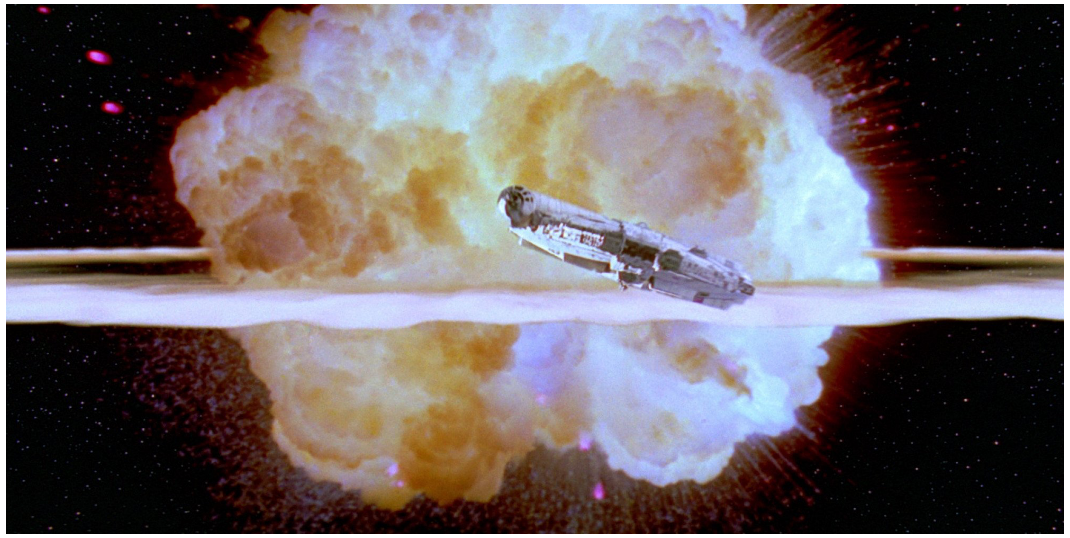
DM Direct Detection in Large ν Detectors

Fermilab ν Seminar

Roni Harnik

Fermilab



Works with J. Eby, P. Fox, G. Kribs (in rapid progress)

with Y. Grossman, O.Telem, Y. Zhang (2017)

A Wide Net for New Physics

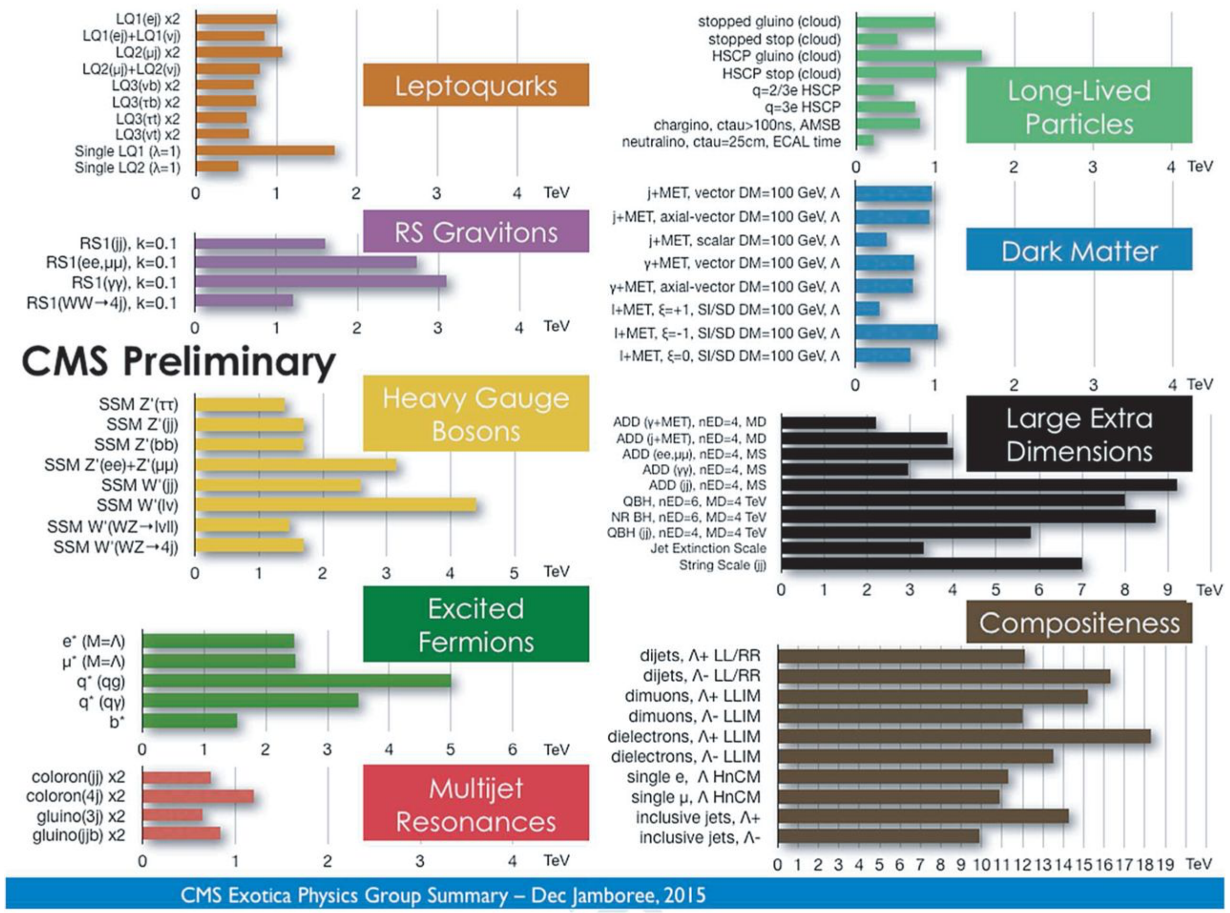
- In general, in the search for new physics we want to cast a wide net!
- Design a wide set of experiments.
- For given experiments look beyond the canonical "signal region"

Multi-Purpose Detectors

- A wide net can be cast by single experiments, if they are versatile and performing well.
- A long tradition in collider experiments- CDF, D0, ATLAS, CMS...

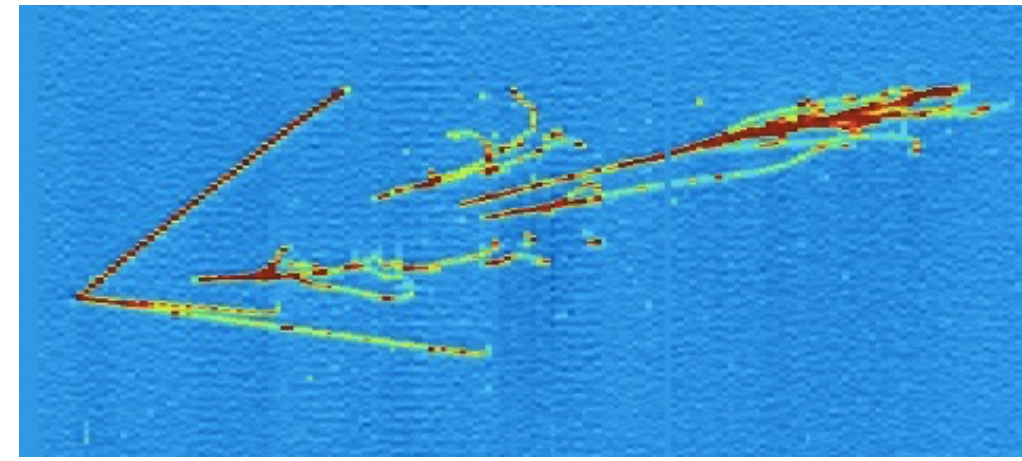
Find low BG regions and simple models that populate them.

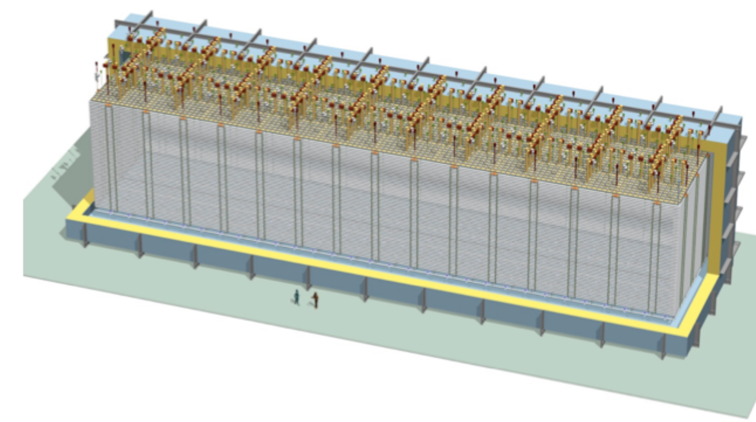
e.g.: mono-photon, di-lepton résonance, ...



Modern ν Detectors (particularly LAr)

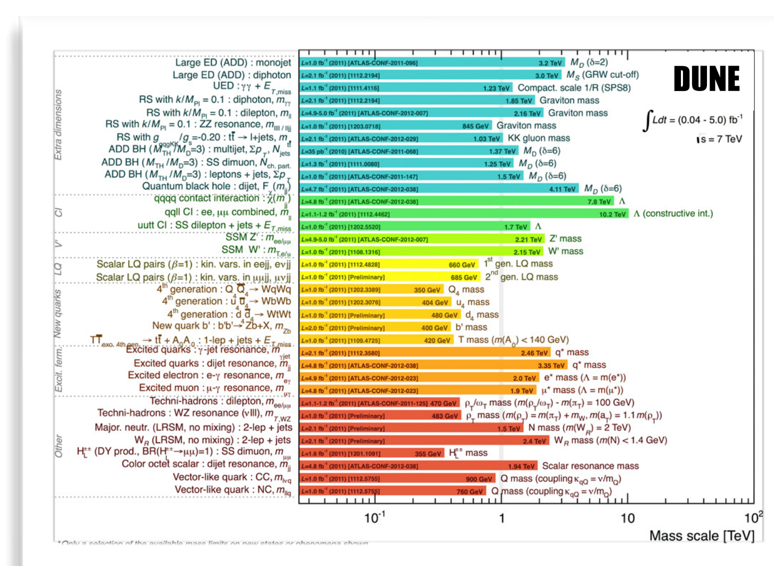
- Large.
- Clean.
- Particle ID.
- Track reconstruction.
- Good energy resolution.





Multi-purpose!

Is there an equivalent menu of searches?

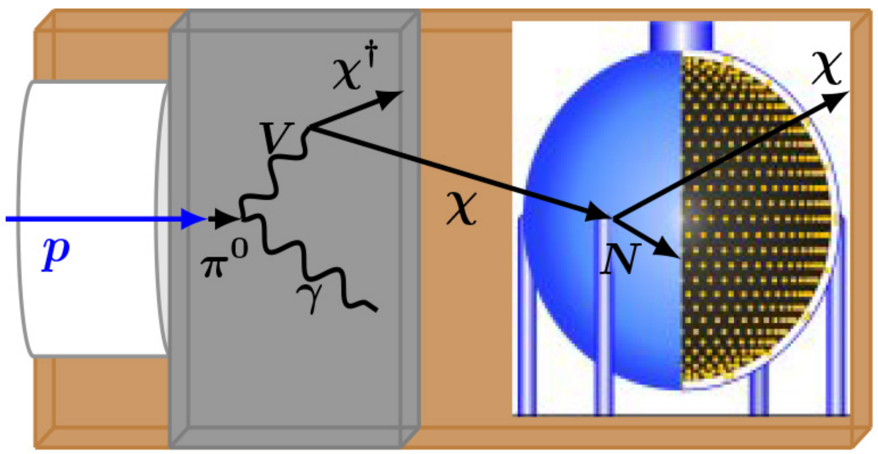


?

Near and Far

- In near detectors, including short baseline, beam related signals have been proposed.

(miniBOONE DM search)



- There may be new opportunities for LAr... (in progress)
- In this talk I will focus on large and deep far detectors....

...Dark Matter

Outline

- DM:
  - Direct Detection, and connections to ν detectors.
  - Non-minimal DM.
- iDM and the Luminous Higgsino
  - Signals at Low threshold (Borexino, ultra-clean DUNE...?)
- Self Destructing DM
  - Models - variations on the SM.
  - Signals in DUNE.

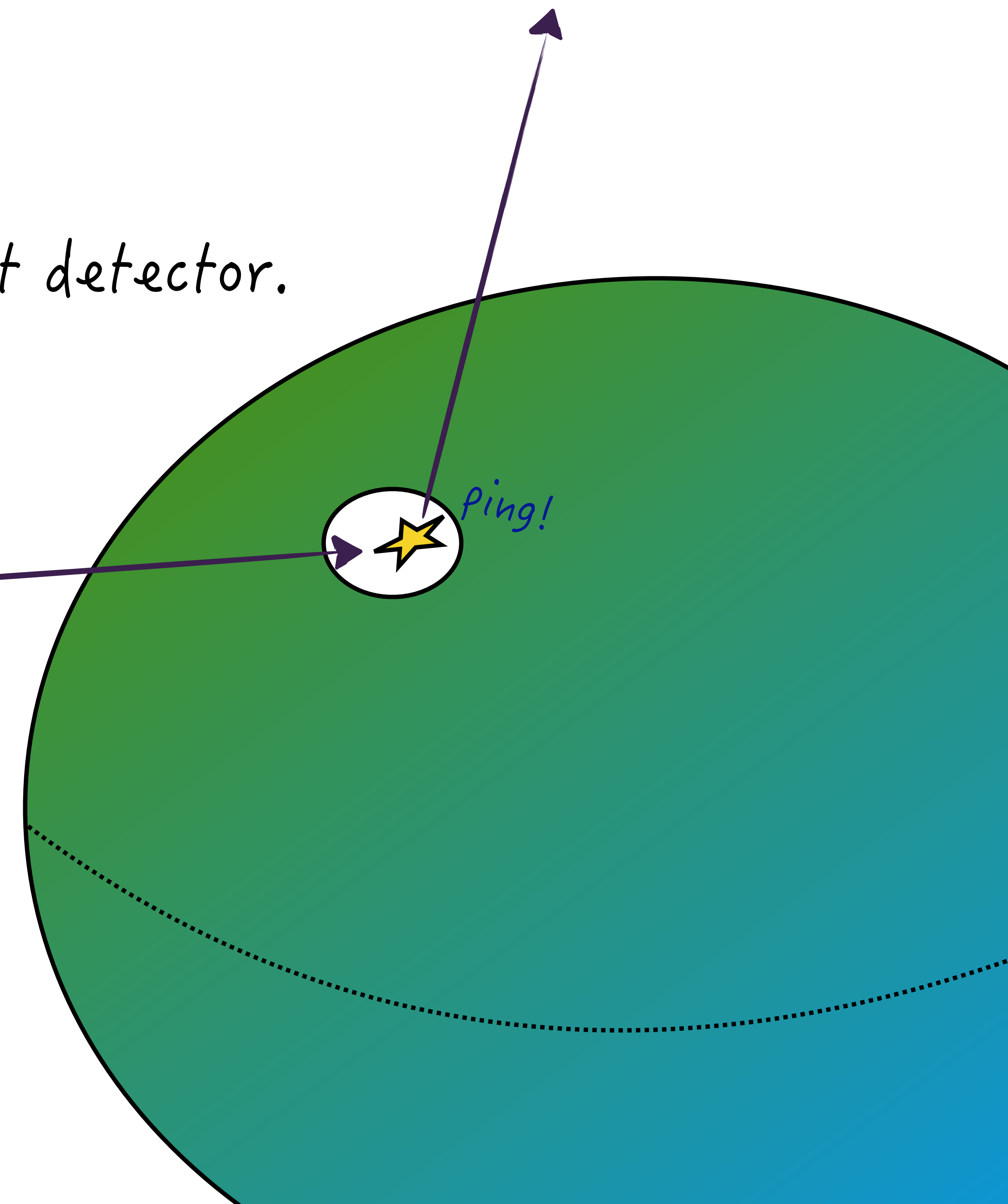
My one slide introduction to DM:

There is Dark Matter in this room!! :-0

Blows your mind.
Makes you want to find it, no?

Direct Detection

- The effort to detect halo DM here:
  - Go underground.
  - Build a **big**, clean, and quiet detector.
  - Wait.

