SEEING THE LIGHT OF DARK MATTER

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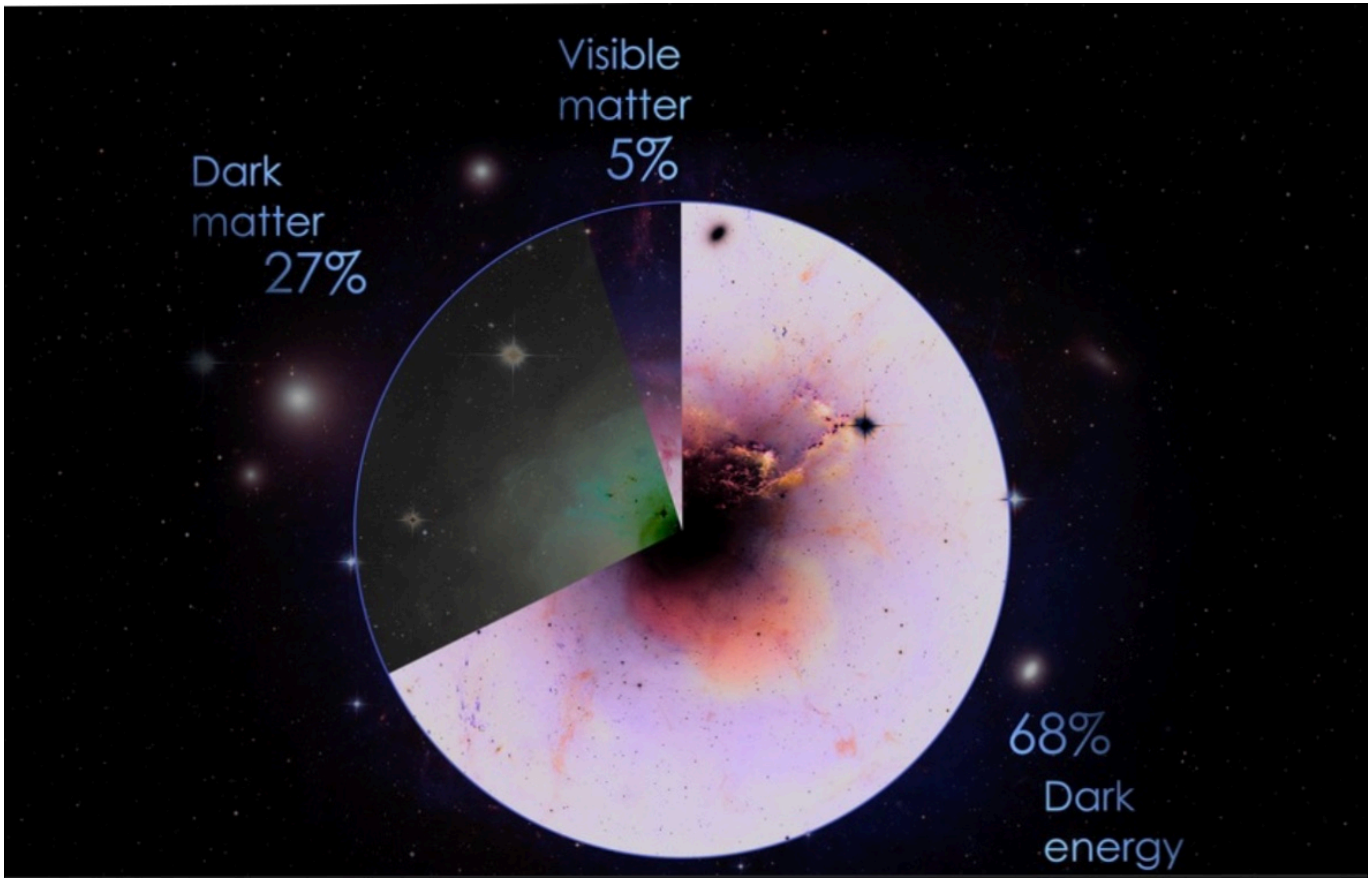
w/ JOE BRAMANTE, PADDY FOX, ADAM MARTIN ← [1608.02662 / PRD

w/ JOSH EBY, PADDY FOX, RONI HARNIK ← [1904.09994 / JHEP
+ WORK IN PROGRESS

UC DAVIS ; 6 APRIL 2020

MOTIVATION



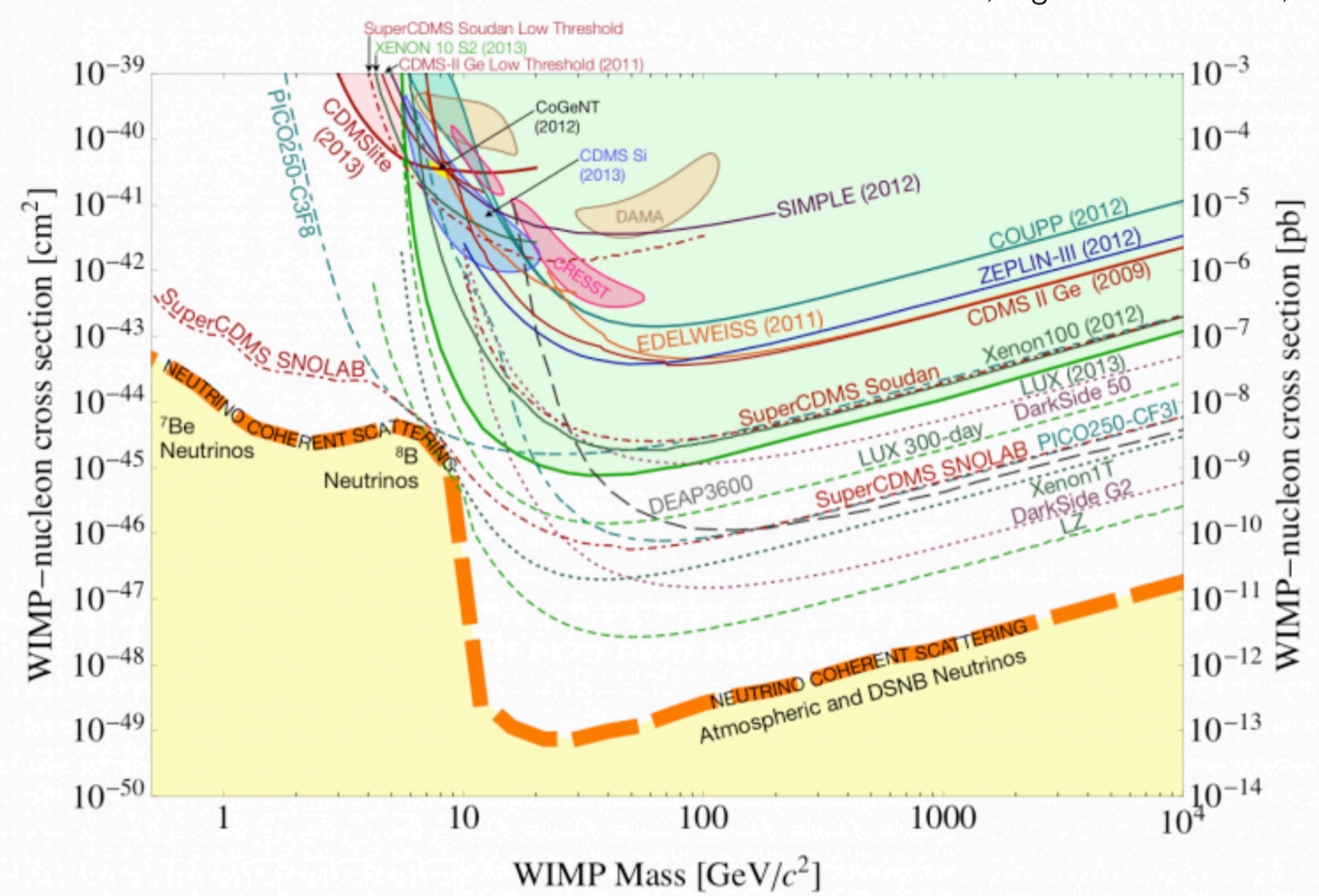
OVERWHELMING EVIDENCE FROM CMB; GALAXIES; CLUSTERS; BAO ...

MOTIVATION

WE'VE LOOKED FOR IT THROUGH SCATTERING OFF MATTER FOR DECADES, BUT NOT YET FOUND IT.

E.G. "NEAR" WEAK SCALE:

Billard, Figueroa-Feliciano, Strigari 1307.5458

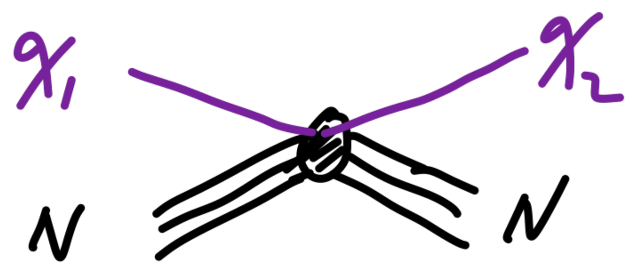


Spin-Independent elastic scattering direct detection bounds on "per nucleon" cross section:

$$\sigma_n \equiv \frac{\mu^2(n,\mathrm{DM})}{\mu^2(N,\mathrm{DM})}\frac{1}{A^2}\sigma_{\mathrm{Nucleus}}$$

MOTIVATION

IF DM INTERACTS INELASTICALLY:

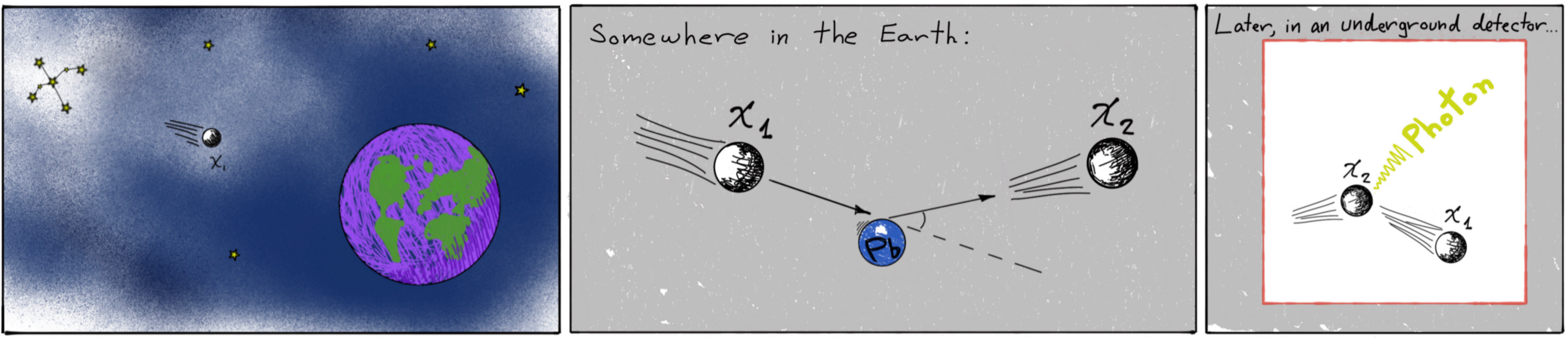


CAN WEAKEN OR EVADE DIRECT DETECTION BOUNDS.

SEEK NEW METHODS / NEW SIGNALS TO PROBE INELASTIC DM THAT MAY COMPLEMENT OR IMPROVE ON SEARCHES USING NUCLEAR RECOIL.

OUR GOAL :

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

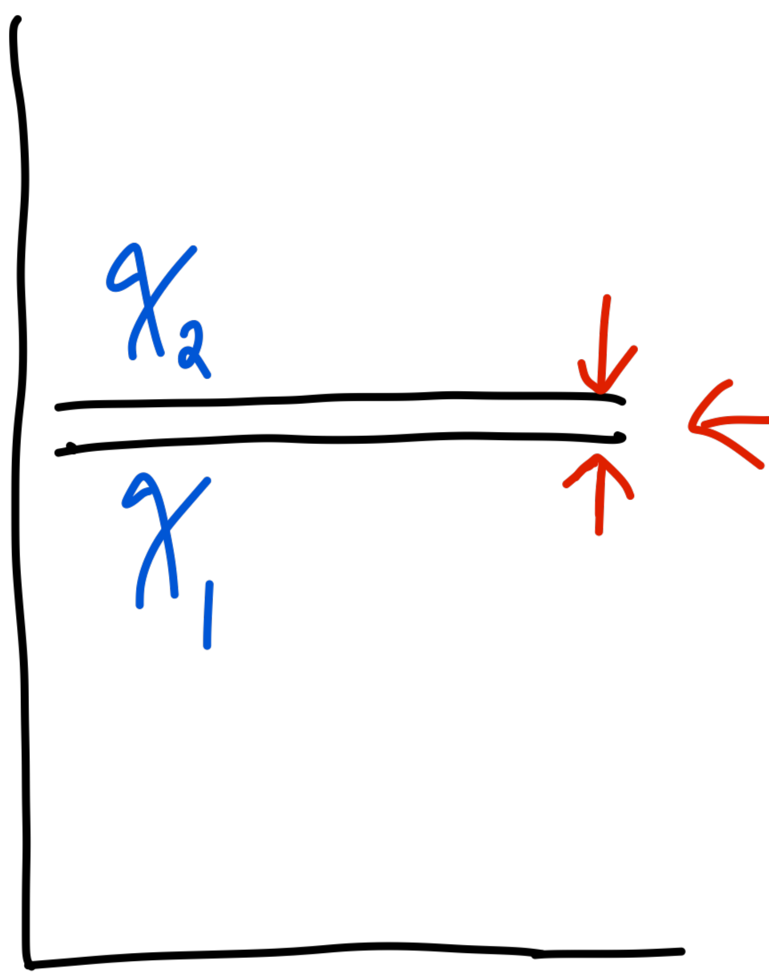
LARGE UNDERGROUND DETECTOR

QUICK REVIEW: INELASTIC DM

INELASTIC DARK MATTER

[HAN, HEMPLING; HALL, MOROI, MURAYAMA; TUCKER-SMITH, WEINER ...]

DARK MATTER HAS AN EXCITED STATE WITH A VERY SMALL MASS SPLITTING.



