The warped dark sector

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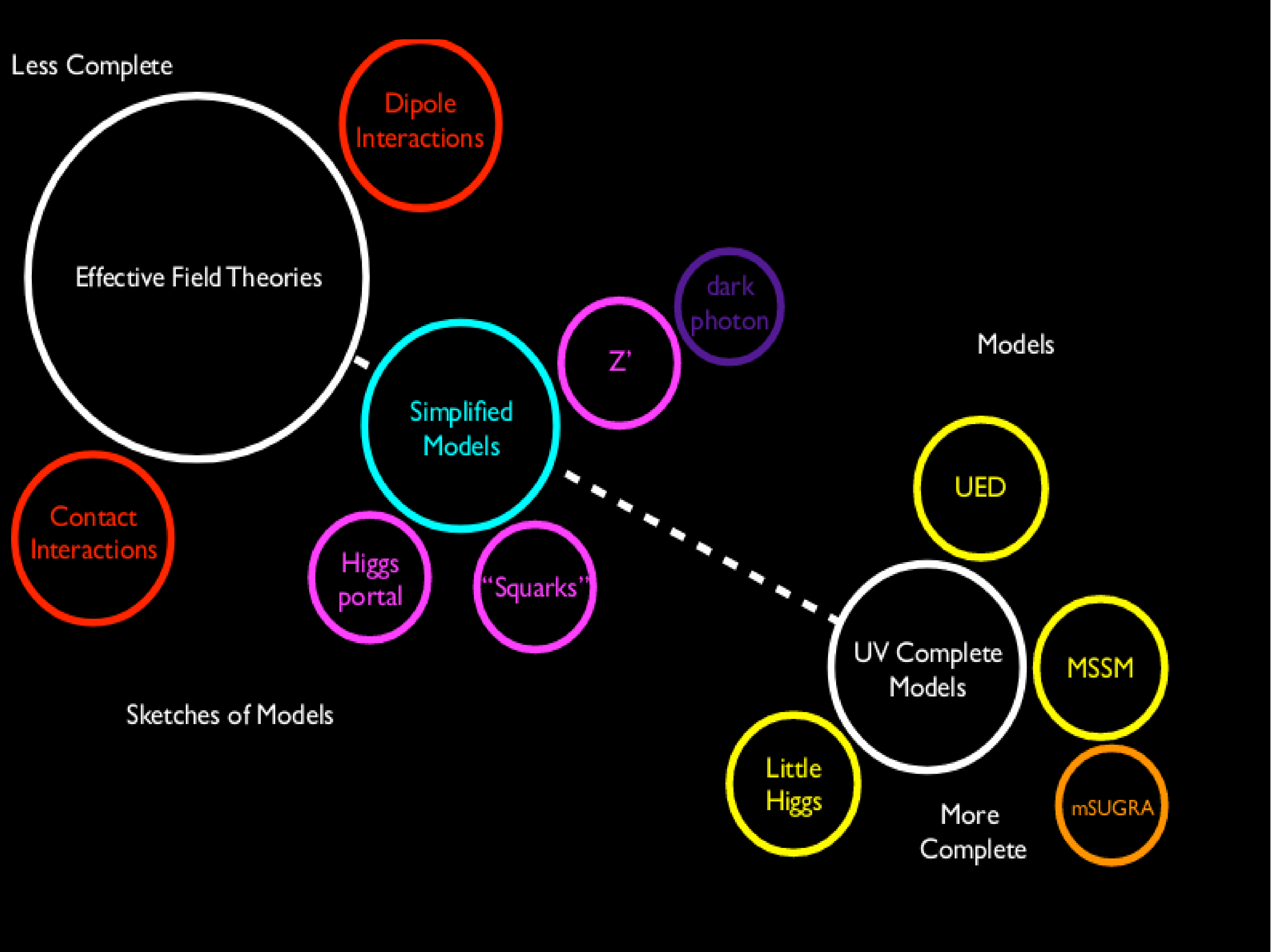
Based on

1906.02199 (with P. Brax, F. Tanedo)

