SEARCHES FOR NEW PARTICLES IN BOUND STELLAR ORBITS

Katelin Schutz, McGill University
TeVPA, August 8th 2022

THEORIES OF DARK SECTORS ARE INCREDIBLY DIVERSE

GRAVITY

WEAK FORCE

ELECTROMAGNETISM

STRONG FORCE

u c t

d s b

(quarks)

(protons & neutrons made of these)

τ

μ

e

(charged leptons)

ν_τ

ν_μ

ν_e

(neutrinos)

GRAVITY

WEAK FORCE

ELECTROMAGNETISM

STRONG FORCE

u c t

d s b

(quarks)

(protons & neutrons made of these)

τ

μ

e

(charged leptons)

ν_τ

ν_μ

ν_e

(neutrinos)

?

Dark matter

GRAVITY

WEAK FORCE

NEW FORCE?

?

ELECTROMAGNETISM

STRONG FORCE

u c t

d s b

(quarks)

(protons & neutrons made of these)

τ

μ

e

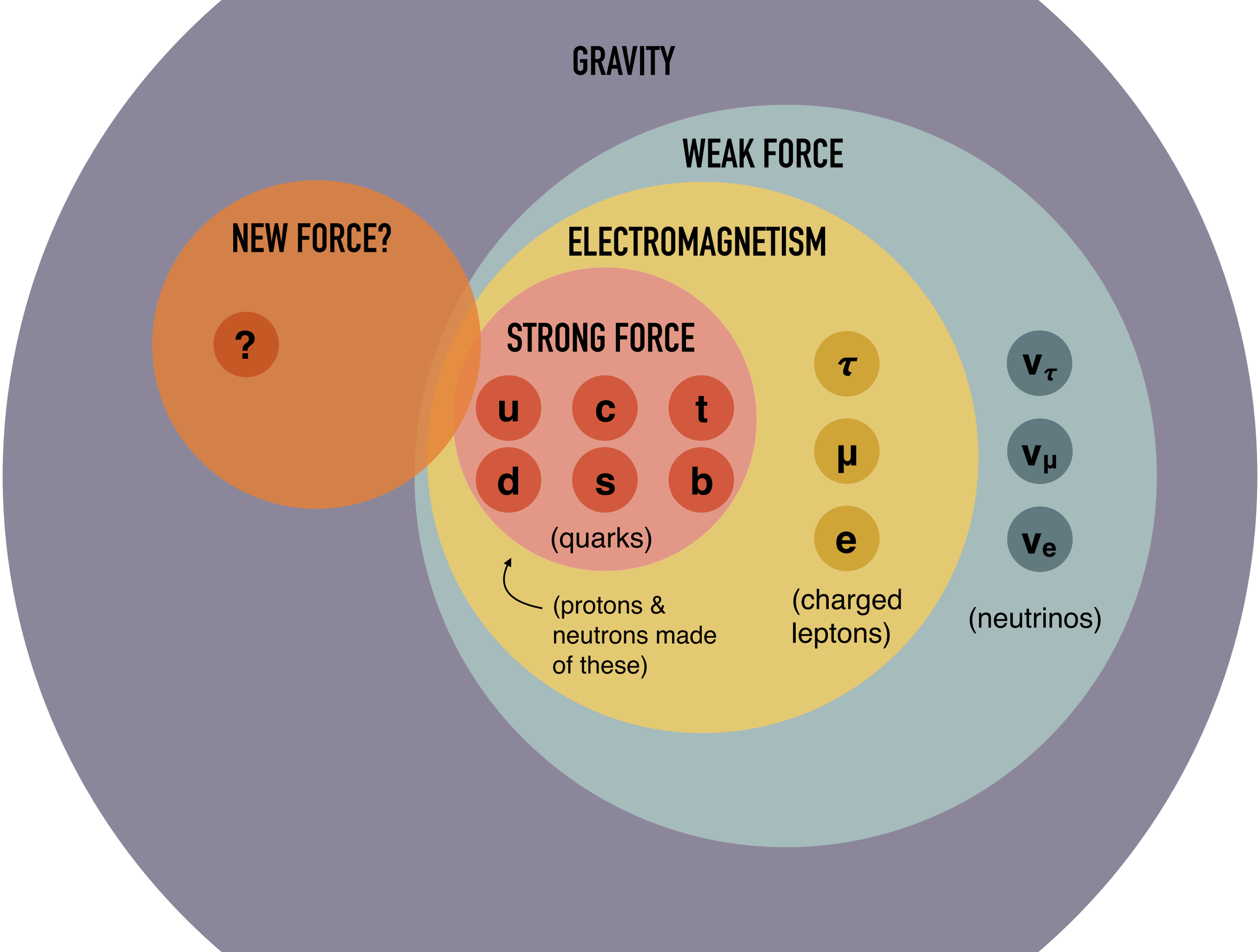
(charged leptons)

ν_τ

ν_μ

ν_e

(neutrinos)


GRAVITY
WEAK FORCE
ELECTROMAGNETISM
STRONG FORCE
NEW FORCE?
?
u
c
t
d
s
b
(quarks)
(protons & neutrons made of these)
τ
μ
e
(charged leptons)
ν_τ
ν_μ
ν_e
(neutrinos)

GRAVITY

WEAK FORCE

NEW FORCE?

?

?

?

Not necessarily DM

ELECTROMAGNETISM

STRONG FORCE

u c t

d s b

(quarks)

(protons & neutrons made of these)

τ

μ

e

(charged leptons)

ν_τ

ν_μ

ν_e

(neutrinos)

GRAVITY

WEAK FORCE

ELECTROMAGNETISM

STRONG FORCE

u c t

d s b

(quarks)

(protons & neutrons made of these)

τ

μ

e

(charged leptons)

ν_τ

ν_μ

ν_e

(neutrinos)

NEW FORCE?

? ? ?

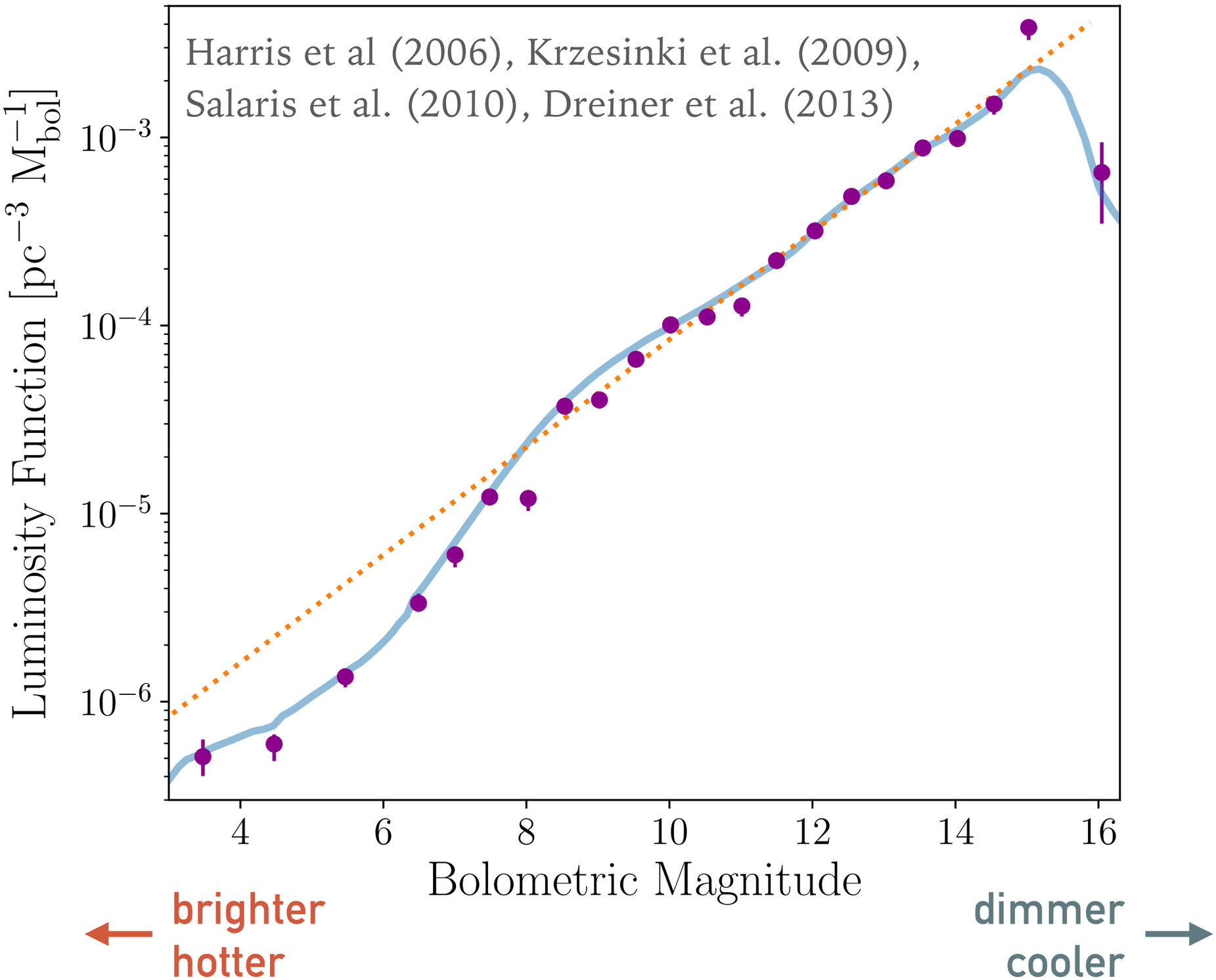
Not necessarily DM

- Finite list of renormalizable interactions
  - Vector portals (kinetic mixing, B-L, etc.)
  - Higgs portal
  - Neutrino portal
  - Pseudoscalar/axion (dimension 5)

