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(Okayama University of Science)

Potential of NEWSdm Revealing DM Physics

NEWSdm collaboration meeting
30 May 2018

Outline

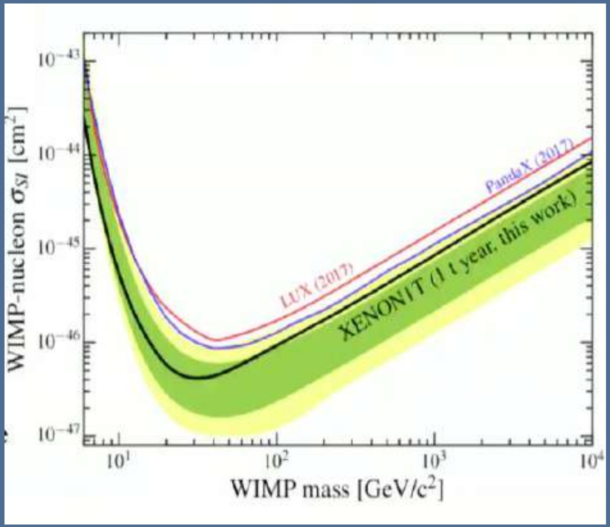
1. **What can we say on physics?**

2. **An example -- velocity distribution**

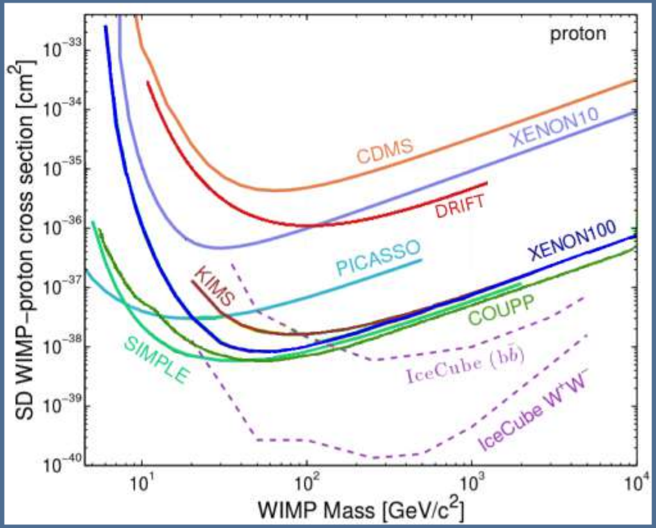
Any comment, question and suggestion are very welcome:
nagao@dap.ous.ac.jp

What can we say on physics

- Ordinally direct detection
  - Recoil energy E_R
  - Cross section < 10^{-46} cm^2 (SI), 10^{-38} cm^2 (SD)



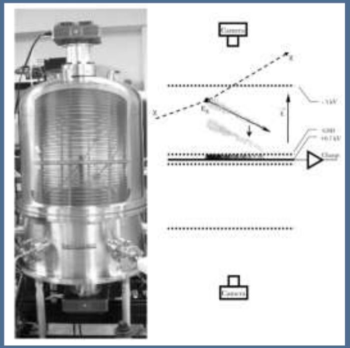
XENON 1T (2018)



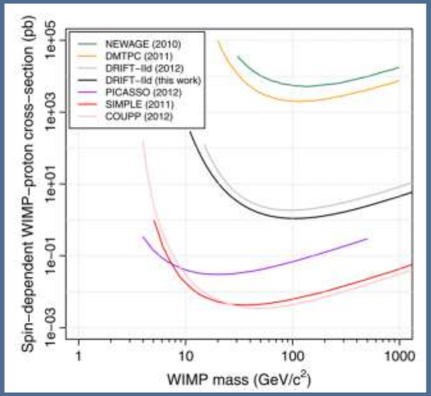
Schumann
arXiv:1501.01200

What can we say on physics

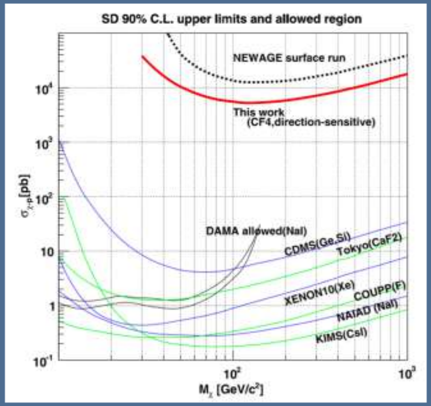
DMTPC
PoS IDM2010 (2011) 042



- Ordinally direct detection
  - Recoil energy E_R
  - Cross section < 10^{-46} cm^2
- Directional detections
  - + Direction of nuclear recoil
  - (+ time)



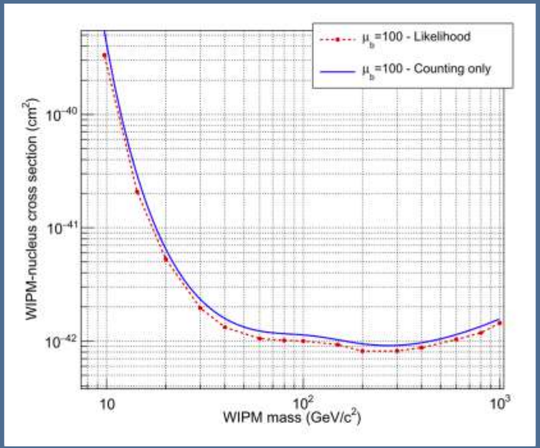
DRIFT
Phys. of the Dark Universe
9–10 (2015)



NEWAGE
Physics Letters B 686 (2010)

What can we say on physics

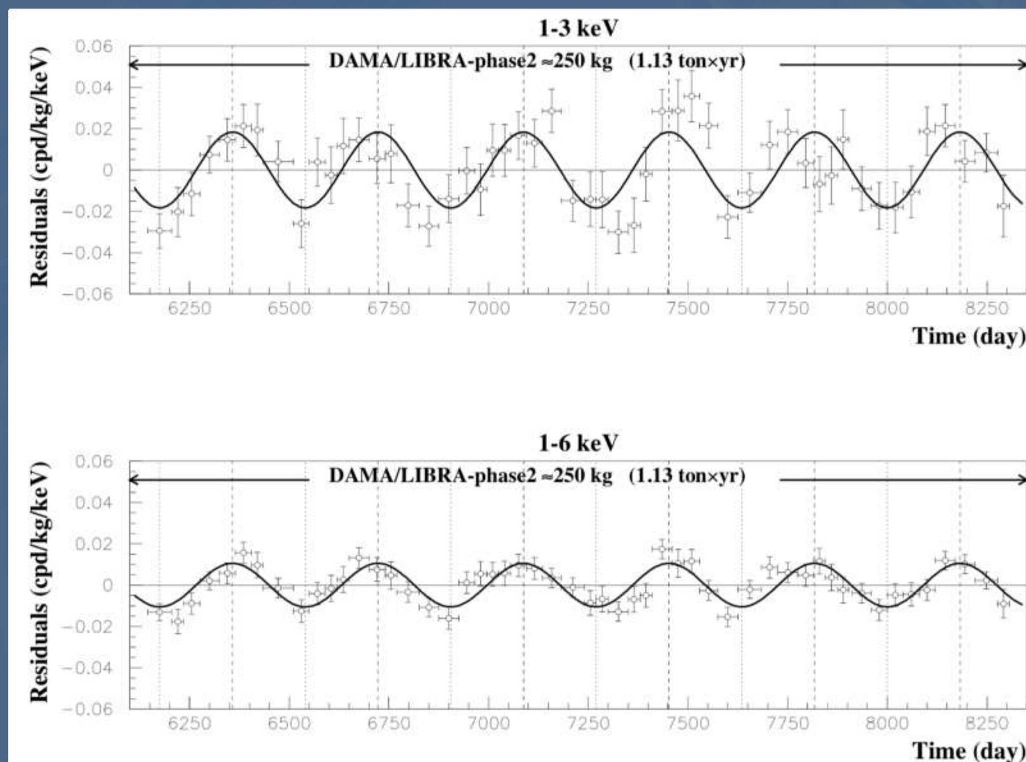
- Ordinally direct detection
  - Recoil energy E_R
  - Cross section $< 10^{-46}$ cm^2
- Directional detections
  - + Direction of nuclear recoil
  - (+ time)
- NEWSdm
  - High sensitivity $\sim 10^{-42}$ cm^2
  - Wide mass range O(10-100)GeV – heavy DM
  - SI int. (SD int. for Ag)