Seattle 08/15/2019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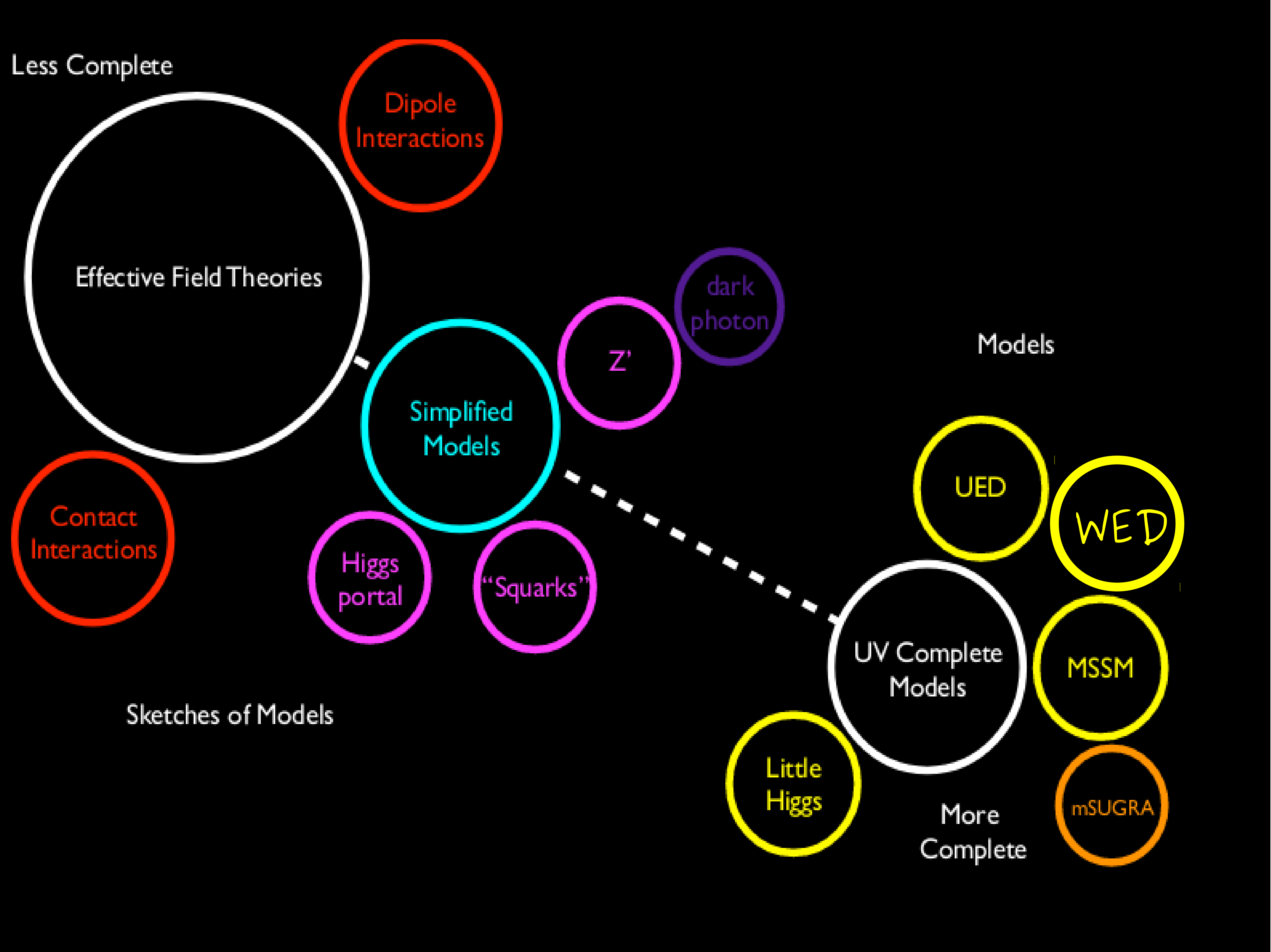
Dipole Interactions
Effective Field Theories
dark photon
Z'
Models
Simplified Models
UED
Contact Interactions
Higgs portal
"Squarks"
UV Complete Models
MSSM
Sketches of Models
Little Higgs
More Complete
mSUGRA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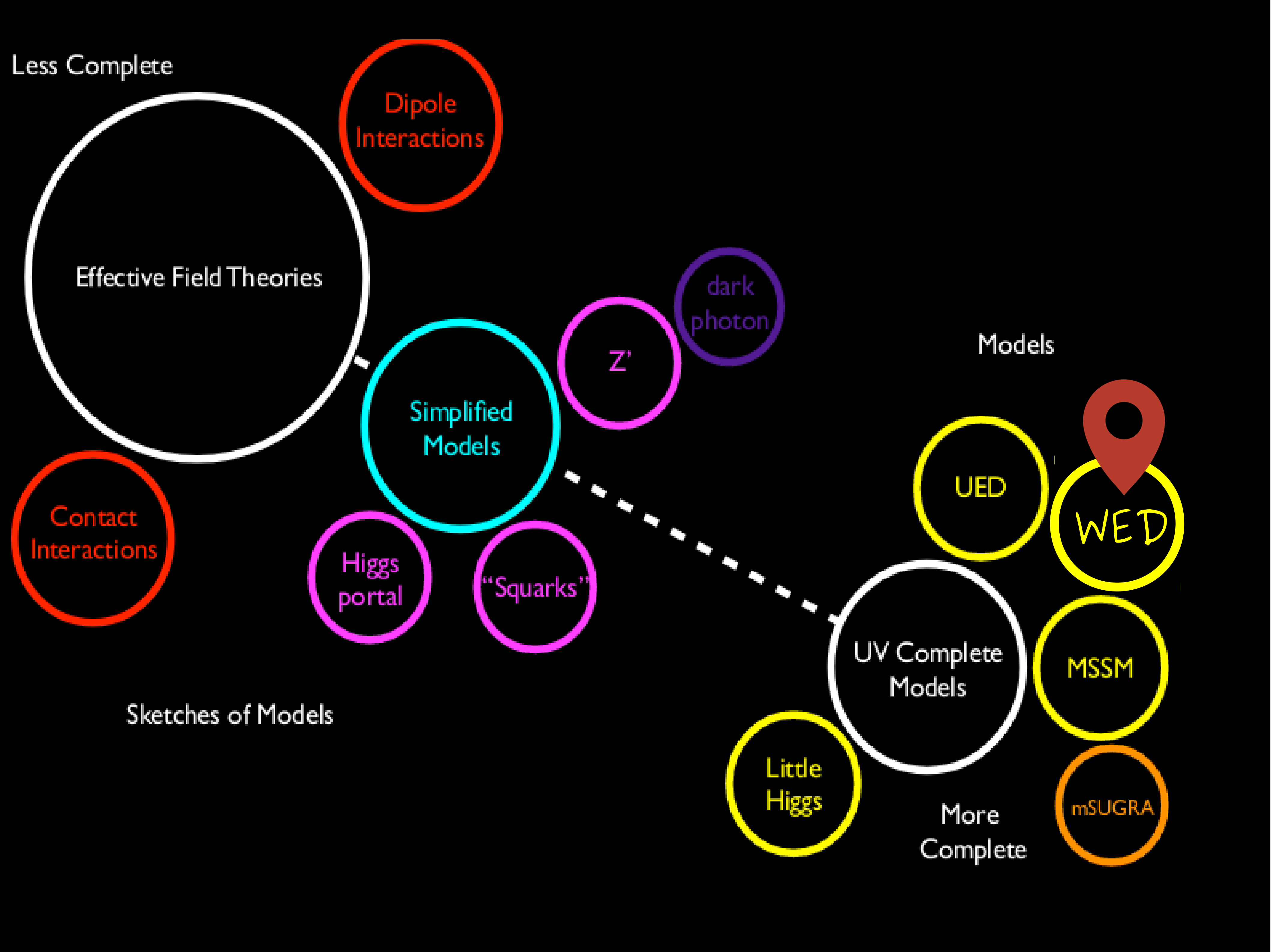
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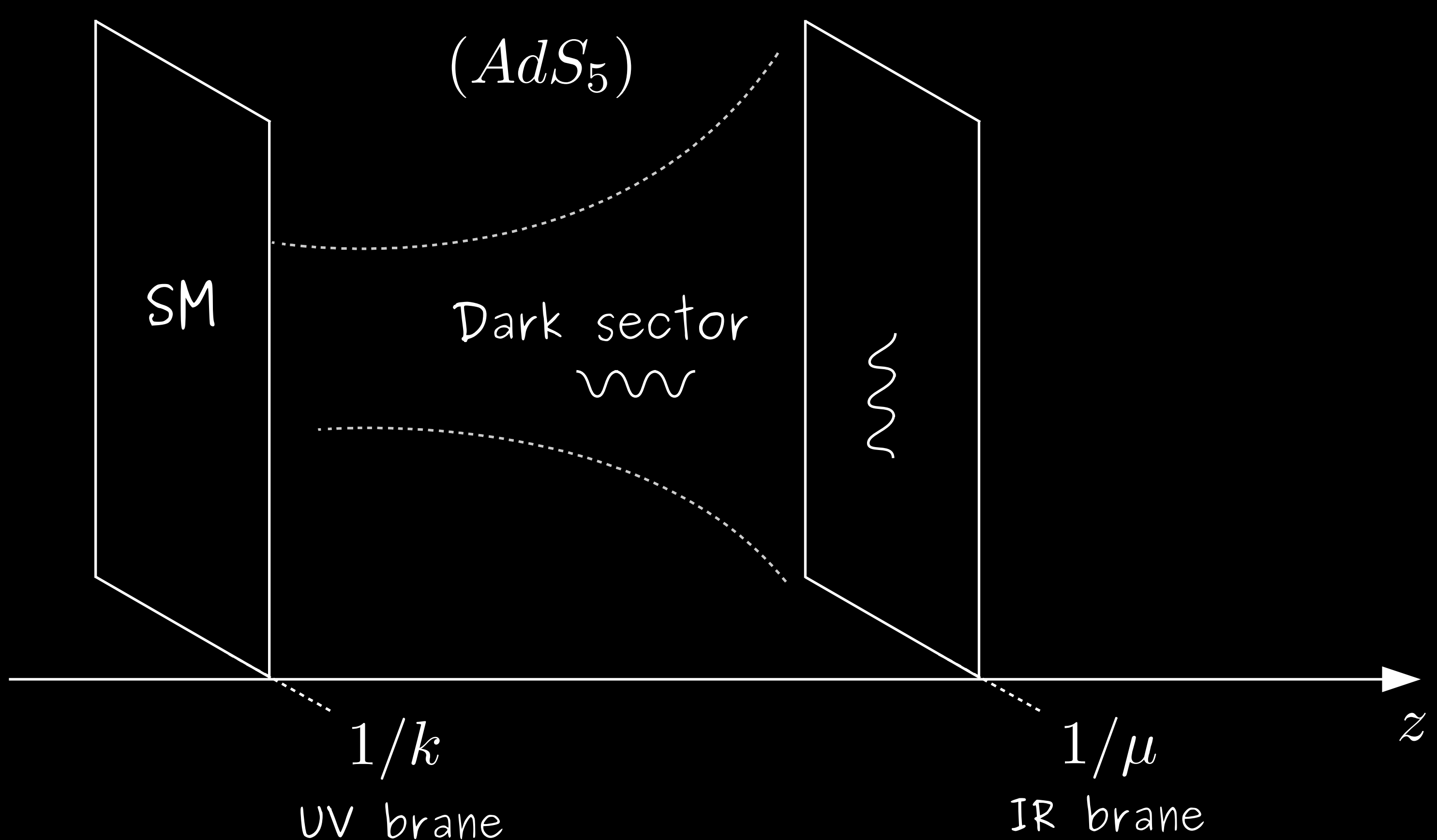
Today's focus

- Only the big picture, nothing too technical

- Will highlight aspects of the model relevant for the topics discussed at the workshop. Right now these aspects are not very developed, but this is an opportunity for further discussion/work

The warped dark sector



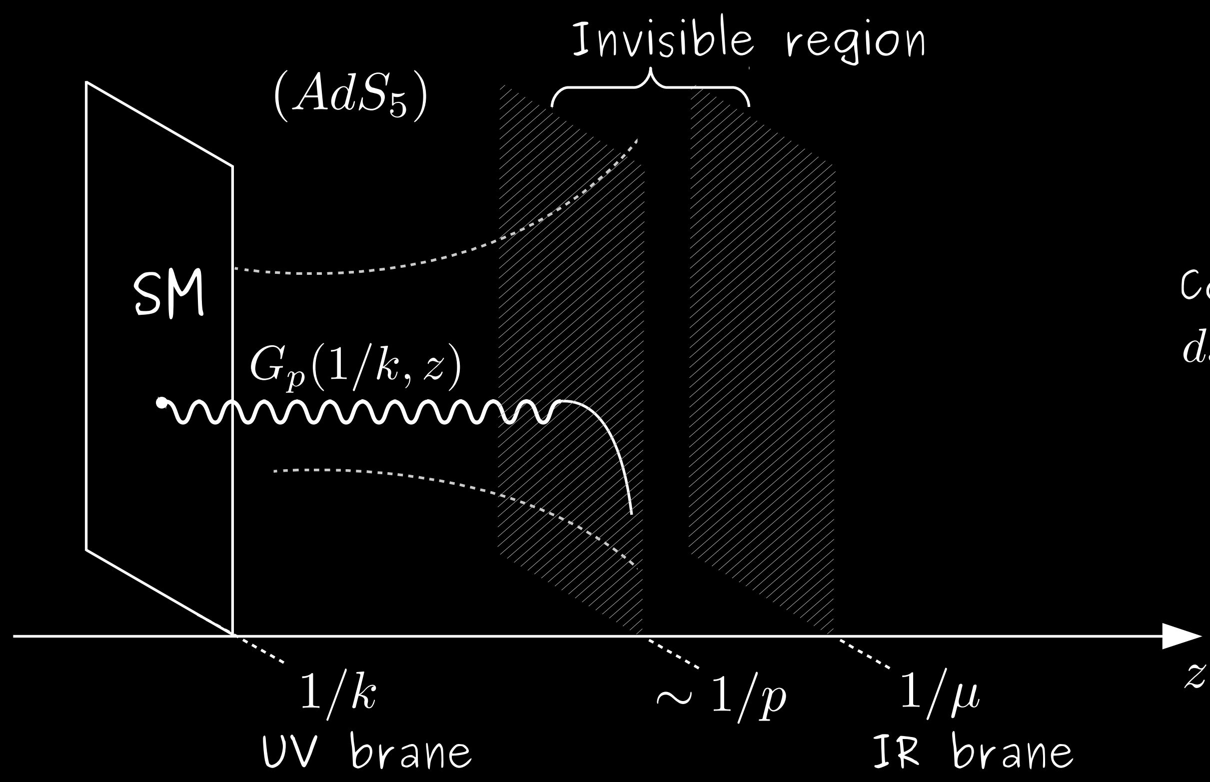
Metric (conformal coordinates): $ds^2 = (kz)^{-2}(\eta_{\mu\nu}x^\mu x^\nu - dz^2)$