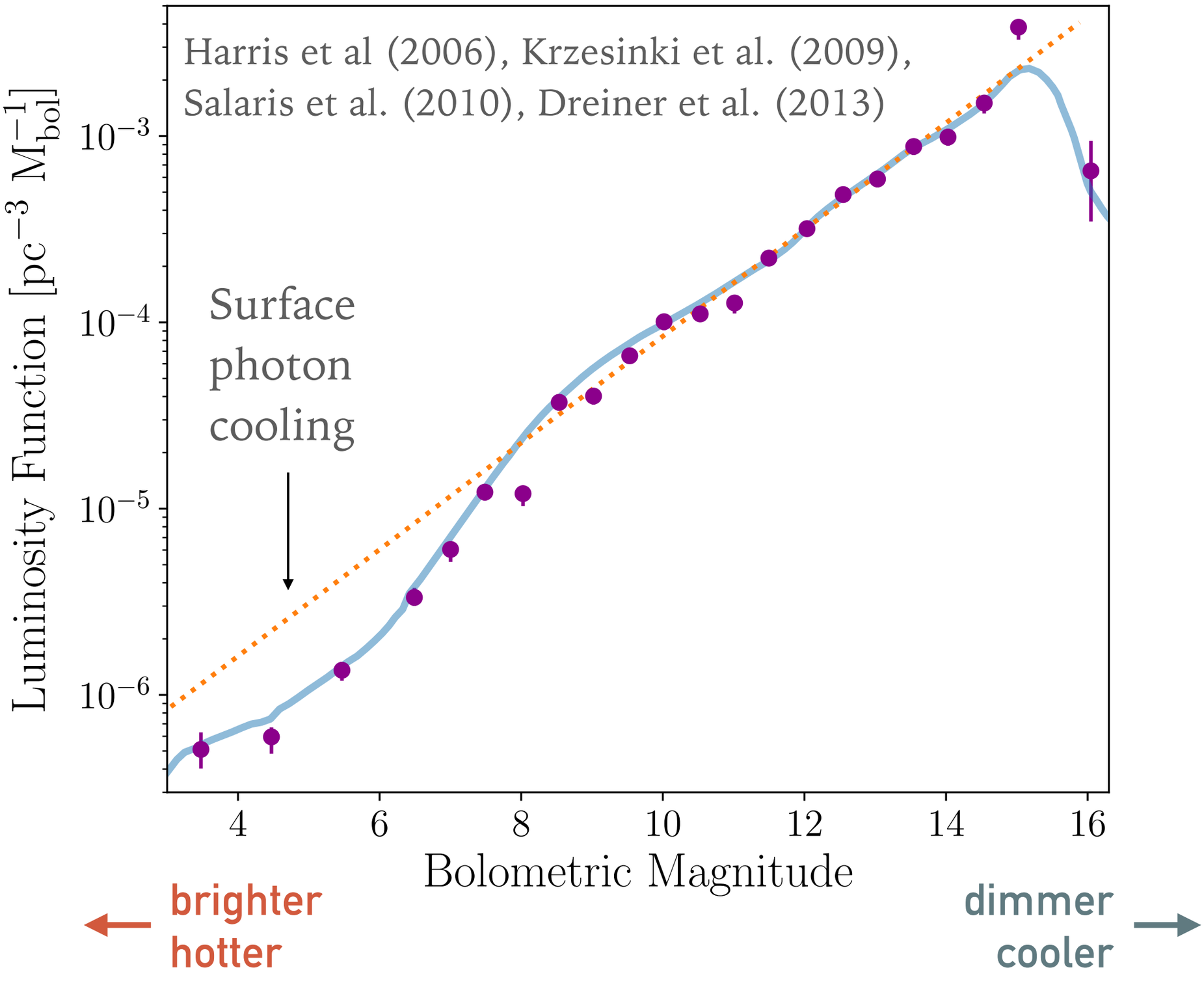
UPSHOT: SPECIFIC DARK SECTOR TARGETS ACCESSIBLE AT A RANGE OF ENERGIES

CLAIM: STARS ARE AMAZING AT TESTING SUB-KEV DARK SECTORS

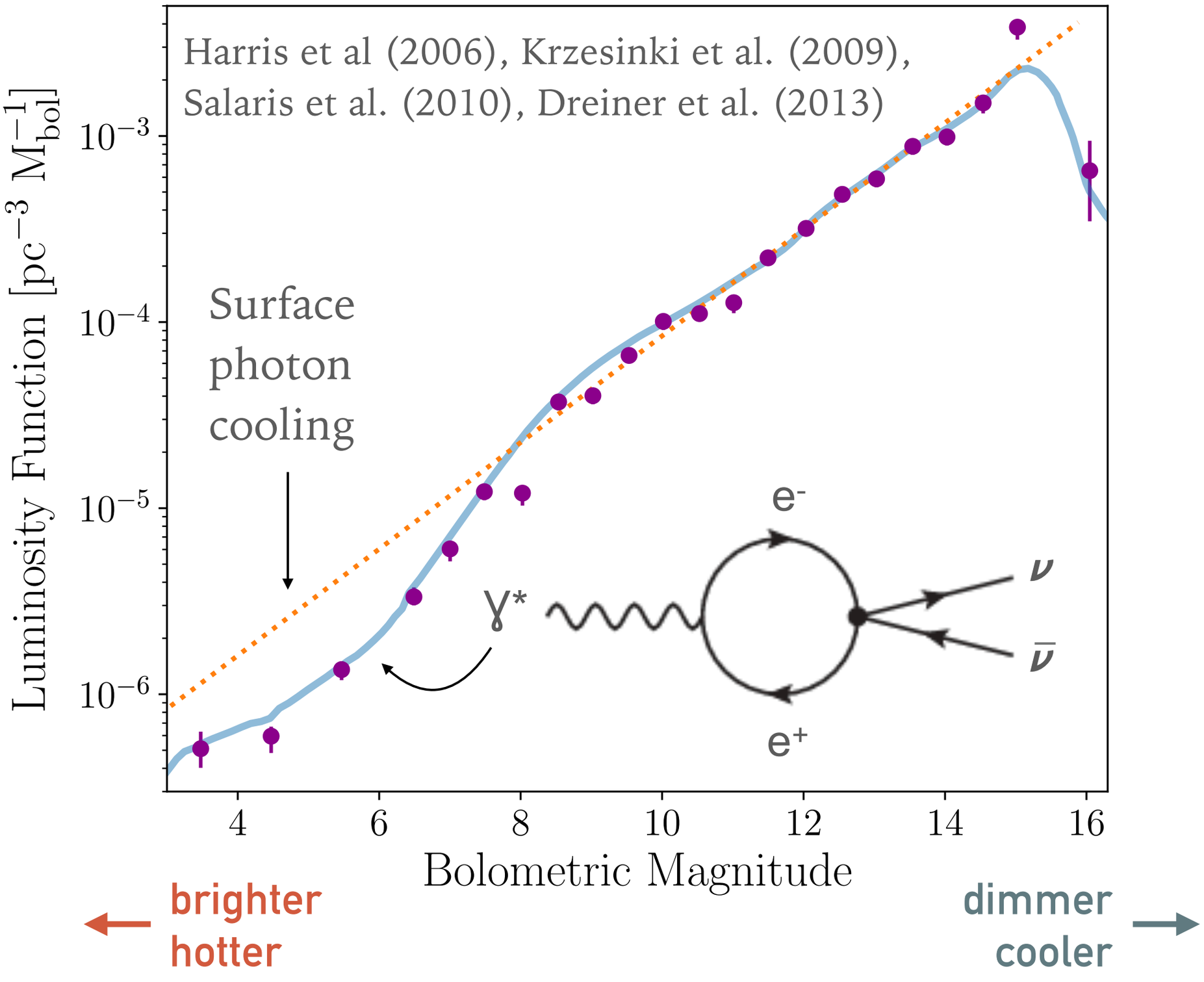
WHITE DWARF COOLING AND POPULATION



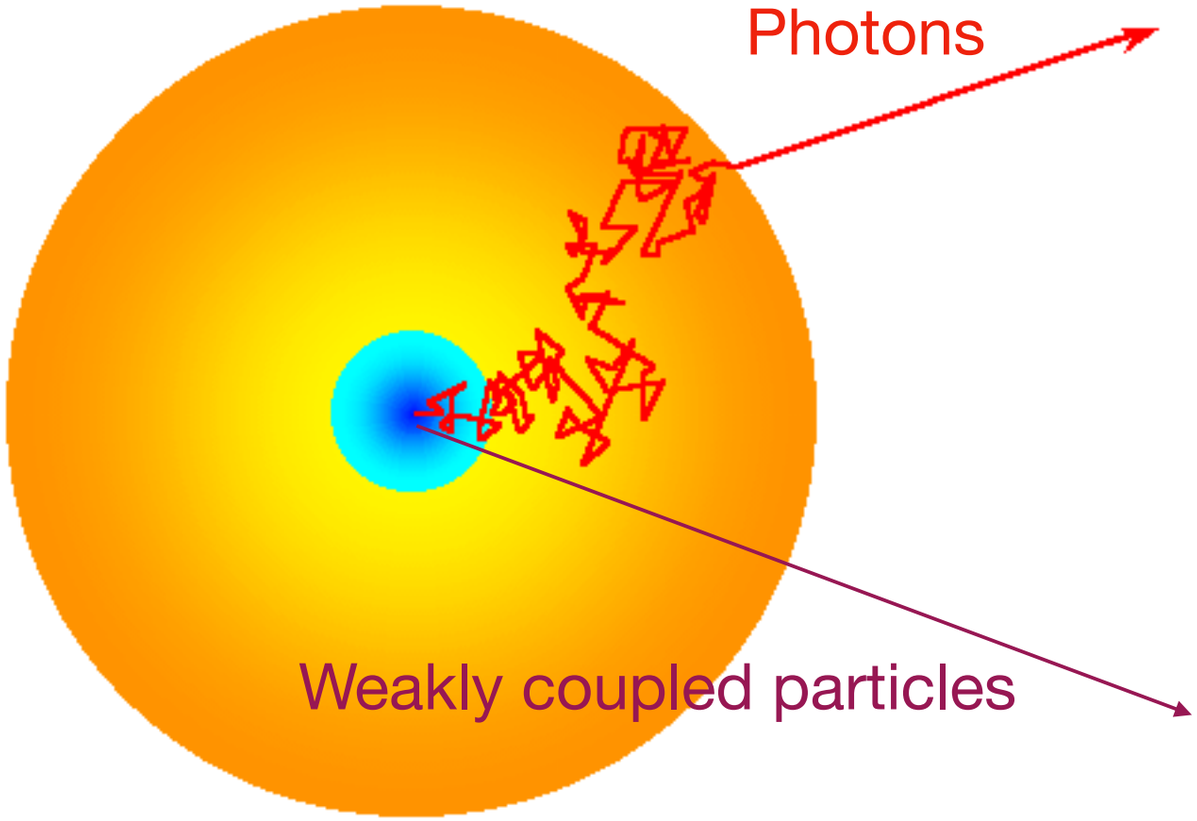
WHITE DWARF COOLING AND POPULATION

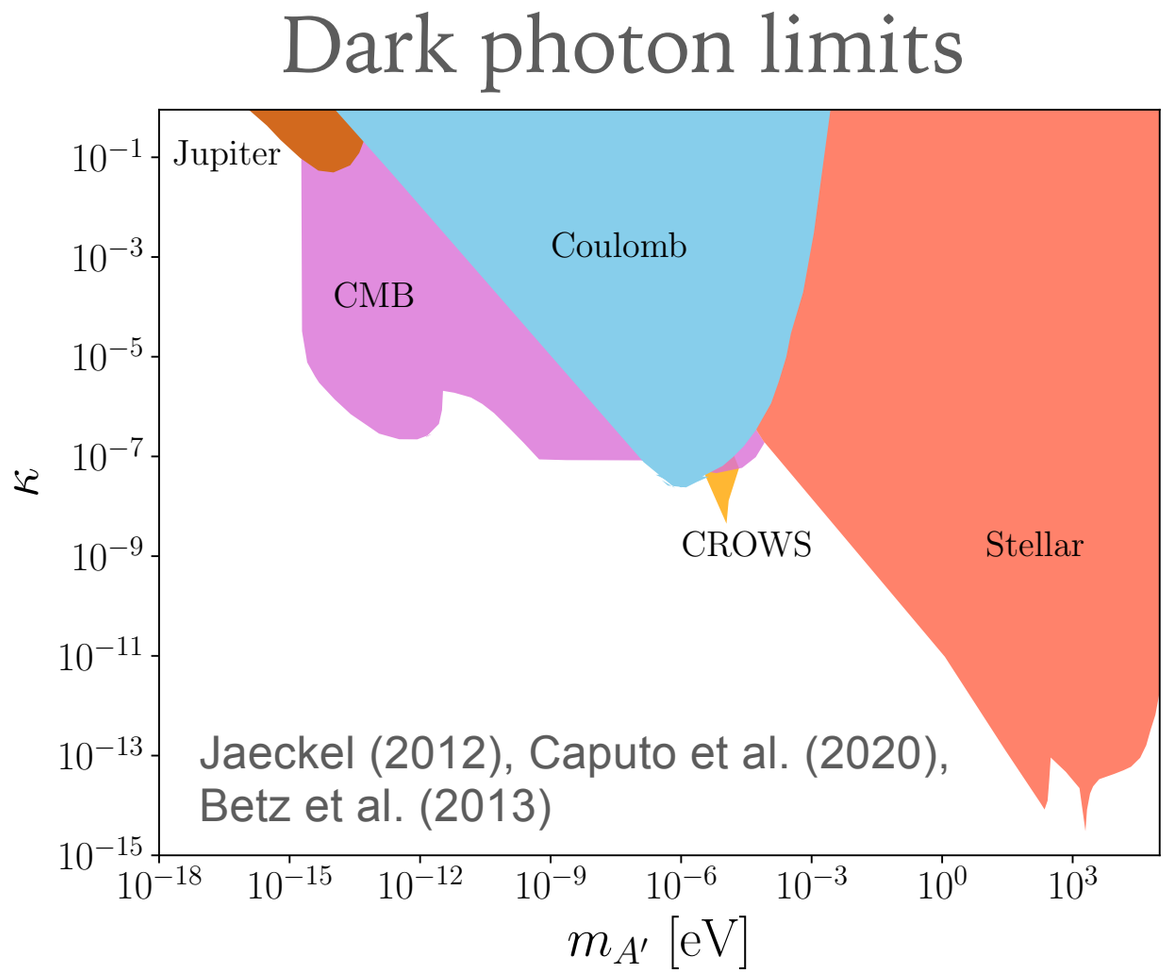


WHITE DWARF COOLING AND POPULATION



STELLAR ENERGY LOSS AND DARK SECTORS



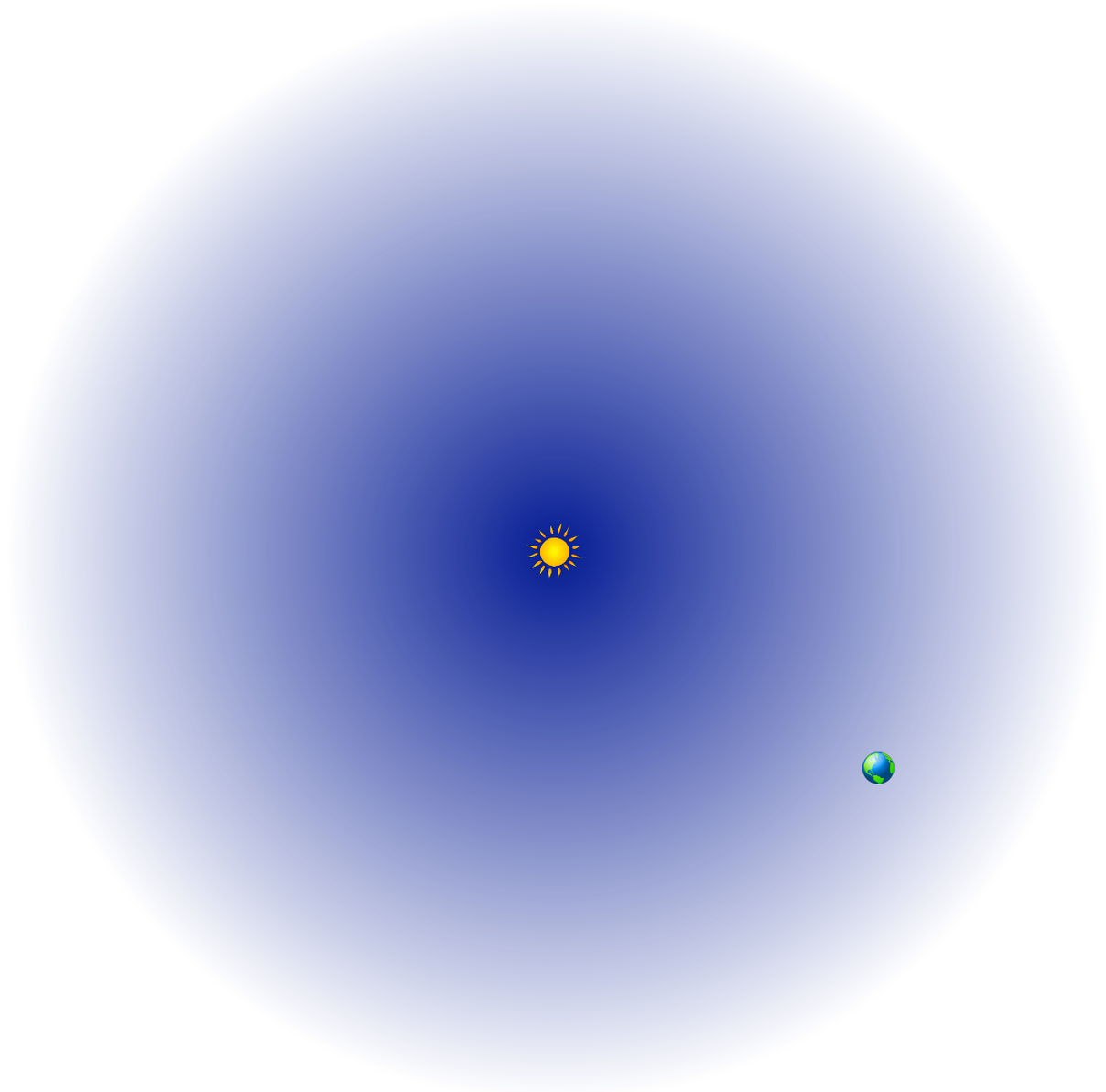


Huge volume and stellar lifetime to compensate for rareness of any kinematically allowed process!

