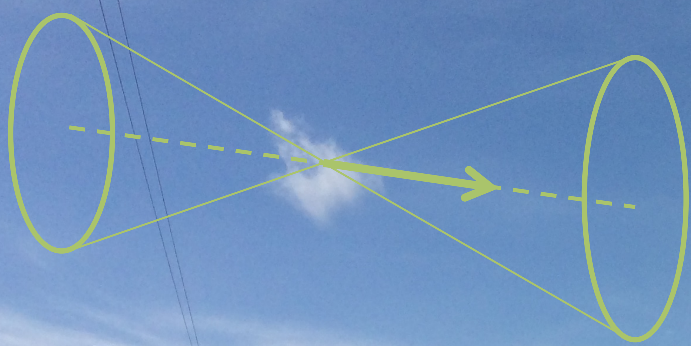
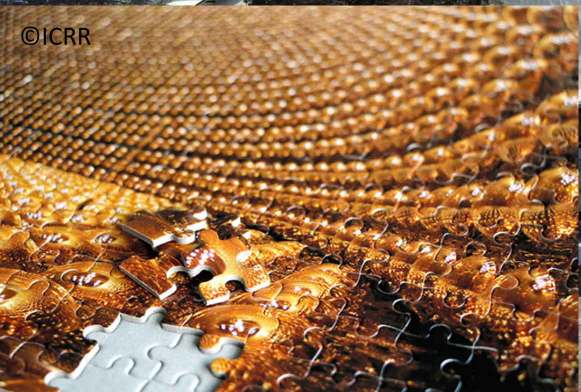
A novel water-Cherenkov detector design with retro-reflectors to produce antipodal rings





Lukas Berns, 2018-02-19

Tokyo Institute of Technology

24th ICEPP symposium


●●●●○ SoftBank 4G 10:46 17%
インターネット共有: 1台接続中
アルピコ交通 八方バスター…
岳美山荘
6分
—
21分
白馬リゾートホテル
ラ・ネージュ本館
白馬
温泉 倉下の湯
2分
早い経路
DGE HOTEL
RTMENTS...
322
23分
23分 (1.6km)
ナビ…



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アルピコ交通 八方バスター…
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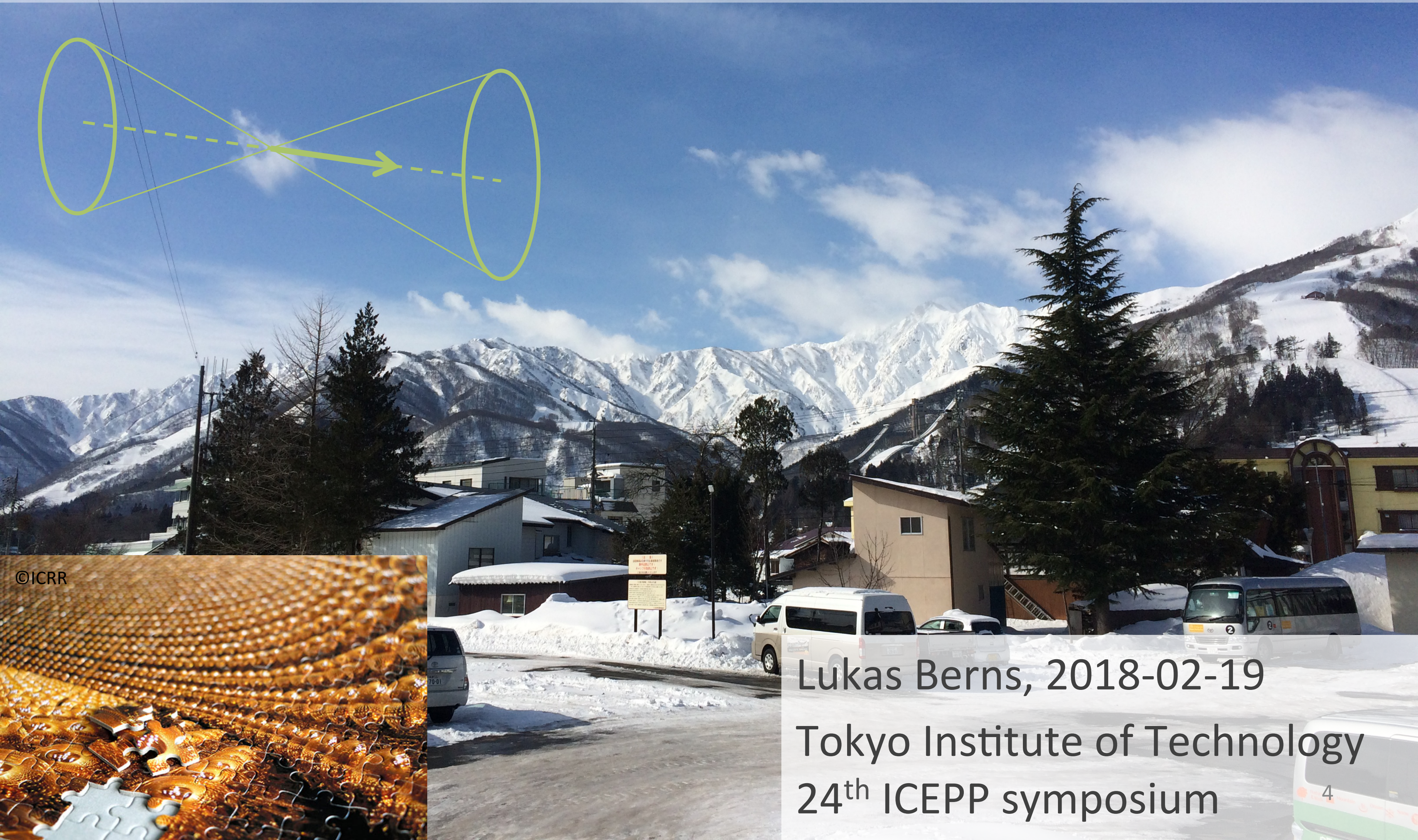

Lukas Berns, 2018-02-19

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Water-Cherenkov detectors

- Basic design has not changed for a long time
- Rich physics program:
  ν osc., leptonic CP violation, proton decay, supernova, ...

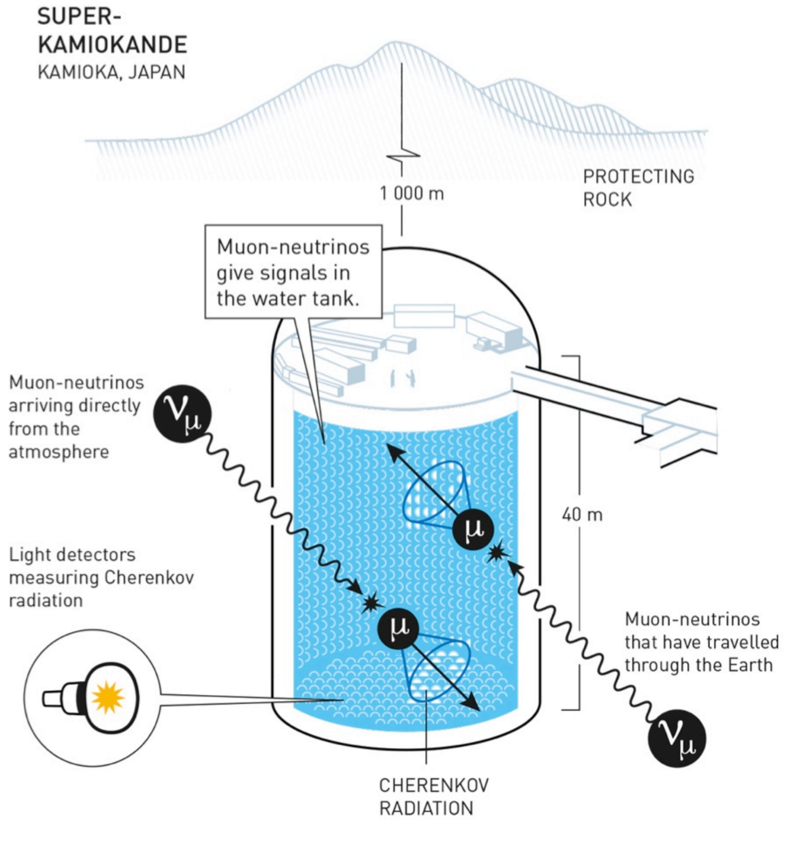
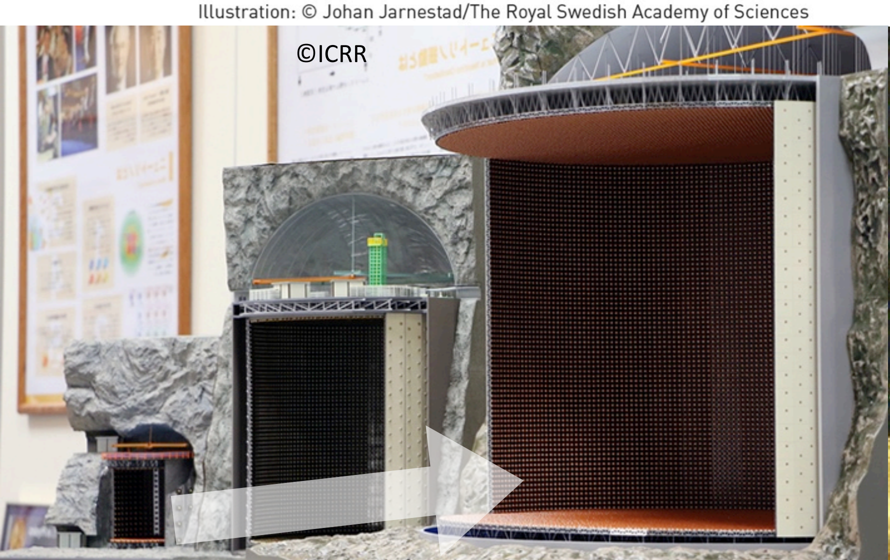
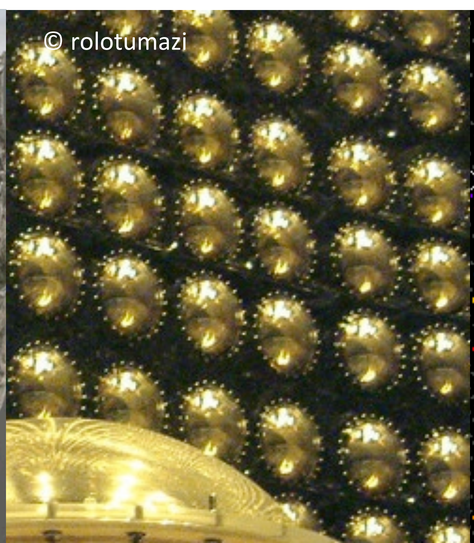
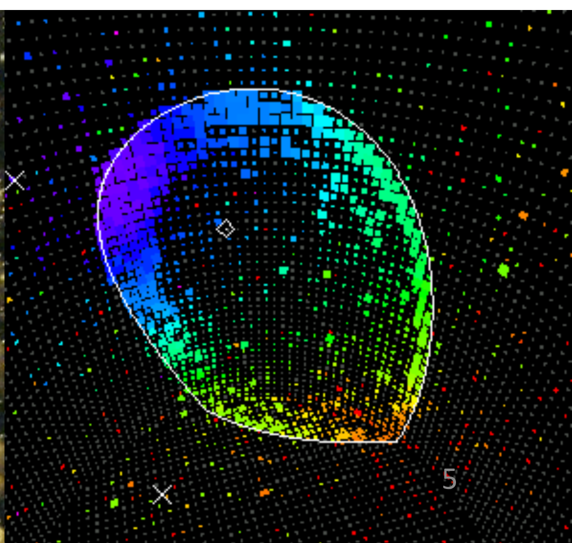


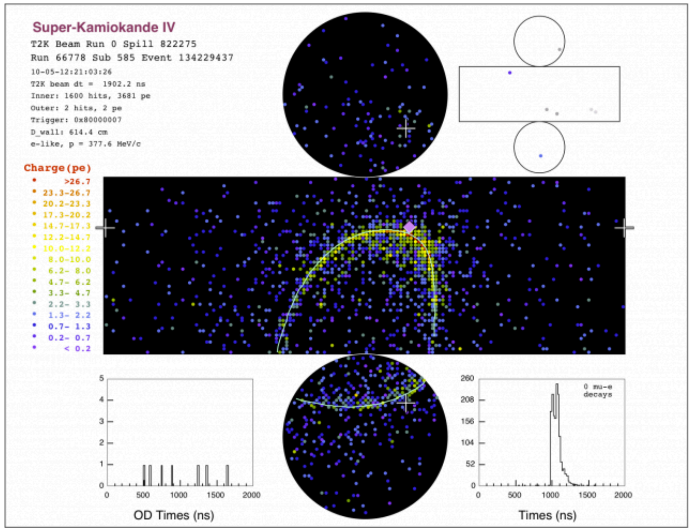
Illustration: © Johan Jarnestad/The Royal Swedish Academy of Sciences



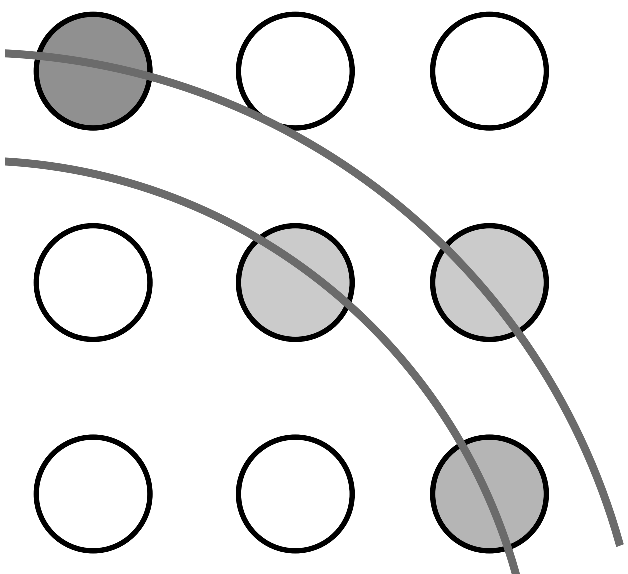




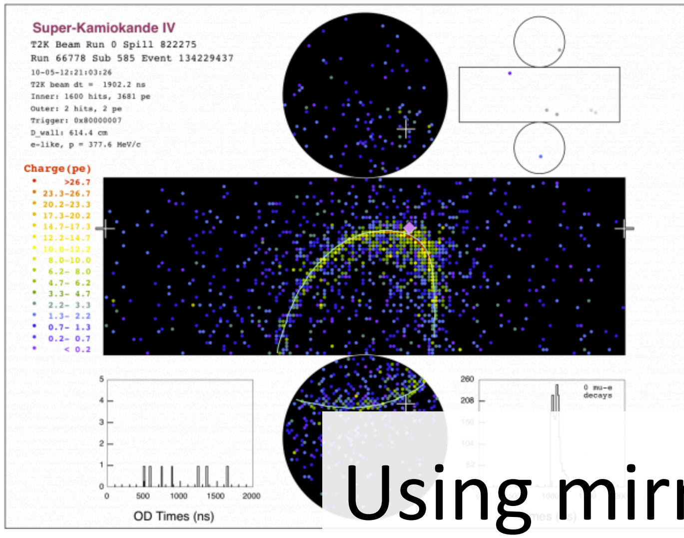
Problems with water-Cherenkov detectors

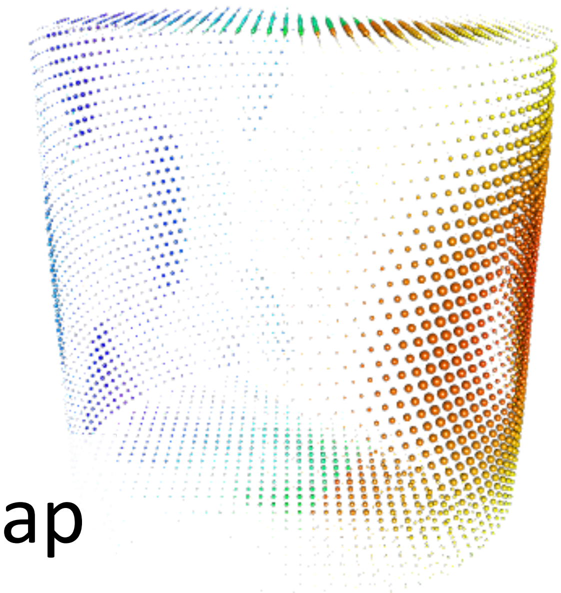


In a ring event, only a fraction of all PMTs provide information.

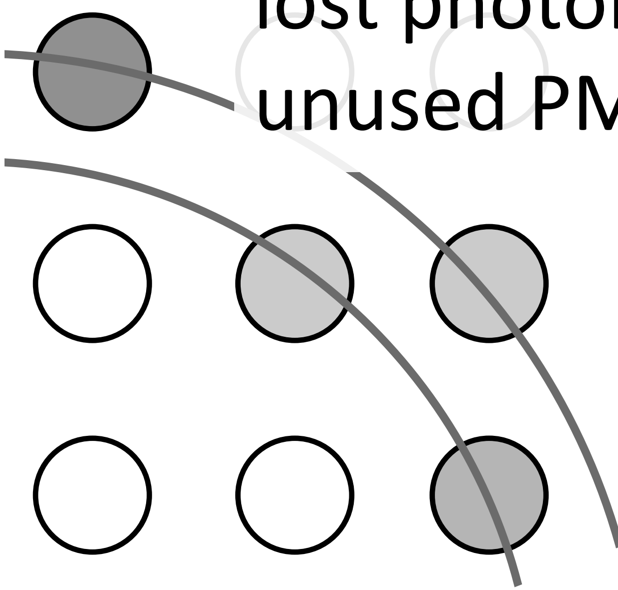


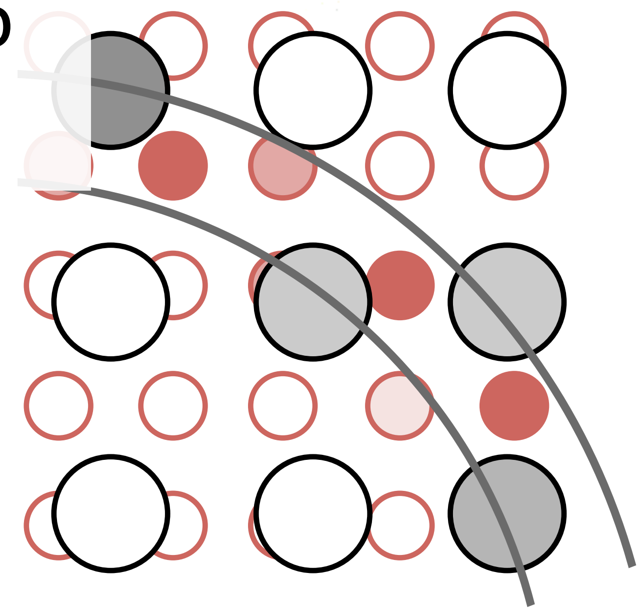
With 40% photo-coverage, we are losing 60% of photons.





Using mirrors, map lost photons onto unused PMTs

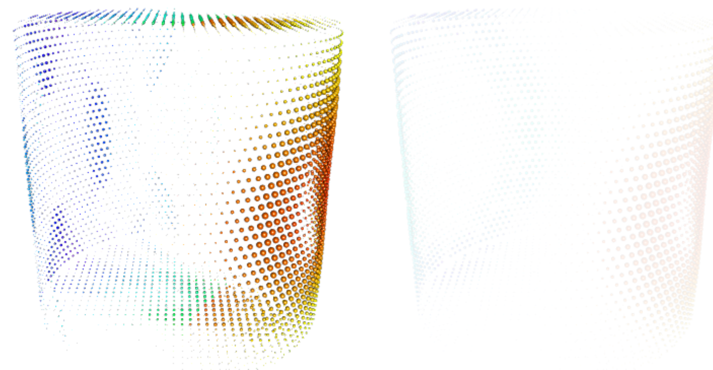




Problems with normal mirrors → Solution: Retro-reflectors

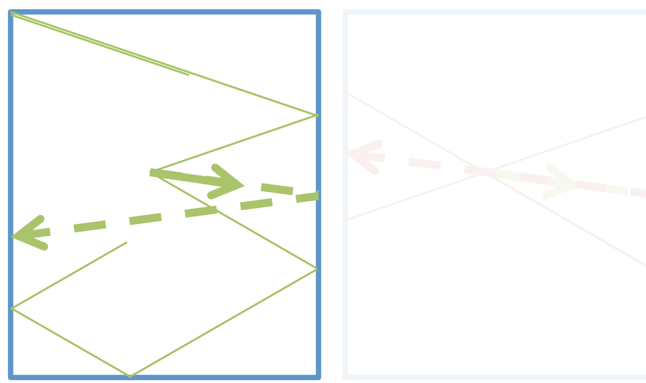
- Need to keep track of ~4 reflections, which is compu-tationally very expensive
- Even 1° misalign-ment causes ~1 m difference in light position over 30m
- Residual light decreases contrast for other rings. . .

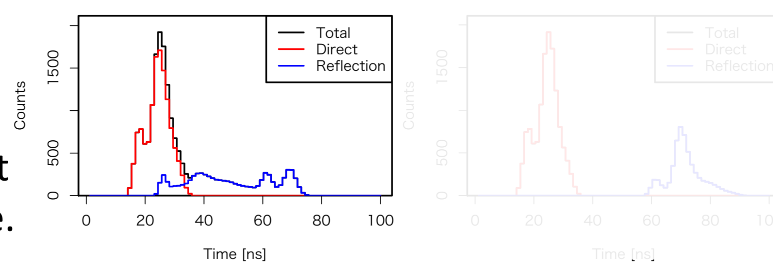
→ impractical



Color: time, sphere cross-section: expected charge

↗ Retro-reflectors (right) create a second ring on other side of tank



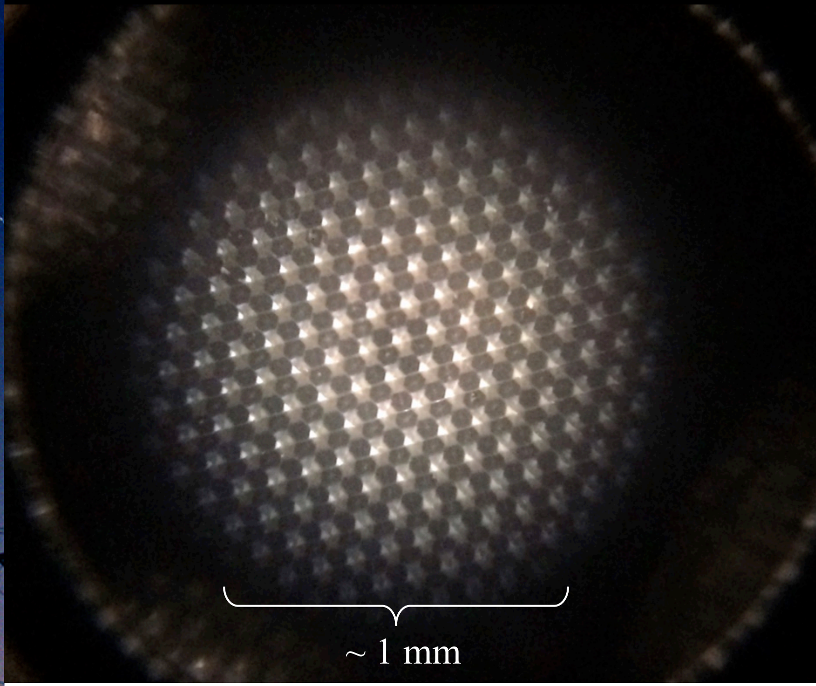


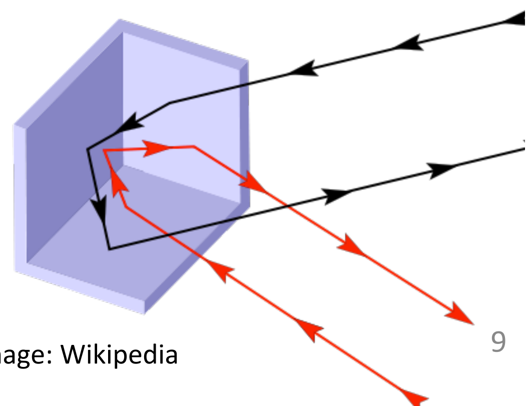
With retro-reflectors (right) the reflected light is well separated in time.

- Reflect light back into same direction
- Reflected light hits PMT or gets trapped in mirrors
  → 1 reflection only!
- Stable against change in mirror orientation.
- Could just be fit as another ring.

Image: Wikipedia

Retro-reflectors





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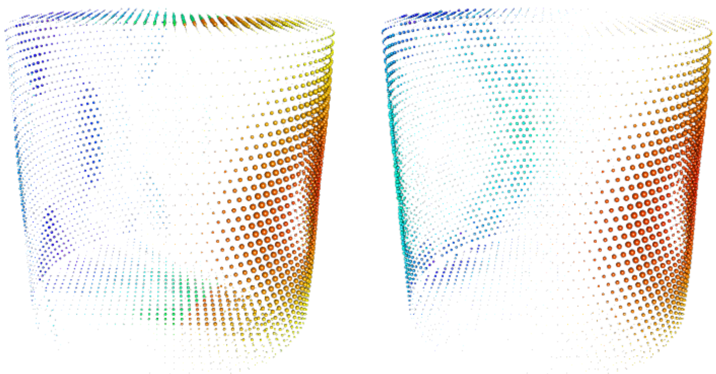

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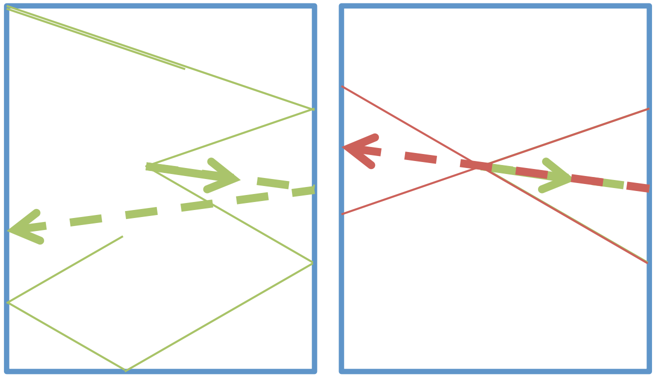

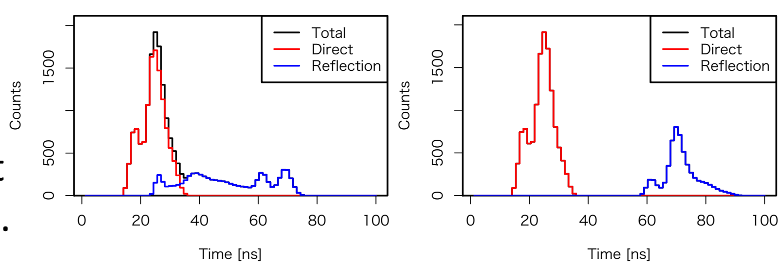

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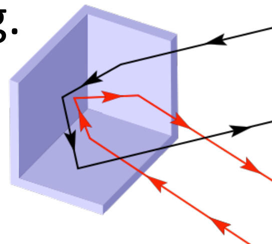
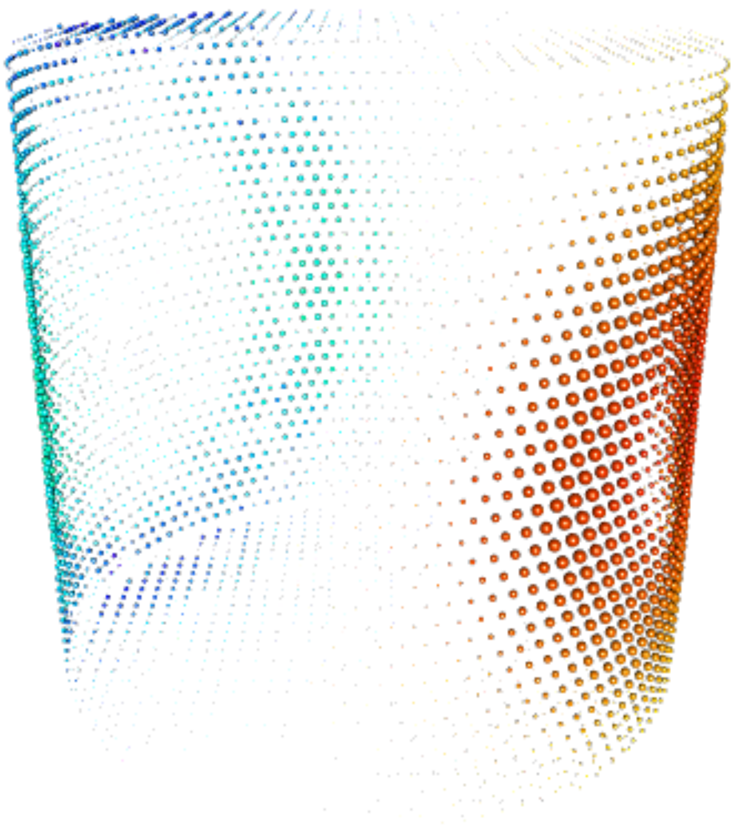
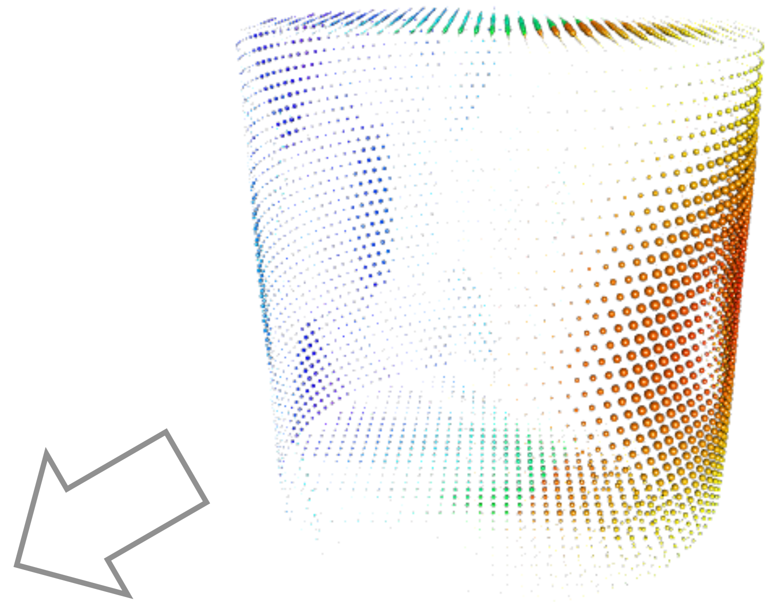


