Monte Carlo for Boosted Dark Matter

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Outline

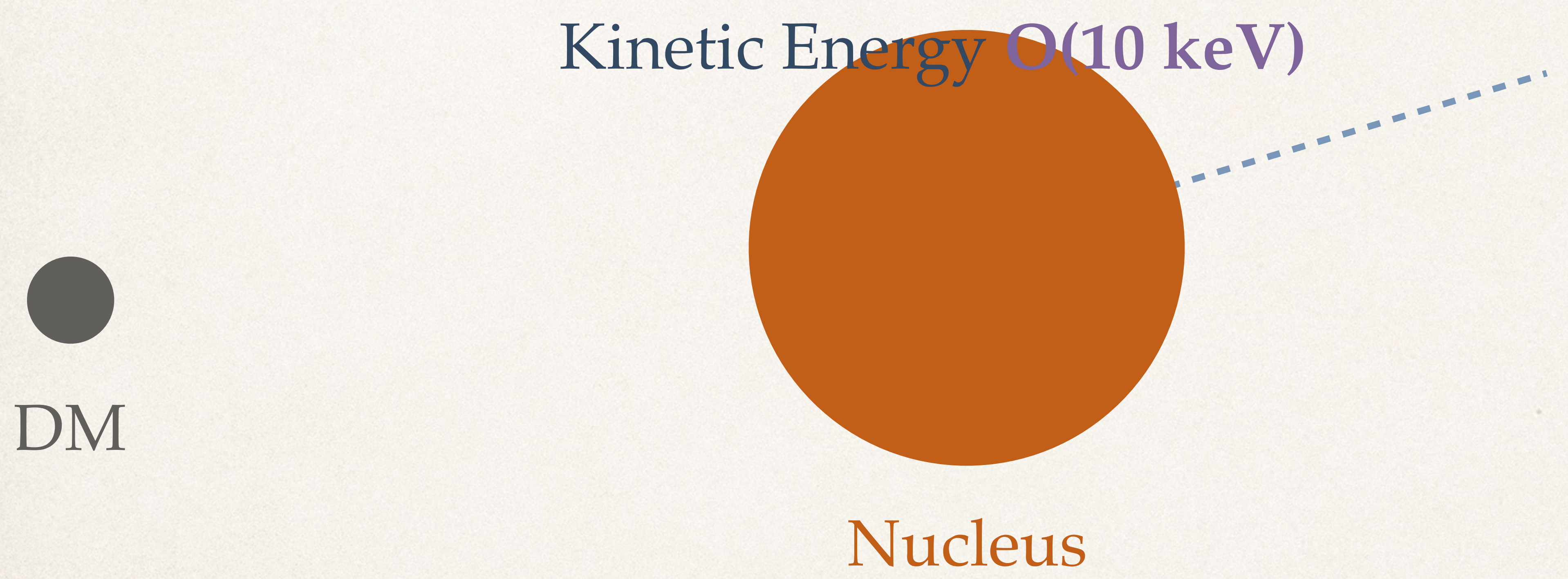
- What is boosted dark matter?

- What do we need from boosted dark matter MC?

- Boosted DM using GENIE

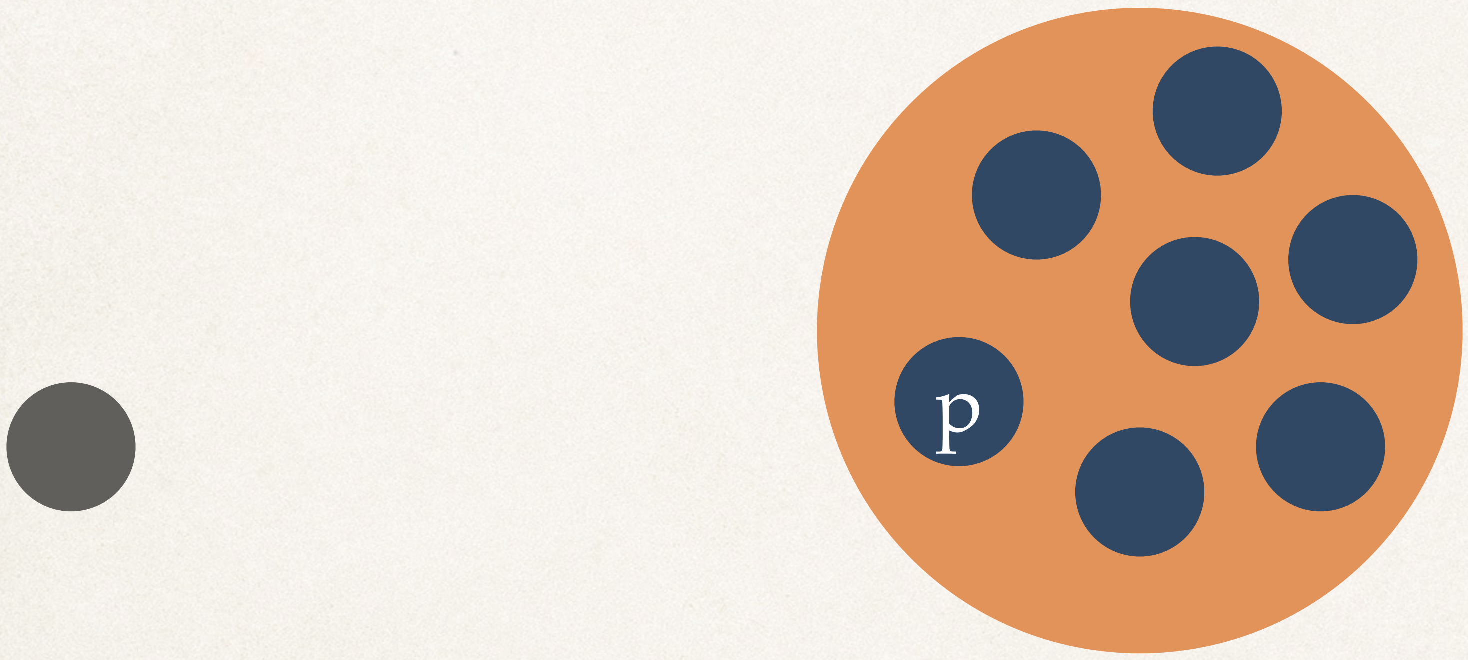
What is Boosted DM?

Relic DM has soft recoils



The difference with boosted

Elastic Nucleon Scattering



$v_{\chi_B} \approx 0.6\,c$

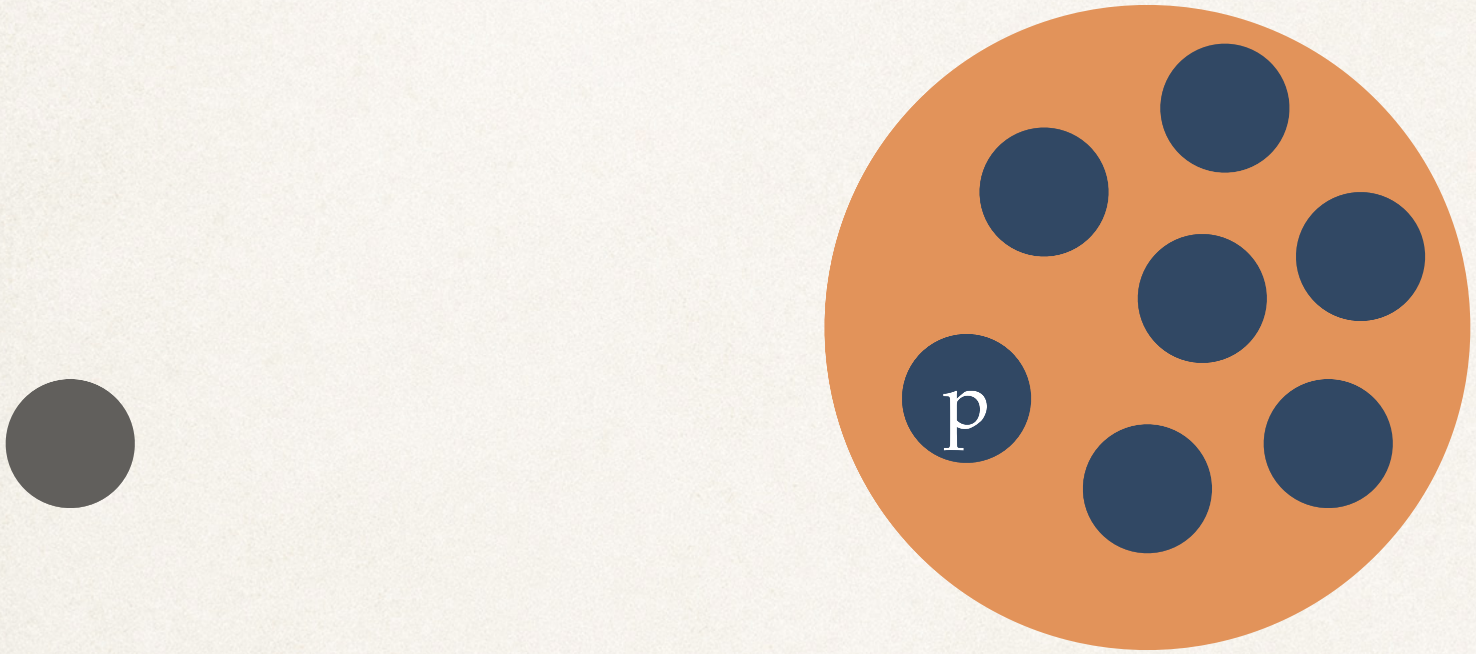
$E_{\mathrm{K,recoil}} \sim 1\ \mathrm{GeV}$

