

Anisotropy of dark matter velocity distribution

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arXiv:1707.05523

Dark Matter

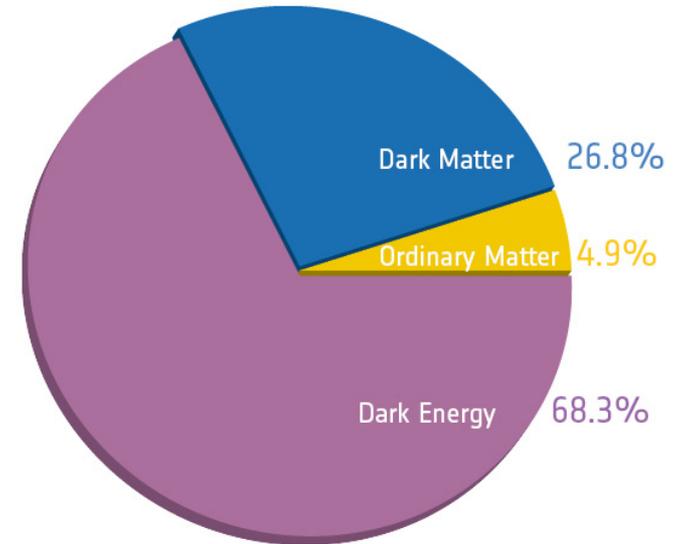
✦ No good candidate in SM

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

...Weakly interacting massive particle (WIMP)?

✦ Observations

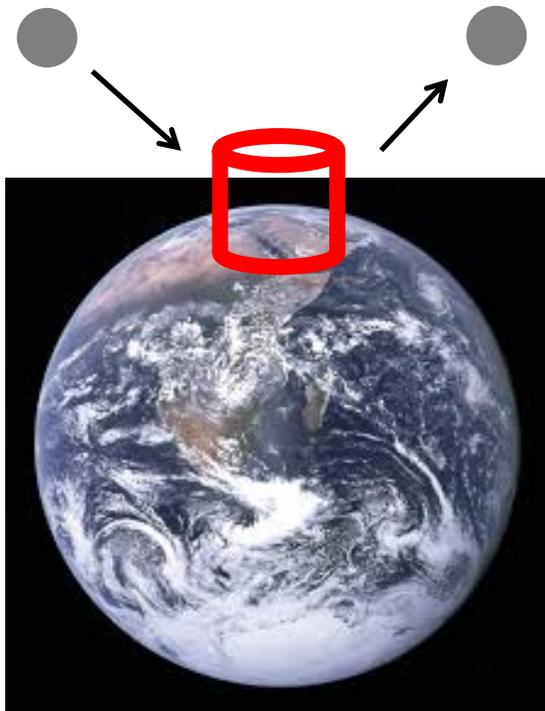
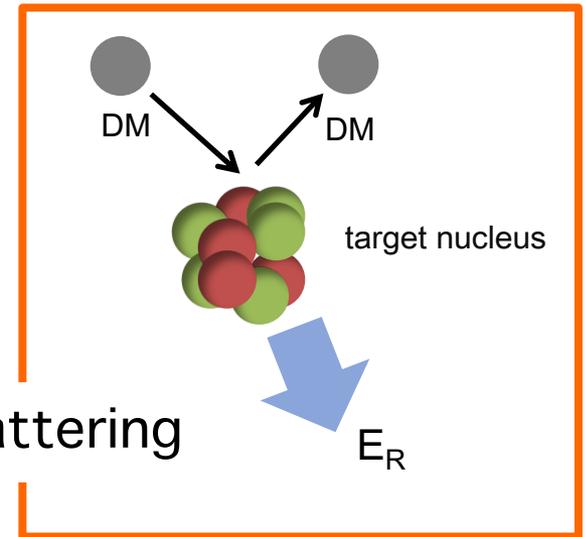
- cosmological measurements
- **direct detections**
- indirect detections
- search at colliders



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

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

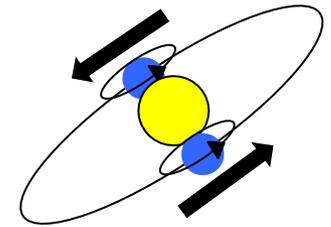
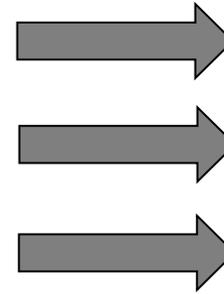
Anisotropy of DM velocity distribution

Directional detection

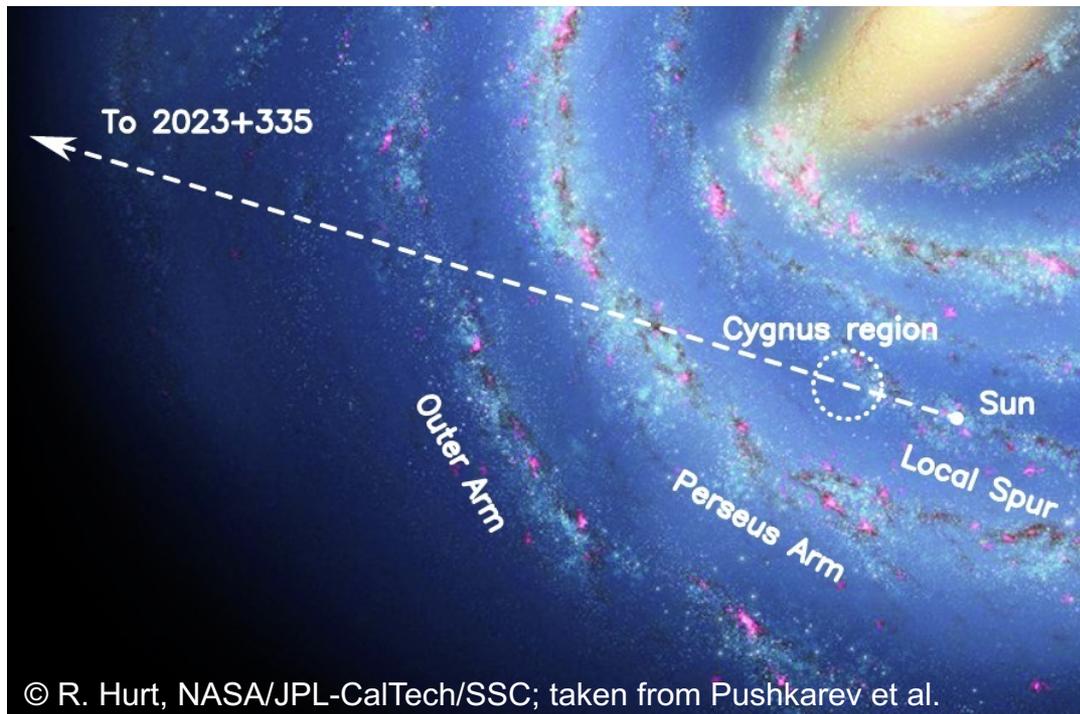
- ✦ Direction of DM
 - detect not only the recoil energy but also **direction** where DM comes from.



DM wind

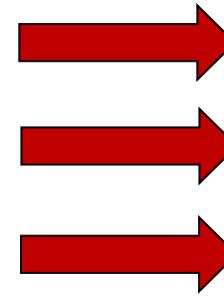
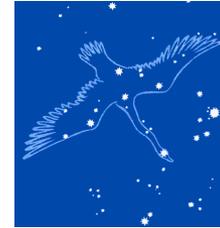


the Solar system

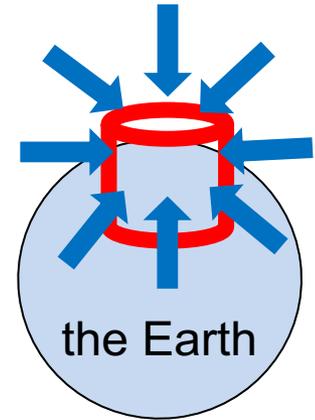


Anisotropy of DM velocity distribution

Advantages of directionality



DM wind

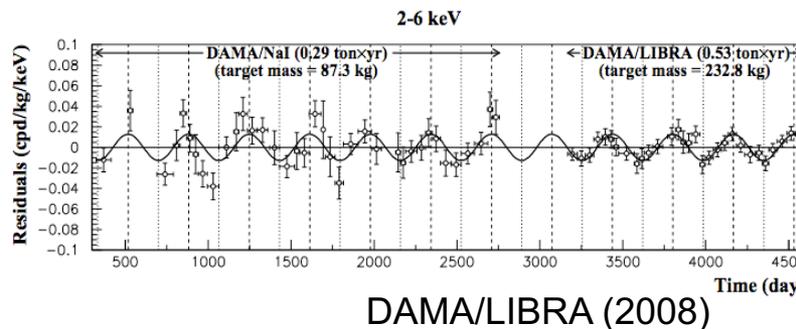


the Earth

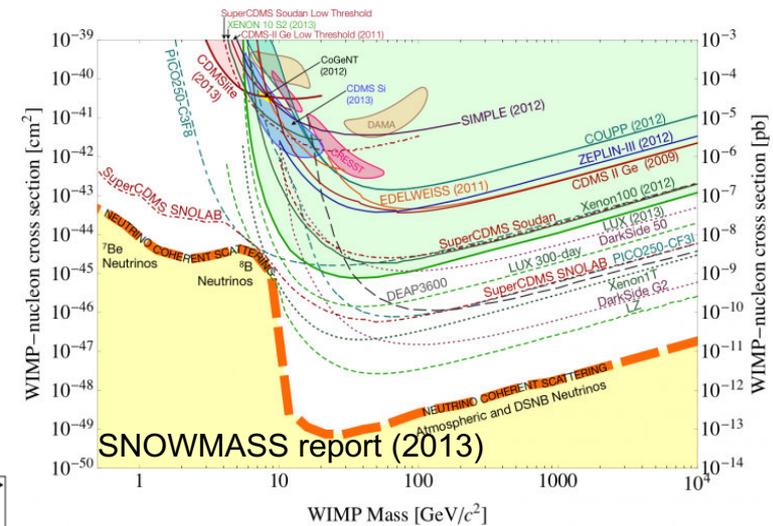
1. Powerful Bkg rejection
 Bkg : isotropic
 DM signal : come from direction of the Cygnus