Image: Wikipedia

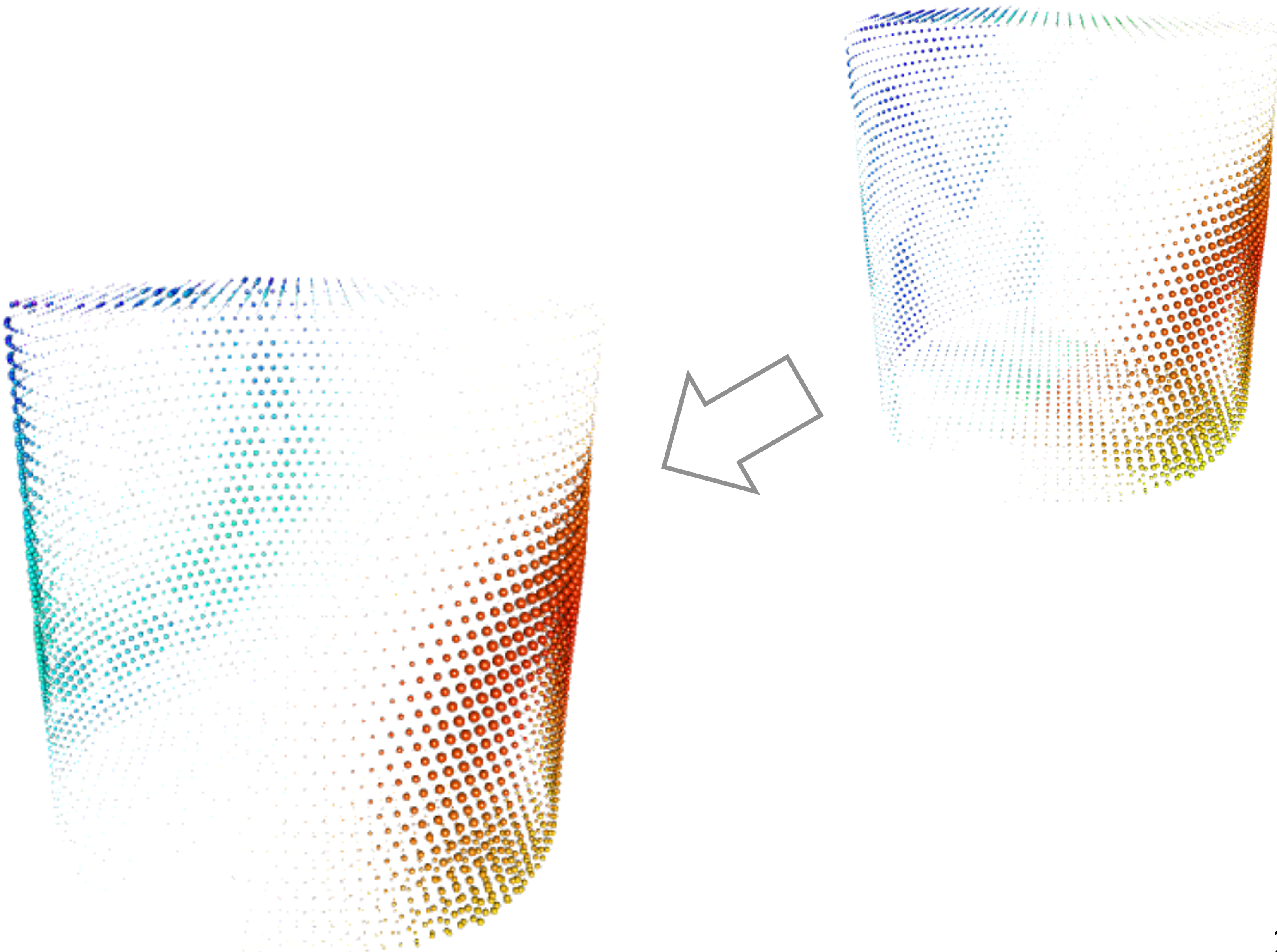
Retro-reflectors



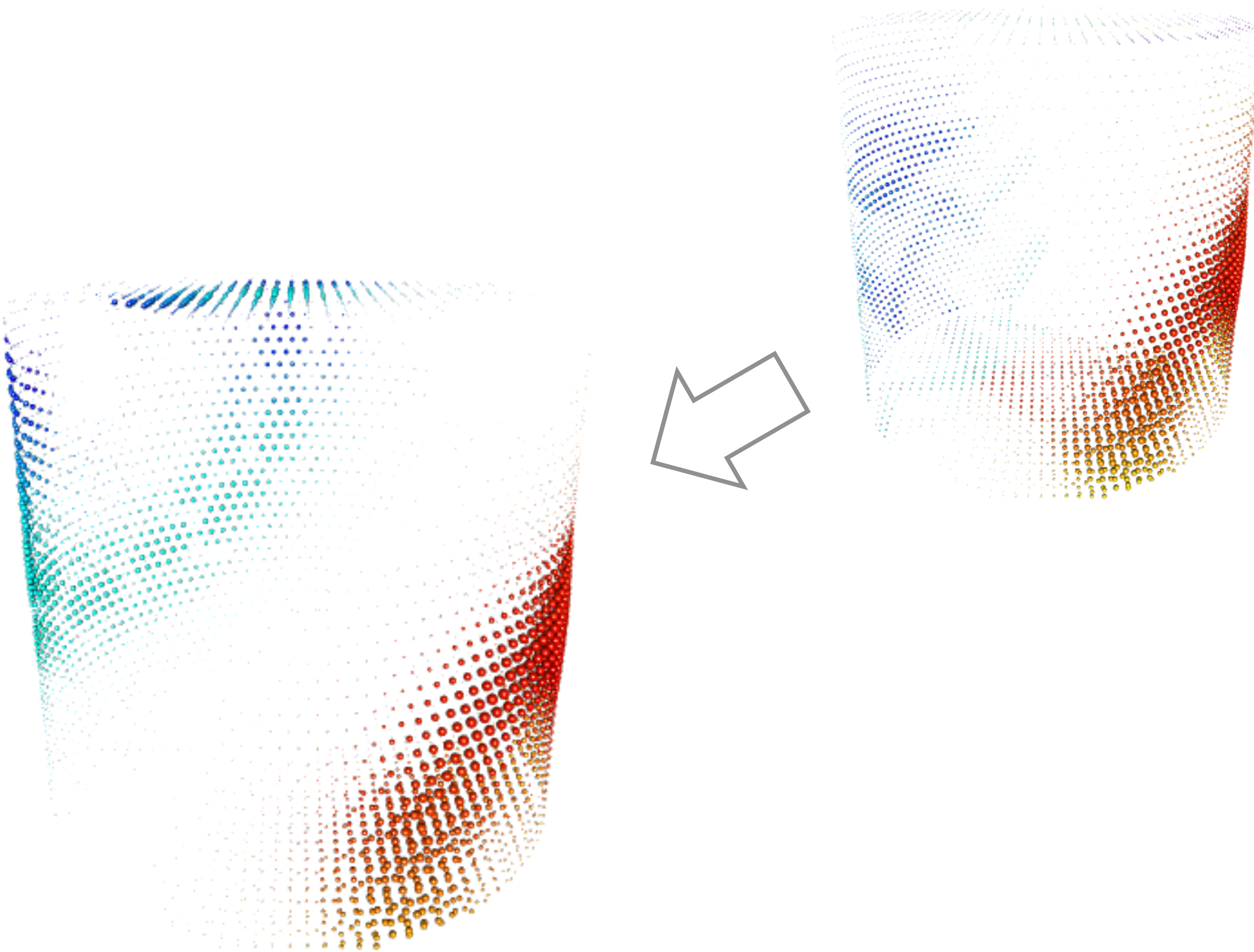


Mirrors

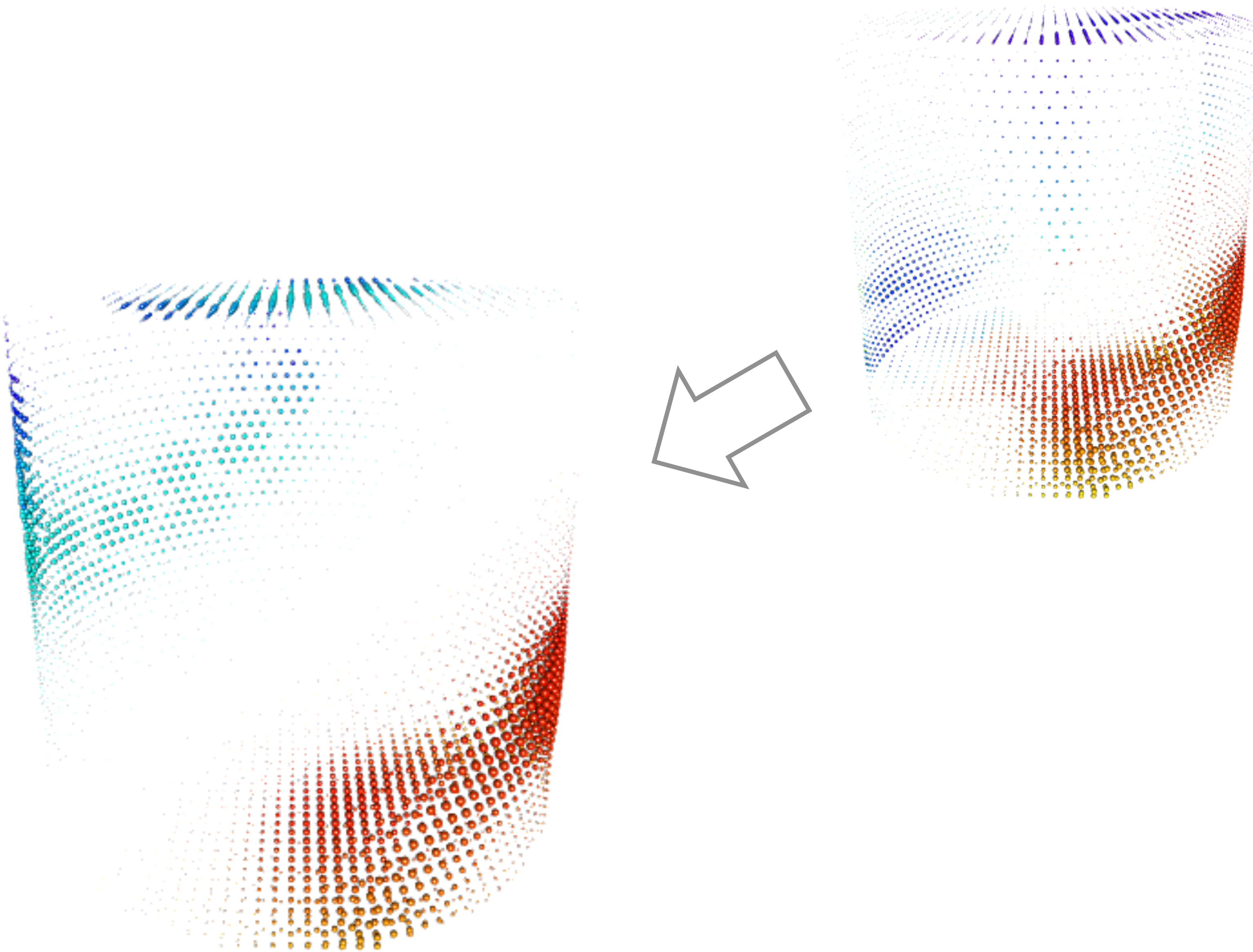
1/25



2/25



3/25



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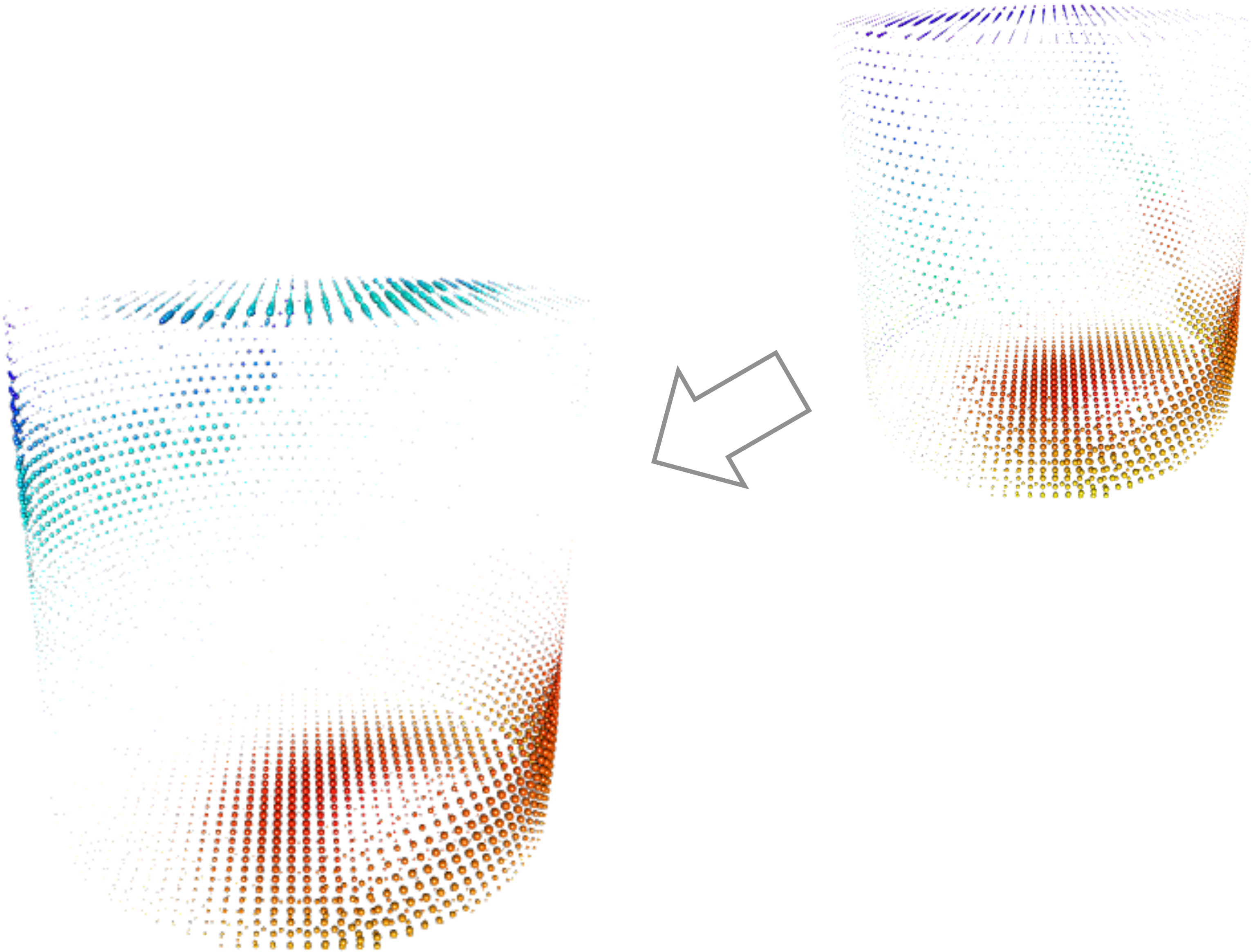

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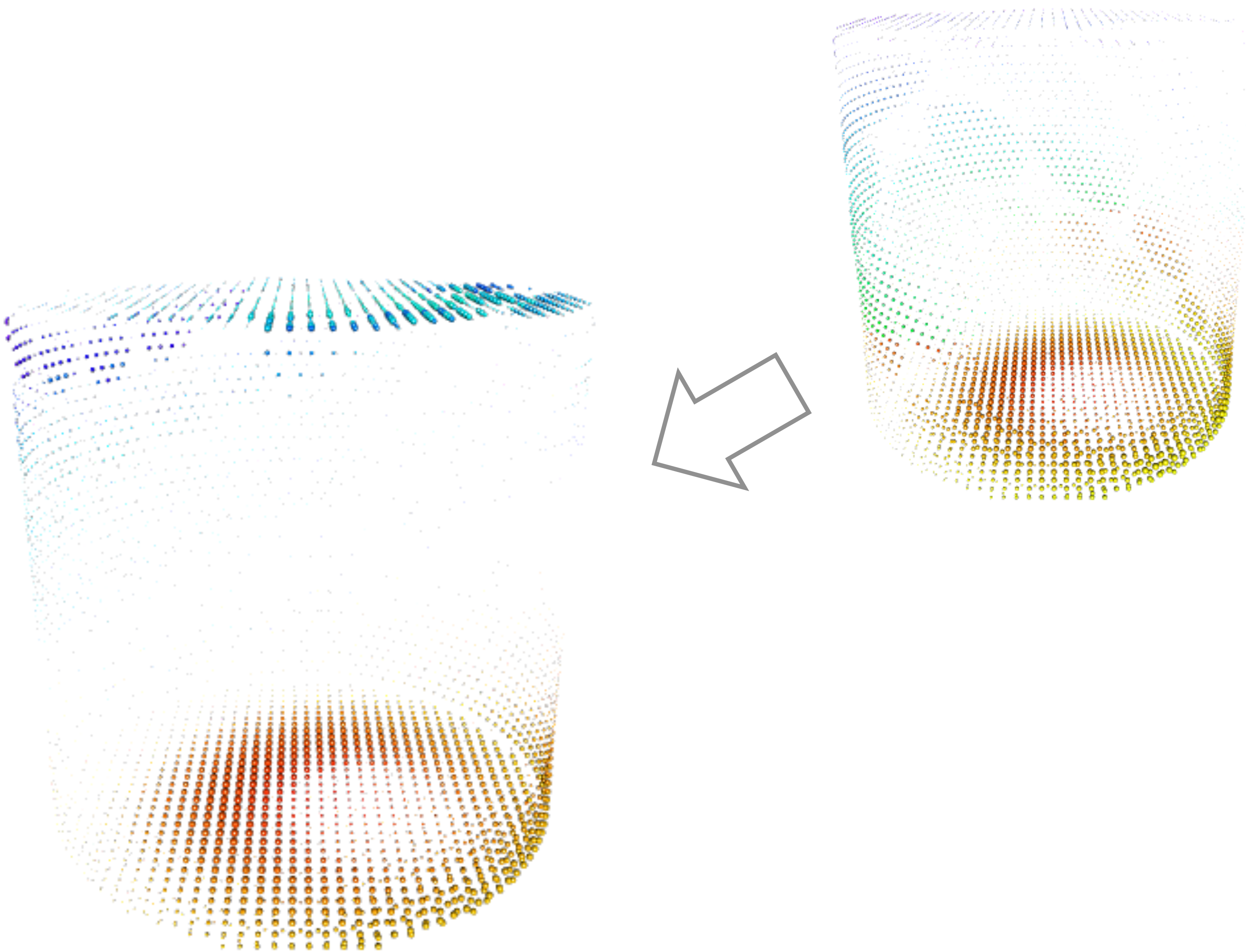

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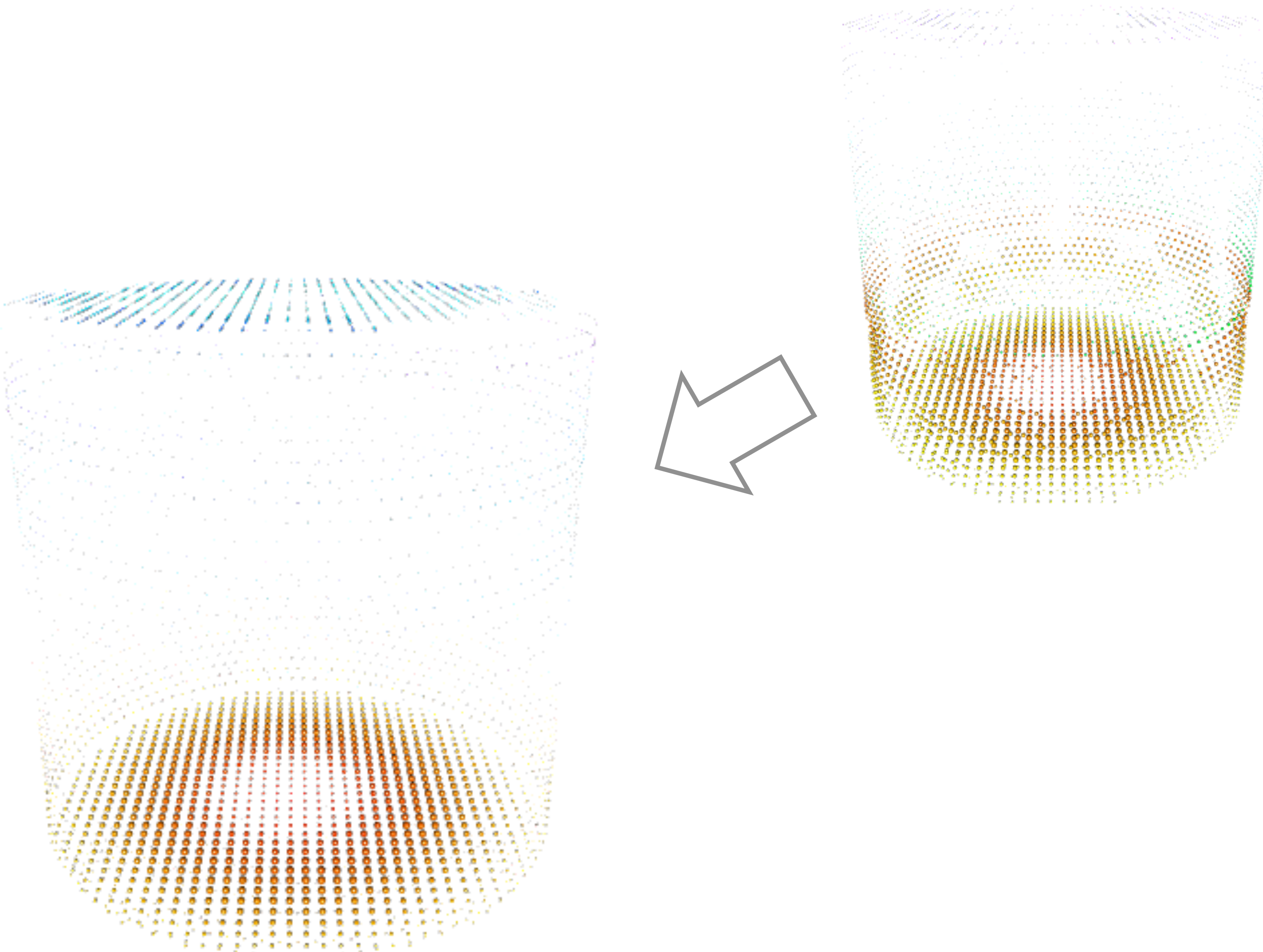

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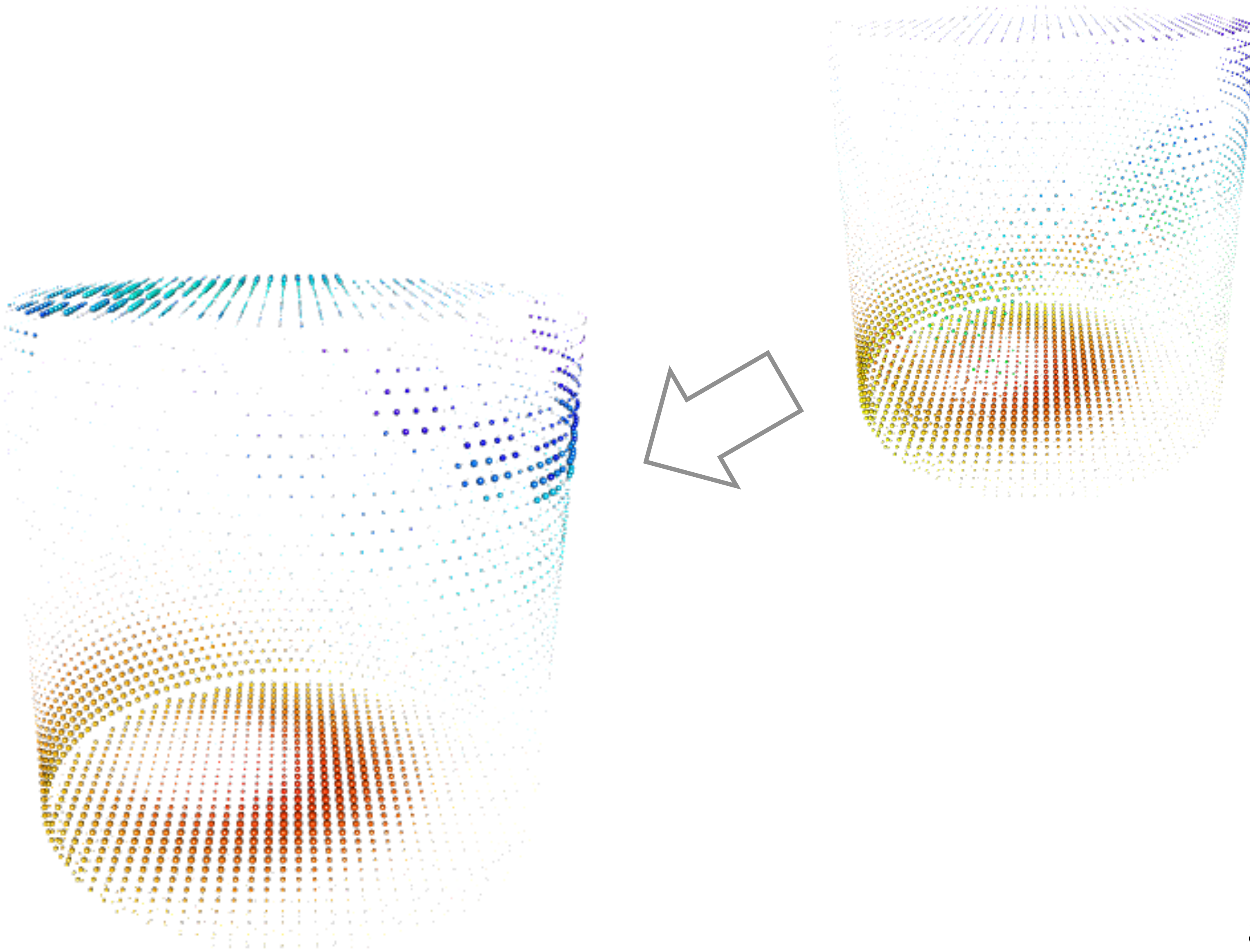

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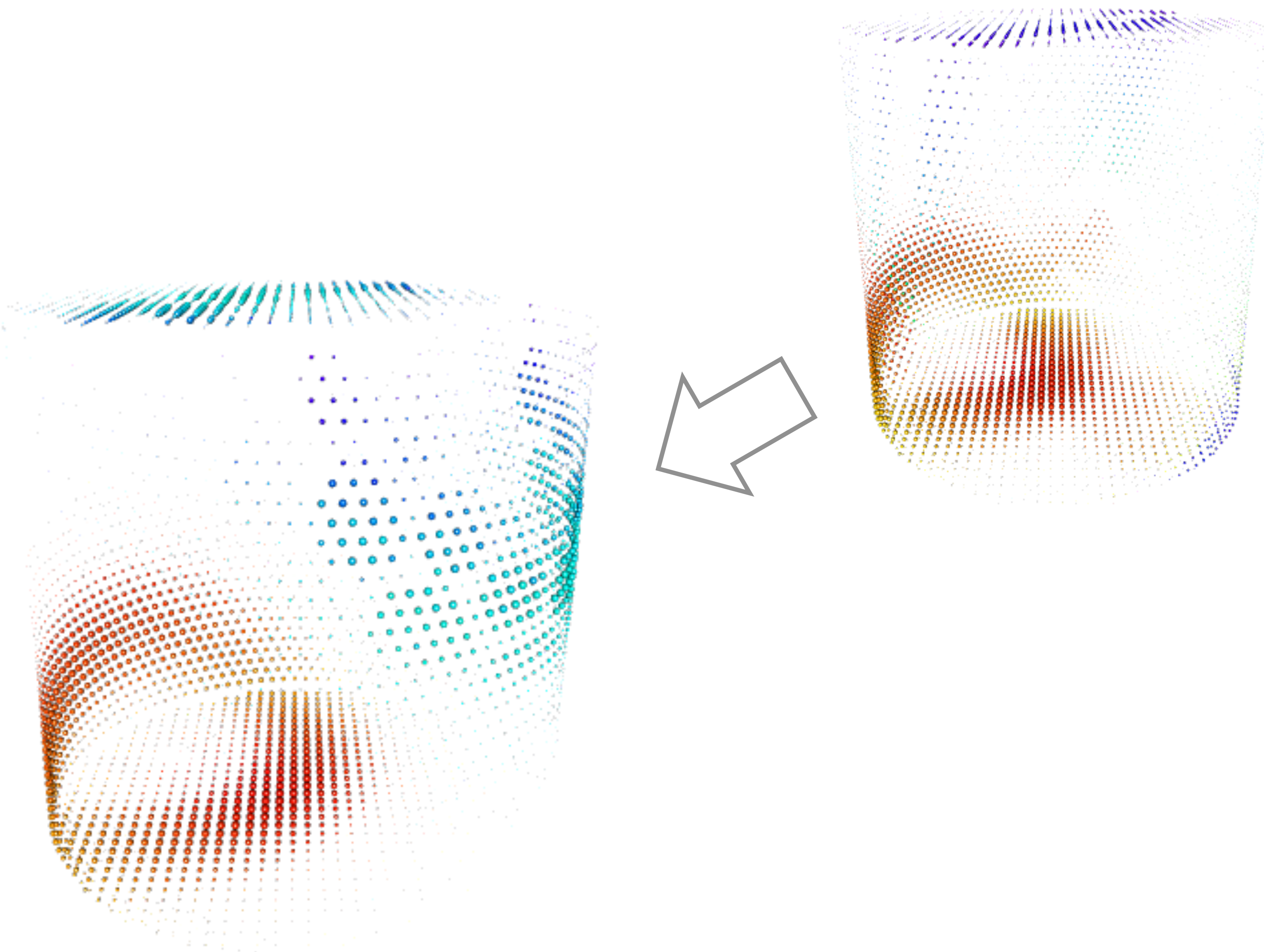

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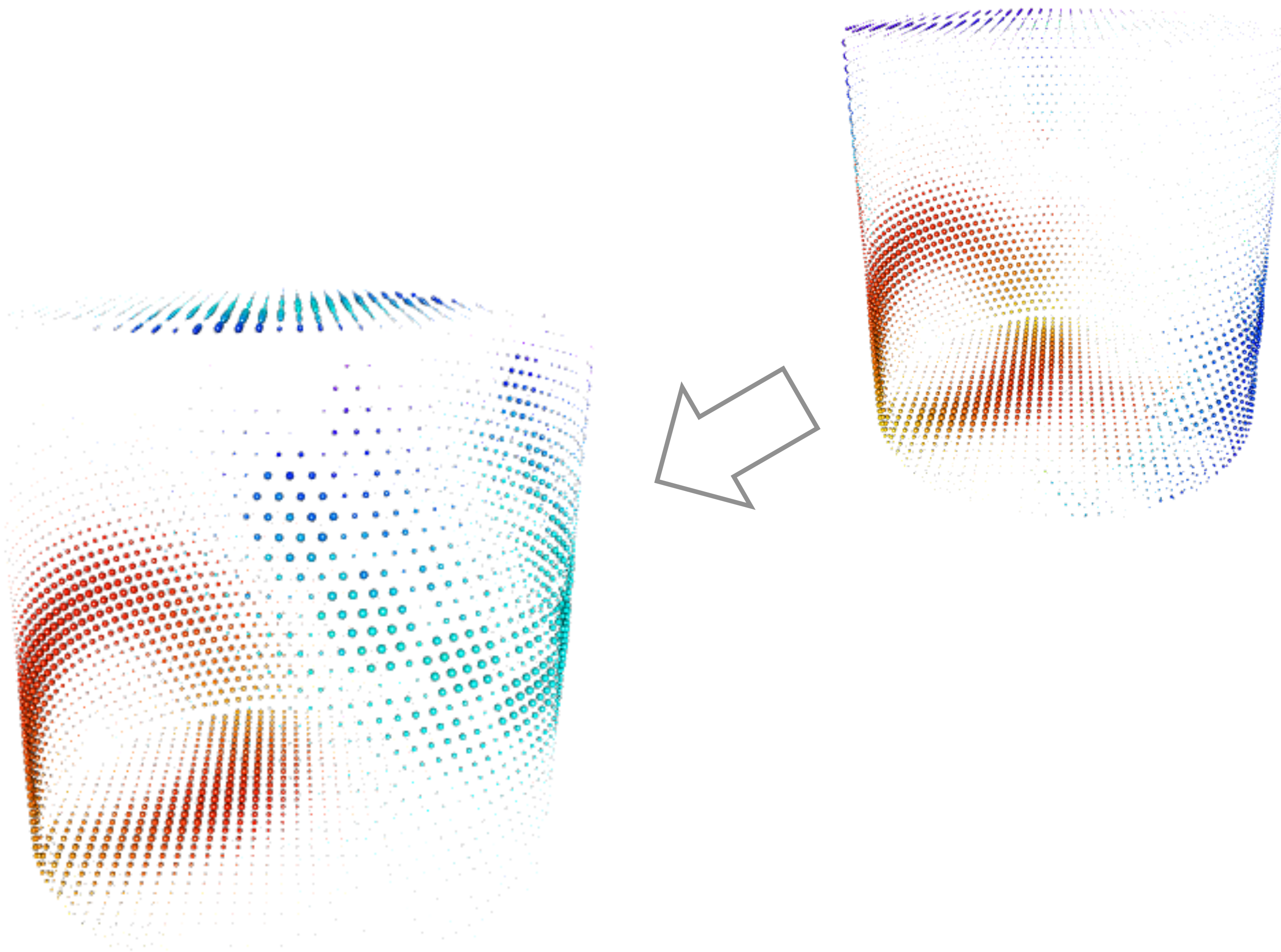

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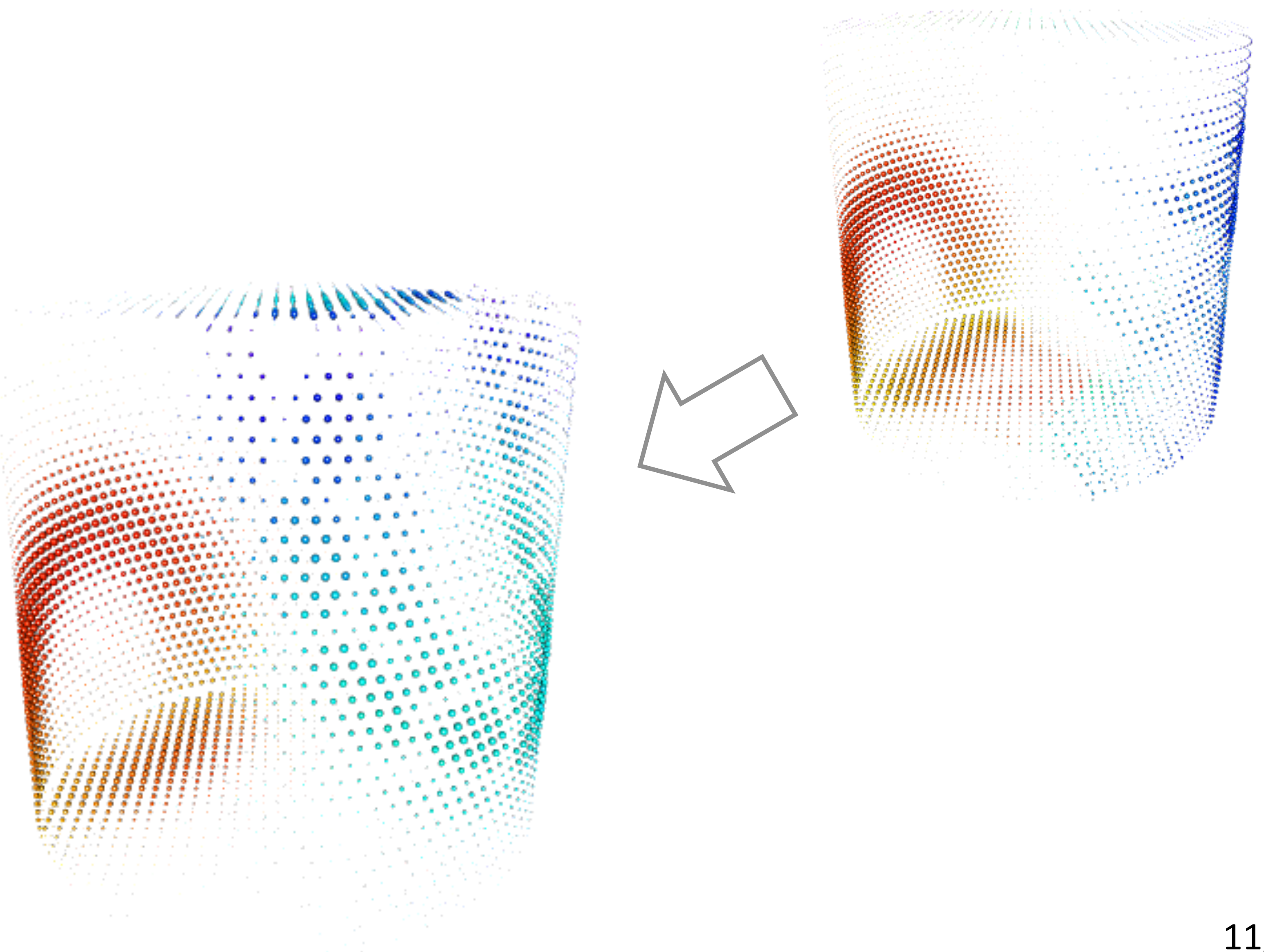

