

Anisotropy of dark matter velocity distribution

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arXiv:1707.05523

Dark Matter

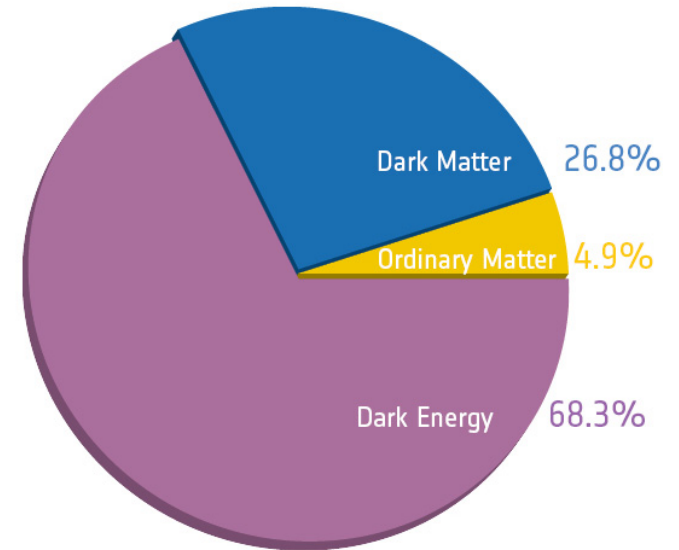
✦ No good candidate in SM

- electrically neutral
- stable
- non-relativistic
- weakly interacting

...Weakly interacting massive particle (WIMP)?

✦ Observations

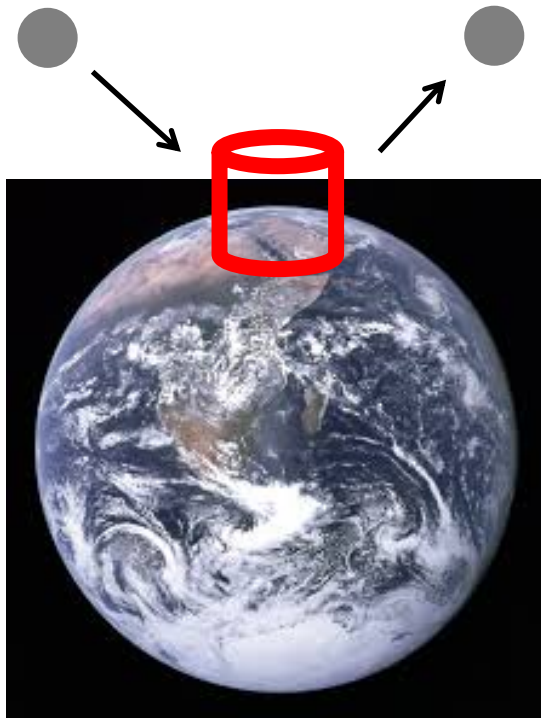
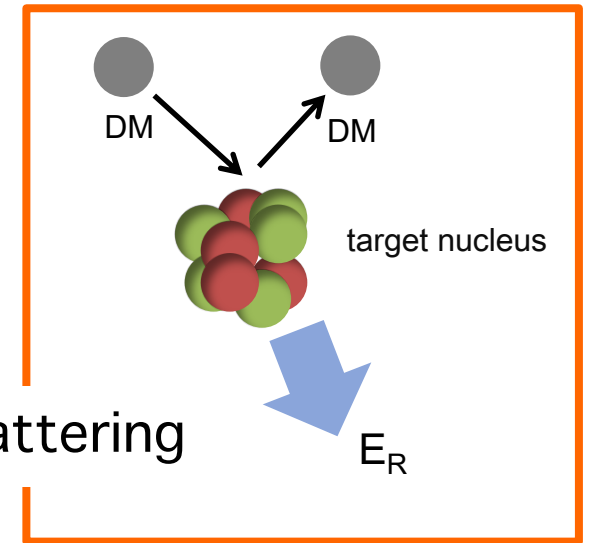
- cosmological measurements
- **direct detections**
- indirect detections
- search at colliders



Direct Detection

✦ Scattering

- Detect **recoil energy** of DM-target scattering



Underground facilities (a partial list)

It has been proven that underground facilities are very important for varieties of science!
For scientific reasons, It would be very nice if there is (at least) one in the Southern hemisphere...



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

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

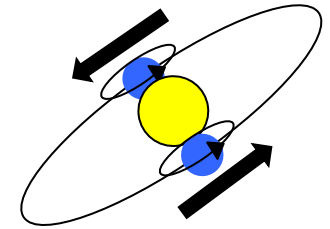
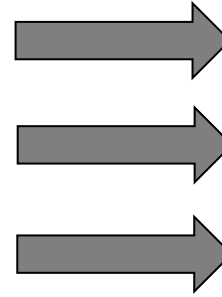
Anisotropy of DM velocity distribution

Directional detection

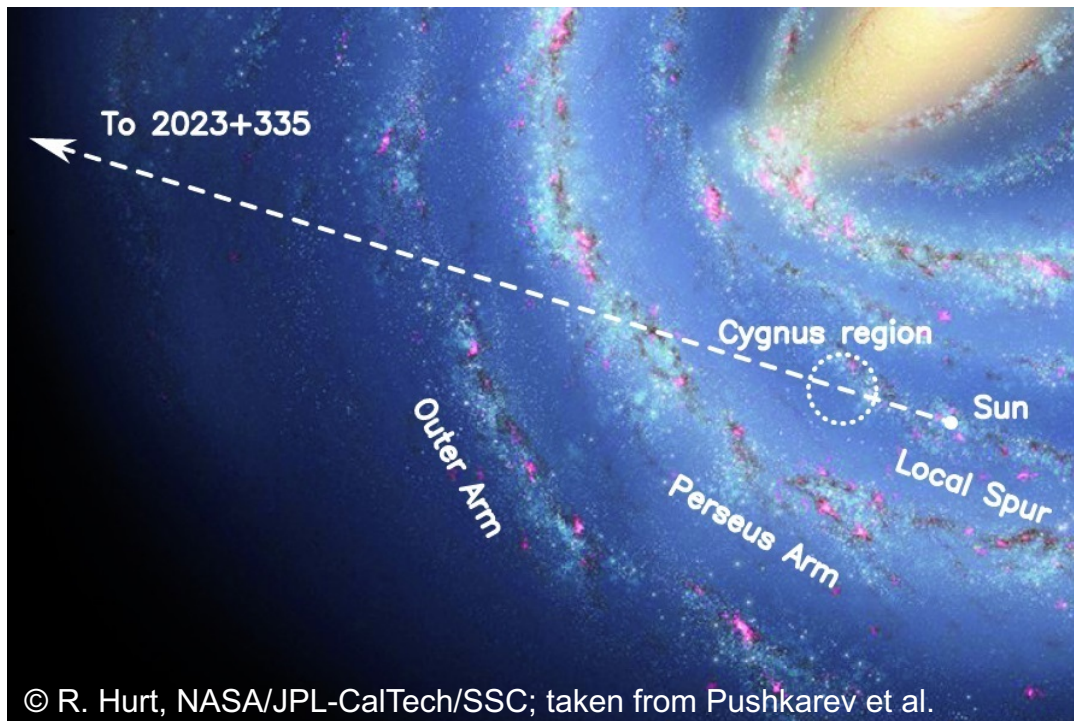
- ✦ Direction of DM
 - detect not only the recoil energy but also **direction** where DM comes from.



DM wind



the Solar system



Anisotropy of DM velocity distribution

Advantages of directionality

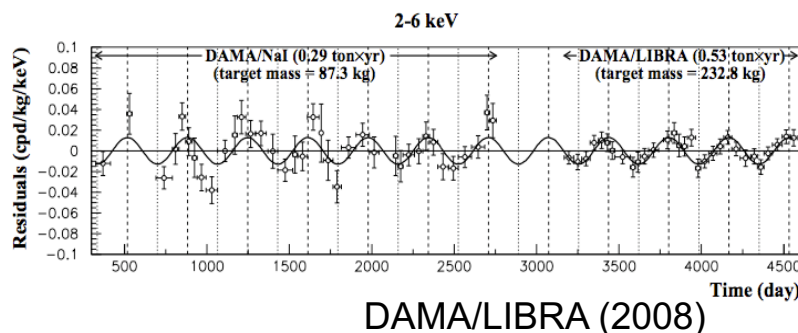
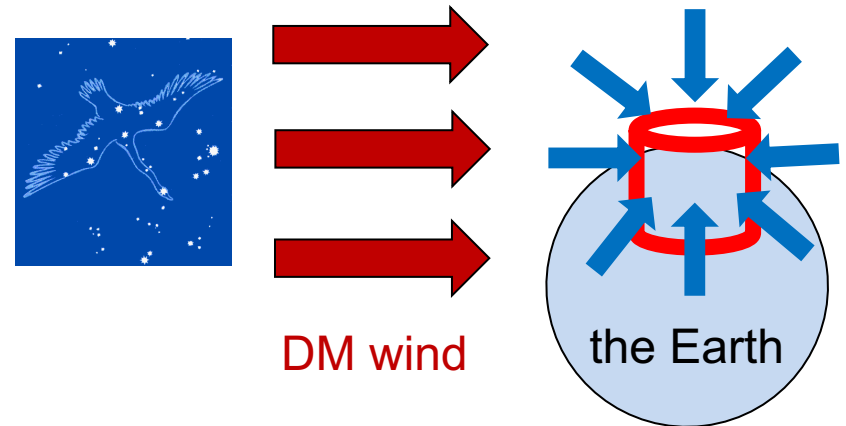
1. Powerful Bkg rejection