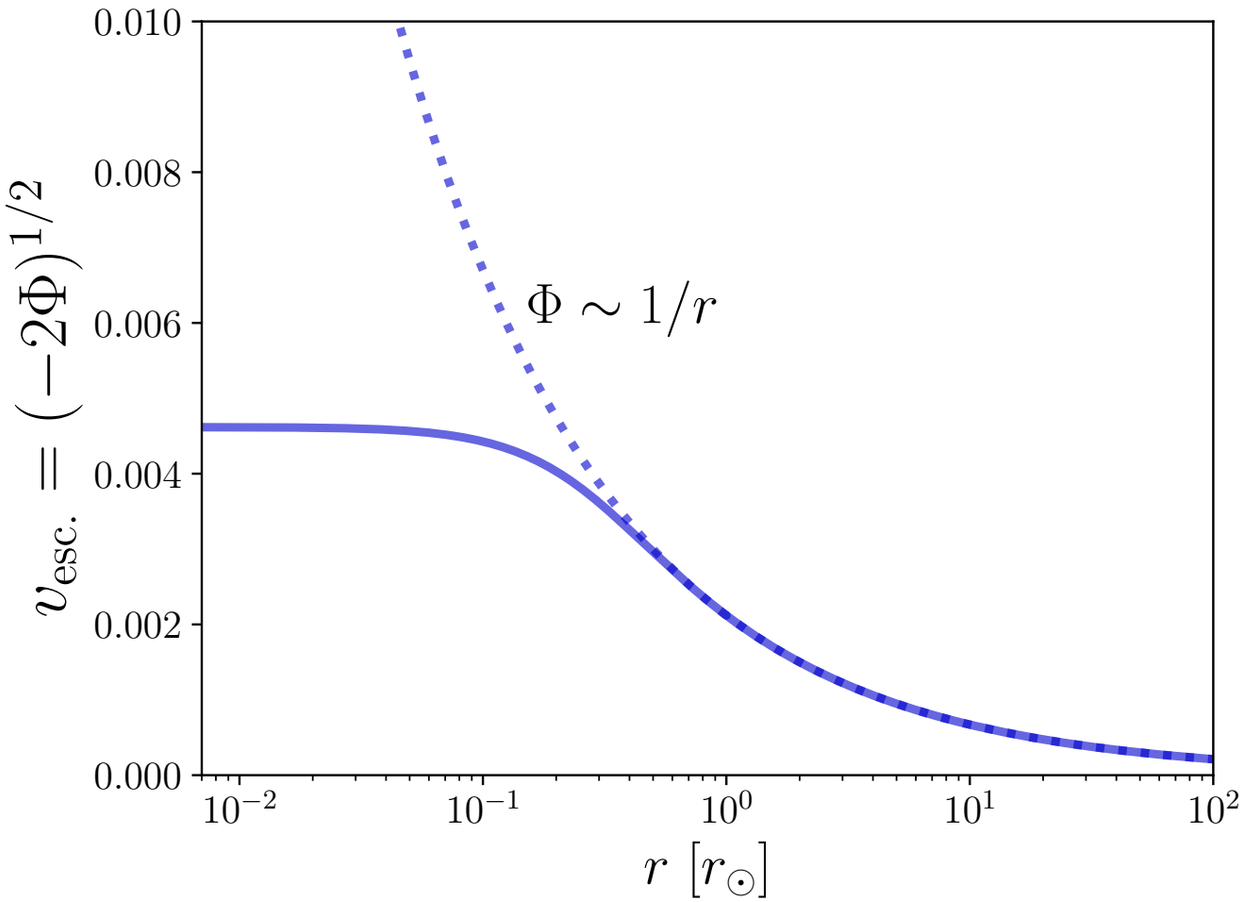
NEW IDEA: WHAT ABOUT SMALL FRACTION OF BOUND PARTICLES?

Van Tilburg (2021)

A SOLAR BASIN OF MCP DUE TO GRAVITY



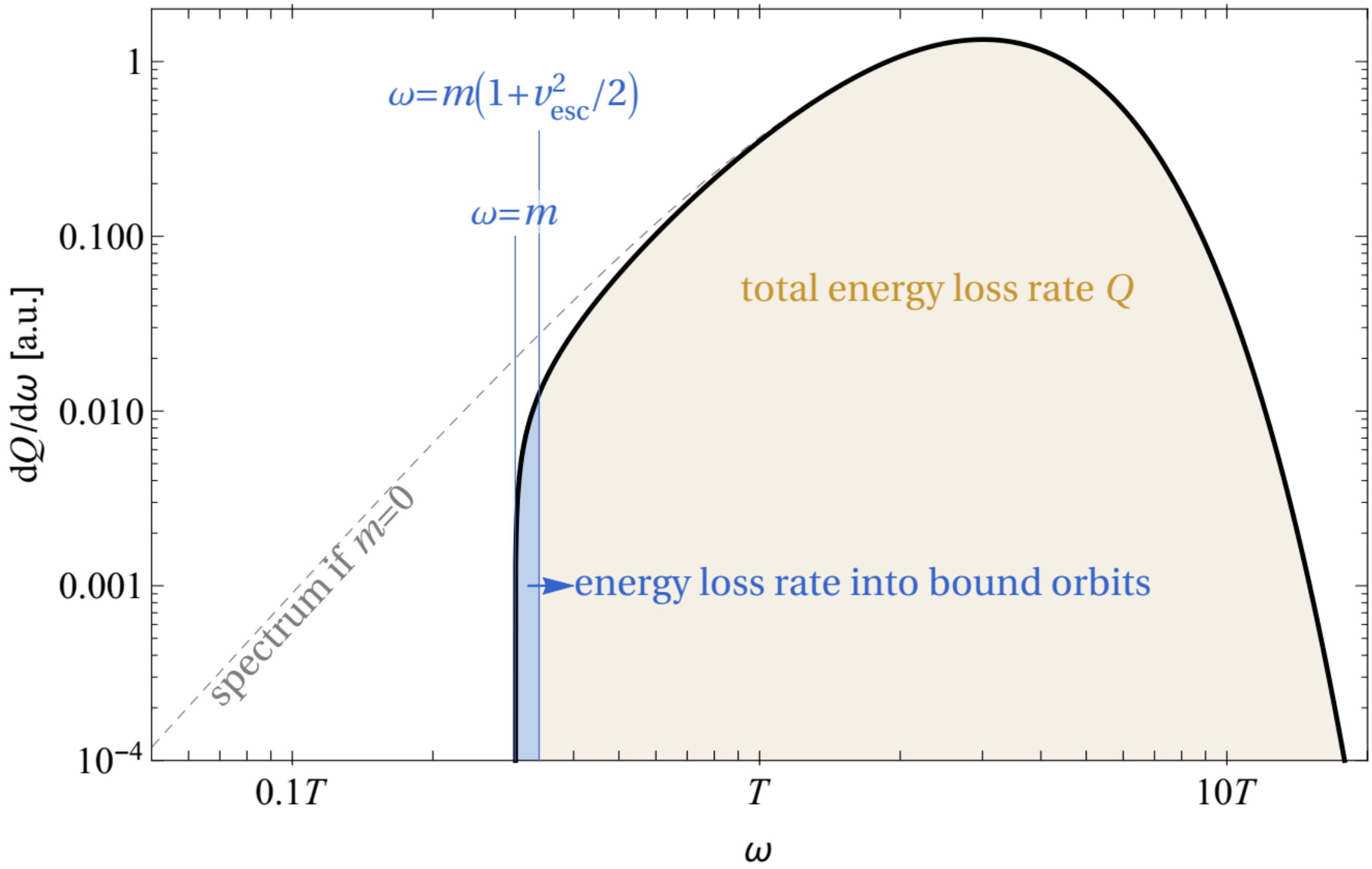
(not to scale)



- MCP produced going slower than ~0.005c will be gravitationally bound, accumulate over time

  Van Tilburg (2021)

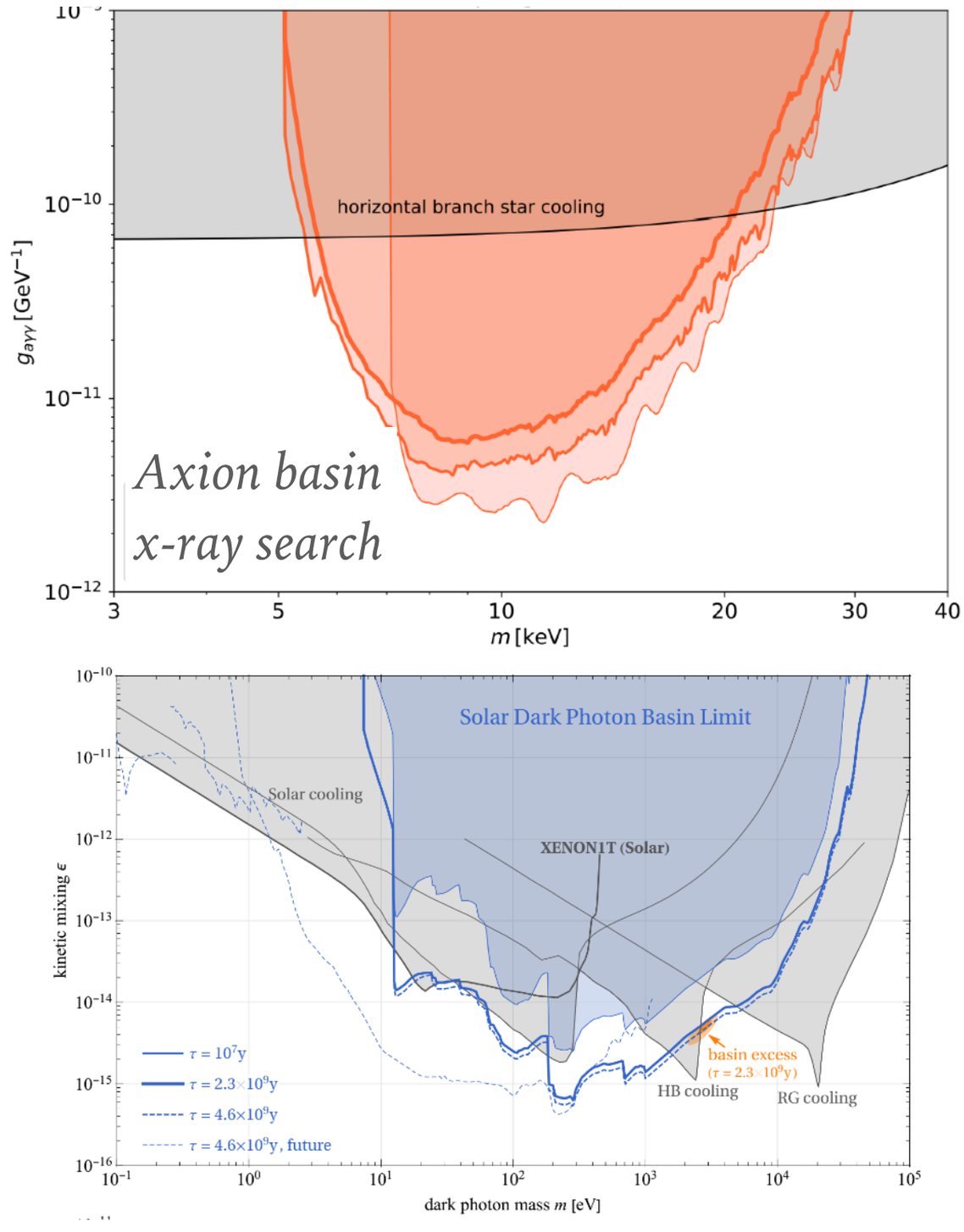
PHASE SPACE DENSITY FOR BOUND ORBITS



Van Tilburg (2021)

RAPID PROGRESS ON SOLAR BASINS

- Production of axion basin, axions can be absorbed in terrestrial direct detection experiments or can decay to X-rays (Van Tilburg 2021, DeRocco et al. 2022)
- Dark photons in basin can also be absorbed in terrestrial experiments (Lasenby & Van Tilburg 2021)
- Millicharged particles (focus of rest of talk, **KS** & Berlin 2022)



A HELIOSCOPE FOR GRAVITATIONALLY BOUND MILLICHARGED PARTICLES

Berlin & **KS** (PRD 2022)

ULTRALIGHT, ABELIAN KINETIC MIXING PORTAL

$$\mathscr{L} \supset \frac{\kappa}{2} F'_{\mu\nu} F^{\mu\nu} + \frac{1}{2} m^2_{A'} A'_\mu A'^{\mu} + g_\chi \bar{\chi} \gamma^\mu \chi A'_\mu$$

Kinetic mixing can come from loops of heavy particles, string theory compactifications

(small) Stueckelberg mass

Dirac fermion charged under U(1)'

ULTRALIGHT, ABELIAN KINETIC MIXING PORTAL

$$\mathscr{L} \supset \frac{\kappa}{2} F'_{\mu\nu} F^{\mu\nu} + \frac{1}{2} m^2_{A'} A'_\mu A'^{\mu} + g_\chi \bar{\chi} \gamma^\mu \chi A'_\mu$$

Kinetic mixing can come from loops of heavy particles, string theory compactifications

(small) Stueckelberg mass

Dirac fermion charged under U(1)'