$$\Delta m \equiv \delta \lesssim 600 \text{ keV}$$

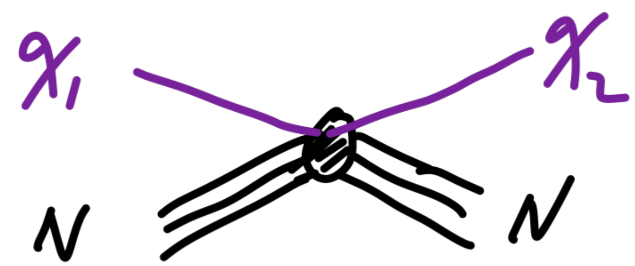
$$\sim \frac{1}{2} \mu v^2$$

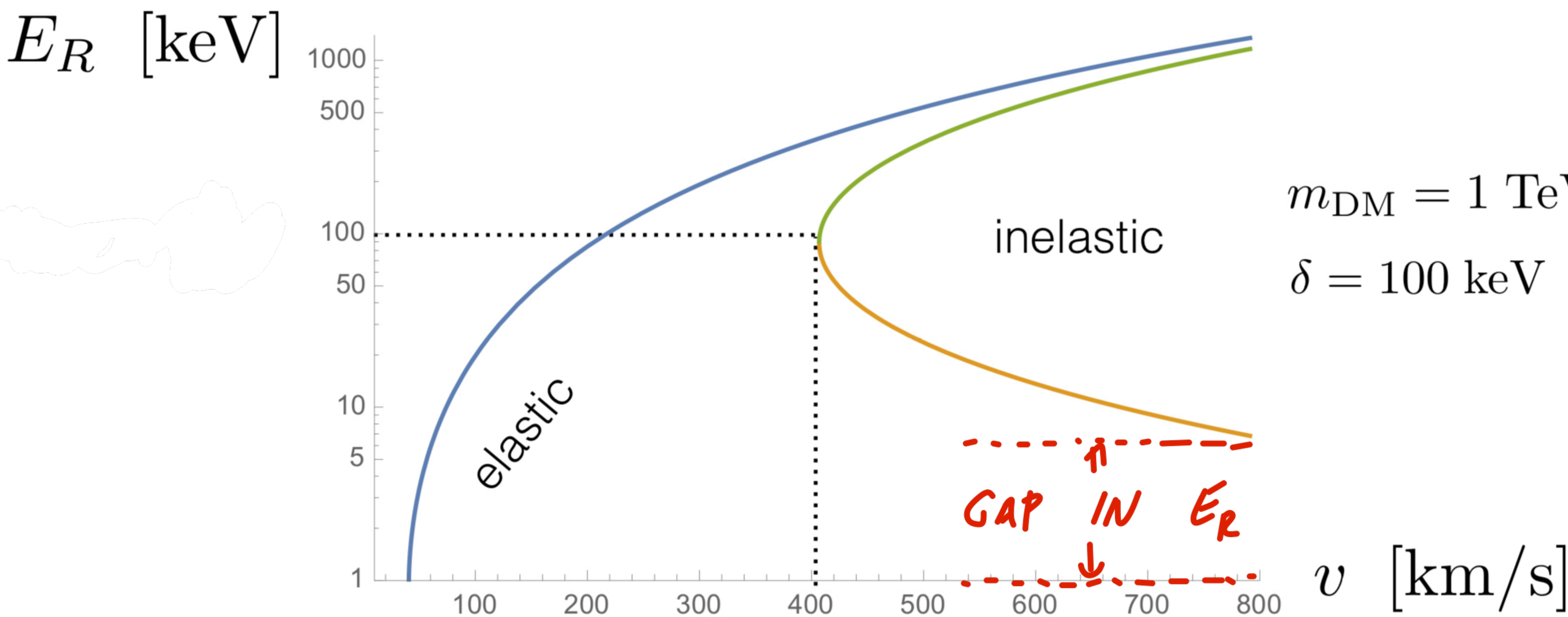
v ← LAB FRAME

μ ← REDUCED MASS OF DM / NUCLEUS

KINEMATICS

SCATTERING DOMINATED BY *INELASTIC* PROCESS





MIN VELOCITY TO SCATTER

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

Bramante, Fox, GK, Martin

HEAVY DM MAXIMIZES SCATTERING

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

HEAVY DM

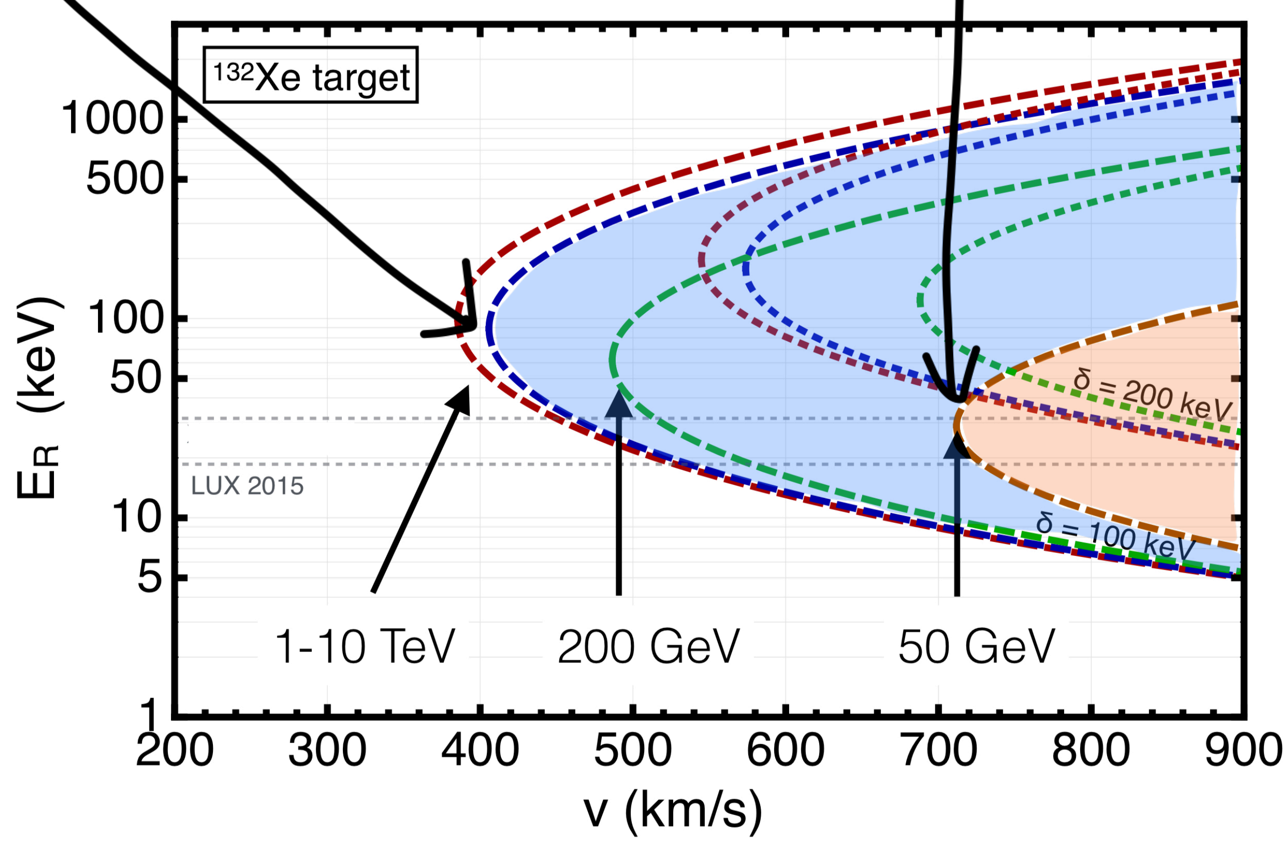
$$m_{DM} \gtrsim m_{Nuc}$$

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

LIGHT DM

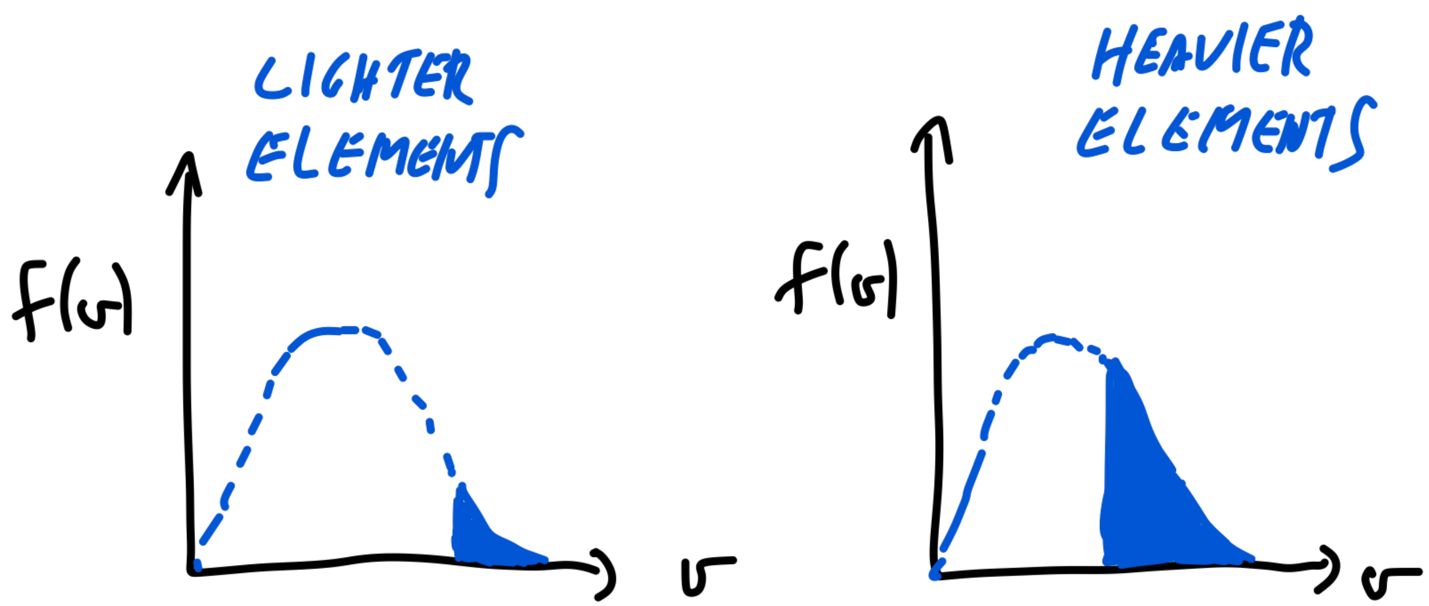
$$m_{DM} \lesssim m_{Nuc}$$

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



HEAVY ELEMENTS WANTED! (LARGE δ)

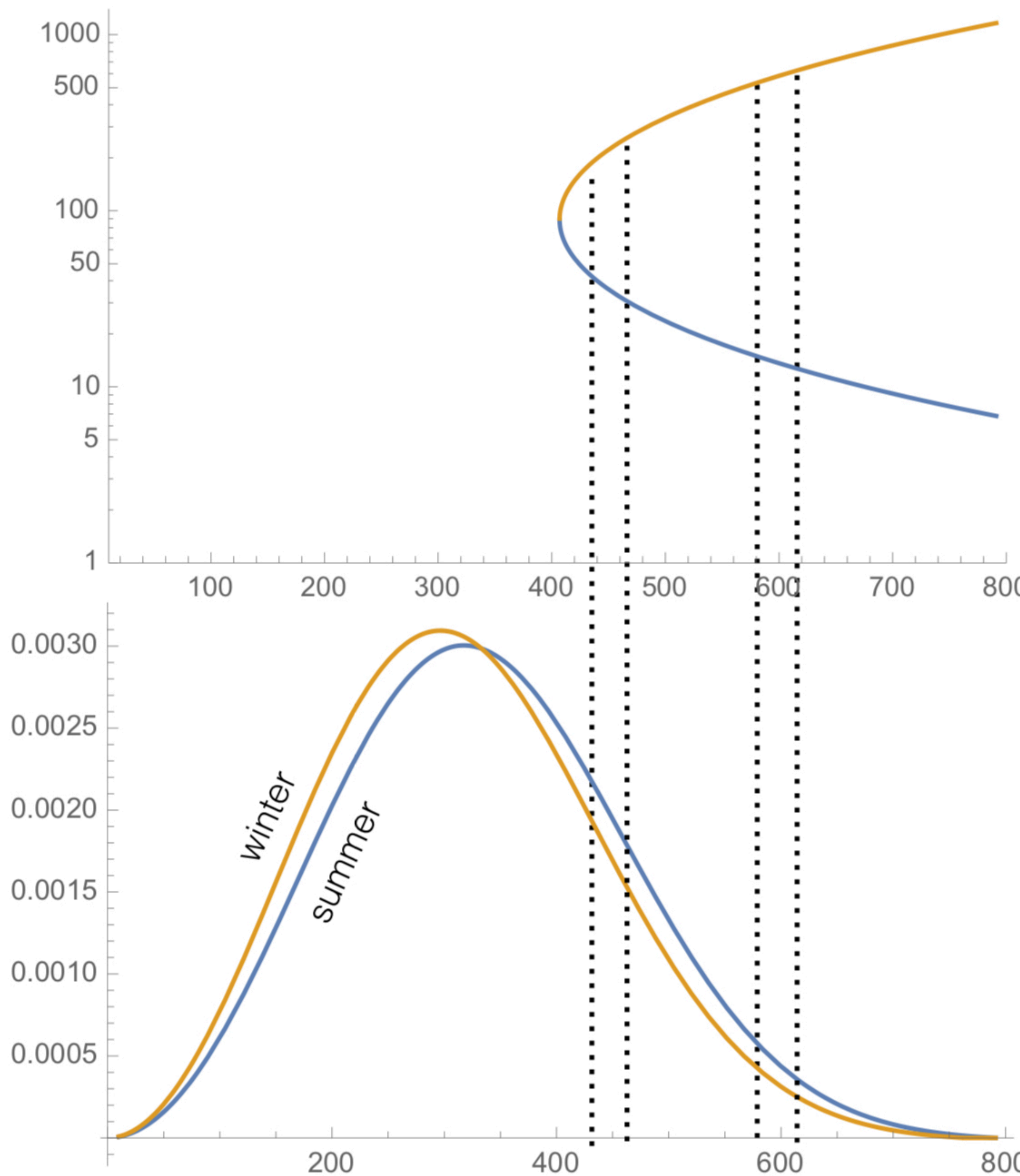
$$v_{min}\Big|_{E_{R,min}} \hat{=} \sqrt{\frac{2\delta}{m_{Nuc}}}$$



MUCH LARGER RATE!

INELASTIC DM SENSITIVE TO TAIL OF VEL DISTRIBUTION

E_R [keV]



$v^2 f(v)$

(Earth frame)

NEED LARGE E_R PROBED IN DIRECT DETECTION EXPTS.

Maxwellian with galactic escape velocity cutoff (boosted to Earth frame)

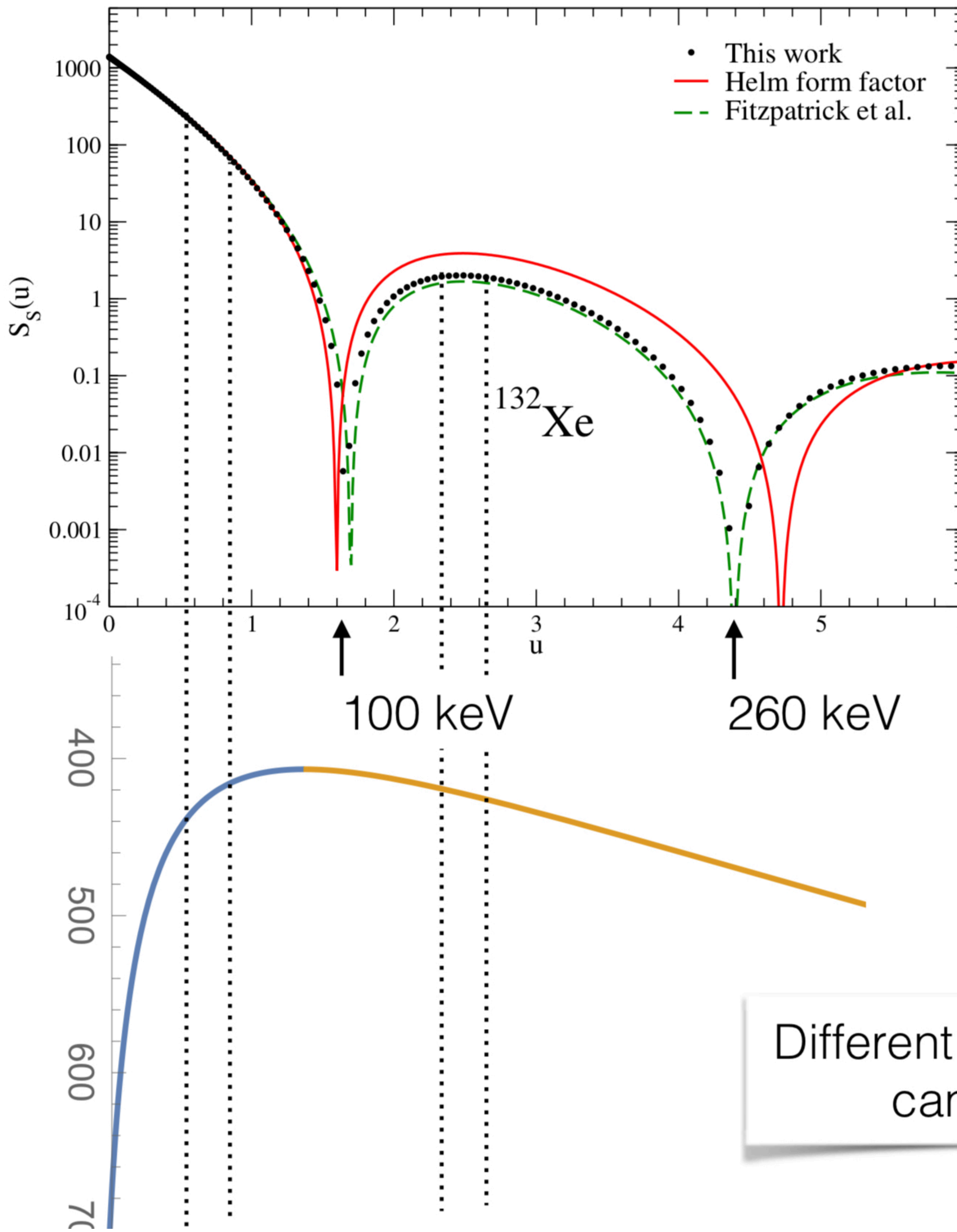
v [km/s]

NUCLEAR STRUCTURE "FORM" FACTOR

Vietze, Klos, Menéndez, Haxton, Schwenk 1412.6091

$|F(E_R)|^2$

(spin-independent)

