Mirror Dark Matter Search with LUX Run3 Electron Recoil Data

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PASCOS 01.07.2019

LUX

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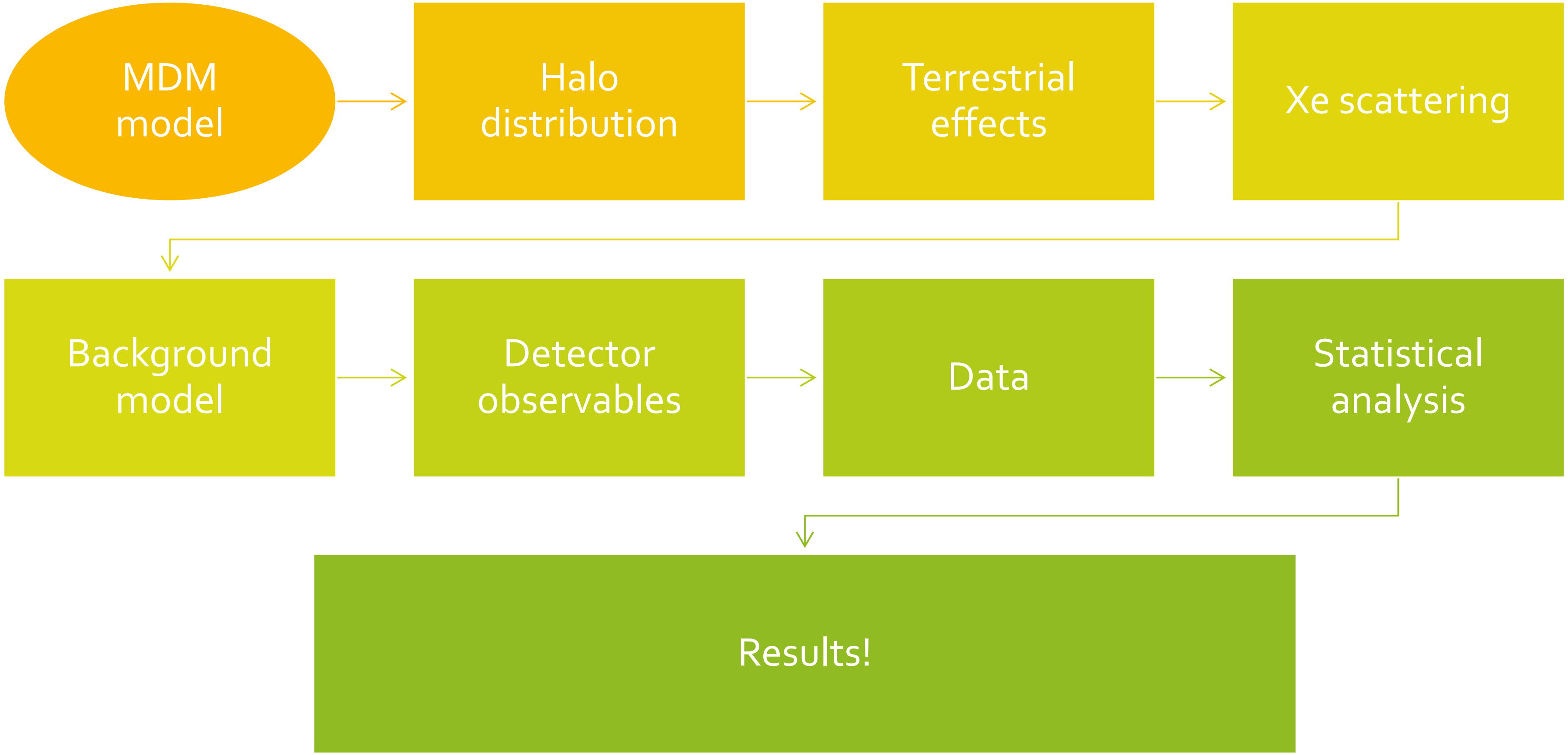
Mirror mirror….

Mirror Dark Matter: hidden sector dark matter – exact mirror copy of the Standard Model.

Can we test this?

?

Testing the model



MDM model

Halo distribution

Terrestrial effects

Xe scattering

Background model

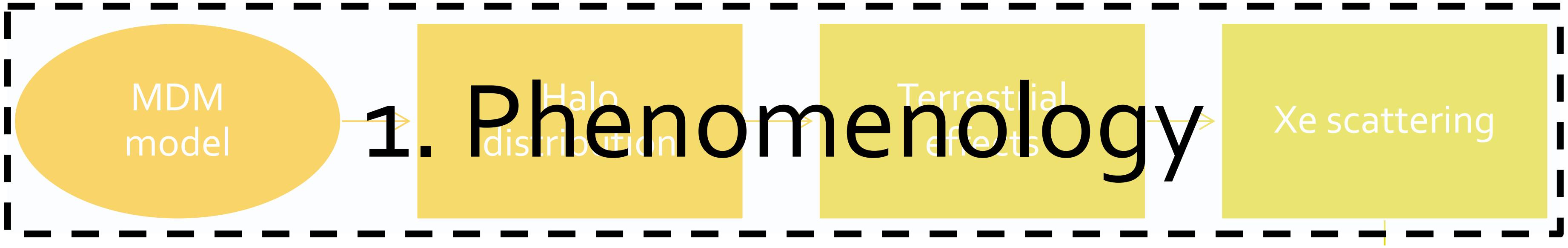
Detector observables

Data

Statistical analysis

Results!

Testing the model



MDM model

Halo distribution

Terrestrial effects

Xe scattering

1. Phenomenology

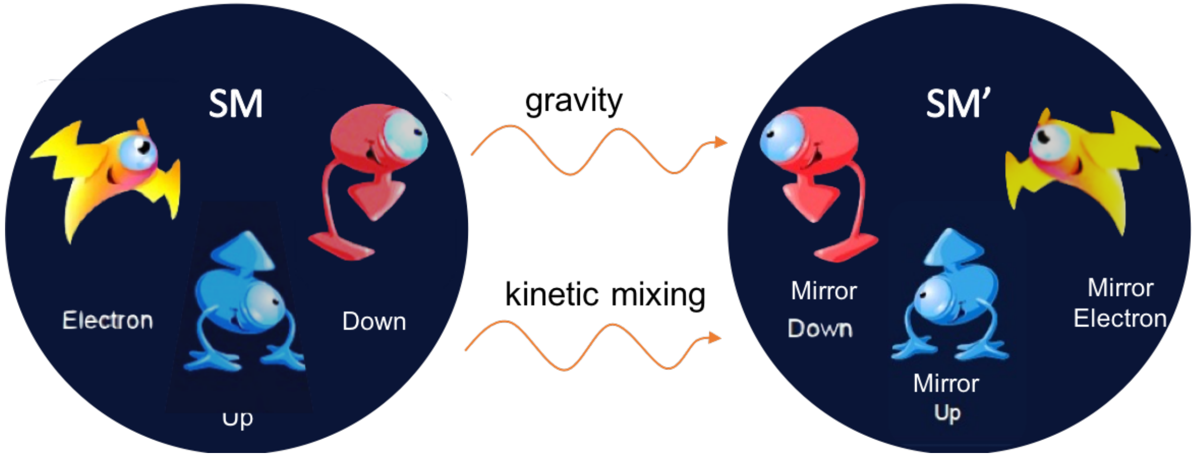
Mirror Dark Matter Model

- Hidden sector isomorphic to Standard Model (SM)
  - contains mirror partner of each SM particle
  - same masses, lifetimes and self interactions
- Symmetry allows kinetic mixing interaction between sectors

$$\mathcal{L} = \mathcal{L}_{SM}(e, u, d, \gamma, W, Z \ldots) + \mathcal{L}_{SM'}(e', u', d', \gamma', W', Z' \ldots) + \mathcal{L}_{mix}$$

