CMB S4: Gatekeeper of Dark Complexity

CMB S4 Summer Collaboration Meeting

10 Aug 2021

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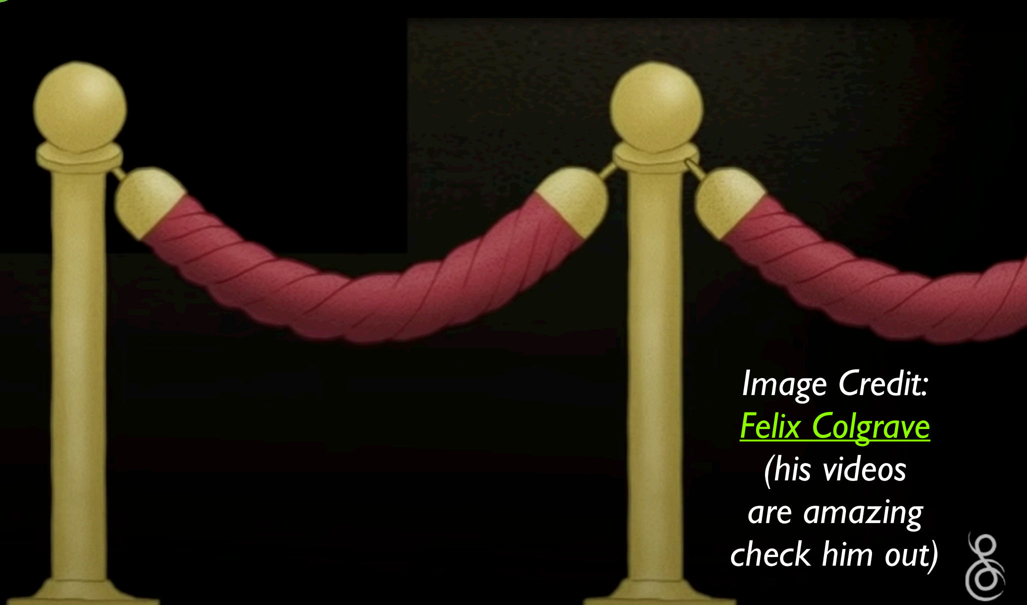
University of Toronto



UNIVERSITY OF TORONTO

Image Credit: Felix Colgrave (his videos are amazing check him out)

Dark Complexity

Perhaps dark matter / dark sectors are not simple or minimal?

Instead of a single WIMP, could have variety of particles & forces.

Theoretical perspective:

The SM is complicated and O(10%) of DM by energy density.
Why not more things like that? More DM sectors, more particles/forces.

Symmetries between SM and dark sector could solve fundamental problems, e.g. Higgs hierarchy problem.
Could imply similarly complex structure for all or part of dark matter.
E.g. **Twin Higgs** implies dark-SM-copy with O(1) different masses.
[see talk by Nathaniel Craig & Joel Meyers] [recent Twin Higgs Cosmo example: 1611.07975 (Chacko, Craig, Fox, Harnik)]

Profound consequences for cosmology and astrophysics.

What if the dark sector was more like the SM?

Consider simple model of "atomic dark matter":

- dark proton mass $m_{p'}$
- dark electron $m_{e'}$
- dark photon (QED force) with coupling strength α_D
- makes up fraction f of total DM
- temperature during decoupling $\xi = T_D/T_\gamma$

Good benchmark for many more complicated possibilities.
"Dark nuclear physics" optional (present e.g. in Twin Higgs)!

Incomplete recent literature sample:
0808.2318 Feng, Tu, Yu
1303.1521 Fan, Katz, Randall, Reece
1310.3278 Cyr-Racine, Putter, Raccanelli
1611.07975 Chacko, Craig, Fox, Harnik
1611.07977 Craig, Koren, Trott
1705.10341 Rosenberg, Fan
1707.03829 Buckley, DiFranzo
1712.04779 Ghalsasi, McQuinn
1805.04512 Gresham, Lou, Zurek
1809.01144 Essig, McDermott, Yu, Zhong
1911.11114 Alvarez, Yu
1912.06757 Huo, Yu, Zhong

I'll focus on our recent work:
Direct Detection: 2104.02074 Chacko, DC, Geller, Tsai
Mirror Neutron Stars: 2103.01965 Hippert, Setford, Tan, DC, Norona-Hostler, Yunes
Microlensing constraints: 2012.07136 Winch, Setford, Bovy, DC
White Dwarf Cooling: 2010.00601 DC, Setford
Mirror Stars: 1909.04071 DC, Setford
Mirror Stars: 1909.04072 DC, Setford
Twin Higgs Cosmology: 1803.03263 Chacko, DC, Geller, Tsai

[in progress] N-body simulations: Sandip Roy, Xuejian Shen, Jack Setford, Mariangela Lisanti, Norman Murray, Philip Hopkins, DC
[in progress] Mirror stars in GAIA: Aaron Howe, Jack Setford, Chris Matzner, DC

The Magic of the CMB

CMB S4 will measure presence of light degrees of freedom very model-independently* with precision $\sigma(\Delta N_{eff}) \approx 0.03$

CMB S4 Science Case 1907.04473

aDM has irreducible signature $\Delta N_{eff} \approx \left(\frac{8}{7}\right)\left(\frac{11}{4}\right)^{4/3}\left(\frac{T_D}{T_\gamma}\right)^4 \approx 4.4\ \xi^4$

ξ naturally wants to be < 1, but unless there are significant dilution mechanisms at play, **good chance for positive detection at CMB S4.**

Note that galaxy surveys can constrain ξ much more due to dark-acoustic oscillations, but **not if DM fraction f < ~ 5%!**

1310.3278 Cyr-Racine, Putter, Raccanelli

The CMB S4 constraint is independent of DM-fraction: **a generic probe of "dark electromagnetism"**. What could it mean?

Dark EM + DM → dissipative dynamics → profound change from ΛCDM

* modulo 2107.13000 Cyr-Racine, Ge, Knox

Once you're past the gate…

say CMBS4 finds
$\Delta N_{eff} \gtrsim 0.06$

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It could mean *many* things. Generic possibility: dark sector with "unbroken" $U(1)_D$ (dark photon!)

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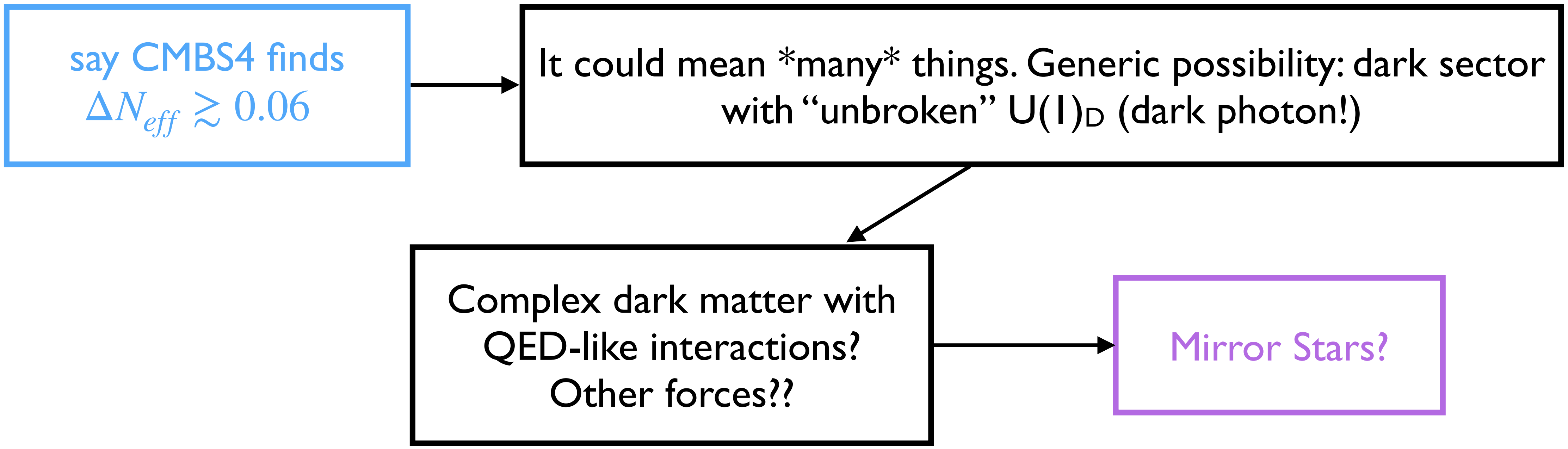
Complex dark matter with QED-like interactions?
Other forces??