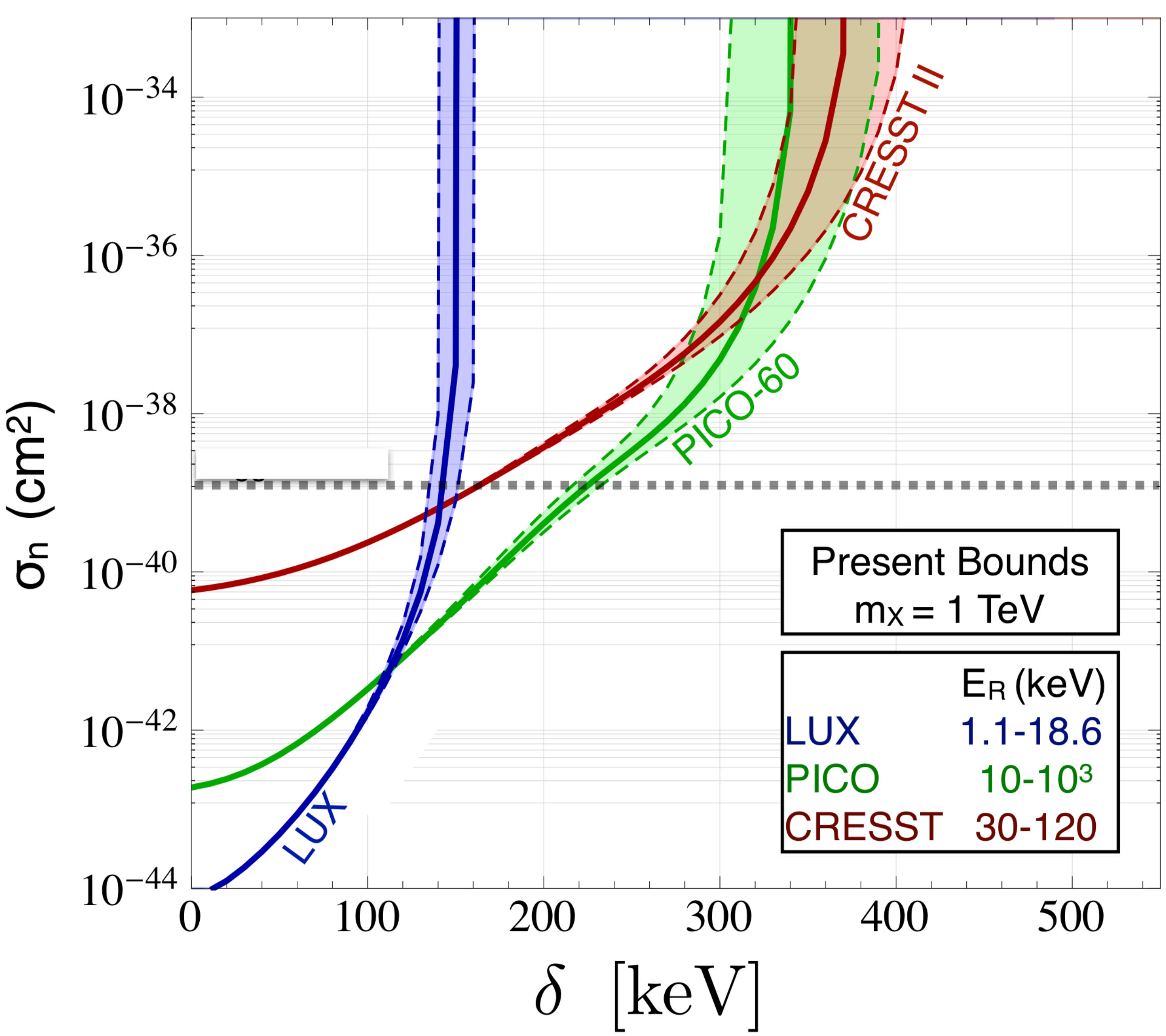


E_R

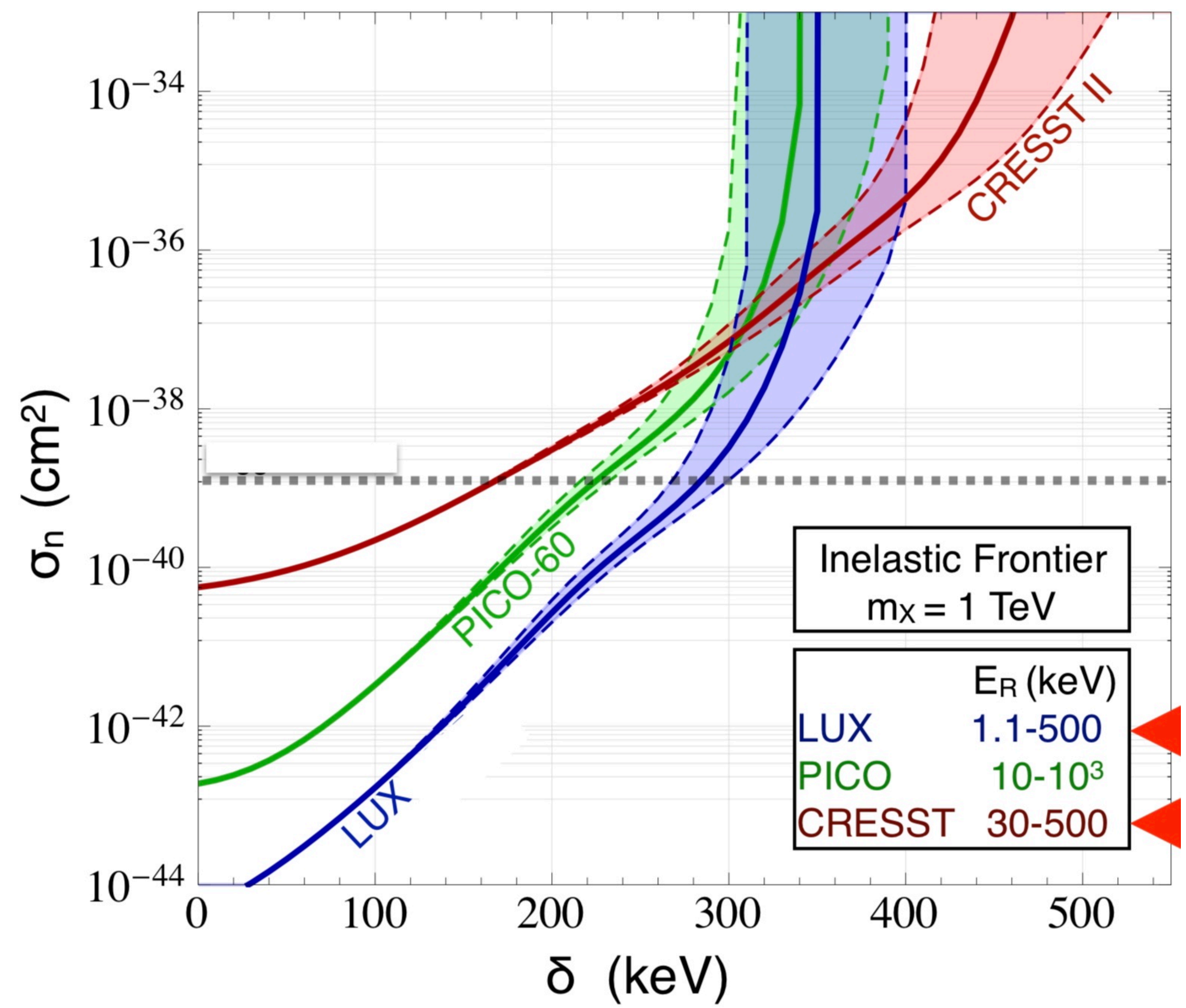
Different regions of $F(E_R)^2$ can contribute

INELASTIC PARAMETER SPACE

OUR BOUNDS IN 2016



OUR PROJECTED IMPROVEMENT

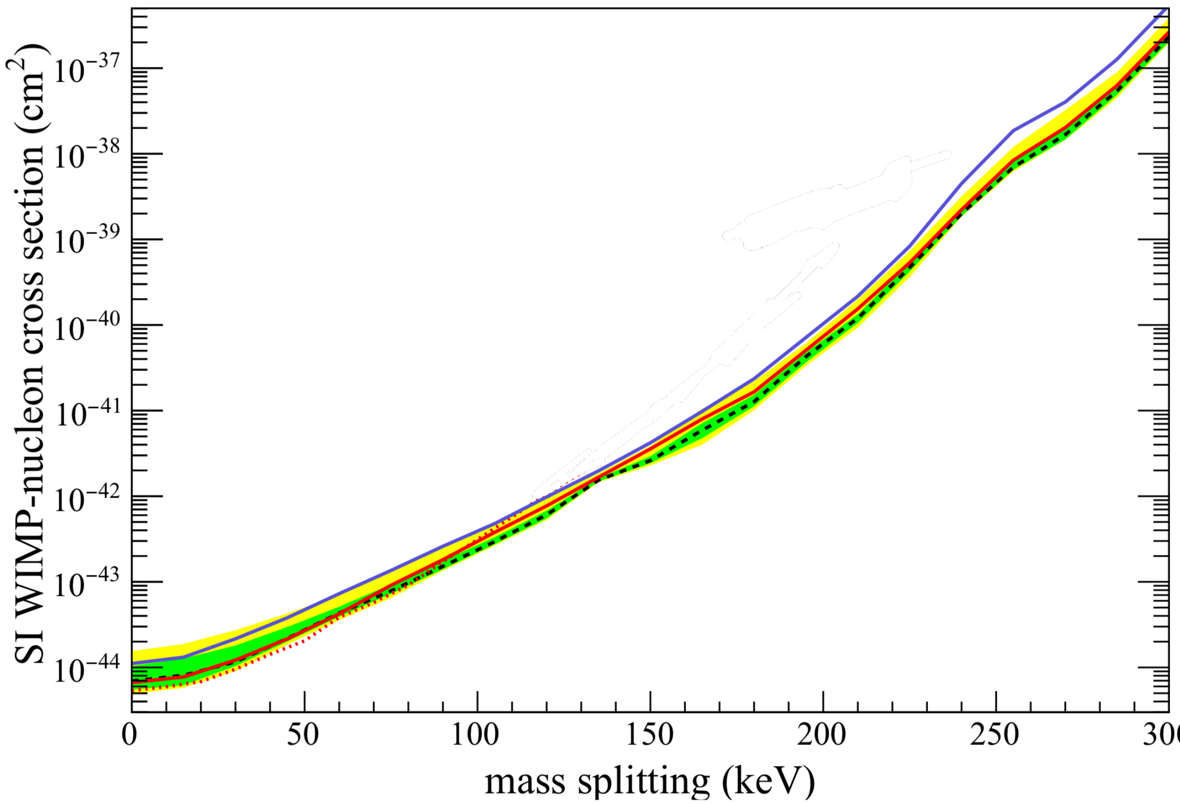


Bramante, Fox, GK, Martin

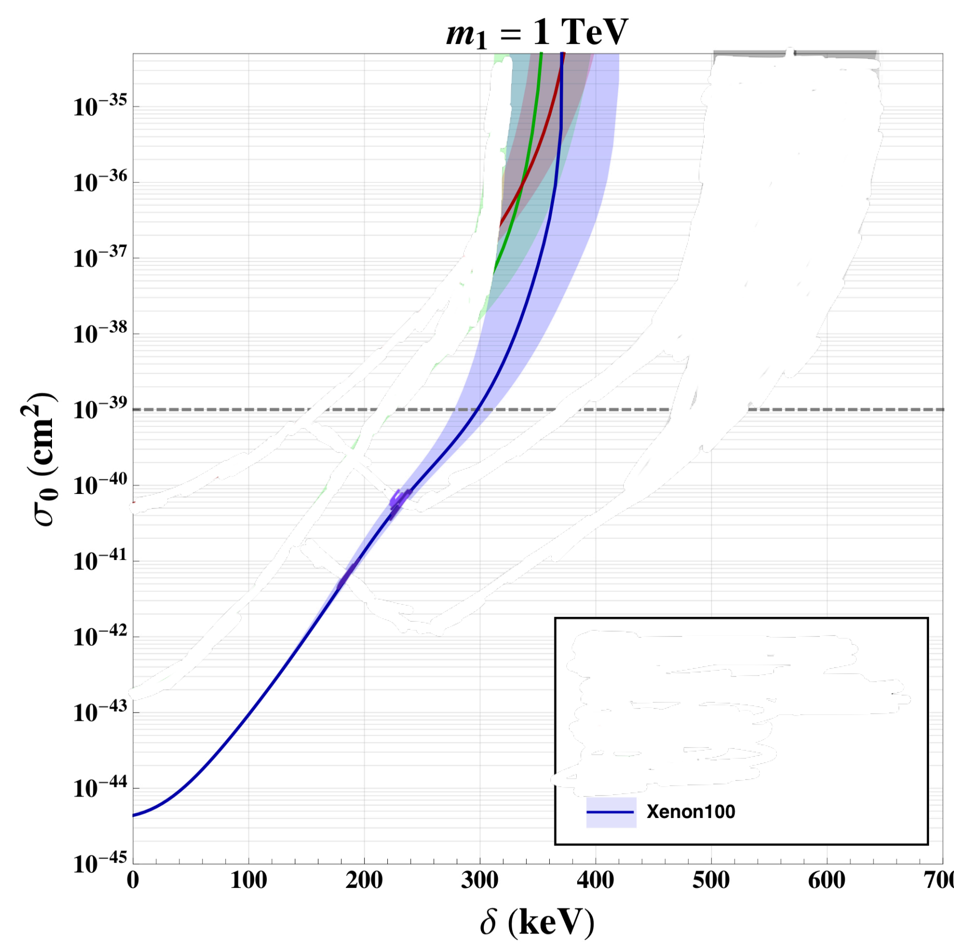
1608.02662

PANDAX & XENON100 LISTENED!

PANDAX: 1708.05825



XENON100: 1705.06655



MODELS

→ NARROWLY SPLIT HIGGSINO (FOX, GK, MARTIN)

- $\sigma(\text{S.I.}) \ll 10^{-47}\ \text{cm}^2$
- $\sigma(\text{iDM}) \sim 10^{-39}\ \text{cm}^2$ (Z EXCHANGE!)

→ MAGNETIC INELASTIC

- DAMA MOTIVATED (LUMINOUS; TWO-STEP) RULED OUT
- GENERALIZED (σ, δ) IS REALLY INTERESTING!* ← IN PREPARATION

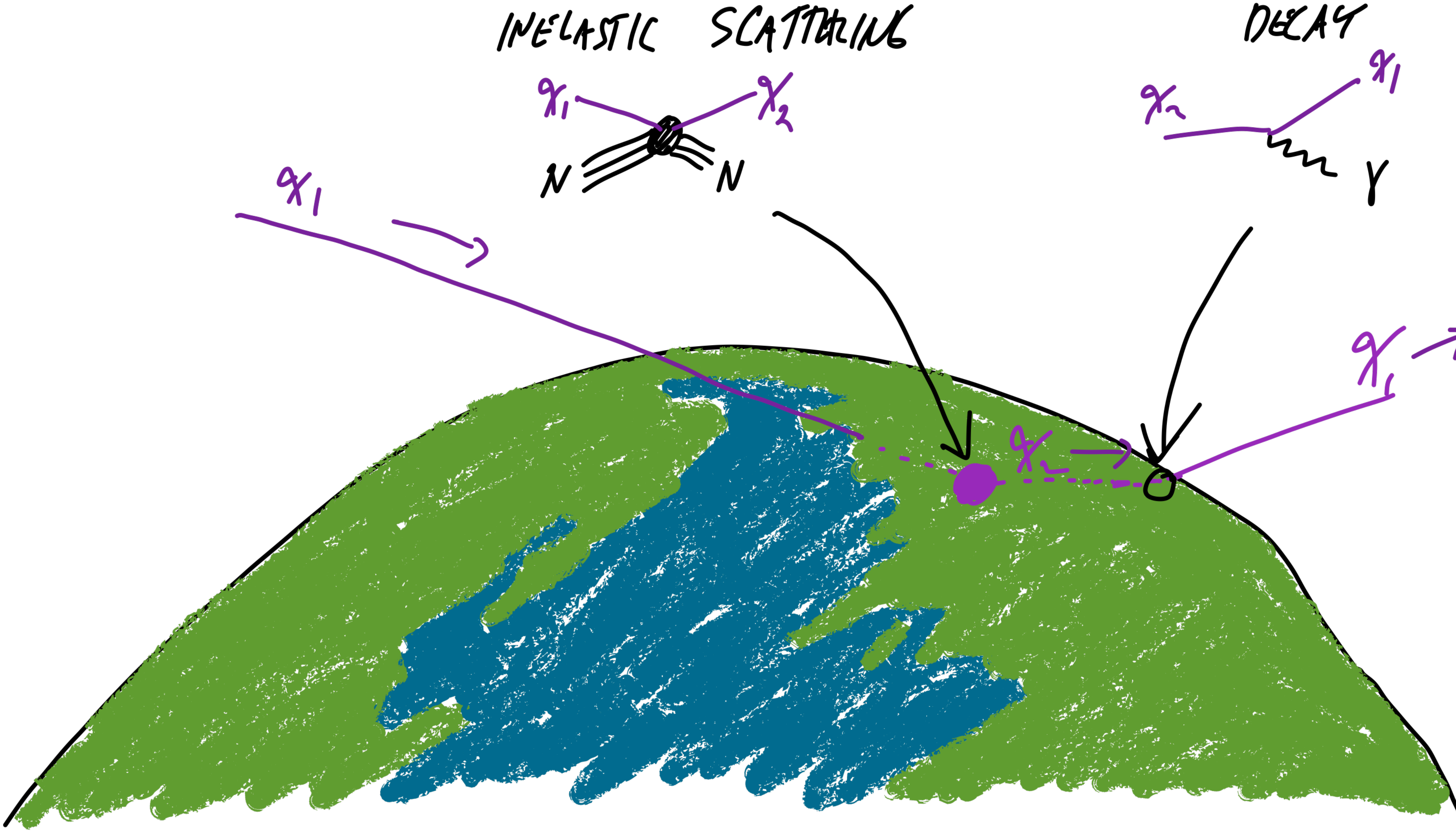
→ ...

FOR REMAINDER: ASSUME $\sigma(\text{iDM};\ \delta \to 0)$ ARBITRARY

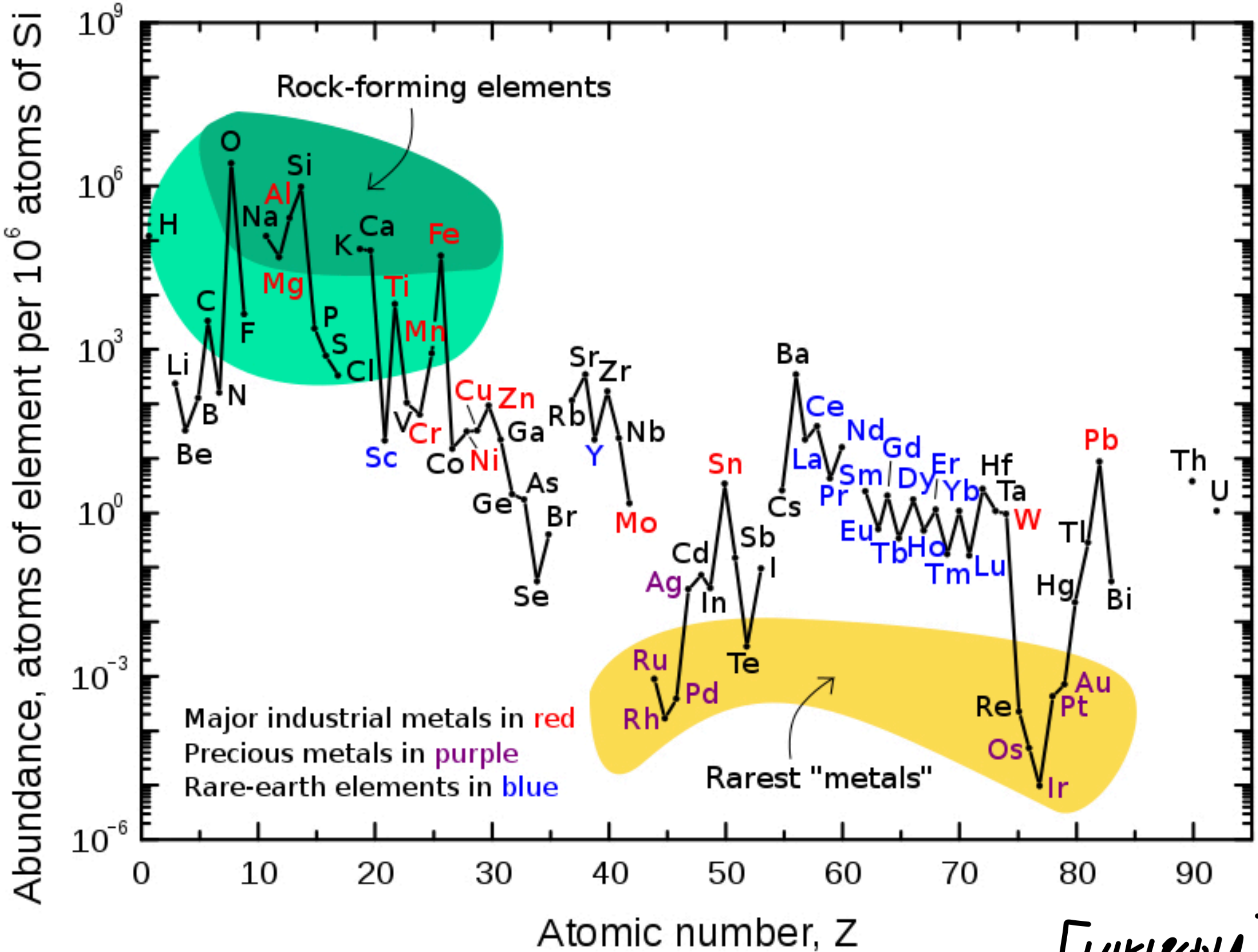
(AND FREE FROM CONSTRAINT ON $\sigma(\text{S.I.})$)

HOW TO GET EXCITED?