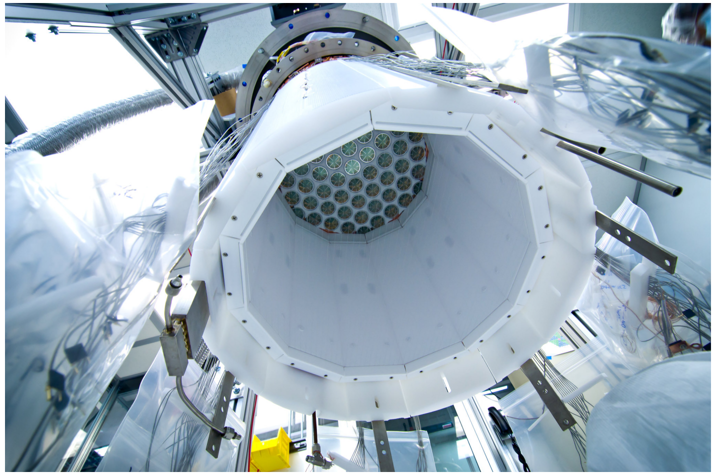
$$\mathcal{L}_{mix} = \frac{\varepsilon}{2} F^{\mu\nu} F'_{\mu\nu} + \Lambda \phi^{\dagger}\phi\, \phi'^{\dagger}\phi'$$

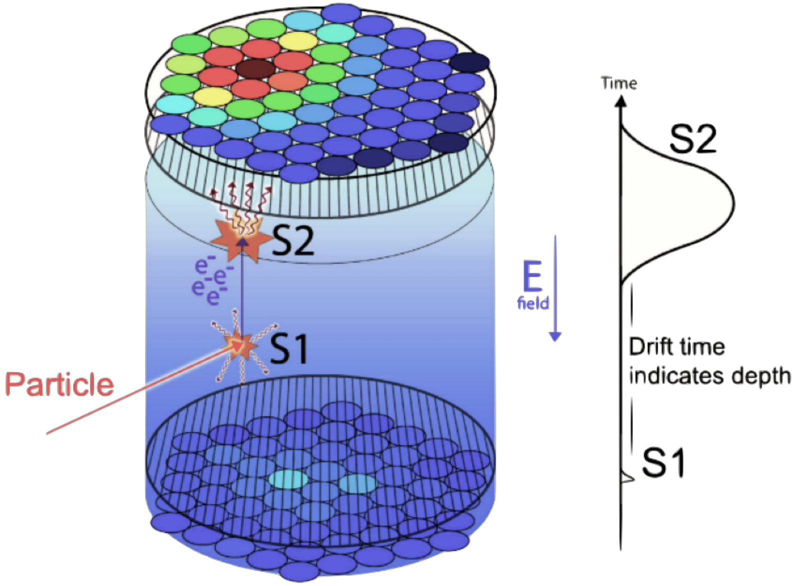
Kinetic mixing term



LUX Experiment

- **What:** dual phase (liquid-gas) xenon TPC
- **Where:** SURF, South Dakota, USA
- **When:** data taking 2013 - 2016
- **Why:** WIMP search - nuclear recoil signal, also electron recoil searches (solar axion, axion like particle, sub GeV dark matter)
- Mirror electrons would interact with atomic electrons via kinetic mixing - electron recoil signal