JB, Cui, Zhao: JCAP 1502 (2015) 005

The difference with boosted

Inelastic Nucleon Scattering

Pions & other Hadrons



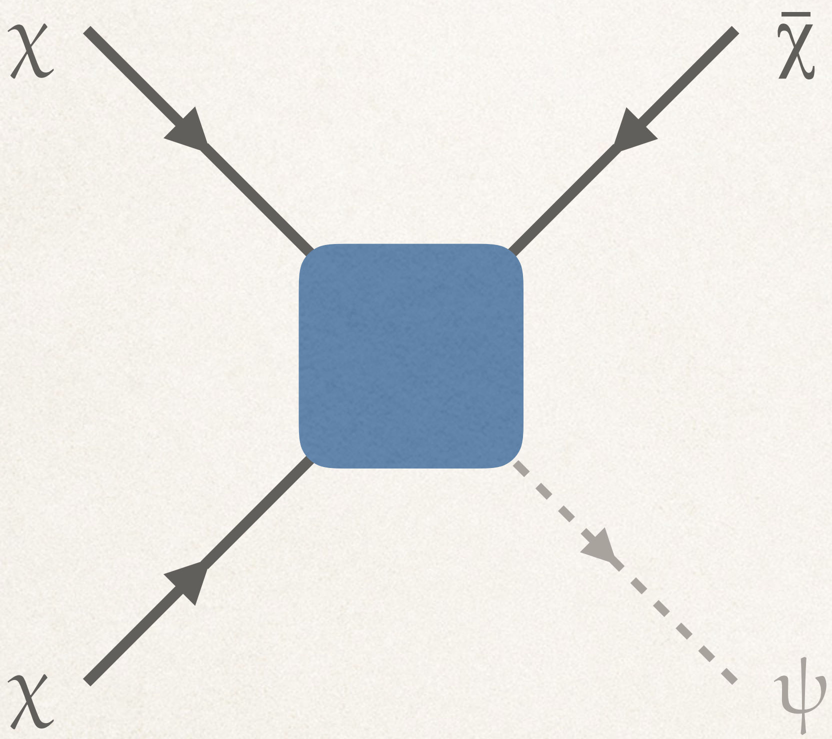
$v_{\chi_B} \gg 0.6\, c$

JB, Cui, Zhao: JCAP 1502 (2015) 005

Simple BDM Models Exist

Z₃ symmetry

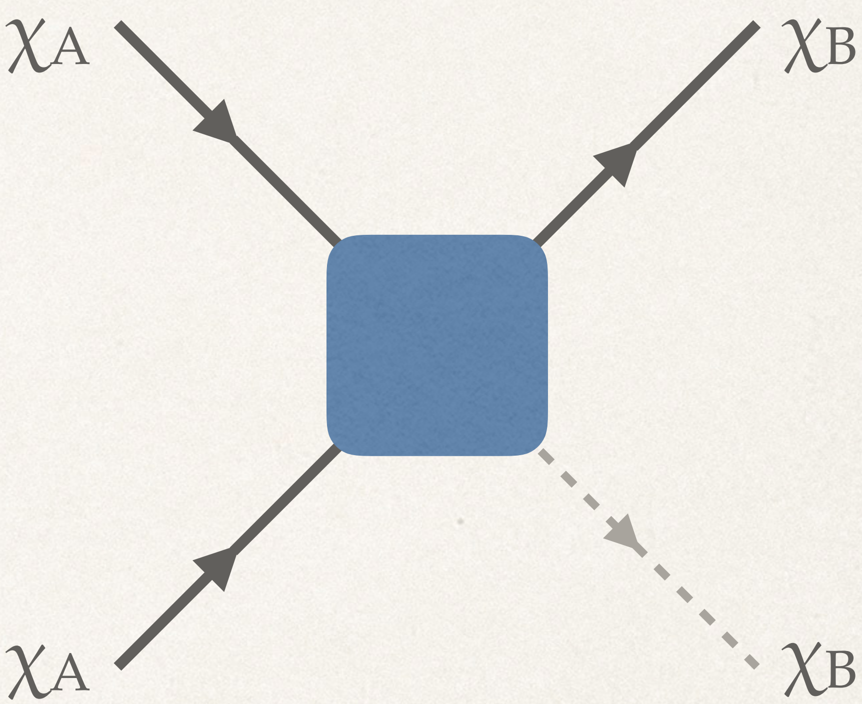
Semi-annihilation



$$v_{\chi_B} \approx 0.6\, c$$

Two component

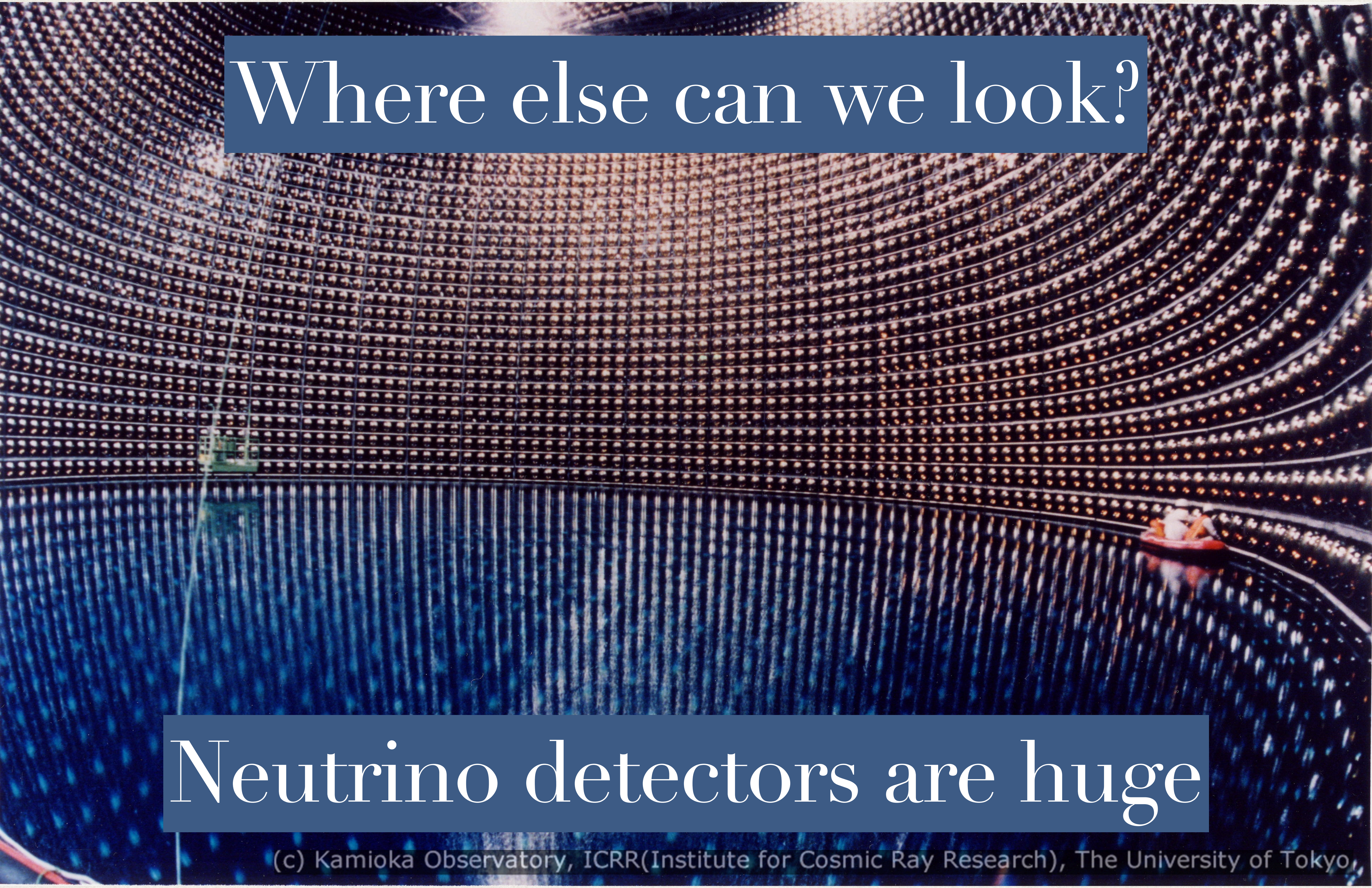
Dark annihilation



$$v_B = c\sqrt{1 - m_B^2/m_A^2}$$

JB, Cui, Zhao: JCAP 1502 (2015) 005

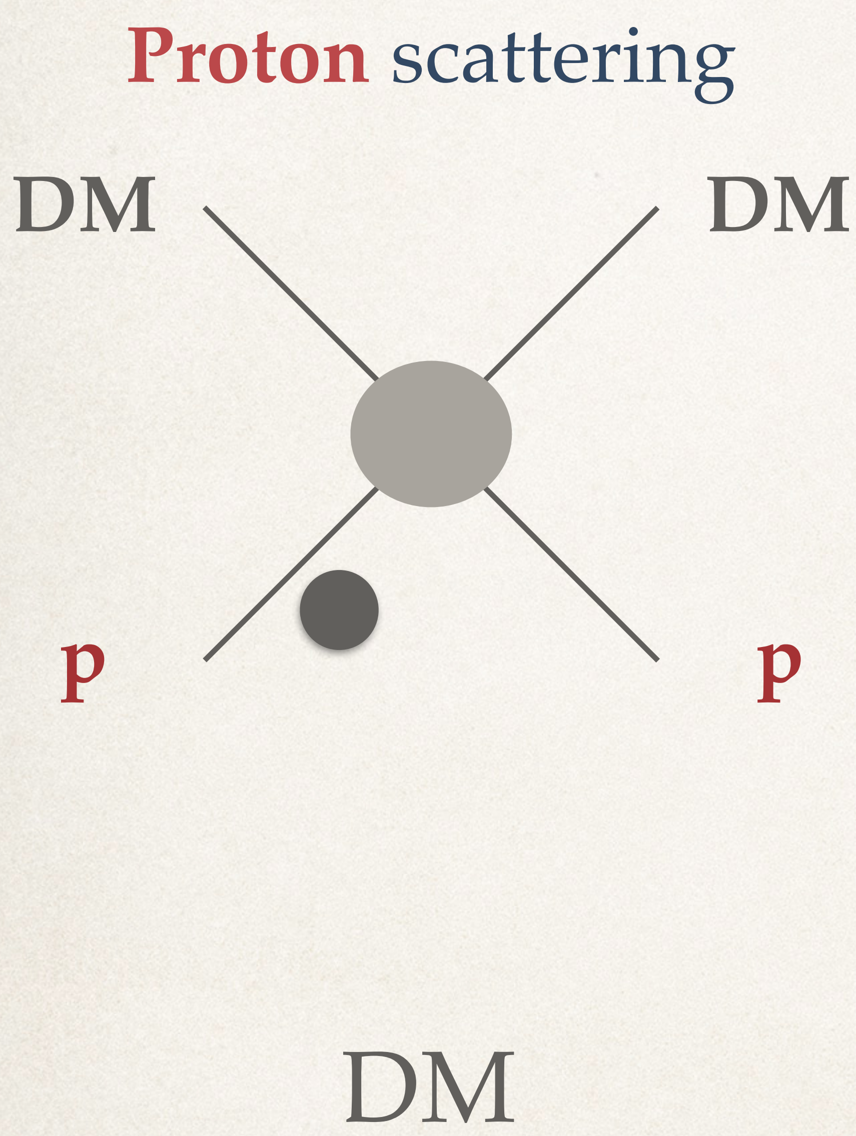
Where else can we look?