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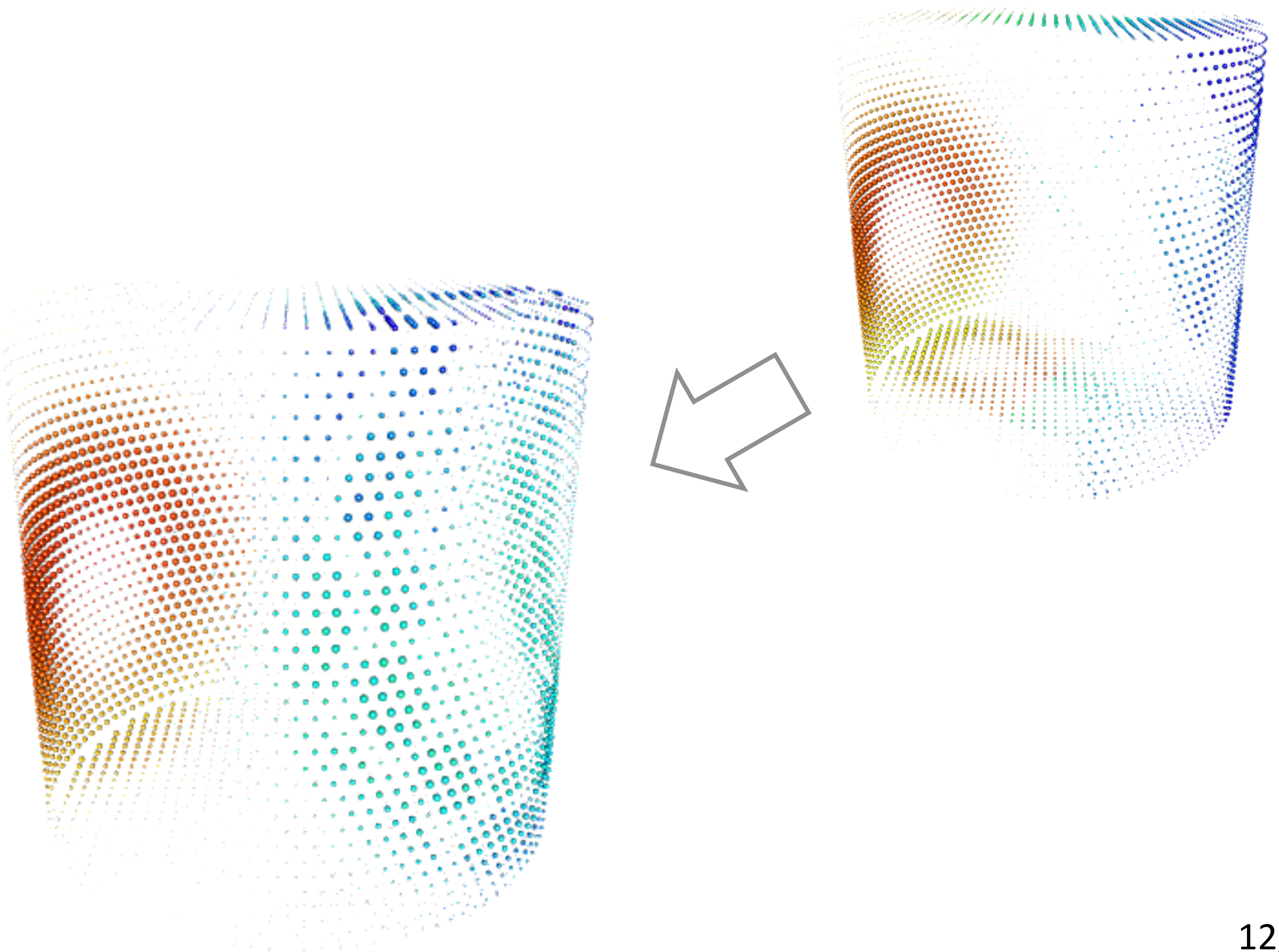

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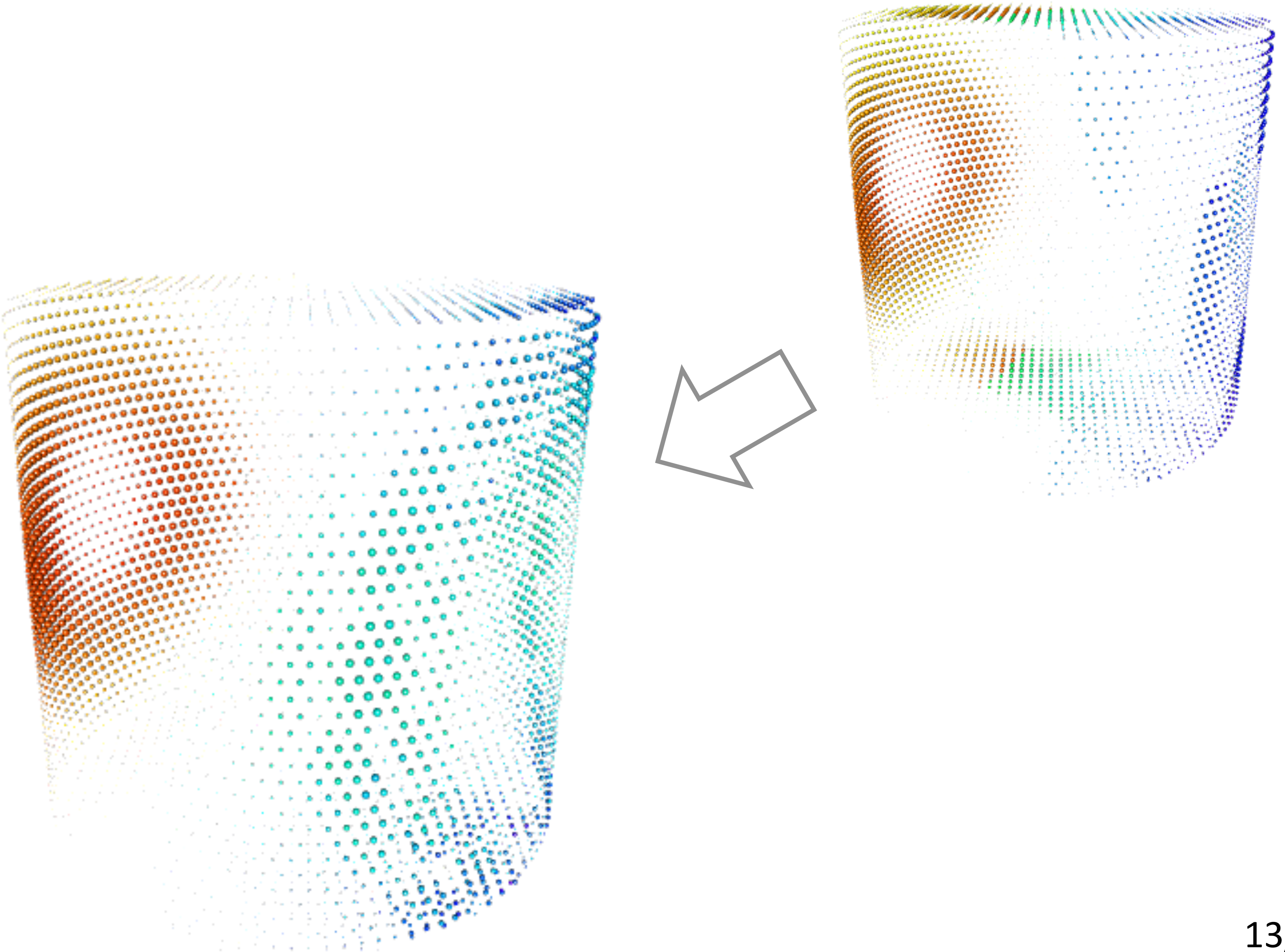

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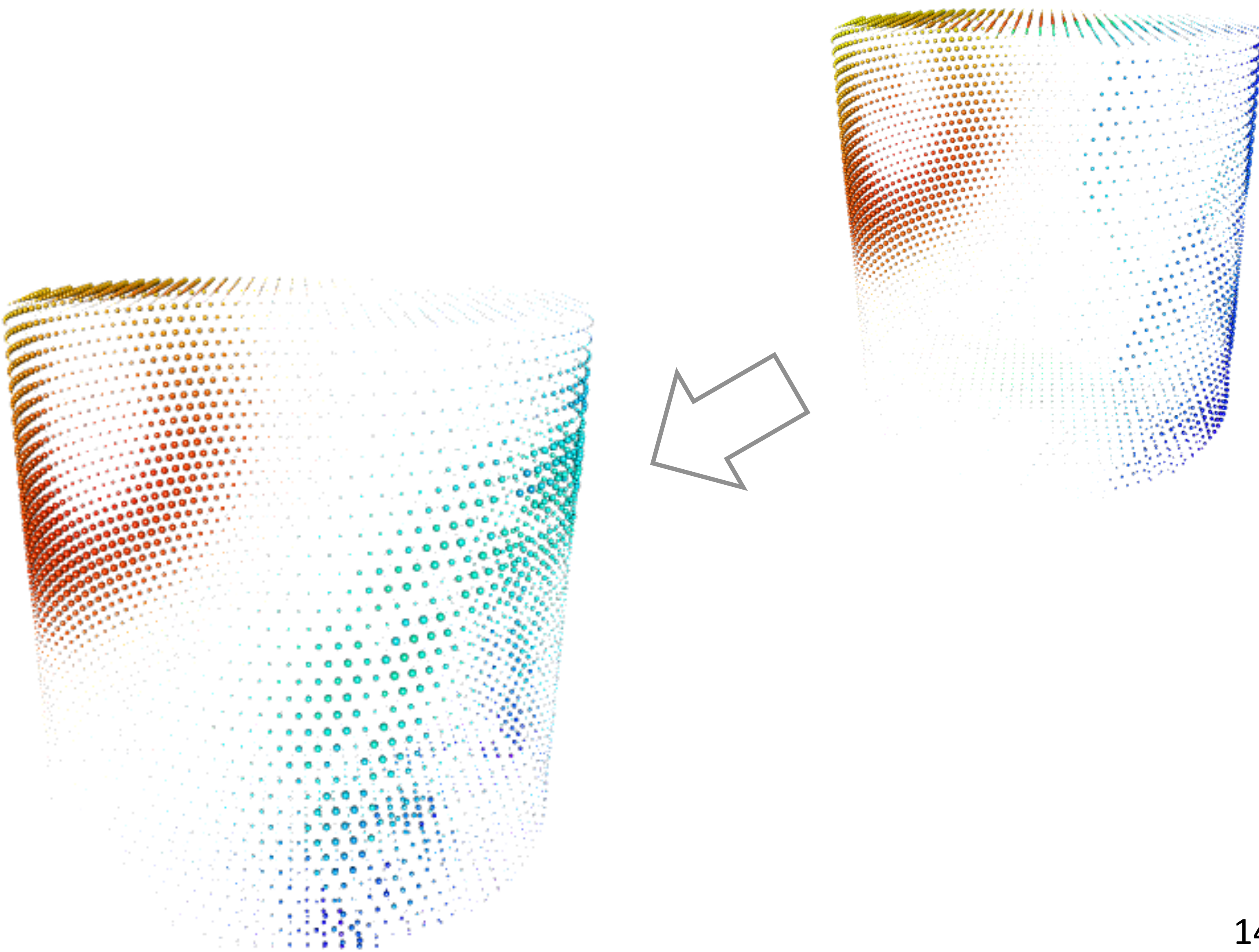

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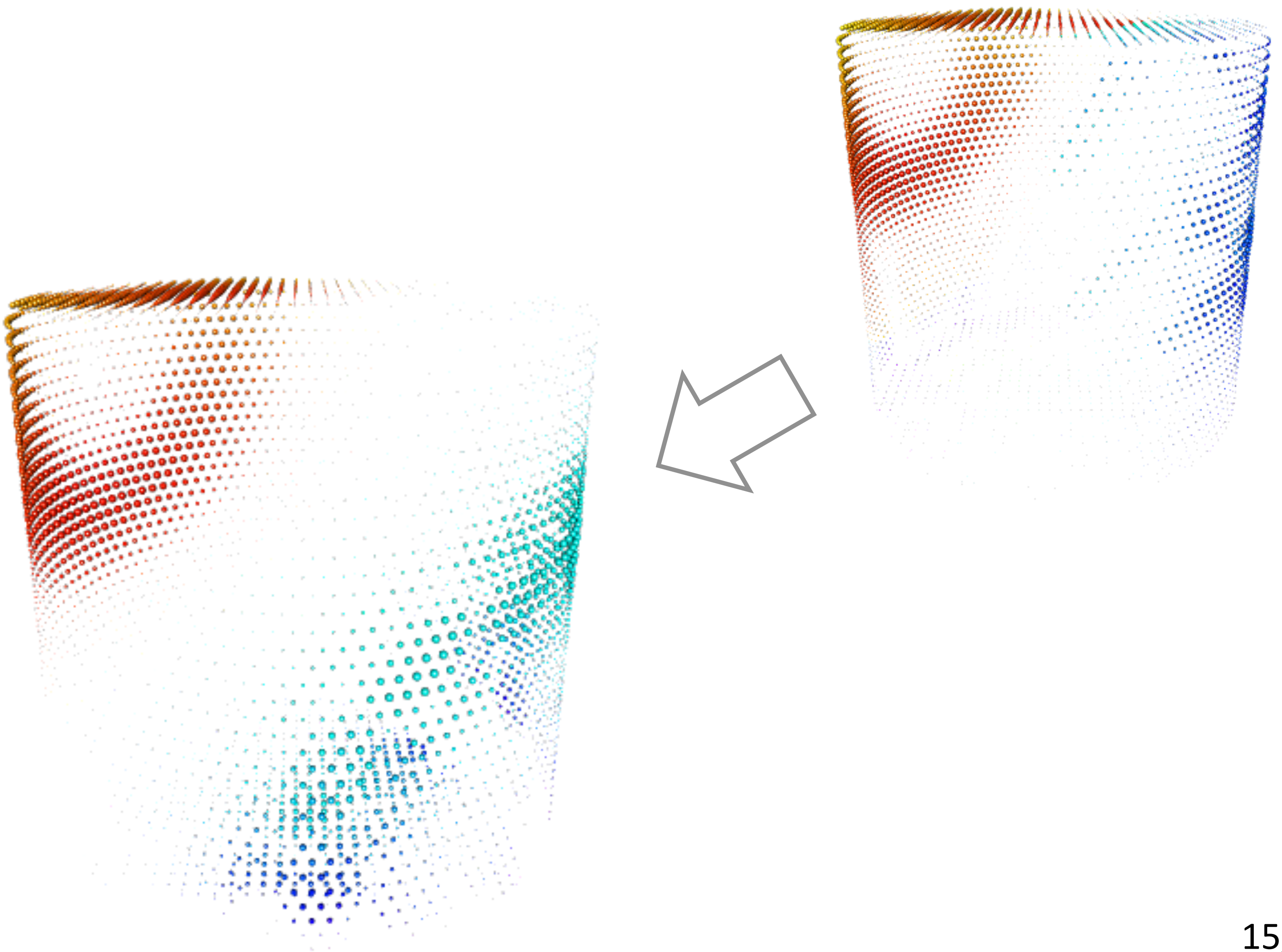

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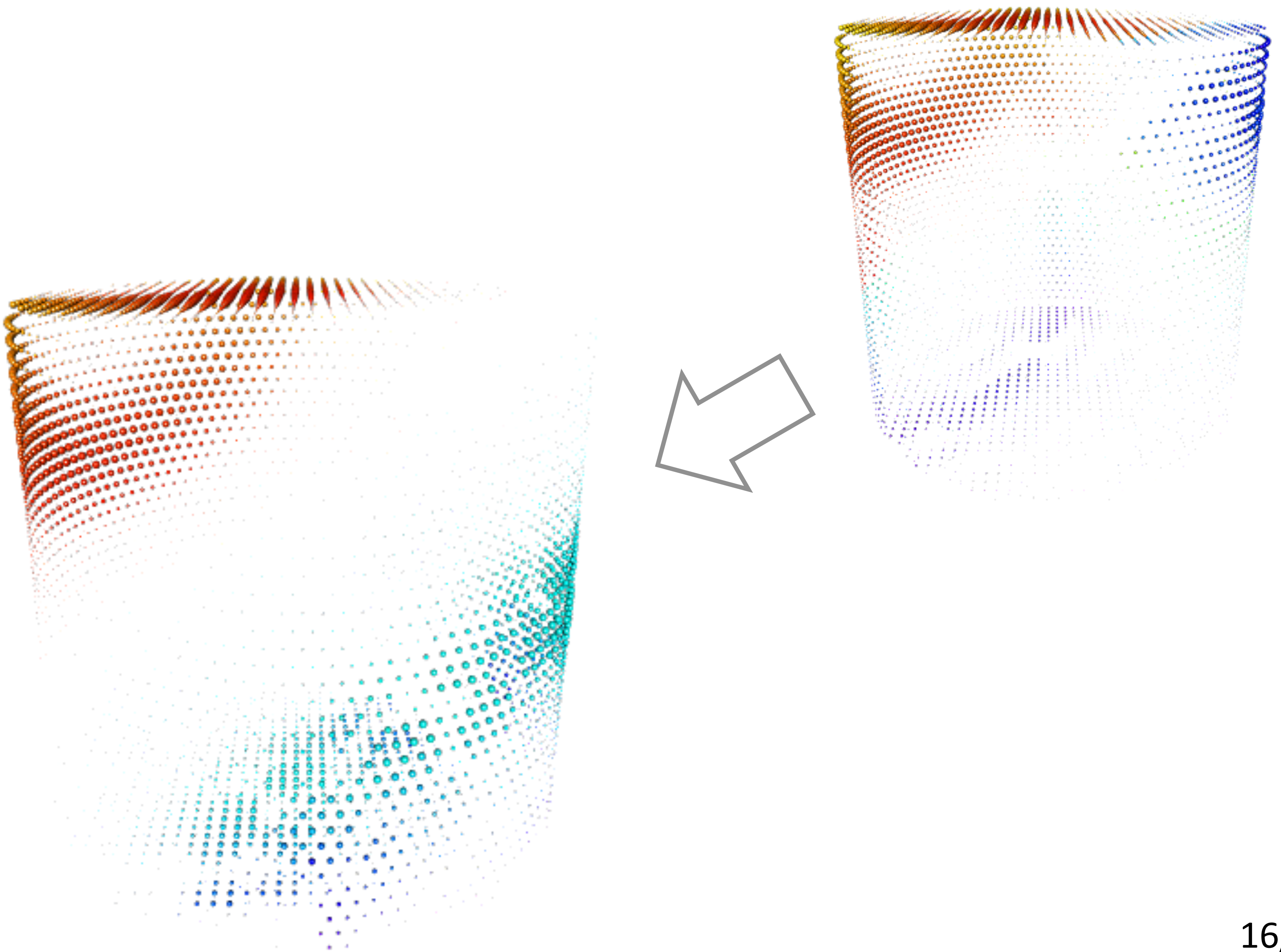

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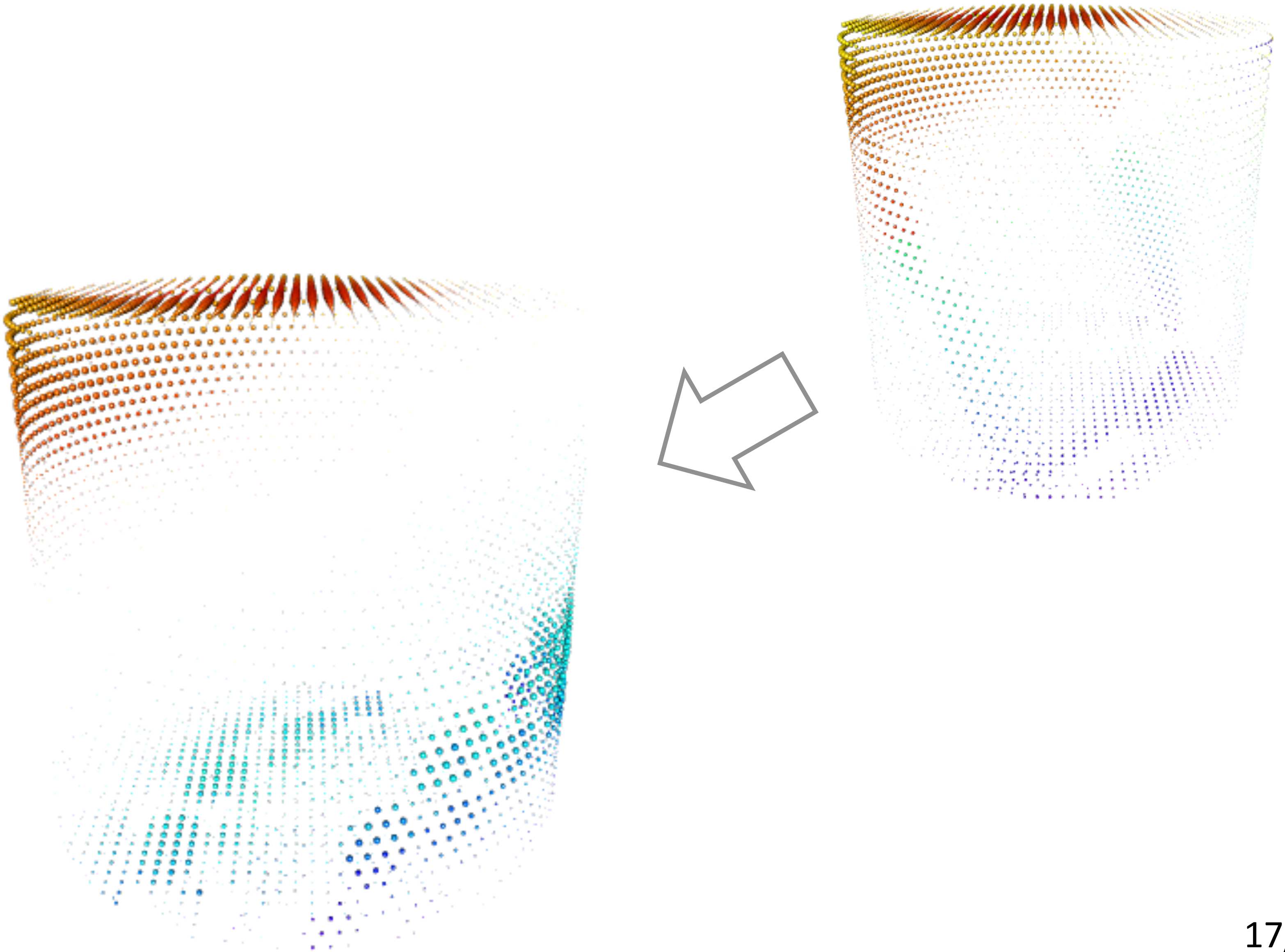

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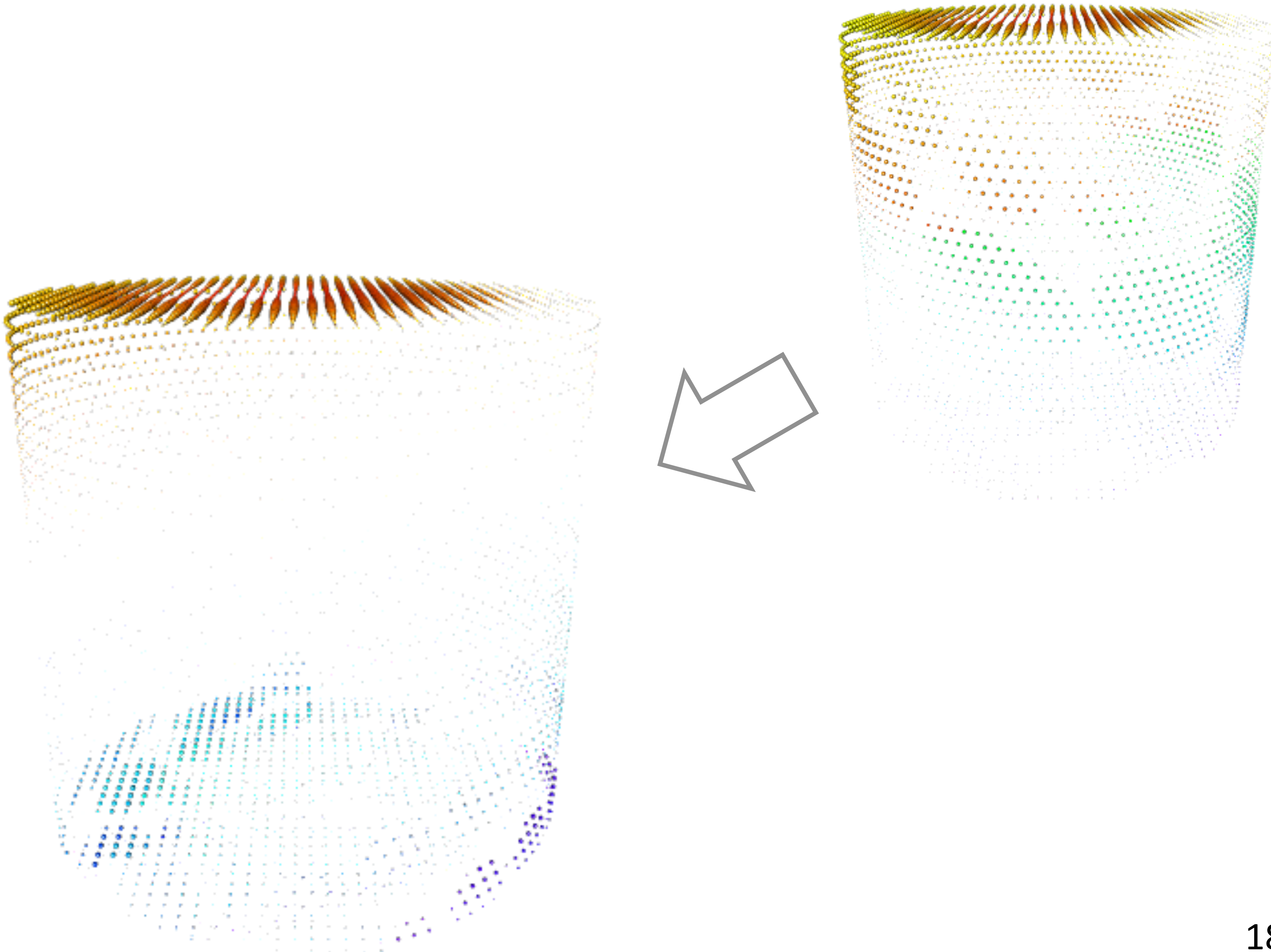

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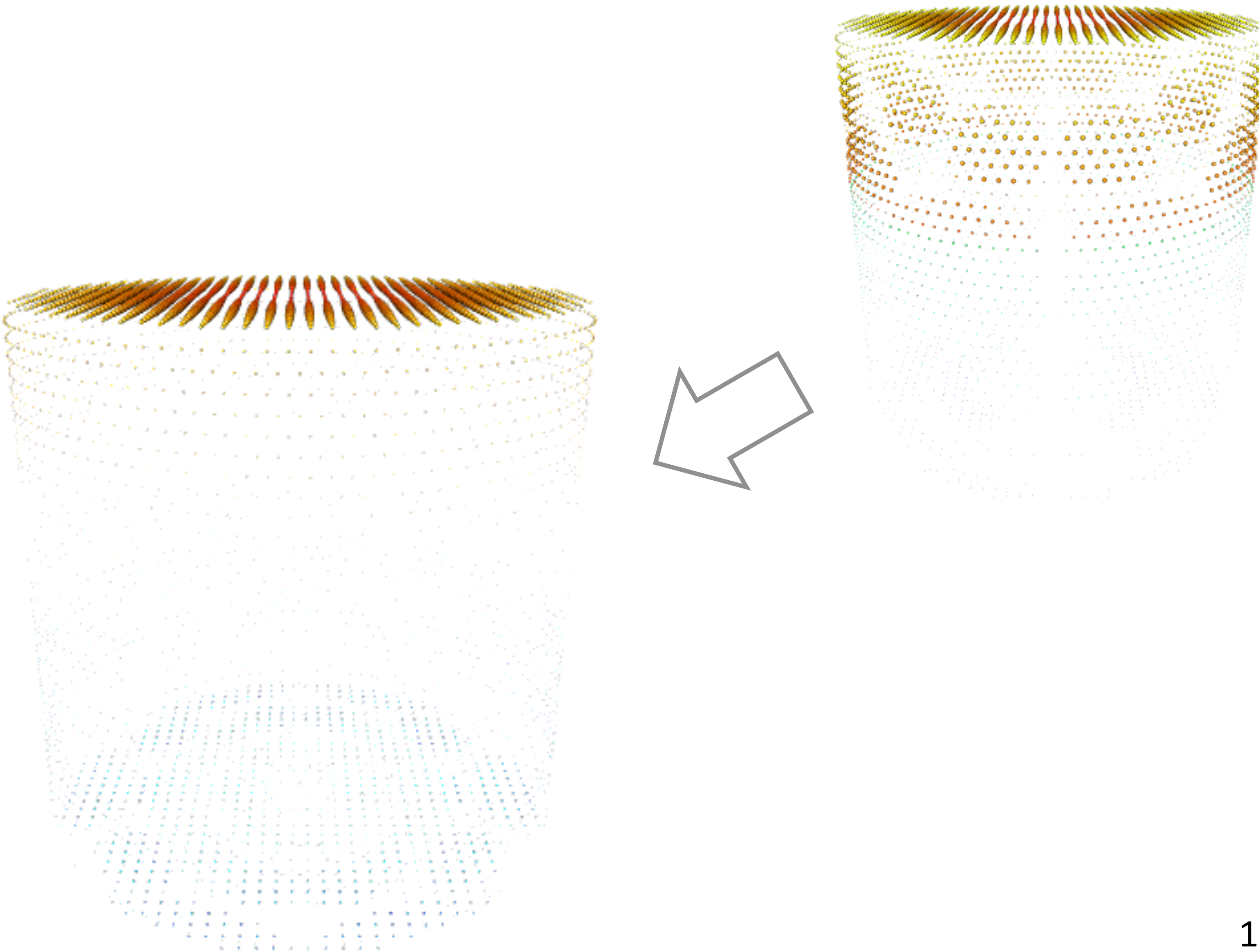

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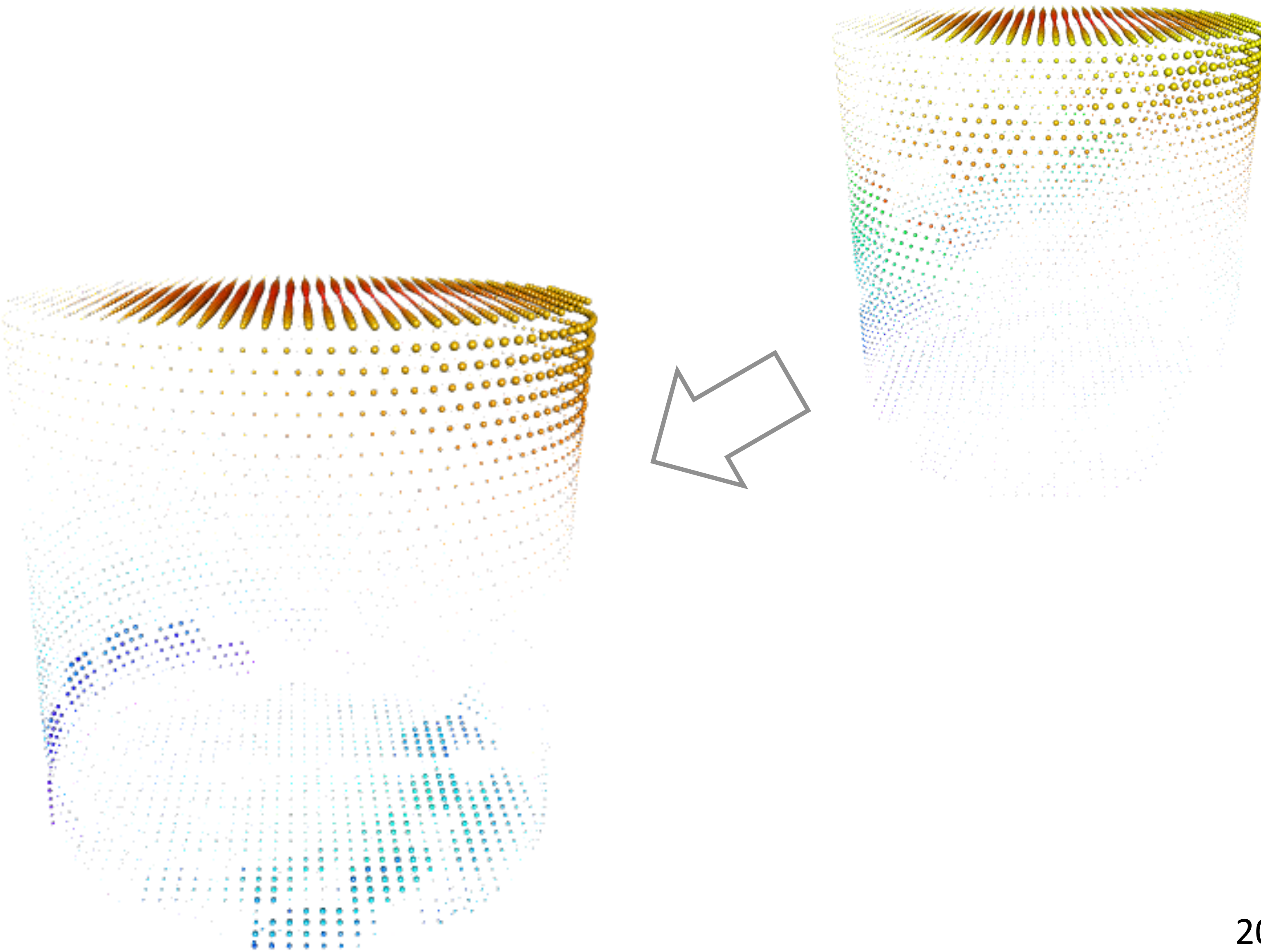