EARTH AS AN UPSCATTER TARGET



EARTH COMPOSITION 101



[WIKIPEDIA]

EARTH COMPOSITION 101

LEAD

$$\begin{cases} Z = 82 \\ A \sim 207 \end{cases}$$

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

ISOTOPES POPULATED BY RADIOACTIVE DECAY:

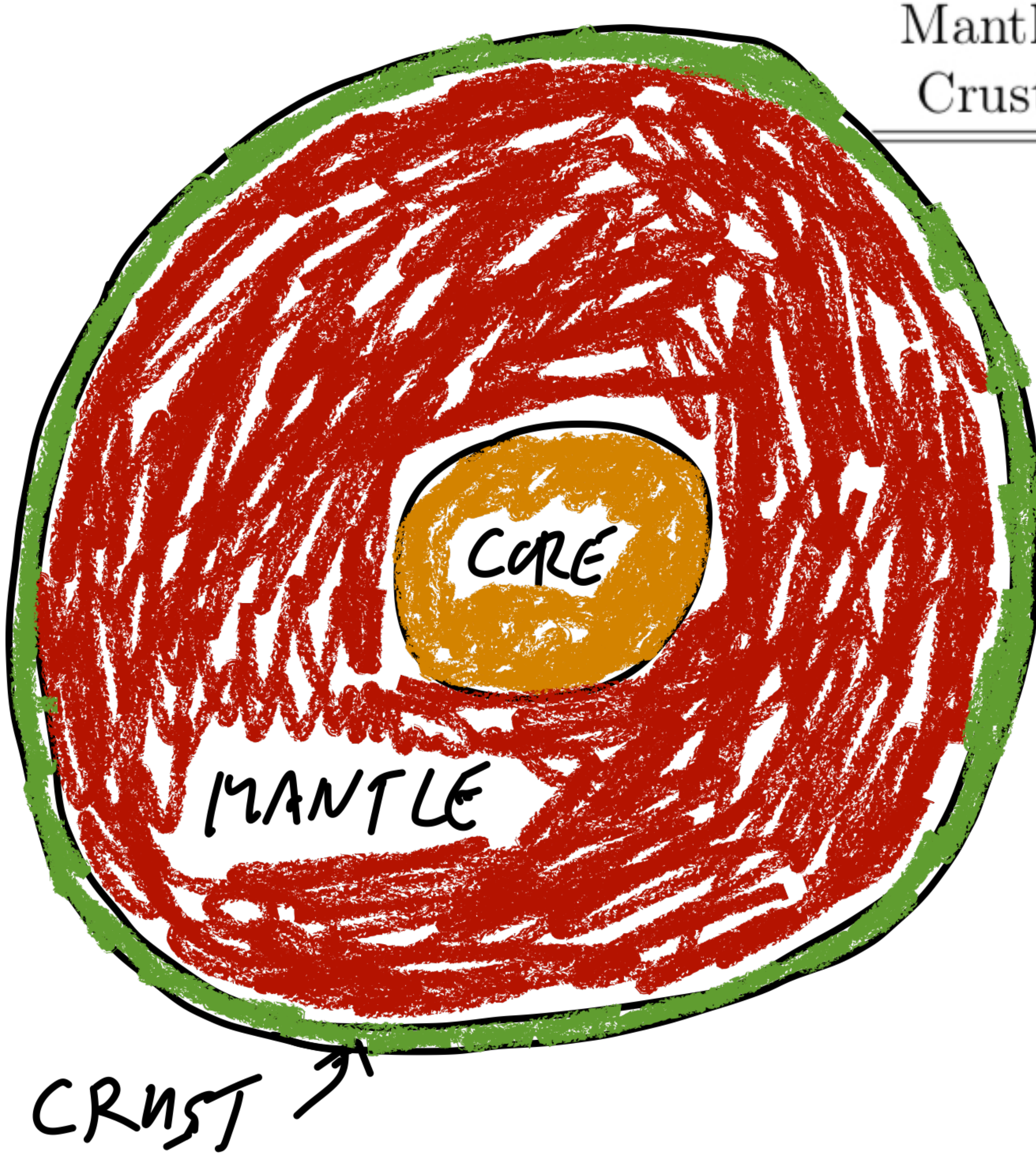
$$^{238}U \rightarrow {}^{206}Pb$$
$$^{235}U \rightarrow {}^{207}Pb$$
$$^{232}Th \rightarrow {}^{208}Pb$$

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

DEPTH DEPENDENCE OF ABUNDANCES

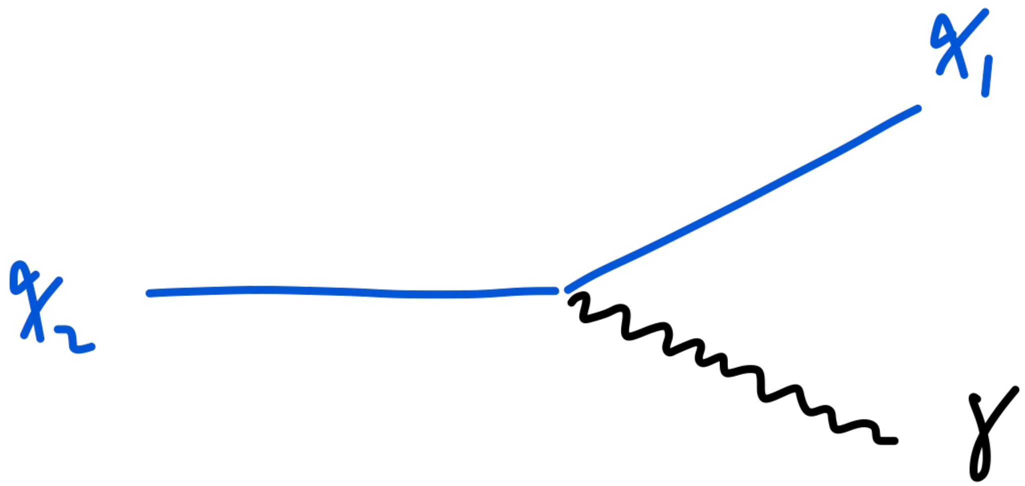
EARTH

-	n_{Fe} [km^{-3}]	n_{Pb} [km^{-3}]	Outer Radius [km]
Core	1.1×10^{38}	1.3×10^{31}	3483
Mantle	3.1×10^{36}	2.4×10^{30}	6341
Crust	2.0×10^{36}	8.4×10^{31}	6371

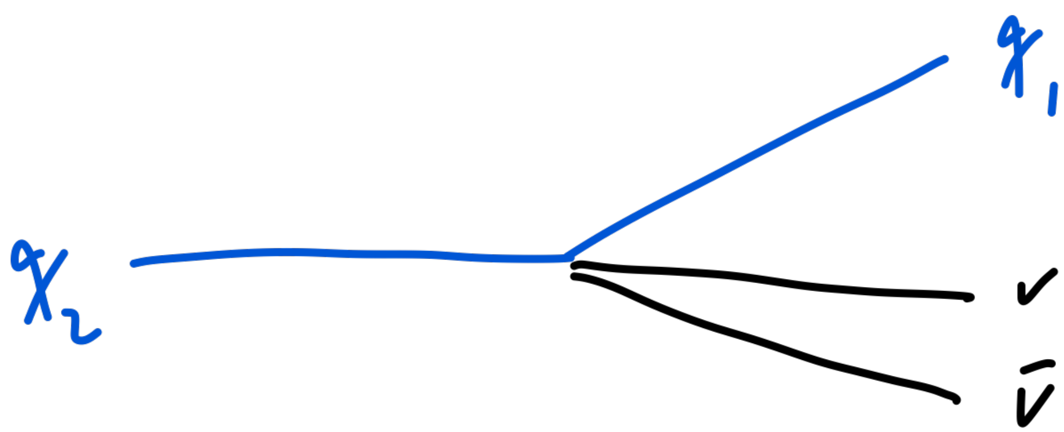


$$n_{Pb}^{CRUST} \sim 35\, n_{Pb}^{MANTLE}$$

EXCITED STATE DECAY



$$\Gamma_{\chi_2 \to \chi_1 \gamma} \simeq \alpha_{\rm em}\, \alpha_W^2 \frac{\delta^3}{4\pi^2 m_1^2}$$



$$\Gamma_{\chi_2 \to \chi_1 \nu \bar{\nu}} \sim \alpha_W^2 \frac{\delta^5}{120 \cos^4 \theta_W \pi m_Z^4}$$

RADIATIVE DECAY WINS

$$\left\{ \begin{array}{l} \delta \lesssim \text{GeV} \\ m_{\chi^\pm} \sim m_{\chi^0} \end{array} \right.$$

DECAY LENGTH

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

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

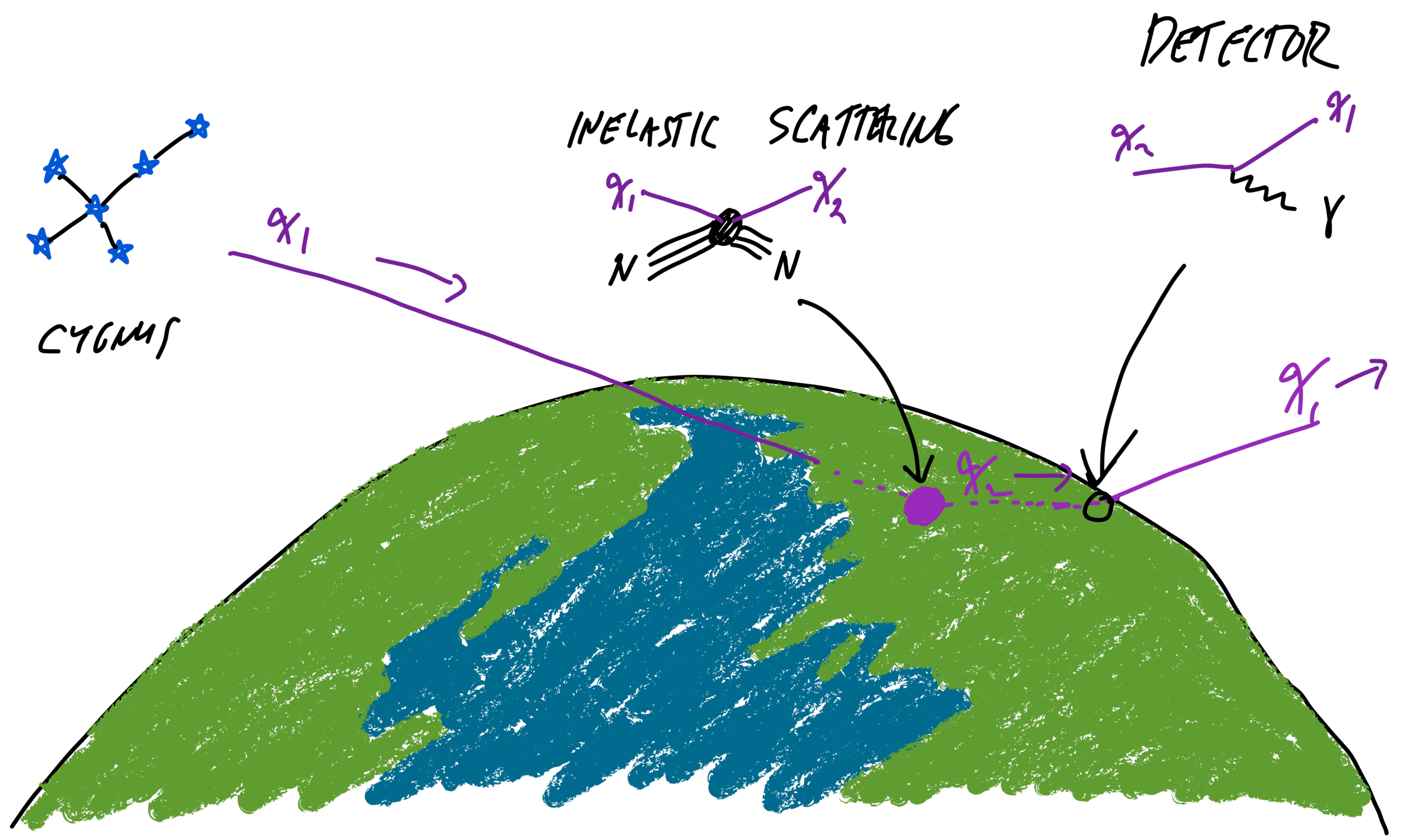
ROUGHLY

$\ell \sim 10 \to 1000$ km

$\delta \sim 100$ keV

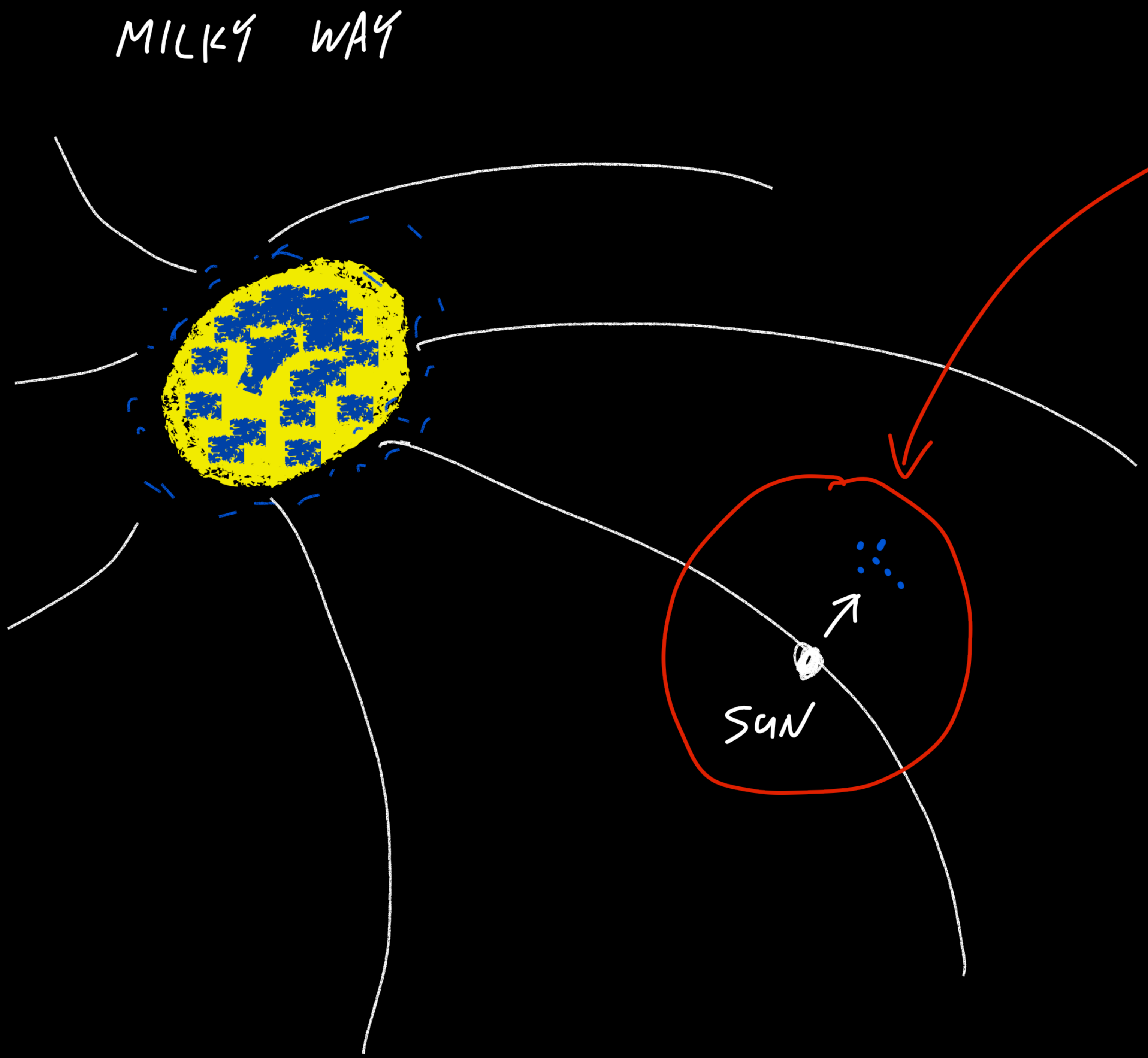
$\delta \sim 550$ keV

MONOENERGETIC PHOTON SIGNAL



DIRECTIONALITY OF DARK MATTER WIND

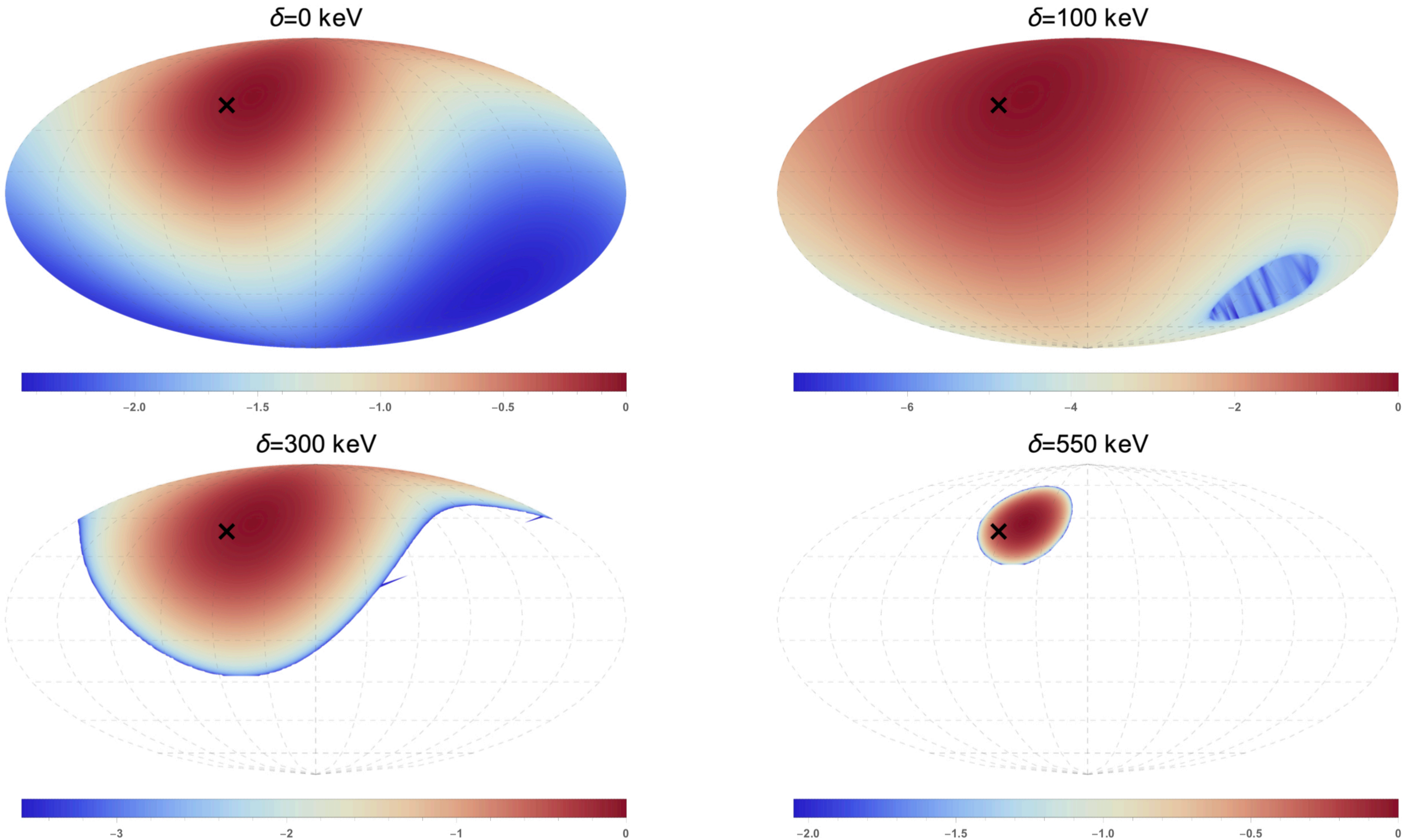
CYGNUS ?