Some context

- Not like a Randall-Sundrum model
- Reminiscent of braneworlds (RSII), but here with bulk matter and an IR brane.
- Recent dark sector works with flat extra dimensions [Rizzo '18, '19]...
- Only a few works exist in warped extra dimensions
  [von Harling/McDonald '12, McDonald '12, McDonald/Morrisey '11, '12]
- Extra motivation: the model is the AdS dual of a 4d strongly interacting dark sector

IR opacity

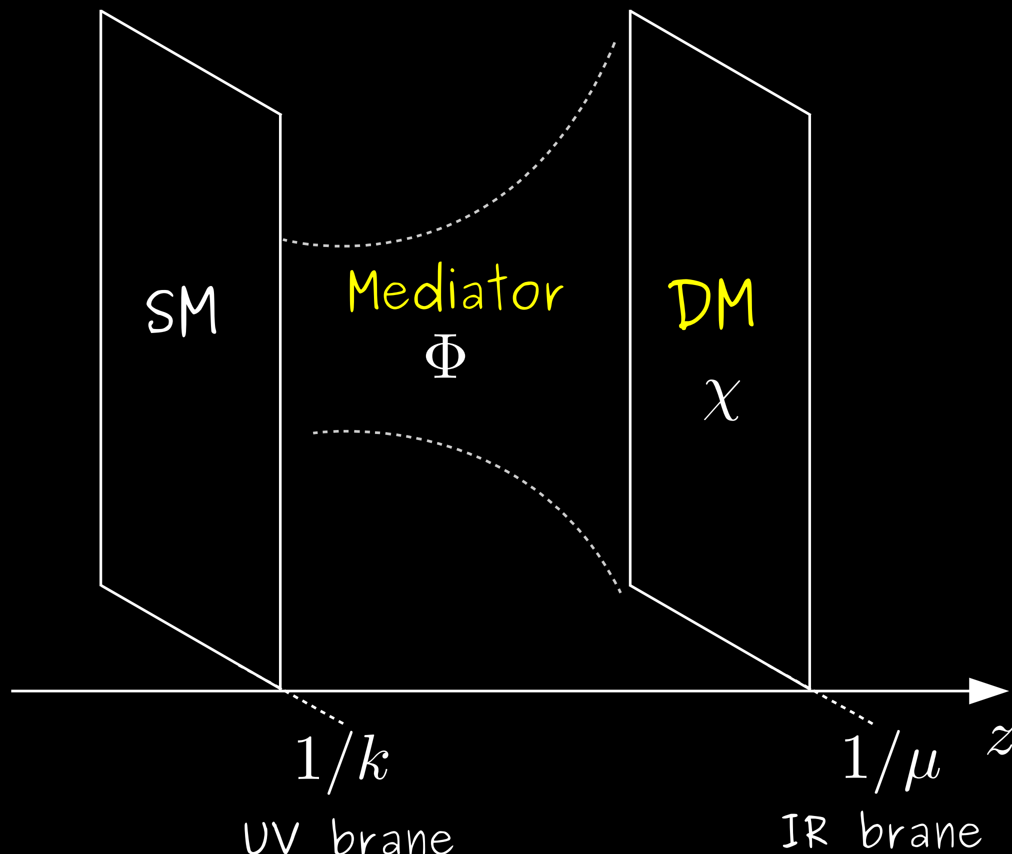
In conformal coordinates, consider UV-brane-to-bulk propagator $G_p(1/k, z)$, with $p = \sqrt{p_\mu p^\mu}$. In the IR region $p \gtrsim 1/z$, $G_p(1/k, z)$ is exponentially suppressed. [Gherghetta/Pomarol '03, SF '19]



Coordinates:
$ds^2 = (kz)^{-2}(\eta_{\mu\nu}x^\mu x^\nu - dz^2)$

Hence any field/operator localized near the IR brane is effectively "emergent" from the UV-brane standpoint. (No such effect in flat space)

Dark matter model



IR scale μ sets the dark sector mass scale and is the main parameter

To be concrete:

SM = quarks

Φ = scalar

χ = Dirac

$\mathcal{O}_{\rm SM} = \bar{N}N(\bar{q}q)$

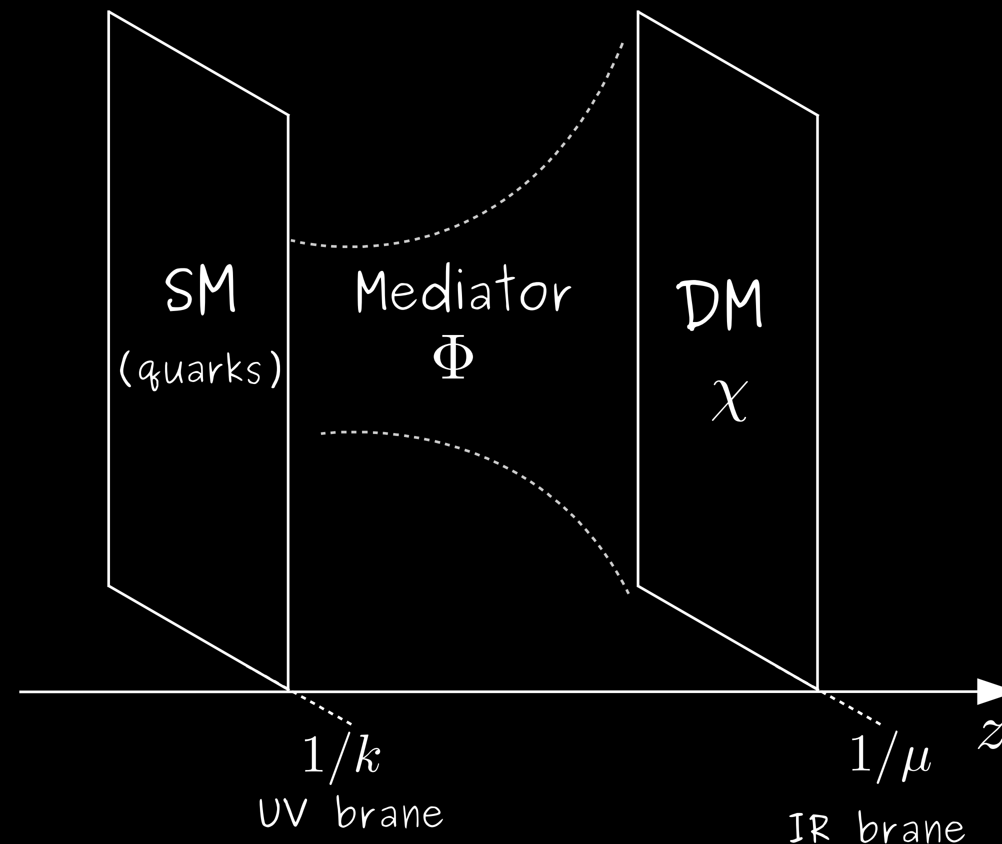
$\mathcal{O}_{\rm D} = \bar{\chi}\chi$

$k \sim M_{\rm Pl}$

$$S \supset \int_{\rm bulk} d^5X\sqrt{|g|}\left(\frac{1}{2}\partial_M\Phi\partial^M\Phi - \frac{m_\Phi^2}{2}\Phi^2\right) + \int_{\rm UV} d^4X\sqrt{|\gamma|}\left(\mathcal{L}_{\rm SM} + \frac{\lambda}{\sqrt{k}}\mathcal{O}_{\rm SM}\Phi - \frac{m_{\rm UV}}{2}\Phi^2\right) + \int_{\rm IR} d^4X\sqrt{|\gamma|}\left(\mathcal{L}_{\rm IR} + \frac{\kappa}{\sqrt{k}}\mathcal{O}_{\rm D}\Phi - \frac{m_{\rm IR}}{2}\Phi^2\right).$$

Dark matter model

- Low-energy (i.e. 4d) regime $|p| < \mu$



KK modes of Φ are integrated out, giving a familiar 4d DM effective theory, with $O(\mu)$ cutoff.