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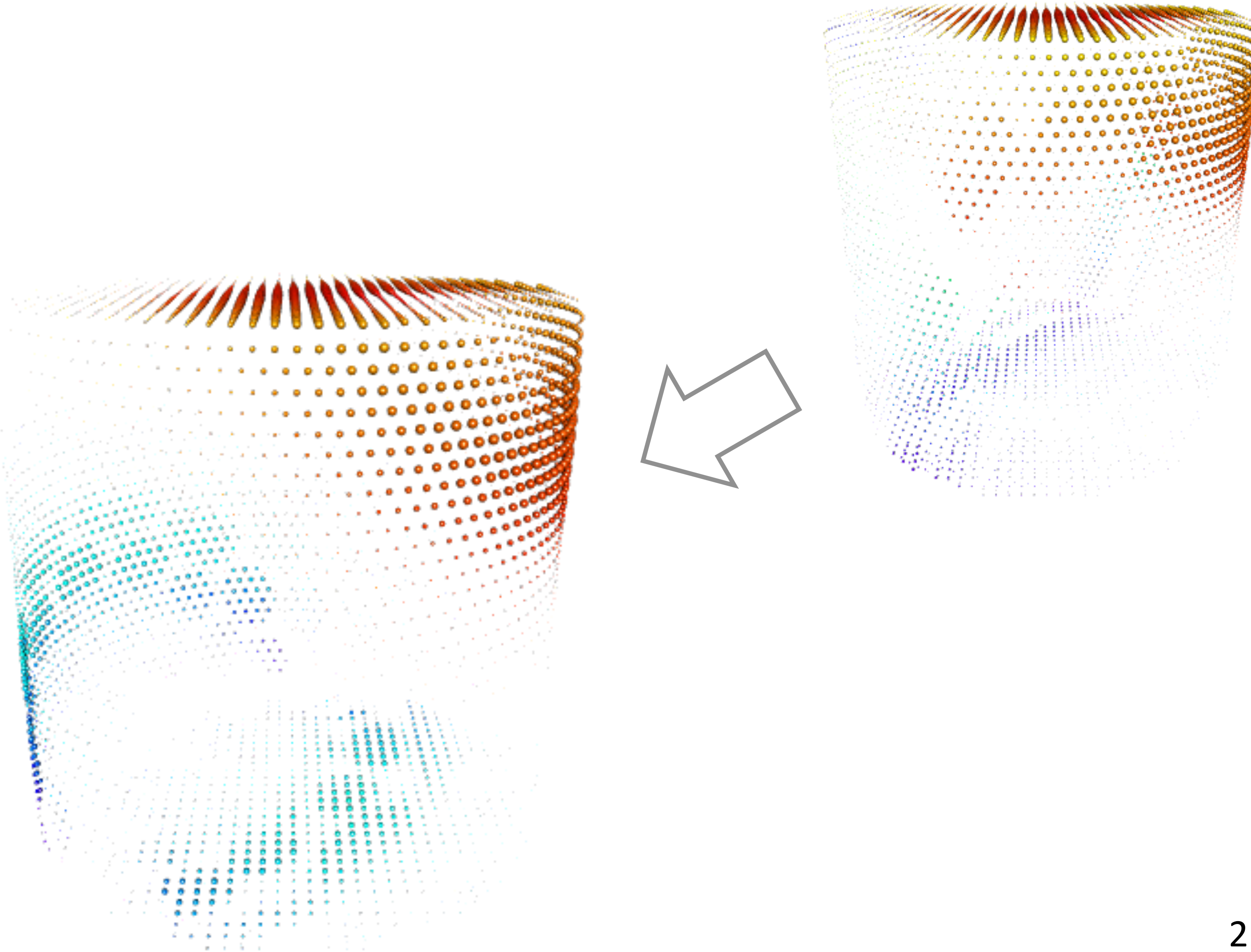

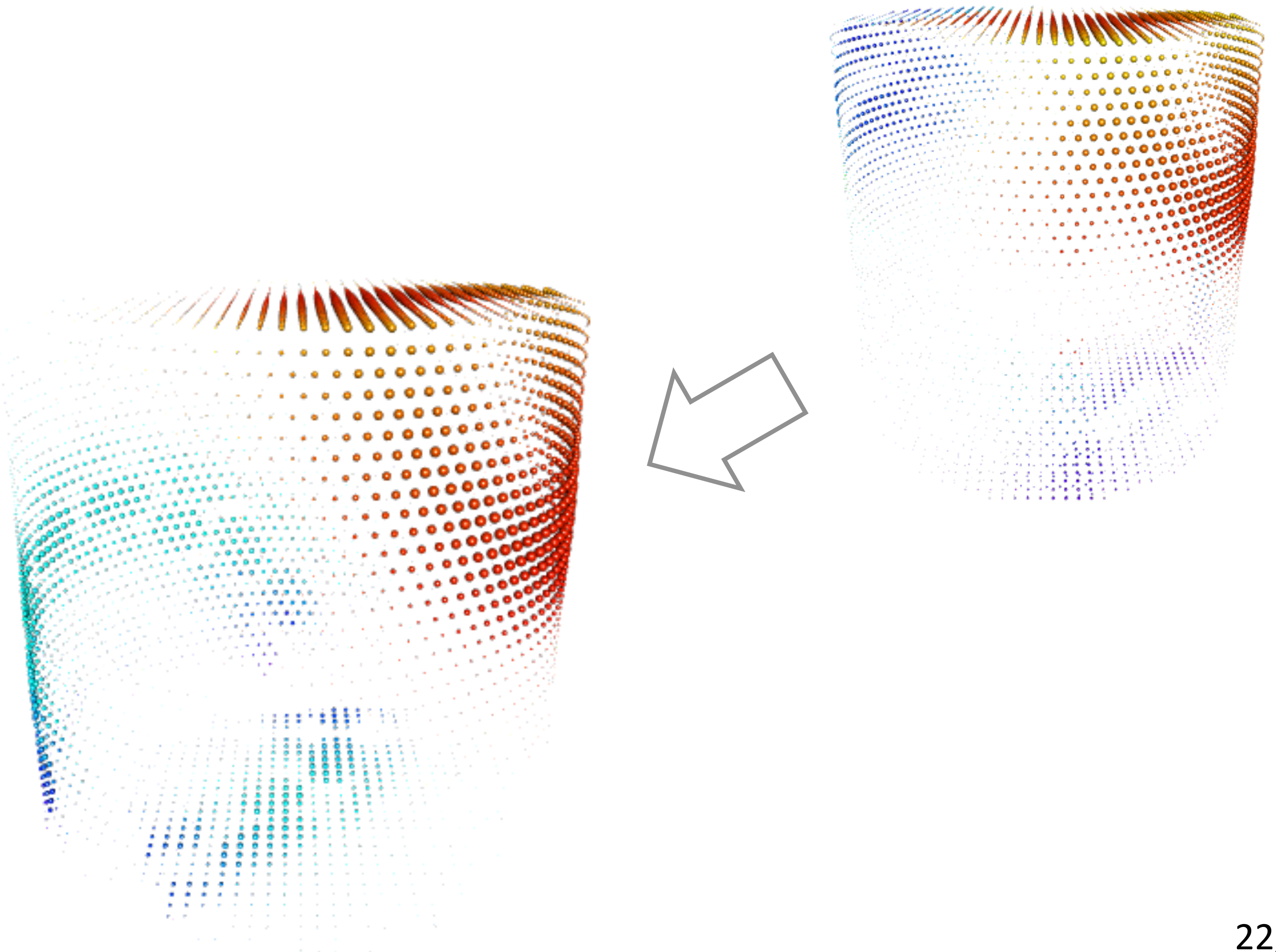

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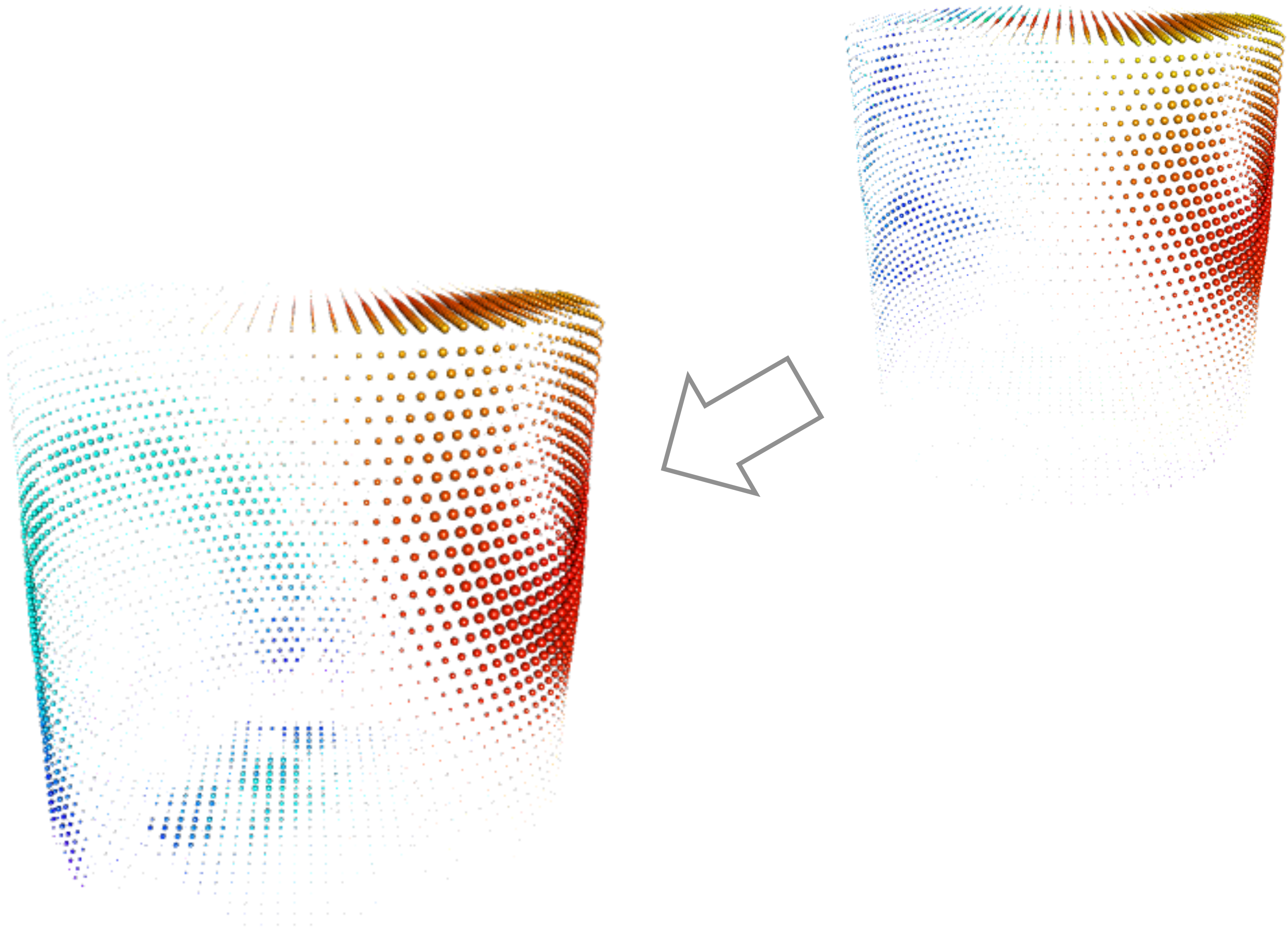

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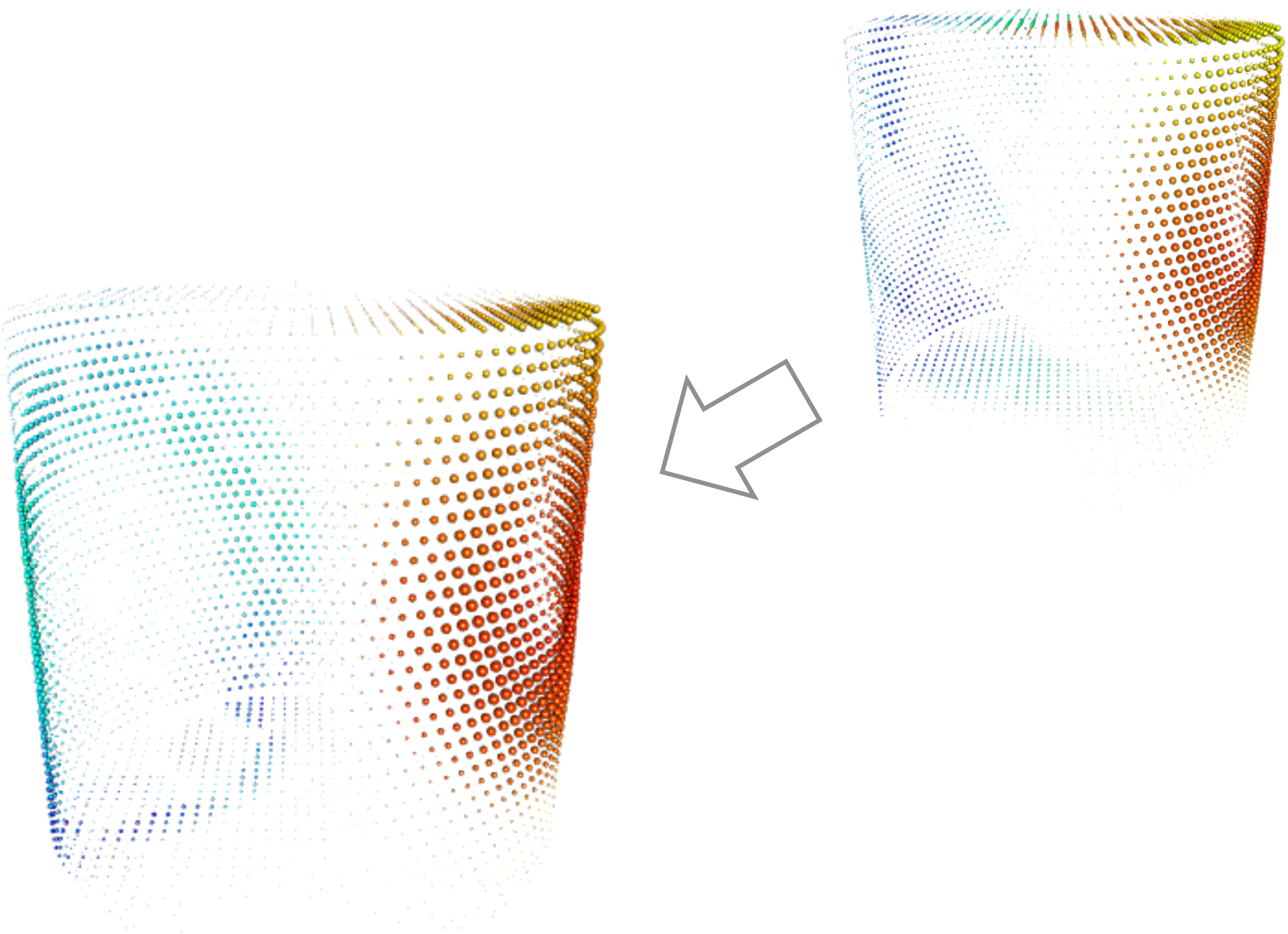

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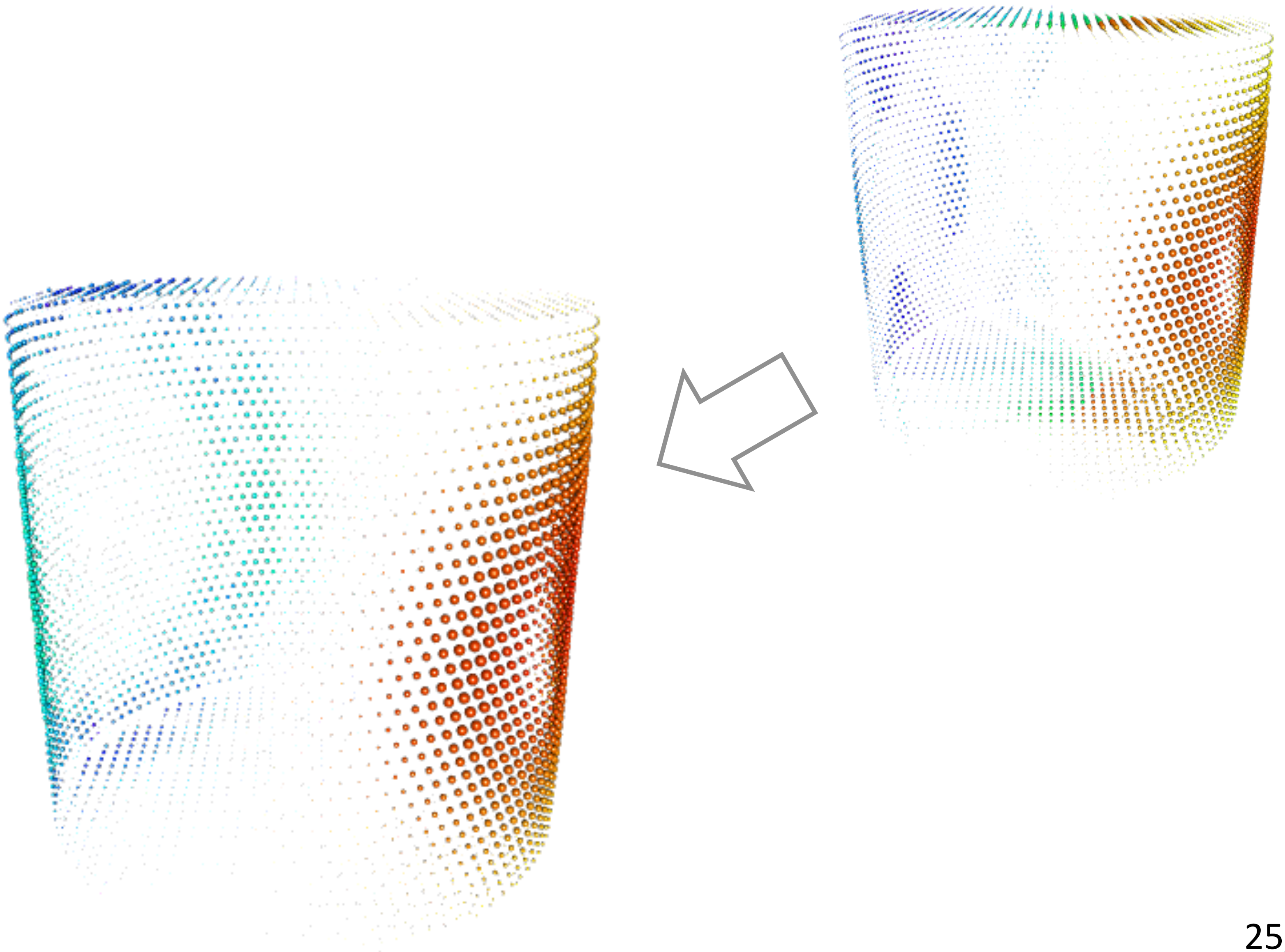


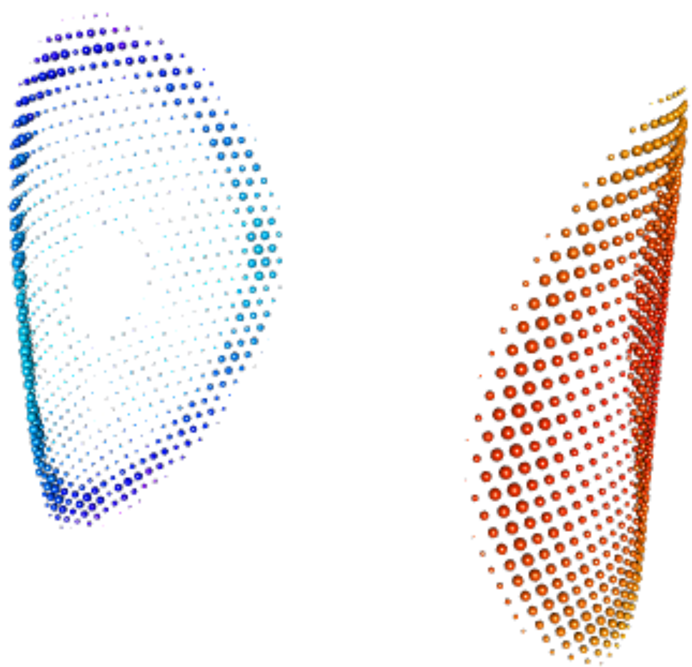
25/25

Simple simulation

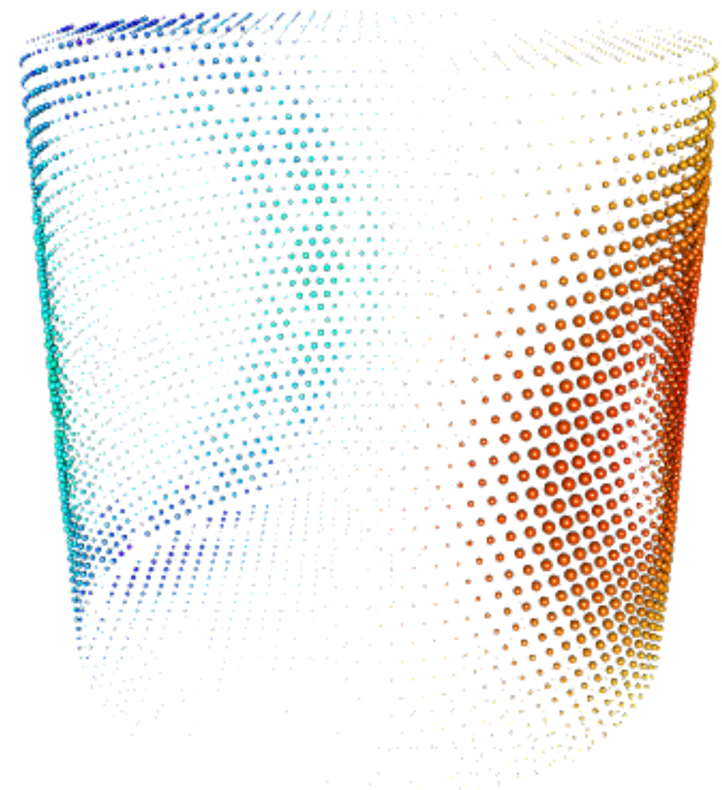
Tank definition

- ID: 33.8 m diameter, 36.2 m height (SuperK)
- 40% photo-coverage, 60% mirror-coverage
- 90% reflectivity (nominal)
- 100 m water absorption length
- PMTs
  - 20 inch
  - 16% efficiency (effective)
  - 1 kHz darkrate
  - 10 ns TTS (FWHM time resolution)

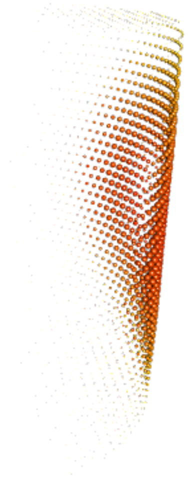
Particle type



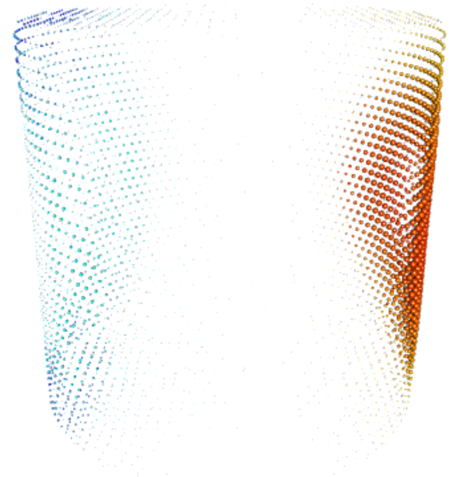
“Muon”



“Electron”

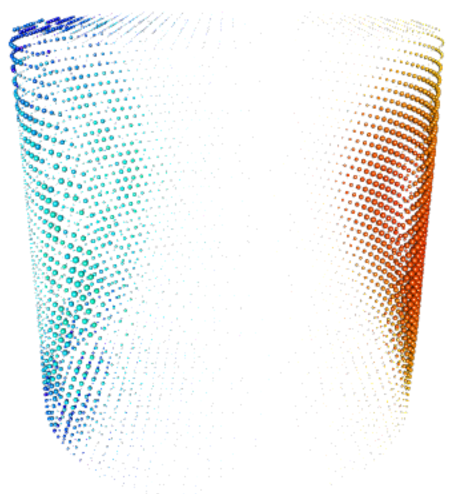


0%

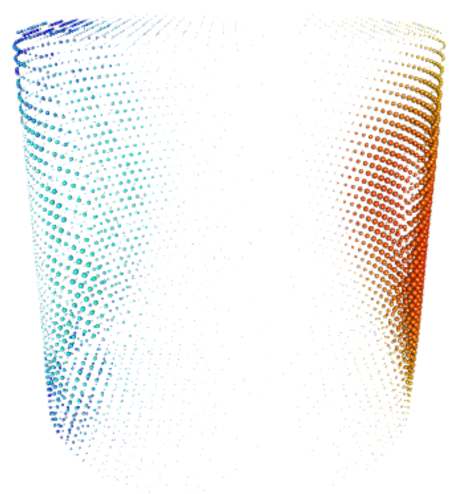


33%

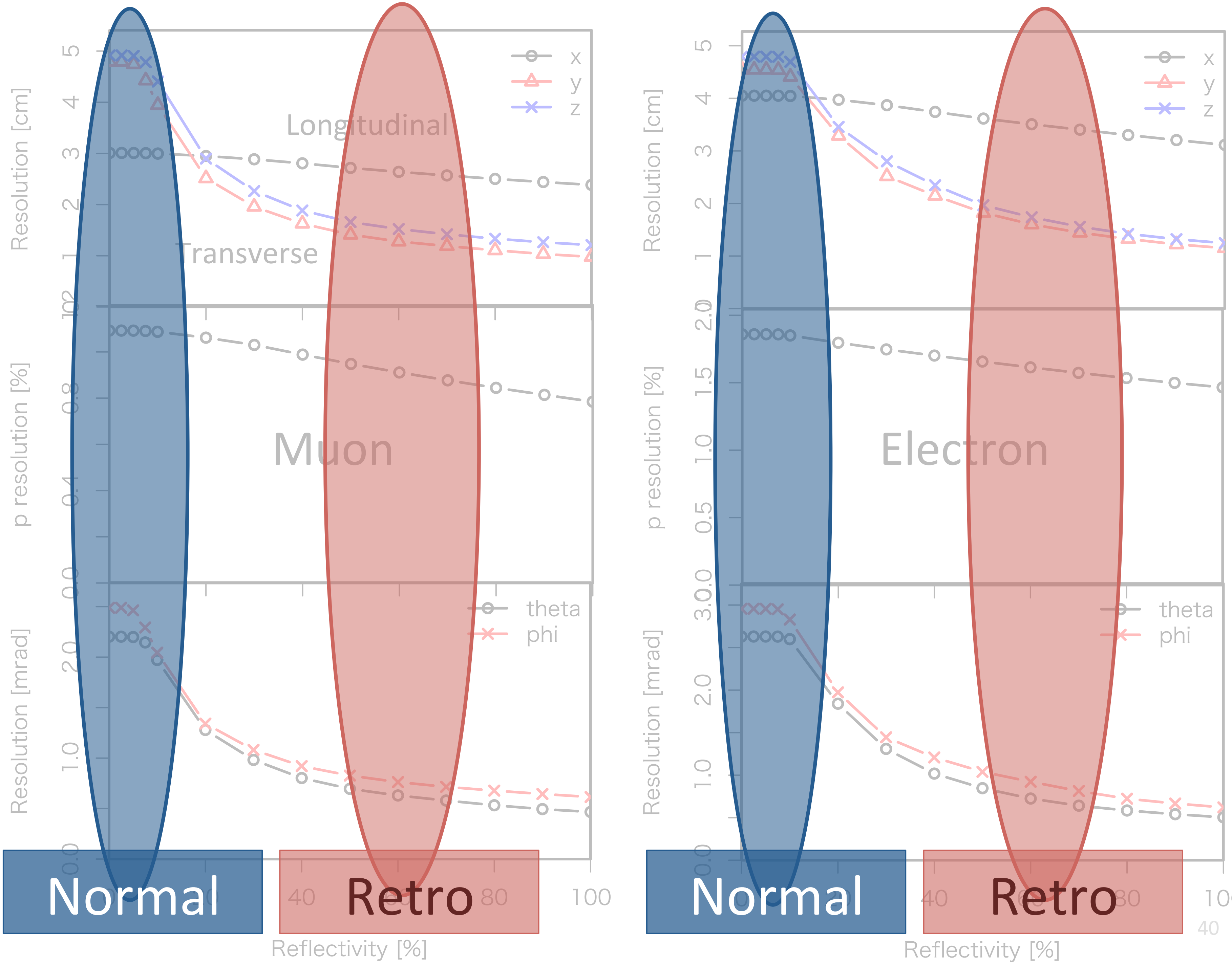
Vary reflectivity for a single side-moving particle

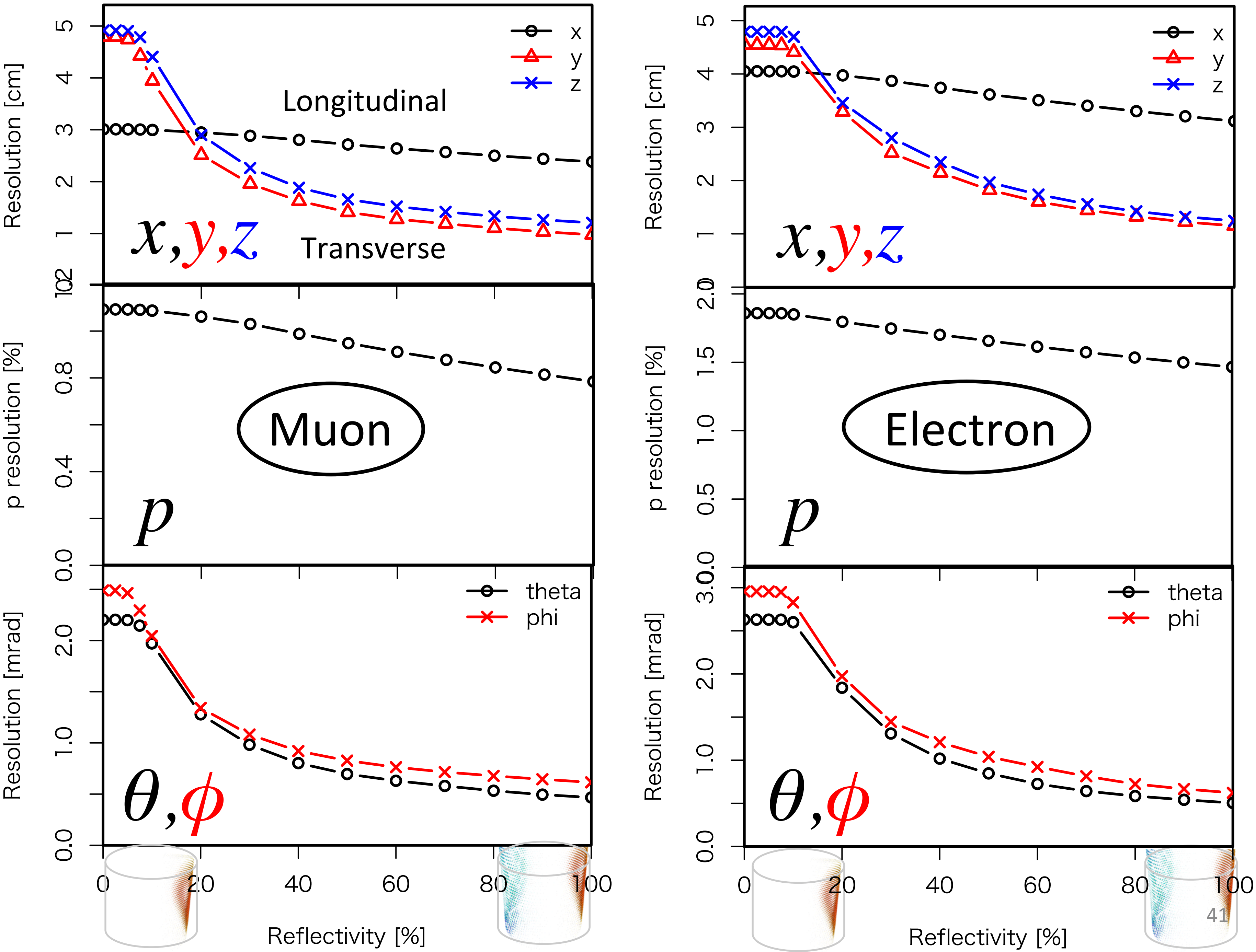


100%



67%

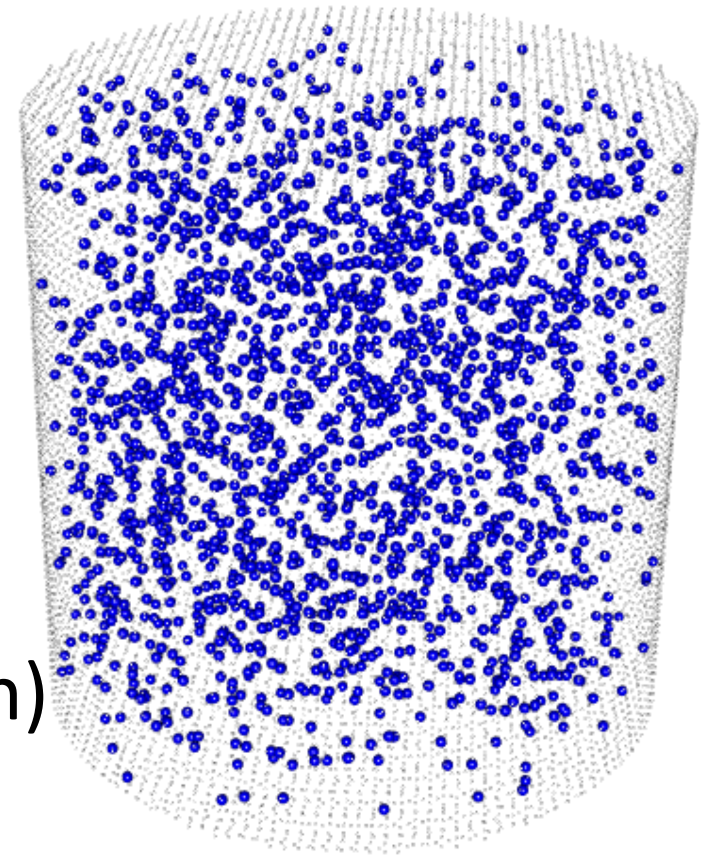

Longitudinal
Transverse
x
y
z
Muon
Electron
theta
phi
Resolution [cm]
p resolution [%]
Resolution [mrad]
Reflectivity [%]
Normal
Retro