NEWSdm
arXiv:1705.00613

With directionality

Annual/daily modulation

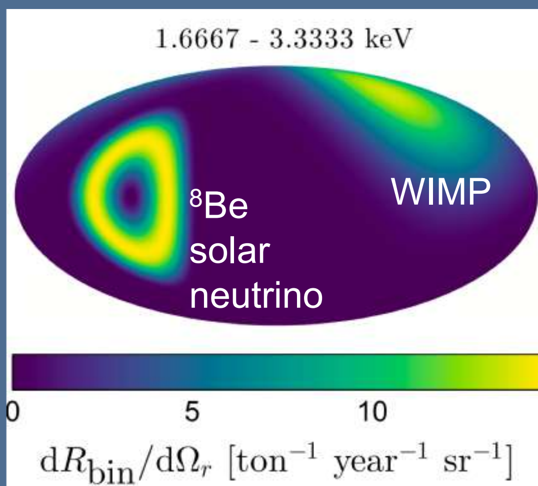


DAMA/LIBRA phase-2
arXiv:1805.10486

With directionality

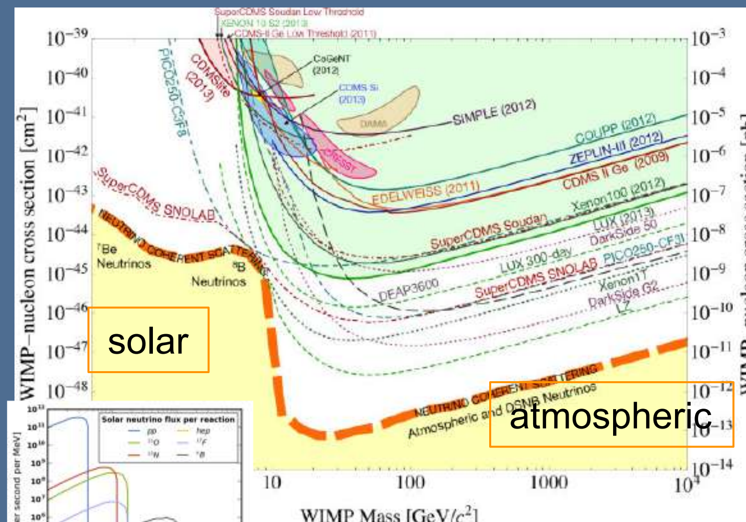
Annual/daily modulation

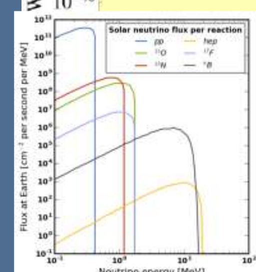
Neutrino floor



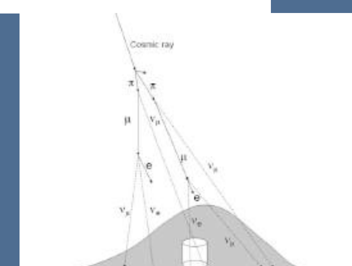
Mayet et.al.
Physics Reports 627 (2016) 1-49
mdm=6 GeV

SNOWMASS report (2013)





Bahcall and Serenelli
Astrophys. J. **621**:
L85–L88



Takaaki Kajita
Proc Jpn Acad Ser B Phys Biol Sci.
2010; 86(4)

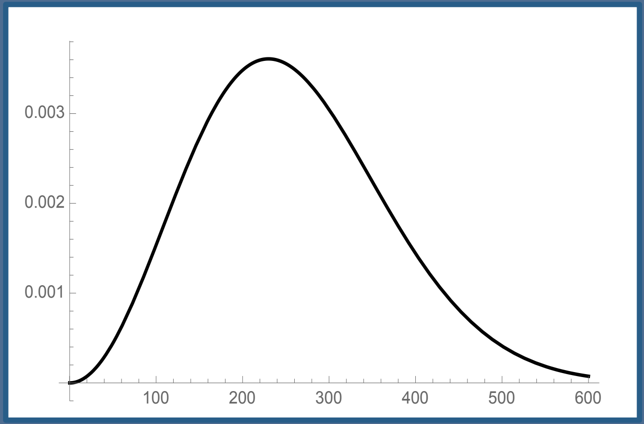
With directionality

Annual/daily modulation

Neutrino floor

Velocity distribution of DM

- ☐ Observation
- ☐ N-body simulation
- ☐ Direct detection
  - Drees, Shan (2007)
- ☐ Directional direct detection
  - Morgan, Green, Spooner (2004)
  - Host, Hansen (2007)
  - KN, Yakabe, Naka, Miuchi (2017) … I discuss it later.



With directionality

Annual/daily modulation

Neutrino floor

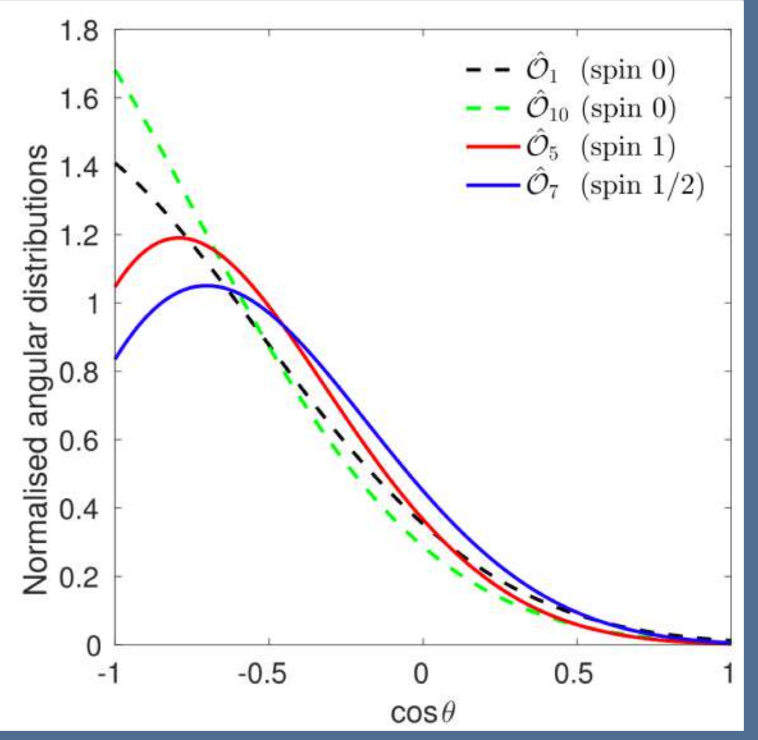
Velocity distribution of DM

Spin

PhysRevD.97.023007
Catena et.al (2017)