2. Neutrino Floor

3. Annual Modulation

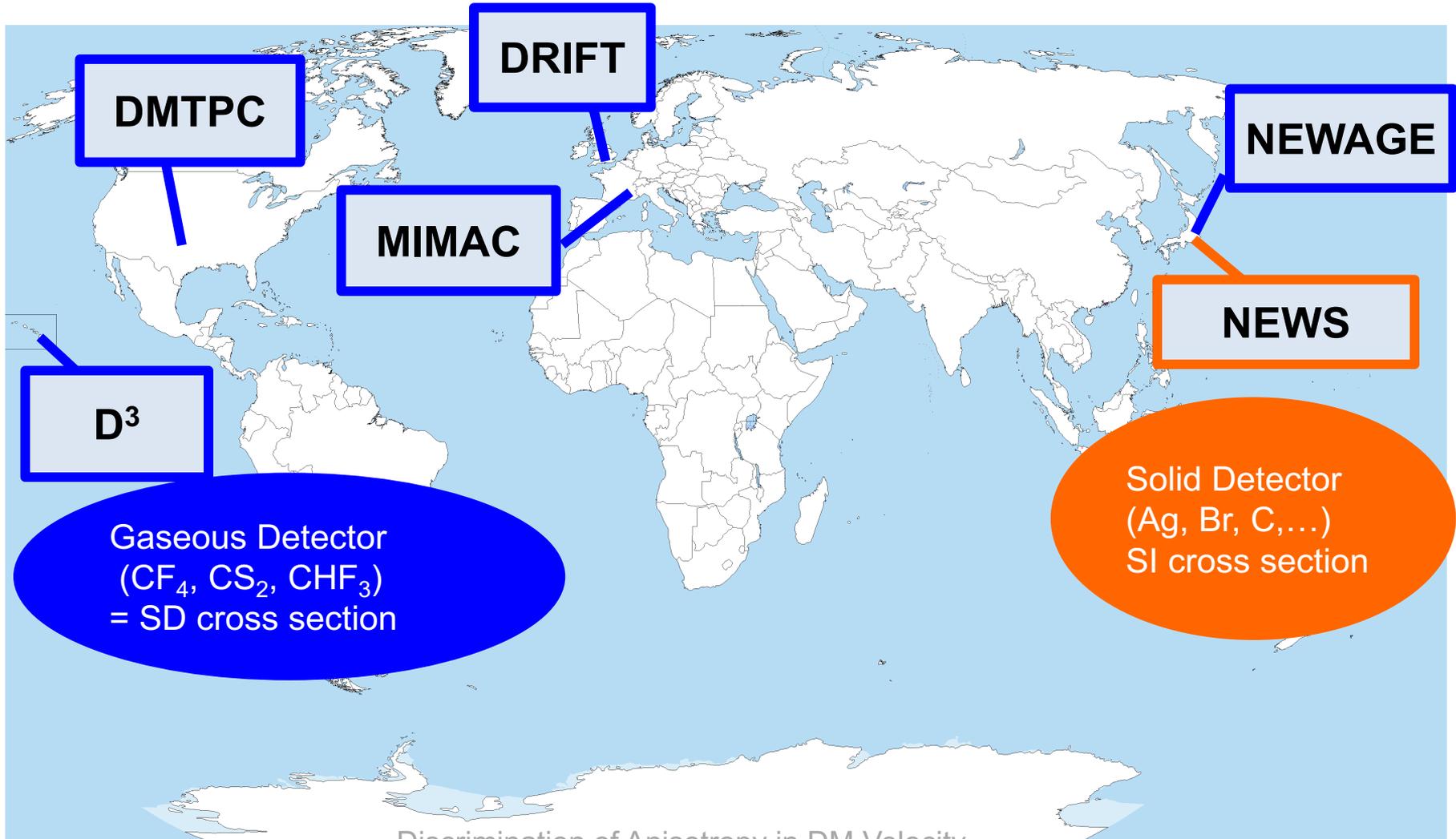


Anisotropy of DM velocity distribution



Directional Searches

(not complete list)



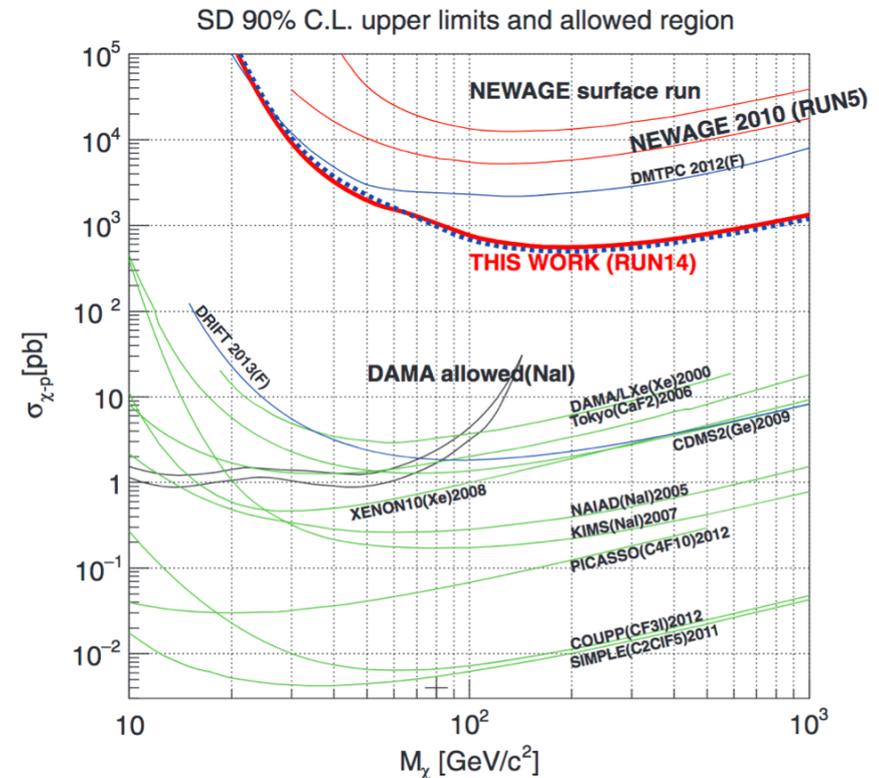
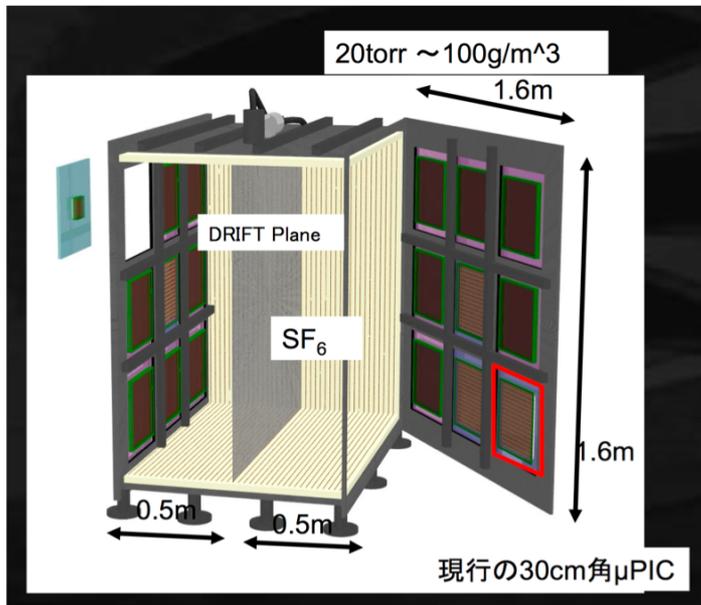
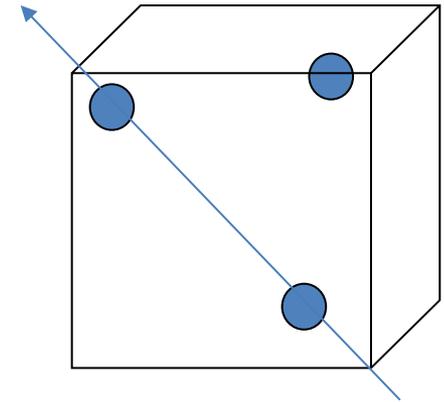
Gaseous Detector
(CF_4 , CS_2 , CHF_3)
= SD cross section

Solid Detector
(Ag, Br, C,...)
SI cross section

Discrimination of Anisotropy in DM Velocity
Distribution with Directional Detector

NEWAGE @Kamioka<Kobe U.

