SEEING THE LIGHT OF DARK MATTER

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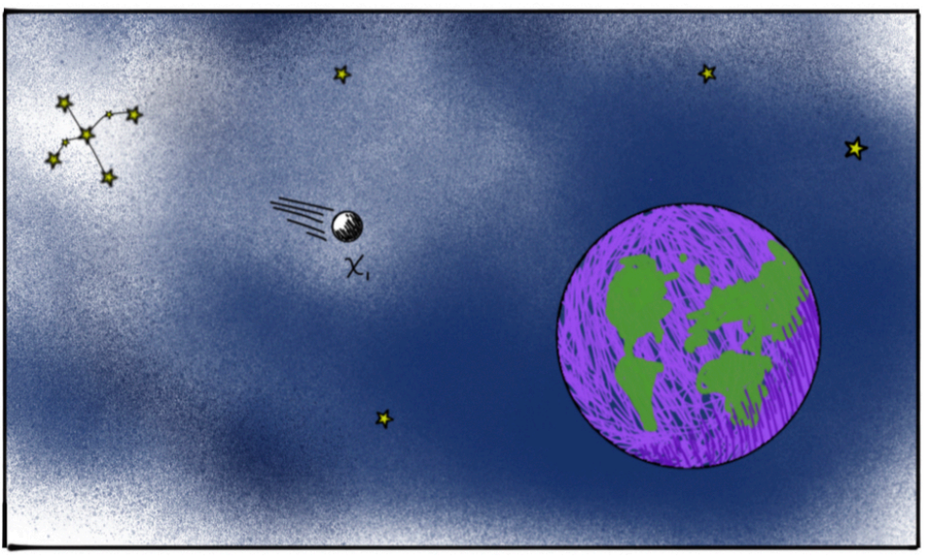
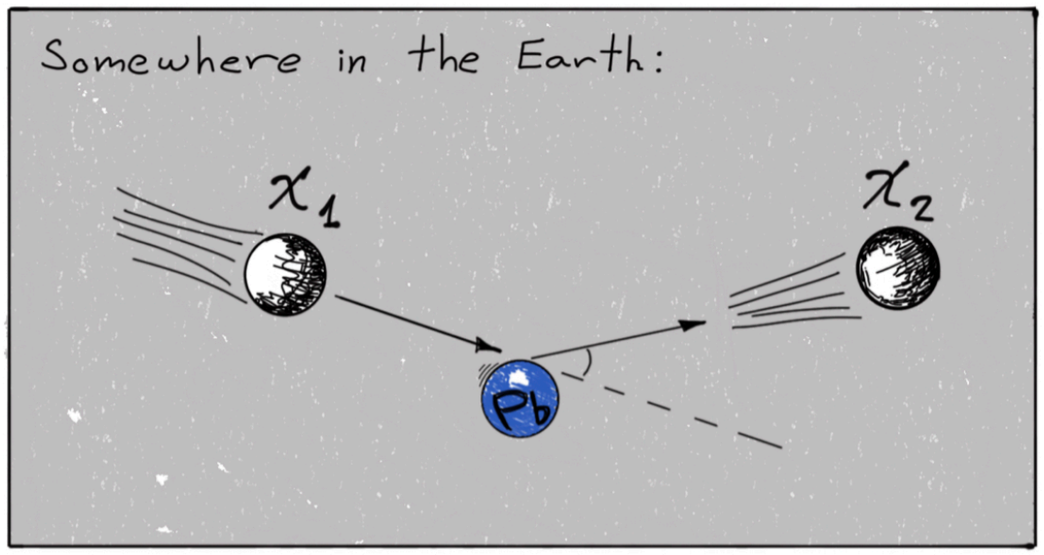
arXiv: 1904.09994

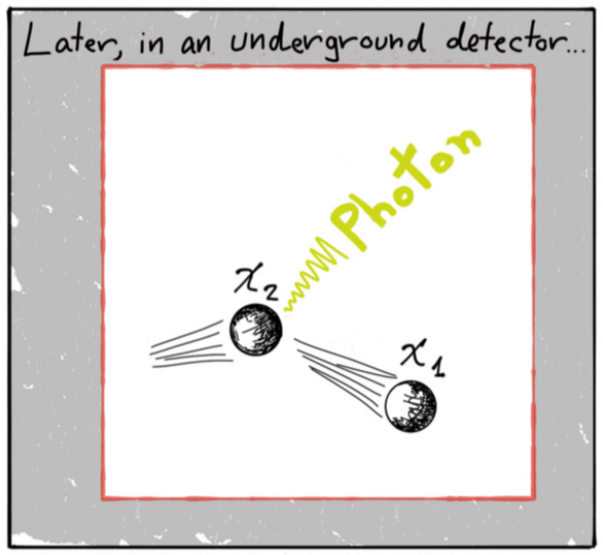
TAMU, MAY 2019

BASIC IDEA

USE ENTIRE EARTH AS UPSCATTER TARGET







FOR INELASTIC DARK MATTER WHERE

$\chi_1 + N \rightarrow \chi_2 + N$ $\qquad$ $\chi_2 \rightarrow \chi_1 + \gamma$

AND WE SEEK THE MONOENERGETIC PHOTON IN

LARGE UNDERGROUND DETECTOR

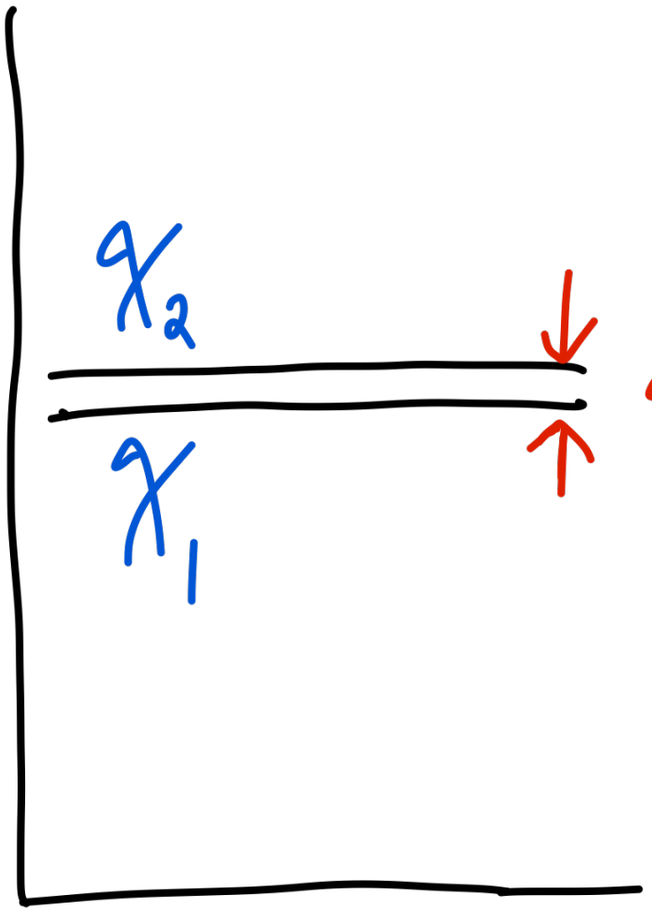
QUICK REVIEW: INELASTIC DM

INELASTIC DARK MATTER

[HALL, MORIOI, MURAYAMA; TUCKER-SMITH, WEINER ...]

DARK MATTER HAS AN EXCITED STATE

WITH A VERY SMALL MASS SPLITTING.

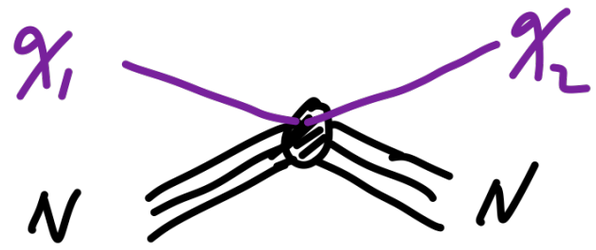


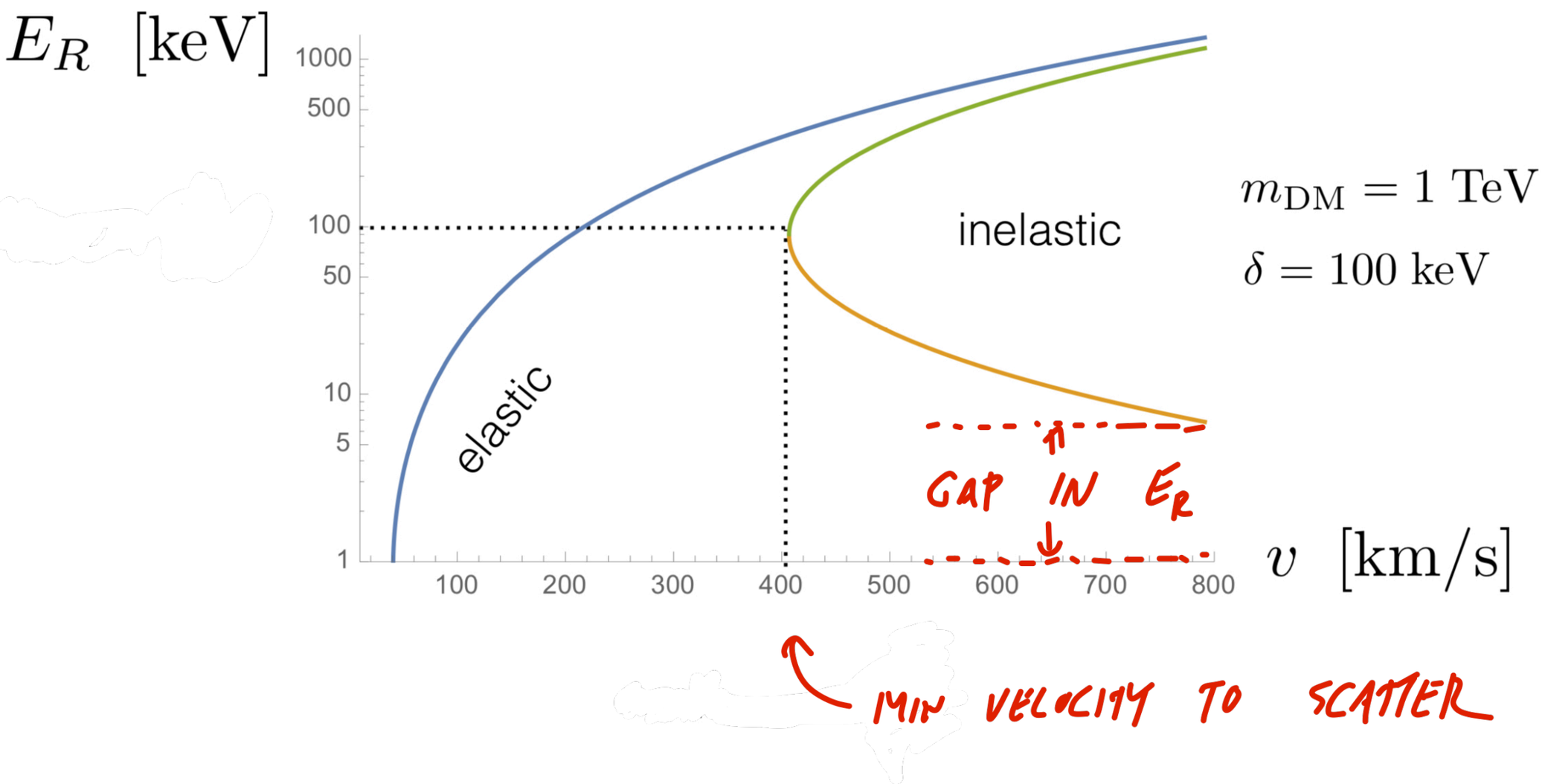
$\Delta m \equiv \delta \lesssim 600$ keV

