New light on light dark sectors

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Seminar Talk

Oslo University

May 24 2023

ÖAW AUSTRIAN ACADEMY OF SCIENCES

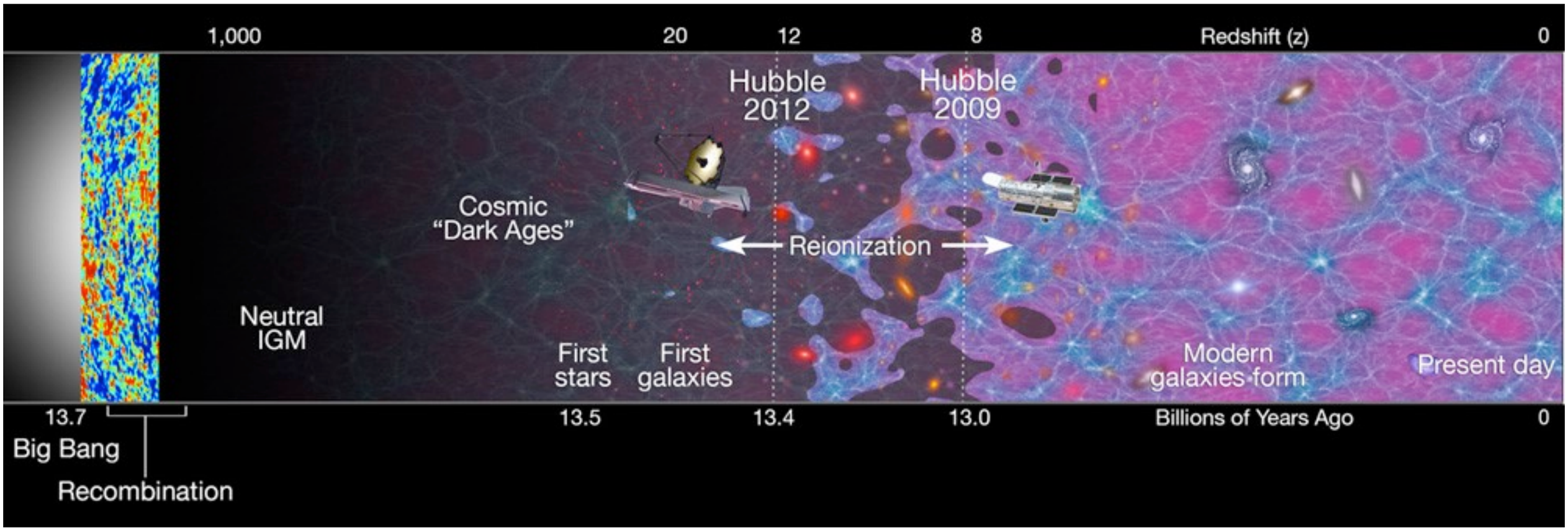
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Cosmic history

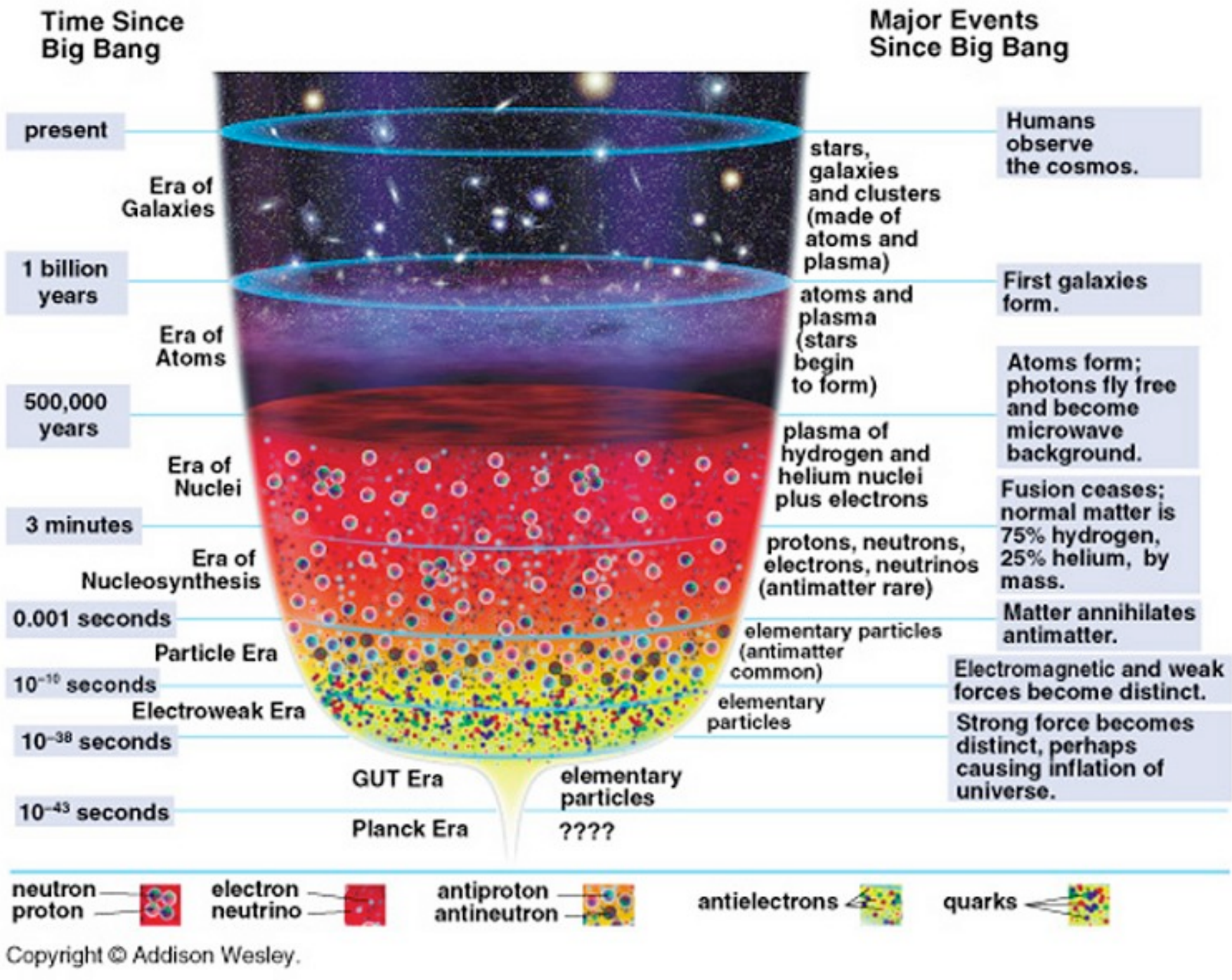
An astronomer's view:



All evidence for Dark Matter (DM) comes from astronomical and cosmological observations, existence is inferred from gravity alone.

Cosmic history

A particle physicist's view



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Our “New Physics Laboratory”

A particle physicist’s view

experimental searches

stellar astrophysics

21cm cosmology

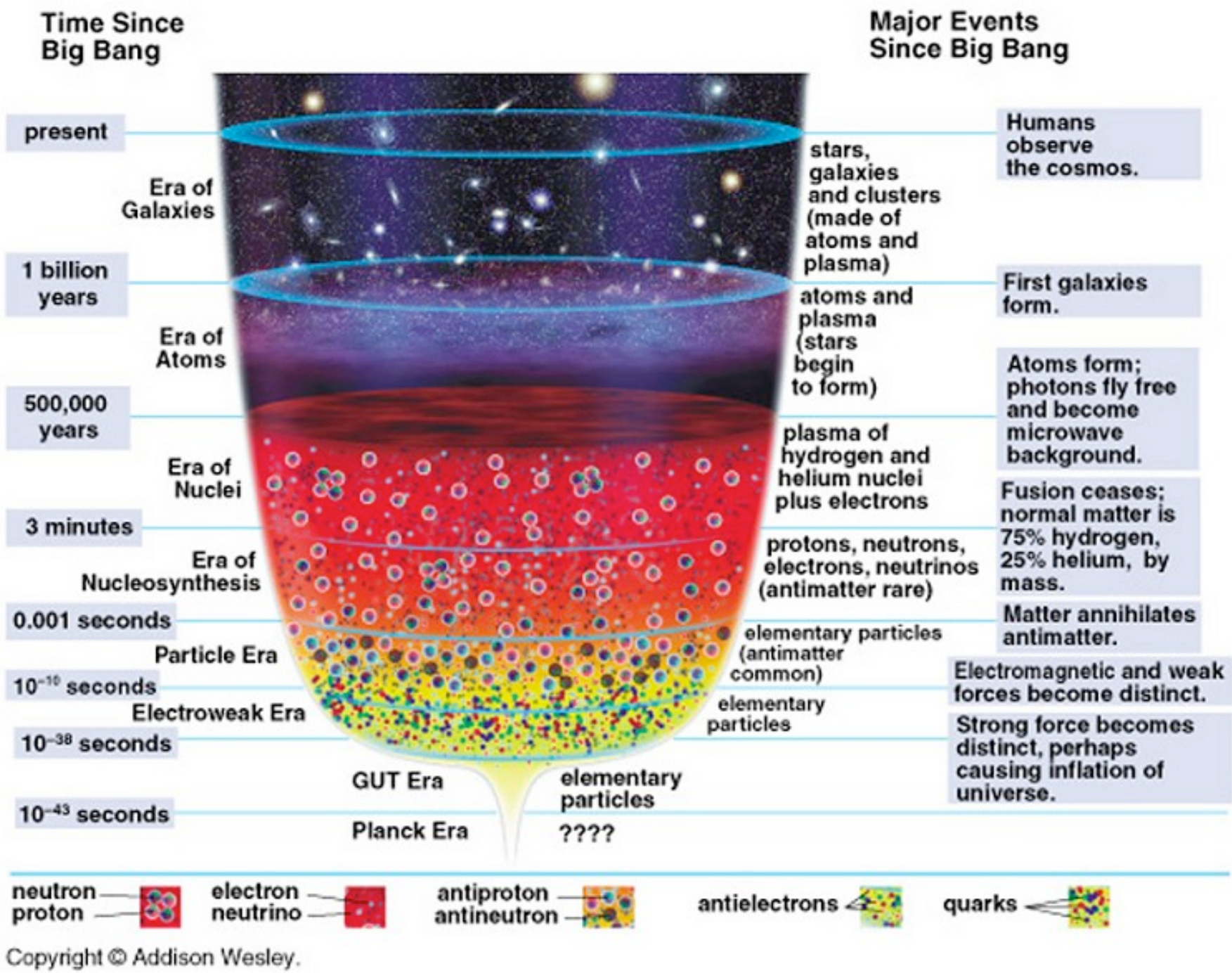
cosmic microwave background

primordial nucleosynthesis

dark matter genesis

Baryogenesis

…



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Outline

- Introduction: evidence of dark matter and potential solutions

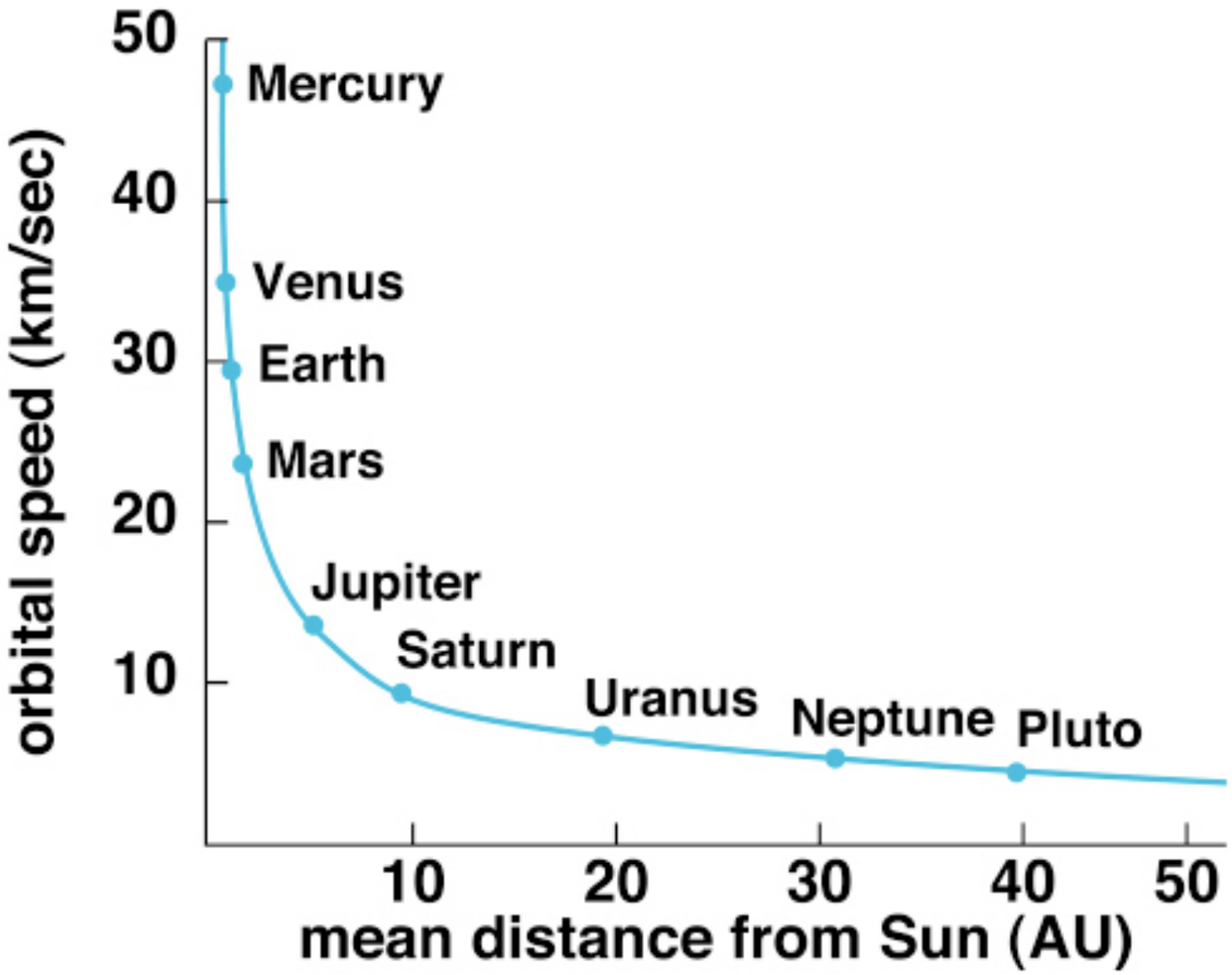
- Showcase of a dark sector below the GeV mass scale

  “photon portal” (experiments, astrophysics, cosmology)

- brief remarks on MeV - scale thermal dark matter freeze-out

Rotation curves

Consider the solar system



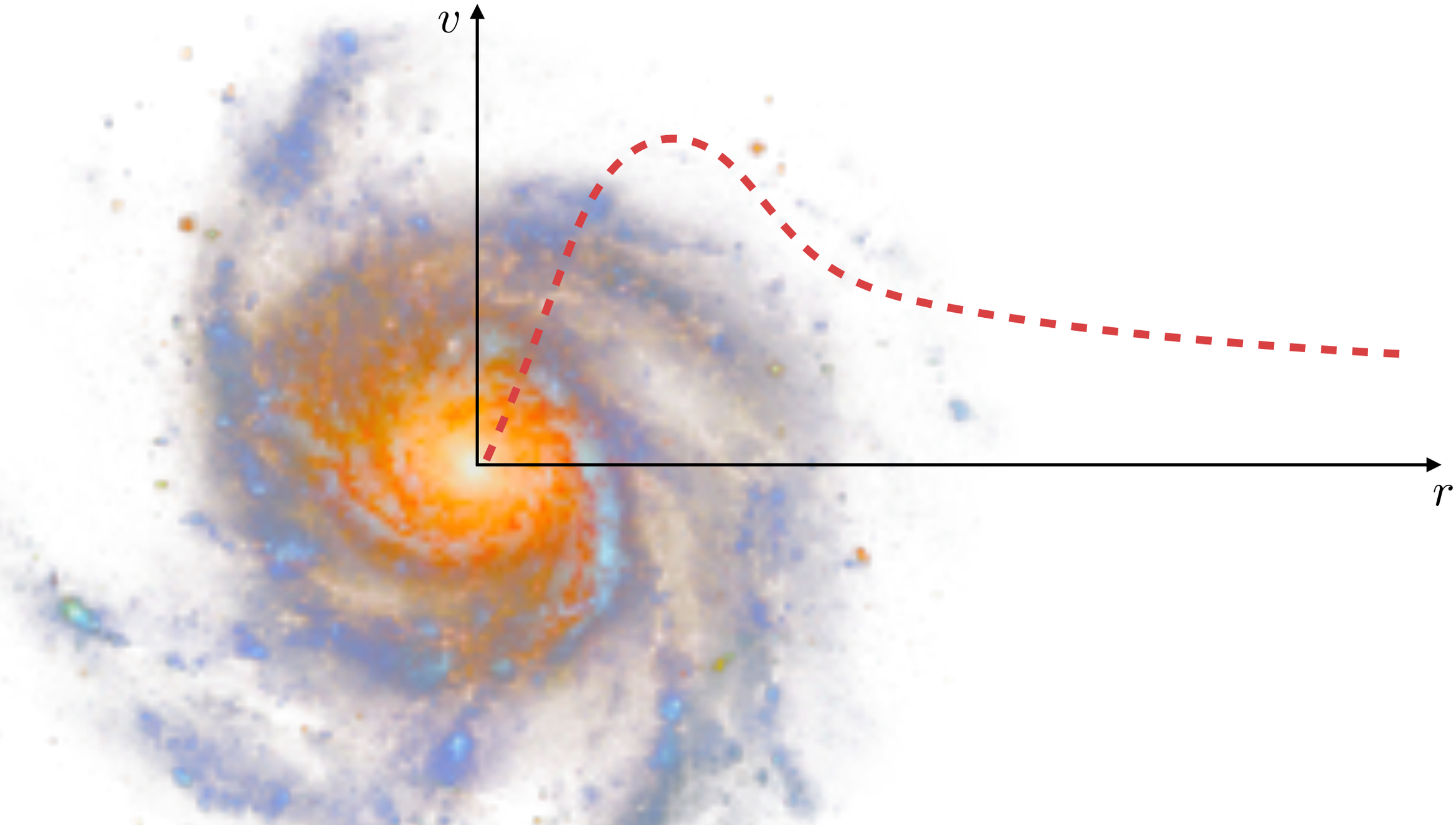
Orbit: $\frac{GmM(r)}{r^2} = \frac{mv^2}{r}$

=> $v = \sqrt{GM(r)/r}$

Observations are explained with $M = M_\odot \simeq 10^{30}\,\mathrm{kg}$

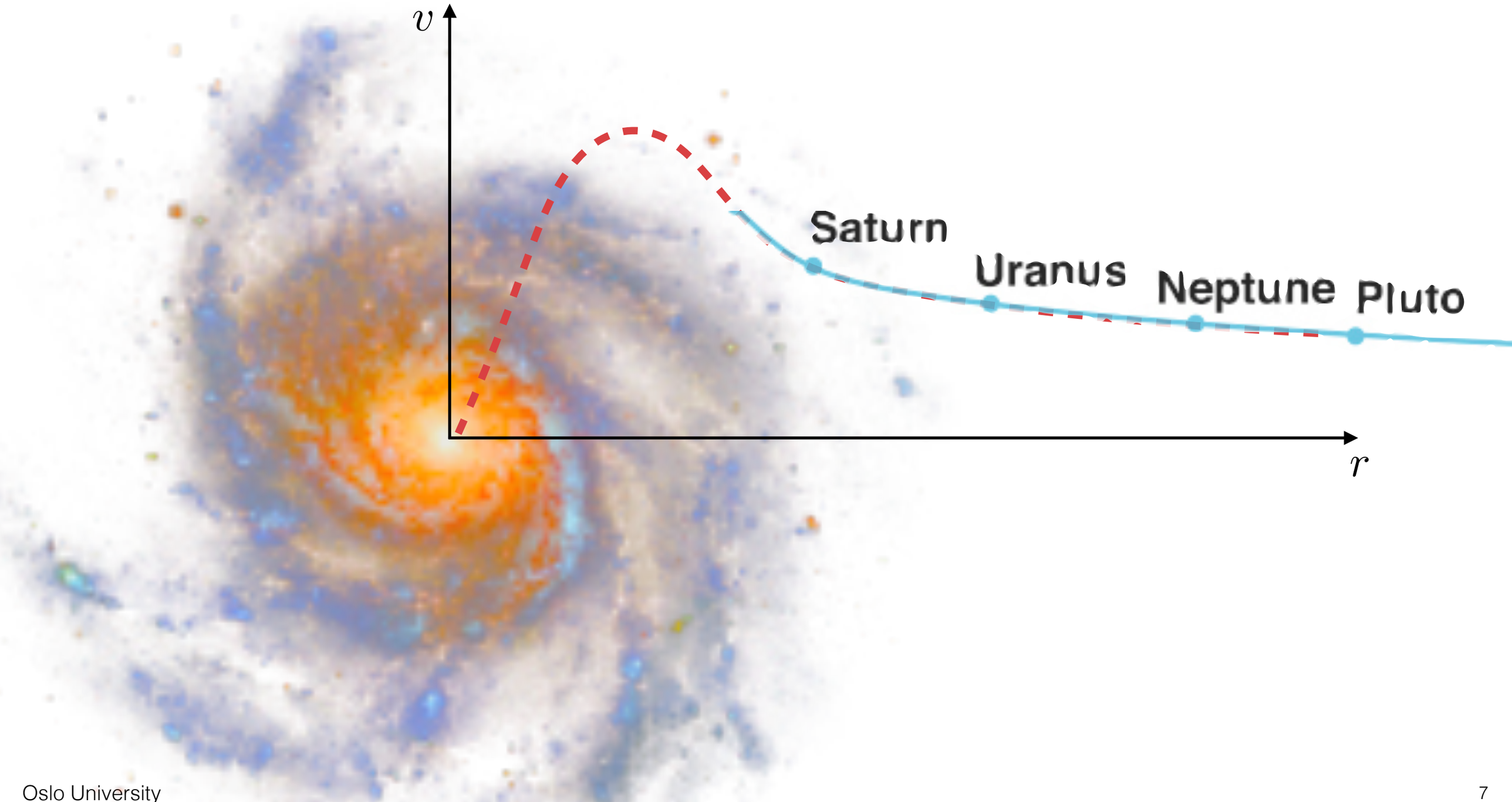
Rotation curves

Spiral galaxies



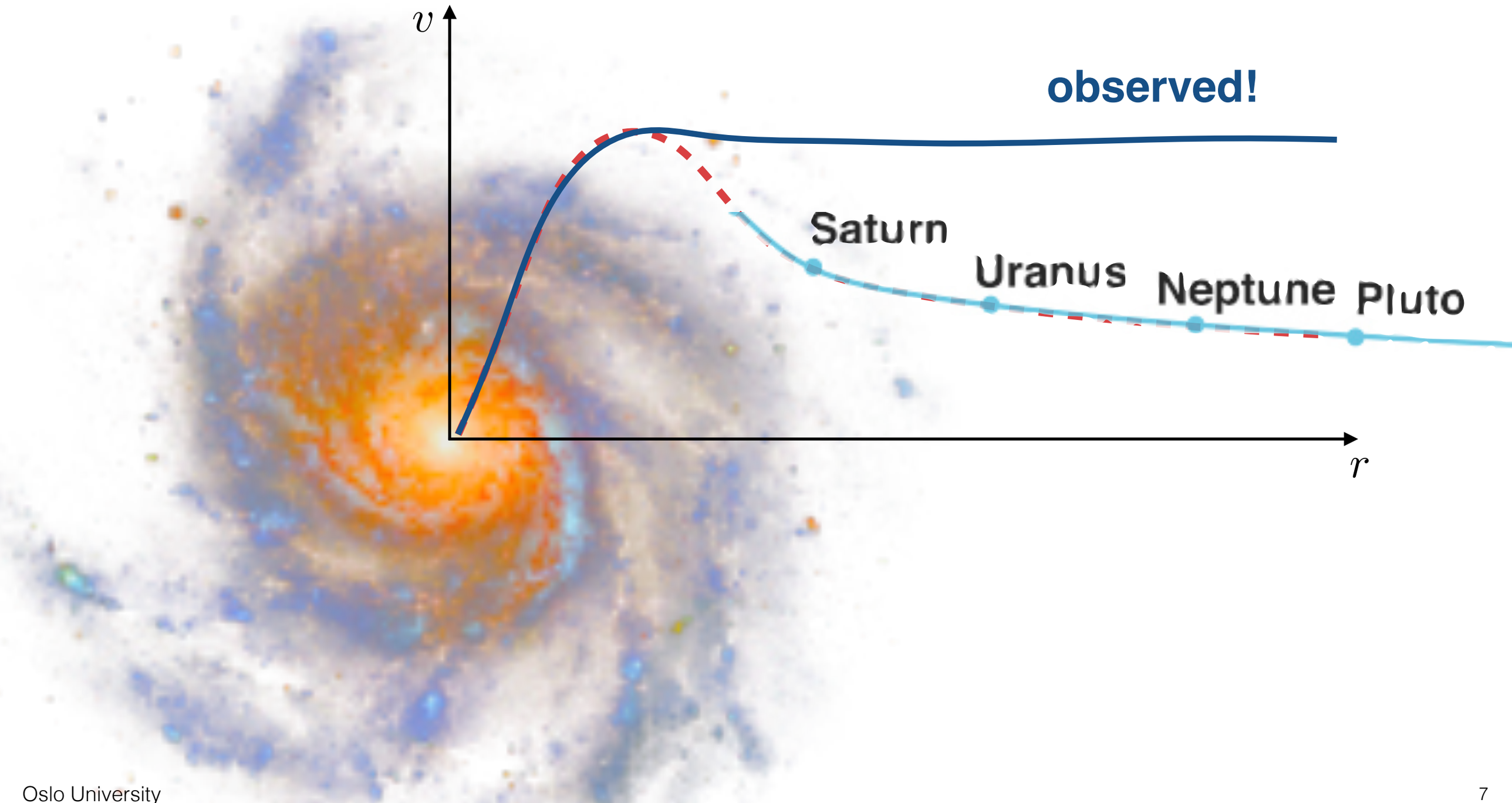
Rotation curves

Spiral galaxies



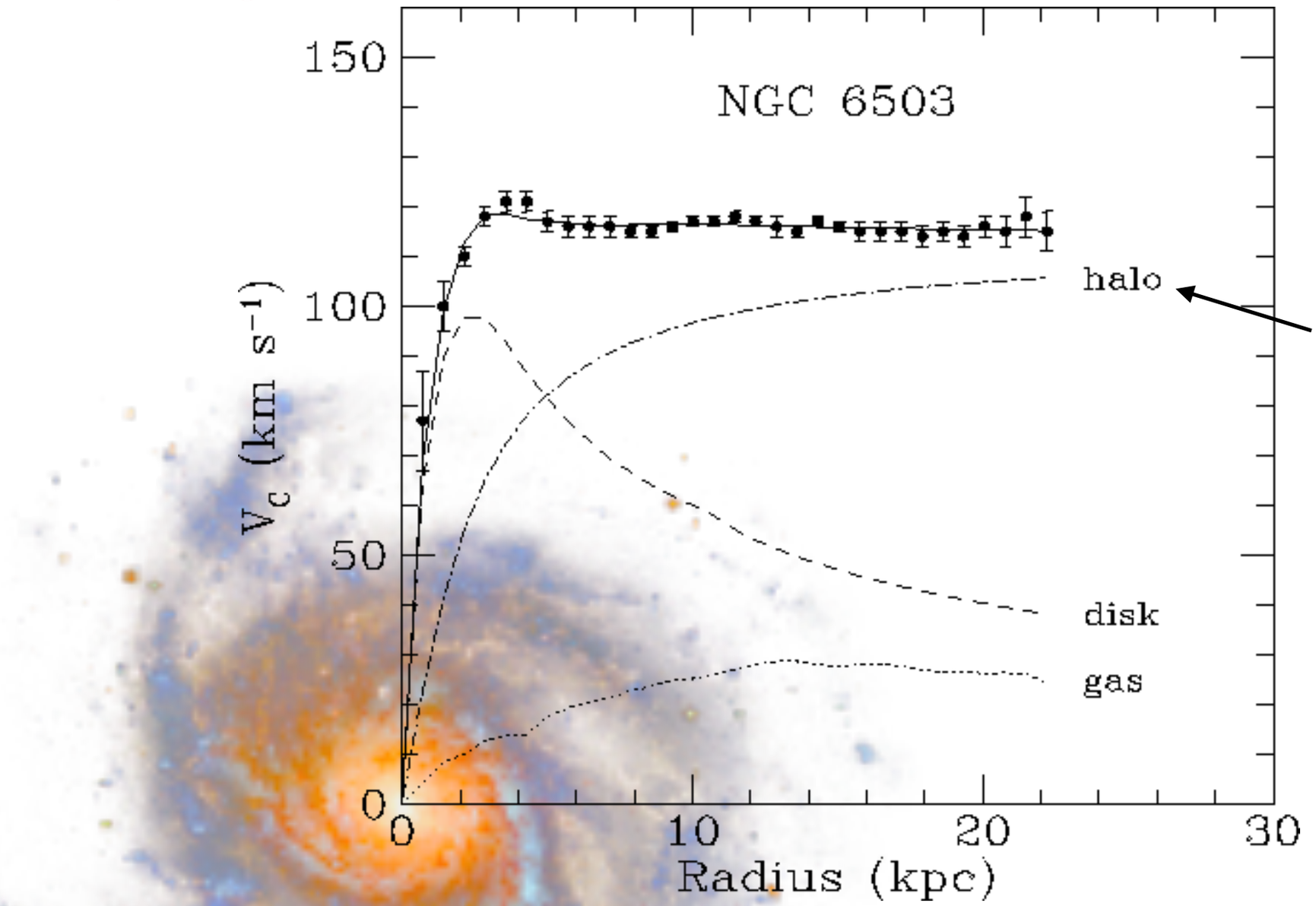
Rotation curves

Spiral galaxies



Rotation curves (kpc scales)

