What we may learn about Dark Matter and the Milky Way Halo Profile with Directional Detection

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Stanford / SLAC

w/ Sonia El Hedri and Jay Wacker

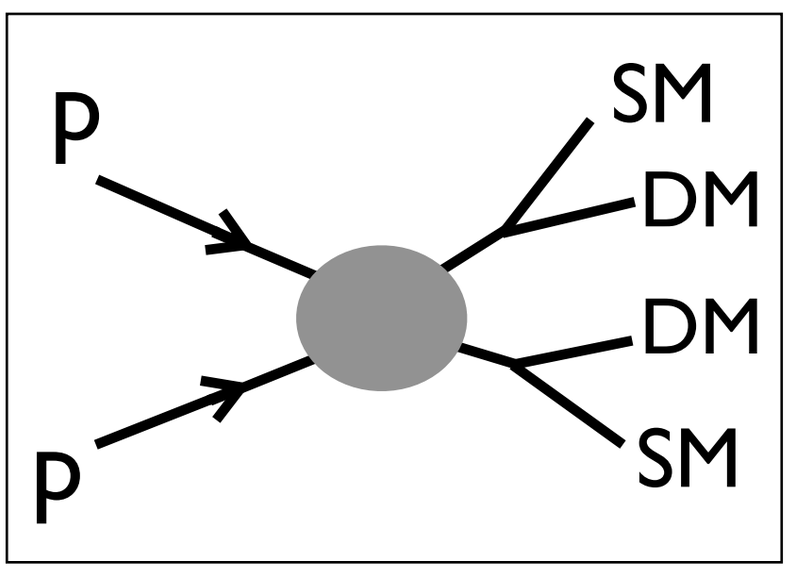
(work in progress)

Fermilab Particle Astrophysics Seminar, Jan 10th 2011

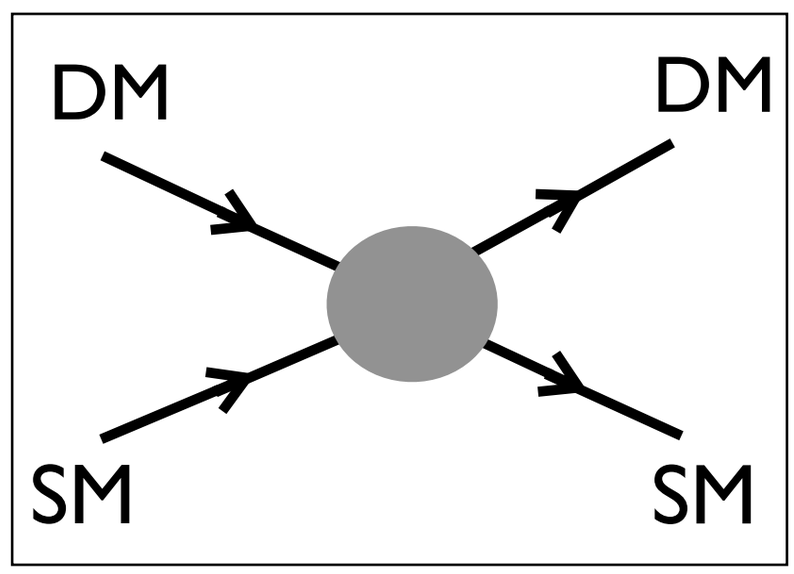
Dark Matter is one of the most exciting puzzles in astro and particle physics

We are tackling it in 3 experimental fronts:

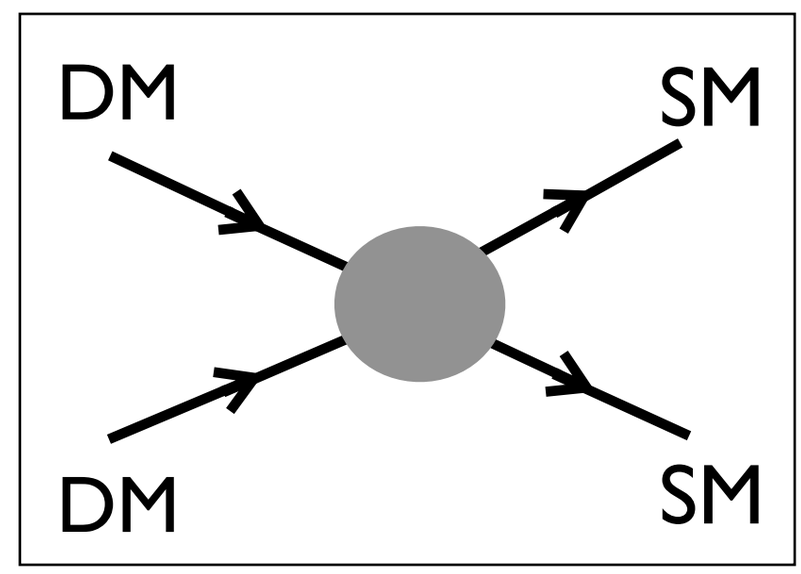
DIRECT PRODUCTION



DIRECT DETECTION



INDIRECT DETECTION



Each front has its own challenges

DIRECT PRODUCTION

- reconstruction of DM properties from visible states
- is it stable at cosmological scales?
- is it really the dark matter particle?

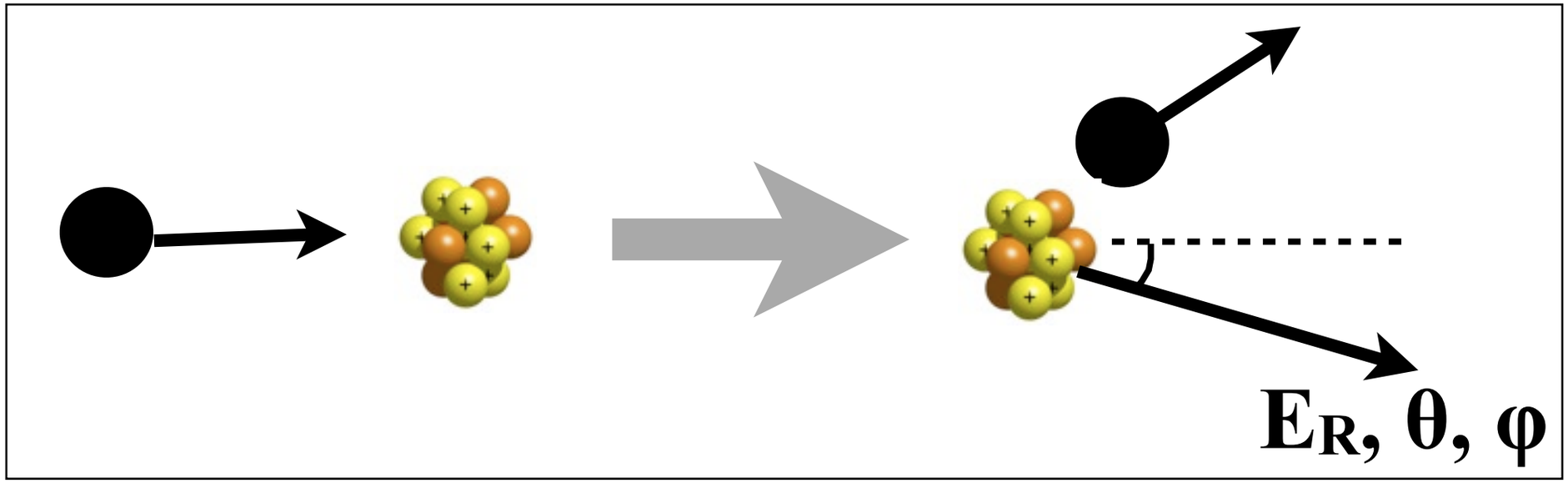
INDIRECT DETECTION

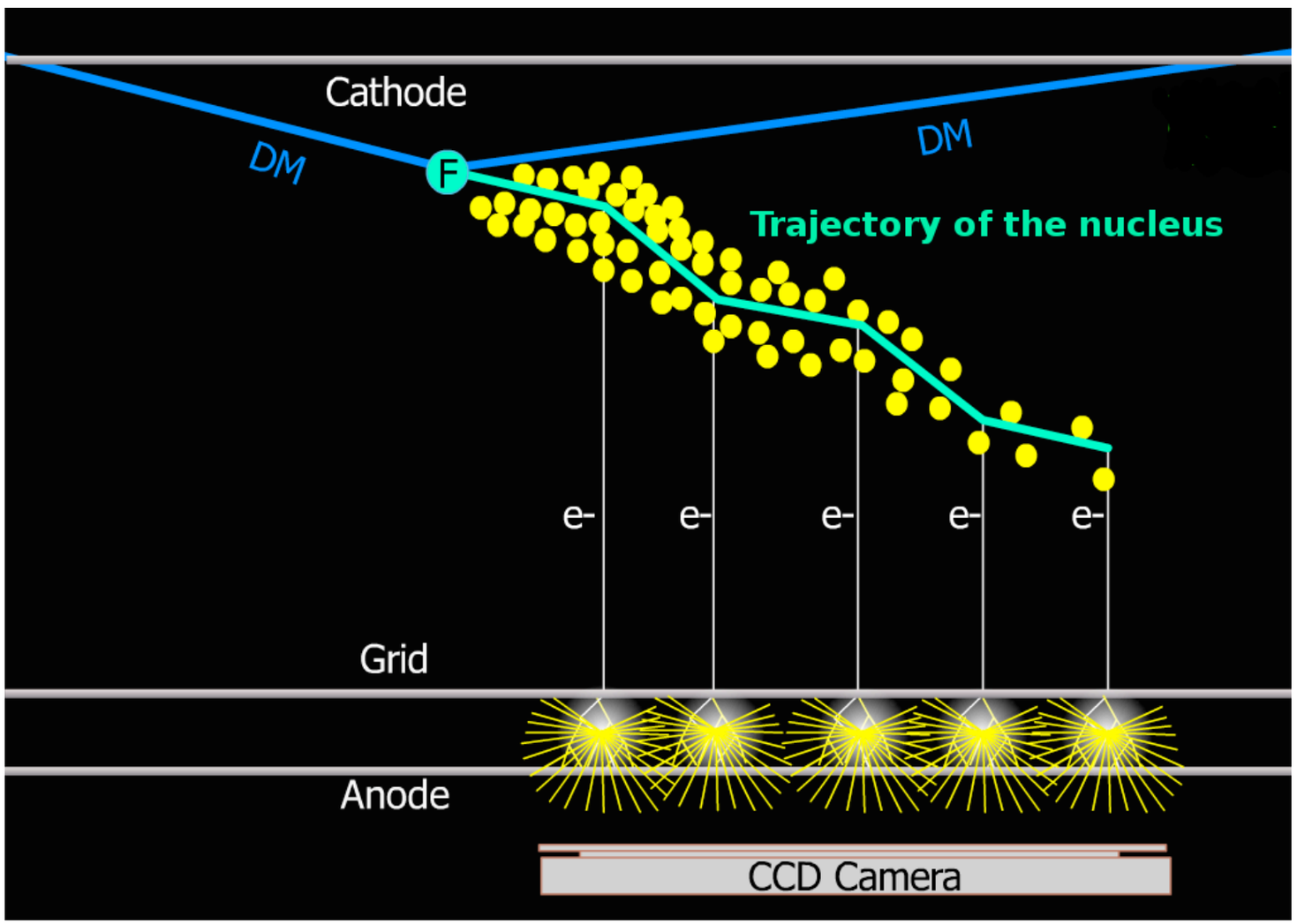
- only if dark matter self-annihilates or decays
- unknown astrophysics sources
- cosmic ray propagation
- halo density profile

DIRECT DETECTION

- DM has to interact with target particles in detector
- understand and eliminate backgrounds
- large exposures

Direct / Directional Detection





Direct / Directional Detection

Collaboration	Technology	Target	Interactions	Head-tail	Readout	V (m^3)
DRIFT	NITPC	CS_2, CS_2-CF_4	SI/SD	yes	MWPC 2D + timing	1
DMTPC	TPC	CF_4	SI/SD	yes	Optical (CCD) 2D	0.01
NEWAGE	TPC	CF_4	SI/SD	no	μPIC 2D + timing	0.03
MIMAC	TPC	$^3He/CF_4$	SI/SD	yes	Micromegas 2D + timing	0.00013
Emulsions	emulsions	AgBr	SI/SD	no	Microscope 3D	N/A

Battat *et.al.*
Cygnus 2009 Whitepaper

<u>PROBLEM</u>

We don't know:

- ✦ DM particle properties
- ✦ Local halo velocity distribution

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~~PROBLEM~~ *OPPORTUNITY*

~~We don't know:~~

measure:

- ✦ DM particle properties
- ✦ Local halo velocity distribution

Outline

What directional information can teach us about

✦ DM particle physics (through scattering kinematics)

inelasticity, compositeness, non-trivial dark sector?

✦ Local Halo Velocity Distribution (anisotropies)

triaxiality, local clumpiness?

✦ Global phase space profile (through Jeans' Theorem)

hints on the density profile?

Directional Detection & DM particle physics

- ✦ directionality can probe inelastic scattering properties of DM off SM nuclei

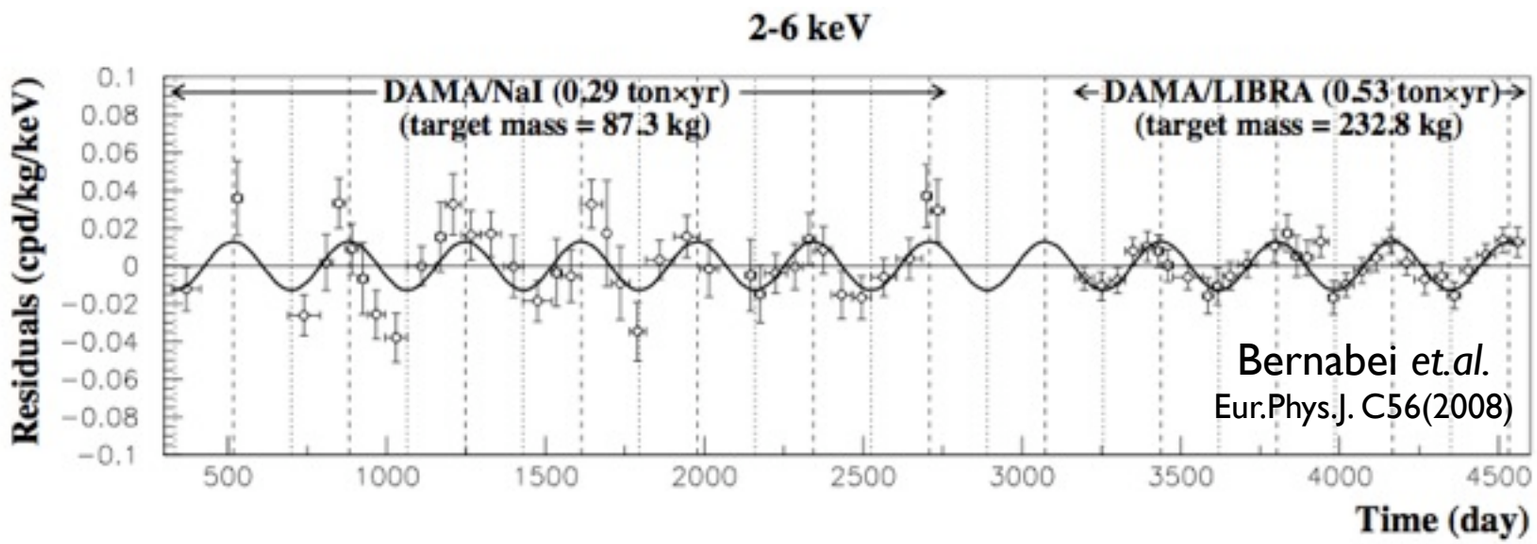
Finkbeiner, Lin & Weiner `09
Lisanti & Wacker `09