4d EFT: $$\mathcal{L}_{4d} \sim \lambda^2 \frac{\varepsilon^{2-2\alpha}}{\mu^2} (\mathcal{O}_{\rm SM})^2 + \lambda\kappa \frac{\varepsilon^{1-\alpha}}{\mu^2} \mathcal{O}_{\rm SM}\mathcal{O}_{\rm D} + \kappa^2 \frac{1}{\mu^2} (\mathcal{O}_{\rm D})^2 + \dots$$

$\mathcal{O}_{\rm SM} = \bar{N}N\,, \dots$

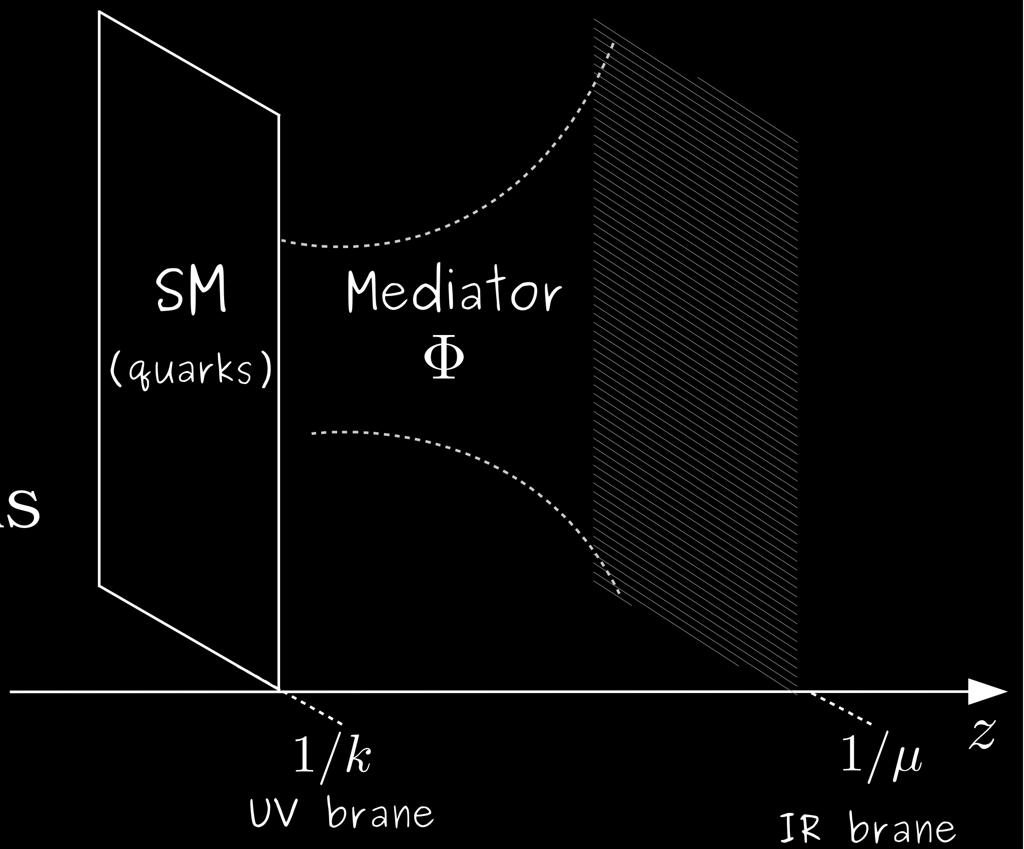
$\mathcal{O}_{\rm D} = \bar{\chi}\chi\,, \dots$

$\lambda, \kappa = O(1)$

$\varepsilon \equiv \mu/k \ll 1$ Warp factor. With e.g. $k \sim M_{\rm p}$

$\alpha \in [0, 1]$ Controls Φ localization. $\alpha = \sqrt{4 + m_\Phi^2/k^2}$

Dark matter model



- High-energy (i.e. 5d) regime $|p| > \mu$

DM vanishes from the amplitudes.
Amplitudes can be described by pure AdS with only mediator and SM as dofs,

E.g. $\mathcal{A}(N\chi \to N\chi) \sim e^{-|p|/\mu}$
for $|p| > \mu$

$\rightarrow$ Dark matter observational complementarity is non-standard!

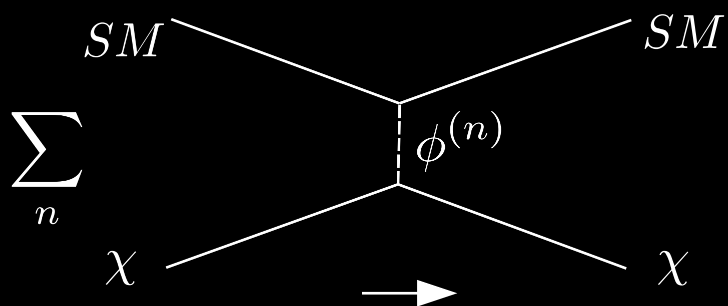
Exact holographic dual:
with $\Delta_{\rm CFT} = 2 - \alpha$
(Δ^- branch, valid for $\alpha \leq 1$)

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm CFT} + \frac{1}{M^{\Delta_{CFT}-1}} \mathcal{O}_{\rm SM} \mathcal{O}_{\rm CFT}$$

Dark matter complementarity

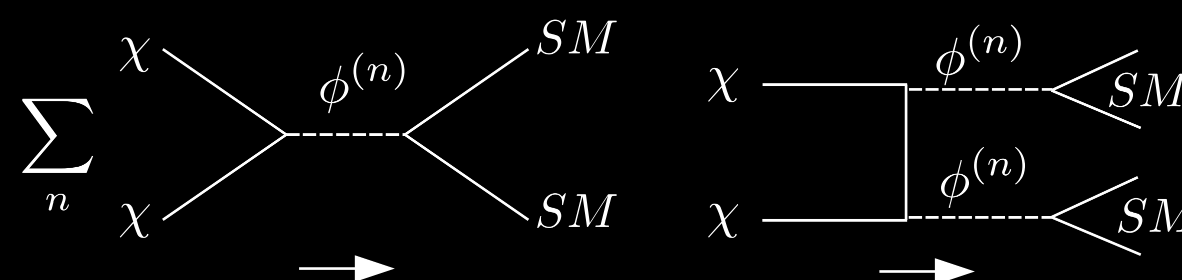
Let's take the 4d viewpoint $\Phi = \sum_n f_n(z)\phi^{(n)}(x^\mu)$. We have a tower of mediators (i.e. the KK modes) starting at mass $O(\pi\mu)$. Assume $m_\chi \sim 4\pi\mu$

Direct detection



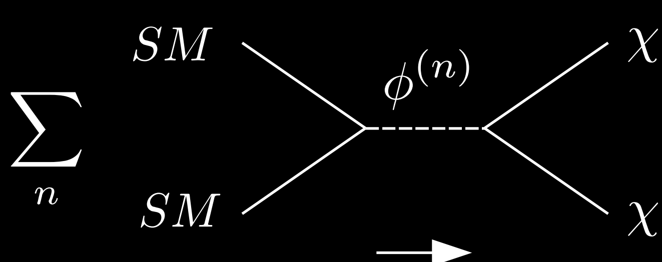
$\sqrt{|t|} < \mu$ hence all mediators are integrated → 4d contact interaction

Indirect detection / relic density



$\sqrt{s} \sim \mu$ hence first KK modes can be on-shell

DM production (colliders)

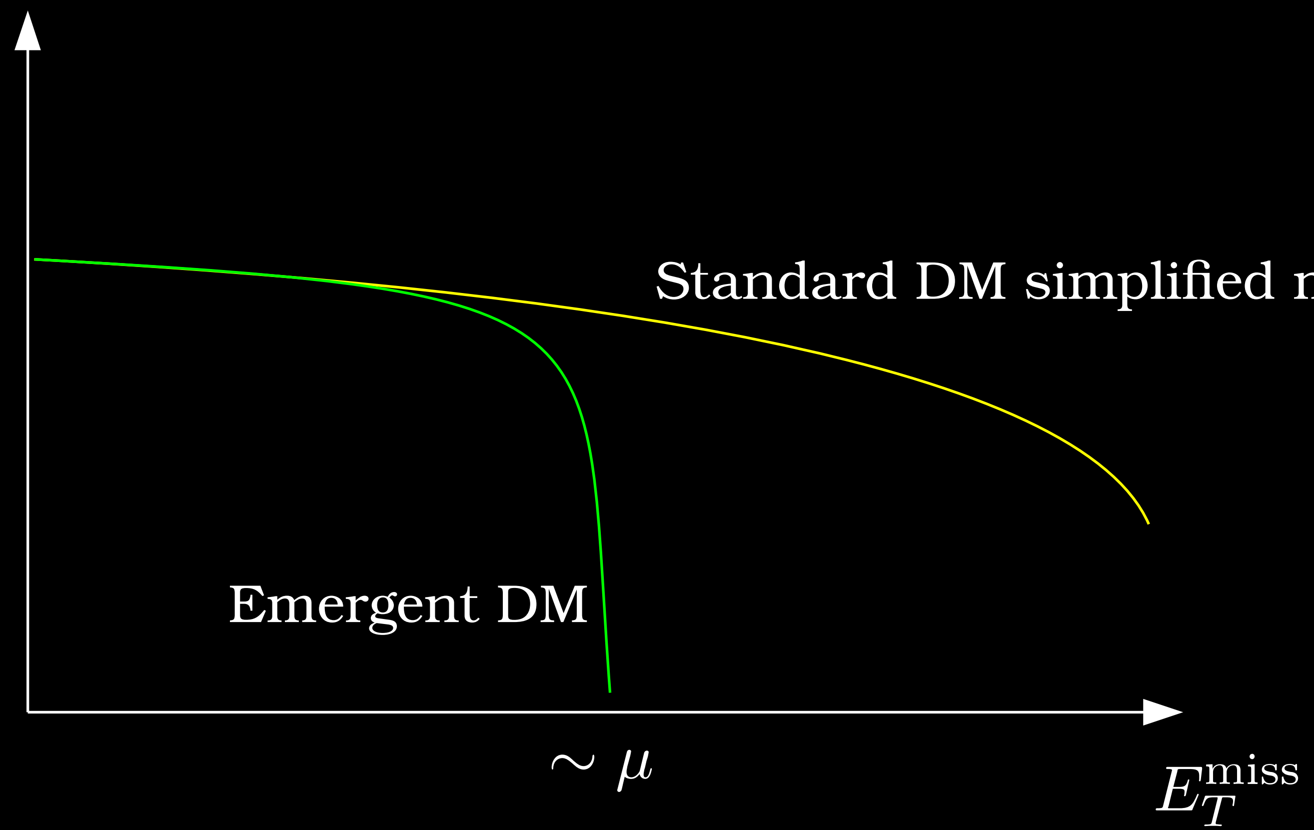


For $\sqrt{s} > \mu$, the mediators conspire such that the full amplitude is exponentially suppressed.