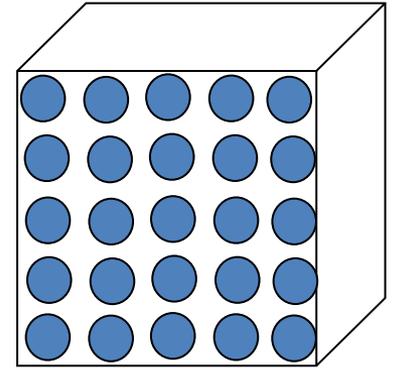
- ✓ CF₄, SF₆ Gass=focusing directionality
- ✓ SD interaction
- ✓ Time information
- ✓ Low mass



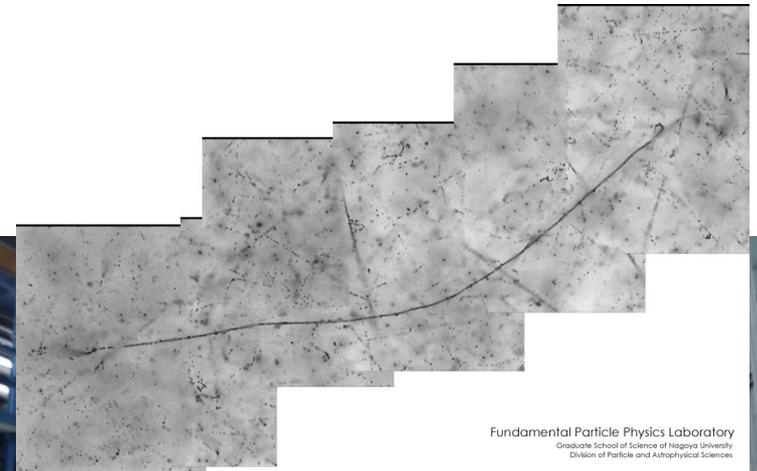
PTEP (2015) 043F01s

Anisotropy of DM velocity distribution

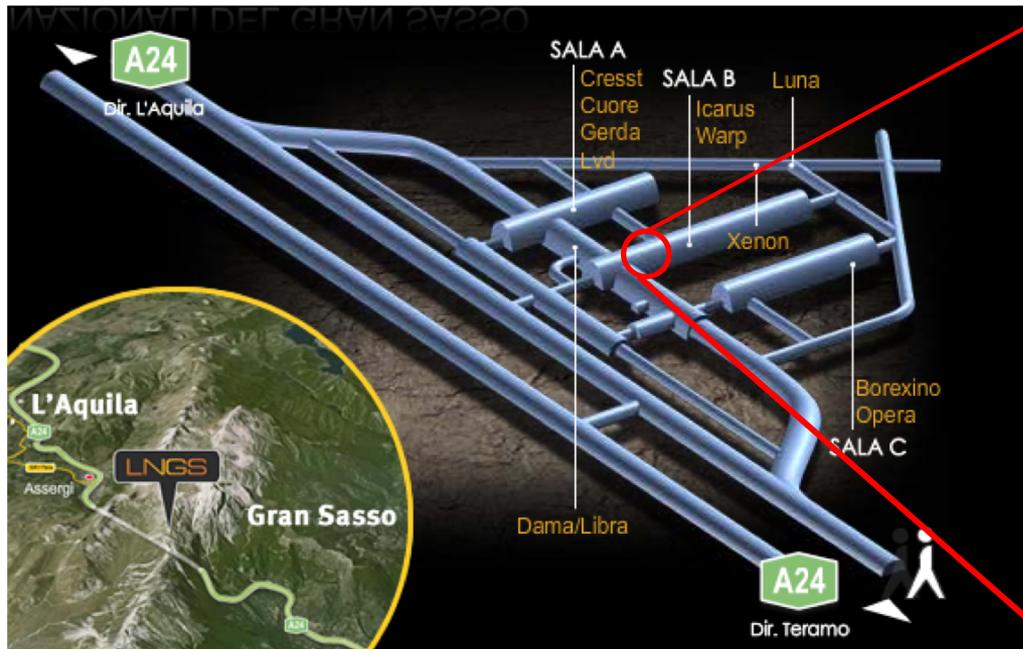
NEWS DM @Gran Sasso < Nagoya U.



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



Fundamental Particle Physics Laboratory
Graduate School of Science of Nagoya University
Division of Particle and Astrophysical Sciences



Typical Targets

Periodic Table of the Elements © www.elementsdatabase.com

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

H ¹																	He ²
Li ³	Be ⁴											B ⁵	C ⁶	N ⁷	O ⁸	F ⁹	Ne ¹⁰
Na ¹¹	Mg ¹²											Al ¹³	Si ¹⁴	P ¹⁵	S ¹⁶	Cl ¹⁷	Ar ¹⁸
K ¹⁹	Ca ²⁰	Sc ²¹	Ti ²²	V ²³	Cr ²⁴	Mn ²⁵	Fe ²⁶	Co ²⁷	Ni ²⁸	Cu ²⁹	Zn ³⁰	Ga ³¹	Ge ³²	As ³³	Se ³⁴	Br ³⁵	Kr ³⁶
Rb ³⁷	Sr ³⁸	Y ³⁹	Zr ⁴⁰	Nb ⁴¹	Mo ⁴²	Tc ⁴³	Ru ⁴⁴	Rh ⁴⁵	Pd ⁴⁶	Ag ⁴⁷	Cd ⁴⁸	In ⁴⁹	Sn ⁵⁰	Sb ⁵¹	Te ⁵²	I ⁵³	Xe ⁵⁴
Cs ⁵⁵	Ba ⁵⁶	La ⁵⁷	Hf ⁷²	Ta ⁷³	W ⁷⁴	Re ⁷⁵	Os ⁷⁶	Ir ⁷⁷	Pt ⁷⁸	Au ⁷⁹	Hg ⁸⁰	Tl ⁸¹	Pb ⁸²	Bi ⁸³	Po ⁸⁴	At ⁸⁵	Rn ⁸⁶
Fr ⁸⁷	Ra ⁸⁸	Ac ⁸⁹	Unq ¹⁰⁴	Unp ¹⁰⁵	Unh ¹⁰⁶	Uns ¹⁰⁷	Uno ¹⁰⁸	Une ¹⁰⁹	Unn ¹¹⁰								

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



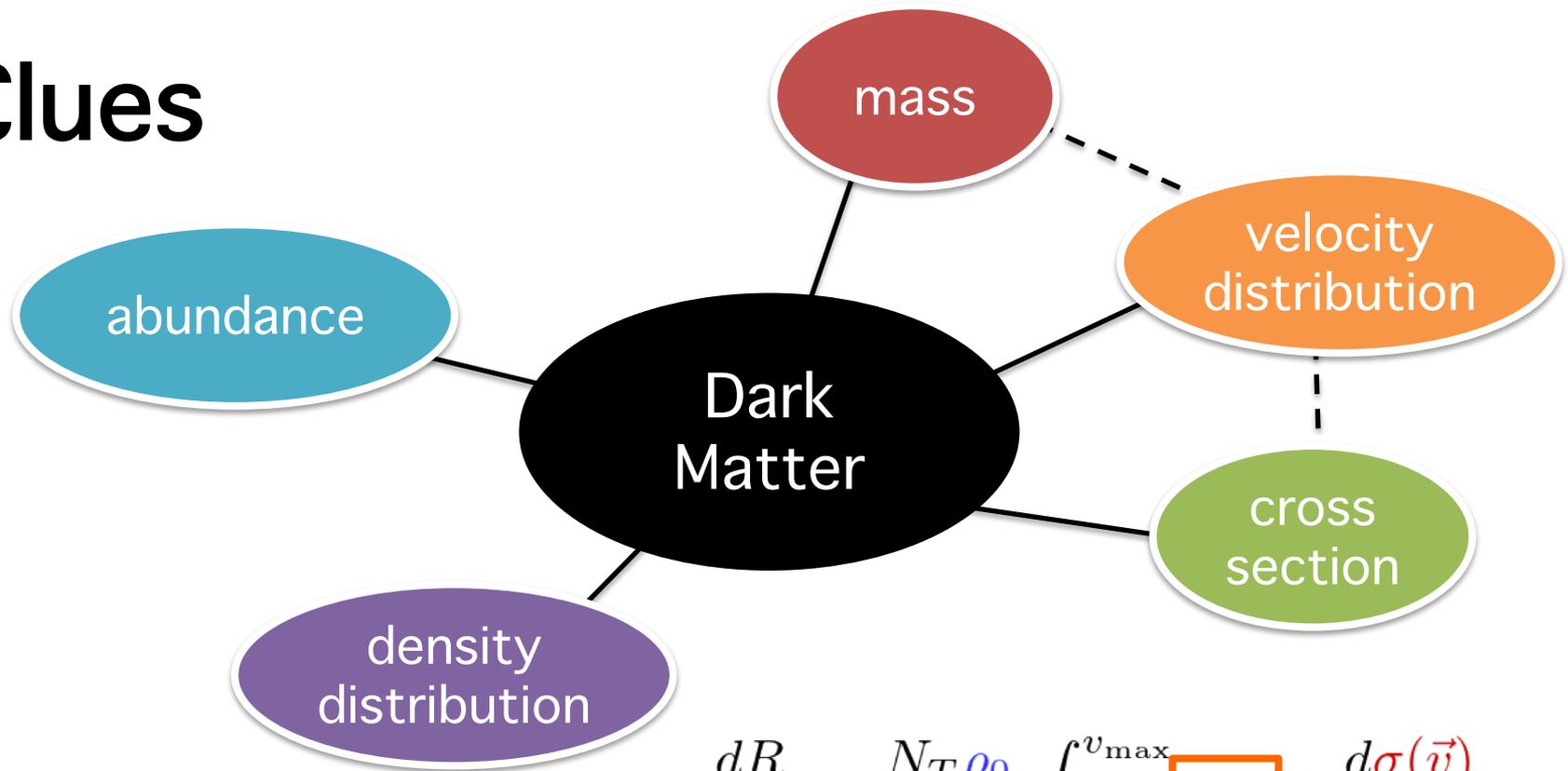
Outline

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

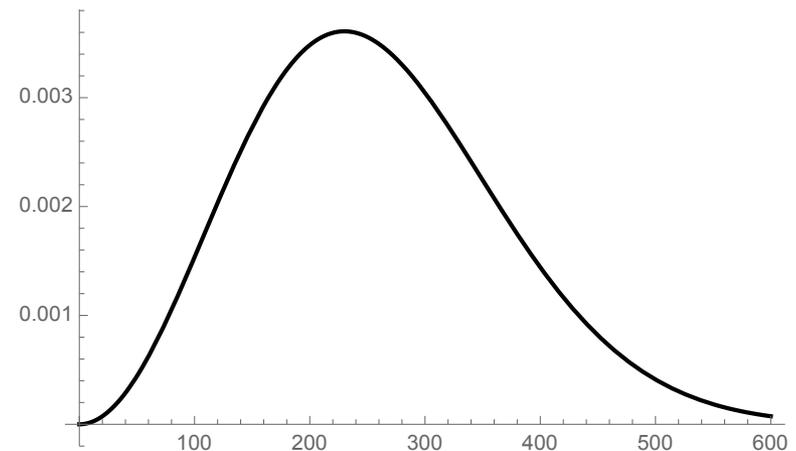
$$f(v) = \frac{1}{(\pi v_0^2)^{3/2}} e^{-(v+v_E)^2/v_0^2}$$