SUN/EARTH ROTATING IN MILKY WAY "TOWARD" CYGNUS CONSTELLATION.

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

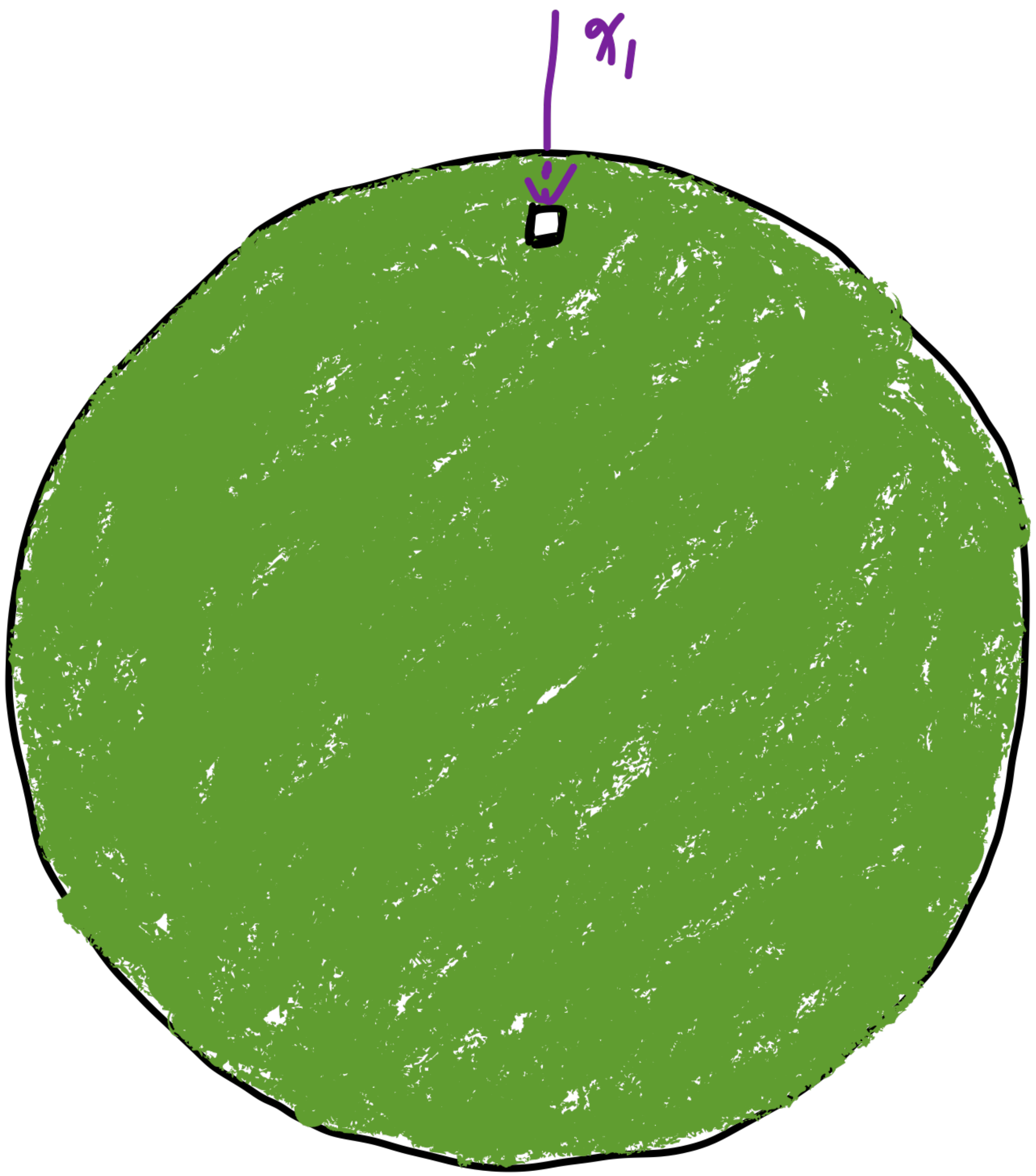
DIRECTIONALITY OF INELASTIC DM

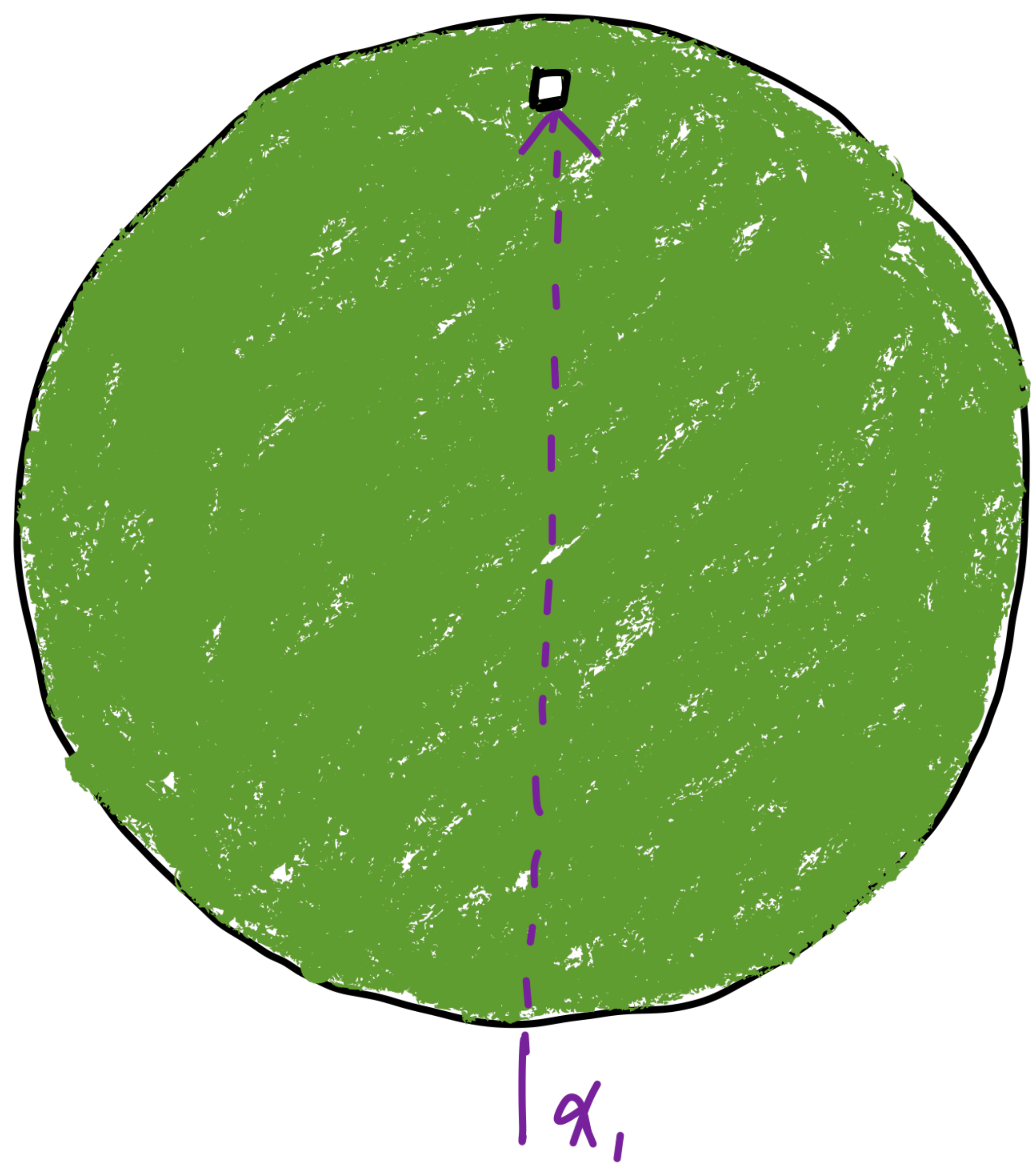


MODULATION

DOWNGOING CAN UPSCATTER ONLY IN ~1 km OVERBURDEN

UPGOING HAVE ENTIRE EARTH TO UPSCATTER

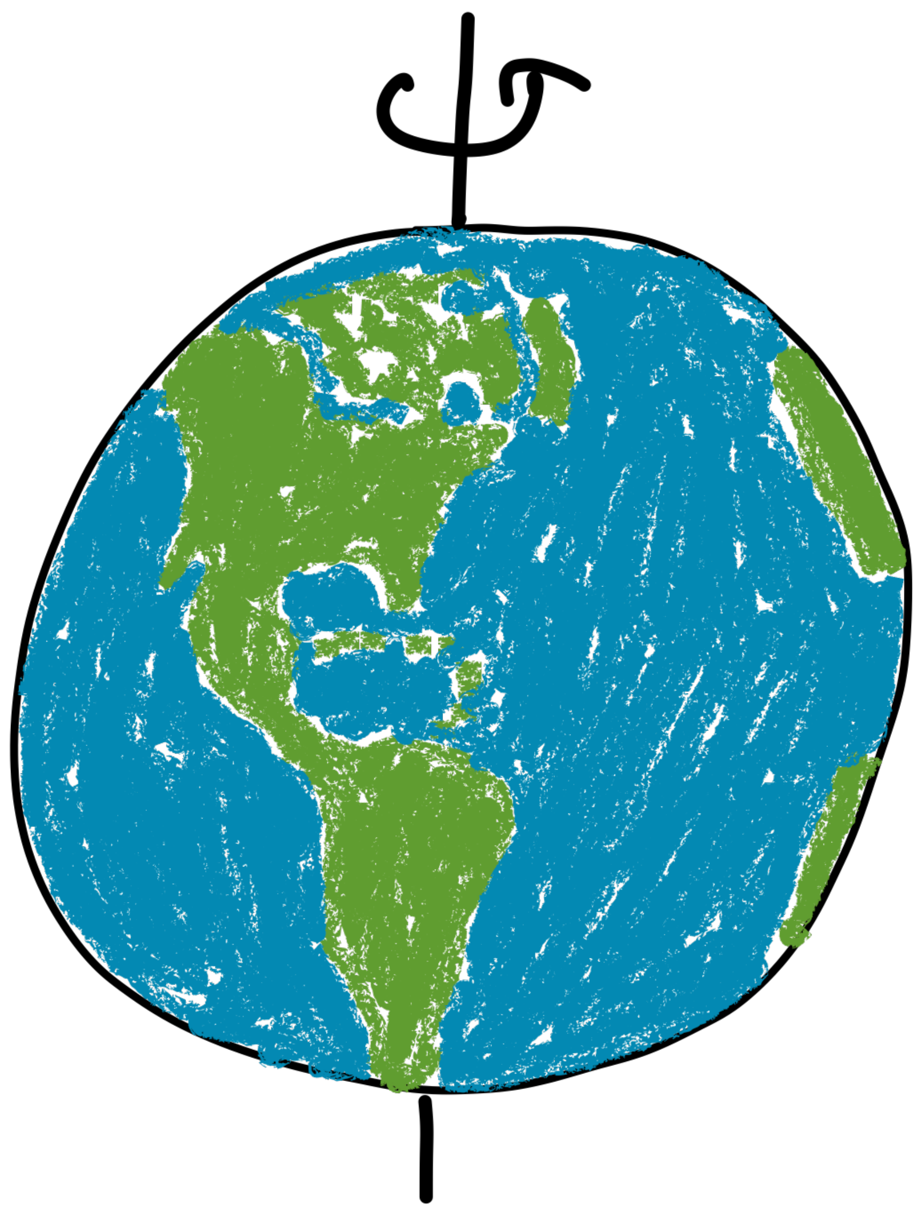




SIDEREAL - DAILY MODULATION

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

DETECTORS

- → LATITUDE MATTERS
- → DETECT ~ 100s keV PHOTON

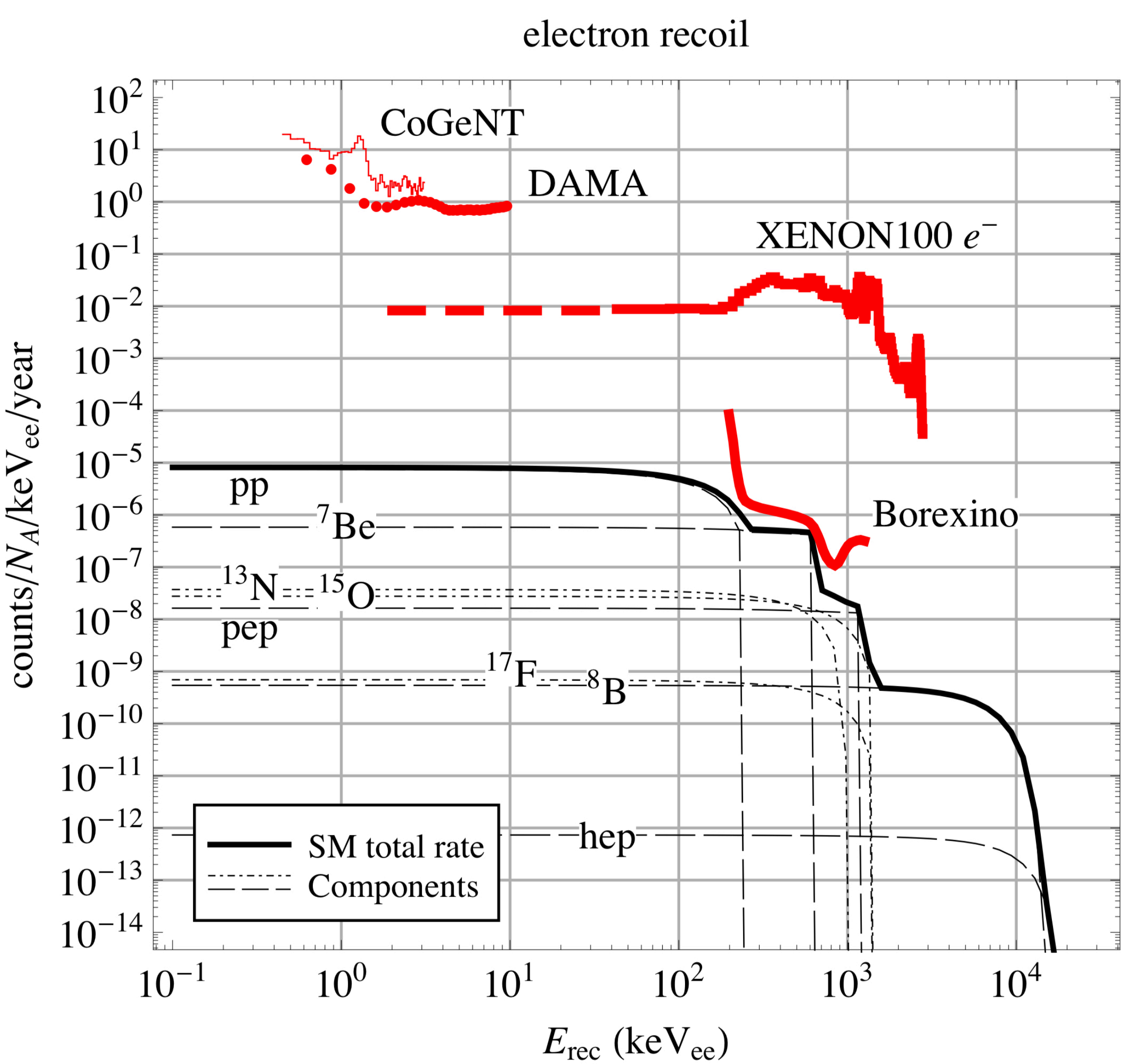
DETECTORS

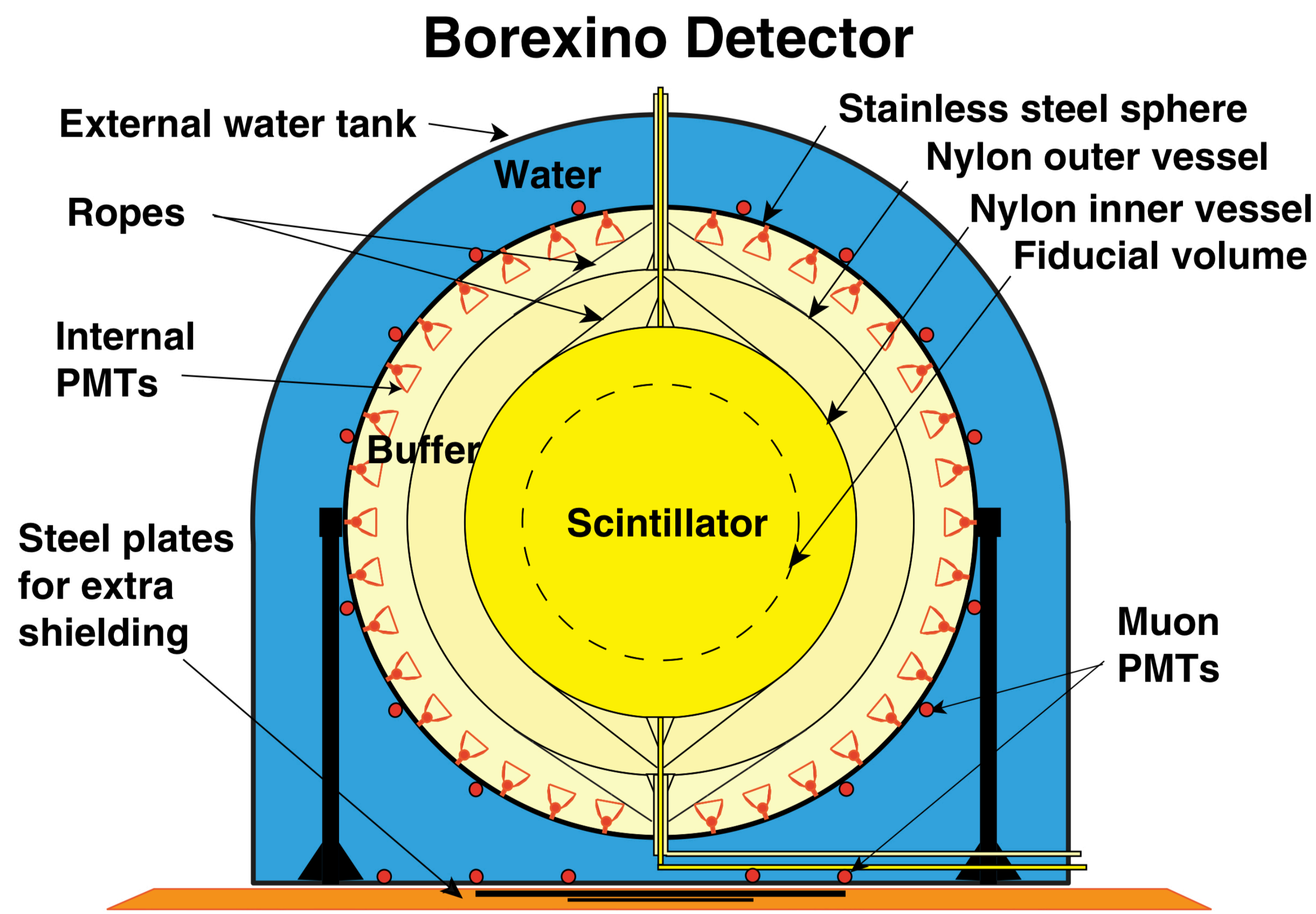
Detector	Threshold	DECLINATION
XENON 100	$E^{th} \gtrsim$ keV	43° N
BOREXINO	$E^{th} \gtrsim 100$ keV	43° N
JUNO		22° N
SUPL (BOREXINO-LIKE)		37° S
CYGNUS	$E^{th} \gtrsim$ keV	43° N ?
SNO +	$E^{th} \gtrsim 200\text{-}400$ keV	46° N
SUPER K	$E^{th} \gtrsim 1$ MeV	
DUNE		
HYPER K		

"LOCATION, LOCATION, LOCATION!"