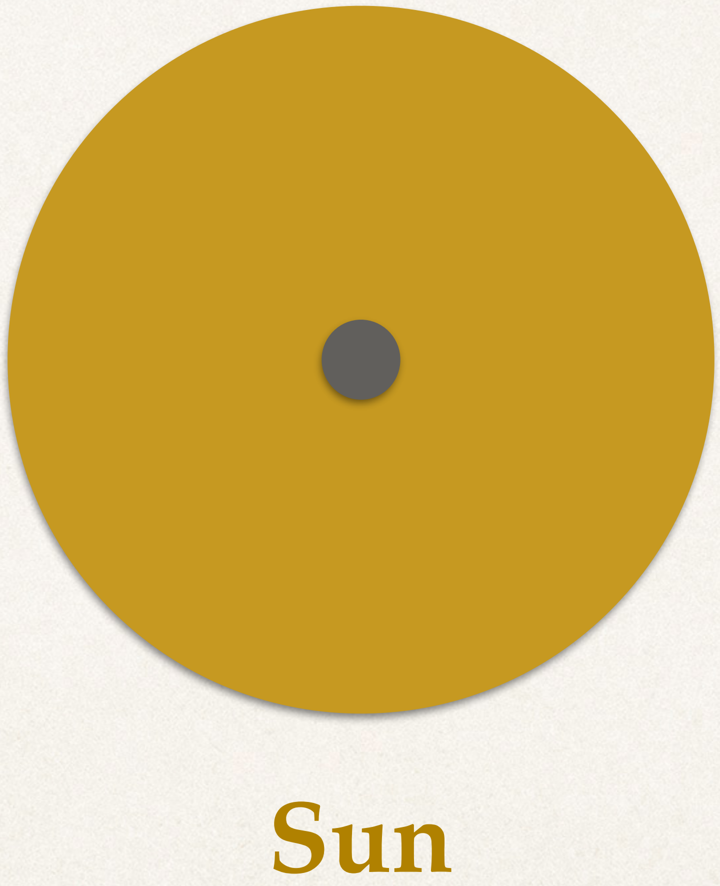


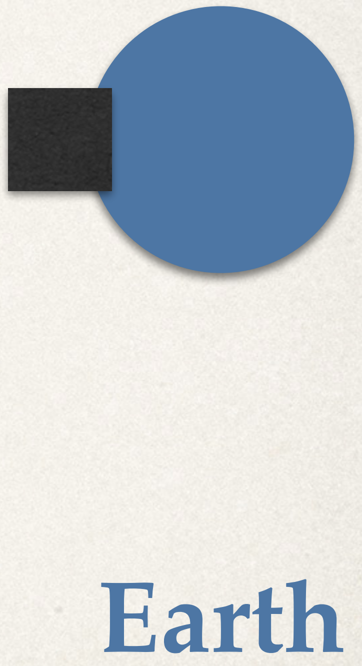
Neutrino detectors are huge

Solar capture & Detection

Solar Capture

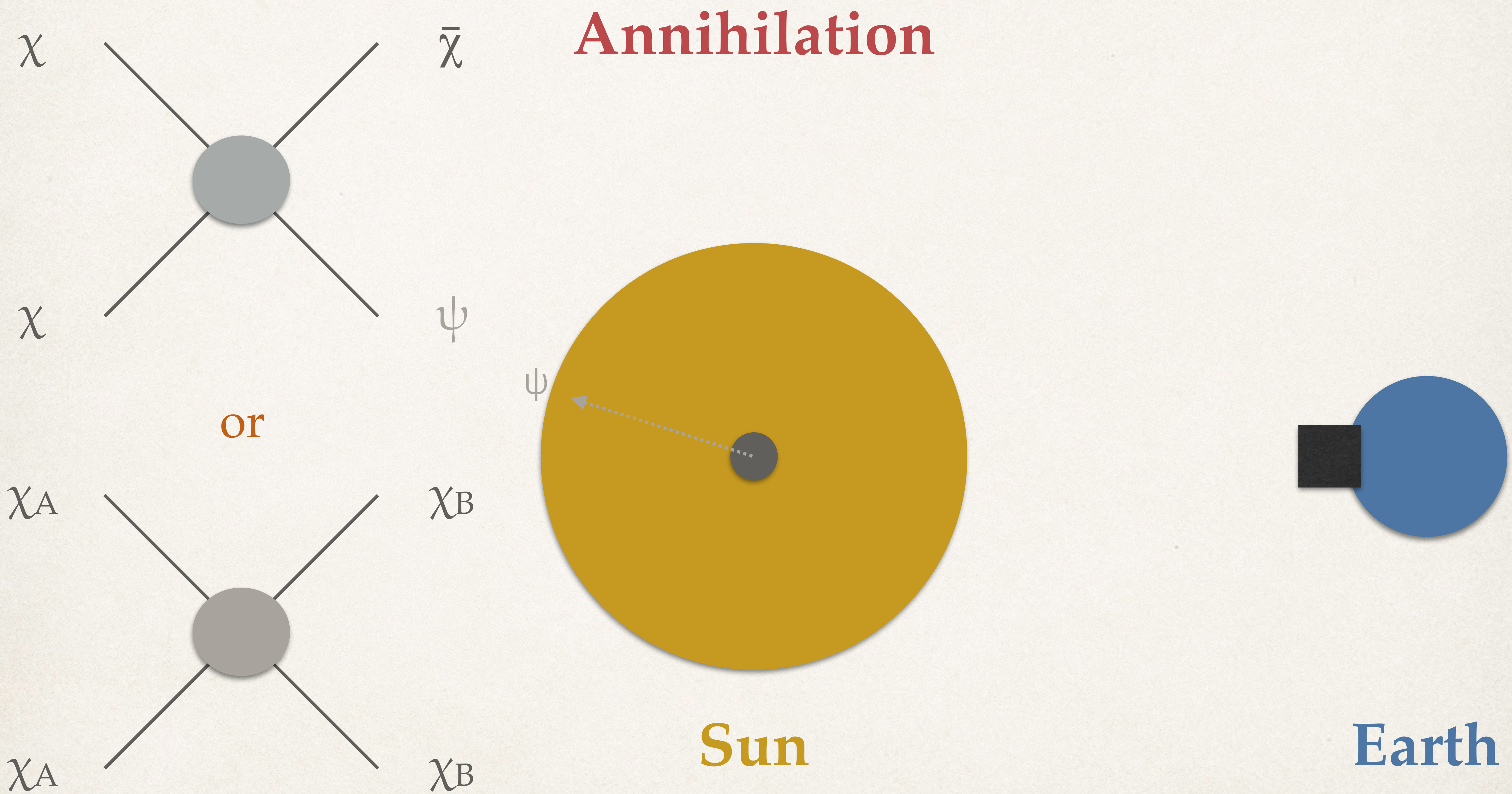






JB, Cui, Zhao: JCAP 1502 (2015) 005

Solar capture & Detection

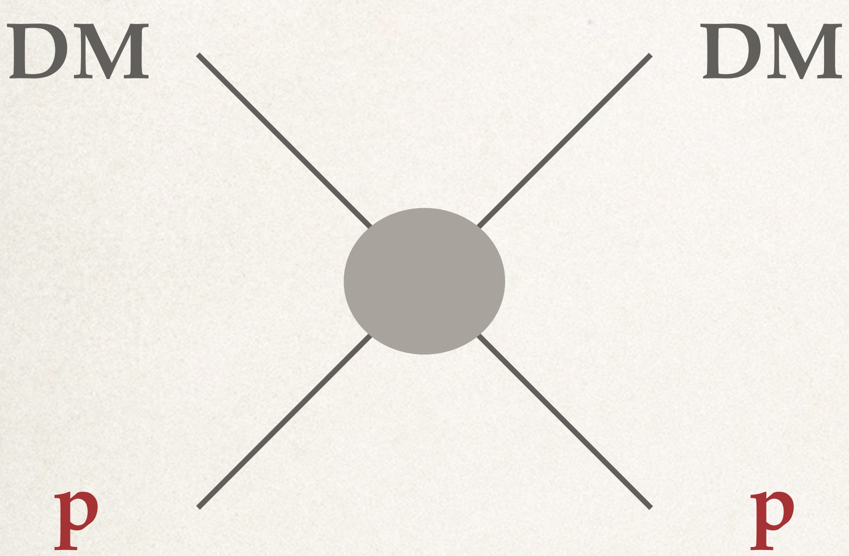


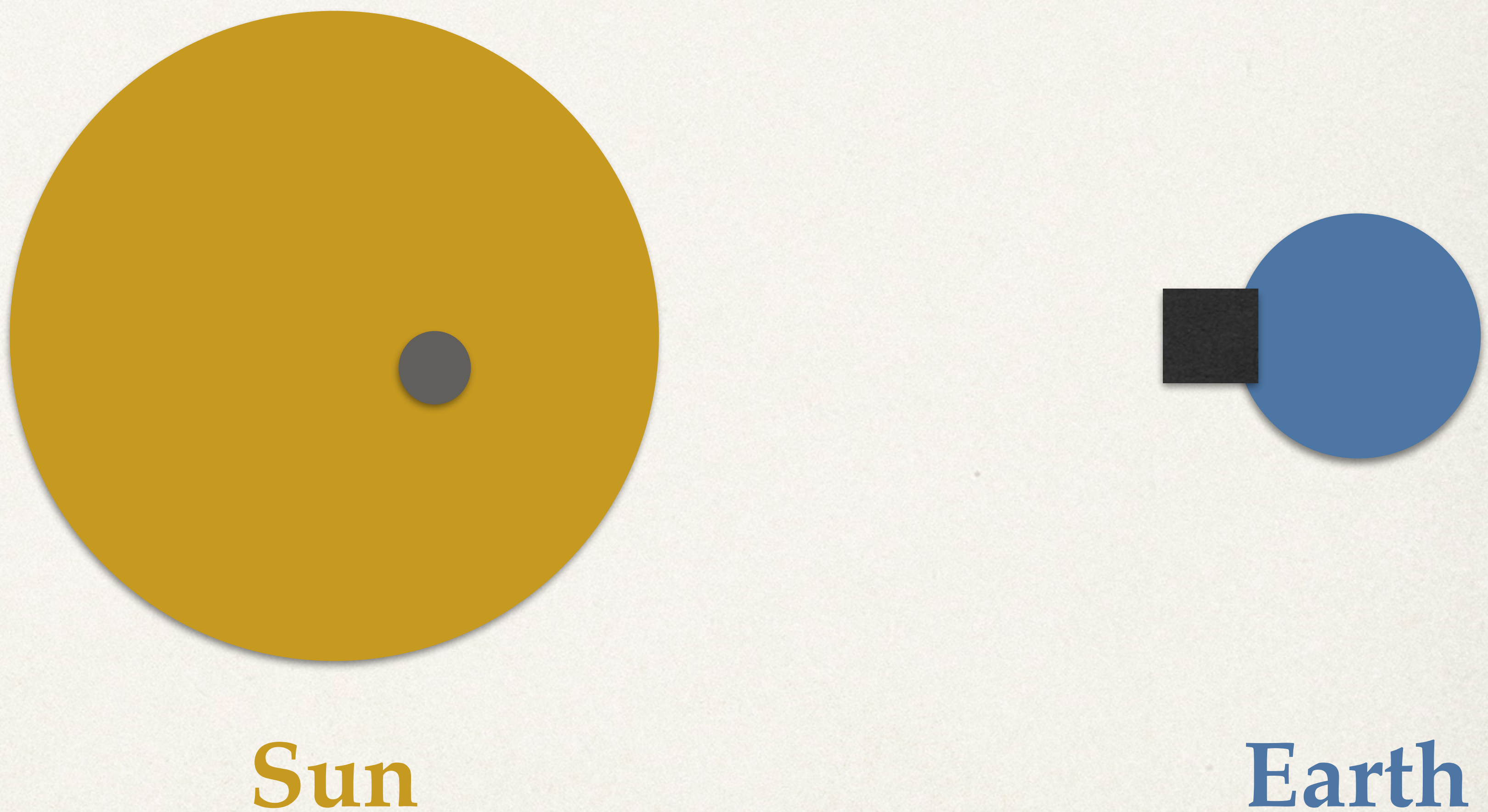
JB, Cui, Zhao: JCAP 1502 (2015) 005