$$\hat{\mathcal{O}}_1 = \mathbb{1}_\chi \mathbb{1}_N$$
$$\hat{\mathcal{O}}_3 = i\hat{\mathbf{S}}_N \cdot \left(\frac{\hat{\mathbf{q}}}{m_N} \times \hat{\mathbf{v}}^\perp\right) \mathbb{1}_\chi$$
$$\hat{\mathcal{O}}_4 = \hat{\mathbf{S}}_\chi \cdot \hat{\mathbf{S}}_N$$
$$\hat{\mathcal{O}}_5 = i\hat{\mathbf{S}}_\chi \cdot \left(\frac{\hat{\mathbf{q}}}{m_N} \times \hat{\mathbf{v}}^\perp\right) \mathbb{1}_N$$
$$\hat{\mathcal{O}}_6 = \left(\hat{\mathbf{S}}_\chi \cdot \frac{\hat{\mathbf{q}}}{m_N}\right)\left(\hat{\mathbf{S}}_N \cdot \frac{\hat{\mathbf{q}}}{m_N}\right)$$
$$\hat{\mathcal{O}}_7 = \hat{\mathbf{S}}_N \cdot \hat{\mathbf{v}}^\perp \mathbb{1}_\chi$$
$$\hat{\mathcal{O}}_8 = \hat{\mathbf{S}}_\chi \cdot \hat{\mathbf{v}}^\perp \mathbb{1}_N$$
$$\hat{\mathcal{O}}_9 = i\hat{\mathbf{S}}_\chi \cdot \left(\hat{\mathbf{S}}_N \times \frac{\hat{\mathbf{q}}}{m_N}\right)$$
$$\hat{\mathcal{O}}_{10} = i\hat{\mathbf{S}}_N \cdot \frac{\hat{\mathbf{q}}}{m_N} \mathbb{1}_\chi$$
$$\hat{\mathcal{O}}_{11} = i\hat{\mathbf{S}}_\chi \cdot \frac{\hat{\mathbf{q}}}{m_N} \mathbb{1}_N$$
$$\hat{\mathcal{O}}_{12} = \hat{\mathbf{S}}_\chi \cdot \left(\hat{\mathbf{S}}_N \times \hat{\mathbf{v}}^\perp\right)$$
$$\hat{\mathcal{O}}_{13} = i\left(\hat{\mathbf{S}}_\chi \cdot \hat{\mathbf{v}}^\perp\right)\left(\hat{\mathbf{S}}_N \cdot \frac{\hat{\mathbf{q}}}{m_N}\right)$$
$$\hat{\mathcal{O}}_{14} = i\left(\hat{\mathbf{S}}_\chi \cdot \frac{\hat{\mathbf{q}}}{m_N}\right)\left(\hat{\mathbf{S}}_N \cdot \hat{\mathbf{v}}^\perp\right)$$
$$\hat{\mathcal{O}}_{15} = -\left(\hat{\mathbf{S}}_\chi \cdot \frac{\hat{\mathbf{q}}}{m_N}\right)\left[\left(\hat{\mathbf{S}}_N \times \hat{\mathbf{v}}^\perp\right) \cdot \frac{\hat{\mathbf{q}}}{m_N}\right]$$
$$\hat{\mathcal{O}}_{17} = i\frac{\hat{\mathbf{q}}}{m_N} \cdot \mathcal{S} \cdot \hat{\mathbf{v}}^\perp \mathbb{1}_N$$
$$\hat{\mathcal{O}}_{18} = i\frac{\hat{\mathbf{q}}}{m_N} \cdot \mathcal{S} \cdot \hat{\mathbf{S}}_N$$

TABLE I. Quantum mechanical operators defining the non-relativistic effective theory of dark matter-nucleon interactions [38, 39]. The notation is the one introduced in



With directionality

Annual/daily modulation

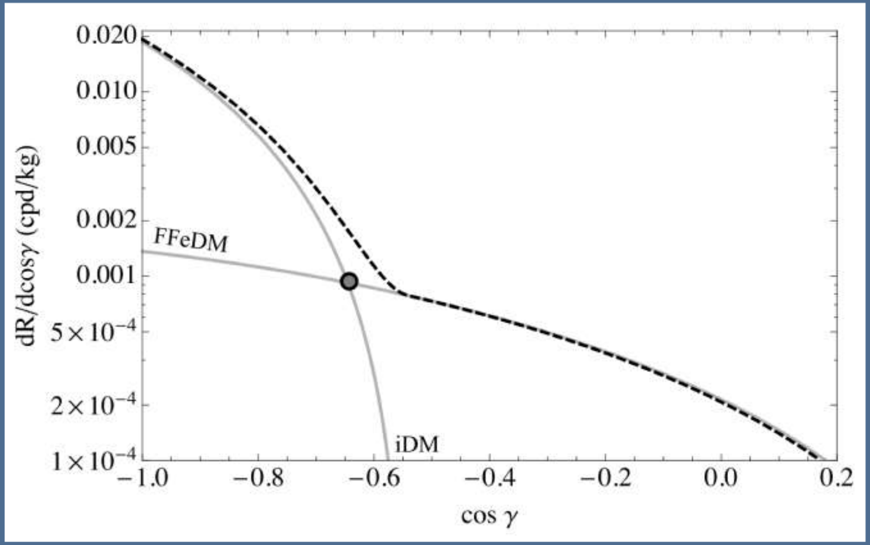
Neutrino floor

Velocity distribution of DM

Spin

Inelastic interaction

$$v_{\min}(E_R) = \begin{cases} \sqrt{\dfrac{m_N E_R}{2\mu^2}} & \text{elastic} \\ \dfrac{1}{\sqrt{2 m_N E_R}} \left(\dfrac{m_N E_R}{\mu} + \delta m \right), & \text{inelastic} \end{cases}$$



$$\cos\gamma_{\max} = \frac{v_{\text{esc}} - v_{\min}}{v_e}$$

Lisanti, Wacker
Phys.Rev.D81:096005 (2010)

Outline

1. **What can we say on physics?**

2. **An example -- velocity distribution**

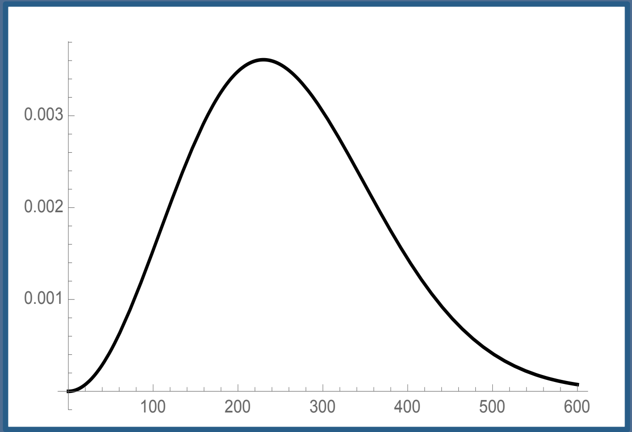
... talk is based on arXiv:1707.05523; KN, Yakabe, Naka, Miuchi (2017)

Velocity distribution 1

- **Maxwell distribution**

$$f(v) = \frac{1}{(\pi v_0^2)^{3/2}} e^{-(v+v_E)^2/v_0^2}$$

$$\frac{dR}{dE_R} = \frac{N_T \rho_0}{m_\chi} \int^{v_{\max}} d\vec{v}\, f(\vec{v}) |\vec{v}| \frac{d\sigma(\vec{v})}{dE_R}$$

