Anisotropy of dark matter velocity distribution

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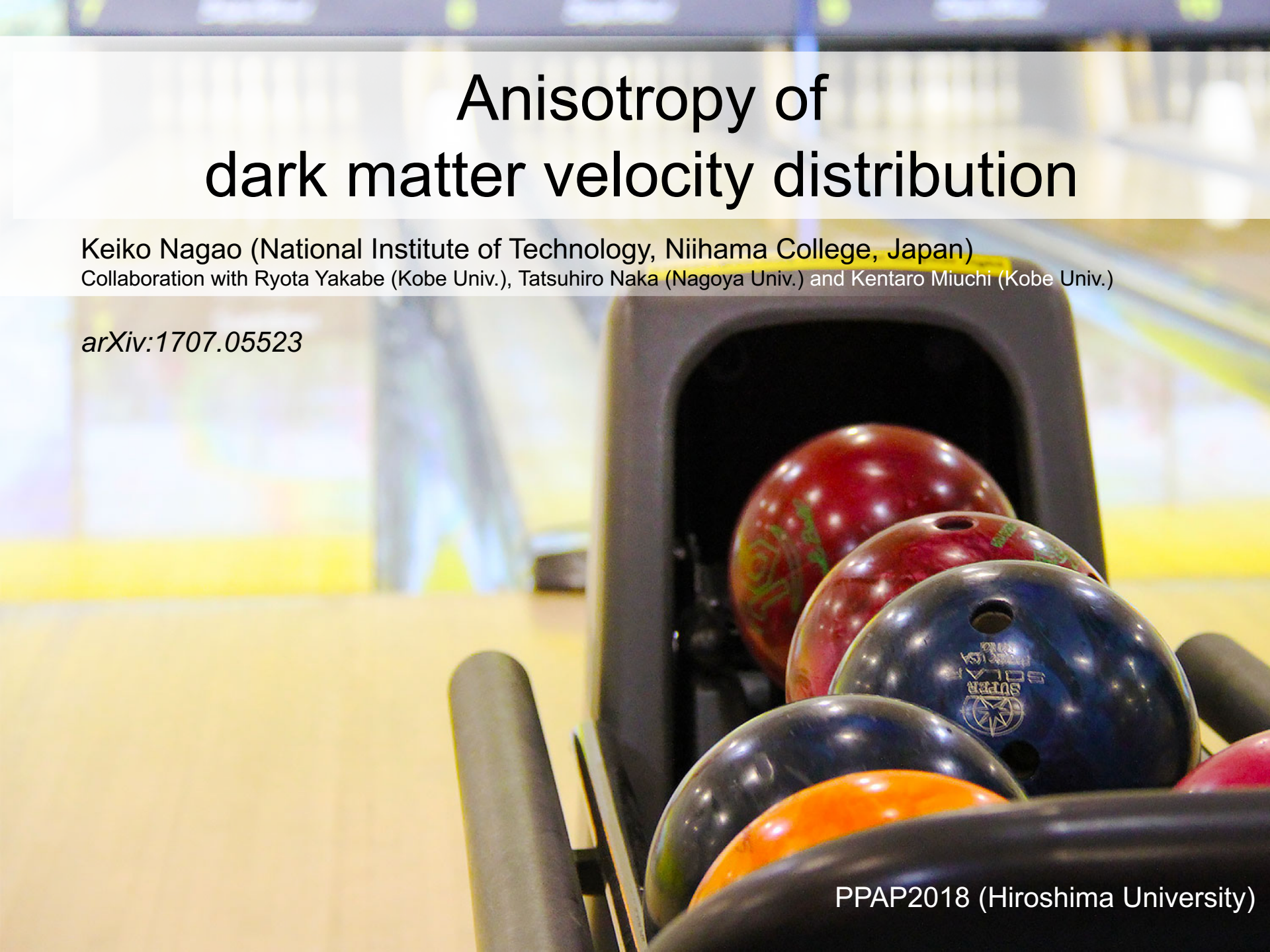
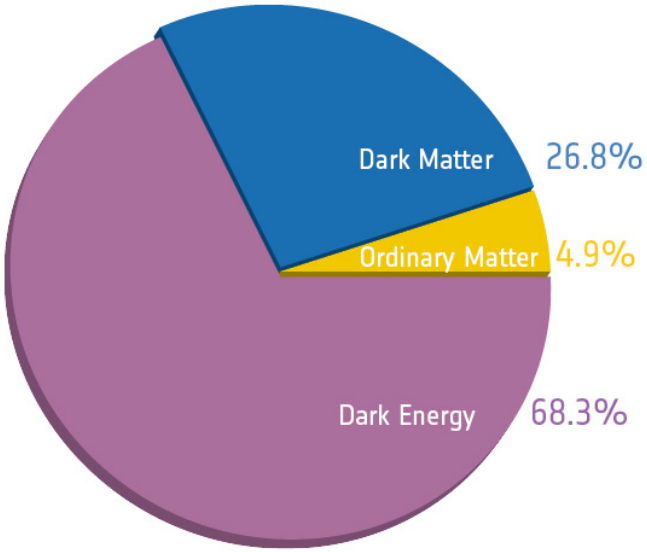
arXiv:1707.05523



PPAP2018 (Hiroshima University)

Dark Matter

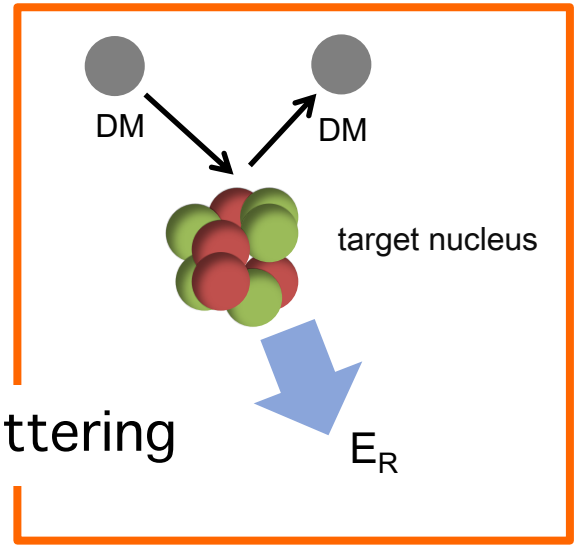


- ✦ No good candidate in SM
  - electrically neutral
  - stable
  - non-relativistic
  - weakly interacting

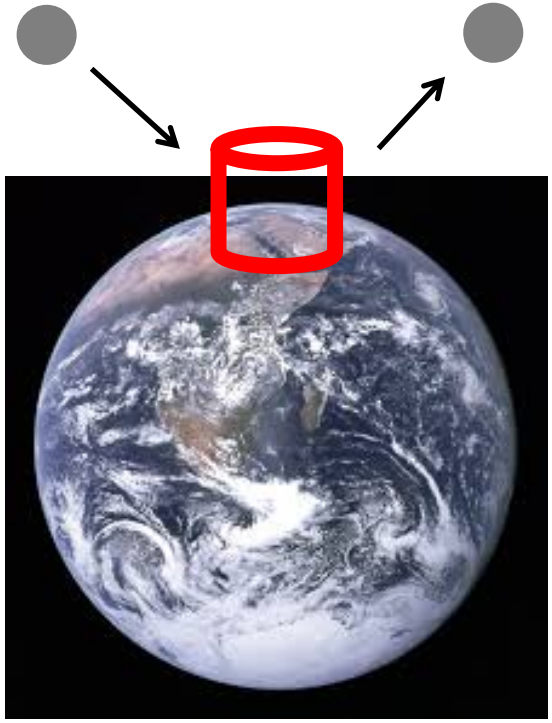
  …Weakly interacting massive particle (WIMP)?

- ✦ Observations
  - cosmological measurements
  - direct detections
  - indirect detections
  - search at colliders

Direct Detection



- Scattering
  - Detect recoil energy of DM-target scattering



TAUP2017 Kajita-san's talk

Anisotropy of DM velocity distribution

Direct Detection

- Roughly speaking:

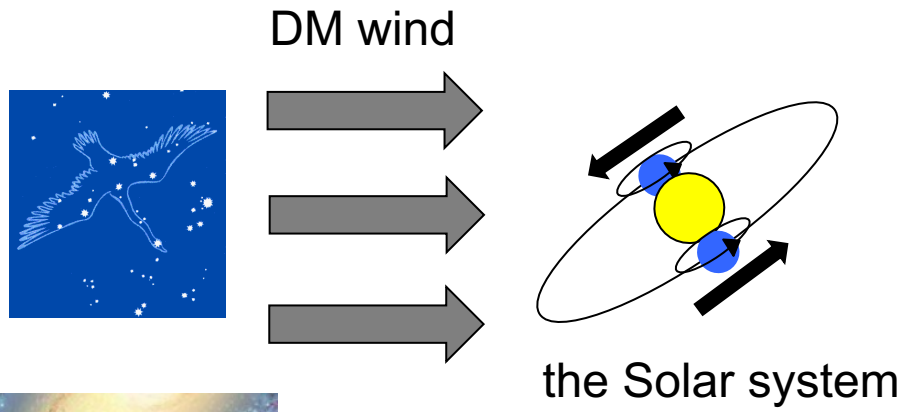
$$R \propto N_T N_\chi f(\vec{v}) \langle v \rangle \sigma$$