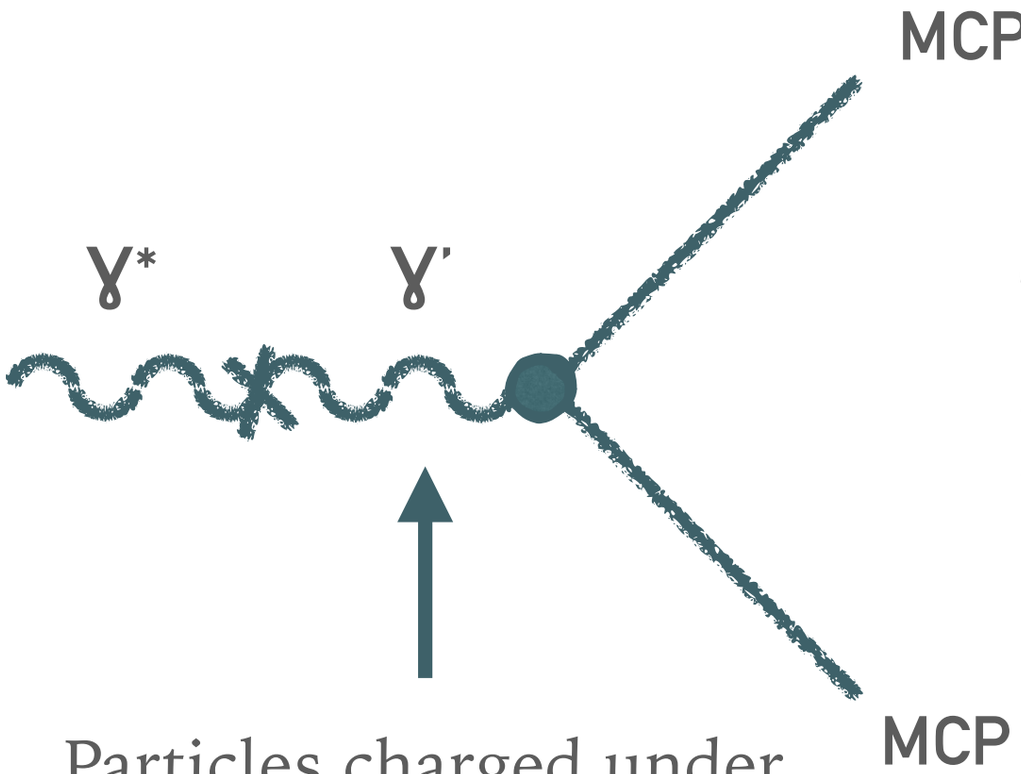
In a medium, rotating away mixing term

$$\mathscr{L} \supset J^\mu_{EM}\left(eA_\mu\right) + g_\chi \bar{\chi} \gamma^\mu \chi \left(A'_\mu + \kappa A_\mu\right) + higher\ order\ in\ \frac{m_{A'}}{m_A}$$

Particle charged under dark U(1) appears to be "millicharged" under E&M, $Q = g_\chi \kappa / e$

Depends on kinematics, medium properties

PLASMON PRODUCTION OF PARTICLES CHARGED UNDER HIDDEN U(1)



Particles charged under dark version of E&M with a “dark photon”

This process efficiently makes millicharged particles (MCP) lighter than half the plasma frequency

ESTIMATING THE BOUND DENSITY AT EARTH AT THRESHOLD

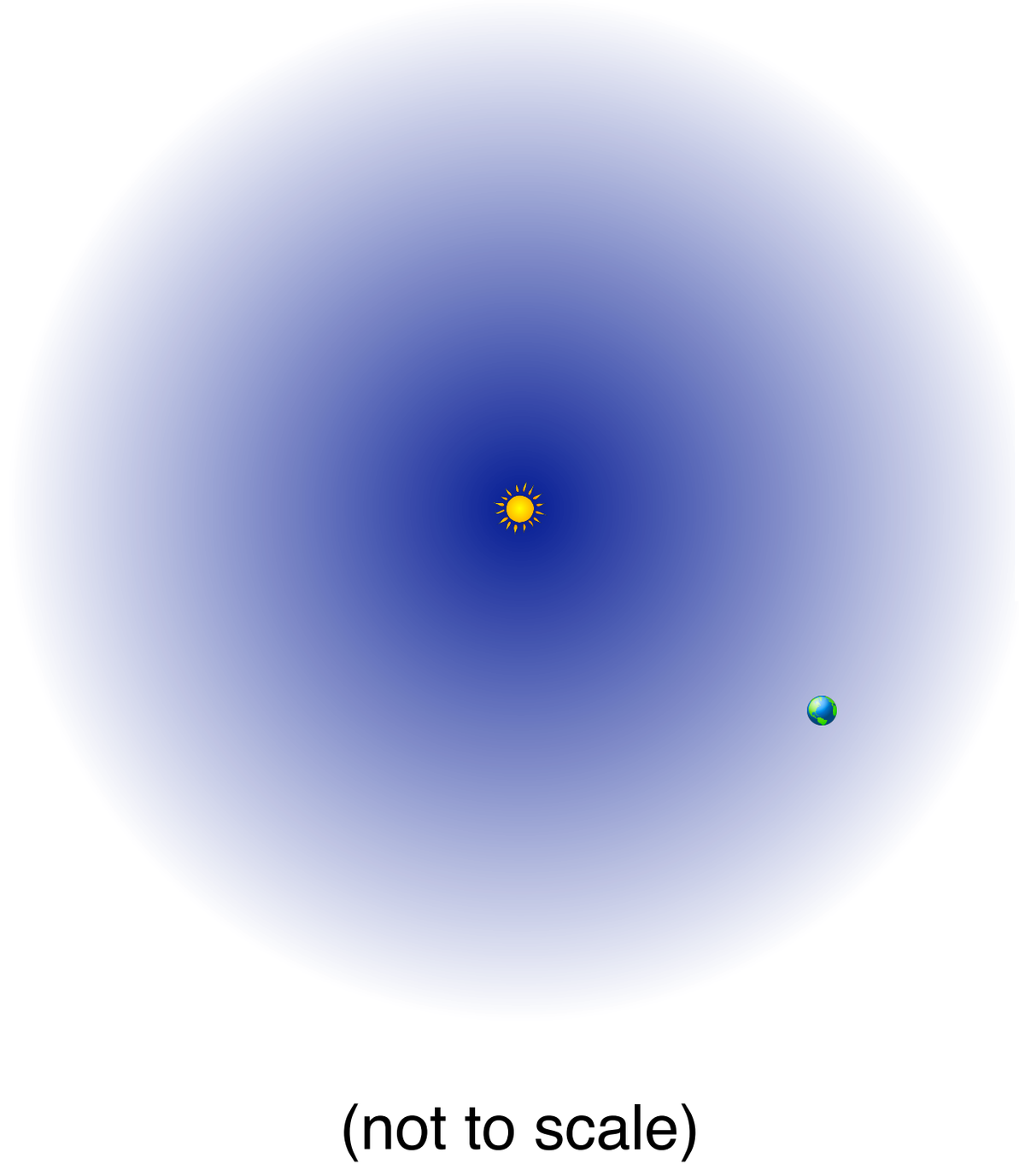
$$n_\oplus \sim \left[\alpha_{\rm em}\, q_{\rm MCP}^2\, \omega_p^4\right] \times \left[\frac{r_\odot^3\, t_\odot}{r_\oplus^3}\right] \times \left[v_{esc.}(r_\odot)\, v_{esc.}(r_\oplus)^2\right] \sim 10^5\,{\rm cm}^{-3}$$

Production rate per Solar volume (vertex counting and dimensional analysis), can have $q \lesssim 10^{-14}$

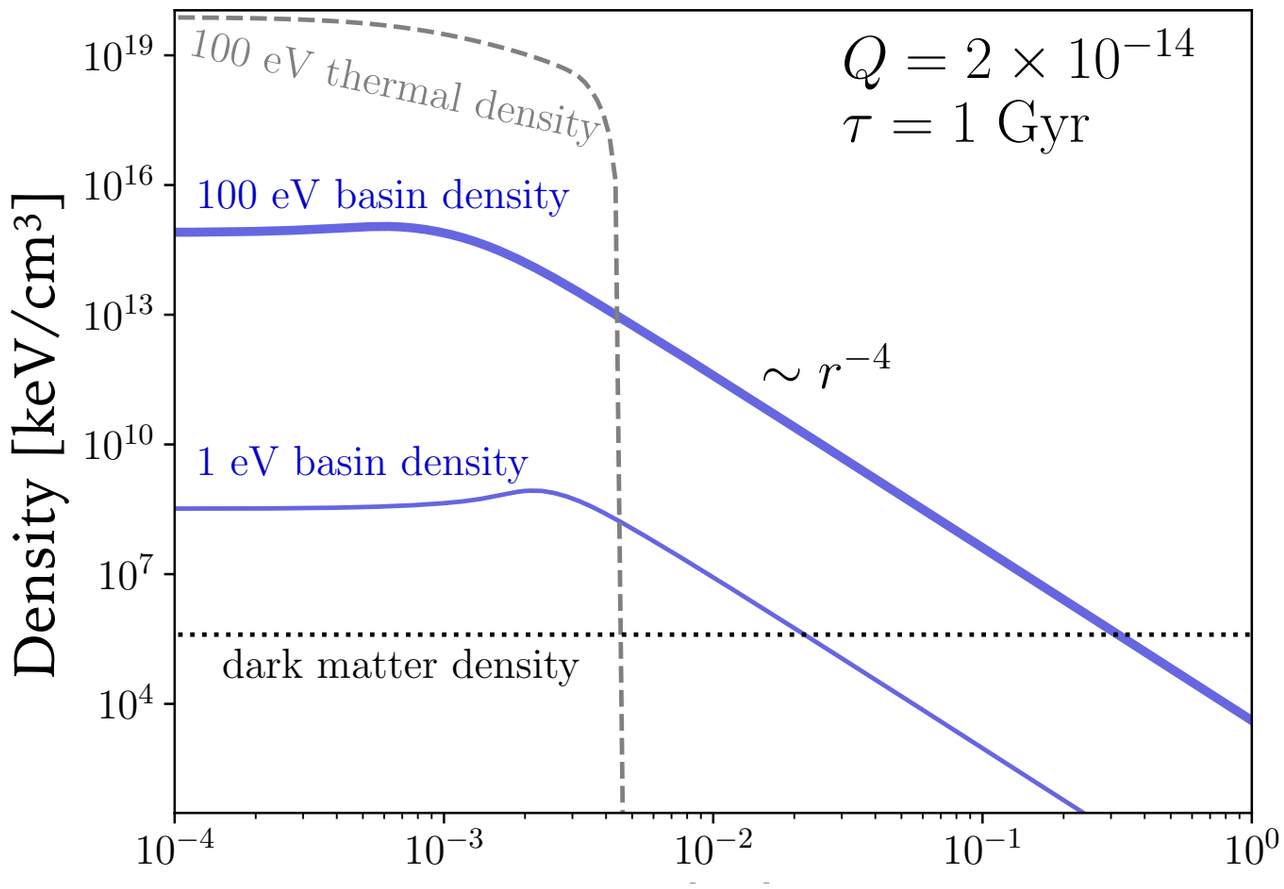
Assuming particles produced over whole Solar volume and lifetime and then spread over volume within 1 au of the Sun

Fraction of particles produced with right speed to be bound, spread in a velocity-space shell at Sun's escape velocity with spread determined by requirement that particles need to climb out of potential and make it to Earth

A SOLAR BASIN OF MCP DUE TO GRAVITY



(not to scale)



- Density falls precipitously but can be non-negligible at Earth

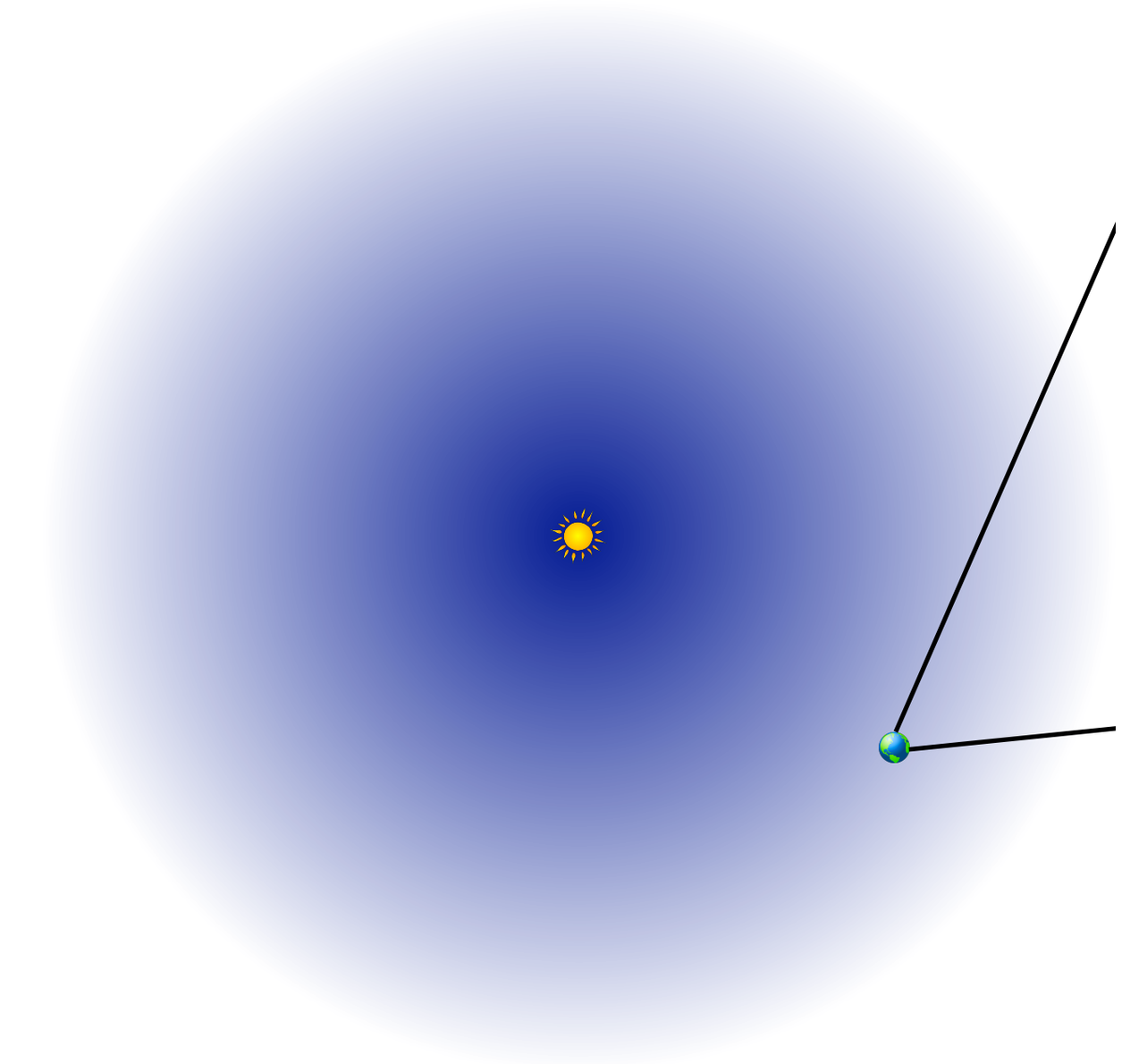
  Berlin & **KS** PRD (2022)

