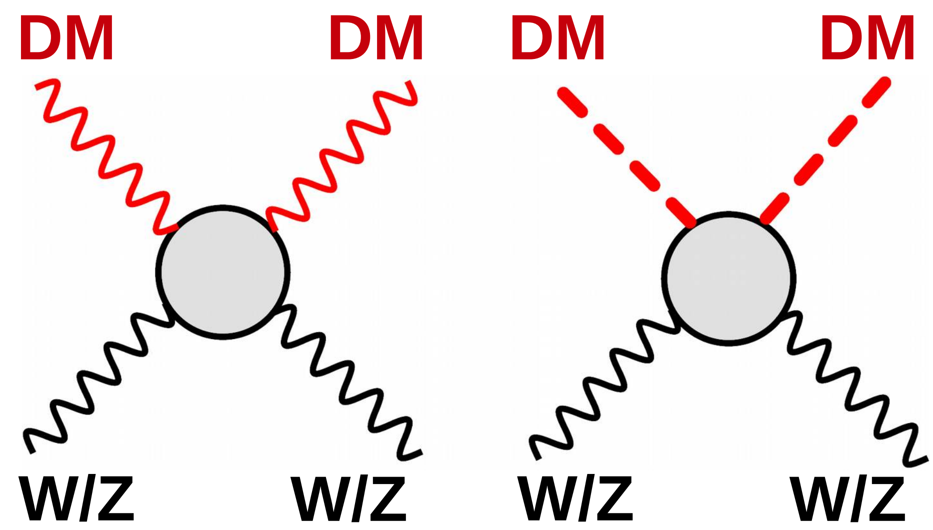
Spectrum of Theory Space




DM
DM
Correct Relic density: efficient (co) annihilation at the time of early Universe
Efficient annihilation now: Indirect Detection
Dark Matter (DM) Signatures
Efficient production at colliders
SM
SM
Efficient scattering off nuclei: Direct Detection

Complementarity of DM searches





Example of DM interactions with negligible/suppressed DD rates

Important: there is no 100%correlation between signatures above. E.g. the high rate of annihilation does not always guarantee high rate for DD!

Actually there is a great complementarity in this:

- **In case of NO DM Signal – we can efficiently exclude DM models**
- **In case of DM signal – we have a way to determine the nature of DM**

General Lagrangian with massless gauge field and massive vector (matter) field

$$
\begin{aligned}
\mathcal{L} \;=\; & -\frac{1}{2}Tr\left\{G_{\mu\nu}G^{\mu\nu}\right\} \\
& -Tr\left\{D_\mu V_\nu D^\mu V^\nu\right\} + (1+a)\,Tr\left\{D_\mu V_\nu D^\nu V^\mu\right\} \\
& +a_1 Tr\left\{\left(D_\mu V_\nu - D_\nu V_\mu\right)\left[V^\mu, V^\nu\right]\right\} \\
& +\frac{a_2}{2}Tr\left\{\left[V_\mu, V_\nu\right]\left[V^\mu, V^\nu\right]\right\} \\
& +i a_3 Tr\left\{G_{\mu\nu}\left[V^\mu, V^\nu\right]\right\} + M^2 Tr\{V_\nu V^\nu\}
\end{aligned}
$$

$$
\begin{aligned}
G_\mu &\rightarrow U G_\mu U^{-1} - \frac{1}{g}\left(\partial_\mu U\right) U^{-1} \\
V_\mu &\rightarrow U V_\mu U^{-1} \\
D_\mu V_\nu &= \partial_\mu V_\nu - i[W_\mu, V_\nu]
\end{aligned}
$$

A. Zerwekh
Int.J.Mod.Phys. A28 (2013)1350054
arXiv:1207.5233

G^μ is the gauge field, while

V_μ transforms homogeniusly under the gauge transformations, heaving the properties of the matter field

It turns out that this theory can be unitary!

$$
\begin{aligned}
\mathcal{L} &= -\frac{1}{2}Tr\left\{G_{\mu\nu}G^{\mu\nu}\right\} \\
&-Tr\left\{D_\mu V_\nu D^\mu V^\nu\right\} + (1+a)\,Tr\left\{D_\mu V_\nu D^\nu V^\mu\right\} \\
&+a_1 Tr\left\{(D_\mu V_\nu - D_\nu V_\mu)\left[V^\mu, V^\nu\right]\right\} \\
&-\frac{g^2}{2}Tr\left\{\left[V_\mu, V_\nu\right]\left[V^\mu, V^\nu\right]\right\} \\
&-igTr\left\{G_{\mu\nu}\left[V^\mu, V^\nu\right]\right\} + M^2 Tr\{V_\nu V^\nu\}
\end{aligned}
$$

$$
\begin{aligned}
a &= 0 \\
a_1 &= 0 \\
a_2 &= -g^2 \\
a_3 &= -g
\end{aligned}
$$

$$
\begin{aligned}
G_\mu &\to UG_\mu U^{-1} - \frac{1}{g}\left(\partial_\mu U\right)U^{-1} \\
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Theory with massive vector field in the adjoint representation interacting with non-abelian gauge field

$$\mathcal{L} = -\frac{1}{2}Tr\left\{G_{\mu\nu}G^{\mu\nu}\right\} - Tr\left\{D_\mu V_\nu D^\mu V^\nu\right\} + Tr\left\{D_\mu V_\nu D^\nu V^\mu\right\}$$
$$-\frac{g^2}{2}Tr\left\{\left[V_\mu, V_\nu\right]\left[V^\mu, V^\nu\right]\right\} - igTr\left\{G_{\mu\nu}\left[V^\mu, V^\nu\right]\right\} + M^2 Tr\{V_\nu V^\nu\}$$

- there is a consistent gauge theory for a massive spin-1 field without scalar degrees of freedom
- Unitarity requires no trilinear V interactions:
  the massive spin-1 field is odd under a new **Z_2 symmetry**
- The massive vector is not a force carrier but a true matter filed
- The theory has bi-gauge origin (see backup slides for details)