□ Isothermal

□ Isotropic

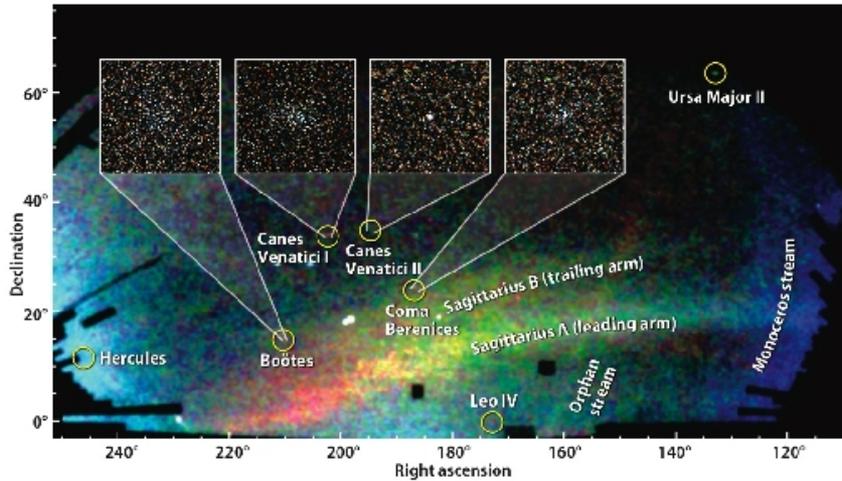
✦ But it may not be true.

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

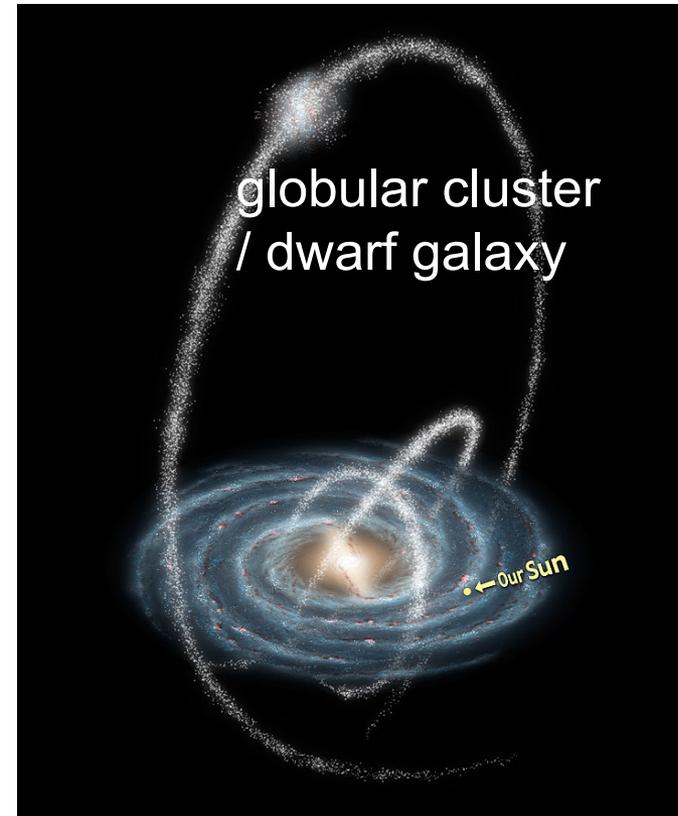


Anisotropy of DM velocity distribution

Stellar streams (潮汐流)



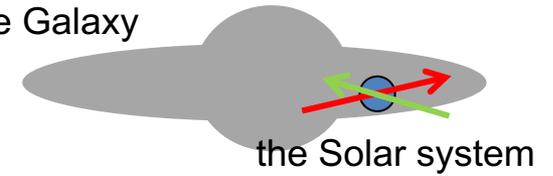
Sloan Digital Sky Survey II data (2006)



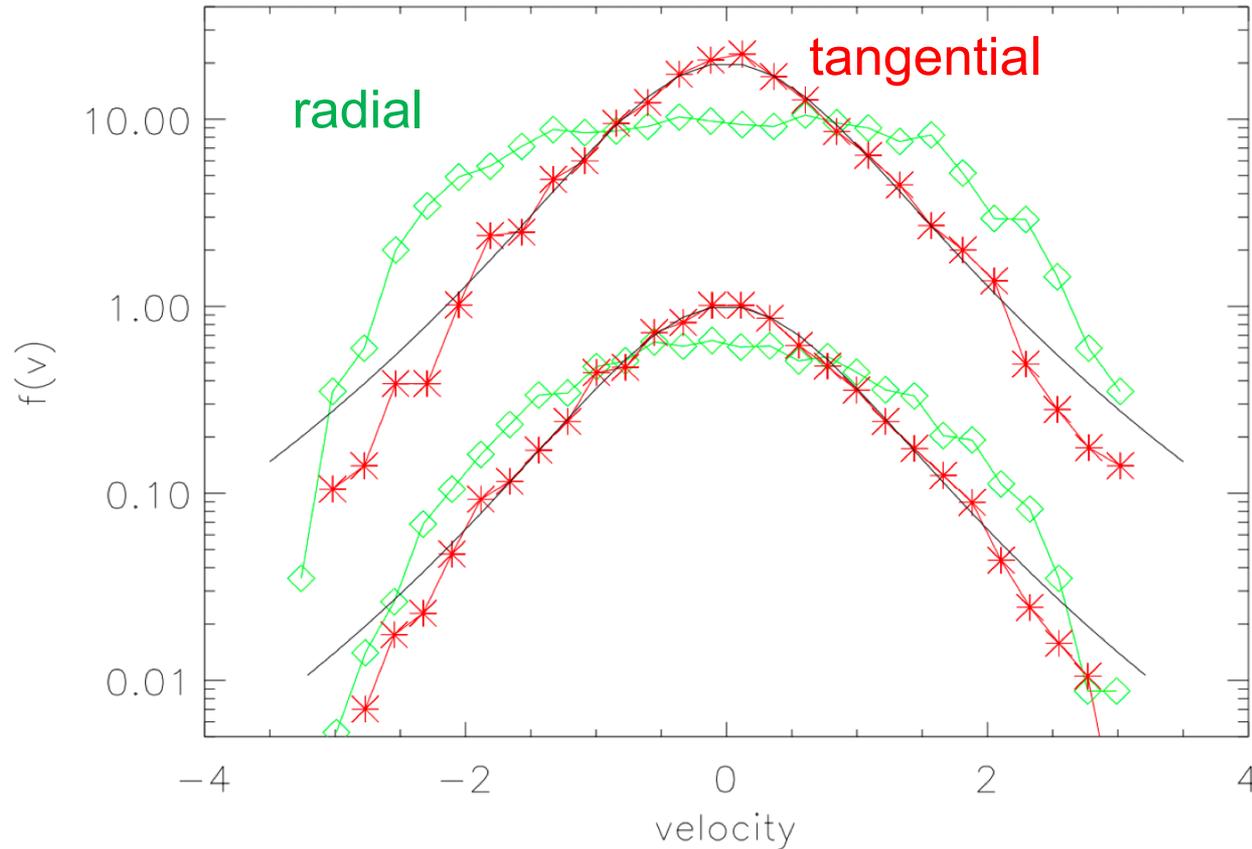
A stellar stream is torn apart and stretched out along its orbit by tidal forces, and flow into a galaxy.