Bkg : isotropic

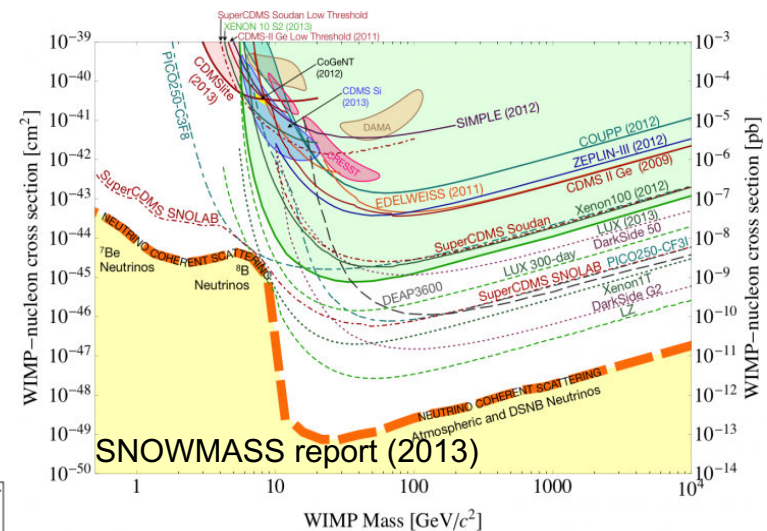
DM signal : come from
direction of the Cygnus

2. Neutrino Floor

3. Annual Modulation

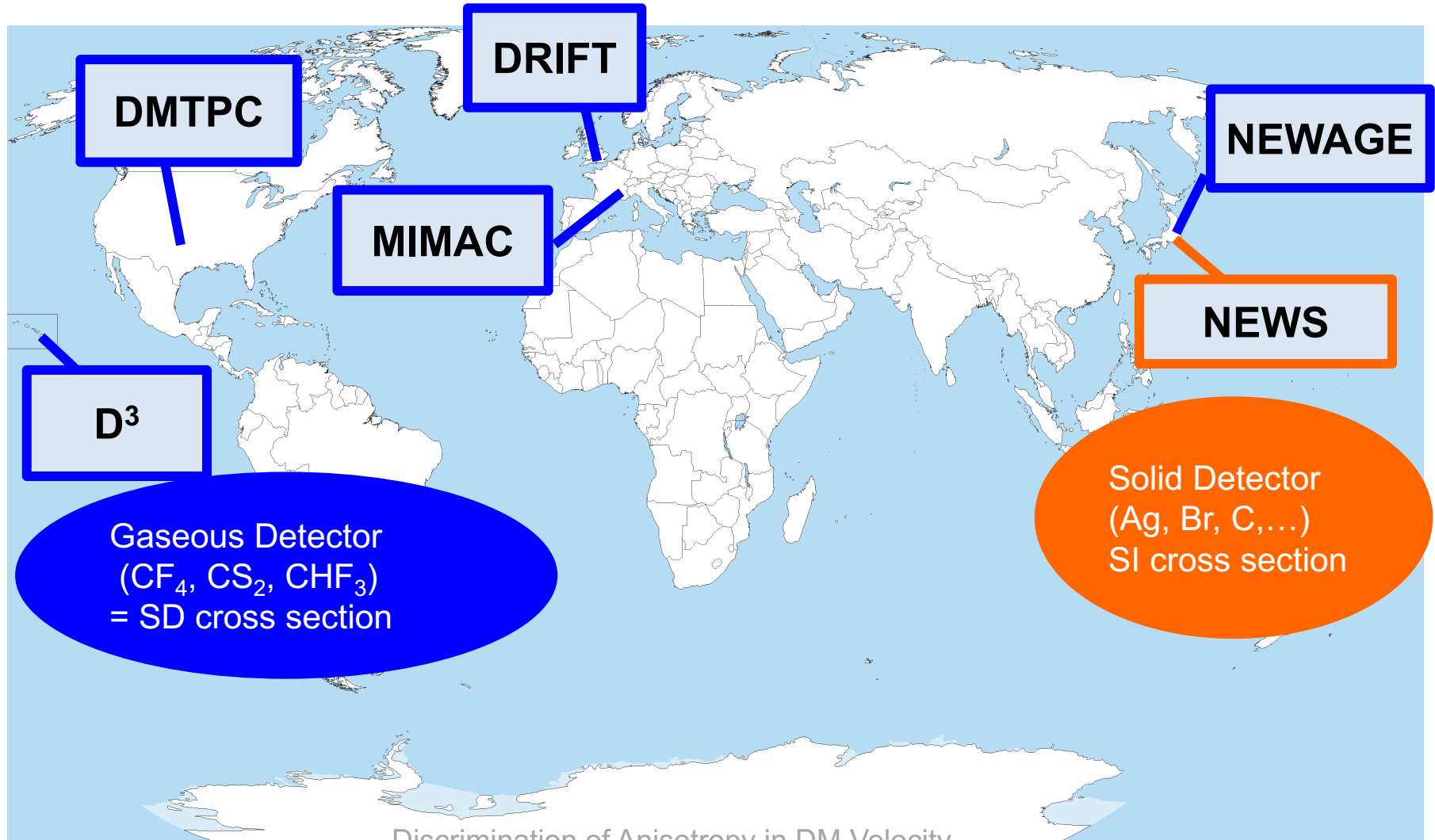


Anisotropy of DM velocity distribution



Directional Searches

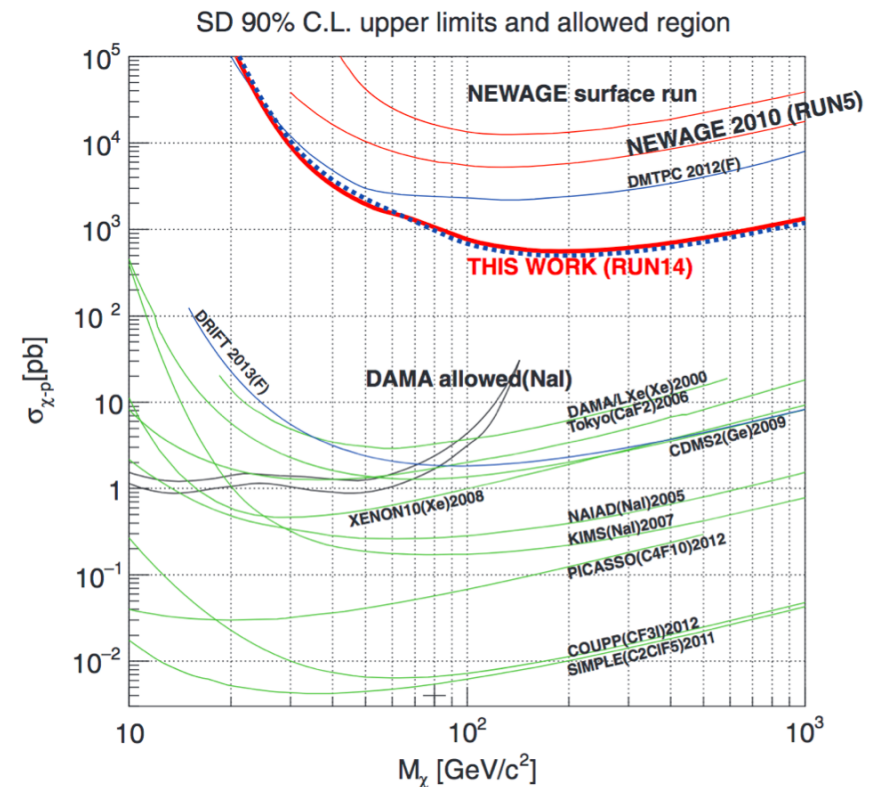
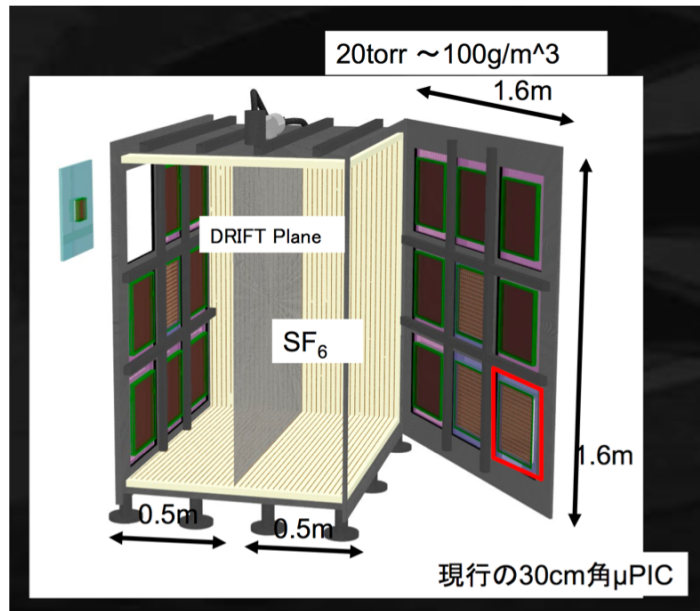
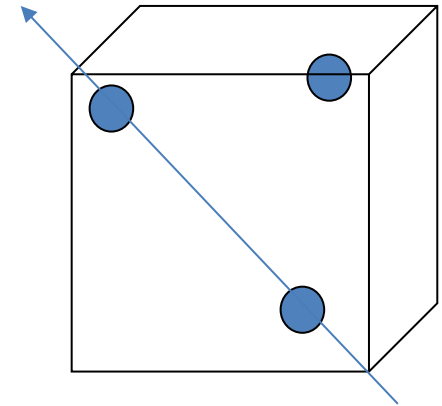
(not complete list)



Discrimination of Anisotropy in DM Velocity
Distribution with Directional Detector

NEWAGE @Kamioka<Kobe U.