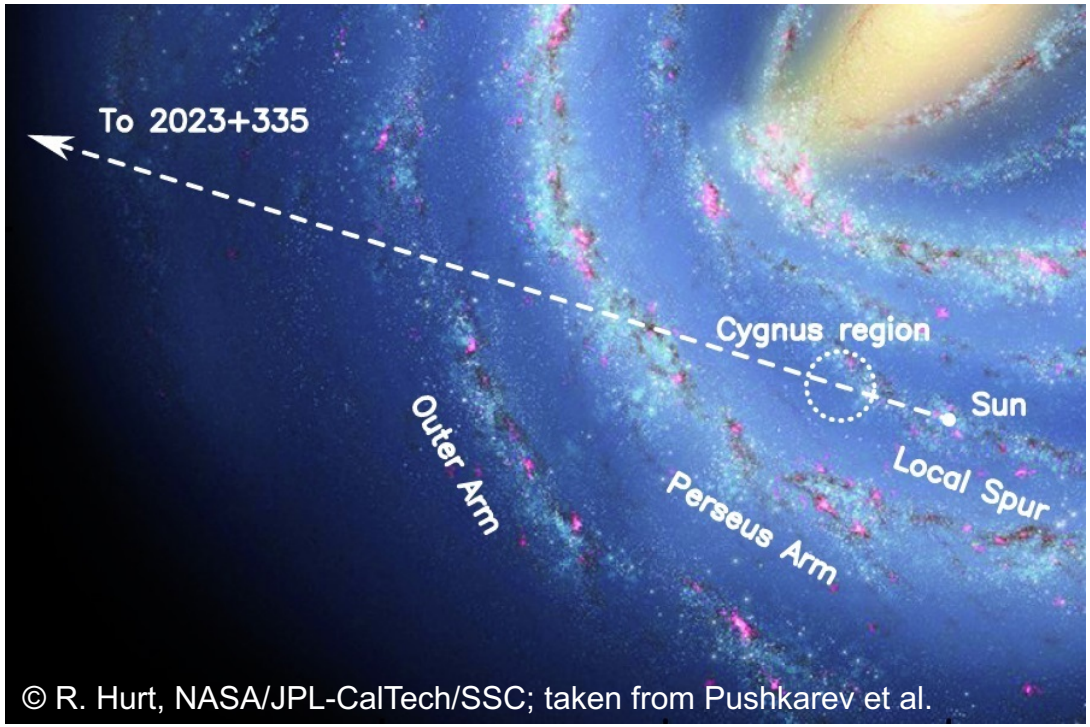
R	Event rate
N_T	# of target particles
$N_\chi = \frac{\rho_0}{m_\chi}$	# of WIMP
$f(\vec{v})$	WIMP velocity distribution
$\langle v \rangle$	Averaged WIMP velocity
σ	Cross section for DM-nucleus scattering

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

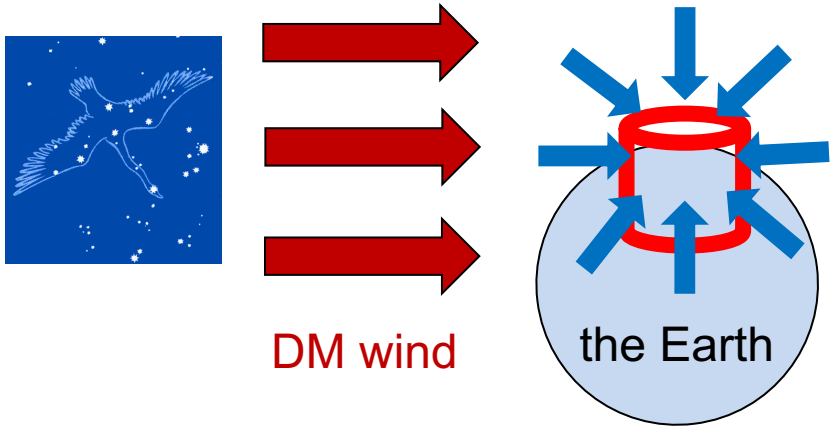
Directional detection

- Direction of DM
  - detect not only the recoil energy but also direction where DM comes from.





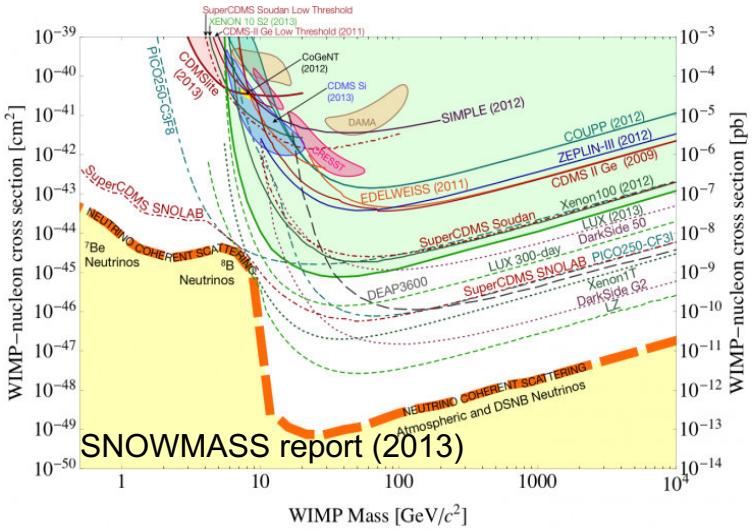
Advantages of directionality

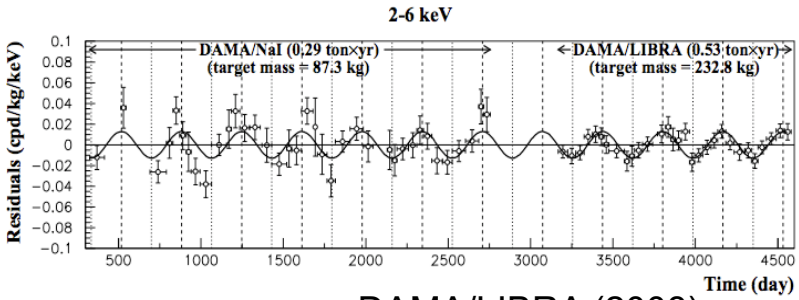


1. Powerful Bkg rejection
   Bkg : isotropic
   DM signal : come from
   direction of the Cygnus

2. Neutrino Floor

3. Annual Modulation



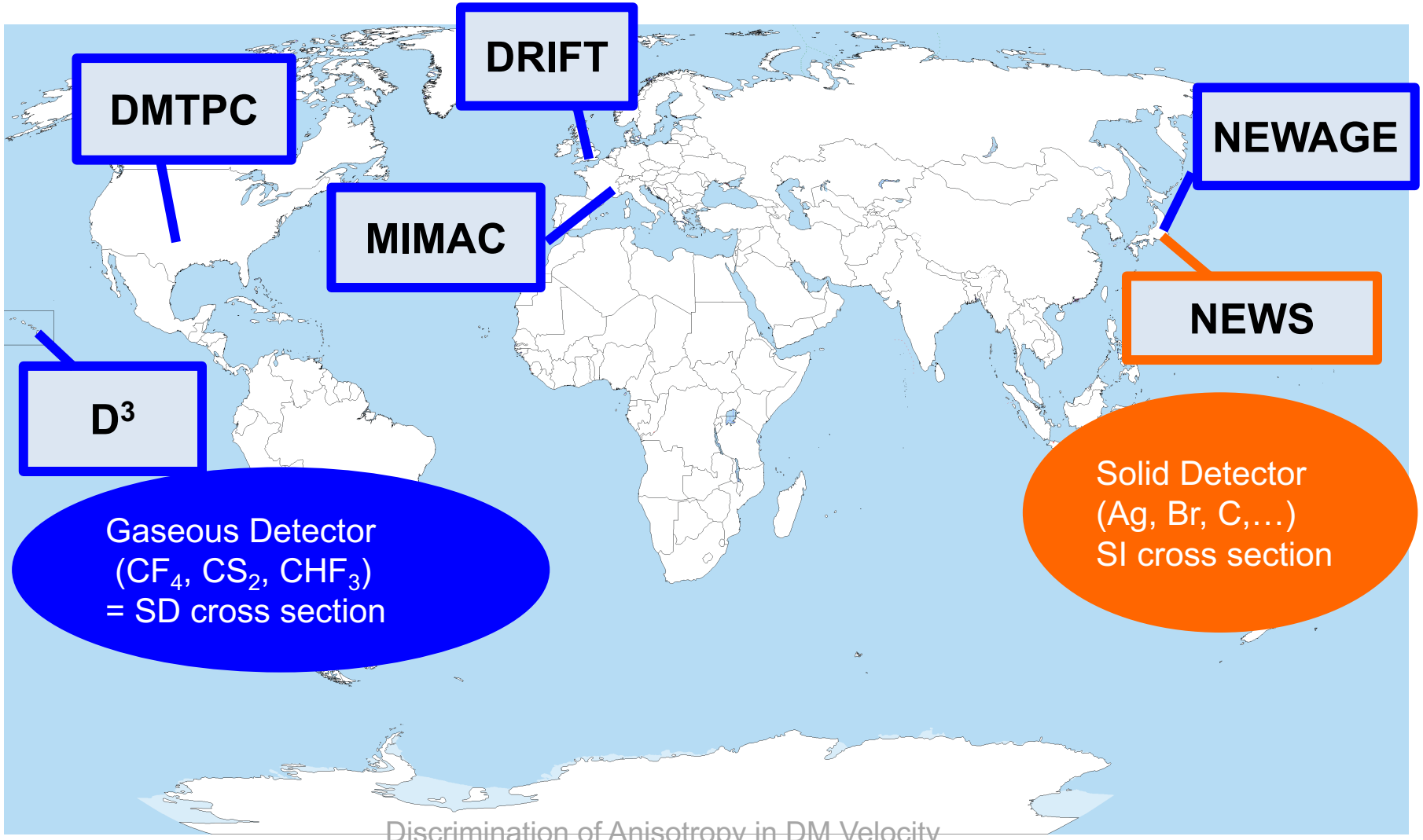


DAMA/LIBRA (2008)

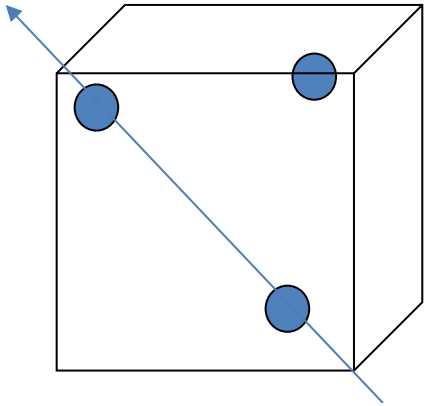
Anisotropy of DM velocity distribution

Directional Searches

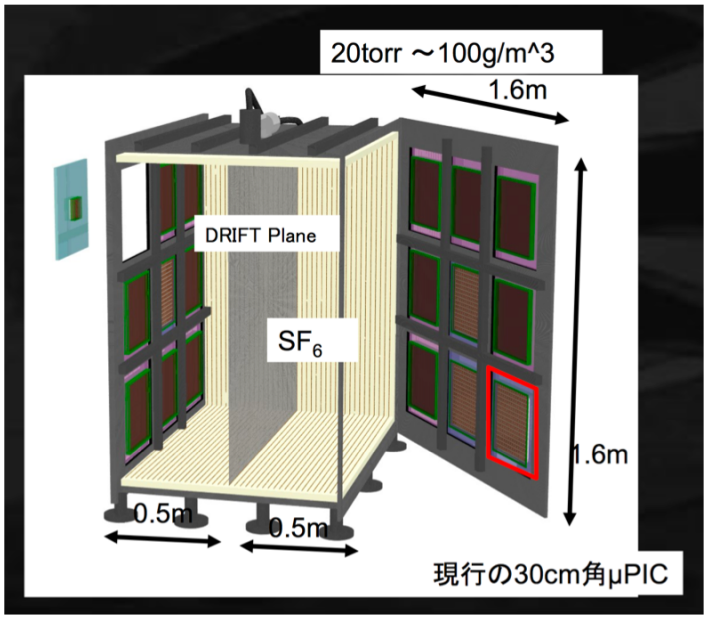
(not complete list)