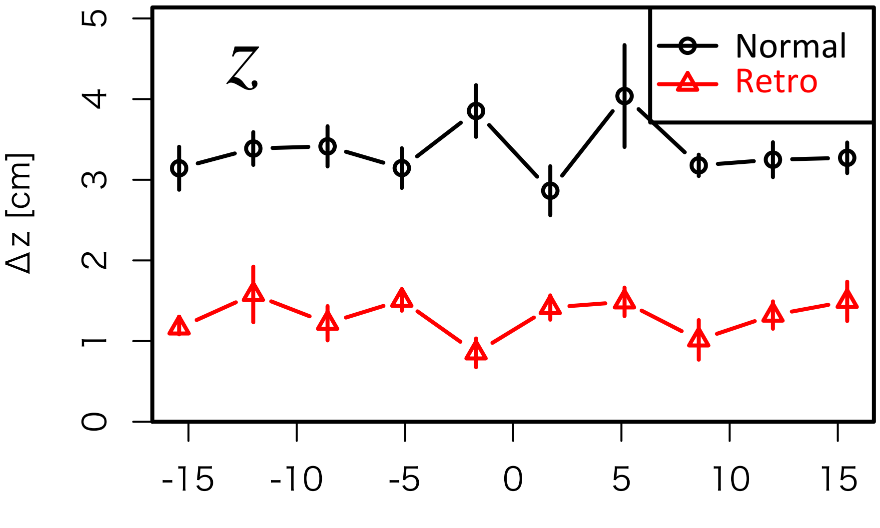


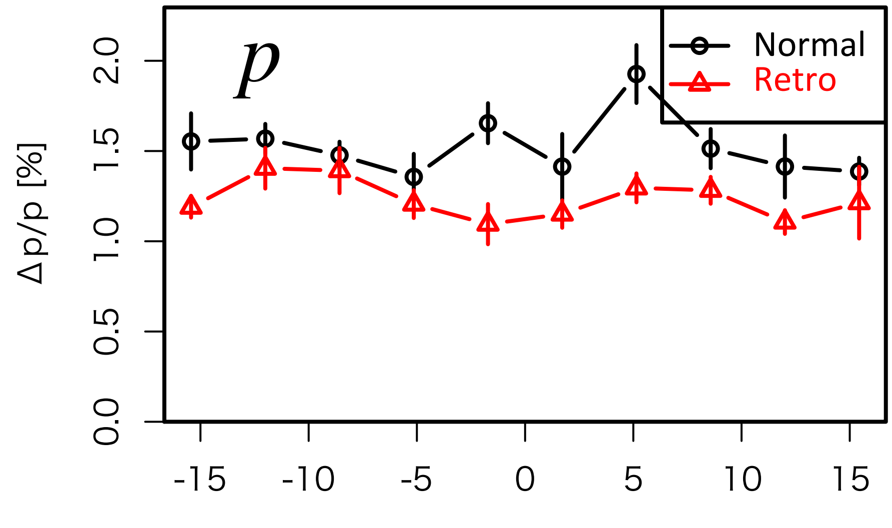
Muon
Electron
Longitudinal
Transverse
x,y,z
p
θ,φ
x
y
z
theta
phi
Resolution [cm]
p resolution [%]
Resolution [mrad]
Reflectivity [%]

Resolution at other positions

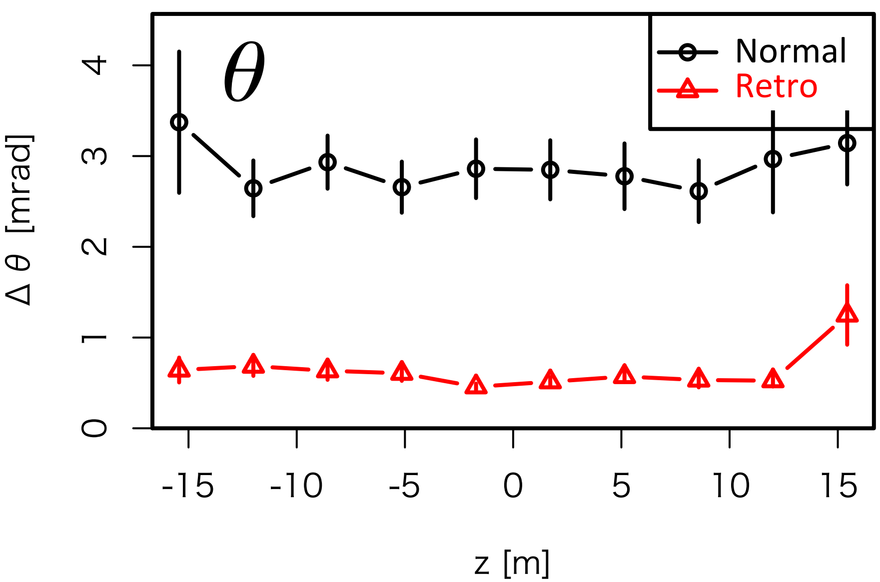
- Generate random vertices
  - uniform in cylindrical volume (rho < 16.1m, |z| < 17.2m)
  - uniform in momentum (0 < p < 3 GeV)
  - isotropic, electrons
- Take mean of precision (expected standard deviation) of params

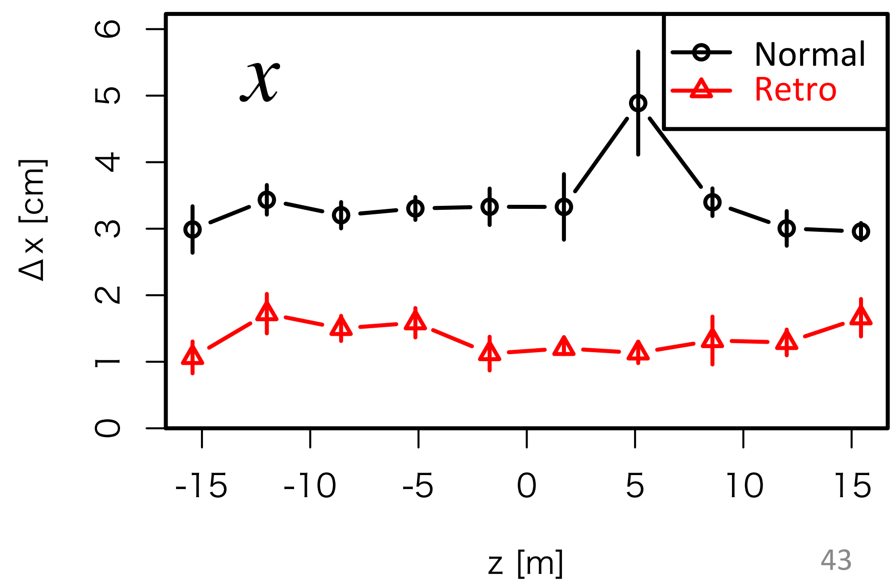




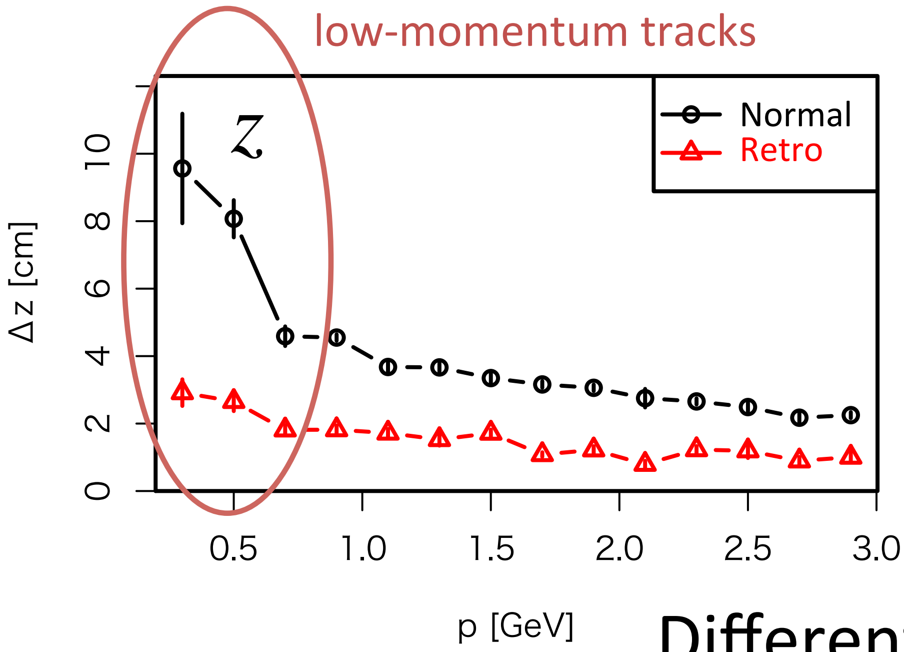


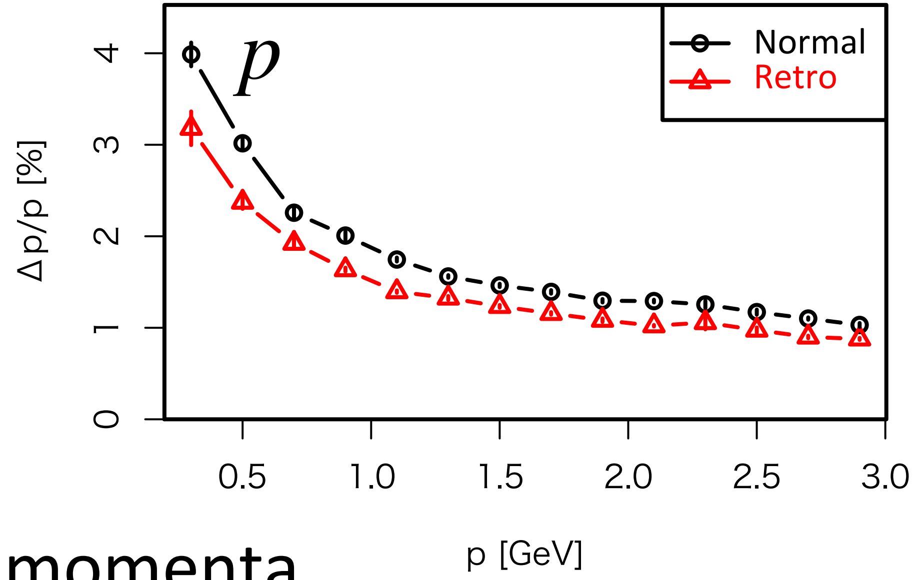
Different z positions



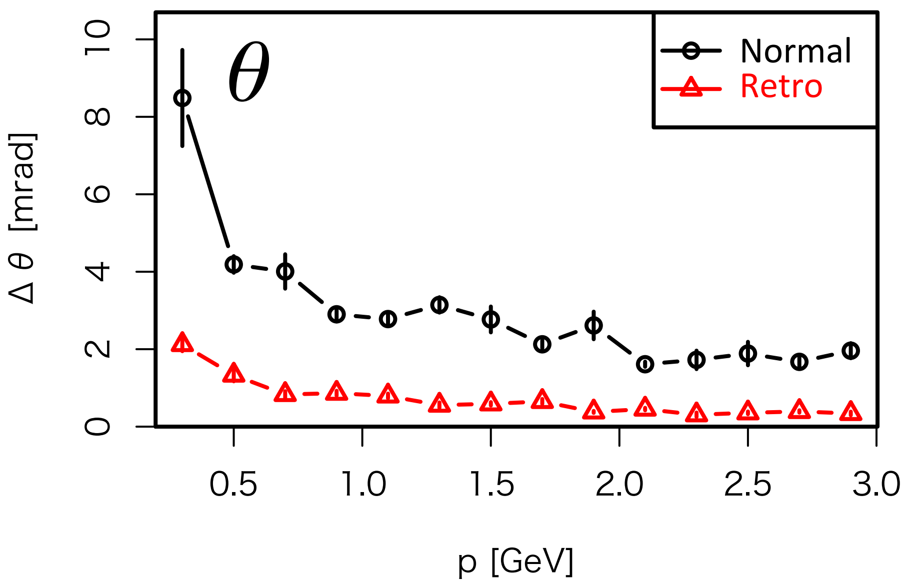


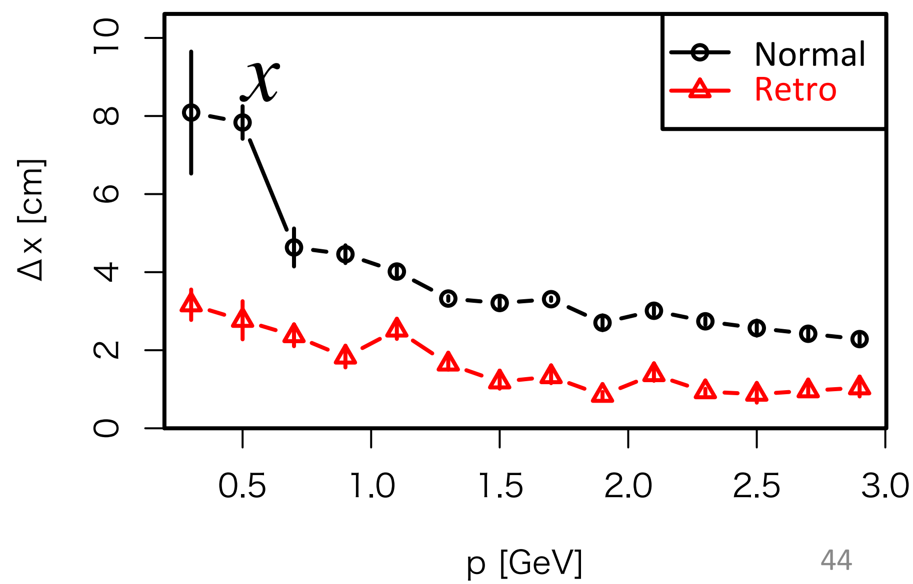
Especially beneficial for
low-momentum tracks





Different momenta





Why does it work?

- Slight increase in momentum resolution ~25%

→ due to increase in total charge

$\sqrt{(1 + 0.6 \times 0.9)} = 1.24$

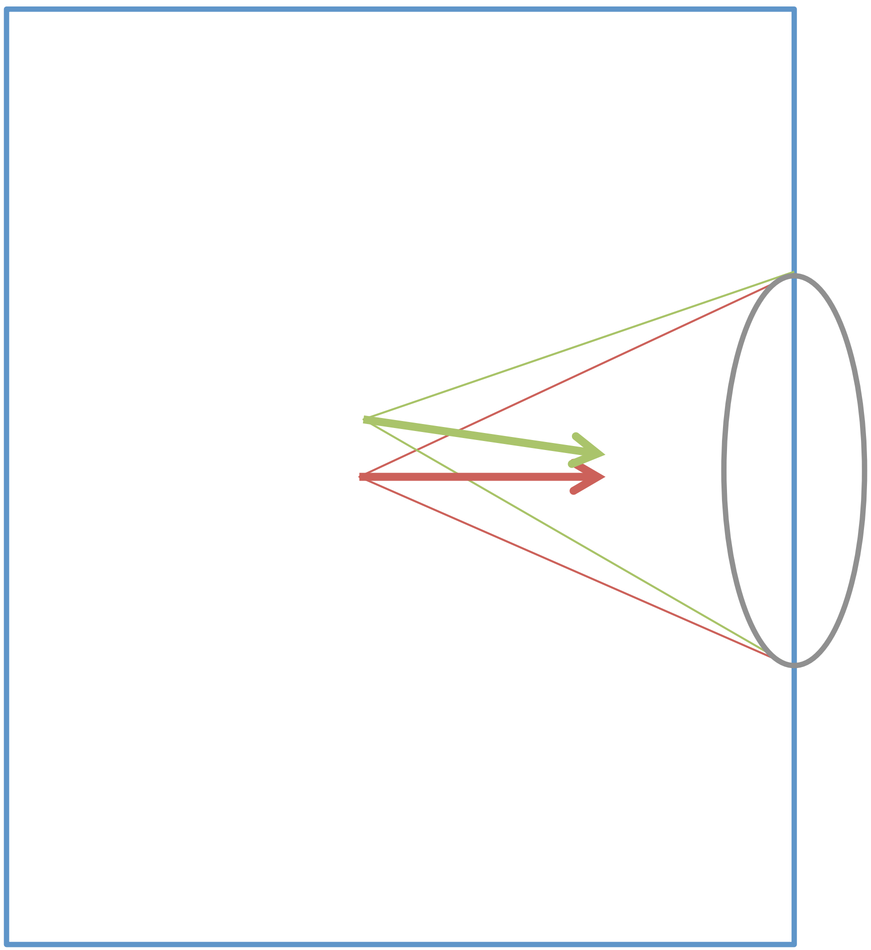
- Significant improvement in vertex position (~2x) and angles (>3x)

a. vertex + angle sensitivity even without timing

b. time difference amplified by 3x

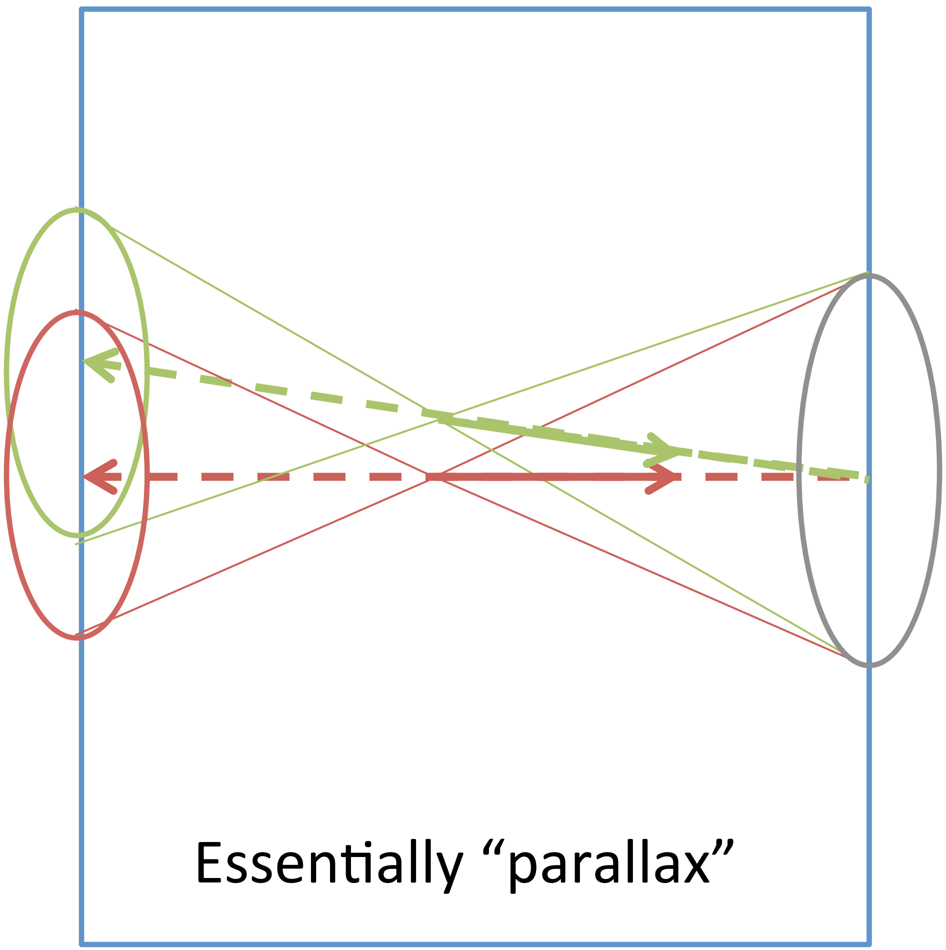
First effect seems to be dominant.

z and θ **without** timing info



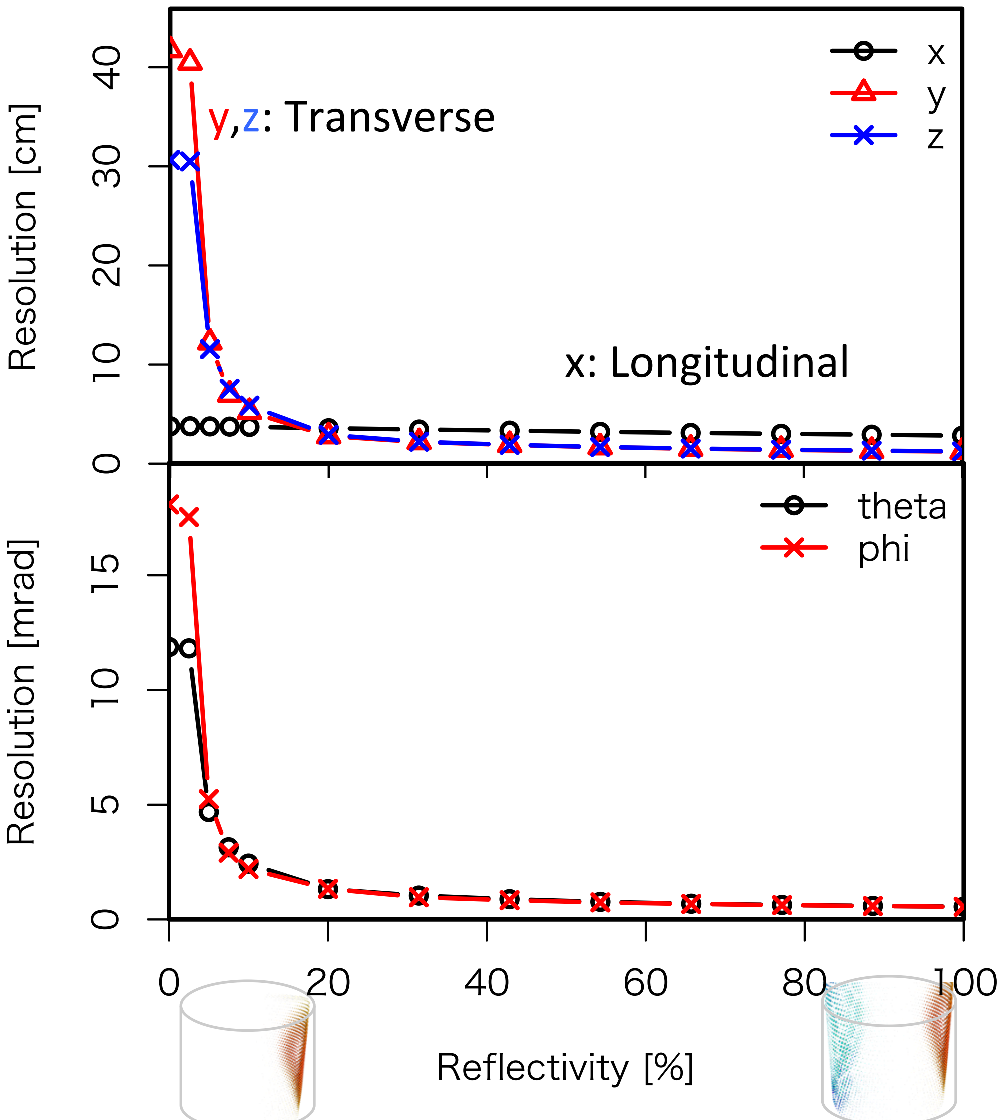
- Without mirrors, a change in z can be compensated by a change in θ.

z and θ **without** timing info



- Without mirrors, a change in z can be compensated by a change in θ.
- Adding mirrors resolves this degeneracy.
- Same with (y, ϕ)

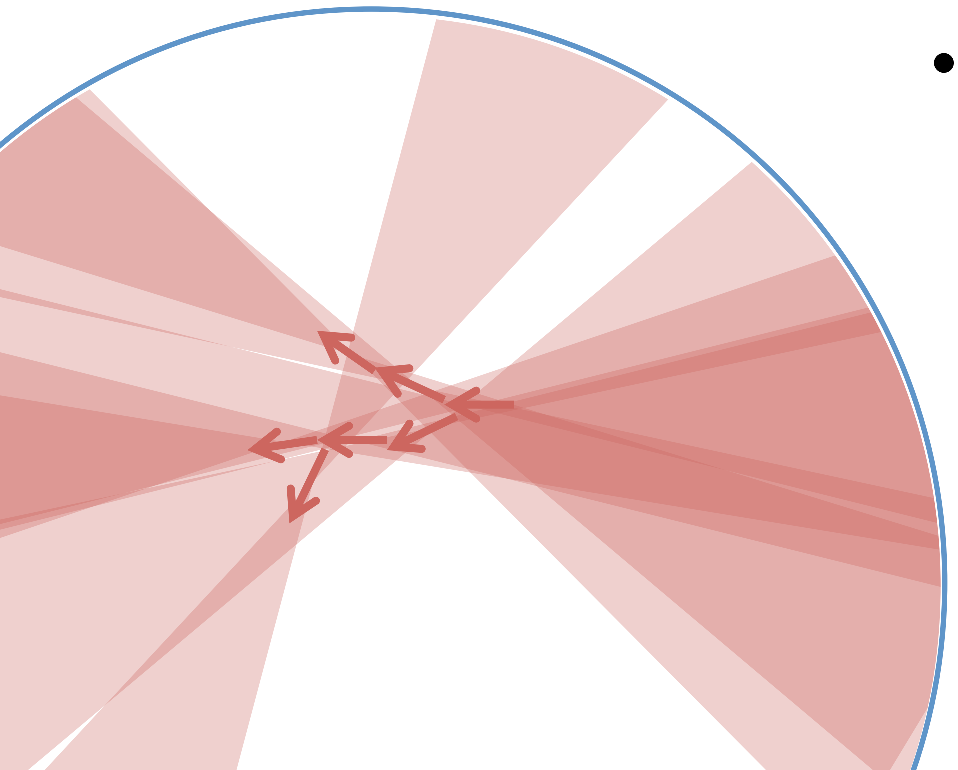
z and θ **without** timing info



- Without mirrors, a change in z can be compensated by a change in θ.
- Adding mirrors resolves this degeneracy.
- Same with (y, ϕ)

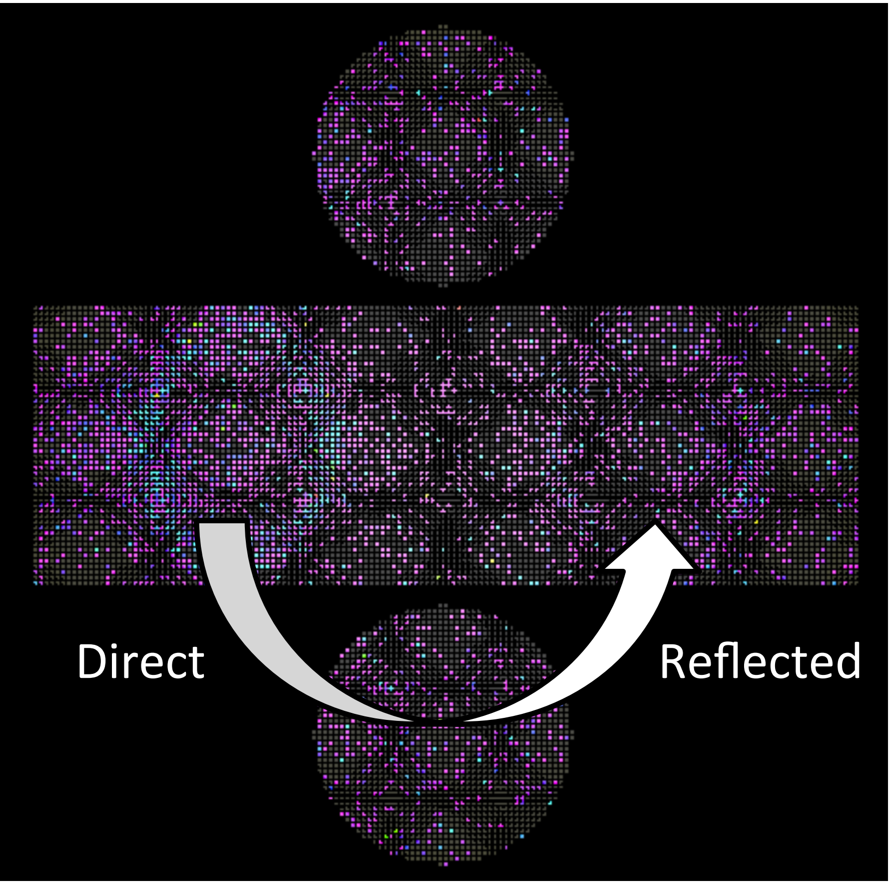
Idea: Full shower reconstruction

- Combine infinitesimal tracks of a charged particle using both direct and reflected light
  - In principle one should be able to reconstruct the full shower
    - Most upstream tracks should have less statistical uncertainty
      - How to fit large number of degrees of freedom?



Suggestions welcome

Idea: data-to-data vertex fit



- Due to retro-reflectors we can look at the same light profile from two perspectives
- Only if we assign the vertex correctly will these match
- Need algorithm to separate direct&reflection (e.g. time) and consider multiple emission points along trajectory

Suggestions welcome

Reflector measurements

Reflector tape measurements

Purchased 3 types

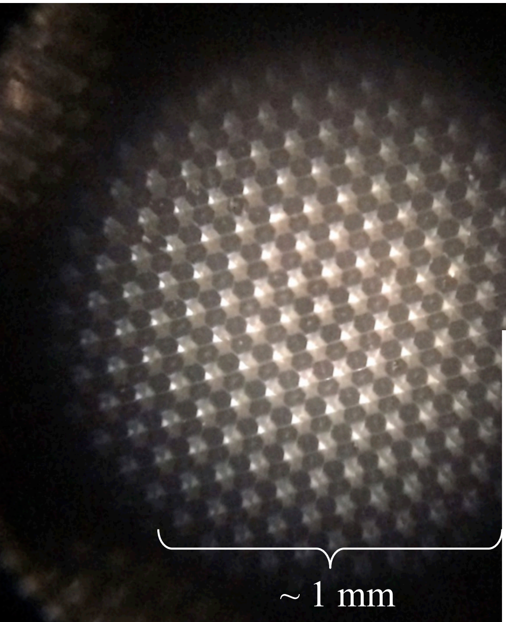
Cost for SK-size (60%)

— ORAFOL micro-prism ¥1500/25x1000mm^2 → ¥2.0-oku

— Nippon Carbide micro-prism ¥1200/25x1000mm^2 → ¥1.6-oku

— ORAFOL glass bead tape ¥200/50x1000mm^2 → ¥0.1-oku

ORAFOL prism



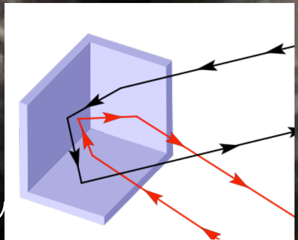
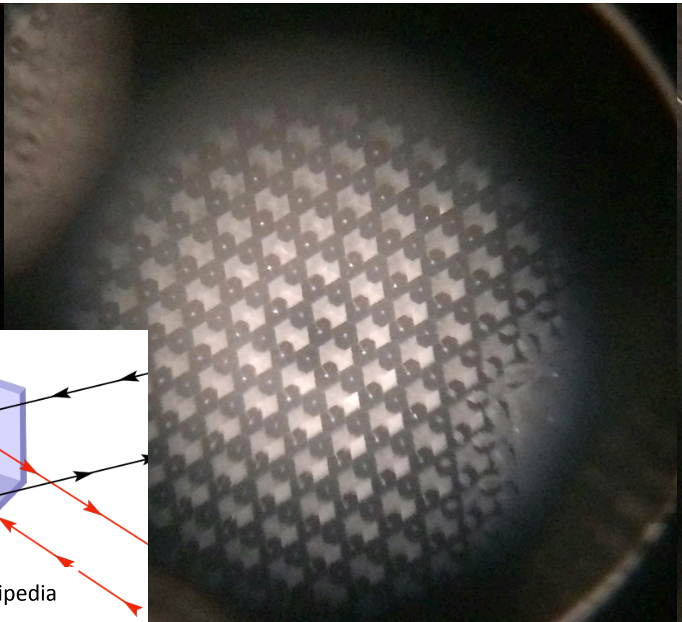
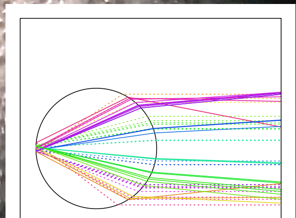


Image: Wikipedia

NIPPON CARBIDE prism



Glass-beads

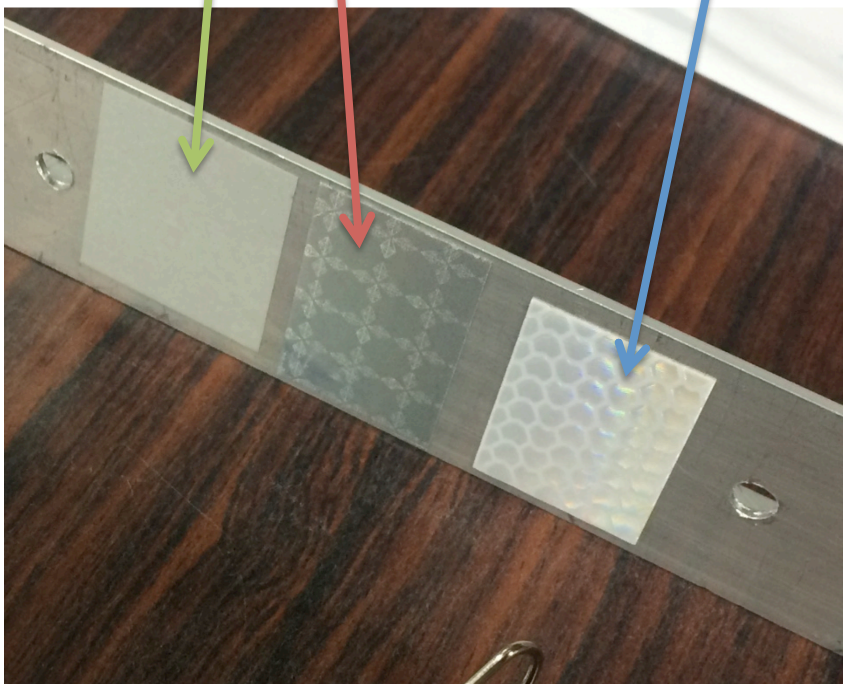


Glass-beads

ORAFOL prism

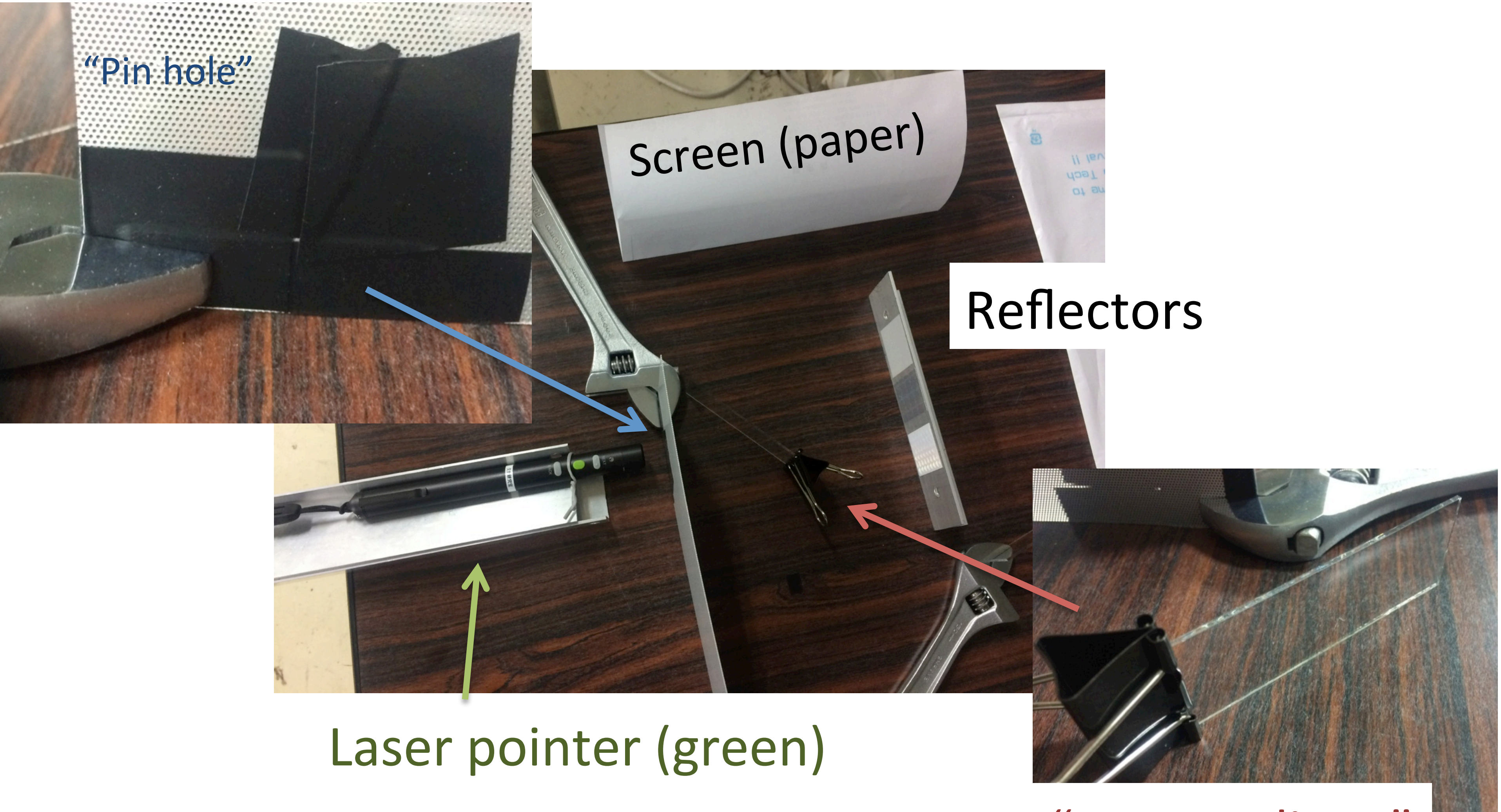
NIPPON CARBIDE prism

Flash!