Once you're past the gate…



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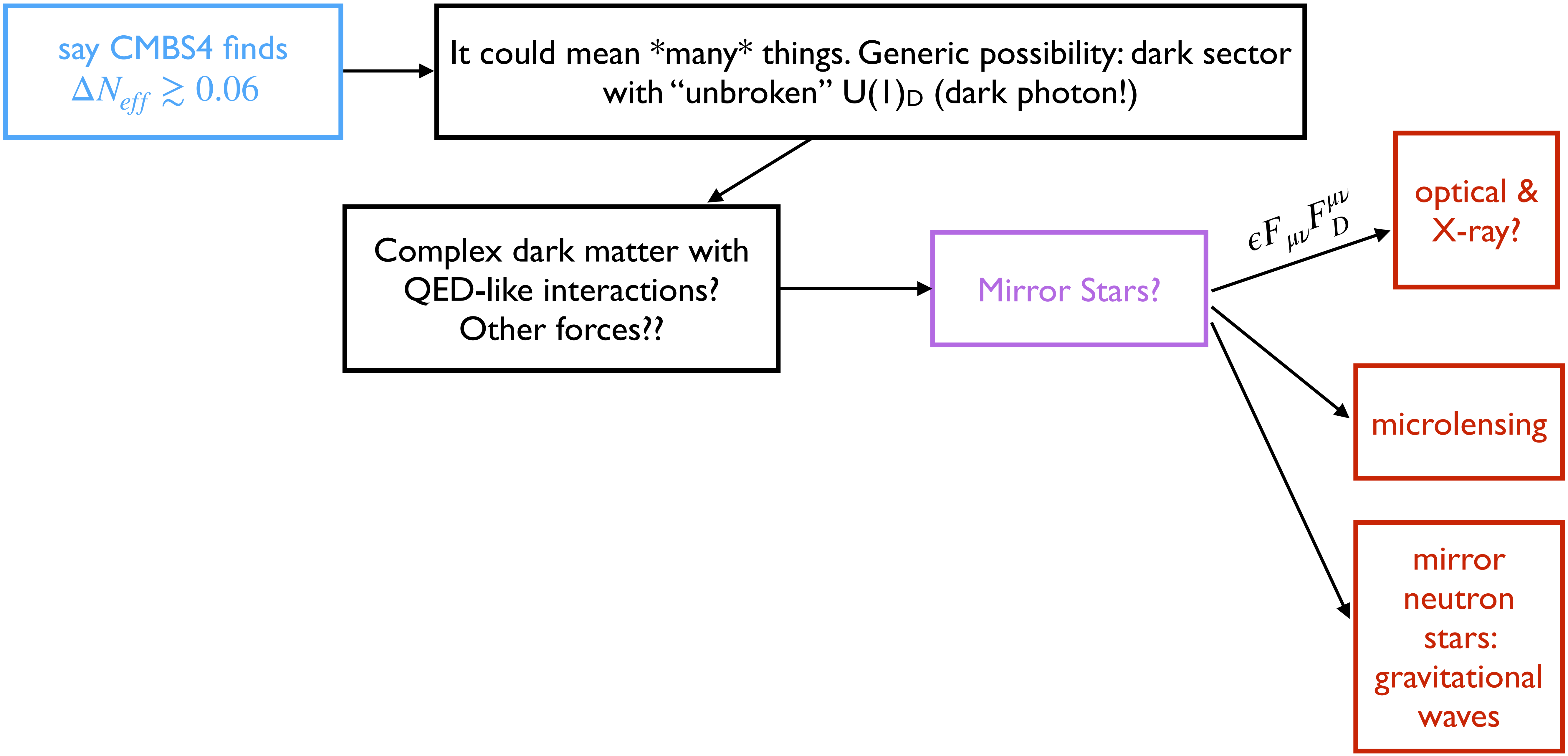

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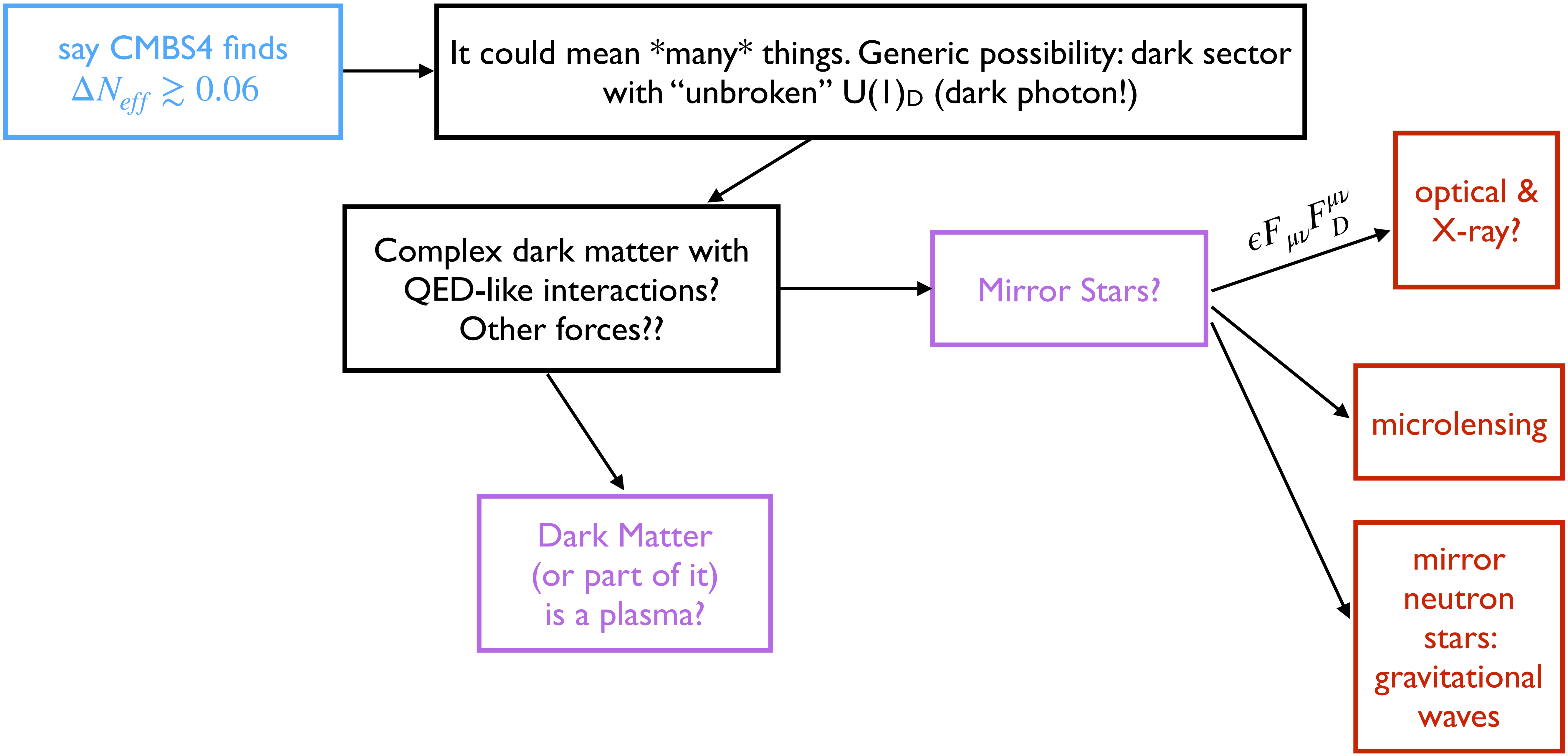

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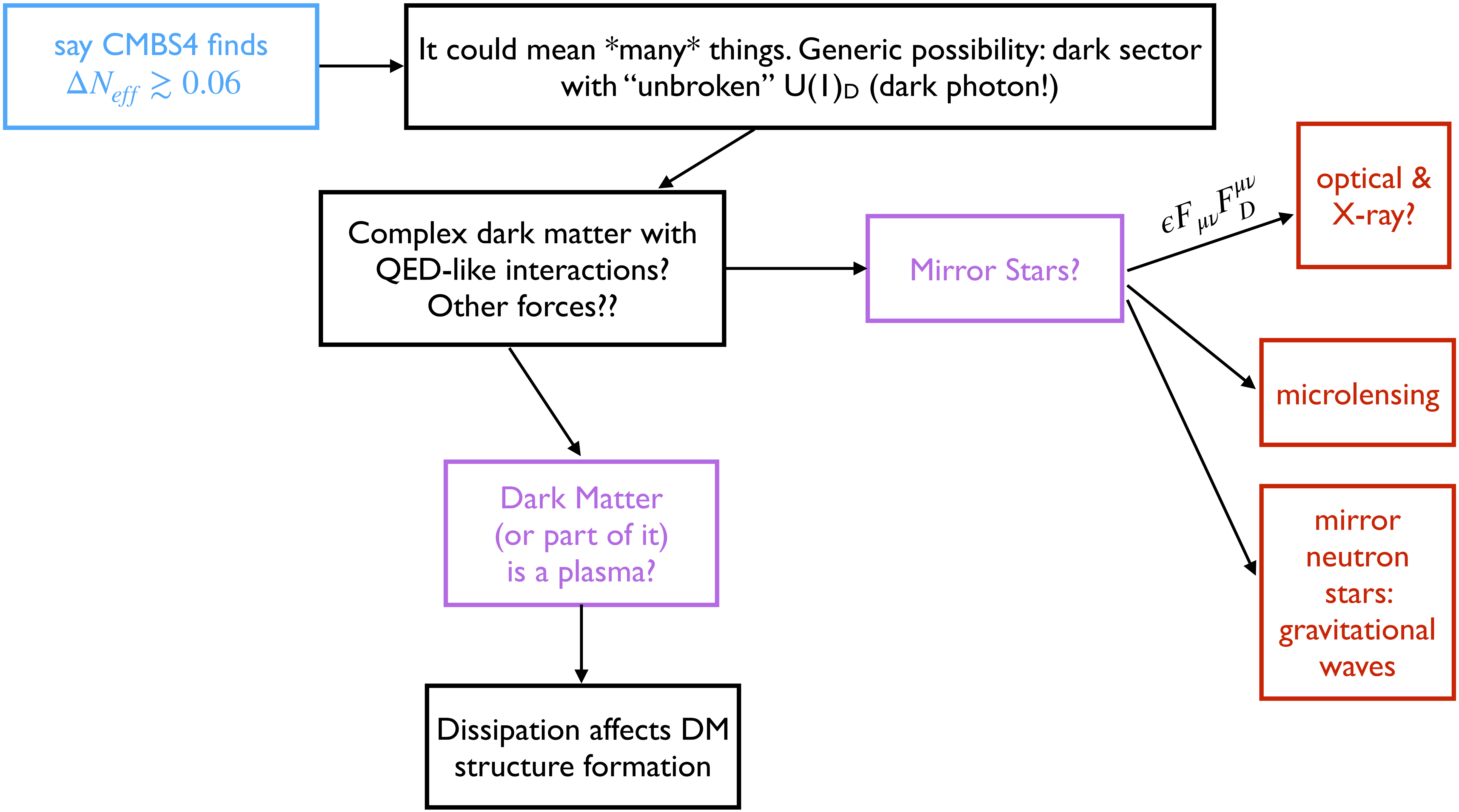