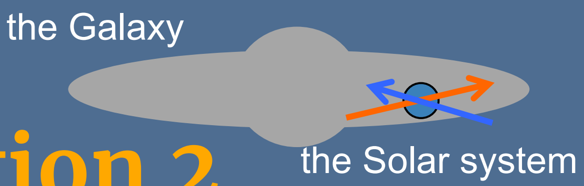


  - commonly supposed in direct detections
  - isotropy also supposed

- **How can we test it?**

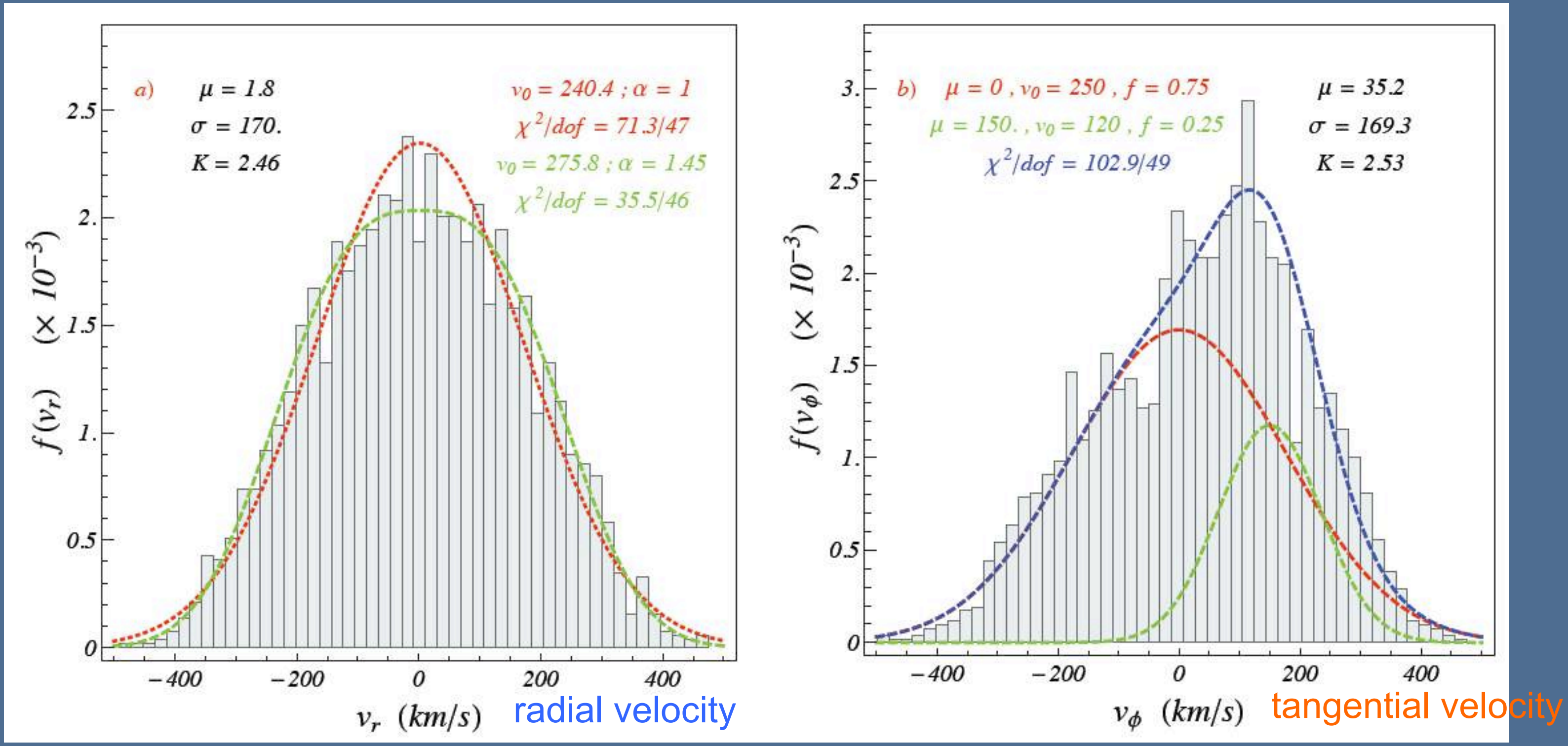
  ~~cosmological observations~~

  directional detection



Velocity distribution 2

- **Some N-body simulations suggest anisotropy**



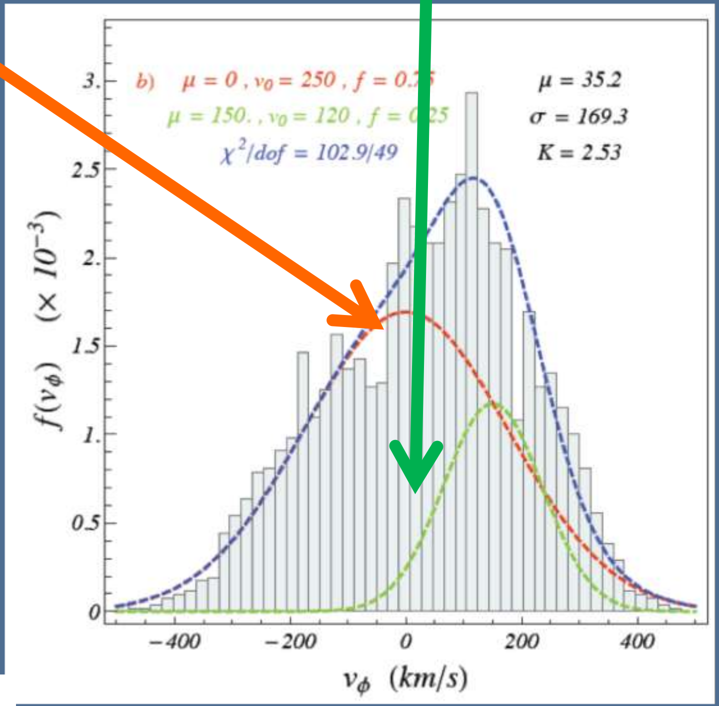
Ling, Nezri, Athanassoula & Teyssier (2009)
cf. Kuhlen et al. (2012), David R. Law (2009) …

Numerical calculation

$$f(v_\phi) = \frac{1-r}{N(v_{0,\mathrm{iso.}})} \exp\left[-v^2/v_{0,\mathrm{iso.}}^2\right] + \frac{r}{N(v_{0,\mathrm{ani.}})} \exp\left[-(v-\mu)^2/v_{0,\mathrm{ani.}}^2\right]$$

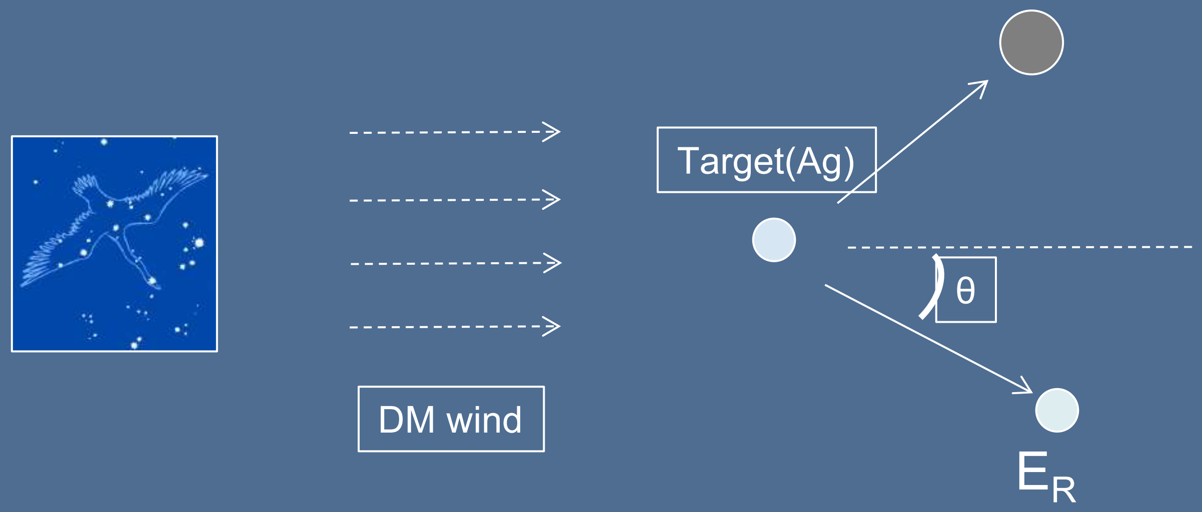
isotropic

anisotropic



- Tangential velocity
  - anisotropy parameter r
  - r=0.25 is suggested by simulation
- Goal: Discrimination
  - isotropic case (r=0) --- anisotropic case (r=0.3)

Numerical calculation



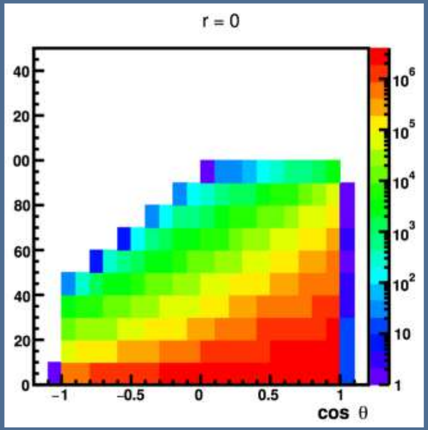
- **Monte Carlo simulation of scattering supposing f(v)**
  Direction (scattering angle) + Recoil energy
  Elastic scattering
  Mass m_{dm}=300 GeV for simplicity
  Target : Ag

Analysis

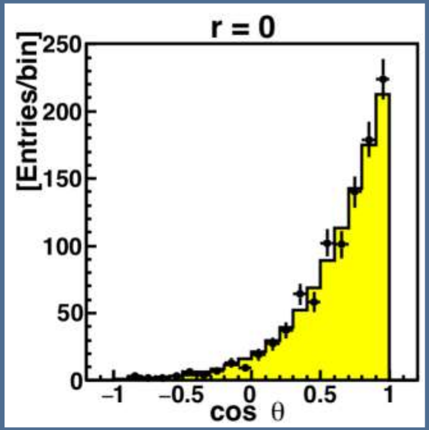
- **depends on resolutions of a detector**