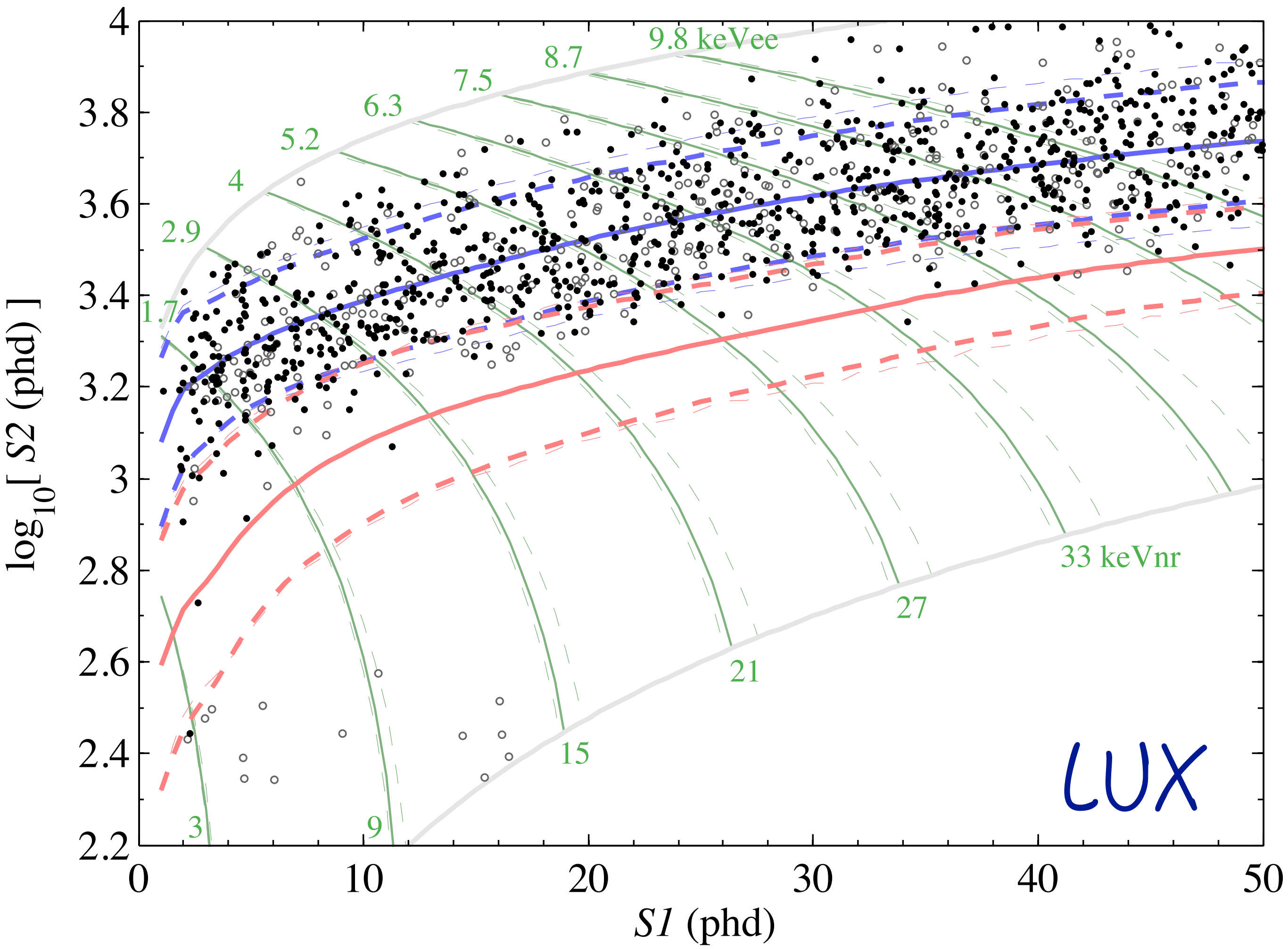


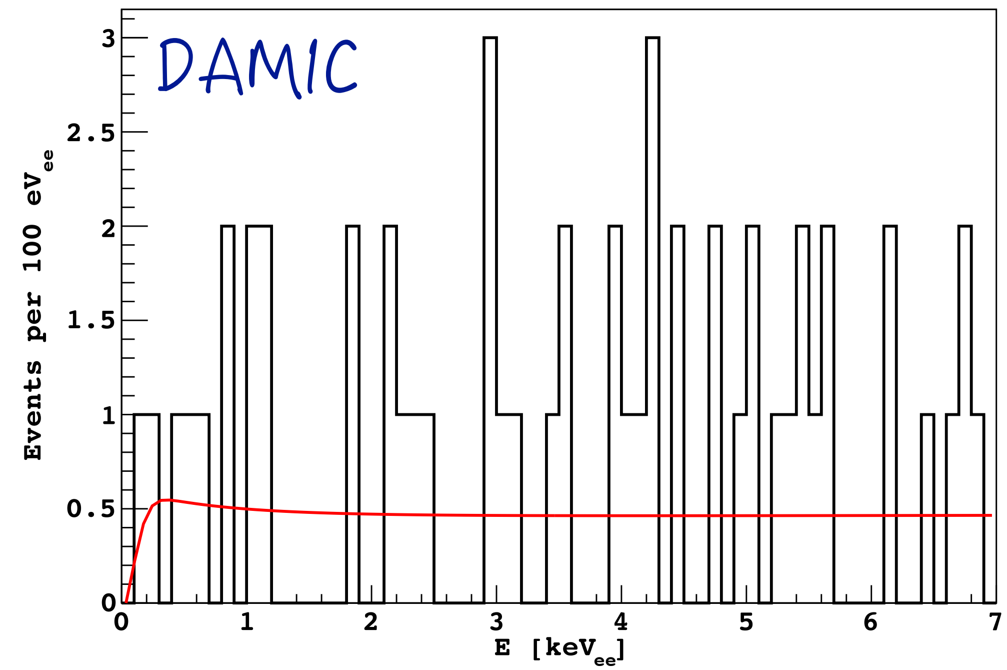
- Available energy:

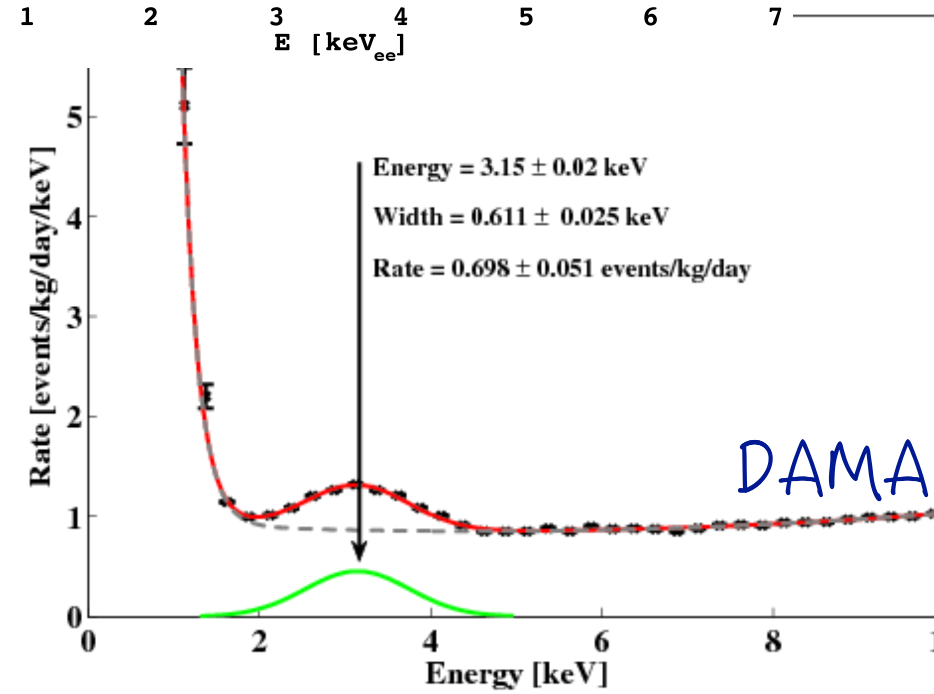
$$E_{recoil} \sim \mu v^2 \sim 10^{-6} \mu$$

μ = reduced mass

Direct Detection



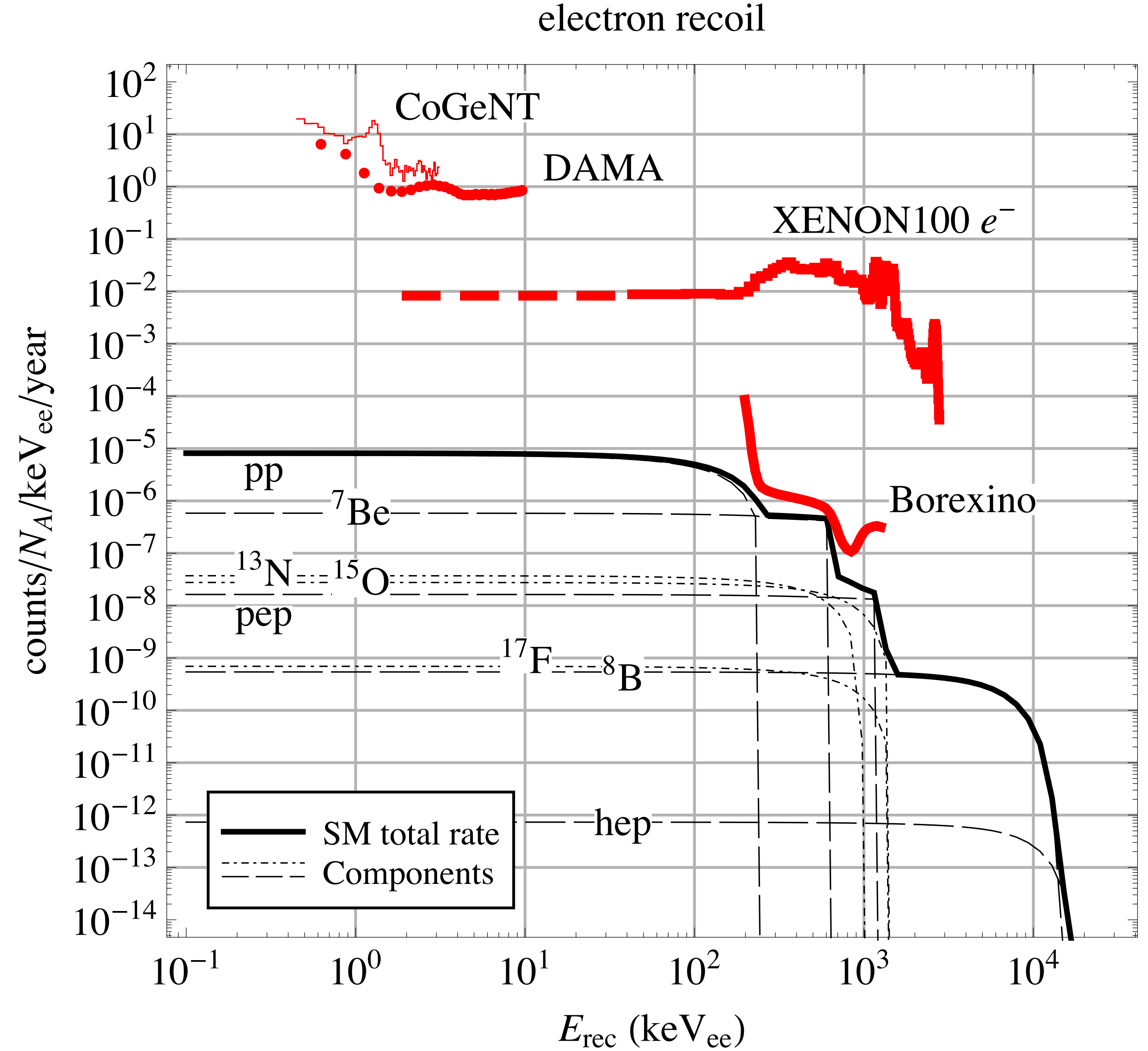




The search for DM (rightly) focus on low thresholds.

Neutrino Detectors

- Neutrino detectors are very big and very clean! Have a higher threshold..



(to be fair, this plot is for electron recoil... still)

Neutrino Detectors

detector	Mass [ton]	Threshold
XENON 1T	1	few keV
Borexino	10^2	~200 keV
SNO	10^3	~ MeV
Super K	5×10^4	~ 6 MeV
DUNE	3×10^4	~ 1-10 MeV? Can we go lower? please...?
Hyper K	5×10^5	~ 6 MeV ?
IceCube?	~ 10^7	~ 10 GeV

Can we use them to search for DM?

Non-Minimal DM

- A non-minimal DM model can bring the signal to higher energies.
  - inelastic DM (iDM)
  - exothermic DM
  - Form Factor DM
  - ...

These models modify DD pheno.
But the search for DM remains in
the domain of low threshold experiments.
LUX, XENON, CDMS, PICO, DAMIC,...

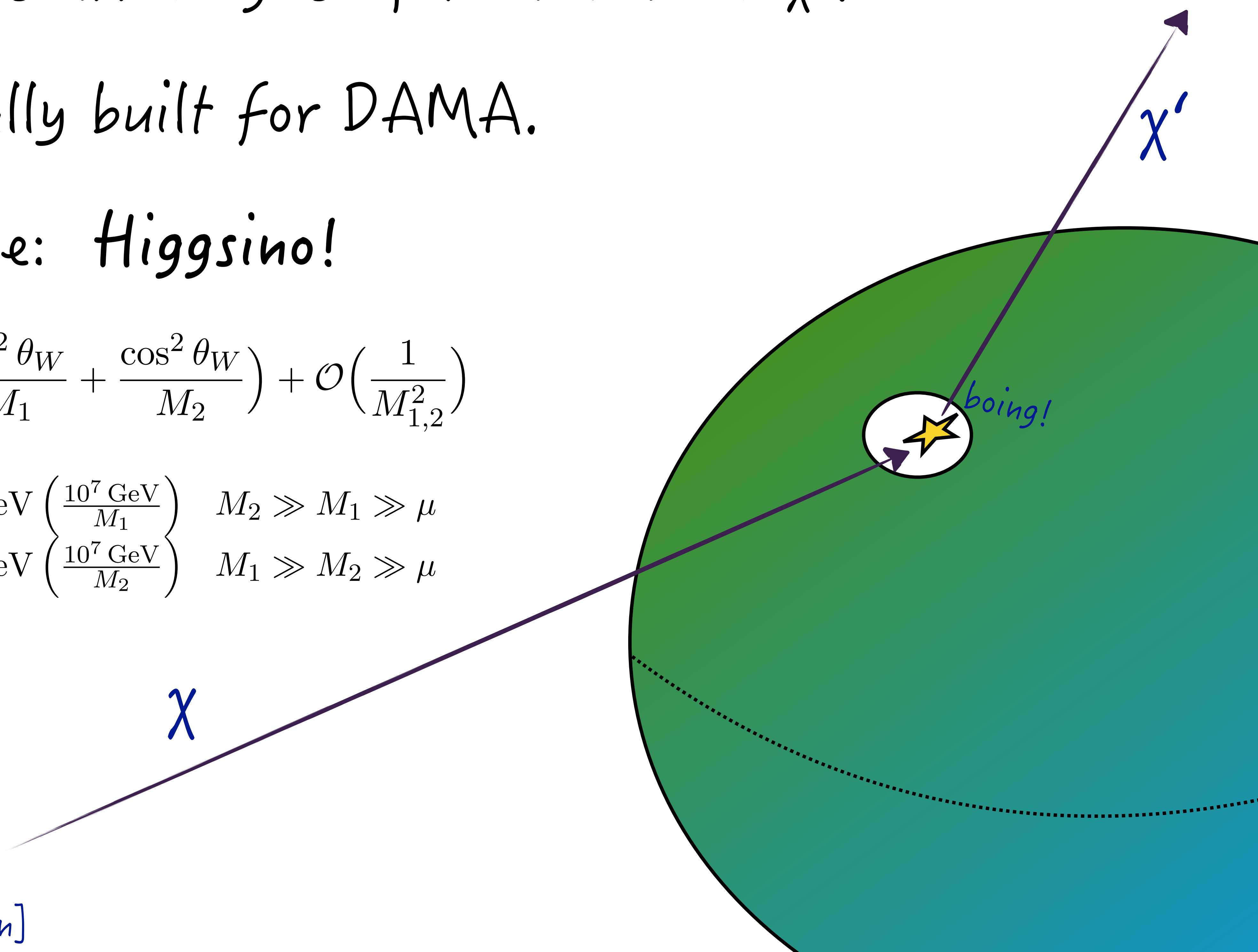
[Weiner, Tucker-Smith]

Inelastic DM

- In iDM scattering is up to a heavier χ'.
- Originally built for DAMA.
- Example: **Higgsino!**

$$\delta_{\tilde{\mathrm{H}}} \simeq m_Z^2 \left(\frac{\sin^2\theta_W}{M_1} + \frac{\cos^2\theta_W}{M_2}\right) + \mathcal{O}\left(\frac{1}{M_{1,2}^2}\right)$$

$$= \begin{cases} 192\,\mathrm{keV}\left(\frac{10^7\,\mathrm{GeV}}{M_1}\right) & M_2 \gg M_1 \gg \mu \\ 640\,\mathrm{keV}\left(\frac{10^7\,\mathrm{GeV}}{M_2}\right) & M_1 \gg M_2 \gg \mu \end{cases}$$

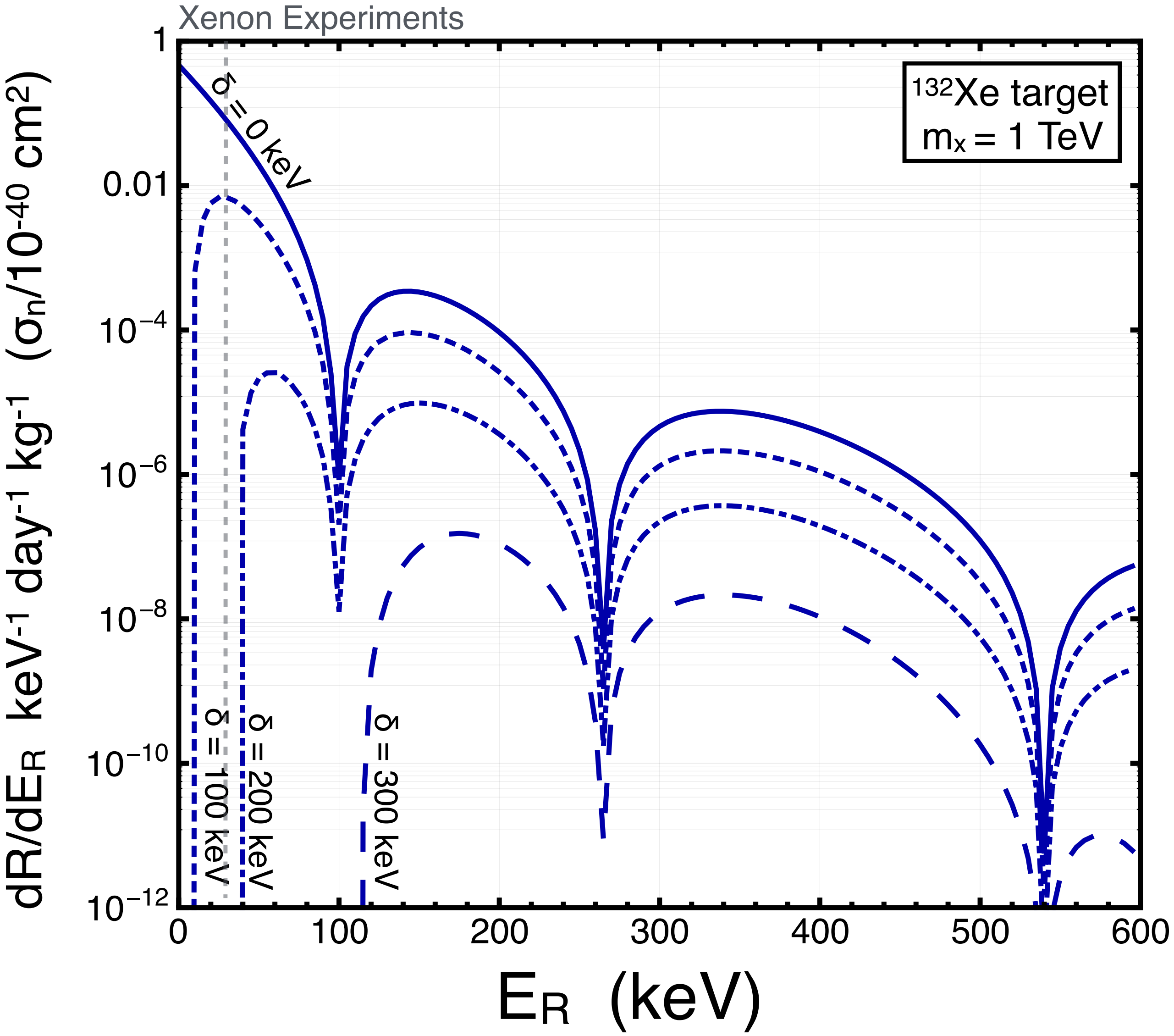


[Bramante, Fox, Kribs, Martin]

[Weiner, Tucker-Smith]