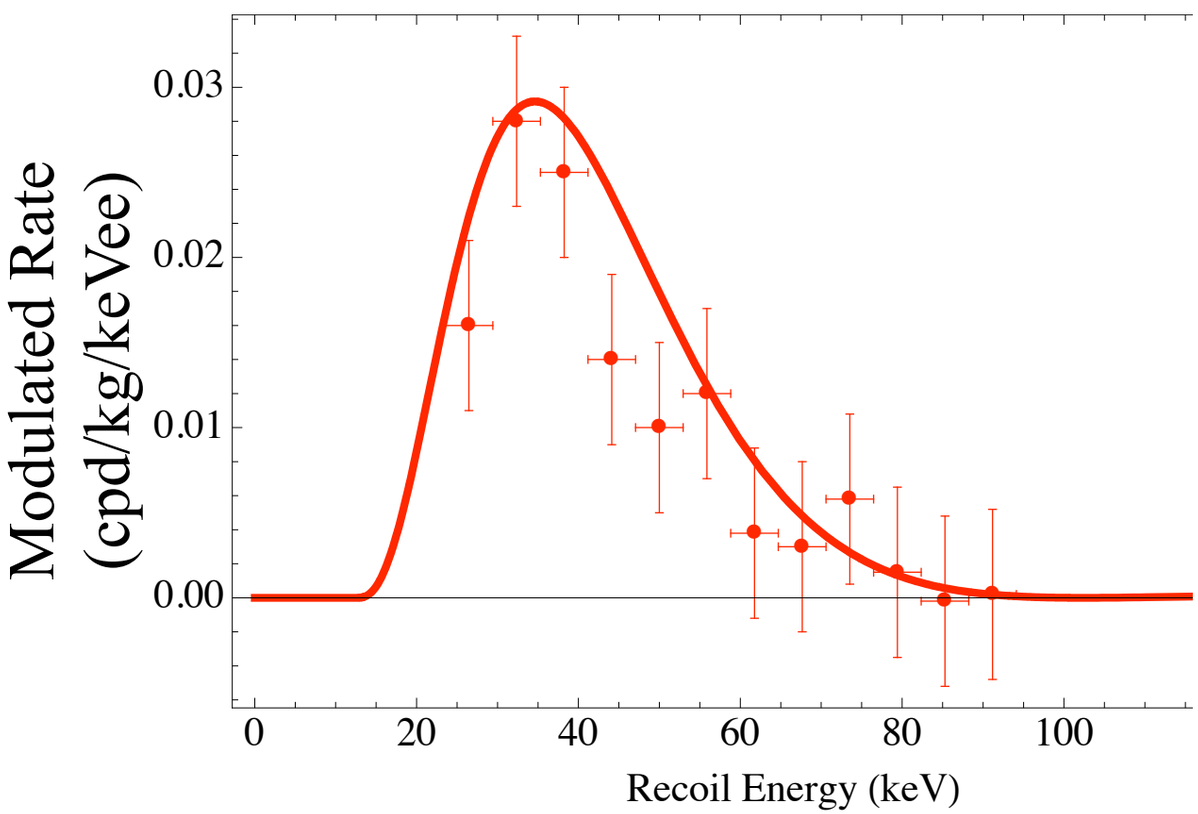
- ✦ reason: simple kinematics

- ✦ indication of non-minimal dark sector, compositeness, more than one DM particle...

Arkani-Hamed *et.al.* `08
Finkbeiner *et.al.* `09
DA, Behbahani *et.al.* `10
Kronh *et.al.* `10

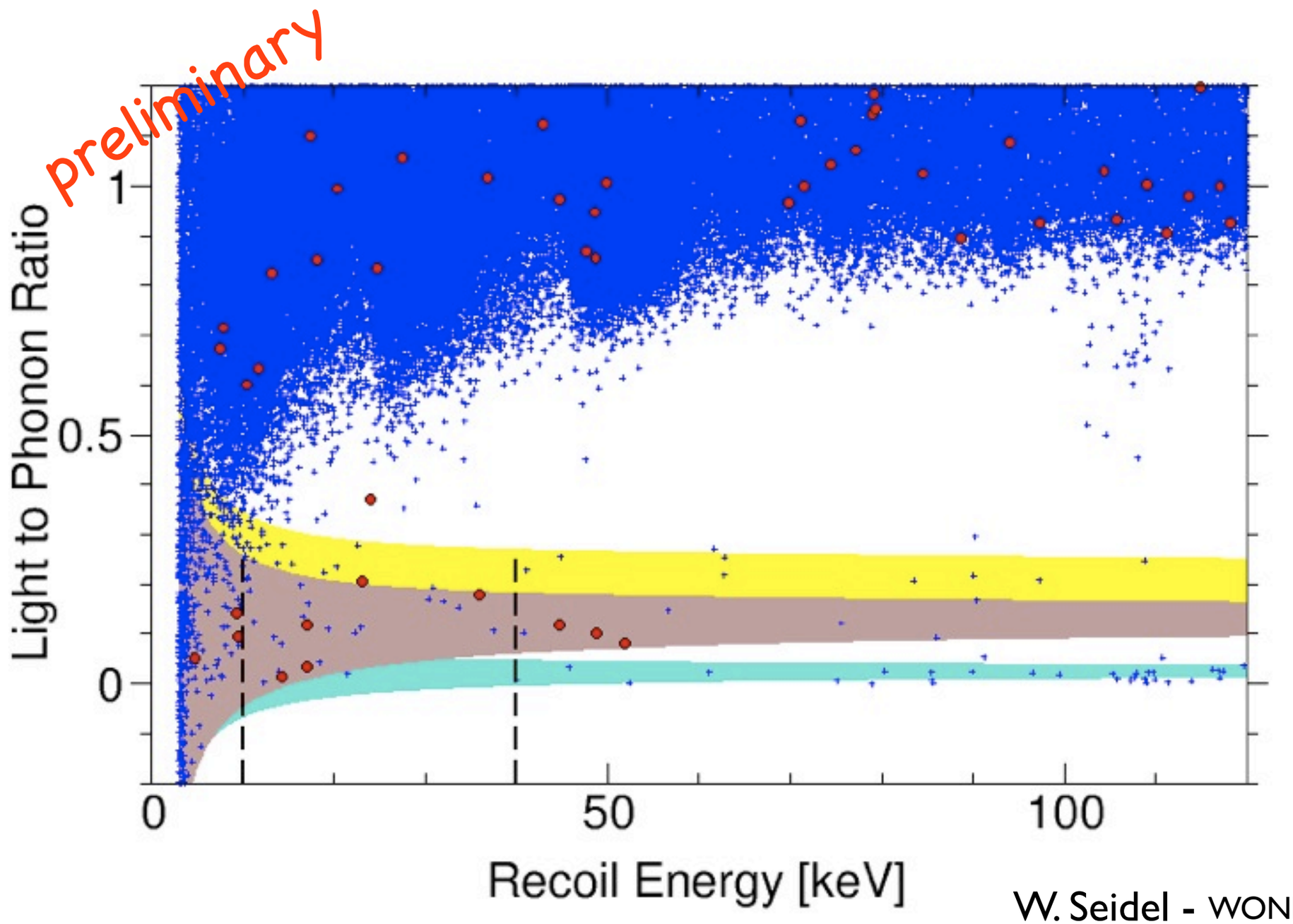
- iDM is a compelling explanation for DAMA's 8.9σ annual modulation signal





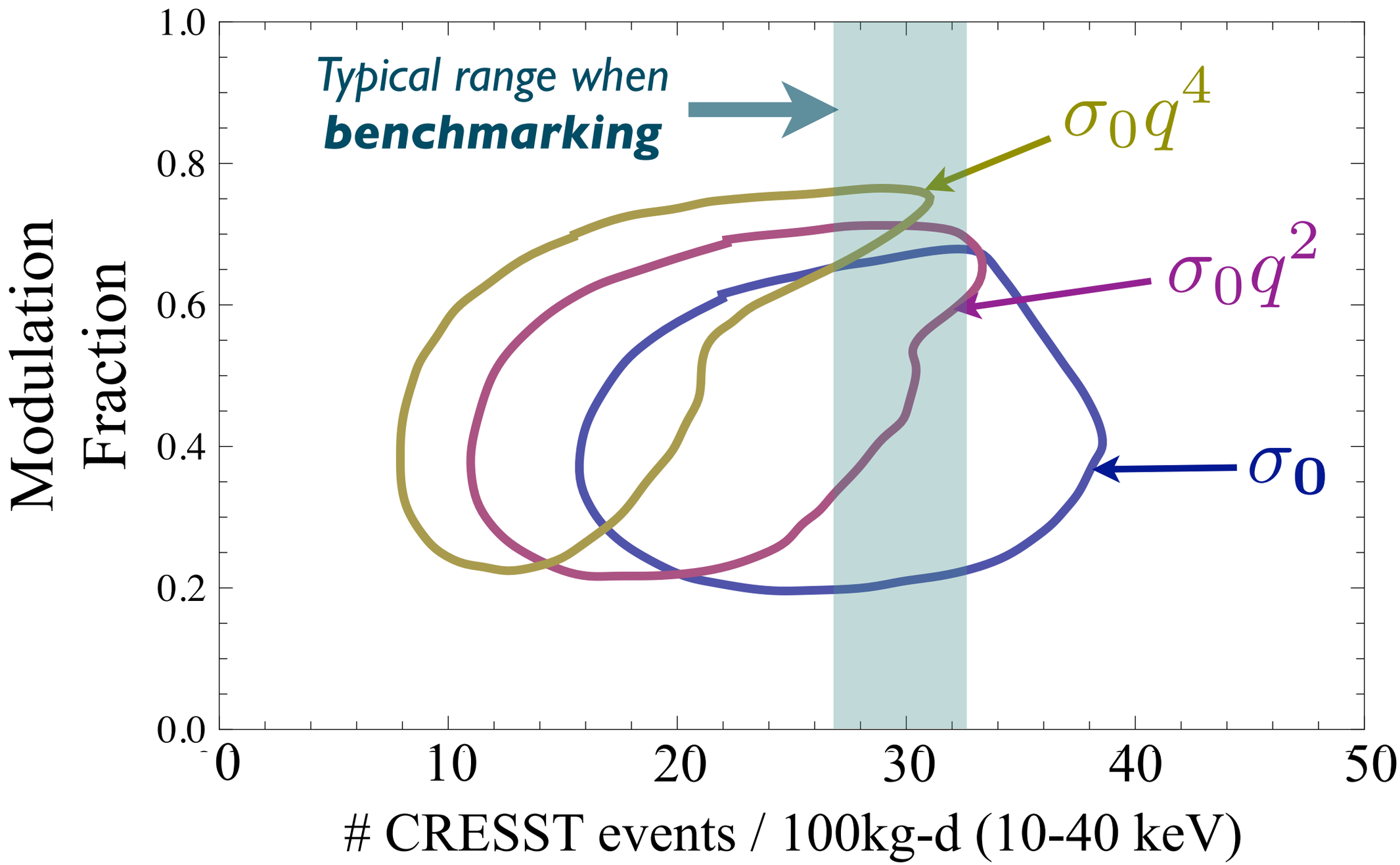
- excellent fit to modulated spectrum
- high modulation fraction
- consistent with other experiments

CRESST: less events that typically predicted by iDM?



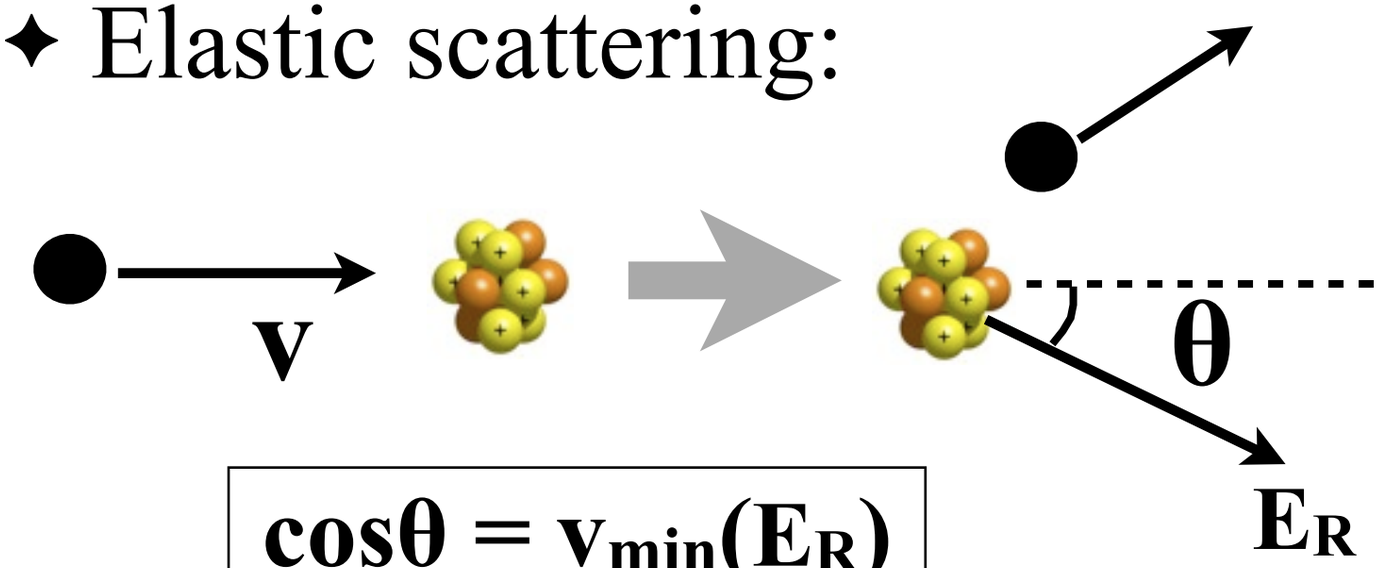
W. Seidel - WONDER 2010 Workshop

Too early to an unambiguous exclusion of iDM

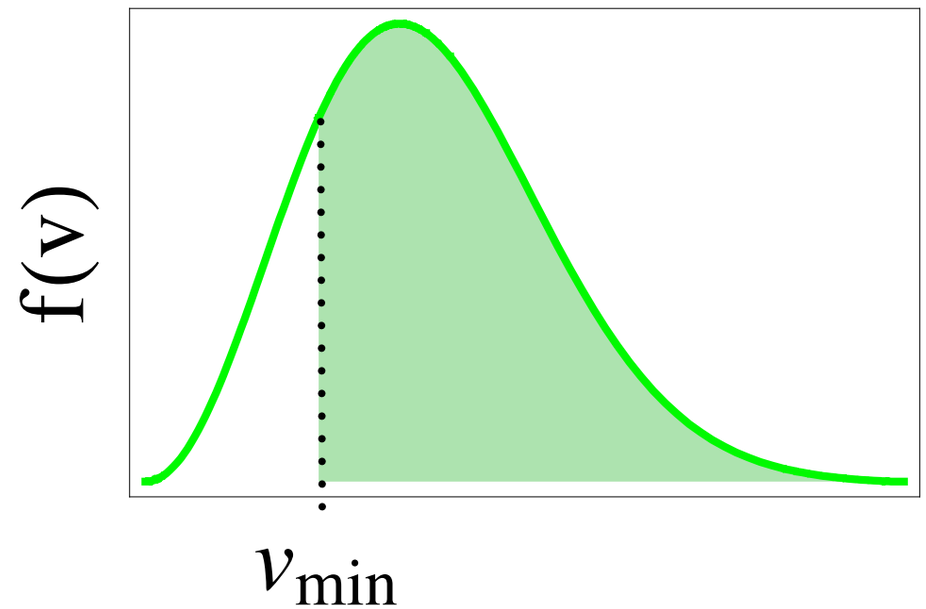


DA, Lisanti & Wacker
Phys.Rev. D82 (2010) 031901

✦ Elastic scattering:



$$\cos\theta = \frac{v_{min}(E_R)}{v}$$



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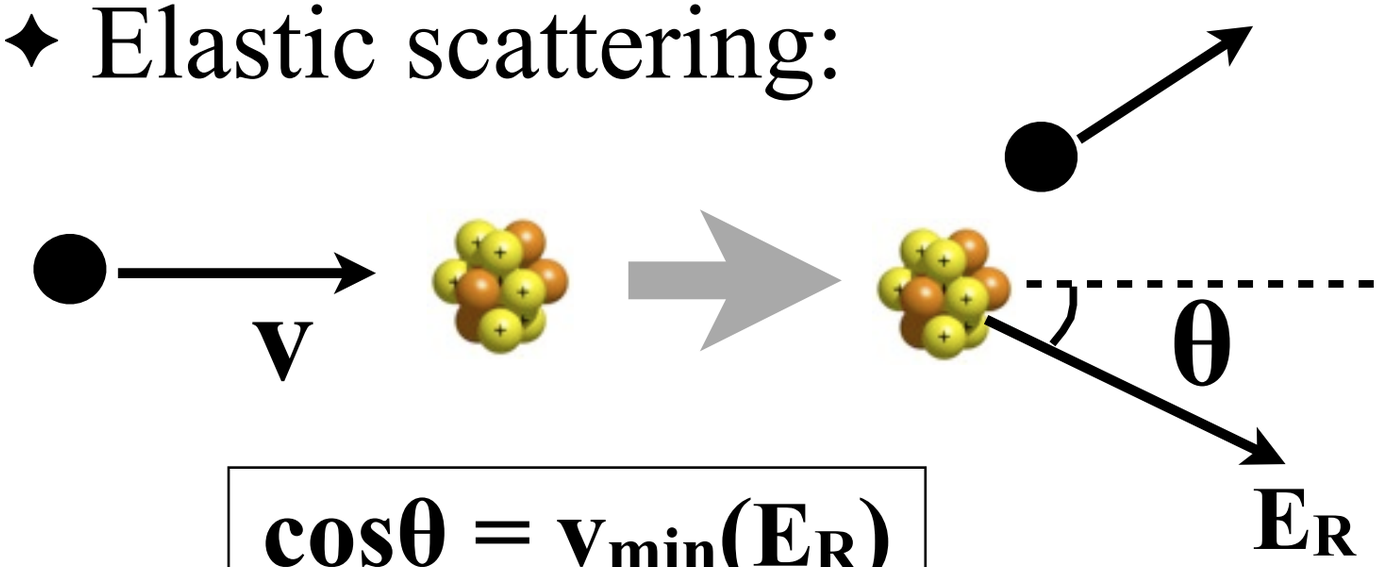