Energy resolution :OK
Angular resolution :OK

Energy resolution :NG
Angular resolution :OK

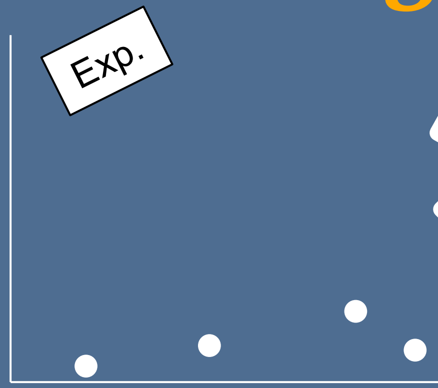


E_R-cosθ distribution

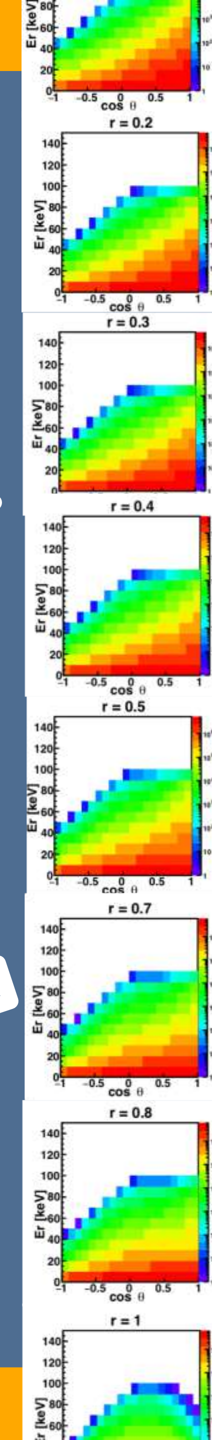


cosθ histogram

Strategy for discrimination



Isotropic



Anisotropic

Which one is the most similar to Exp.?

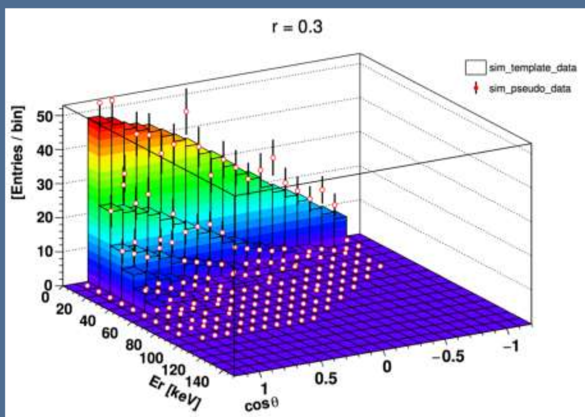
- **Statistical test to examine the similarity of distributions.**
  - ✓ Chi-squared test
  - ✓ Kolmogorov–Smirnov test
  - ✓ Likelihood analysis
  - ✓ …

Chi squared test

Many Data (#10^8)

- ✓ ideal
- ✓ difficult to achieve

ideal “**template**”



chi squared test

$$\chi^2 = \sum \frac{(\text{observed} - \text{expected})^2}{\text{expected}}$$

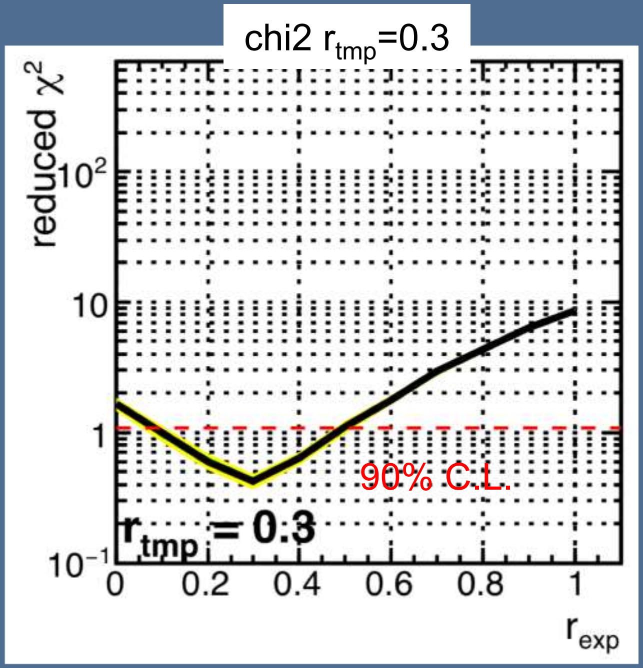
Fewer Data (#10^4)

- ✓ realistic (relatively…)

“**pseudo-experimental**” data

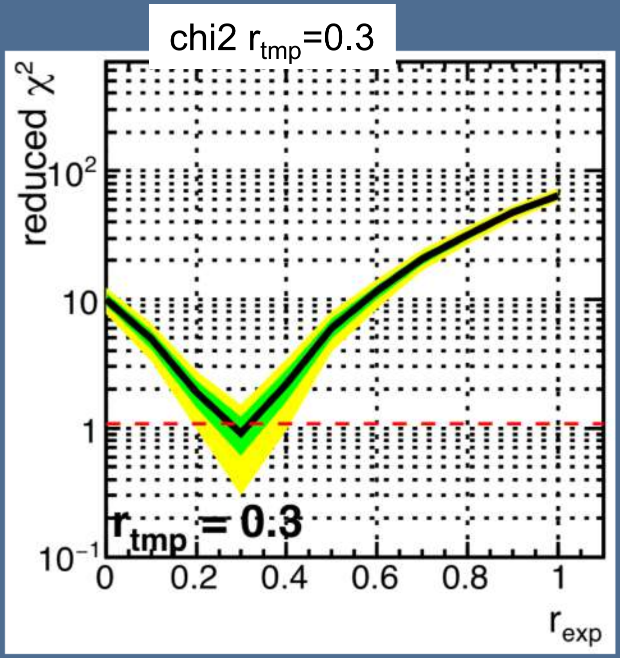
Chi squared test

Ethr is optimized to DM mass



E_R-cosθ

#exp.=6*10^4
Ethr=50keV (Ag)



cosθ hist.

#exp.=2*10^4
Ethr=50keV (Ag)

Summary

- Possibility to explore dark matter physics through NEWSdm (large DM mass/high sensitivity/…)

  Annual/daily modulation

  Neutrino floor

  Velocity distribution of DM

  Spin

  Inelastic interaction

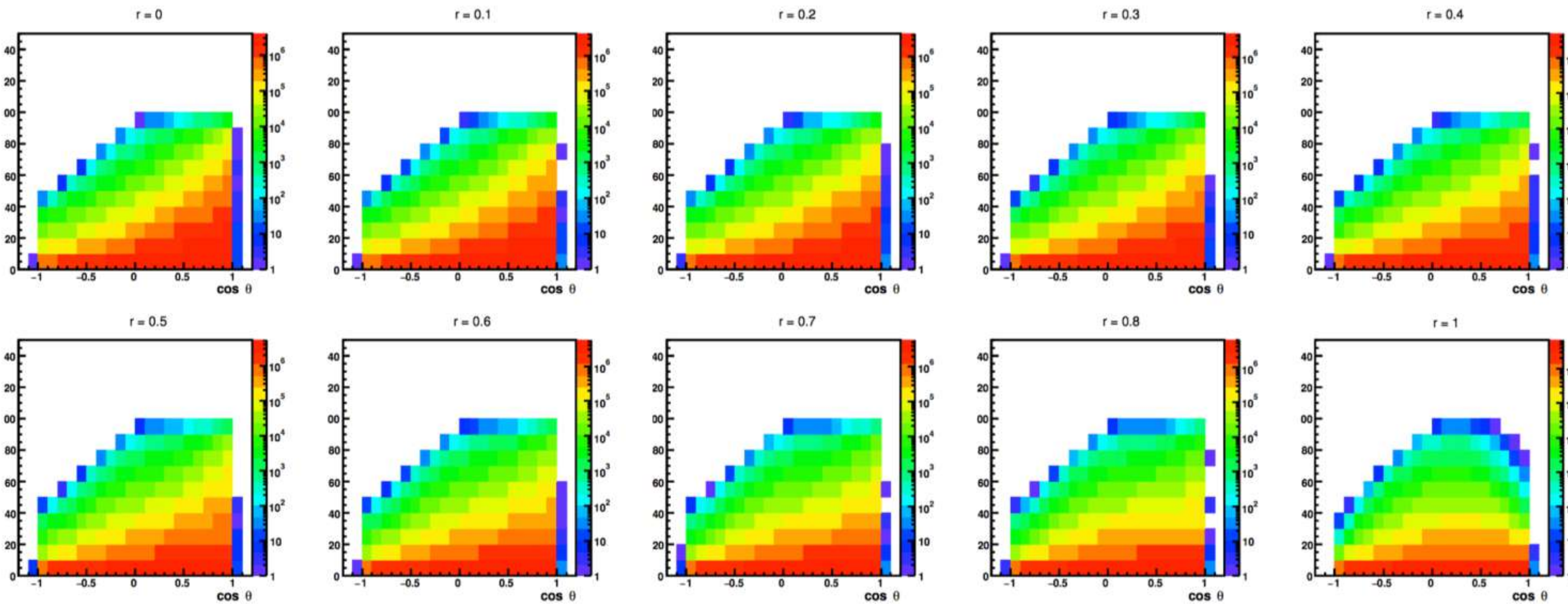
  ……

- An example: velocity distribution of DM

  ~$O(10^4)$ events required for discrimination (once m_{dm} is known).