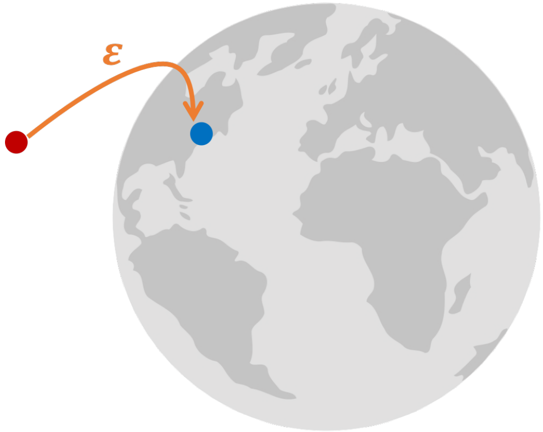




Terrestrial effects

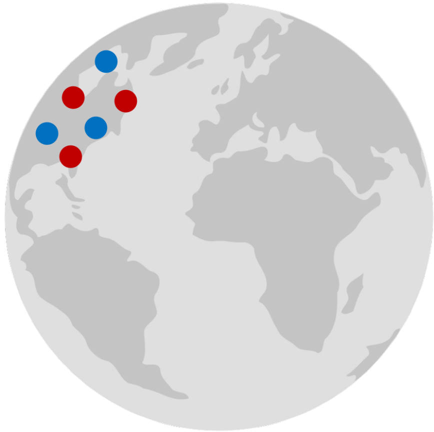
1. Energy loss

from kinetic mixing
causes occasional capture



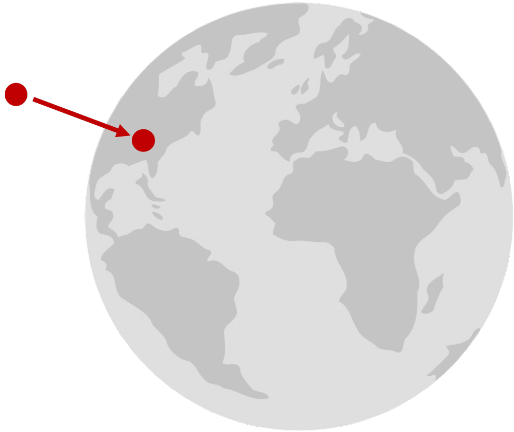
2. Distribution builds up

and thermalizes



3. Self shielding

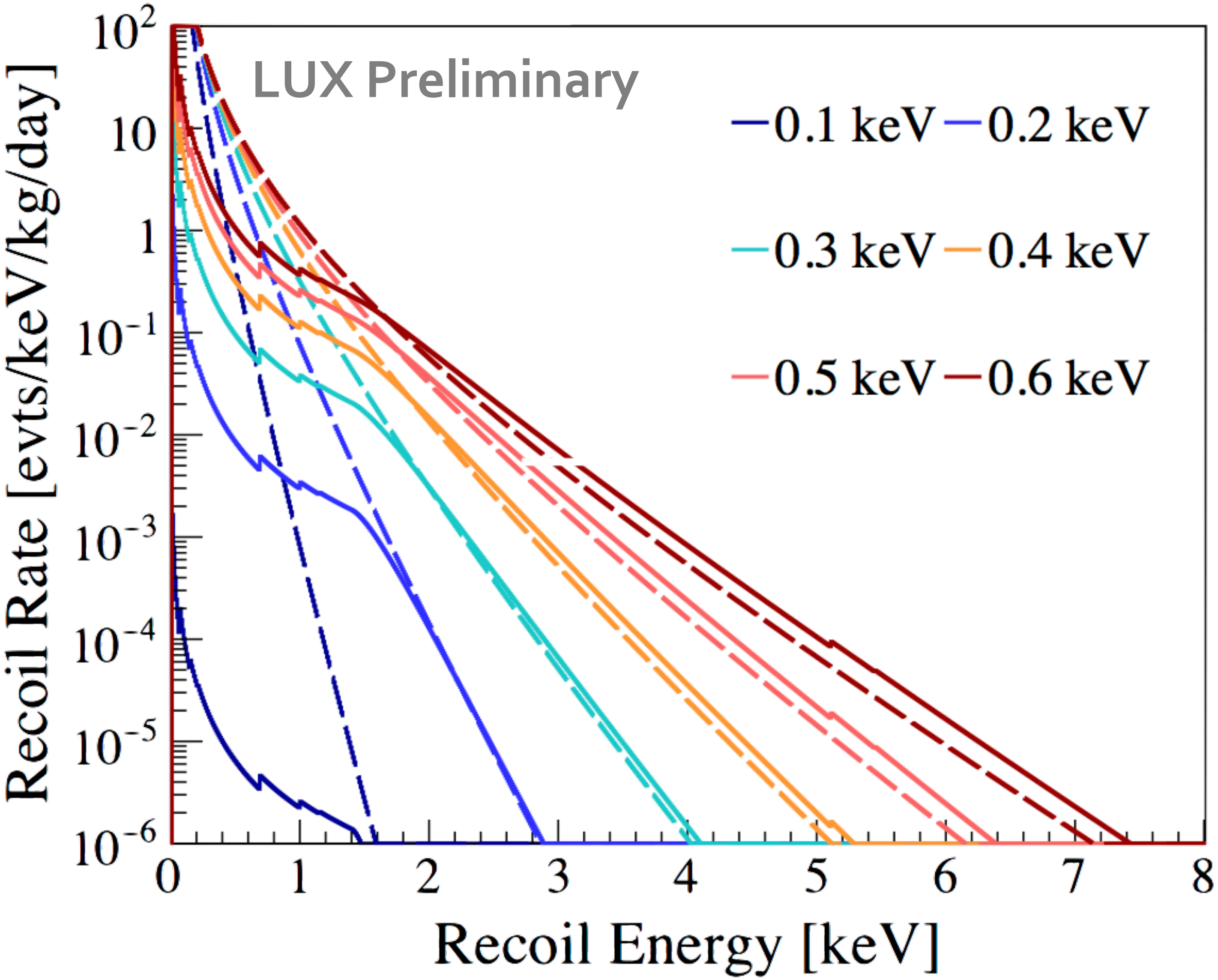
from MDM self
interactions



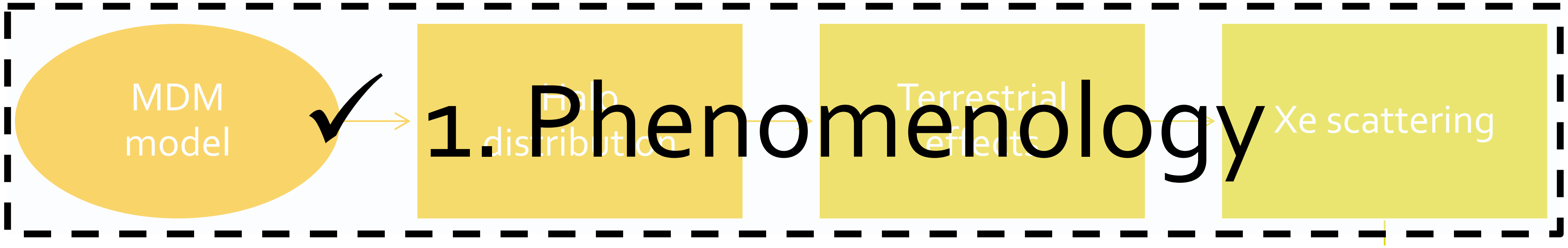
Interaction Rate

Rate depends on *kinetic mixing parameter* and local mirror electron *temperature* (velocity)

Shielding, modulation and atomic shell effects accounted for (solid lines)