$\sim \frac{1}{2} \mu v^2$

KINEMATICS

SCATTERING DOMINATED BY INELASTIC PROCESS





Bramante, Fox, GK, Martin

HEAVY DM MAXIMIZES SCATTERING

$$v_{min} = \sqrt{\frac{2\delta}{\mu}}$$

HEAVY DM

$m_{DM} \geq m_{Nuc}$

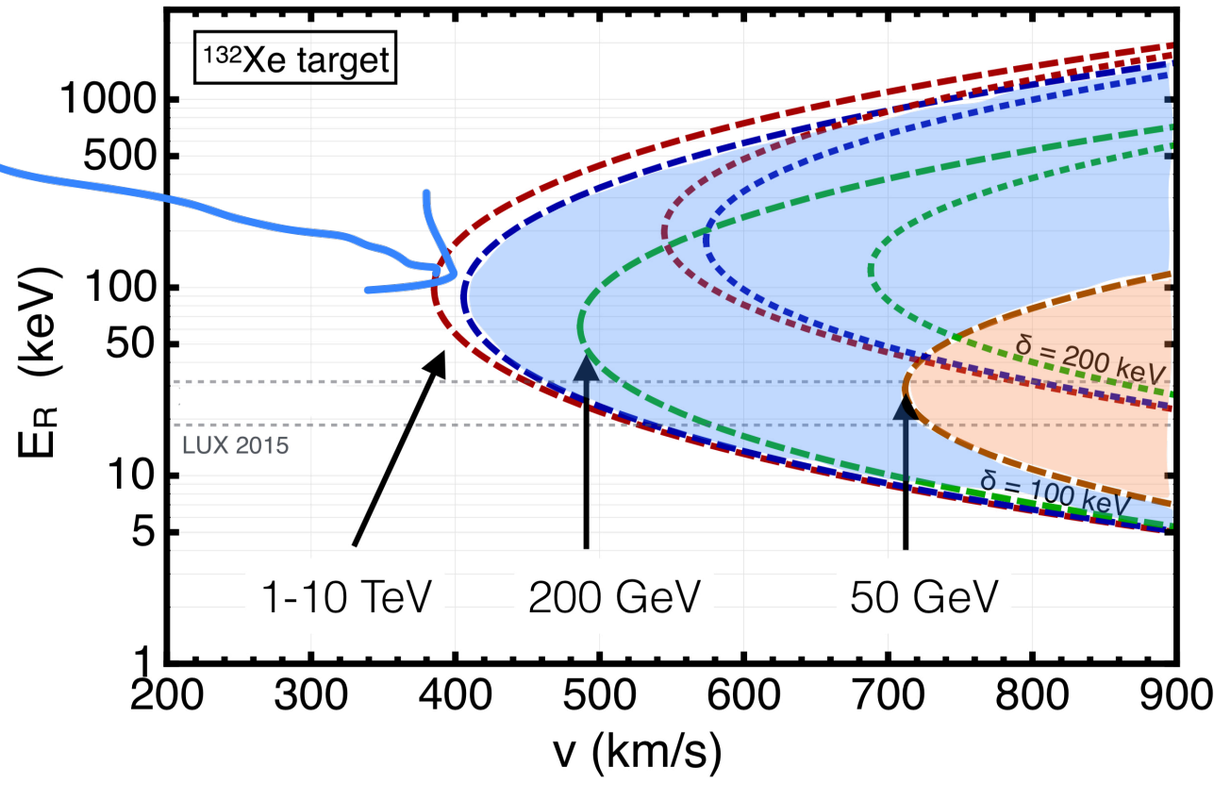
$v_{min} \simeq \sqrt{\frac{2\delta}{m_{Nuc}}}$

vs.

LIGHT DM

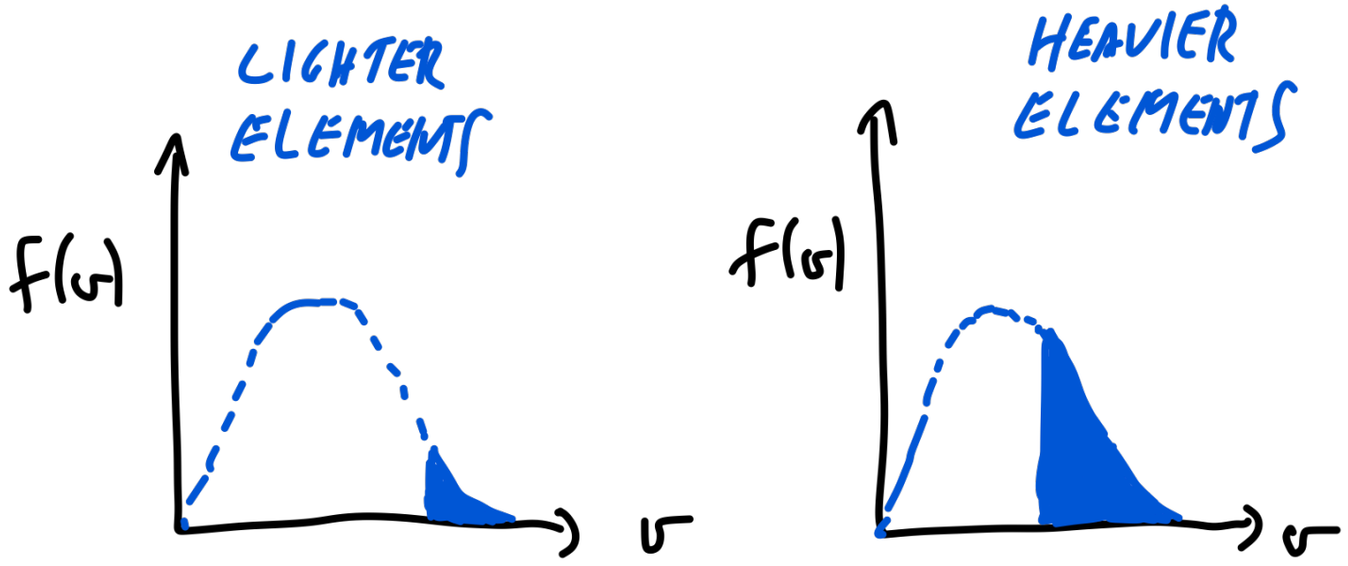
$m_{DM} \leq m_{Nuc}$

$v_{min} \simeq \sqrt{\frac{2J}{m_{DM}}}$



HEAVY ELEMENTS WANTED!

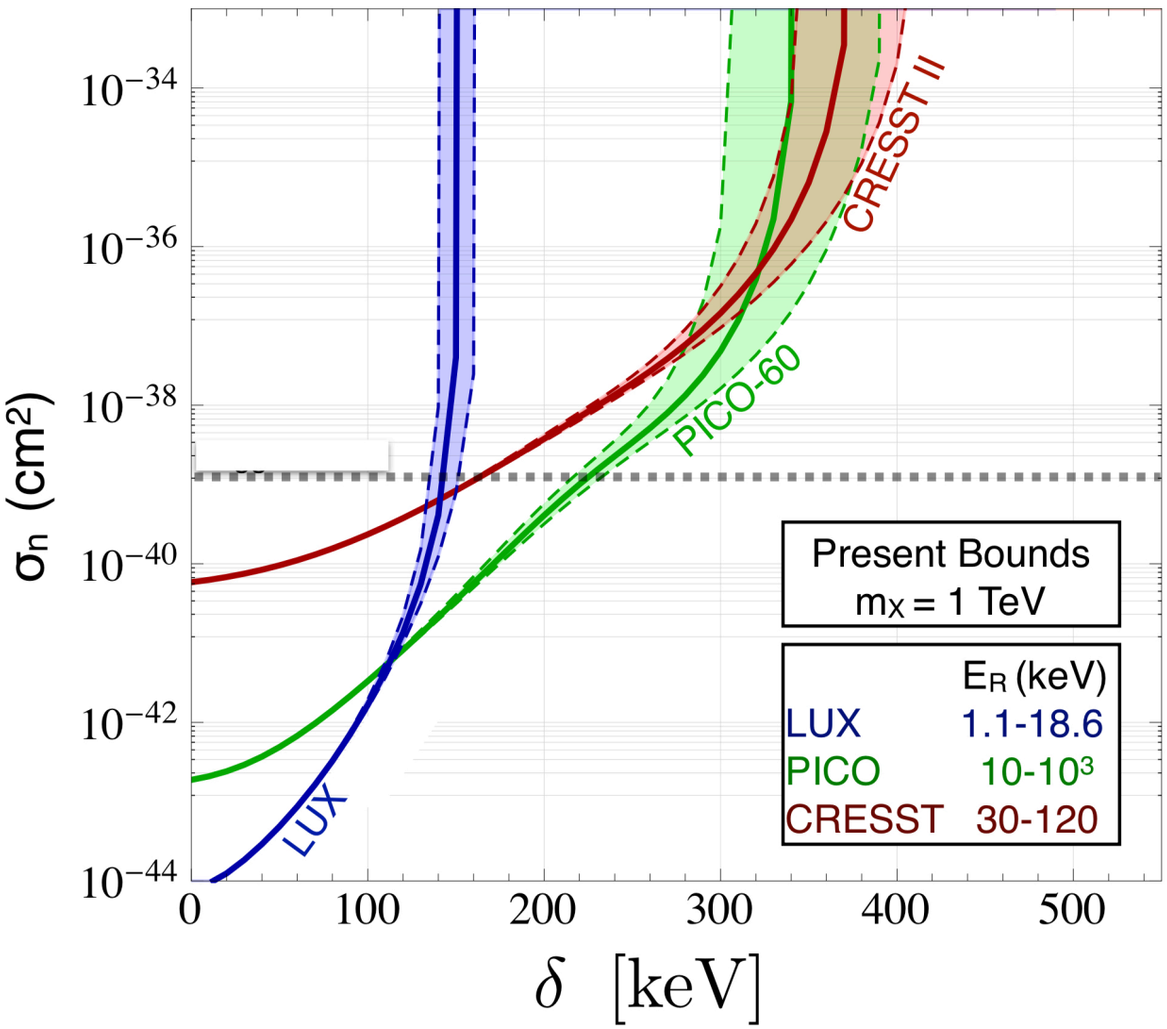
$$v_{min}\Big|_{E_R,min} \simeq \sqrt{\frac{2\delta}{m_{NUC}}}$$



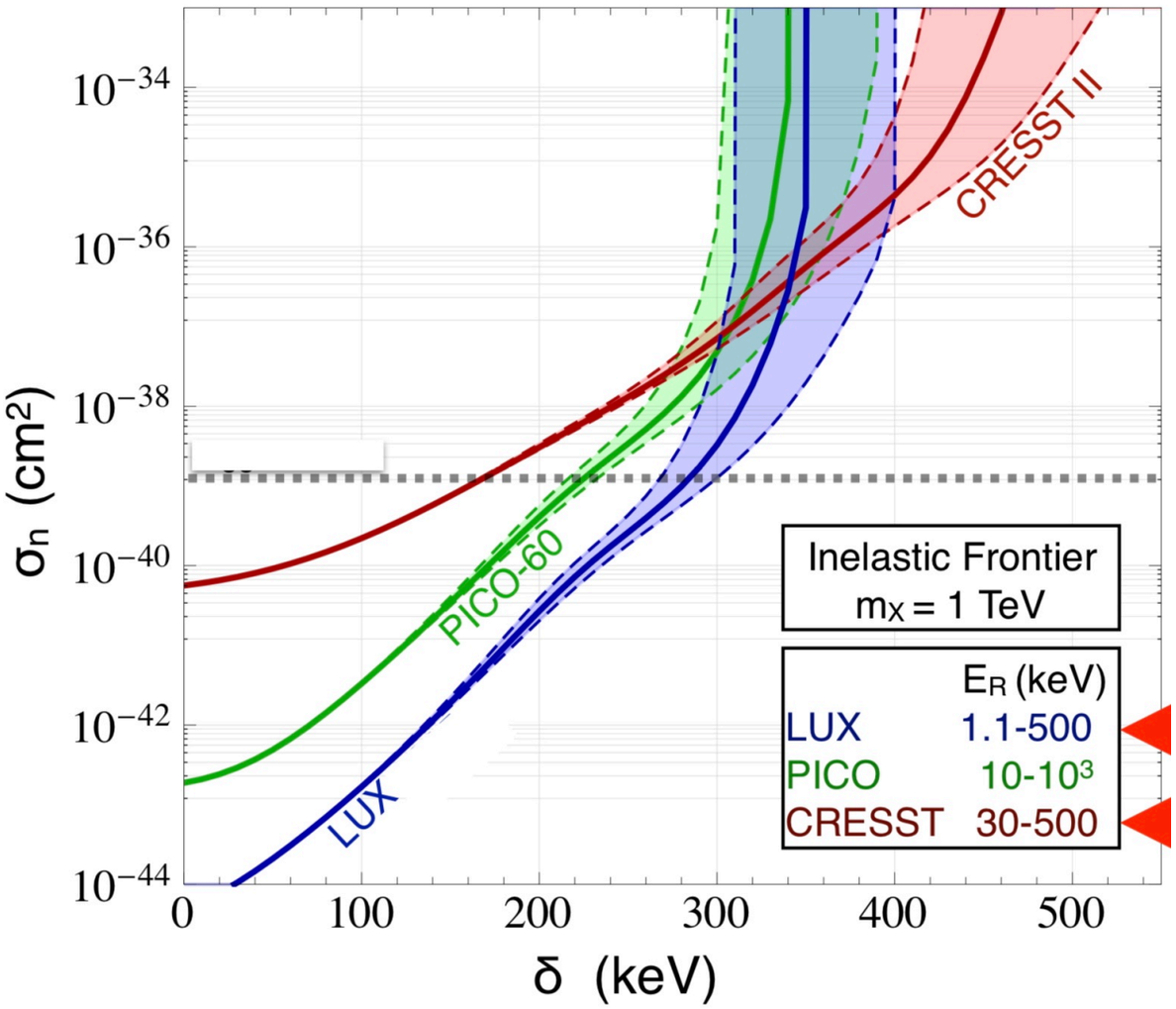
MUCH LARGER RATE!