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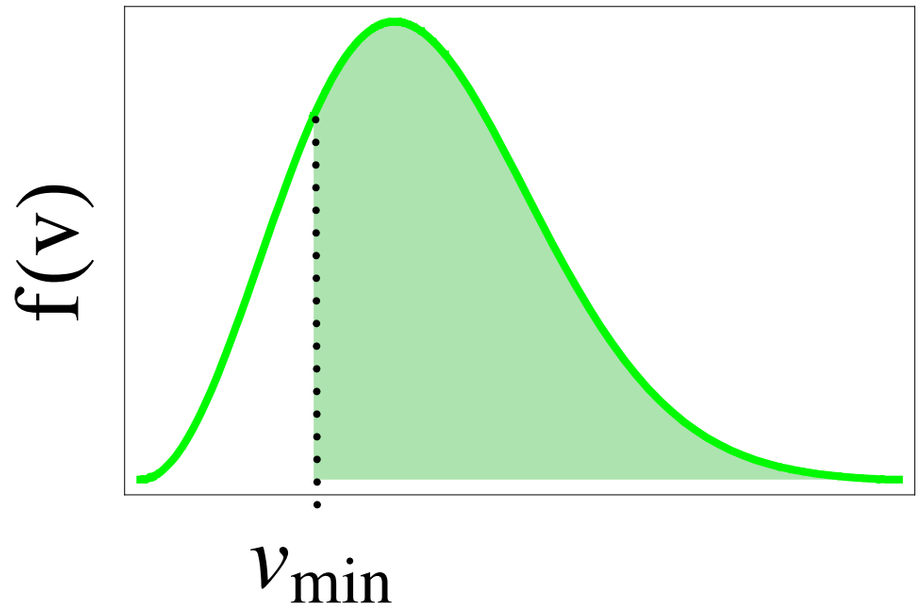
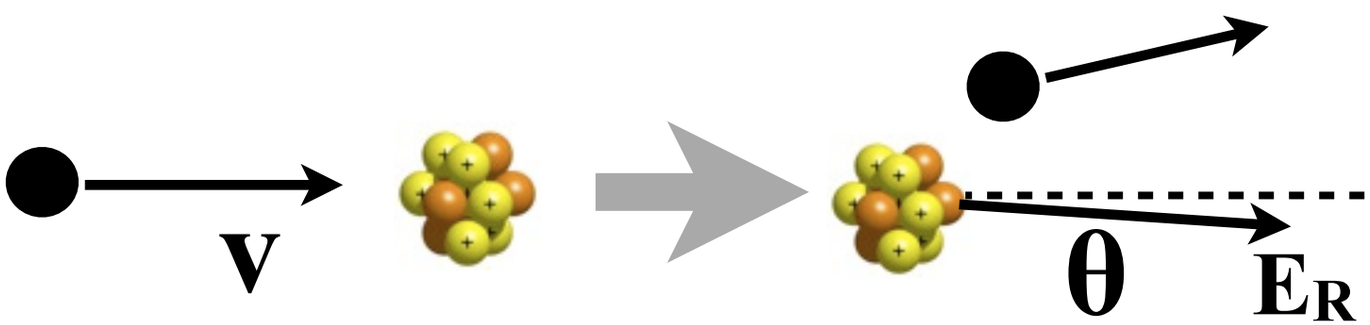
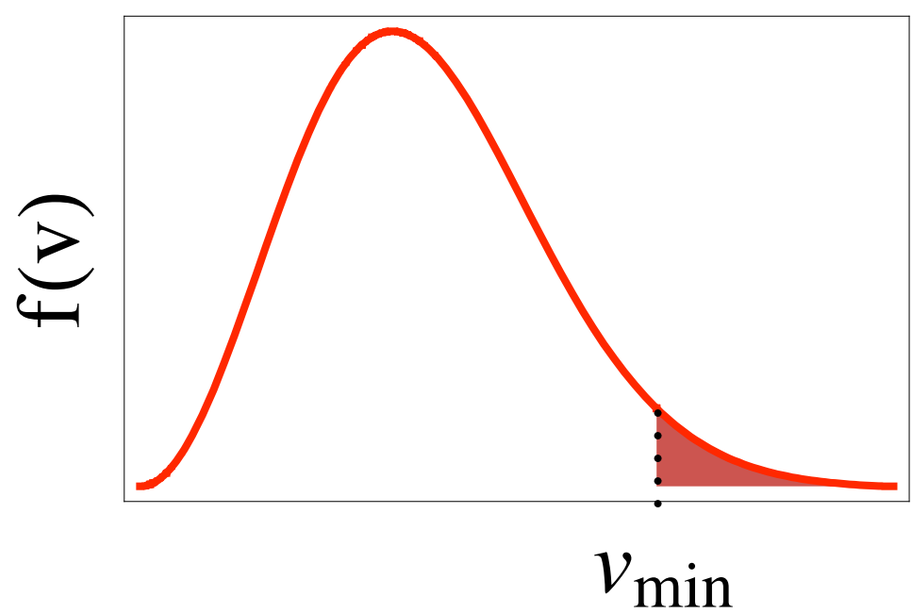


✦ Inelastic scattering:

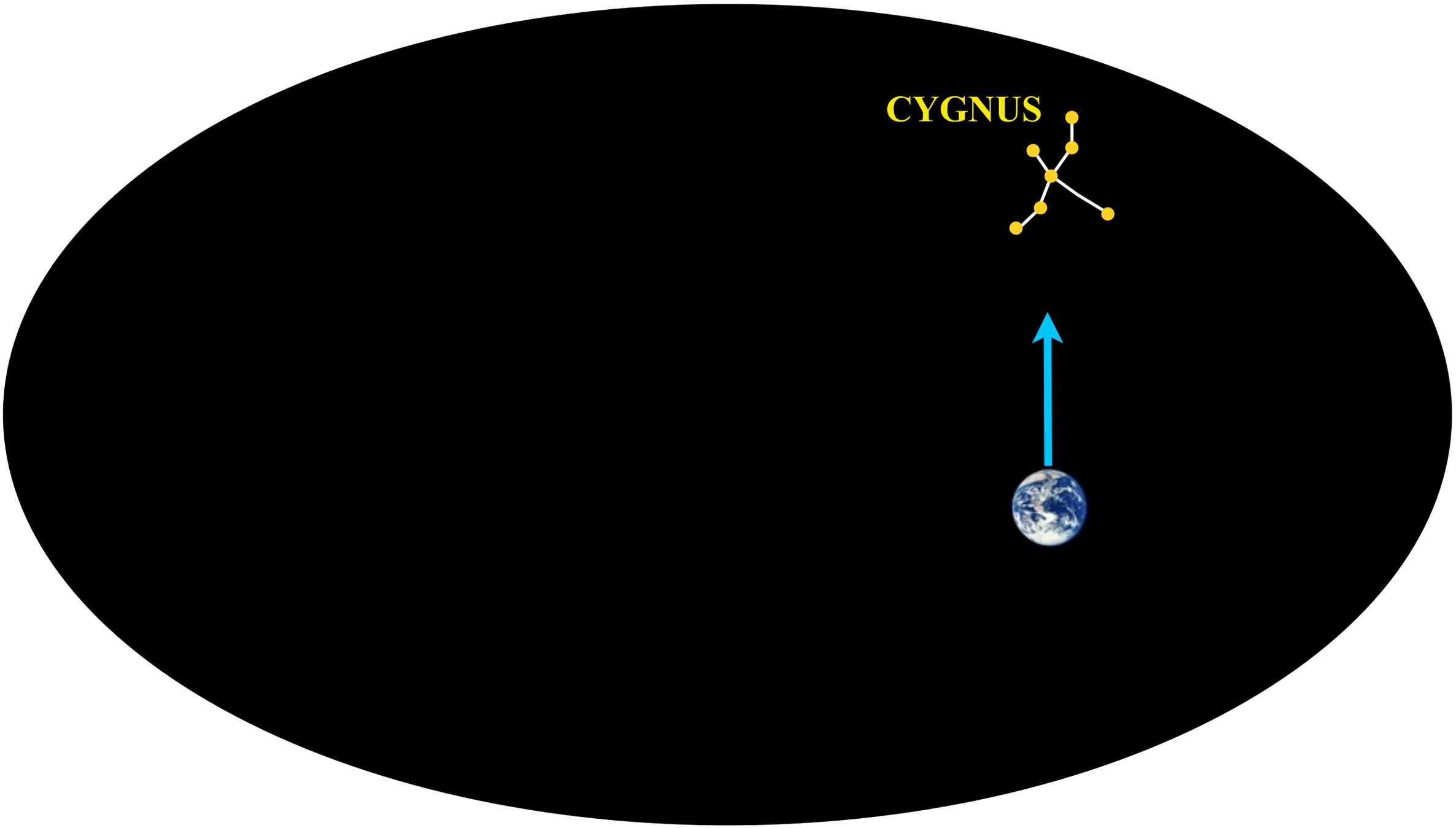


$$\cos\theta = \frac{v_{min}(E_R, \delta m)}{v}$$



Directional Signatures

- It is believed that the DM halo and the baryonic disk do NOT co-rotate



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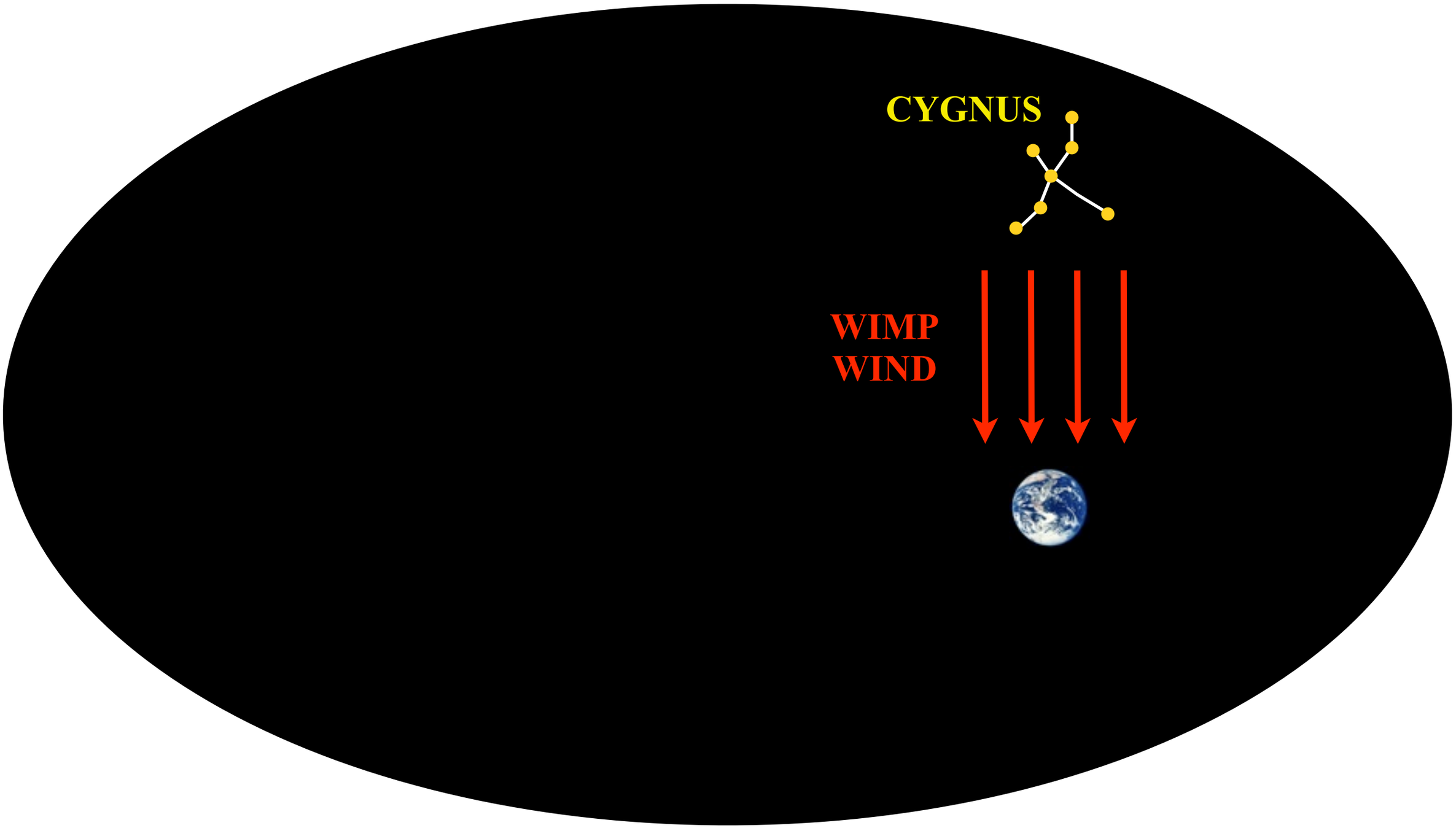
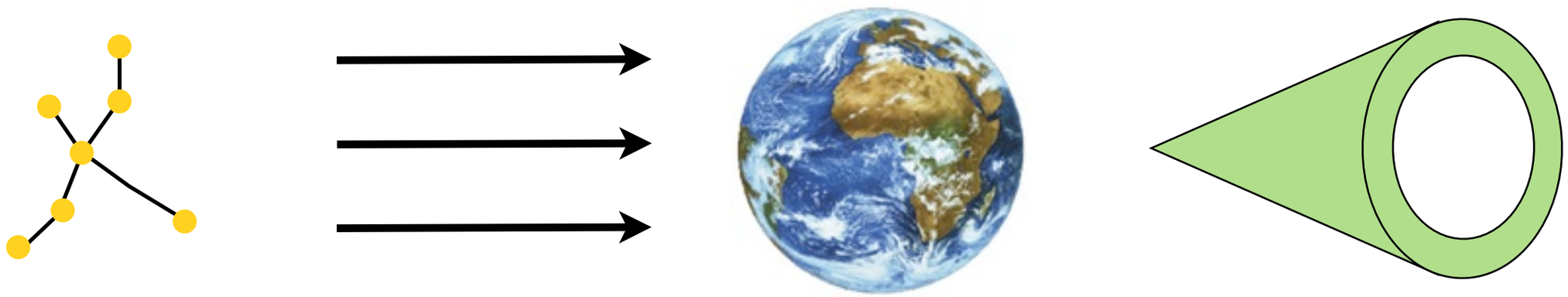
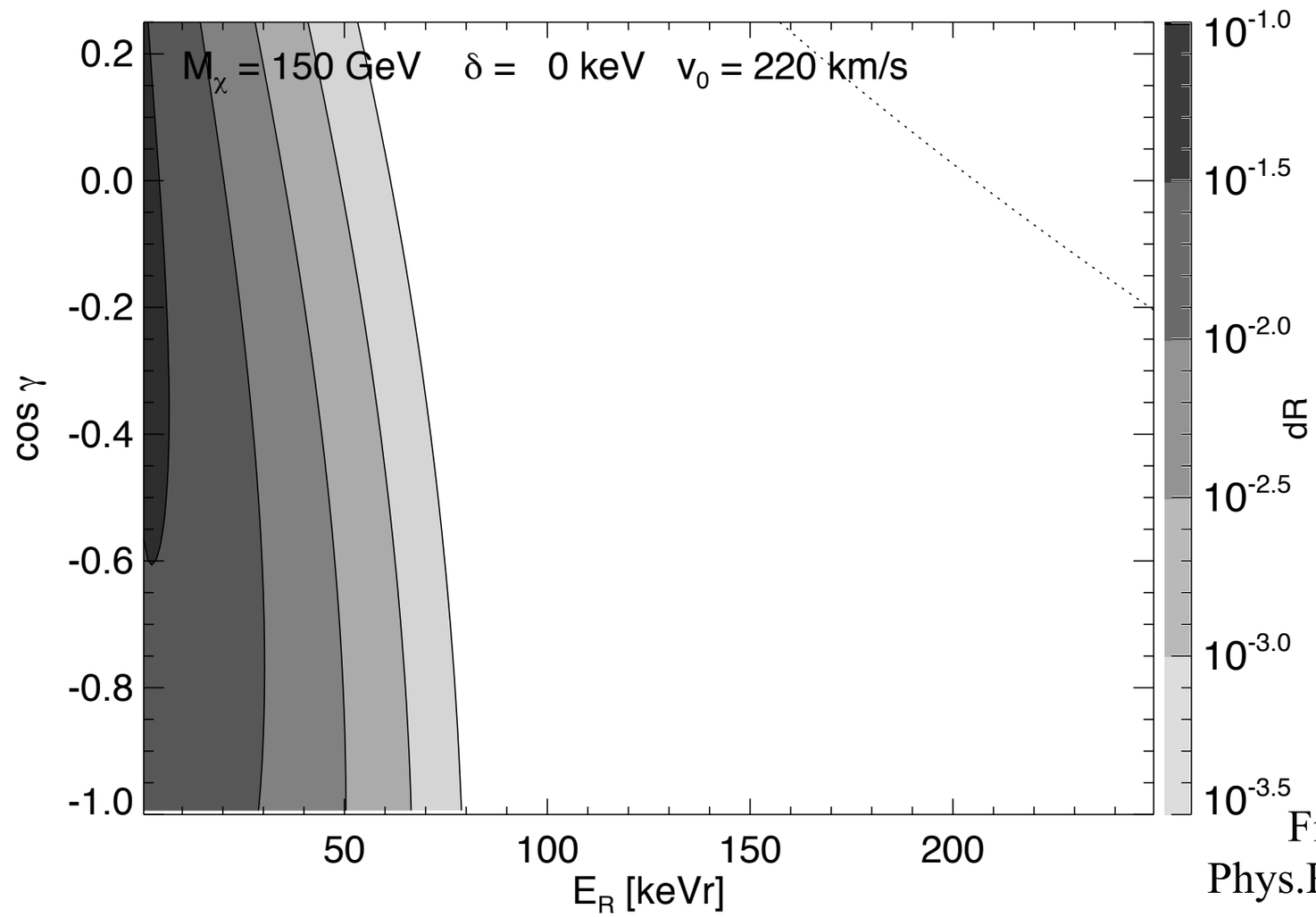