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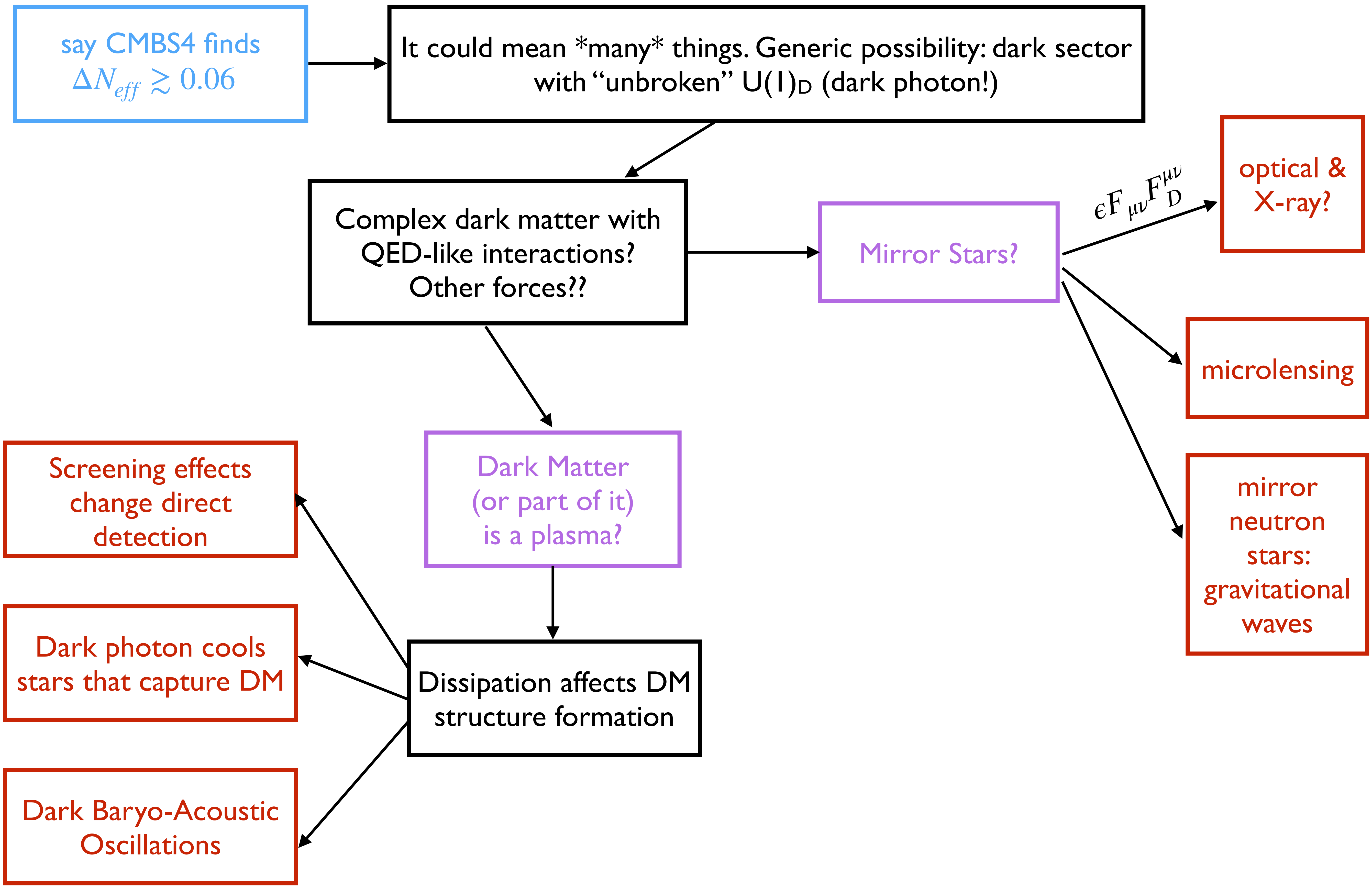

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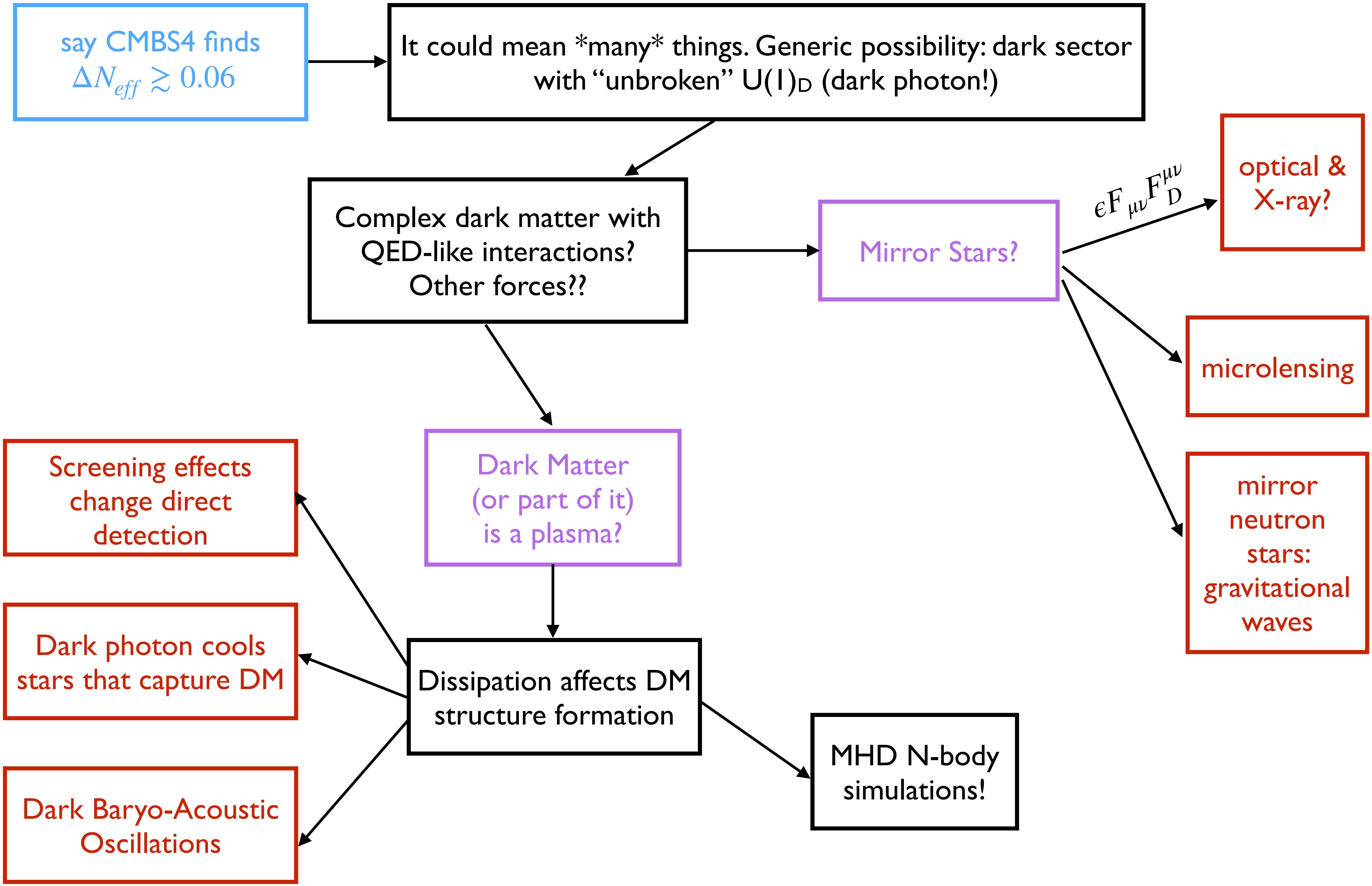

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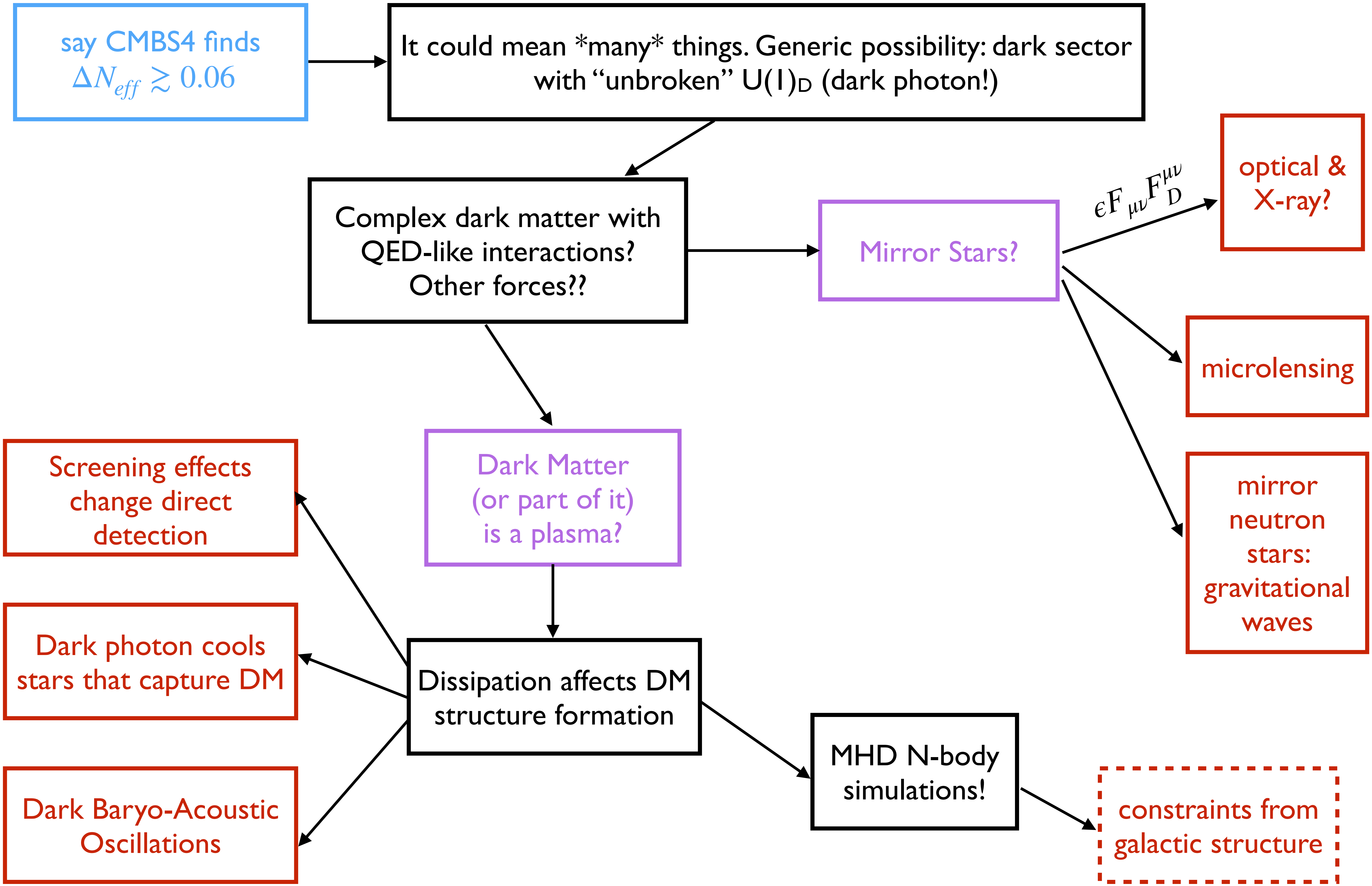