Anisotropy

the Galaxy



the Solar system



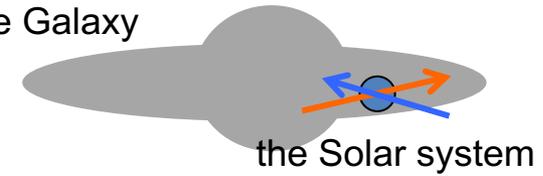
0812.1048

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

Anisotropy of DM velocity distribution

Co-rotating DM

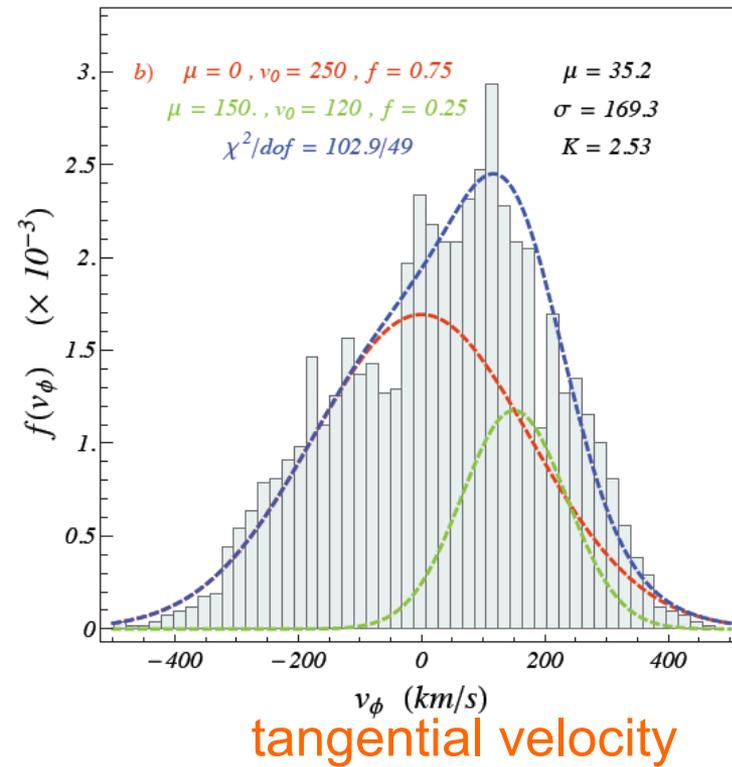
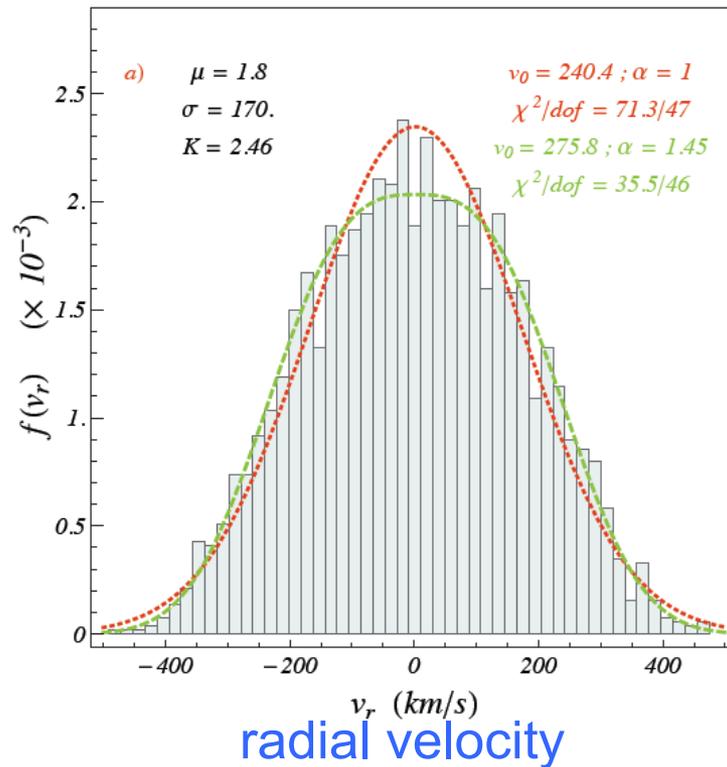
the Galaxy



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

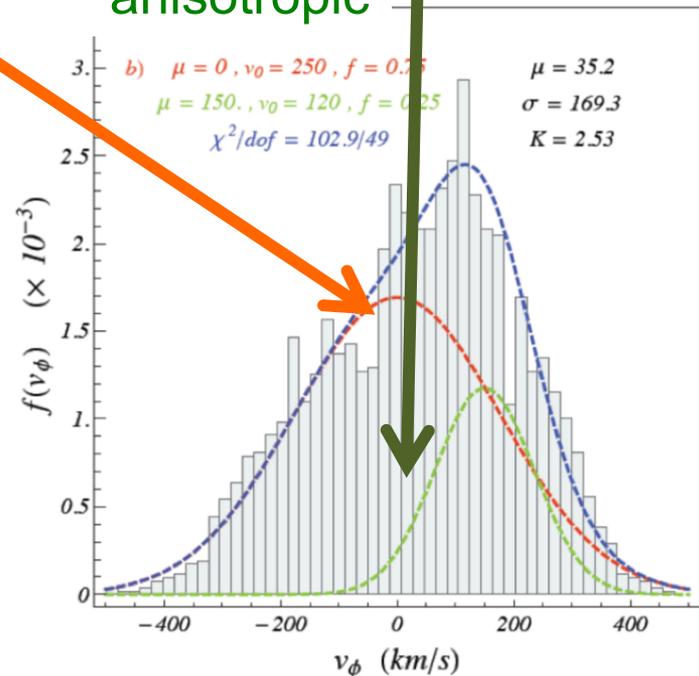
Anisotropy parameter “r”

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

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 ($r=0.2-0.3$)



Outline

1. Introduction
2. ~~Velocity Distribution of Dark Matter~~
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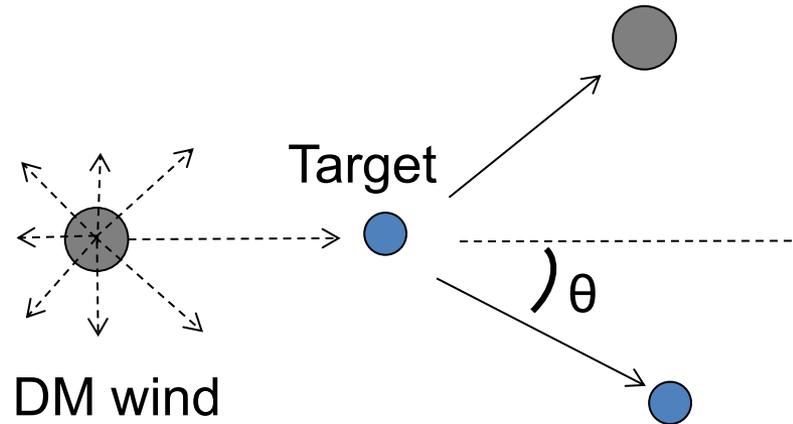
Velocity Distribution observed in Directional Detector

cf.

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

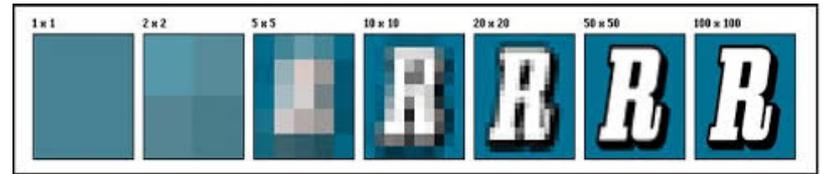
Ole Host, Steen H Hansen (2007)

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

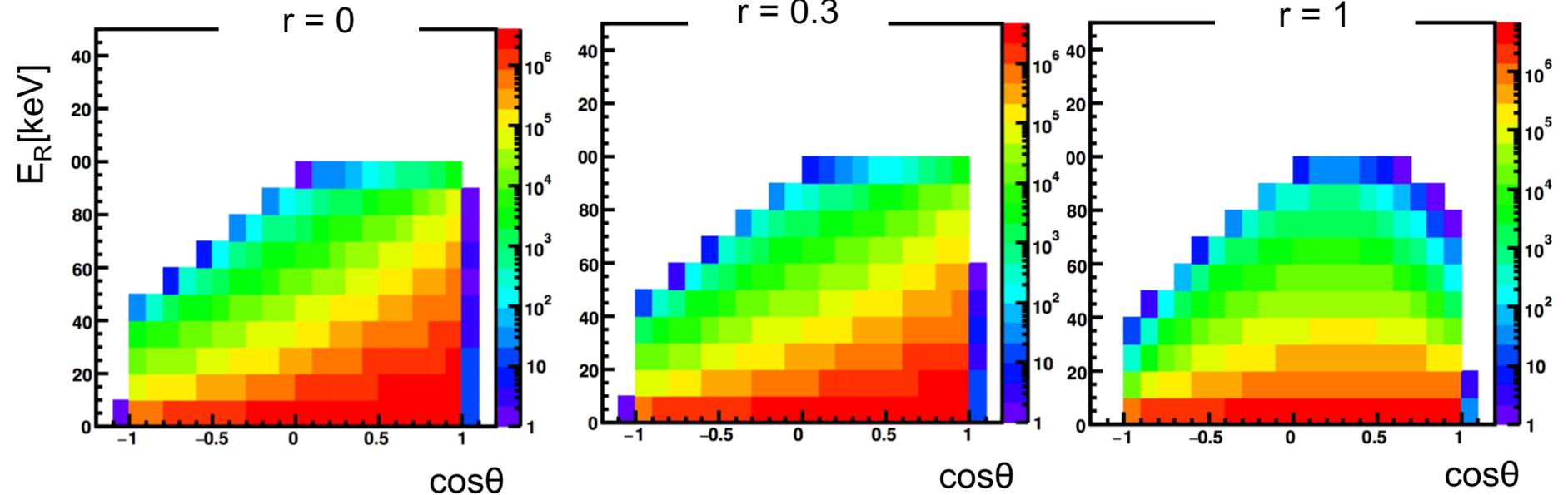
Limited information,
but maybe worth to study

Energy resolution :OK
Angular resolution :OK

Most hopeful case!