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

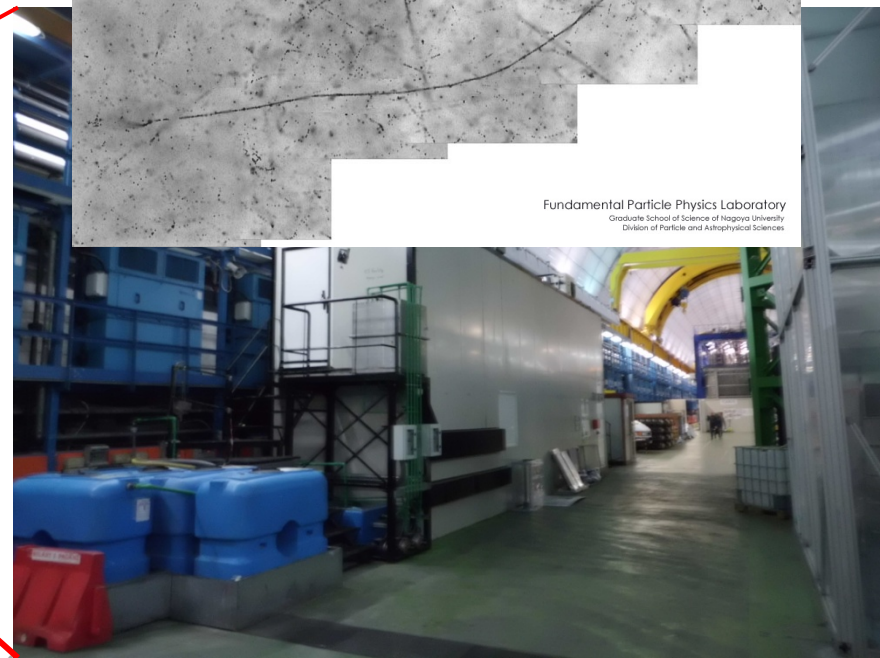
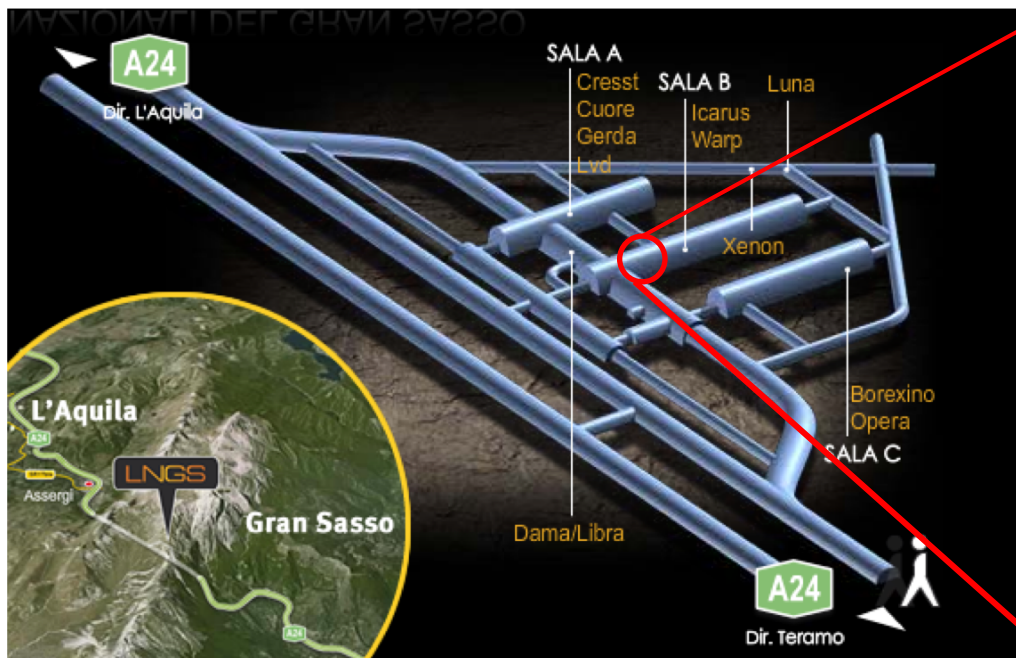
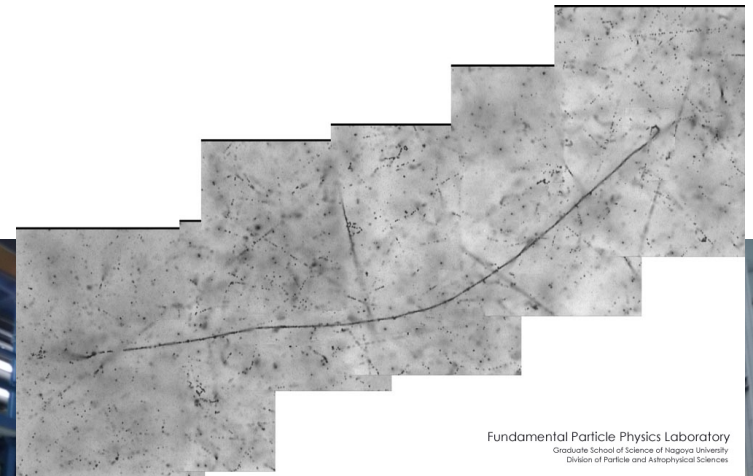
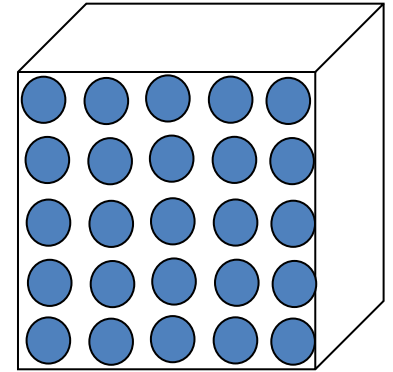


PTEP (2015) 043F01s

Anisotropy of DM velocity distribution

NEWs DM @Gran Sasso < Nagoya U.

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



Anisotropy of DM velocity distribution

Typical Targets

Periodic Table of the Elements

© www.elementsdatabase.com

Legend:

- hydrogen
- alkali metals
- alkali earth metals
- transition metals
- poor metals
- nonmetals
- noble gases
- rare earth metals

The periodic table is color-coded by groups: hydrogen (green), alkali metals (yellow), alkali earth metals (light blue), transition metals (orange), poor metals (blue), nonmetals (white), noble gases (red), and rare earth metals (grey). The elements C, N, O, S, and F are highlighted with blue and orange boxes. The table includes elements from Hydrogen (1) to Oganesson (118), with the lanthanide and actinide series shown separately at the bottom.

1 H	2 He																																						
3 Li	4 Be	5 B	6 C	7 N	8 O	9 F	10 Ne																																
11 Na	12 Mg	13 Al	14 Si	15 P	16 S	17 Cl	18 Ar																																
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr																						
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe																						
55 Cs	56 Ba	57 La	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn																						
87 Fr	88 Ra	89 Ac	104 Unq	105 Unp	106 Unh	107 Uns	108 Uno	109 Une	110 Unn																														
																		58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu								
																		90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr								