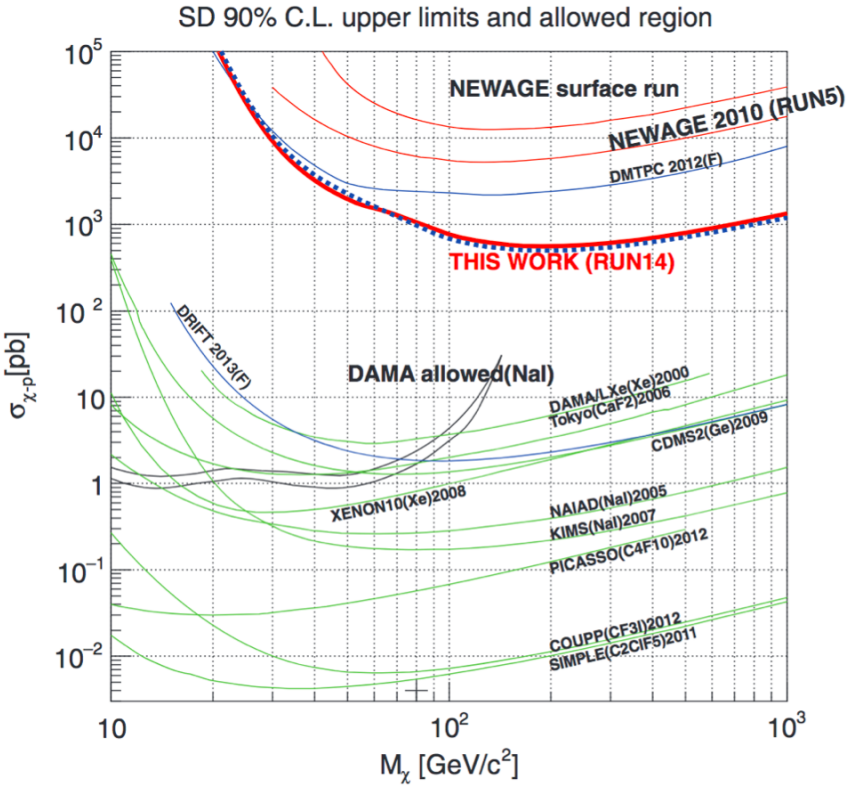


NEWAGE @Kamioka<Kobe U.



- ✓ CF4,SF6 Gass=focusing directionality
- ✓ SD interaction
- ✓ Time information
- ✓ Low mass

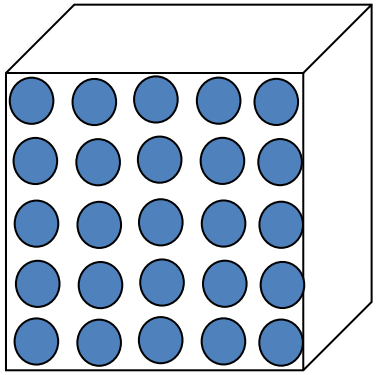




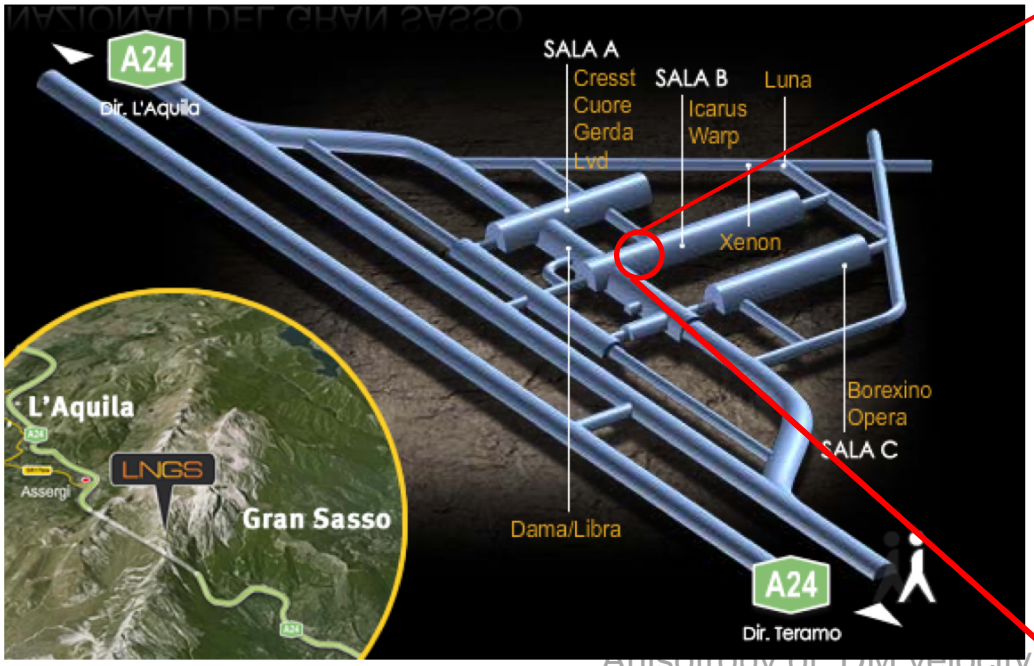
PTEP (2015) 043F01s

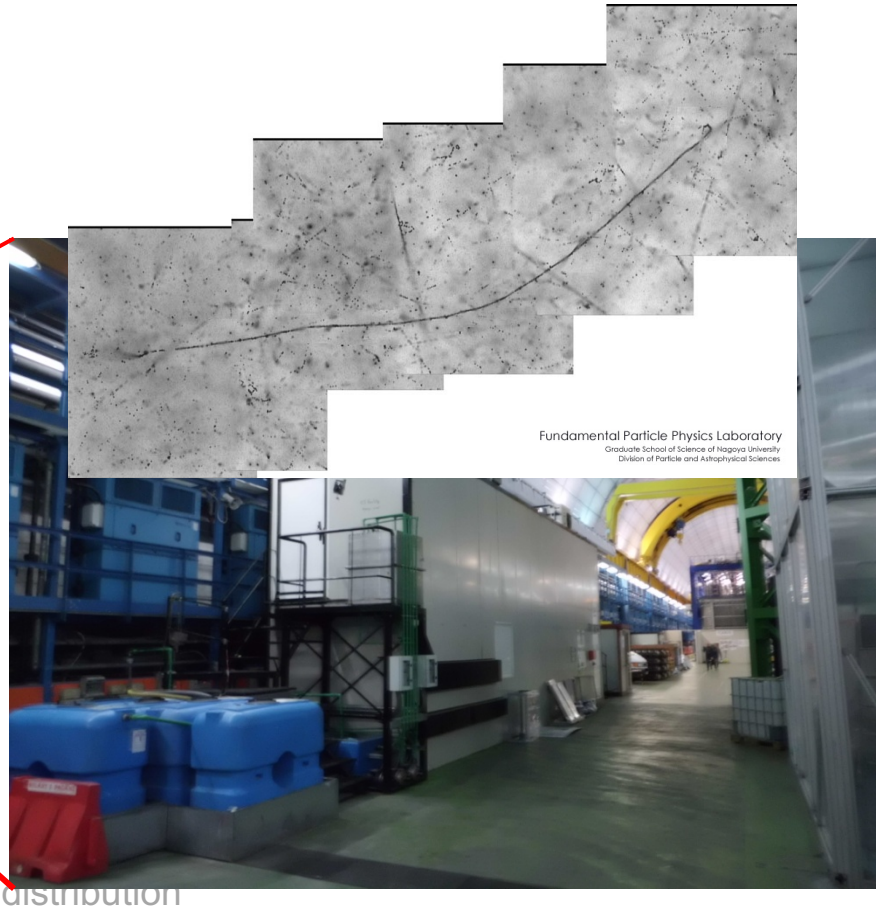
Anisotropy of DM velocity distribution

NEWs DM @Gran Sasso<Nagoya U.