Spiral galaxies



observation

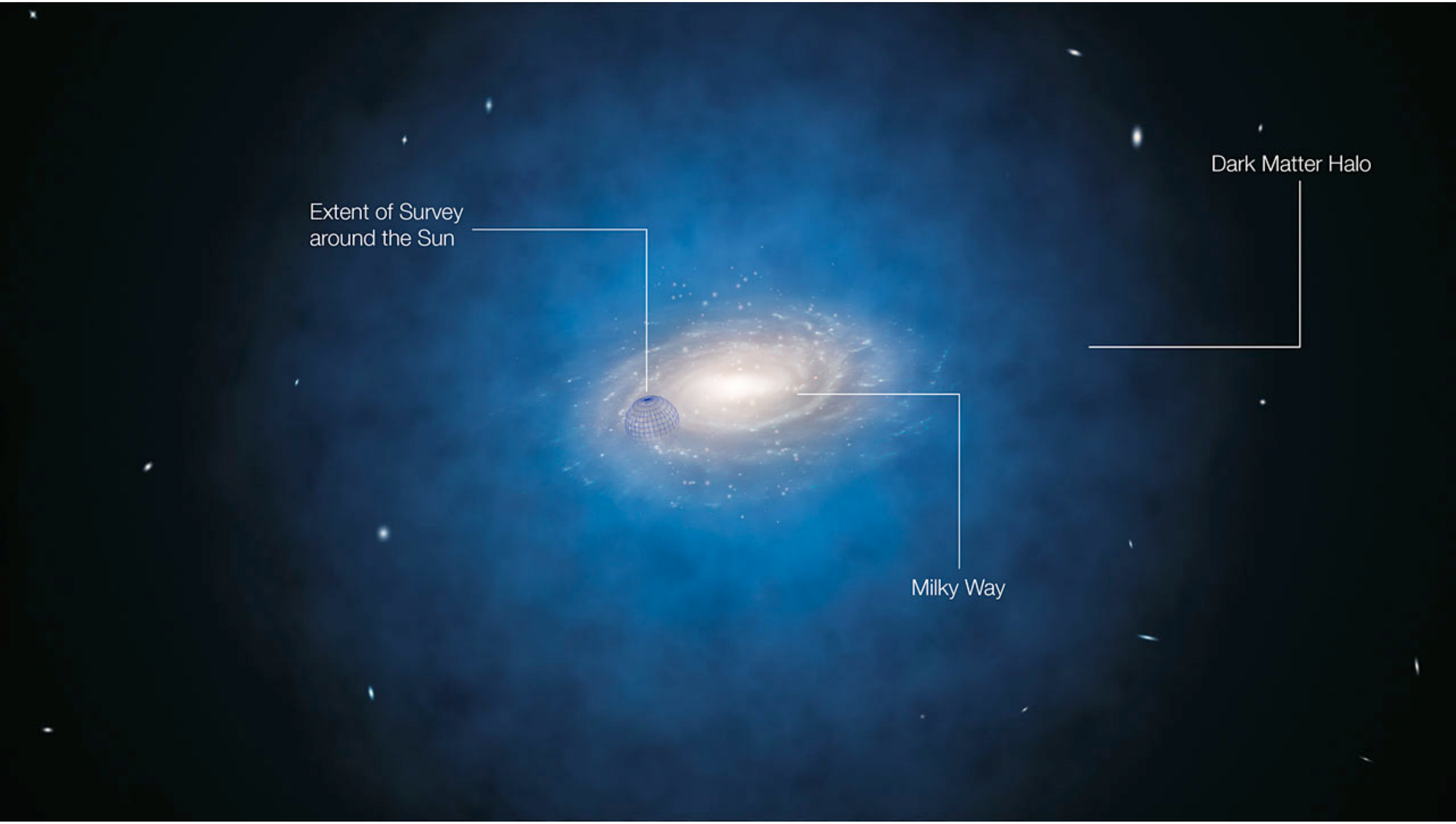
missing mass

expectation

For the Milky Way, fit yields at sun's position

$$\rho_\odot \simeq (0.3 \pm 0.1)\,\mathrm{GeV/cm^3}$$

Dark Matter halos (kpc scales)



Motion of galaxies (Mpc scales)

Equilibrated cluster of galaxies

Virial theorem connects average kinetic and gravitational binding energy

$$\langle E_{\rm kin} \rangle = -\frac{1}{2} \langle E_{\rm grav} \rangle$$

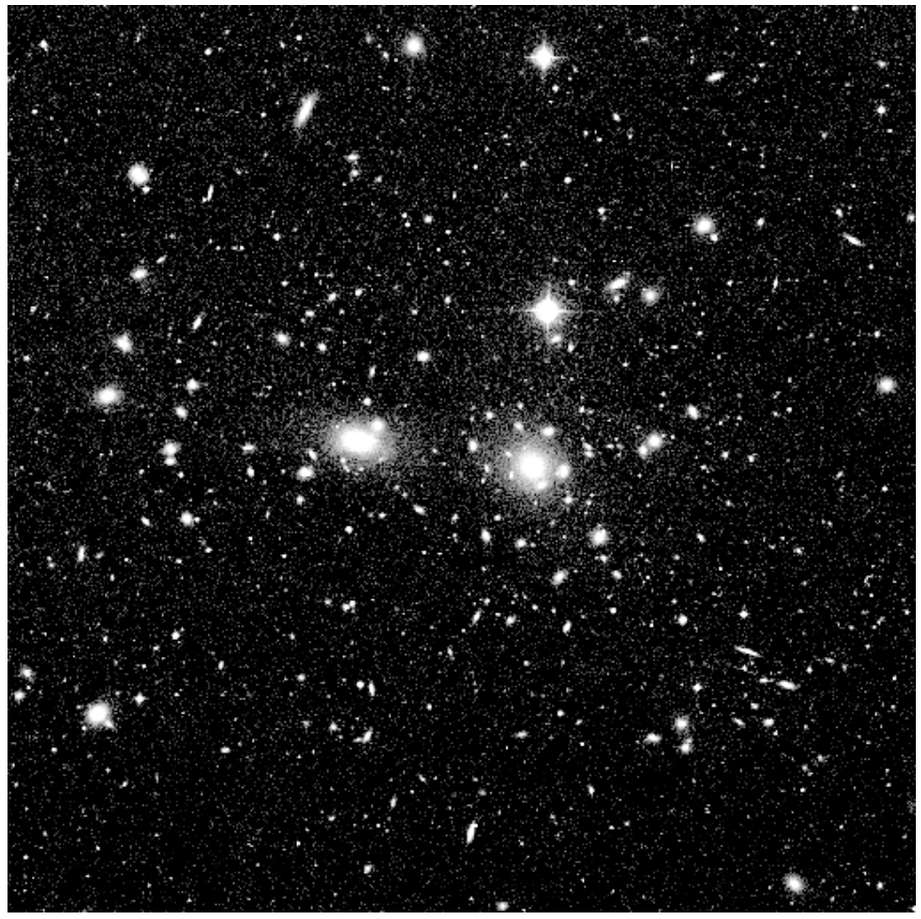
can be inferred from the motion of galaxies

depends on the mass of the entire cluster of galaxies

Zwicky first observed 1932 that there are 1000s of galaxies in Coma Cluster and measured radial velocities and their dispersion
=> "*kalte dunkle Materie*"

$$\left. \frac{M}{L} \right|_{\rm Coma} \simeq 160 \frac{M_\odot}{L_\odot}$$

Fusco-Femiano, Hughes 1994



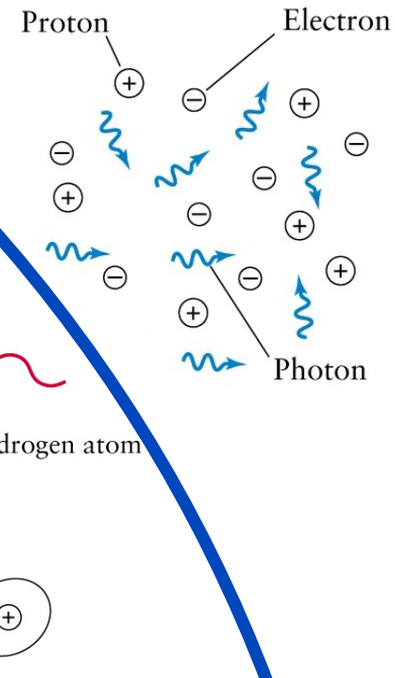
Coma cluster



Fritz Zwicky

Cosmic Microwave Background (Gpc)

surface of last scattering



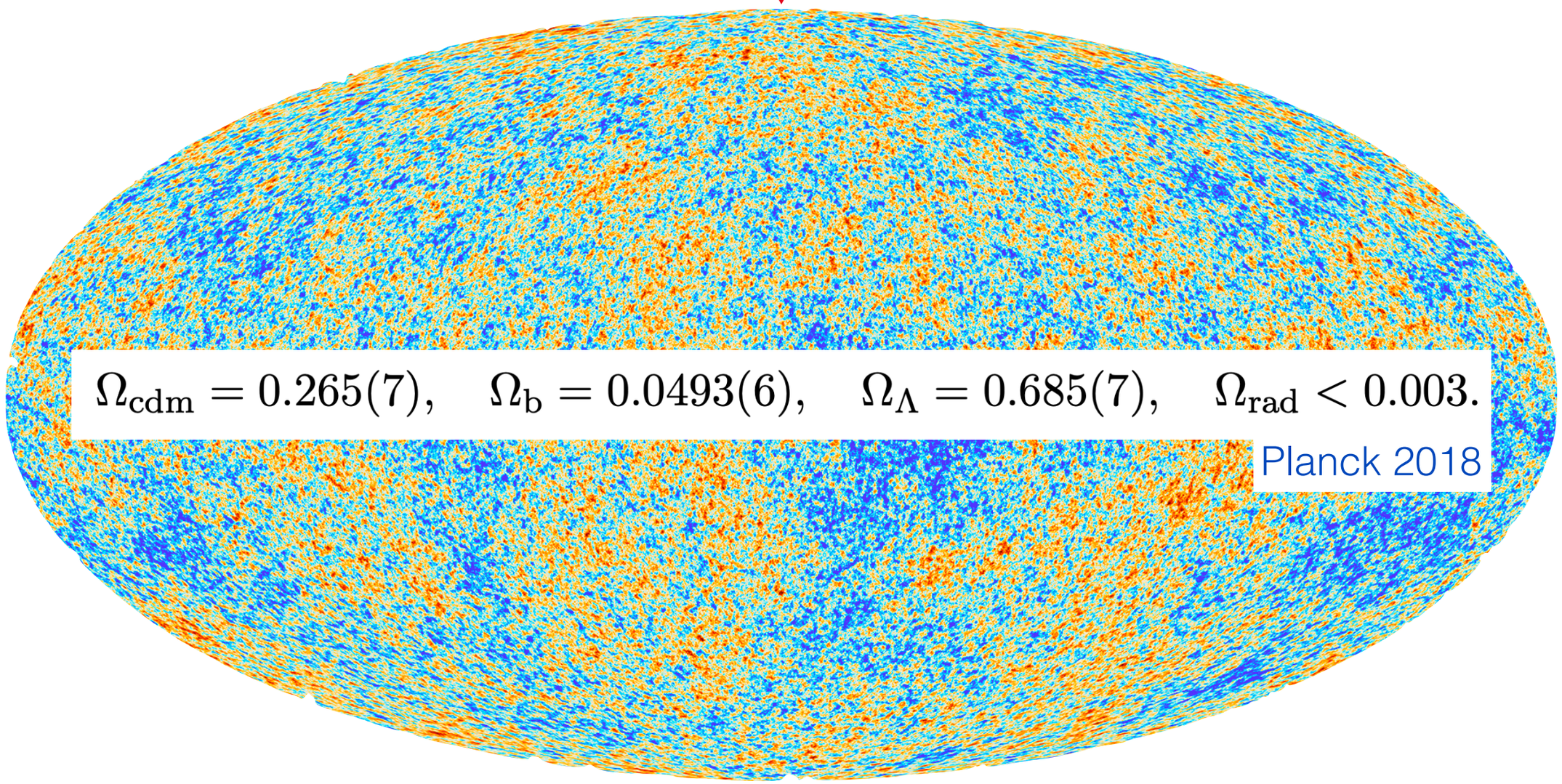
$$T_0 = 2.72548 \pm 0.00057\,\mathrm{K}$$



redshift 1100

Dark Matter is key…

… in explaining the observations of the CMB (linear theory)

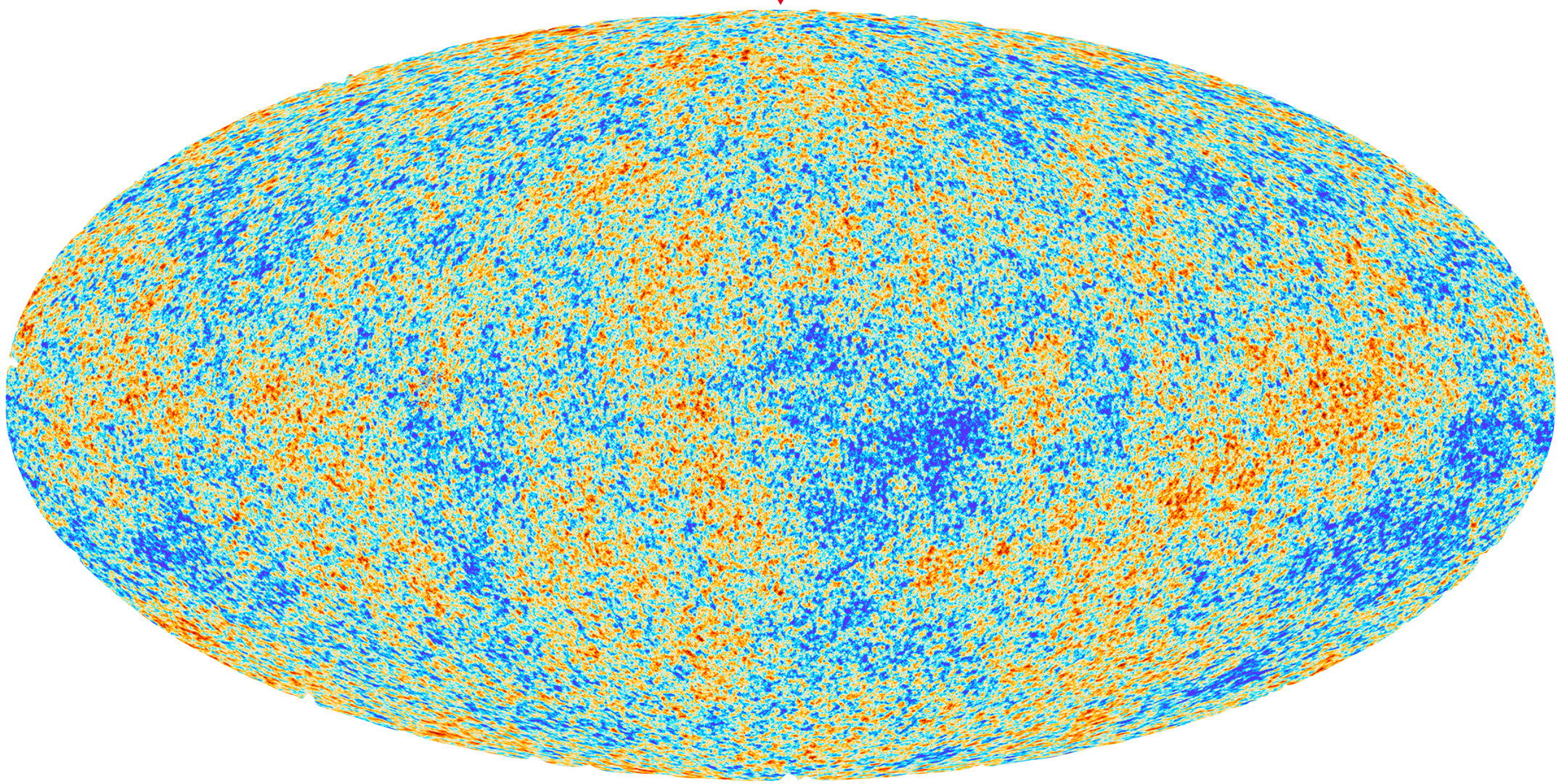


$$\Omega_{\rm cdm} = 0.265(7), \quad \Omega_{\rm b} = 0.0493(6), \quad \Omega_\Lambda = 0.685(7), \quad \Omega_{\rm rad} < 0.003.$$

Planck 2018

Dark Matter is key…

… in explaining the observations of the cosmic microwave background



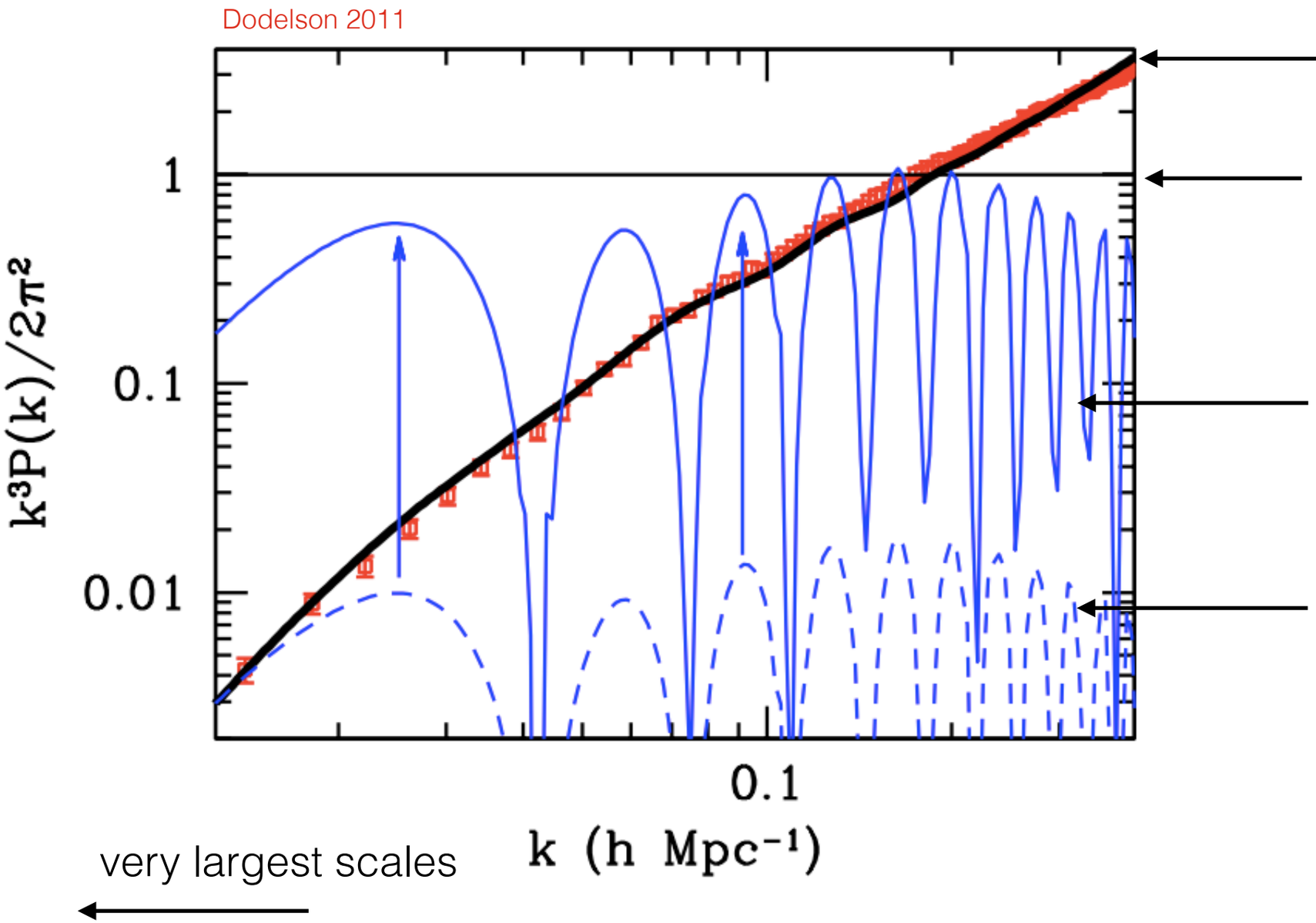
… in the formation of large scale structure such as galaxies and clusters of galaxies

Dark Matter assisted growth

Growth of structure is quantified by the power spectrum

$$\frac{k^3 P(k)}{2\pi^2} = \left(\frac{\delta\rho}{\rho}\right)^2_k$$

Dodelson 2011



solid: with Dark Matter

growth has become non-linear

Modified Gravity

dashed: baryon-only Universe

very largest scales

OK, the Dark Matter is there.

What can it be?

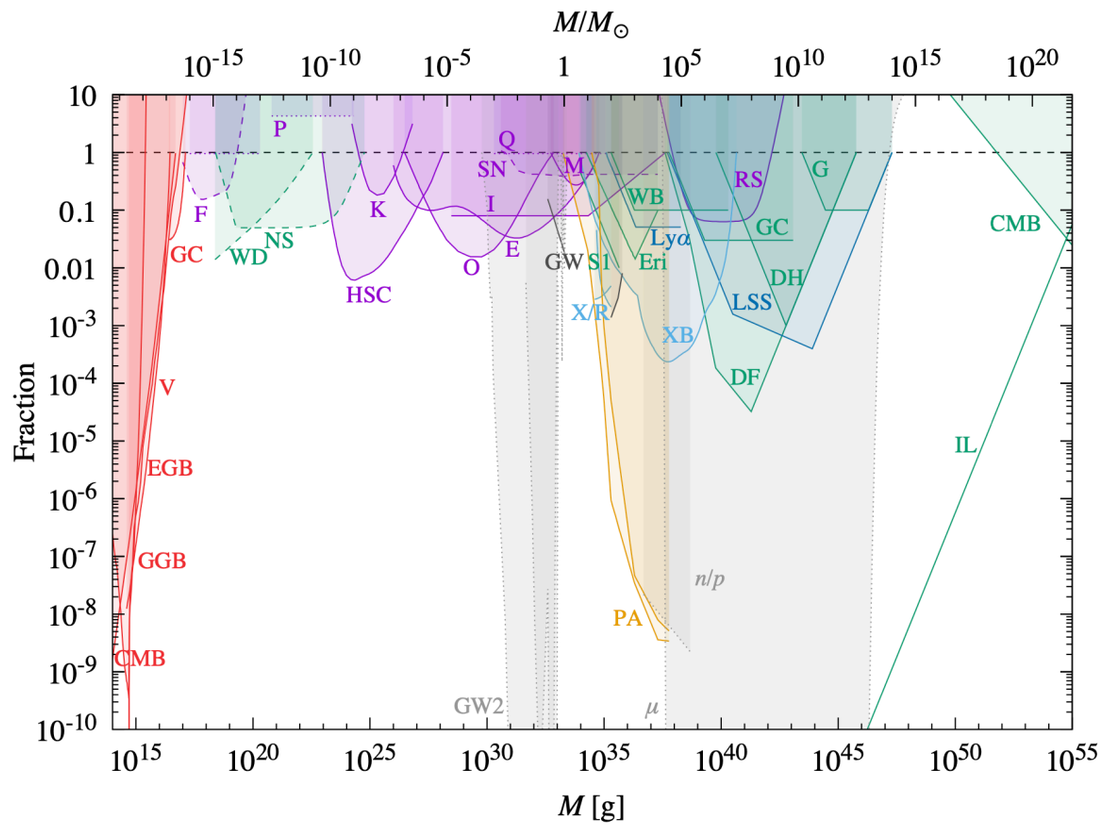
Modified Gravity?

successes on Galaxy scales,
but fails elsewhere

Primordial Black holes?

asteroid mass black holes may
still make up 100% of DM

New particle(s) of nature?



our best bet. This talk.

The missing mass - what is it?