Solar Capture & Detection

Re-scattering

Proton scattering



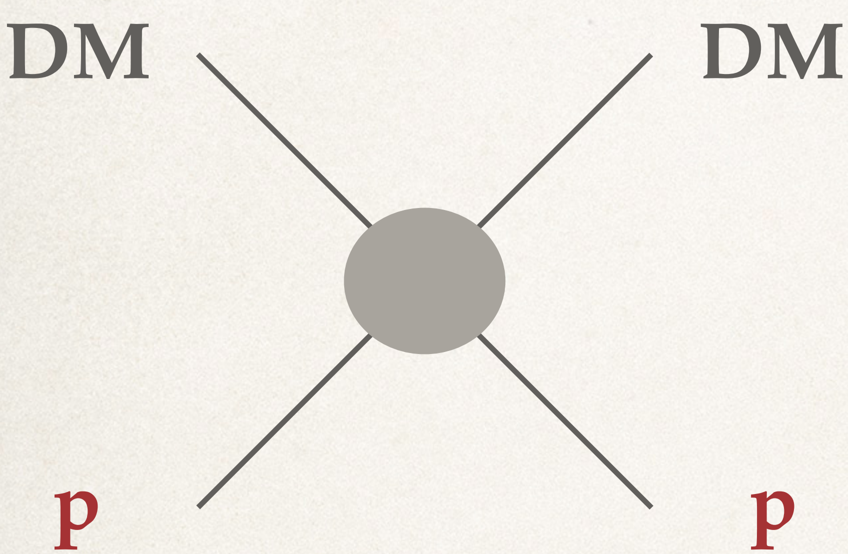


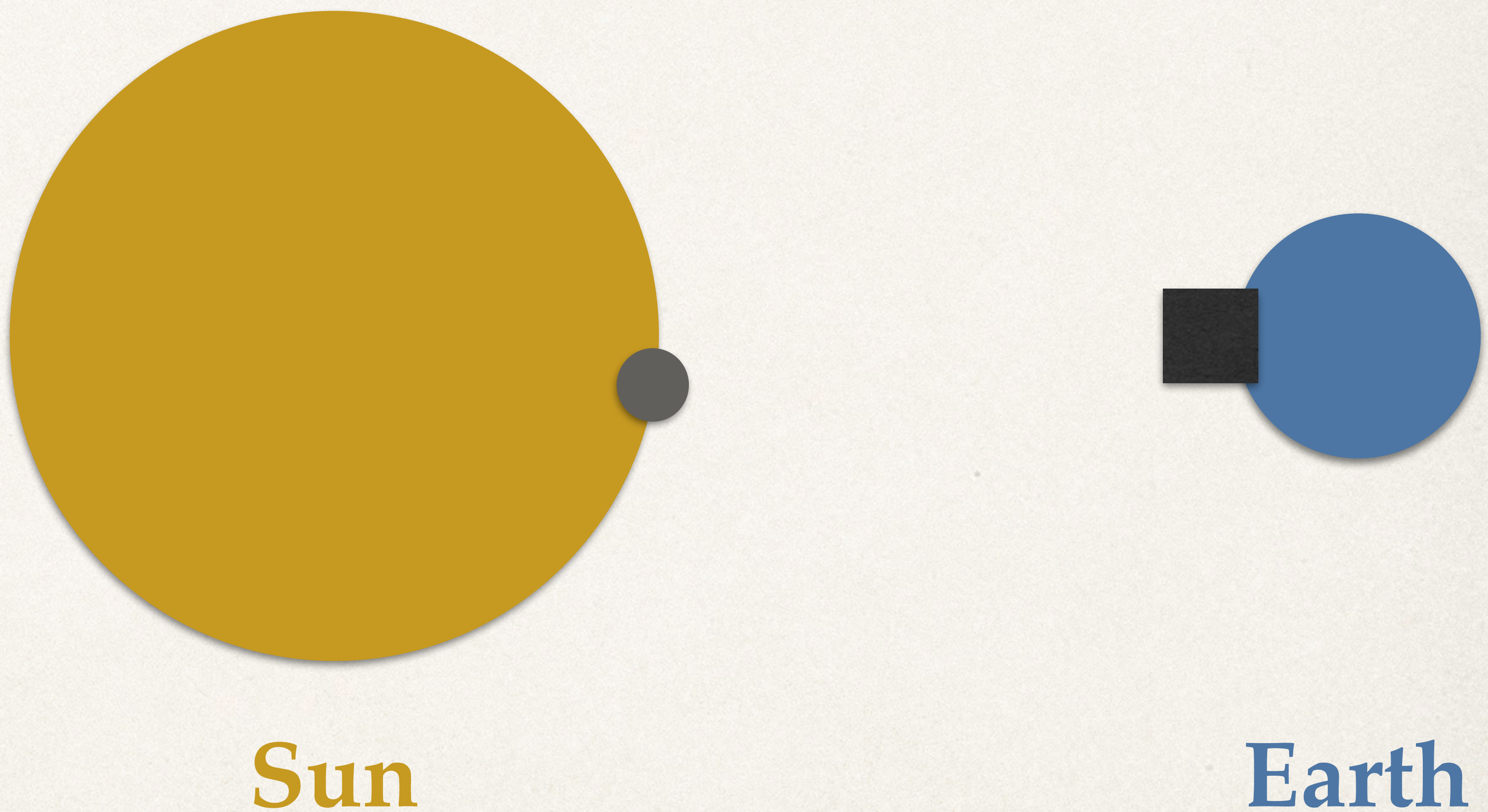
JB, Cui, Zhao: JCAP 1502 (2015) 005

Solar Capture & Detection

Detection

Proton scattering





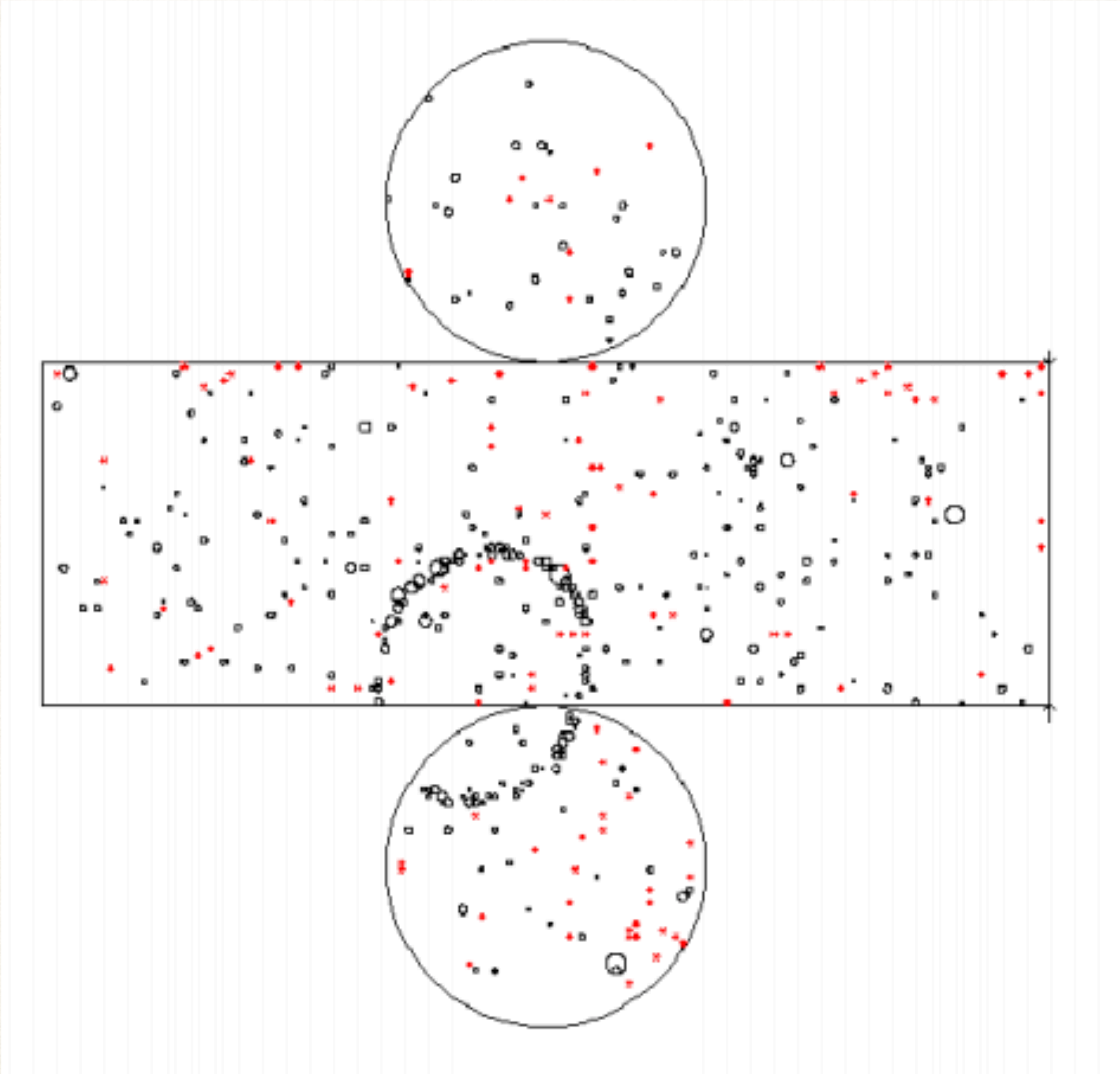
JB, Cui, Zhao: JCAP 1502 (2015) 005

Looking with Water Cherenkov