The Minimal Isotriplet Vector Dark Matter Model (MI VDM)

$$\begin{aligned}\mathcal{L} &= \mathcal{L}_{SM} - Tr\left\{D_\mu V_\nu D^\mu V^\nu\right\} + Tr\left\{D_\mu V_\nu D^\nu V^\mu\right\} \\ &-\frac{g^2}{2} Tr\left\{\left[V_\mu, V_\nu\right]\left[V^\mu, V^\nu\right]\right\} - igTr\left\{W_{\mu\nu}\left[V^\mu, V^\nu\right]\right\} + \tilde{M}^2 Tr\{V_\nu V^\nu\}\end{aligned}$$

$$D_\mu V_\nu = \partial_\mu V_\nu - i[W_\mu, V_\nu]$$

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$$\mathcal{L} = \mathcal{L}_{SM} - Tr\left\{D_\mu V_\nu D^\mu V^\nu\right\} + Tr\left\{D_\mu V_\nu D^\nu V^\mu\right\}$$
$$-\frac{g^2}{2} Tr\left\{[V_\mu, V_\nu][V^\mu, V^\nu]\right\} - igTr\left\{W_{\mu\nu}[V^\mu, V^\nu]\right\} + \tilde{M}^2 Tr\{V_\nu V^\nu\}$$
$$+a\left(\Phi^\dagger\Phi\right) Tr\{V_\nu V^\nu\}$$

we must add interactions with Φ Higgs doublet

$$D_\mu V_\nu = \partial_\mu V_\nu - i[W_\mu, V_\nu]$$
$$M_V^2 = \tilde{M}^2 + \frac{1}{2} a v^2$$

only two parameters: **a** and **M**

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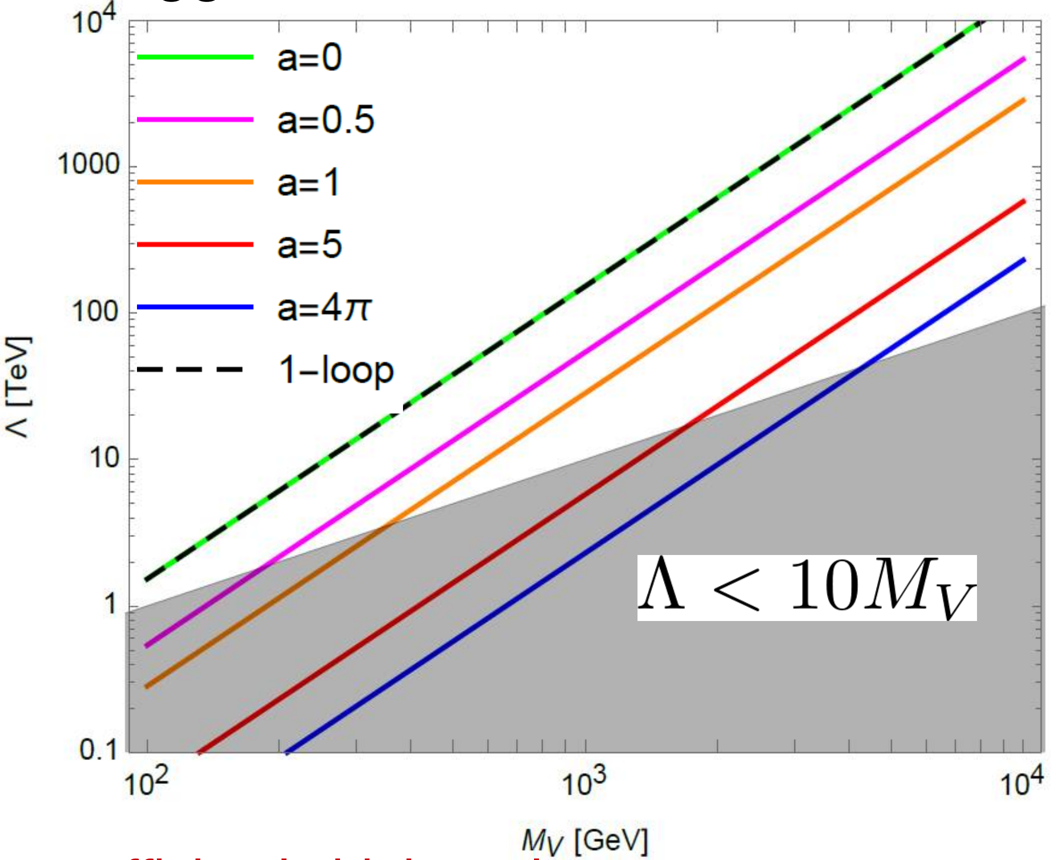
only two parameters: **a** and **M**

- due to the V-H interaction, Unitarity became an issue:

$$V_L^+ V_L^- \to V_L^+ V_L^- \qquad |a_0| < 1/2$$

$$\Lambda \approx \frac{8\sqrt{\pi} M_V^2}{\sqrt{4a^2 v^2 + 3g^2 M_W^2}}$$



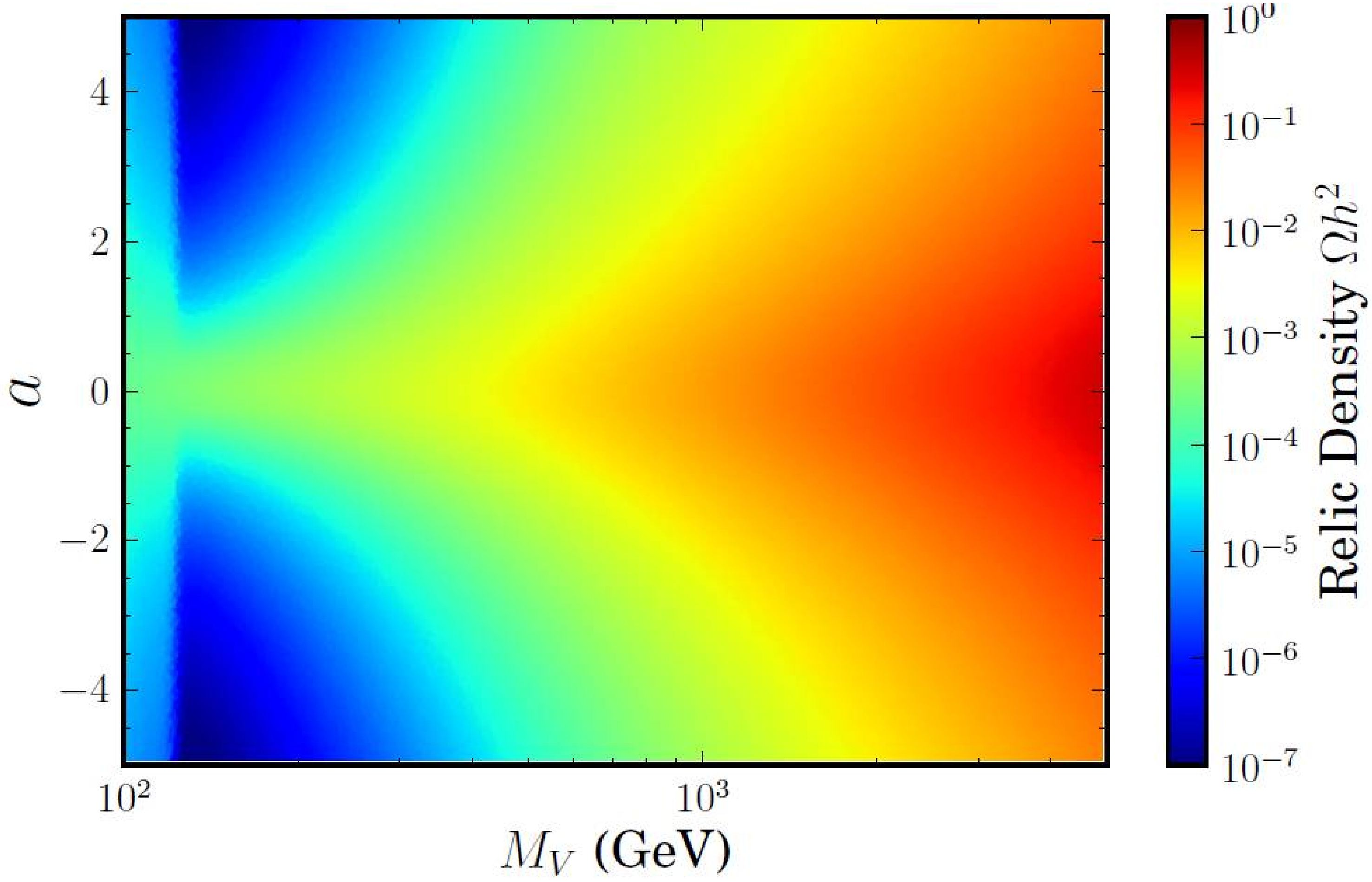
For M_V > 2TeV, unitarity violation occurs at sufficiently high scales