Inelastic Frontier

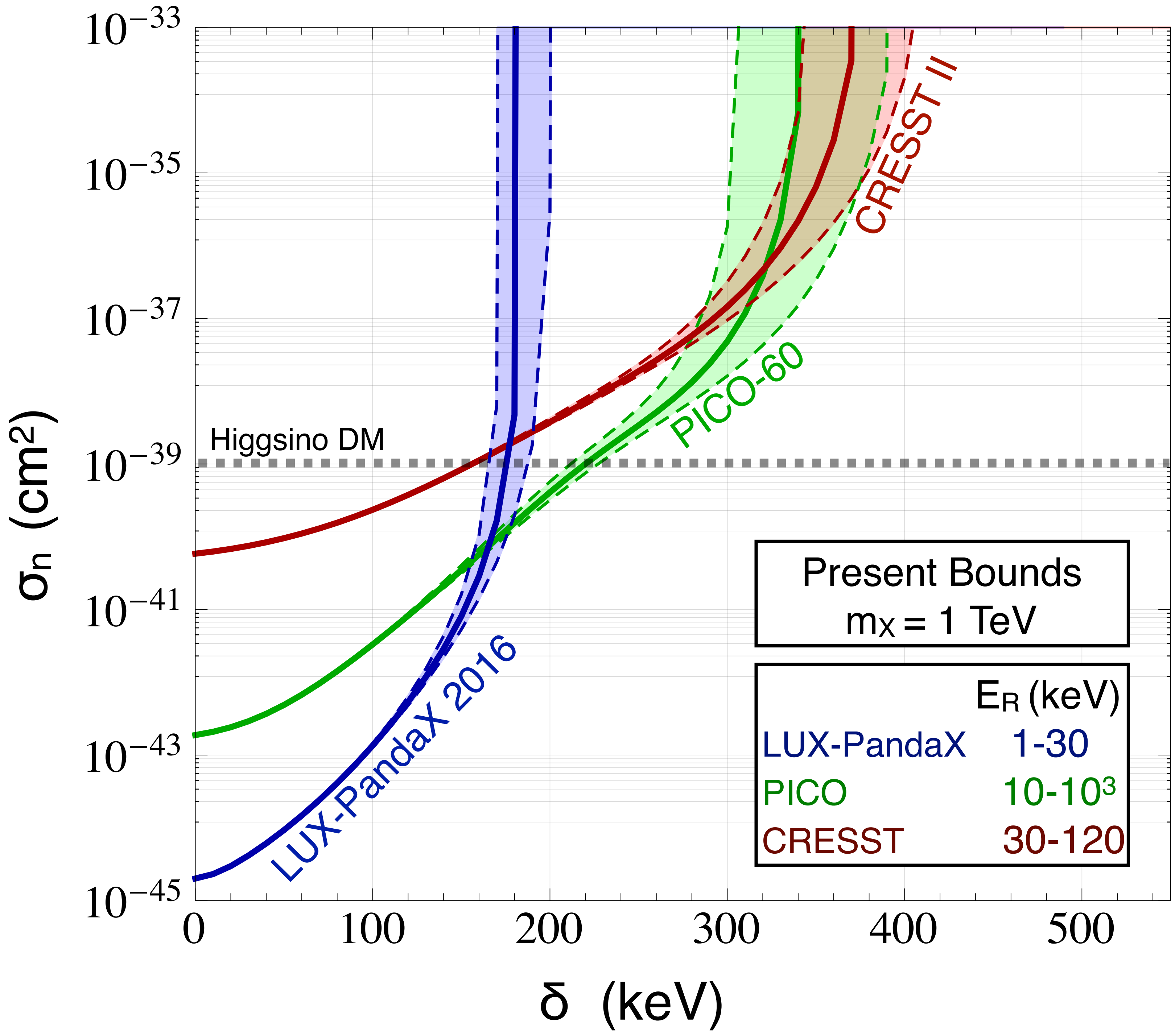
- In iDM we get a modified pheno:
  - Scaling with target mass (heavy nuclei preferred).
  - Modified recoil spectrum. (Pushed to higher recoil)
  - Modified modulation.



[Bramante, Fox, Kribs, Martin]

[Weiner, Tucker-Smith]

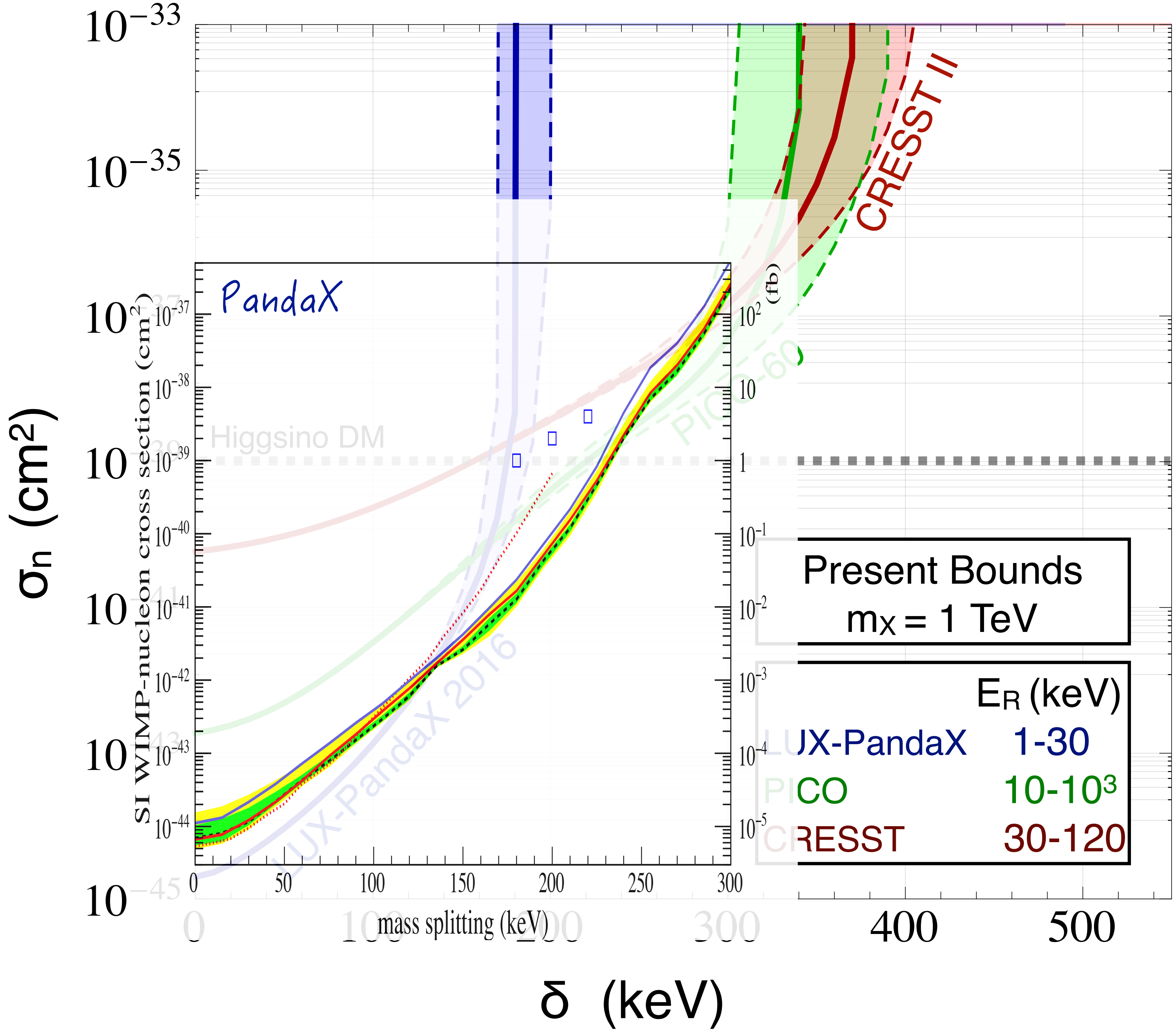
Inelastic Frontier



[Bramante, Fox, Kribs, Martin]

[Weiner, Tucker-Smith]

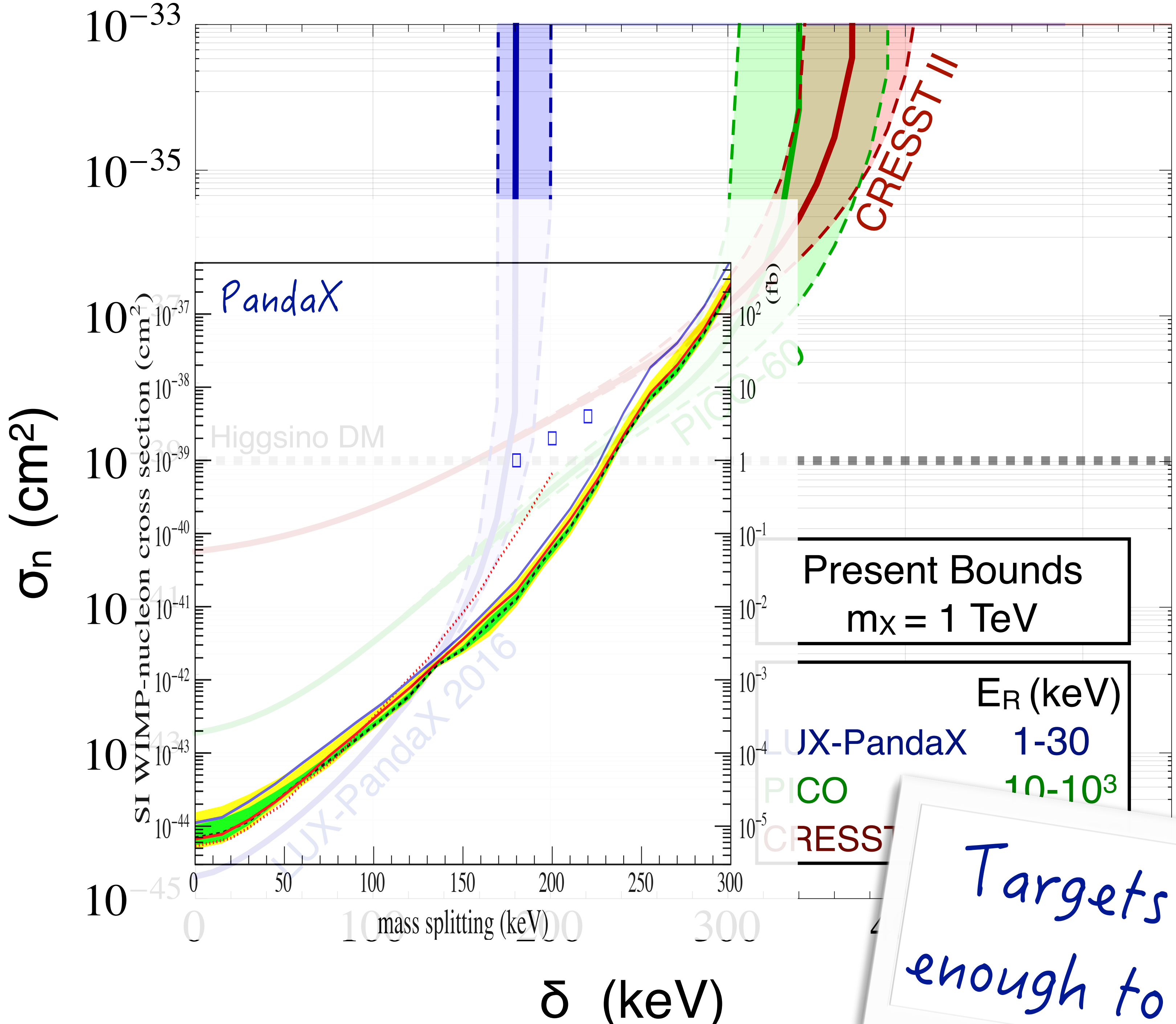
Inelastic Frontier



[Bramante, Fox, Kribs, Martin]

[Weiner, Tucker-Smith]

Inelastic Frontier



Targets are not heavy enough to go to higher δ.

[Bramante, Fox, Kribs, Martin]

What Happens Next?

- After excitation χ' decays back to χ. Often $\chi' \rightarrow \chi + \gamma$ via a dipole operator.
- For Higgsino:

$$\tau(X_2 \rightarrow X_1 + \gamma) \approx \frac{4\pi^2\, m^2}{\alpha\, \alpha_W^2\, \delta^3} = (.1 \text{ sec})\Big(\frac{350 \text{ keV}}{\delta}\Big)^3 \Big(\frac{m}{1 \text{ TeV}}\Big)^2$$

At 10^{-3} it takes about 10 seconds to cross the earth.

Can we detect the decay?

[Feldstein, Graham, Rajendran - written for DAMA....]

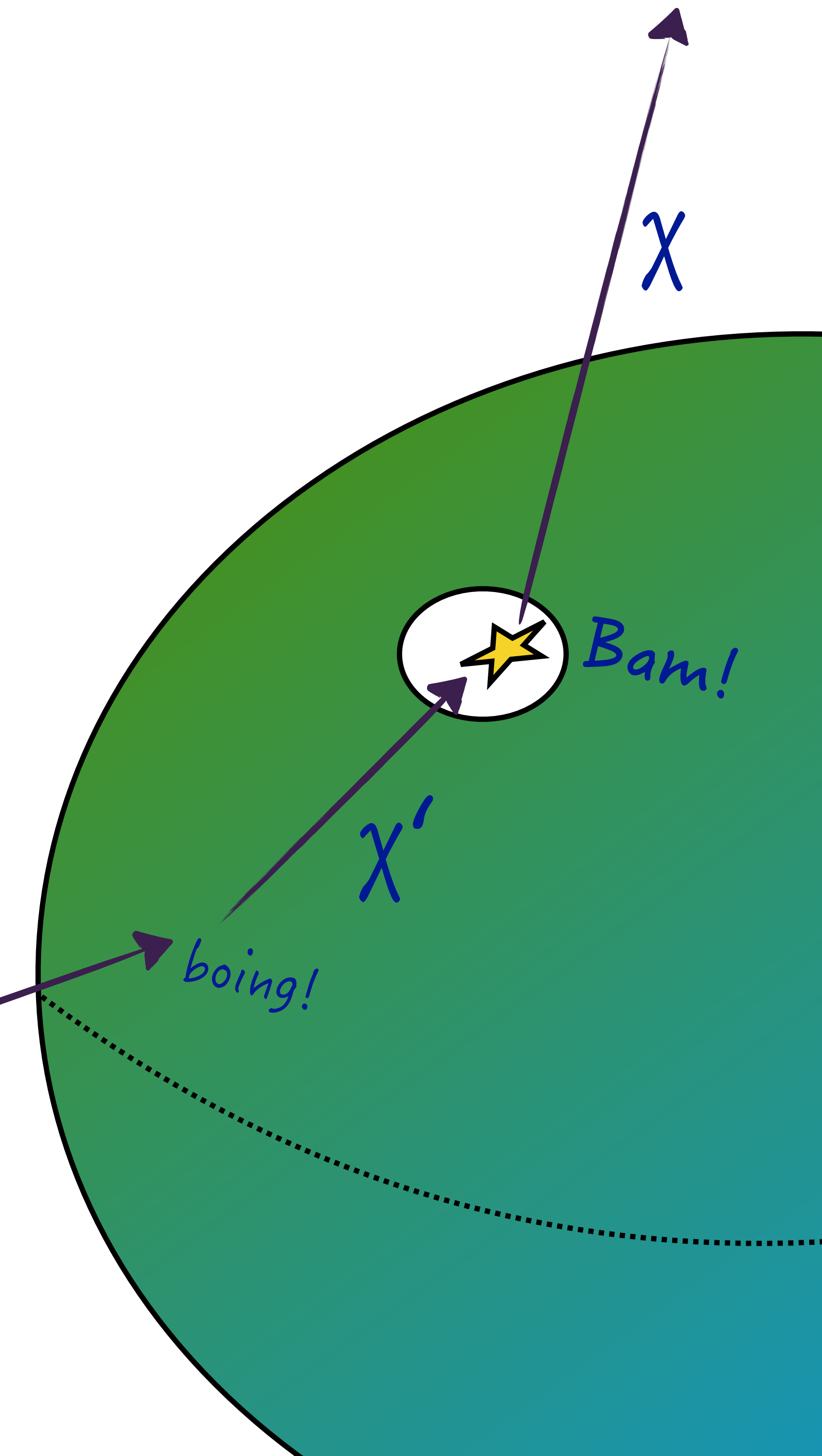
[Eby, Fox, RH, Kribs - not for DAMA. in progress]

Luminous DM

- Scatter somewhere in earth.
  Say off of <u>lead</u>, reach higher δ!
- Signal rate is insensitive* to τ:

$$\text{Rate} \propto \frac{\text{target volume}}{\text{solid angle}} \propto \frac{R^2}{R^2}$$

$$\text{Rate} \sim (V_{det}\, n_{\oplus})\, n_\chi \langle \sigma v \rangle$$



χ

[Feldstein, Graham, Rajendran - written for DAMA....]