INELASTIC PARAMETER SPACE

OUR BOUNDS IN 2016



OUR PROJECTED IMPROVEMENT

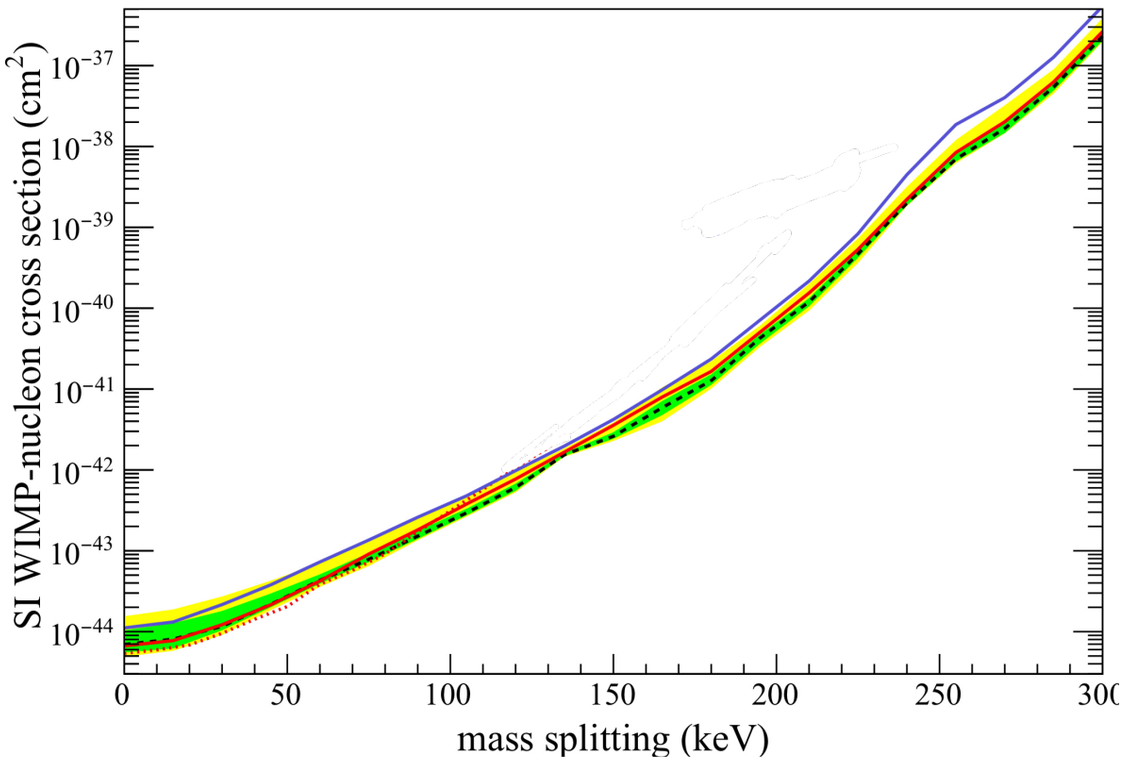


Bramante, Fox, GK, Martin

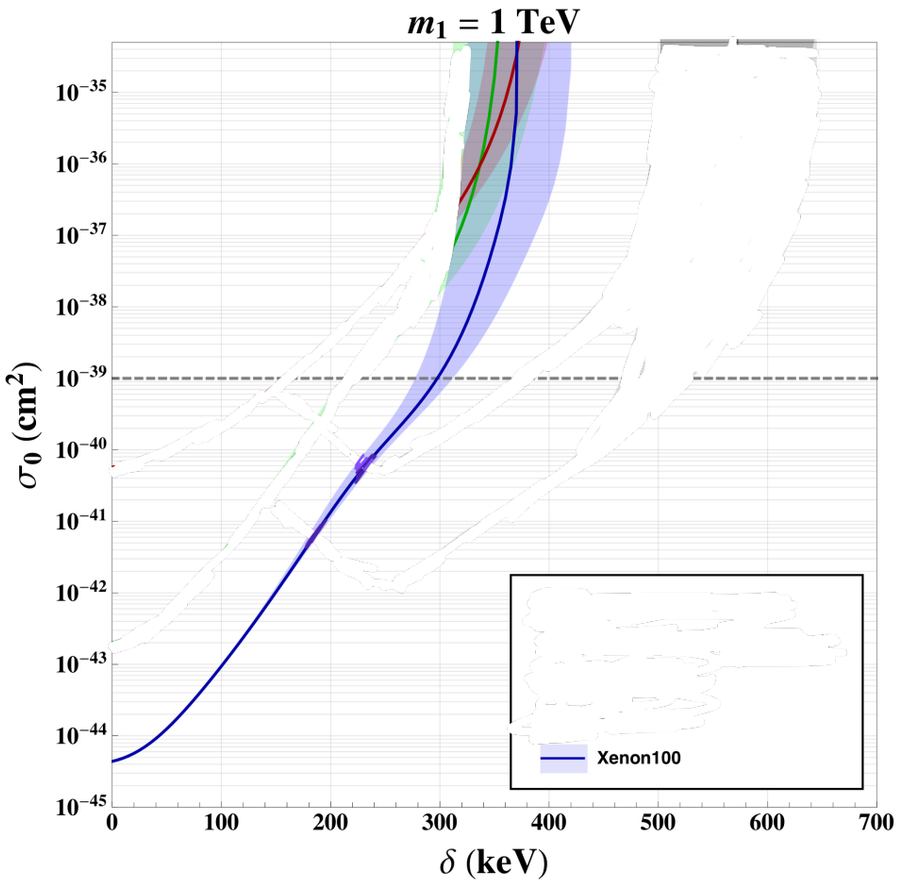
1608.02662

PANDAX & XENON100 LISTENED!

PANDAX: 1708.05825



XENON100: 1705.06655



MODELS

→ NARROWLY SPLIT HIGGSINO (FOX, GK, MARTIN)

$\sigma(S.I.) \ll 10^{-47}\ cm^2$

$\sigma(iDM) \sim 10^{-39}\ cm^2$ (Z EXCHANGE!)

→ MAGNETIC INELASTIC*

- LUMINOUS DM (FOR DAMA; RULED OUT)
- TWO-STEP (EXCITE OFF LEAD SHIELDING → RULED OUT* BY BRAMANTE, FOX, GK, MARTIN)

→ ...