New particle(s) of nature?

electroweak scale
WIMPs, GeV-scale DM

axion, ALPs

keV sterile neutrinos

gravitinos

other super-WIMPs such as Dark Photons



A model beloved for its **inner** beauty

$$
\begin{aligned}
\frac{1}{e}\mathscr{L}_{\rm sugra} = & -\frac{M_P^2}{2}R + g_{ij^*}\tilde{\mathscr{D}}_\mu\phi^i\tilde{\mathscr{D}}^\mu\phi^{*j} - \frac{1}{2}g^2\left[({\rm Re}f)^{-1}\right]^{ab}D_{(a)}D_{(b)} \\
& + ig_{ij^*}\overline{\chi}_L^j\gamma^\mu\tilde{\mathscr{D}}_\mu\chi_L^i + \varepsilon^{\mu\nu\rho\sigma}\overline{\psi}_{L\mu}\gamma_\nu\tilde{\mathscr{D}}_\rho\psi_{L\sigma} \\
& - \frac{1}{4}{\rm Re}f_{ab}F_{\mu\nu}^{(a)}F^{\mu\nu(b)} + \frac{1}{8}\varepsilon^{\mu\nu\rho\sigma}{\rm Im}f_{ab}F_{\mu\nu}^{(a)}F_{\rho\sigma}^{(b)} \\
& + \frac{i}{2}{\rm Re}f_{ab}\overline{\lambda}^a\gamma^\mu\tilde{\mathscr{D}}_\mu\lambda^b - e^{-1}\frac{1}{2}{\rm Im}f_{ab}\tilde{\mathscr{D}}_\mu\left[e\overline{\lambda}_R^a\gamma^\mu\lambda_R^b\right] \\
& + \Bigg[- \sqrt{2}g\partial_i D_{(a)}\overline{\lambda}^a\chi_L^i + \frac{1}{4}\sqrt{2}g\left[({\rm Re}f)^{-1}\right]^{ab}\partial_i f_{bc}D_{(a)}\overline{\lambda}^c\chi_L^i \\
& + \frac{i}{16}\sqrt{2}\partial_i f_{ab}\overline{\lambda}^a[\gamma^\mu,\gamma^\nu]\chi_L^i F_{\mu\nu}^{(b)} - \frac{1}{2M_P}gD_{(a)}\overline{\lambda}_R^a\gamma^\mu\psi_\mu \\
& - \frac{i}{2M_P}\sqrt{2}g_{ij^*}\tilde{\mathscr{D}}_\mu\phi^{*j}\overline{\psi}_\nu\gamma^\mu\gamma^\nu\chi_L^i + {\rm h.c.}\Bigg] \\
& - \frac{i}{8M_P}{\rm Re}f_{ab}\overline{\psi}_\mu[\gamma^m,\gamma^n]\gamma^\mu\lambda^a F_{mn}^{(b)} \\
& - e^{K/2M_P^2}\Bigg[\frac{1}{4M_P^2}W^*\overline{\psi}_{R\mu}[\gamma^\mu,\gamma^\nu]\psi_{L\nu} - \frac{1}{2M_P}\sqrt{2}D_iW\overline{\psi}_\mu\gamma^\mu\chi_L^i \\
& + \frac{1}{2}\mathscr{D}_iD_jW\overline{\chi_L^c}^i\chi_L^j + \frac{1}{4}g^{ij^*}D_{j^*}W^*\partial_i f_{ab}\overline{\lambda}_R^a\lambda_L^b + {\rm h.c.}\Bigg] \\
& - e^{K/M_P^2}\left[g^{ij^*}(D_iW)(D_{j^*}W^*) - 3\frac{|W|^2}{M_P^2}\right] + \mathcal{O}(M_P^{-2}),
\end{aligned}
$$

Supergravity

A model beloved for its **outer** beauty

$$\mathcal{L} = \frac{1}{2}(\partial_\mu S)^2 - \frac{1}{2}m_S^2 S^2 - \lambda S^2 (H^\dagger H)$$

Higgs portal

A model beloved for its **outer** beauty

$$\mathcal{L} = \frac{1}{2}(\partial_\mu S)^2 - \frac{1}{2}m_S^2 S^2 - \lambda S^2 (H^\dagger H)$$

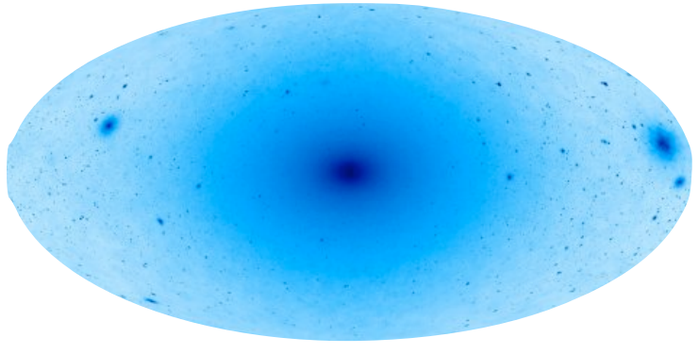
=> experiment decides!

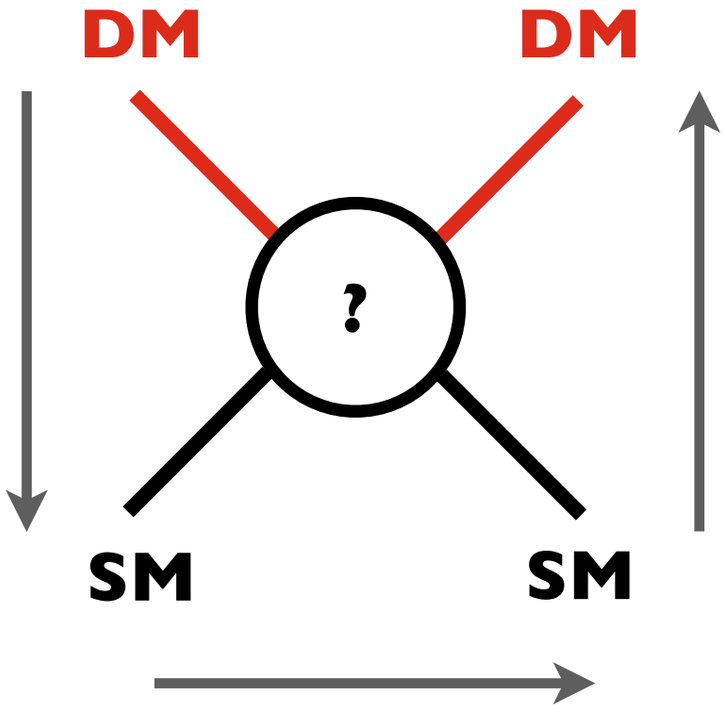
Higgs portal

Where to look for a signal?

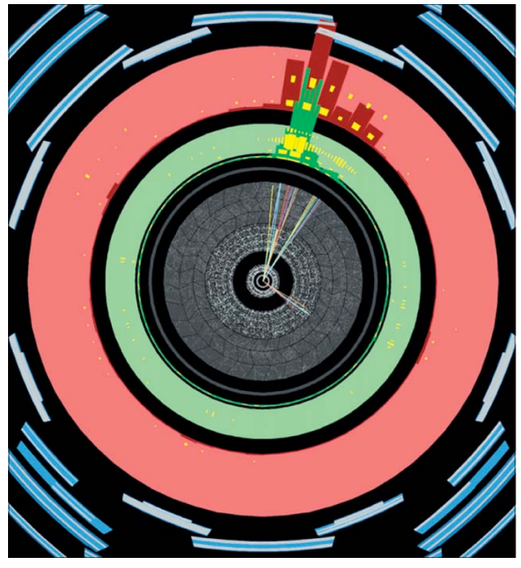
Look anywhere you can!

astrophysics
and cosmology





direct production

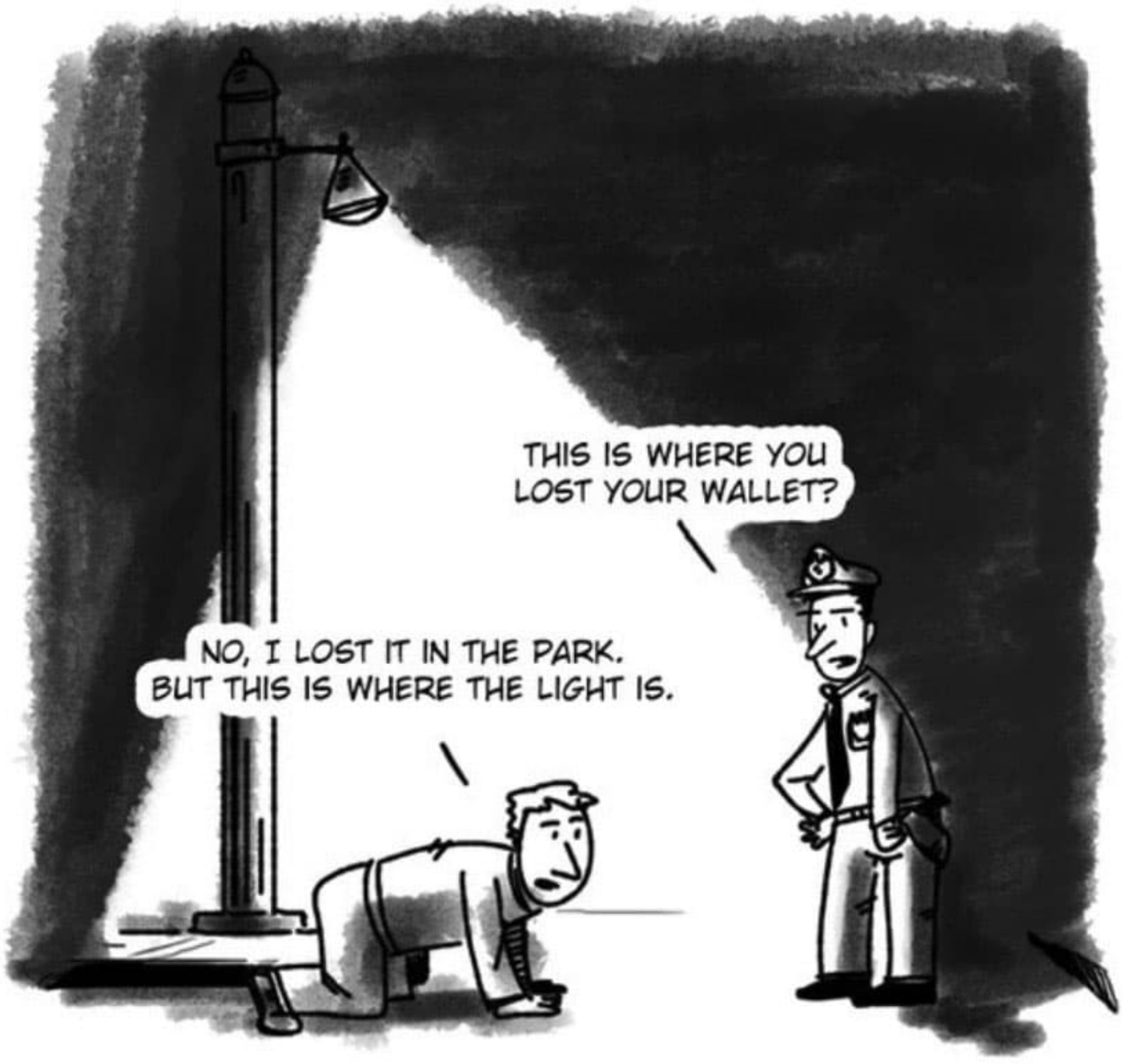


direct detection



Philosophy of this talk

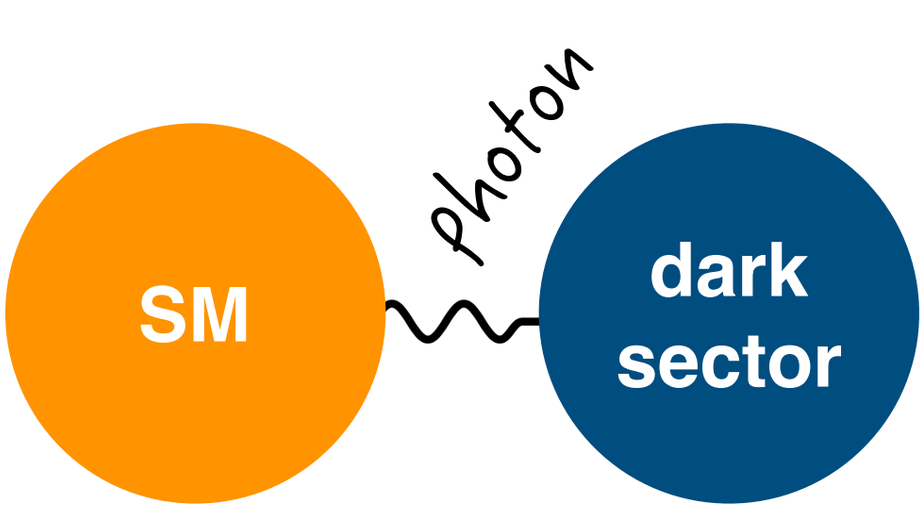
Streetlight effect or Drunkard search principle

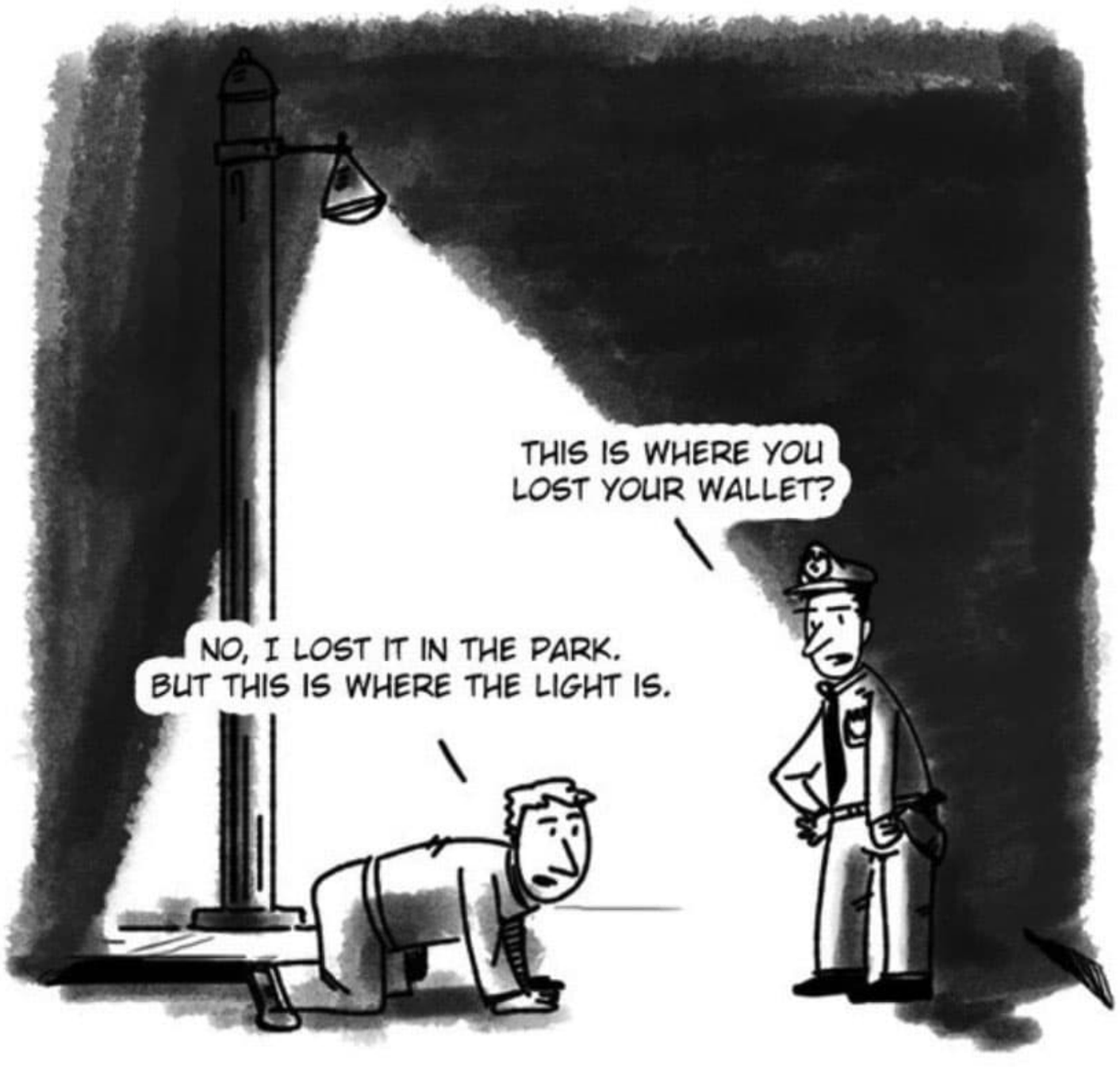


Philosophy of this talk

Streetlight effect or Drunkard search principle

=> let's search under the lamppost

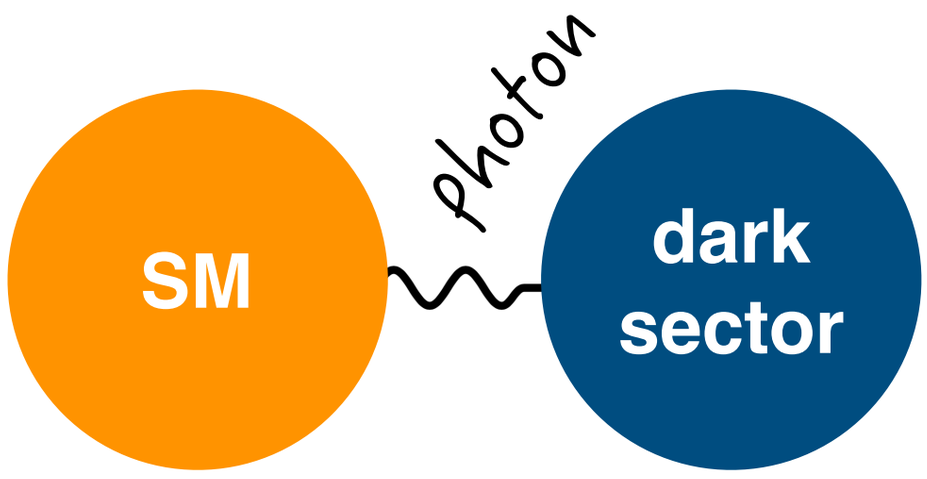




Dark states with EM form factors

Photon-portal

Dark Matter obviously needs to be
(largely) neutral, but how dark is dark?



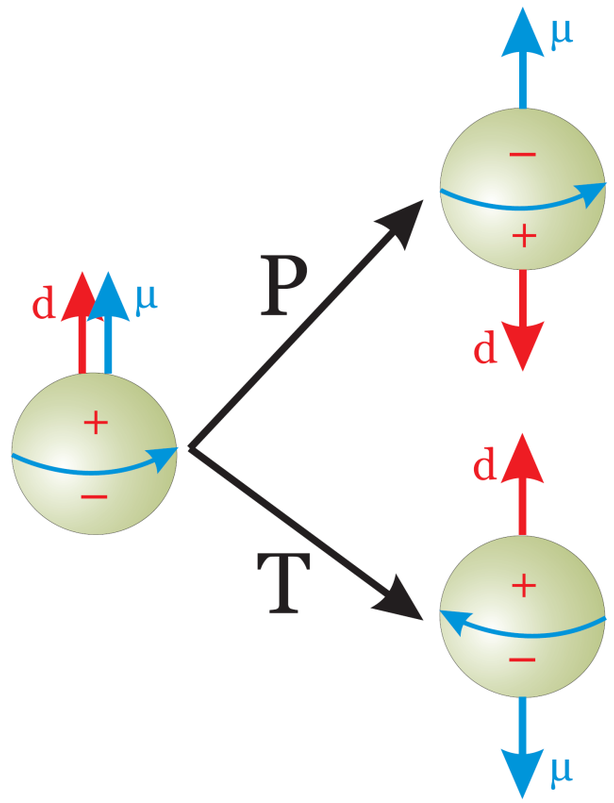
Even perfectly neutral particles can couple to photons

$$H_{\mathrm{MDM}} = -\mu_\chi(\vec{B}\cdot\vec{\sigma}_\chi)$$

magnetic dipole moment (P and T even)

$$H_{\mathrm{EDM}} = -d_\chi(\vec{E}\cdot\vec{\sigma}_\chi)$$

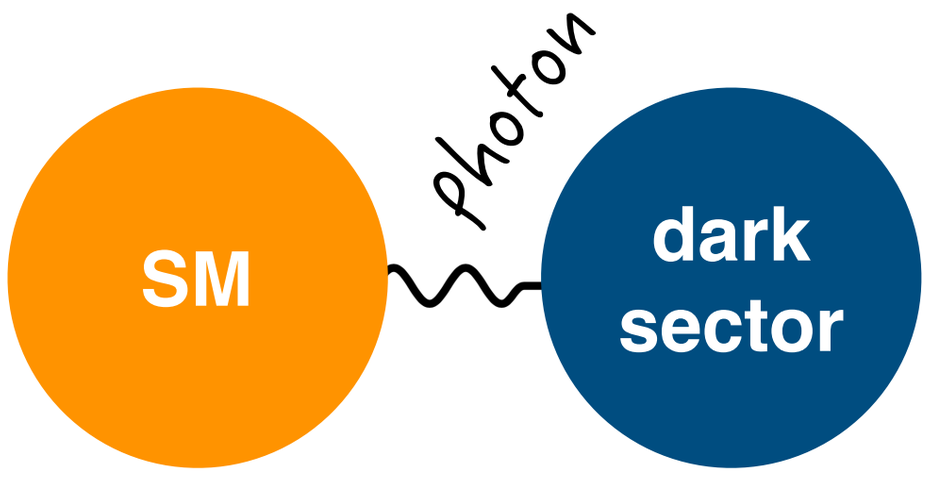
electric dipole (P and T odd => CP violating)



Dark states with EM form factors

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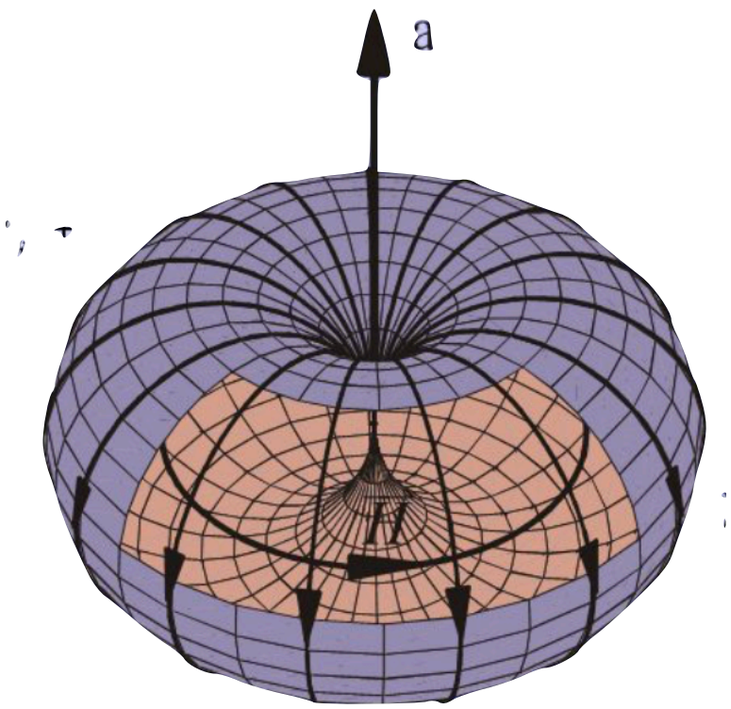
Even perfectly neutral particles can couple to photons

$$H_{\mathrm{AM}} = -a_\chi(\vec{J}\cdot\vec{\sigma}_\chi)$$

anapole moment (P odd but CP even)

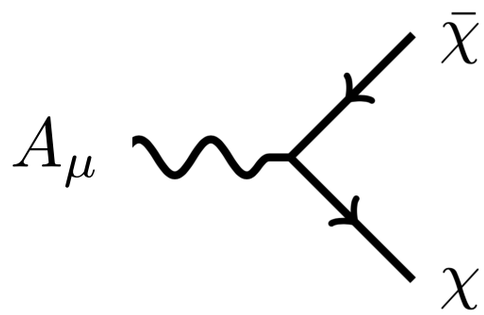
$$H_{\mathrm{CR}} = -b_\chi(\vec{\nabla}\cdot\vec{E})$$

charge radius (P and T even)



Dark states with EM form factors

Photon-portal



Effective operators

millicharge (ϵQ):	$\epsilon e\, \bar{\chi}\gamma^\mu \chi A_\mu,$	dim 4
magnetic dipole (MDM):	$\frac{1}{2}\mu_\chi\, \bar{\chi}\sigma^{\mu\nu}\chi F_{\mu\nu},$	.....
electric dipole (EDM):	$\frac{i}{2}d_\chi\, \bar{\chi}\sigma^{\mu\nu}\gamma^5\chi F_{\mu\nu},$	dim5
anapole moment (AM):	$a_\chi\, \bar{\chi}\gamma^\mu\gamma^5\chi\partial^\nu F_{\mu\nu},$	.....
charge radius (CR):	$b_\chi\, \bar{\chi}\gamma^\mu\chi\partial^\nu F_{\mu\nu}.$	dim6

Vertex

$$\Gamma^\mu(q) = i\sigma^{\mu\nu}q_\nu\left[M(q^2) + iD(q^2)\gamma^5\right] + \left(q^2\gamma^\mu - q^\mu \not{q}\right)\left[V(q^2) - A(q^2)\gamma^5\right]$$

$$\mu_\chi = M(0), \quad d_\chi = D(0), \quad a_\chi = A(0), \quad b_\chi = V(0)$$

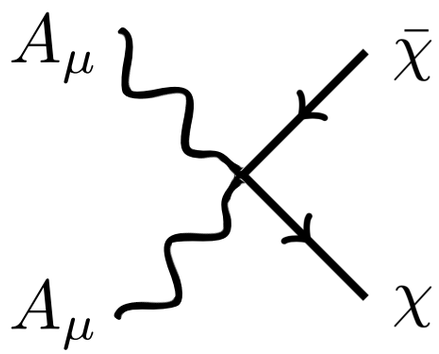
Dark states with EM form factors

Photon-portal

Rayleigh/Susceptibility ops

$\bar{\chi}\chi$ $\quad\otimes\quad$ $F_{\mu\nu}F^{\mu\nu}$

$\bar{\chi}\gamma^5\chi$ $\quad\otimes\quad$ $F_{\mu\nu}\tilde{F}^{\mu\nu}$



.....

dim 7

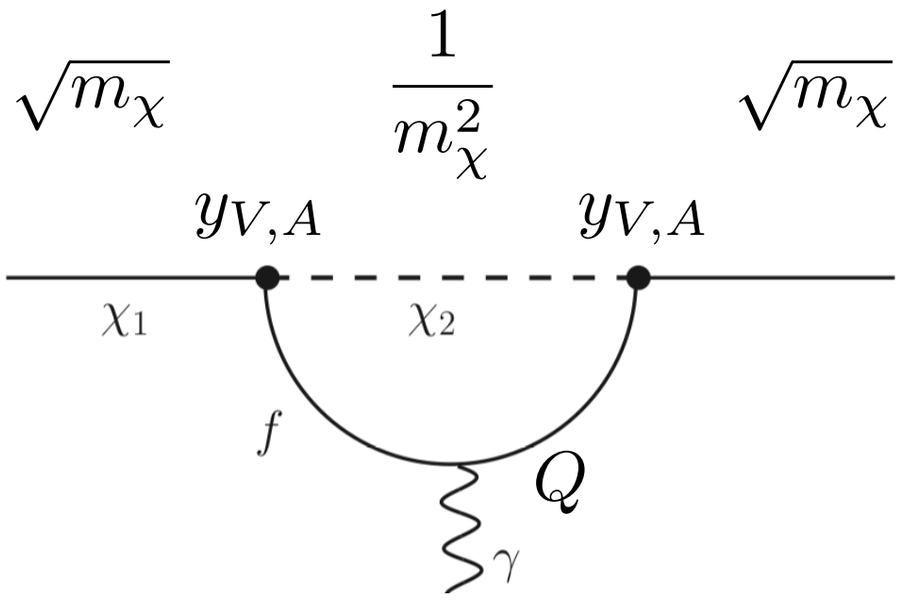
=> different (or loop-suppressed) phenomenology

Complex scalars: dim-6 Rayleigh and charge radius interaction

Vectors: also quadrupole moments exist

Dark states with EM form factors

Photon-portal



$$\mu_\chi \sim \frac{Q|y_{A,V}|^2}{m_\chi} \qquad d_\chi \sim \frac{Q\,\mathrm{Im}[\mathrm{y_V y_A^*}]}{m_\chi}$$

$$a_\chi,\, b_\chi \sim \frac{Q|y_{A,V}|^2}{M^2}$$

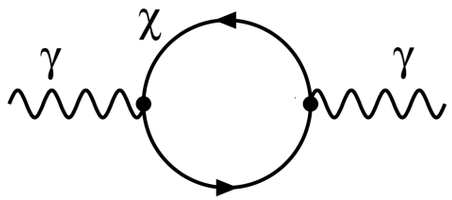
or $$a_\chi,\, b_\chi \sim \frac{Q|y_{A,V}|^2}{m_\chi} \times \frac{1}{\Delta m}$$

e.g. Bagnasco, Dine, Thomas 1994; Foadi, Frandsen, Sannino 2009; Antipin, Redi, Strumia, and Vigiani 2015; Kavanagh, Panci, Ziegler 2018

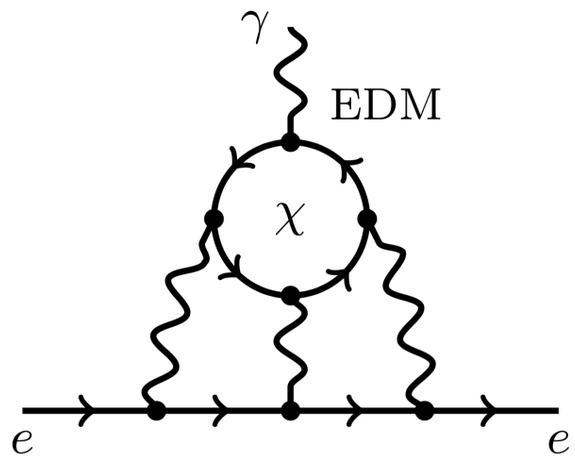
Dark states with EM form factors

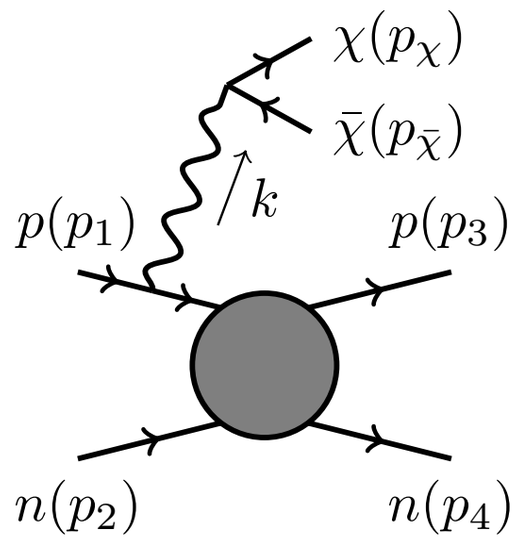
Photon-portal

Tinkering with the photon may affect many known phenomena



- changes the strength of the EM interaction at various energy scales
- affects SM precision observables, e.g. g-2
- provides new photon-mediated decay channels of particles
- can we produce those “dark states” in the laboratory?
- can we have a “theory of dark matter” through the photon coupling?
- implications for astrophysics? is it cosmologically viable?