Elastic WIMP



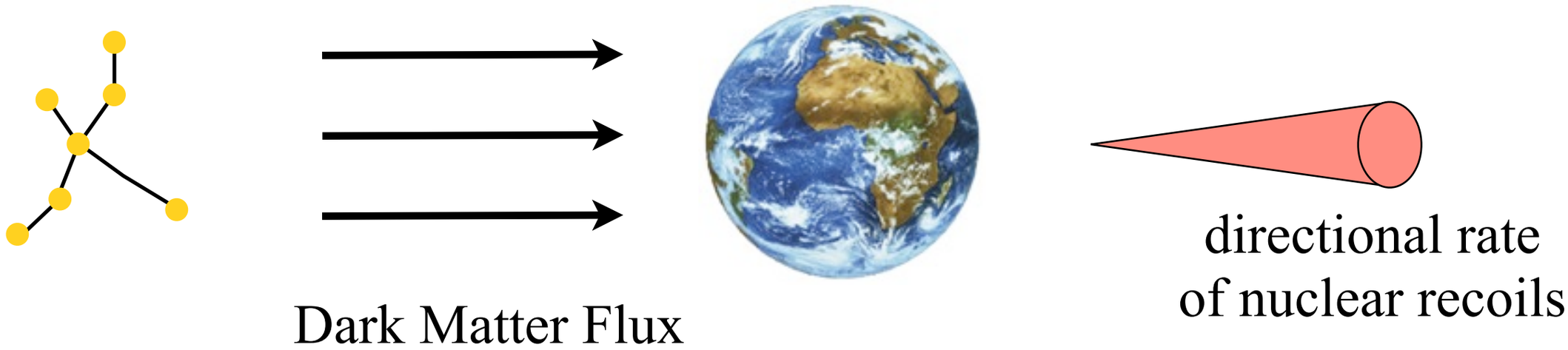
Dark Matter Flux

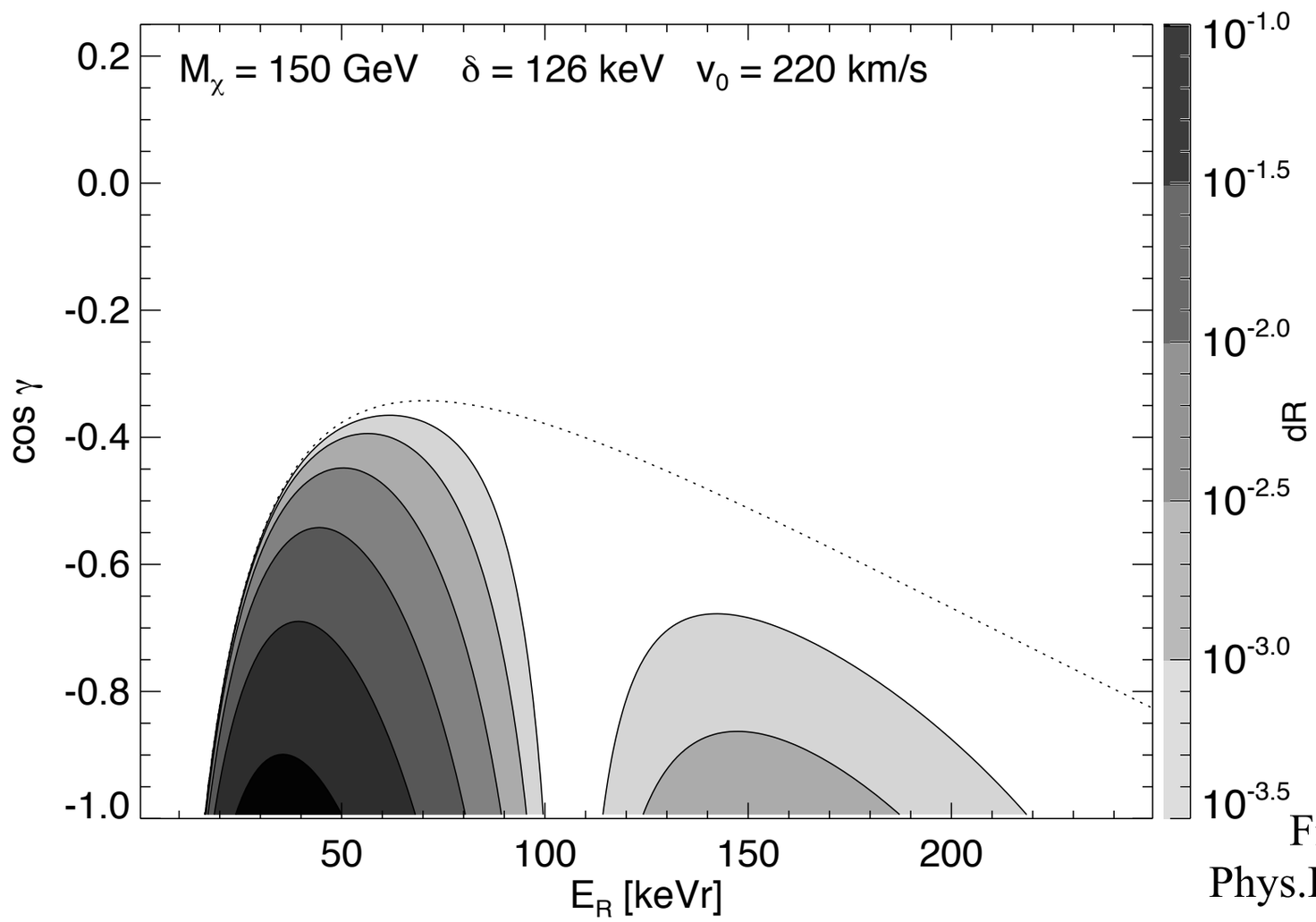
directional rate
of nuclear recoils



Finkbeiner, Lin & Weiner
Phys.Rev. D80 (2009) 115008

Inelastic WIMP





Finkbeiner, Lin & Weiner
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- Pinpoint iDM parameters (mass, splitting, origin of inelasticity) by looking at:

  - Rate at other experiments (CRESST, XENON100)
  - Shape of recoil spectrum
  - Modulation fraction
  - Directional information

- Predictions are entangled with velocity distribution

- f(v): headache when making unambiguous statements in direct detection (iDM+CRESST, light DM+CoGeNT+XENON100)

- ρ(r): headache for indirect detection

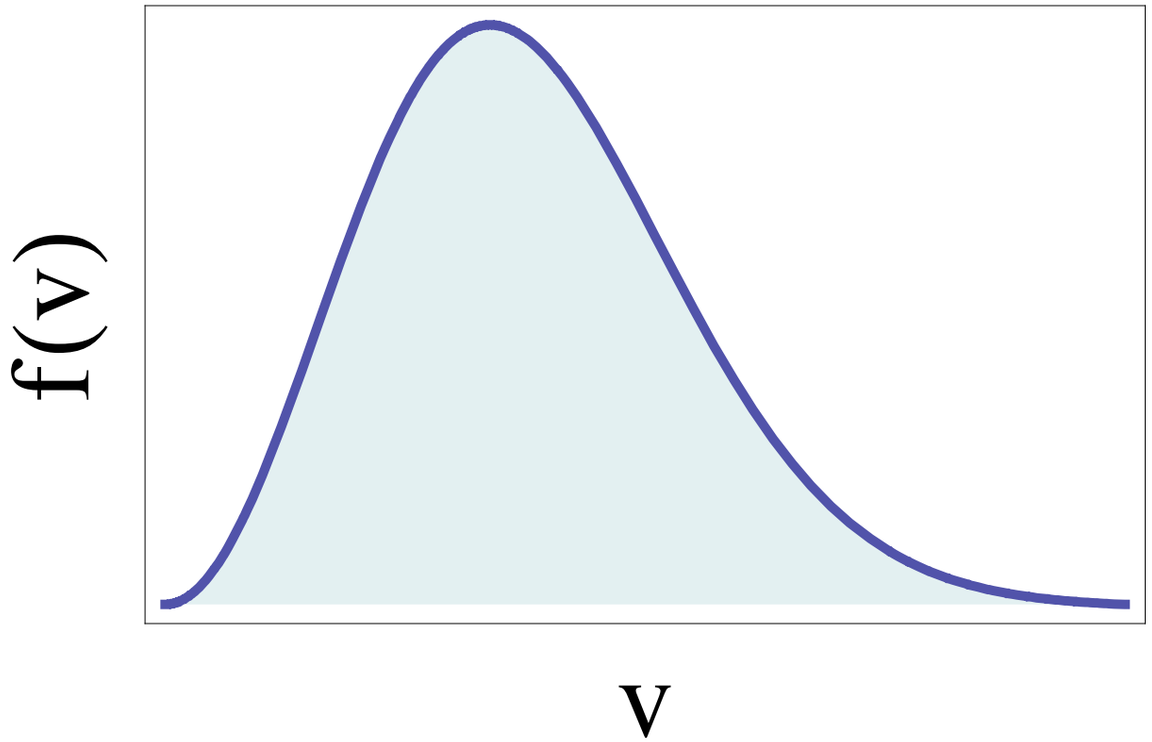
- Numerical simulations: departures of f(v) from the Standard Maxwellian distribution

- Rotation curves: hard to measure if you’re an inside observer

DM velocity distribution is unknown

- Standard Maxwellian distribution

$$f(\vec{v}) \propto e^{-\frac{v^2}{v_0^2}} \; \Theta(v - v_{\rm esc})$$

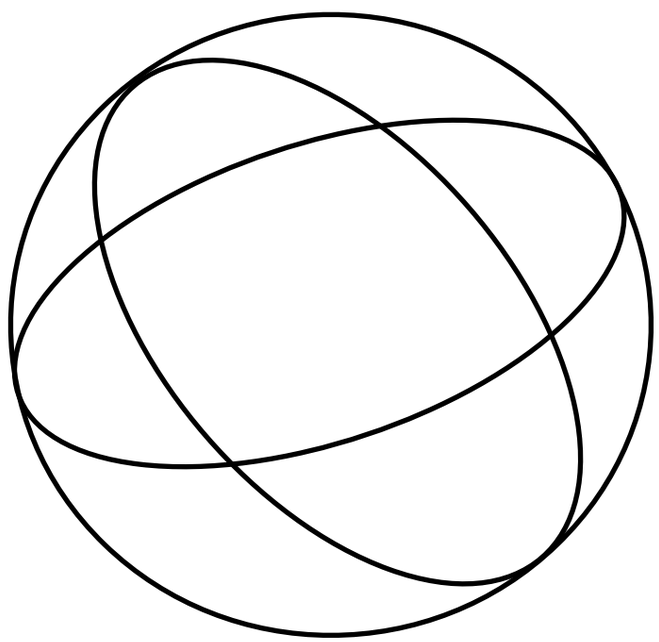


DM velocity distribution is unknown

✦ Anisotropic distribution (Michie)

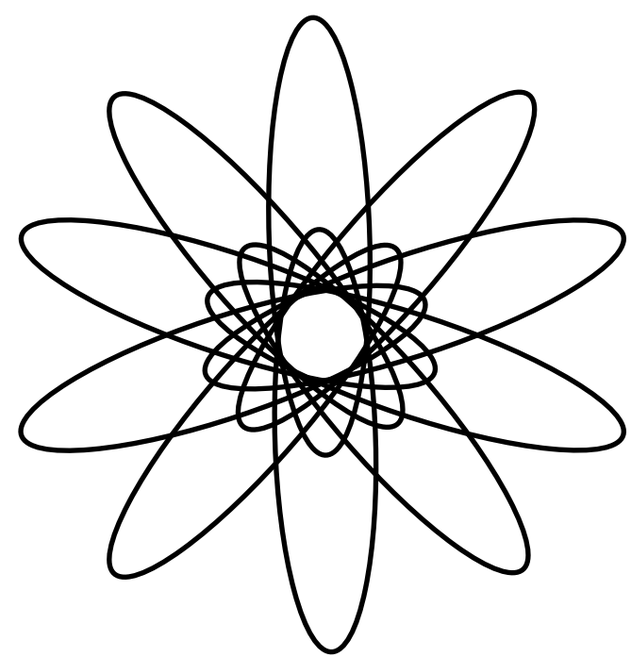
$$f(\vec{v}) \propto e^{-\alpha v_R^2}\, e^{-v^2}\, \Theta(v - v_{\rm esc})$$