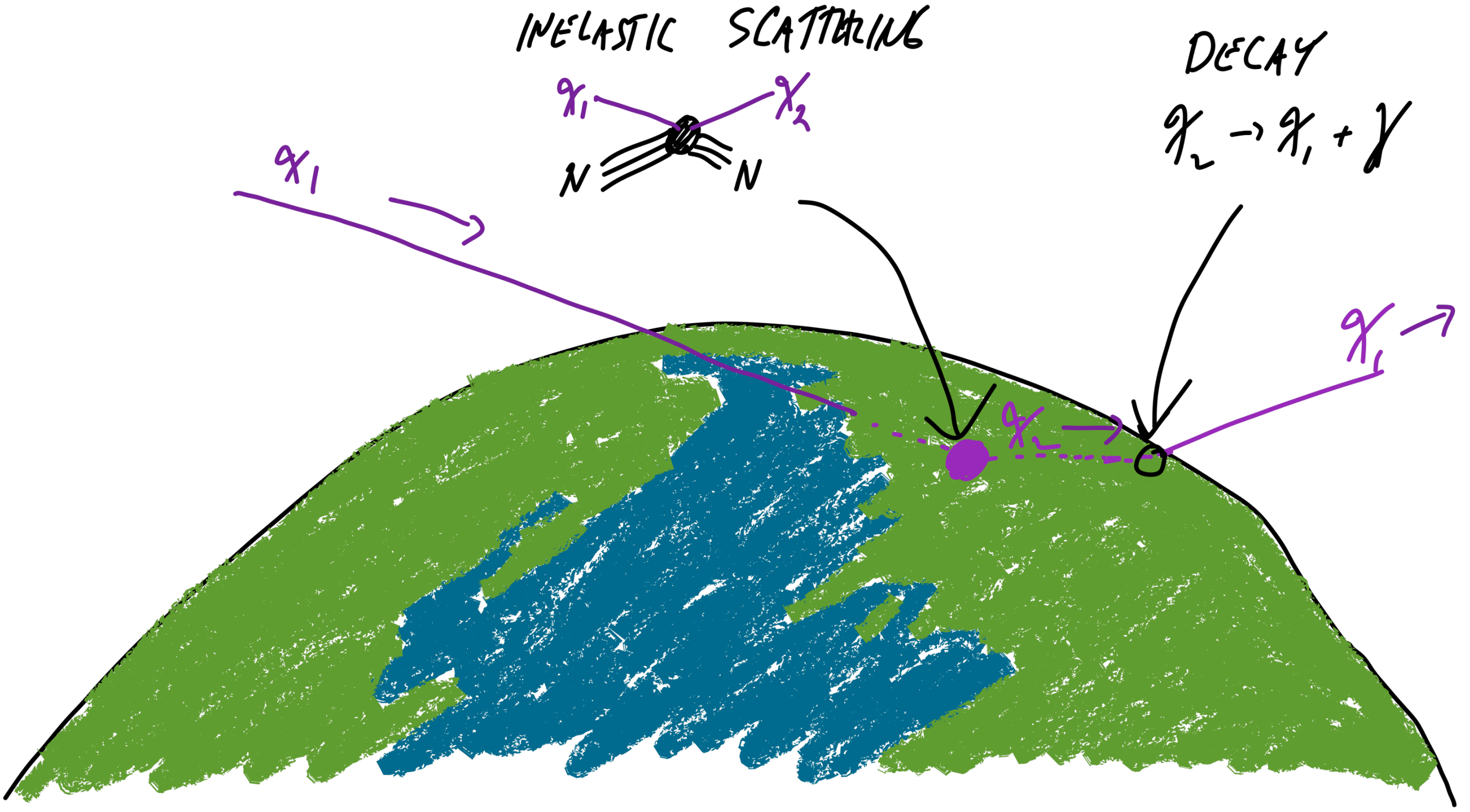
*ASK ME LATER

ASSUME $\sigma(iDM;\ \delta \to 0)$ ARBITRARY

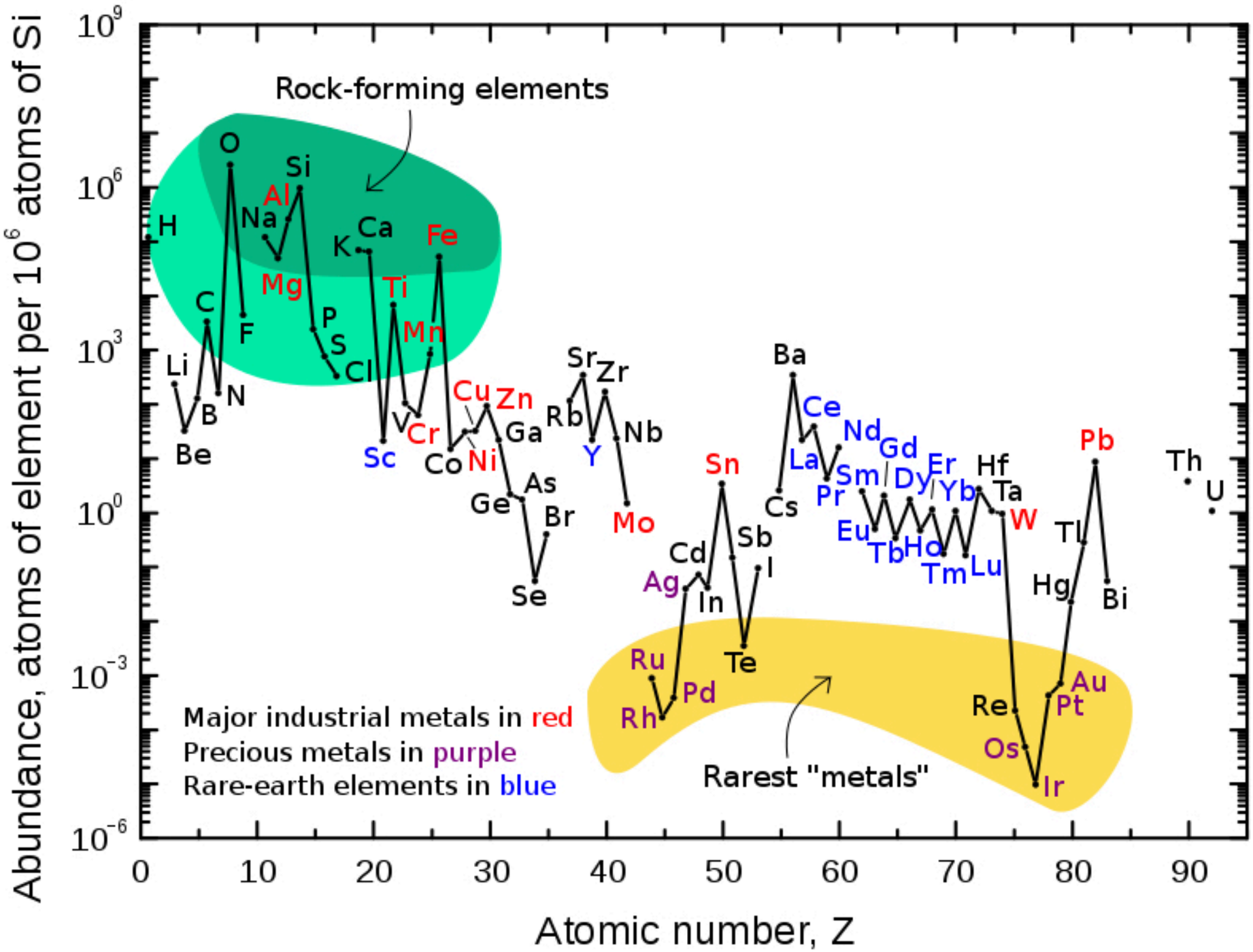
(AND FREE FROM CONSTRAINT ON $\sigma(S.I.)$)

HOW TO GET EXCITED?

EARTH AS AN UPSCATTER TARGET



EARTH COMPOSITION 101



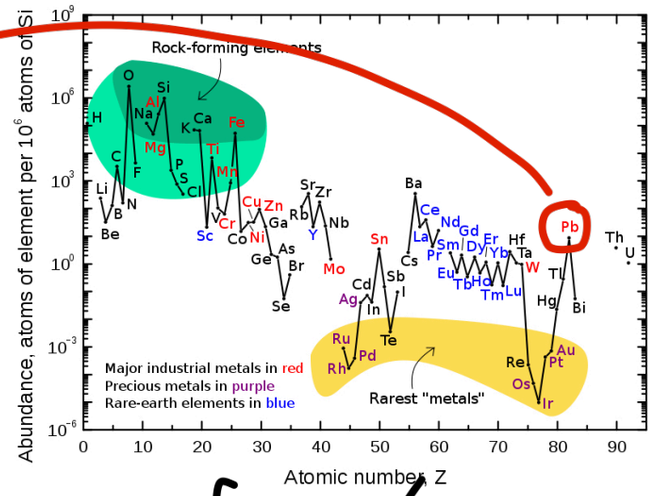
WIKIPEDIA

EARTH COMPOSITION 101

$Z = 82$

$A \sim 206$

LEAD



AVG ABUNDANCE : 10^{-5} g/g

ISOTOPES POPULATED BY RADIOACTIVE DECAY:

$^{238}U \rightarrow {}^{206}Pb$

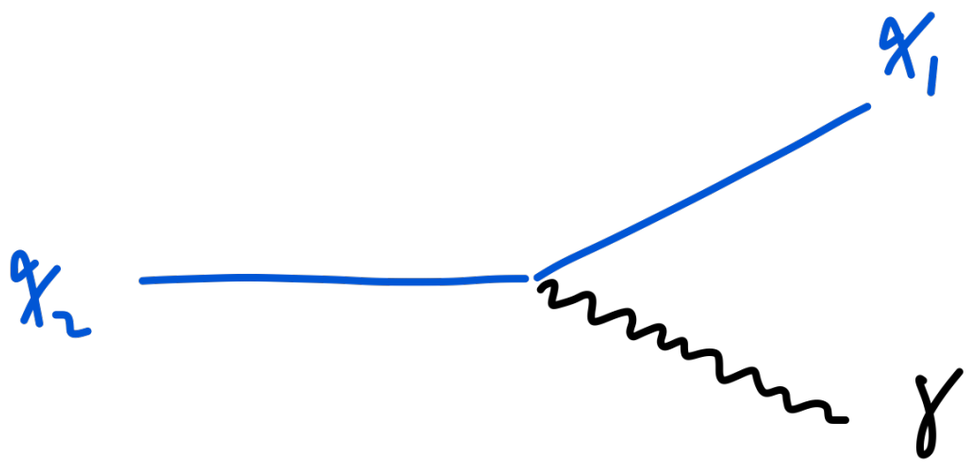
$^{235}U \rightarrow {}^{207}Pb$

$^{232}Th \rightarrow {}^{208}Pb$

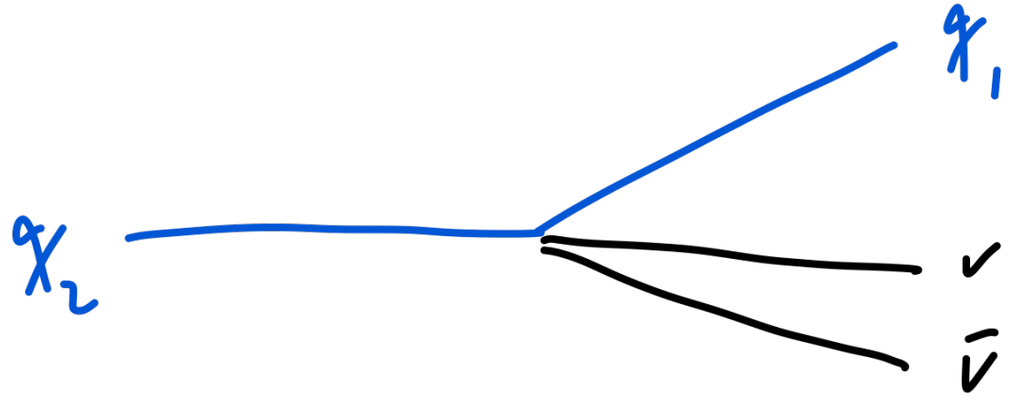
LED TO THE FIRST DECENT MEASUREMENT OF AGE OF EARTH: 4.55 Gyr (1956!)

How does excited state decay?

EXCITED STATE DECAY



$$\Gamma \sim \alpha_{EM}\,\alpha_W^2 \cdot \frac{\delta^3}{m_{\chi^\pm}^2}$$



$$\Gamma \sim \alpha_W^2 \cdot \frac{\delta^5}{m_Z^4}$$

RADIATIVE DECAY WINS $\begin{cases} \delta \lesssim \text{GeV} \\ m_{\chi^\pm} \sim m_{q^0} \end{cases}$

DECAY LENGTH

FOR RADIATIVE DECAY $(m_{\chi^\pm} \sim m_{\chi^0})$

$$\ell_{\chi_2} = \frac{cv}{\Gamma_{\chi_2 \to \chi_1 \gamma}} = 20\ \text{km} \left(\frac{cv}{400\ \text{km/s}}\right) \left(\frac{400\ \text{keV}}{\delta}\right)^3 \left(\frac{m_1}{1\ \text{TeV}}\right)^2$$

ROUGHLY

$\ell \sim 10 \to 1000$ km

$\delta \sim 100$ keV

$\delta \sim 550$ keV

MONOENERGETIC PHOTON SIGNAL

CYGNUS CONSTELLATION

χ_1

INELASTIC SCATTERING

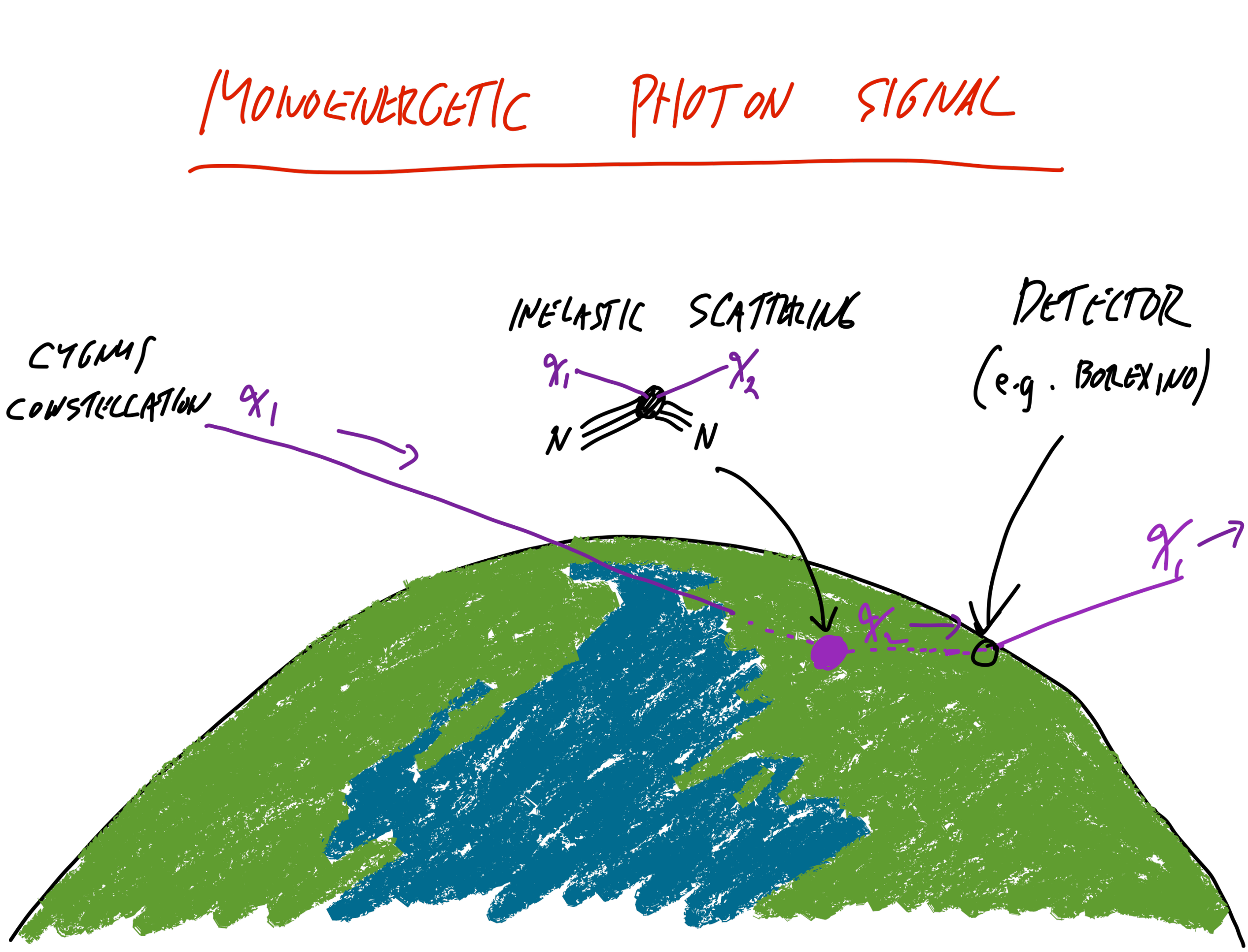
χ_1 χ_2

N N

DETECTOR (e.g. BOREXINO)