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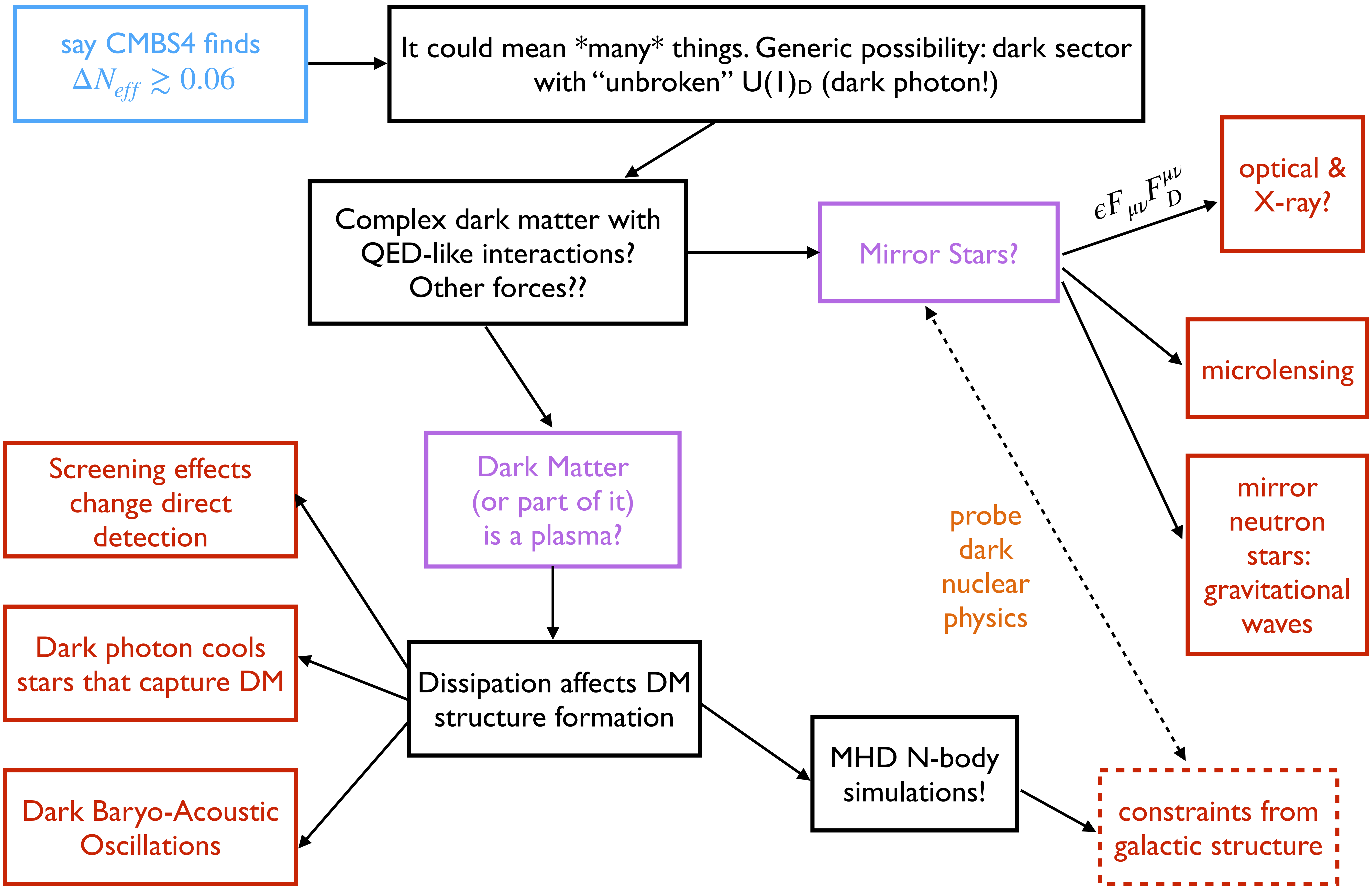
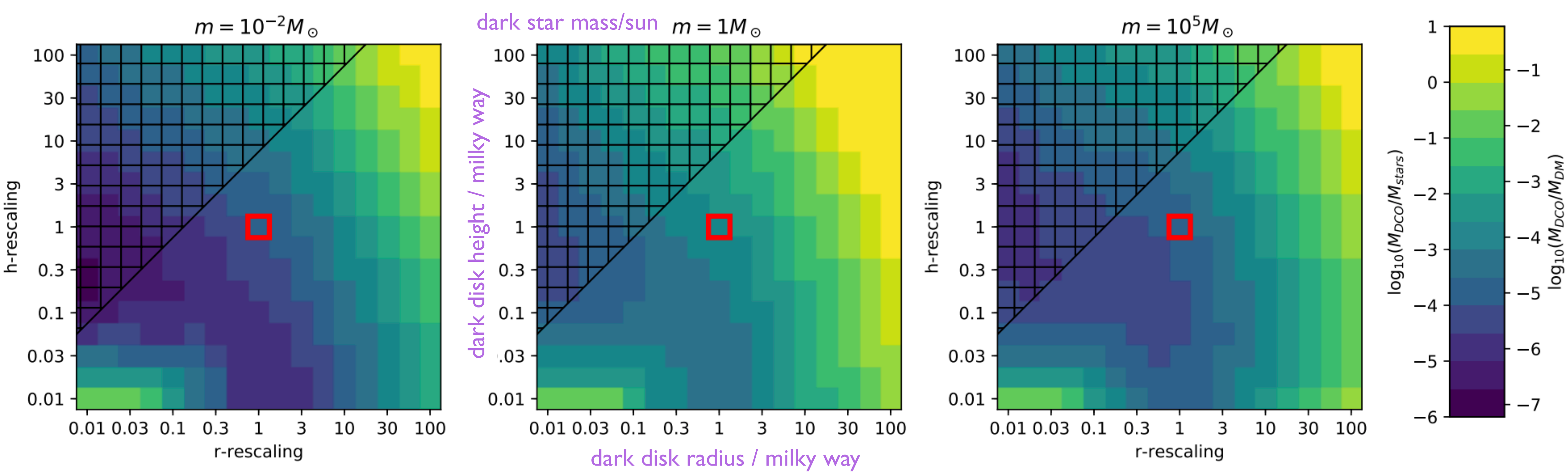


Mirror Stars

Atomic DM can cool and collapse into *mirror stars* in our galaxy

- just like regular stars, but shine in dark light
- If no dark nuclear physics, cool in Kelvin-Helmholz time.
- If dark nuclear physics, could live & dark-shine much longer
- eventually produce relics (*like* white dwarfs, neutron stars, black holes)

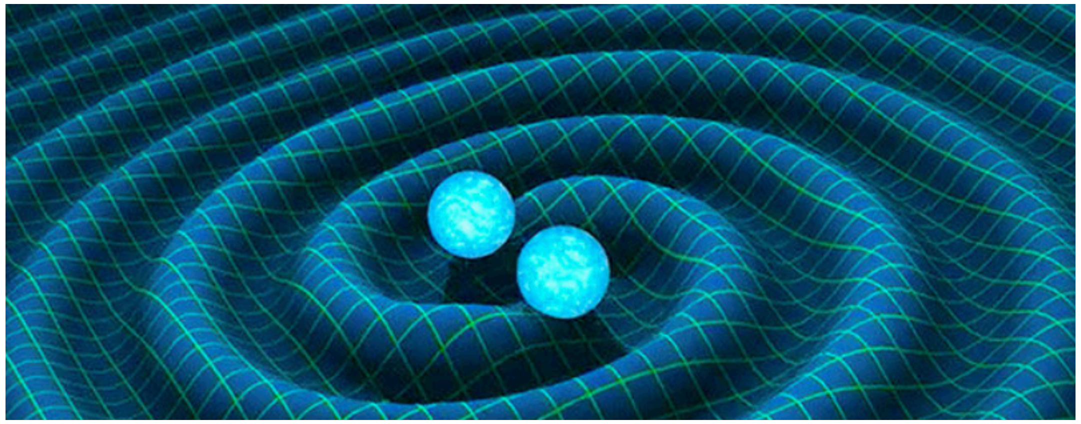
Abundance hard to predict, but can look for them with **microlensing**