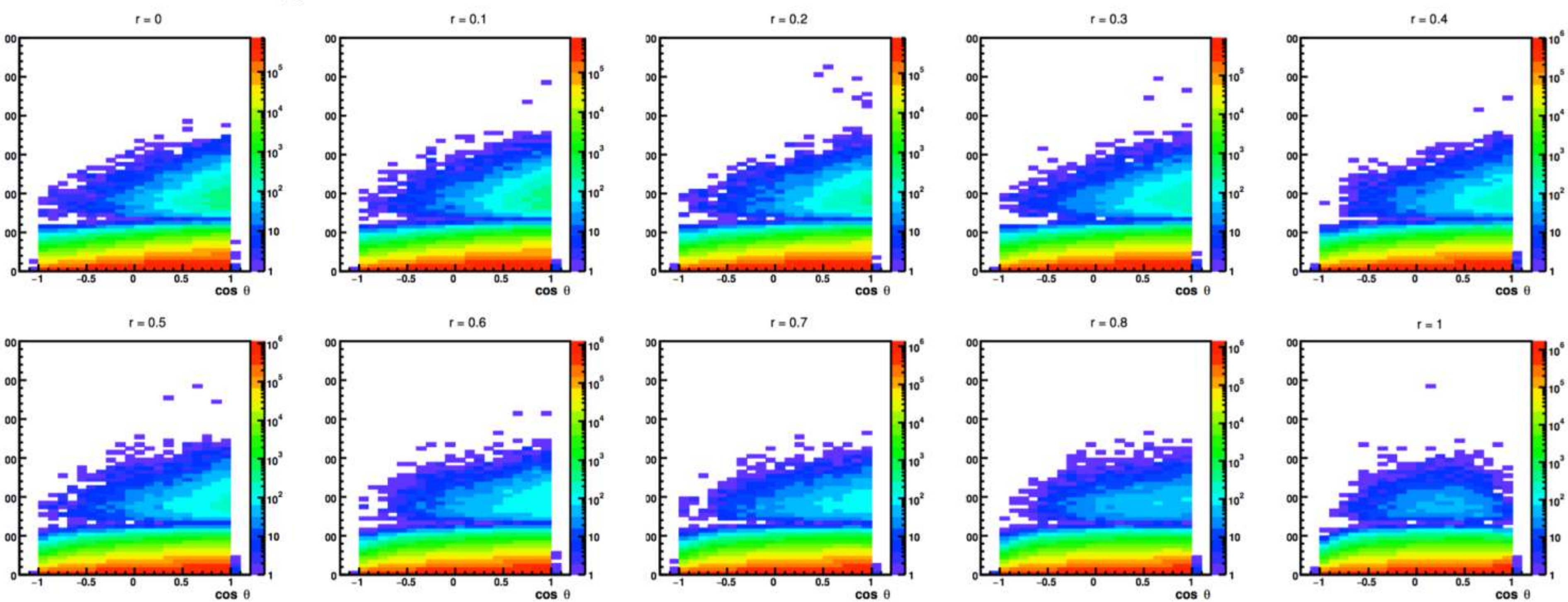
BACKUP

Energy-angular distribution (light target)



Ethr = 0keV

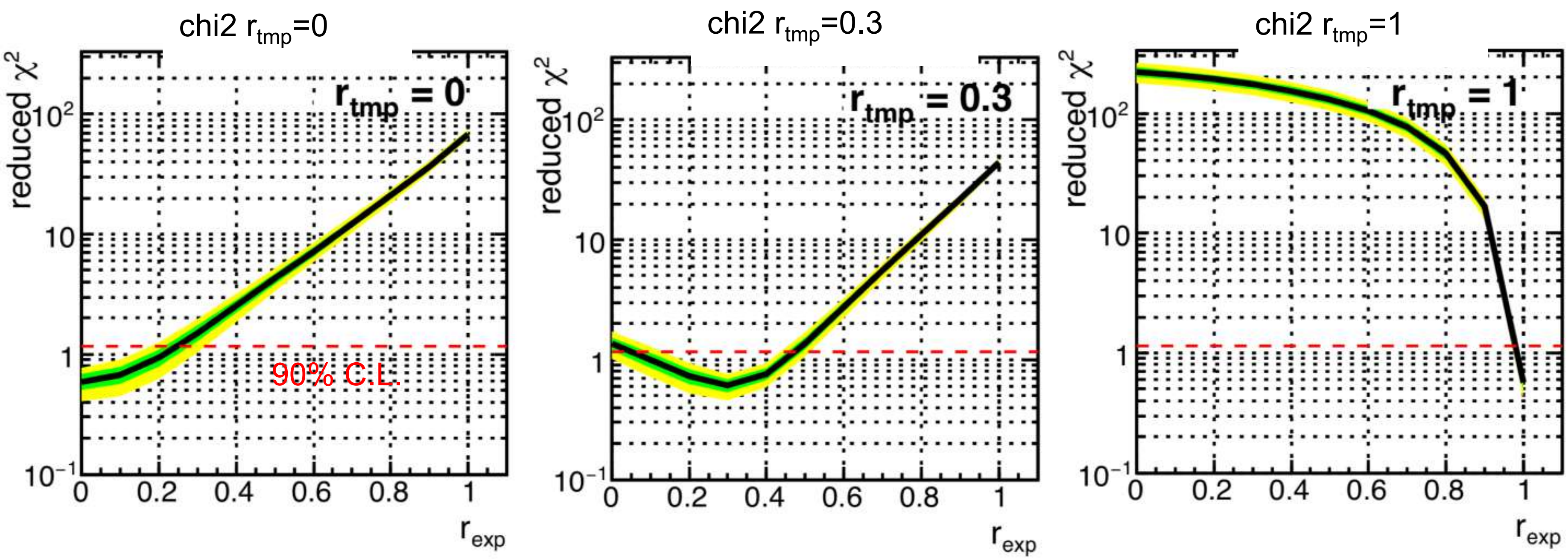
Energy-angular distribution (heavy target)



Ethr = 0keV

Chi squared test of E_R-cos θ (light target)

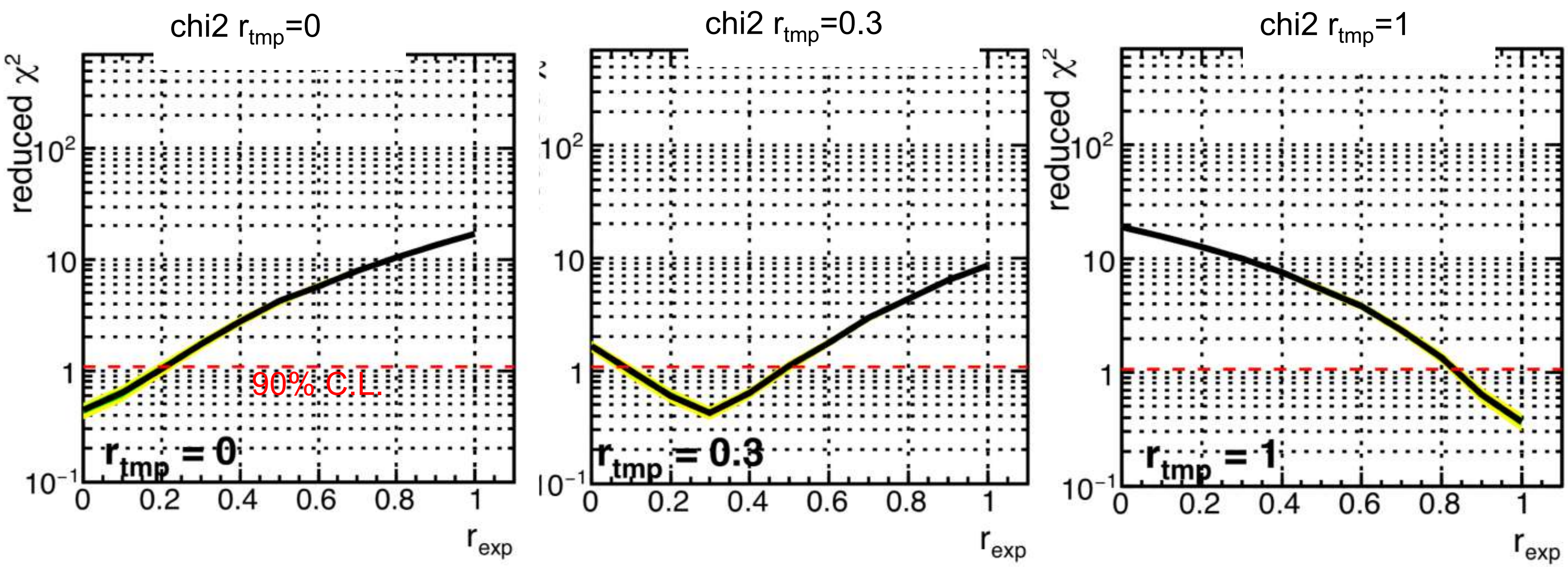
#exp.=6*10^3
Ethr=20keV (F)