Energy-angular distribution

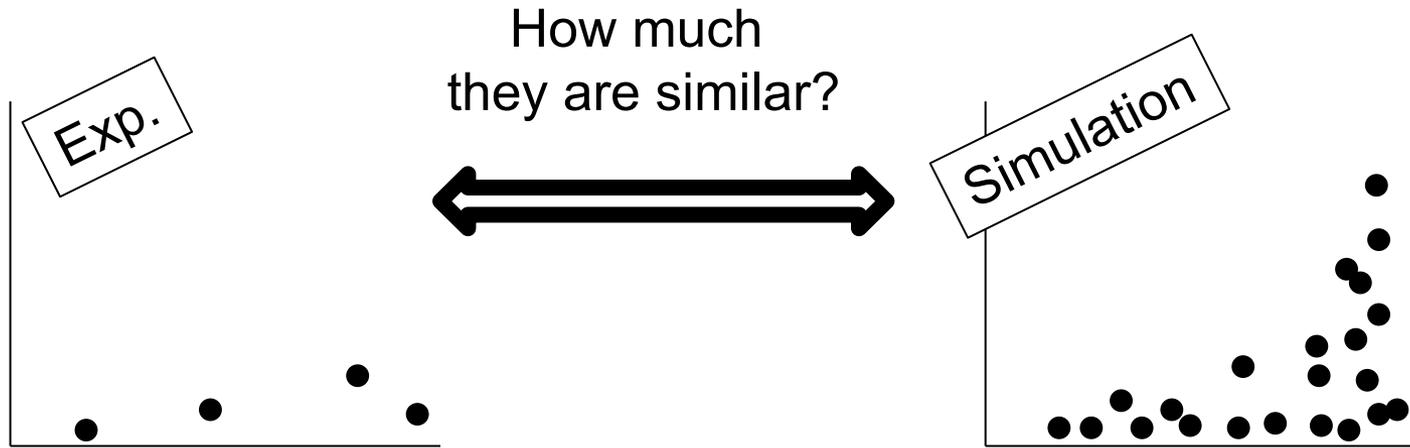
light target (F)



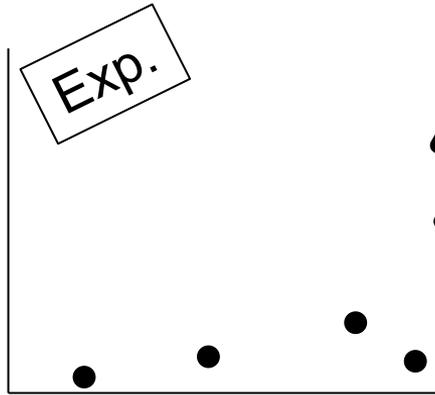
$E_{thr} = 0 \text{ keV}$

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

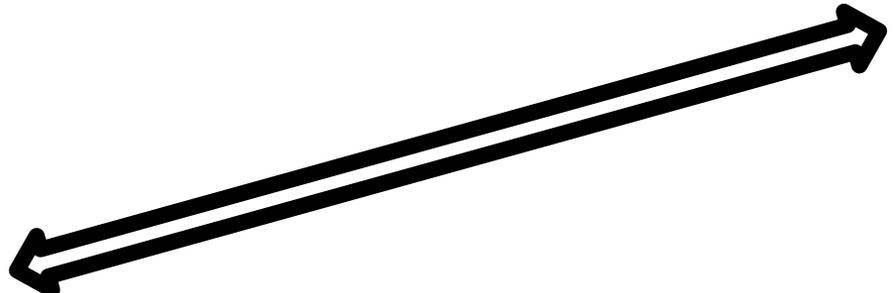
Strategy



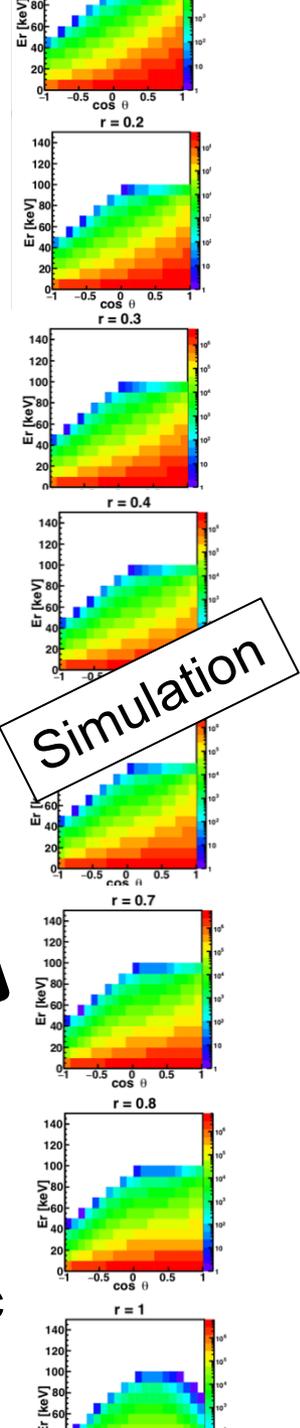
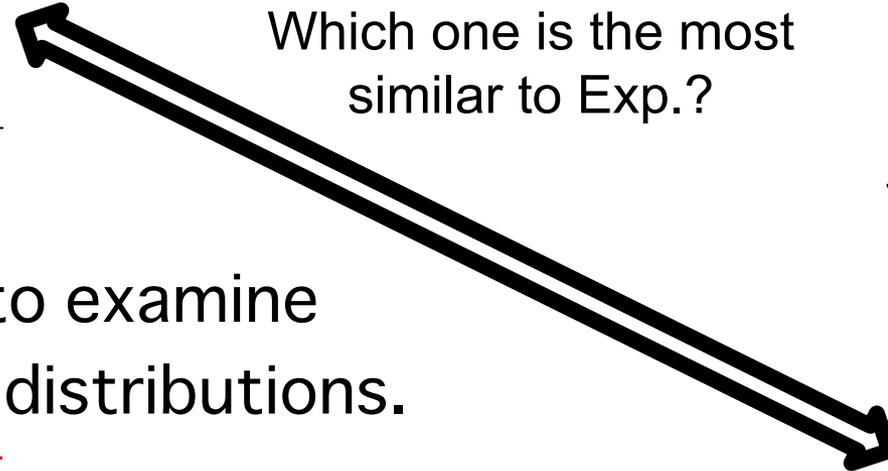
Strategy



Isotropic



Which one is the most similar to Exp.?



Anisotropic

◆ Statistical test to examine the similarity of distributions.

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

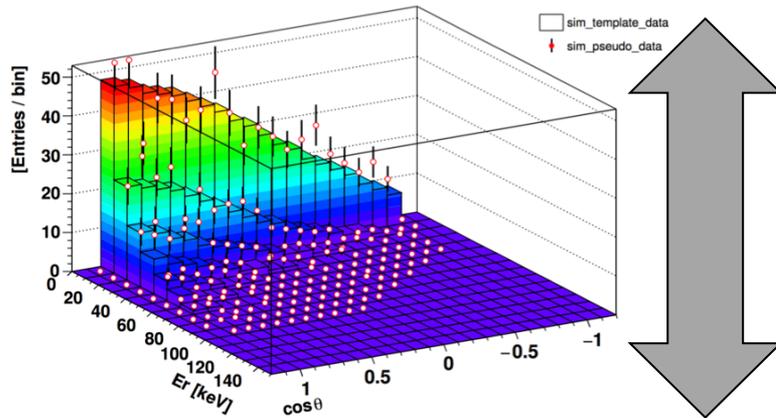
Anisotropy of DM velocity distribution

Chi squared test

Many Data
(#10⁸)

- ✓ ideal
- ✓ difficult to achieve

ideal “**template**”



chi squared test

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

Fewer Data
(#10⁴)

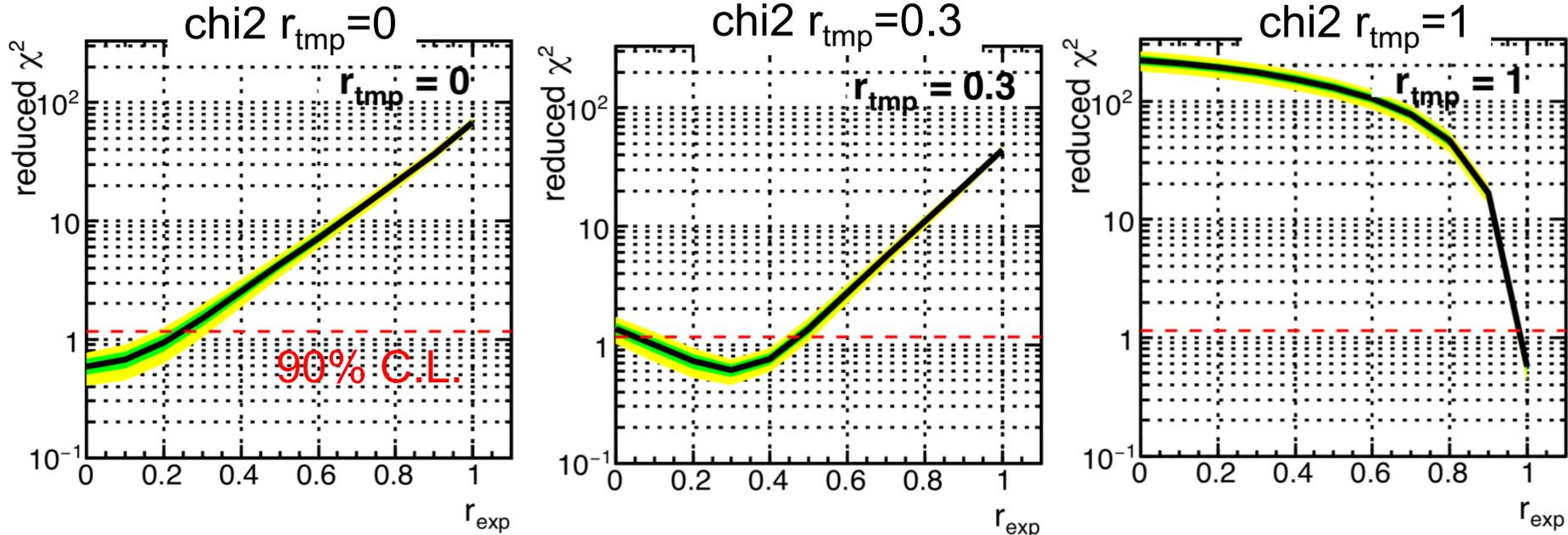
- ✓ realistic
(relatively...)