Phenomenology of MI VDM

- The model is implemented into CalcHEP package using LanHEP
  - DM observables with micrOMEGAs
  - DM Collider phenomenology with CalcHEP
  - Available at HEPMDB (hepmdb.soton.ac.uk) as hepmdb:0118.0283 model

- Main relevant observables/constraints:
  - DM relic density
  - DM direct detection (XENON1T)
  - Collider observables
    - disappearing charged tracks from V^+ due to the small V^0-V^+ mass split
    - from $H \to \gamma\gamma$ decay branching ratio

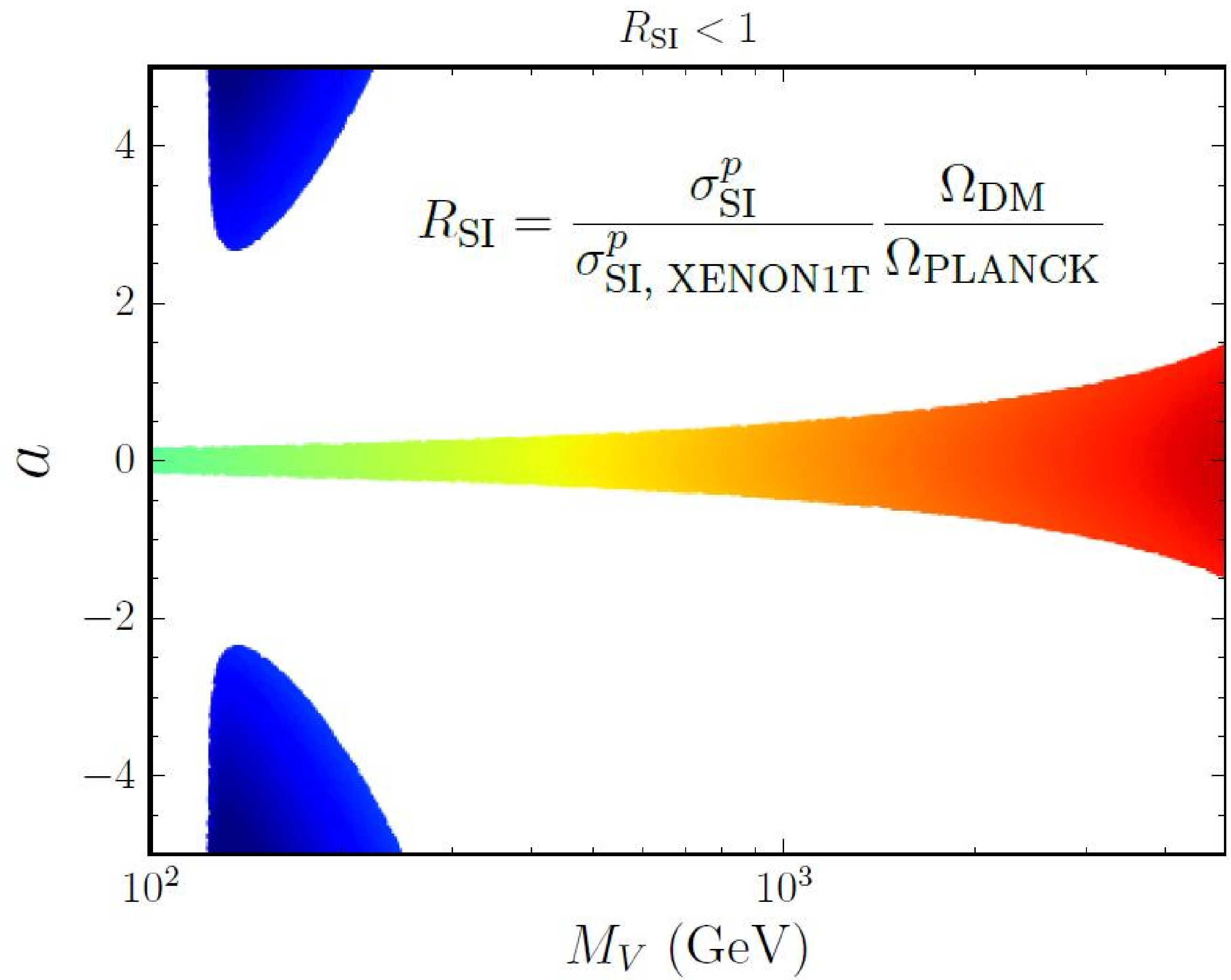
The probe of MI VDM parameter space



The relic density map in M_V-a parameter space

The probe of MI VDM parameter space

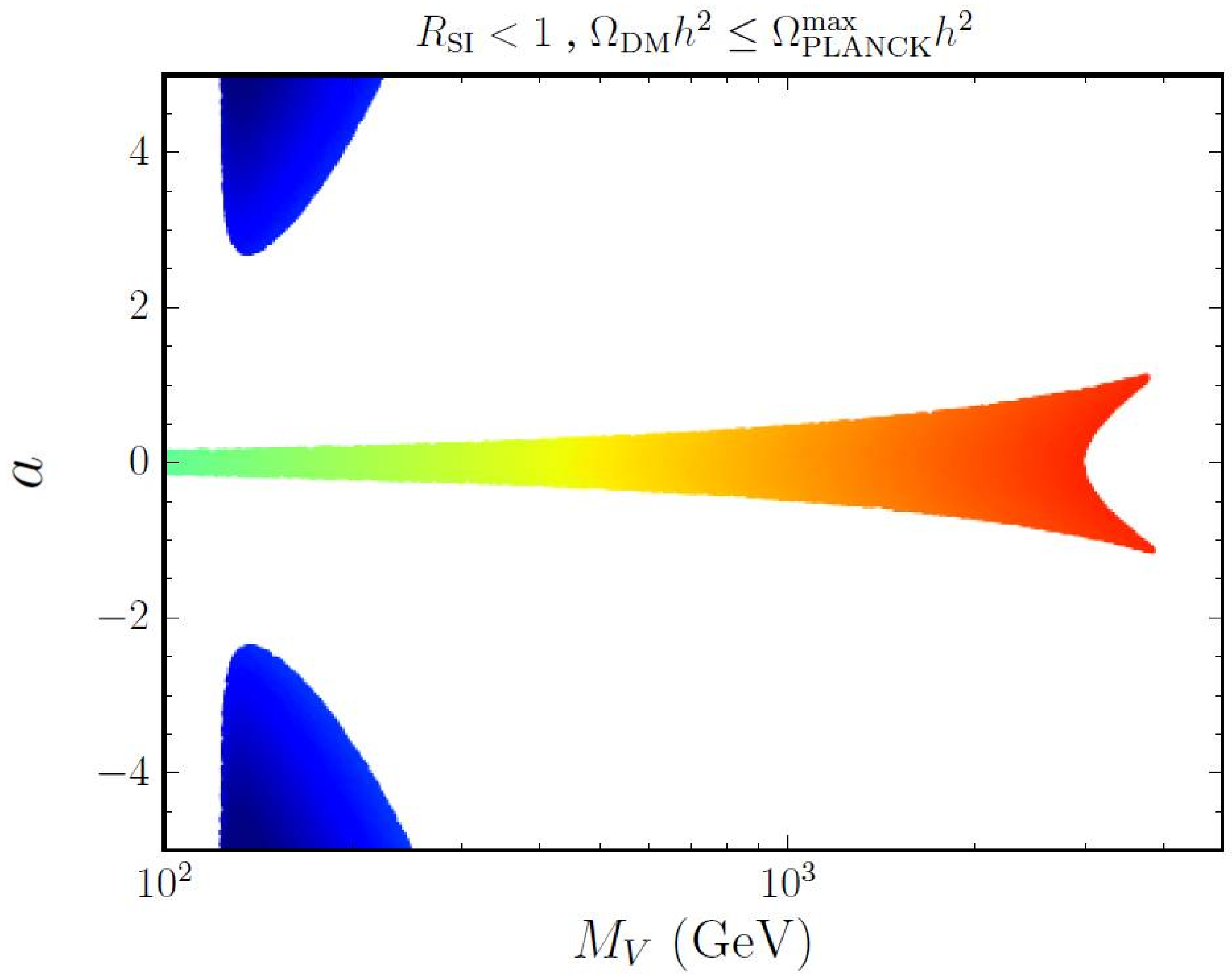
The relic density map in M_V-a parameter space



DM DD constraints from XENON1T: limiting HVV interactions

The probe of MI VDM parameter space

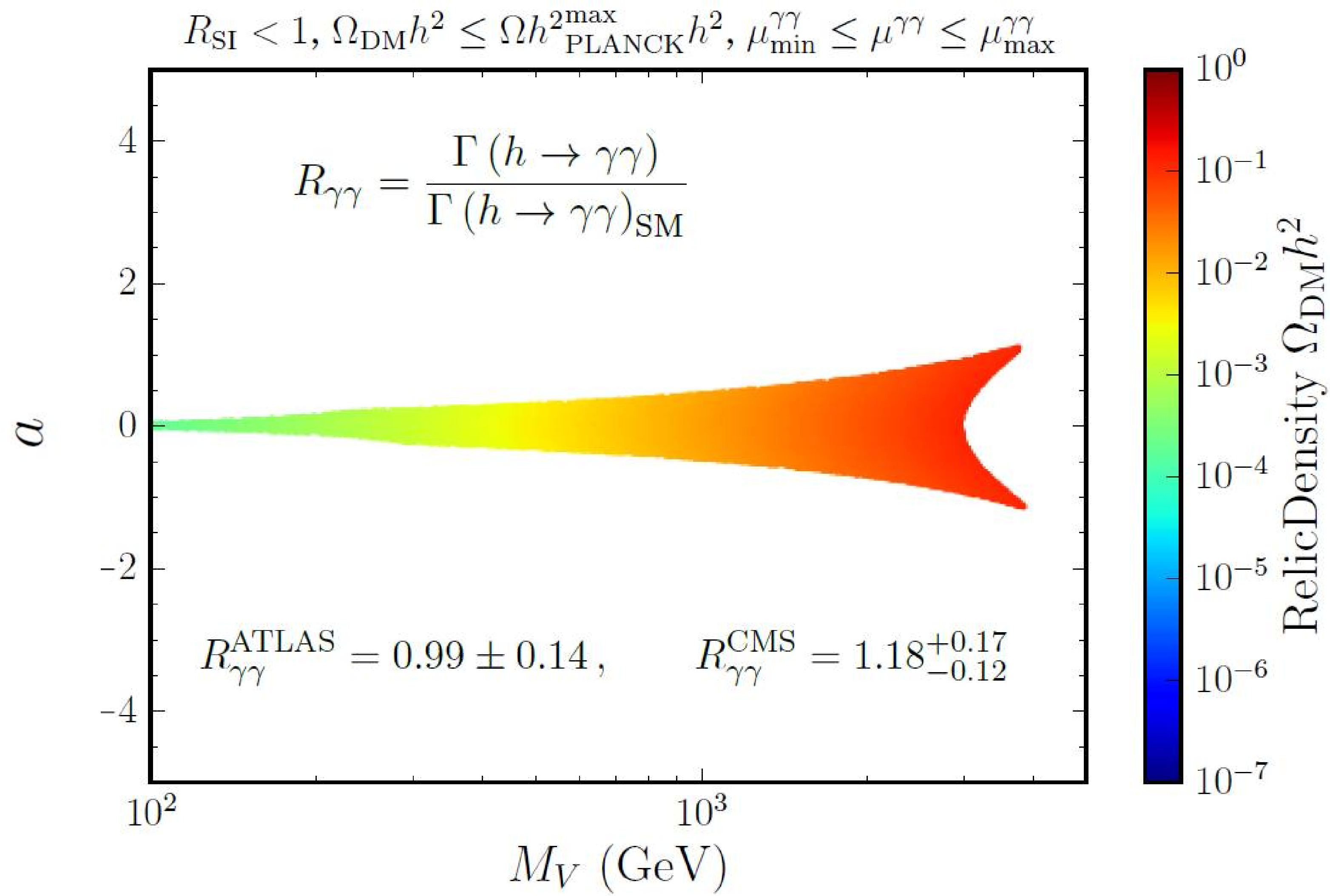
The relic density map in M_V-a parameter space