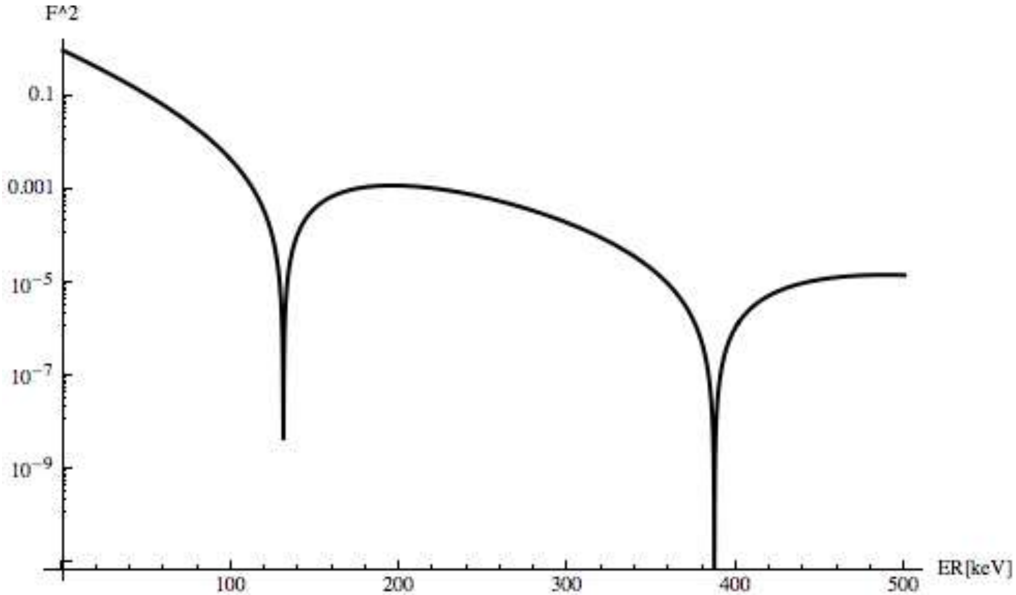
- ✓ If r=0.3, isotropic case (r=0) can be excluded at 90% C.L.
- ✓ Energy threshold is a factor to clearly characterize the difference between r=0 and 0.3.

Chi squared test of E_R-cos θ (heavy target)

#exp.=6*10^4
Ethr=50keV (Ag)

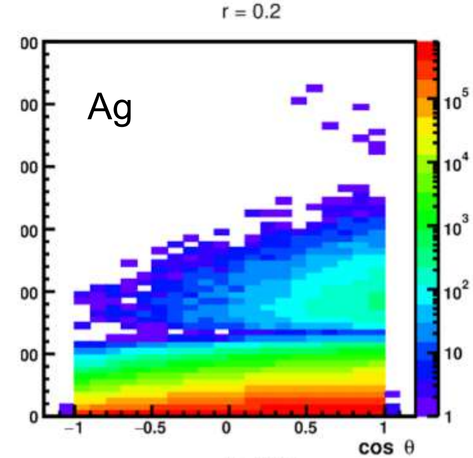


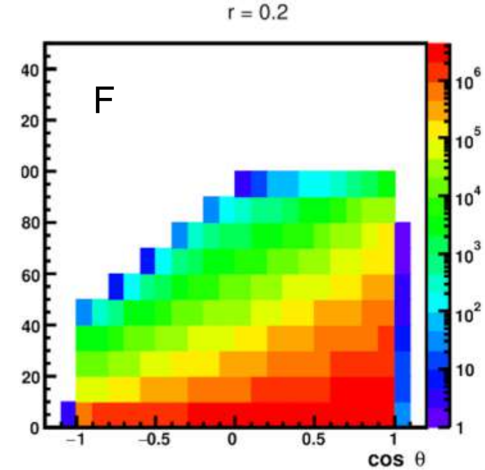
✓ Isotropic case can be rejected in heavy target case, but required event # is 6×10^4 (in light target case: 6×10^3).



$$F(qr_n) = 3\frac{j_1(qr_n)}{qr_n}e^{-(qs)^2/2}$$

$$r_n^2 \simeq (1.23A^{1/3} - 0.60)^2 + \frac{7}{3}\pi^2(0.52)^2 - 5 \cdot 0.9^2[\mathrm{fm}^2]$$

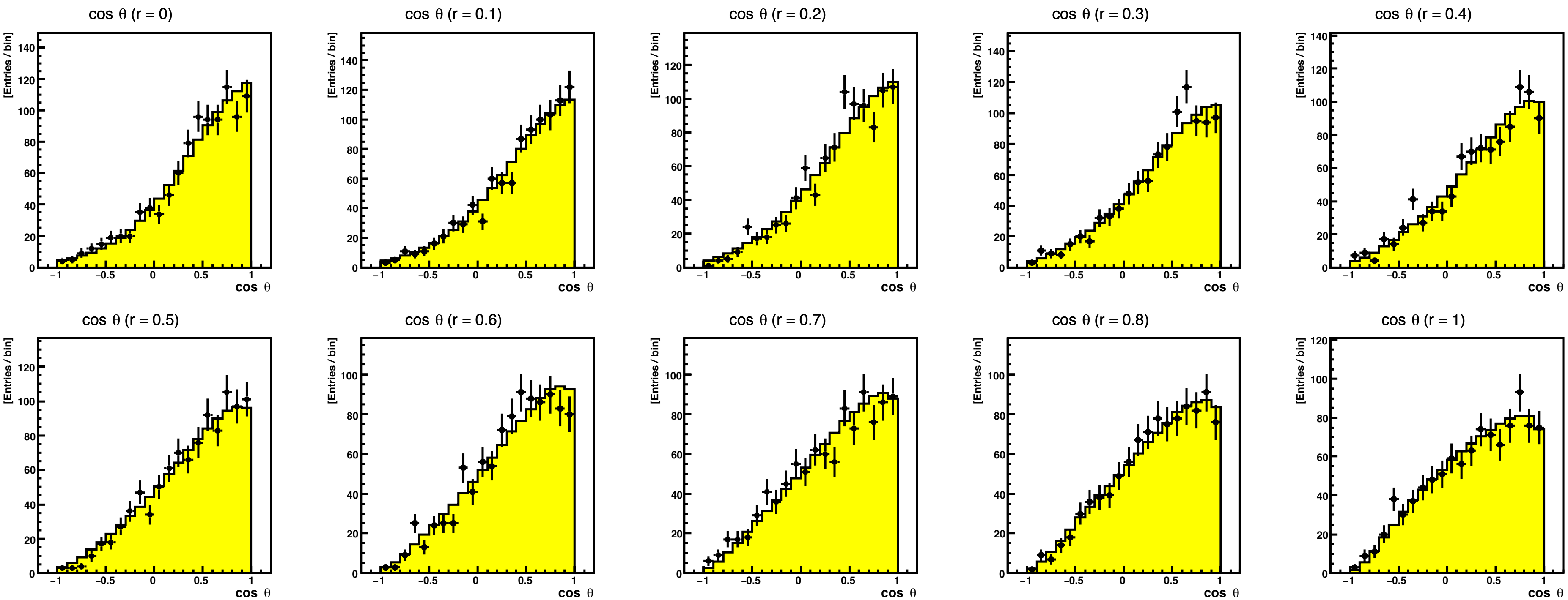




✓ Due to form factor effect, more signal number is required in heavy target case than light target case.