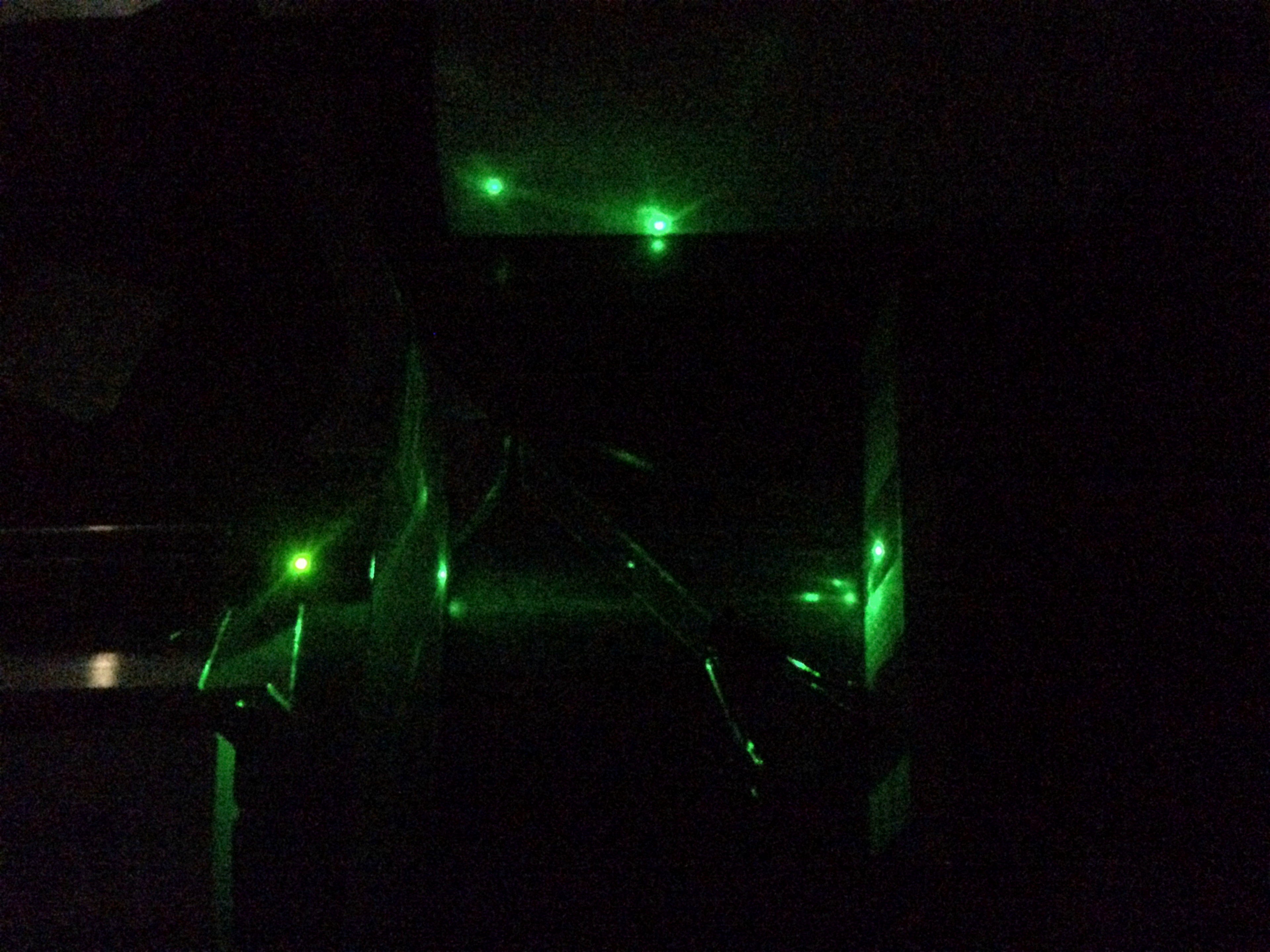


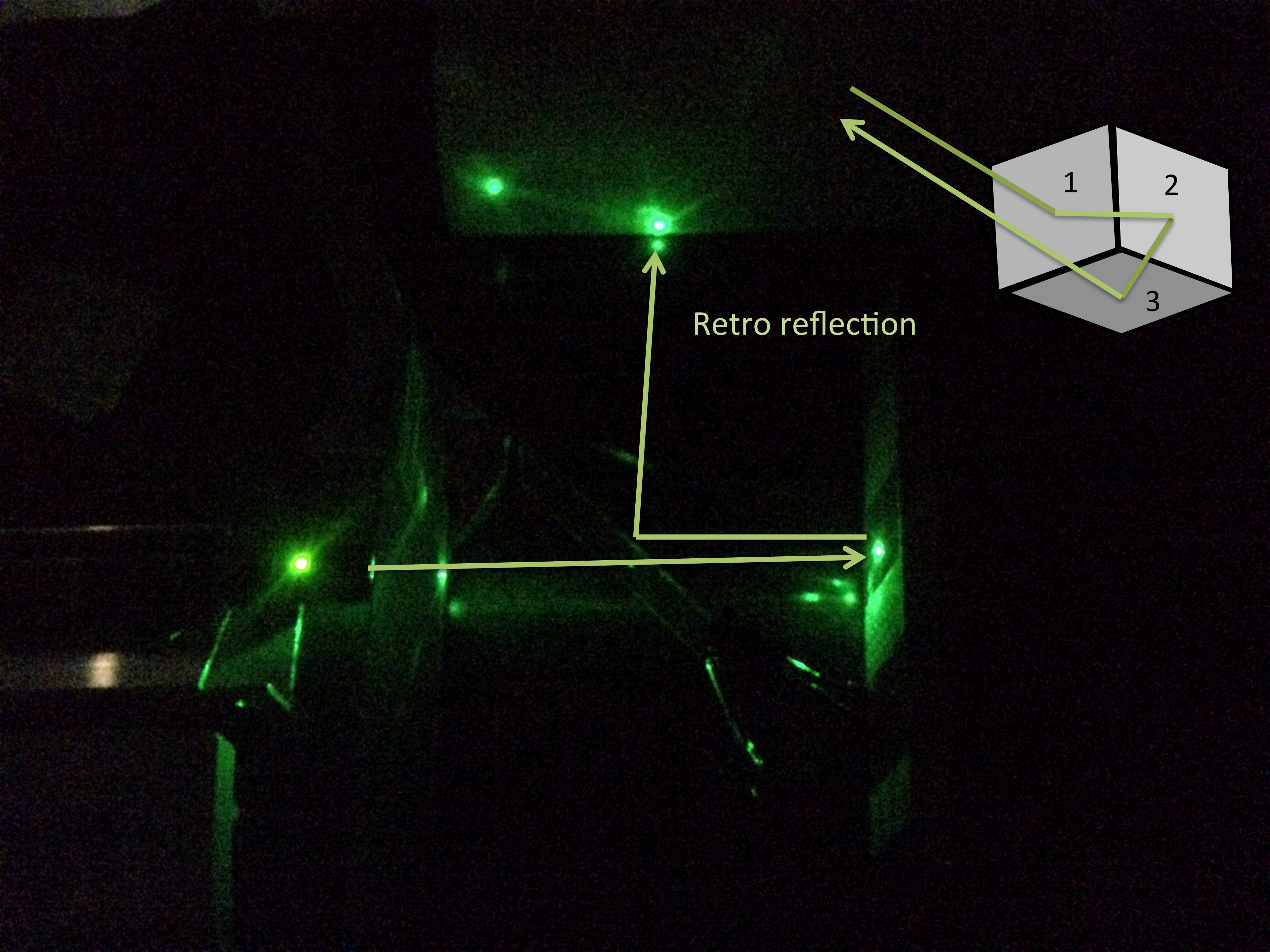
ORAFOL shows noticably strong retro-reflection at distances ($\sim 0.5^{o}$ accuracy)

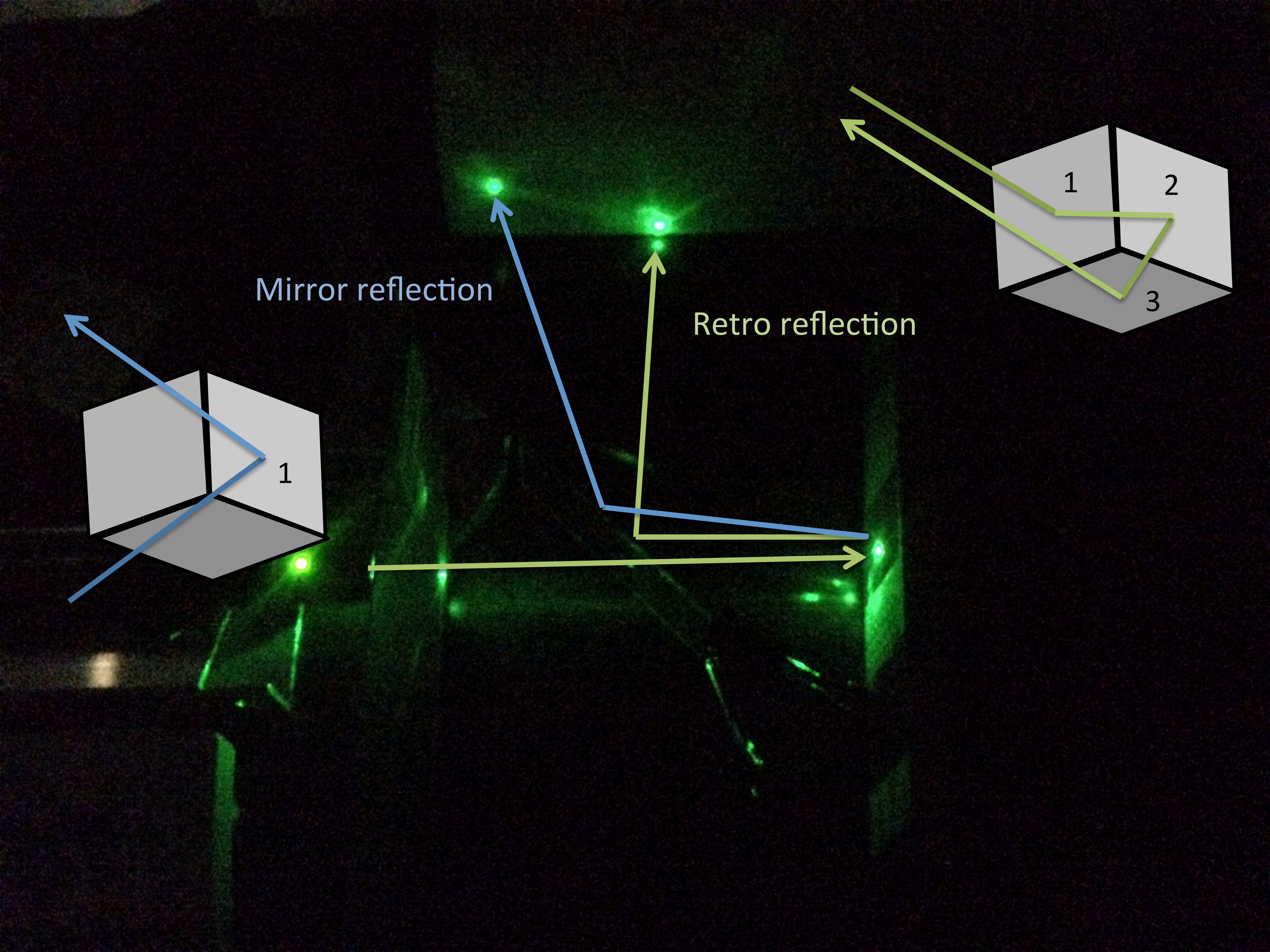
Experimental setup

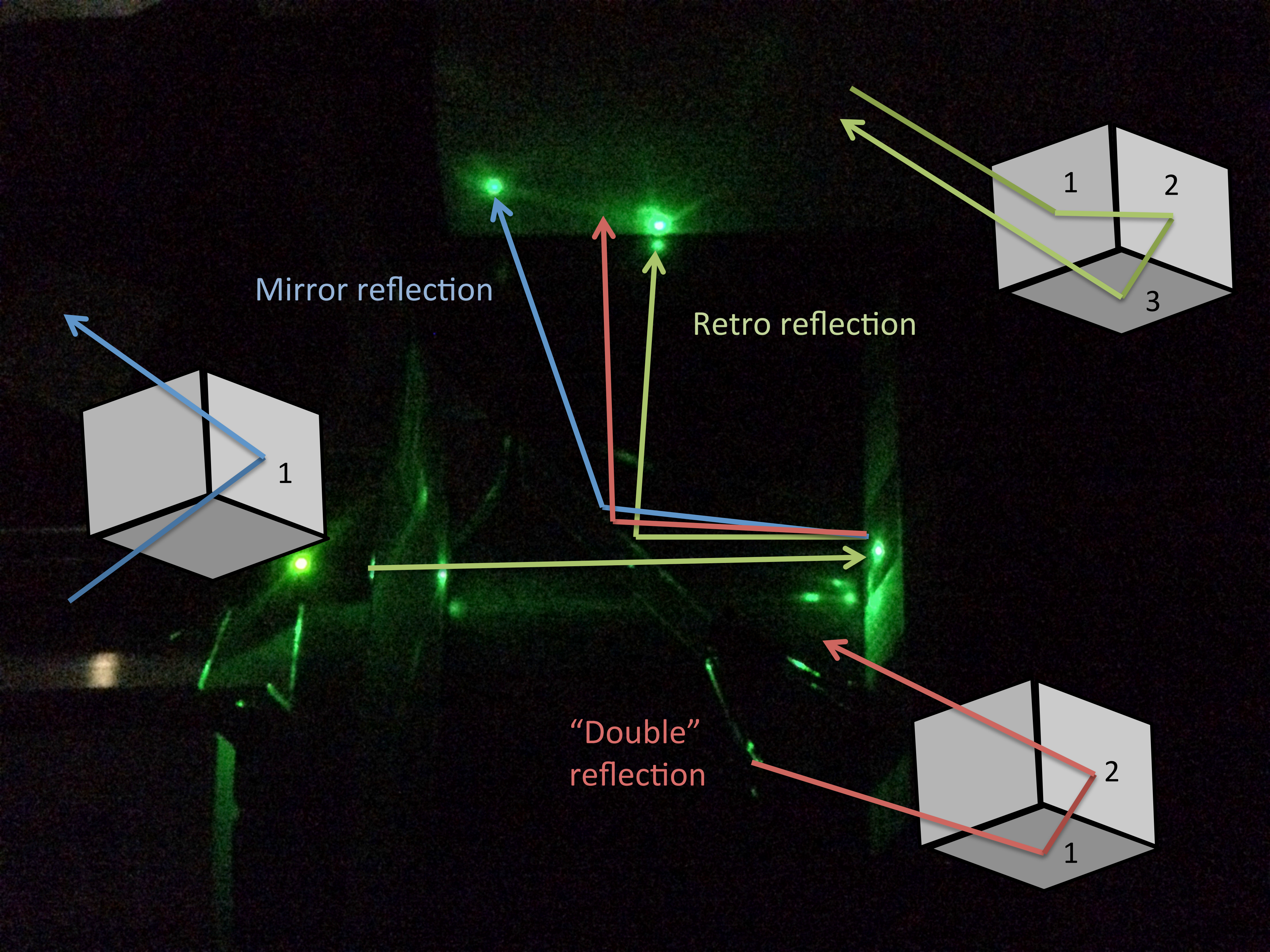


Camera is iPhone (currently hand-held) with Night Cap Pro (fixed focus/ISO etc.)




Retro reflection
1
2
3


Mirror reflection
Retro reflection
1
1
2
3


Mirror reflection
Retro reflection
"Double" reflection
1
1
2
3
2
1

© ORAFOL

Practical problems

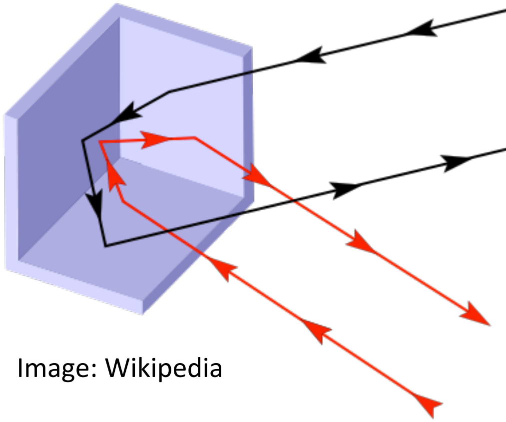


Image: Wikipedia

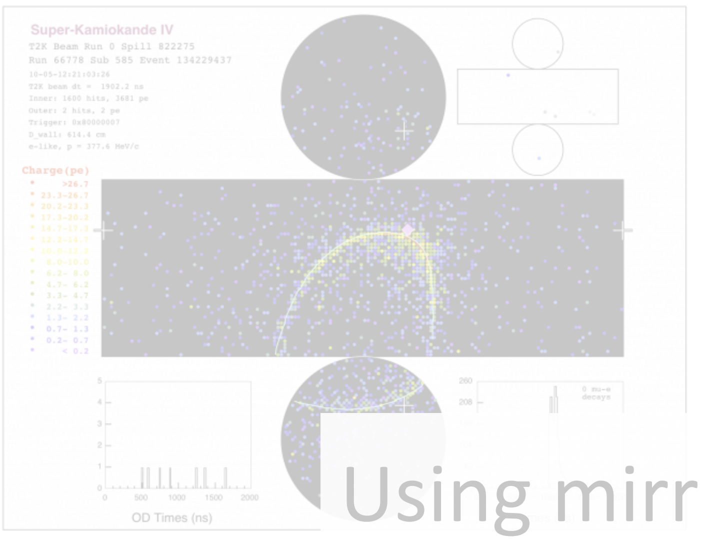
- Real-world reflector tapes reflect light in non-retro patterns, too
- Causes problems with multiple reflection & alignment
- Is there any way to eliminate alternative reflections?

Suggestions welcome

Summary

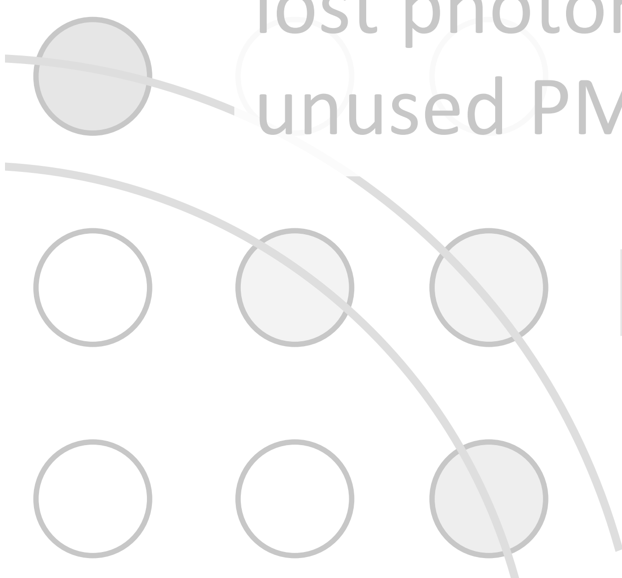
- By adding reflectors between PMTs, we might be able to improve vertex and angular resolution ~2x in water-Cherenkov detectors.
- Problems like multiple reflections and alignment difficulties are handled by using retro-reflectors instead of normal mirrors.
- Parallax opens many possibilities for new fitting techniques including PMT correlations, which need to be studied (ideas welcome)
- Improvements should help with kinematic selection of multi-ring events and reduce cost of water-Cherenkov detectors by requiring less number of PMTs.

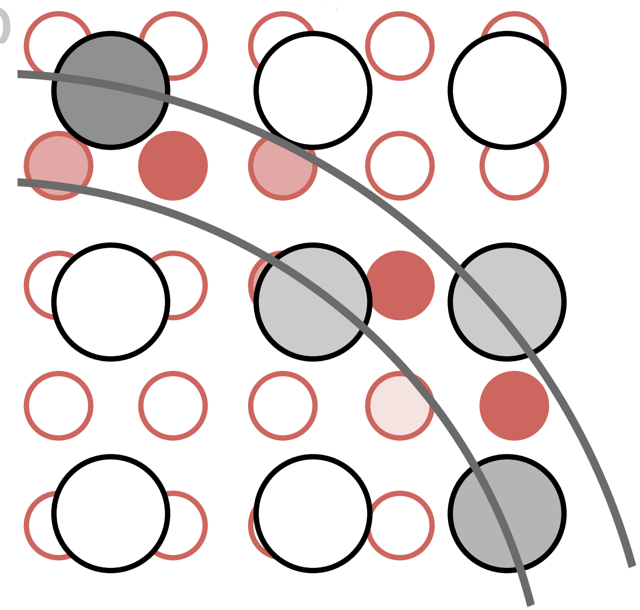
backup



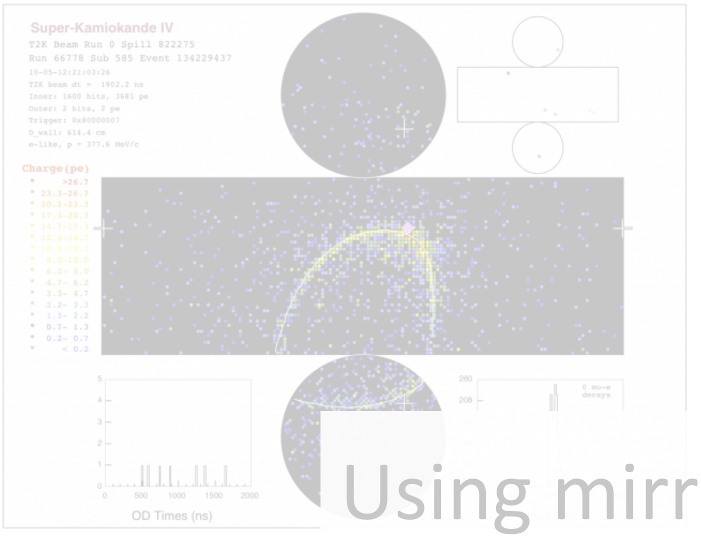
Using mirrors, map lost photons onto unused PMTs

Parallax



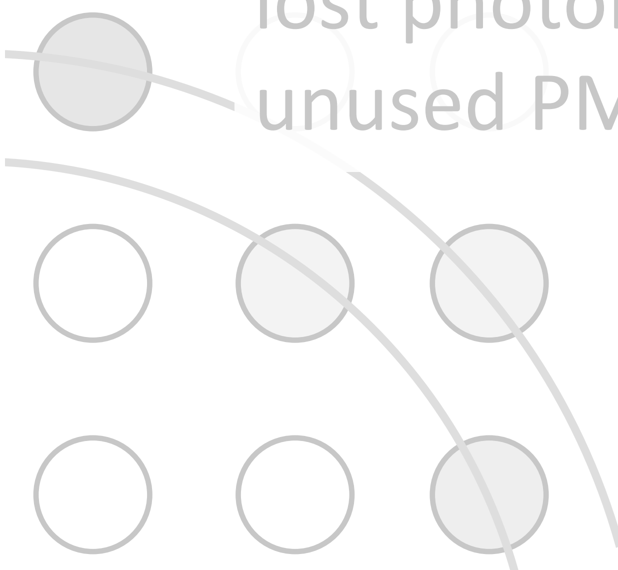


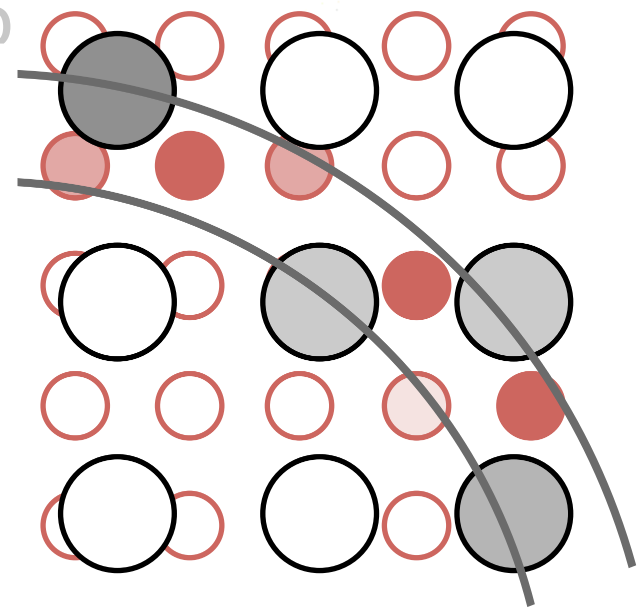
1/5



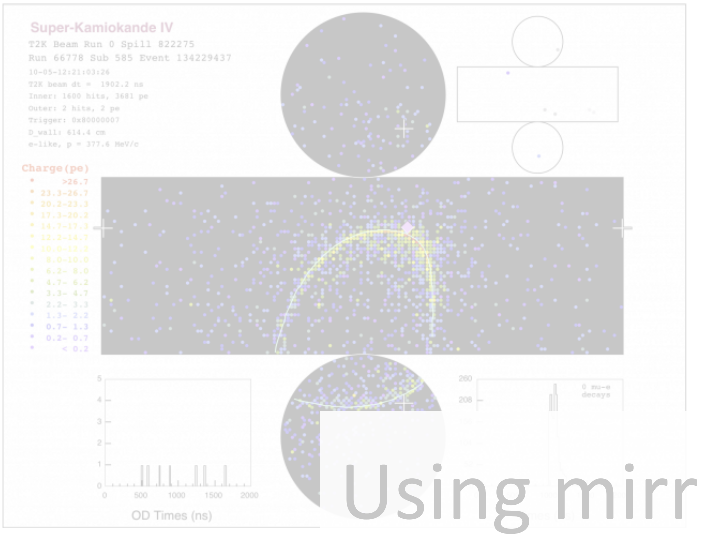
Using mirrors, map lost photons onto unused PMTs

Parallax



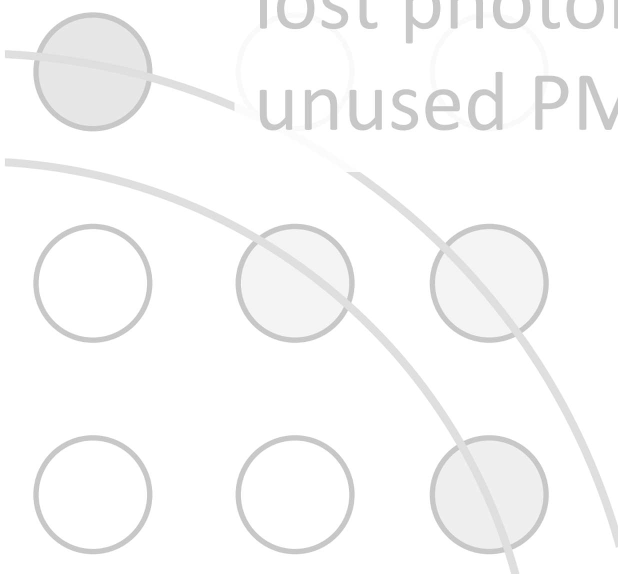


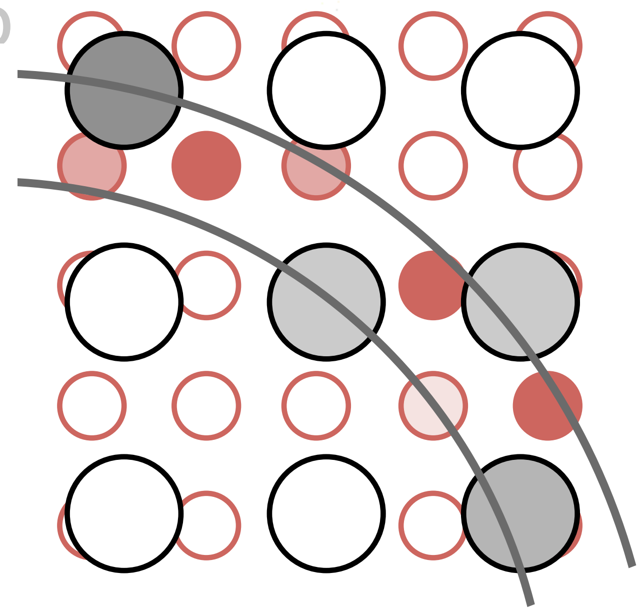
2/5



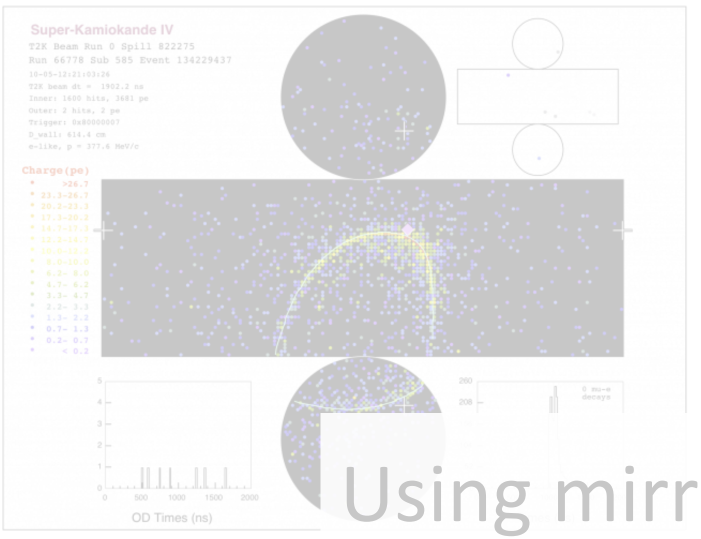
Using mirrors, map lost photons onto unused PMTs

Parallax



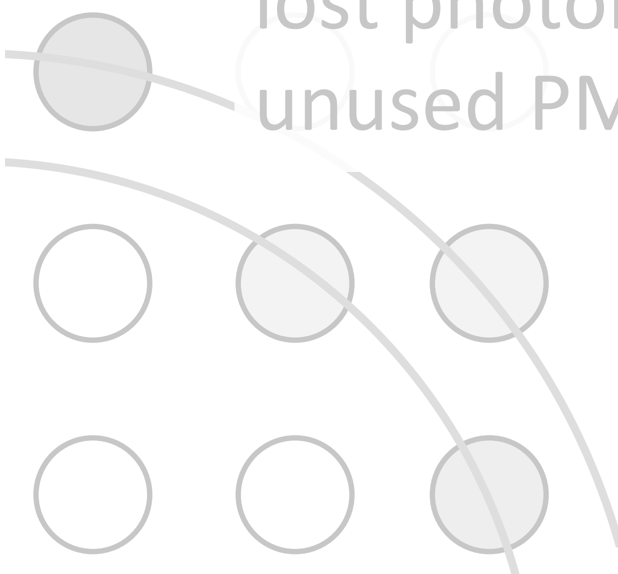


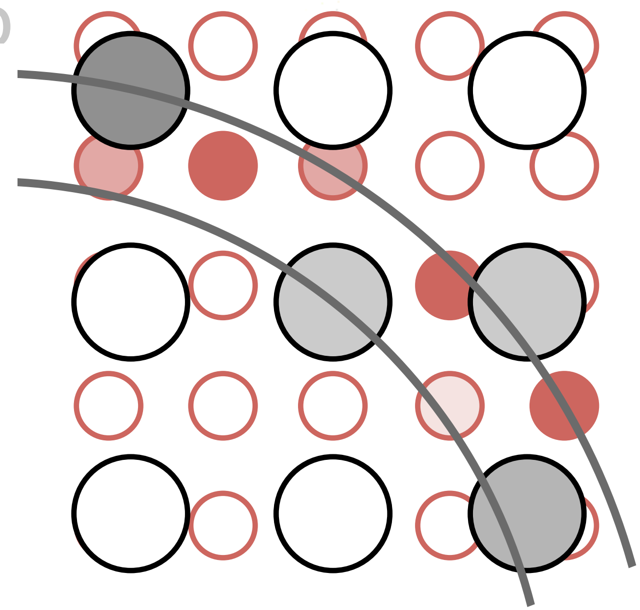
3/5



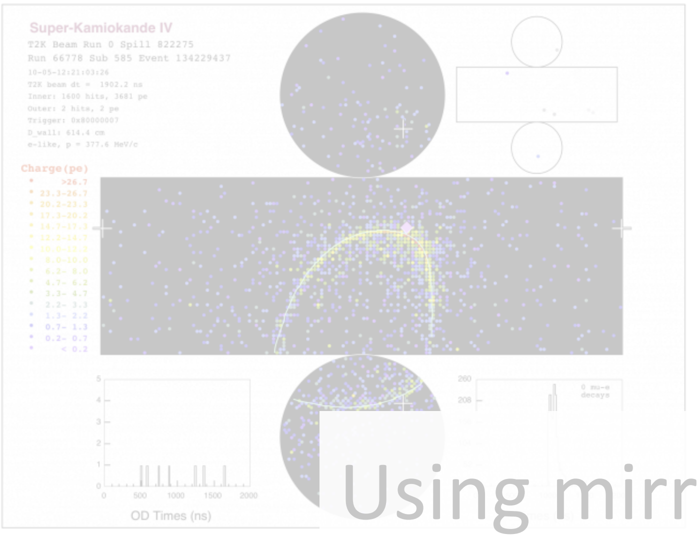
Using mirrors, map lost photons onto unused PMTs