“**pseudo-experimental**” data

Chi squared test of E_R -cos θ

(light target)

#exp.= $6 \cdot 10^3$
E_{thr}=20keV (F)

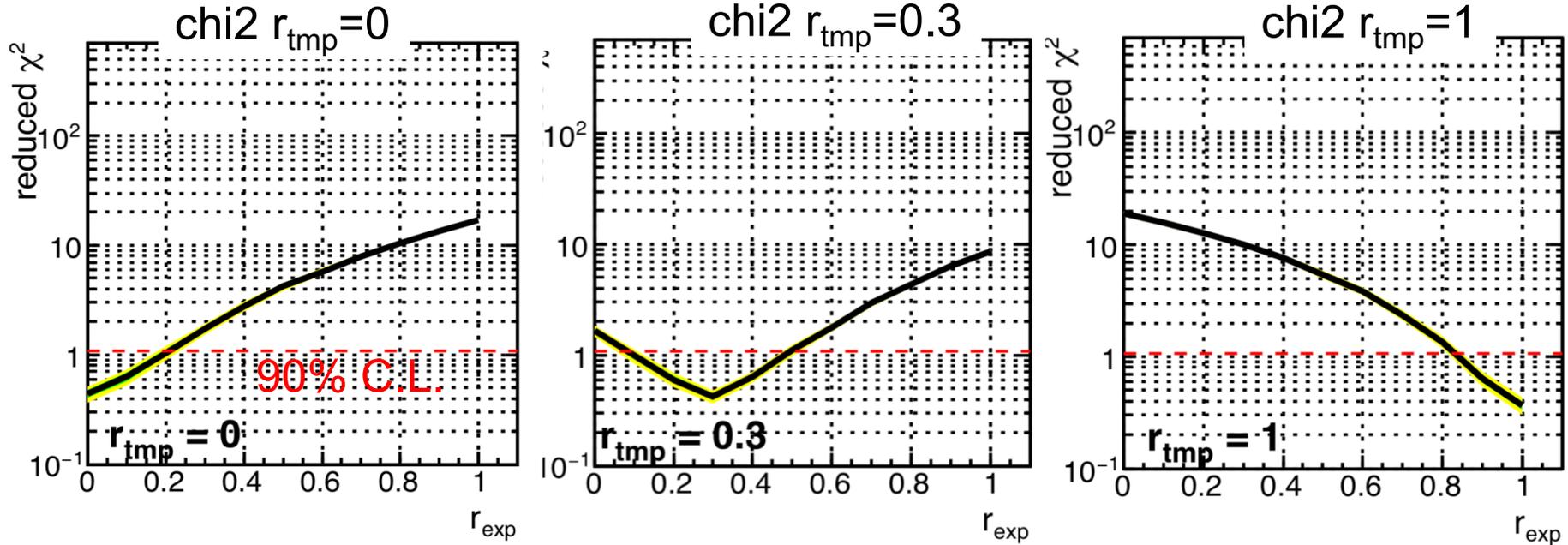


- ✓ If $r=0.3$, isotropic case ($r=0$) can be excluded at 90% C.L.
- ✓ Energy threshold is a factor to clearly characterize the difference between $r=0$ and 0.3.

Chi squared test of E_R -cos θ

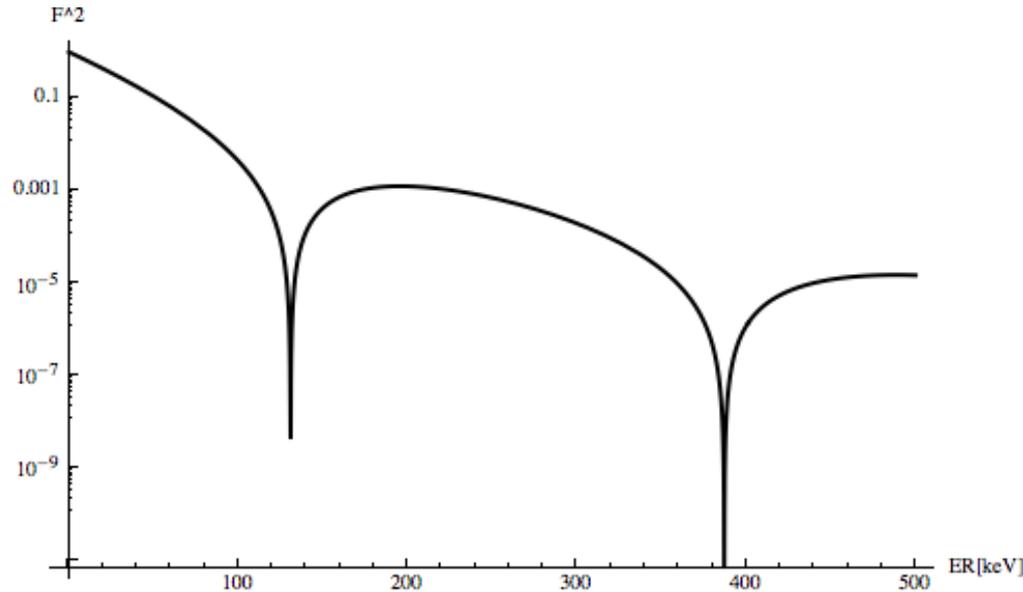
(heavy target)

#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).

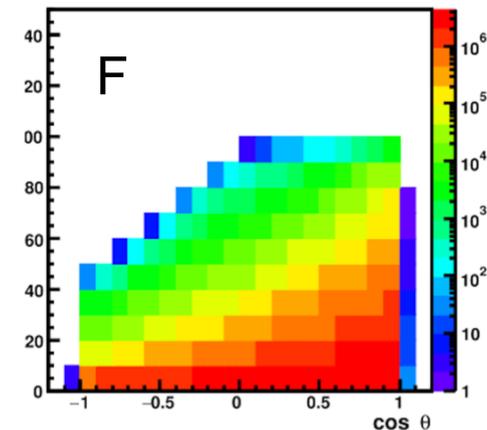
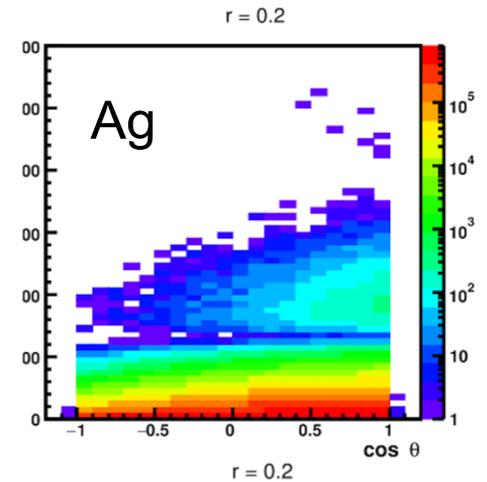
Form factor



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

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

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



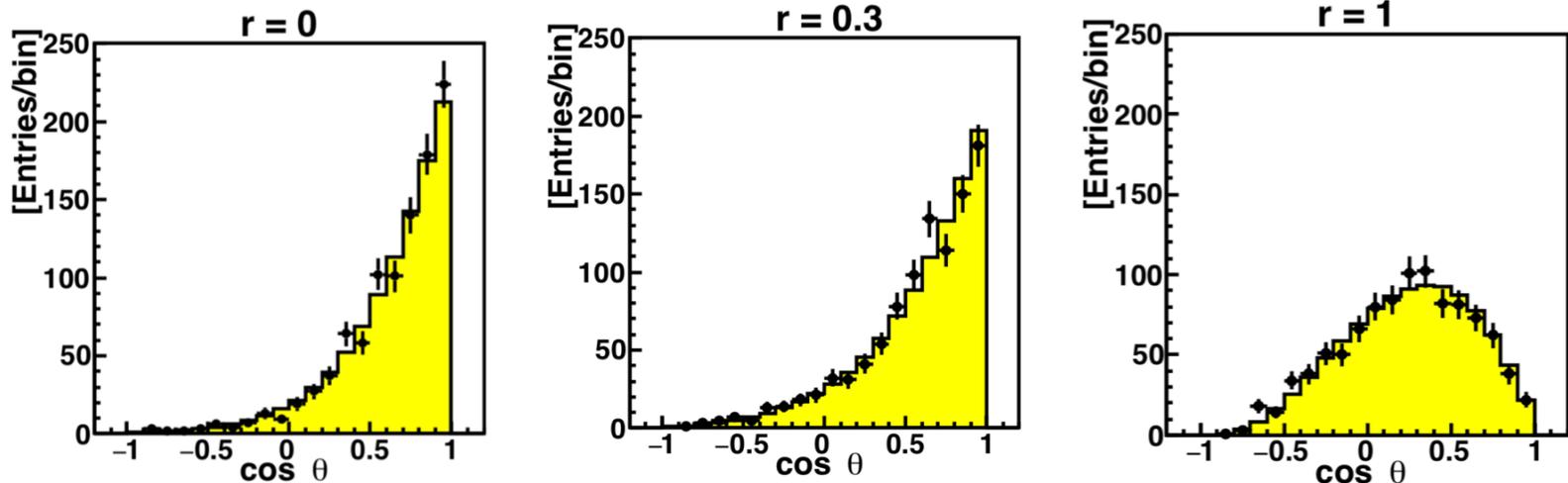
Energy resolution :NG
Angular resolution :OK