Threshold:

$E_{\mathrm{K,recoil}} = 480\ \mathrm{MeV}$

Hard to reconstruct **inelastic**



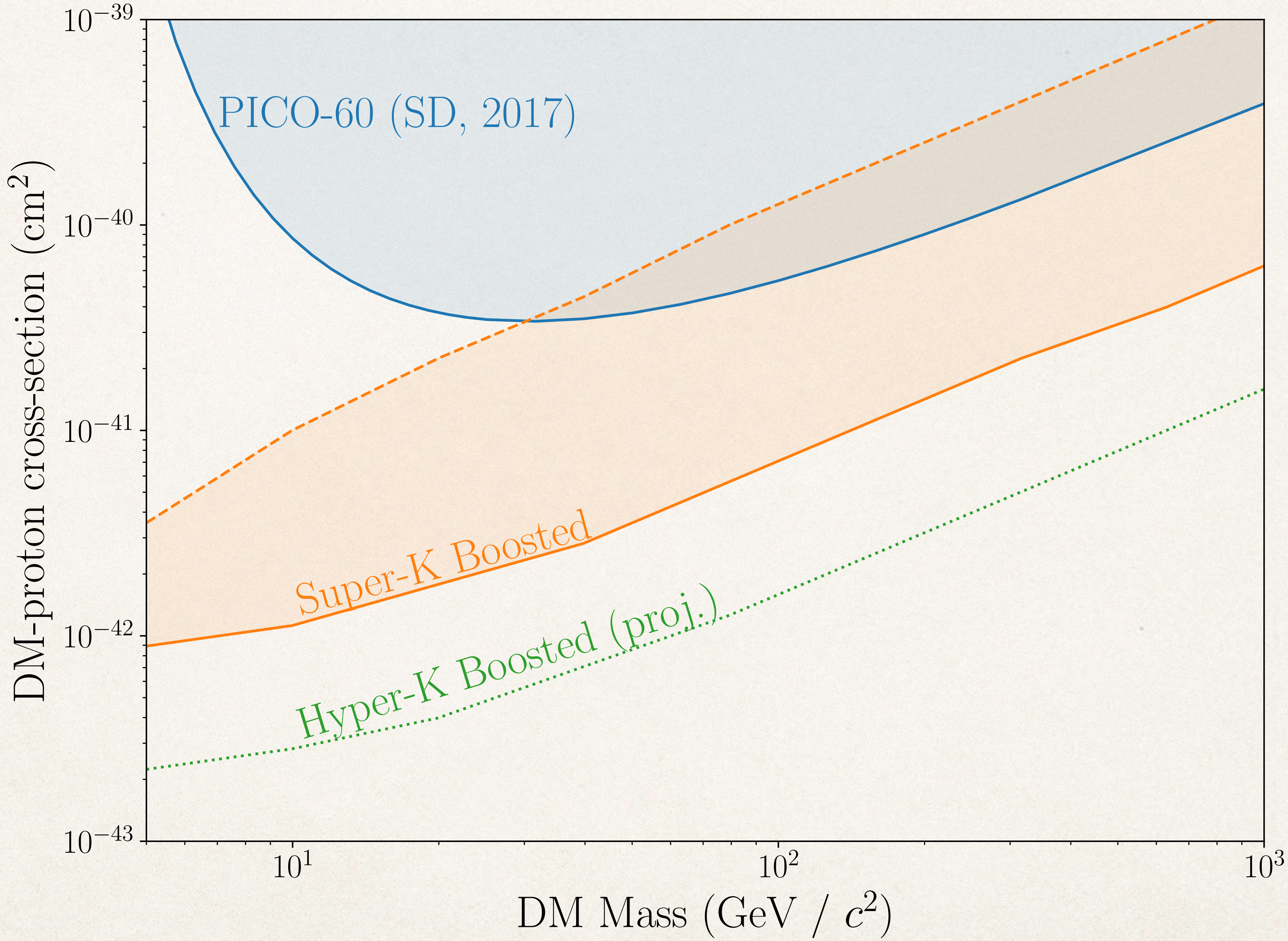
Experiments:

Super-Kamiokande

Hyper-Kamiokande

Super-Kamiokande: PRD79 (2009) 112010

Water Cherenkov Results



JB, Cui, Zhao: JCAP 1502 (2015) 005

A Future in Liquid Argon TPC

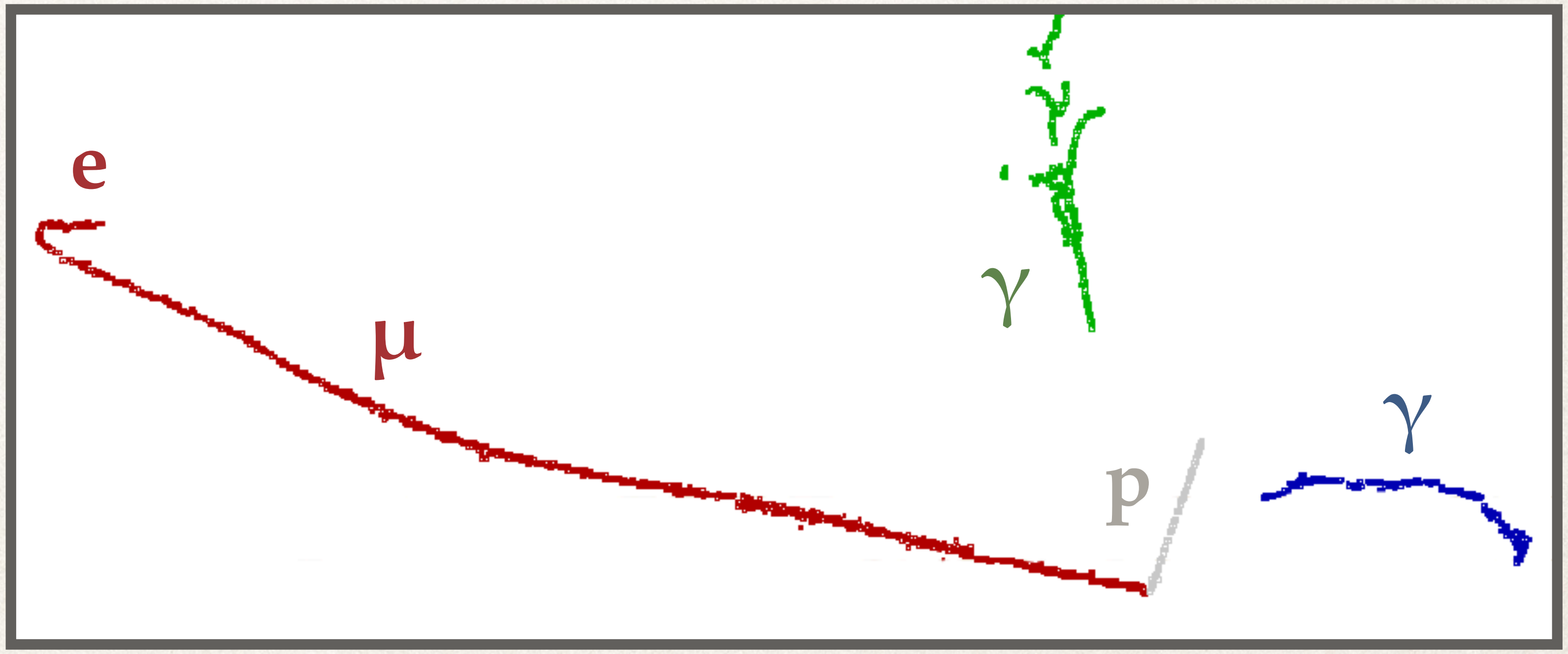
Threshold:

$E_{\mathrm{K,recoil}} \lesssim 50\ \mathrm{MeV}$

Inelastic reconstruction possible

Experiments:

- **LArIAT**
- **ICARUS**
- **MicroBooNE**
- **DUNE**



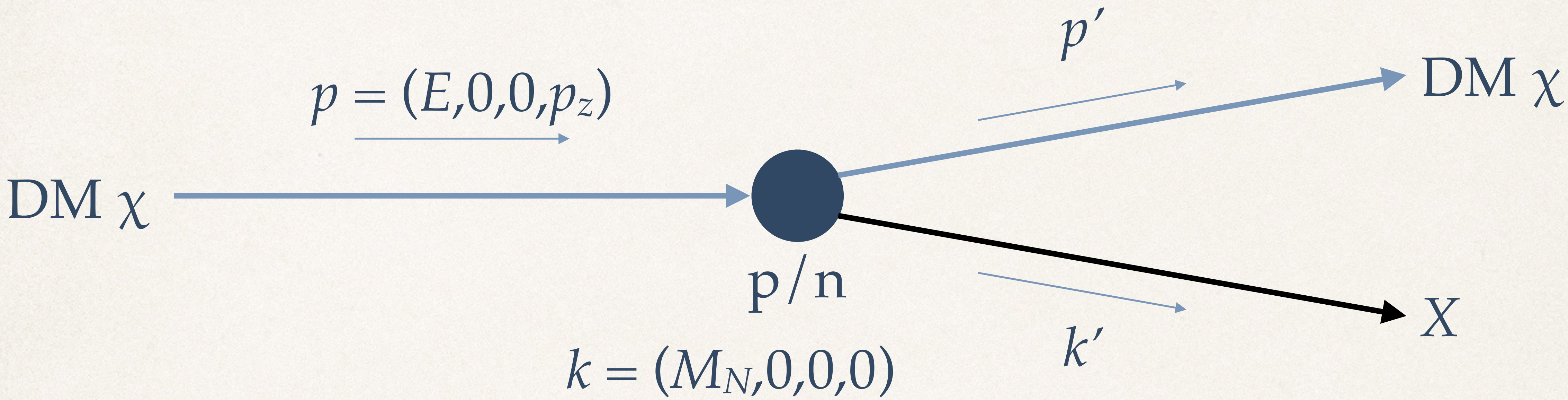
LArSoft

What do we need from Boosted Dark Matter Monte Carlo?

Overview of Requirements

- Dark matter is one of the **beams**
- Dark matter flux is not fixed **direction** in lab frame
- **Fixed target** for scattering
- Covers a **range** of energy scales: elastic nucleon recoil, baryon resonance dominated inelastic, deep inelastic
- Scattering off of nuclei, so need **nuclear** effects

Fixed target kinematics primer



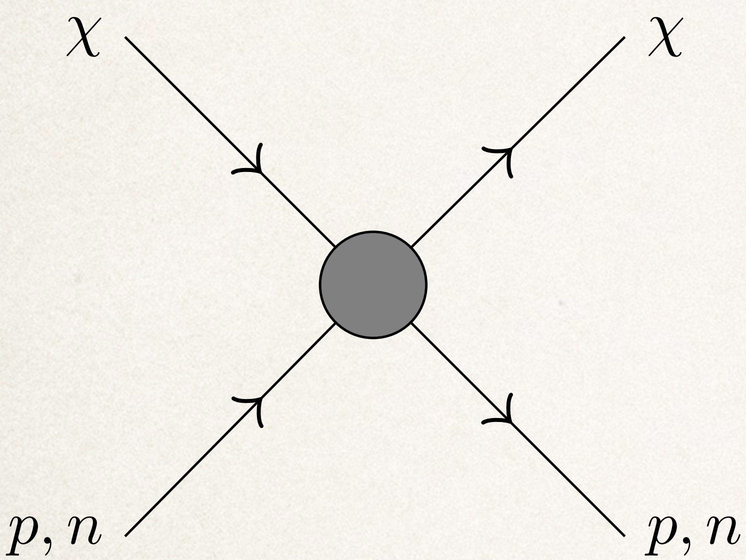
X: p/n for elastic, mess of hadrons for inelastic

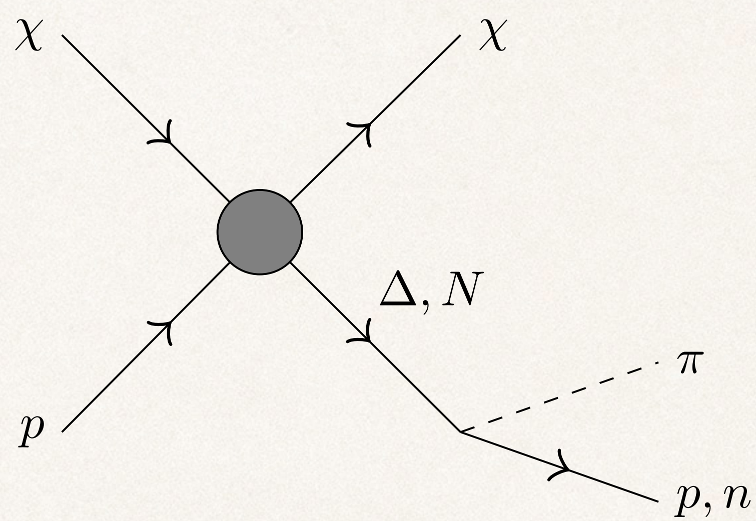
$$q^2 = -Q^2 = (p'-p)^2 \quad \& \quad W^2 = k'^2$$

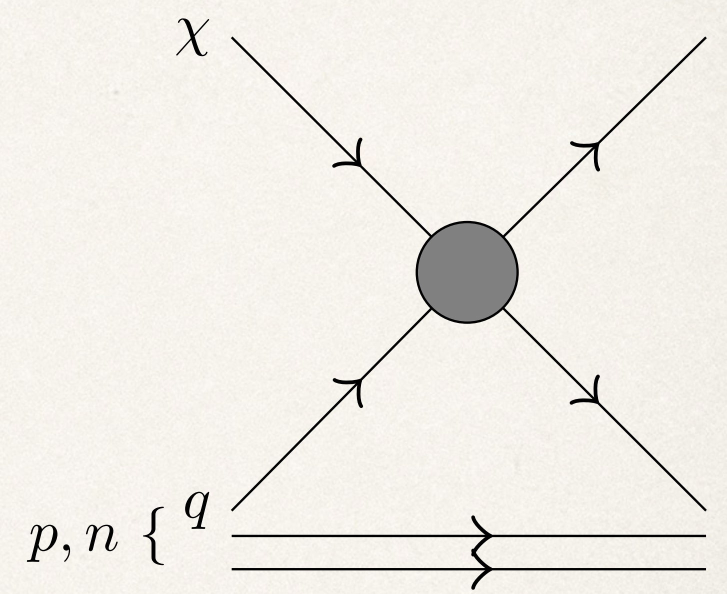
$$0 \leq Q^2 \leq 4\, p_{1,\mathrm{CM}}^2 \quad \& \quad M_N \leq \mathrm{W} \leq \sqrt{s} - M_\chi$$