Muon g-2

- Muon g-2 puzzle: (3-4)σ tension between SM prediction and measurement

$$\Delta a_\mu = a_\mu^{\rm exp} - a_\mu^{\rm SM} = (290 \pm 90) \times 10^{-11}$$

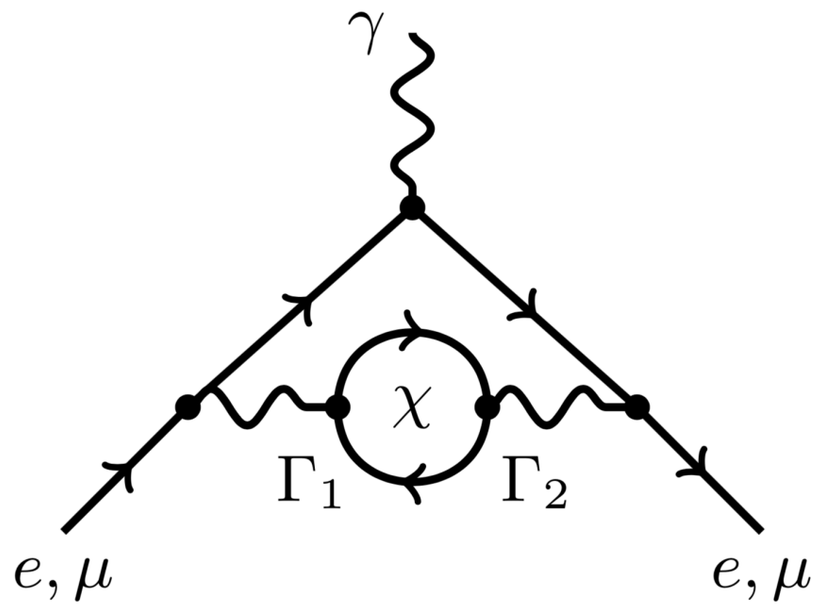
- For form-factor interactions, contributions enter through the vacuum polarization

e.g. use dispersion relation + unitarity

$$\Delta a_\mu = \frac{1}{4\pi^3} \int_{4m_\chi^2} ds\, \sigma_{e^+e^- \to \chi\bar{\chi}}(s) K(s)$$

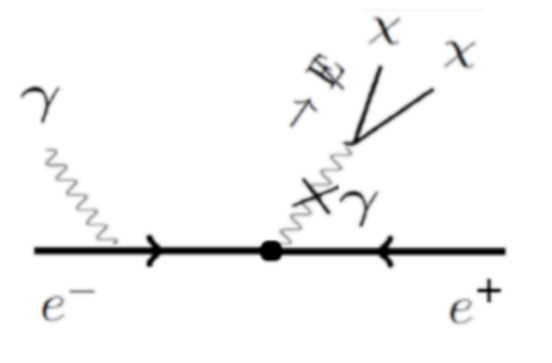
solution to g-2 for

$|\mu_\chi|,\ |d_\chi| \sim \text{few} \times 10^{-3} \mu_{\rm B}$

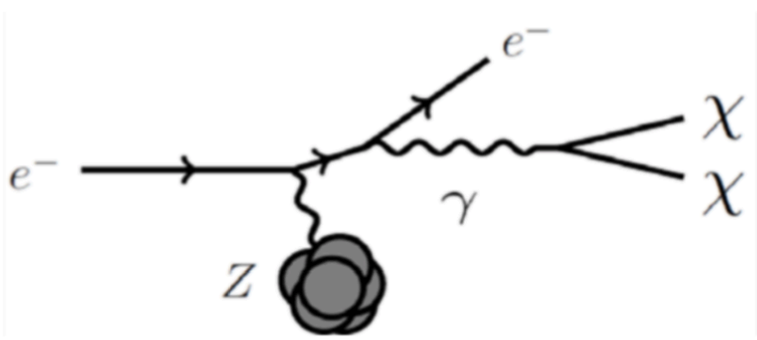


sub-GeV states: a target for intensity frontier

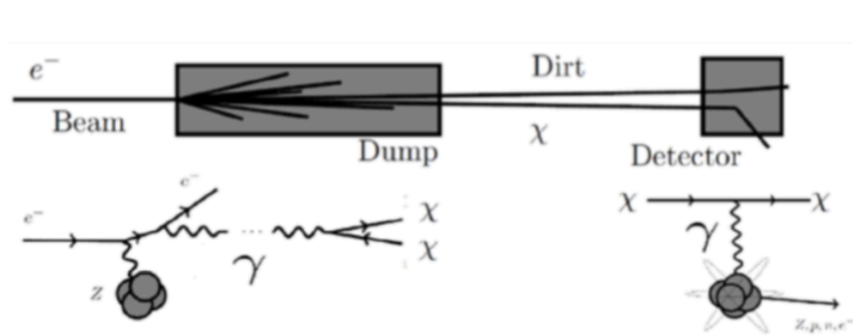
missing momentum



missing energy



direct search



BaBar:
- CM energy: 10 GeV
- Luminosity: 28/19 fb^{-1}

Belle II (projected)**:**
- Luminosity: 50 ab^{-1}

Main Backgrounds:
- $e^+e^- \to \gamma\gamma$
- $e^+e^- \to \gamma\gamma\gamma$
- $e^+e^- \to \gamma\, e^+e^-$

NA64:
- Beam energy: 100 GeV
- Lead Target
- EOT: 10^{10}

LDMX (projected)**:**
- Beam energy: 4/8 GeV
- Tungsten/Aluminum Target
- EOT: 10^{14} / 10^{15}

Almost no Backgrounds:
- Active veto system
- Cuts on search region

mQ:
- Beam energy: 30 GeV
- Tungsten Target
- EOT: 10^{19}

BDX (projected)**:**
- Beam energy: 11 GeV
- Aluminum Target
- EOT: 10^{22}

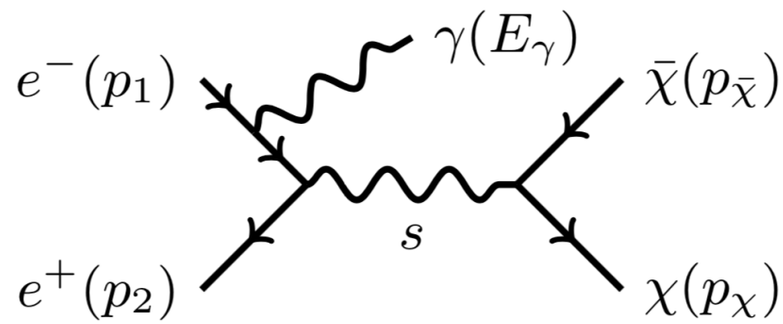
Main Backgrounds:
- High energy neutrinos

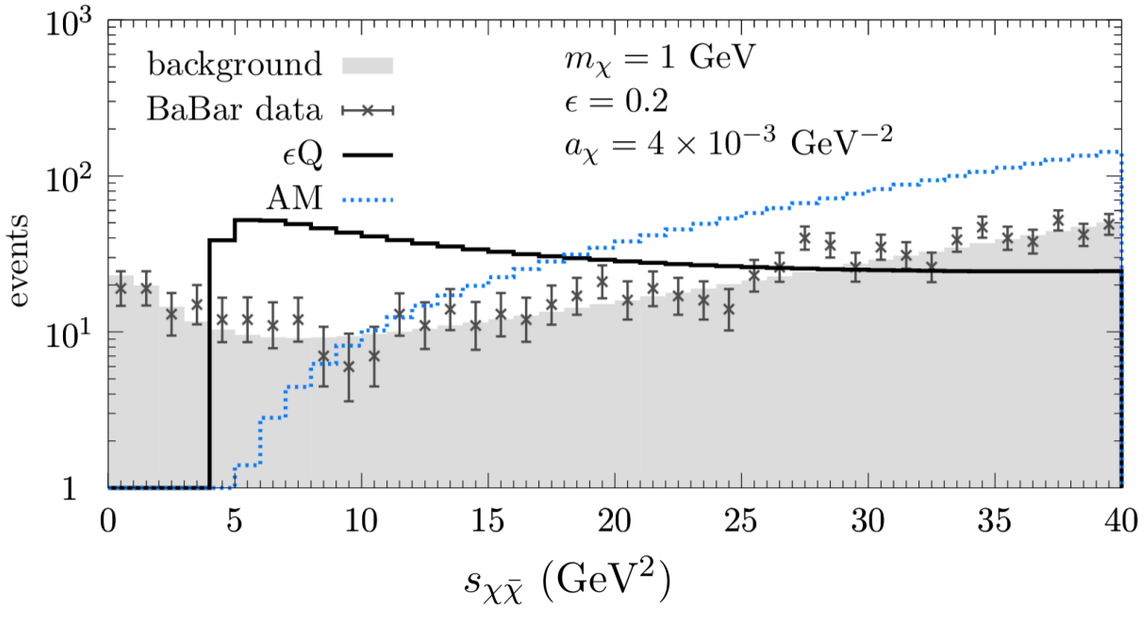
Intensity frontier prospects

Production in e+ e- annihilation, e.g. at BaBar, Belle-II

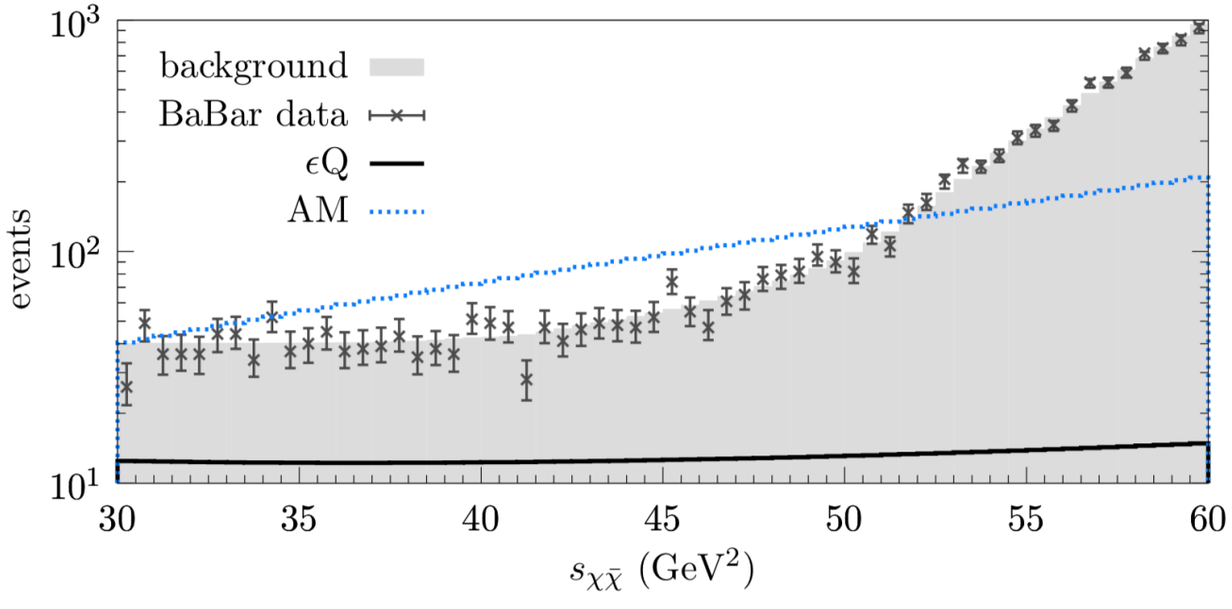
Mono-photon search $x_\gamma = E_\gamma/\sqrt{s}$

$$\frac{d\sigma_{e^+e^-}}{dx_\gamma d\cos\theta_\gamma} = \sigma_{e^+e^-}\left(s, s_{\chi\bar{\chi}}\right)\mathcal{R}^{(\alpha)}(x_\gamma, \theta_\gamma, s)$$





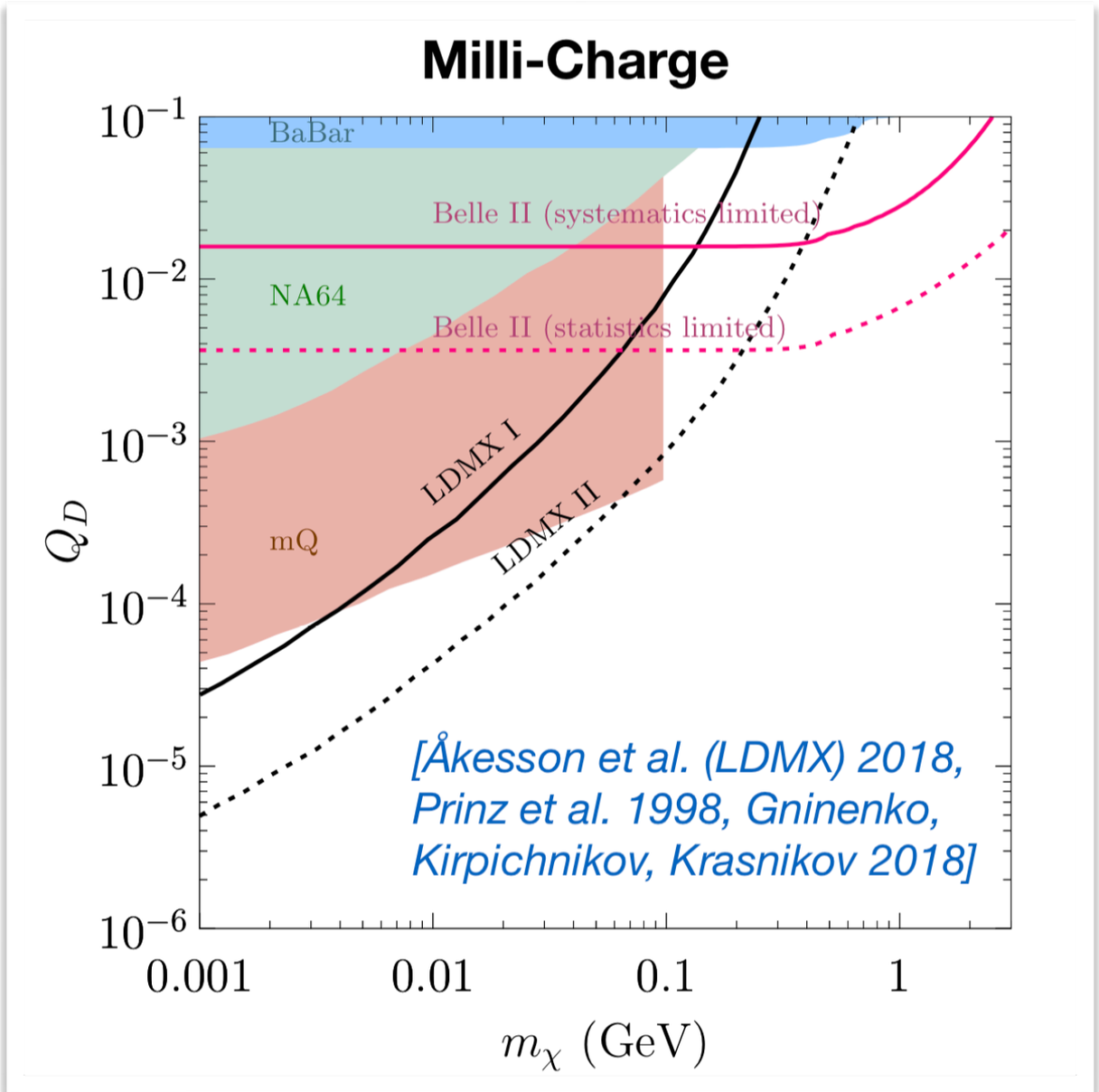
high-energy photon region



low-energy photon region

Dark states with EM form factors

Photon-portal



MeV-GeV mass bracket

Chu, JP, Semmelrock 2019

Chu, Kuo, JP 2020

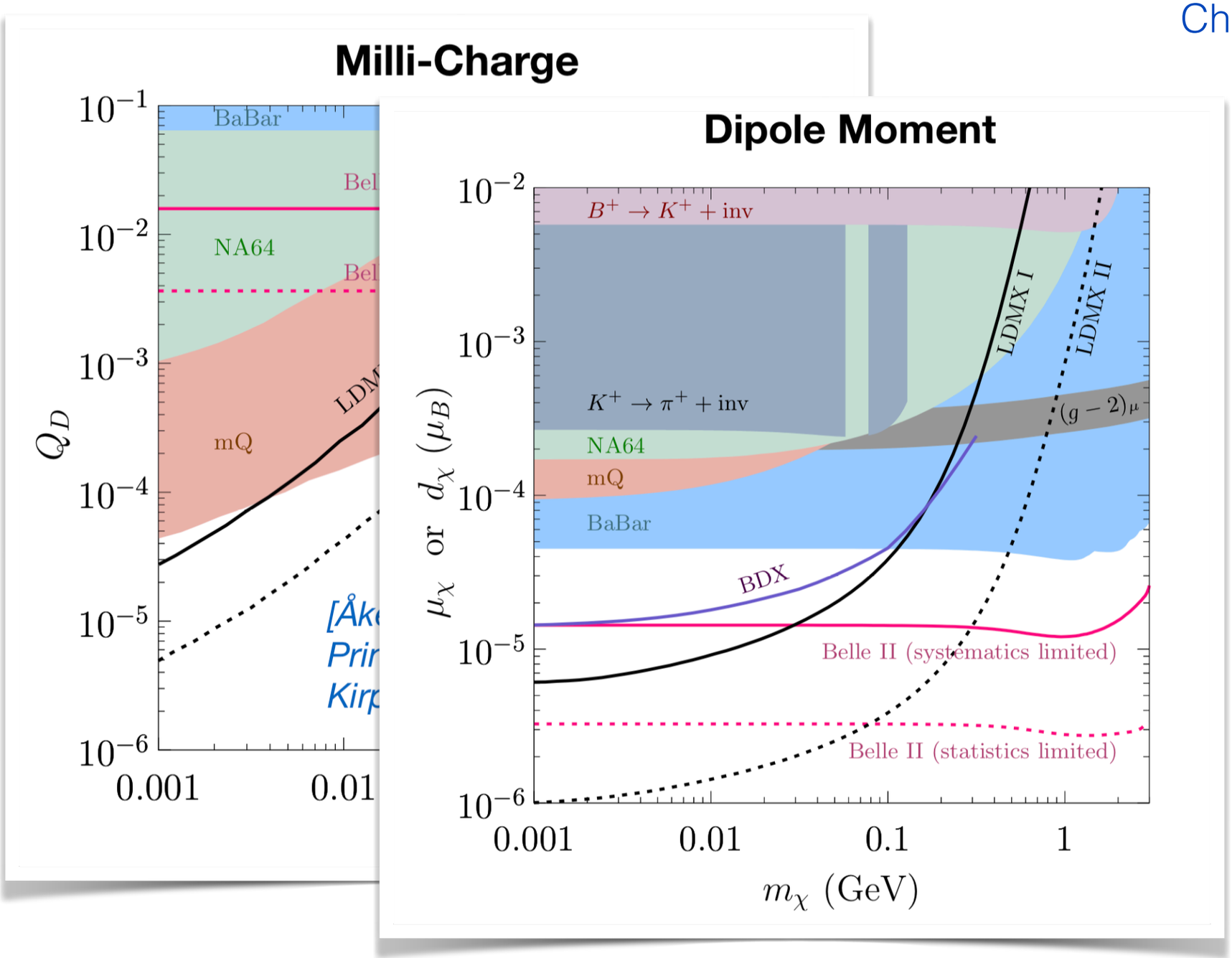
Dark states with EM form factors

Photon-portal

MeV-GeV mass bracket

Chu, JP, Semmelrock 2019

Chu, Kuo, JP 2020



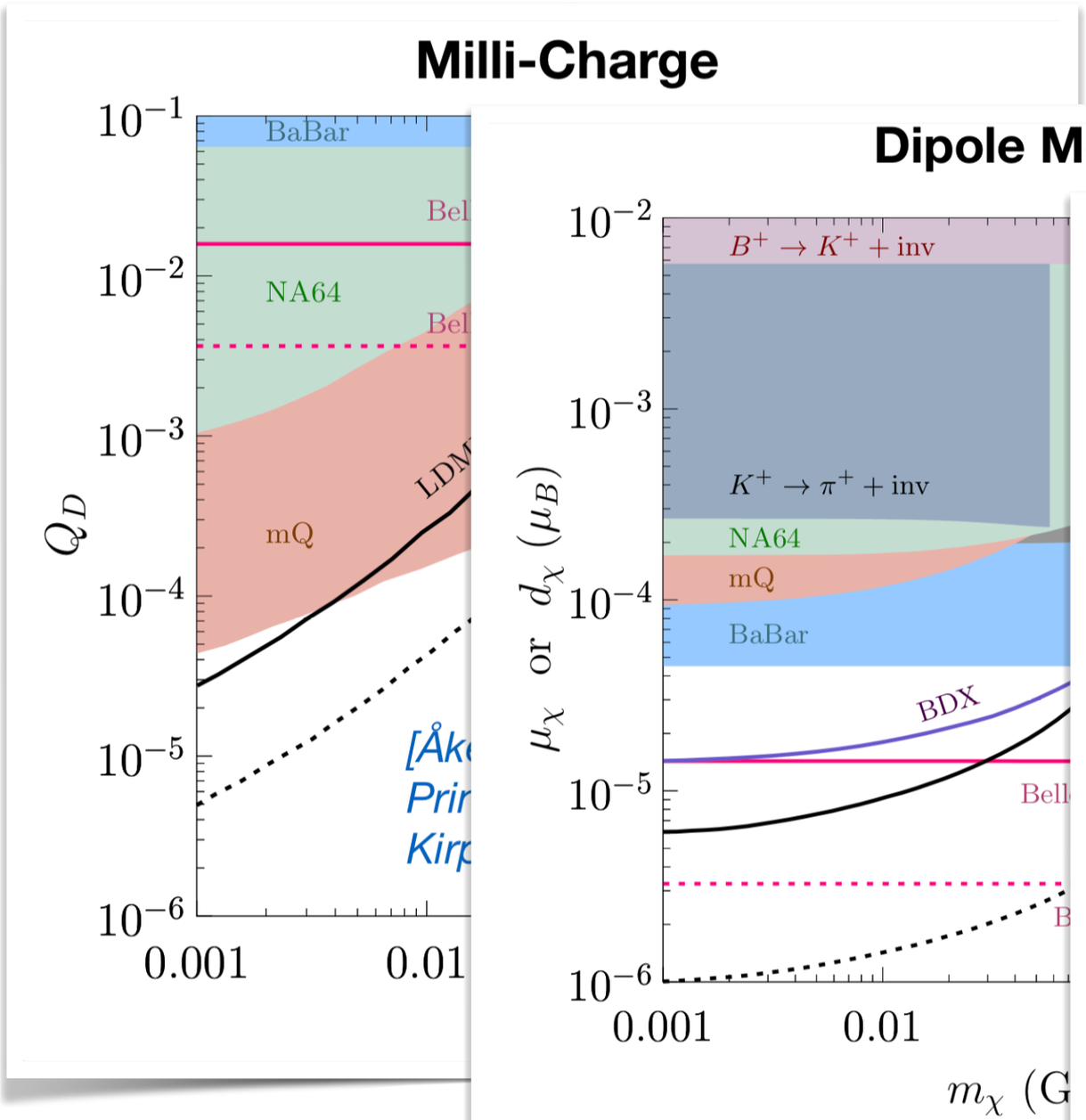
Dark states with EM form factors

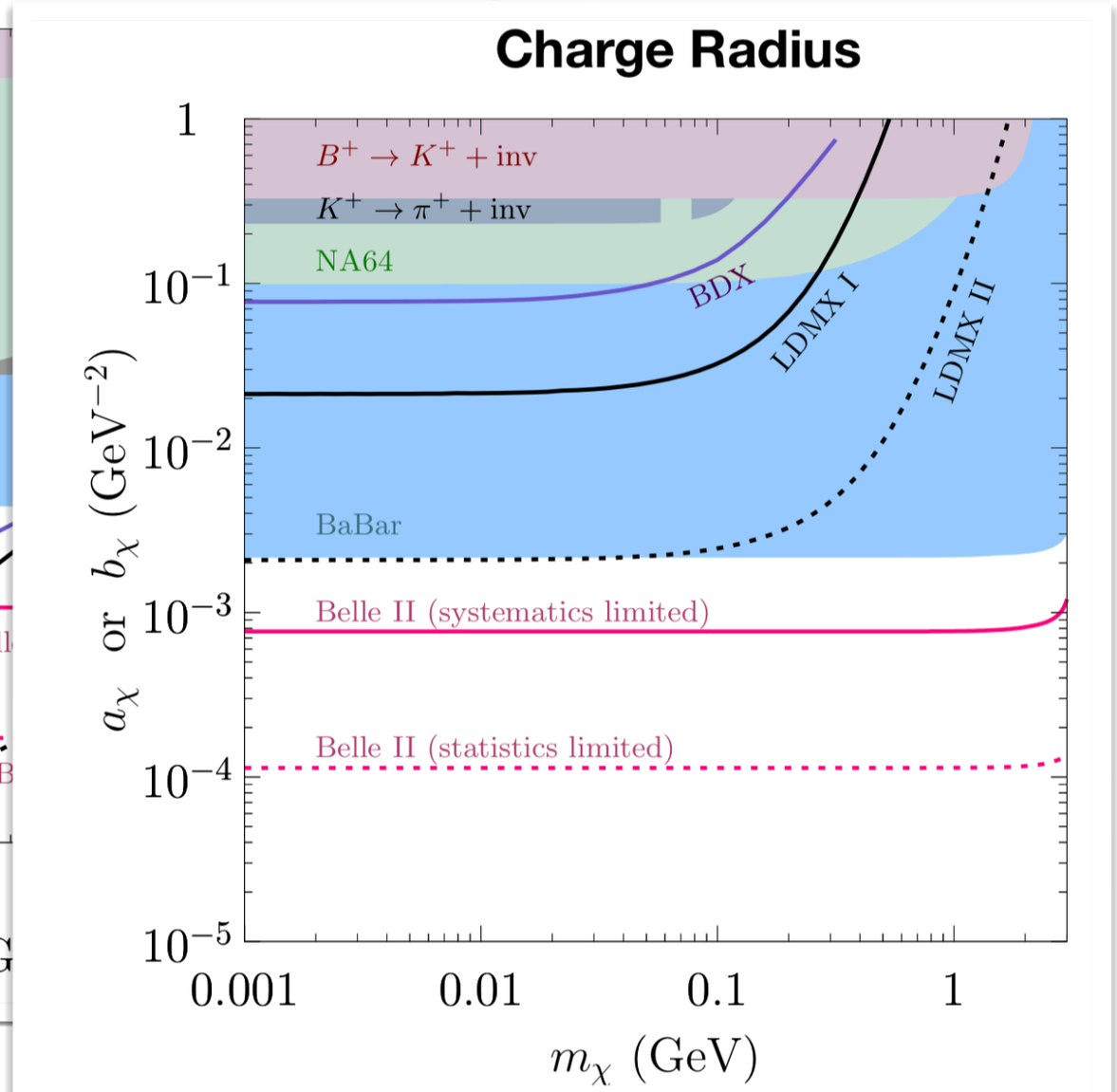
Photon-portal

MeV-GeV mass bracket

Chu, JP, Semmelrock 2019

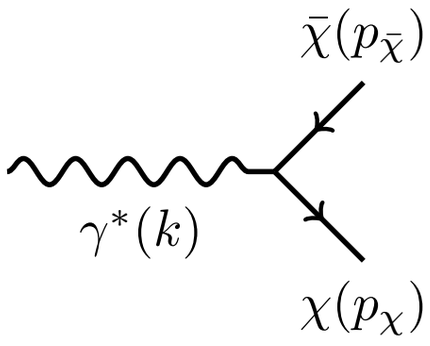
Chu, Kuo, JP 2020





Stars as laboratories

Anomalous energy loss



$$\omega_p \sim \begin{cases} 0.3\,\mathrm{keV} & \text{Sun's core} \\ 2.6\,\mathrm{keV} & \text{HB's core} \\ 8.6\,\mathrm{keV} & \text{RG's core} \\ 17.6\,\mathrm{MeV} & \text{SN's core} \end{cases}$$