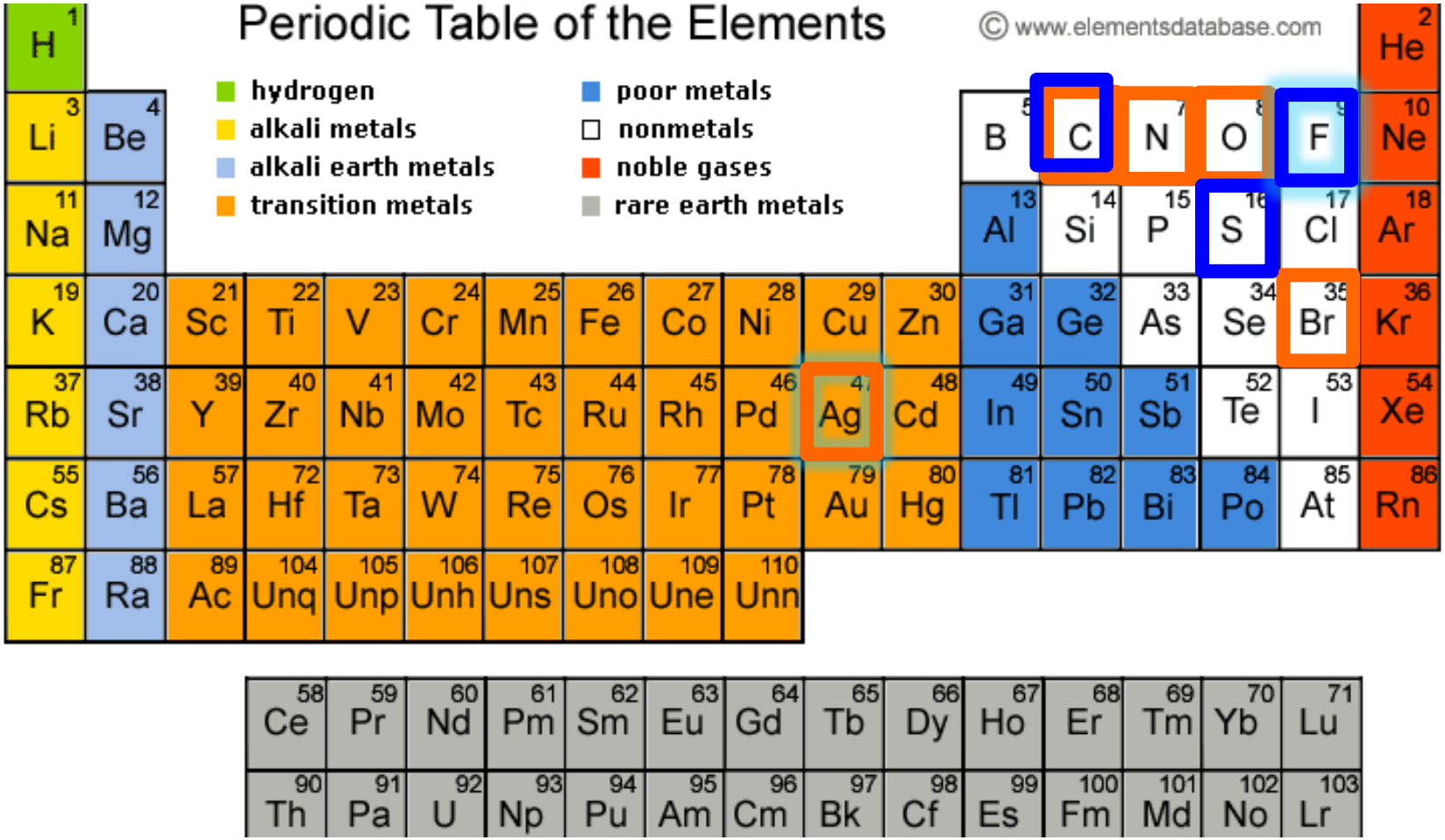


- ✓ Nuclear emulsion=sensitivity
- ✓ SI interaction
- ✓ Time information
- ✓ Sensitivity





Typical Targets

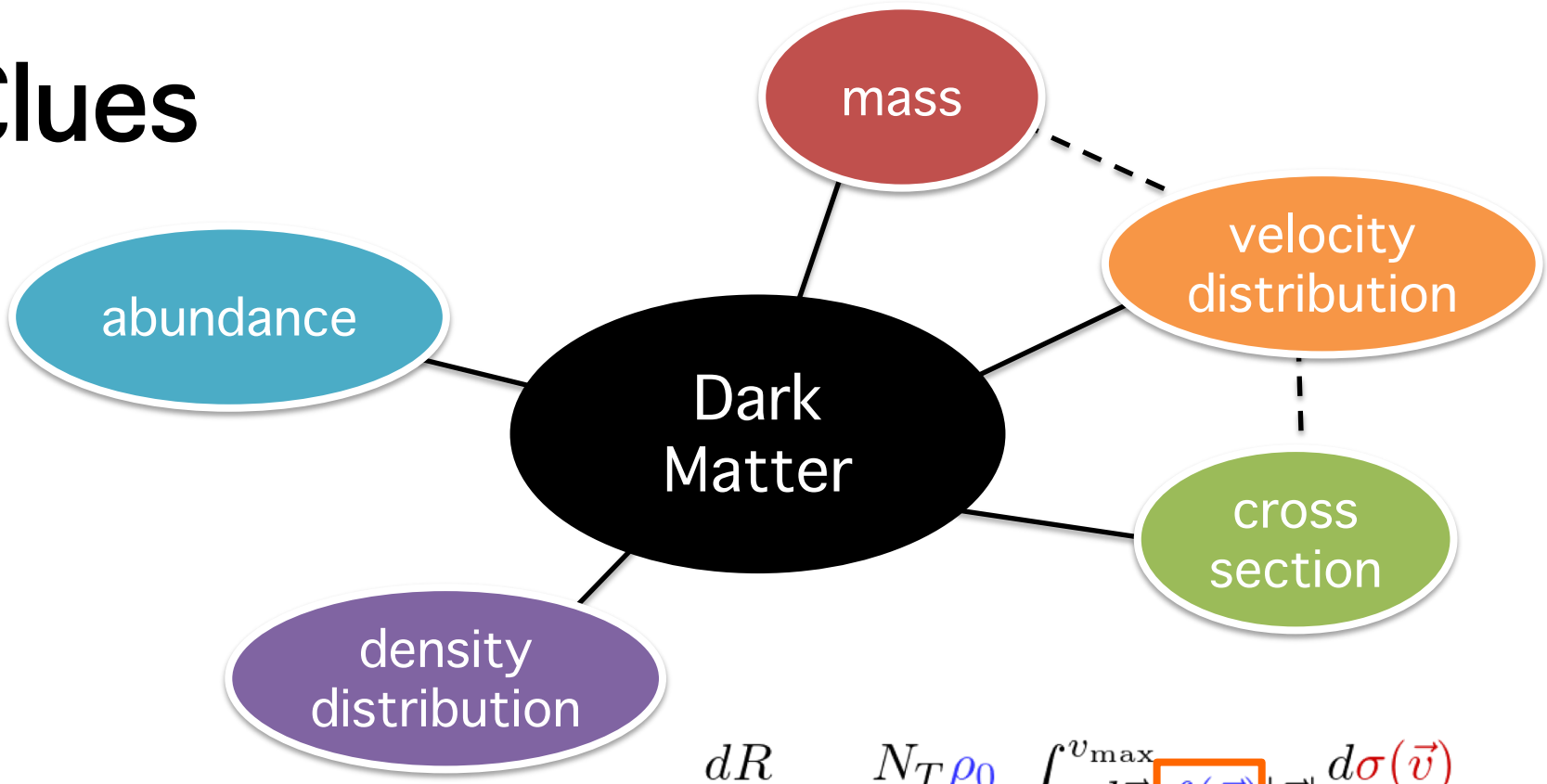


Outline

1. ~~Introduction~~
2. Velocity Distribution of Dark Matter
3. Velocity Distribution Observed in the Directional Detector
4. Conclusion

Velocity Distribution of Dark Matter

Clues



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

- In the directional DM search, it can be possible to make a constraint for the velocity distribution.
- Correct distribution is required to derive appropriate constraints for the interaction

Distribution for Direct Detection

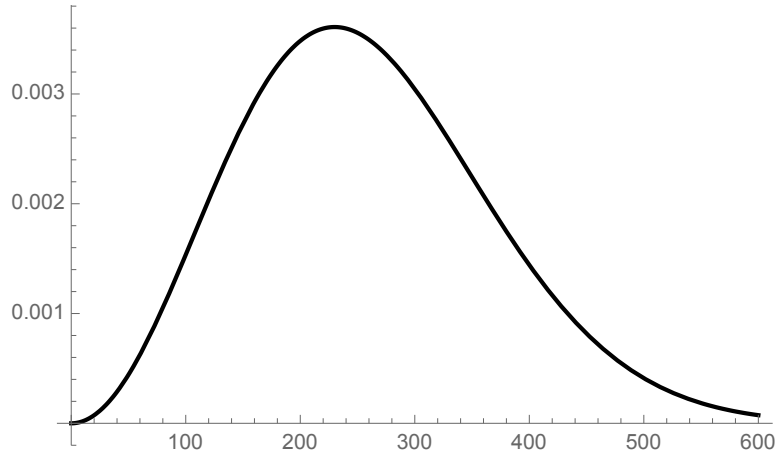
- Usually we suppose:
  - Maxwell distribution

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

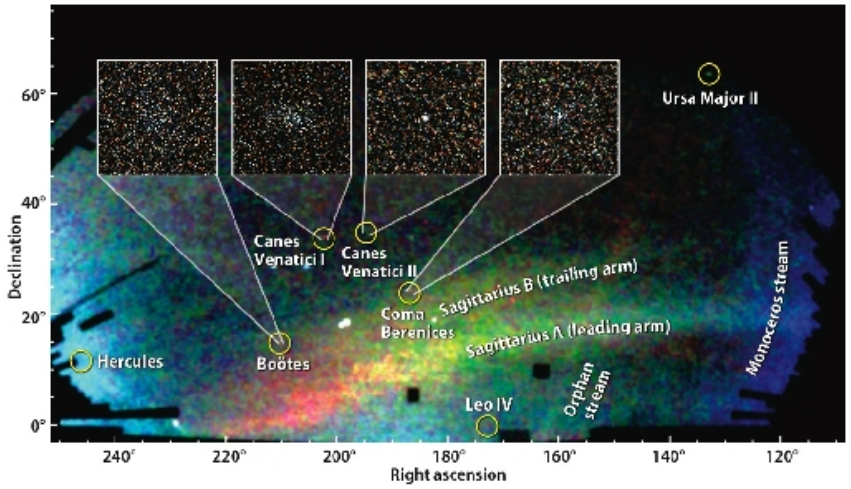
  - Isothermal
  - Isotropic

- But it may not be true.

v_0: velocity of the Solar system
v_E: Earth's velocity relative to DM

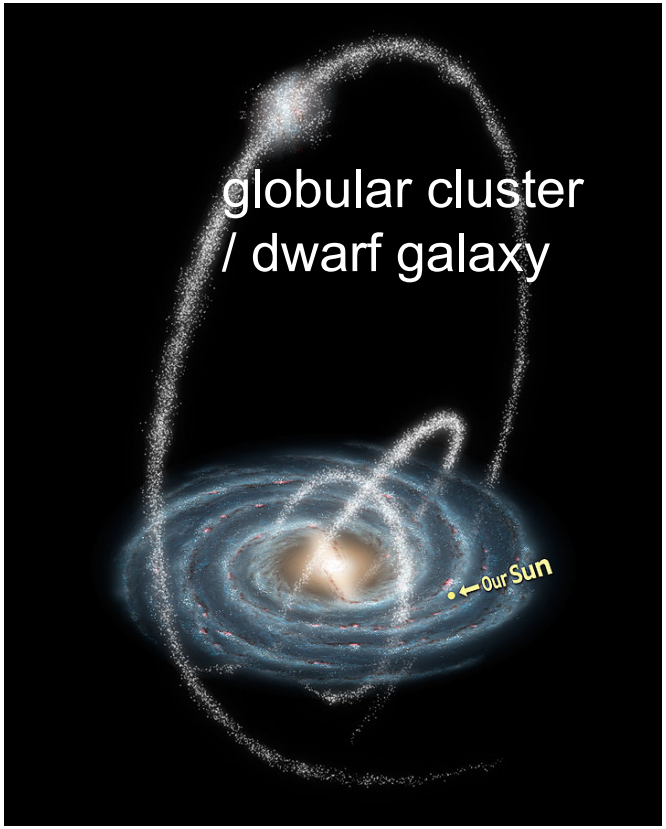


Steller streams (潮汐流)