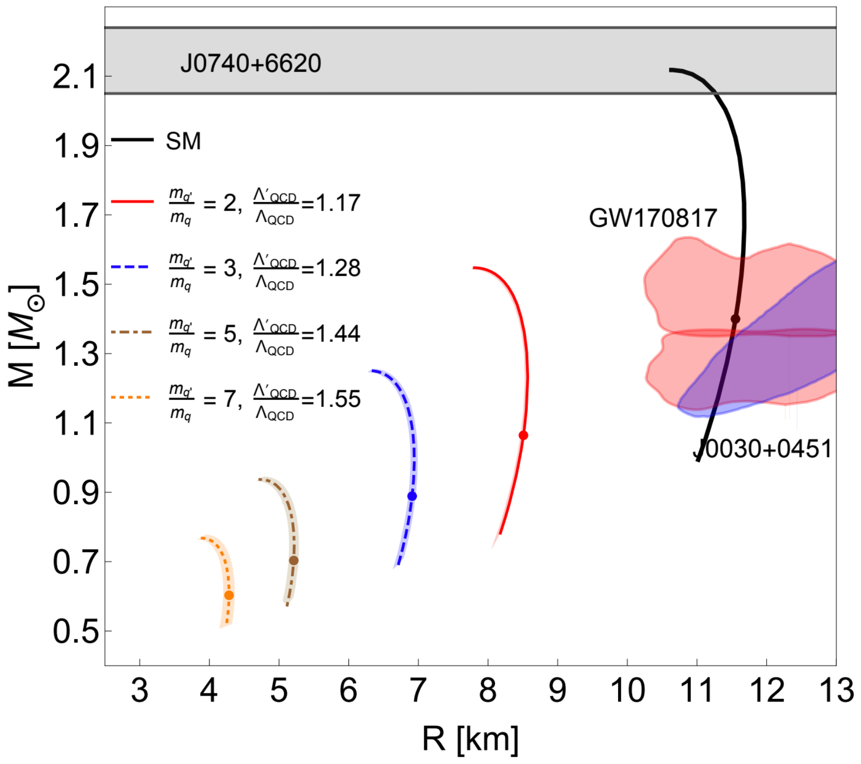
2012.07136
Winch,
Setford,
Bovy,
Curtin

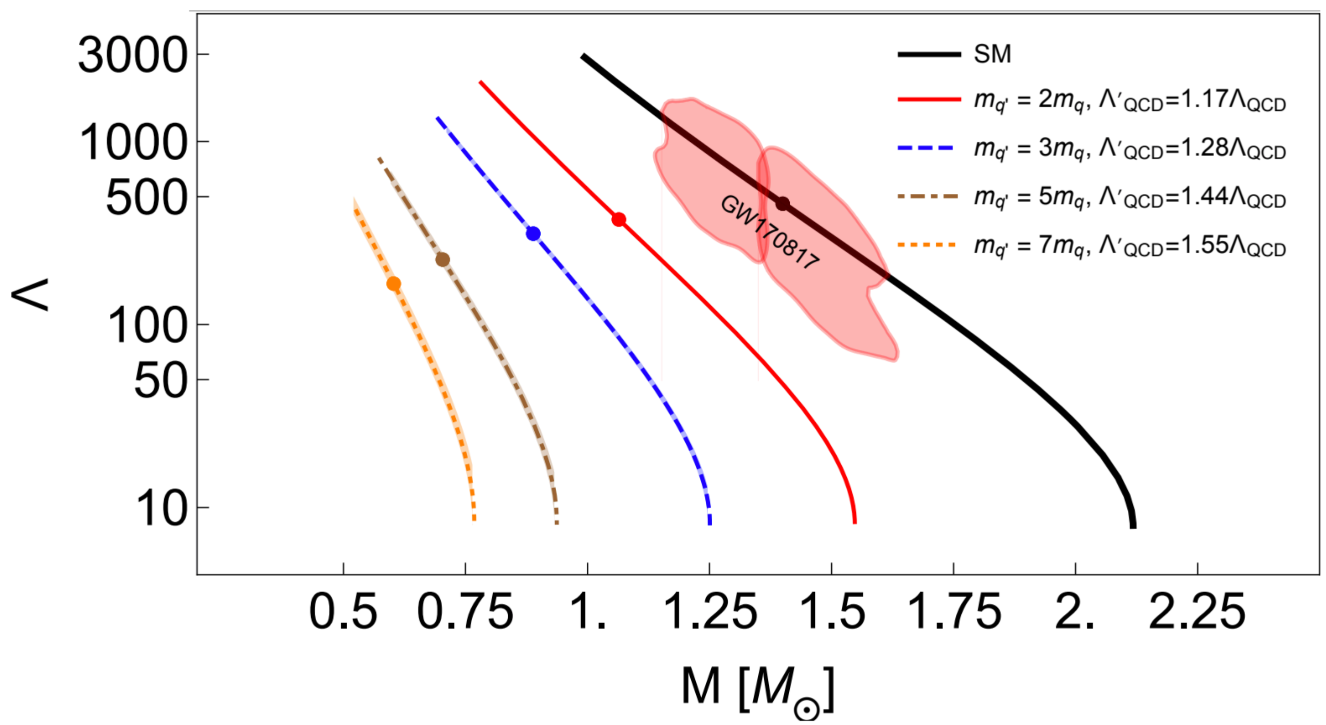
Vera Rubin Observatory should be able to detect sub-percent DM-fractions of dark stars in a dark disk*

Mirror Neutron Stars



Mirror neutron stars in the Twin Higgs: lighter than regular neutron stars, but can be detected by Advanced LIGO with standard analysis techniques!



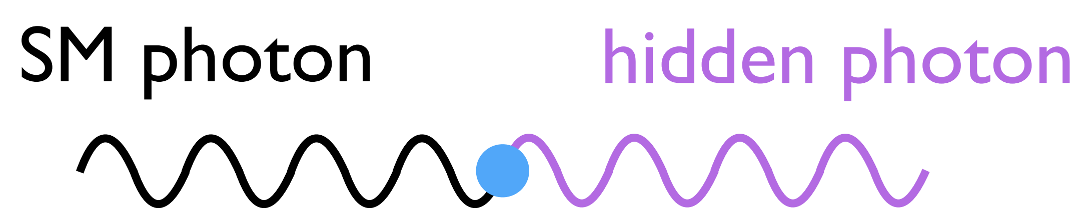


2103.01965 Hippert, Setford, Tan, DC, Norona-Hostler, Yunes

Electromagnetic Mirror Star Signals

Could Mirror Stars emit regular photons that we would see in telescopes?

Yes! Generally, dark QED photon will mix with SM photon:

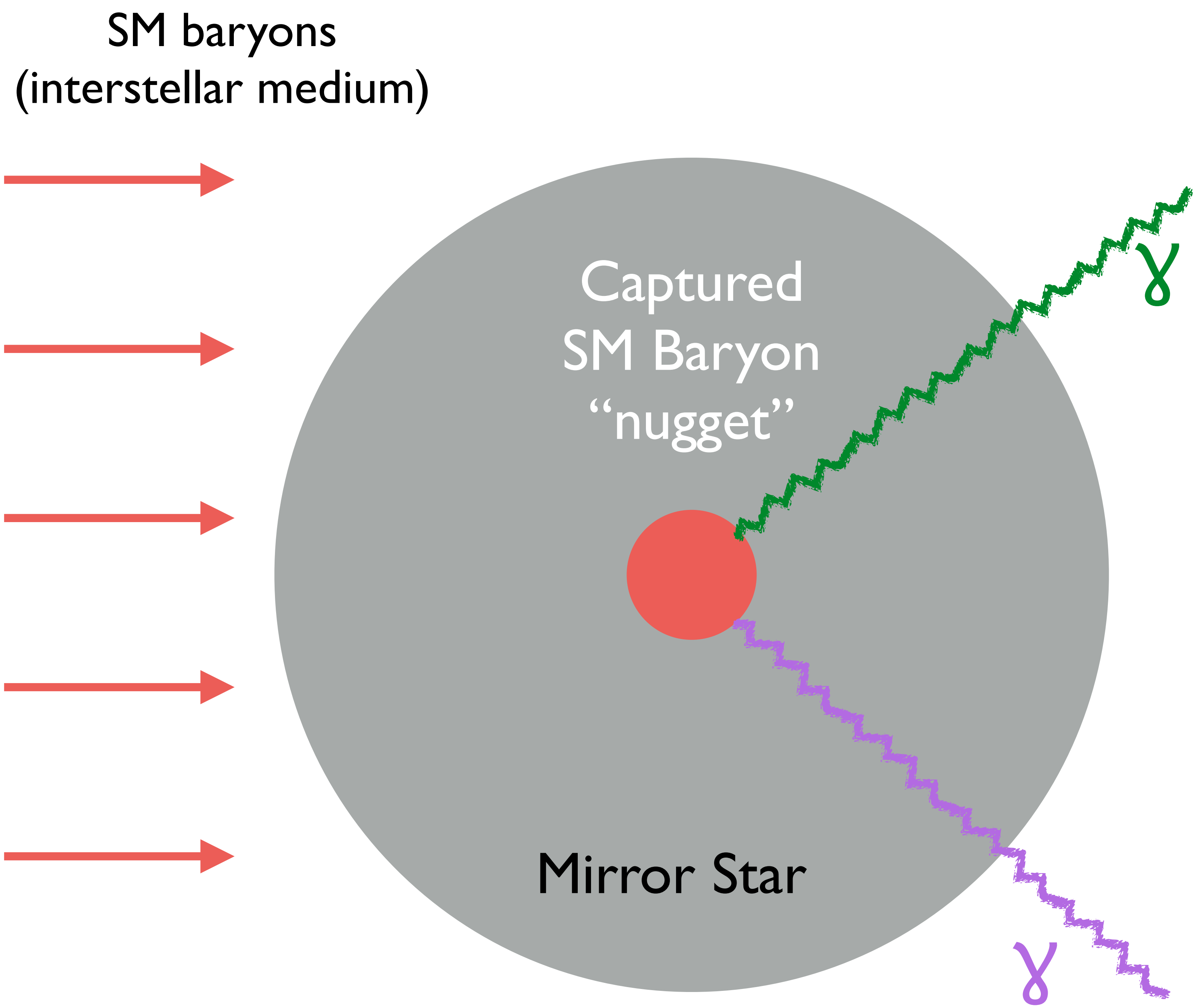


$\epsilon \gtrsim 10^{-13}$

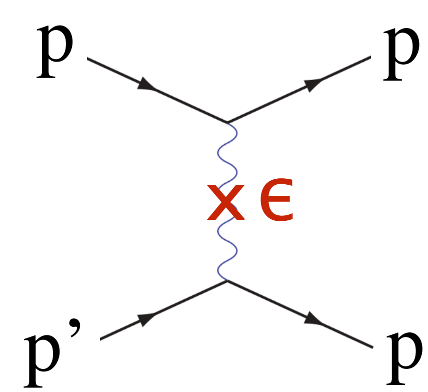
1909.00696 Gherghetta, Kersten, Olive, Pospelov

Incredibly faint interactions are not relevant for galaxy/stellar evolution, but can produce signals!