$\langle E_{\rm kin} + E_{\rm grav} \rangle$ becomes smaller from stellar energy loss

1. Stars supported by radiation pressure (active stars):

Virial theorem: $\langle E_{\rm kin} \rangle = -\frac{1}{2}\langle E_{\rm grav} \rangle$

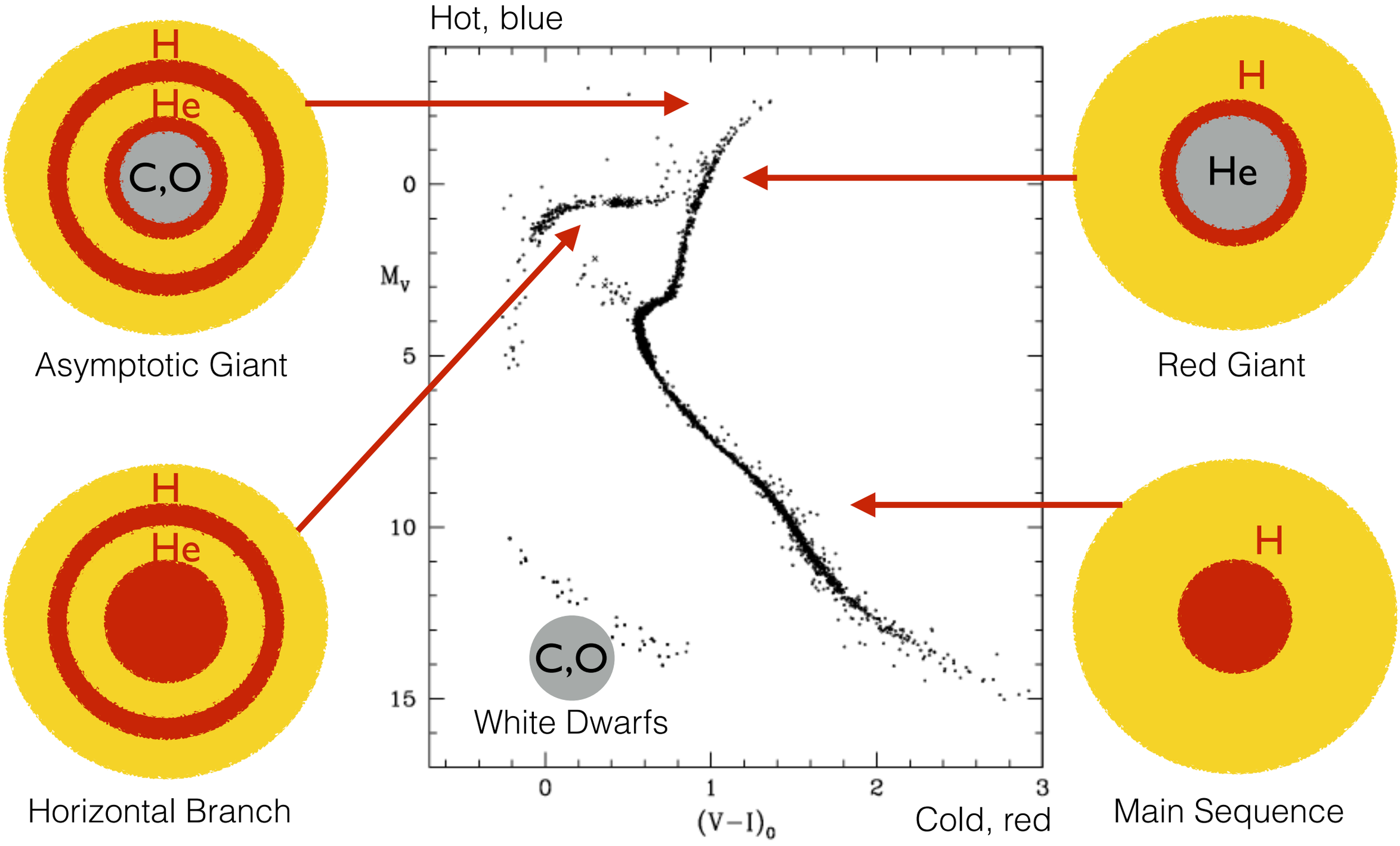
=> Gravitational potential energy becomes more negative (tighter bound)

=> average kinetic energy increases, star becomes hotter

2. Stars supported by degeneracy pressure (white dwarfs, neutron stars):

=> star cools by the energy loss

Stars as laboratories



Globular Cluster color-magnitude diagram

Stars as laboratories

Observationally inferred criteria limiting energy loss

Sun $\int_{\rm sun} dV\,\dot{Q} < 10\% \times L_\odot$ Inferred from observed boron neutrino flux

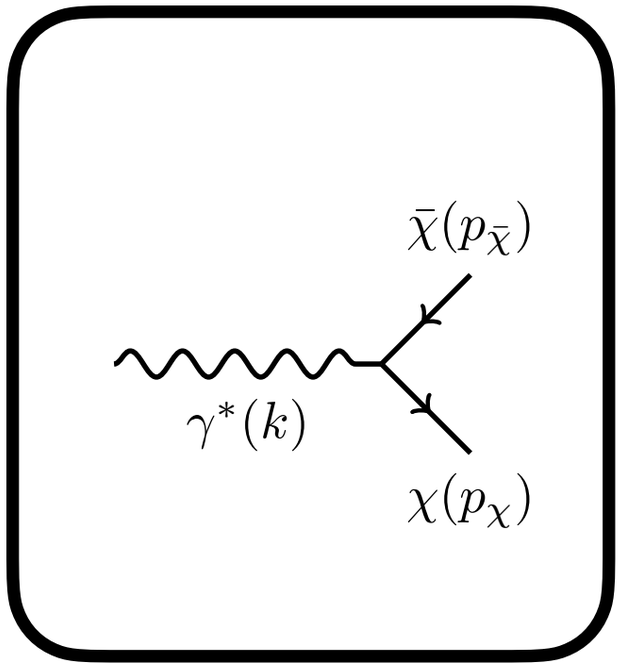
HB $\int_{\rm core} dV\,\dot{Q} < 10\% \times L_{\rm HB}$ Inferred from He-burning lifetime

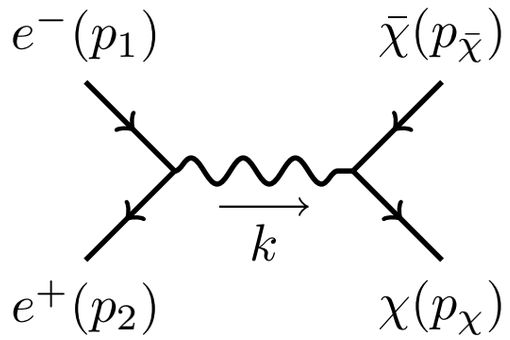
RG $\dot{Q} < 10\,{\rm erg/g/s} \times \rho_{\rm RG}$ Inferred from maximum RG core mass

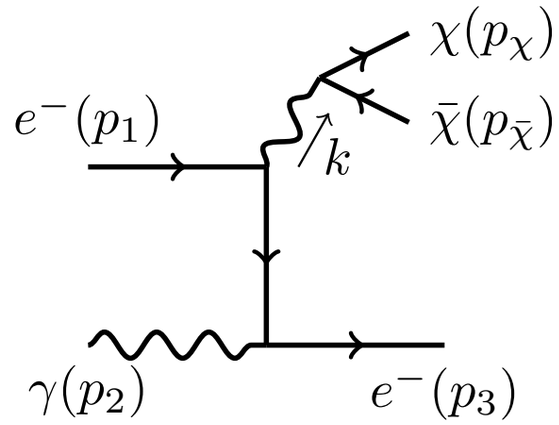
SN $\int_{\rm core} dV\,\dot{Q} < L_\nu$ Inferred from cooling curve of SN1987A

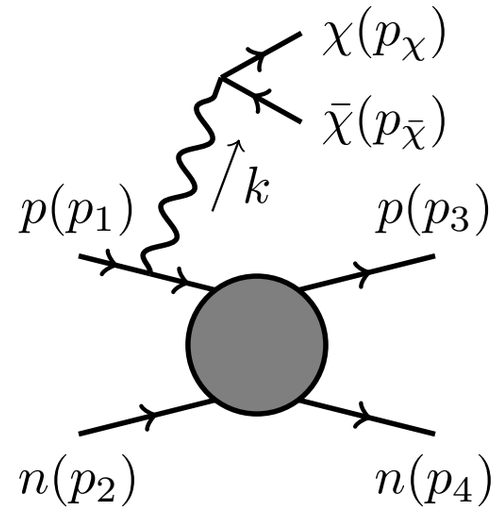
Energy loss in dark states

Stellar probes of dark sector - photon interactions









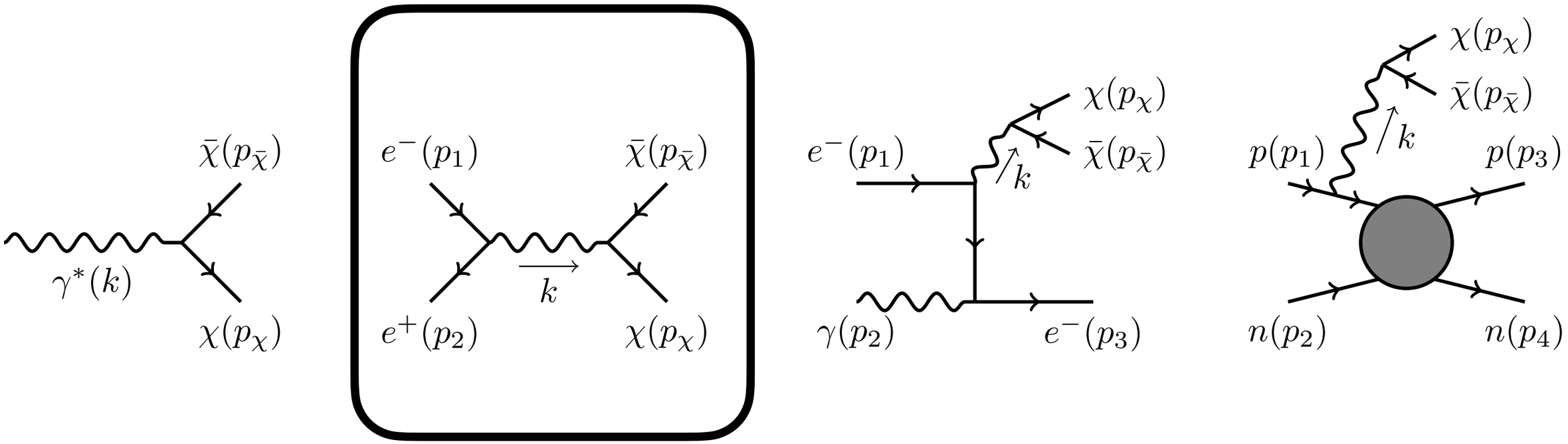
T/L “Plasmon” decay

(all)

$$\omega_p \sim \begin{cases} 0.3\,\mathrm{keV} & \text{Sun's core} \\ 2.6\,\mathrm{keV} & \text{HB's core} \\ 8.6\,\mathrm{keV} & \text{RG's core} \\ 17.6\,\mathrm{MeV} & \text{SN's core} \end{cases}$$

Energy loss in dark states

Stellar probes of dark sector - photon interactions



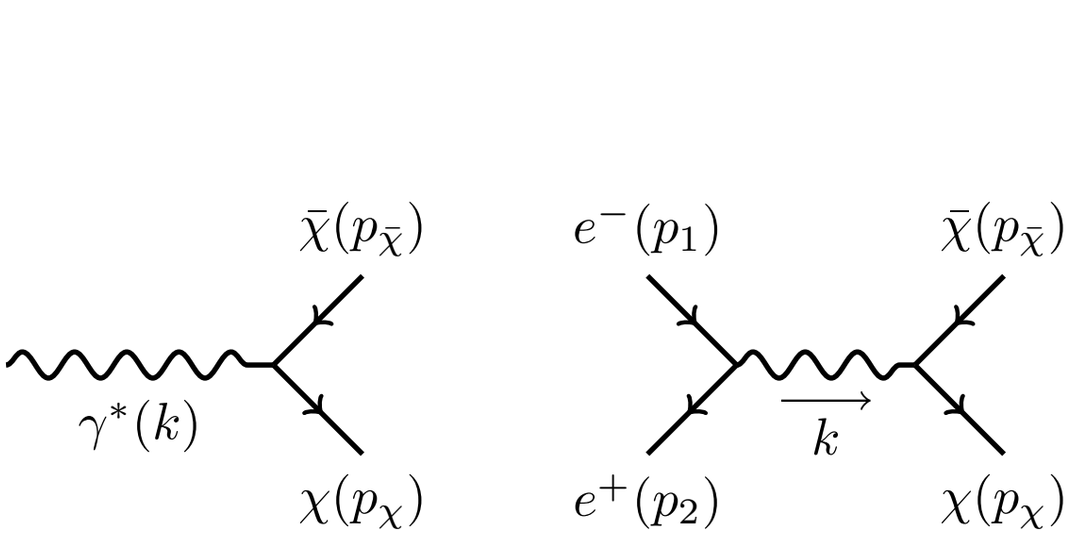
e+e- annihilation

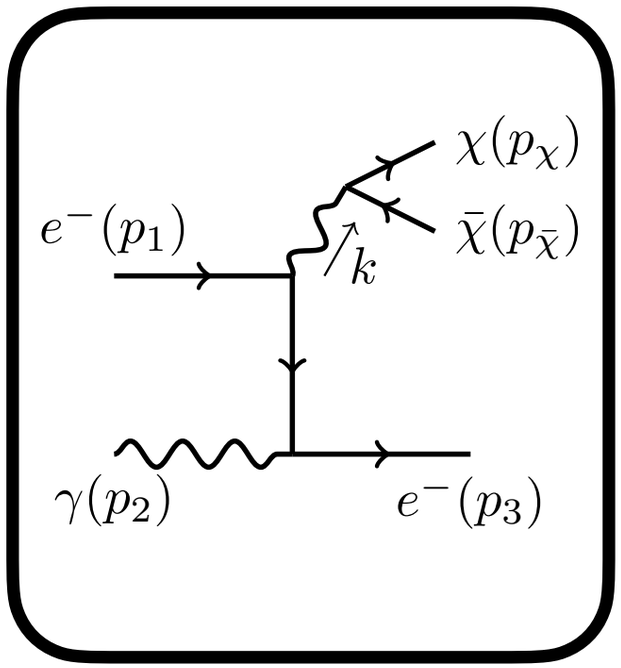
(SN)

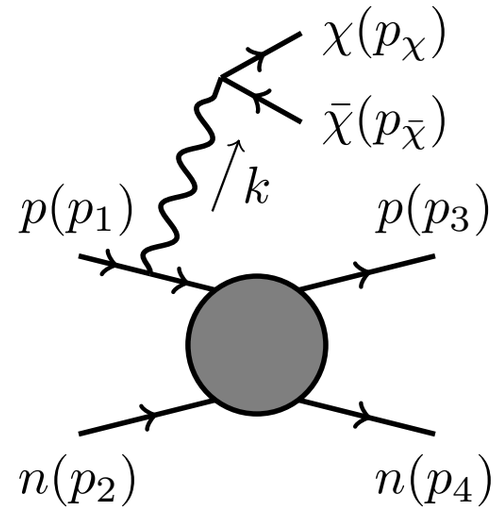
NB: no overlap with plasmon decay

Energy loss in dark states

Stellar probes of dark sector - photon interactions





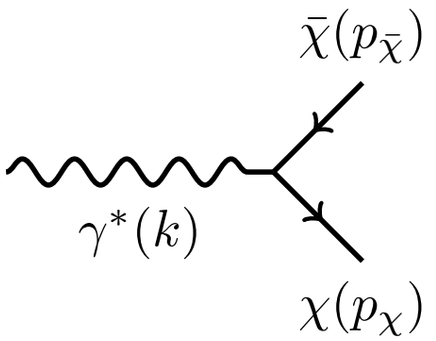


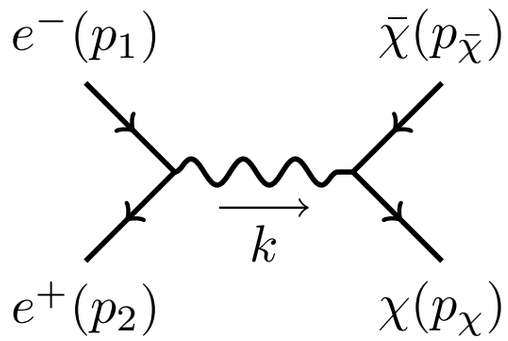
Compton 2->3 production

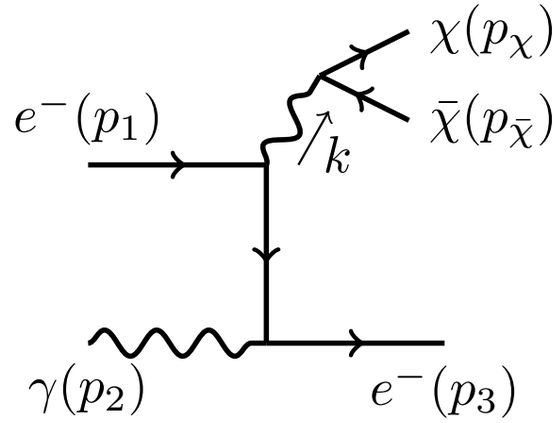
(all)

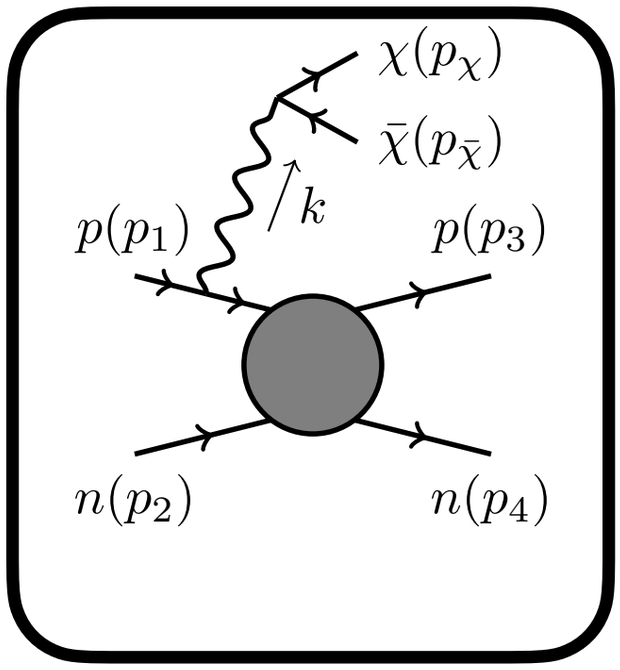
Energy loss in dark states

Stellar probes of dark sector - photon interactions









Electron-nucleus Bremsstrahlung

(RG, HB, Sun)

Neutron-proton Bremsstrahlung

(SN)

NB: soft-photon approximation not applicable

NB: we use exp. data for np-brems

Rrapaj, Reddy 2016

Energy loss in dark states

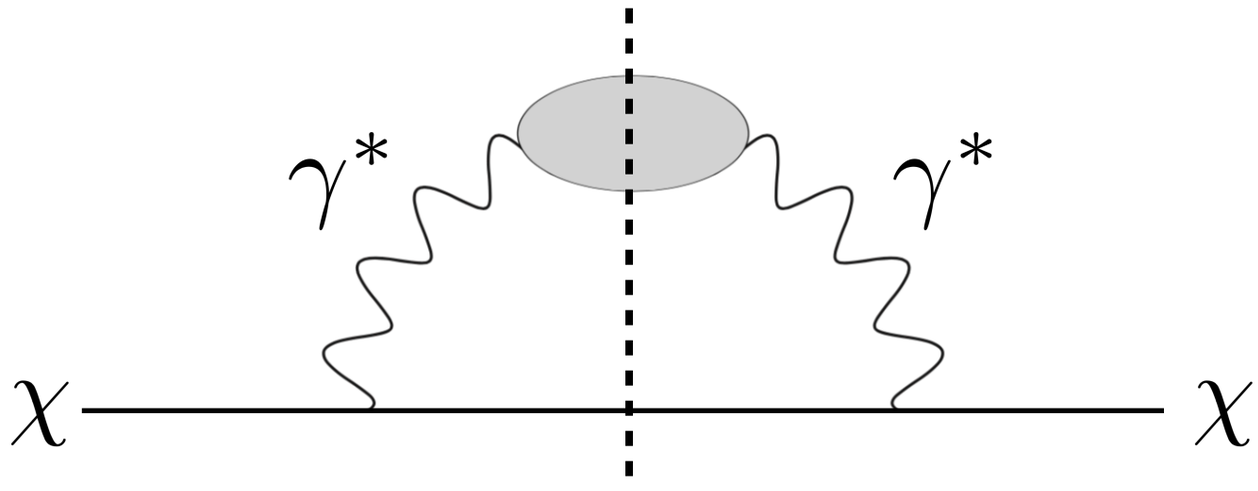
Unifying formula for pair emission

$$\dot{N}_\chi = -\int \frac{d^3\vec{p}_\chi}{(2\pi)^3} \frac{1}{(e^{E_\chi/T}+1)} \frac{\mathrm{Im}\,\Pi_\chi(E_\chi,\vec{p}_\chi)}{E_\chi}$$

Finite-T optical theorem: rate with which a particle comes into thermal equilibrium is given by the discontinuity of the self energy

$$\mathrm{Im}\,\Pi_\chi(E_\chi,\vec{p}_\chi) = \bar{u}(p_\chi)\Sigma(E_\chi,\vec{p}_\chi)u(p_\chi)$$

Weldon 1983



Energy loss in dark states

Unifying formula for pair emission

$$\frac{d\dot{N}_\chi}{ds_{\chi\bar{\chi}}} = -\sum_{i=\mathrm{T,L}} g_i \int \frac{d^3\vec{k}}{(2\pi)^3} \frac{1}{(e^{\omega/T}-1)} \frac{\mathrm{Im}\,\Pi_i(\omega,\vec{k})}{\omega} \times \frac{f(s_{\chi\bar{\chi}})}{16\pi^2 |s_{\chi\bar{\chi}} - \Pi_i|^2} \sqrt{1-\frac{4m_\chi^2}{s_{\chi\bar{\chi}}}}$$

In this version (derived from works on dilepton-production in hot matter) the imaginary part of the *photon self-energy* enters

$$\Pi^{\mu\rho} = (\epsilon^\mu_{\mathrm{T},1}\epsilon^\rho_{\mathrm{T},1} + \epsilon^\mu_{\mathrm{T},2}\epsilon^\rho_{\mathrm{T},2})\,\Pi_\mathrm{T} + \epsilon^\mu_\mathrm{L}\epsilon^\rho_\mathrm{L}\,\Pi_\mathrm{L}$$

=> leading contribution from the pole $s_{\chi\bar{\chi}} = \mathrm{Re}\,\Pi_{\mathrm{L,T}}$
recover plasmon-decay rate