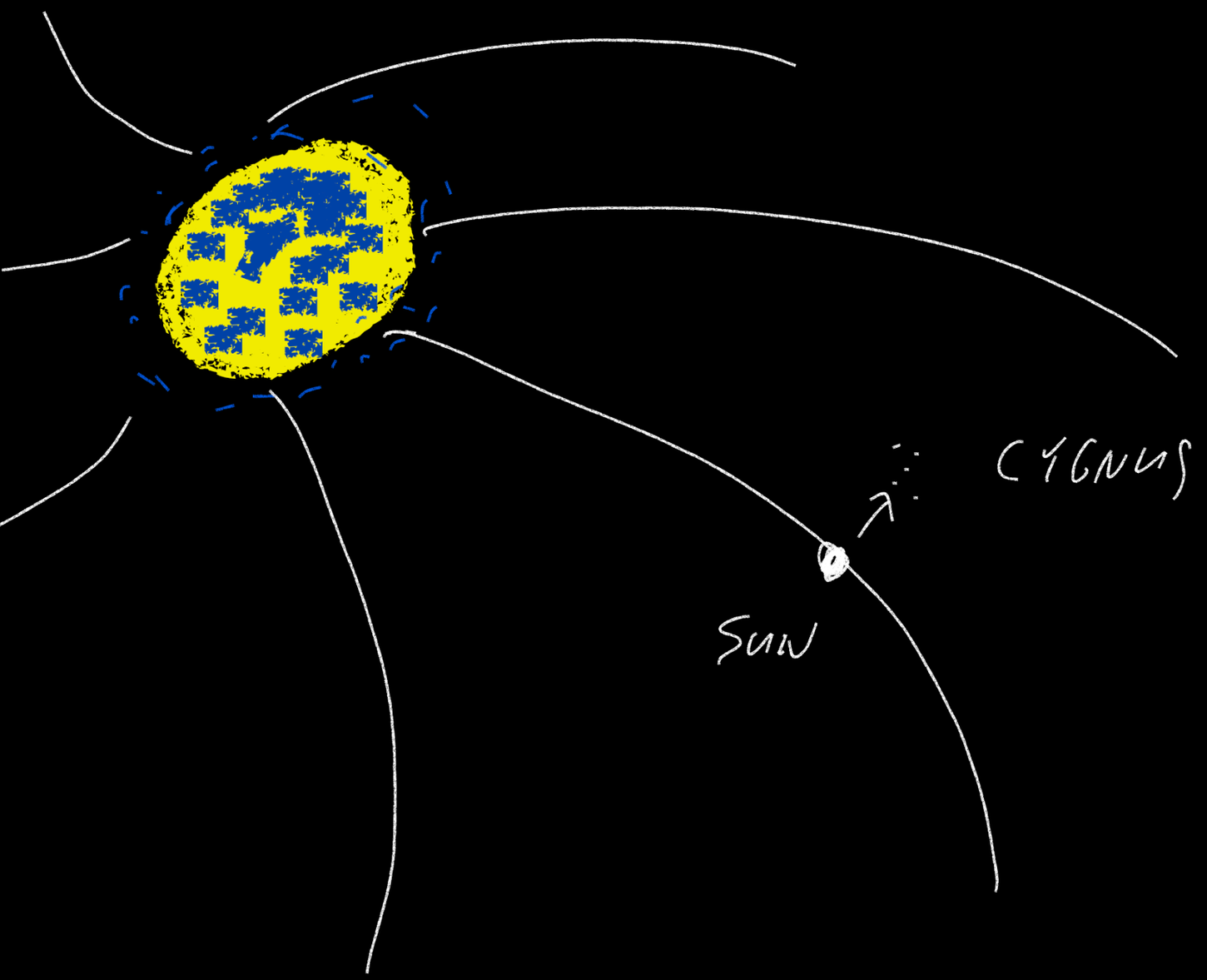
χ_1

χ_2



DIRECTIONALITY OF DARK MATTER WIND

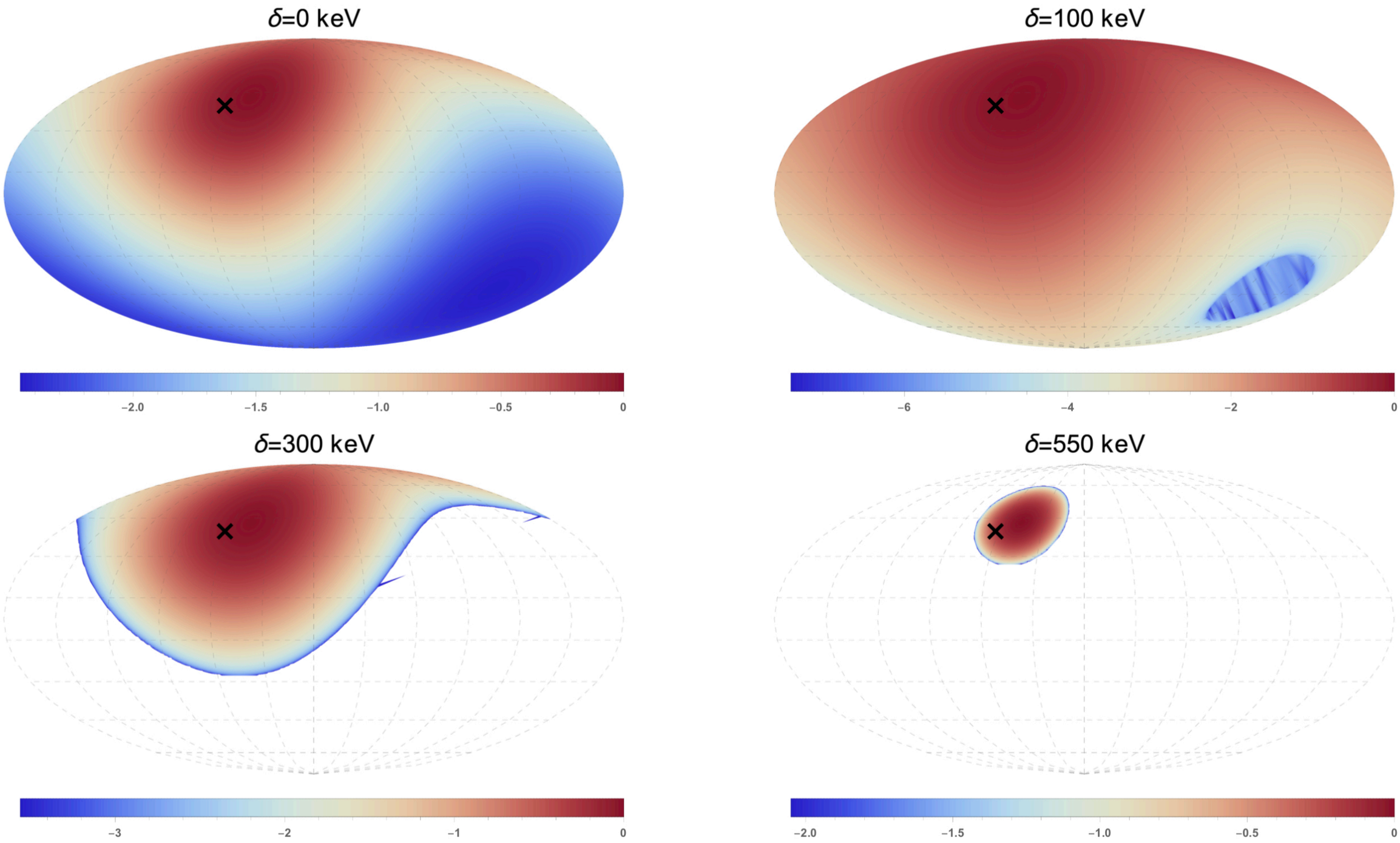
CYGNUS ?



⇒ SUN/EARTH ROTATING IN MILKY WAY "TOWARD" CYGNUS

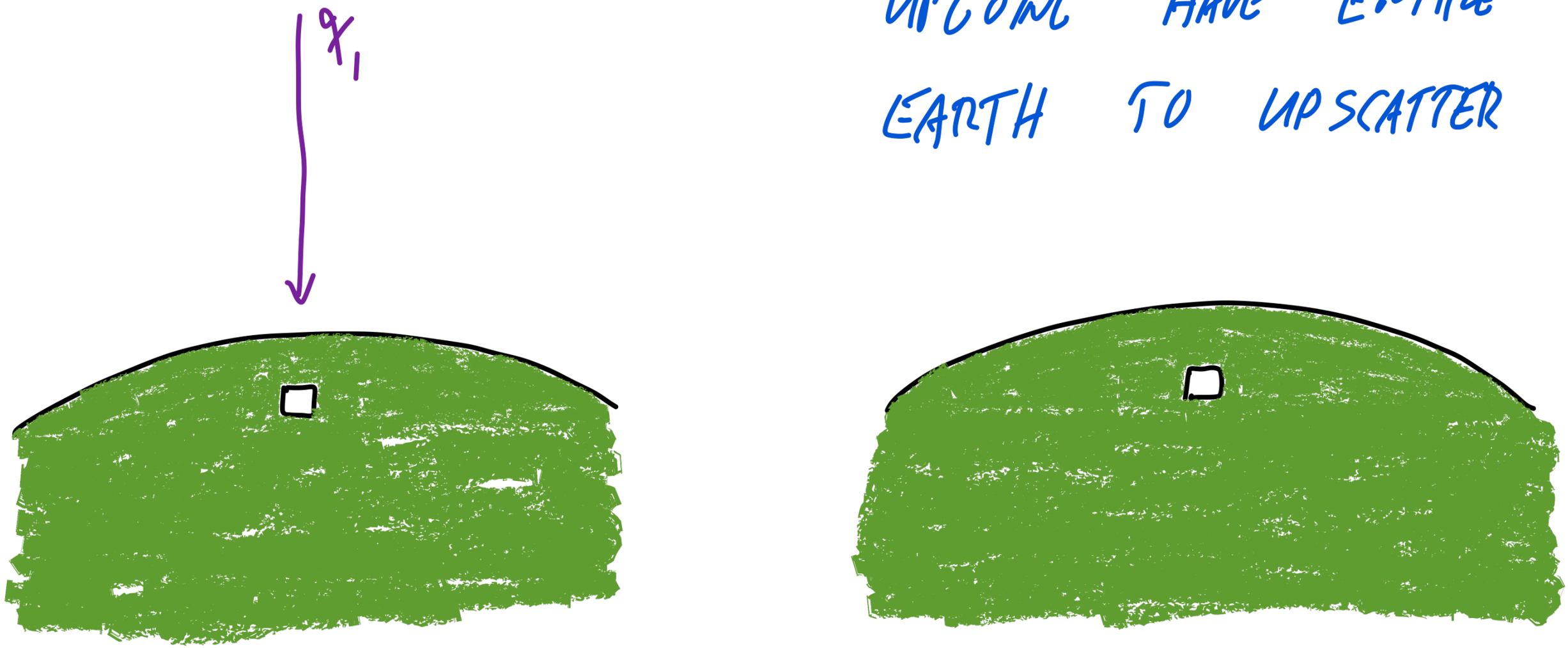
⇒ IN EARTH FRAME, DM APPEARS AS A WIND FROM CYGNUS