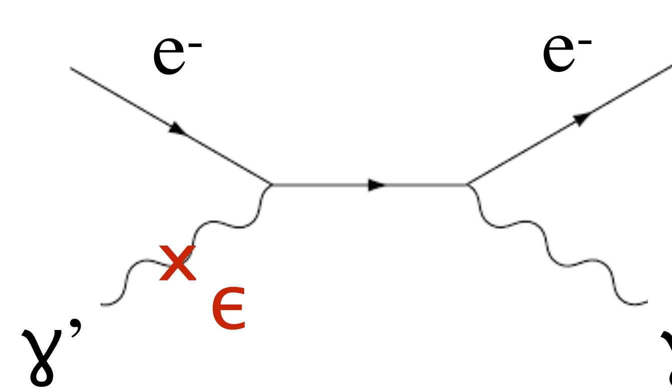
Electromagnetic Mirror Star Signals



Optical/IR: Thermal emission from captured SM matter



X-ray photons straight from core via mirror-Thomson conversion

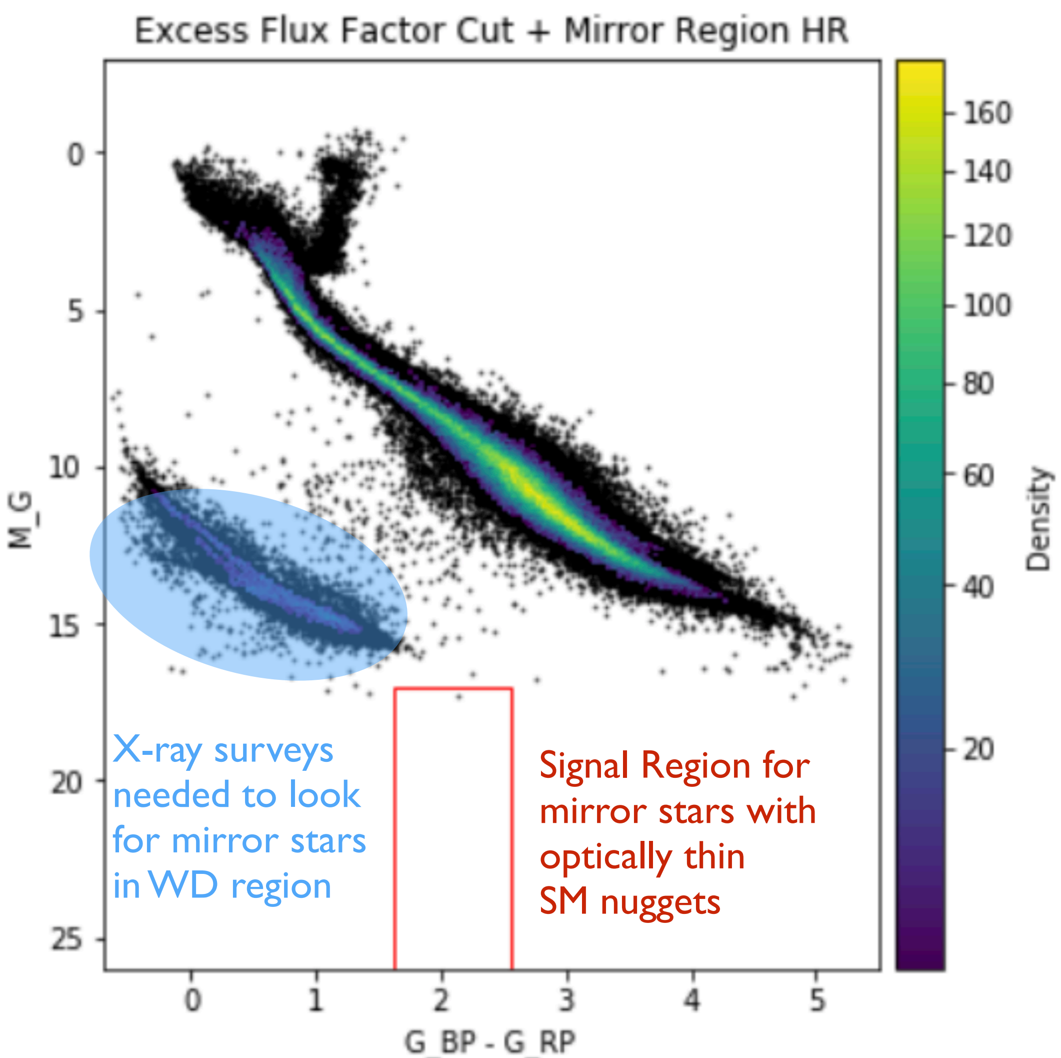


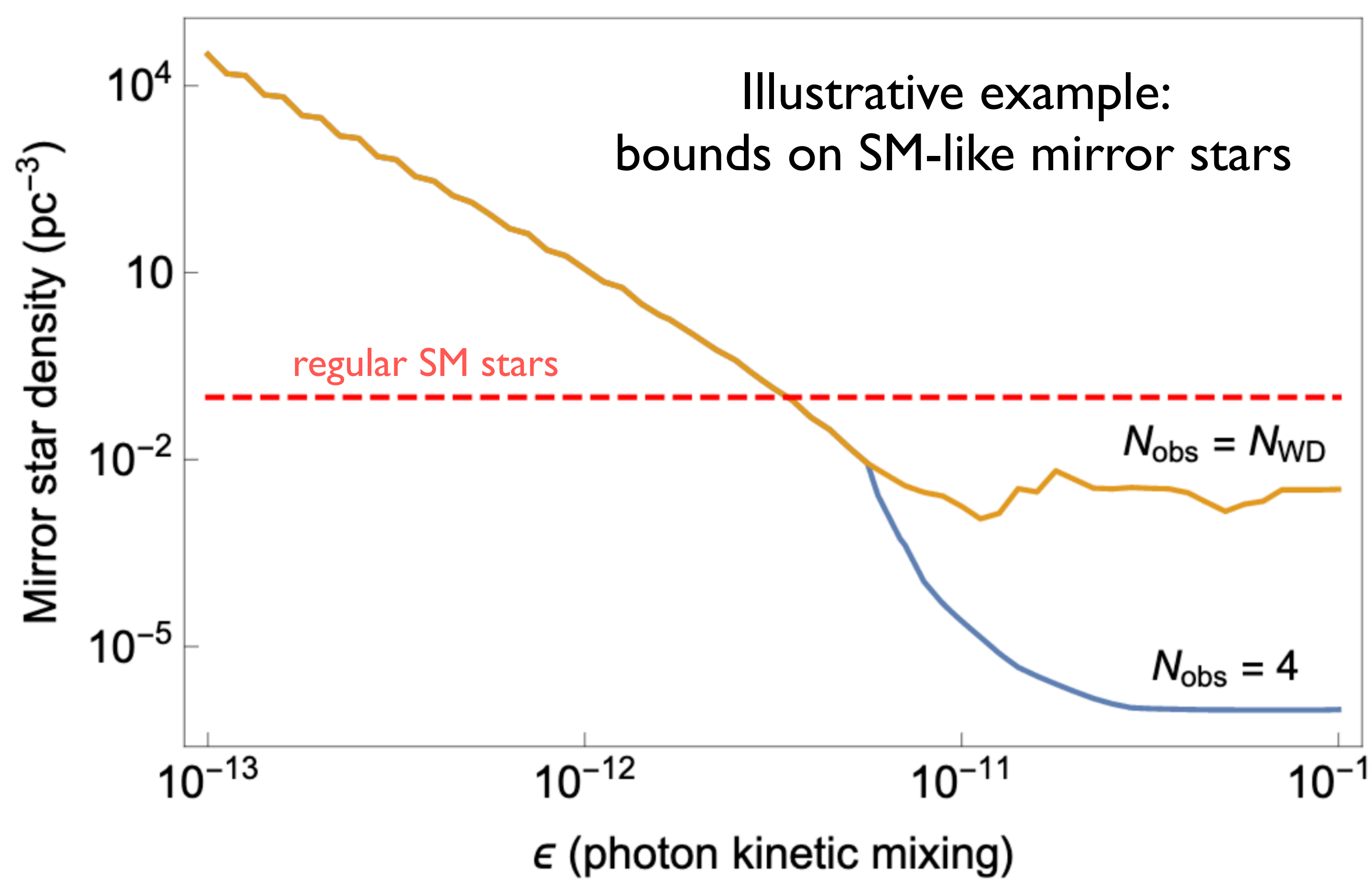
1909.04071 DC, Setford
1909.04072 DC, Setford

Mirror Stars in GAIA

Thermal emissions of captured SM matter in mirror stars should live in different region of HR diagram than regular stars (faint and hot).