LIST OF CAVEATS/REQUIREMENTS

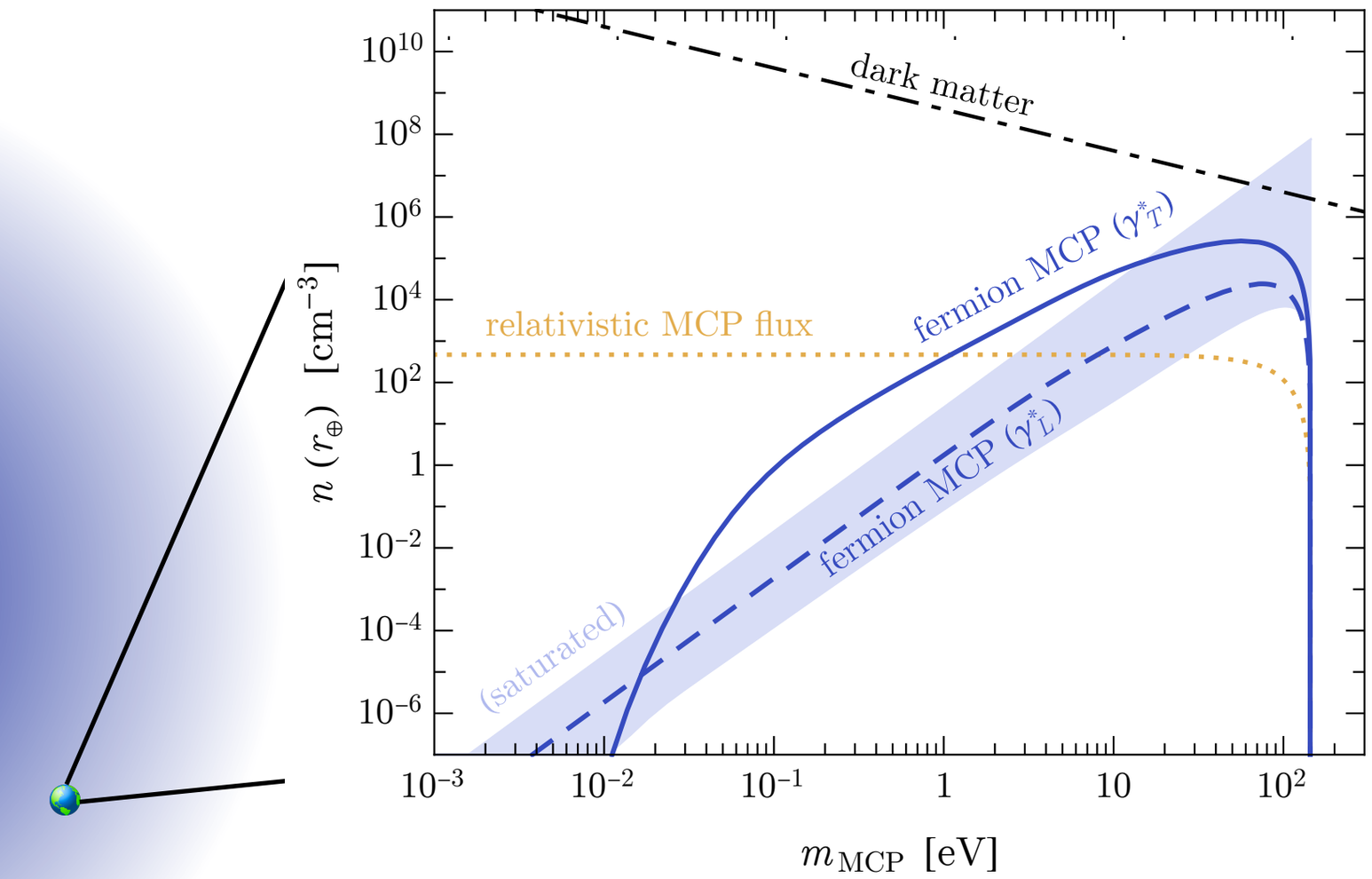
- ☑ MCP can't be trapped by scattering in the Sun or the Sun's ~Gauss magnetic field
- ☑ Annihilation can't efficiently deplete the abundance
- ☑ Scattering can't efficiently transport orbital energy and distort the density profile and phase space
- ☑ MCP needs to be able to reach experiment at sea level in spite of Earth atmospheric voltage

  Claim: these can be satisfied with massive dark photon and small charge in wide portions of parameter space

DENSITY AT EARTH



(not to scale)



- Density from the basin exceeds the unbound flux over a few orders of magnitude in mass

Berlin & **KS** PRD (2022)

WHAT ABOUT THE KINEMATICS?

- Populate one part of 6D phase space inside Sun at a given time when a particle is produced
- At some later time, solve for where in 6D phase space it has to be given conserved quantities (orbital energy, angular momentum vector)
- Integrate over all kinematically accessible Solar volume to get velocity phase space

$$f(r, v_r, v_\theta) = \frac{t}{t_{\text{orb.}}} \int_{r'<r_\odot} dr' \left(\frac{v_{\text{tot.}}(r')}{v_r(r')} \right)^2 \frac{Q_v}{m} \, \Theta(v_r(r')^2)$$

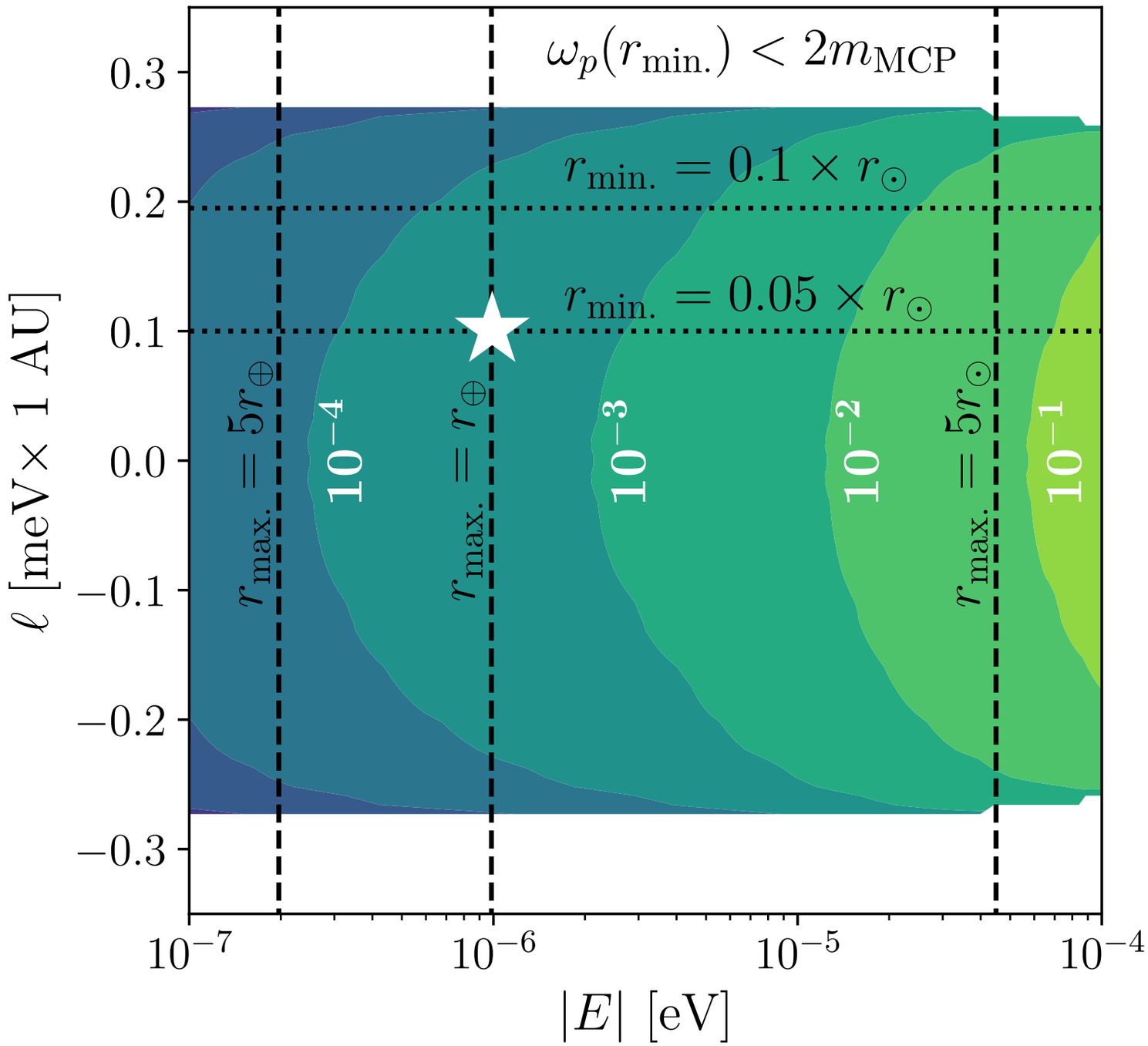
Total and radial velocities at production in the Sun

Production rate per phase space volume per mass

Ensures we don't go past centrifugal barrier in 1D effective potential

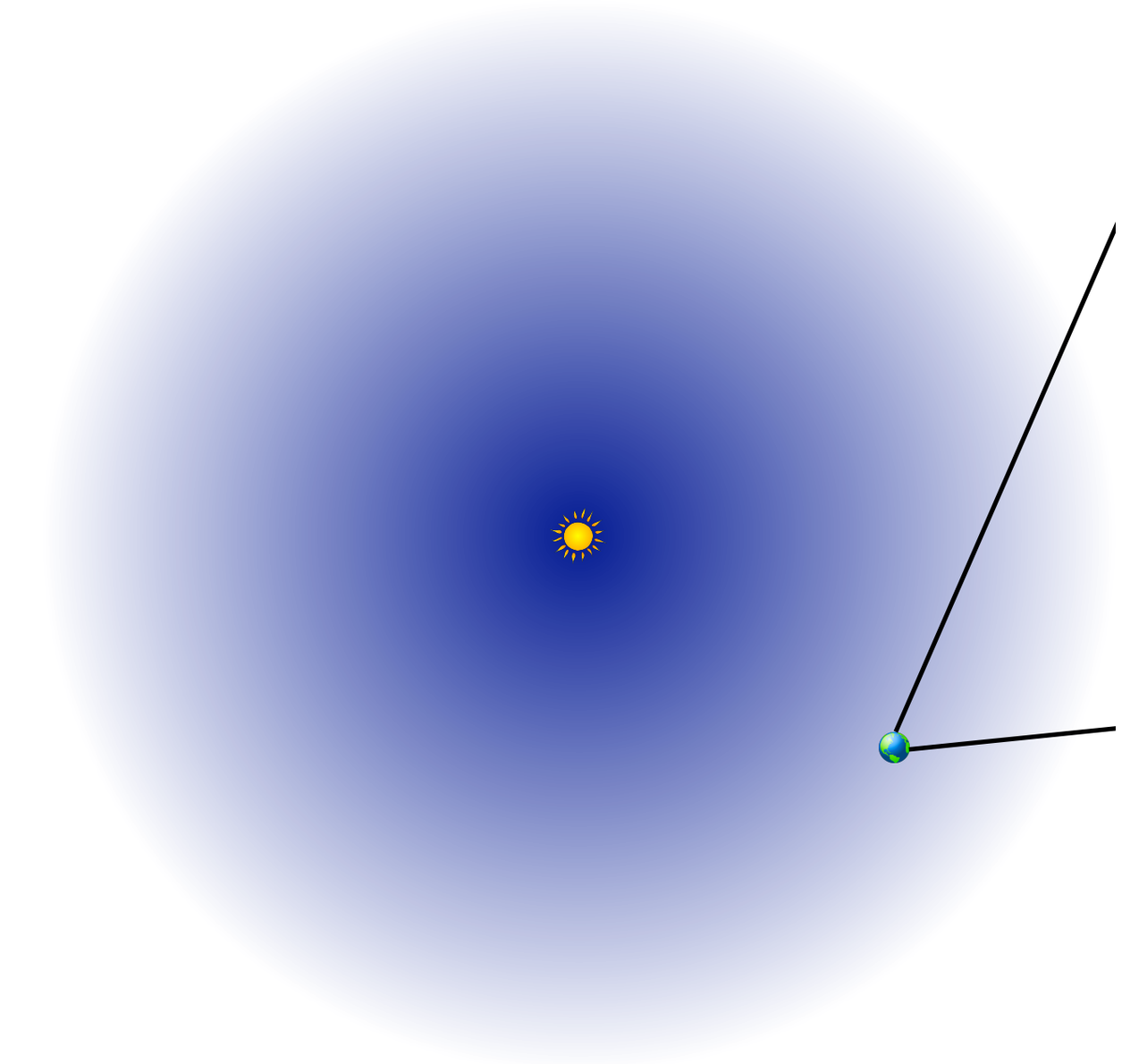
PHASE SPACE AT EARTH FROM PRODUCTION AND ORBITAL MOTION