Hence one expects suppression of missing energy above the IR scale μ

(more on mediator-only processes in next slides)

Very very roughly:



→ An example of behaviour qualitatively different from simplifed models/SUSY-like expectations

Some generic signatures

Phenomenology of the warped model is rich and only partly familiar.

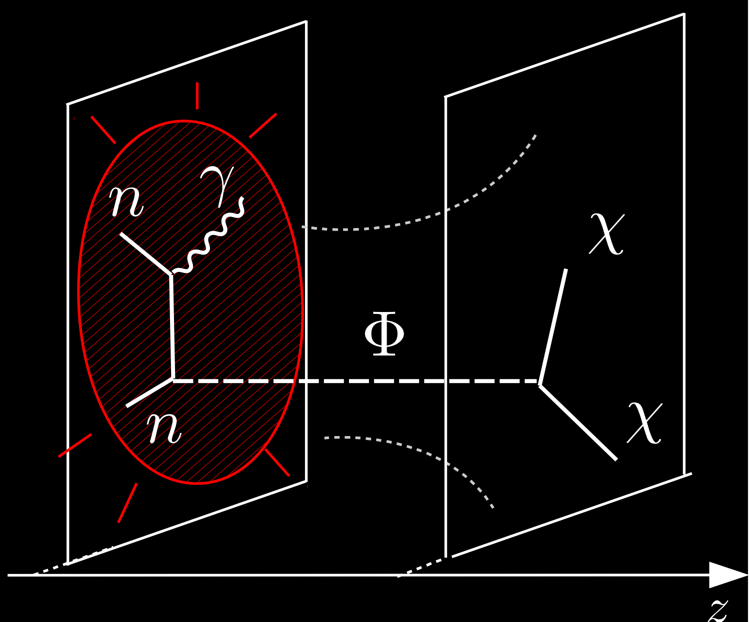
Some features:

- Non integer fifth force $V(r) \propto -\frac{k}{(kr)^{3-2\alpha}}$
  active for $r < 1/\mu$

- Non-standard momentum losses
  (meson decays, star cooling)

- Dark radiation $\rho_d \sim T^4 \left(\frac{T^2}{4k^2}\right)^{1-\alpha}$
  for $T > \mu$

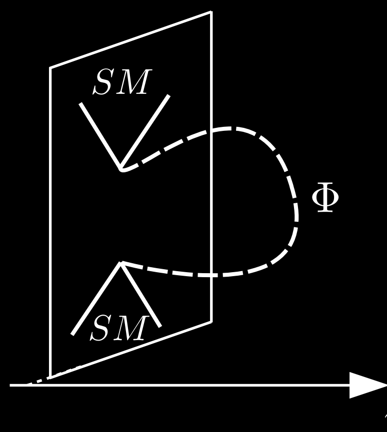
- Dark phase transition around $T \sim \mu$



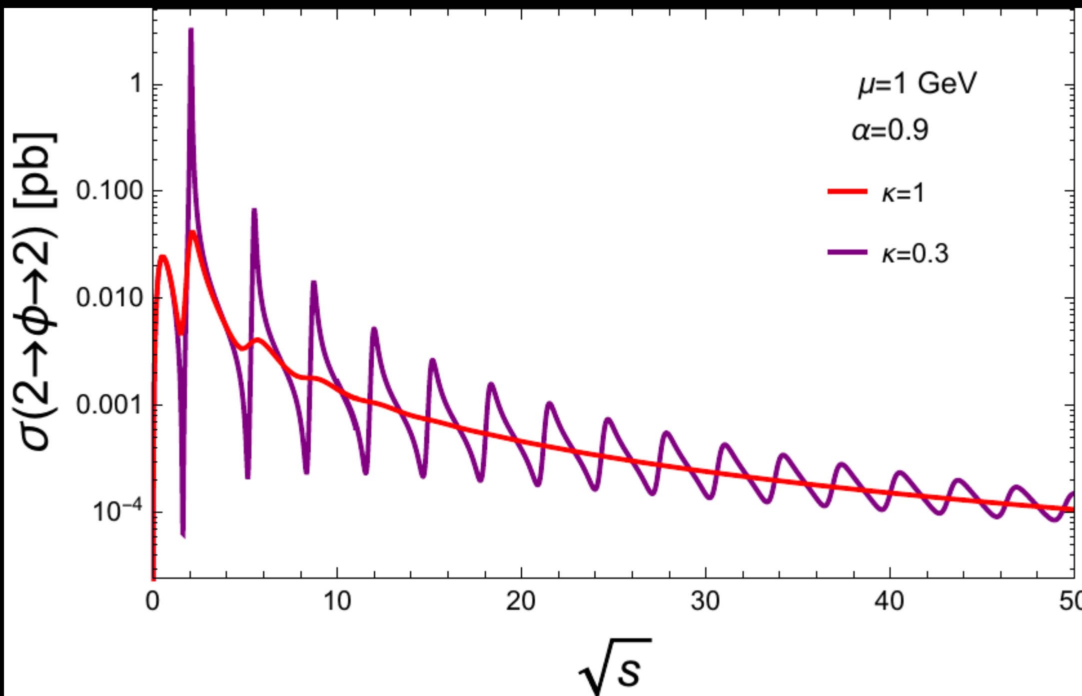
At the LHC: Periodic signals

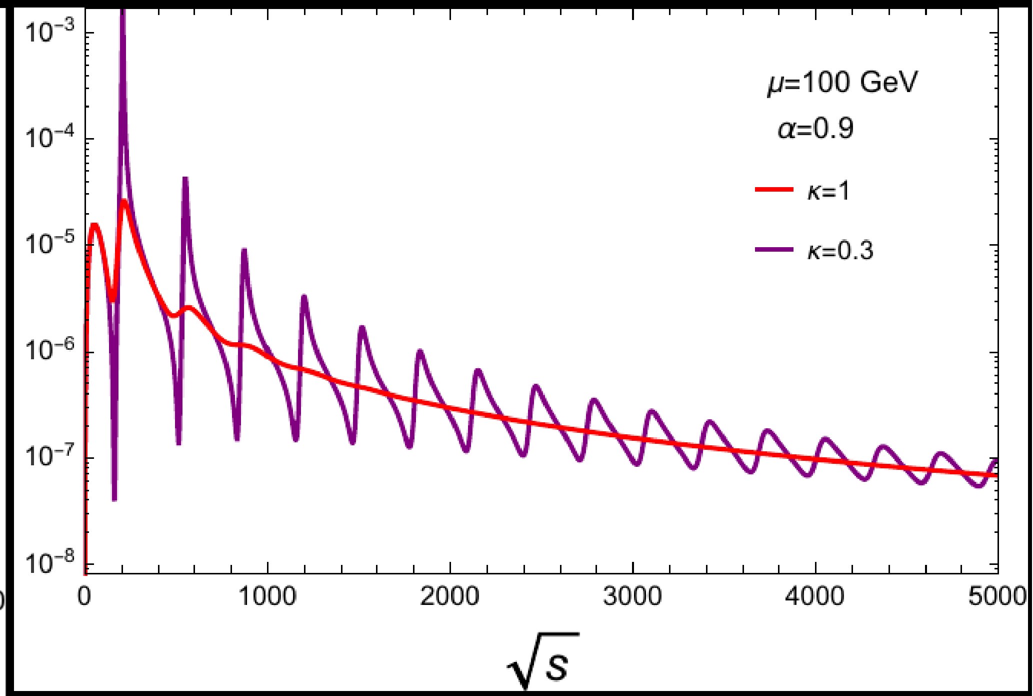
- Collider signals with periodic bumps and dips

  (Similar signal pointed out in linear dilaton model [Giudice et al '18])

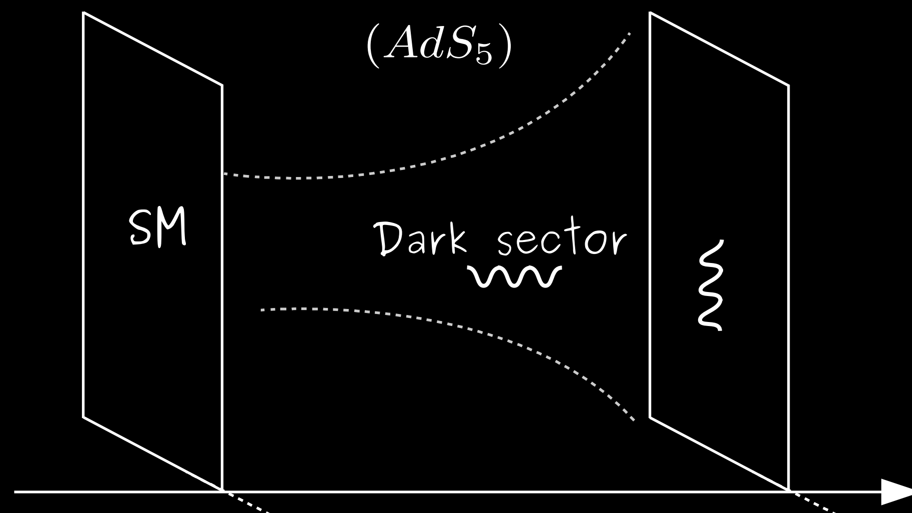


- Smearing of structures depends on $\kappa = k/M_\mathrm{p}$
- Here only the cross section for $|\mathcal{M}_\mathrm{BSM}|^2$ is shown
- Search for signal by taking the Fourier transform of the lineshape (recent technical developments in [Beauchesne/Kats '19])