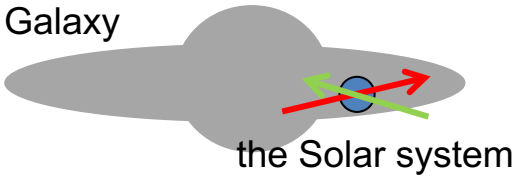


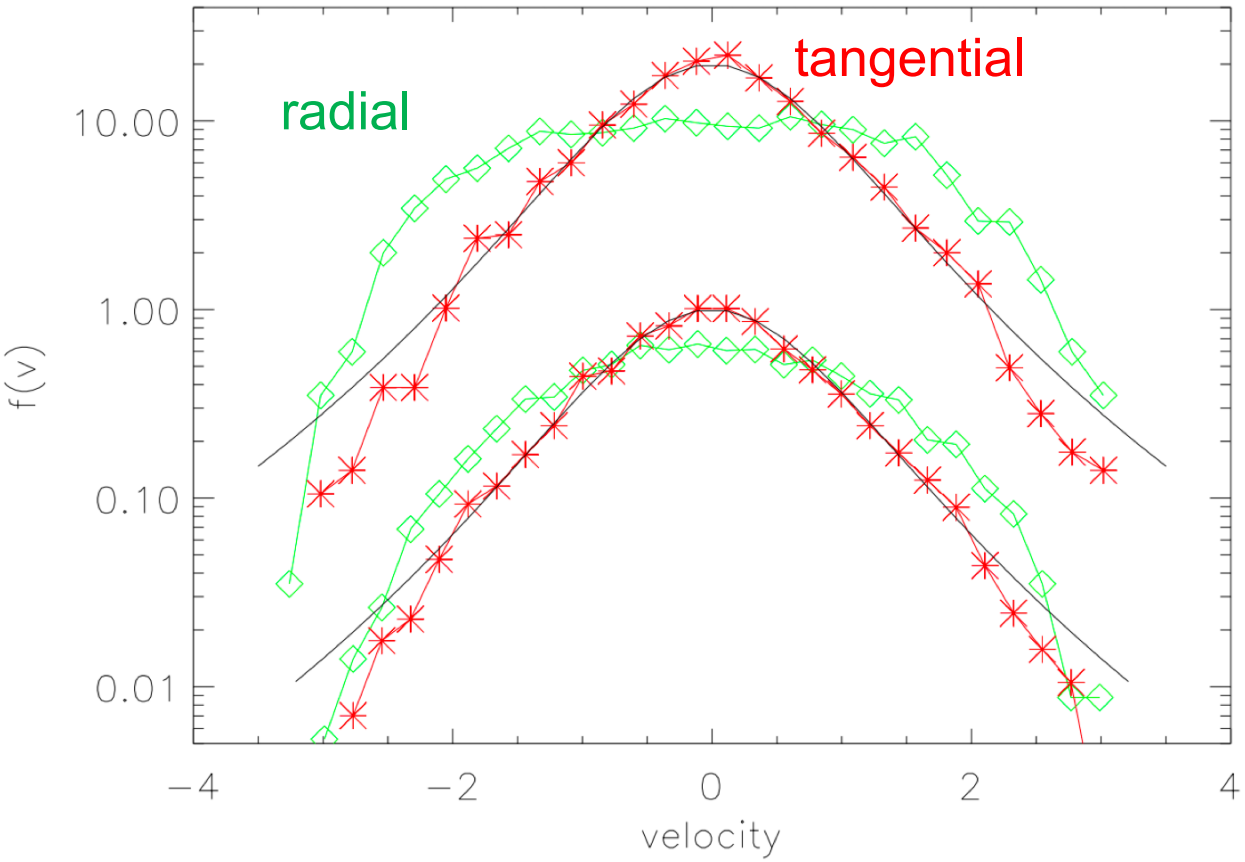
A stellar stream is torn apart and stretched out along its orbit by tidal forces, and flow into a galaxy.

Sloan Digital Sky Survey II data (2006)



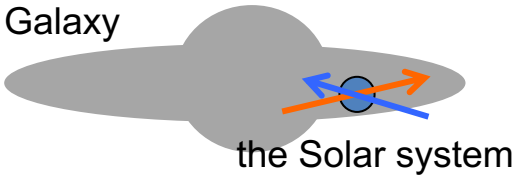
Anisotropy





0812.1048
cosmological simulation by Sommer-Larsen astro-ph/0602595, astro-ph/0204366

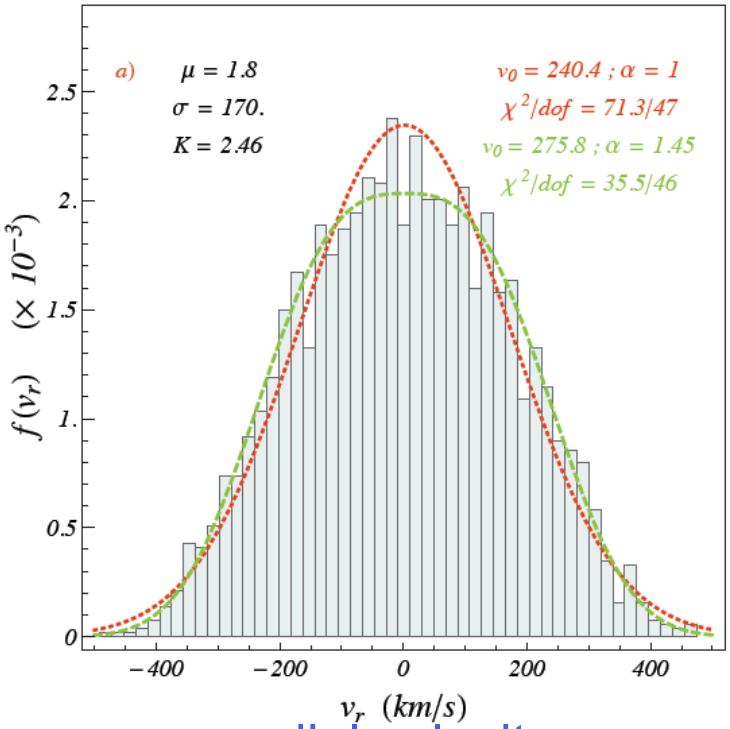
Co-rotating DM



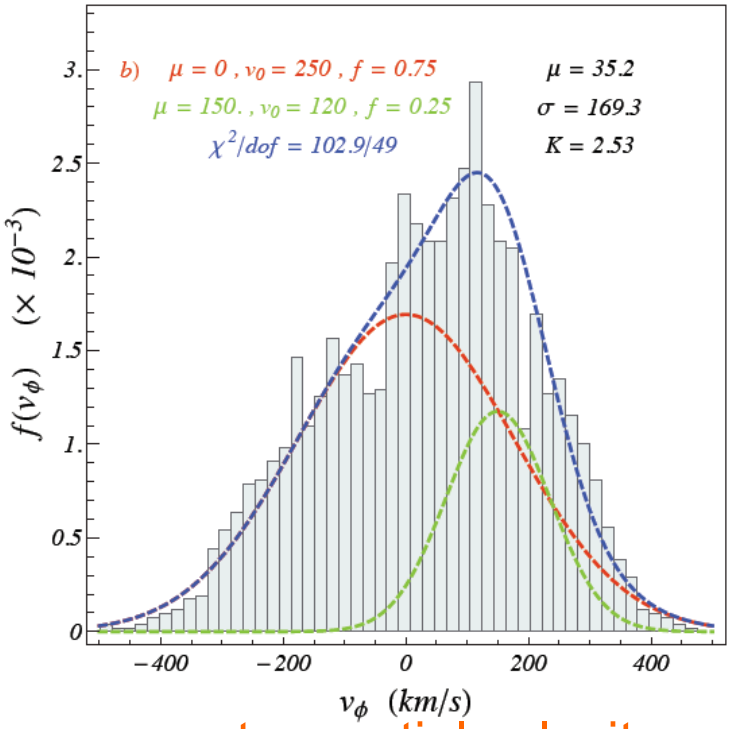
- N-body simulation including baryons and gas
  - DM co-rotates with baryons in the galaxy

Ling, Nezri, Athanassoula & Teyssier (2009)

cf. Kuhlen et al. (2012), David R. Law (2009) …



radial velocity



tangential velocity

Anisotropy of DM velocity distribution

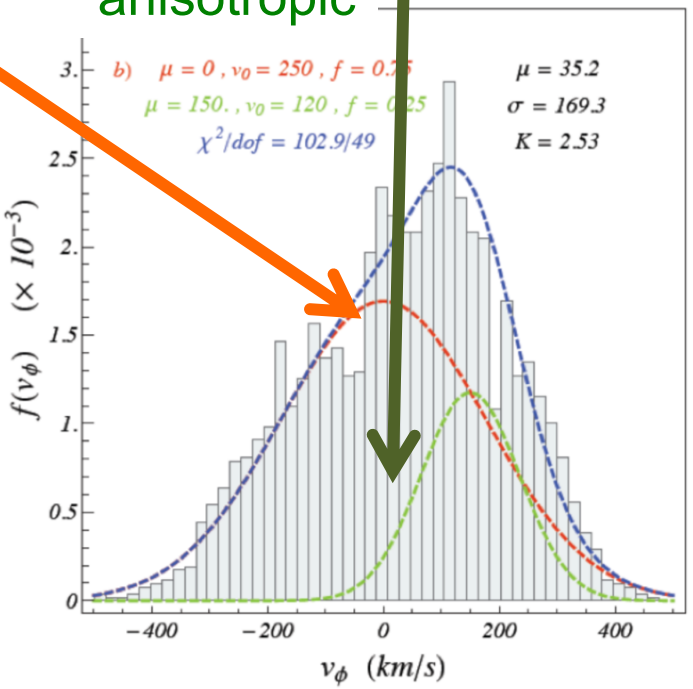
Anisotropy parameter “r”

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

isotropic

anisotropic

- ✦ Tangential velocity
  - Anisotropy parameter 0 < r < 1
  - r=0.25 is suggested by N-body simulation
- ● Goal: isotropic case (r=0) --- anisotropic case (r=0.2-0.3)