GAIA constrains many possible mirror star scenarios, but still need to connect mirror star properties to atomic-DM microphysics





[in progress] **Aaron Howe**, Jack Setford, Chris Matzner, DC

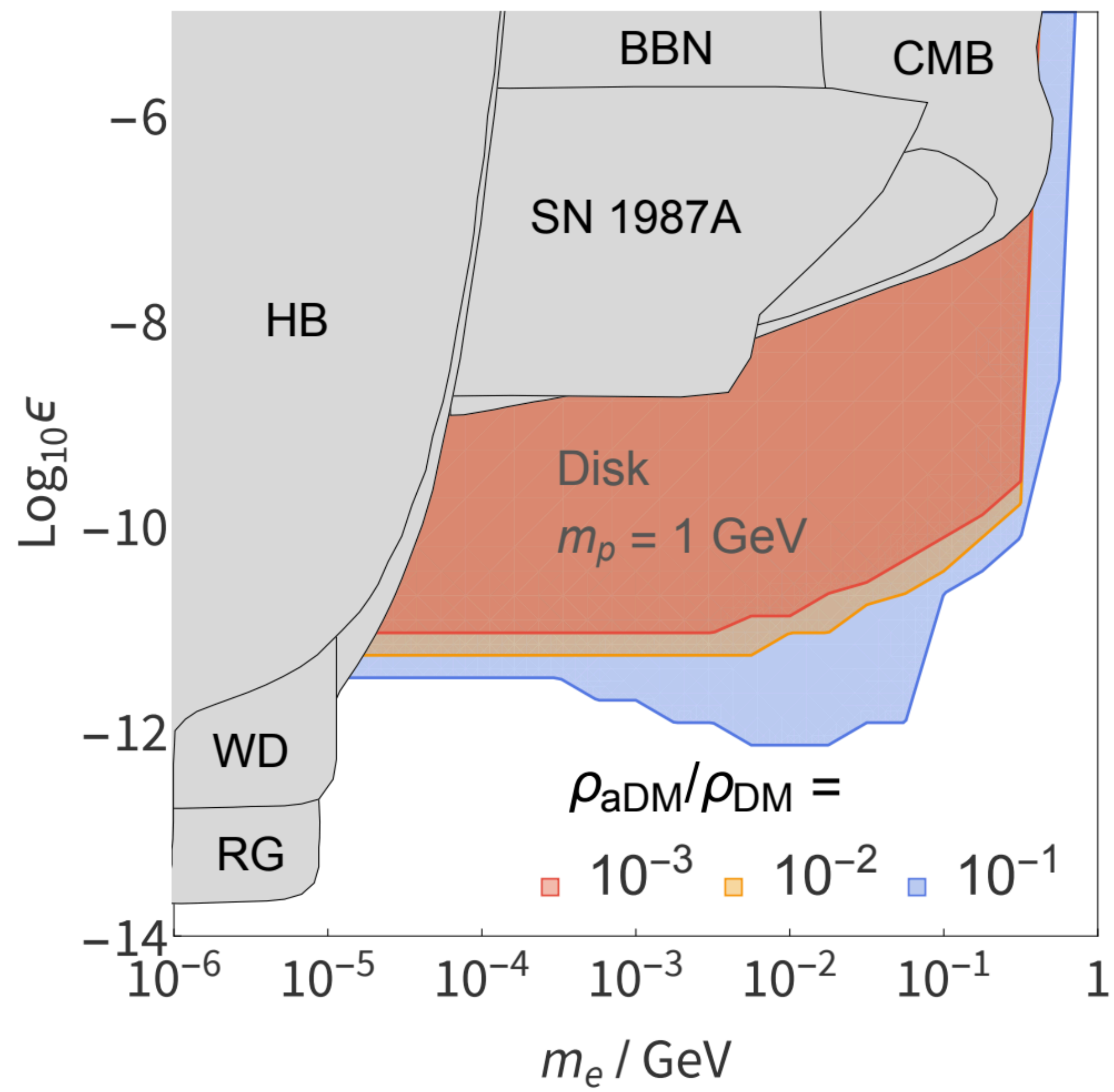
Stellar Cooling

Flip this around: if there is a photon portal, atomic Dark Matter will accumulate in **regular stars** and provide an **additional cooling channel by dark photon emission**

White Dwarf cooling provides strongest constraints on photon portal in atomic DM models.

Plenty of room for future detection, however.

Big fly in the ointment: unknown aDM distribution today!



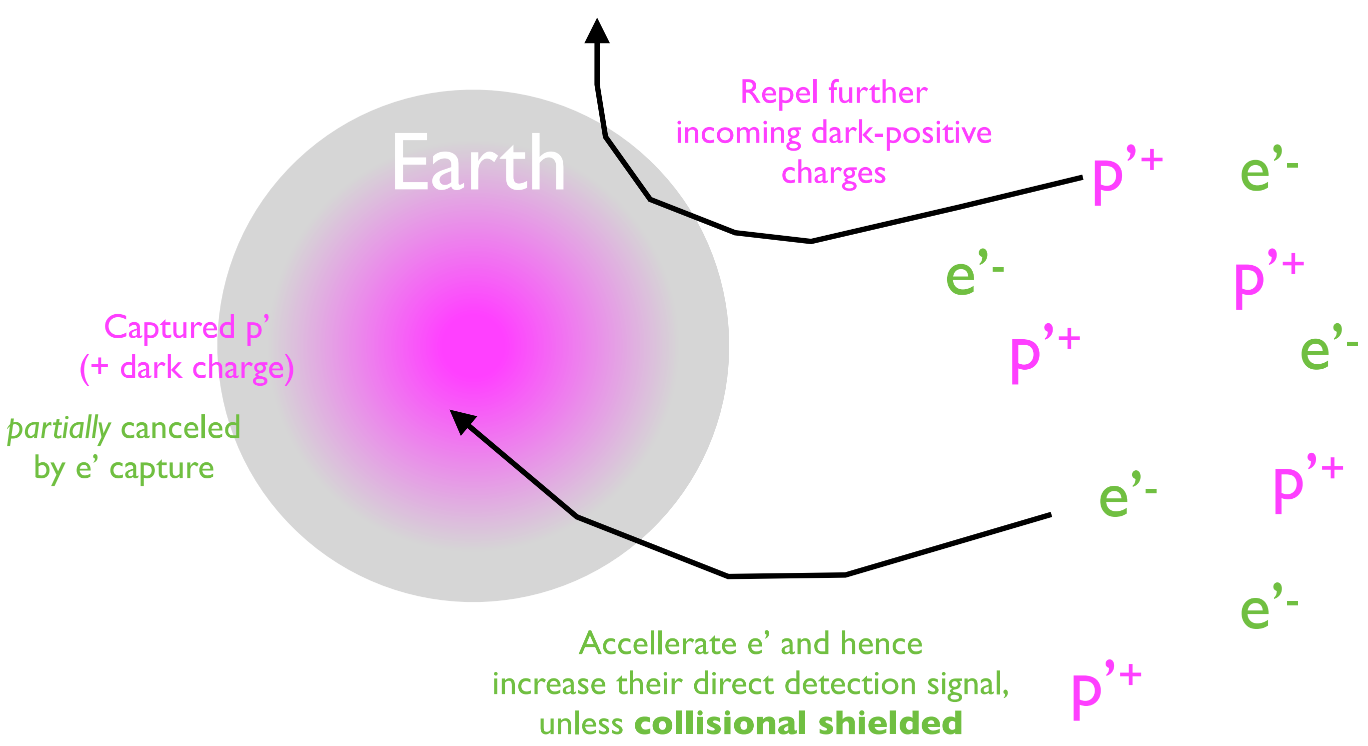
2010.00601 DC, Setford

Direct Detection of atomic DM

Complicated story for such a simple model.

Depends on DM-SM interaction of course, but also on the **local density and velocity distribution, i.e. distribution in the galaxy**.

Novel effects can dramatically affect scattering rates at local experiments:
capture, evaporation, and dark-plasma screening!



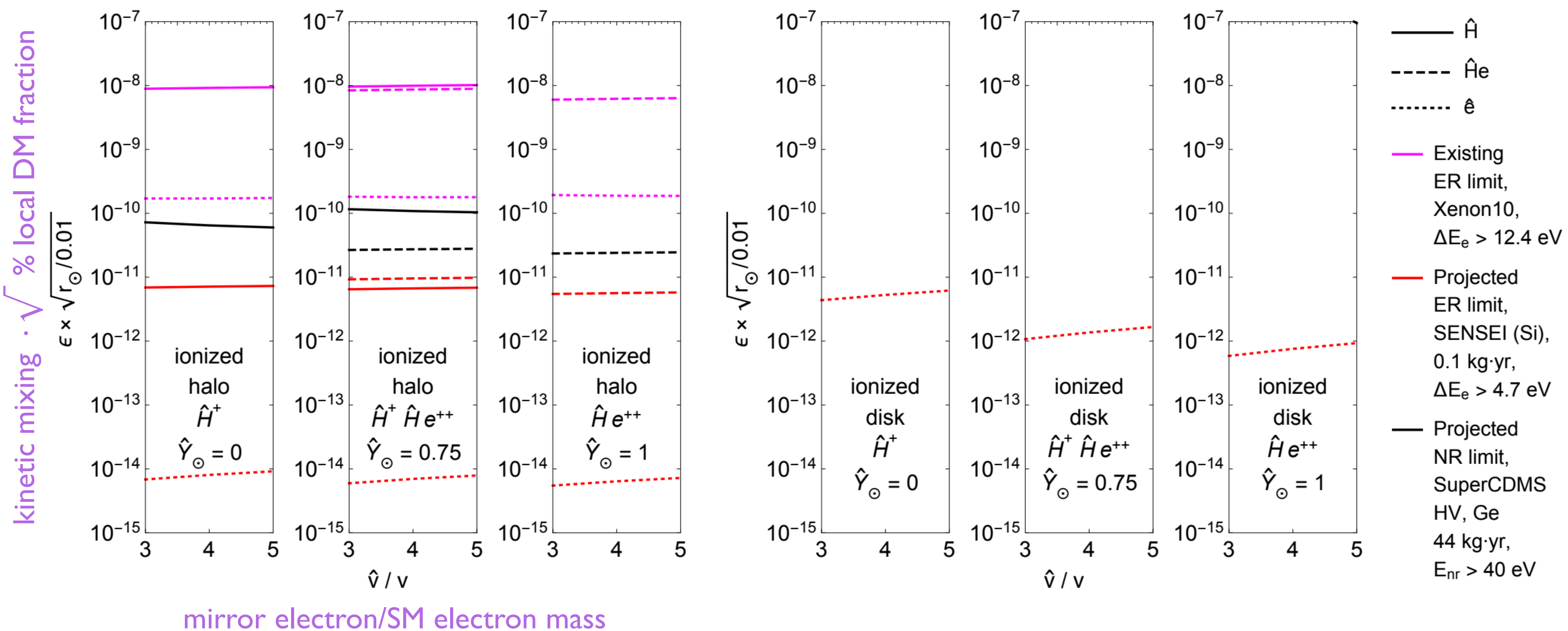
These effects turn on exponentially as function of aDM masses/parameters, so either don't matter at all **or** completely dominate behavior.