$\alpha > 0$



MOSTLY CIRCULAR

$\alpha < 0$

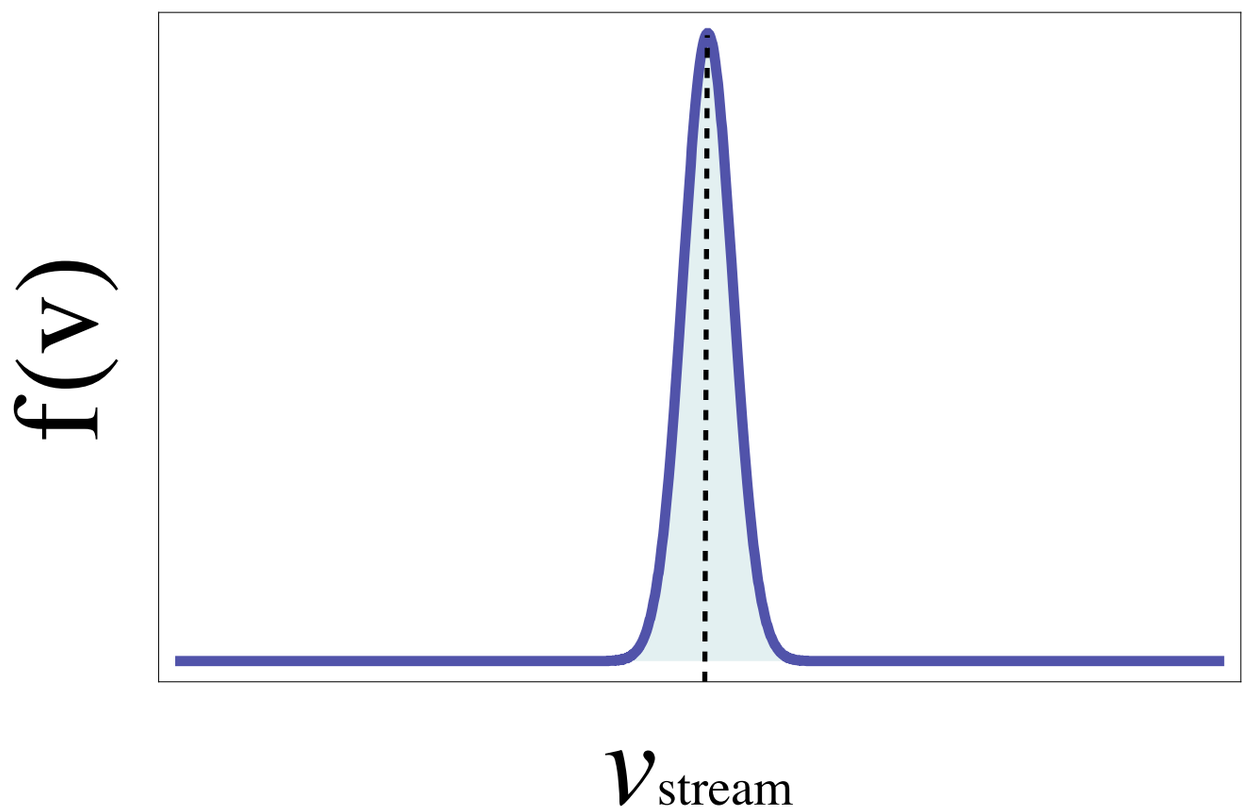


MOSTLY RADIAL

DM velocity distribution is unknown

- Substructure with low velocity dispersion (streams or clumps)

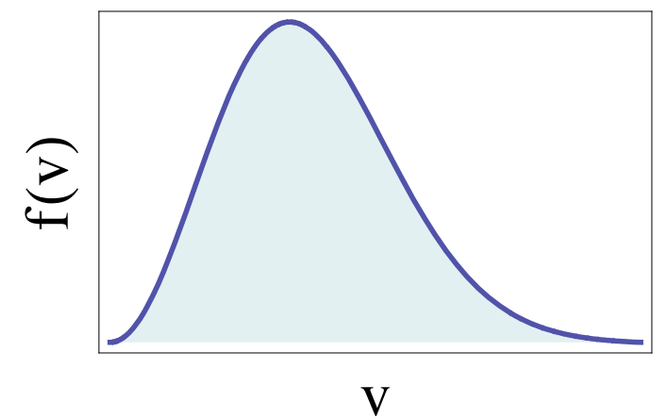
$$f(\vec{v}) \propto \delta(\vec{v} - \vec{v}_{\rm stream})$$

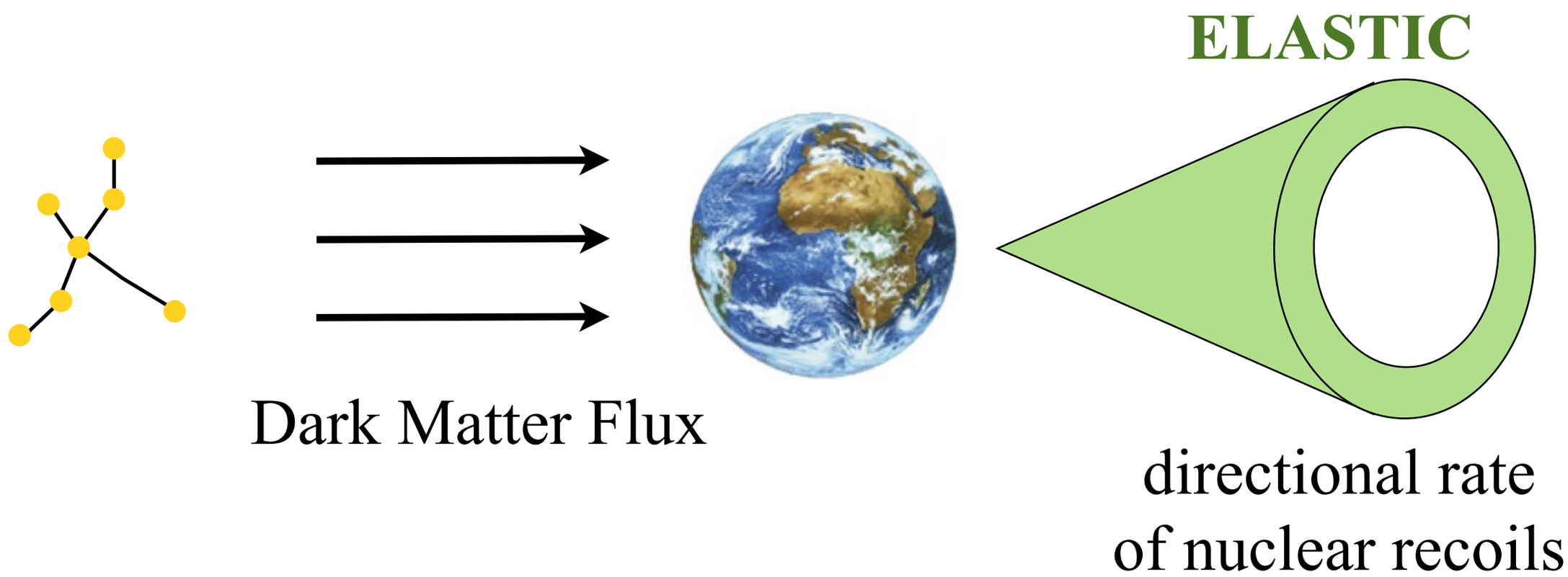


Directional Signatures

✦ Isotropic Maxwellian distribution

$$f(\vec{v}) \propto e^{-v^2}\ \Theta(v - v_{\rm esc})$$





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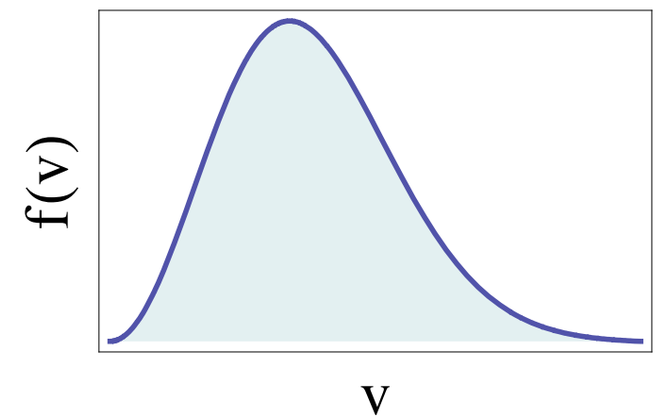

INELASTIC

Dark Matter Flux

directional rate
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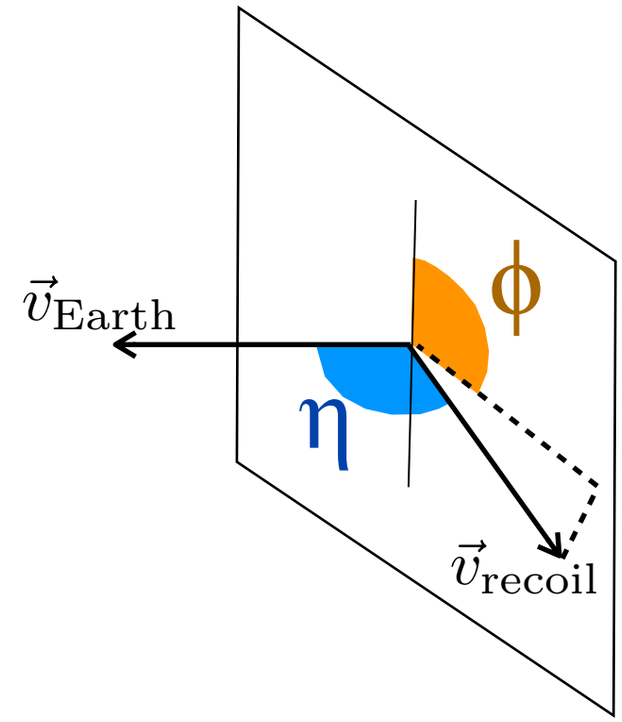
Directional Signatures



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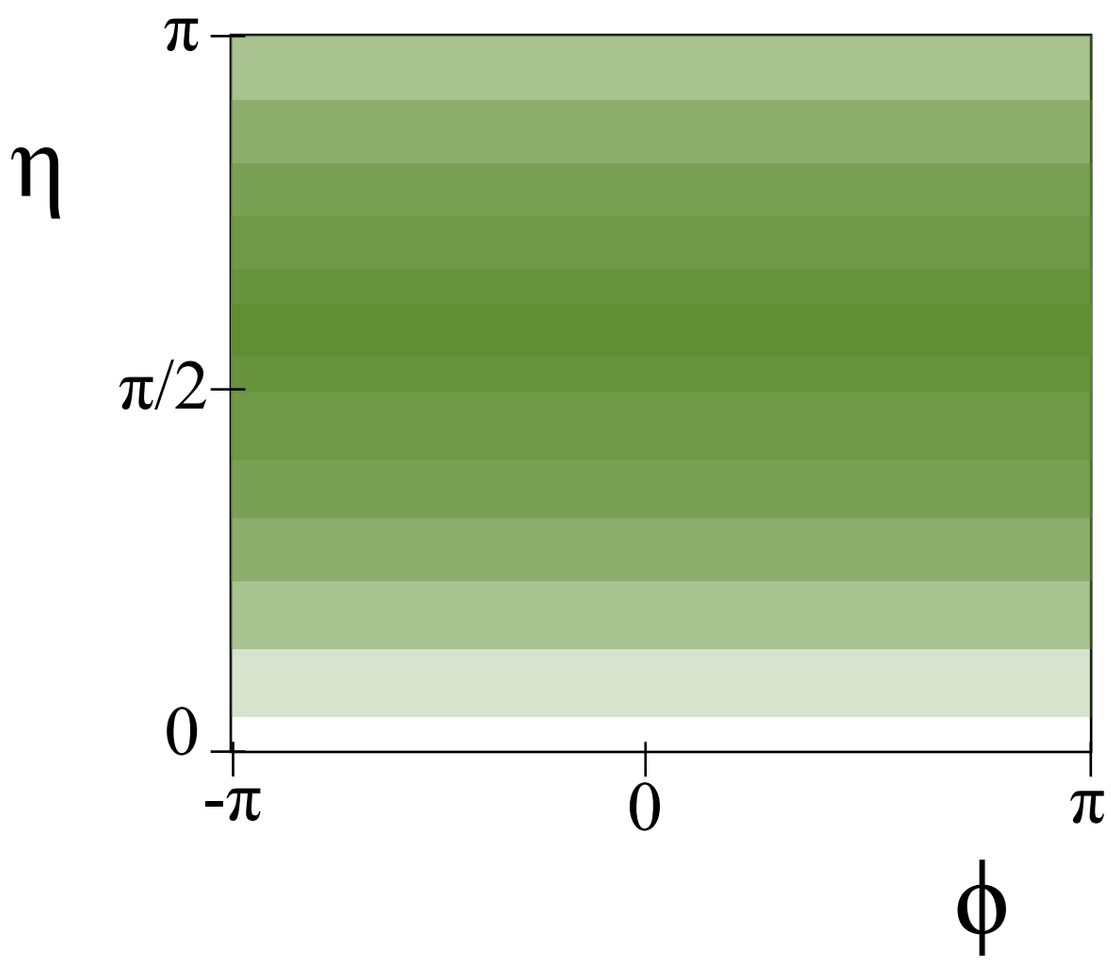

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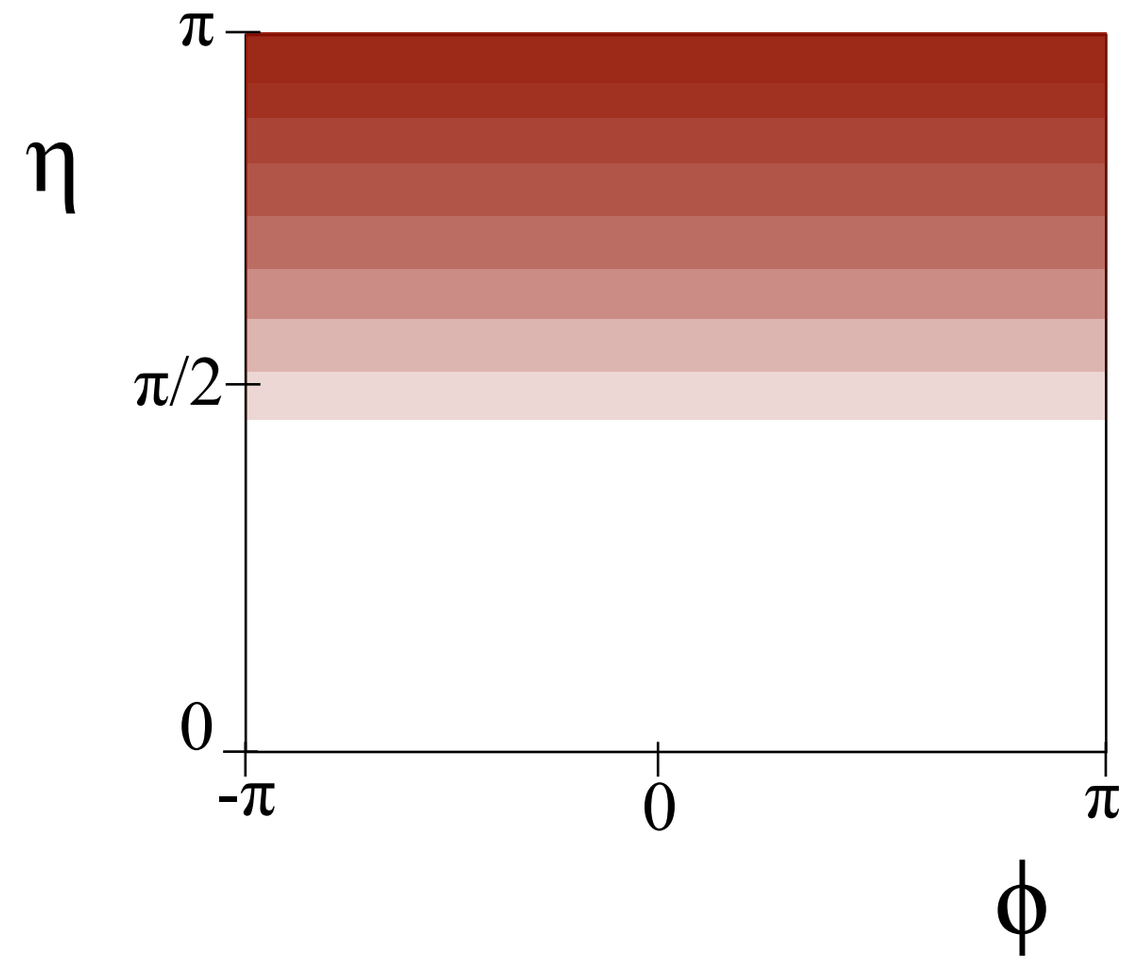