Anisotropy of DM velocity distribution



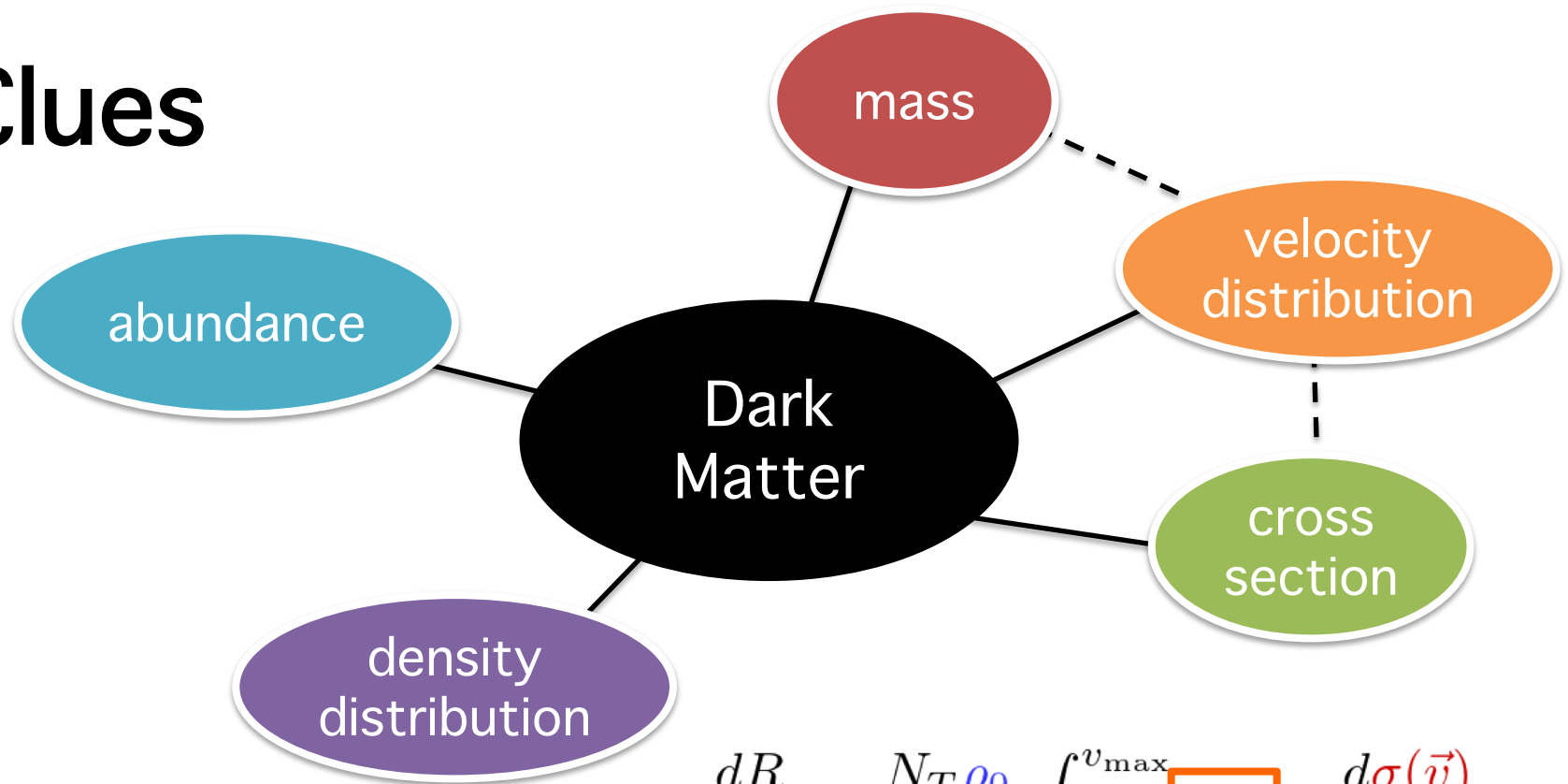
Outline

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



Velocity Distribution of Dark Matter

Clues



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

- ✦ 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

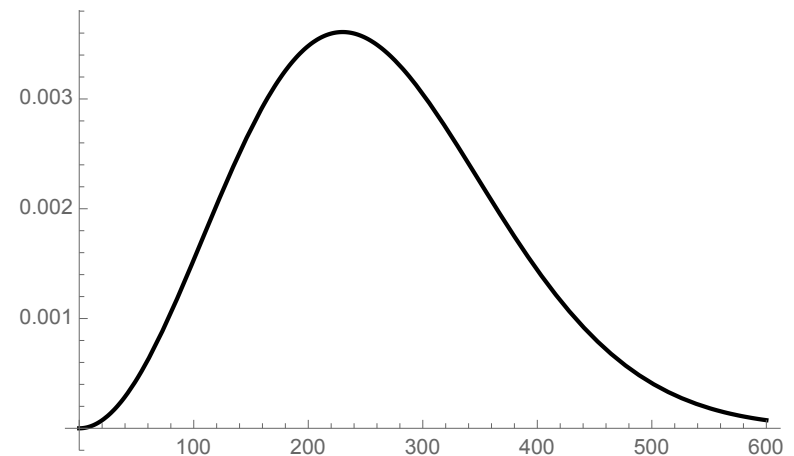
$$f(v) = \frac{1}{(\pi v_0^2)^{3/2}} e^{-(v+v_E)^2/v_0^2}$$

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

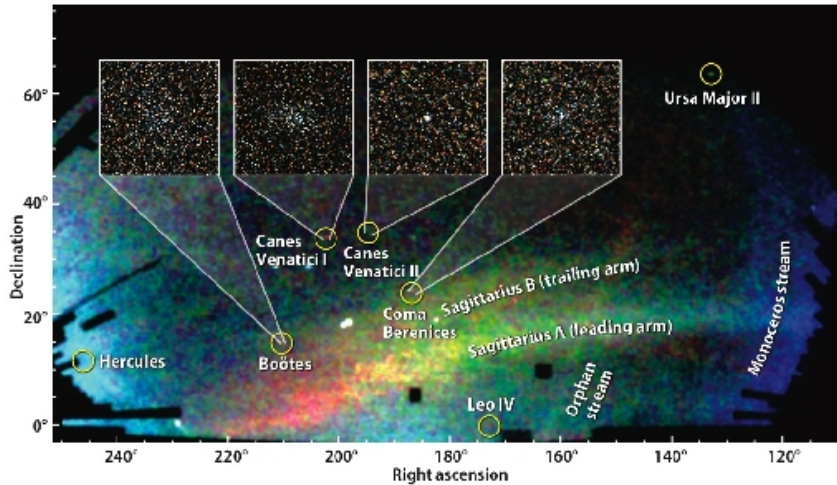
□ Isothermal

□ Isotropic

✦ But it may not be true.

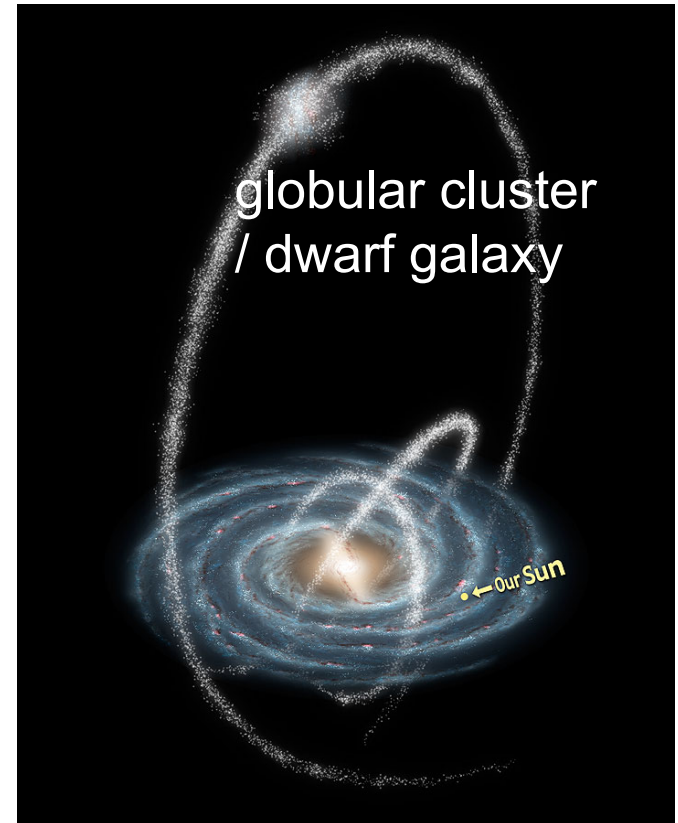


Stellar streams (潮汐流)



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

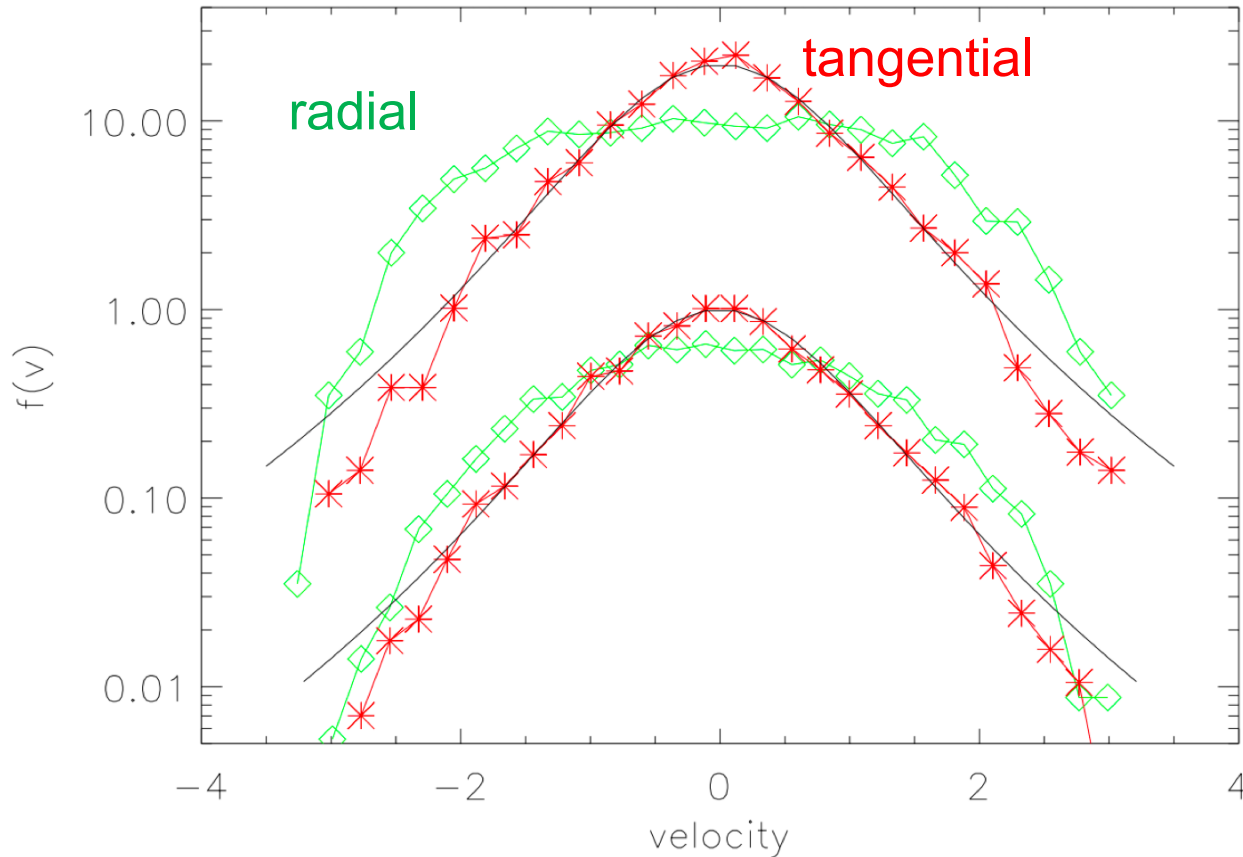
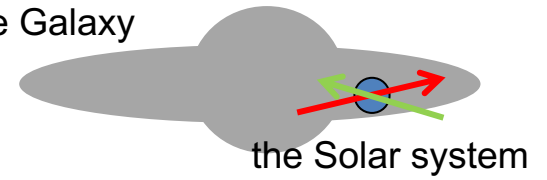
Sloan Digital Sky Survey II data (2006)