2104.02074 Chacko, DC, Geller, Tsai

Direct Detection

Twin Higgs with photon portal. Consider *benchmark* halo or disk distributions.

Electron-Recoil Direct Detection experiments will be able to probe tiny kinetic mixings $\epsilon \sim 10^{-14}$ in %-fraction aDM halo.



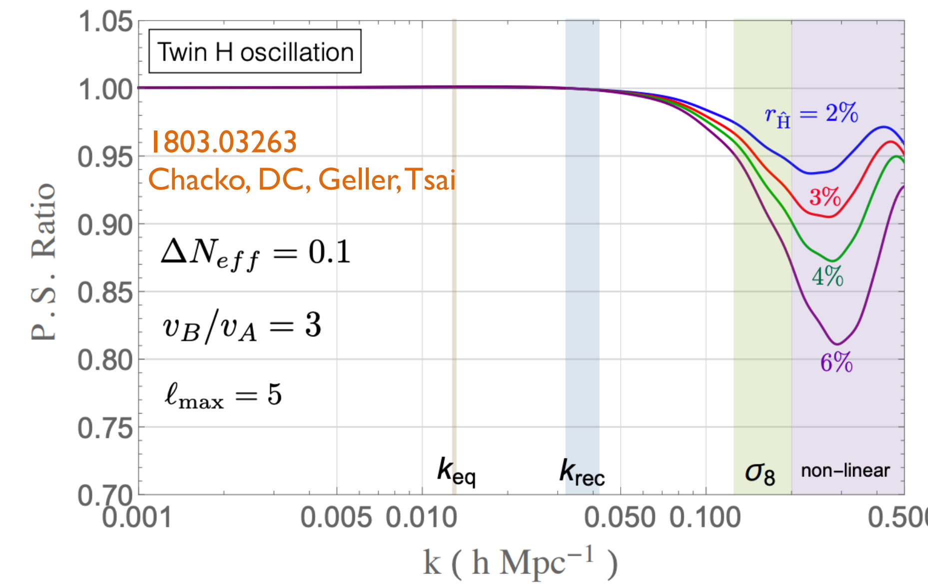
2104.02074 Chacko, DC, Geller, Tsai

Distribution of atomic DM

The most difficult question.

At large scales we can understand the **linear** effects of aDM, like **dark baryo-acoustic oscillations,** constrained by galaxy surveys.

1310.3278 Cyr-Racine, Putter, Raccanelli



%-level effects will be detected by future surveys.

(1308.4164 Font-Ribera, McDonald, Mostek, Reid, Seo, Slosar)

At smallest scales we can understand what kinds of phenomena will occur (mirror stars, capture, etc) but everything has a free unknown parameter: **the present-day aDM distribution in our galaxy!**

Can we ever predict aDM distribution from first principles?

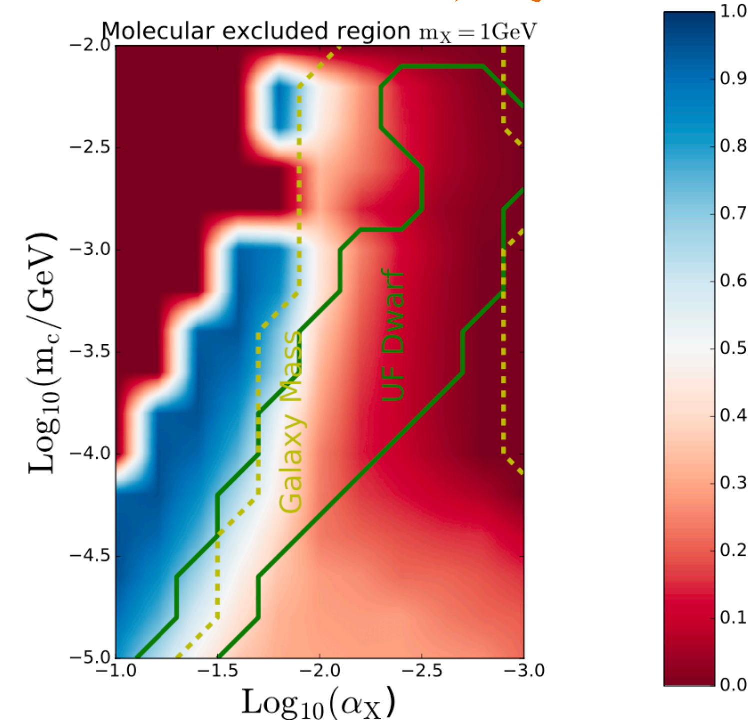
Vital to connect astrophysical observations/bounds to parameters of BSM model.

Galactic Structure

If we could predict aDM distribution in our galaxy, we could apply galaxy rotation curves, microlensing bounds, dwarf galaxy observations, to constrain aDM parameter space. (+ everything discussed on prev slides)

So far, cutting edge is application of semi-analytical methods for galactic structure formation.

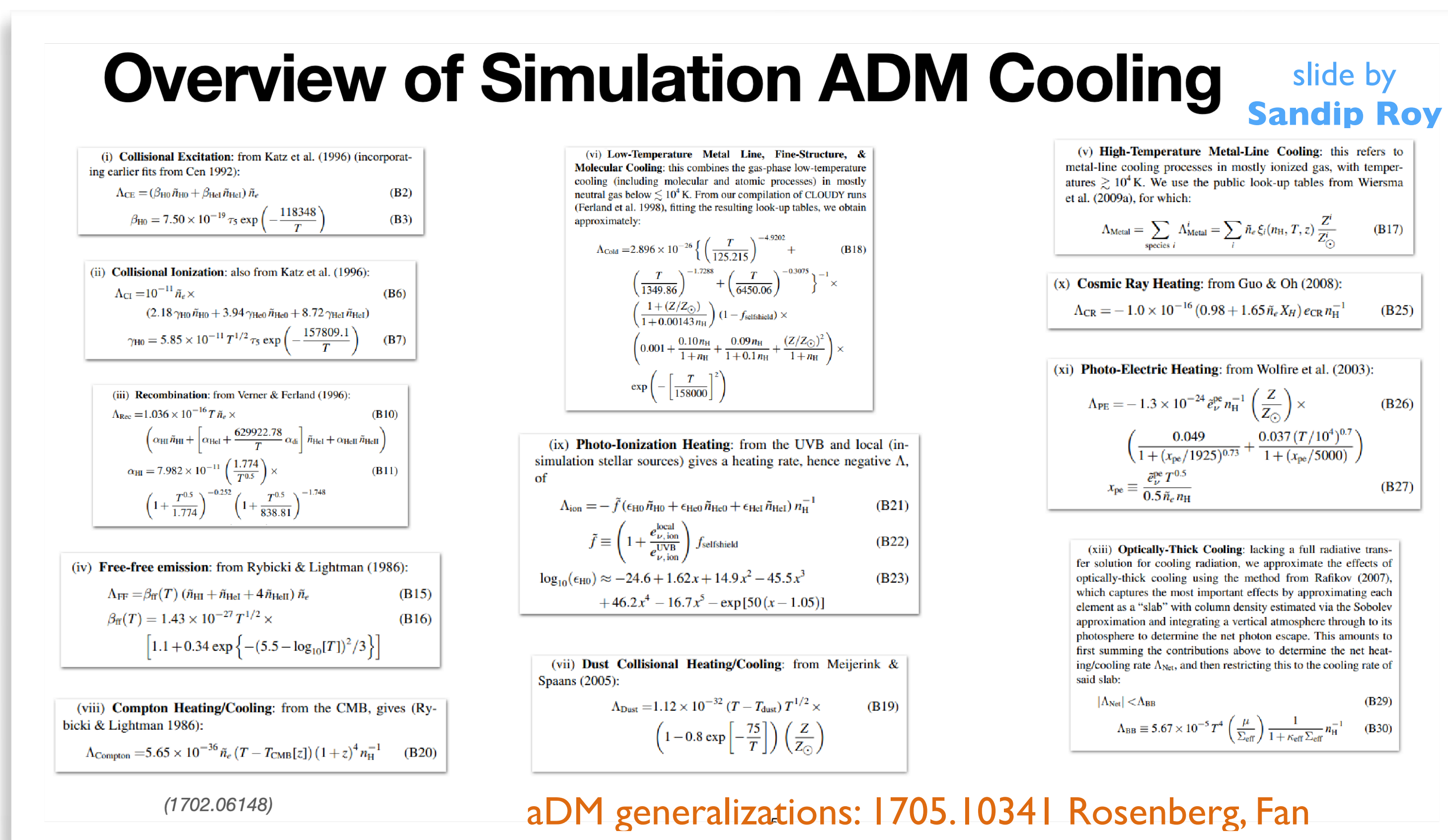
1712.04779 Ghalsasi, McQuinn



Need to be able to run full **MHD N-body simulations with aDM**.

- predict aDM distributions from first principles
- understand importance of **feedback and dark nuclear physics**

Currently extending GIZMO to add aDM capability.



[in progress] **Sandip Roy, Xuejian Shen**, Jack Setford, Mariangela Lisanti, Norman Murray, Philip Hopkins, DC

Conclusions

The CMB-S4 ΔN_{eff} measurement is a gate-keeper of rich dark dynamics.

If there is a signal, then all these possibilities become very real.

- Need to understand complicated dark dynamics on many scales
- Plethora of astrophysical signals:
  optical, X-ray, gravitational waves, microlensing, large-scale structure, direct detection & local dark plasma effects, galactic structure, …

What if CMB-S4 finds nothing?

If DM fraction interacting with DR is < ~ 5% and $T_D/T_\gamma \lesssim 0.3$, ΔN_{eff} and other cosmological bounds could be evaded in minimal aDM models
→ important to look for these direct astrophysical signals!

… but many complete and very motivated theories like the Mirror Twin Higgs have extra light dof and would be **severely constrained or excluded**.

Question: What would it take, hypothetically, to improve ΔN_{eff} precision even further? Seems CMB-S4 is near cosmic variance limit (???)…