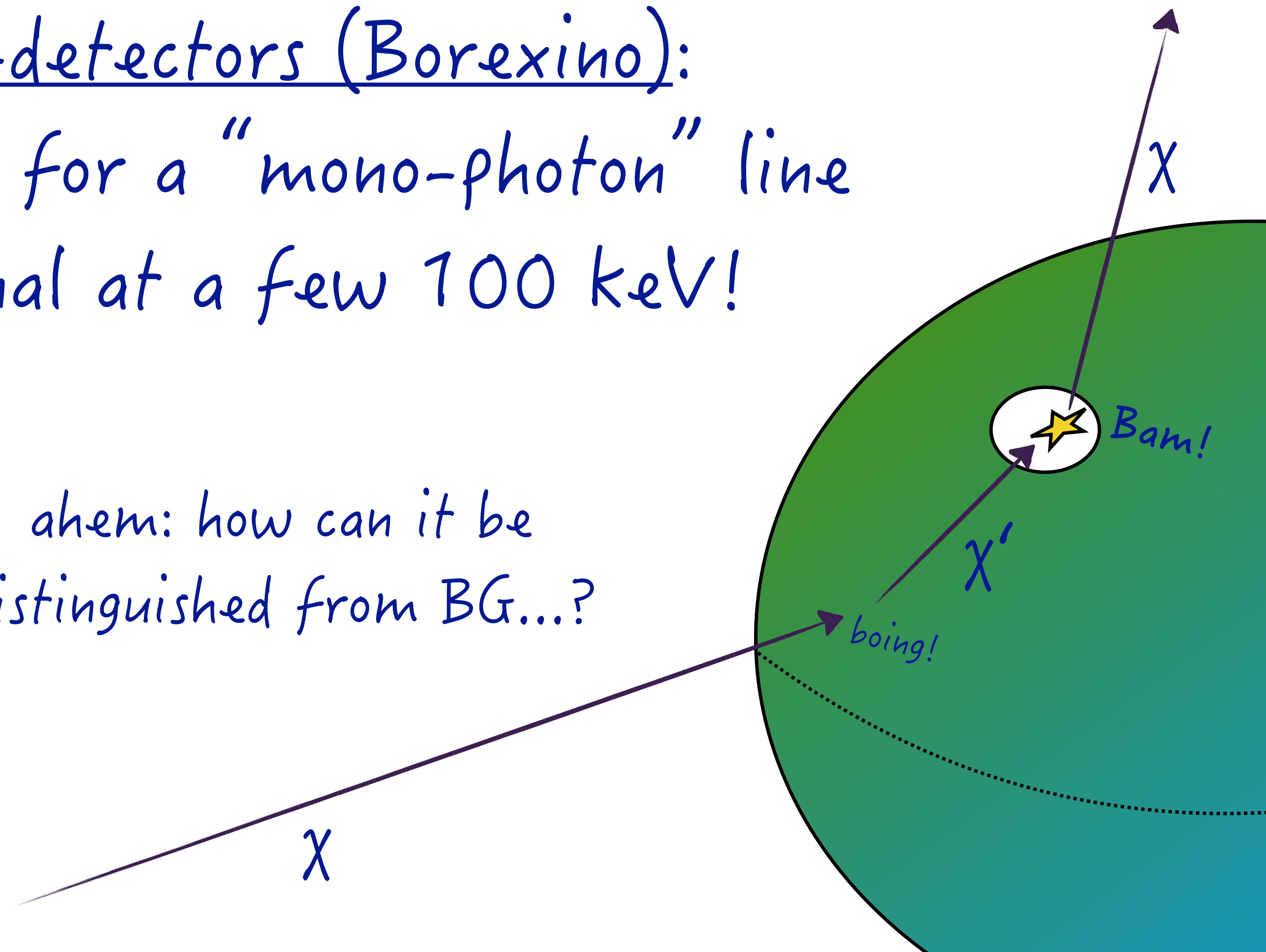
[Eby, Fox, RH, Kribs - not for DAMA. in progress]

Luminous DM

<u>ν-detectors (Borexino)</u>:

Search for a "mono-photon" line signal at a few 100 keV!

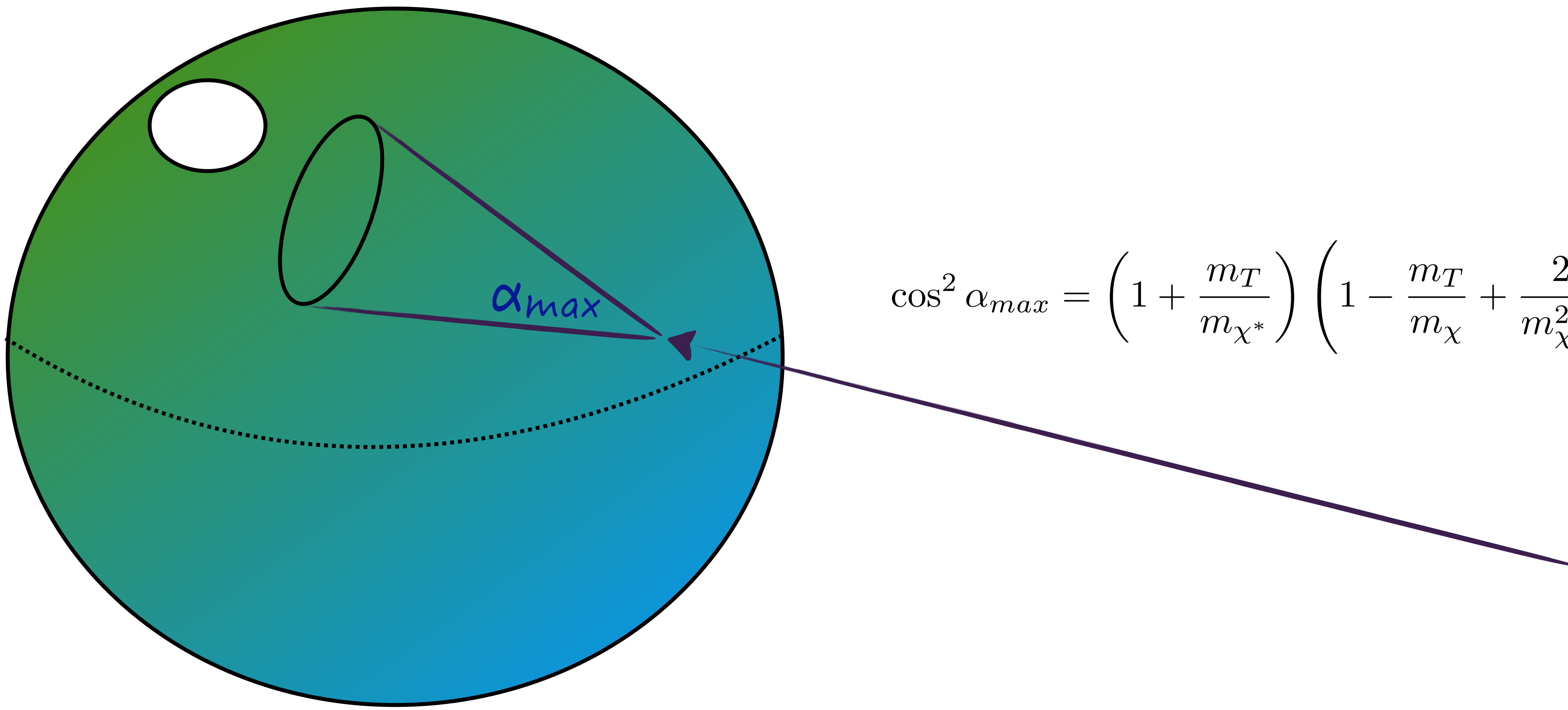
ahem: how can it be distinguished from BG...?



[Eby, Fox, RH, Kribs - in progre

Modulation

- DM is heavy → The "boing" is mostly **forward!**



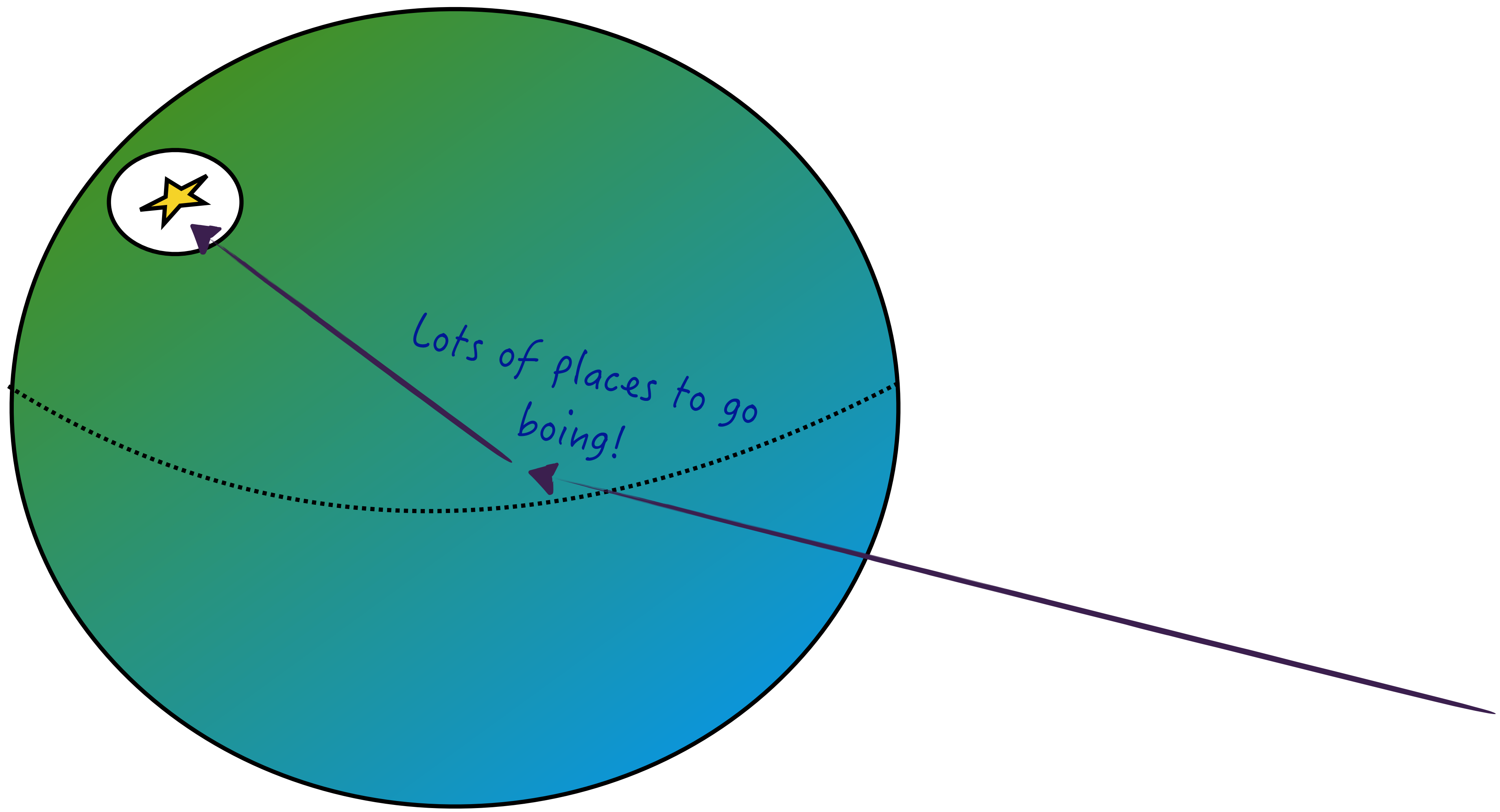
$$\cos^2 \alpha_{max} = \left(1 + \frac{m_T}{m_{\chi^*}}\right)\left(1 - \frac{m_T}{m_\chi} + \frac{2\, m_T\, \delta}{m_\chi^2\, (v_{in}^{lab})^2}\right)$$

- Defines a cone of height ~$v\tau_{\chi'}$ and an opening angle α_{max} for the decay.

[Eby, Fox, RH - in progress]

Modulation

- → strong dependence on initial DM direction.



Strong daily modulation.
Strong dependence on latitude!

[Eby, Fox, RH - in progress]

Modulation

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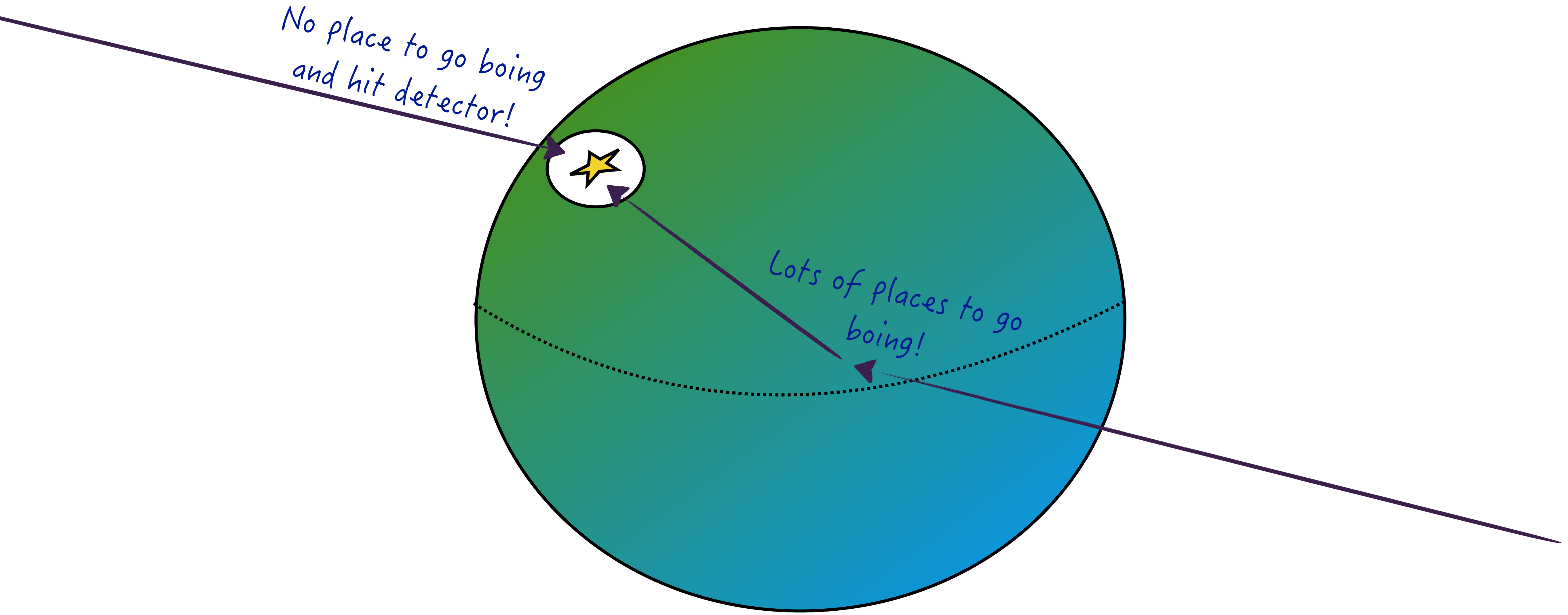


Strong daily modulation.
Strong dependence on latitude!

[Eby, Fox, RH, Kribs - in progress]

Cygnus Time

- The DM "wind" comes from Cygnus (the Swan), a northern constellation...

[Eby, Fox, RH, Kribs - in progress]

Cygnus Time

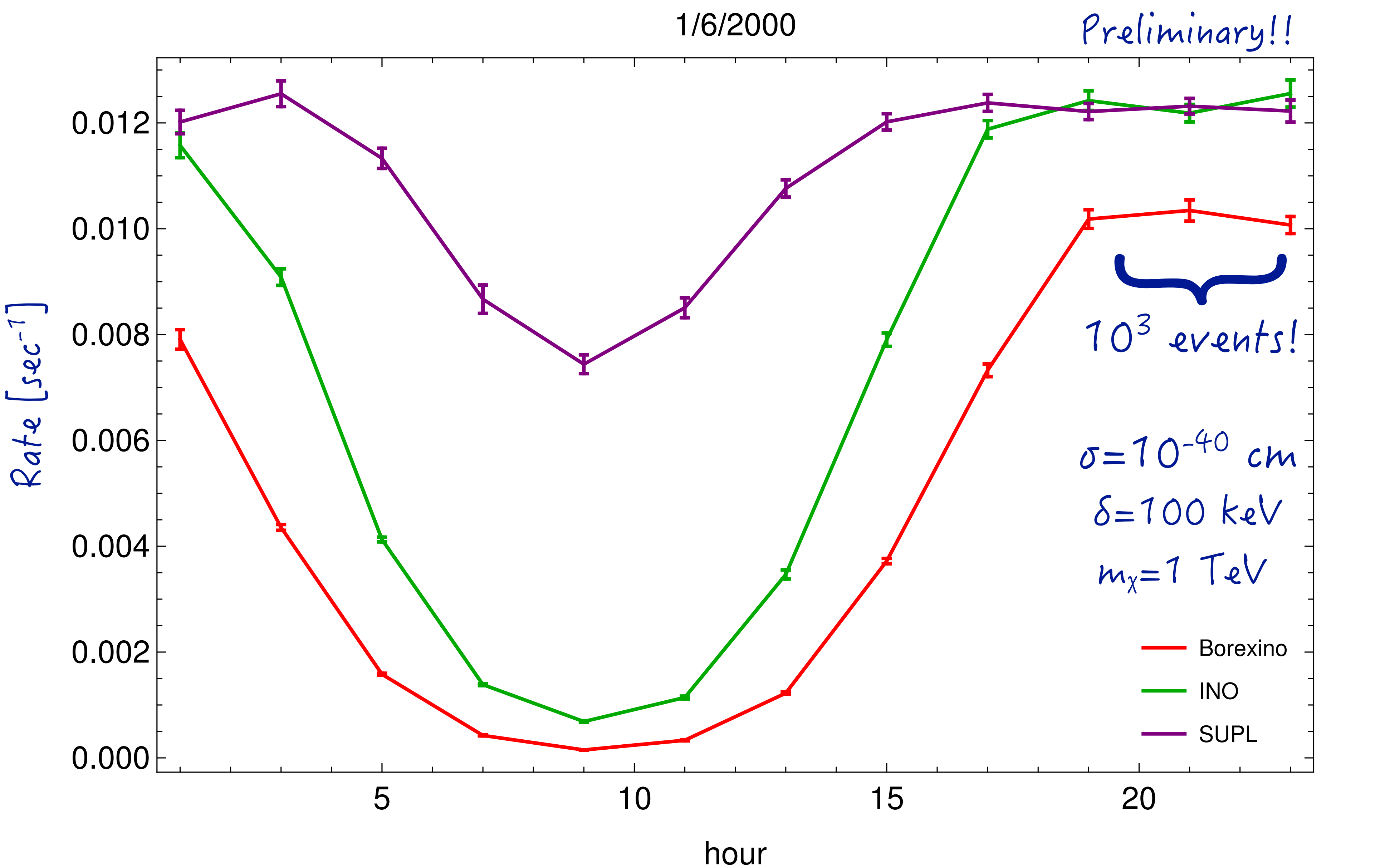
- The DM "wind" comes from Cygnus (the Swan), a northern constellation...

Cygnus Noon = Cygnus is highest in the sky.
Cygnus midnight = its lowest in the sky.