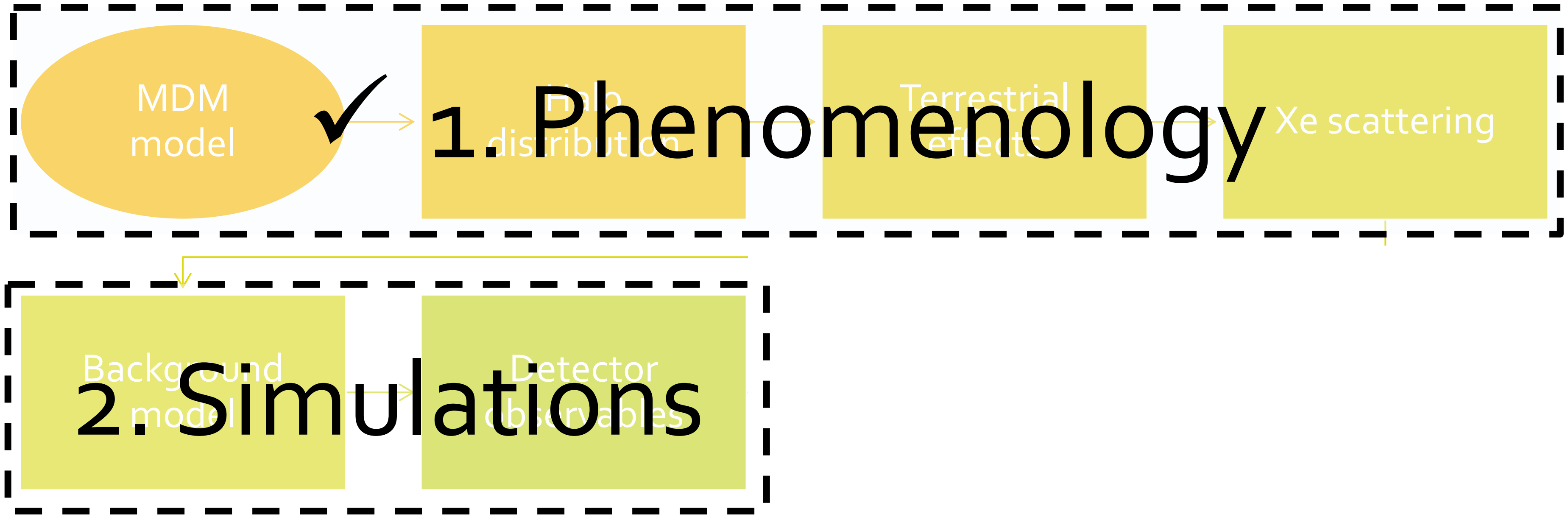


Testing the model



✓ 1. Phenomenology

Testing the model



MDM model ✓

Halo distribution

Terrestrial effects

Xe scattering

1. Phenomenology

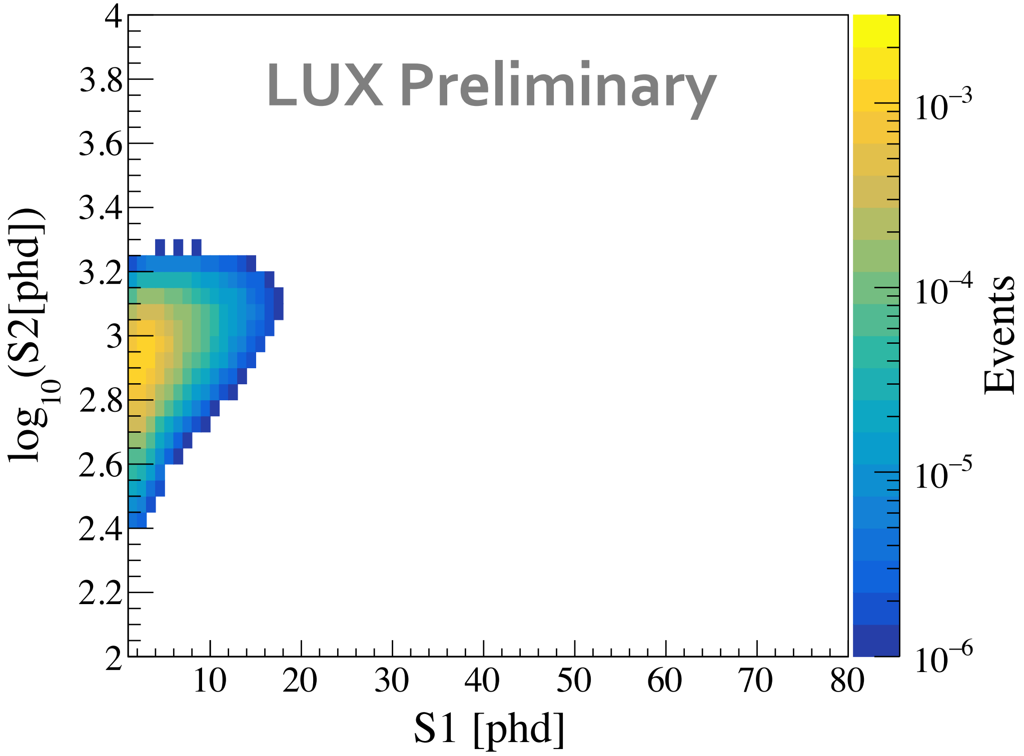
Background model

Detector observables

2. Simulations

Simulations

- Electron recoil backgrounds from:
    - external gammas
    - internal betas
- Use energy spectra to simulate expected distributions of detector observables: S1, S2 ,r, z
- Use NESTv2.0 to simulate liquid xenon response



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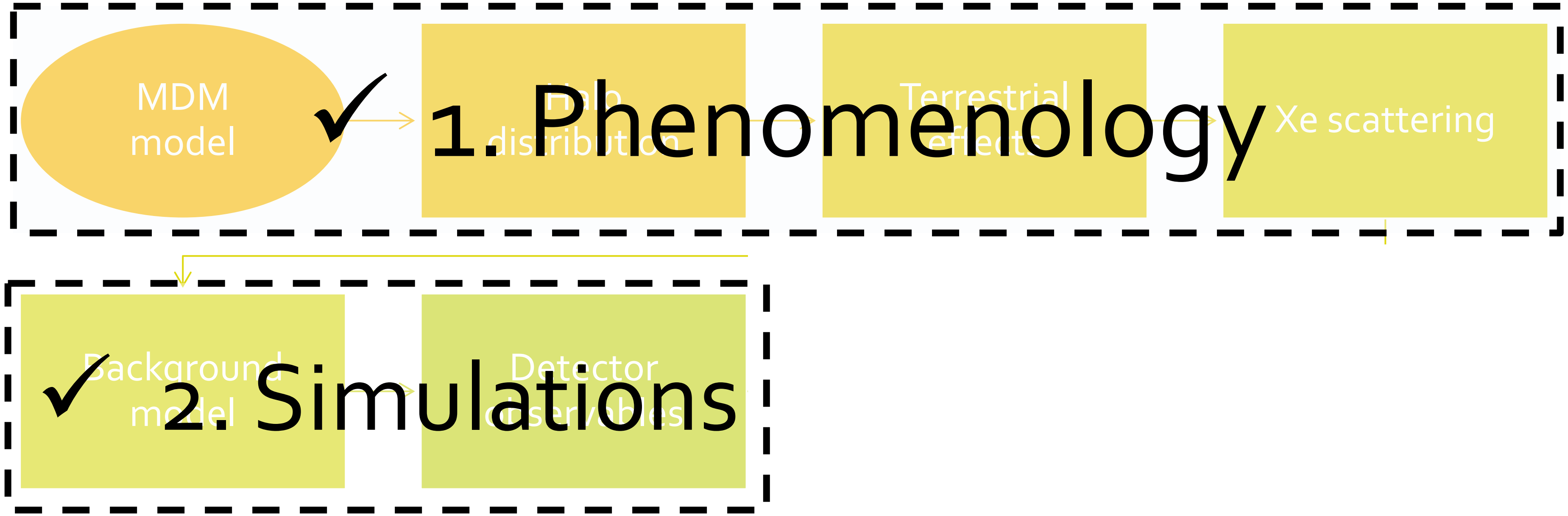
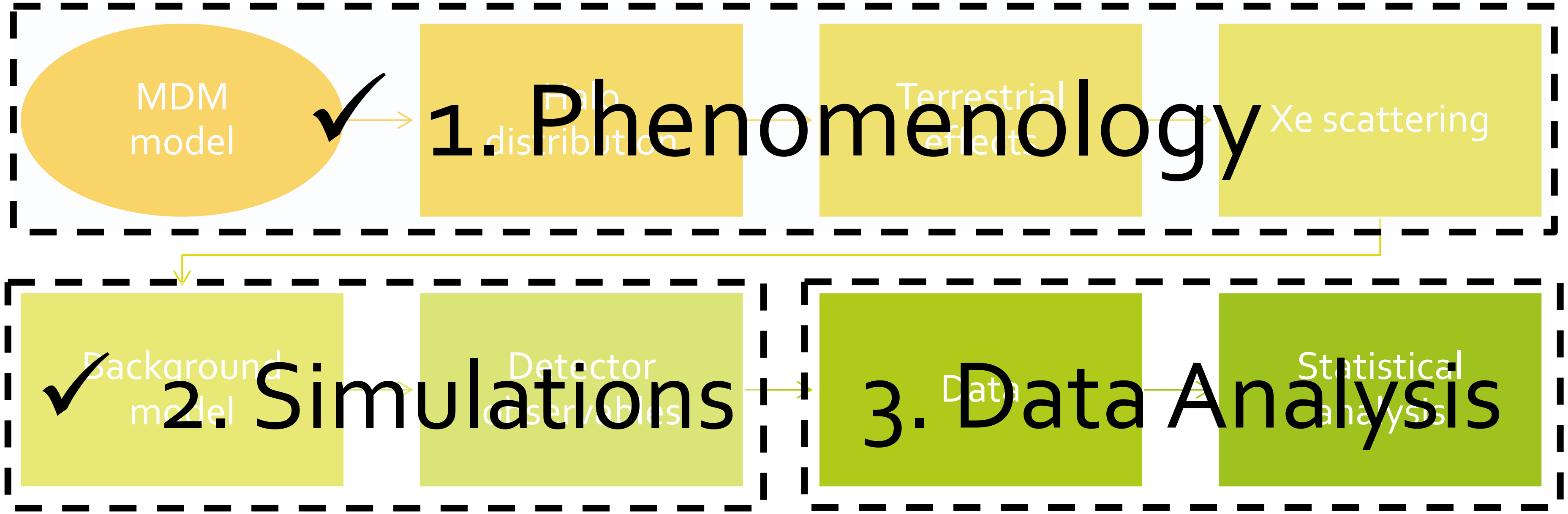