Anisotropy of DM velocity distribution

Anisotropy

the Galaxy



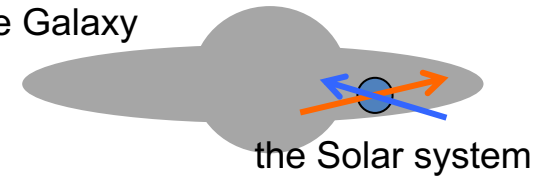
0812.1048

cosmological simulation by Sommer-Larsen [astro-ph/0602595](#), [astro-ph/0204366](#)

Anisotropy of DM velocity distribution

Co-rotating DM

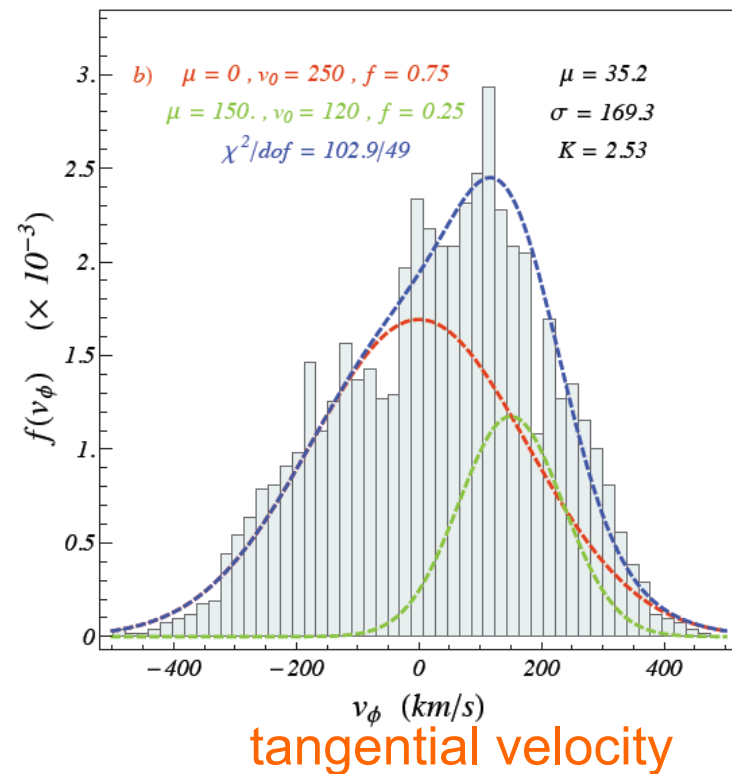
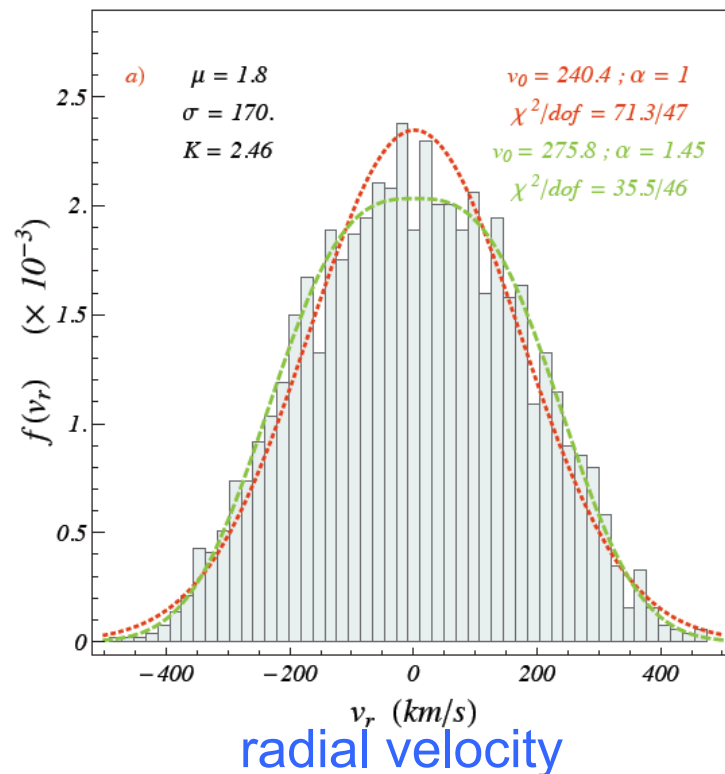
the Galaxy



the Solar system

- ★ 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) ...



Anisotropy of DM velocity distribution

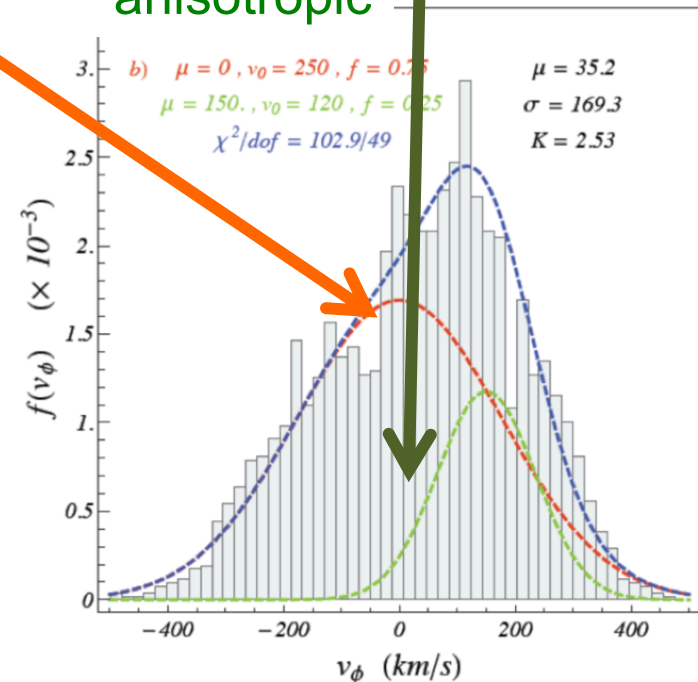
Anisotropy parameter “r”

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

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 ($r=0.2-0.3$)





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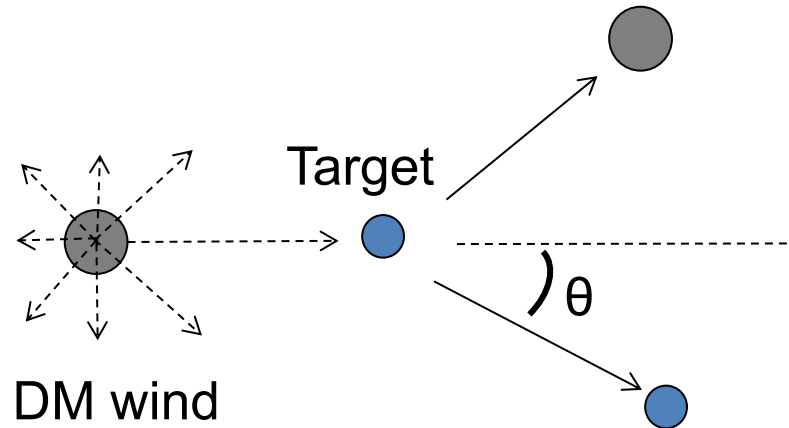
Velocity Distribution observed in Directional Detector

cf.