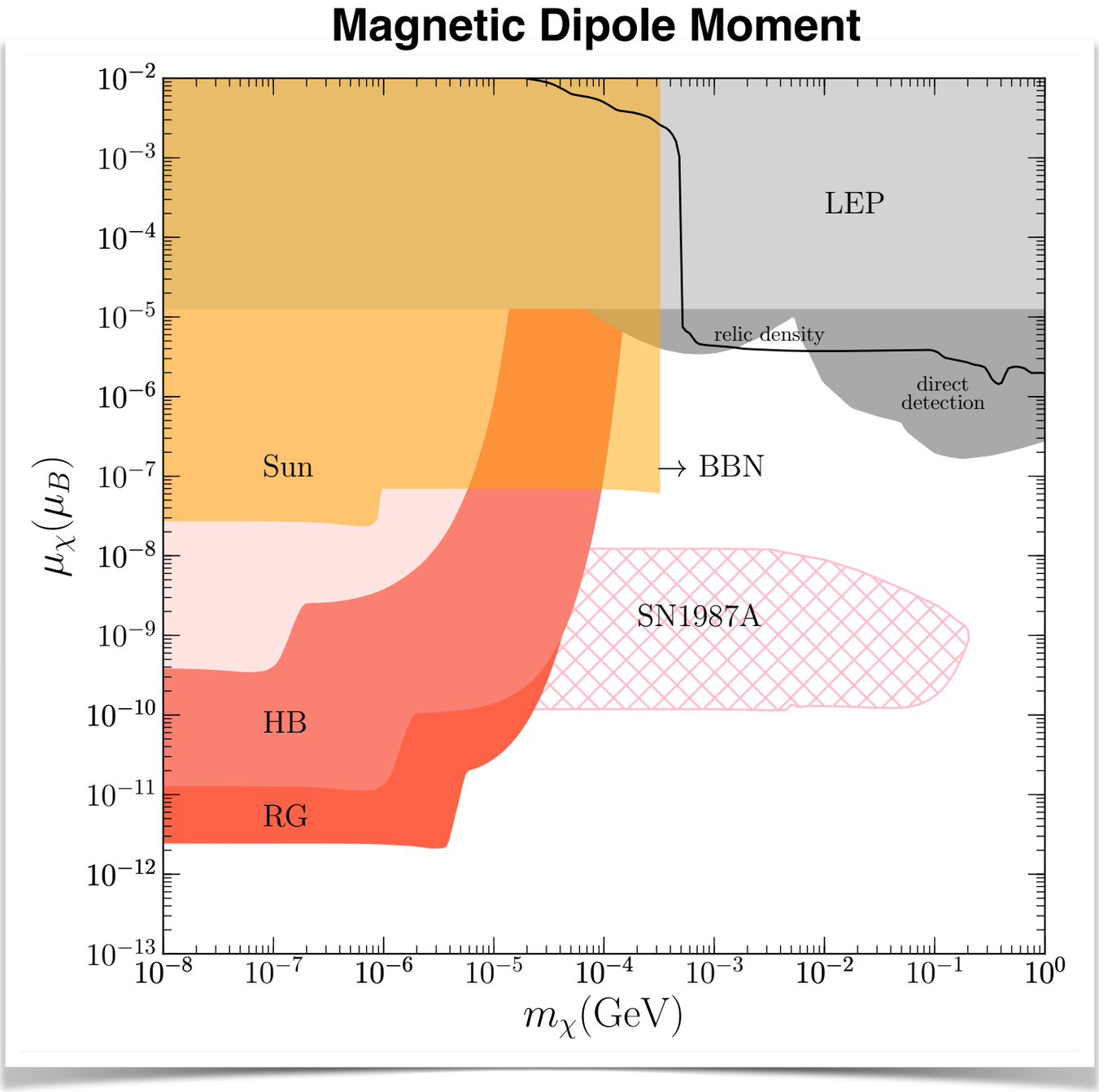
=> further contributions to chi-pair production found from identifying the contributions to the photon self-energy

Application 1

keV-MeV mass bracket

Photon-portal

Chu, Kuo, JP, Semmelrock 2019

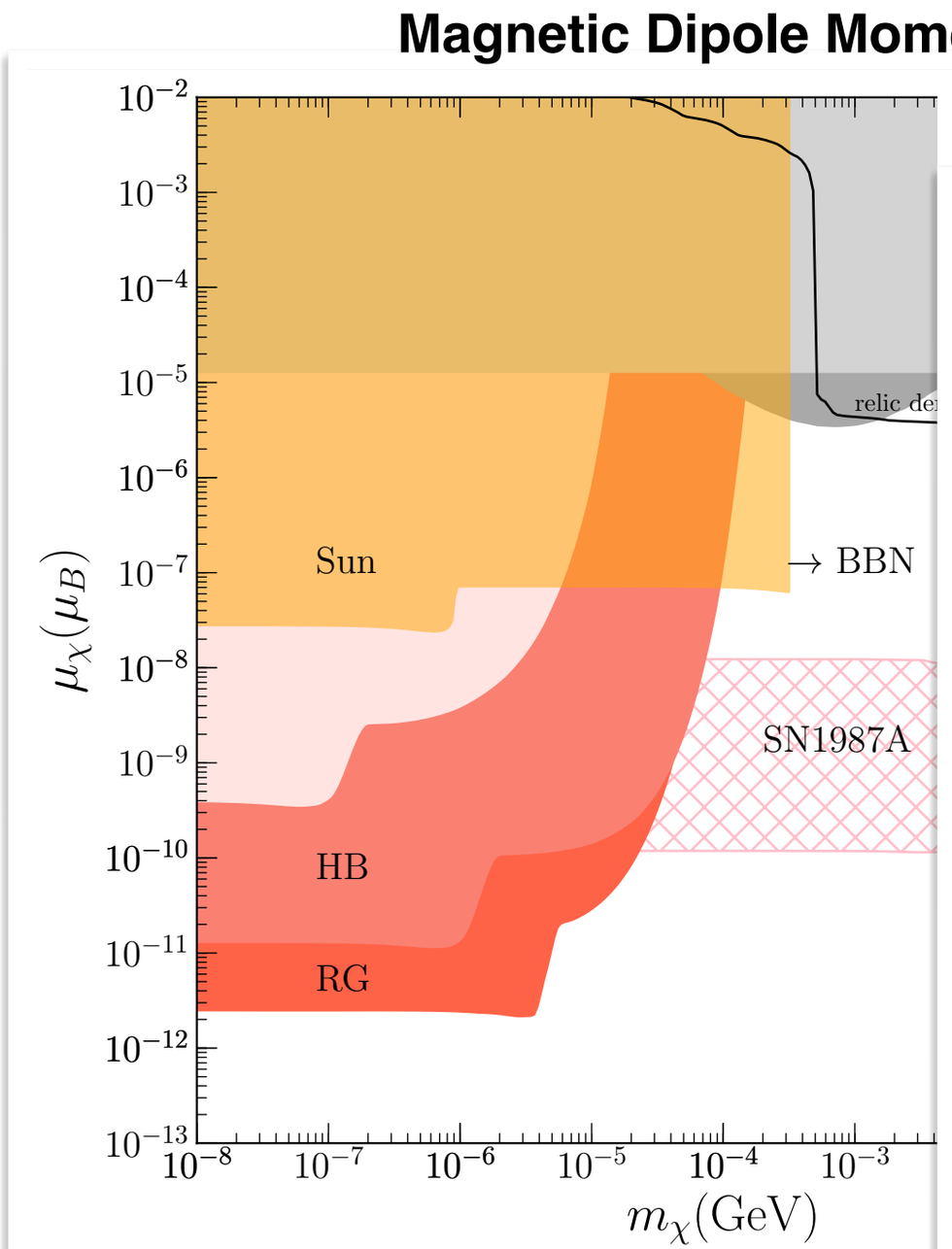


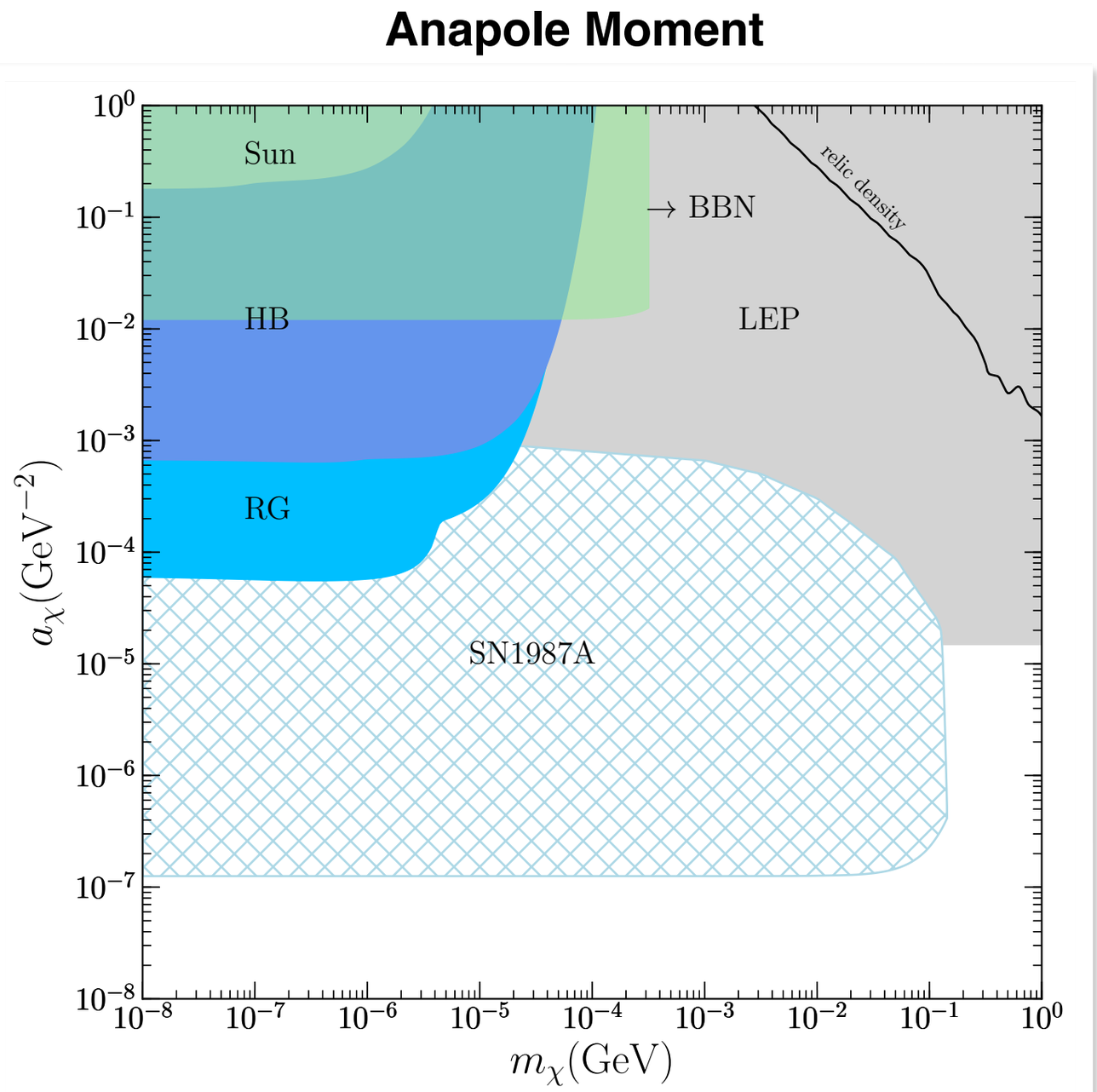
Application 1

keV-MeV mass bracket

Photon-portal

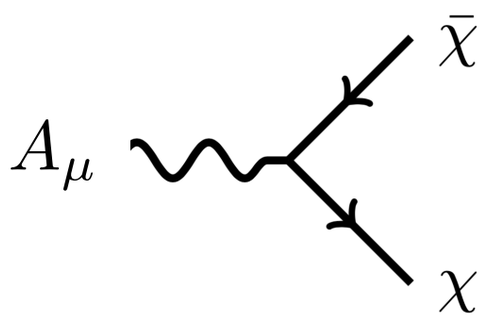
Chu, Kuo, JP, Semmelrock 2019





Dark states with EM form factors

SPIN 1/2 case is now familiar ✓



Effective operators

millicharge (ϵQ):	$\epsilon e\, \bar{\chi}\gamma^\mu \chi A_\mu,$	dim 4
magnetic dipole (MDM):	$\frac{1}{2}\mu_\chi\, \bar{\chi}\sigma^{\mu\nu}\chi F_{\mu\nu},$	.....
electric dipole (EDM):	$\frac{i}{2}d_\chi\, \bar{\chi}\sigma^{\mu\nu}\gamma^5\chi F_{\mu\nu},$	dim5
anapole moment (AM):	$a_\chi\, \bar{\chi}\gamma^\mu\gamma^5\chi\partial^\nu F_{\mu\nu},$	.....
charge radius (CR):	$b_\chi\, \bar{\chi}\gamma^\mu\chi\partial^\nu F_{\mu\nu}.$	dim6

=> SPIN 1 case has comparatively received much less attention

Vector Dark States

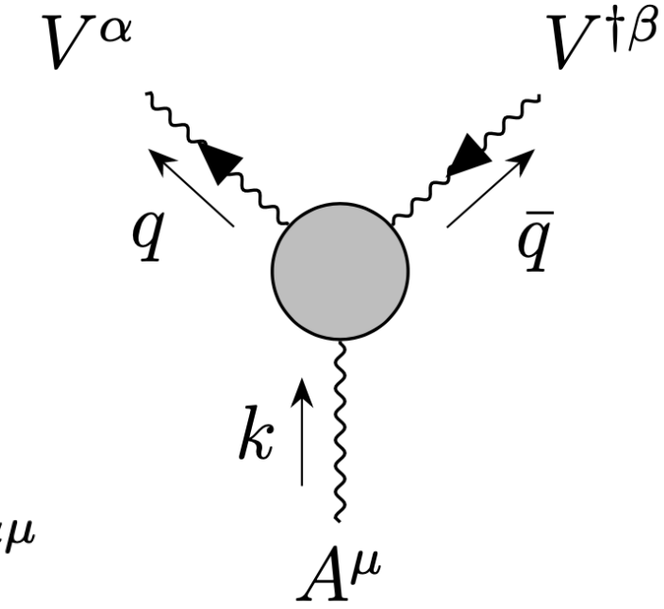
Chu, Ibarra, Hisano, Kuo, JP
2303.13643

SPIN1 case: construction

Consider all possible Lorentz structures

=> yields 9 structures

$$i\Gamma^{\alpha\beta\mu}_{VV^\dagger\gamma}(q,\bar{q},k) \;=$$



$$\begin{aligned}\Gamma^{\alpha\beta\mu}_{VV^\dagger\gamma} \;=\; & c_1(k^2)\,p^\mu g^{\alpha\beta} + c_2(k^2)\,k^\alpha g^{\beta\mu} + c_3(k^2)\,k^\beta g^{\alpha\mu} \\ & +\; c_4(k^2)\,k_\lambda \epsilon^{\mu\alpha\beta\lambda} + c_5(k^2)\,p_\lambda \epsilon^{\mu\alpha\beta\lambda} \\ & +\; c_6(k^2)\,k^\alpha k^\beta p^\mu \\ & +\; c_7(k^2)\,p^\mu [kp]^{\alpha\beta} + c_8(k^2)\,k^\alpha [kp]^{\beta\mu} + c_9(k^2)\,k^\beta [kp]^{\mu\alpha}\end{aligned}$$

$$p = q - \bar{q} \qquad \partial_\mu V^\mu = 0$$

$$[kp]^{\mu\nu} = \epsilon^{\mu\nu\rho\sigma} k_\rho p_\sigma$$

Hagiwara, Peccei, Zeppenfeld 1987
Ibarra, Hisano, Ryo 2022

Vector Dark States

Chu, Ibarra, Hisano, Kuo, JP
2303.13643

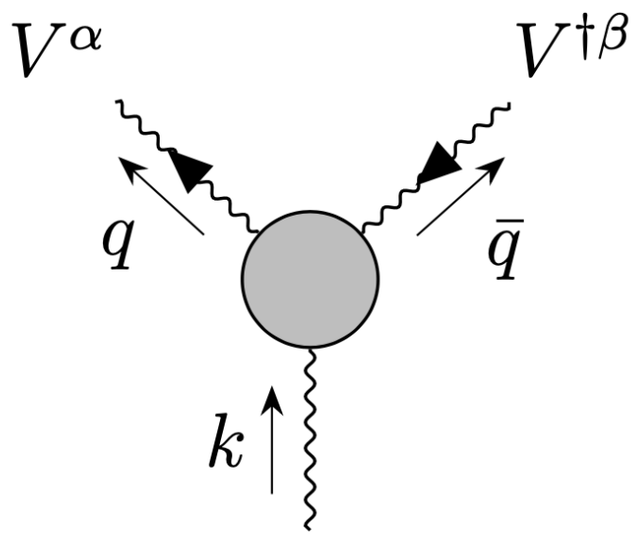
SPIN1 case: construction

Consider all possible Lorentz structures

=> yields 9 structures

only seven out of the nine helicity states of the V pair can be reached by s-channel vector boson exchange (J = 1 channel)

$$i\Gamma^{\alpha\beta\mu}_{VV^\dagger\gamma}(q,\bar{q},k) =$$



=> 7 independent structures

$$\Gamma^{\alpha\beta\mu}_{VV^\dagger\gamma}/e = f_1^A(k^2)p^\mu g^{\alpha\beta} - \frac{f_2^A(k^2)}{m_V^2}p^\mu k^\alpha k^\beta + f_3^A(k^2)(k^\alpha g^{\mu\beta} - k^\beta g^{\mu\alpha})$$
$$+ if_4^A(k^2)(k^\alpha g^{\mu\beta} + k^\beta g^{\mu\alpha}) + if_5^A(k^2)\epsilon^{\mu\alpha\beta\rho}p_\rho$$
$$- f_6^A(k^2)\epsilon^{\mu\alpha\beta\rho}k_\rho - \frac{f_7^A(k^2)}{m_V^2}p^\mu[kp]^{\alpha\beta}.$$

Hagiwara, Peccei, Zeppenfeld 1987
Ibarra, Hisano, Ryo 2022

Vector Dark States

Chu, Ibarra, Hisano, Kuo, JP
2303.13643

SPIN1 case: construction

Consider all possible Lorentz structures

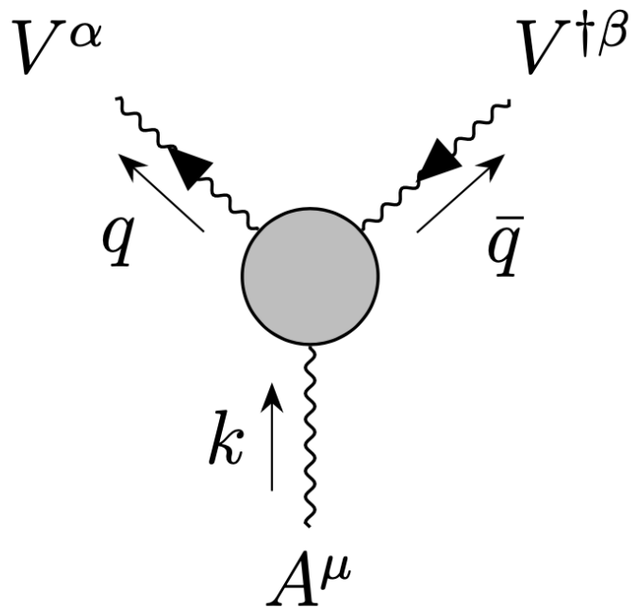
=> yields 9 structures

=> 7 independent structures

neutrality of V and gauge invariance of A require

=> $f^A_{1,4,5}(0) = 0$

$$i\Gamma^{\alpha\beta\mu}_{VV^\dagger\gamma}(q,\bar{q},k) =$$



$$f_1^A(k^2) = f_1^A(0) + \frac{k^2}{2\Lambda^2}\left[g_1^A(k^2) + \lambda_A(k^2)\right]$$

$$f_4^A(k^2) = f_4^A(0) + \frac{k^2}{\Lambda^2} g_4^A(k^2)$$

$$f_5^A(k^2) = f_5^A(0) + \frac{k^2}{\Lambda^2} g_5^A(k^2)$$

$$f_2^A(k^2) = \lambda_A(k^2)$$
$$f_3^A(k^2) = \kappa_A(k^2) + \lambda_A(k^2)$$
$$f_6^A(k^2) = \tilde{\kappa}_A(k^2) - \tilde{\lambda}_A(k^2)$$
$$f_7^A(k^2) = -\frac{1}{2}\tilde{\lambda}_A(k^2)$$

Hagiwara, Peccei, Zeppenfeld 1987
Ibarra, Hisano, Ryo 2022

Vector Dark States

Chu, Ibarra, Hisano, Kuo, JP
2303.13643

SPIN1 case: construction

Matched onto the following effective Lagrangian

$$
\begin{aligned}
\frac{\mathcal{L}}{e} = & \frac{i g_1^\Lambda}{2\Lambda^2}\left[\left(V^\dagger_{\mu\nu}V^\mu - V^{\dagger\mu}V_{\mu\nu}\right)\partial_\lambda F^{\lambda\nu} - V^{\dagger\mu}V^\nu \Box F_{\mu\nu}\right] \\
& + \frac{g_4^\Lambda}{\Lambda^2} V^\dagger_\mu V_\nu \left(\partial^\mu \partial_\rho F^{\rho\nu} + \partial^\nu \partial_\rho F^{\rho\mu}\right) \\
& + \frac{g_5^\Lambda}{\Lambda^2}\epsilon^{\mu\nu\rho\sigma}\left(V^\dagger_\mu \overleftrightarrow{\partial_\rho} V_\nu\right)\partial^\lambda F_{\lambda\sigma} \\
& + i\kappa_\Lambda V^\dagger_\mu V_\nu F^{\mu\nu} + \frac{i\lambda_\Lambda}{\Lambda^2} V^\dagger_{\lambda\mu} V^\mu{}_\nu F^{\nu\lambda} \\
& + i\tilde{\kappa}_\Lambda V^\dagger_\mu V_\nu \tilde{F}^{\mu\nu} + \frac{i\tilde{\lambda}_\Lambda}{\Lambda^2} V^\dagger_{\lambda\mu} V^\mu{}_\nu \tilde{F}^{\nu\lambda} \,,
\end{aligned}
$$

Vector Dark States

Chu, Ibarra, Hisano, Kuo, JP
2303.13643

SPIN1 case: construction

Matched onto the following effective Lagrangian

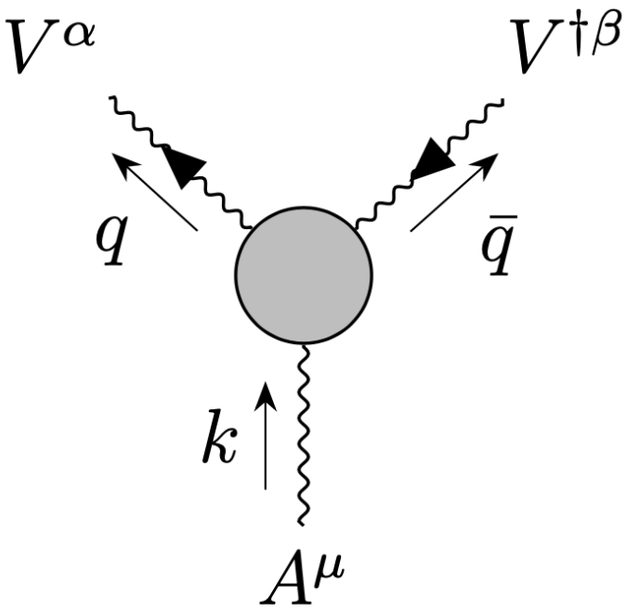
$$\frac{\mathcal{L}}{e} = \frac{ig_1^\Lambda}{2\Lambda^2}\left[\left(V^\dagger_{\mu\nu}V^\mu -\right.\right.$$
$$+\frac{g_4^\Lambda}{\Lambda^2}V_\mu^\dagger V_\nu\left(\partial^\mu\partial_\rho F^\right.$$
$$+\frac{g_5^\Lambda}{\Lambda^2}\epsilon^{\mu\nu\rho\sigma}\left(V_\mu^\dagger\overleftrightarrow{\partial_\rho}V\right.$$
$$+i\kappa_\Lambda V_\mu^\dagger V_\nu F^{\mu\nu}+\frac{i}{}$$
$$+i\tilde{\kappa}_\Lambda V_\mu^\dagger V_\nu \tilde{F}^{\mu\nu}+\frac{i}{}$$

interaction type	coupling	C	P	CP
magn. dipole	$\mu_V = \frac{e}{2m_V}(\kappa_\Lambda + \frac{m_V^2}{\Lambda^2}\lambda_\Lambda)$	$+1$	$+1$	$+1$
elec. dipole	$d_V = \frac{e}{2m_V}(\tilde{\kappa}_\Lambda + \frac{m_V^2}{\Lambda^2}\tilde{\lambda}_\Lambda)$	$+1$	-1	-1
magn. quadrupole	$Q_V = -\frac{e}{m_V^2}(\kappa_\Lambda - \frac{m_V^2}{\Lambda^2}\lambda_\Lambda)$	$+1$	$+1$	$+1$
elec. quadrupole	$\tilde{Q}_V = -\frac{e}{m_V^2}(\tilde{\kappa}_\Lambda - \frac{m_V^2}{\Lambda^2}\tilde{\lambda}_\Lambda)$	$+1$	-1	-1
charge radius	$g_1^A/m_V^2 = g_1^\Lambda/\Lambda^2$	$+1$	$+1$	$+1$
toroidal moment	$g_4^A/m_V^2 = g_4^\Lambda/\Lambda^2$	-1	$+1$	-1
anapole moment	$g_5^A/m_V^2 = g_5^\Lambda/\Lambda^2$	-1	-1	$+1$

Vector Dark States

Vertex factor

Consider all possible Lorentz structures $i\Gamma^{\alpha\beta\mu}_{VV^\dagger\gamma}(q,\bar{q},k) =$



$$
\begin{aligned}
i\Gamma^{\mu\alpha\beta}(k,p) &= -\frac{ieg_1^A}{2m_V^2}k^2p^\mu g^{\alpha\beta} \\
&- \frac{eg_4^A}{m_V^2}k^2(k^\alpha g^{\mu\beta}+k^\beta g^{\mu\alpha}) - \frac{eg_5^A}{m_V^2}k^2\epsilon^{\mu\alpha\beta\rho}p_\rho \\
&- 2im_V\mu_V\left[k^\alpha g^{\mu\beta}-k^\beta g^{\mu\alpha}+\frac{1}{4m_V^2}\left(k^2g^{\alpha\beta}p^\mu-2k^\alpha k^\beta p^\mu\right)\right] \\
&- \frac{iQ_V}{4}\left(k^2g^{\alpha\beta}p^\mu-2k^\alpha k^\beta p^\mu\right) \\
&- \frac{id_V}{2m_V}p^\mu\left[kp\right]^{\alpha\beta} - \frac{i\tilde{Q}_V}{4}\left(p^\mu\left[kp\right]^{\alpha\beta}+4m_V^2\epsilon^{\mu\alpha\beta\rho}k_\rho\right) ,
\end{aligned}
$$

=> interactions grouped by their CP properties and familiar nomenclature; defined such that mV is the only explicit scale

Vector Dark States

Chu, Ibarra, Hisano, Kuo, JP

2303.13643

Universal description of V-pair production

Spin-summed matrix element of VV production

$$\sum_{\lambda,\lambda'} \left|\mathcal{M}^{\lambda\lambda'}\right|^2 = D_{\mu\nu}(k) D^*_{\rho\sigma}(k) \mathcal{T}^{\mu\rho}_{\rm SM} \mathcal{T}^{\nu\sigma}_{\rm DM}$$

any SM-current producing $\gamma^*(k)$
(can receive medium corrections)

interaction type	$f(s)$
magnetic dipole	$\frac{\mu_V^2 s(s-4m_V^2)(16m_V^2+3s)}{12m_V^2}$
electric dipole	$\frac{d_V^2 s(s-4m_V^2)^2}{6m_V^2}$
magnetic quadrupole	$\frac{Q_V^2 s^2(s-4m_V^2)}{16}$
electric quadrupole	$\frac{\tilde{Q}_V^2 s^2(s+8m_V^2)}{24}$
charge radius	$\frac{e^2(g_1^A)^2 s^2(s-4m_V^2)(12m_V^4-4m_V^2 s+s^2)}{48m_V^8}$
toroidal moment	$\frac{e^2(g_4^A)^2 s^3(s-4m_V^2)}{3m_V^6}$
anapole moment	$\frac{e^2(g_5^A)^2 s^2(s-4m_V^2)^2}{3m_V^6}$

$$\int d\Phi_2 \mathcal{T}^{\nu\sigma}_{\rm DM} = \frac{1}{8\pi}\sqrt{1-\frac{4m_V^2}{s}} f(s) \left(-g^{\nu\sigma} + \frac{k^\nu k^\sigma}{s}\right)$$

f(s) with mass-dimension 2 summarizes all effective interactions when VV phase space can be integrated