✓ 1. Phenomenology

✓ 2. Simulations

Testing the model



✓ 1. Phenomenology

MDM model → Halo distribution → Terrestrial effects → Xe scattering

✓ 2. Simulations

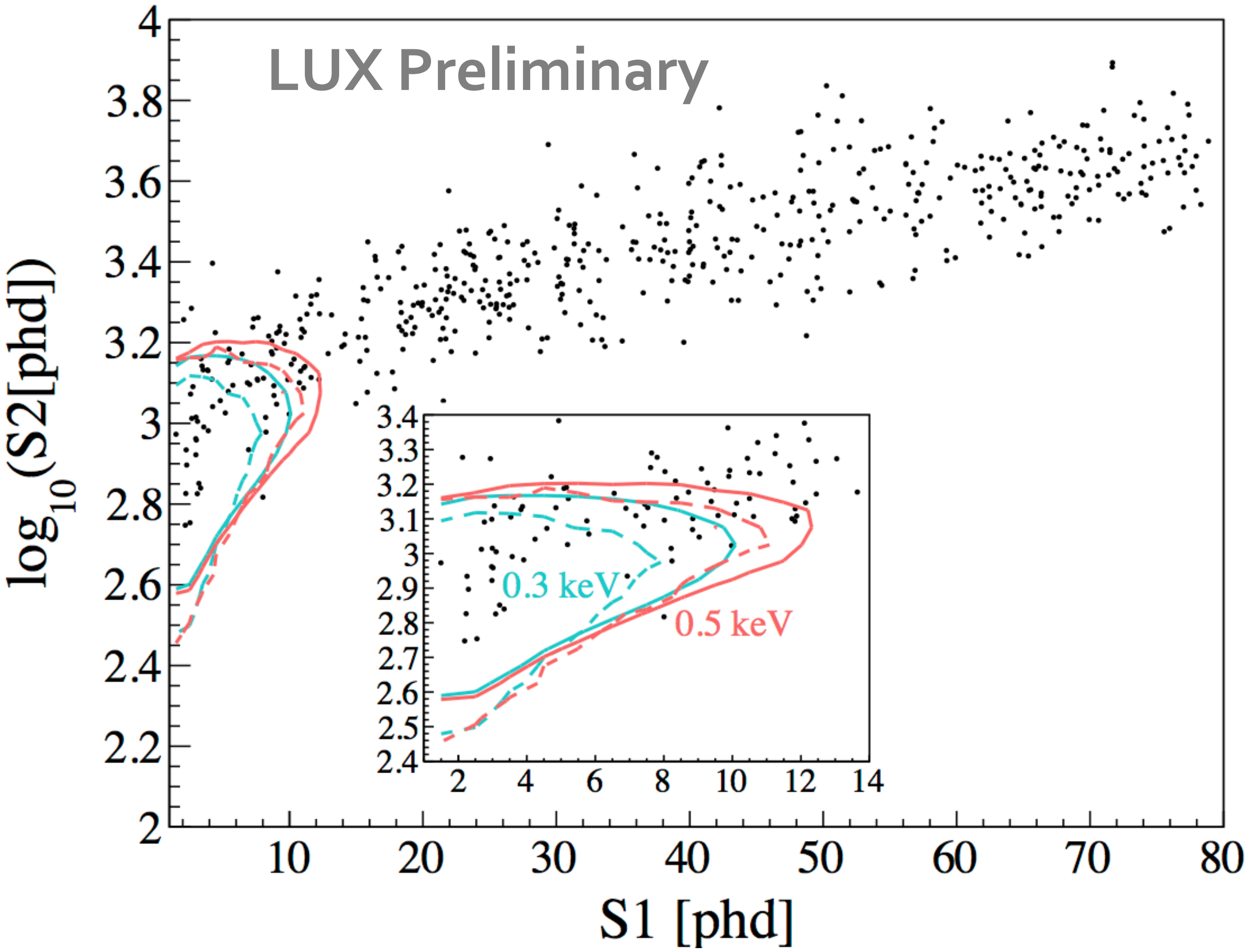
Background model → Detector observables

3. Data Analysis

Data → Statistical analysis

Data

- LUX Run3 Apr-Sept 2013
- S1, logS2 (energy) and r, z (position) information
- Data shown along with 95% signal contours here - dashed line without shielding and solid line with



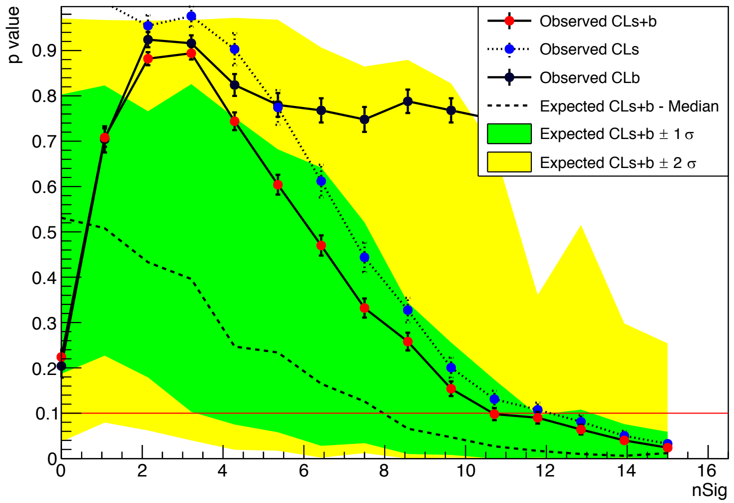
Statistical Analysis

Aim: find 90% confidence interval for kinetic mixing

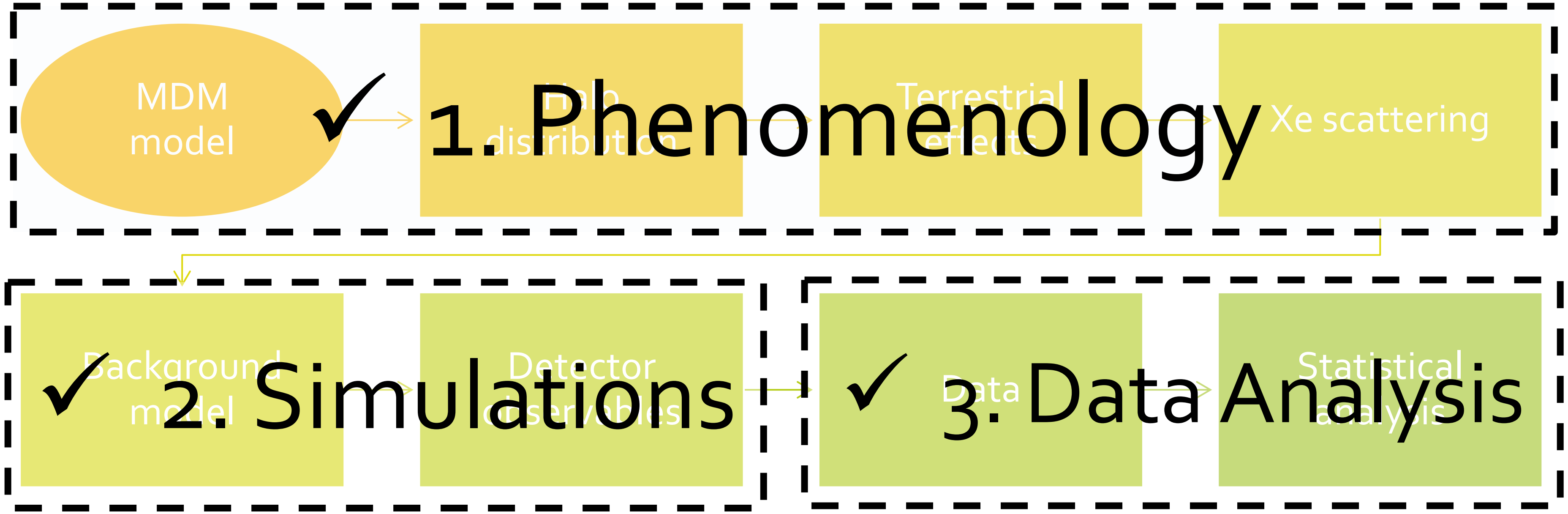
Use: two sided frequentist test (parameter of interest: number of signal events, nuisance parameters: background events)