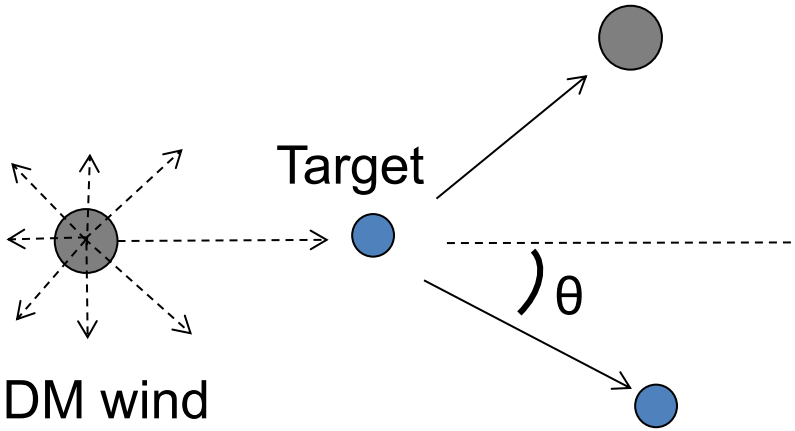
Outline

1. ~~Introduction~~
2. ~~Velocity Distribution of Dark Matter~~
3. Velocity Distribution Observed in the Directional Detector
4. Conclusion

Velocity Distribution observed in Directional Detector

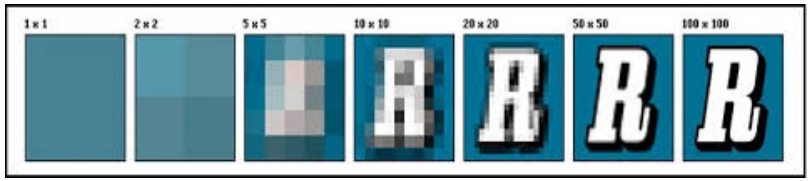
cf.
Ben Morgan, Anne M. Green, Neil J. C. Spooner (2004)
Ole Host, Steen H Hansen (2007)

Set up of simulation



- Monte Carlo simulation of scattering supposing f(v)
  - Direction (scattering angle)
  - Recoil energy
- Elastic scattering
- mass relation $m_{dm}=3m_N$ for simplicity

Analysis



… depends on resolution of detectors.

Energy resolution :OK
Angular resolution :OK

→ Energy-Angular distribution

Most hopeful case!

Energy resolution :OK
Angular resolution :NG

→ ~~Ordinary direct detection~~

~~had been studied so far…~~

Energy resolution :NG
Angular resolution :OK

→ Directionality histogram

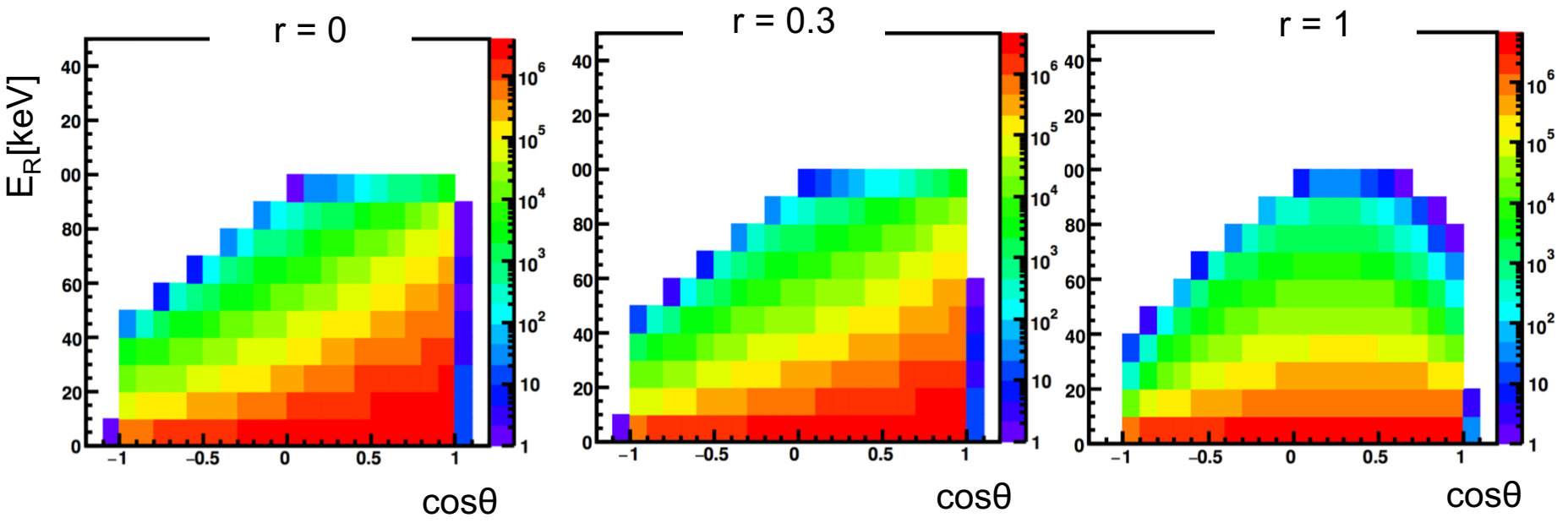
Limited information,
but maybe worth to study

Energy resolution :OK
Angular resolution :OK

Most hopeful case!

Energy-angular distribution

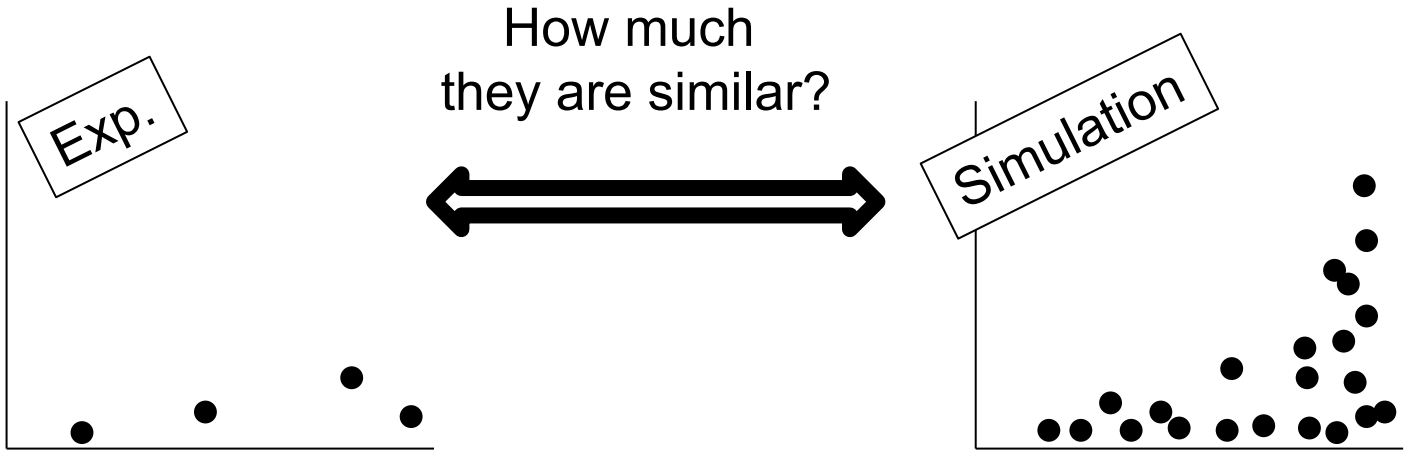
light target (F)



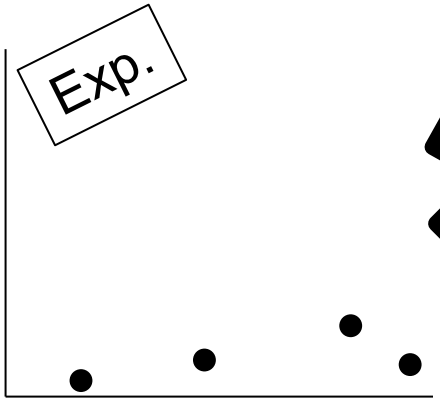
Ethr = 0keV

- Isotropic one does not differ from anisotropic one so much.
- Method to compare similar distributions is required.

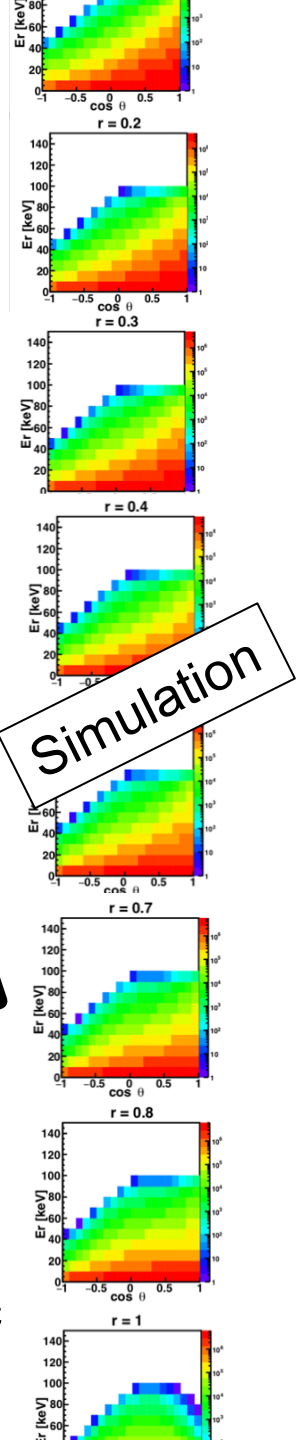
Strategy



Strategy



Isotropic



Which one is the most similar to Exp.?