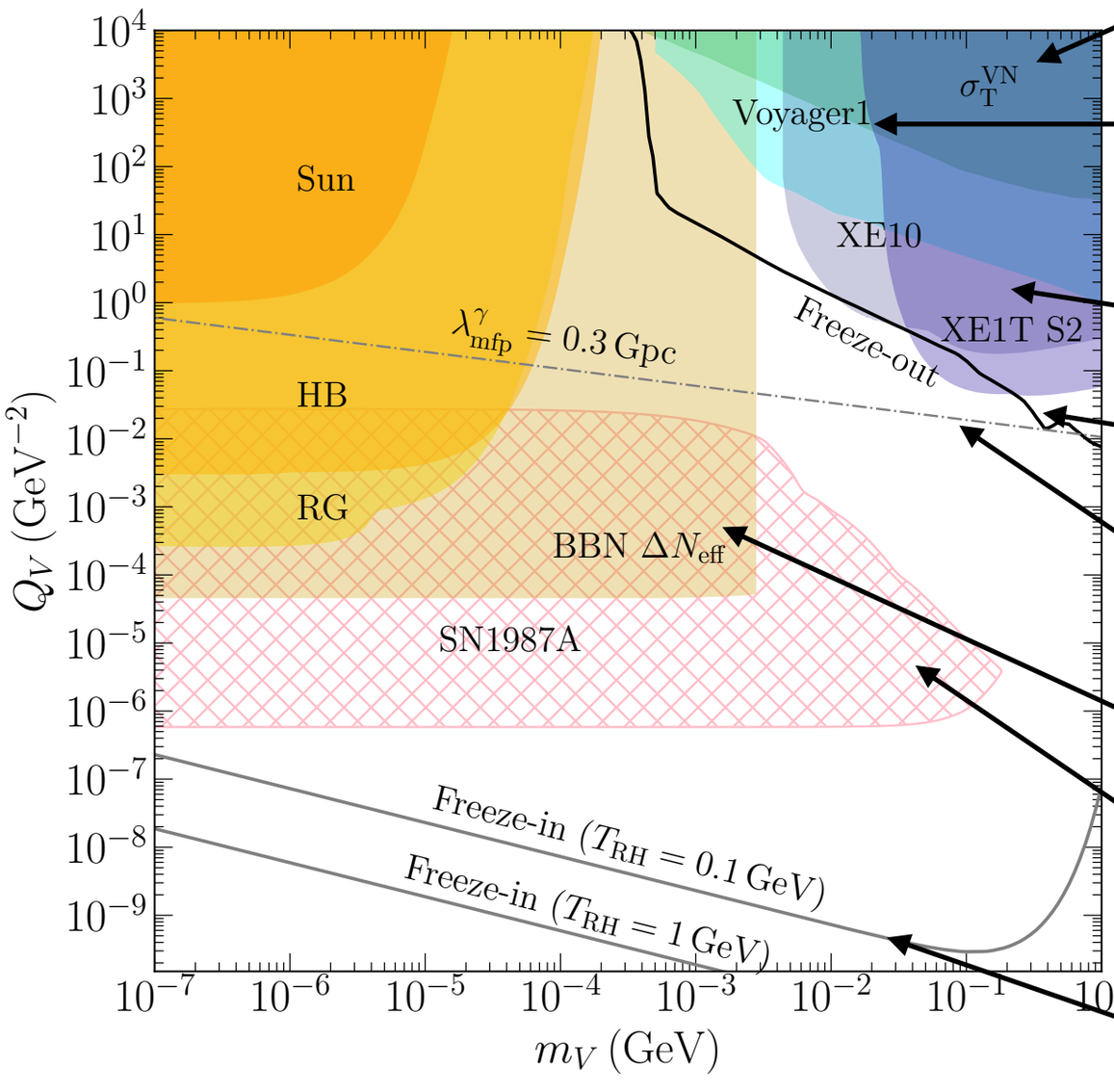
Vector DM

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2303.13643

Mass vs. coupling plane

magnetic quadrupole



modification of matter power spectrum

indirect detection limit by annihilation
(weak because of velocity suppression)

direct detection DM-e scattering

annihilation into e^+e^- and $\gamma\,\gamma$
(typically p- or d-wave)

transparency to TeV photons

BBN limit on N_{eff} from minimal T_R

SN-limit bounded from above by trapping

UV-dominated freeze-in

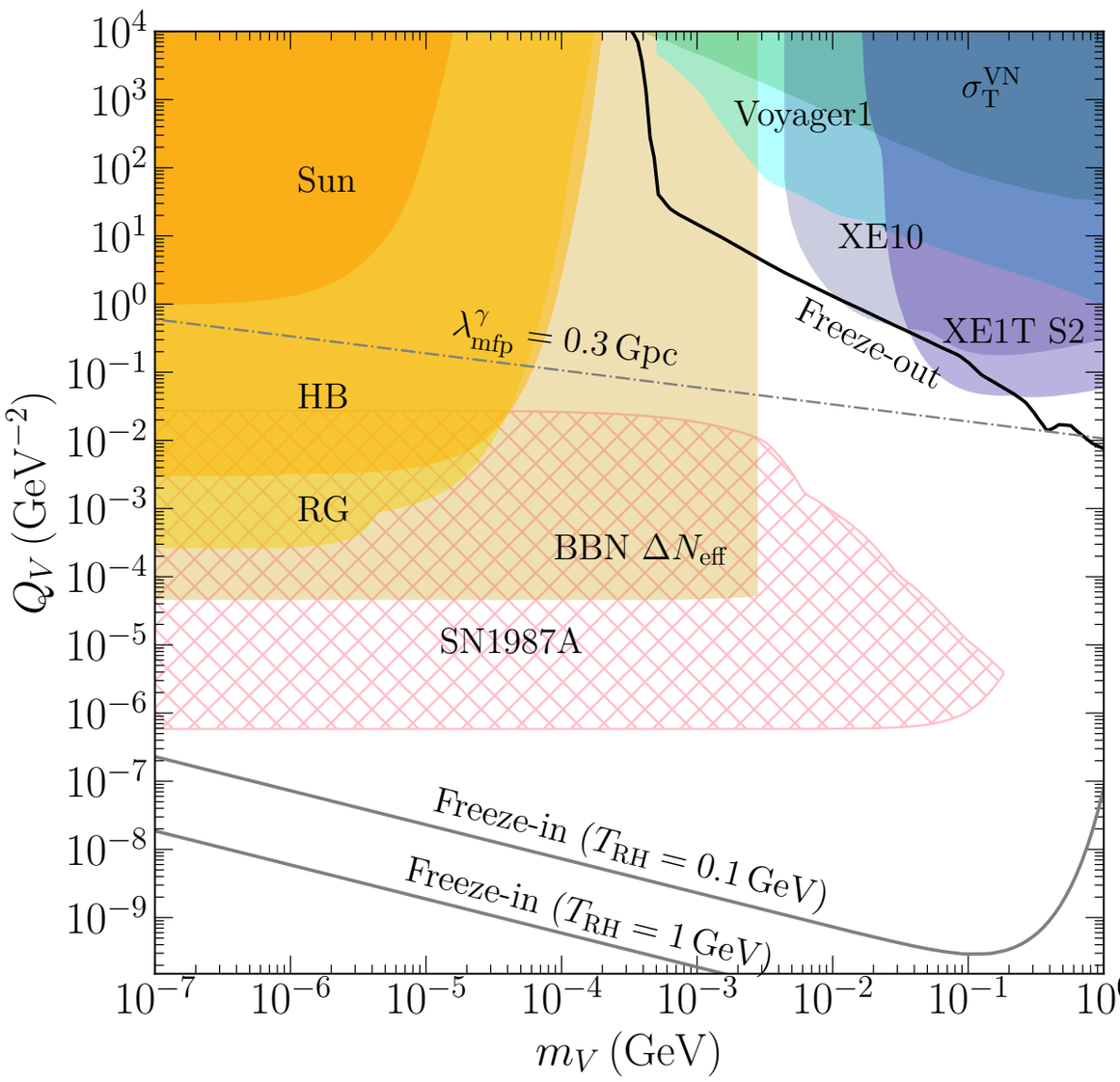
Vector DM

Mass vs. coupling plane

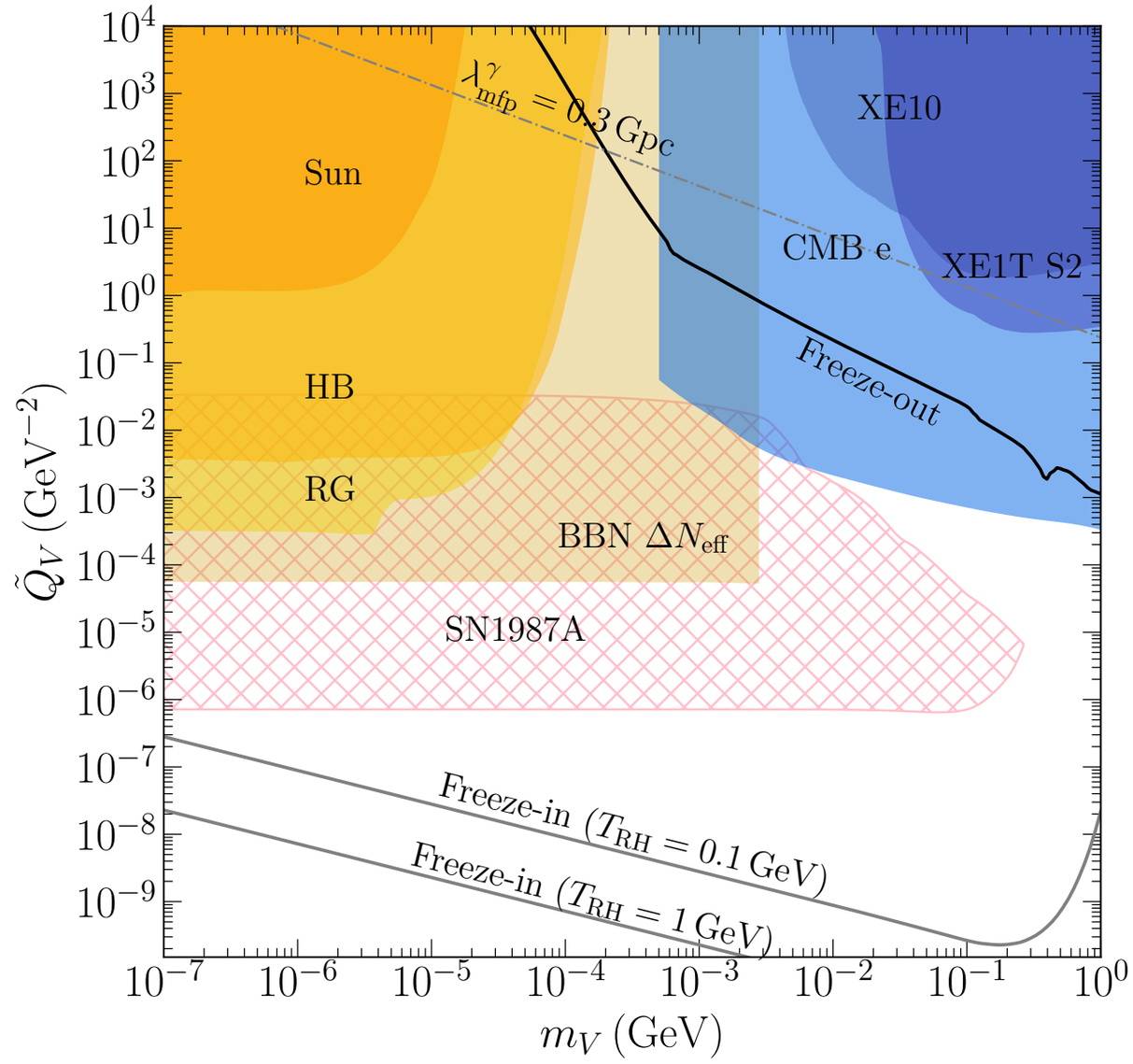
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magnetic quadrupole



electric quadrupole



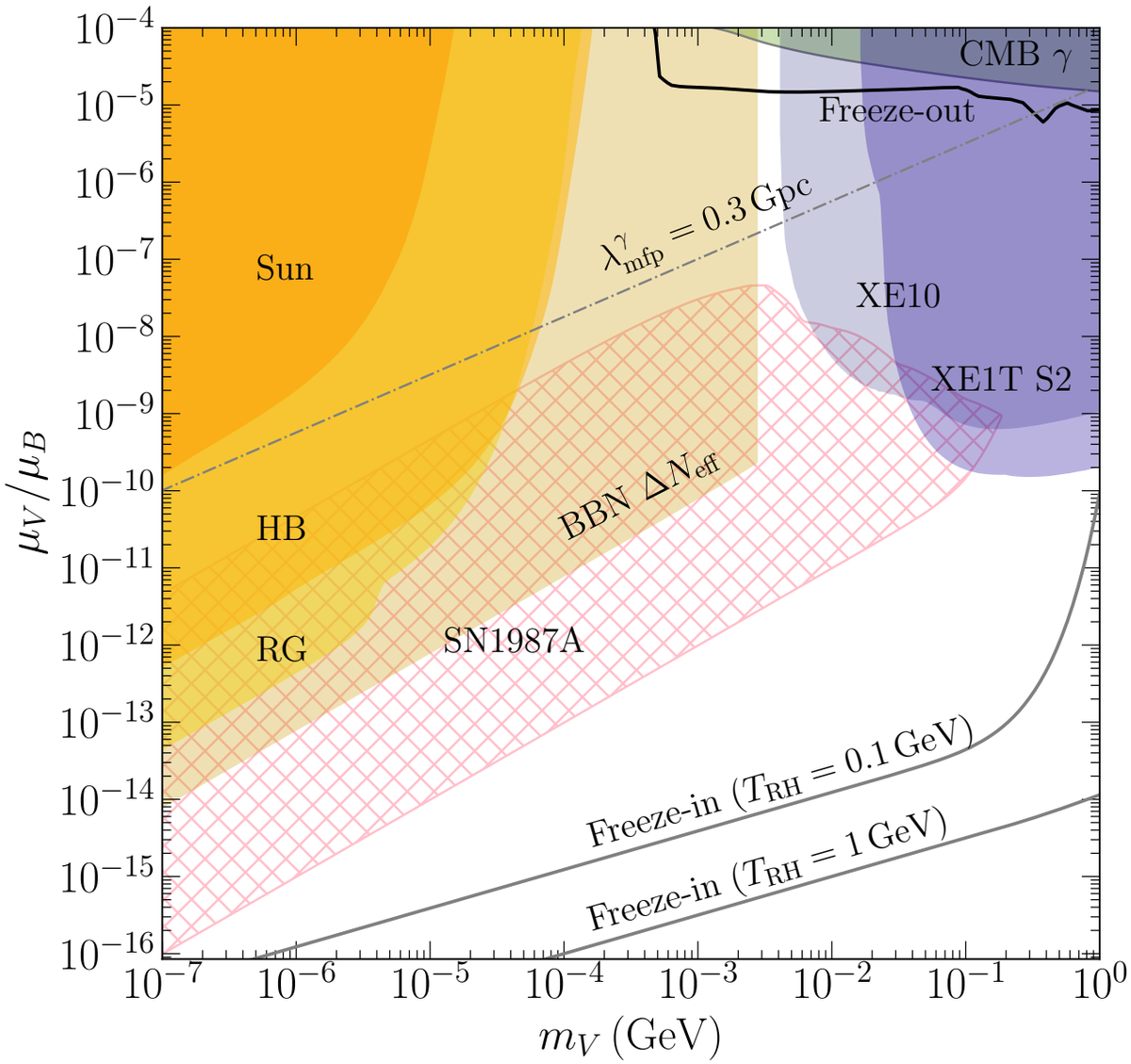
Vector DM

Mass vs. coupling plane

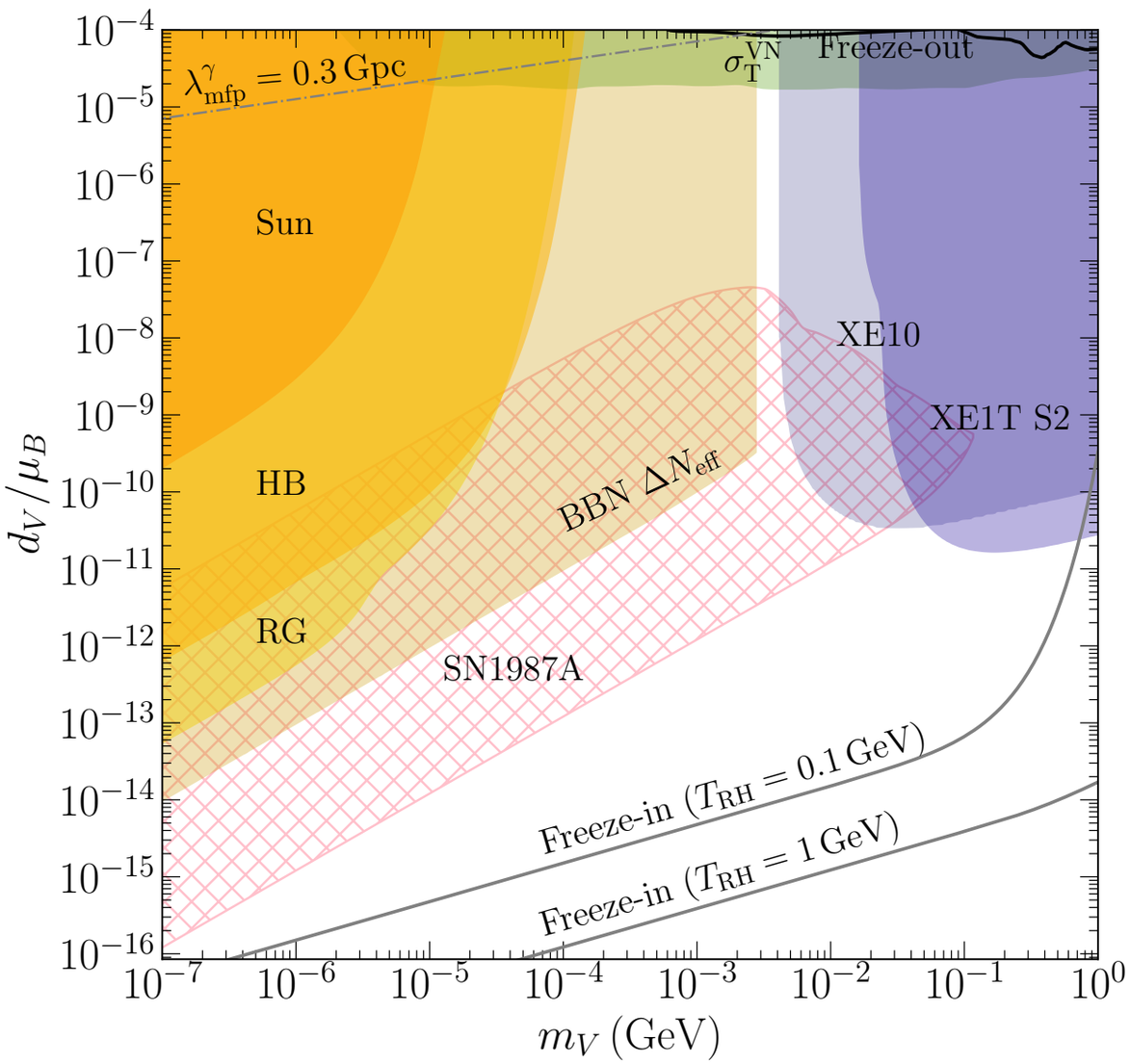
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magnetic dipole



electric dipole



Vector DM

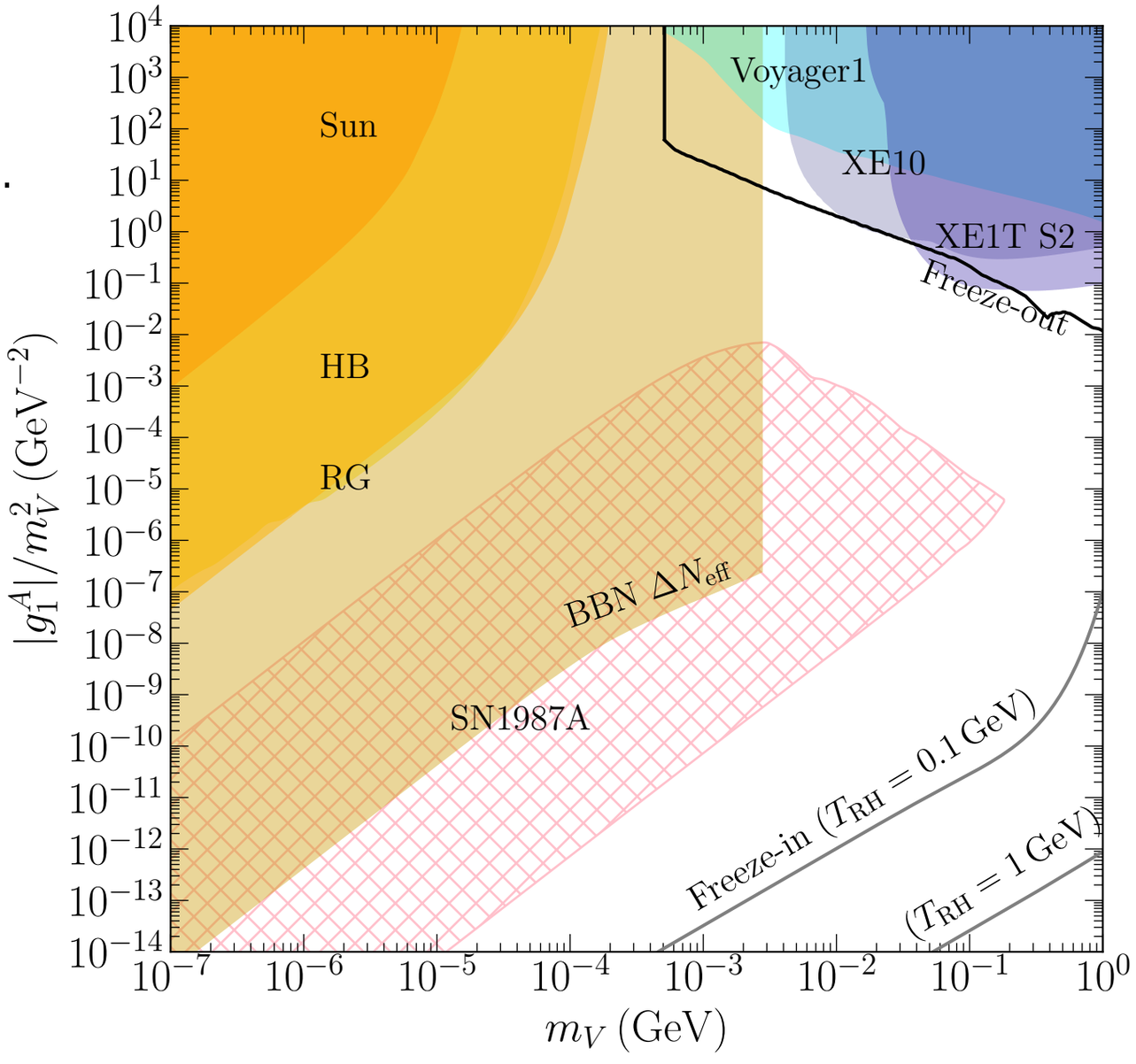
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Validity of the effective approach?

$m_V \to 0$ limit appears worrisome for most of the effective interactions. Appears as if rates diverge in the zero mass limit.

$\sqrt{s} \lesssim v_D$ must hold as otherwise contributions from the dark Higgs will enter.

charge radius



Vector DM

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Expected scaling of rates from naive dimensional analysis

Production rates should scale according to their transverse (T) and longitudinal (V) polarity as

$$\dot{Q}_{\lambda\lambda'} \propto \begin{cases} g_D^4/m_V^4 & \lambda\lambda' = \mathrm{LL}, \\ g_D^4/m_V^2 & \lambda\lambda' = \mathrm{LT}, \\ g_D^4 & \lambda\lambda' = \mathrm{TT}. \end{cases}$$

for $\sqrt{s}/m_V \gg 1$ (high-energy limit)

$$\epsilon_{\mathrm{L}} = \left(\frac{p}{m_V}, 0, 0, \frac{E}{m_V}\right), \ \epsilon_{\mathrm{T}}^{\pm} = \left(0, \frac{1}{\sqrt{2}}, \pm\frac{i}{\sqrt{2}}, 0\right)$$

For example, in the UV-picture $m_V \sim g_D v_D$

$$\dot{Q}_{\mathrm{LL}} \propto |(g_D \epsilon_{L,1})(g_D \epsilon_{L,2})|^2 \propto \frac{g_D^4}{m_V^4} \propto \frac{1}{v_D^4}$$

FINITE, independent of gauge coupling
(Goldstone boson equivalence thm.)