Relic density constraints from PLANCK: an upper limit on DM mass

The probe of MI VDM parameter space

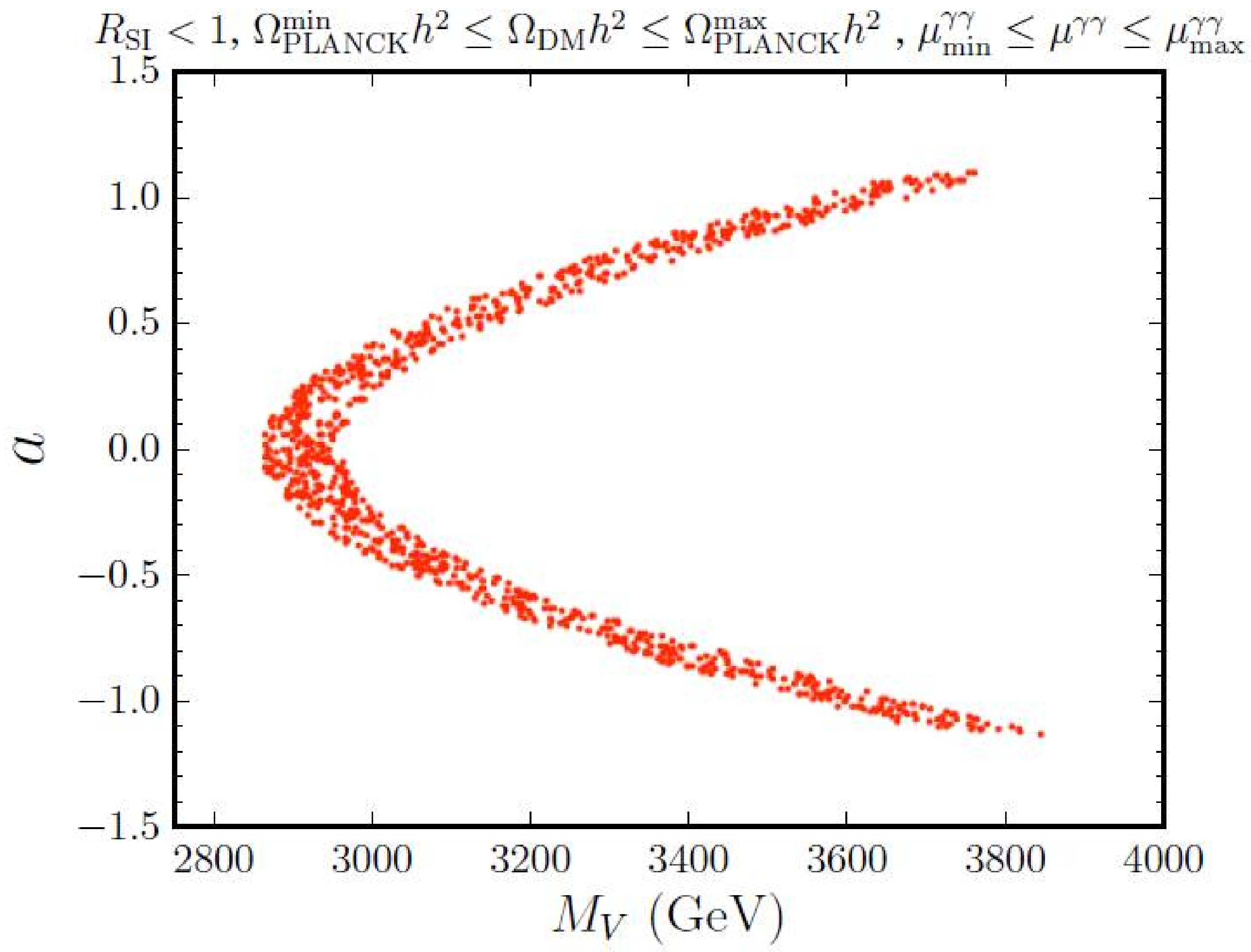
The relic density map in M_V-a parameter space