Directionality Histogram
(heavy target)

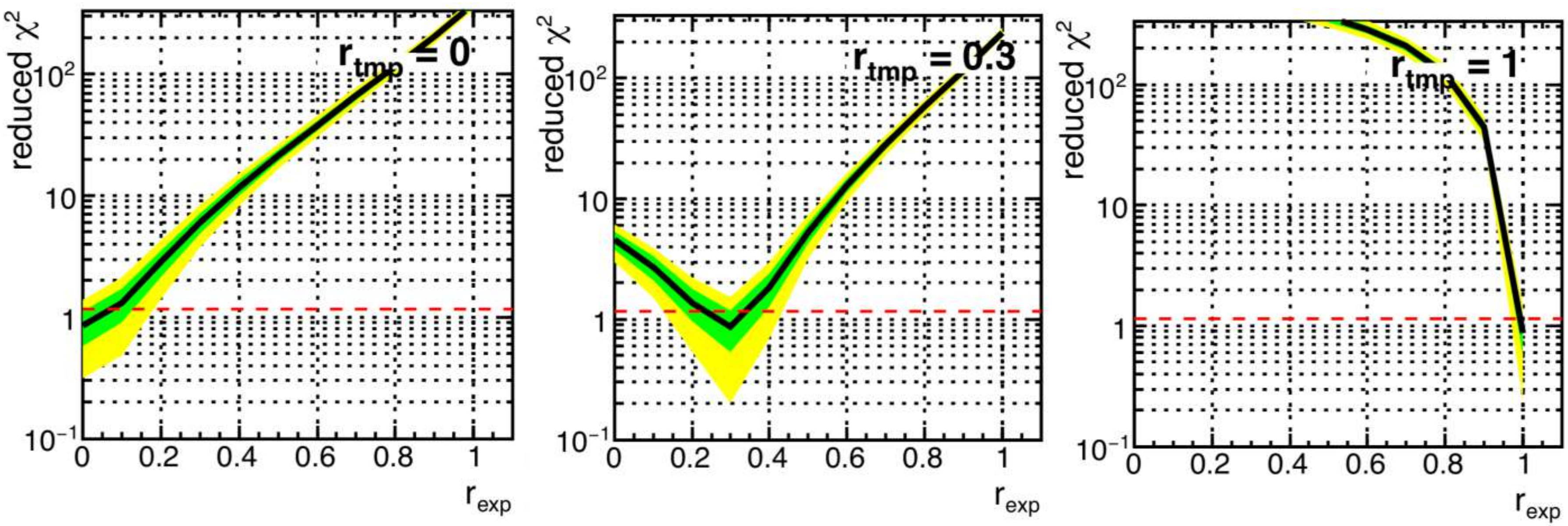
Ethr=50keV (Ag)



✓ Shape for r=0.3 is quite similar to that for r=1 in both case target F and Ag.

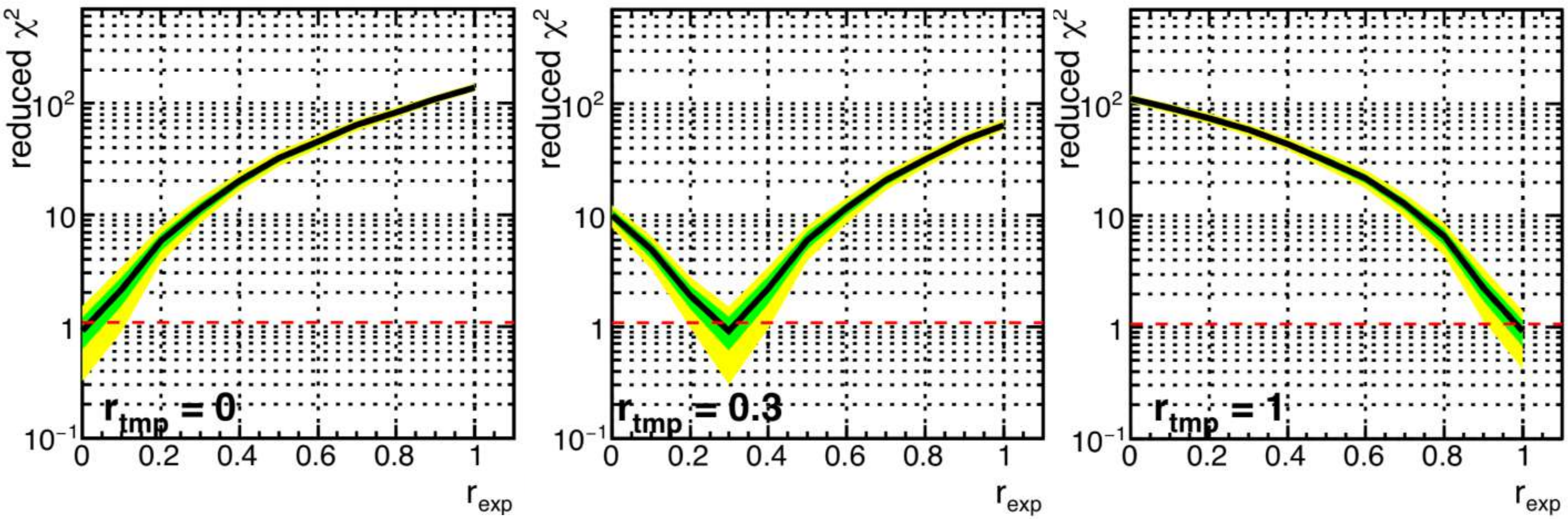
#exp.=5*10^3
Ethr=20keV (F)

✦ Chi squared test (light target)



#exp.=6*10^4
Ethr=50keV (Ag)

✦ Chi squared test (heavy target)



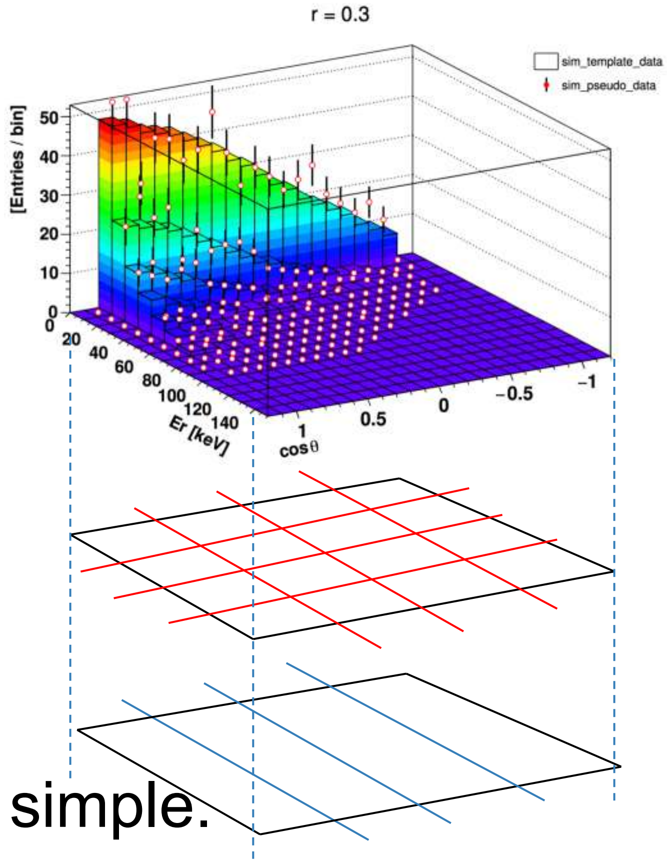
✦ To discriminate the anisotropy, required event # are…

- $6\times10^3/6\times10^4$

(Energy-angular distribution)

- $5\times10^3/2\times10^4$

(Directional histogram)



Event number for one bin is missed in test of energy-angular distribution.

[ER+ θ] is worse than only [θ]?

✦ Test efficiency also depends on ER, so the comparison is not so simple.