BOREXINO

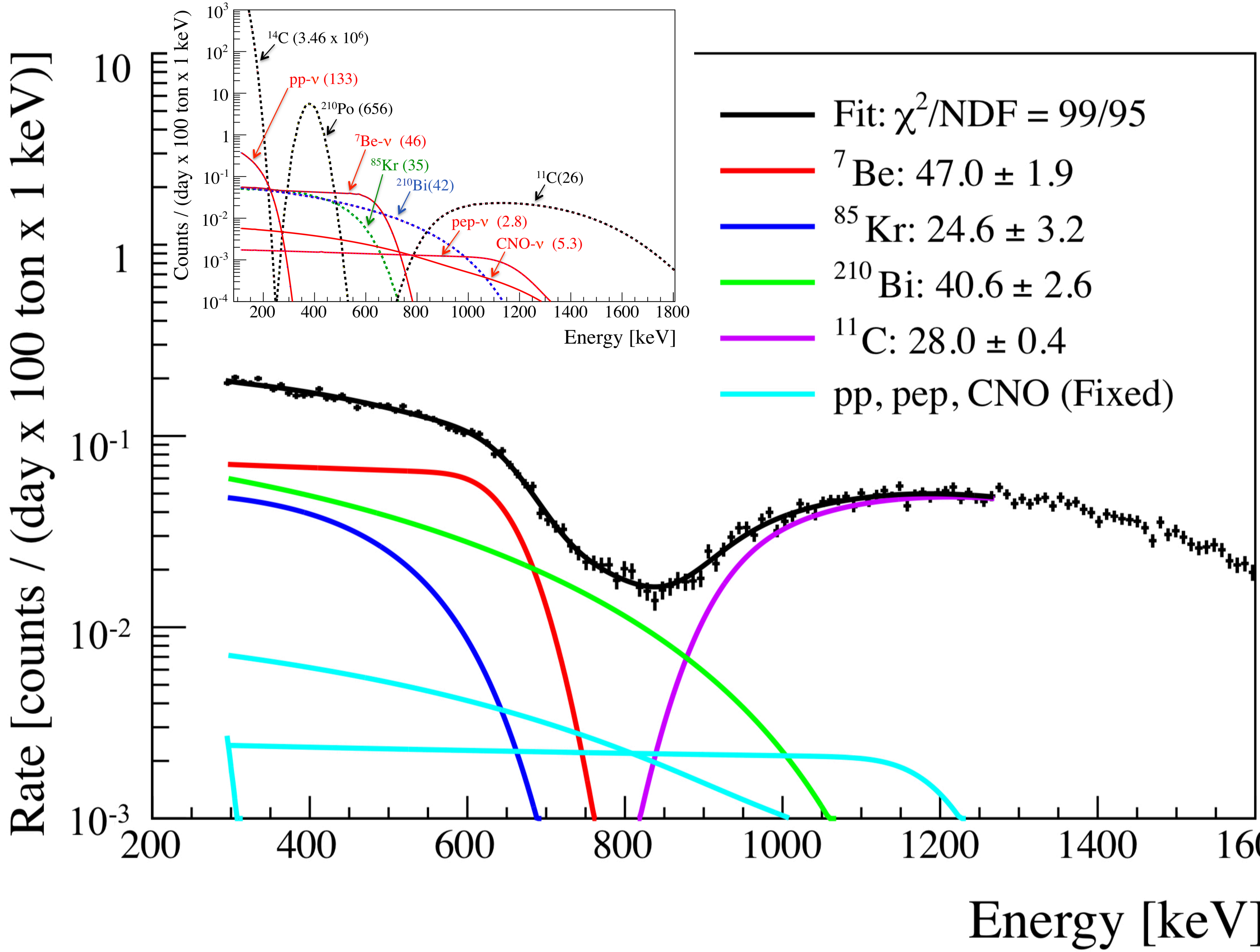
- LIQUID SCINTILLATOR ~ 280 TONS, 2000 days EXPOSURE!
- SUPER-LOW BACKGROUNDS



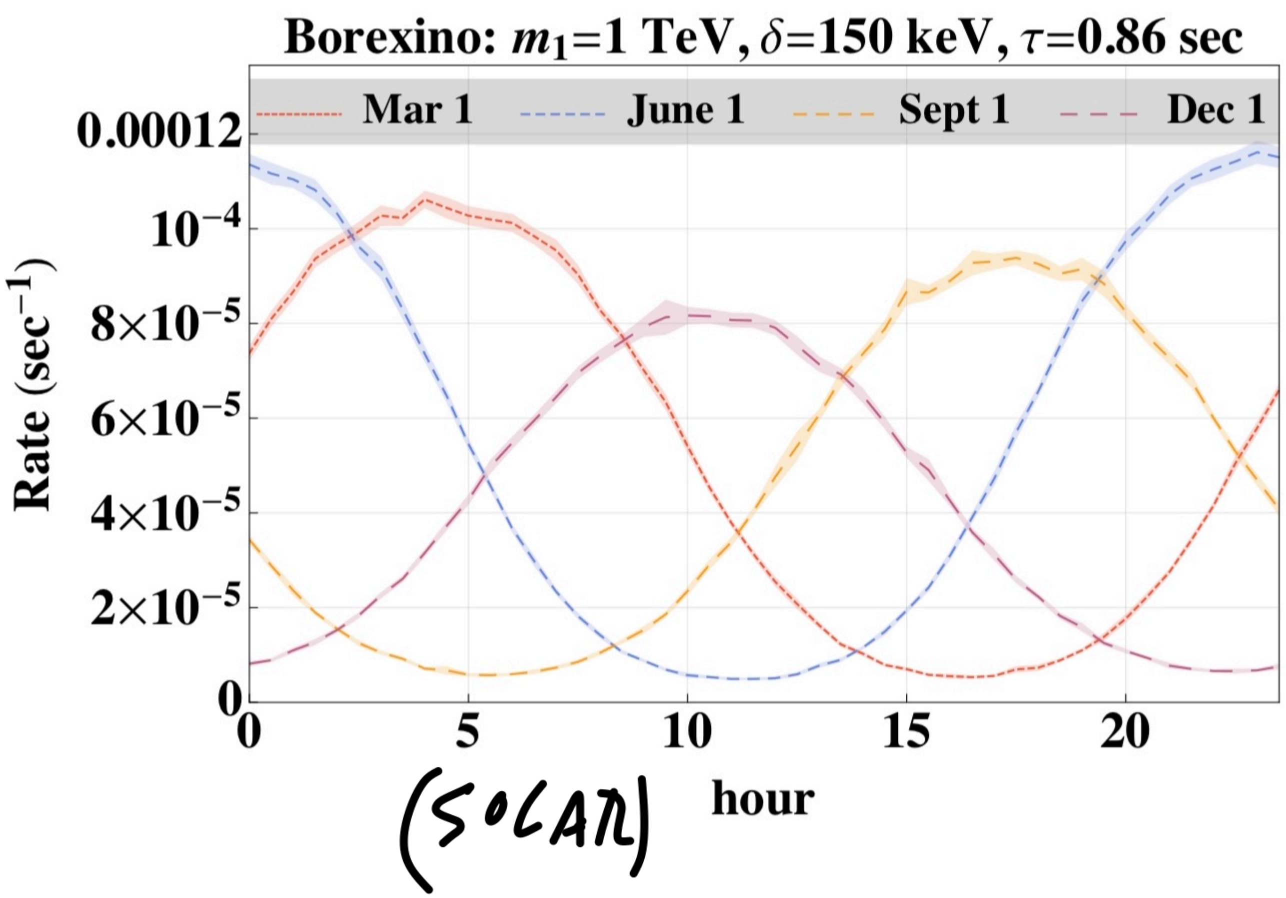


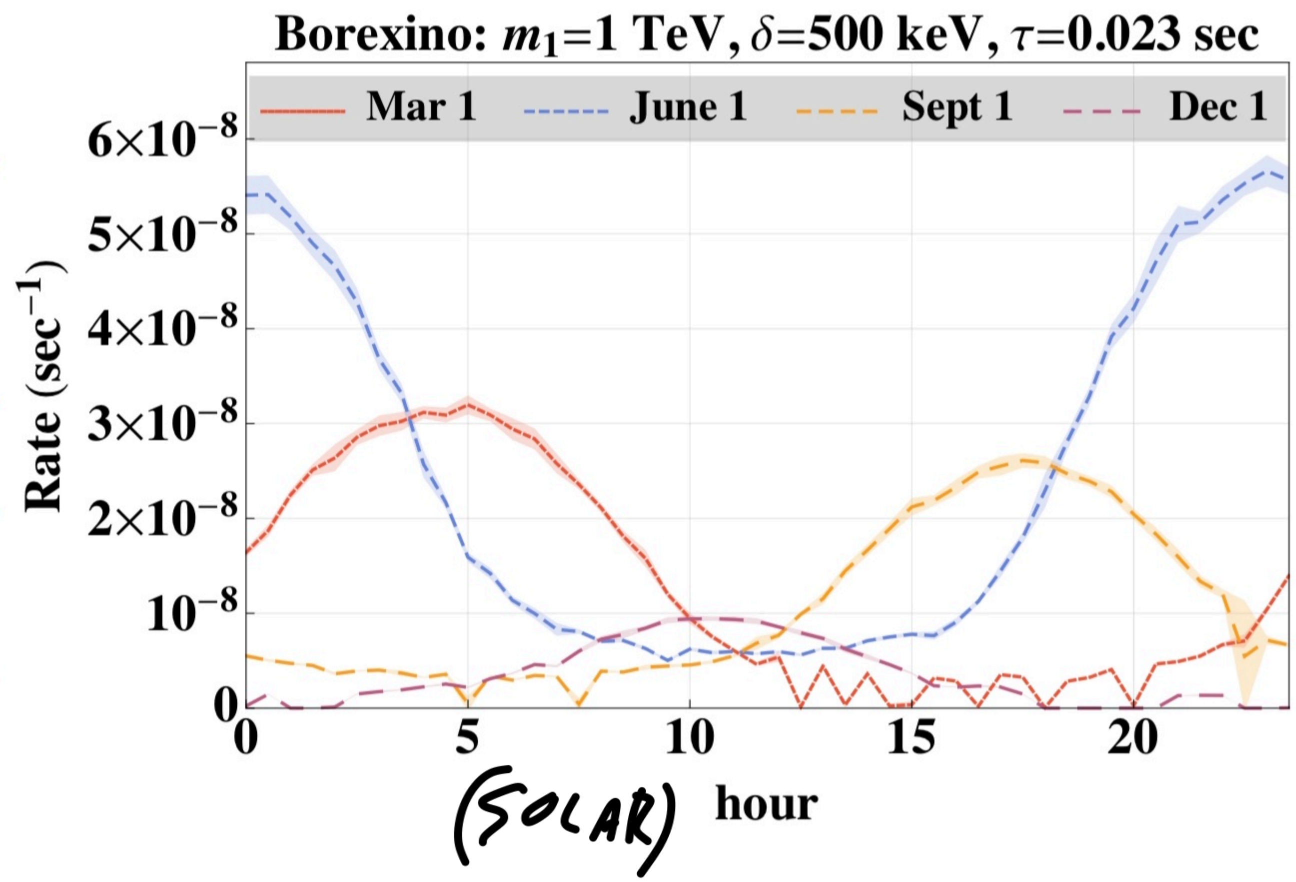
PHYSICAL REVIEW D **89,** 112007 (2014)

"BACKGROUNDS"



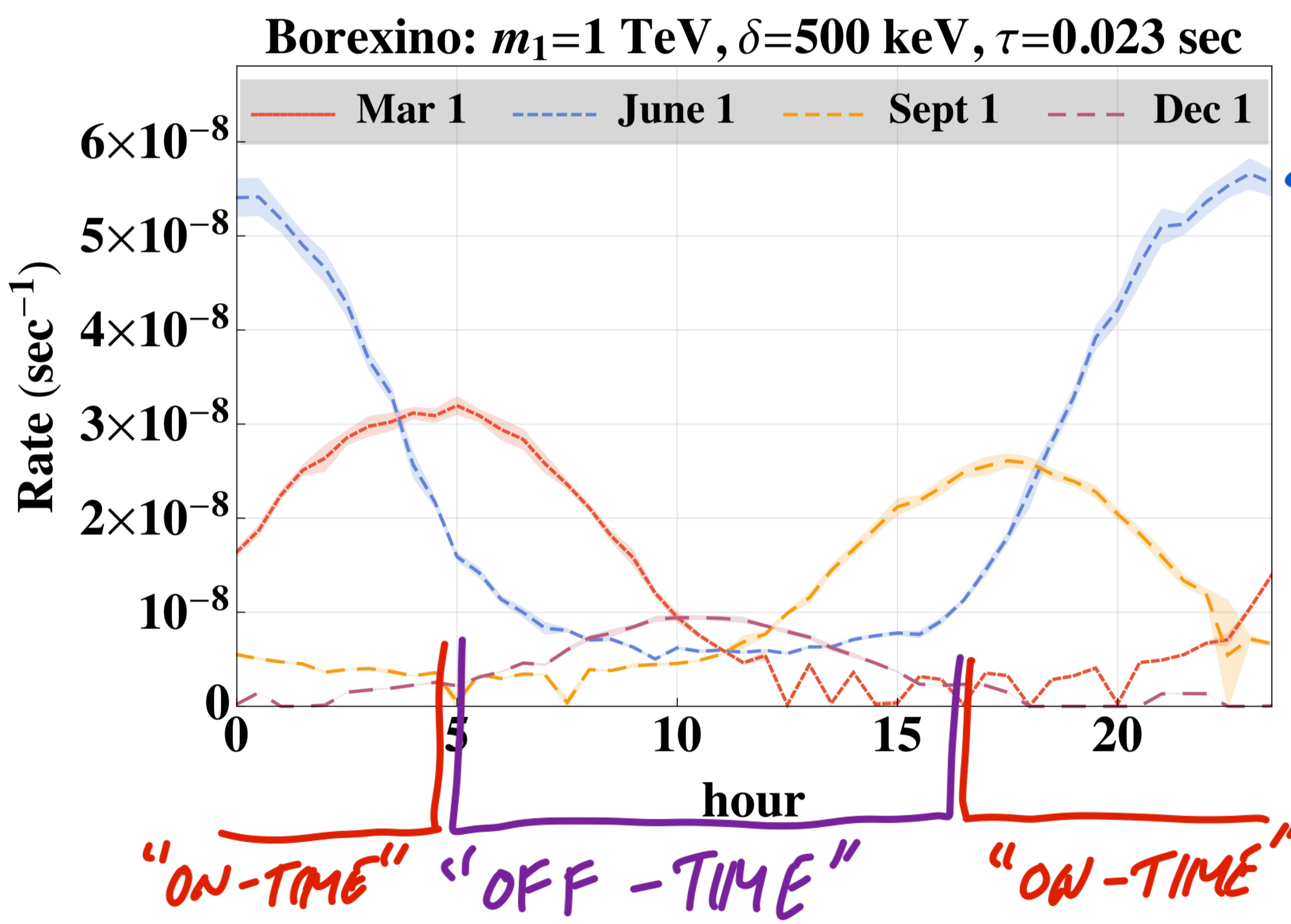
MODULATION @ BOREXINO





EXPLOIT TO SIGNIFICANTLY INCREASE SENSITIVITY

ESTIMATING THE SENSITIVITY

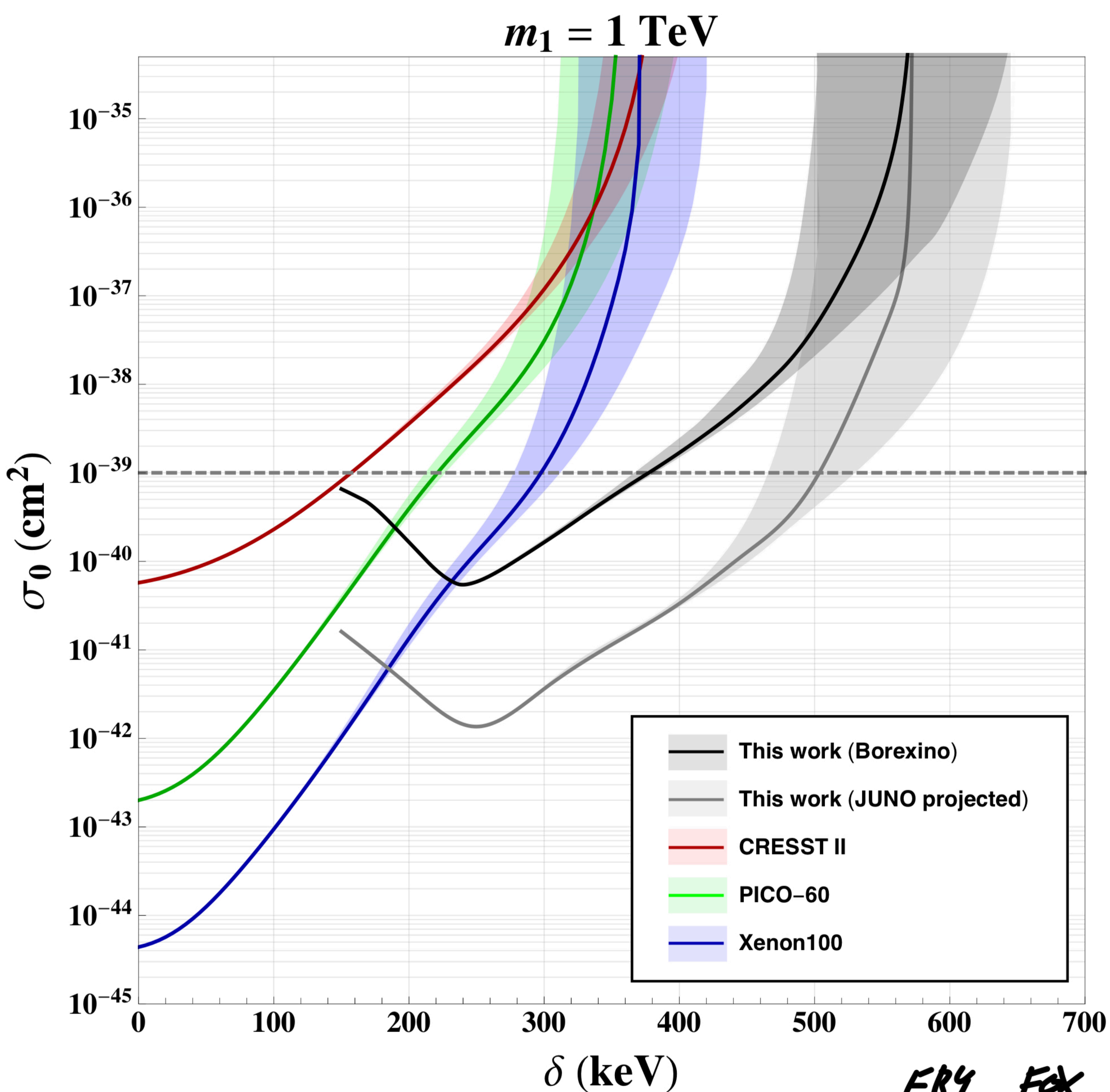


← CONSIDER JUNE 1

- BACKGROUND DETERMINED DURING "OFF-TIME"
- SENSITIVITY DETERMINED BY

$$\Gamma_{\text{SIGNAL}} \lesssim \frac{\Gamma_{\text{OFF}}}{\sqrt{N_{\text{OFF}}}}$$