[Eby, Fox, RH, Kribs - in progress]

Daily Modulation

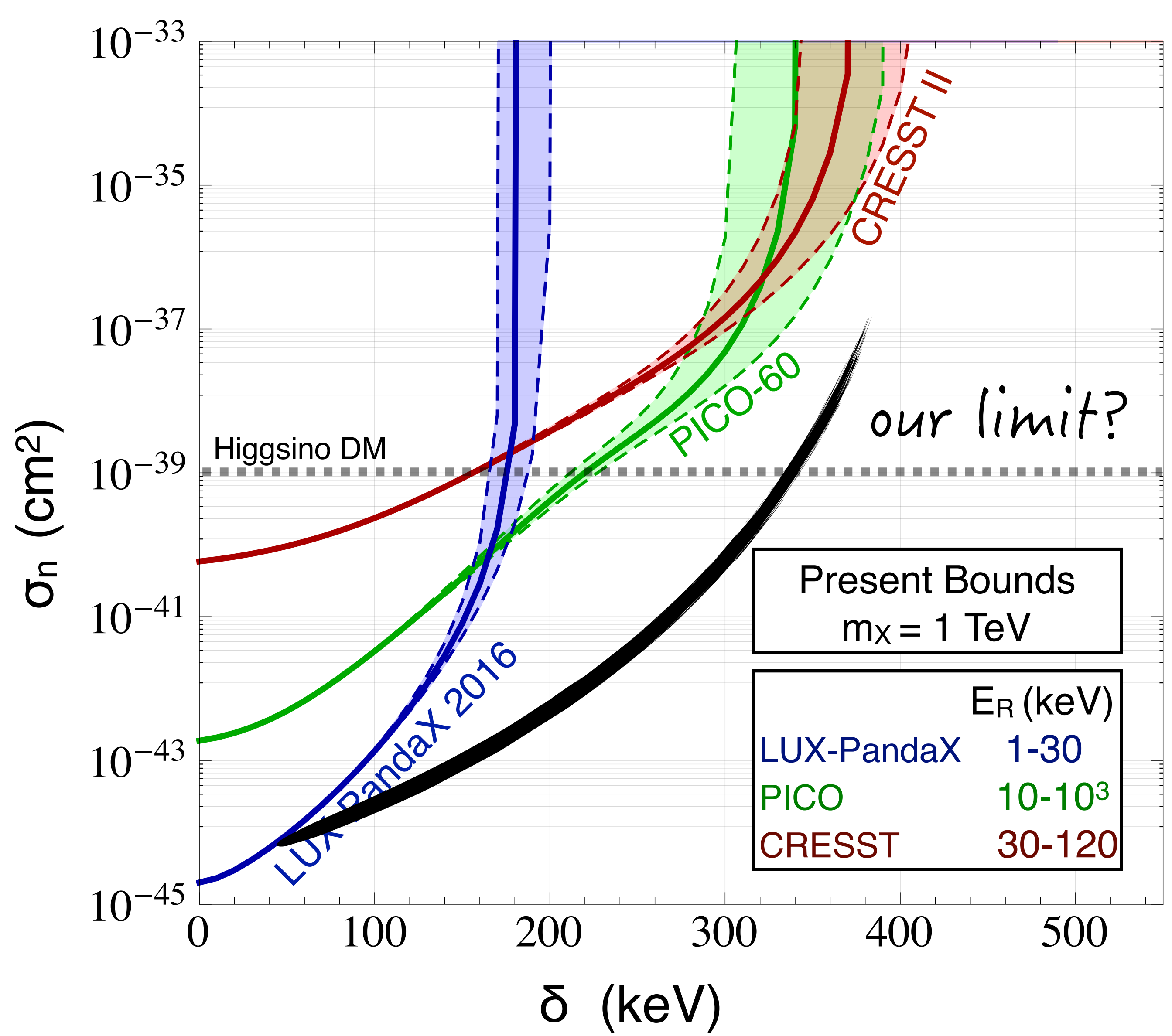
- Signal rate peaks at midnight (Cygnus time).
- Will depend on the lab's latitude.



Inelastic Frontier

- Sorry. We dont have a ready money-plot. just a guess.

Leveraging daily modulation Borexino can improve limits:



Message So Far:

With Luminous DM, and a bit of lead, we were able to bring DM signals to 100's of keV, and to **Borexino.**

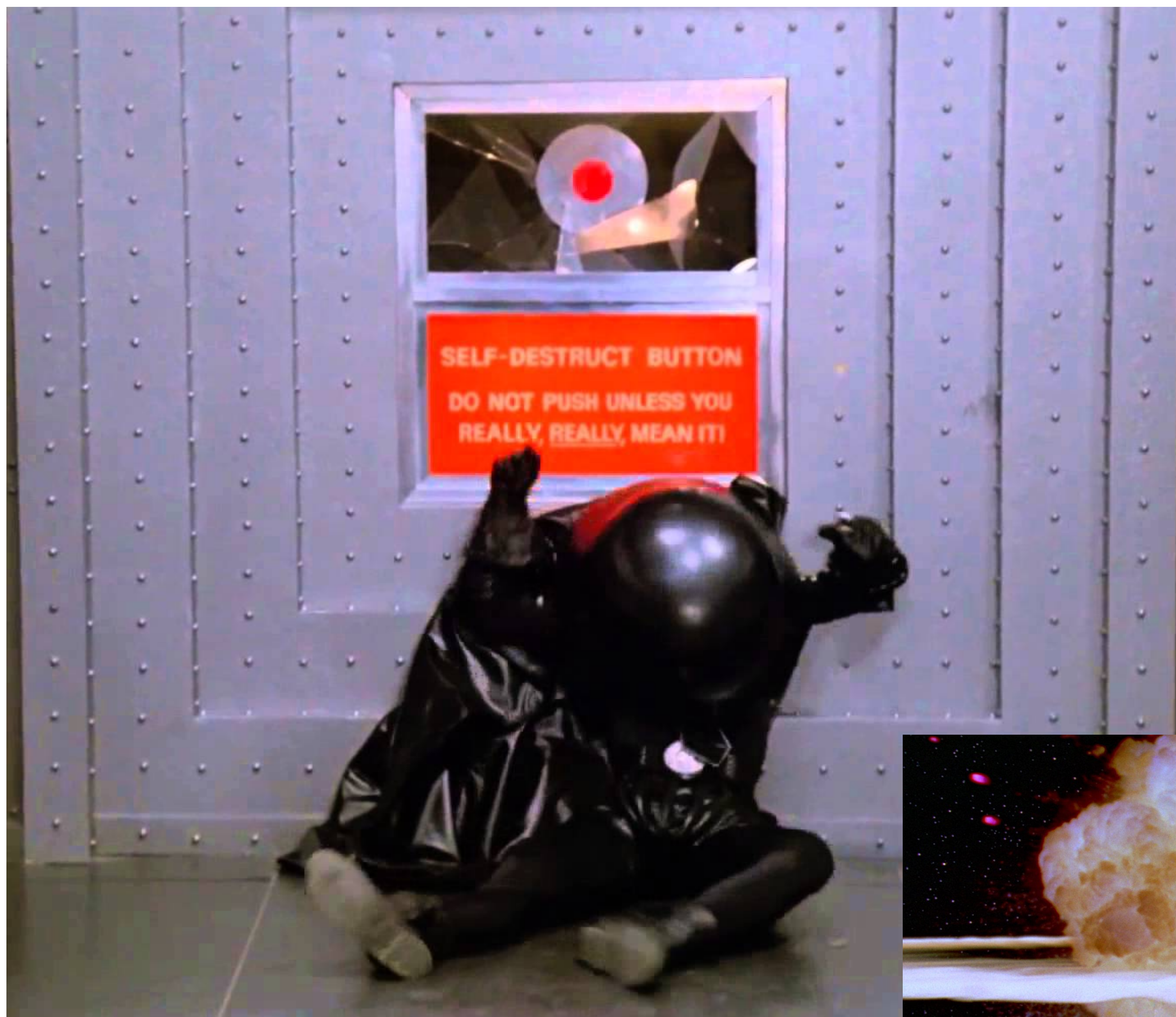
But we are still within the realm of

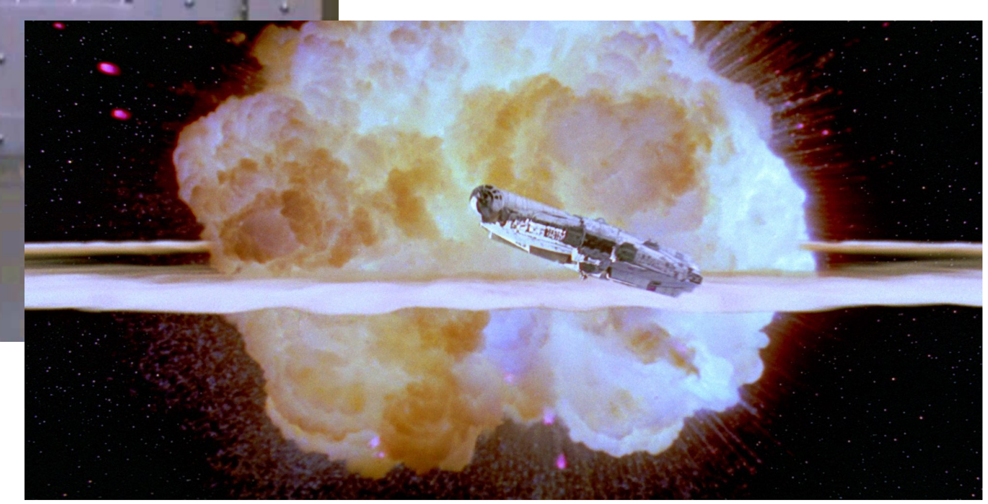
$$E_{signal} \sim \mu v^2 \sim 10^{-6}\mu$$

Can we go beyond this?

Can we find DM signals in the **10 MeV - 10 GeV** range?
Use Super-K? **DUNE?**

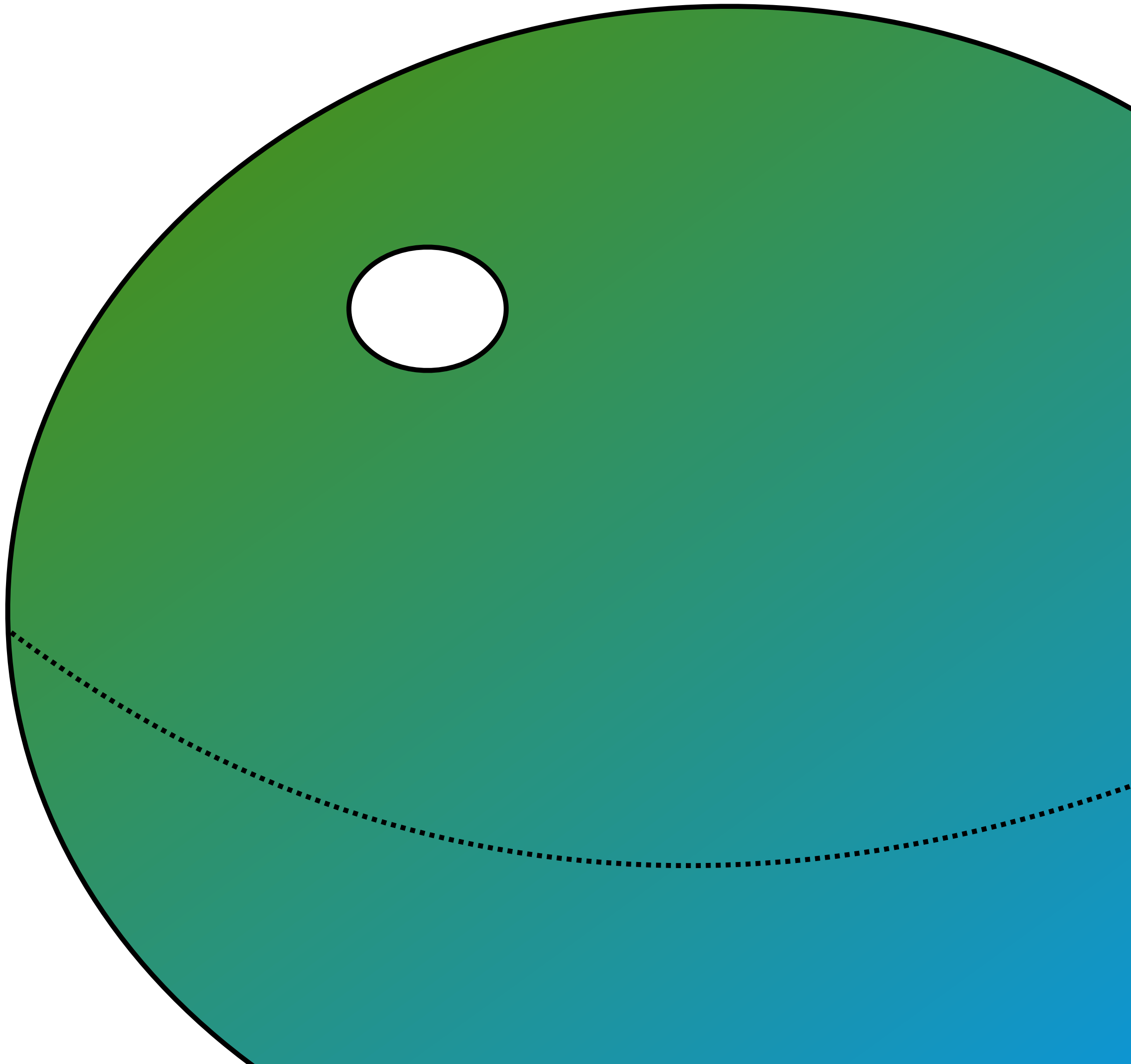
Self Destructing DM





Self Destructing DM

- A DM particle, ψ (can be a subcomponent), scatters somewhere in the Earth.
- Transforms into a different species, ψ'.



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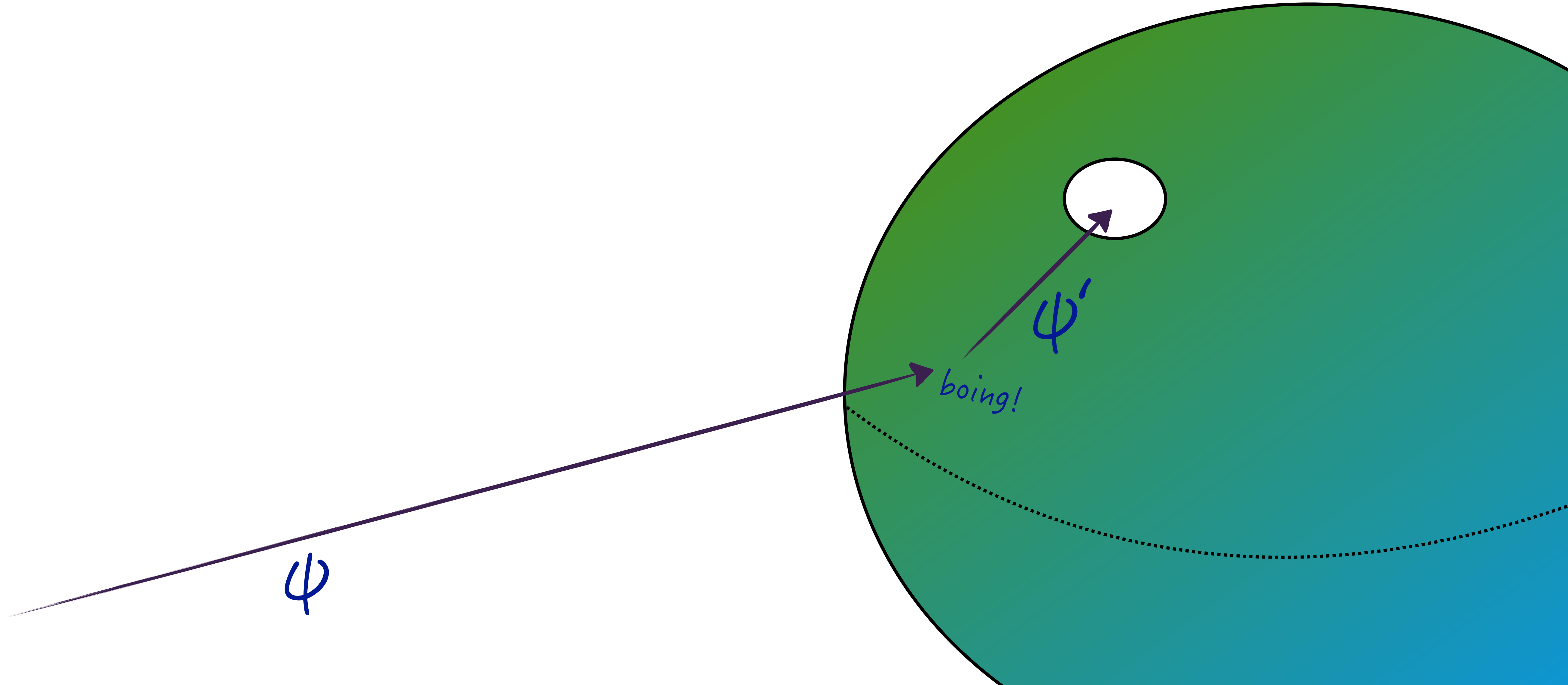
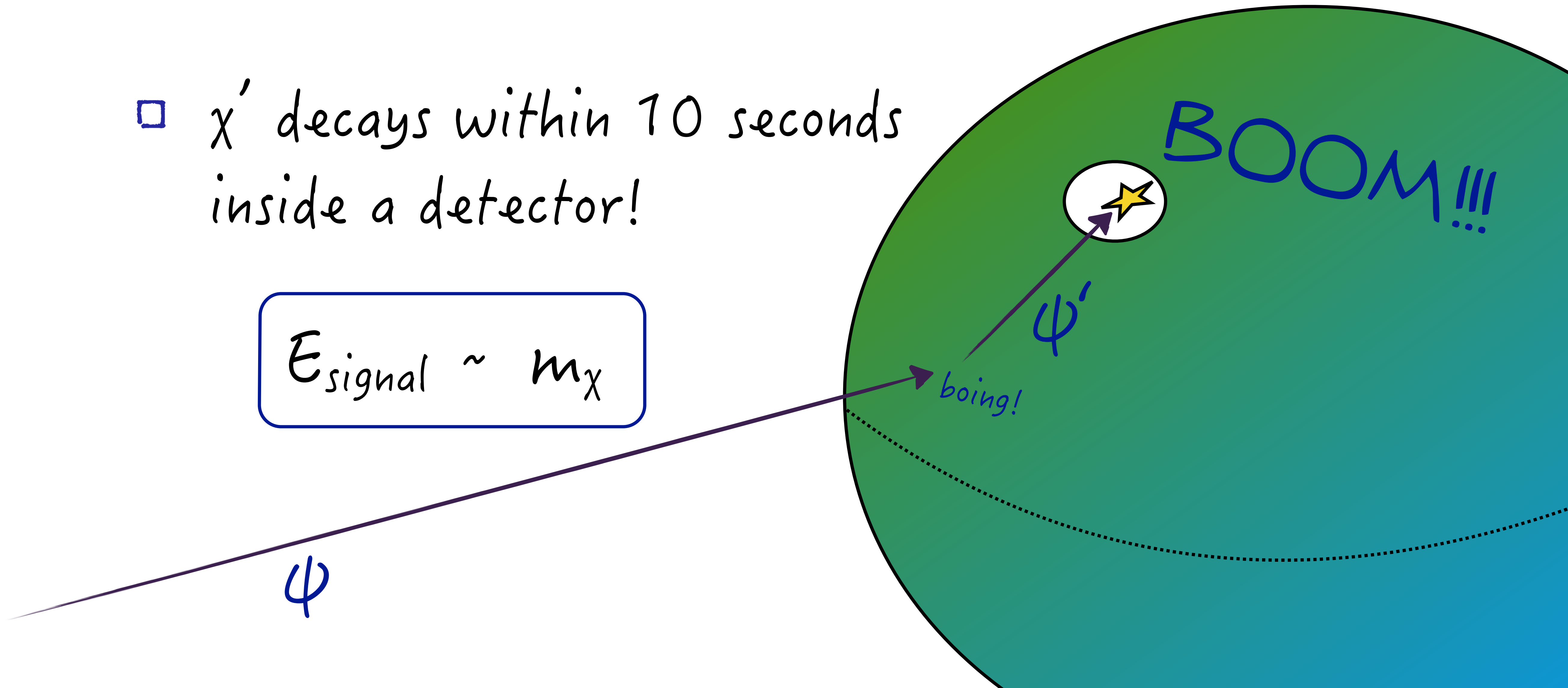


Self Destructing DM

- A DM particle, ψ (can be a subcomponent), scatters somewhere in the Earth.
- Transforms into a different species, ψ'.
- χ' decays within 10 seconds inside a detector!

$$E_{signal} \sim m_\chi$$



Self Destructing DM

- This sounds crazy!!
  Why would DM decide to self destruct just when it gets to us?

from the journal of a DM particle:

Place	Time spent, Δt	Density of stuff, n
Galactic Halo	10^{17} sec	~ 1 cm^{-3} (DM@1GeV)
Earth	10 sec	10^{23} cm^{-3}

$\langle N_{interactions} \rangle \sim n\sigma v \cdot \Delta t$ → There is room.