DIRECTIONALITY OF INELASTIC DM



MODULATION

UPCOMG HAVE ENTIRE EARTH TO UPSCATTER

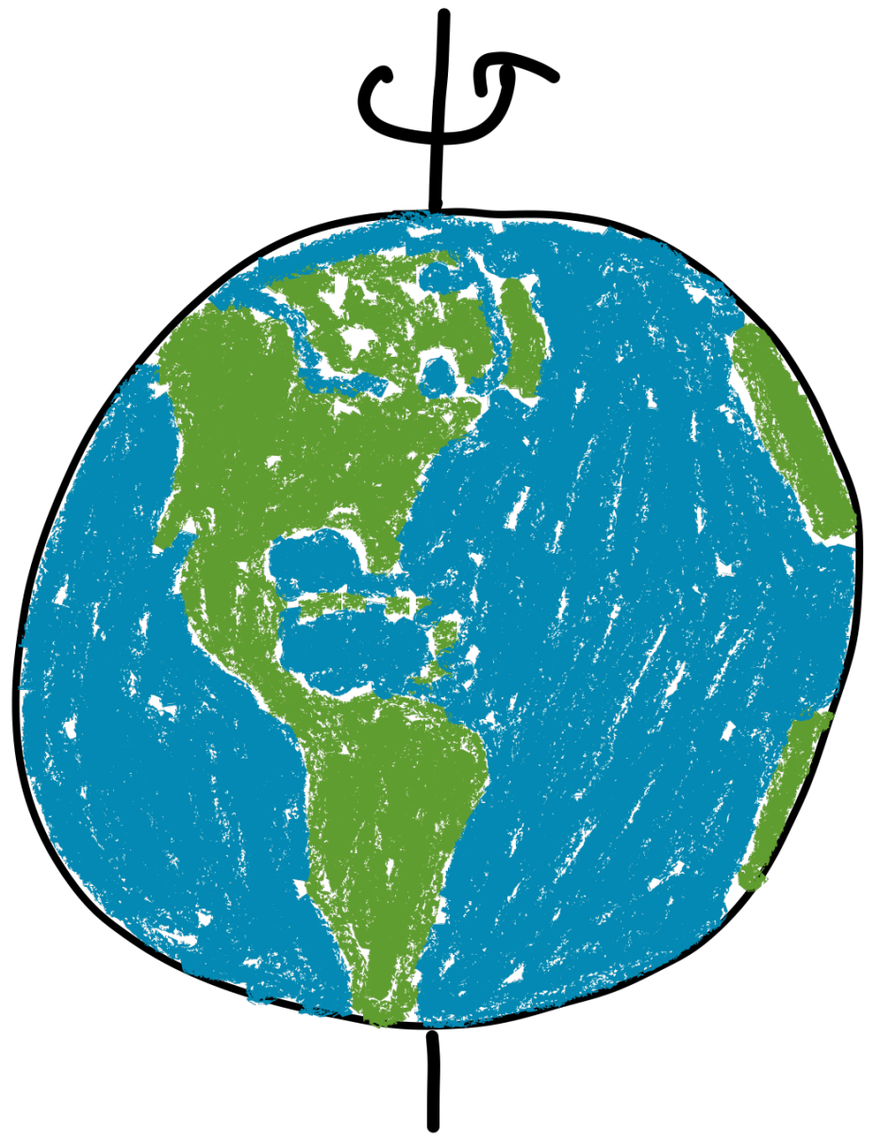


DOWNGOING CAN UPSCATTER ONLY IN ~ 1 km OVERBURDEN

SIDEREAL - DAILY MODULATION

WELL KNOWN FROM ASTRONOMY (& ASTROLOGY),

EARTH ROTATION PROVIDES REFERENCE FRAME



CONSTELLATIONS APPEAR AT SAME SIDEREAL TIME EACH SIDEREAL DAY

↑ 23h 56m

CYGNUS

CYGNUS IS A NORTHERN HEMISPHERE CONSTELLATION.

DECLINATION ~ 45° N

DETECTOR	VISIBICITY
$\gtrsim$ 45° N	ALWAYS RISEN
45° S - 45° N	PARTIAL
$\lesssim$ 45° S	ALWAYS SET

DETECTORS

→ LATITUDE MATTERS

→ DETECT ~ 100s keV PHOTON

→ LARGE VOLUME (NOT LARGE MASS)

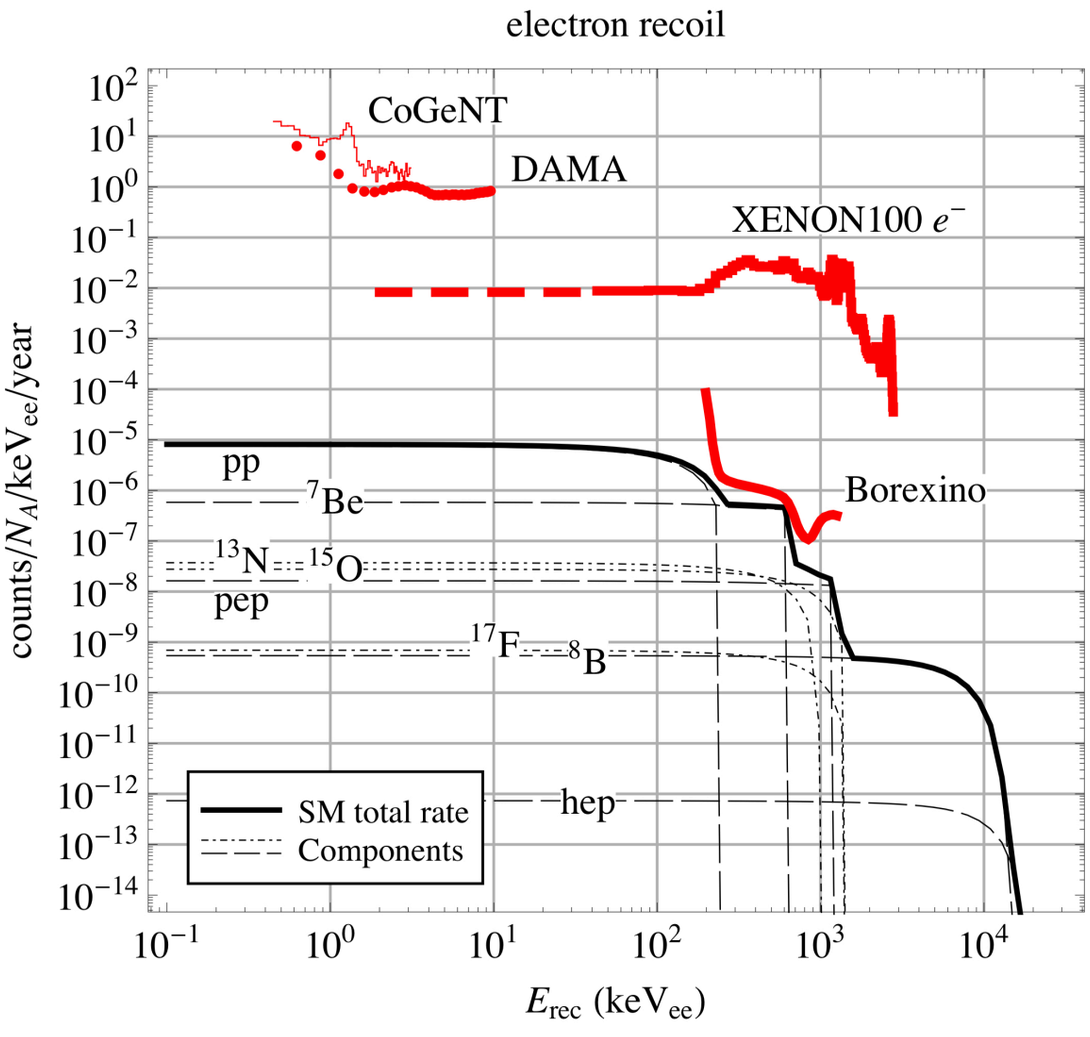
DETECTORS

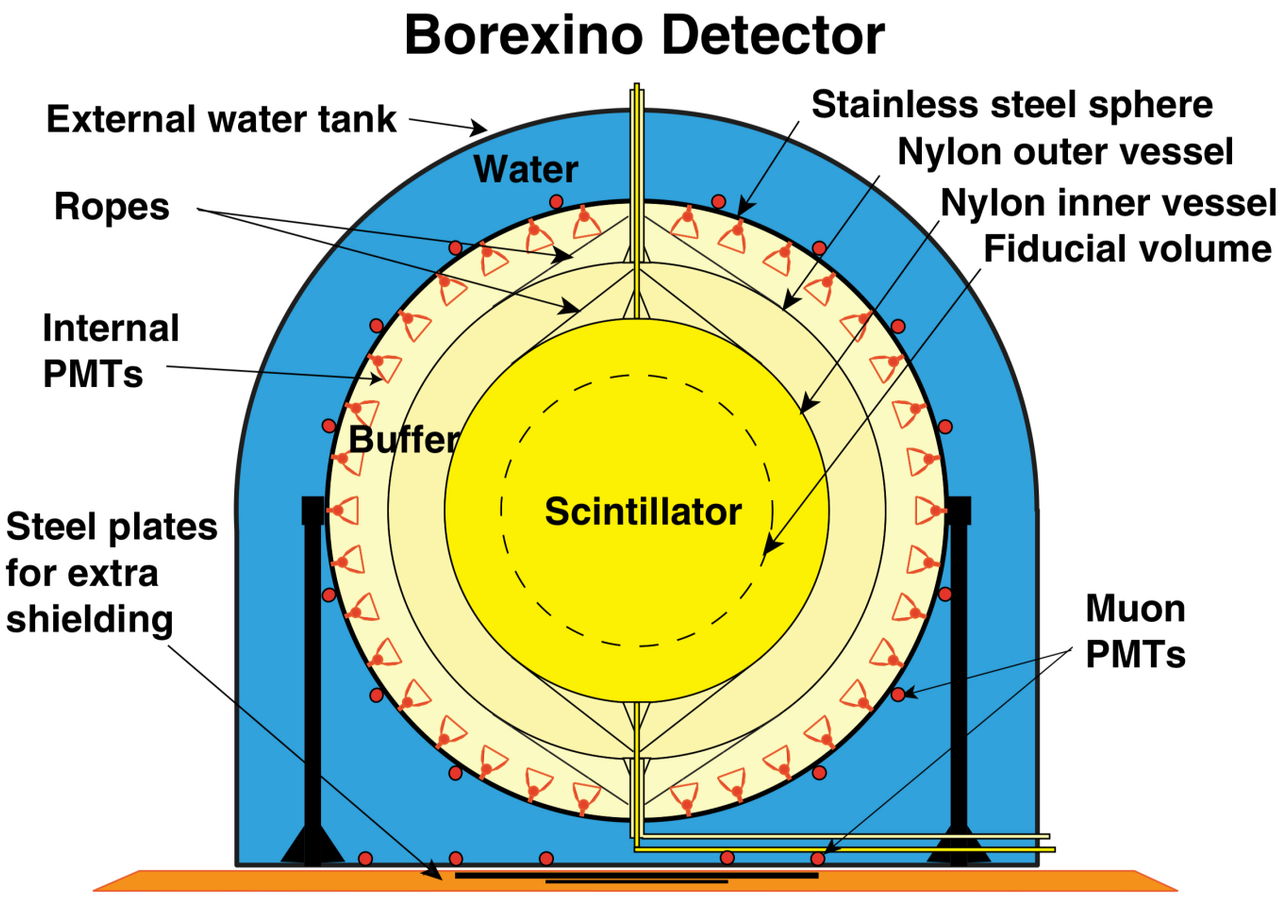
		DECLINATION
• XENON 100	$E^{th} \gtrsim$ keV	43° N
• BOREXINO	$E^{th} \gtrsim$ 100 keV	43° N
• JUNO		22° N
• SUPL (BOREXINO-LIKE)		37° S
• CYGNUS	$E^{th} \gtrsim$ keV	43° N ?
• SNO +	$E^{th} \gtrsim$ 200-400 keV	46° N
• SUPER K	$E^{th} \gtrsim$ 1 MeV	
• DUNE		
• HYPER K		

"LOCATION, LOCATION, LOCATION!"