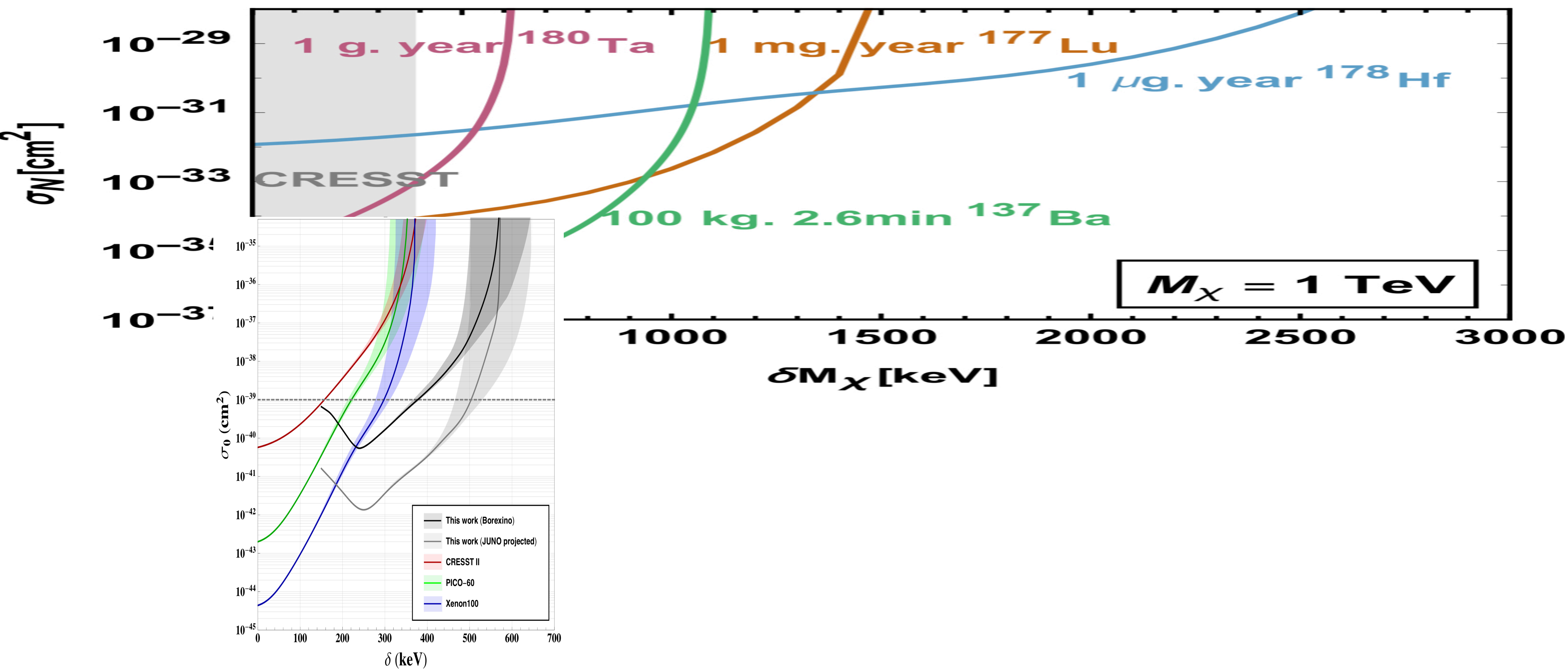
ν DETECTORS ARE AWESOME!



EBY, FOX, HARNIK, GK

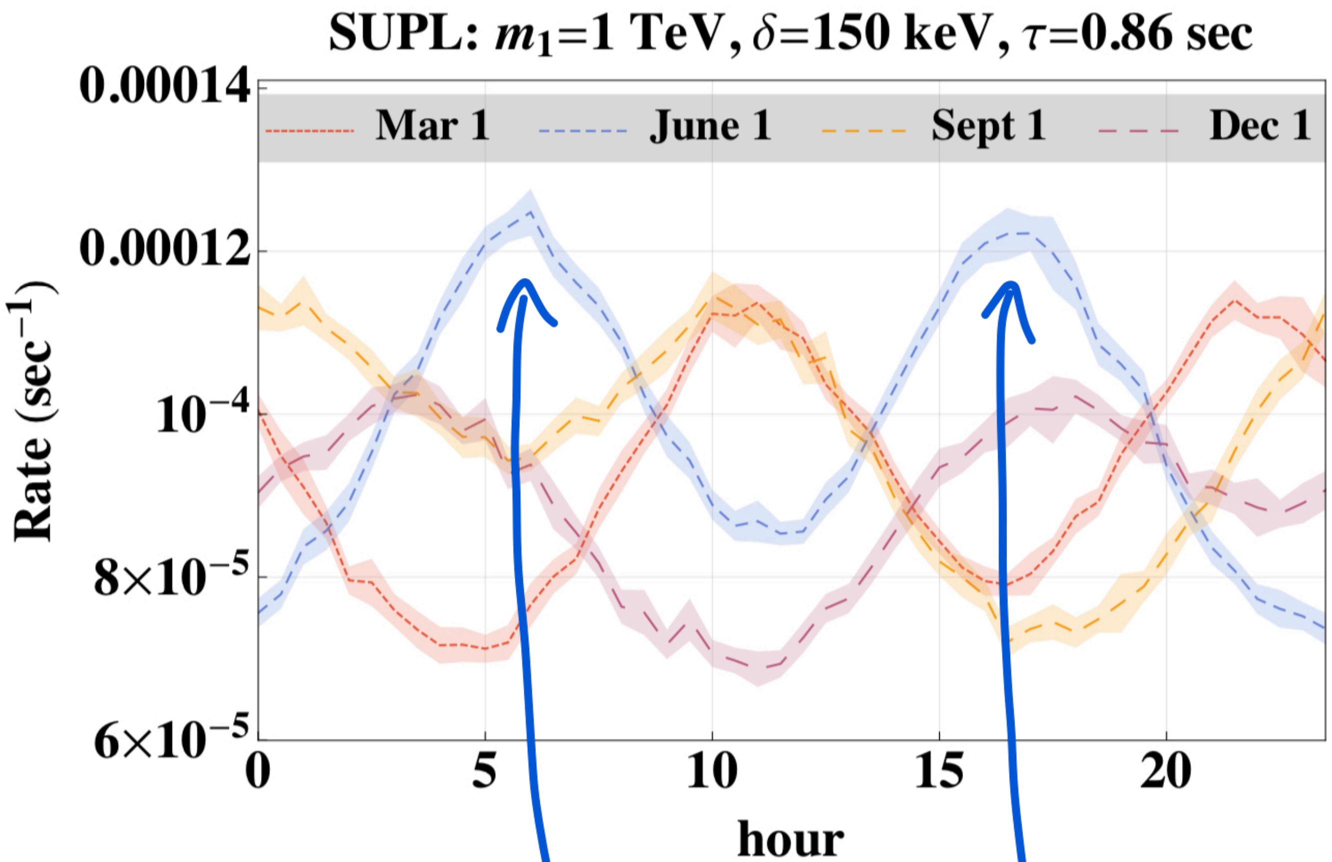
COLLISIONAL DE-EXCITATION OF NUCLEAR ISOMERS

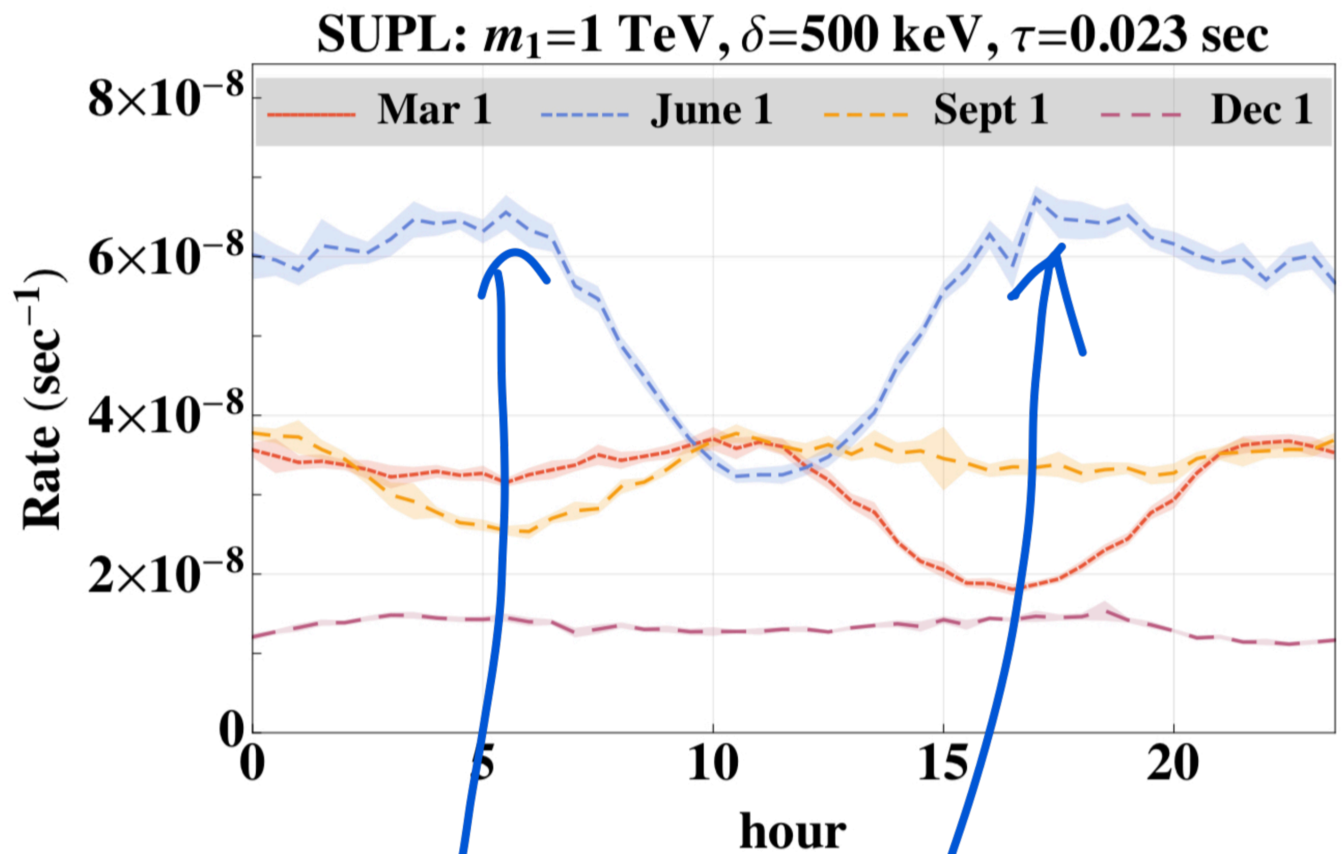
POSPELOV, RAJENDRAN, RAMANI
1907.00011



BUT, THERE'S MORE ...

SOUTHERN HEMISPHERE





TWO MAXIMA FOR EACH SIDEREAL DAY!

2 MAXIMA PER SIDEREAL DAY

-	n_{Fe} [km^{-3}]	n_{Pb} [km^{-3}]	Outer Radius [km]
Core	1.1×10^{38}	1.3×10^{31}	3483
Mantle	3.1×10^{36}	2.4×10^{30}	6341
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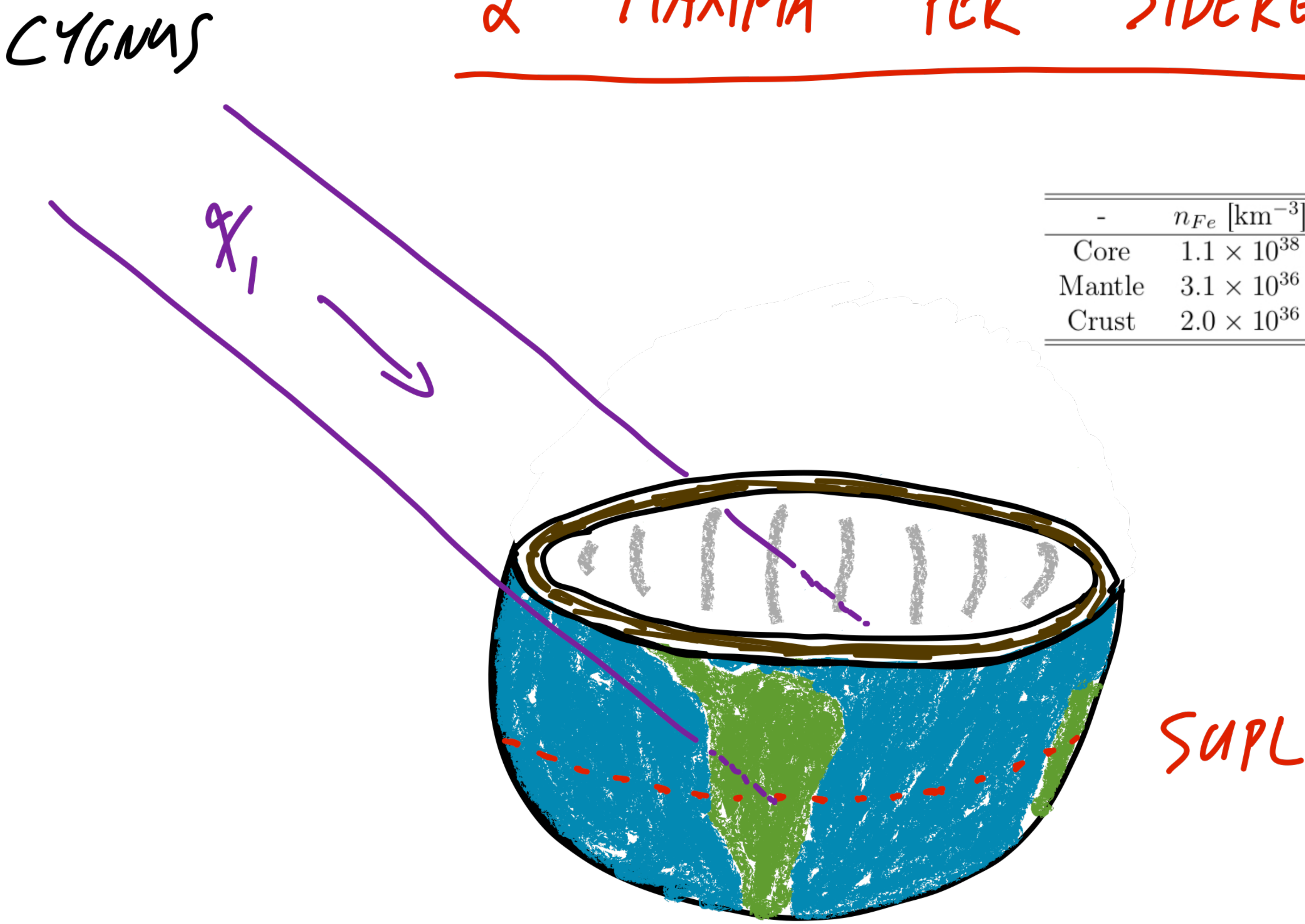


MAXIMUM COLUMN DEPTH OF CRUST AT

{ CYGNUS RISE
  CYGNUS SET

BUT THERE'S STILL MORE...

VOLUME, VOLUME, VOLUME!

PHOTON SIGNAL SCALES WITH THE <u>VOLUME</u>

NOT THE MASS OF THE DETECTOR.

<u>IDEAL</u> DETECTOR WOULD HAVE LARGE

VOLUME AND LOW MASS .....

⟹ GAS SCINTILLATION!

CYGNUS DETECTOR

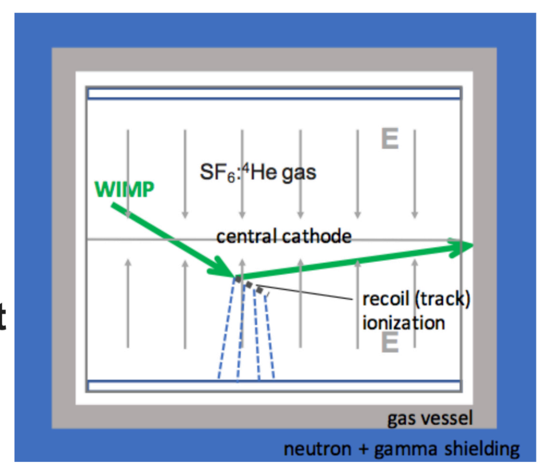
→ GAS SCINTILLATOR (DRIFT OPERATED 1 m^3)

→ LARGE VOLUME!