Limited information,
but maybe worth to study

Directionality Histogram

(light target)

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

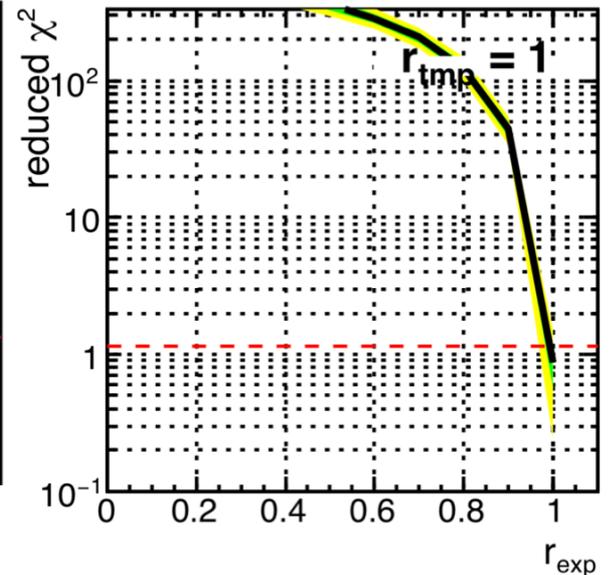
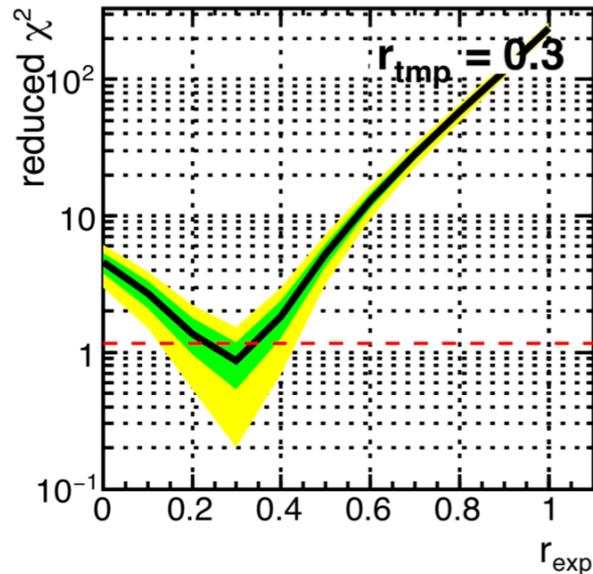
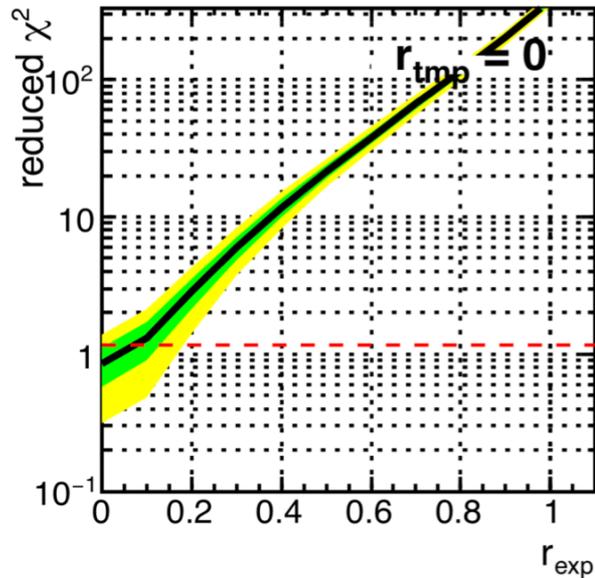


- ✓ Shape for $r=0.3$ is quite similar to that for $r=0$. It is same for heavy target case.
- ✓ We need statistical test again.

Chi-squared test of directionality

✦ Chi squared test (light target)

#exp.= $5 \cdot 10^3$
E_{thr}=20keV (F)

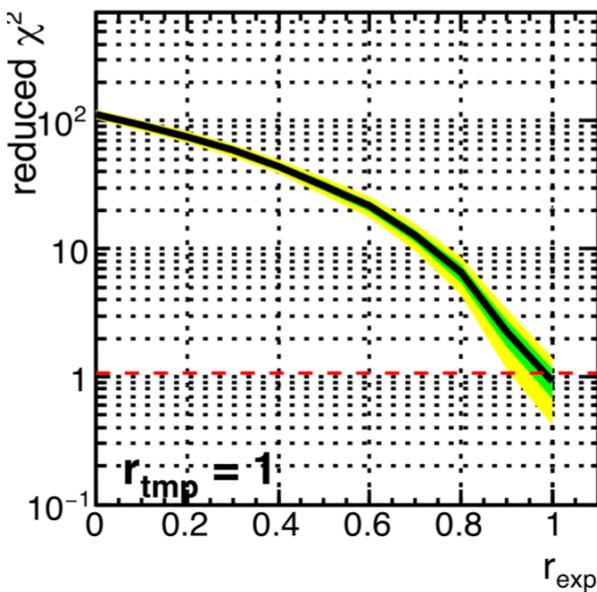
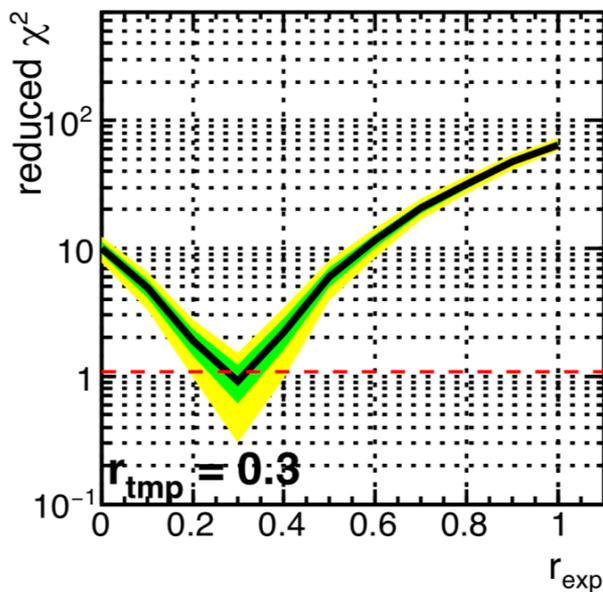
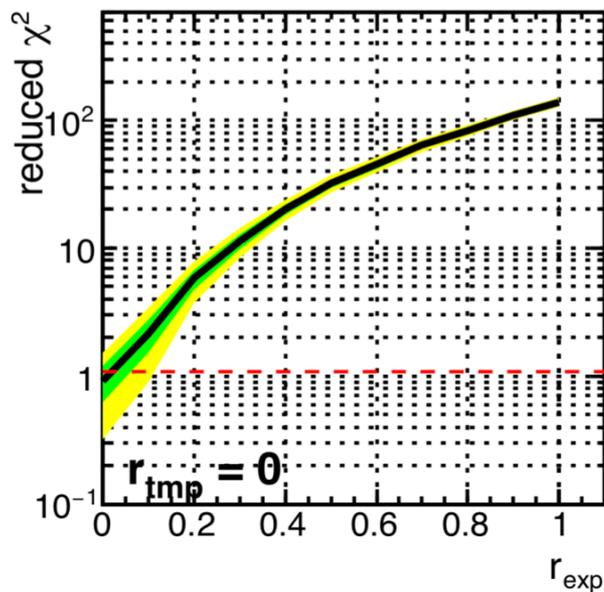


Anisotropy of DM velocity distribution

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]?

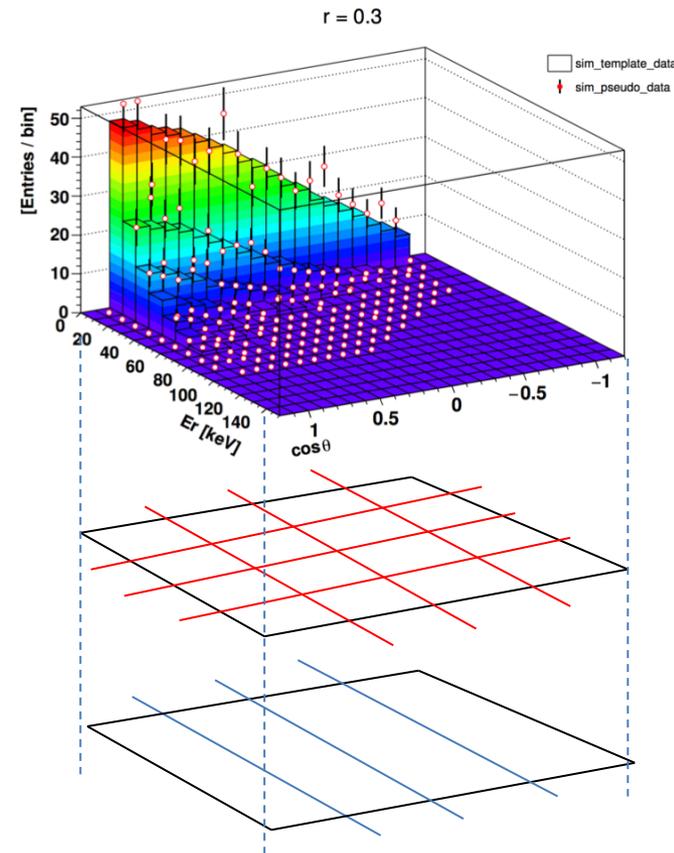
✦ To discriminate the anisotropy, required event # are...

- $6 \times 10^3 / 6 \times 10^4$
(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