Parallax



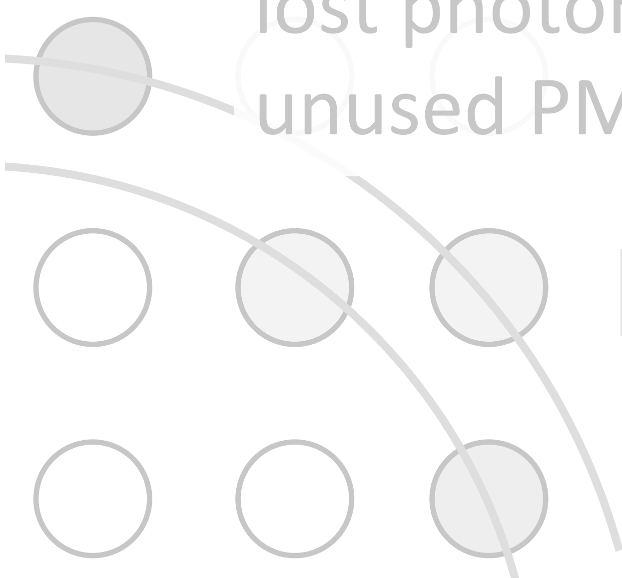


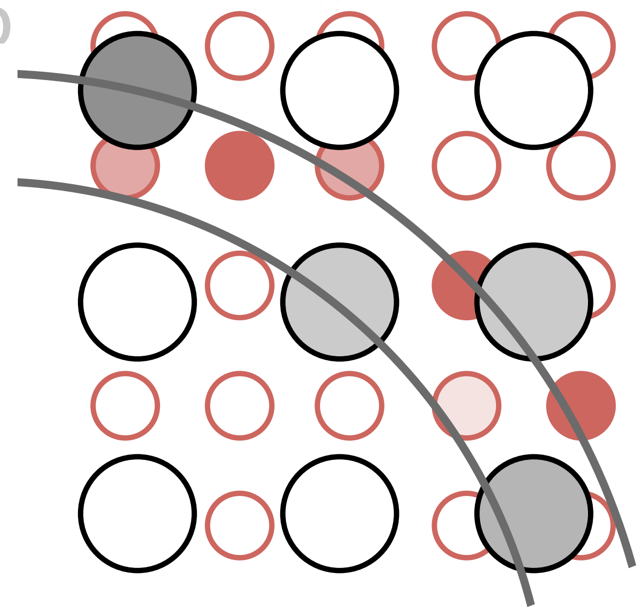
4/5



Using mirrors, map lost photons onto unused PMTs

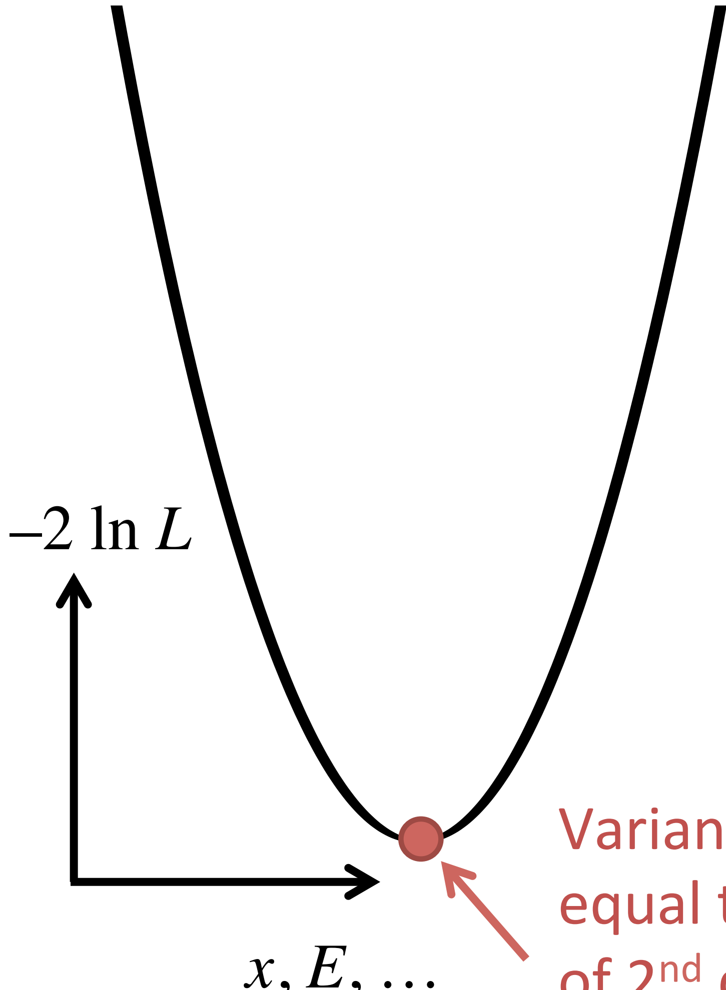
Parallax





5/5

Expected resolution

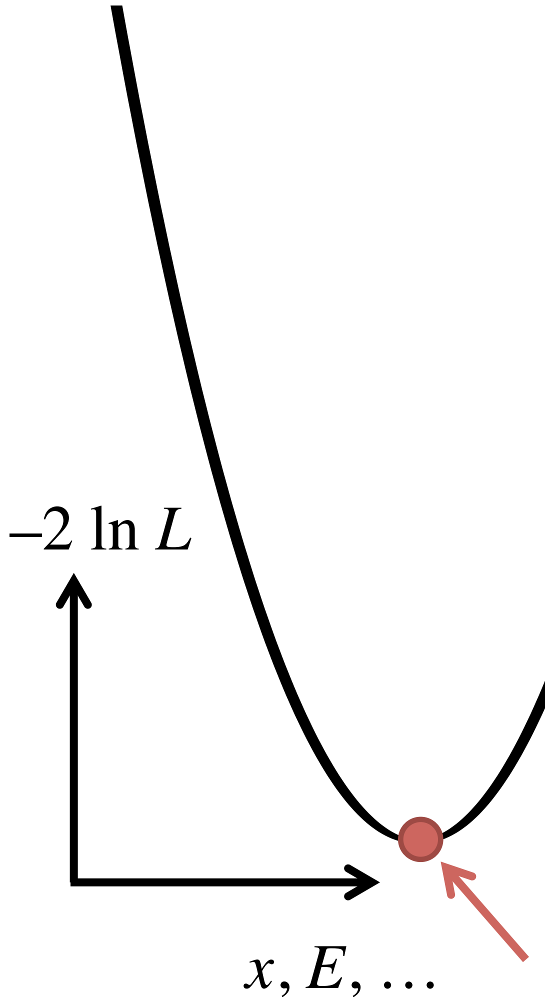


Variance is equal to inverse of 2nd derivative at minimum

Construct log-likelihood function for input variables x_j

- calculate expected PMT hits λ_i per PMT and time bin i
- assume Poisson distribution
- input variables x_j :
  - timing (t)
  - position (x,y,z)
  - momentum (p)
  - direction (θ,ϕ)

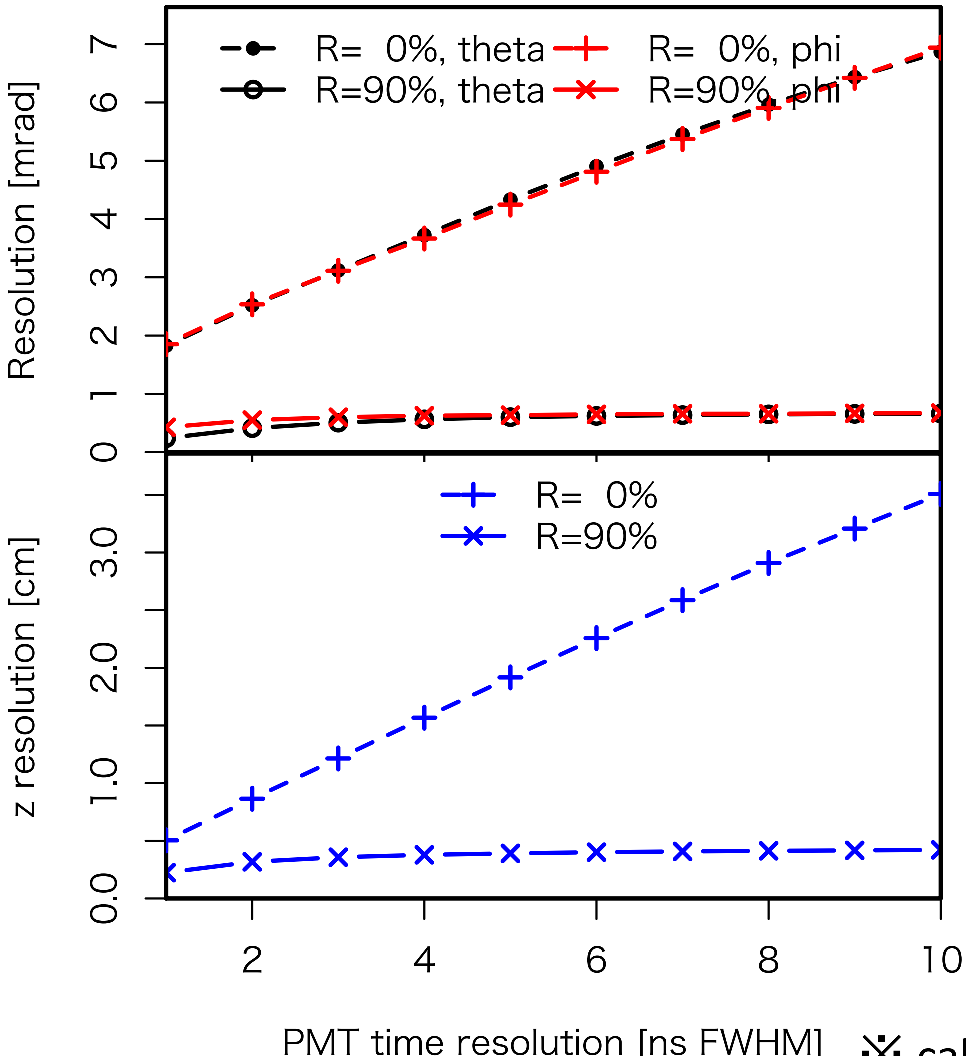
Expected resolution



Variance is equal to inverse of 2nd derivative at minimum

- Numerically calculate jacobian
  $J_{ij} = \partial\lambda_i / \partial x_j$
- Hessian of negative log-likelihood function is
  $H_{ij} = \sum_k J_{ik}\, 1/\lambda_k\, J^T{}_{kj}$
- Covariance matrix
  $C = H^{-1}$
  provides expected precision $\sigma(x_i) = \sqrt{C_{ii}}$

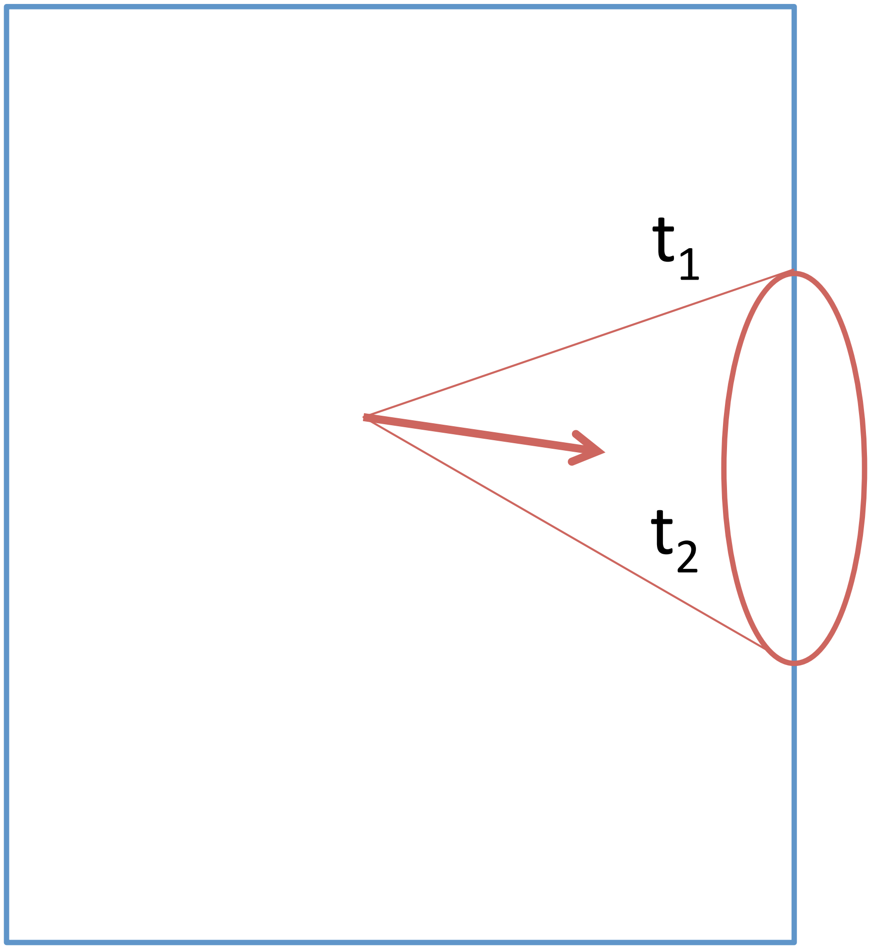
Varying the time resolution



- Without mirrors, vertex and angle resolution depend linearly on time resolution
- With mirrors, resolution improves only at TTS < 2 ns, so parallax effect is dominant

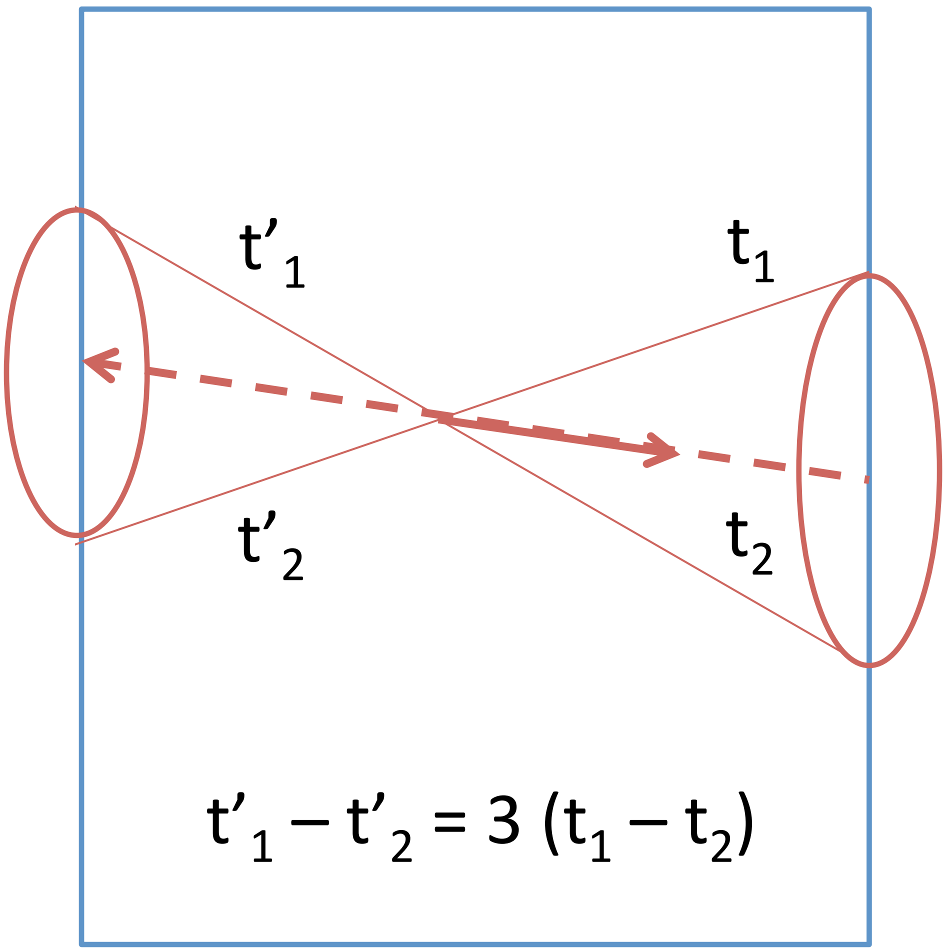
※ calculation with E61 size tank

Sensitivity to timing differences



- Normally vertex sensitivity comes from timing difference $t_1 - t_2$

Sensitivity to timing differences



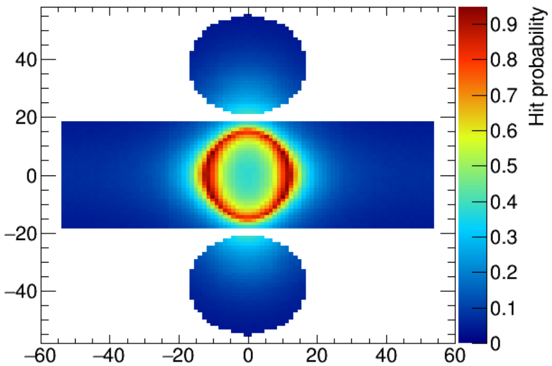
- Normally vertex sensitivity comes from timing difference $t_1 - t_2$
- Reflected light has 3x path length

→ 3x sensitivity to timing diff at same time resolution.

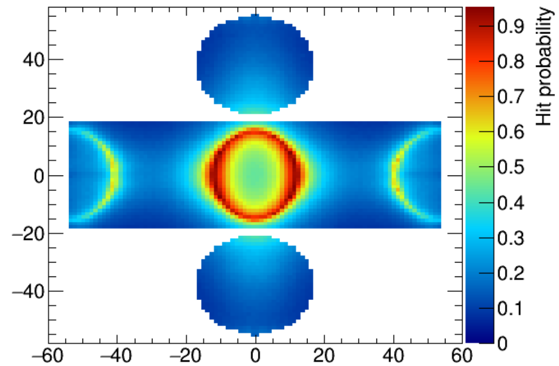
* Combining the direct light and reflection, we have 3.16x the timing resolution.
The resolution on the vertex time itself only scales as momentum due to more statistics.

Verify with Geant4-based WCSim

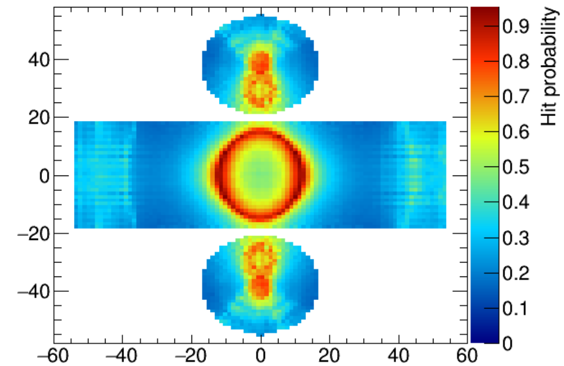
Blacksheet



Perfect retro-reflector
(R=73%)



Mirrors
(R=90%)



- About 1.5x improvement seen, but with somewhat different characteristics (e.g. no improvement in θ, ϕ)
- Difference might be due to analysis method, so a full fitting procedure is being developed

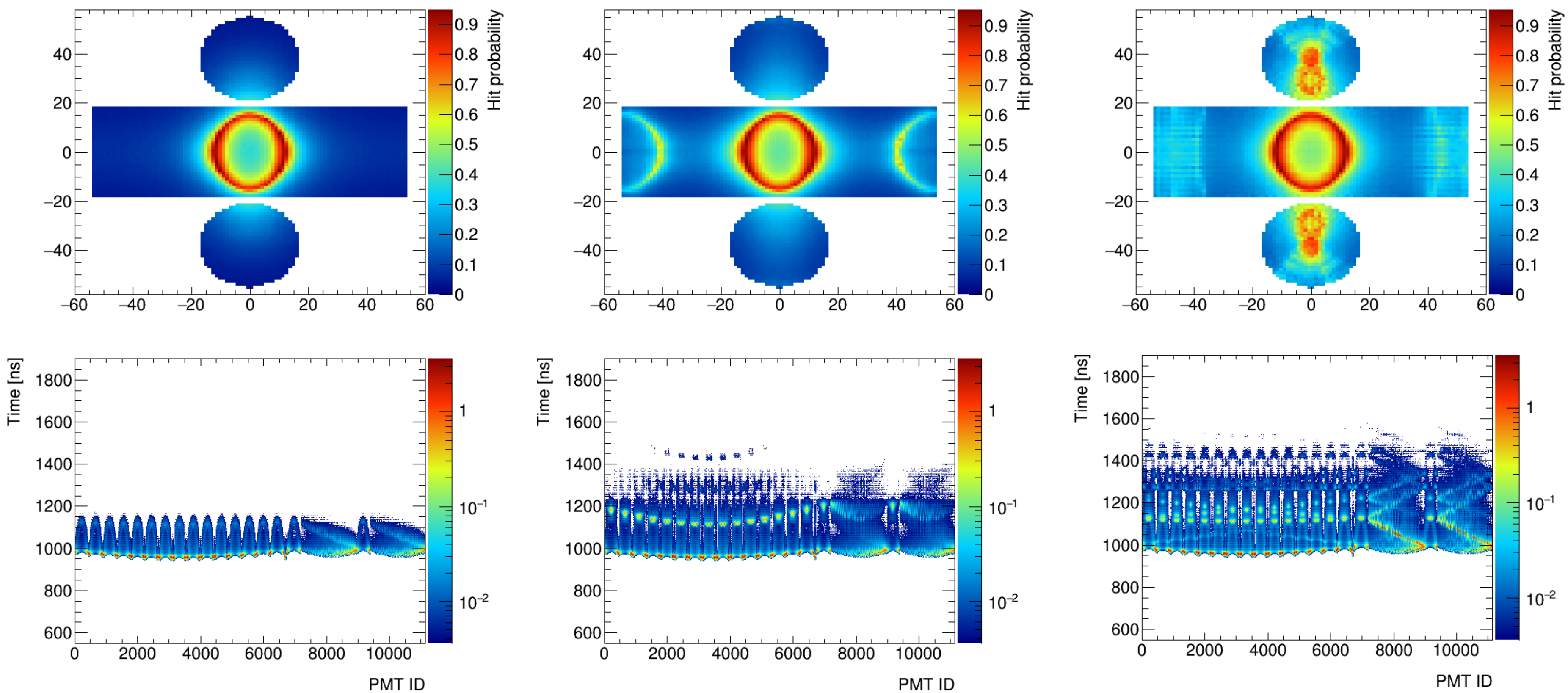
We simply replace blacksheet between PMTs with reflective materials.
Retro-reflector has 100% acceptance and no star- or ordinary- reflection (see later).
Realistic retro-reflector will show worse performance.

Reflector implementation

Blacksheet

Perfect retro-reflector
(R=73%)

Mirrors
(R=90%)



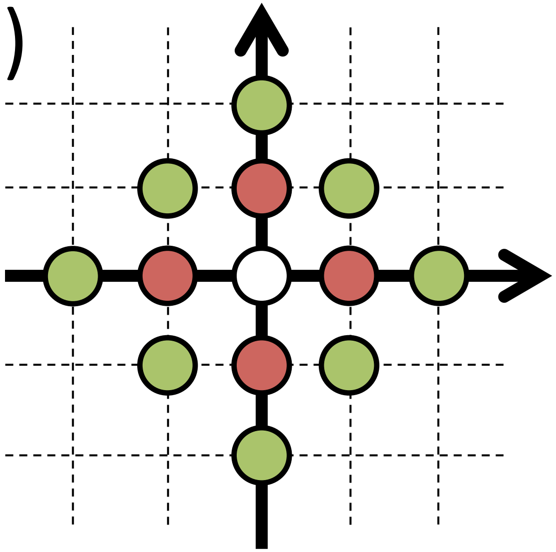
We simply replace blacksheet between PMTs with reflective materials.

Retro-reflector has 100% acceptance and no star- or ordinary- reflection (see later).

Realistic retro-reflector will show worse performance.

Precision estimation with WCSim

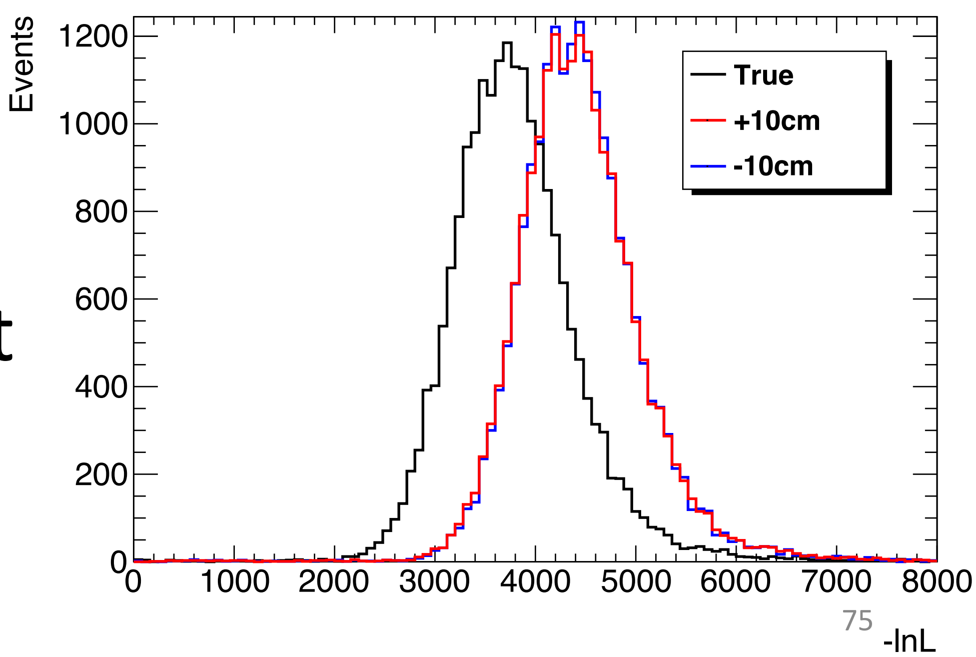
- Generate 20,000 events with same initial parameters (500 MeV electron moving from tank center into x direction)



- Repeat this for slightly shifted paramters:
  $\Delta x,y,z$ = 10 cm
  ΔE = 10 MeV (2%)
  $\Delta\theta,\phi$ = 35 mrad (2^{o})
  We calculate all single shift and double-shifts in both directions (85 x 20,000 events total)

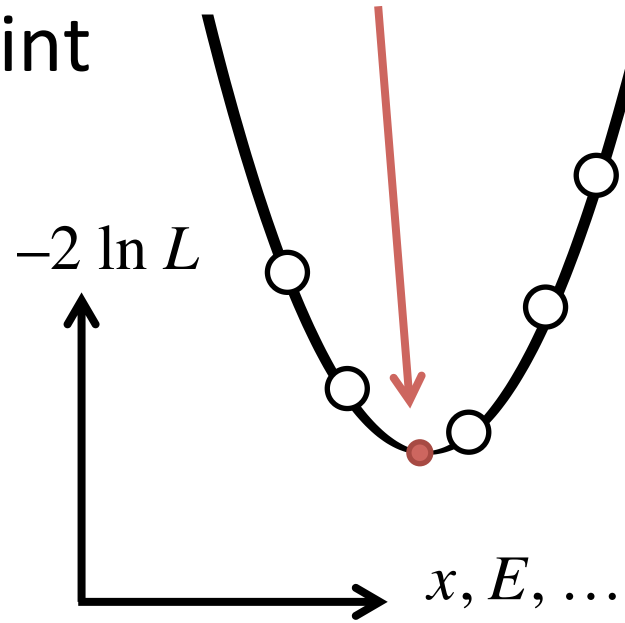
Precision estimation with WCSim

- For each ensemble of 20,000 events, we construct empirical probability distributions for each random variable (combination of Q+time), which are treated as being independent.
- Using these we calculate the likelihood of each event from the 0-shift ensemble, in all shifted ensembles



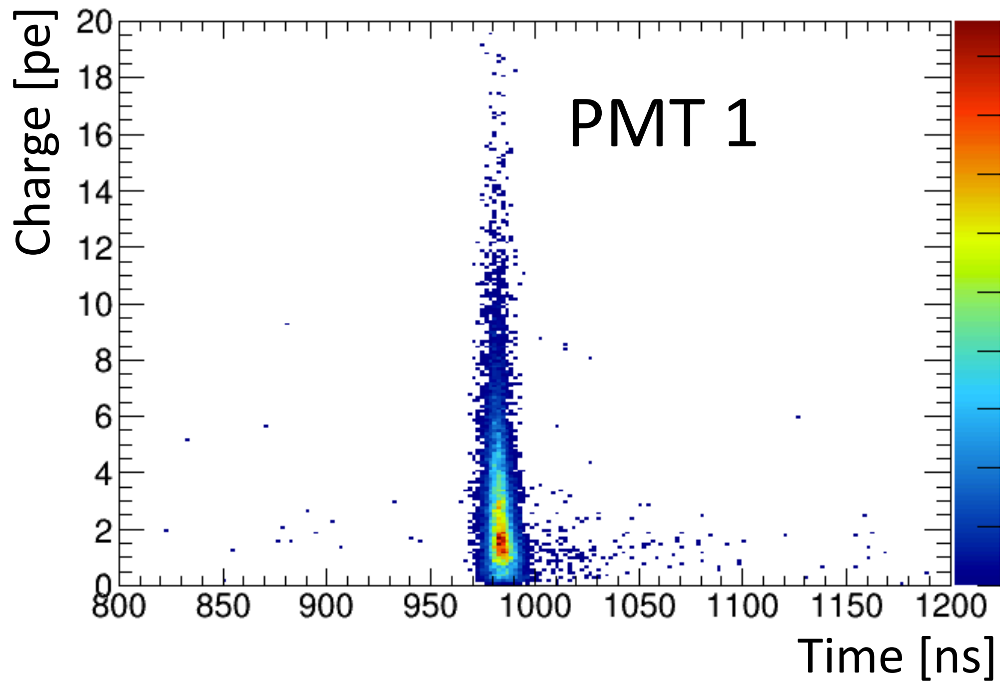
Best-fit point estimation

- Once we have the 85 likelihoods for each event, we fit these with a paraboloid in the 6-dimensional shift space $(x, y, z, E, \theta, \phi)$
- The minimum of this parabolid will be our best-fit point



Random variables when ignoring PMT correlations

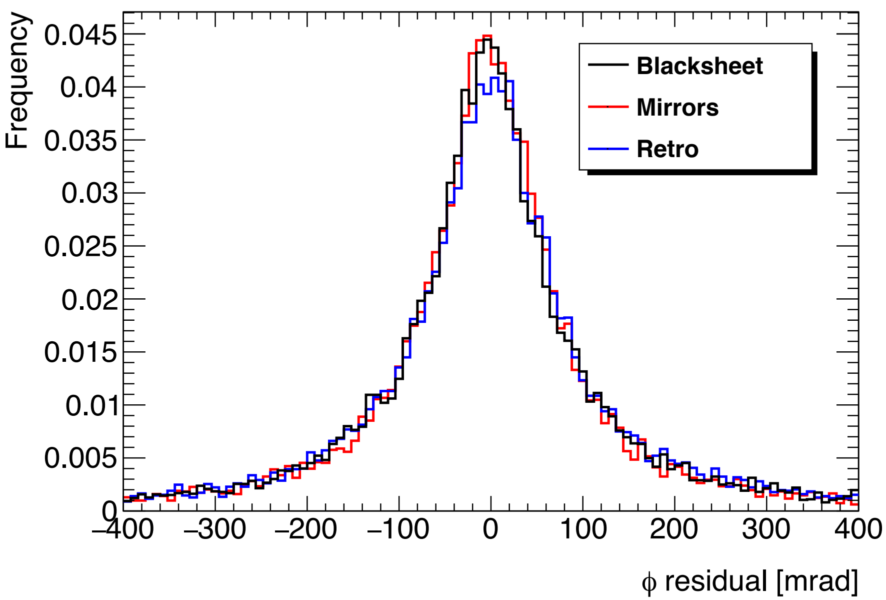
- Each PMT will have only one hit at most, so store probability of falling into time bin i, or having no hit.
- The charge distribution in one time bin is assumed to be log-normal.



* the reason I'm using log-likelihood, is because the PMT charges do NOT follow a poisson distribution. In hindsight this is partly because the particle scattering causes variations in the cherenkov profile, which causes not just correlations between PMTs, but also adds an extra variance on top of the poissonian variance.

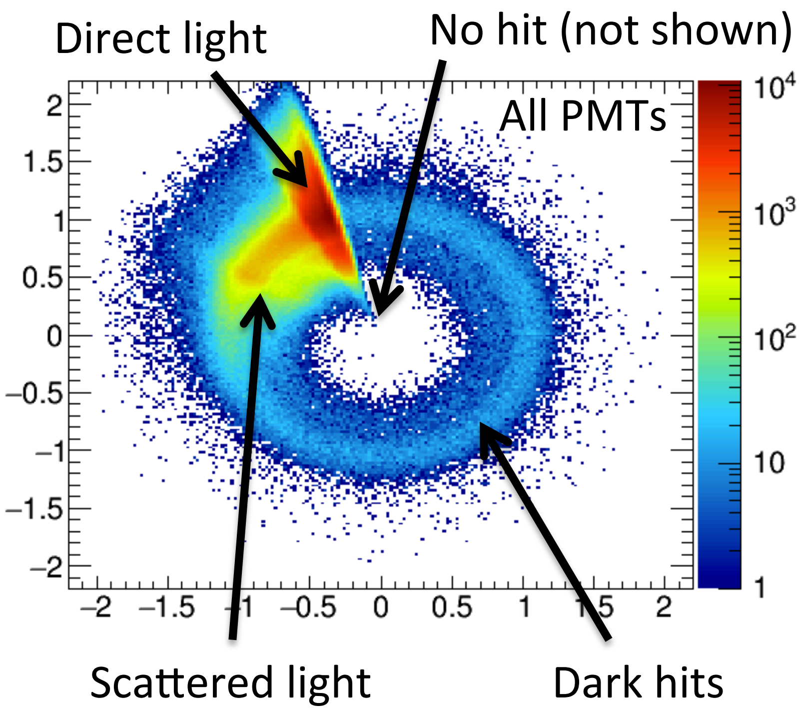
Problem!