Simulation

Anisotropic

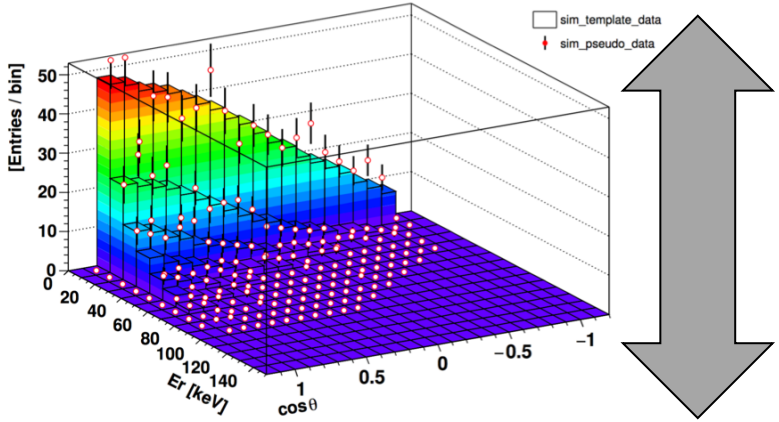
- Statistical test to examine the similarity of distributions.
  - Chi-squared test
  - Kolmogorov–Smirnov test
  - …

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)

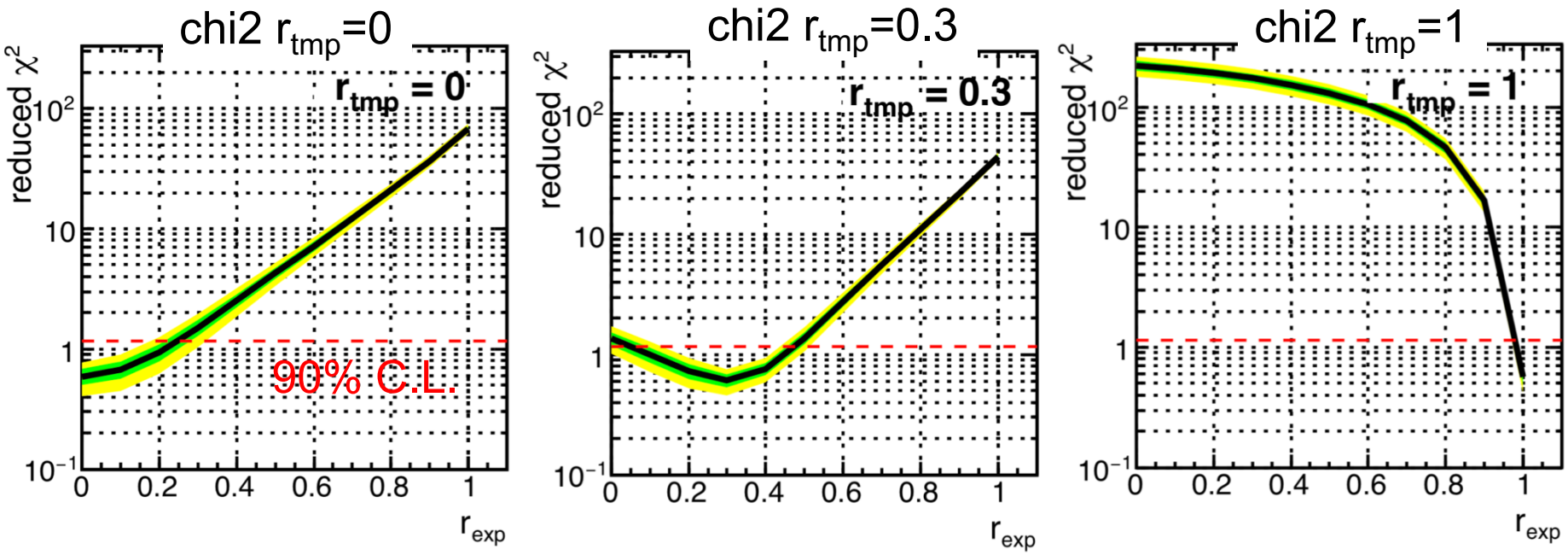
- ✓ realistic
(relatively…)

"**pseudo-experimental**" data

Chi squared test of E_R-cos θ

(light target)

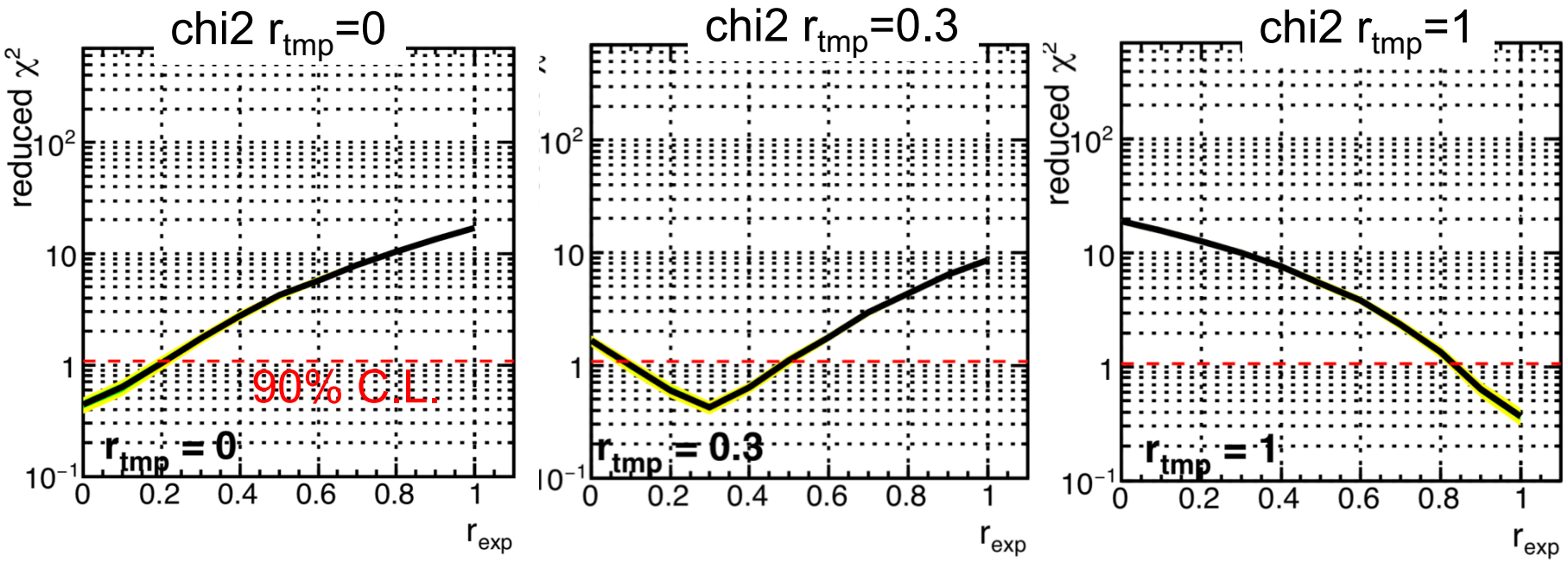
#exp.=6*10^3
Ethr=20keV (F)



- ✓ 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.

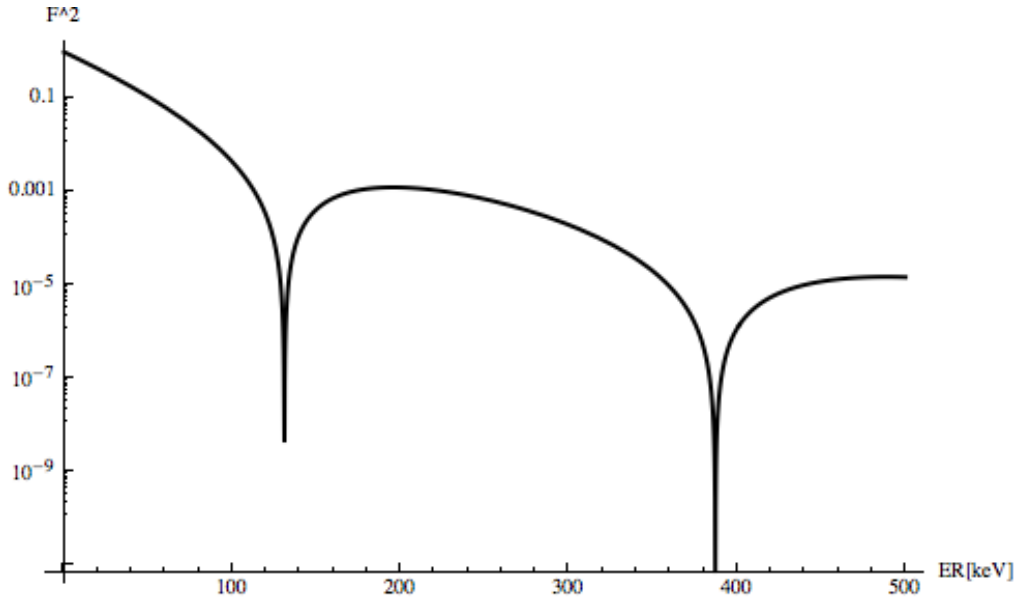
Chi squared test of E_R-cos θ
(heavy target)

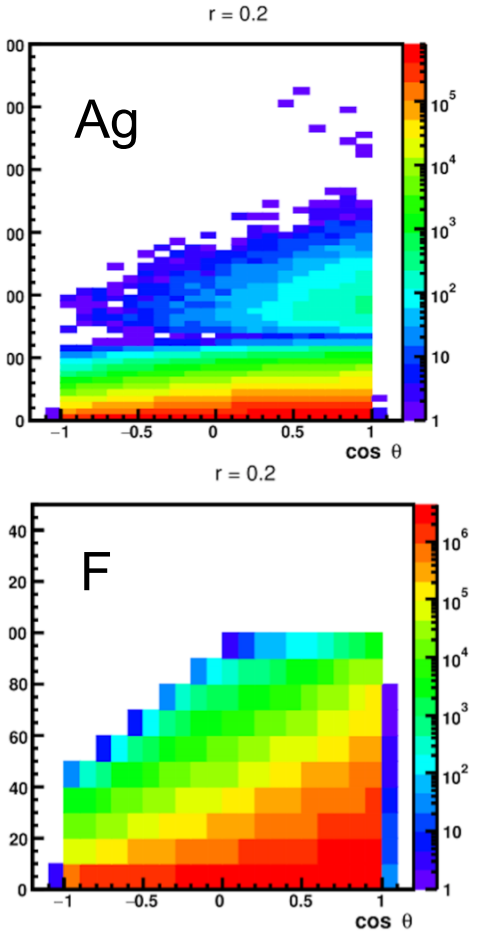
#exp.=6*10^4
Ethr=50keV (Ag)