Ben Morgan, Anne M. Green, Neil J. C. Spooner (2004)

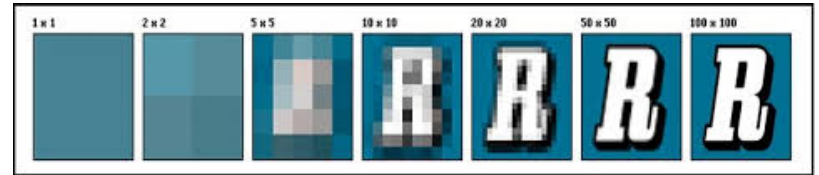
Ole Host, Steen H Hansen (2007)

Set up of simulation



- ✦ Monte Carlo simulation of scattering supposing $f(v)$
 - Direction (scattering angle)
 - Recoil energy
- ✦ Elastic scattering
- ✦ mass relation $m_{\text{dm}} = 3m_{\text{N}}$ 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

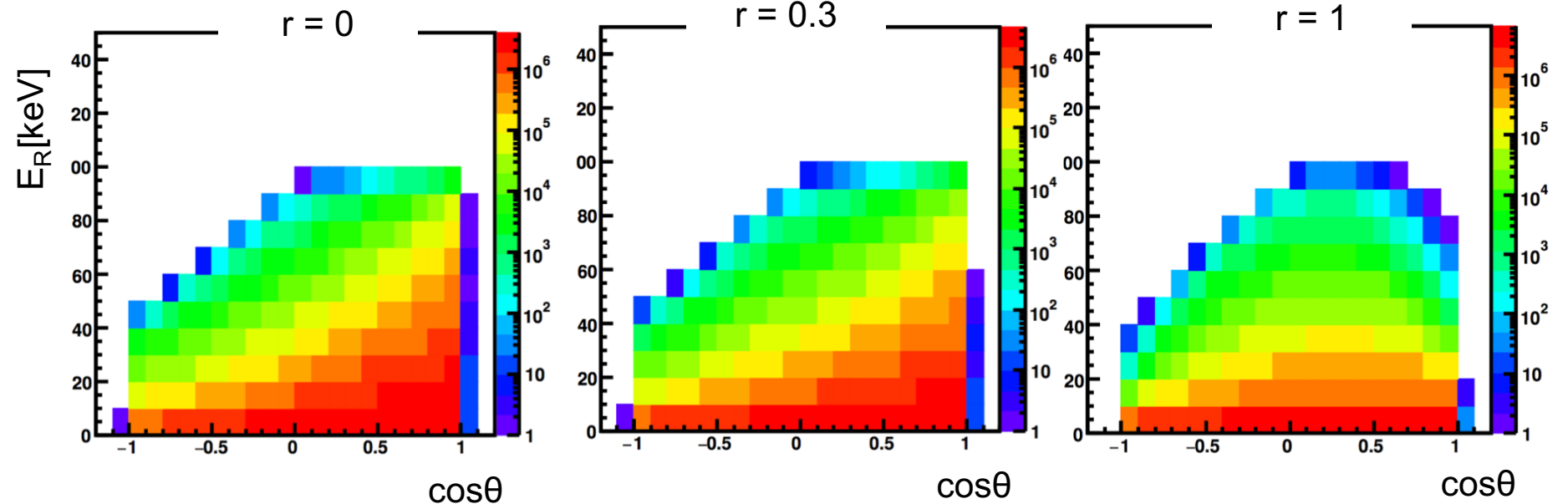
Limited information,
but maybe worth to study

Energy resolution :OK
Angular resolution :OK

Most hopeful case!

Energy-angular distribution

light target (F)

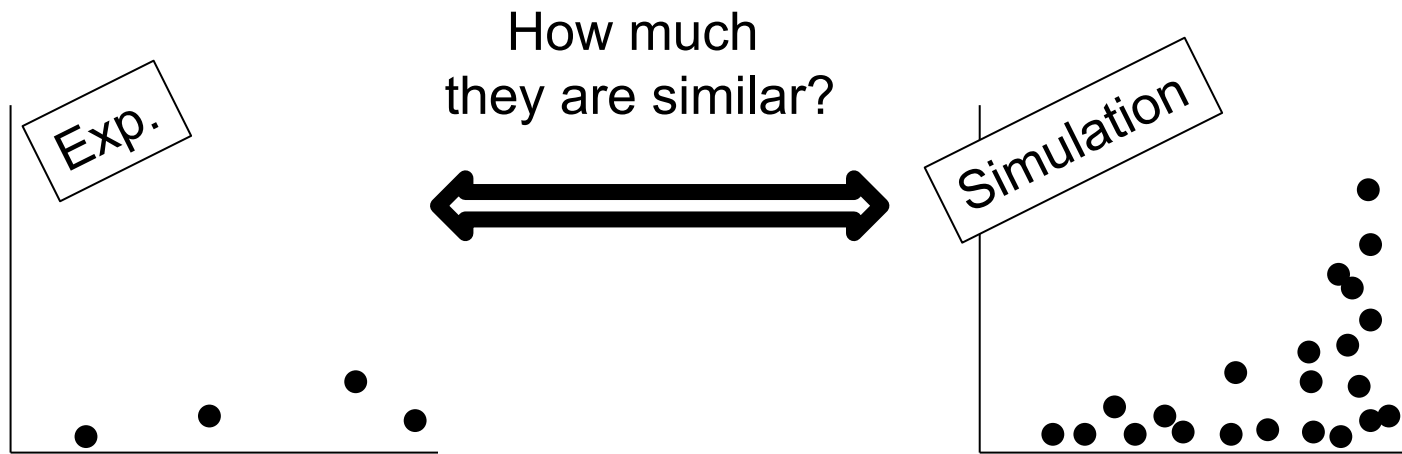


$E_{thr} = 0 \text{ keV}$

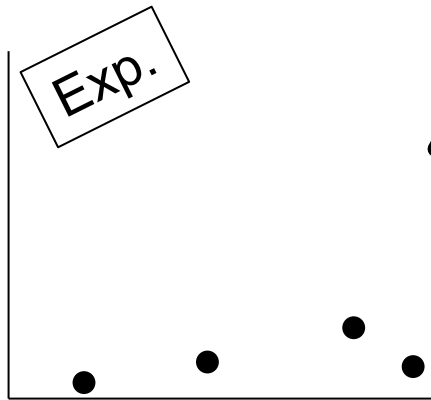
- ❑ Isotropic one does not differ from anisotropic one so much.
- ❑ Method to compare similar distributions is required.

Anisotropy of DM velocity distribution

Strategy



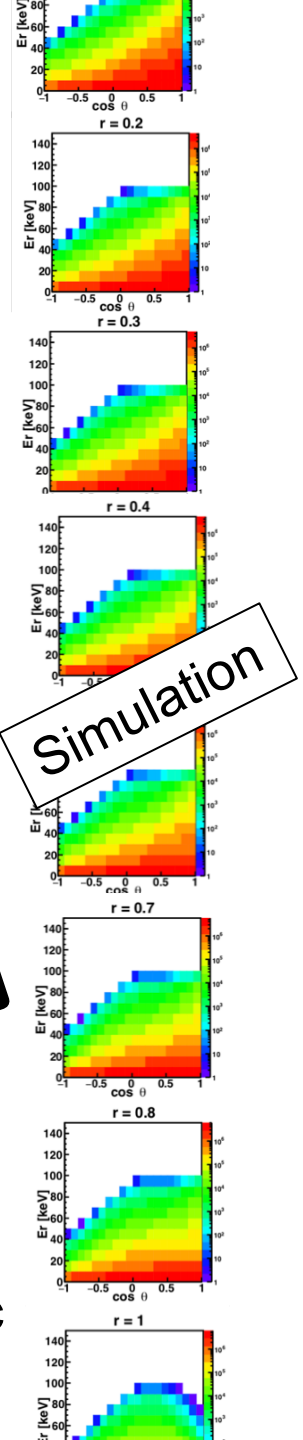
Strategy



Isotropic

Which one is the most similar to Exp.?

Anisotropic



✦ Statistical test to examine the similarity of distributions.

- ❑ Chi-squared test
- ❑ Kolmogorov–Smirnov test
- ❑ ...

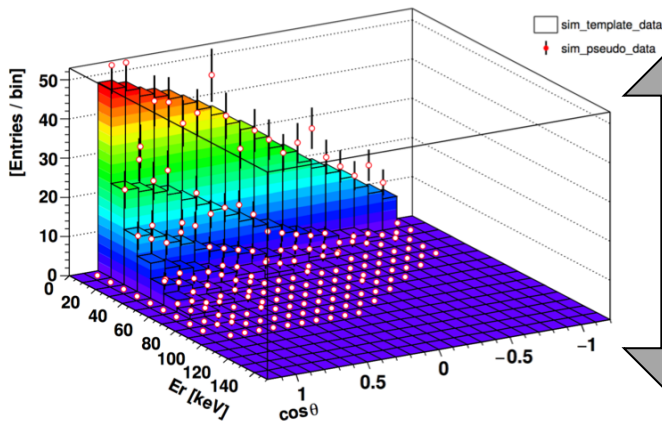
Anisotropy of DM velocity distribution

Chi squared test

Many Data
(#10⁸)

- ✓ ideal
- ✓ difficult to achieve

ideal “**template**”



Fewer Data
(#10⁴)

- ✓ realistic
(relatively...)