$H \to \gamma\gamma$ constraints from LHC: eliminates large a & low M_V region

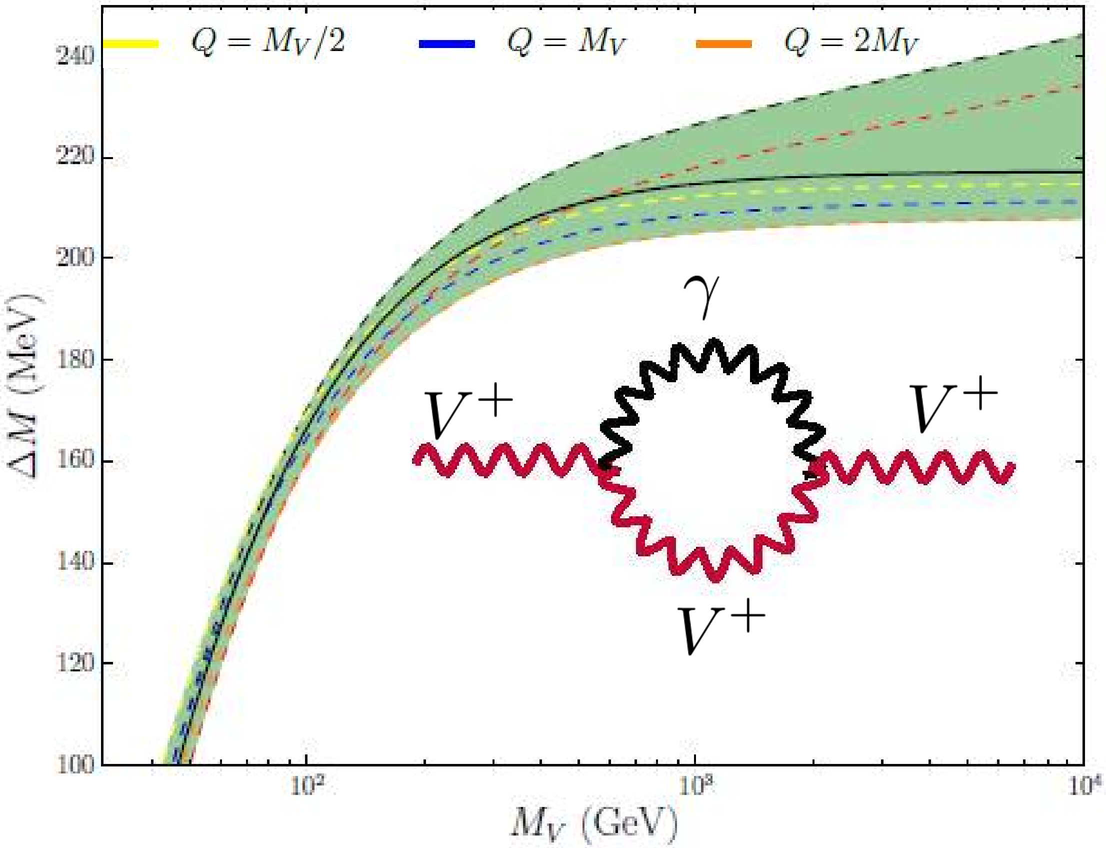
Upper and lower limit on DM mass!

application of upper and lower PLANCK limits on relic density



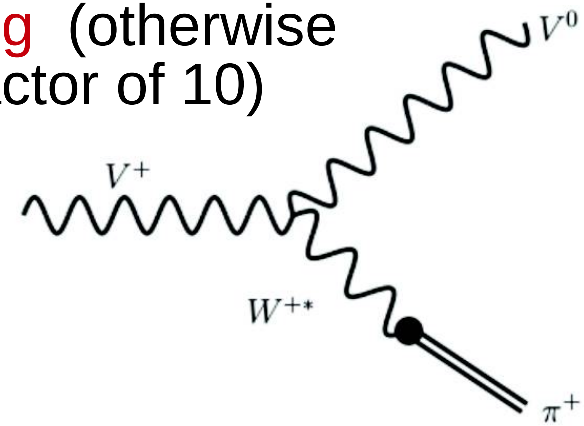
we have found narrow region for viable DM mass: 2.8-3.8 TeV
Can we probe it?

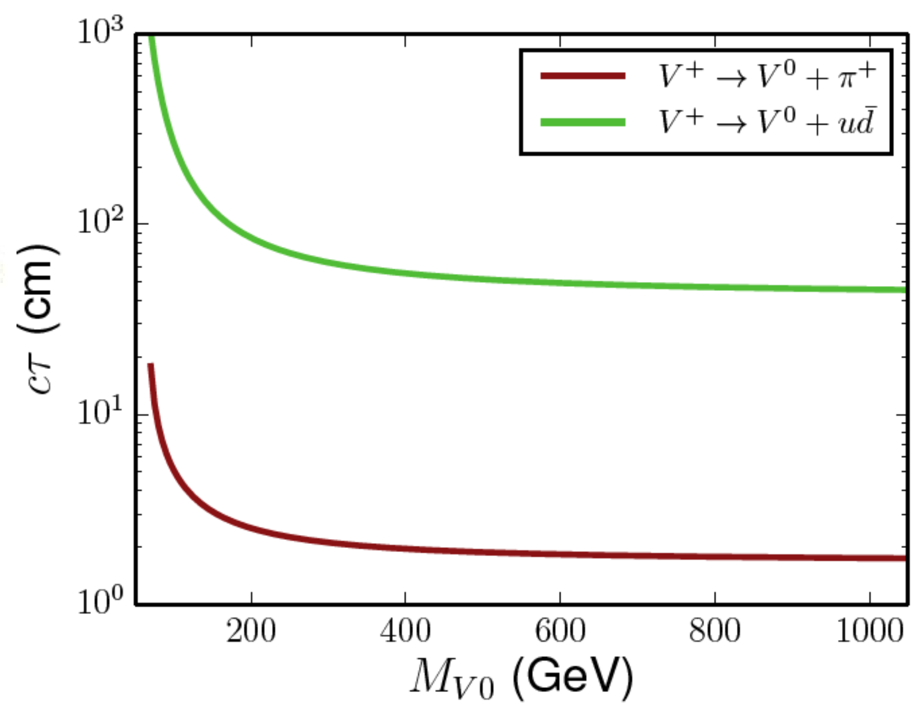
Disappearing Charged tracks from MI VDM



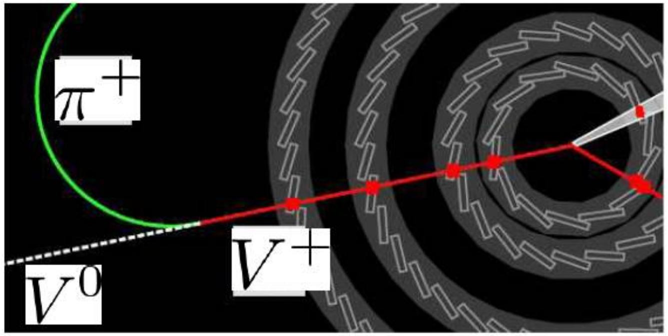
The small mass gap due to radiative mass corrections (~200MeV ~ pion mass) between DM and its charged partner will lead to the disappearing charge tracks signatures

The life-time should be properly evaluated using W-pion mixing (otherwise overestimated by factor of 10)