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

Form factor





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

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

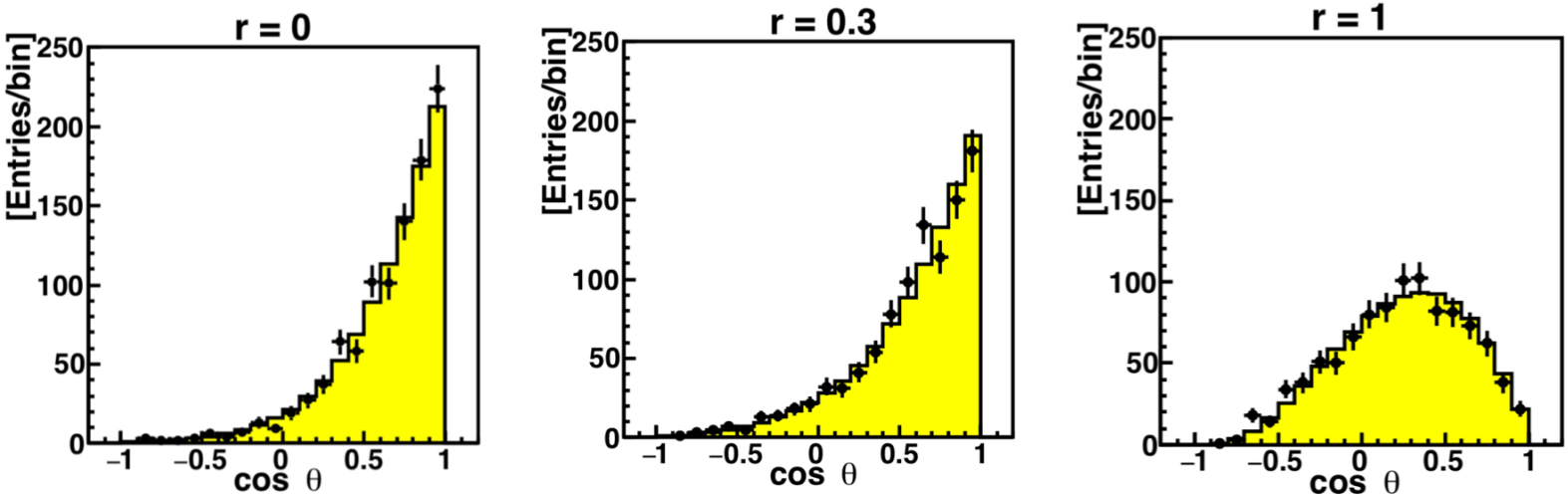
- ✓ Due to form factor effect, more signal number is required in heavy target case than light target case.

Energy resolution :NG
Angular resolution :OK

Limited information,
but maybe worth to study

Directionality Histogram
(light target)

Ethr=20keV (Light target F)

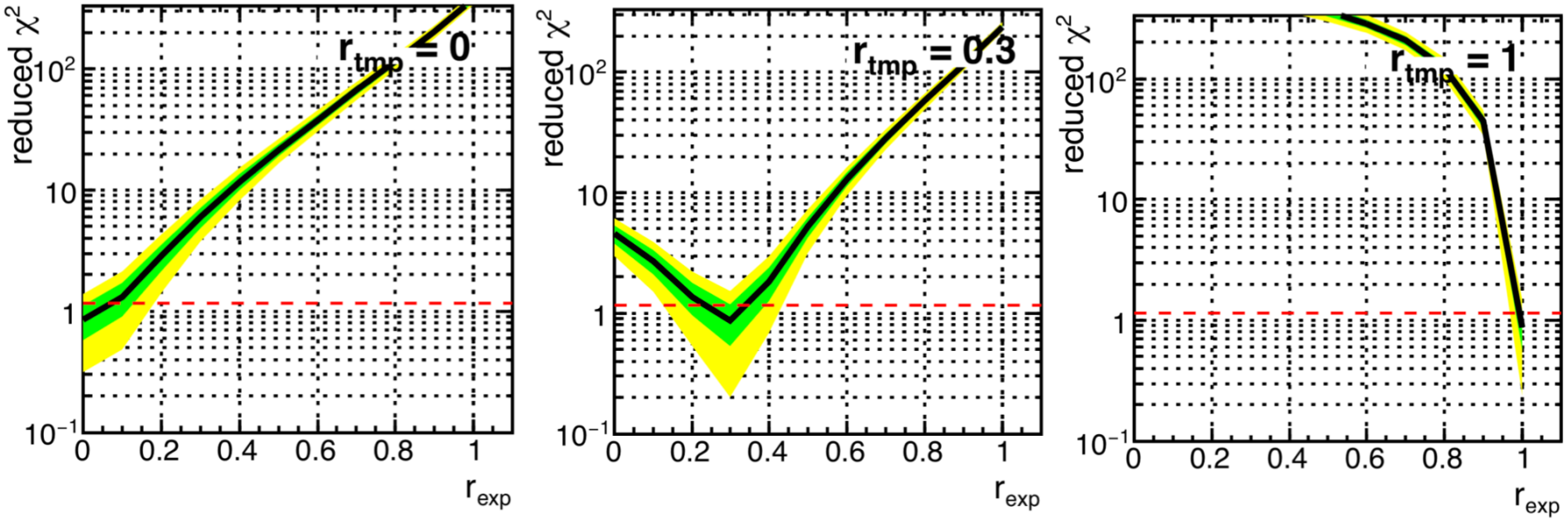


- ✓ Shape for r=0.3 is quite similar to that for r=0. It is same for heavy target case.
- ✓ We need statistical test again.

Chi-squared test of directionality

✦ Chi squared test (light target)

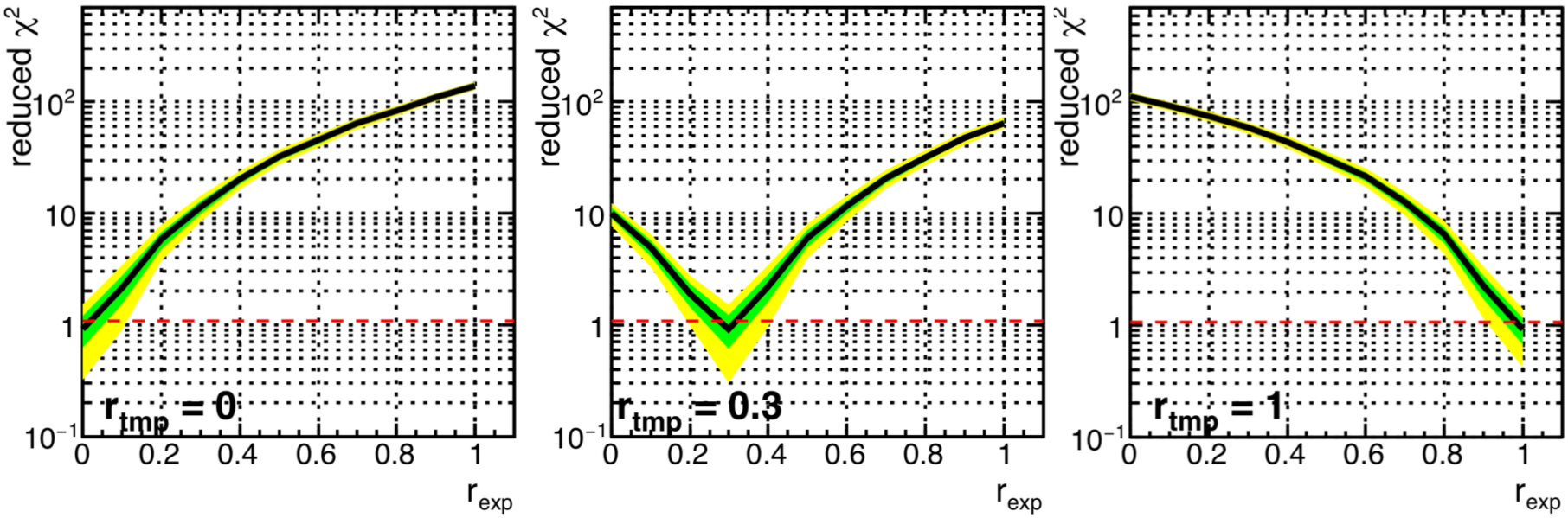
#exp.=5*10^3
Ethr=20keV (F)



Chi-squared test of directionality

✦ Chi squared test (heavy target)

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

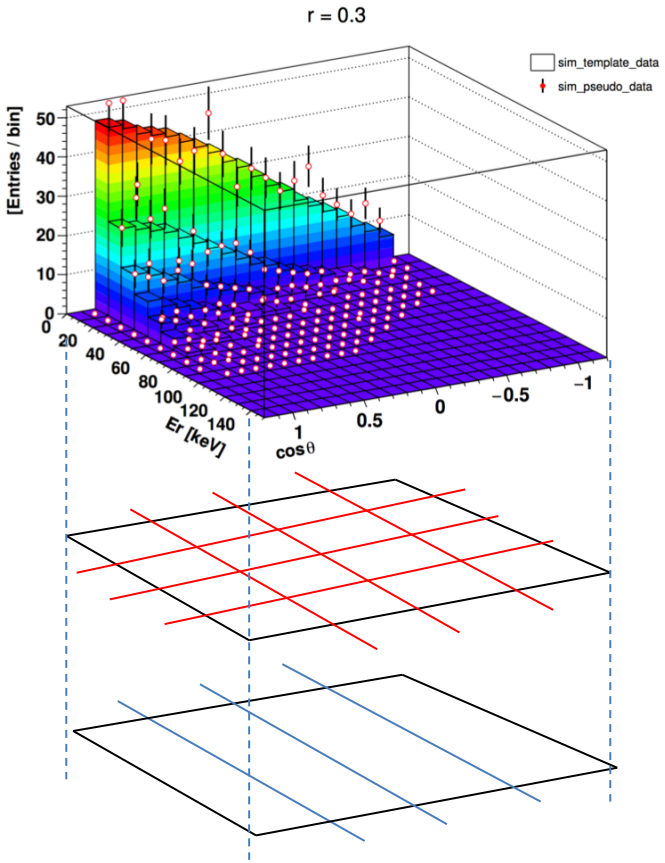


[ER+ θ] is worse than only [θ]?

- To discriminate the anisotropy, required event # are…
  - $6 \times 10^3 / 6 \times 10^4$ (Energy-angular distribution)

    v
  - $5 \times 10^3 / 2 \times 10^4$ (Directional histogram)

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



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

Conclusion

✦ Possibility to discriminate the anisotropy in the velocity distribution of DM is discussed.

✦ With “template data”, the chi squared test is helpful to figure out anisotropy if O(10^4) data is obtained.

✦E_R-cos θ distribution

/ directionality histogram

Thank you for your attention.