BUT: even effective operators that do NOT permit LL mode (e.g. electric dipole) show same scaling

=> resolution in the UV-picture

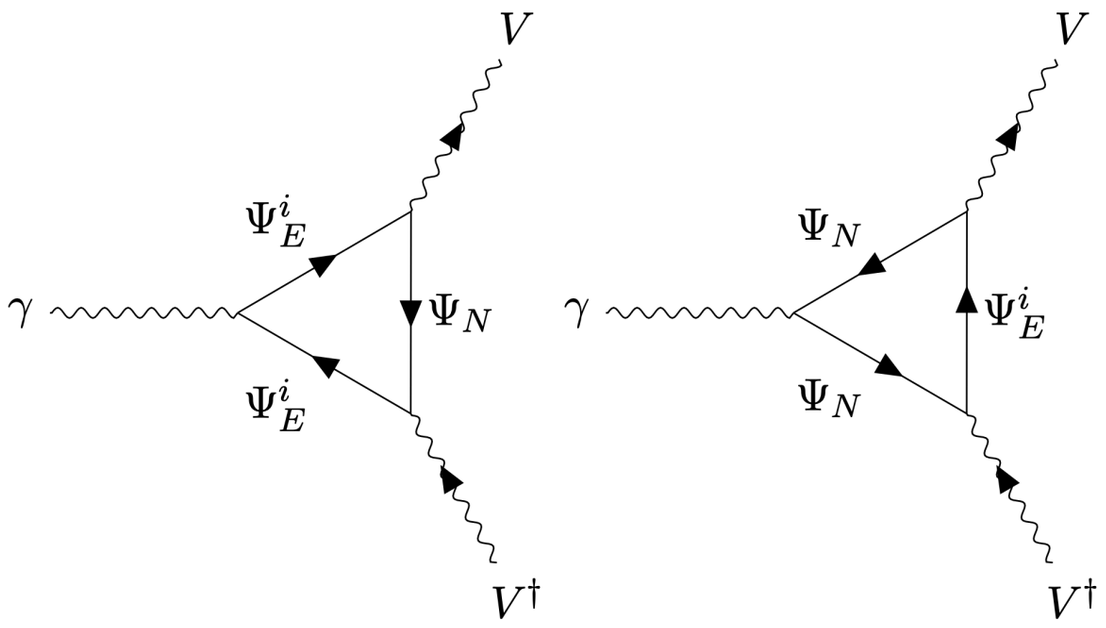
Vector DM

UV-completion

Dark SU(2)$_D$ x global U(1)$_X$ with a vector triplet W_D^a, dark fermions Ψ , Higgsed by Φ_D

=> six of the seven operators radiatively induced

Ibarra, Hisano, Ryo (2020)



$$\langle \Phi_D \rangle = v_D/\sqrt{2}$$

$$m_{W_D} = g_D v_D/2$$

$$\mathcal{L}_{\rm int} = -\frac{g_D}{\sqrt{2}}\left(\bar{\Psi}_E^i\left[(V_L)_{1i}\,P_L + (V_R)_{1i}\,P_R\right]\gamma^\mu \Psi_N W_{D\mu}^- + \text{h.c.}\right) - e\Psi_N\gamma^\mu\Psi_N A_\mu - e\bar{\Psi}^i{}_E\gamma^\mu\Psi_E^i A_\mu.$$

V's diagonalize Ψ's after SSB

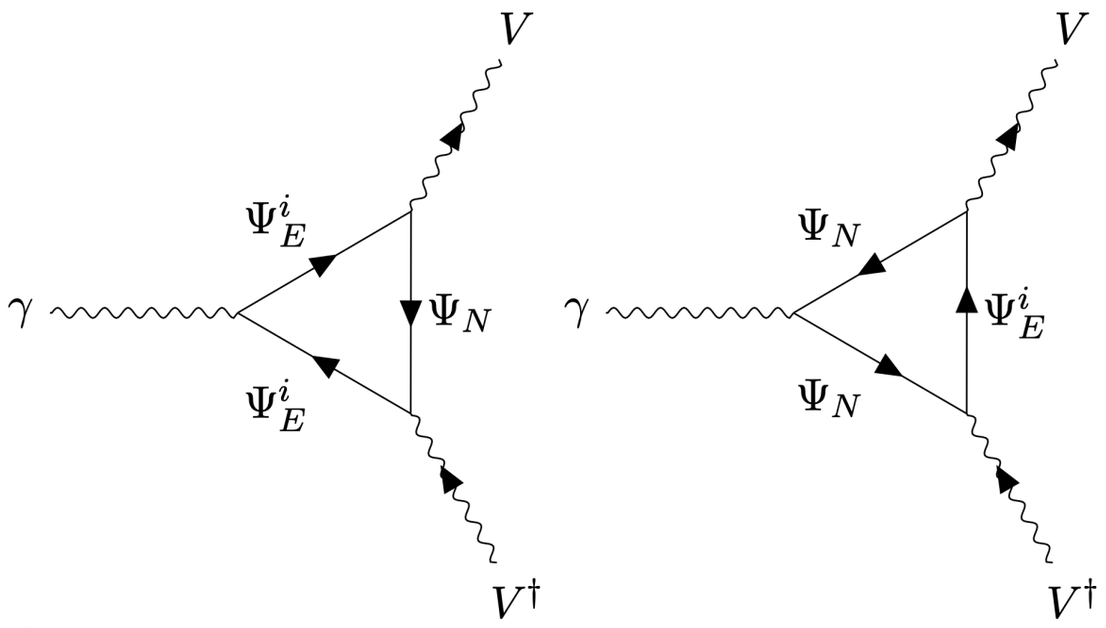
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$$\langle \Phi_D \rangle = v_D/\sqrt{2}$$

$$m_{W_D} = g_D v_D/2$$

For example:

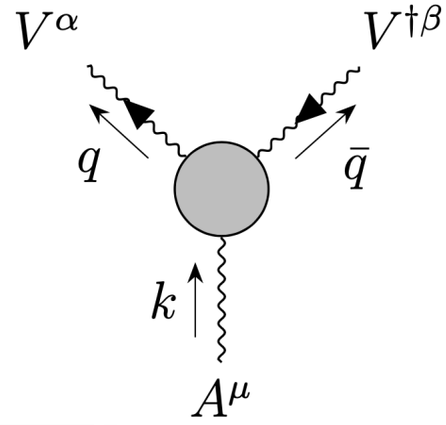
$$\mu_V = -e\frac{g_D^2}{64\pi^2}\frac{1}{m_V}\sum_{i=1}^{2}(1-x_i^2)\left[\left(\left|(V_L)_{1i}^2\right|^2+\left|(V_R)_{1i}^2\right|^2\right)\right. \text{ x loop function}$$

$$d_V = e\frac{g_D^2}{64\pi^2}\frac{1}{m_V}\sum_{i=1}^{2}\mathrm{Im}\left((V_L)_{1i}^\star\,(V_R)_{1i}^\star\right) \text{ x loop function}$$

Vector DM

proper high energy limit

$$i\Gamma^{\alpha\beta\mu}_{VV^\dagger\gamma}(q,\bar{q},k) =$$



Coupl.	UV model	$\dot{Q} \propto f(s)$	$\dot{Q}\|_{m_V\to 0}$	pol.
μ_V	$\frac{g_D^2}{m_V} \propto \frac{g_D}{v_D}$	$\frac{\mu_V^2}{m_V^2} \propto \frac{1}{v_D^4}$	finite	all
d_V	$\frac{g_D^2}{m_V} \propto \frac{g_D}{v_D}$	$\frac{d_V^2}{m_V^2} \propto \frac{1}{v_D^4}$	finite	TT

From the UV perspective, multipole moments are not independent, emission rate probes $i\Gamma^{\alpha\beta\mu}$

magn. dipole	$\mu_V = \frac{e}{2m_V}(\kappa_\Lambda + \frac{m_V^2}{\Lambda^2}\lambda_\Lambda)$
elec. dipole	$d_V = \frac{e}{2m_V}(\tilde{\kappa}_\Lambda + \frac{m_V^2}{\Lambda^2}\tilde{\lambda}_\Lambda)$

=> switch basis

	κ_Λ	λ_Λ	g_1^A
UV	g_D^2	$\frac{g_D^2\Lambda^2}{m_N^2}$	$\frac{g_D^2 m_V^2}{m_N^2}$
C,P	$(+,+)$		
$\dot{Q}_{\rm LL}$	$\frac{\kappa_\Lambda^2}{m_V^4} \propto \frac{g_D^4}{m_V^4}$		
$\dot{Q}_{\rm LT}$	$\frac{\kappa_\Lambda^2}{m_V^2} \propto \frac{g_D^4}{m_V^2}$		
$\dot{Q}_{\rm TT}$	$\left(\frac{\lambda_\Lambda}{\Lambda^2} + \frac{g_1^A}{m_V^2}\right)^2 \propto g_D^4$		

=> when all operators that share C,P properties are considered jointly, rates scale precisely as NDA suggests!

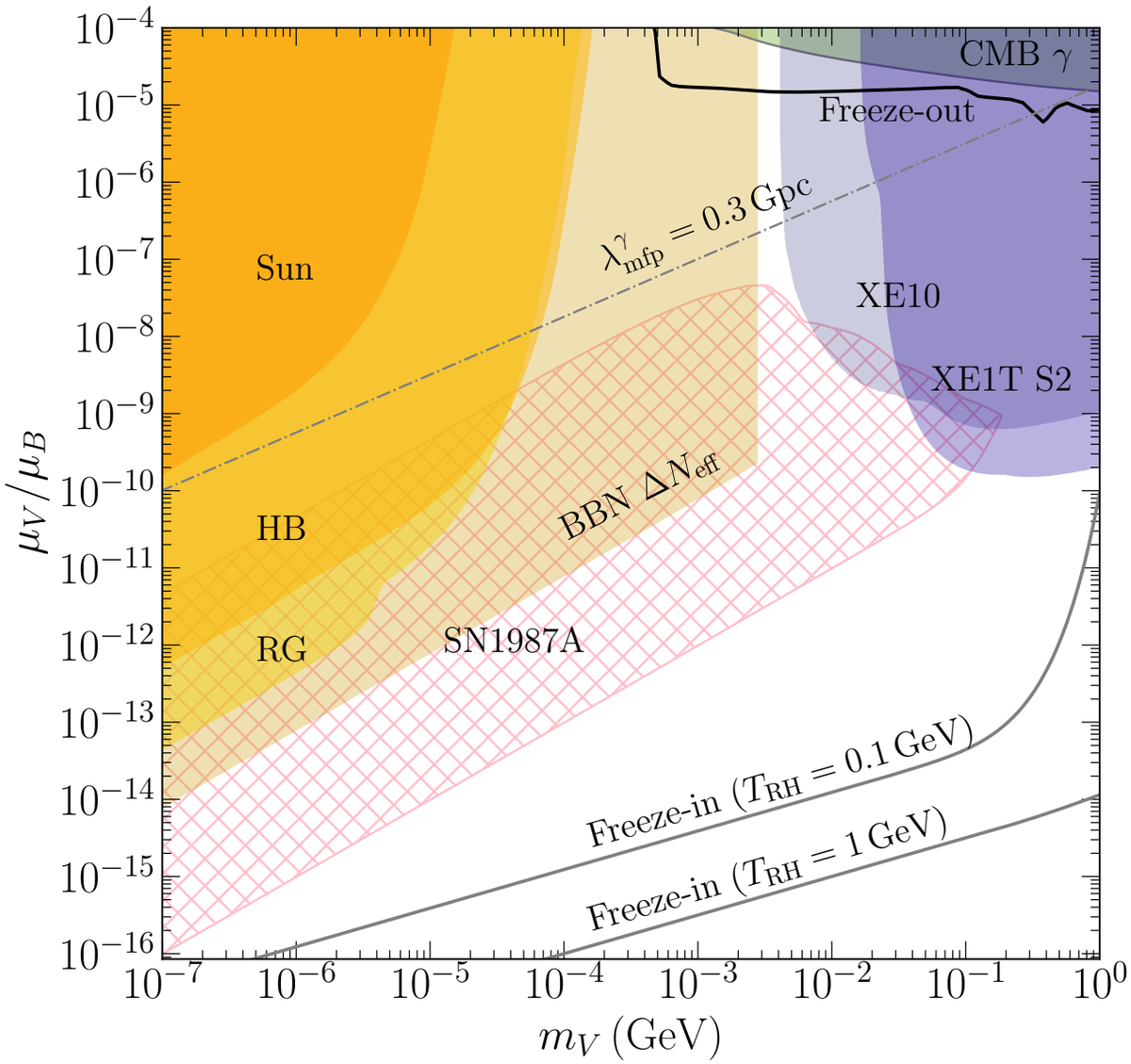
Vector DM

Mass vs. coupling plane

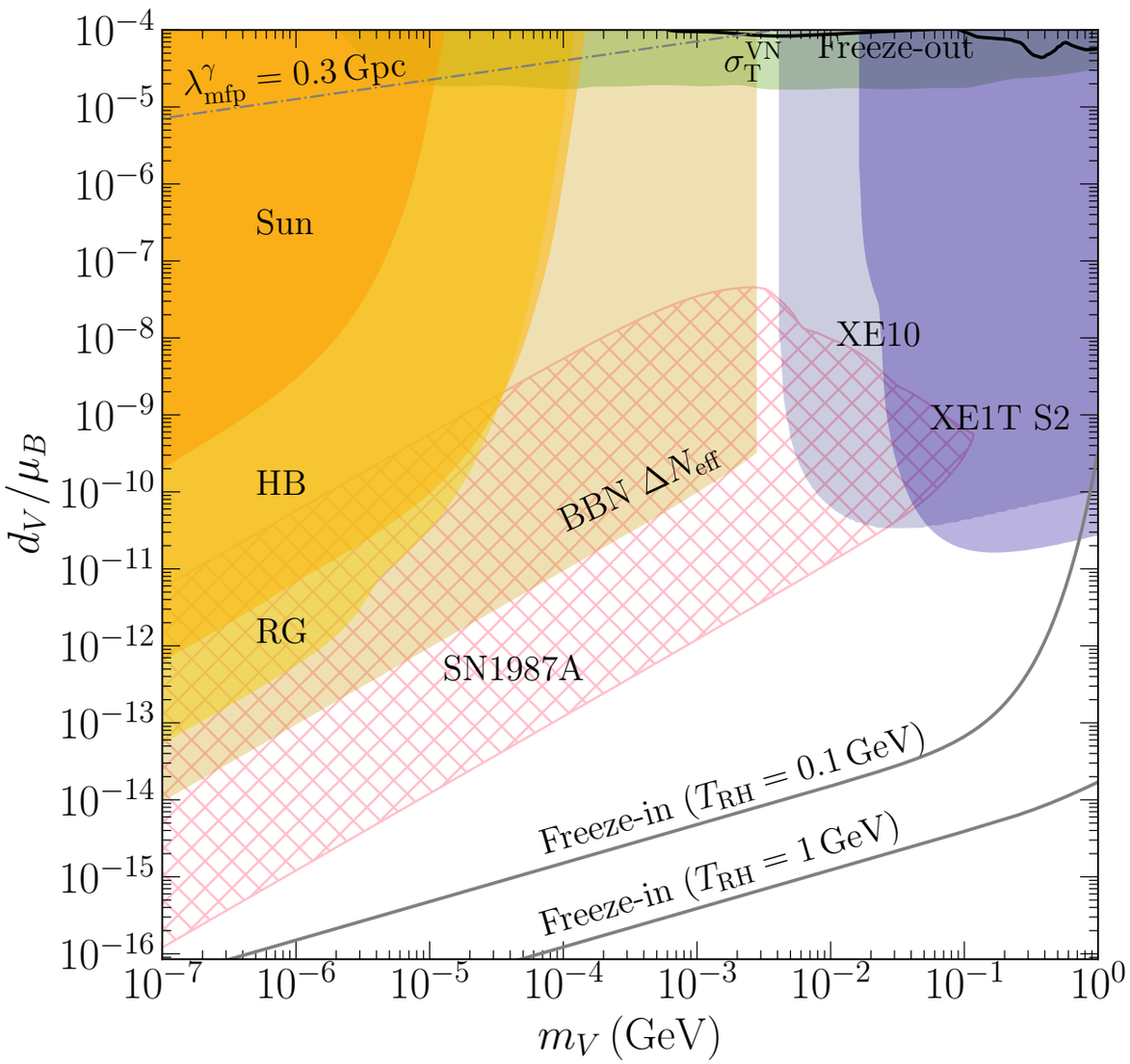
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magnetic dipole



electric dipole



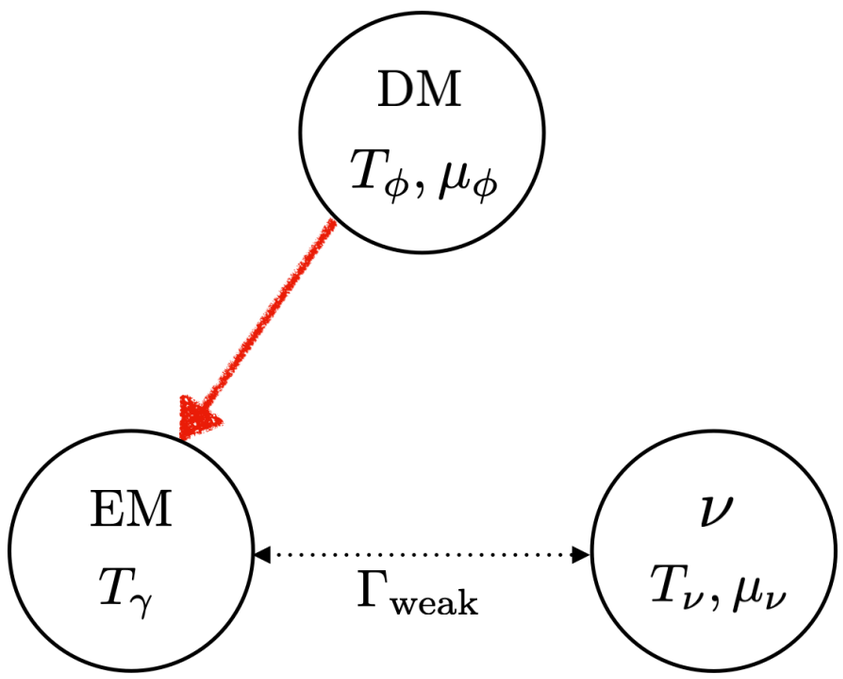
Light DM freeze out

Chu, Kuo, JP
(2022 & in preparation)

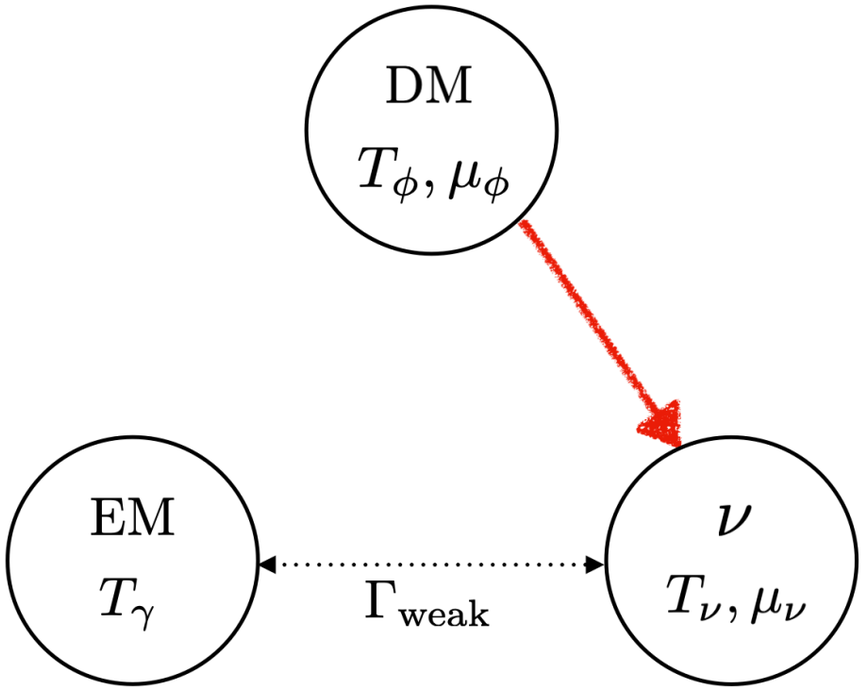
What is the lightest thermal DM mass?

Well known that MeV-DM subject to Neff bound from heating by annihilation

Previous treatments had to assume a branching either into EM-sector OR neutrinos:



OR



Light DM freeze out

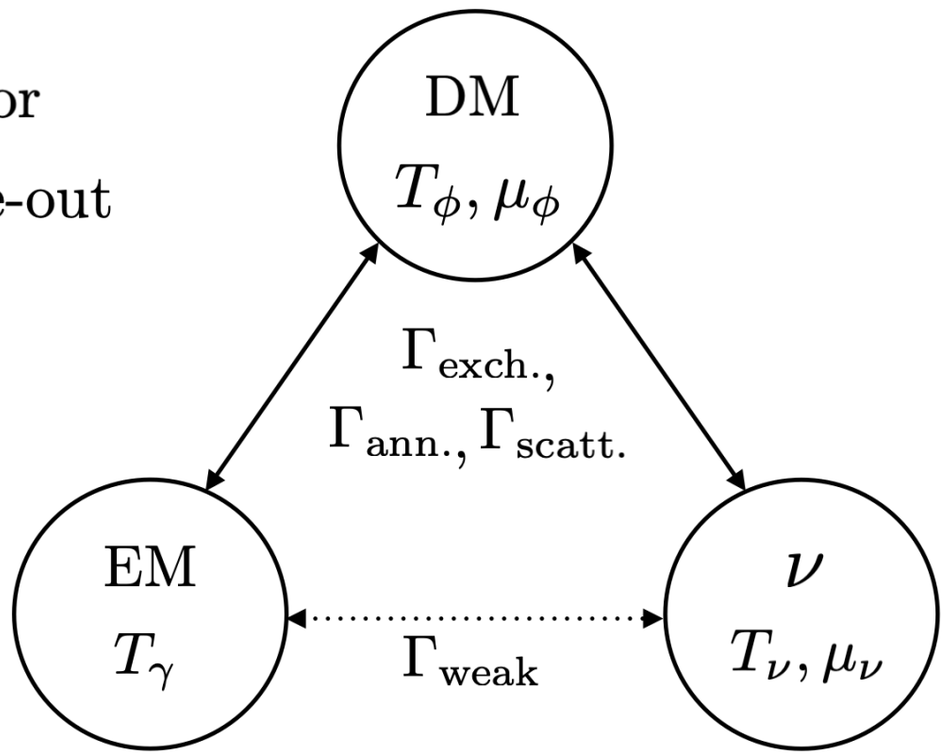
Chu, Kuo, JP
(2022 & in preparation)

What is the lightest thermal DM mass?

Well known that MeV-DM subject to Neff bound from heating by annihilation

In the full picture, joint treatment of the three coupled sectors is necessary

three-sector
DM freeze-out



$$\Gamma_{\rm weak} \equiv n_e G_F^2 T_\gamma^2 \,,$$
$$\Gamma_{\rm ann.} \equiv n_\phi \langle \sigma_{\rm ann.} v \rangle \,,$$
$$\Gamma_{{\rm exch.},i} \equiv n_\phi^2 \langle \sigma_{{\rm ann.},i} v \delta E \rangle / \rho_i \,,$$
$$\Gamma_{{\rm scatt.},i} \equiv n_i \langle \sigma^{\phi i}_{\rm scatt.} v \rangle \,.$$

=> we are the first to be able to treat a relative branching AND to include energy transfer from elastic scattering

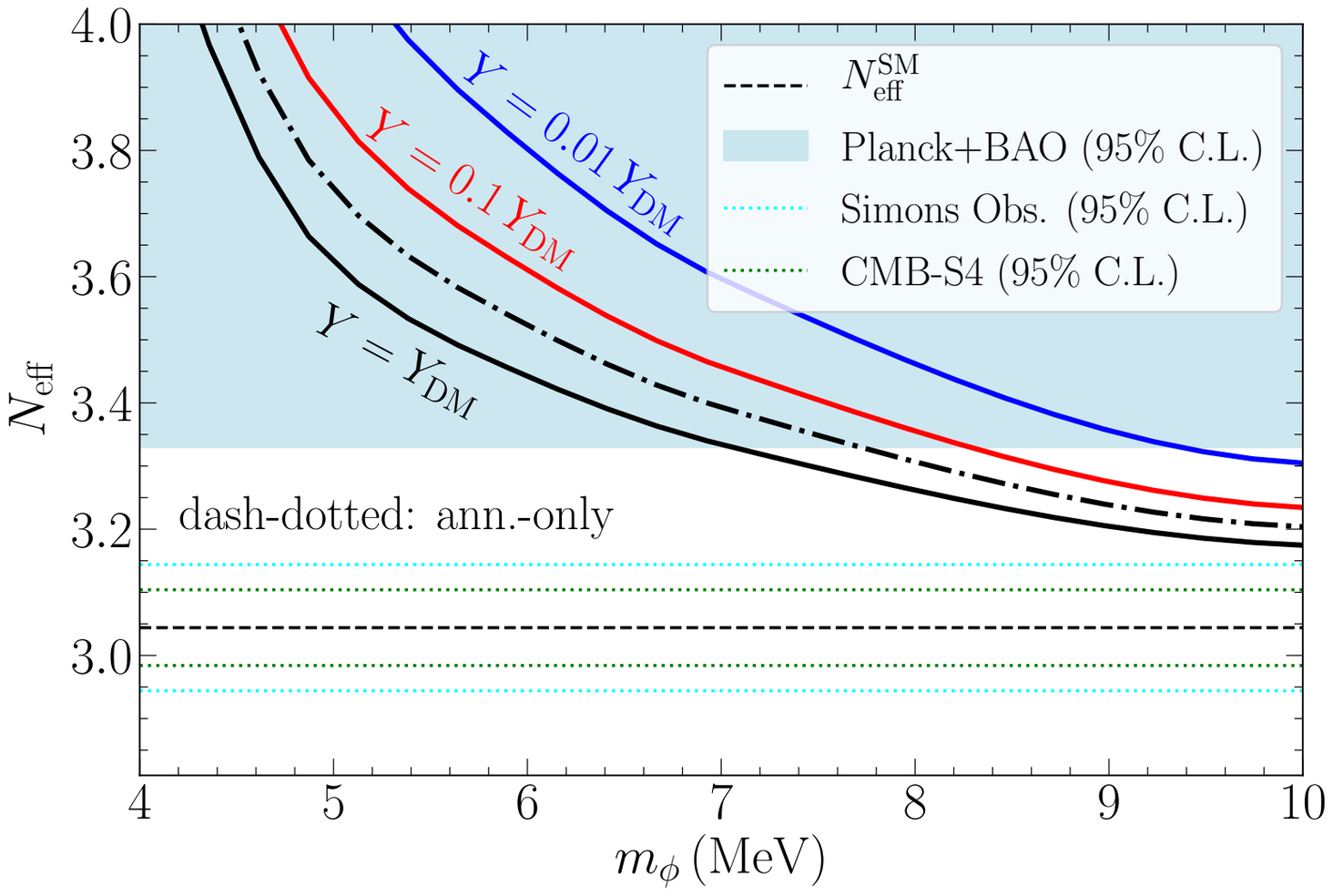
=> allows to track DM temperature (feeds into efficiency of annihilation for p-, d- … wave)

=> allows for a precision prediction of Neff and to derive a lower bound on the DM mass

Light DM freeze out

What is the lightest thermal DM mass?

Example: flavor-blind Z' mediated p-wave annihilation (approximate equal branchings to nu and e)



Chu, Kuo, JP (2022)

Positive contribution to N_{eff}, unless Br(neutrinos) < 10^{-4}! **Chu, Kuo, JP (in preparation)**

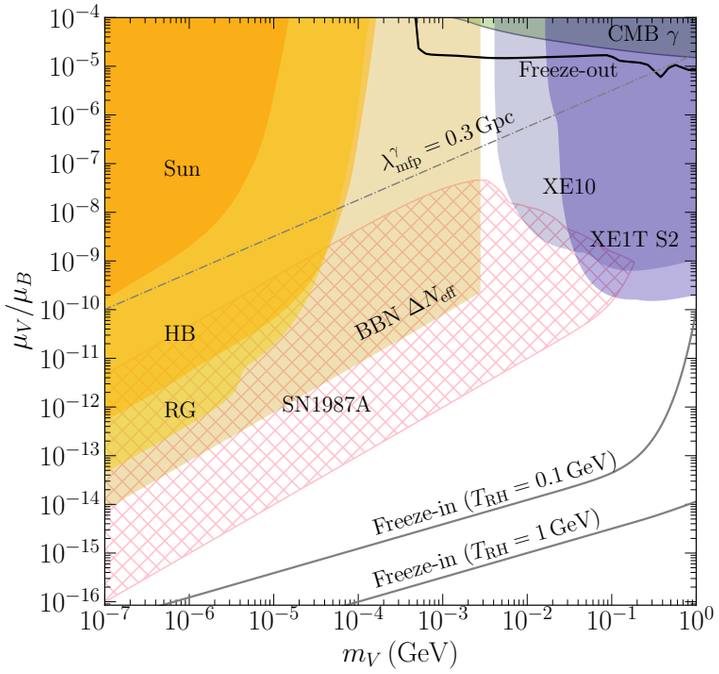
Fine tuned point that escapes the Neff constraint; requires Br(neutrinos) < 10^{-4}

Summary

sub-GeV dark state phenomenology

- neutral dark particles can couple to the photon through higher dimensional electromagnetic moment interactions. Spin-1/2 and 1 particles have many

- thermal freeze-out excluded by direct detection and indirect detection constraints (exceptions are anapole and toroidal moment interactions)



- thermal freeze-in line is never touched by any considered probes, but dark state parameter space otherwise severely constrained by astrophysical limits

.....

- A comprehensive assessment of thermal MeV-scale DM necessitates a three-sector treatment of vastly changing rates => found a systematic formulation