Summary and outlook

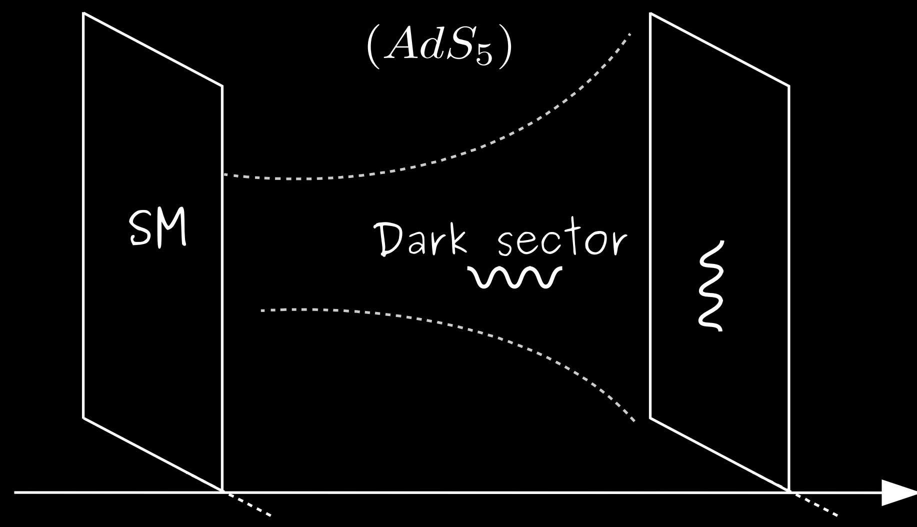


- A warped extradimension naturally gives rise to dark sector physics.
  A conceptually simple possibility, which is further motivated as the AdS dual of a composite dark sector.

- If DM is on IR brane, it is effectively "emergent": At high-energy it vanishes from all amplitudes as a result of IR opacity. This implies non-standard DM complementarity.

- Model features a variety of "exotic" signatures. At the LHC, periodic signals and vanishing of E_T^{miss} above IR scale

Summary and outlook



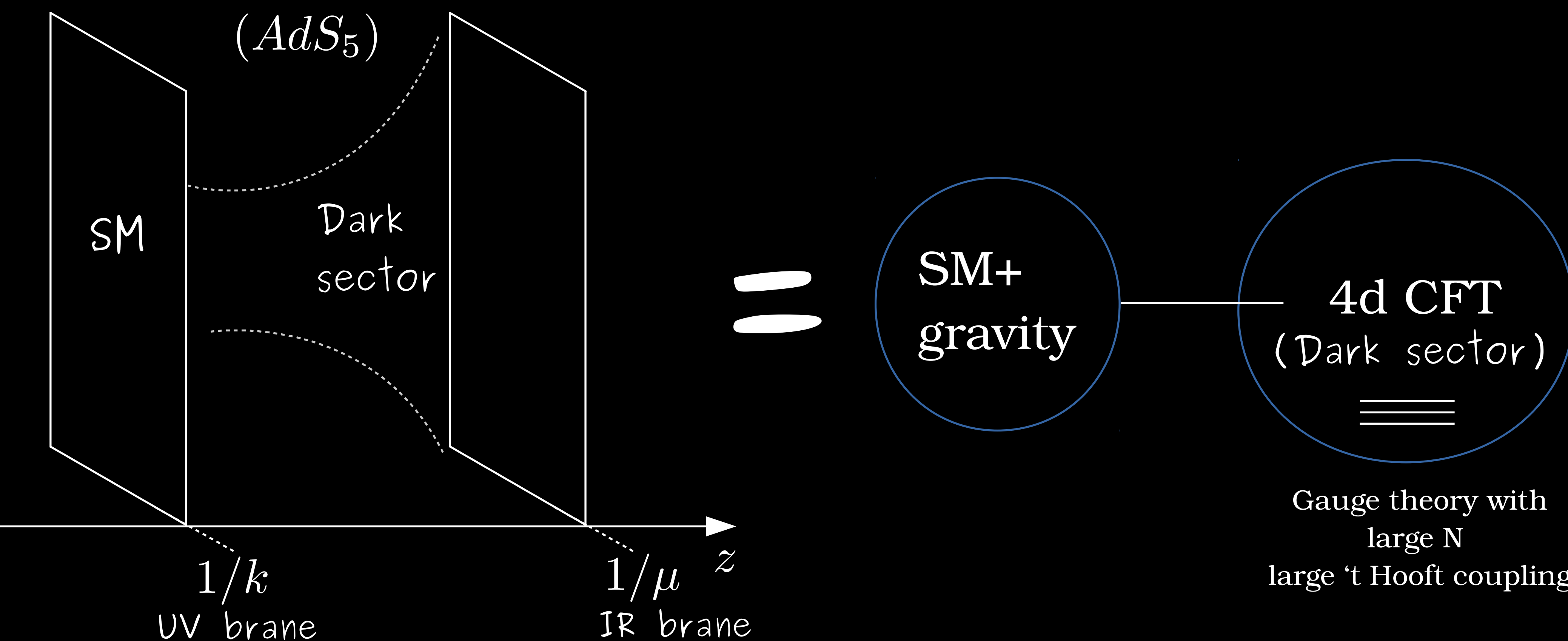
- Many important developments remain to be done, both on theoretical and phenomenological sides. The next papers on our to-do list are about
  - dark photon
  - dark radiation (cosmology)
  - screened modified gravity
  - more phenomenology: leptophilic case, stellar bounds, ...

- A collider-oriented study, for instance using the recent developments from [Beauchesne/Kats '19], would be very welcome!
  Let me know if you are interested

THANKS

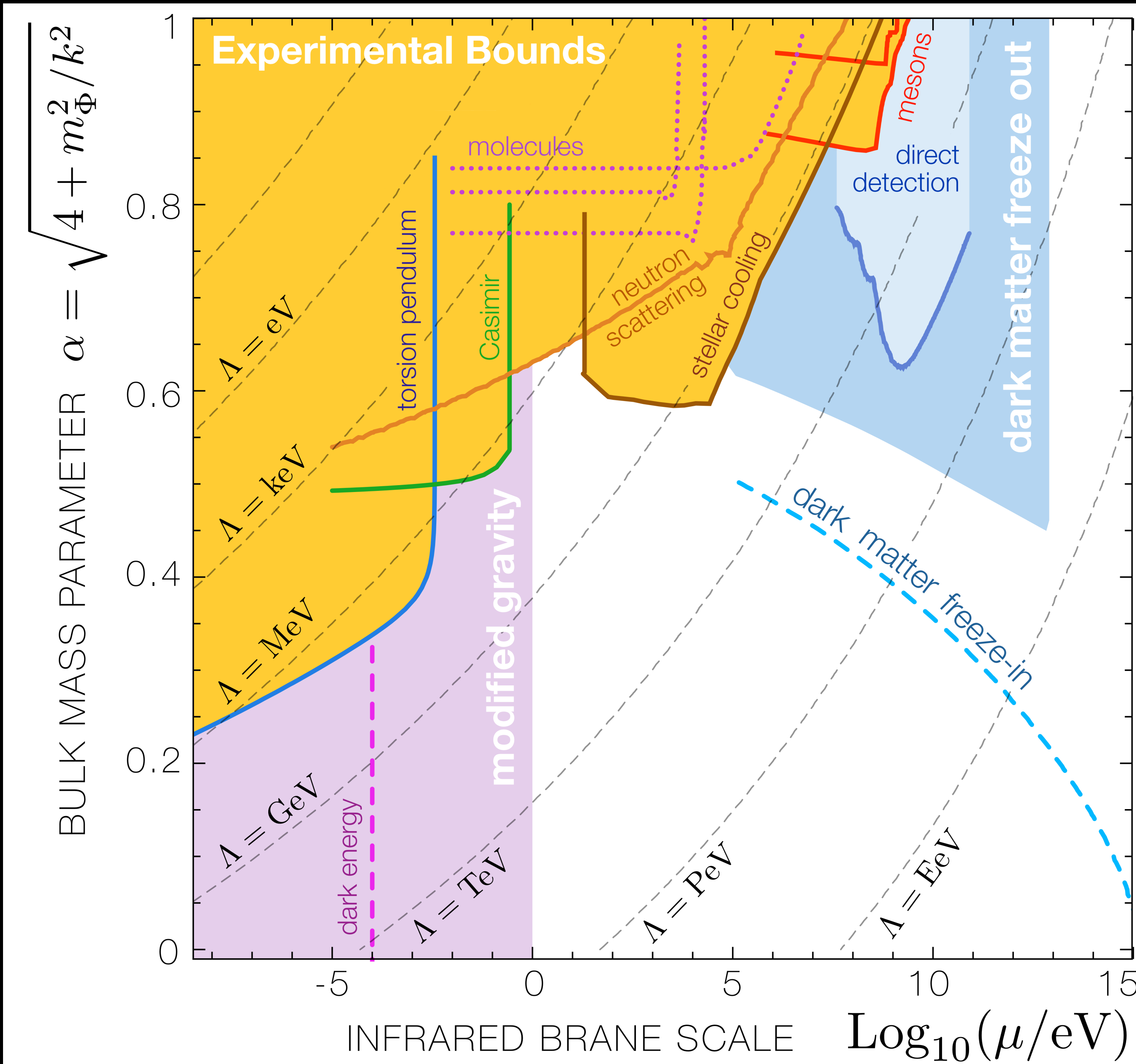
More

Duality



AdS model is the holographic description of a strongly interacting dark sector with IR confinement scale at $\sim \mu$.