BOREXINO

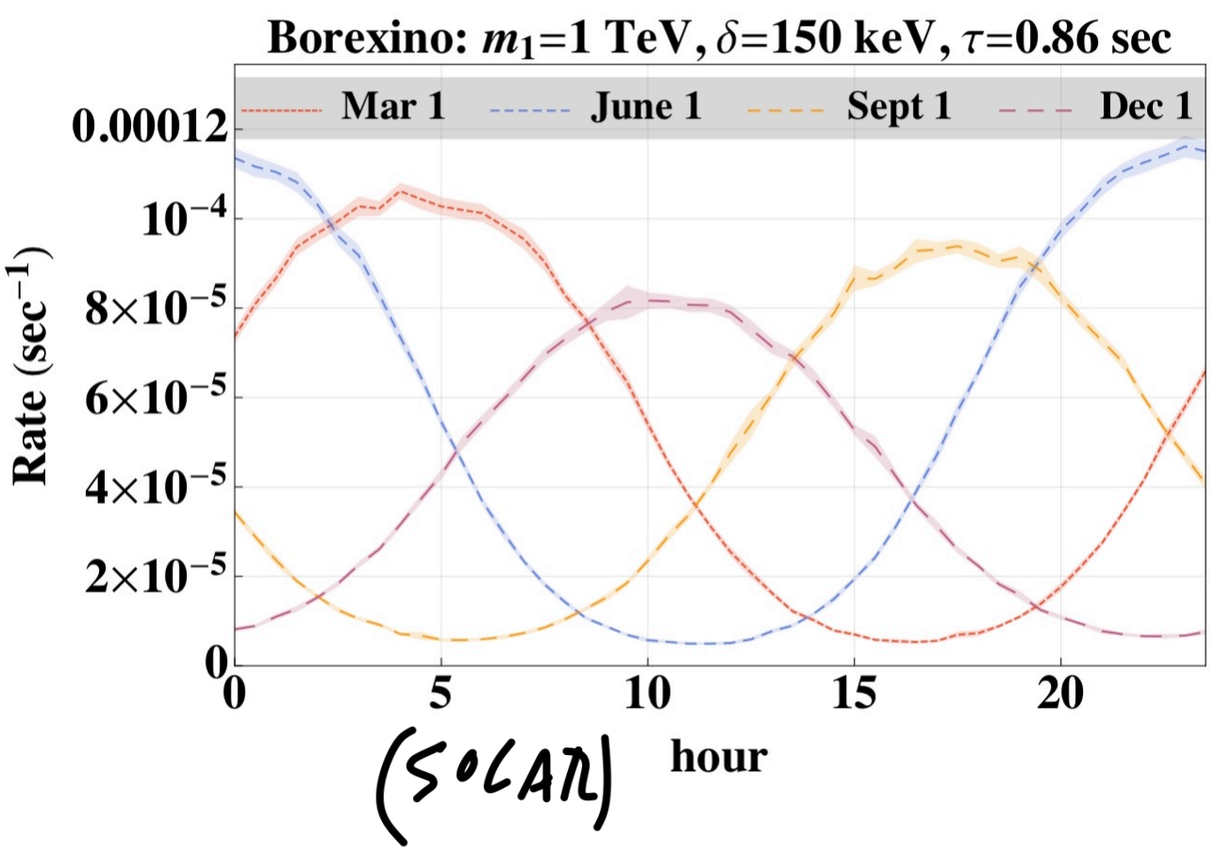
- LIQUID SCILINTILATOR ~ 280 TONS, 2000 days EXPOSURE!
- SUPER-LOW BACKGROUNDS

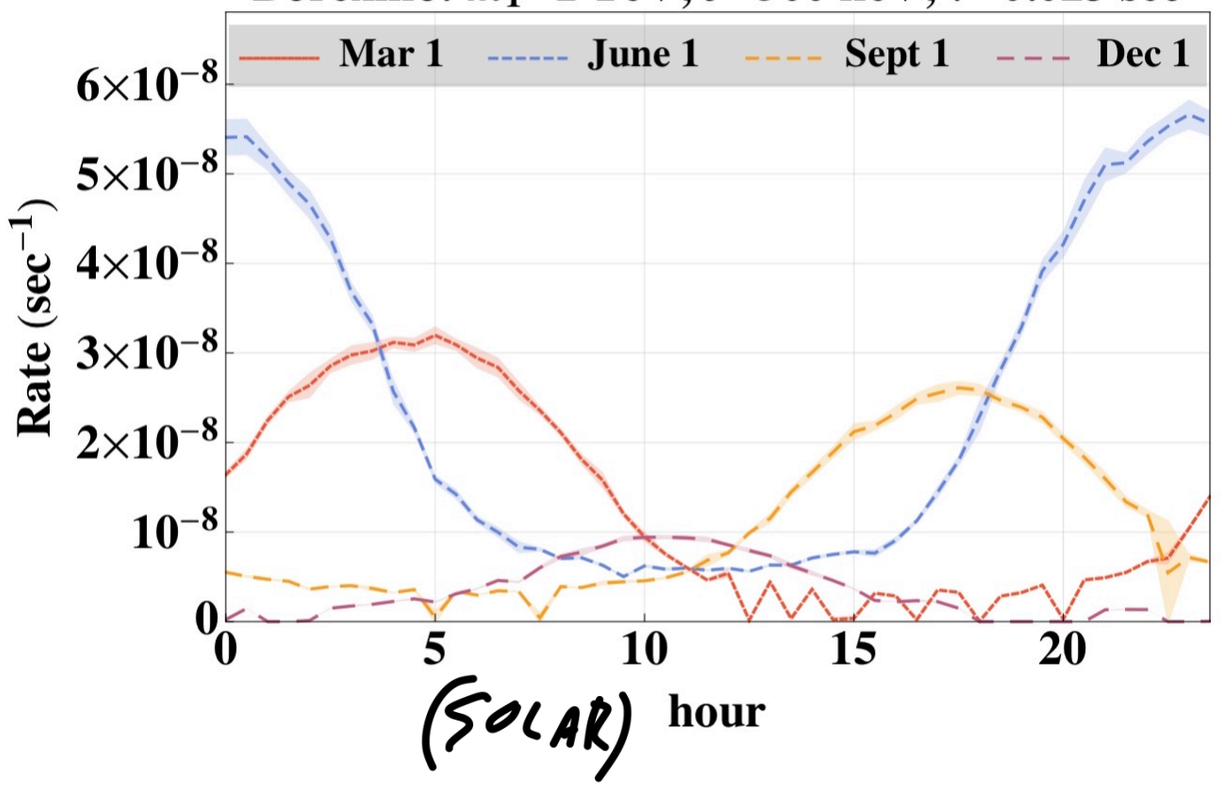




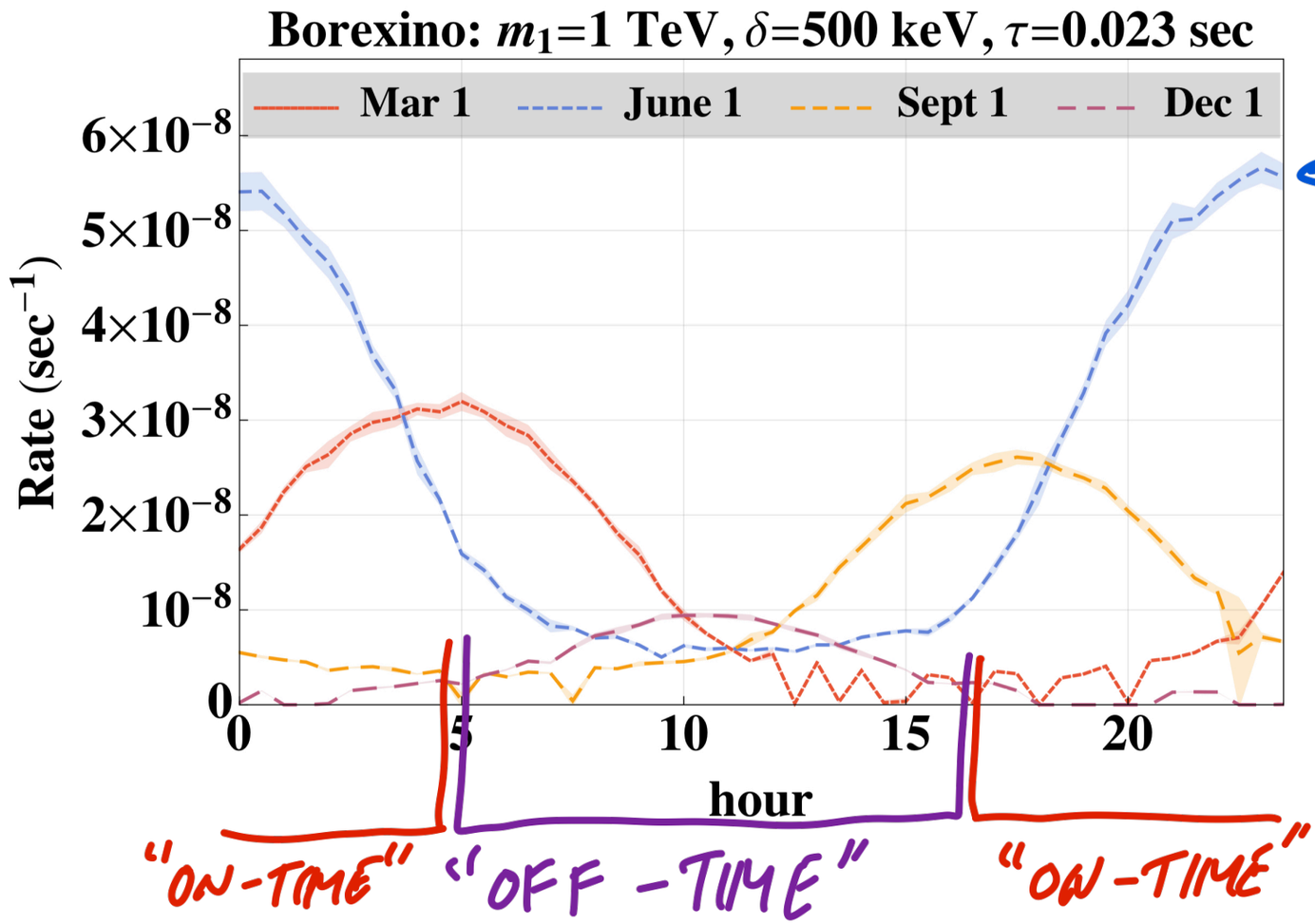
PHYSICAL REVIEW D **89,** 112007 (2014)

MODULATION @ BOREXINO





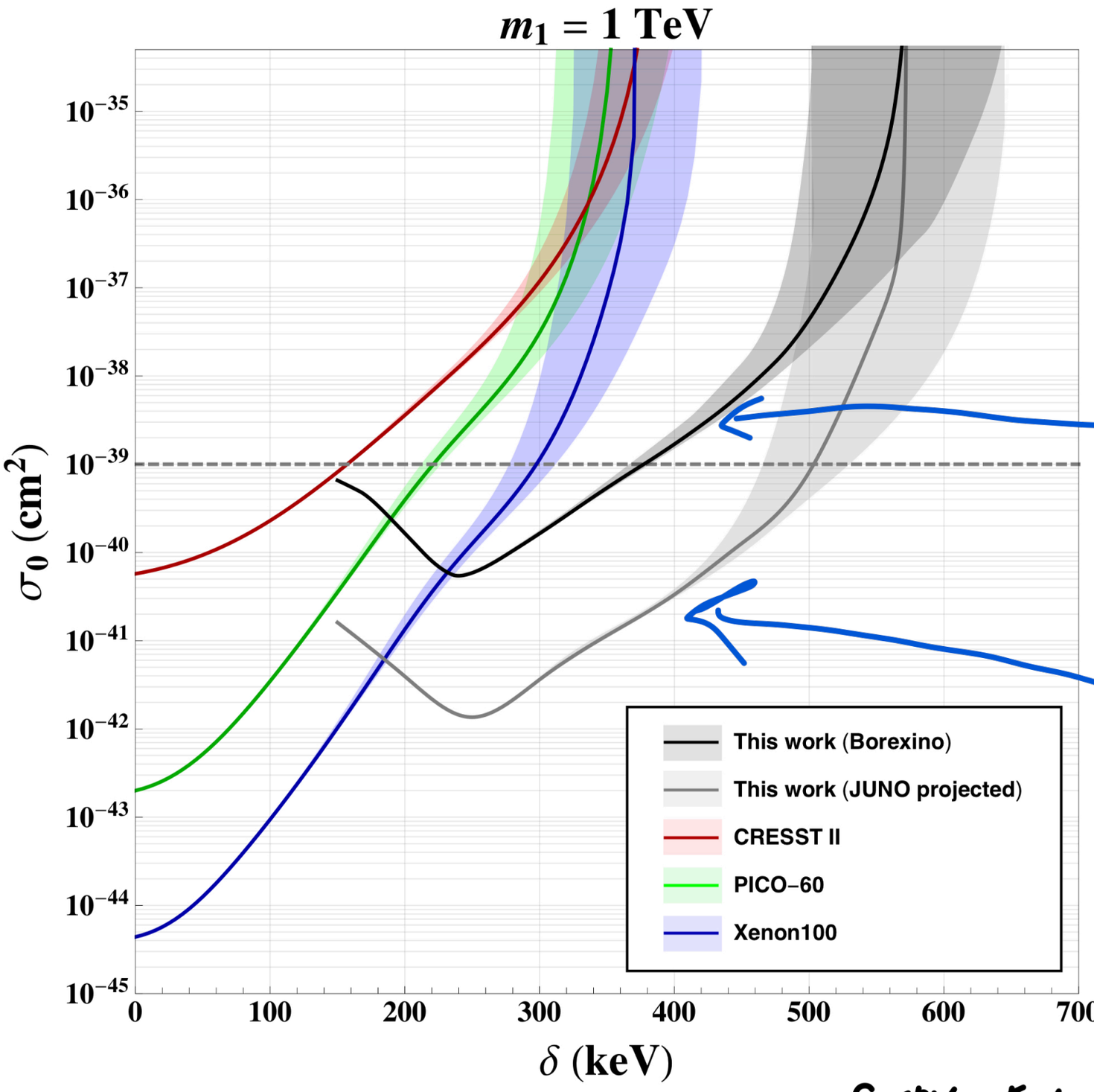
ESTIMATING THE SENSITIVITY



← CONSIDER JUNE 1

- BACKGROUND DETERMINED DURING "OFF-TIME"
- SENSITIVITY DETERMINED BY STATISTICAL FLUCTUATION (OFF-BIN UPWARD TO ON-BIN)

✓ DETECTORS ARE AWESOME!