- Motion of particles coming from Sun is radially collimated (low angular momentum/high orbital eccentricity ~0.9998 at starred point)
- Occupation numbers can be very high, even Pauli blocked in some parts of phase space that saturate
- Gravitational encounters with planets can scramble phase space, “isotropize” orbits on long timescales

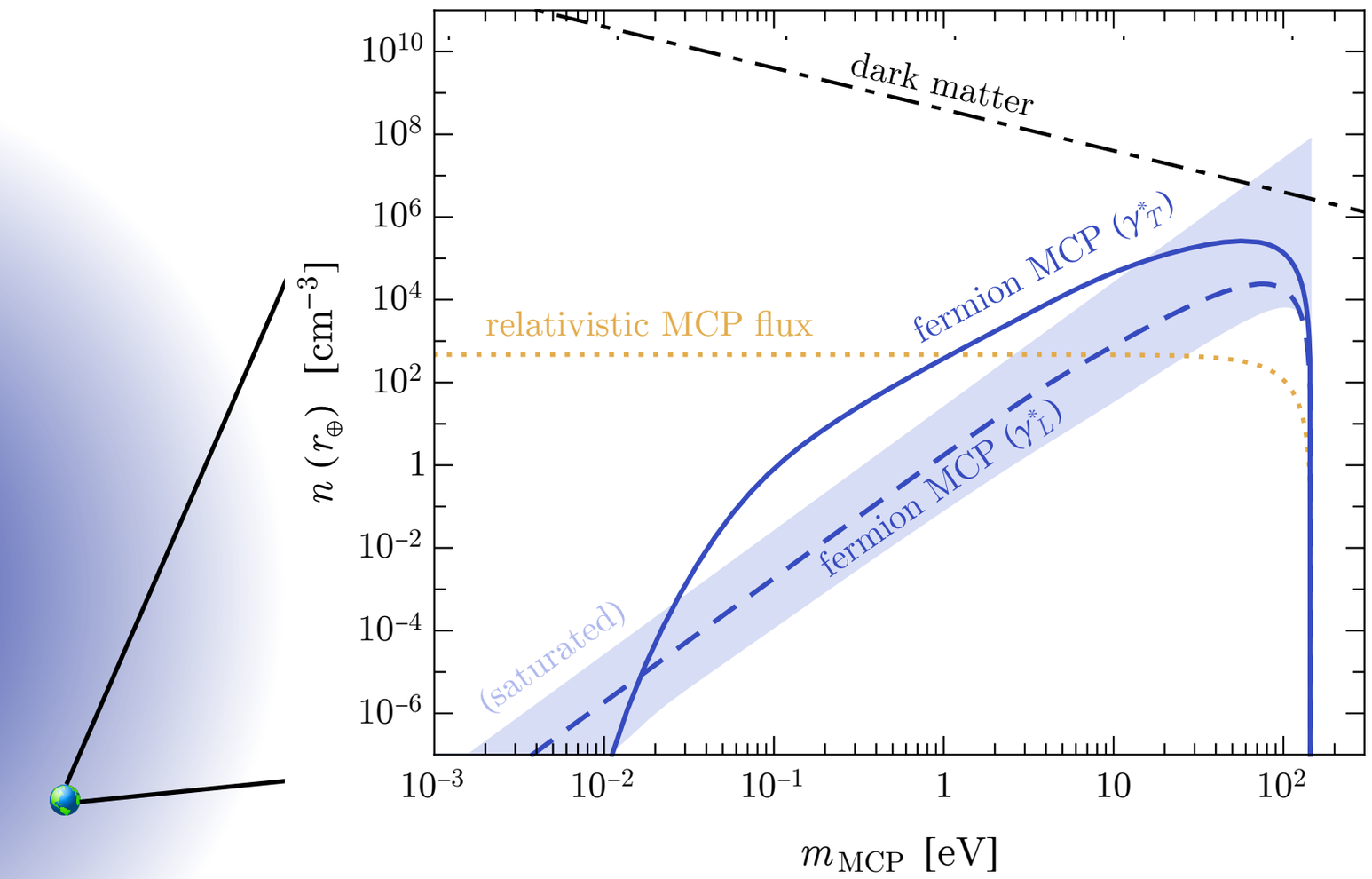


Berlin & **KS** PRD (2022)

DENSITY AT EARTH



(not to scale)



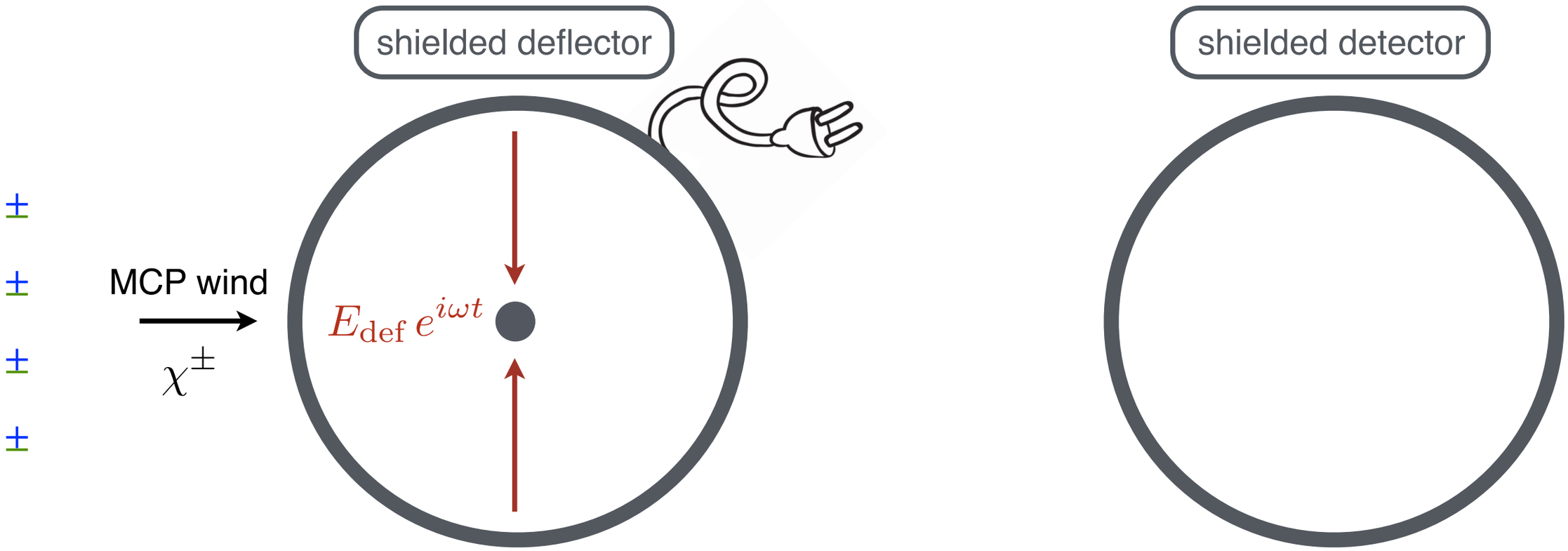
- Density from the basin exceeds the unbound flux over a few orders of magnitude in mass

Berlin & **KS** PRD (2022)

TRADITIONAL METHODS OF DETECTION WILL BE CHALLENGING

- Particles with conserved charge can only scatter elastically
- Unlike previous stellar basins (axions and dark photons considered by van Tilburg, Lasenby) particle absorption in terrestrial experiment is not a viable detection strategy
- Typical particle speed in basin is 10^{-4} c, so sub-keV particles will have at most μeV kinetic energy, not enough to be above experimental energy threshold
- Need to exploit collective effects that are not penalized for low particle speed in order to observe something

DEFLECTION OVERVIEW (BERLIN ET AL. 2020)

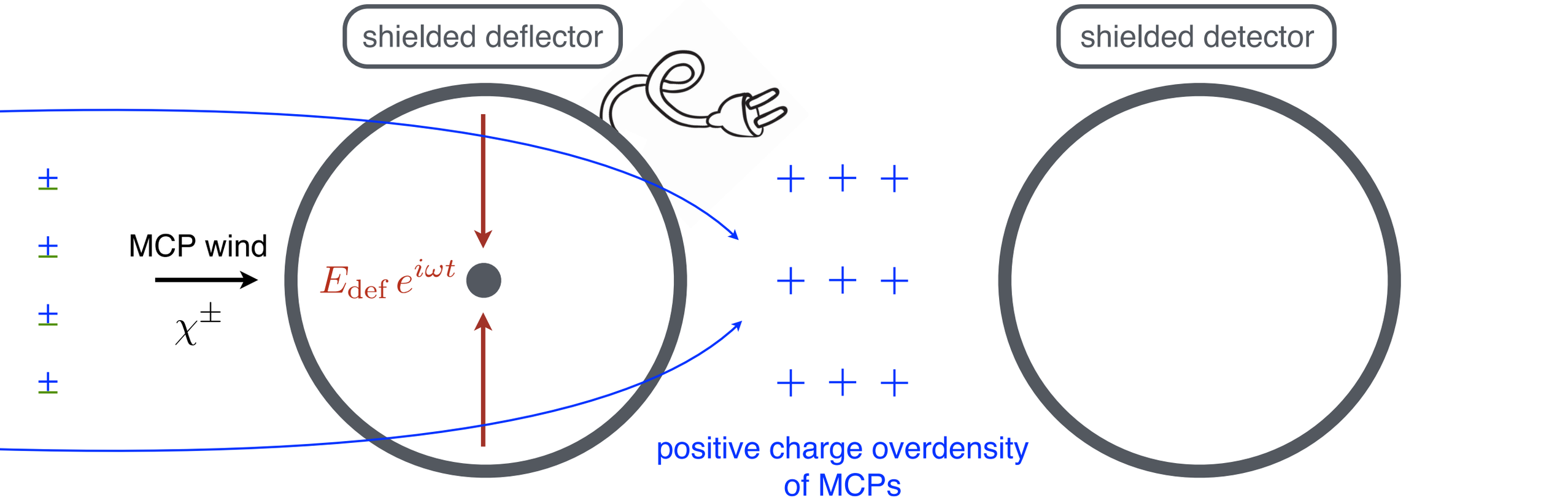


wind-blowing

(similar to ~~"light-shining-through-wall"~~ experiments)

Slide credit: Asher Berlin

DEFLECTION OVERVIEW (BERLIN ET AL. 2020)

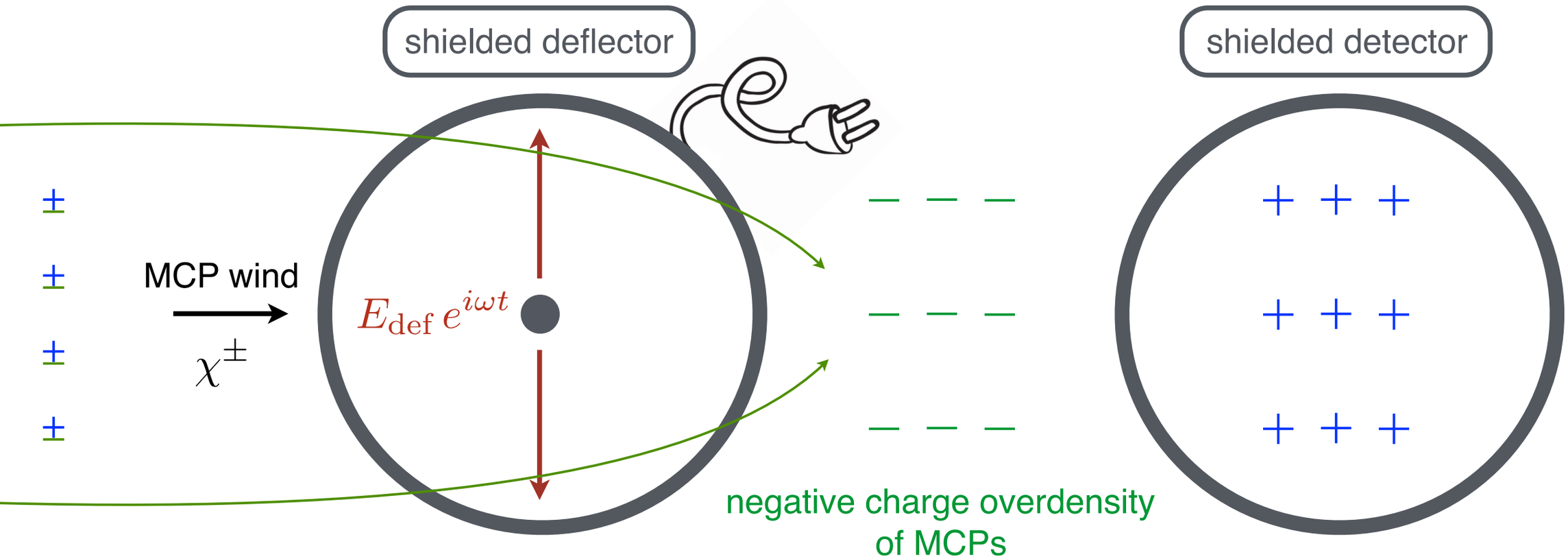


wind-blowing

(similar to ~~"light-shining-through-wall"~~ experiments)

Slide credit: Asher Berlin

DEFLECTION OVERVIEW (BERLIN ET AL. 2020)