Profile Likelihood Ratio

1. **Profile** over nuisance parameters, by maximizing the **likelihood**
   a) For all parameters (global)
   b) For fixed number of signal events (conditional)
2. Create test statistic from **ratio:** $t_\mu = -2\ln\lambda(\mu)$, $\lambda(\mu) = \frac{L(\mu, \hat{\hat{\boldsymbol{\theta}}})}{L(\hat{\mu}, \hat{\boldsymbol{\theta}})}$,
3. Repeat for each number of signal events, calculating the p-value $p_\mu = \int_{t_{obs}}^{\infty} f(t_\mu|\mu)\,dt_\mu$,
4. Confidence limit on number of signal events where p-vale intersects 0.1
5. Convert to limit on kinetic mixing



Testing the model



✓ 1. Phenomenology

MDM model → Halo distribution → Terrestrial effects → Xe scattering

✓ 2. Simulations

Background model → Detector observables

✓ 3. Data Analysis

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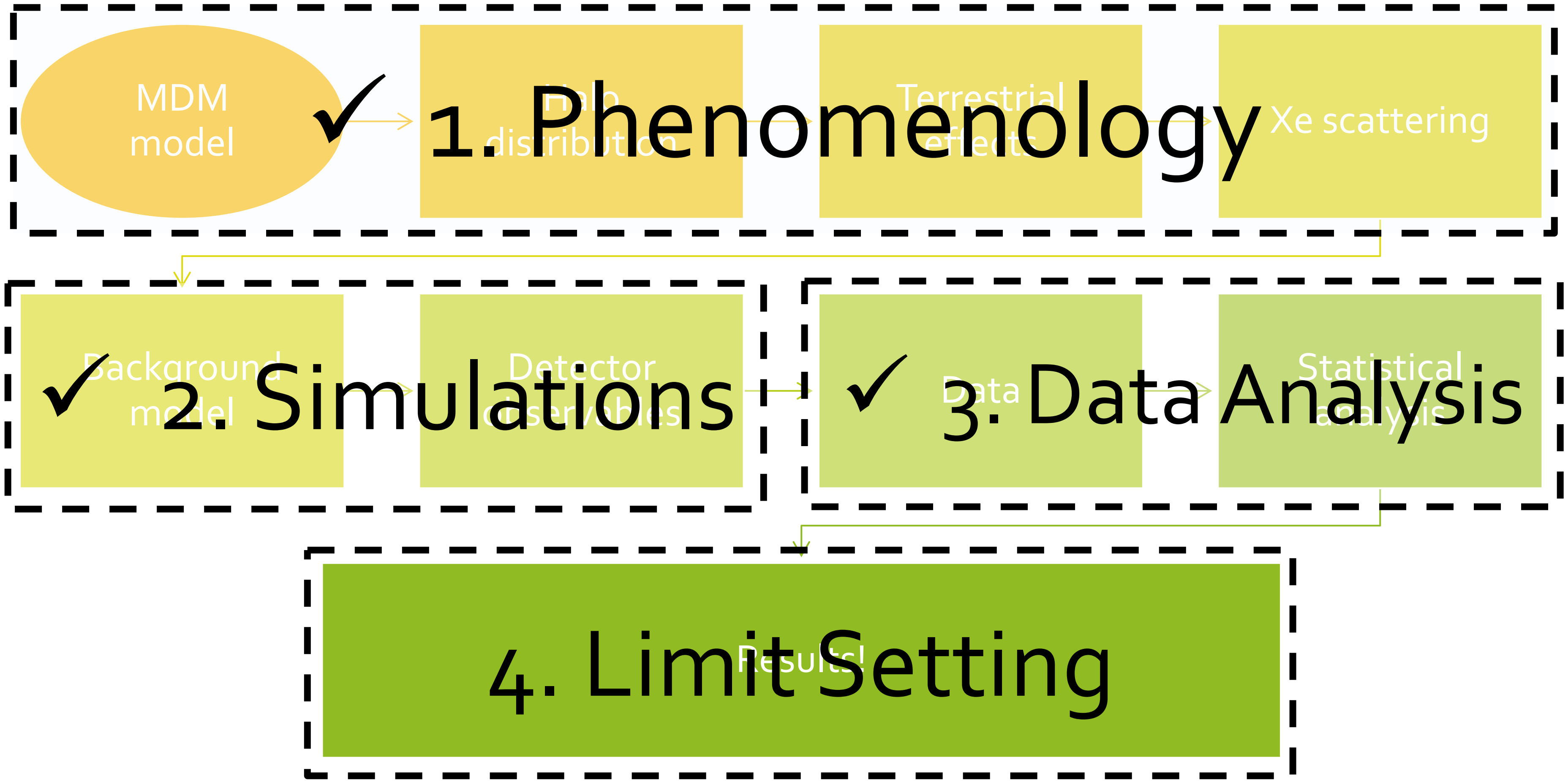
Testing the model