Self Destructing DM

- Want to dynamically turn off the stabilizing "symmetry" of DM by scattering.

$$(\tau_\chi > 10^{17} \text{ to } 10^{28} \text{ sec}) \rightarrow (\tau_{\chi'} < 10 \text{ sec})$$

- Require both meta-stable and sort lived states.
- Note: the SM has a variety of dynamical mechanisms and timescales.

We will relax minimality.

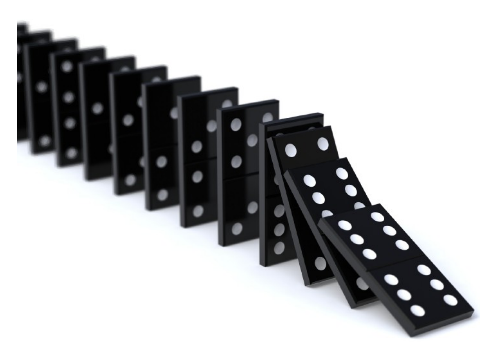
Focus on variation on the standard model.

Variations on the SM

(The Grossman variations)

- The angular momentum variation.
- The molecular variation.
- The baryon to meson variation.
- ...

Examples of dramatic event triggered by trifles:



Angular Momentum

- A sub-component of DM is stabilized by rotational invariance (angular momentum).
- Ingredients -
  - Constituents: χ and $\bar{\chi}$.
  - Heavy dark photon V.
  - Light dark photon ϕ.

$$\mathcal{L} = \bar{\chi} i \not{D} \chi - m_\chi \bar{\chi}\chi + \frac{1}{2}\partial_\mu\phi\partial_\mu\phi - \frac{1}{2}m_\phi^2\phi_\mu\phi^\mu - \frac{1}{4}V^{\mu\nu}V_{\mu\nu} + \frac{1}{2}m_V^2 V_\mu V^\mu - \frac{\kappa}{2}V_{\mu\nu}F^{\mu\nu}$$

Angular Momentum

- Requirements:
  - ϕ mediates long range force, $(\chi\bar{\chi})$ bound states $\equiv \Psi$.
  - ϕ is heavier than Rydberg.

$$\alpha_\phi^2 m_\chi < m_\phi < \alpha_\phi m_\chi$$

  - V is a lighter than χ

$$m_V < m_\chi$$

Angular Momentum

- Consider a high ℓ state.
  χ and $\bar{\chi}$ have small wave function overlap.

$$\Gamma_{n,\ell \to V's} \sim \left(\frac{\alpha_V}{n}\right)^{2\ell+3} \alpha_V^{N_V} m_\chi$$

→ $\ell=9$ is cosmologically stable.

- The decay $(n,\ell) \to (n-1,\ell-1)$ is kinematically suppressed. (Either to 3 photons or 2 ν's).

$(\chi\bar{\chi})$ can be (part of) dark matter.

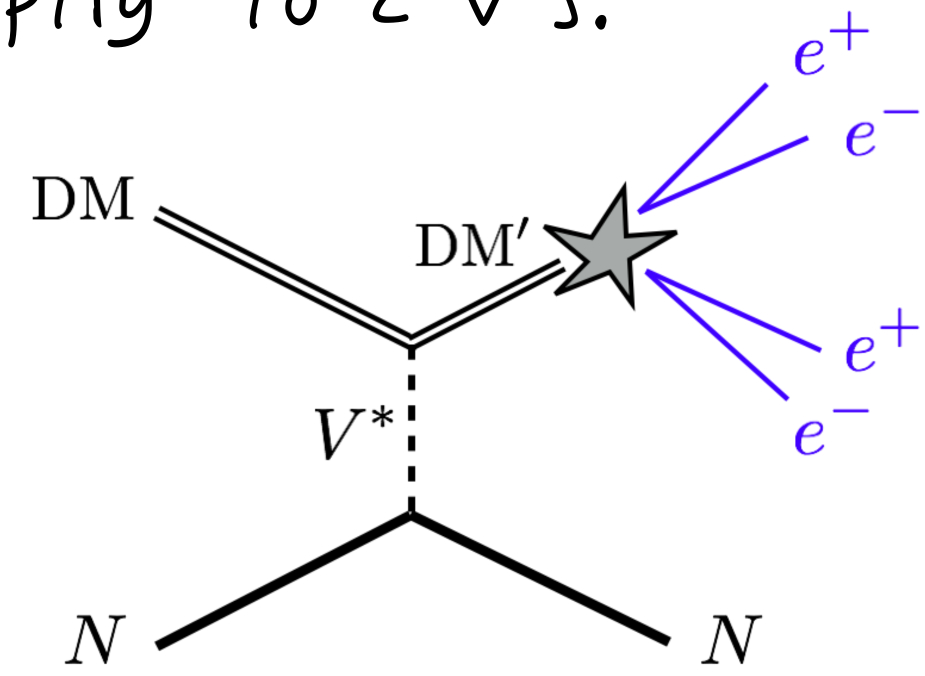
Stabilized by angular momentum.

Self Destruction

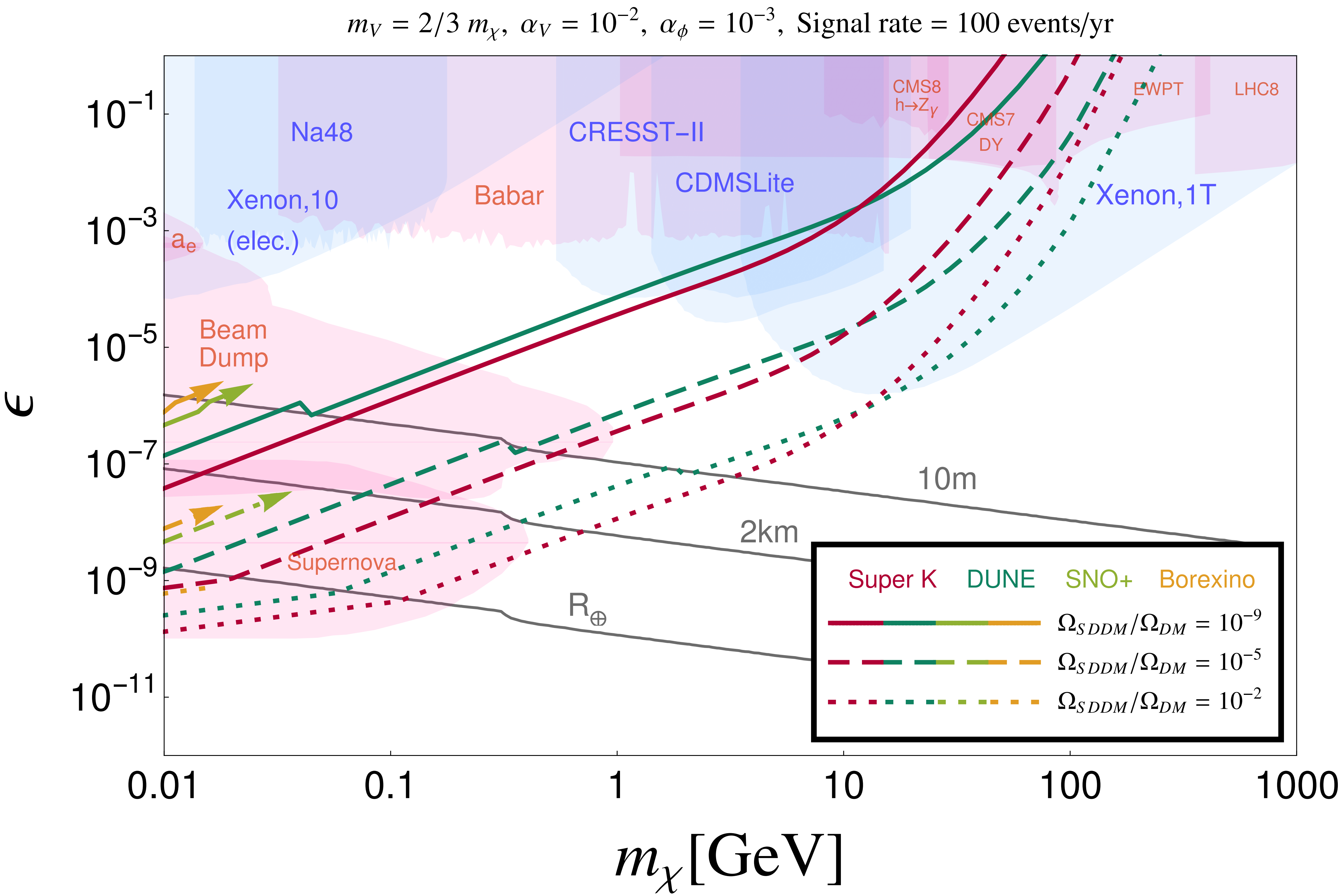
- $\chi\bar{\chi}$ can loose angular momentum by interaction with an external nucleus.

$$\sigma_{(\text{high-}\ell)\to(\text{low-}\ell)} \sim \frac{g_V^2 \kappa^2 e^2 Z^2}{v\, m_V^2} \times (\text{form-factorology})$$

- Once ℓ is low, $\chi\bar{\chi}$ can go "promptly" to 2 V's. Then to 4e.



Self Destruction



Phenomenology

- Putting the angular momentum story aside:
  - What are "generic" signals of SDDM?
  - How can results be presented?

- Common Ingredients for the framework:
  - "Short lived" state ϕ'
  - Mediator V
  - $\phi' \rightarrow VV \rightarrow SM$

Phenomenology

- Final states:
  - e^+e^- resonances
  - $\mu^+\mu^-$ resonances
  - $\gamma\gamma$ resonances (say, for axion-like mediators)
- Kinematics of each pair:
  - Invariant mass.
  - Energy.
  - Opening angle.

$$m_{\rm pair} = m_V$$

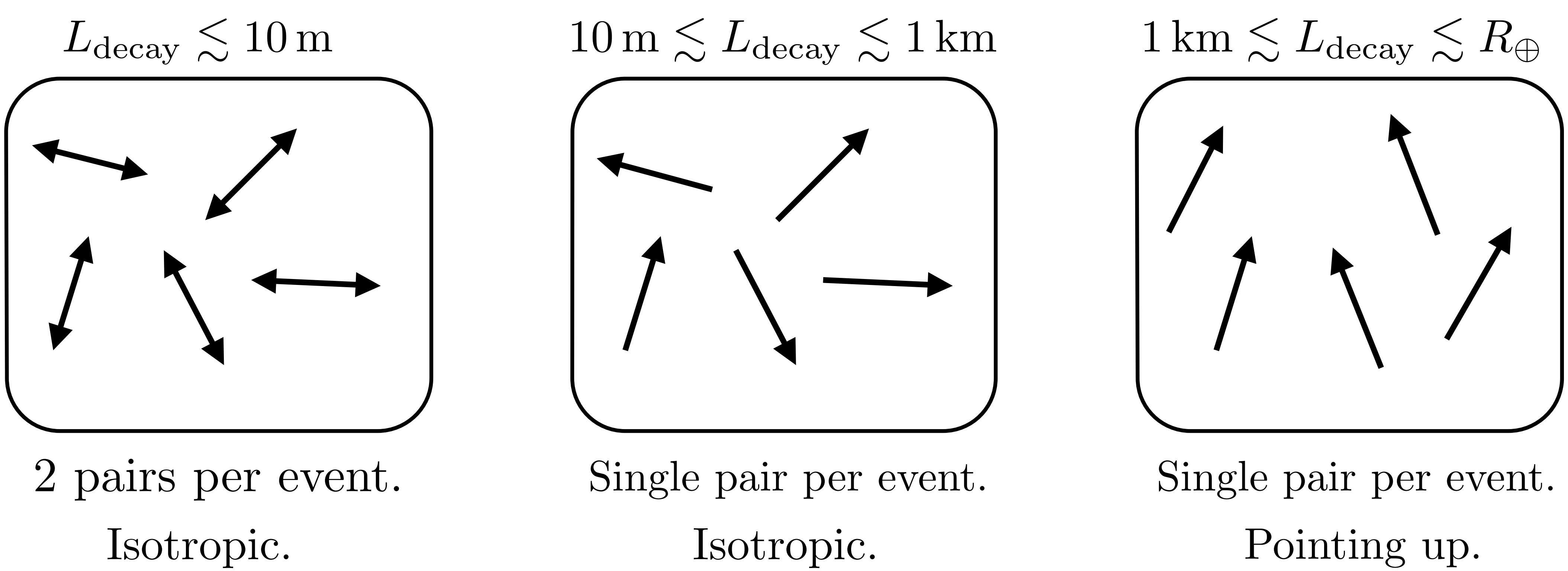
$$E_{\rm pair} = \frac{m_{\Psi'}}{2}$$

$$\cos\theta_{\ell^+\ell^-} \sim 1 - \frac{8m_V^2}{m_{\Psi'}^2}$$

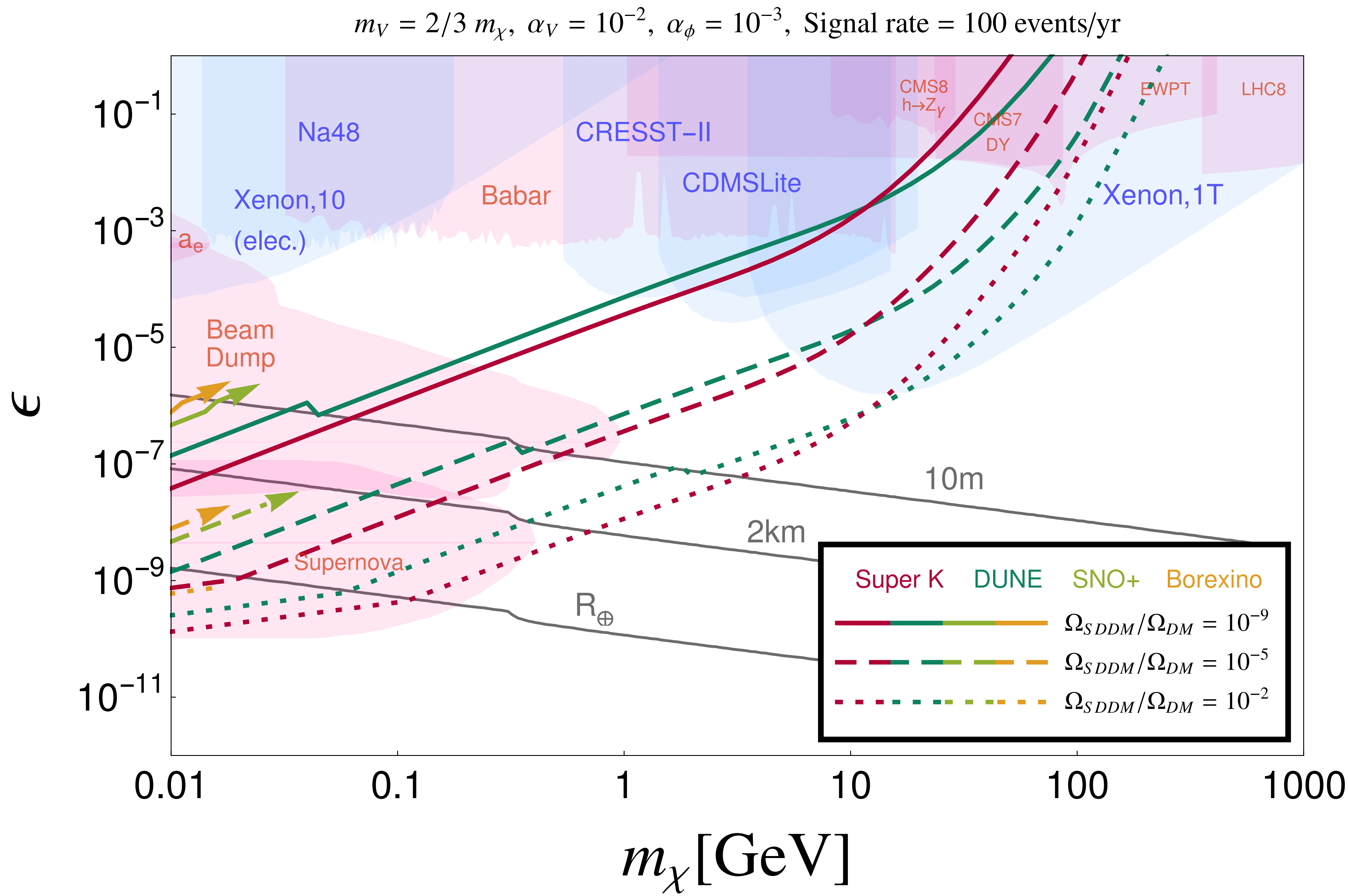
We can do a bump hunt!

Directionality

- Dark Photon lifetime determines multiplicity and direction of signal:
  - ($c\tau_V < 10$m): can see two lepton pairs in the detector.
  - (10m $< c\tau_V < 1$km): single pair, isotropic.
  - (1km $< c\tau_V < 10^4$km): single pair, up-going.