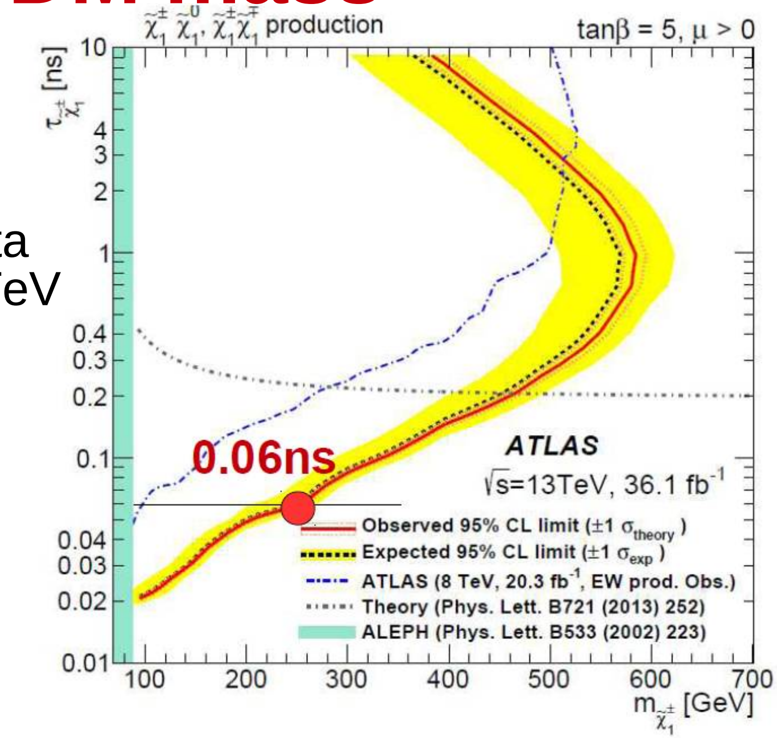




Collider sensitivity to VDM mass

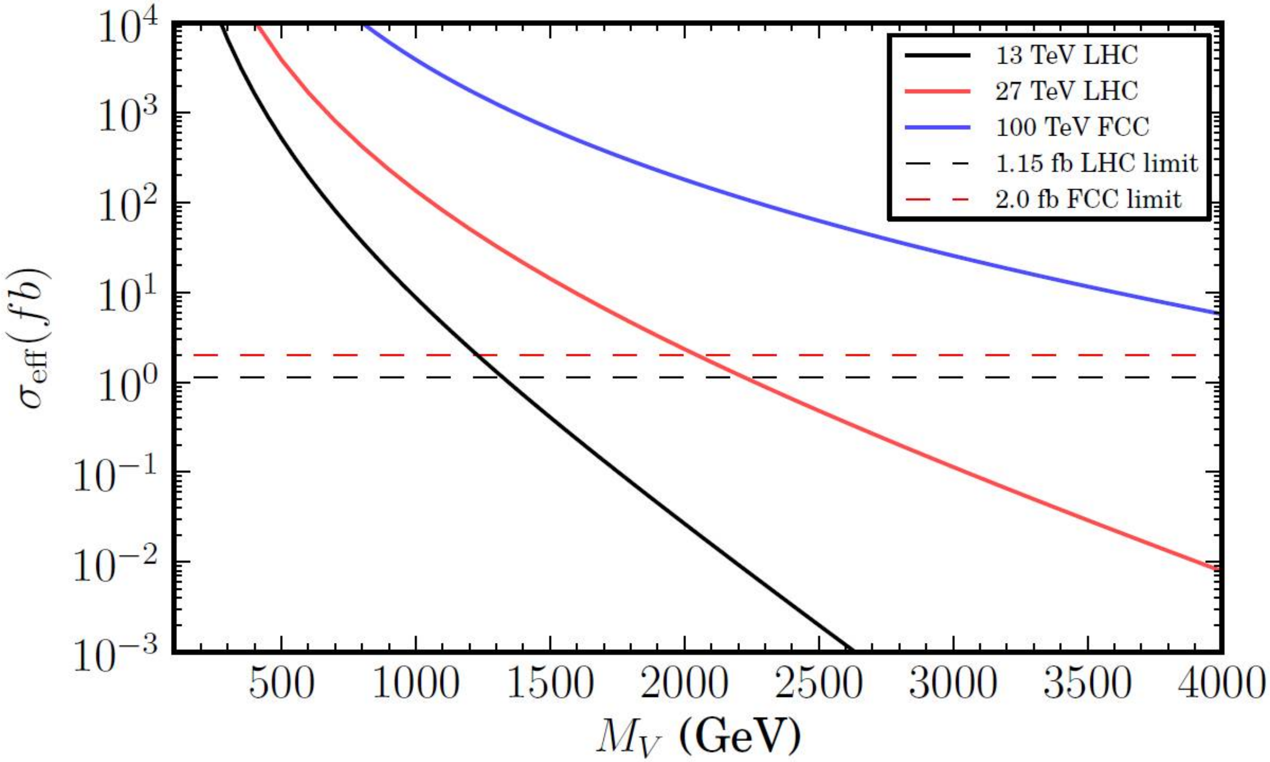


using ATLAS arXiv:1712.02118 for LHC interpretation and Mahbubani,Schwaller, Zurita arXiv:1703.05327 for 100 TeV FCC projections



AB, Cacciapaglia, McKay, Martin, Zerwekh arXiv:**1808.10464**

LHC@13, @27TeV and FCC@100 TeV constraints from LLP searches



Current bound from LHC on DM mass from the minimal vector triplet model: **1.3 TeV** !

100 TeV FCC will cover DM mass **beyond 4 TeV:** will discover or close the model

Summary

➪we have build an extension of the SM with the new massive spin-one isotriplet field with only two new parameters: M_V and V coupling to H

➪perturbative unitarity, requires new Z_2 symmetry (so it is motivated by theory and not imposed by hand), making V^0 a DM candidate

➪If DM has a mass in the range 2.8-3.8TeV, the model explains the measured DM relic density and simultaneously satisfies complementary current experimental constraints

➪Spectacular feature of V^+ – long lifetime due to a small (radiative) mass split with V^0 , providing disappearing tracks signature

➪ future hadron collider with a centre-of-mass energy of 100TeV will probe masses beyond 4TeV – completely covering the allowed parameter space of the model with disappearing tracks signature.

So, we have an opportunity to discover or exclude the model

Thank you!