1. Phenomenology

MDM model ✓

Halo distribution

Terrestrial effects

Xe scattering

2. Simulations

✓ Background model

Detector observables

3. Data Analysis

✓ Data

Statistical analysis

4. Limit Setting

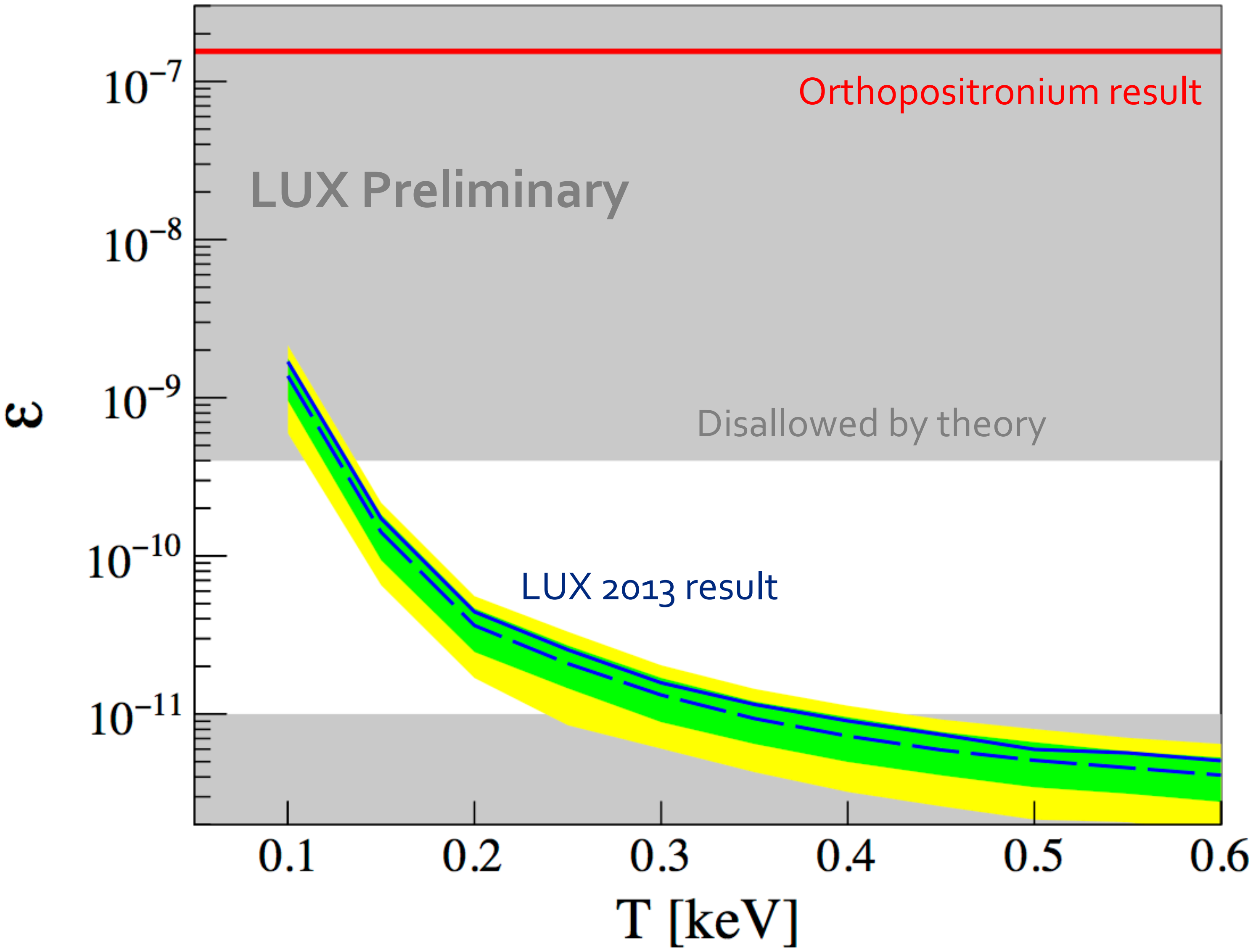
Results!

Results

First direct detection search for mirror dm.

Theory constraint:
$10^{-11} \leq \varepsilon \leq 4\times10^{-10}$

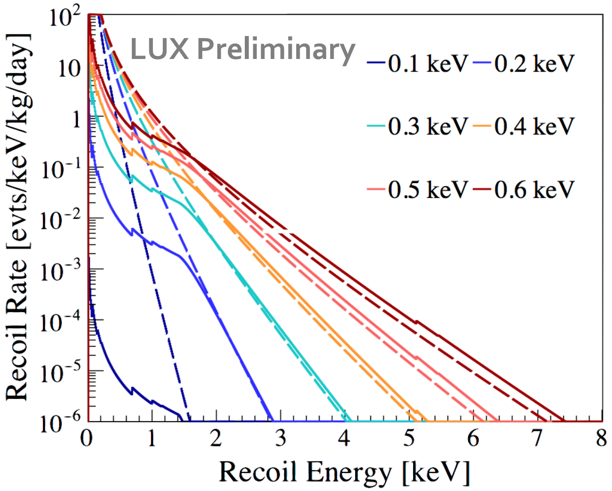
Other experimental constraint from invisible decays of orthopositronium

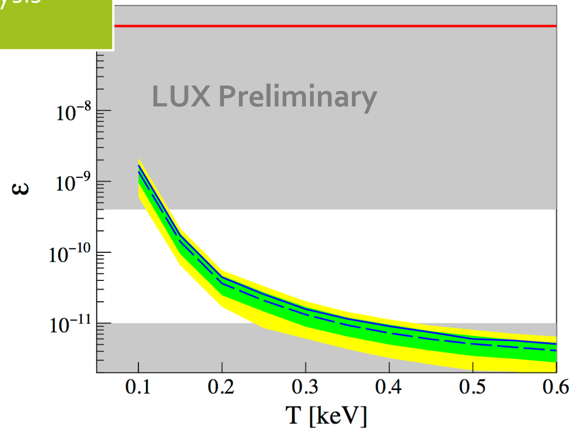


Summary

- Mirror dark matter model – *hidden sector* dm with *exact mirror symmetry*
- Search for *electron recoils* with Xe atomic electrons
- Need to account *for terrestrial capture and shielding*
- **First** direct detection search for mirror dark matter, setting 90% limit on *kinetic mixing*

MDM model → Halo distribution → Terrestrial effects → Xe scattering → Background model → Detector observables → Data → Statistical analysis → Results!





Backup

References

- Mirror dark matter model: R.Foot, Mirror dark matter: Cosmology, galaxy structure and direct detection, Int. J. Mod. Phys. A, 29, 1430013 (2014)
- LUX experiment: D. Akerib et al. (LUX Collaboration) First results from the LUX dark matter experiment at the Sanford underground research facility, Phys. Rev. Lett., 112, 091393 (2014)
- Mirror dark matter shielding and modulation: R.Foot, Shielding of a direct detection experiment and implications for the DAMA annual modulation signal, Phys. Lett. B., 789, 592-597 (2019)
- NESTv2: M.Szydagis et al., NESTv2.0, 10.5281/zenodo.1314669,https://doi.org/10.5281/zenodo.1314669 (2018)
- Orthopositronium result: C.Vigo et al., First search for invisible decays of orthopositronium confined in a vacuum cavity, Phys. Rev. D, 97, 092008 (2018)

Rate Calculation

Differential scattering rate: $\frac{dR}{dE_R} =$

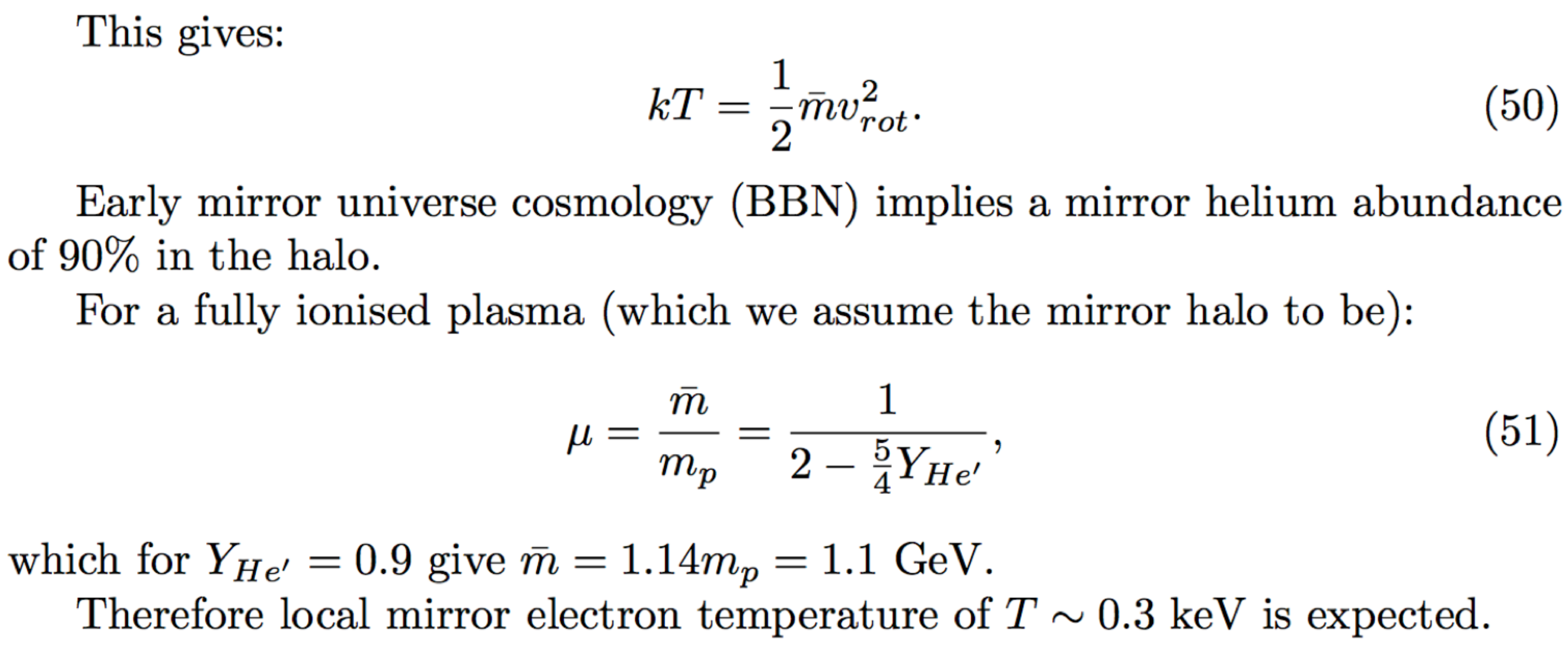
$$g_T N_T n_{e'}^0 \frac{\lambda}{v_c^0 E_R^2}\begin{bmatrix}1 + A_v cos\omega(t - t_0) \\ +A_\theta(\theta - \bar{\theta})\end{bmatrix}$$