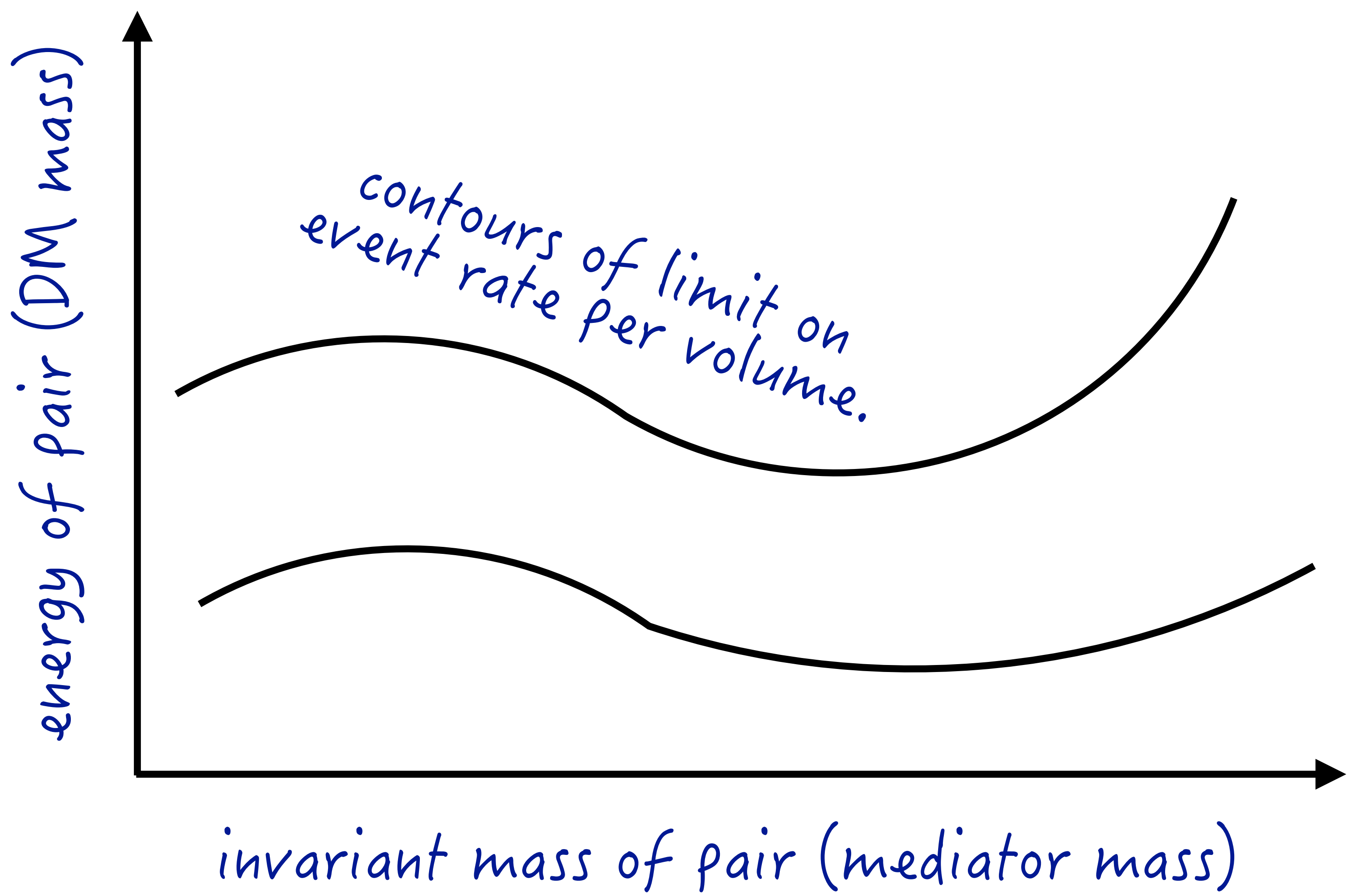


Phenomenology



Simplified Model Analyses

- We can do more model independent analyses, a la "simplfied models" searches at LHC.
- Pick a final state.



Can be repeated for various angular distributions ion and final states.

General Remarks

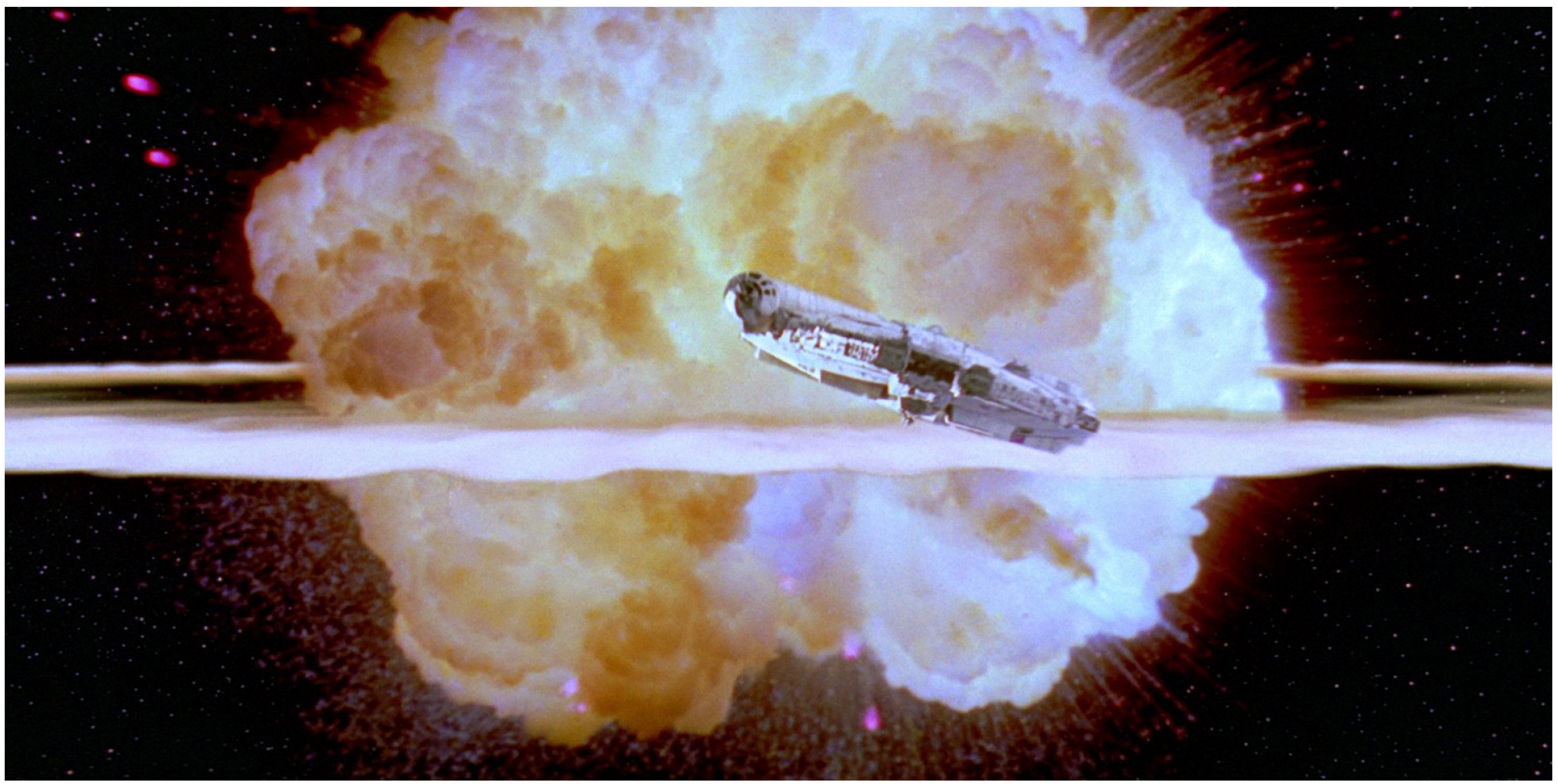
- Large ν detectors have a big exposure to DM.
- Dark matter does not have to be simple! (the SM is nowhere near minimal!).
- Can have sensitivity to non-minimal frameworks. LDM, SDDM, ...?
- Di-lepton, mono-photon, di-photons. These are non just signals for LHC !!

General Remarks

- Experimental questions to study:
  - What are the background rates for these signals?
  - Can angular distributions be leveraged?
  - Can daily or annual modulation be leveraged?
  - Can DUNE's threshold be pushed down?
    (Well motivated! the lower the threshold the simpler the models)
  - What can the near detectors do?

Let's keep talking!

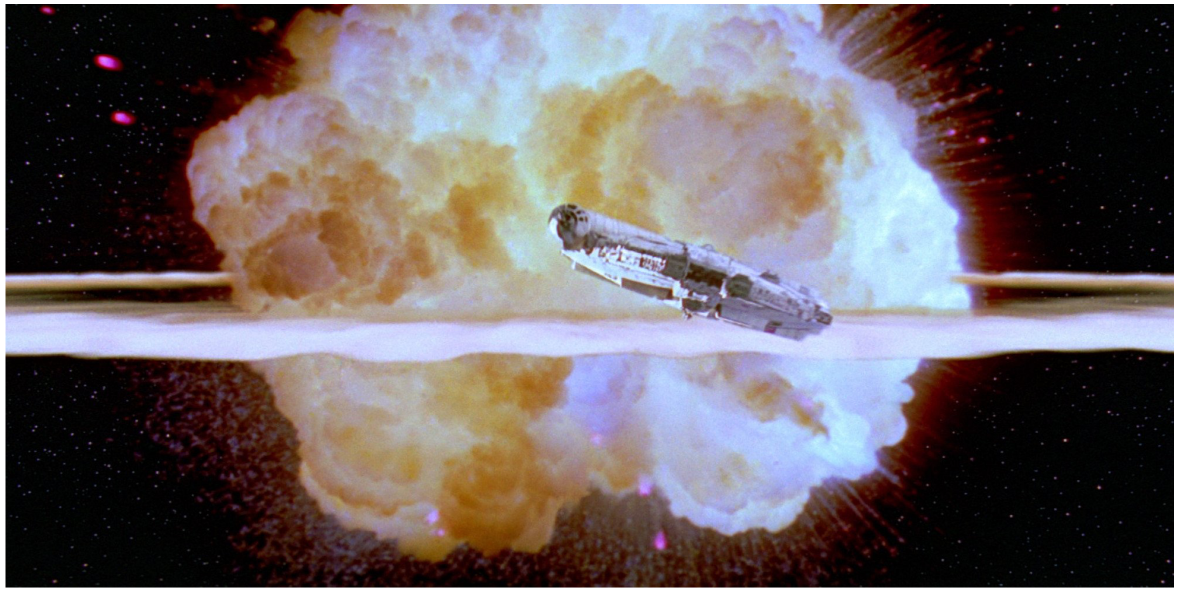
Deleted Scenes



Exploding DM

Conclusions

- We do not know what DM is.
  We should cast a wide net.
- Non-minimal DM models can bring the search for DM to large detectors w/ high thresholds.
- Variations on the SM can give dramatic new effects and new pheno.



[see also An, Wise, Zhang]

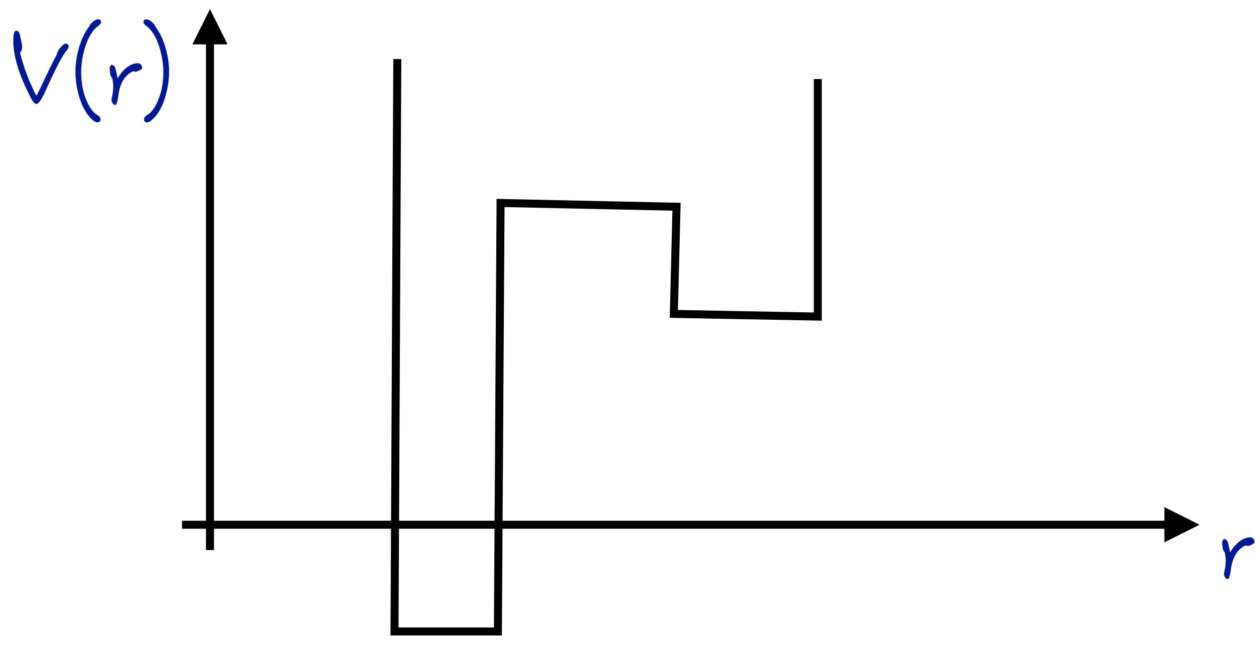
Cosmology

- Yes. We have a cosmological story for this!
- χ and $\bar{\chi}$ freeze out to dark photons, giving only a sub component of DM.
- Fraction of χ's in a bound state can be estimated:

$$\frac{n_\Psi}{n_\chi} = \frac{n_\chi \langle \sigma_{\chi\bar{\chi}\to\Psi\phi} v \rangle}{H} \quad \longrightarrow \quad \frac{n_{\Psi_{n=10,\ell=9}}}{n_\chi} \sim 10^{-2}$$

Molecular Variations

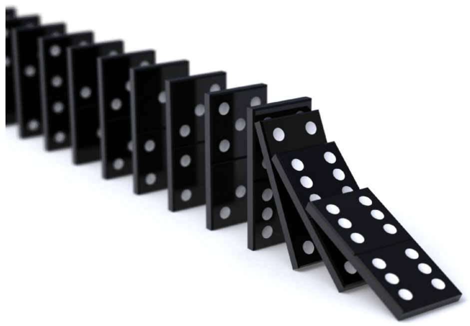
- In the real world, a D2 molecule can fuse to helium-4.
- An "excited molecule" could have larger wavefunction overlap → faster fusion rate.
- A designer potential can work:

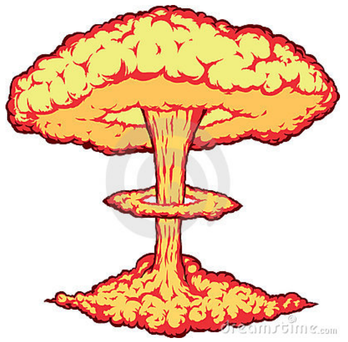


Still working on a SM variation...

Other variations

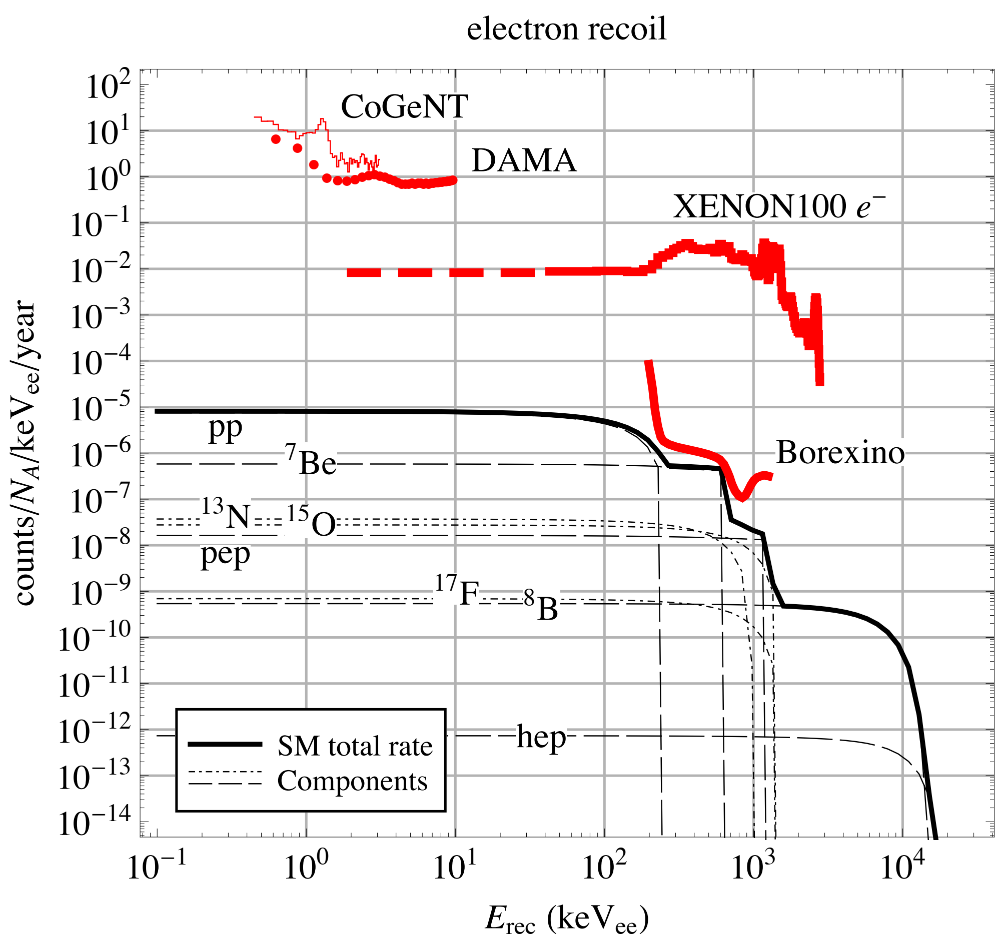
- A scattering can convert a dark baryon to a dark meson.
- Other dramatic phenomena....