Inelastic can begin at $\gamma \gtrsim 1 + M_\pi \,/\, M_N$

Three Different Processes



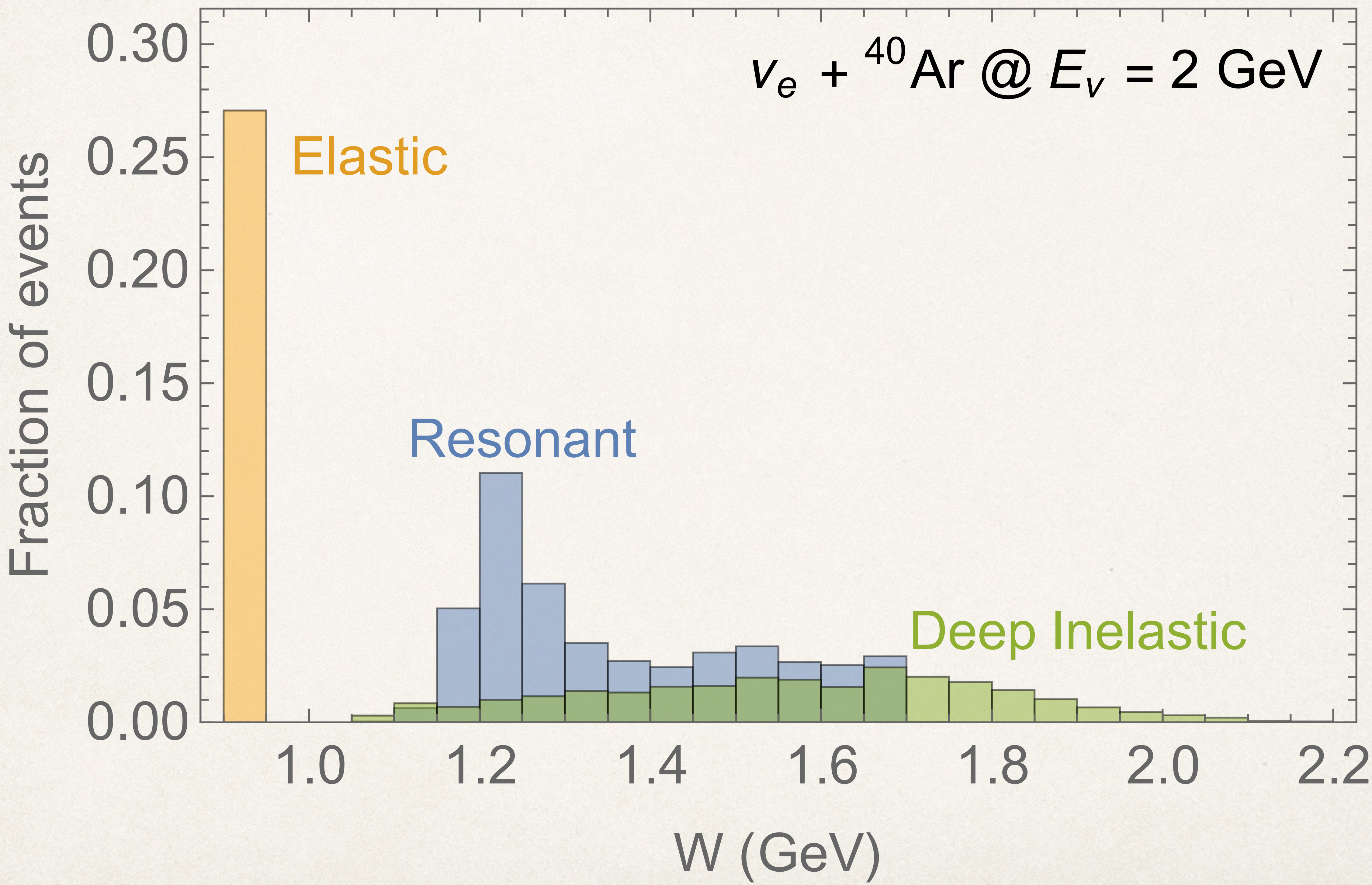




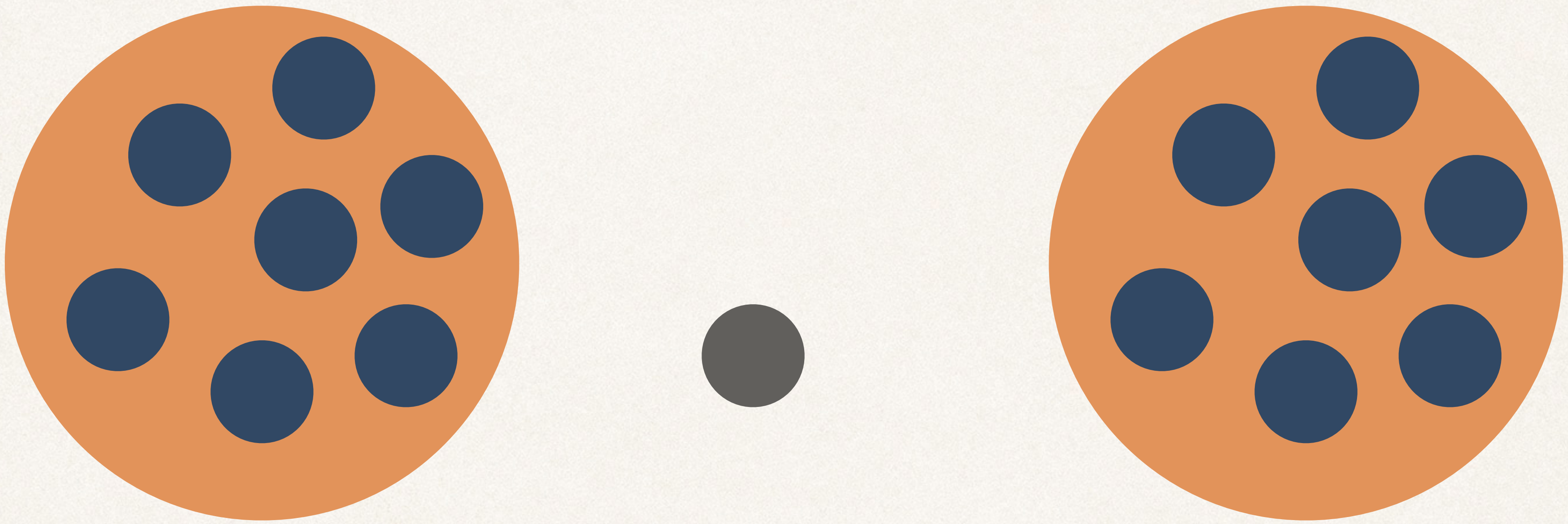
Elastic	**Resonant**	**Deep Inelastic**
Relatively easy	Dominated by Δ,N 1 GeV < W < 2 GeV	Use standard parton model
Needs a form factor near 1 GeV	Need a model	DM beam?

Rein & Sehgal:
Ann. of Phys. 133, 79-153 (1981)

All Processes Could Be Important



Nuclear effects are important!

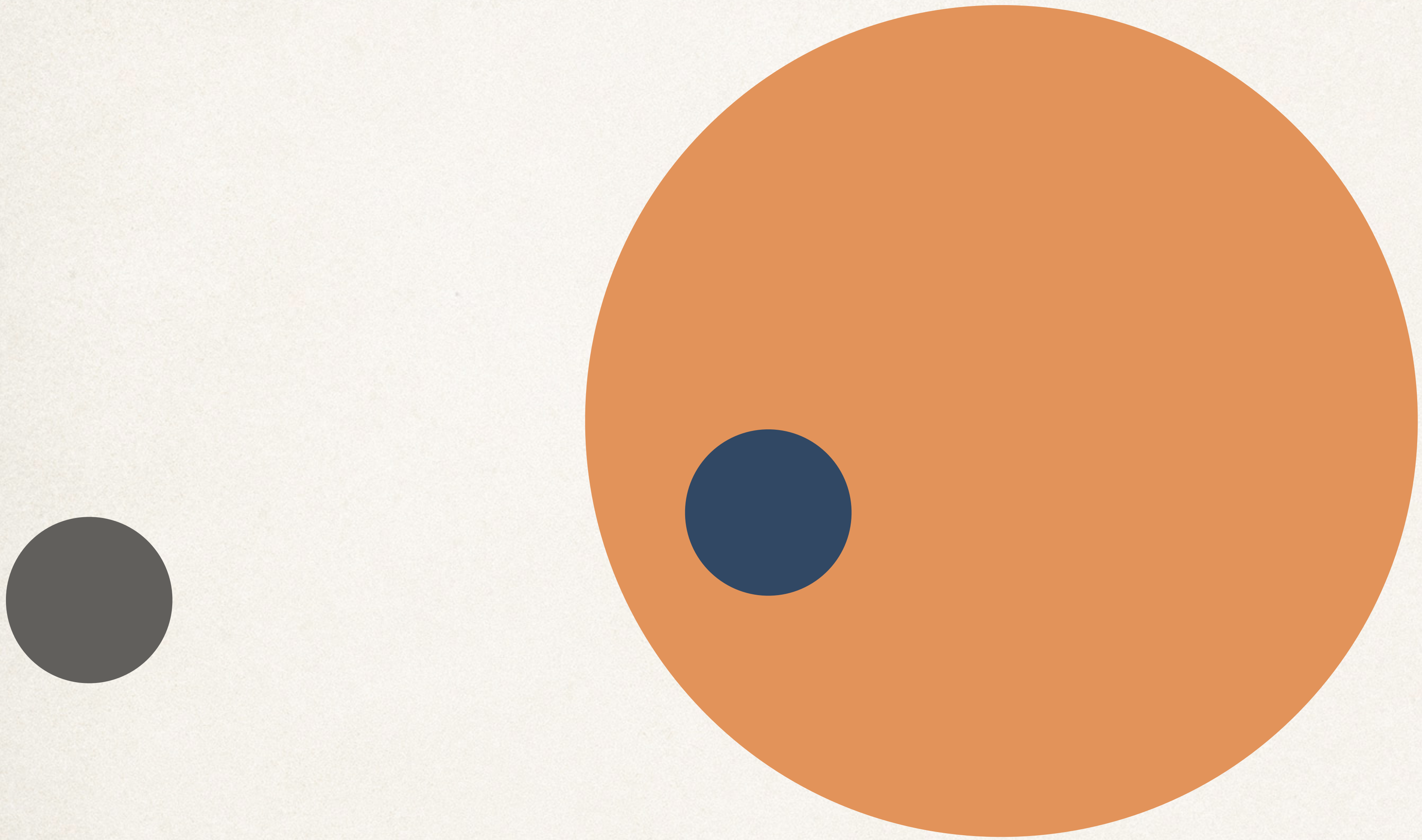


Fermi Motion **Pauli Blocking**

Think of large nucleus as a **Fermi gas**

For large nucleus (say Ar): p_F ~ **250 MeV**

Other nuclear effects are important!



Nuclear Rescattering!

Including: elastic, inelastic, charge exchange, pion production, absorption, …

Boosted DM in GENIE

What is GENIE?

- Monte Carlo for neutrino interactions
- Used by FNAL-based neutrino experiments & beyond
- Includes all of the above requirements for neutrinos
- Also has n-$\bar{n}$ oscillation simulation (history of BSM!)