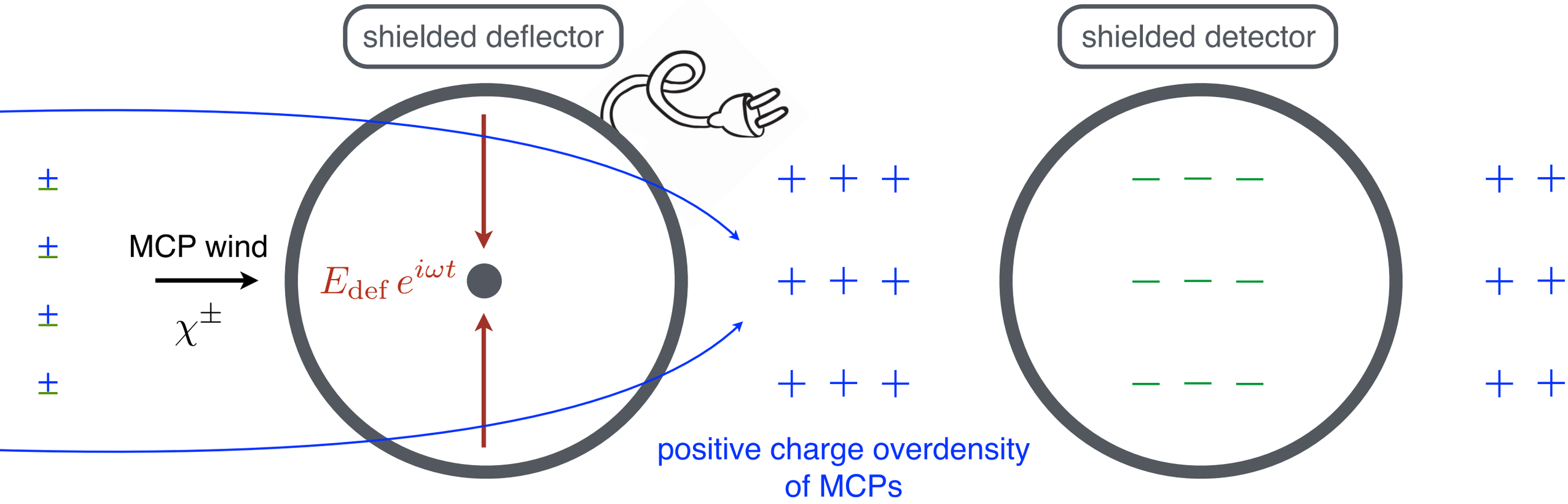


wind-blowing

(similar to ~~"light-shining-through-wall"~~ experiments)

Slide credit: Asher Berlin

DEFLECTION OVERVIEW (BERLIN ET AL. 2020)

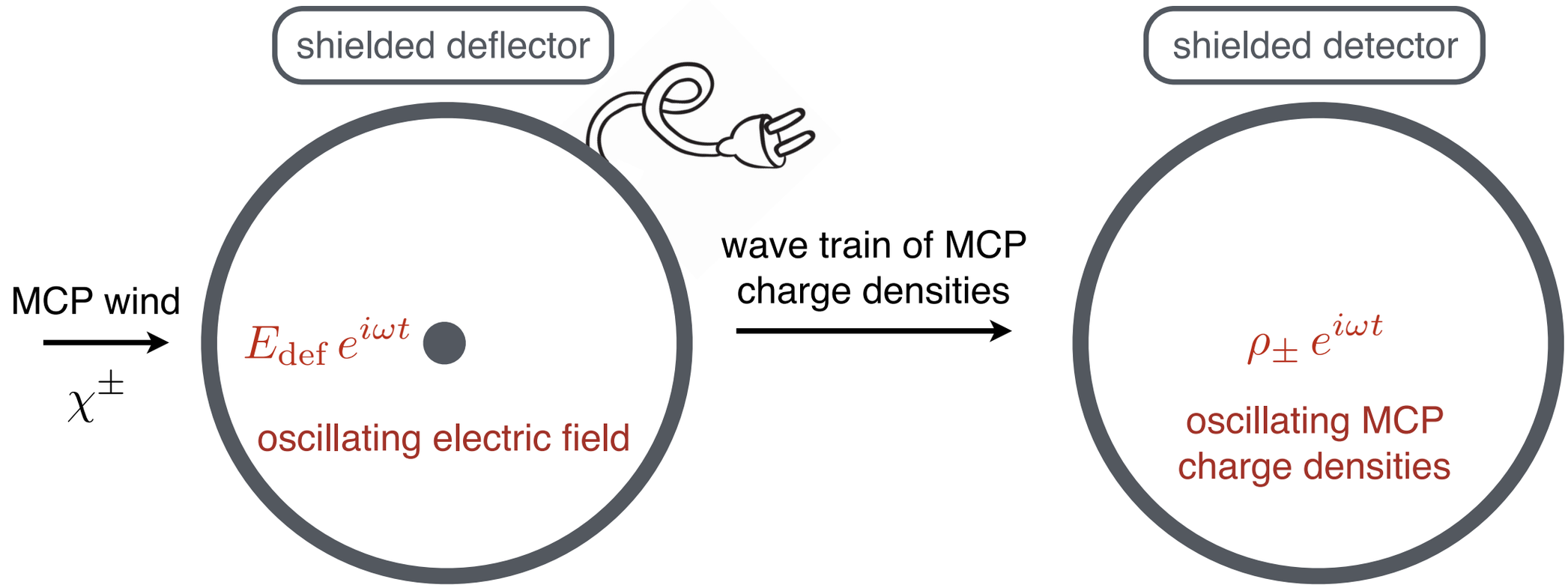


wind-blowing

(similar to ~~"light-shining-through-wall"~~ experiments)

Slide credit: Asher Berlin

DEFLECTION OVERVIEW (BERLIN ET AL. 2020)

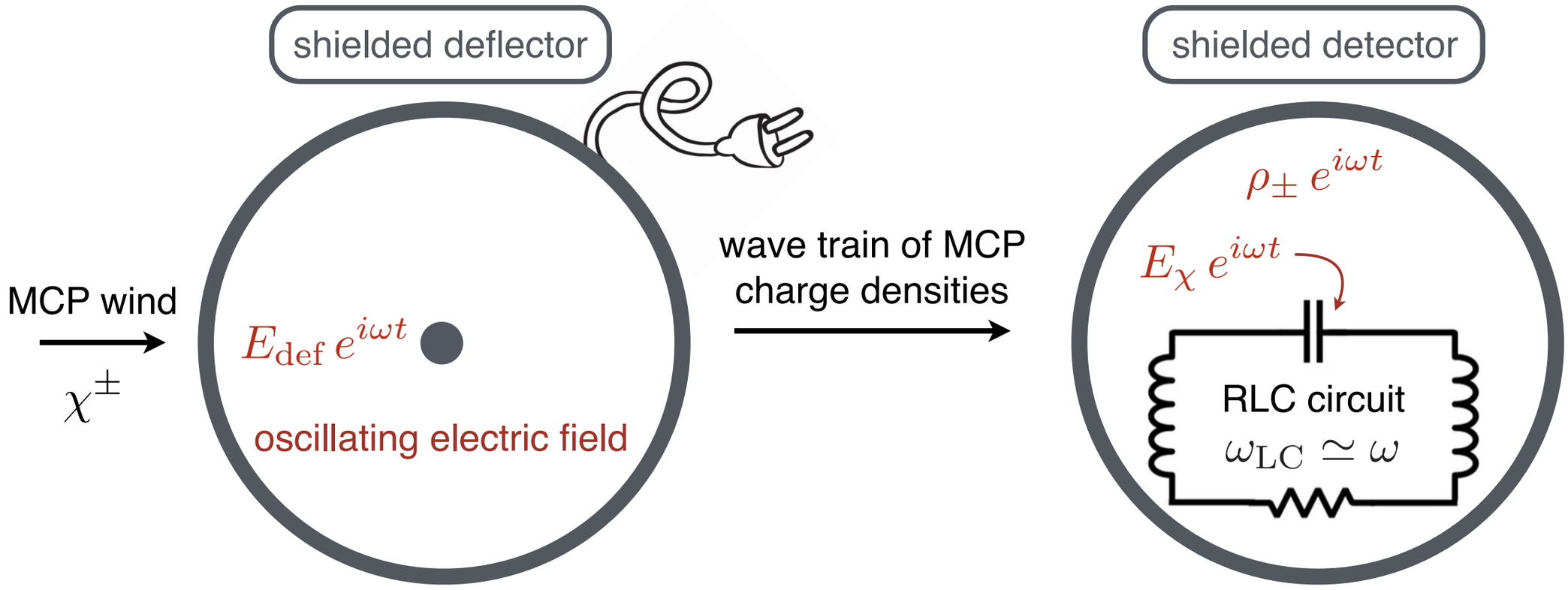


wind-blowing

(similar to ~~"light-shining-through-wall"~~ experiments)

Slide credit: Asher Berlin

DEFLECTION OVERVIEW (BERLIN ET AL. 2020)



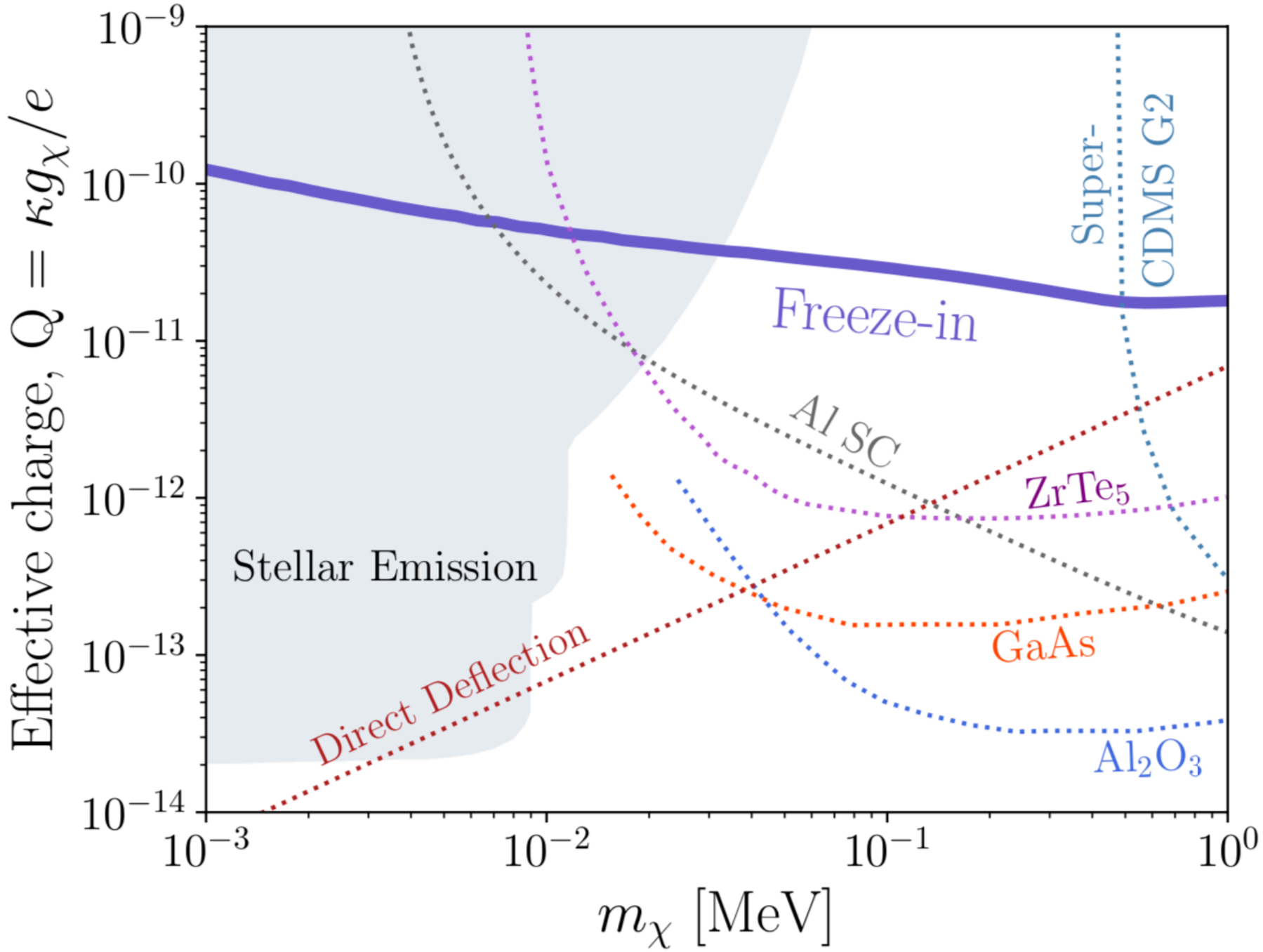
wind-blowing

(similar to ~~"light-shining-through-wall"~~ experiments)

inducing and detecting collective disturbances $\Longrightarrow$ no kinematic barrier