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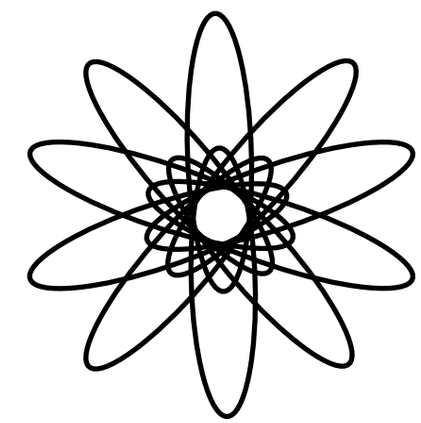

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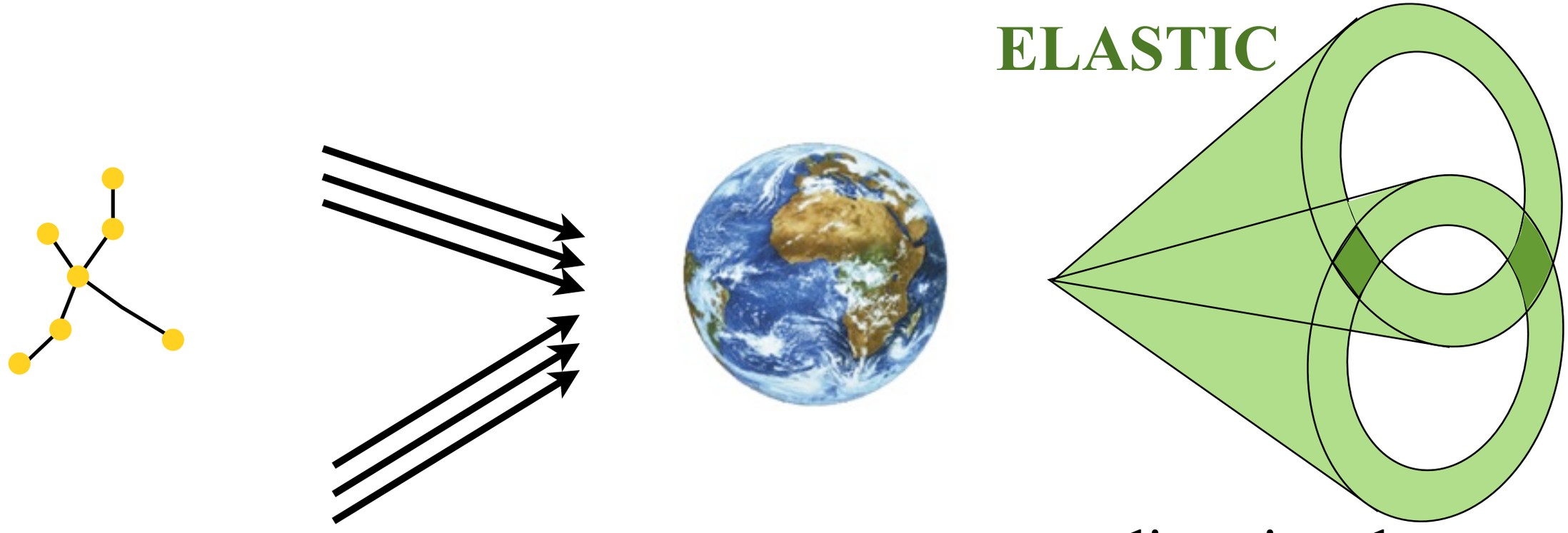

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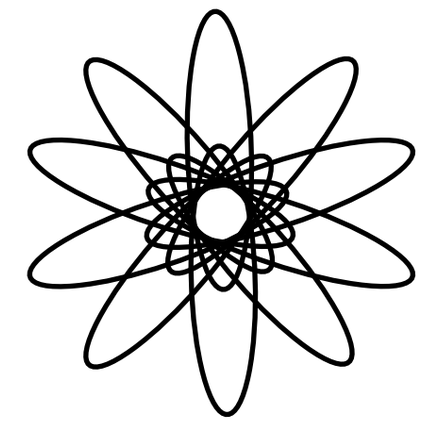

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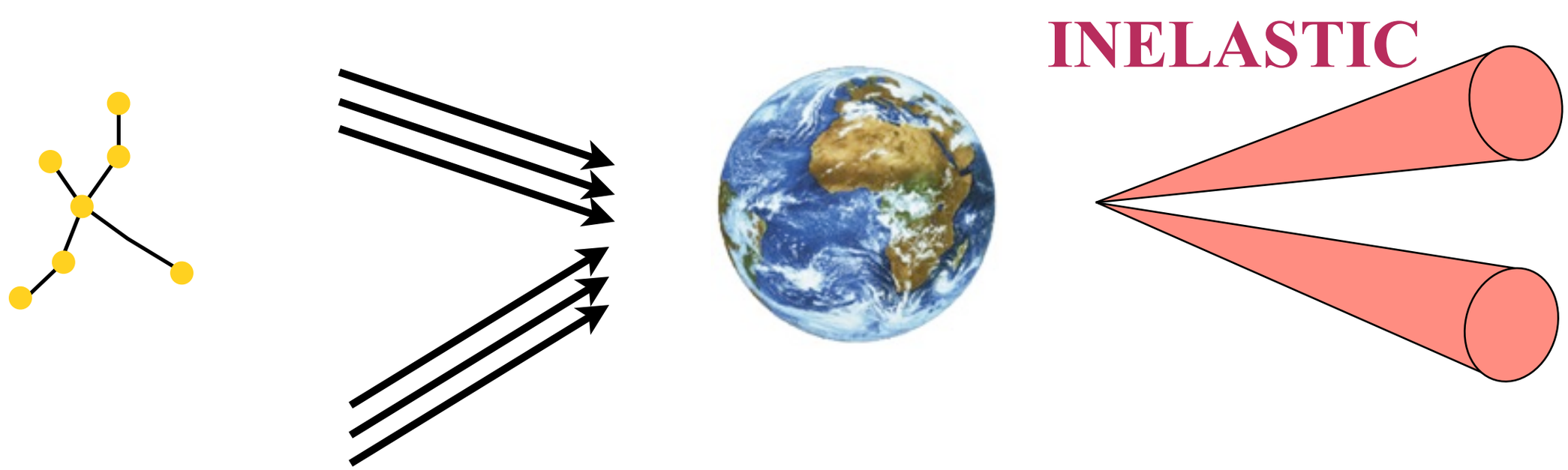

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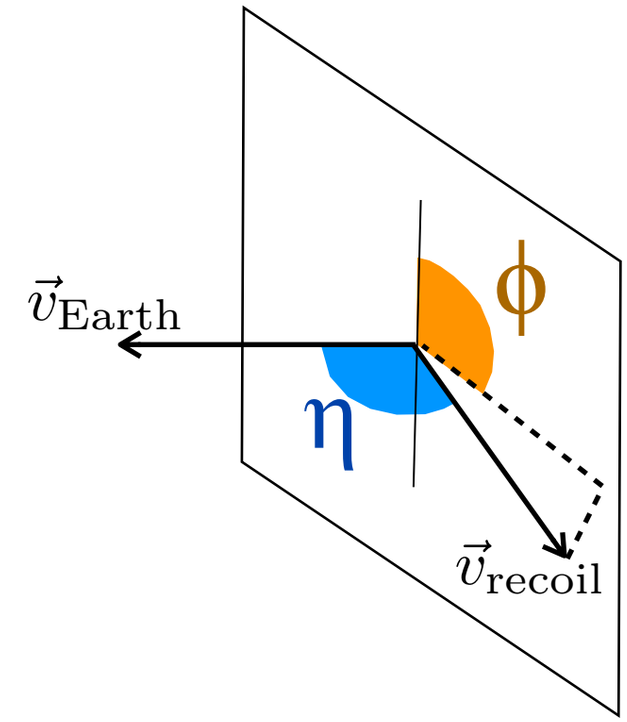
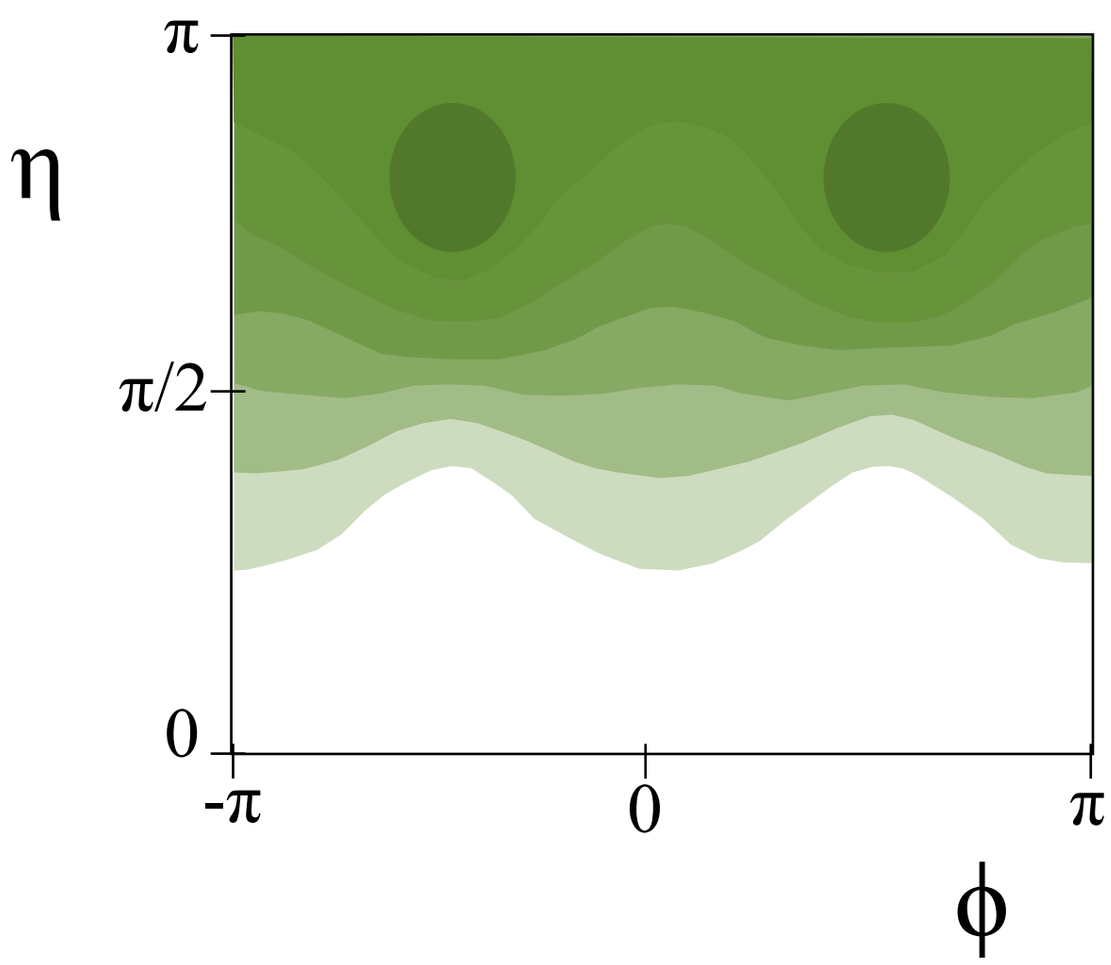


ELASTIC



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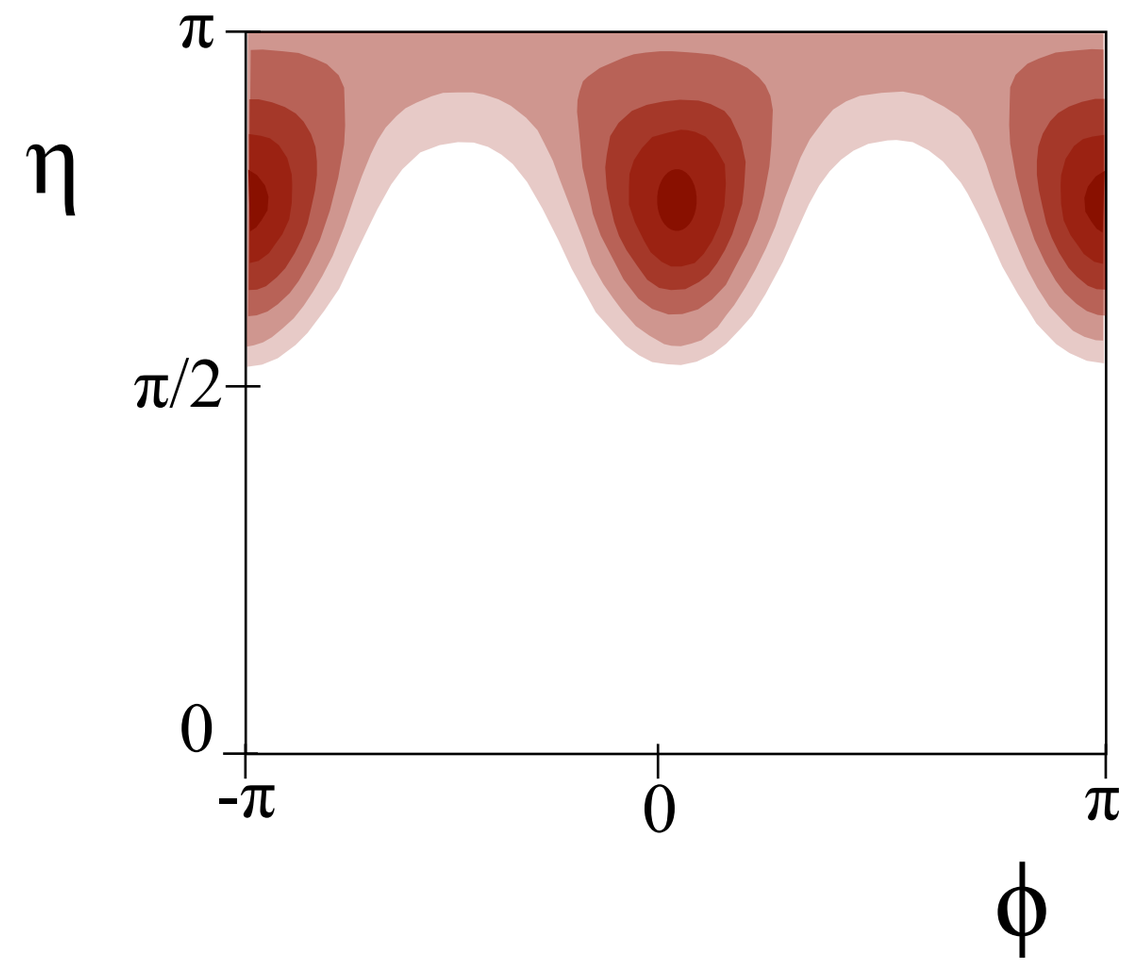
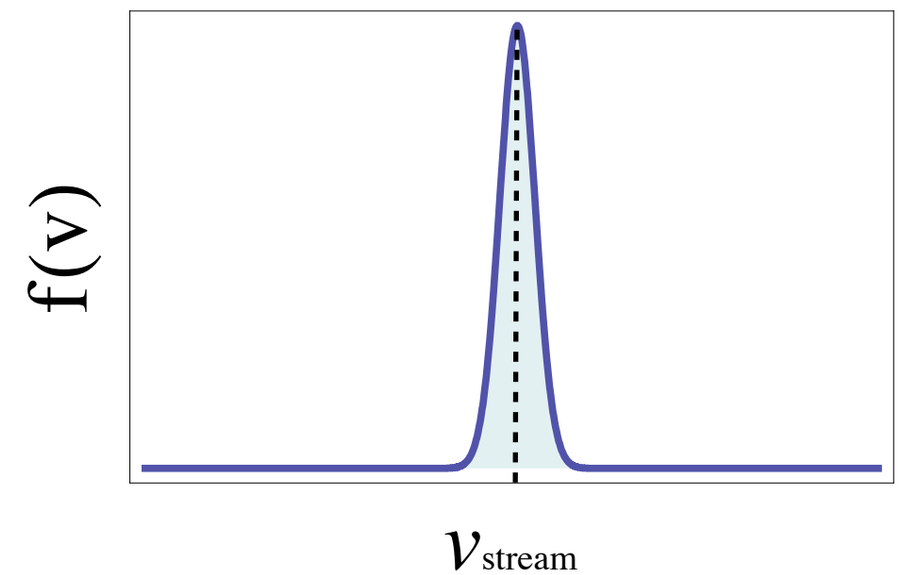
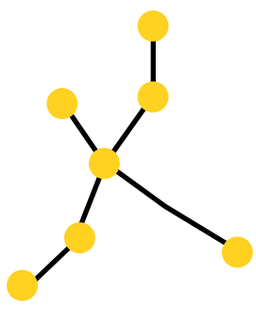