- Detector, N_T: atoms per kg
- *Atomic effects,* g_T: number of electrons with binding energy < E_R
- *Kinetic mixing interaction:* $\lambda = \frac{2\pi\varepsilon^2\alpha^2}{m_e^2}$
- *Shielding effects:*
  - $n_{e'}^0$: mirror electron number density
  - v_c^0: velocity distribution
- *Modulation terms:* $1 + A_v cos\omega(t - t_0) + A_\theta(\theta - \bar{\theta})$

Mirror cosmology

- Z.Berezhiani, D. Comelli and F. Villante, 'The Early Mirror Universe: Inflation, Baryogenesis, Nucleosynthesis and Dark Matter', Phys.Lett.B503:362-375(2001) and Z.Berezhiani, 'Mirror World and it's Cosmological Consequences' IntJModPhys.A19:3775-3806(2004)
- In BBN effective number of degrees of freedom at T~1MeV is $g_*=10.75$ (from γ, e^-, ν). With mirror particles this becomes ~~g~~$_* = g_*(1+(T`/T)^4)$. Difference from 10.75 is written in terms of effective number of extra neutrino species: $\Delta g$ = ~~g~~$*-10.75=1.75\Delta N\nu$. $\Delta N\nu = 6.14(T`/T)^4<1$ from observations gives limit: **$T`/T<0.64$.**
- Different means different cosmological evolution, but with same microphysics.
- Lower temperature means larger baryon asymmetry than observable sector, so mirror baryons can contribute to DM (completely or along with CDM).
- Different conditions at BBN gives higher mirror He abundance.
- Large scale structure formation looks like CDM.

MDM Temperature



This gives:

$$kT = \frac{1}{2}\bar{m}v_{rot}^2. \tag{50}$$

Early mirror universe cosmology (BBN) implies a mirror helium abundance of 90% in the halo.

For a fully ionised plasma (which we assume the mirror halo to be):

$$\mu = \frac{\bar{m}}{m_p} = \frac{1}{2 - \frac{5}{4}Y_{He'}}, \tag{51}$$

which for $Y_{He'} = 0.9$ give $\bar{m} = 1.14m_p = 1.1$ GeV.

Therefore local mirror electron temperature of $T \sim 0.3$ keV is expected.

Assuming all mirror halo particles in thermal equilibrium.

[From J.Clarke, R.Foot,PhysLettB.2016.12.047]

THEORETICAL LIMITS

$$10^{-11} \leq \varepsilon \leq 4\times10^{-10}$$

- J.Clarke, R.Foot,PhysLettB.2016.12.047
- Lower limit required for halo equilibrium [R.Foot, IntJModPhysA.29.1430013] – heating from supernovae ($e'^{-}e'^{+}$ created in SN escape and annihilate to γ' absorbed by mirror nuclei in halo) must balance energy loss from dissipative processes
- Upper limit – if ϵ is too high structure formation is too heavily damped by acoustic oscillations [R.Foot, S.Vagnozzi, JCAP1607.014]

LUX Calibrations

Characterize the detector response

PRD 97, 102008 (2018)

- Energy deposition in the detector:

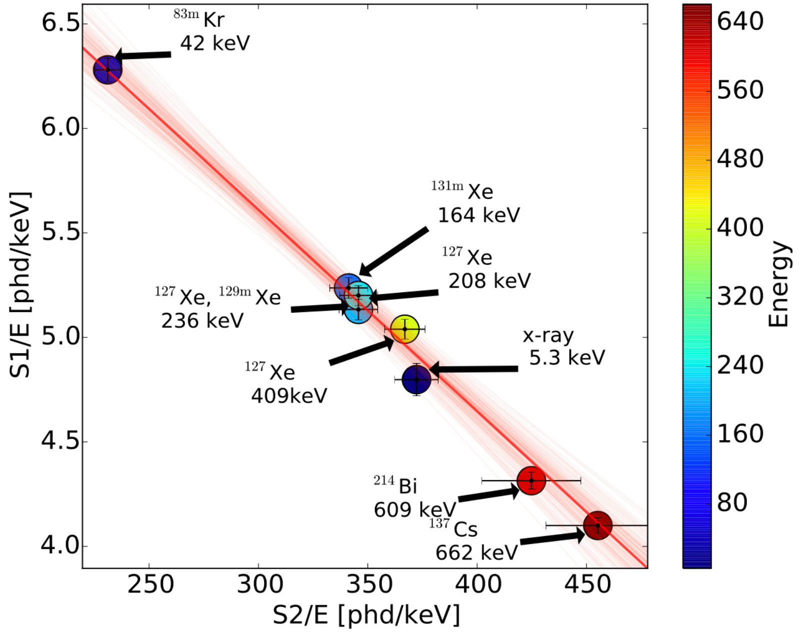
$$E = W(n_\gamma + n_e) = W\left(\frac{S1}{g_1} + \frac{S2}{g_2}\right)$$

number photons detected

number electrons detected

- Detector specific gains g_1,g_2 obtained from calibration.
- DD neutron: characterize nuclear reco [arXiv:1608.05381]
- Tritium: characterize electron recoils [PRD 93, 072009 (2016)]
- Kr83m: monitor detector performance [PRD 11.112009 (2017)]

Important for low energy ERs! Tritium β spectrum with 18.6keV end point/ Allows dertermination of ER band.



LUX Background Model

[arXiv:1403.1299]

- ERs from gamma rays:
  - Decay of radioisotope impurities in detector construction materials (U238, Th232, Co60)
- ERs from beta decays
  - Decay of intrinsic radioisotope contaminants in the liquid xenon (rn, KR85m)
  - Homogeneous distribution volume due to mixing by convection and diffusion
- NRs
  - Sub dominant background from neutron scatters
  - (α, n) interactions in construction materials
  - Spontaneous fission of U238
- Estimates of background rates from component screening, Xe monitoring during run and data are used to normalize Monte Carlo spectra of background components.