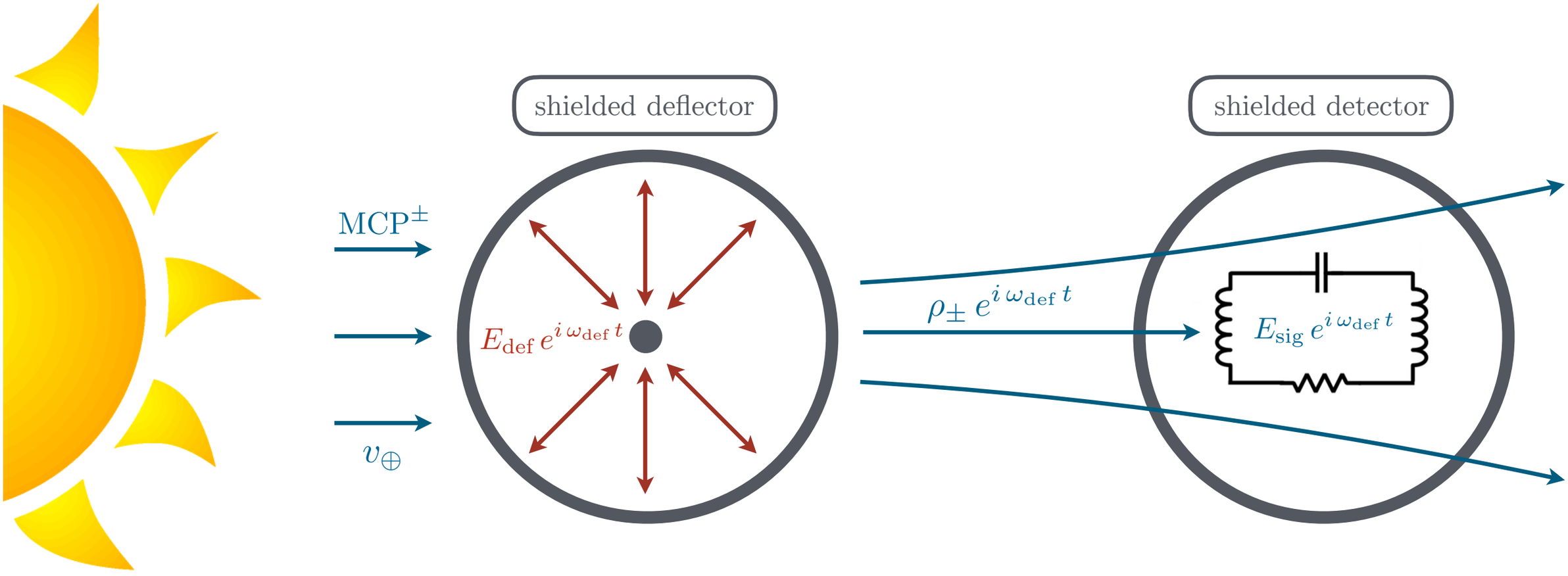
Slide credit: Asher Berlin

DIRECT DEFLECTION SENSITIVITY TO DARK MATTER



Dvorkin, Lin, **KS** (PRD 2019)

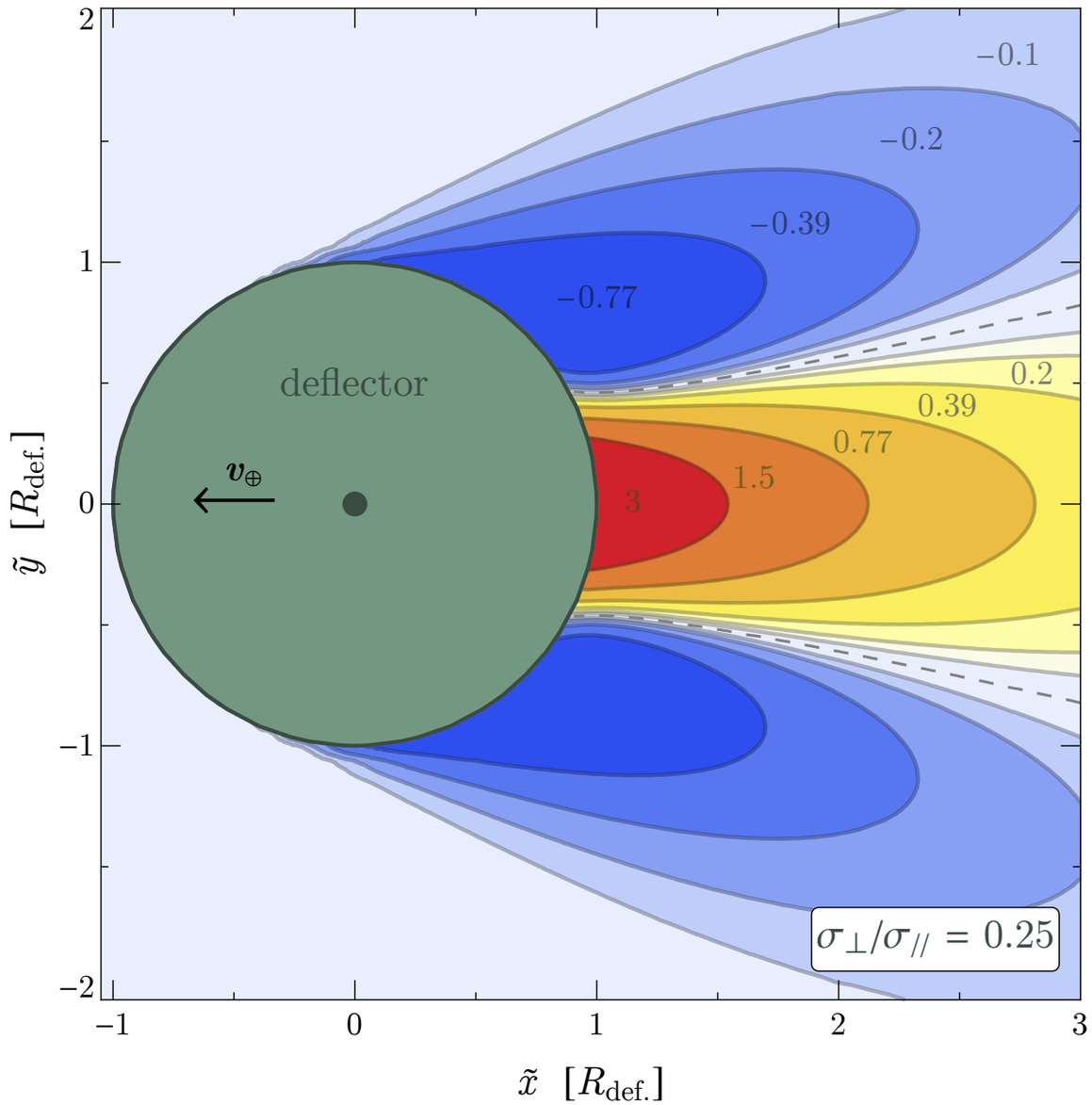
DEFLECTION OF MCPS FROM THE SUN

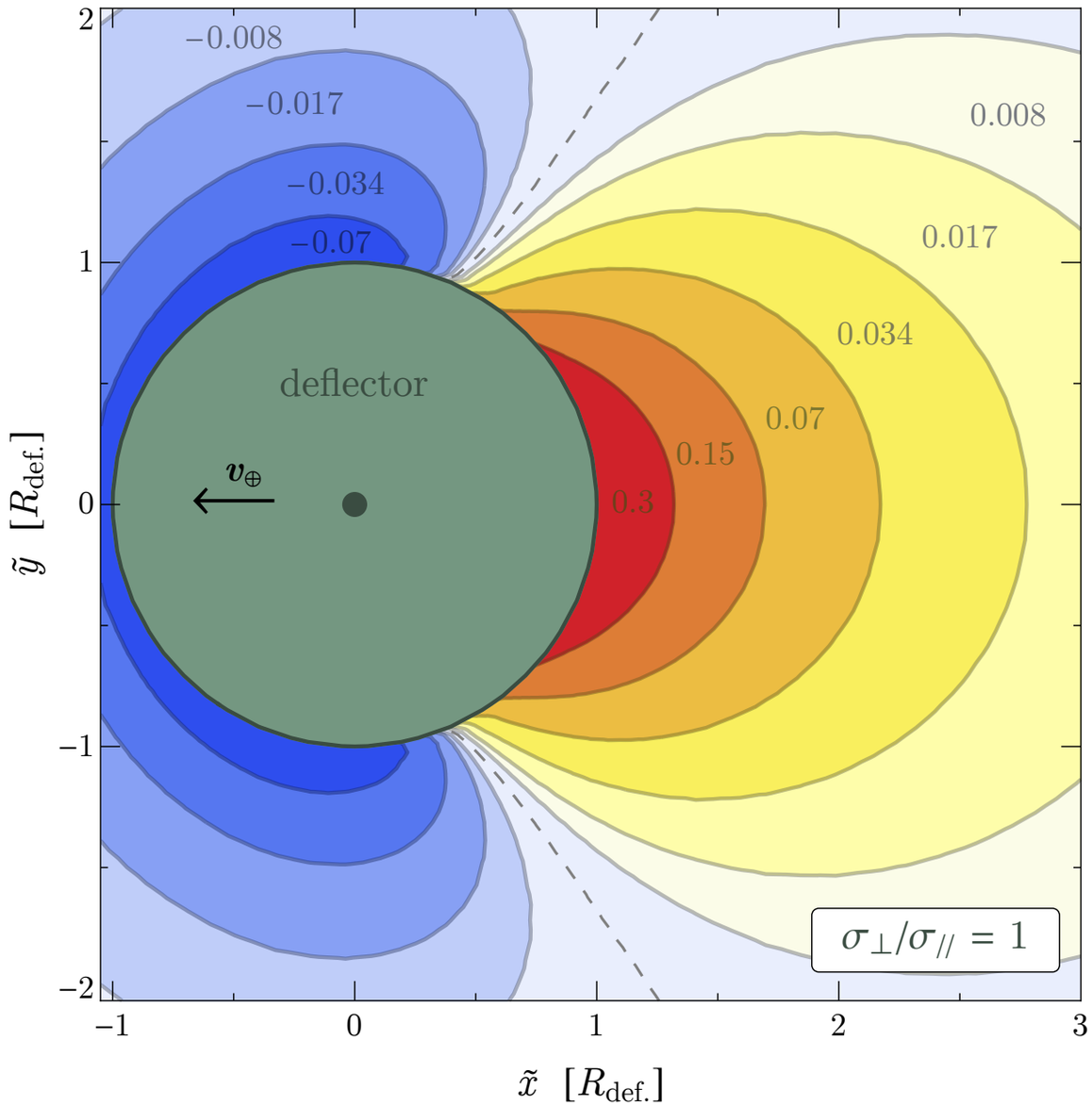


- MCP velocity distribution determines how easy particles are to deflect and size of resulting charge overdensity

  Berlin & **KS** PRD (2022)

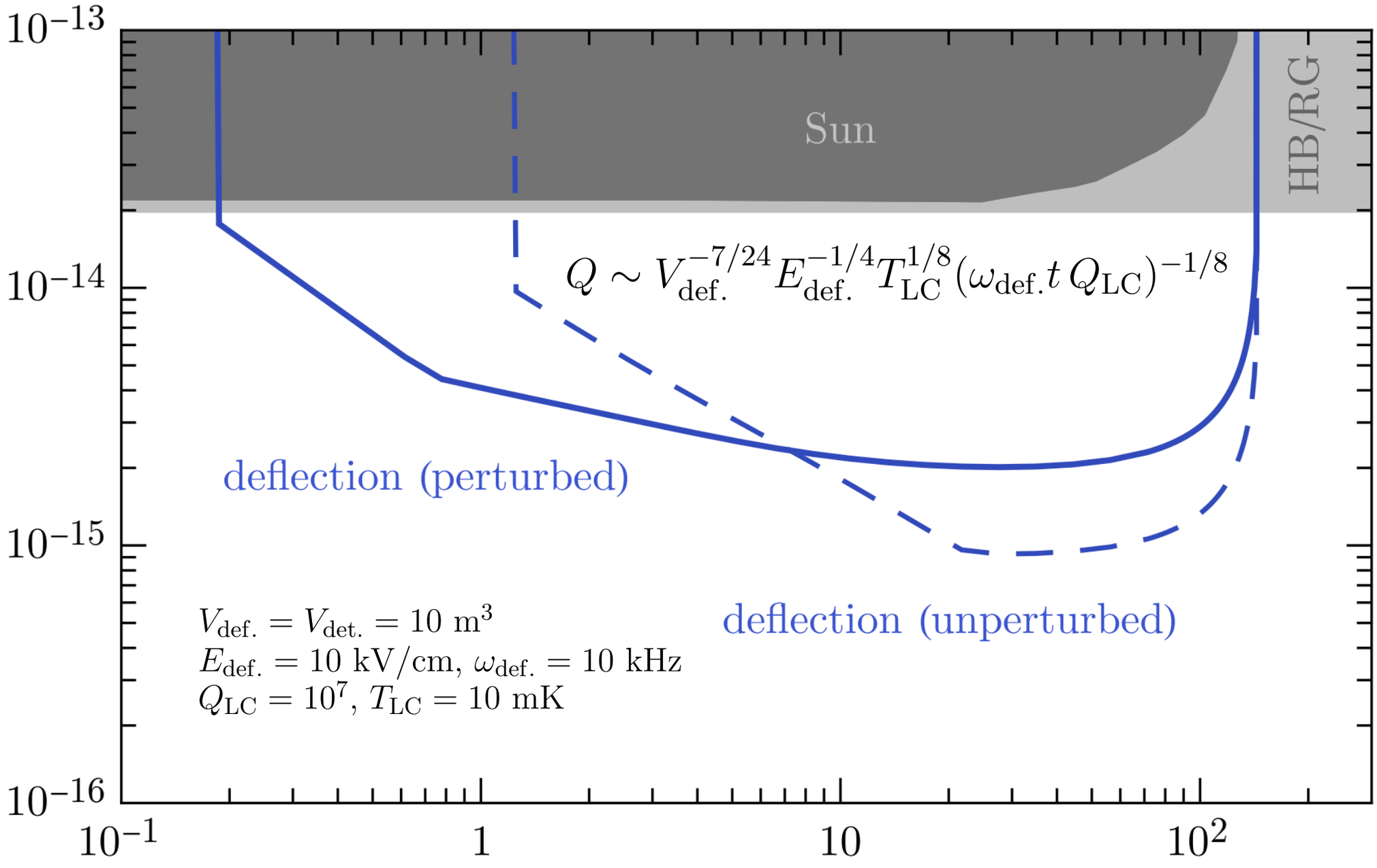
DEFLECTION DEPENDENCE ON PHASE SPACE





- More coherent velocity phase space leads to an enhanced charge density in the wake Berlin & **KS** PRD (2022)

PREDICTED REACH



Davidson et al. (2000)

Berlin & **KS** PRD (2022)

SUMMARY

- In a small part of phase space stars emit a gravitationally bound population of light particles whose density grows with time
- Due to low momentum of emitted particles, terrestrial detection of solar basin requires coherent detection strategy like deflection
- Other phenomenological consequences of gravitationally bound population are still being explored… let’s chat if you have ideas :)