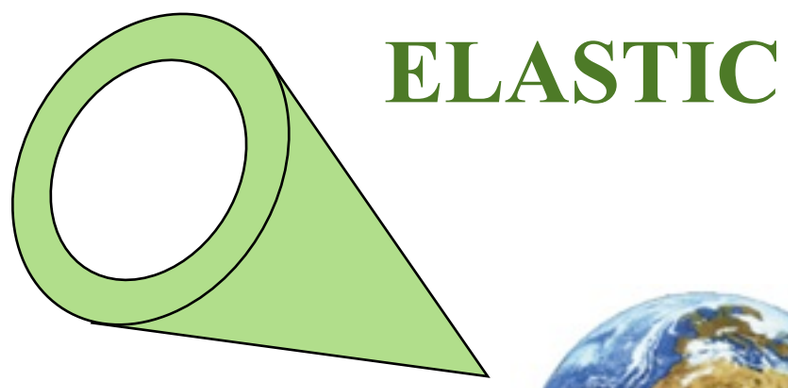
Directional Signatures

✦ Dark Matter stream

$$f(\vec{v}) \propto \delta(\vec{v} - \vec{v}_{\text{stream}})$$







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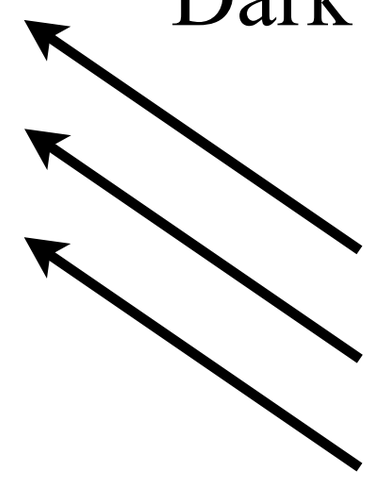

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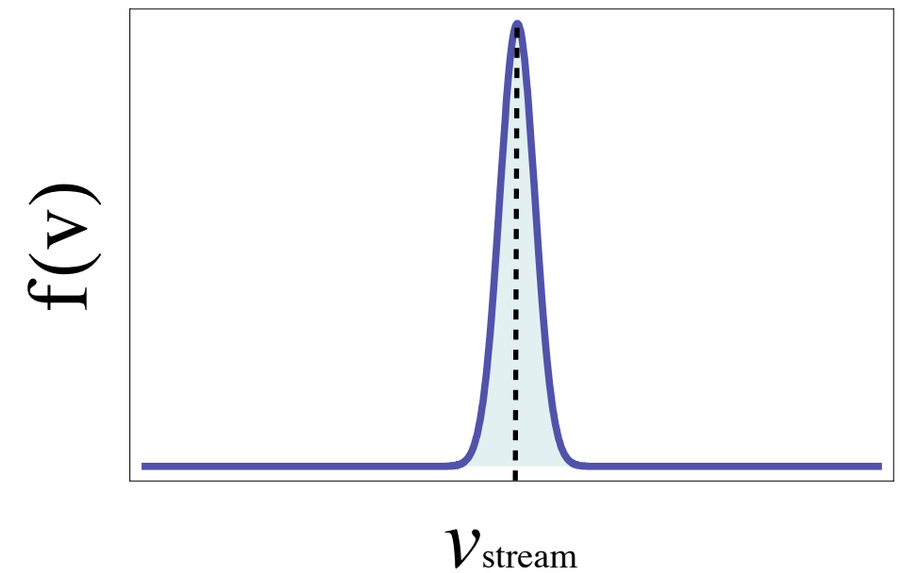

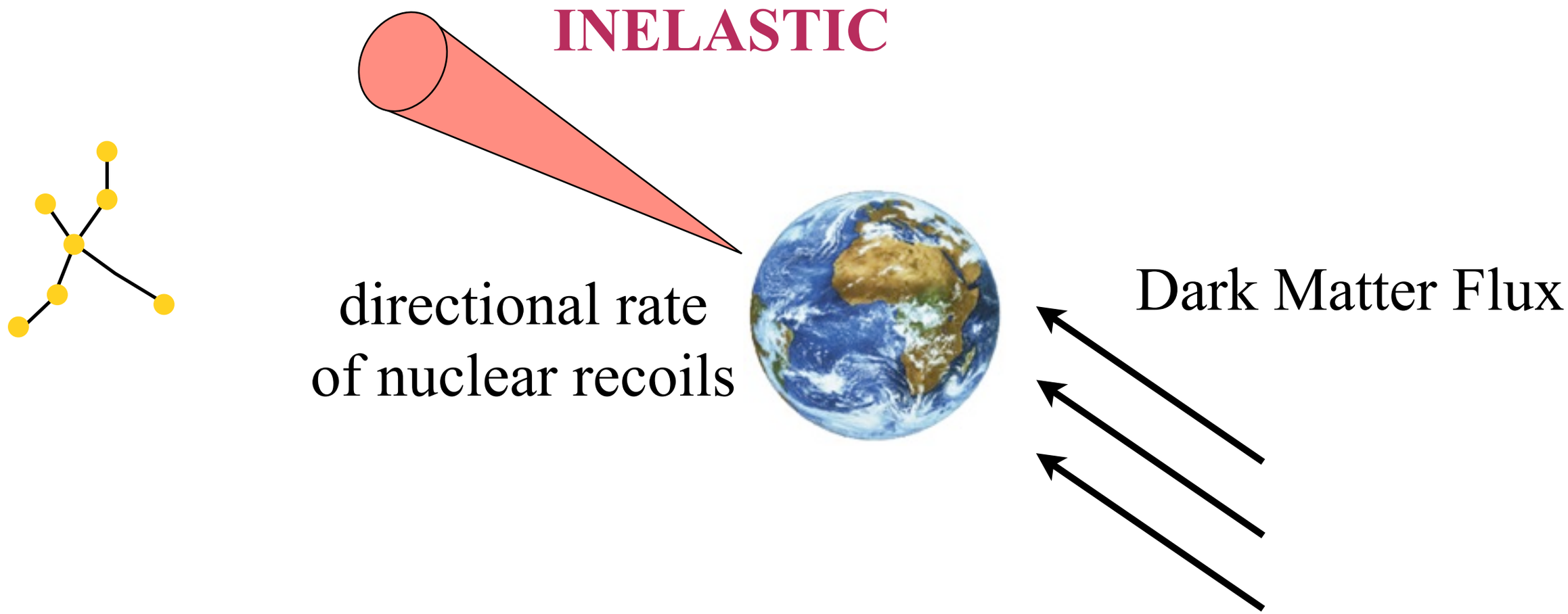

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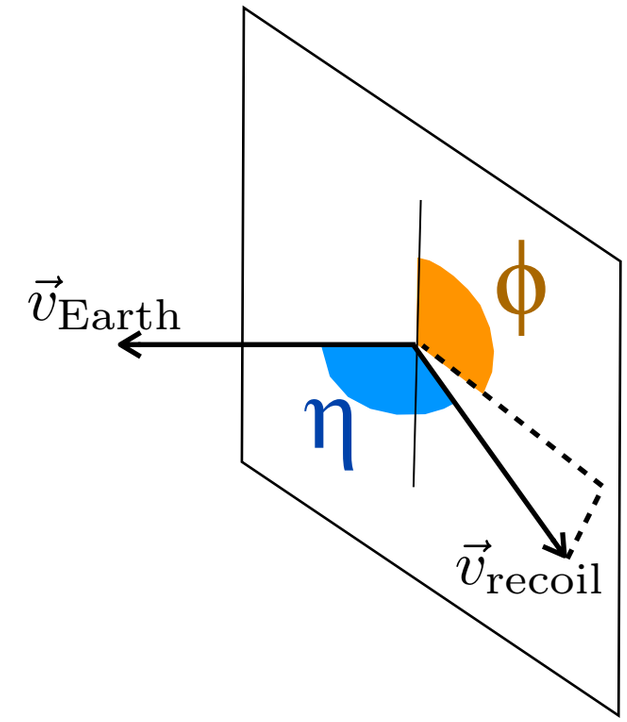

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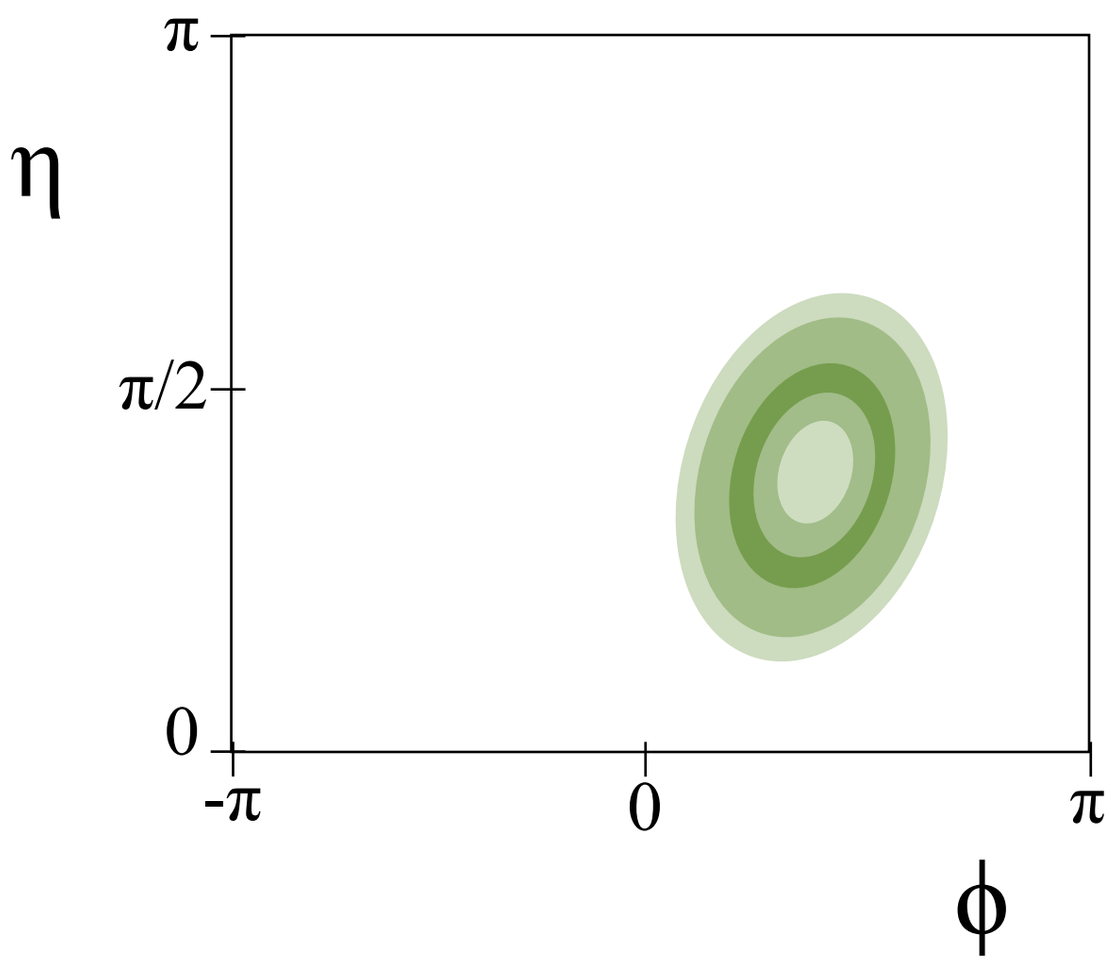
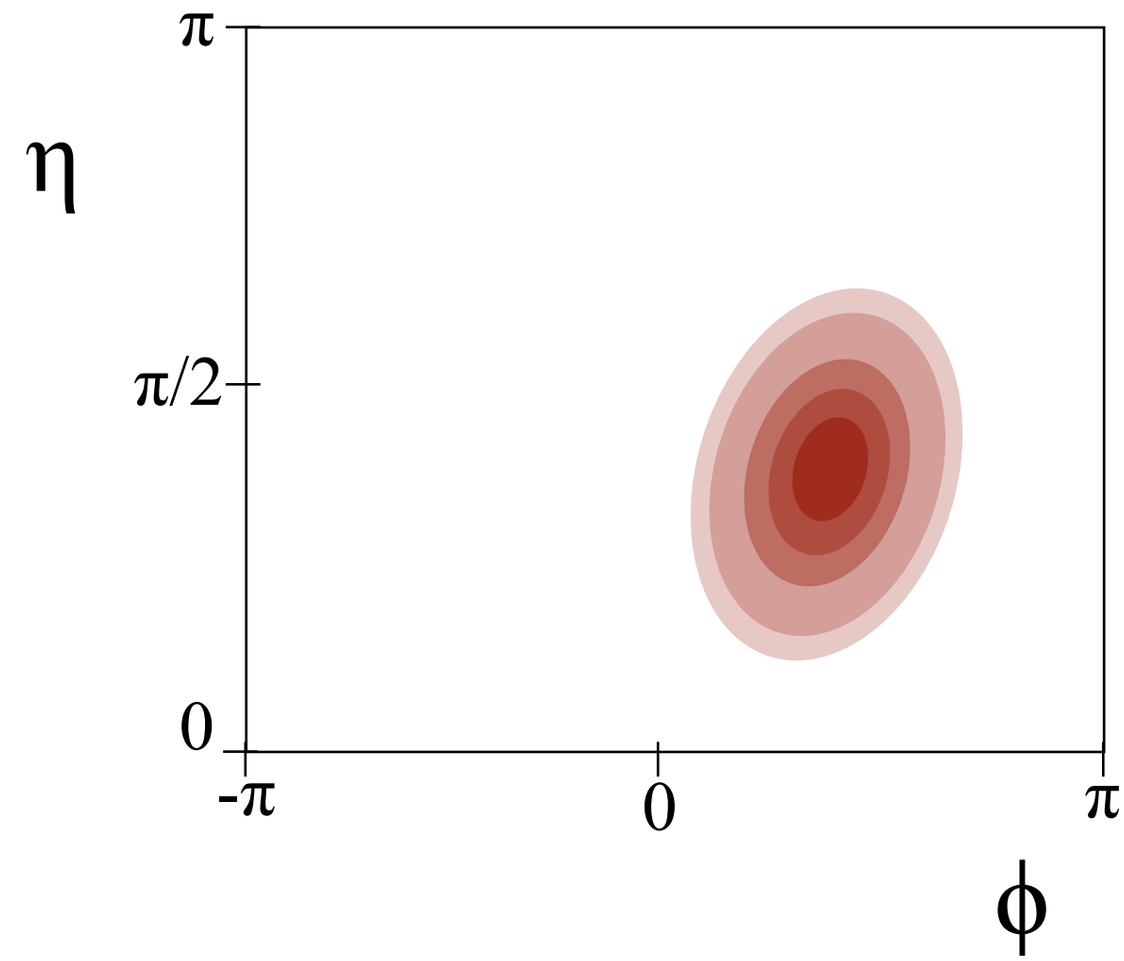
ELASTIC