“**pseudo-experimental**” data

chi squared test

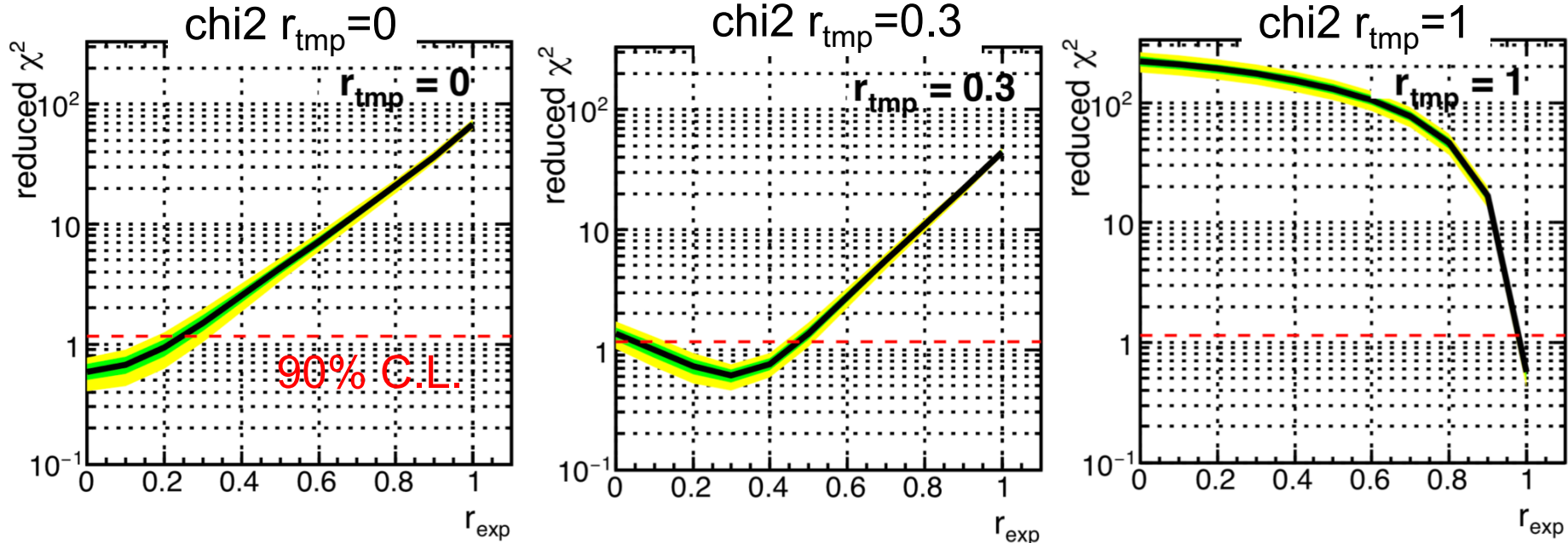
$$\chi^2 = \sum \frac{(\text{observed} - \text{expected})^2}{\text{expected}}$$

Chi squared test of E_R -cos θ

(light target)

#exp.= $6 \cdot 10^3$

E_{thr}=20keV (F)

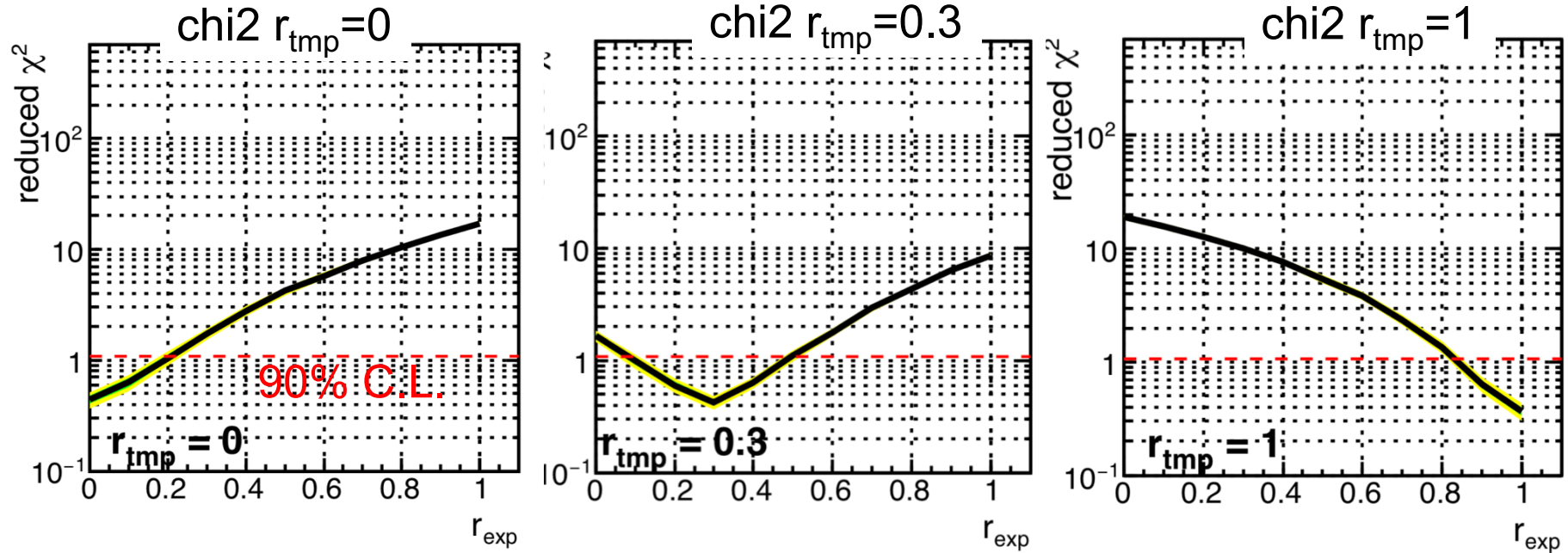


- ✓ If $r=0.3$, isotropic case ($r=0$) can be excluded at 90% C.L.
- ✓ Energy threshold is a factor to clearly characterize the difference between $r=0$ and 0.3.

Chi squared test of E_R -cos θ

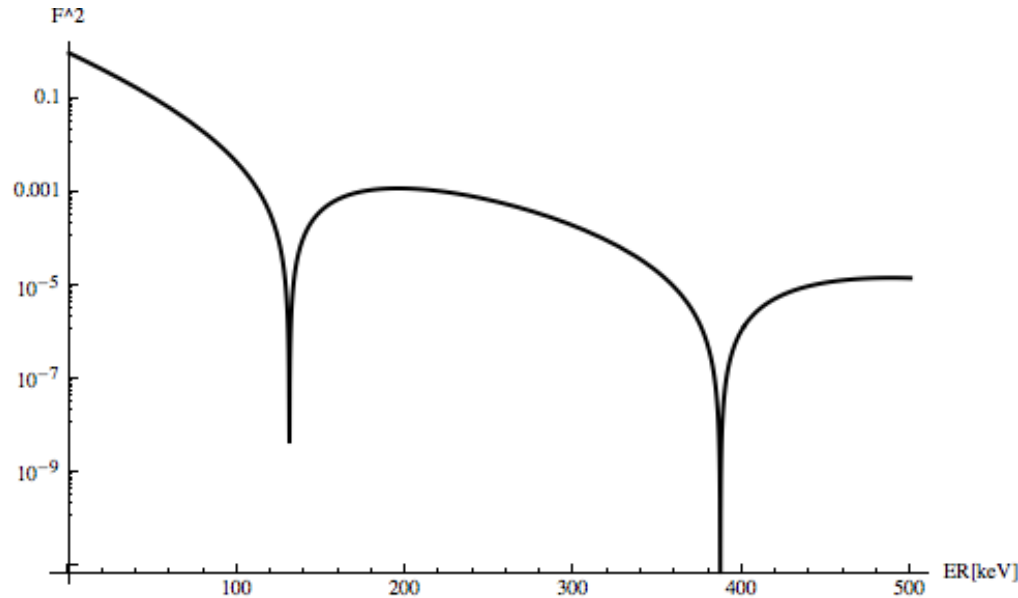
(heavy target)

#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).

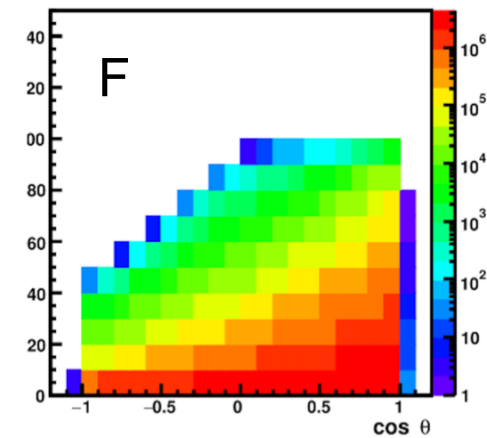
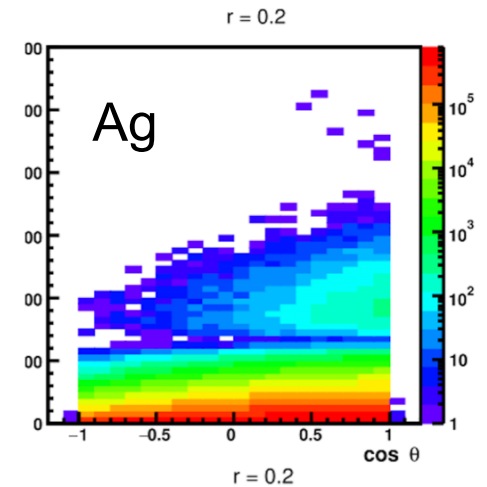
Form factor