Bounds in hadronic case



Λ^{-2} is the low-energy SM-DS effective coupling

$$\mathcal{L} \supset \frac{1}{\Lambda^2}\bar{N}N\bar{\chi}\chi$$

Cutoff of the low-energy 4d EFT is $O(\mu)$

μ and Λ can be very low and still evade bounds

Some formalism

5d action (an exact slice of AdS):

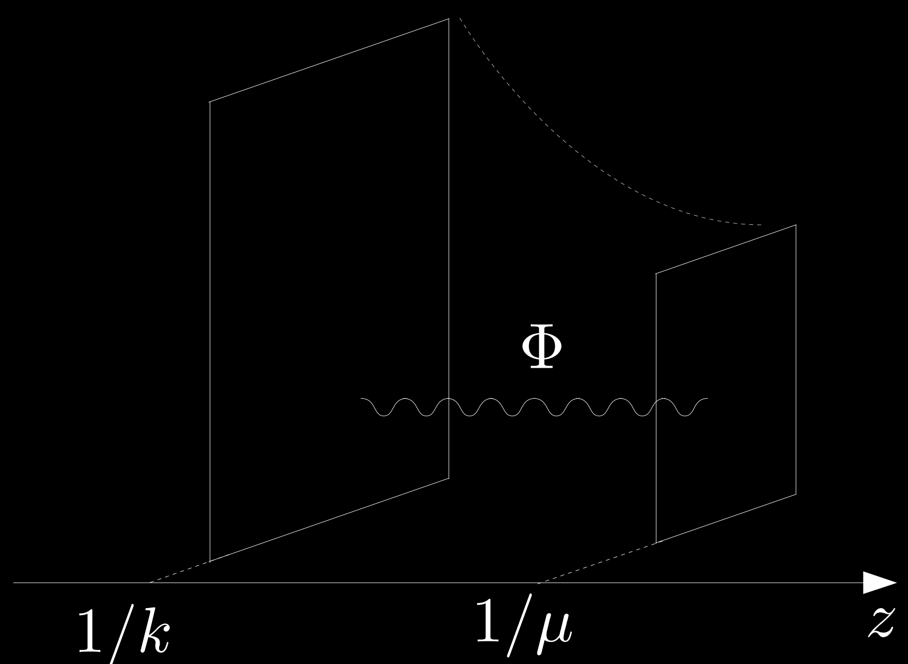
$$S_{\mathrm{AdS}} = \int d^5x^M \sqrt{g} \left(\frac{1}{2} \nabla_M \Phi \nabla^M \Phi - \frac{1}{2} m_\Phi^2 \Phi^2 \right) + S_{\mathcal{B}} + S_{\mathrm{int}}$$

Metric (conformal coordinates):

$$ds^2 = g_{MN} dx^M dx^N = (kz)^{-2} (\eta_{\mu\nu} x^\mu x^\nu - dz^2)$$

Brane mass terms:

$$S_{\mathcal{B}} = \int d^5x^M \sqrt{\bar{g}} \, \frac{1}{2} \left(\delta(z - z_0)\, M_{\mathrm{UV}} - \delta(z - z_1)\, M_{\mathrm{IR}} \right) \Phi^2$$



Some definitions:

$z_0 = 1/k, \quad z_1 = 1/\mu$

$M_{\mathrm{UV}} = (\alpha - 2)k - b_{\mathrm{UV}} k\,,$

$M_{\mathrm{IR}} = (\alpha - 2)k + b_{\mathrm{IR}} k\,.$

Spectrum has a massless mode for

$b_{\mathrm{UV}} = b_{\mathrm{IR}} = 0, \; 2\alpha$

Some formalism

Green function:

$$\langle\hat{\Phi}(z)\hat{\Phi}(z')\rangle \equiv iG_p(z,z') = i\frac{\pi k z z'}{2}\frac{\left[\tilde{Y}_\alpha^{\rm UV} J_\alpha(pz_<) - \tilde{J}_\alpha^{\rm UV} Y_\alpha(pz_<)\right]\left[\tilde{Y}_\alpha^{\rm IR} J_\alpha(pz_>) - \tilde{J}_\alpha^{\rm IR} Y_\alpha(pz_>)\right]}{\tilde{J}_\alpha^{\rm UV}\tilde{Y}_\alpha^{\rm IR} - \tilde{Y}_\alpha^{\rm UV}\tilde{J}_\alpha^{\rm IR}}$$

Structure of the propagator in different regions, away from the poles:

$p < \mu$ $\quad G_p(z,z') = f(z,z',b_{\rm UV},b_{\rm IR})$ (+ possible light mode)

Holomorphic
Contact interaction
Encodes heavy KK modes
$b_{\rm IR}$ dependence vanishes for $z_> < 1/\mu$

Has branch cut
Encodes light continuum of KK modes
CFT-like

$\mu < p < \frac{1}{z_>}$ $\quad G_p(z,z') = f(z,z',b_{\rm UV},0) \quad + \quad h(z,z',b_{\rm UV})p^{2\alpha}$

Exponentially suppressed if p has imaginary part

$\frac{1}{z_>} < p < \frac{1}{z_<}$ $\quad G_p(z,z') = j(z,z',b_{\rm UV})\dfrac{\cos\left(\frac{p}{\mu} - pz_>\right)}{\cos\left(\frac{p}{\mu} + \frac{\pi}{4}(1-2\alpha)\right)}$

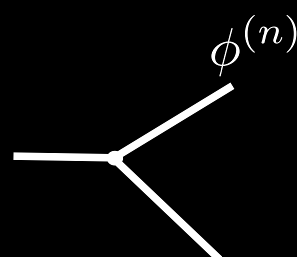
A KK continuum trick

It can be often useful to think in terms of Kaluza Klein modes,

$$G_p(z, z') = \sum_{n=0}^{\infty} \frac{f_n(z) f_{n'}(z)}{p^2 - m_n^2}$$

But a sum over KK modes can be tricky to perform. Consider for instance, KK mode emission from the brane,

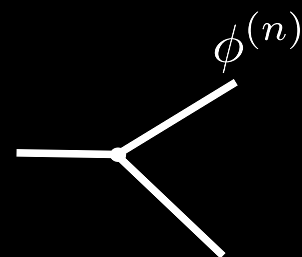
$$\sum_{n=0}^{n_{\rm th}} \int d\Phi_2 \left| \quad \right|^2 \equiv \sum_{n=0}^{n_{\rm th}} f_n(z_0)^2 \Gamma_n = \quad ?$$



A KK continuum trick

Trick: re-express the sum as a contour integral of the propagator, enclosing the poles allowed by the process.

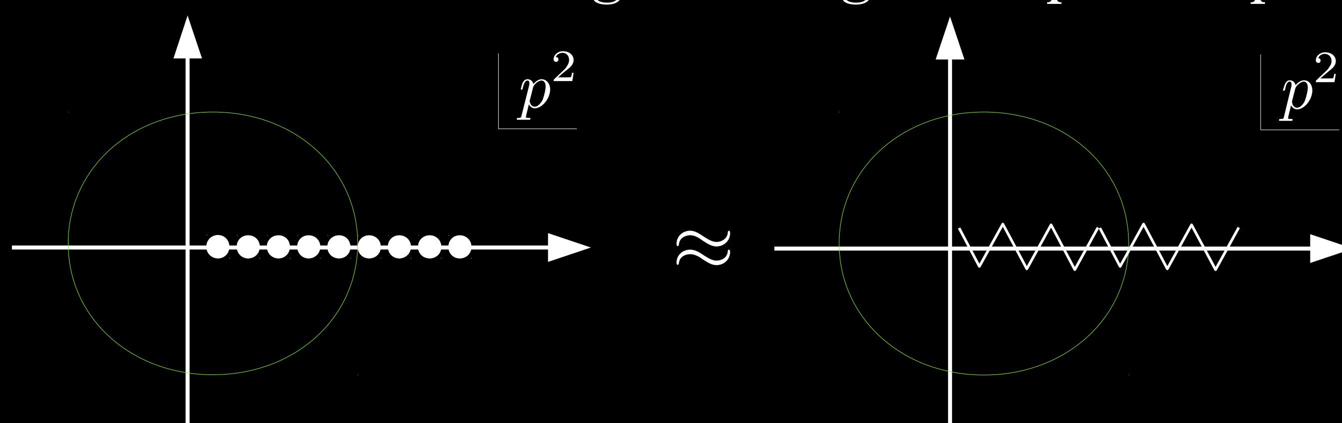
$$\sum_{n=0}^{n_{\rm th}} \int d\Phi_2 \left| \quad \right|^2$$



$$\equiv \sum_{n=0}^{n_{\rm th}} f_n(z_0)^2 \Gamma_n$$

$$= \frac{1}{2i\pi} \int_{\mathcal{C}[n_{\rm th}]} d\rho \Gamma(\sqrt{\rho}) G_{\sqrt{\rho}}(z_0, z_0)$$

Then, evaluate the contour integral using the explicit expression for G_p



The contact term does not contribute. Main contribution comes from the non-holomorphic $p^{2\alpha}$ term. This provides a very simple way to perform KK sums.