BOREXINO SENSITIVITY

JUNO SENSITIVITY

[EBY, FOX, HARLIK, GK]

CYGNUS DIRECTIONAL DETECTOR

CYGNUS DETECTOR

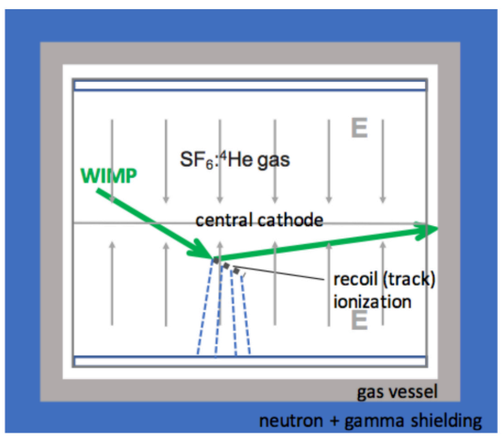
→ GAS SCINTILATOR (DRIFT OPERATED 1 m^3)

→ LARGE VOLUME!

CYGNUS: Gas TPC Conceptual Design

These advances show how to reach the required technical goals:

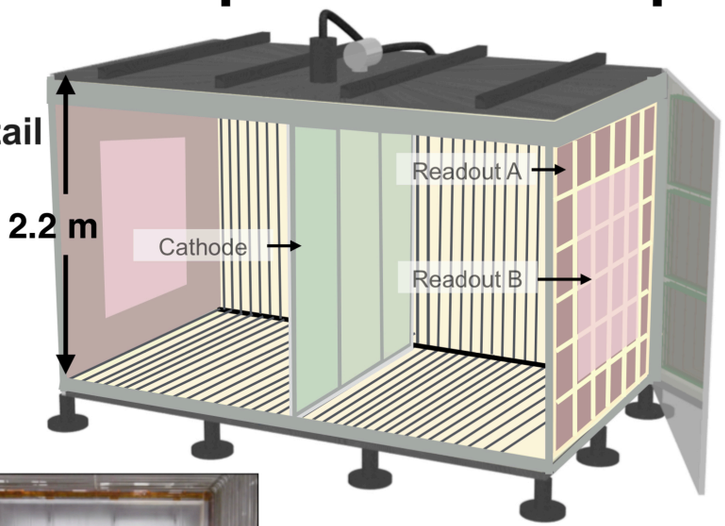
- **Gas Mixtures: SF_6:He,(CF_4) p ~1atm**
  - Can switch between higher density (search mode) and lower density gas for (improved) directional confirmation of WIMP signal
- **Threshold at <1 keV_e**
  - Use of high gain stages
  - Ultimate is W~30 eV
- **Active electron rejection at ~GeV**
- **Reduced diffusion via -ve ion drift**
- **3D Fiducialisation**
  - SF_6 minority carriers
  - charge cloud profile
- **He target**
  - Improved sensitivity to low mass WIMP
  - Longer recoil tracks, extending directionality to lower energies
- **Reasonable detector volumes (10 m^3 to 1000 m^3)**



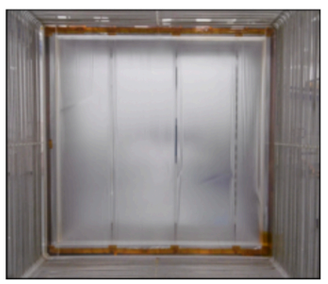
Neil Spooner, IDM 2018

CYGNUS 10m^3 - example first concept

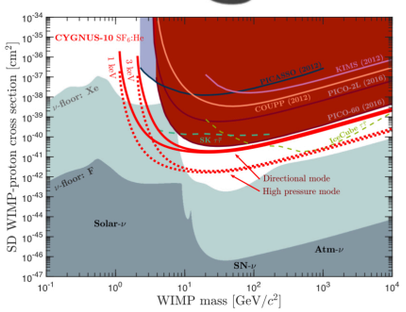
- **10m^3 SF_6:He**
- **Thin central cathode**
- **Charge readout, head-tail**
- **Water block shielding**
- **Possible Boulby site**



DRIFT-II with water blocks



UNM thin cathode in DRIFT



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CYGNUS DETECTOR ADVANTAGES

→ NEGLIGIBLE ✓ BACKGROUNDS

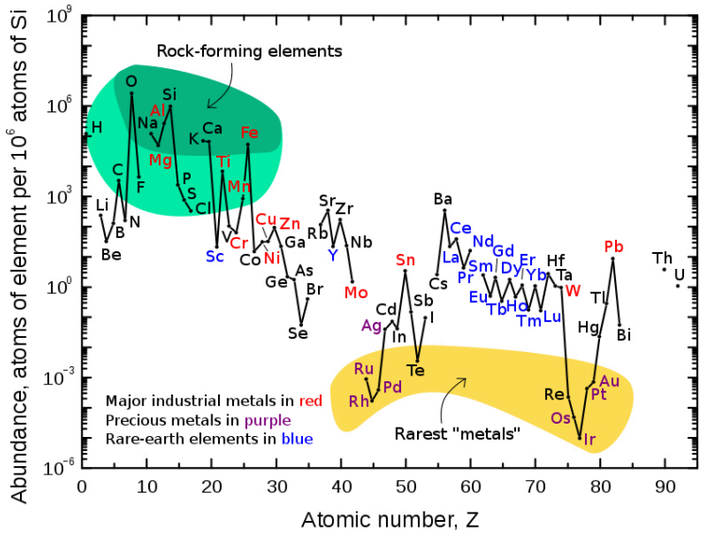
→ LOW THRESHOLD (~ 1 keV_{ee})

→ SCALABLE TO LARGE VOLUME

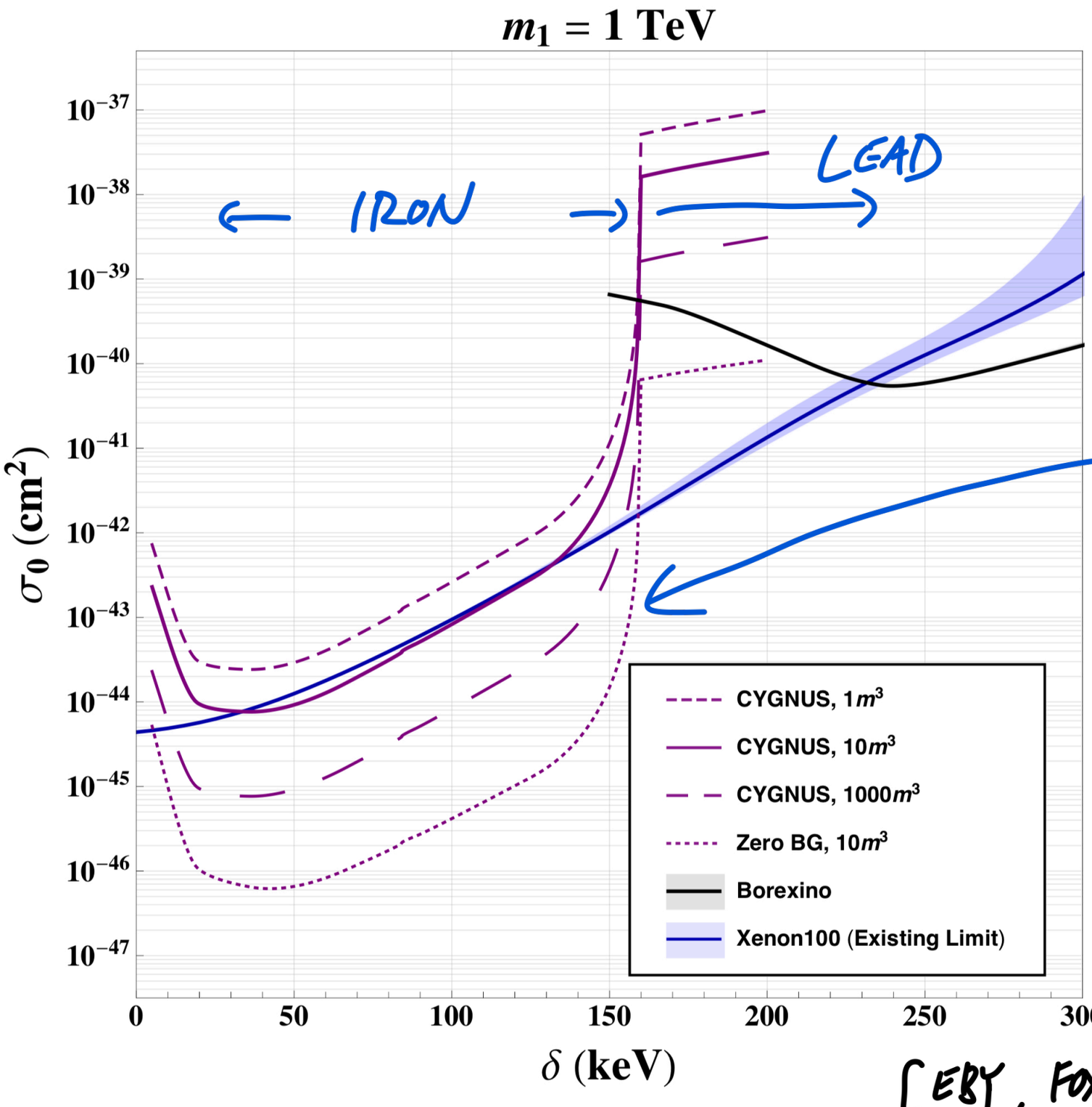
FOR INELASTIC, LOW THRESHOLD IMPLIES

LIGHTER, MORE COMMON ELEMENTS CAN BE USED

FOR UPSCATTER.



CYGNUS PROJECTIONS



PHOTON SIGNAL BETTER THAN DIRECT DETECTION!

[EBY, FOX, HARNIK, GK]

CONCLUSIONS

- EXCITING PROSPECTS FOR DETECTING γ FROM INELASTIC DM EXCITED STATE DECAY
- BOREXINO ALREADY HAS SUPERIOR SENSITIVITY

$$240\ \text{keV} \lesssim \delta \lesssim 600\ \text{keV}$$

$\Rightarrow$ SMOKING GUN IS LARGE SIDEREAL-DAILY MODULATION

- CYGNUS DETECTOR COULD SEE VAST IMPROVEMENT

$$\text{few keV} \lesssim \delta \lesssim 150\ \text{keV}$$

(LARGE VOLUME, LOW BACKGROUNDS IS CRITICAL)

LONG LIVE THE (INELASTIC) WIMP!