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

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

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



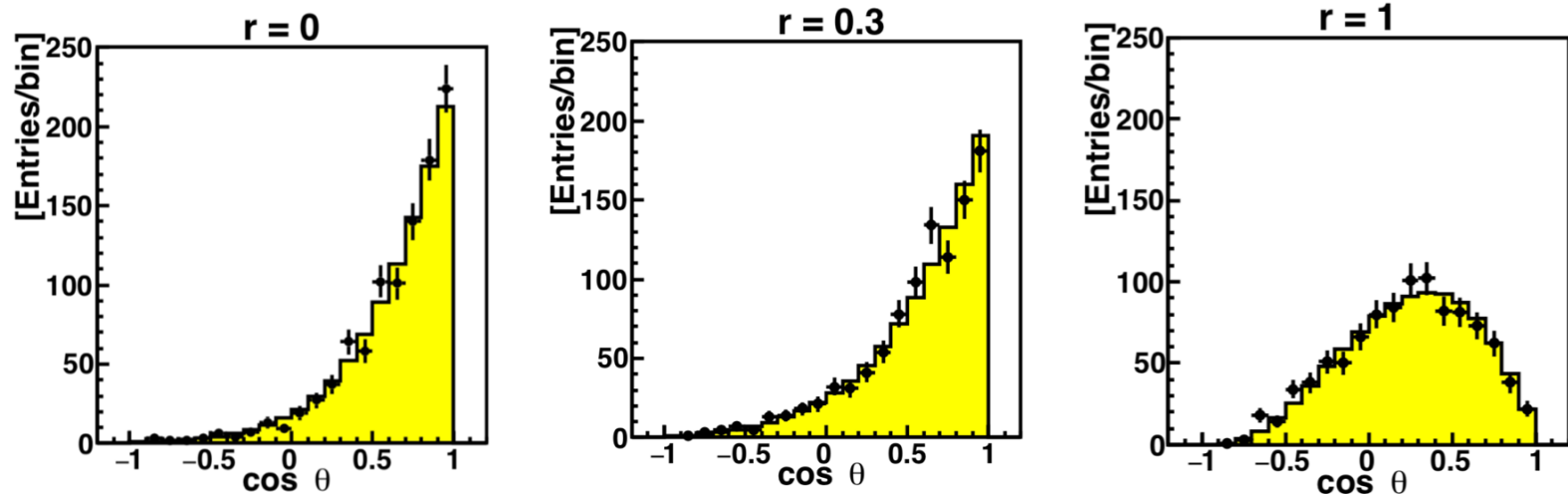
Energy resolution :NG
Angular resolution :OK

Limited information,
but maybe worth to study

Directionality Histogram

(light target)

E_{thr}=20keV (Light target F)

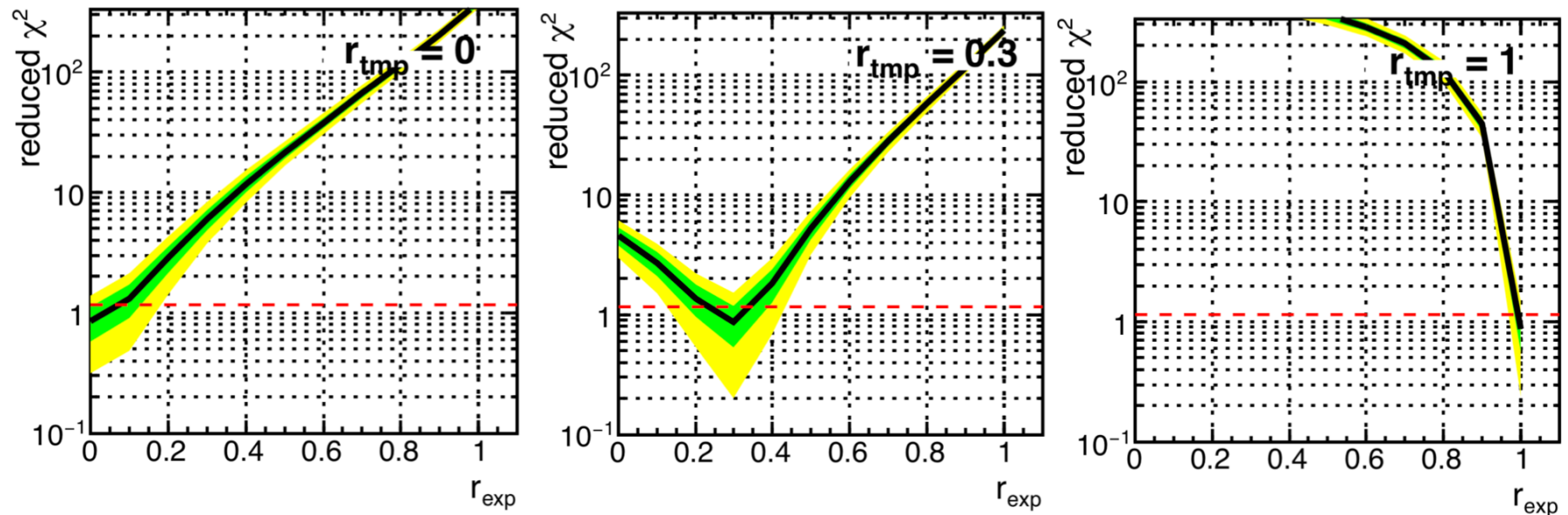


- ✓ Shape for $r=0.3$ is quite similar to that for $r=0$. It is same for heavy target case.
- ✓ We need statistical test again.

Chi-squared test of directionality

✦ Chi squared test (light target)

#exp.= $5 \cdot 10^3$
Ethr=20keV (F)

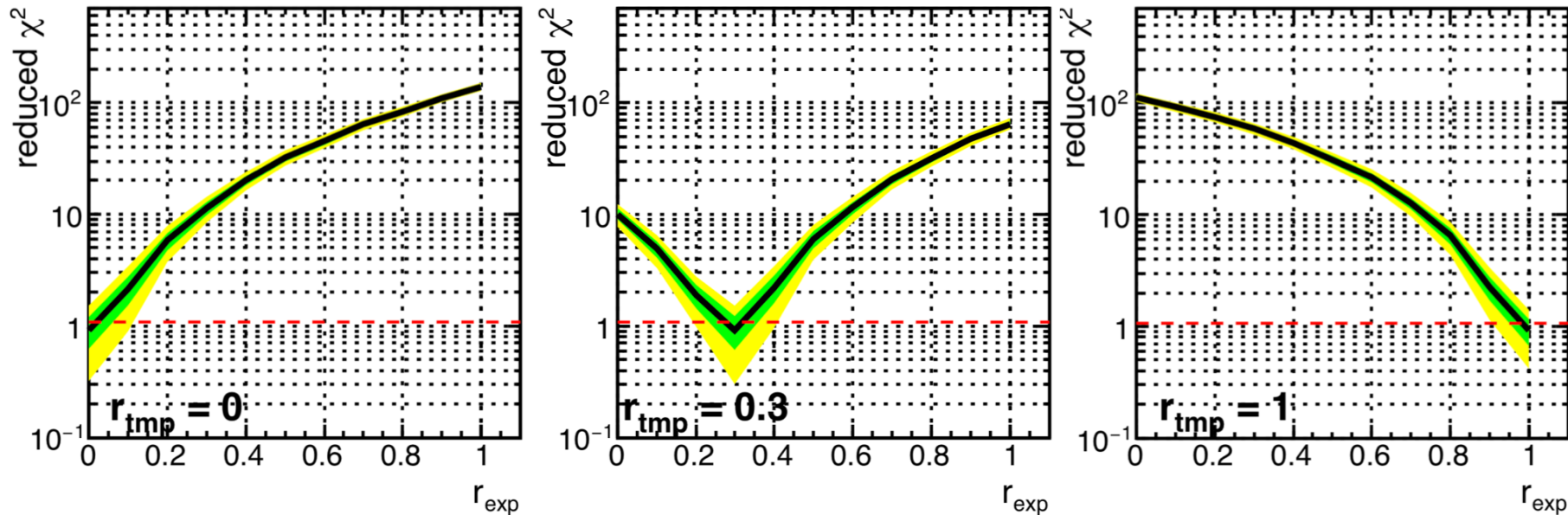


Anisotropy of DM velocity distribution

Chi-squared test of directionality

✦ Chi squared test (heavy target)

#exp.= $6 \cdot 10^4$
Ethr=50keV (Ag)



Anisotropy of DM velocity distribution

[ER+ θ] is worse than only [θ]?

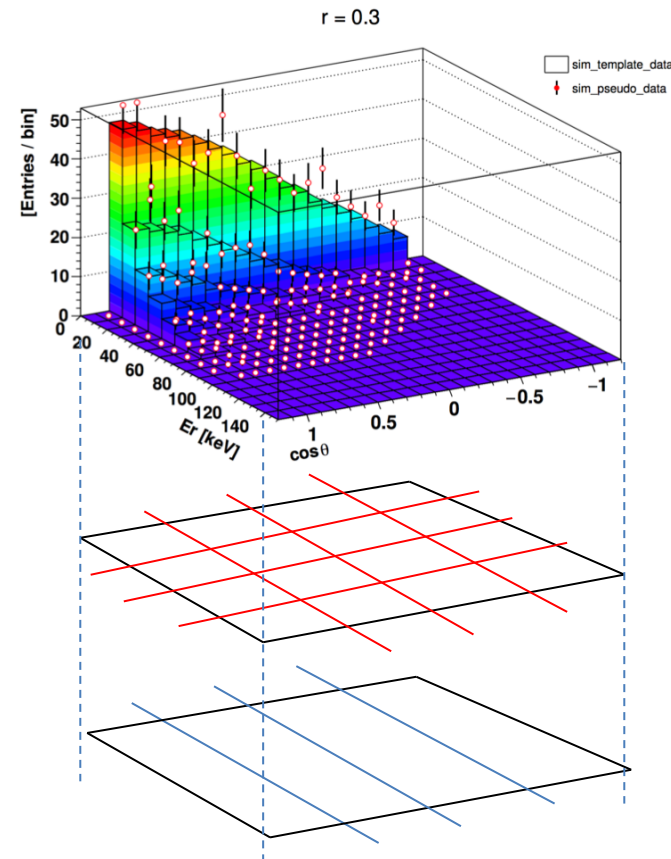
✦ To discriminate the anisotropy, required event # are...

- $6 \times 10^3 / 6 \times 10^4$
(Energy-angular distribution)

- $5 \times 10^3 / 2 \times 10^4$
(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 - $\cos \theta$ distribution
/ directionality histogram

Thank you for your attention.



Anisotropy of DM velocity distribution