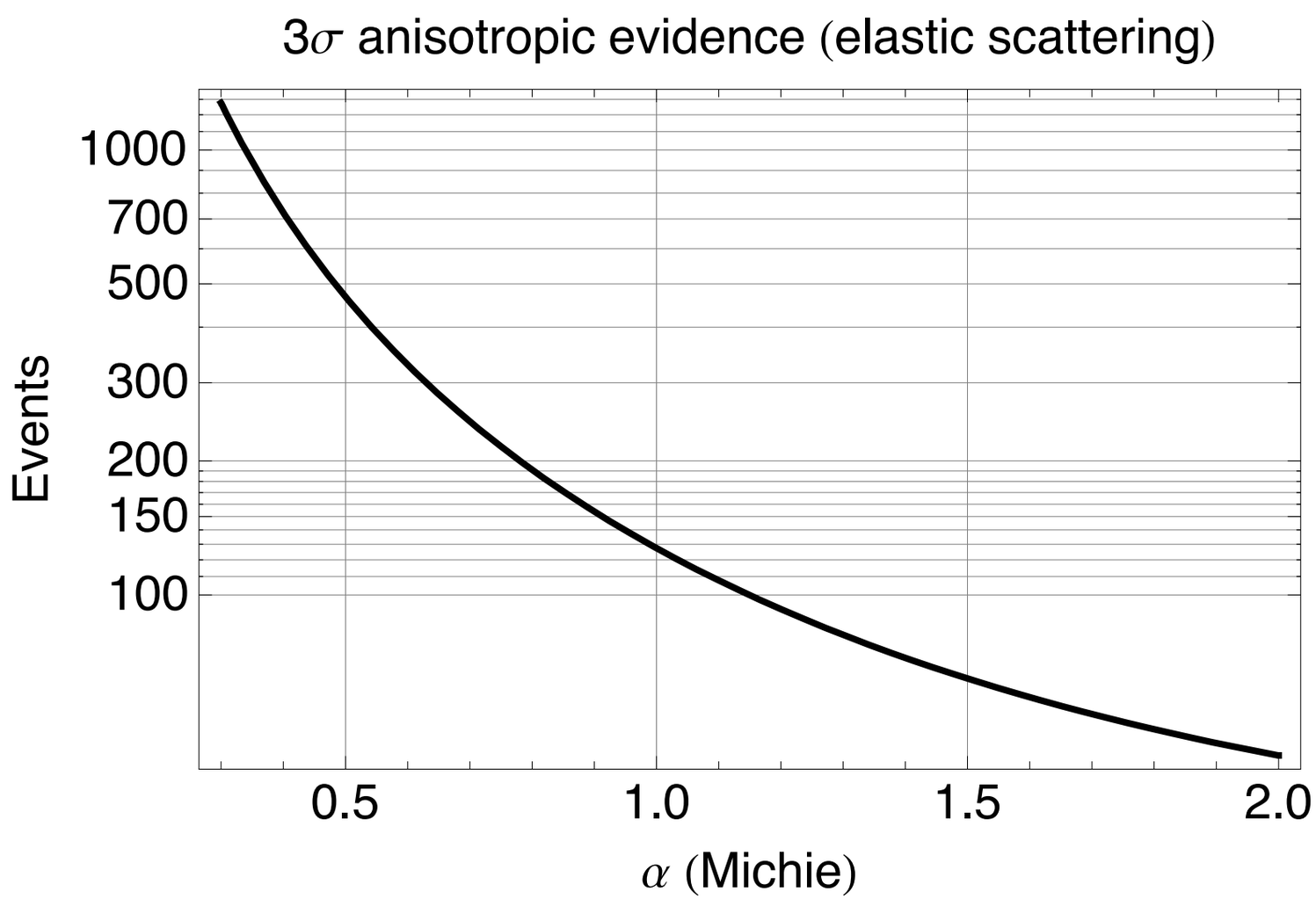


INELASTIC



Statistics...

- Significant number of events needed to detect anisotropy
- Prelim studies: promising if iDM of light DM are correct explanations for DAMA and/or CoGeNT



- Not so optimistic for heavy elastic WIMP

We can learn more

Local velocity distribution
+
Halo Stability

→

Global
dark matter profile

Jeans Theorem

Any steady-state solution of the collisionless Boltzmann equation depends on the phase-space coordinates only through integrals of motion, and any function of the integrals is a steady-state solution of the collisionless Boltzmann equation

$$f(\vec{v}, \vec{r}) = f(E, L^2, L_z, ...)$$

✦ Isotropic Maxwellian distribution

$$f(\vec{v})_{\text{local}} \propto e^{-v^2}\ \Theta(v - v_{\text{esc}})$$

$$\Downarrow$$

$$f(\vec{v}, \vec{r})_{\text{global}} \propto e^{-E}\ \Theta(-E)$$

$$E = \frac{v^2}{2} - \Psi(r) \qquad\qquad \frac{v_{\text{esc}}^2}{2} = \Psi(r_0)$$

✦ Anisotropic Michie distribution

$$f(\vec{v})_{\rm local} \propto e^{\alpha' v_R^2}\ e^{-v^2}\ \Theta(v - v_{\rm esc})$$

$$f(\vec{v}, \vec{r})_{\rm global} \propto e^{-\alpha L^2}\ e^{-E}\ \Theta(-E)$$

$$E = \frac{v^2}{2} - \Psi(r) \qquad \frac{v_{\rm esc}^2}{2} = \Psi(r_0)$$

$$L = r\ v_T$$

Density Distribution

- Written in terms of integrals of motion, $f(E, L, L_z, ...)$ describes the global phase-space distribution

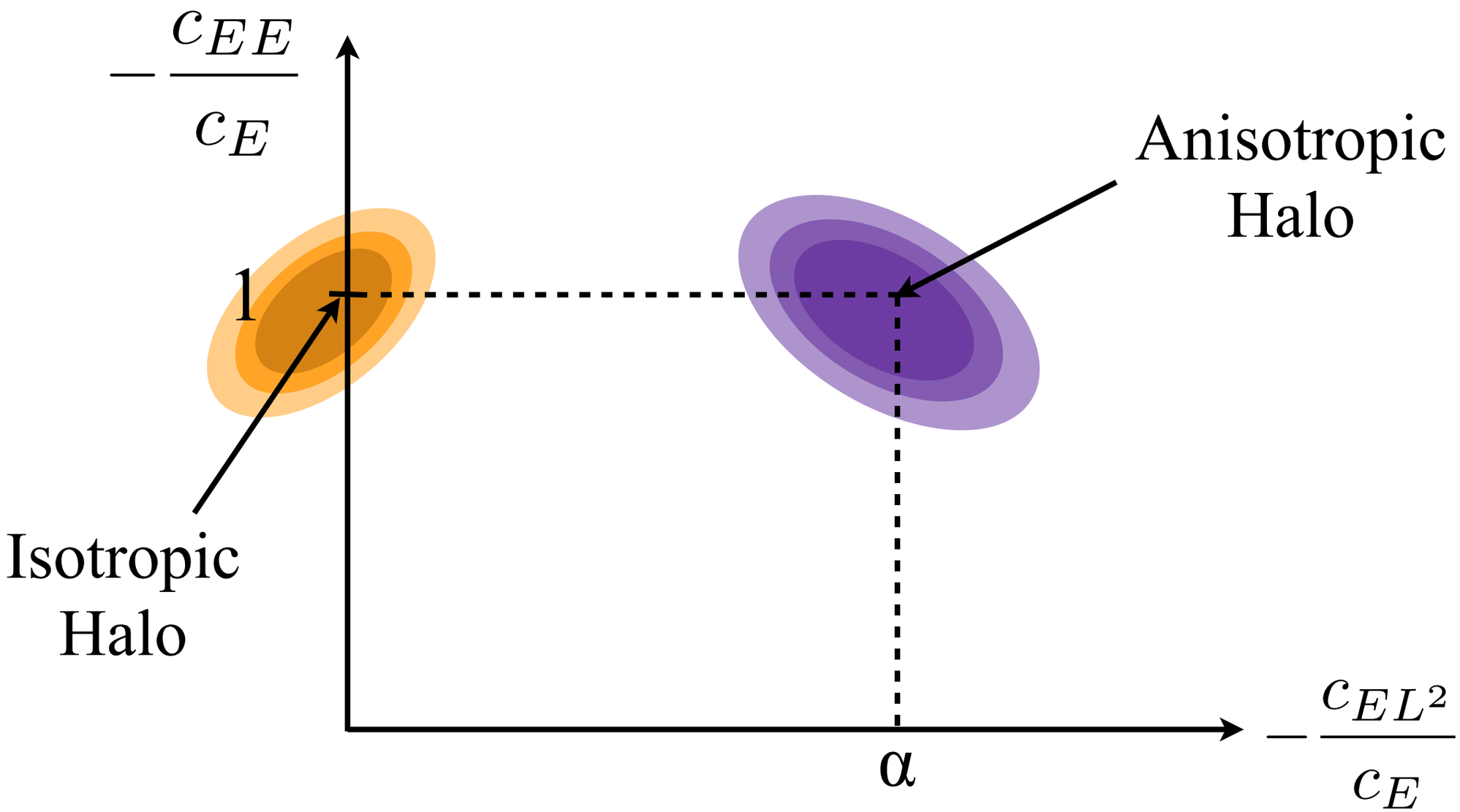
$$\boxed{f(E, L) = f\left(\frac{v^2}{2} - \Psi(r), rv_t\right)}$$

→ $\rho(r)$ is obtainable

$$\boxed{\begin{gathered}\rho(r) = \int d^3v \; f\left(\frac{v^2}{2} - \Psi(r), rv_t\right) \\ \nabla^2\Psi(r) = -\rho(r)\end{gathered}}$$

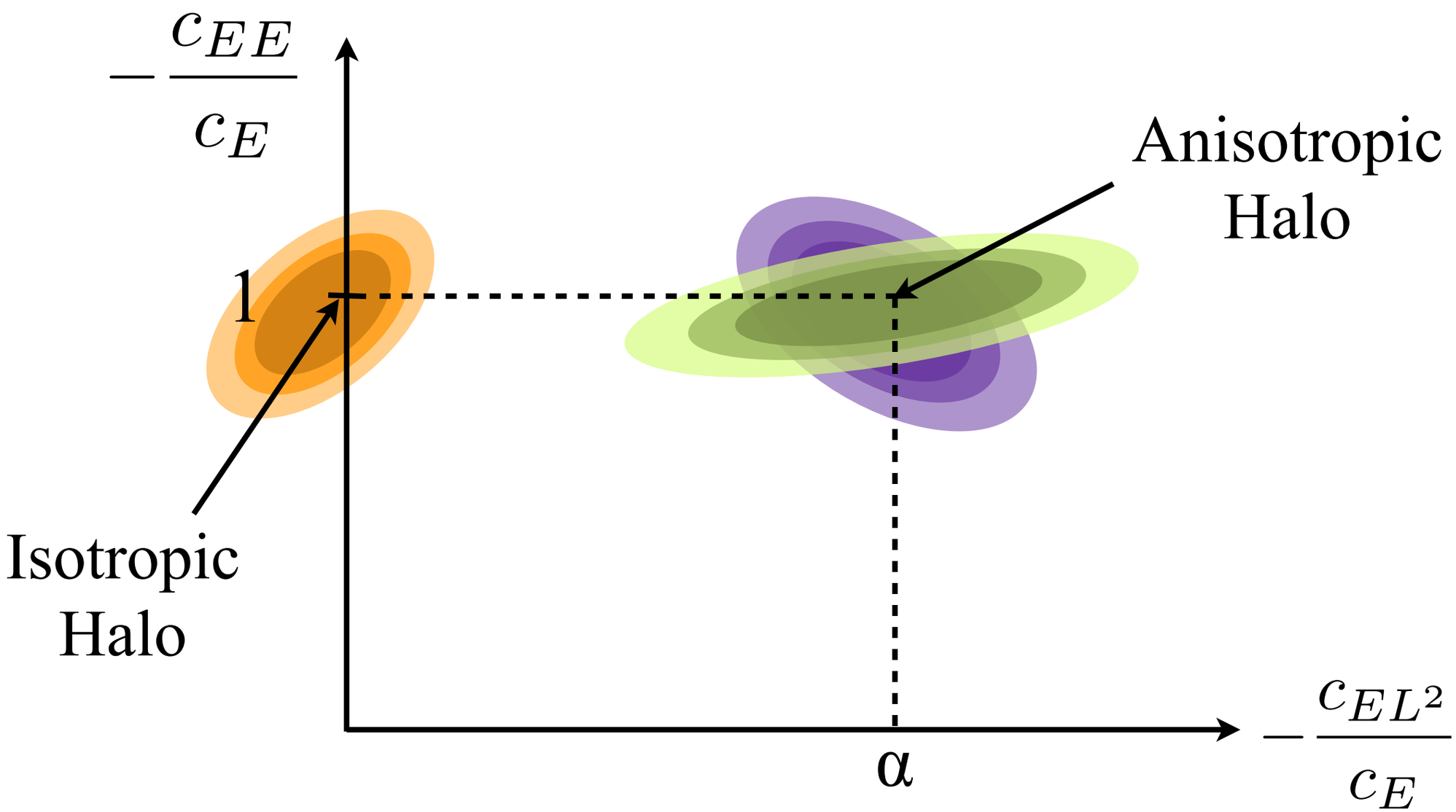
In practice

$$f(E,L) = c_0 \; + \; c_E E \; + \; c_{L^2} L^2 \; + \; c_{EE}\frac{E^2}{2} \; + \; c_{L^4}\frac{L^4}{2} \; + \; c_{EL^2} E \, L^2 \; + \; \ldots$$



In practice

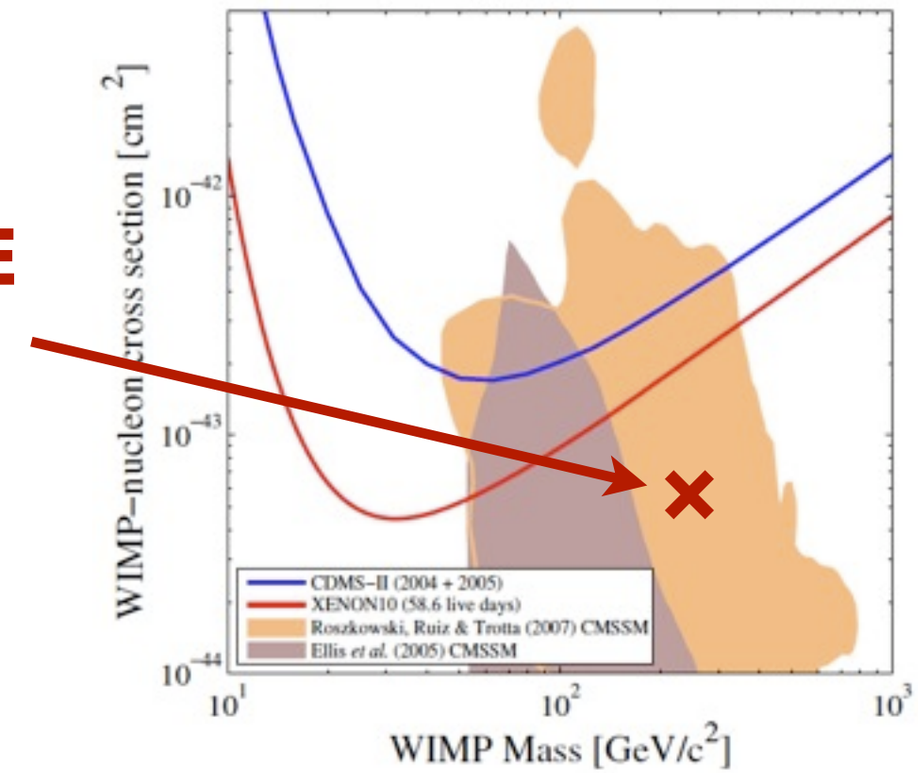
$$f(E,L) = c_0 \; + \; c_E E \; + \; c_{L^2} L^2 \; + \; c_{EE}\frac{E^2}{2} \; + \; c_{L^4}\frac{L^4}{2} \; + \; c_{EL^2} E \, L^2 \; + \; \ldots$$



Closing Remarks

- Direct detection will tell us more than

YOU ARE HERE



- In case of a positive signal, we will have the opportunity to learn about the DM interactions with the SM...

- ... and to infer local and global properties of DM profile

- That will be complementary to what collider and indirect detection will tell us

Thank You