L. Alvarez-Ruso, **C. Andreopoulos**, C. Barry, F. Bench , S. Dennis, S. Dytman, H. Gallagher, **R. Hatcher**, L. Jiang, R. Jones, I. Kakorin, K. Kuzmin, A. Meregaglia, D. Naples, V. Naumov, G. Perdue, **M. Roda**, J. Wolcott, J. Tena Vidal, J. Yarba

Current Status of BDM in GENIE

- ✔ 2 models: fermion or scalar DM, axial Z' coupling
- ✔ Elastic and Deep Inelastic scattering implemented
- ✔ Framework mostly set for further models
- ✔ Integrated into upcoming GENIE v3

What You Need to Put In

```
gevgen_dm [-h]
          [-r run#]
          -n nev
          -e energy (or energy range)
          -m mass
          -t target_pdg
          [-g zp_coupling]
          [-z med_ratio]
          [-f flux_description]
          [-o outfile_name]
          [-w]
          [--seed random_number_seed]
          [--cross-sections xml_file]
          [--event-generator-list list_name]
          [--message-thresholds xml_file]
          [--unphysical-event-mask mask]
          [--event-record-print-level level]
          [--mc-job-status-refresh-rate  rate]
          [--cache-file root_file]
```

Sample event

```
|--------------------------------------------------------------------------------------------------------------------|
|GENIE GHEP Event Record [print level:   3]                                                                          |
|--------------------------------------------------------------------------------------------------------------------|
| Idx |          Name | Ist |        PDG |   Mother  | Daughter  |      Px |      Py |      Pz |       E |      m   |
|--------------------------------------------------------------------------------------------------------------------|
|   0 |        chi_dm |   0 | 2000010000 |  -1 |  -1 |   4 |   4 |   0.000 |   0.000 |  17.321 |  20.000 |  10.000 |
|   1 |          Ar40 |   0 | 1000180400 |  -1 |  -1 |   2 |   3 |   0.000 |   0.000 |   0.000 |  37.216 |  37.216 |
|   2 |        proton |  11 |       2212 |   1 |  -1 |   5 |   5 |   0.109 |  -0.063 |   0.028 |   0.926 | **0.938 | M = 0.917
|   3 |          Cl39 |   2 | 1000170390 |   1 |  -1 |   8 |   8 |  -0.109 |   0.063 |  -0.028 |  36.290 |  36.290 |
|   4 |        chi_dm |   1 | 2000010000 |   0 |  -1 |  -1 |  -1 |   1.084 |  -0.475 |  16.318 |  19.175 |  10.000 | P = …
|   5 |        proton |  14 |       2212 |   2 |  -1 |   6 |   7 |  -0.975 |   0.412 |   1.031 |   1.750 |   0.938 | FSI = 4
|   6 |        proton |   1 |       2212 |   5 |  -1 |  -1 |  -1 |  -0.012 |   0.056 |   0.053 |   0.941 |   0.938 |
|   7 |       neutron |   1 |       2112 |   5 |  -1 |  -1 |  -1 |  -1.073 |   0.139 |   0.884 |   1.684 |   0.940 |
|   8 |      HadrBlob |  15 | 2000000002 |   3 |  -1 |  -1 |  -1 |   0.054 |   0.154 |  -0.075 |  35.356 | **0.000 | M = 35.356
|   9 |      NucBindE |   1 | 2000000101 |  -1 |  -1 |  -1 |  -1 |  -0.026 |   0.123 |   0.118 |   0.029 | **0.000 | M = -0.170
|  10 |      NucBindE |   1 | 2000000101 |  -1 |  -1 |  -1 |  -1 |  -0.027 |   0.004 |   0.022 |   0.029 | **0.000 | M = -0.020
|--------------------------------------------------------------------------------------------------------------------|
|      Fin-Init:                                                 |   0.000 |  -0.000 |  -0.000 |  -0.000 |          |
|--------------------------------------------------------------------------------------------------------------------|
|      Vertex:         chi_dm @ (x =     0.00000 m, y =     0.00000 m, z =     0.00000 m, t =    0.000000e+00 s)  |
|--------------------------------------------------------------------------------------------------------------------|
| Err flag [bits:15->0] : 0000000000000000    |  1st set:                                                   none |
| Err mask [bits:15->0] : 1111111111111111    |  Is unphysical:    NO |   Accepted:   YES                        |
|--------------------------------------------------------------------------------------------------------------------|
| sig(Ev) =       1.02127e-34 cm^2  | dsig(Q2;E)/dQ2 =         3.32007e-37 cm^2/GeV^2 | Weight =          1.00000 |
|--------------------------------------------------------------------------------------------------------------------|
```

Another Sample Event

```
|---------------------------------------------------------------------------------------------------------------|
|GENIE GHEP Event Record [print level:   3]                                                                     |
|---------------------------------------------------------------------------------------------------------------|
| Idx |          Name | Ist |        PDG |   Mother  | Daughter  |        Px |        Py |        Pz |        E |       m  |
|---------------------------------------------------------------------------------------------------------------|
|   0 |        chi_dm |   0 | 2000010000 |  -1 |  -1 |   4 |   4 |     0.000 |     0.000 |    17.321 |   20.000 |   10.000 |
|   1 |          Ar40 |   0 | 1000180400 |  -1 |  -1 |   2 |   3 |     0.000 |     0.000 |     0.000 |   37.216 |   37.216 |
|   2 |       neutron |  11 |       2112 |   1 |  -1 |   5 |   5 |    -0.020 |    -0.071 |    -0.205 |    0.929 | **0.940 | M = 0.903
|   3 |          Ar39 |   2 | 1000180390 |   1 |  -1 |  16 |  16 |     0.020 |     0.071 |     0.205 |   36.286 |   36.286 |
|   4 |        chi_dm |   1 | 2000010000 |   0 |  -1 |  -1 |  -1 |    -0.614 |     0.353 |    15.958 |   18.846 |   10.000 | P = …
|   5 |      HadrSyst |  12 | 2000000001 |   2 |  -1 |   6 |   8 |     0.594 |    -0.424 |     1.158 |    2.083 | **0.000 | M = 1.571
|   6 |       neutron |  14 |       2112 |   5 |  -1 |   9 |   9 |     0.273 |    -0.296 |     0.574 |    1.172 |    0.940 | FSI = 5
|   7 |           pi+ |  14 |        211 |   5 |  -1 |  13 |  14 |     0.148 |     0.053 |    -0.049 |    0.216 |    0.140 | FSI = 4
|   8 |           pi- |  14 |       -211 |   5 |  -1 |  15 |  15 |     0.172 |    -0.181 |     0.633 |    0.695 |    0.140 | FSI = 1
|   9 |      HadrClus |  16 | 2000000300 |   6 |  -1 |  10 |  12 |     0.273 |    -0.296 |     0.574 |    1.172 | **0.000 | M = 0.940
|  10 |        proton |   1 |       2212 |   9 |  -1 |  -1 |  -1 |    -0.182 |    -0.362 |     0.153 |    1.033 |    0.938 |
|  11 |        proton |   1 |       2212 |   9 |  -1 |  -1 |  -1 |     0.353 |    -0.071 |     0.109 |    1.011 |    0.938 |
|  12 |       neutron |   1 |       2112 |   9 |  -1 |  -1 |  -1 |     0.102 |     0.137 |     0.312 |    1.005 |    0.940 |
|  13 |           pi+ |   1 |        211 |   7 |  -1 |  -1 |  -1 |     0.038 |    -0.107 |     0.039 |    0.184 |    0.140 |
|  14 |       neutron |   1 |       2112 |   7 |  -1 |  -1 |  -1 |    -0.080 |     0.228 |    -0.019 |    0.970 |    0.940 |
|  15 |           pi- |   1 |       -211 |   8 |  -1 |  -1 |  -1 |     0.172 |    -0.181 |     0.633 |    0.695 |    0.140 |
|  16 |      HadrBlob |  15 | 2000000002 |   3 |  -1 |  -1 |  -1 |     0.210 |     0.004 |     0.136 |   33.472 | **0.000 | M = 33.471
|---------------------------------------------------------------------------------------------------------------|
|       Fin-Init:                                                 |     0.000 |    -0.000 |     0.000 |    0.000 |          |
|---------------------------------------------------------------------------------------------------------------|
|       Vertex:         chi_dm @ (x =     0.00000 m, y =     0.00000 m, z =     0.00000 m, t =    0.000000e+00 s) |
|---------------------------------------------------------------------------------------------------------------|
| Err flag [bits:15->0] : 0000000000000000    |  1st set:                                                  none |
| Err mask [bits:15->0] : 1111111111111111    |  Is unphysical:    NO |   Accepted:   YES                       |
|---------------------------------------------------------------------------------------------------------------|
| sig(Ev) =       5.68527e-35 cm^2  | d2sig(x,y;E)/dxdy =       1.66546e-33 cm^2       | Weight =          1.00000 |
|---------------------------------------------------------------------------------------------------------------|
```

What do we need for **DUNE**?

✓ Develop a **Monte Carlo**

- Based on **GENIE** neutrino MC
- Does **inelastic** and **nuclear** effects
- Merged into GENIE v3

Integrate into LArSoft detector simulation

Develop analysis strategy

Projections for DUNE TDR

Theory: **JB**, Cui, Joglekar, Necib, Zhao
Experiment: Petrillo, Russell, Tsai

Other Future Directions

- Include baryon resonance production
- More models: general interaction, inelastic DM, etc.

  See talk today by Doojin Kim
- Fluxes for various common sources
- Tweaks and debugging

Conclusions

Boosted DM Monte Carlo is here!

- Boosted dark matter is a new, well motivated dark matter scenario arising in several recent models
- Studying these models at large neutrino detectors requires new Monte Carlo tools
- These tools have now been developed within GENIE and should hopefully see official release shortly