CYGNUS: Gas TPC Conceptual Design

These advances show how to reach the required technical goals:

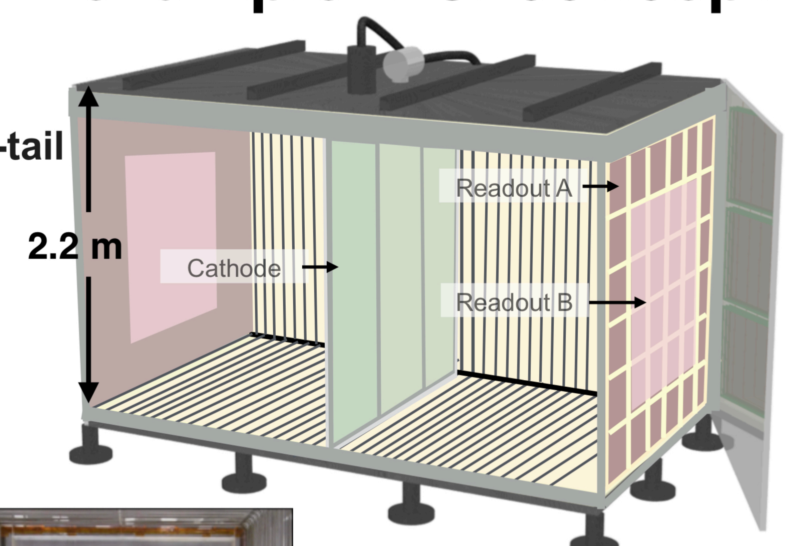
- **Gas Mixtures: SF_6:He,(CF_4) p ~1atm**
  - Can switch between higher density (search mode) and lower density gas for (improved) directional confirmation of WIMP signal
- **Threshold at <1 keV_e**
  - Use of high gain stages
  - Ultimate is W~30 eV
- **Active electron rejection at ~GeV**
- **Reduced diffusion via -ve ion drift**
- **<u>3D Fiducialisation</u>**
  - 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)**



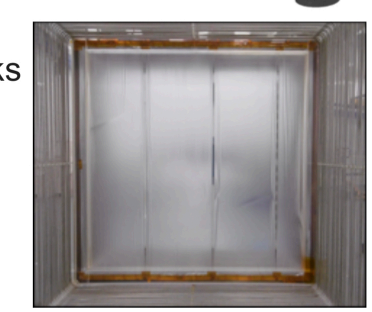
Neil Spooner, IDM 2018

CYGNUS 10m³ - example first concept

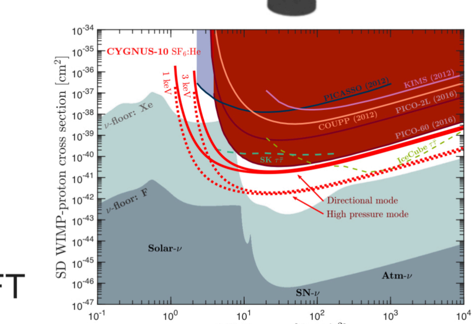
- **10m^3 SF_6:He**
- **Thin central cathode**
- **Charge readout, head-tail**
- **Water block shielding**
- **Possible Boulby site**



DRIFT-II with water blocks



UNM thin cathode in DRIFT



Neil Spooner, IDM 2018

CYGNUS DETECTOR ADVANTAGES

→ NEGLIGIBLE ✓ BACKGROUNDS

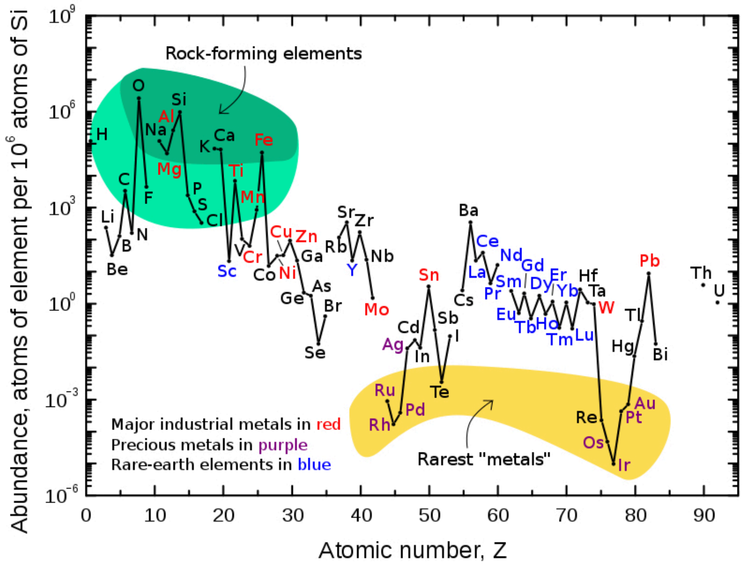
→ LOW THRESHOLD ($\sim 1\ \mathrm{keV_{ee}}$)

→ SCALABLE TO LARGE VOLUME

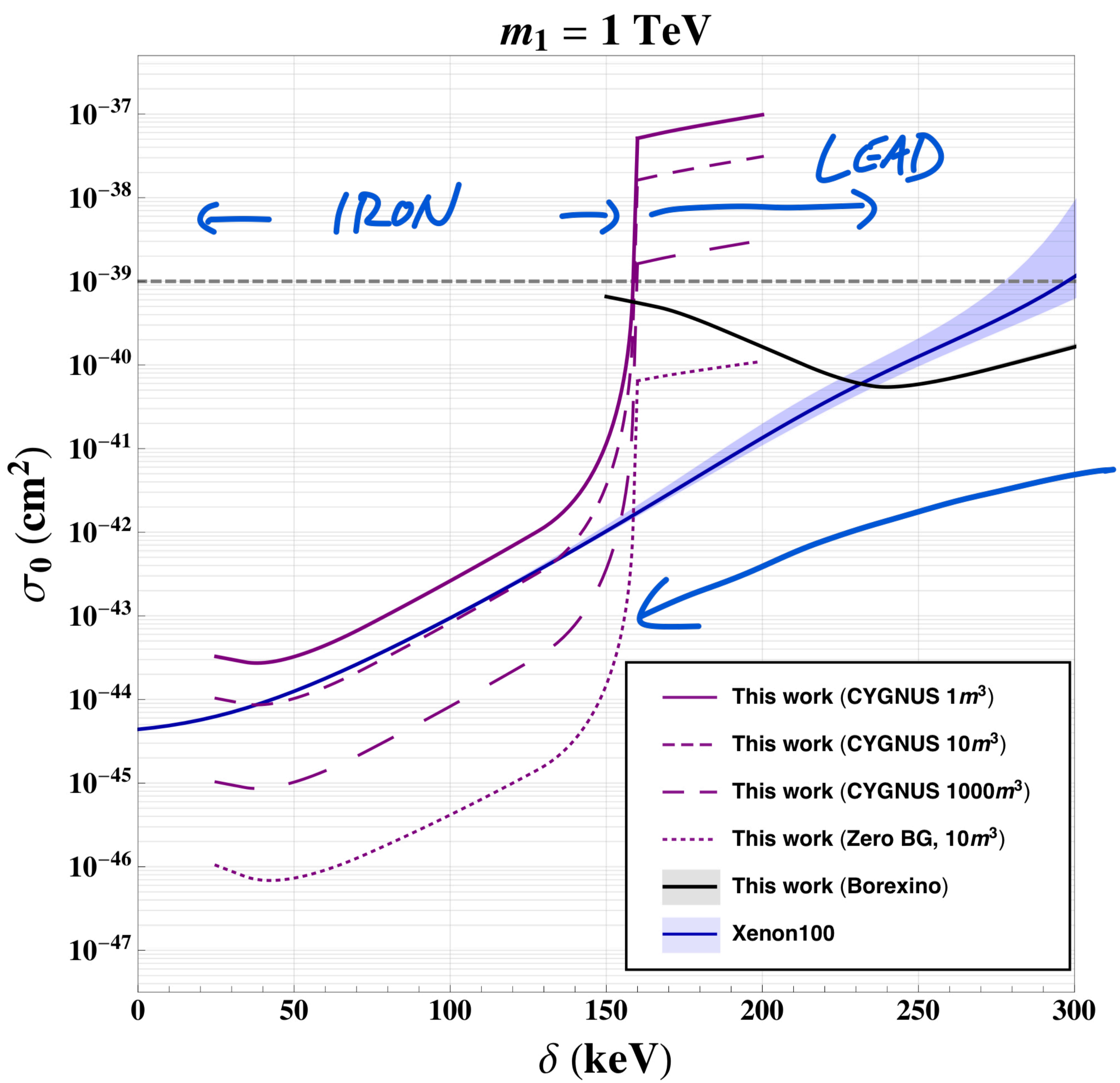
FOR INELASTIC, LOW THRESHOLD IMPLIES

LIGHTER, MORE COMMON ELEMENTS CAN BE USED

FOR UPSCATTER.



CYGNUS PROJECTIONS



PHOTON SIGNAL BETTER THAN DIRECT DETECTION

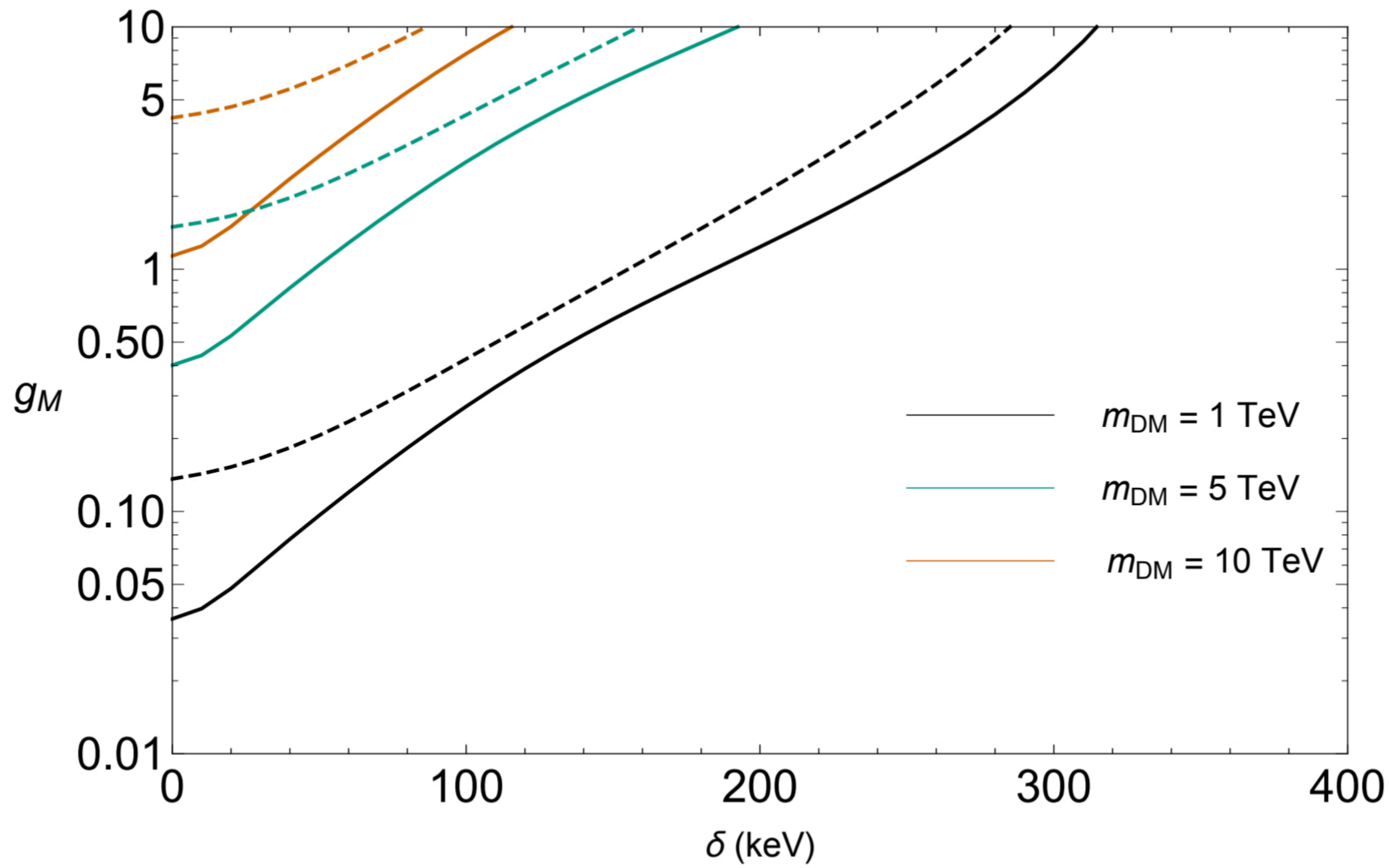
MAGNETIC INELASTIC @ CYGNUS

→) CONSIDER $\left(\frac{g_M}{4}\right)\frac{e}{2m_\chi}\chi_2\,\sigma_{\mu\nu}\,\chi_1 F^{\mu\nu}$

(UPSCATTER & DECAY BY SAME OPERATOR)

PICO BOUND ↓

EXPECTED XENON BOUND ↙

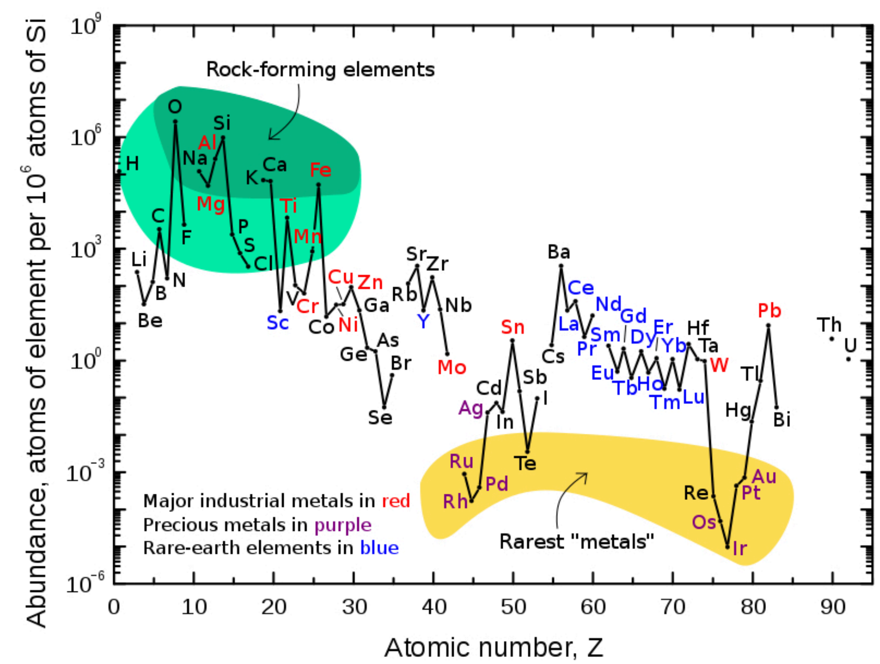


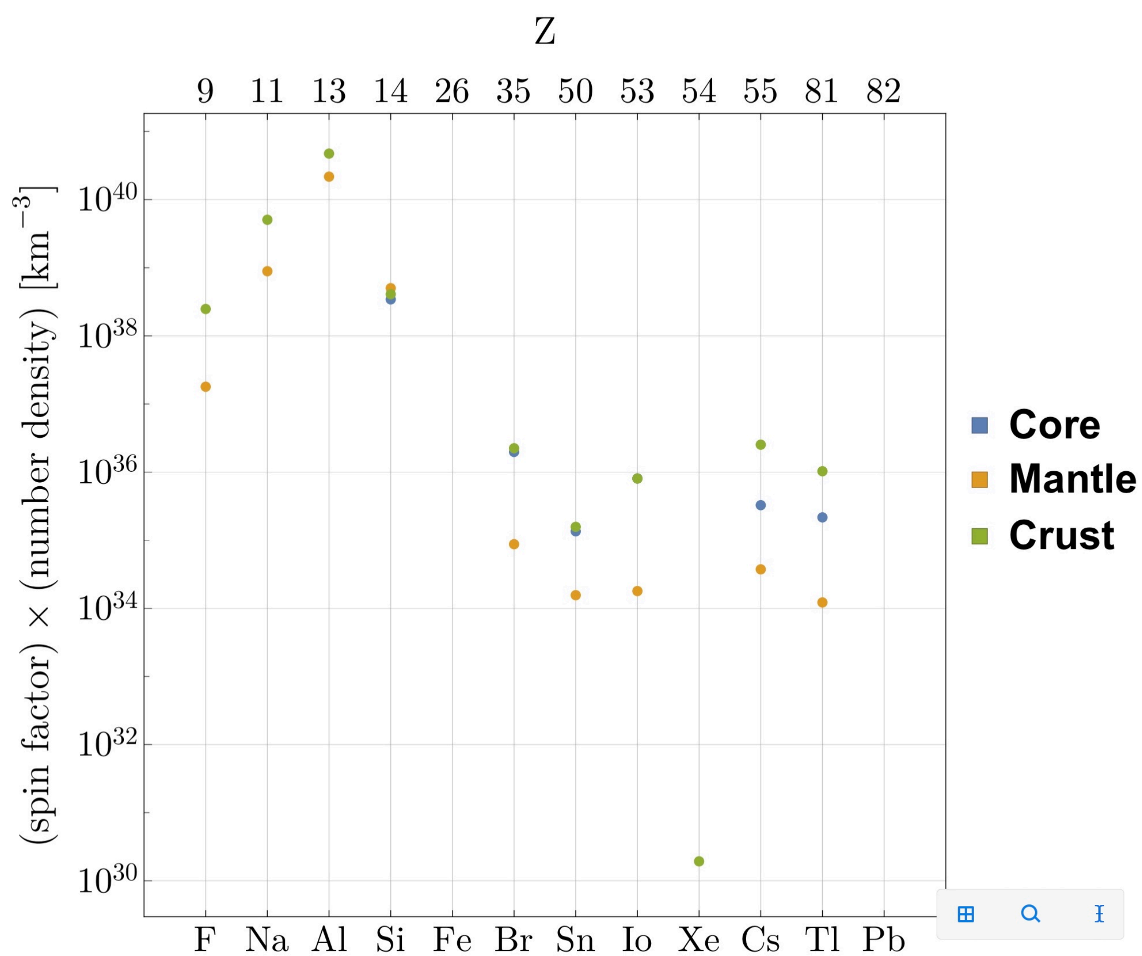
BRAMANTE, FOX, GK, MARTIN

MAGNETIC INELASTIC @ CYGNUS

EXPLOIT HIGH SPIN ELEMENTS IN EARTH!

$\Rightarrow$ Al, Na, Si, F, etc.





COULD BE MUCH MORE COMPETITIVE THAN DIRECT DETECTION!

EBY, FOX, HARNIK, GK (IN PROGRESS)

CONCLUSIONS

- WIMPS THAT SCATTER INELASTICALLY ARE VIABLE, WELL MOTIVATED, AND PROVIDE NEW METHODS TO SEARCH
- 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)