Dressed propagator

The dressed propagator satisfies the "dressed EOM":

$$\frac{1}{\sqrt{g}}\partial_M\left(g^{MN}\sqrt{g}\partial_N\Delta(X,X')\right)+\int dY\,\Pi(X,Y)\Delta(Y,X')=-i\frac{1}{\sqrt{g}}\delta^{(d)}(X)\,.$$

The 1PI subdiagram.
Contains the bulk mass $\Pi(X,X')\supset M^2\delta^{(d)}(X-X')$

$\Delta(X,X') =$

Our interest is in the imaginary part induced by bulk interactions. Let us first consider a cubic scalar interaction λ . Focussing on the potentially exponentially suppressed regime $1/z_> < p$, we get (using the continuum trick)

$$\mathrm{Im}\Pi(z,z')\approx\lambda^2\frac{1}{k^6z^3z'^3}\frac{1}{64\pi^3}\frac{\pi^2k^2}{\Gamma^2(\beta+1)\Gamma^2(\beta+2)}\left(\frac{z_<}{2z_>}\right)^{4\beta+2}$$

Dressed propagator

Then let us consider a narrow width expansion:

$$\Pi(z,z') = F_0(z)\delta(z,z') - F_1(z)\delta^{(1)}(z,z') + \frac{1}{2}F_2(z)\delta^{(2)}(z,z') + \dots$$

where $F_i(z) = \int dz' z^i \Pi(z,z')$

($F_i(z)/F_0(z)$ are the moments of the distribution)

Results take the form

$$F_0(z) = \lambda^2 k C_0 \frac{1}{(kz)^5}\,, F_1(z) = \lambda^2 C_1 \frac{1}{(kz)^4}\,, F_2(z) = \frac{\lambda^2}{k} C_2 \frac{1}{(kz)^3}\,,$$

C_0 gives an imaginary bulk mass
C_1 gives an imaginary bulk mass and some harmless phases
C_2 gives an imaginary part to the 4-momentum!

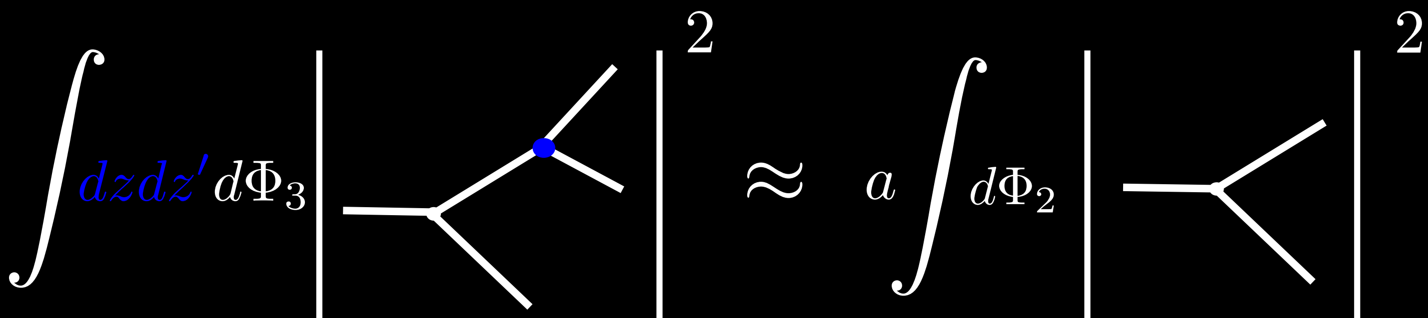
Hence the propagator with timelike momentum is exponentially suppressed as

$$G_p^{1-\mathrm{loop}}(z,z') \propto e^{-\lambda^2 \frac{C_2}{2k} p z_>}\,.$$

Cascade decays

Even though the propagators with timelike momentum cannot access the deep IR, another possibility may be the cascade decay of the continuum.
As the field fragments, p reduces and the daughters progressively reach further in the IR.

One finds an approximate recursion relation



$$a = \frac{\lambda^2}{k}\frac{\Gamma(-\alpha)^2}{(\Gamma(\alpha+1)\Gamma(\alpha+2))^2}\frac{1}{16\pi^2}\frac{1}{(3\alpha+1)^2}\frac{1}{4^{5\alpha+4}} \ll 1$$

λ is cubic scalar coupling
Uncertainty is likely $O(1)$

This can be used to estimate the rate of a cascade decay:

$$|\mathcal{M}|^2(1 \to n) \sim a^{2^n - 1}$$

Cascade decays

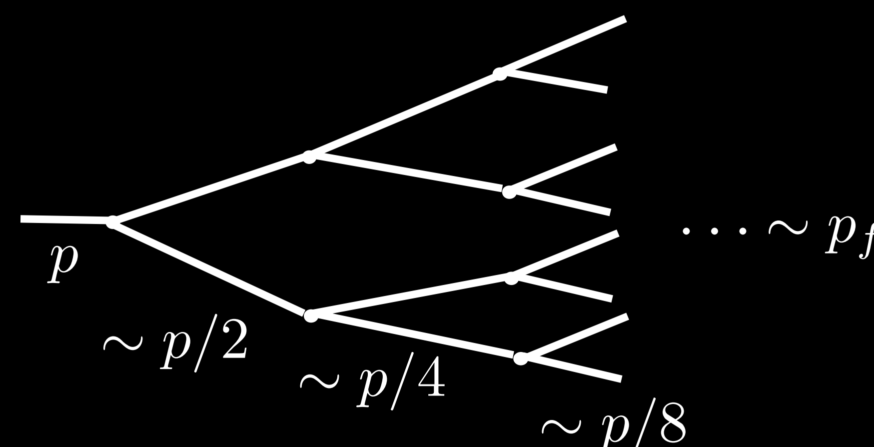
Moreover, from the KK continuum trick, one has

$$\frac{1}{2i\pi}\int_{\mathcal{C}[n_{\rm th}]} d\rho\,\Gamma(\sqrt{\rho})\underbrace{G_{\sqrt{\rho}}(z,z')}_{\propto\,\rho^{\alpha}}$$

which means that decays into heaviest modes are preferred.

(Implies that events will tend to be spherical and soft, same conclusion as [Csaki/Reece/Terning '08])

To make a gross estimate, let us consider the most likely phase space configuration,



For final states with momentum $p_f = p/2^n$ we have thus

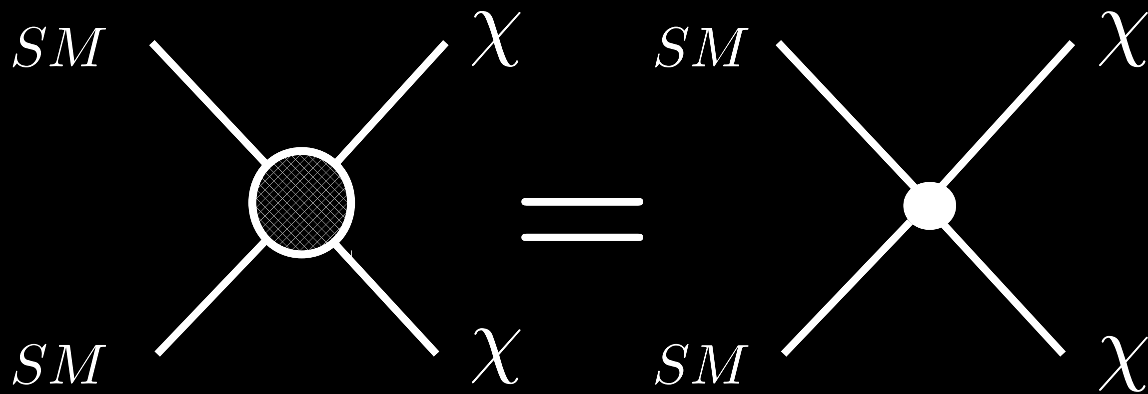
$$|\mathcal{M}|^2 \sim a^{p/p_f - 1}$$

Since $a \ll 1$, this is a strong exponential suppression.

(The value chosen for p_f depends on the other scales of the object considered (detector, star...), because lifetime of final states depends on p_f)

DM low-energy EFT

At energies $E < \Lambda$



$$\cdot \left(1 + O\left(\frac{1}{\Lambda}\right)\right)$$

Low–energy effective description based on local operators (DM EFT):

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm DM} + \frac{1}{\Lambda}\mathcal{O}_{\rm SM}\mathcal{O}_{\rm DM} + \ldots$$

with $\mathcal{O}_{\rm DM}$ bilinear in χ

Interaction described by local operators of higher dimension.
Valid up to $E \sim \Lambda$