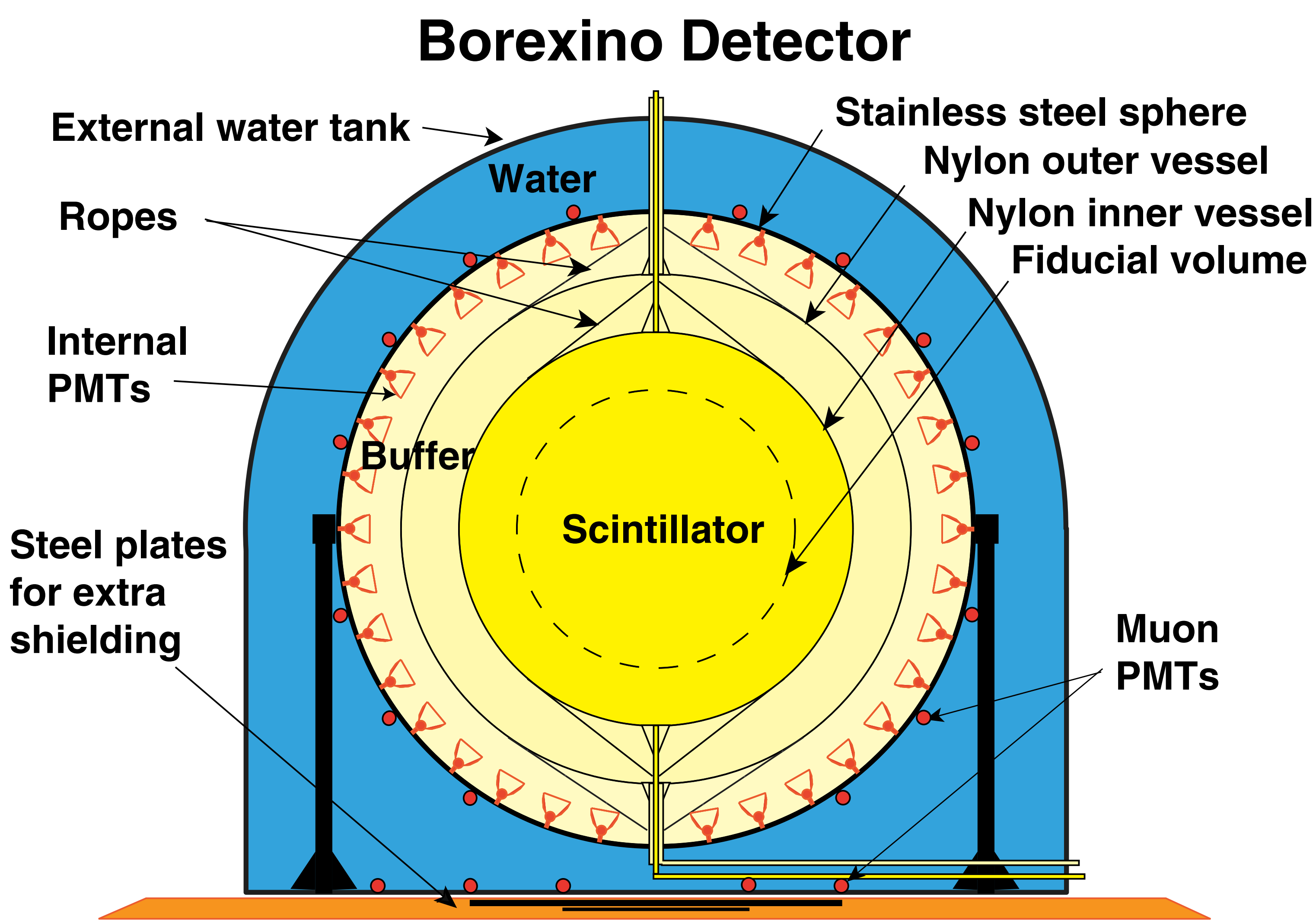




Borexino

- A large scintillator detector in Gran Sasso. Superduper clean! over 2000 days exposure!

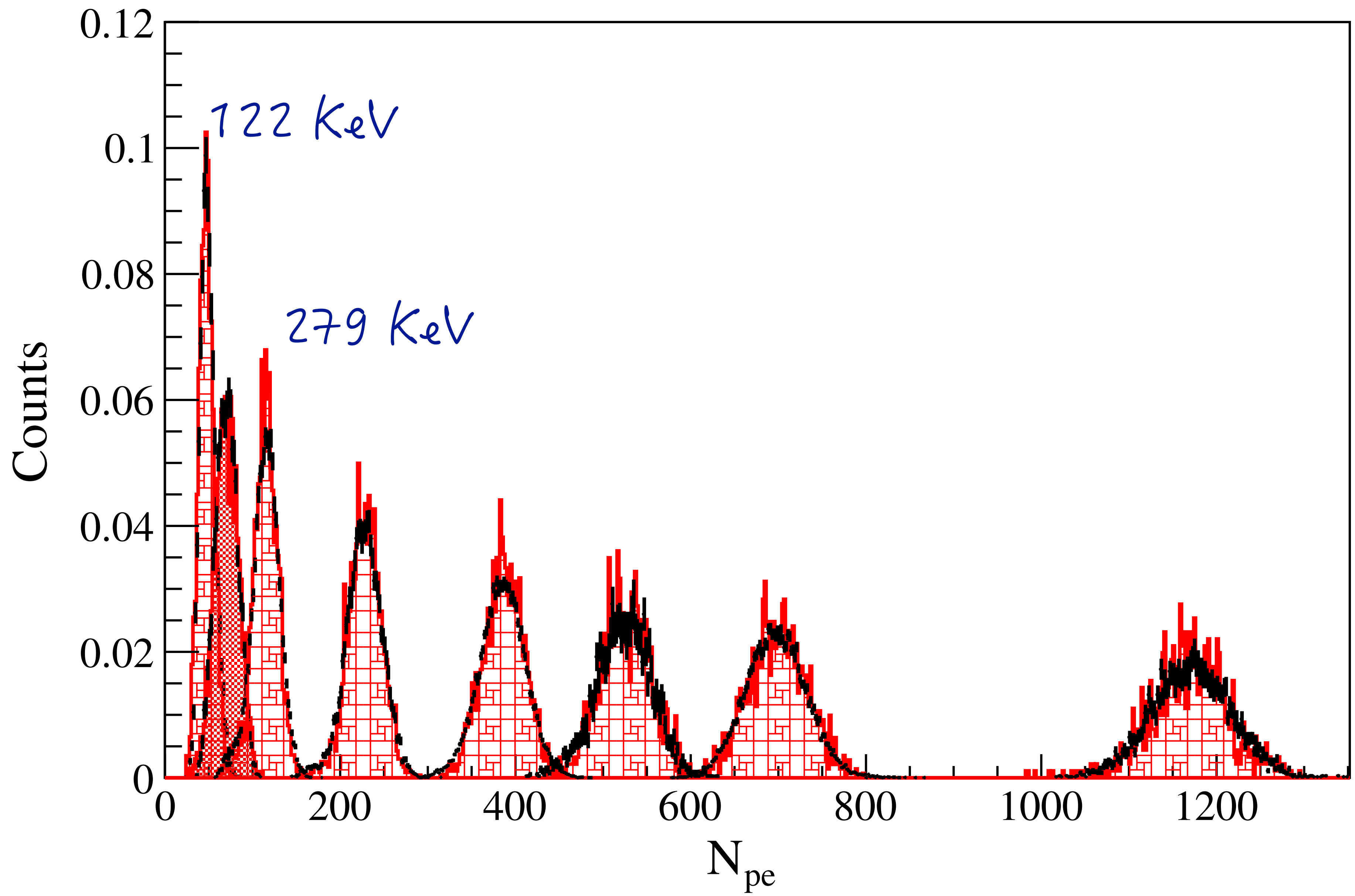




PHYSICAL REVIEW D **89,** 112007 (2014)

Borexino

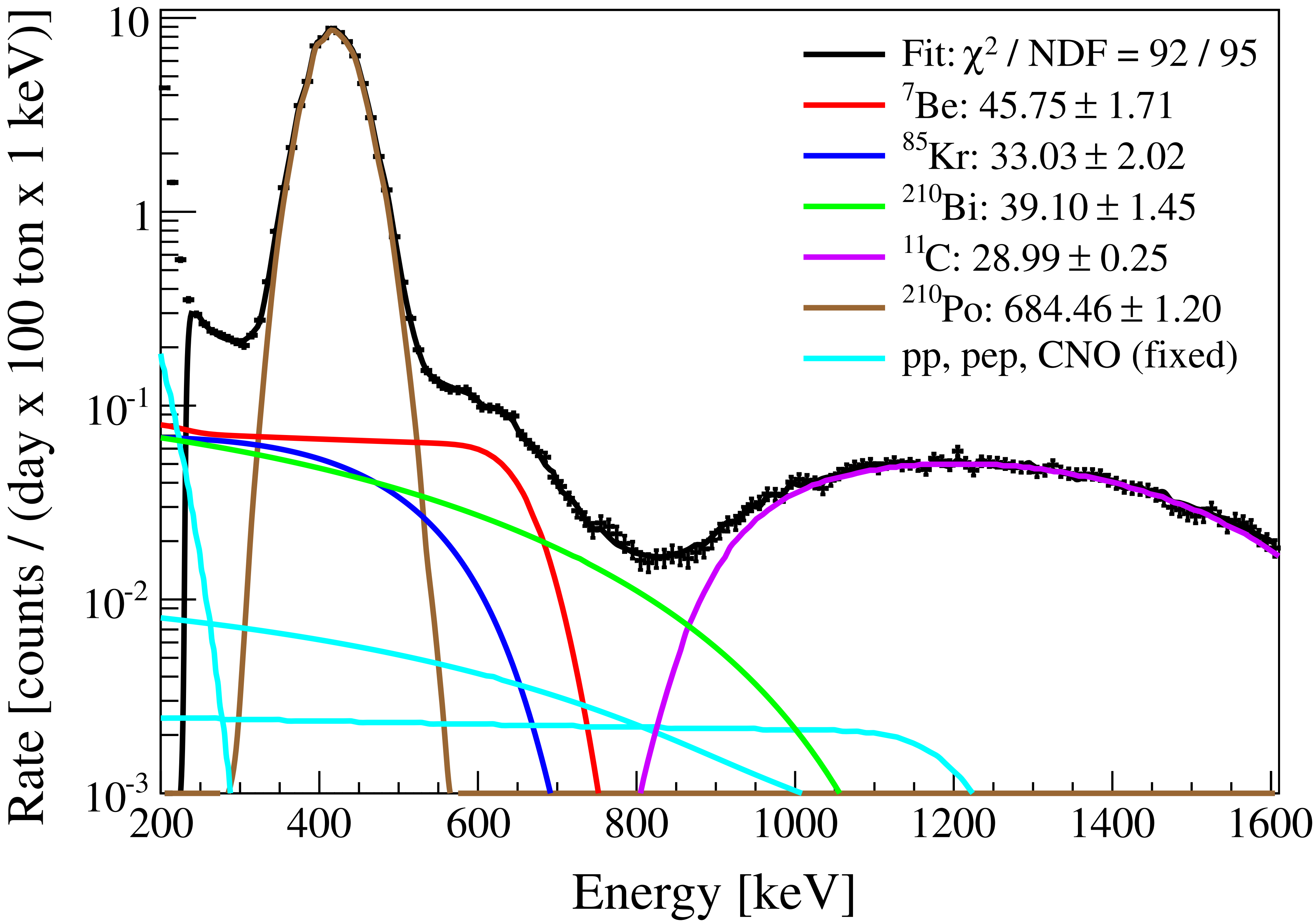
- Reasonable energy resolution.



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

Borexino

- Observed spectrum:

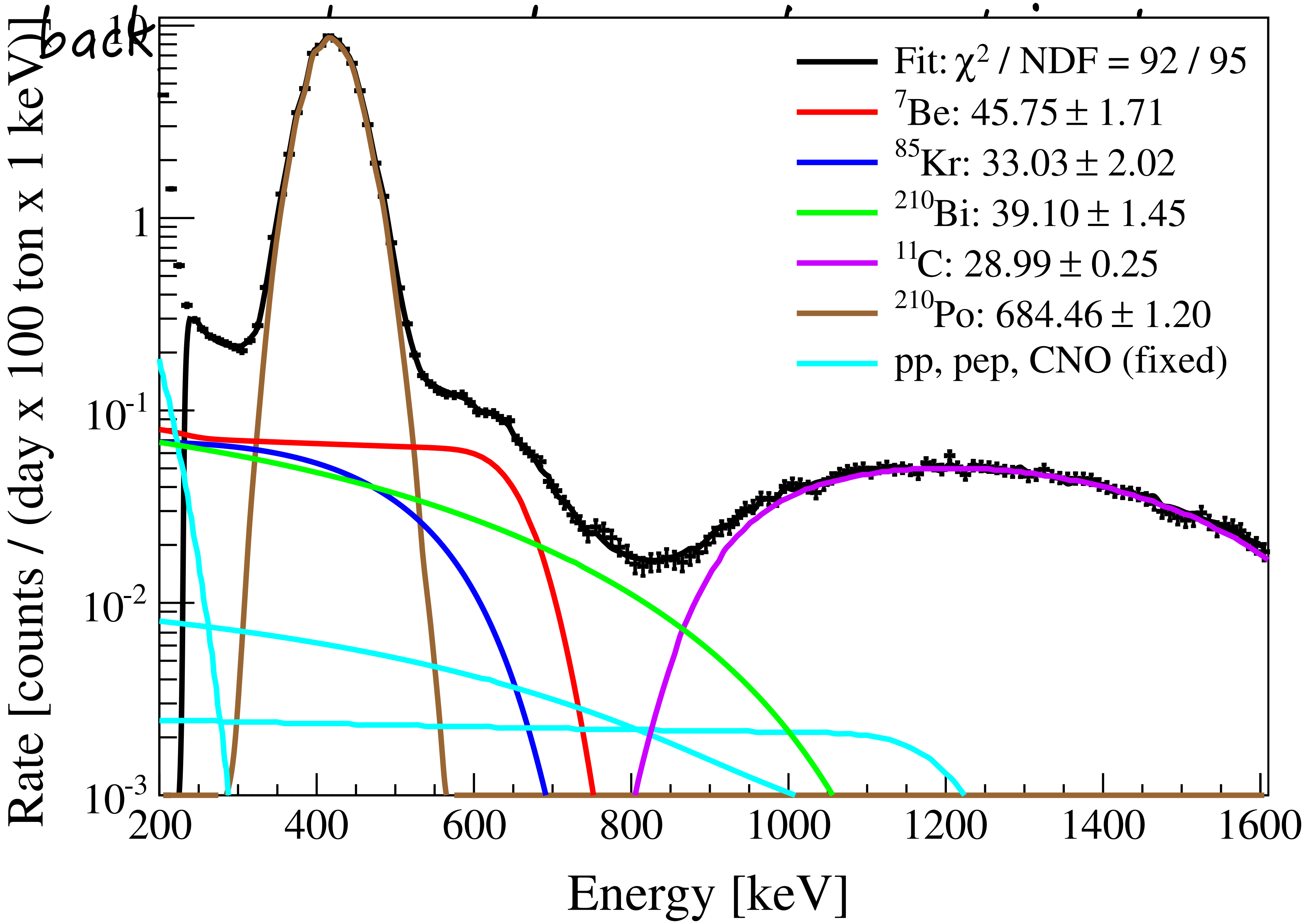


Borexino

- Common practice for DM experiments BG: DM signal cannot exceed the observed BG.
- In a 50 keV window, Borexino has ~ 15 event per day around 200 keV.
- → LDM rate < 15 events per day.
- No gain from large exposure. :-(
- We (they) can do better....

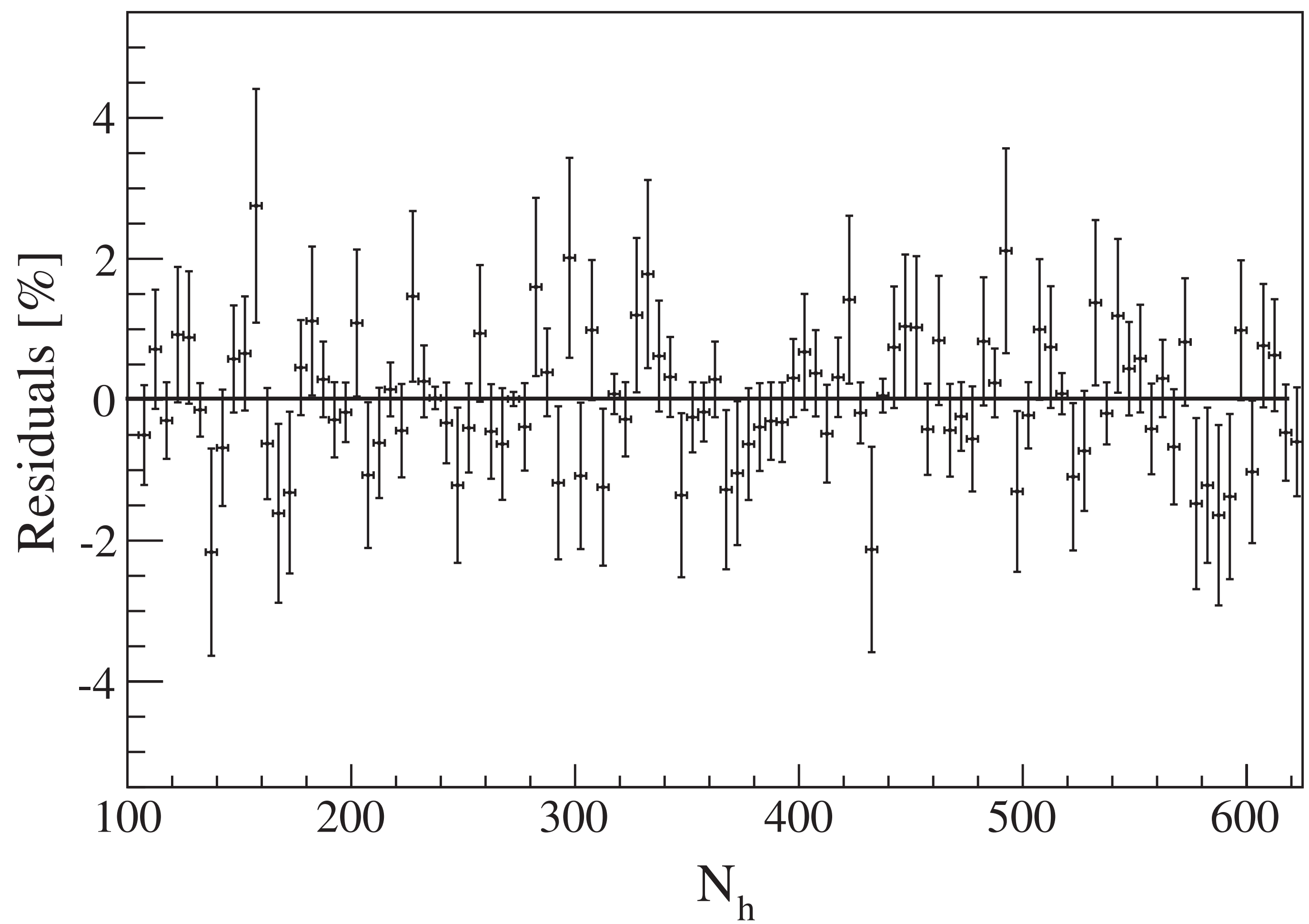
Borexino

- Using a big fit, Borexino understands their back



Borexino

- The fit residuals are at the few percent level.



Is the limit thus 15events/day x few percent?

I doubt it... but we can do much better!

Borexino Modulation

- A strong daily modulating signal is striking!
- Expected limit:

$$N \sim 15 \text{ events}/\text{day} \times 2000 \text{ days} \sim 3\times10^4 \text{ events!}$$

$$\text{Limit} \sim \frac{15}{N^{1/2}} \text{ events/day}$$

- For δ=300 keV the signal rate for our benchmark is 1.5/day. :-)