Backup Slides

A bi-gauge origin of the theory with massive vector field

A simple rotation

$$G = \frac{1}{\sqrt{2}}(A1 + A2)$$

$$V = \frac{1}{\sqrt{2}}(A1 - A2)$$

$$\mathcal{L} = -\frac{1}{2}Tr\left[F_{1\mu\nu}F_1^{\mu\nu}\right] - \frac{1}{2}Tr\left[F_{2\mu\nu}F_2^{\mu\nu}\right] + \frac{M^2}{2}Tr\left[\left(A_{1\mu} - A_{2\mu}\right)^2\right]$$

$$F_{1\mu\nu} = \partial_\mu A_{1\nu} - \partial_\nu A_{1\mu} - i\sqrt{2}g\left[A_{1\mu}, A_{1\nu}\right]$$

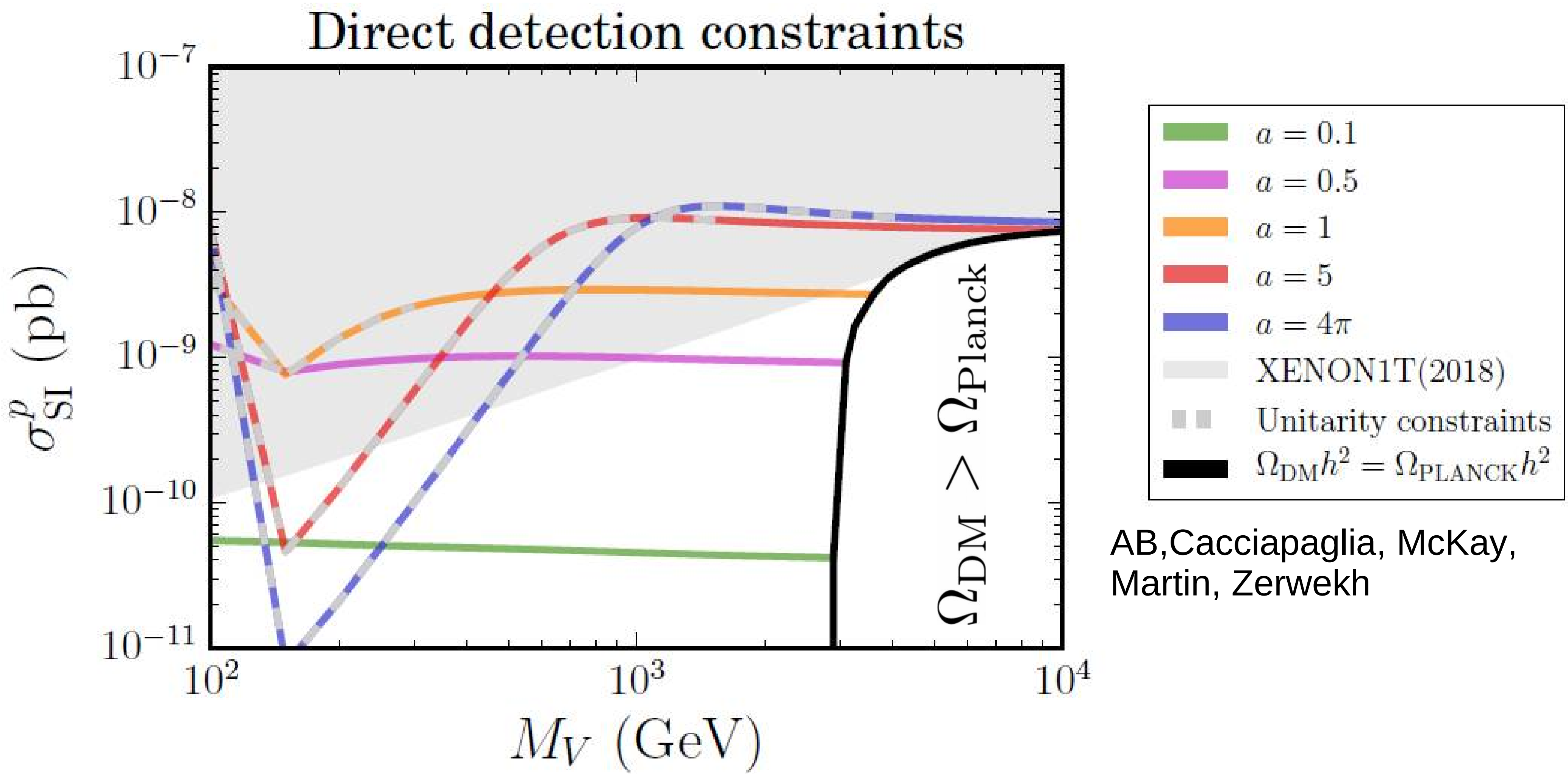
Same coupling constant

$$F_{2\mu\nu} = \partial_\mu A_{2\nu} - \partial_\nu A_{2\mu} - i\sqrt{2}g\left[A_{2\mu}, A_{2\nu}\right]$$

$$A_{i\mu} \to U A_{i\mu} U^{-1} - \frac{1}{\sqrt{2}g}(\partial_\mu U)U^{-1} \quad (i = 1, 2)$$

Power of DM DD to rule out theory space

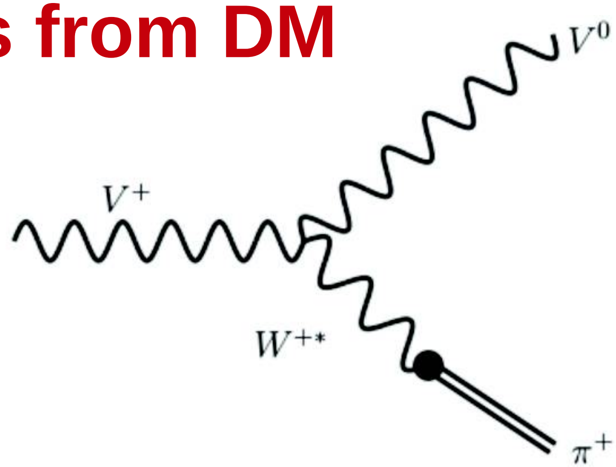
Vector DM Model



AB,Cacciapaglia, McKay, Martin, Zerwekh

- ZENON 1T excludes **both** large $HV_{DM}V_{DM}$ couplings and large M_{DM}
- The **lower masses** (rest of space) can be covered at future colliders

Disappearing Charged Tracks from DM



The small mass gap between (~ pion mass) DM and its charged partner will lead to the disappearing charge tracks

The life-time should be properly evaluated using W-pion mixing

$$\mathcal{L}_{\pi^- V^+ V^0} = \frac{g^2 f_\pi}{2\sqrt{2} M_W^2} [(p_{V^+} - p_{V^0})_\alpha g_{\beta\gamma} + p_{V^0\beta} g_{\alpha\gamma} - p_{V^+\gamma} g_{\alpha\beta}] p^\alpha_{\pi^-} \pi^- V^{+\beta} V^{0\gamma}$$