- While I was able to more-or-less reproduce the fiTQun sensitivity using this method, the sensitivity calculated with retro-reflectors or mirrors is identical!



How is that possible? Maybe the reflected light is so weak, it gets treated as darkrate. Taking correlations into account might improve?

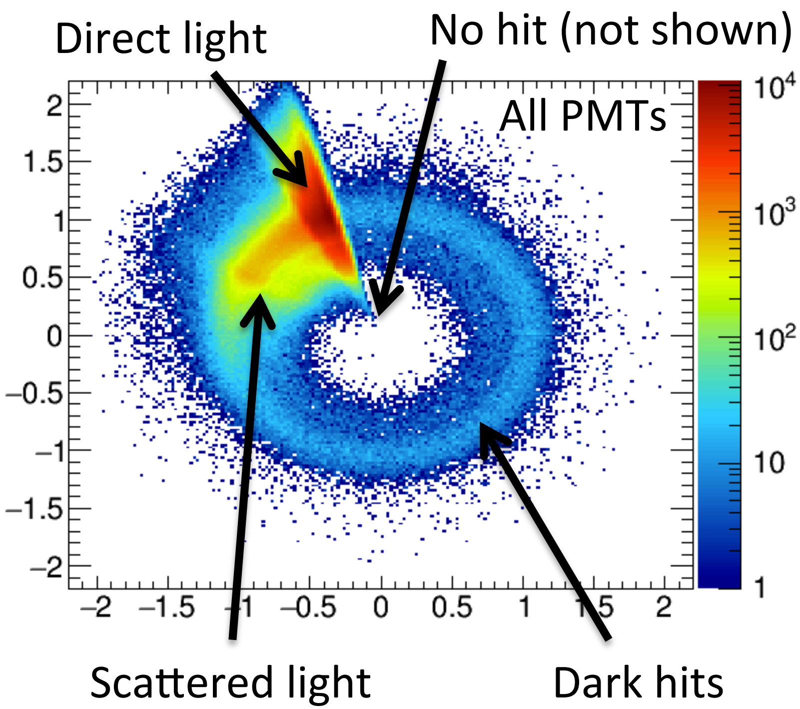
Random variables when considering PMT correlations



For now we simply assume a single 2d gaussian in this polar representation.

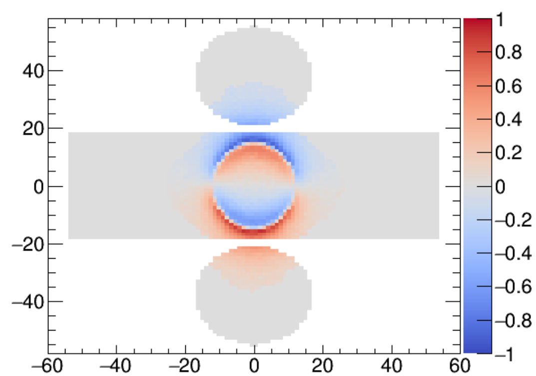
- To calculate correlations both in charge and time, we represent these in a polar representation with $r = Q^{1/4}$, $\theta = 2\pi t / T$, which allows consistent treatment of hit and no-hit PMTs.
- The quartic root gives us a more-or-less gaussian hit-distribution in this 2d space and increases distance between low-charge hits happening at very different times.

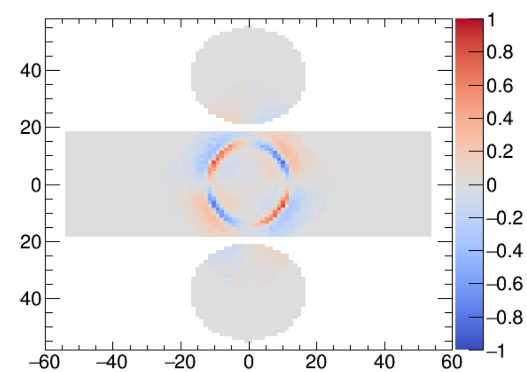
Random variables when considering PMT correlations

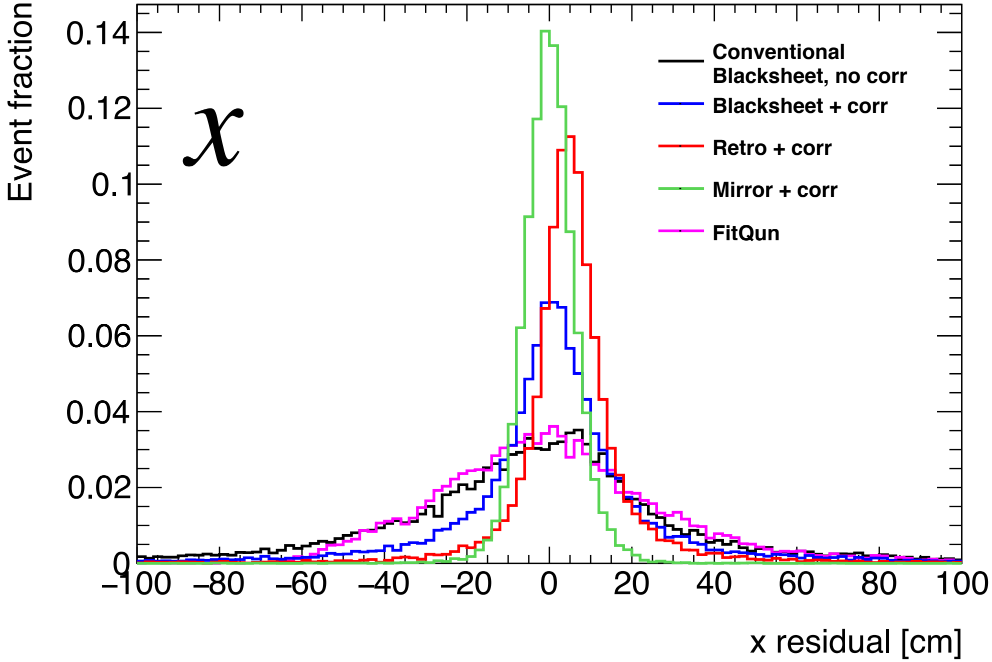


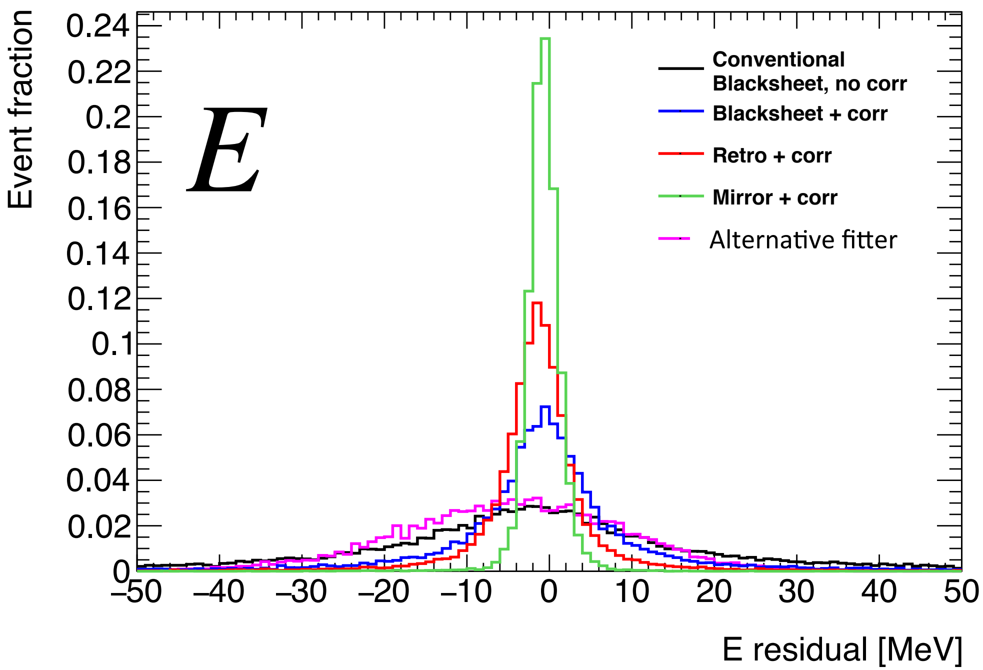
- Instead of looking at each PMT individually, we look at linear combinations which are eigenvectors of the correlation matrix (which we calculate from the 0-shift sample)

For now we simply assume a single 2d gaussian in this polar representation.





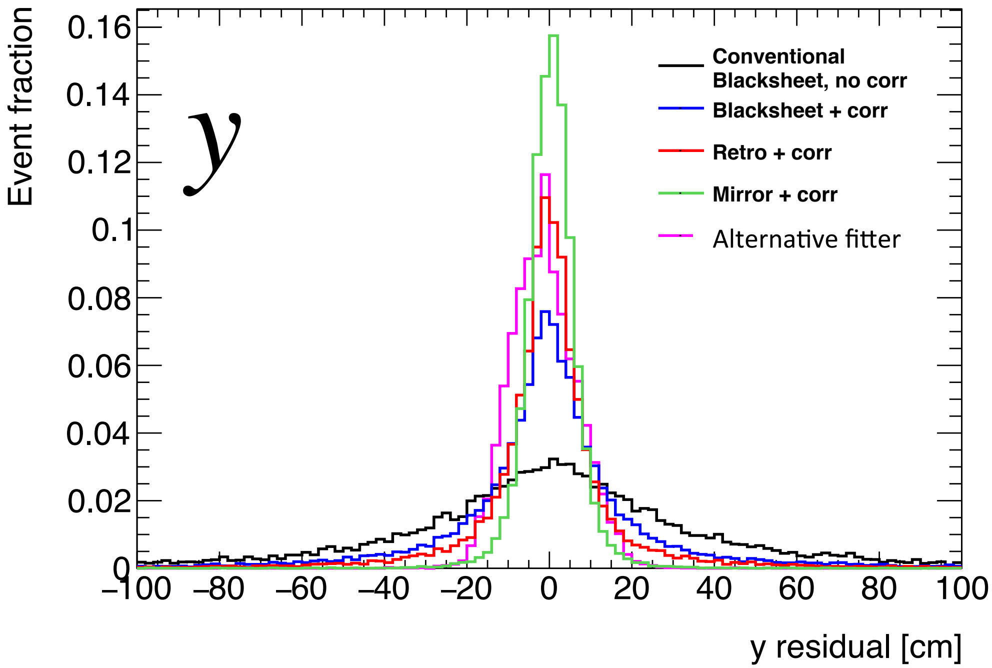


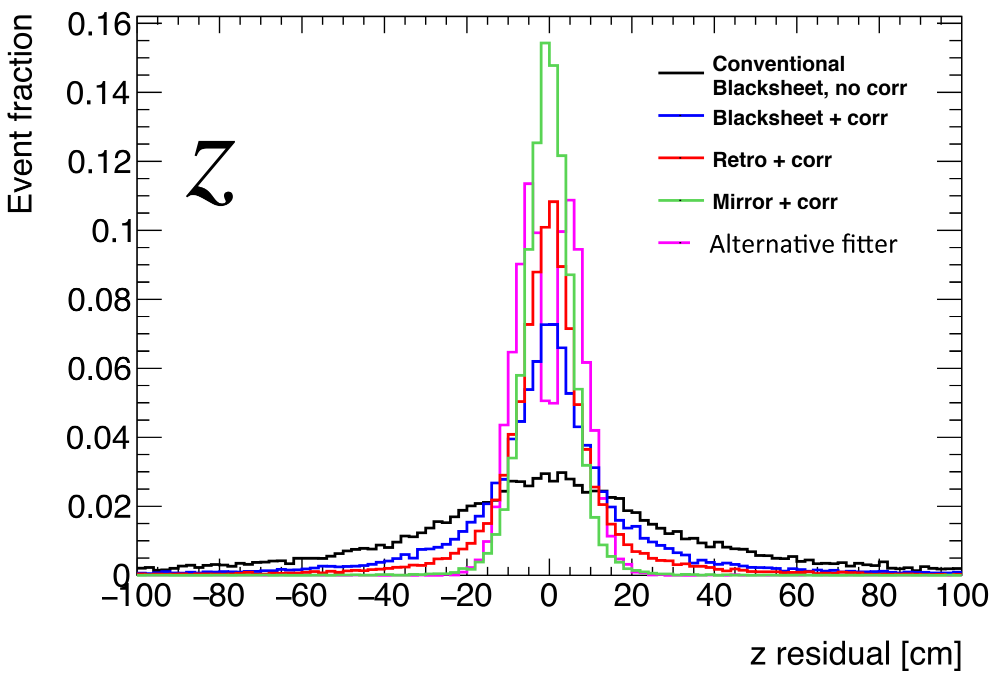


x, E residuals

- Adding correlations improves resolution ~2x
- Reflectors or mirrors further improve the resolution ~1.5x

※fiTQun is run out-of-the-box and might be able to achieve better results by tuning.



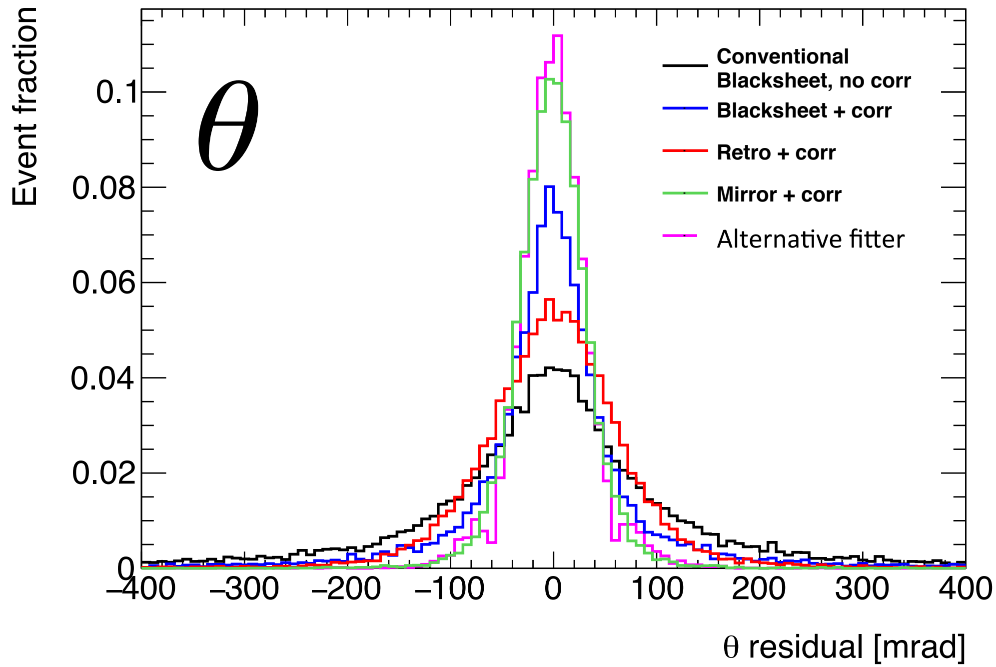


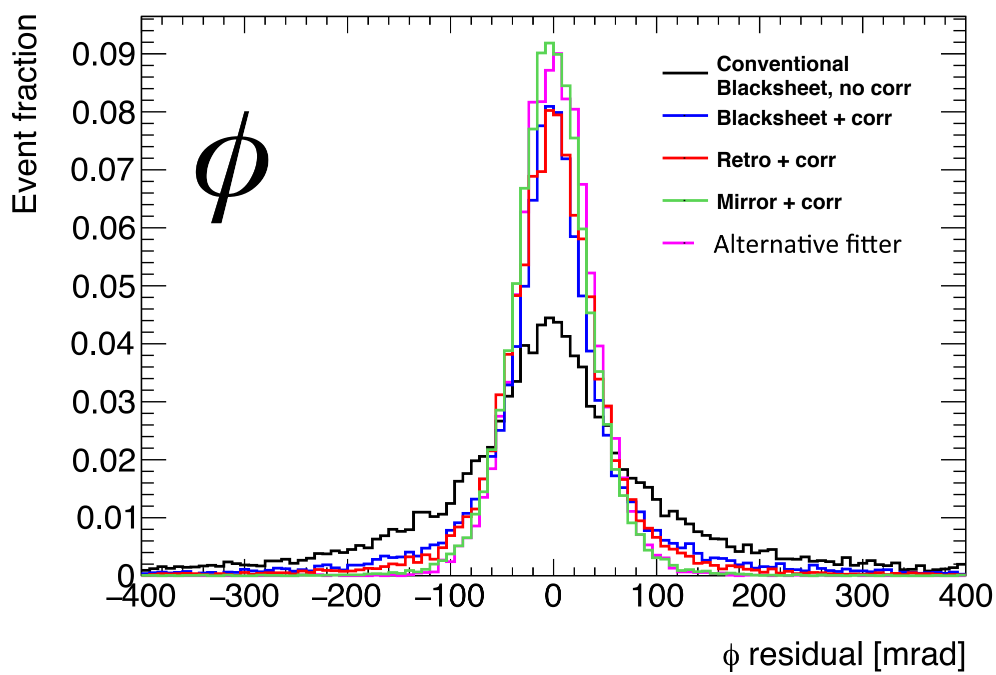
y, *z* residuals

- Adding correlations improves, but fiTQun is better
- Reflectors or mirrors further improve the resolution

※fiTQun is run out-of-the-box and might be able to achieve better results by tuning.

θ, ϕ residuals





- Adding correlations improves, but fiTQun is better
- Benefit of mirrors/reflectors is quite limited (surprising)

※fiTQun is run out-of-the-box and might be able to achieve better results by tuning.

Precision comparison

Impressive (0.3%)

Sheet material	polar corr Blacksheet	retro corr Retro	mirror corr Mirrors
x [cm]	11	6.1	5.1
y [cm]	11	6.7	4.6
z [cm]	11	6.7	4.8
E [MeV]	**5.3**	3	**1.5**
θ [mrad]	36	**47**	27
ϕ [mrad]	35	33	30

–45%

–43%

What happened?

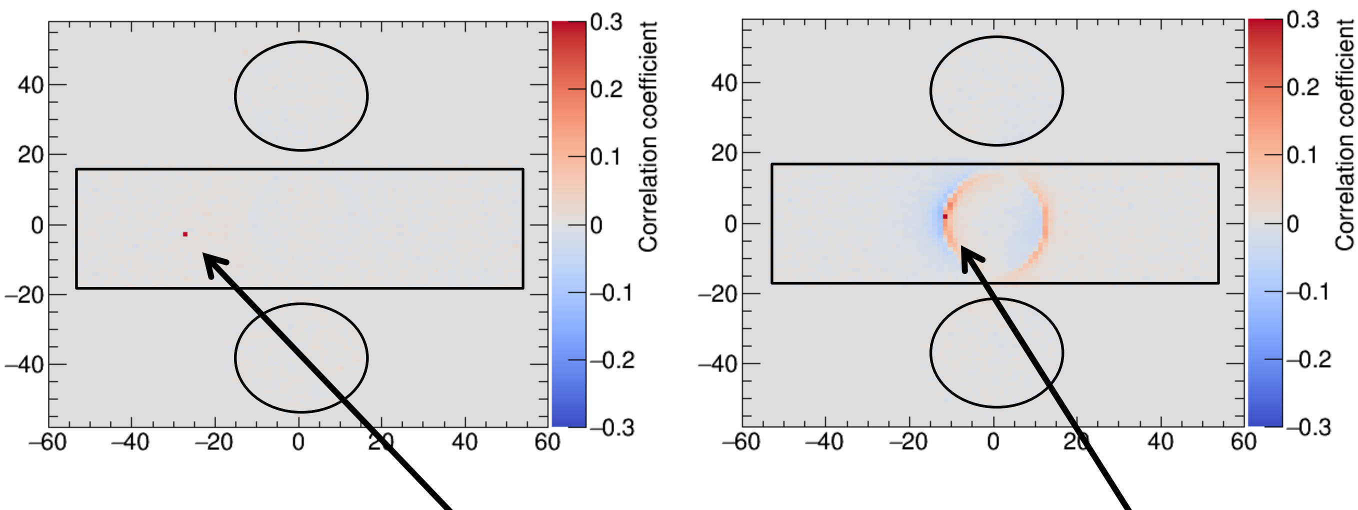
Estimated using minimial covariance determinant (MCD) method.
Please note that while normal mirrors give great results, it is likely that when considering alignment uncertainties, these benefits vanish.
For retro-reflectors alignment uncertainties should not be a big problem.

The surprising part

- From simple simulation I was expecting reflector benefits in y, z, θ, ϕ due to parallax
- In this WCSim study these show not much improvement, yet E, x show great improvement
- Maybe we already have enough parallax from blacksheet reflections?
- Could also be related to shift width. (θ, ϕ) shifts are quite smaller than resolution.

PMT correlations

- Conventional fitting method
  - calculate hit probability and mean charge for cherenkov profile (#photons/azimuth)
  - calculate likelihoods assuming independently poisson-distributed PMT charges



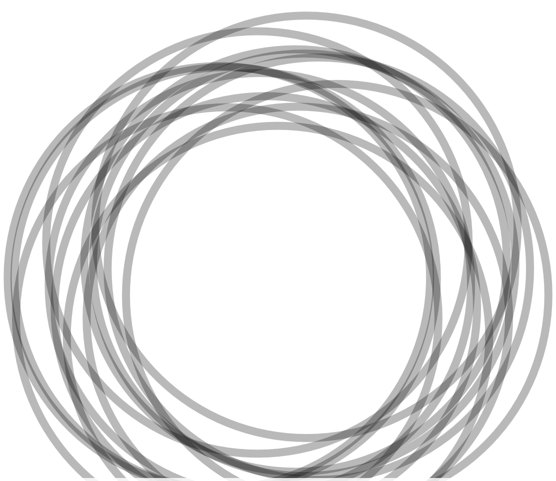
PMT correlations for off-ring PMT

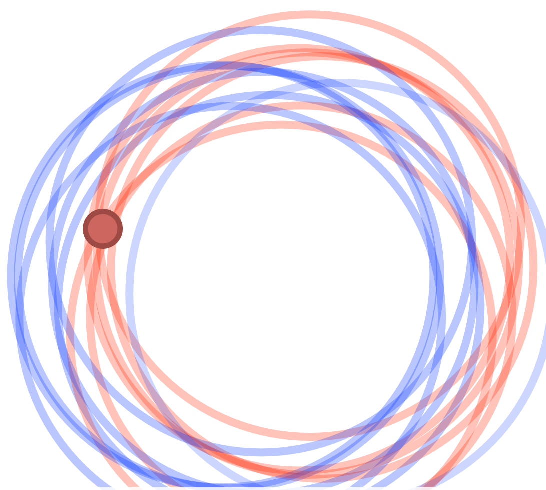
PMT correlations for on-ring PMT

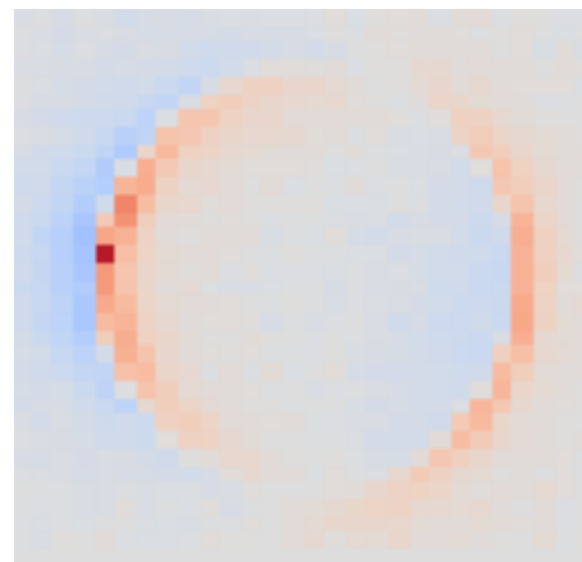
← As it turns out, PMTs are correlated! Why? Cherenkov profile variations

PMT correlations

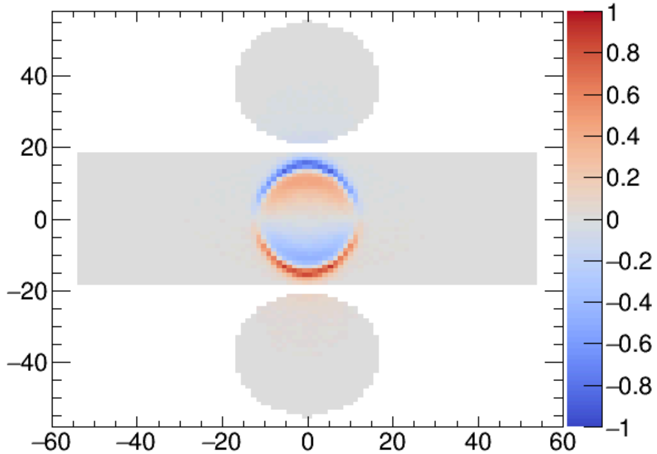
- One of the difficuties is treating PMT correlations, which are completely ignored in the current fitting procedure
- EM shower and scattering produce overlapping rings, so consider an ensemble of slighly shifted rings
- If you pick a PMT, it will be positively correlated with other PMTs that fall on intersecting rings
- If total charge is conserved, it will be negatively correlated with PMTs falling on non-intersecting rings

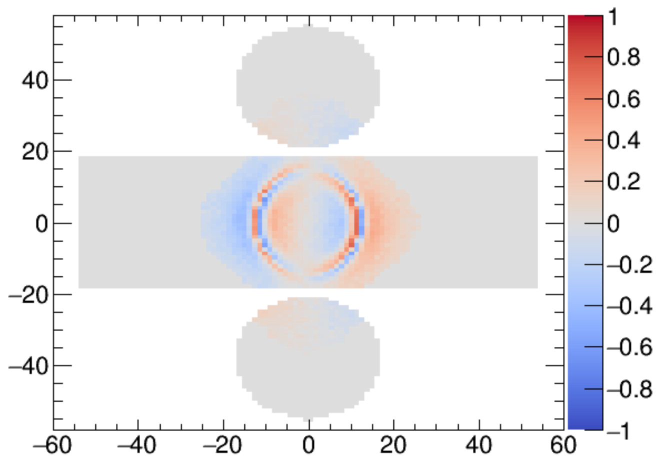


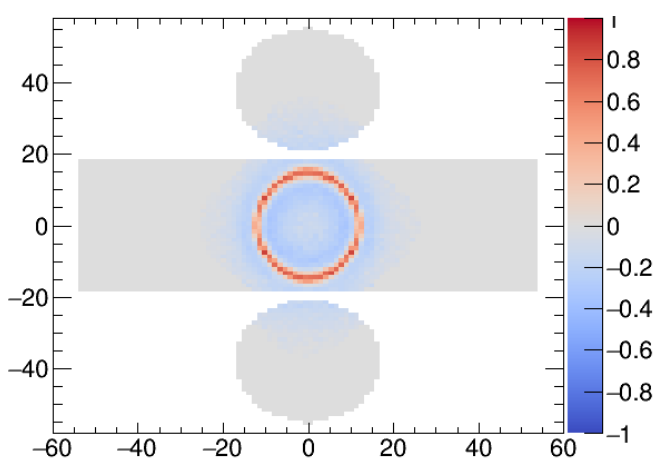




Incorporating correlations seems to be necessary to benefit from retro-reflectors

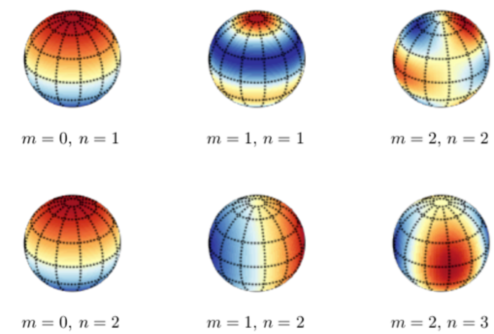






Idea: Spherical harmonics

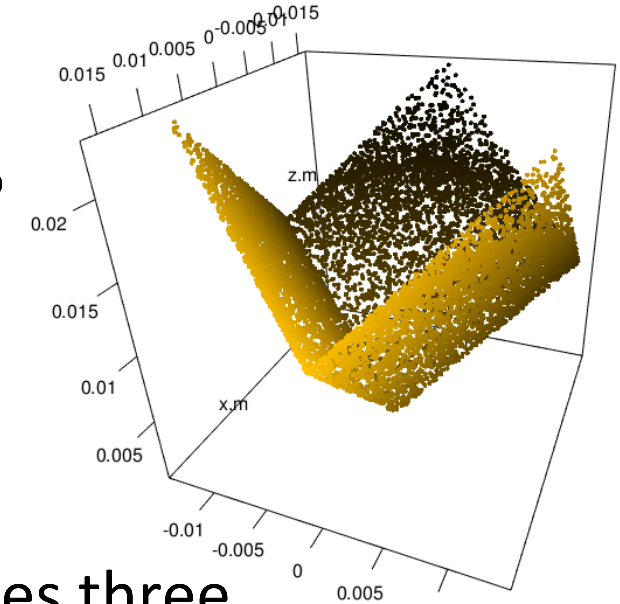
- Eigenmodes of Cherenkov variations look a lot like spherical harmonics



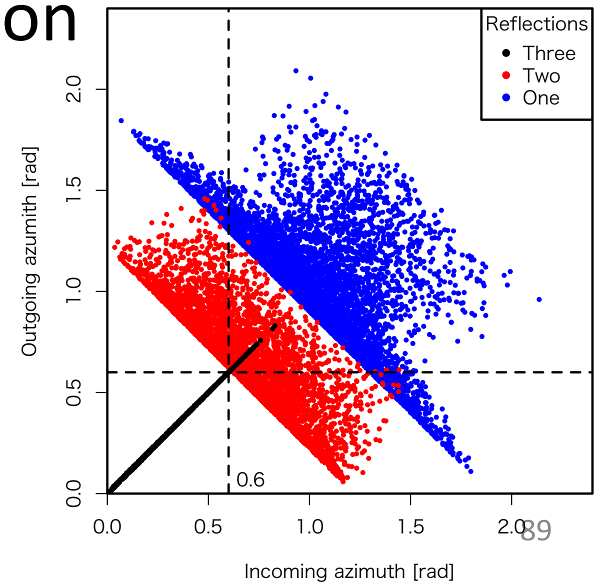
- When fitting rings, one can include constrained spherical harmonic variations
- How to fit large number of degrees of freedom?

Suggestions welcome

Corner cube retro-reflectors

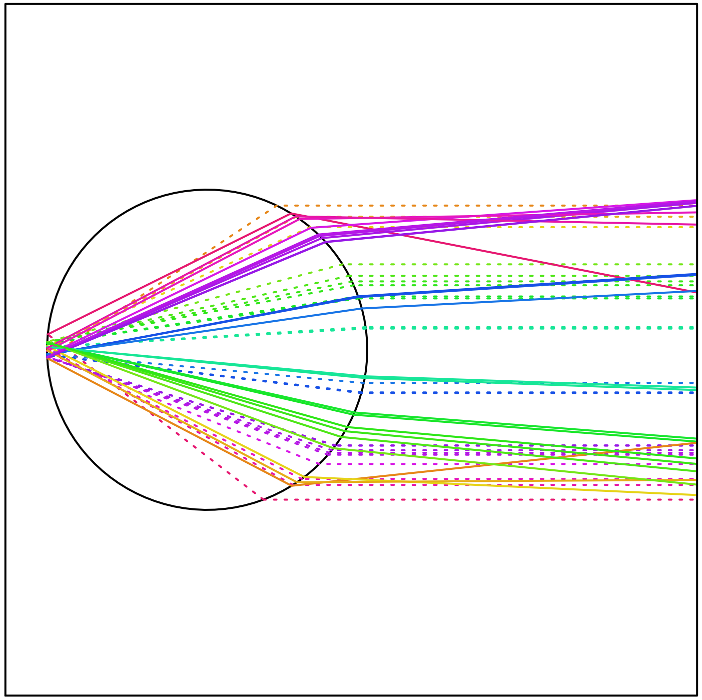


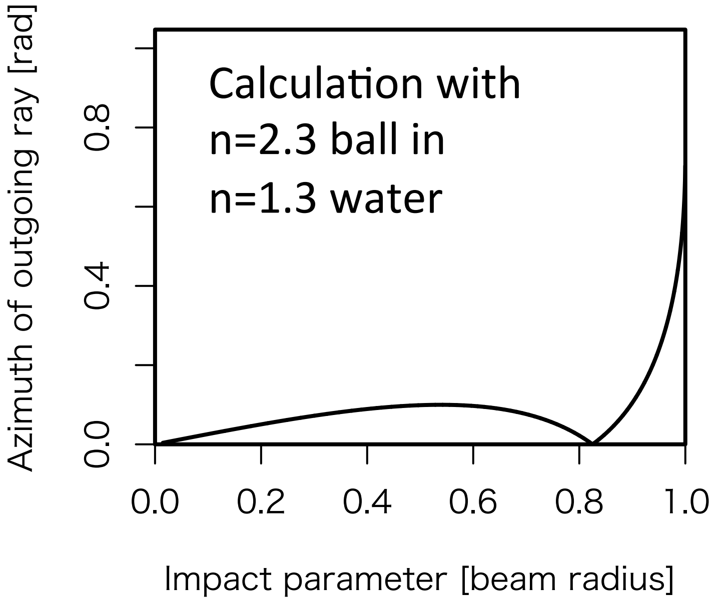
- Reflection types
  - **triple**-reflection: retro-reflective
  - double-reflection: 1D mirror.
    reflection from point source becomes three straight lines (might be usable for alignment)
  - single-reflection: ordinary mirror (also surface reflection)
- If prisms are aligned and no refraction azimuth cut at 0.6 rad (34 deg) allows selection of **triple** only.
  = 17% of 2π influx (used in calc), practically (shades) ~8% of 2π

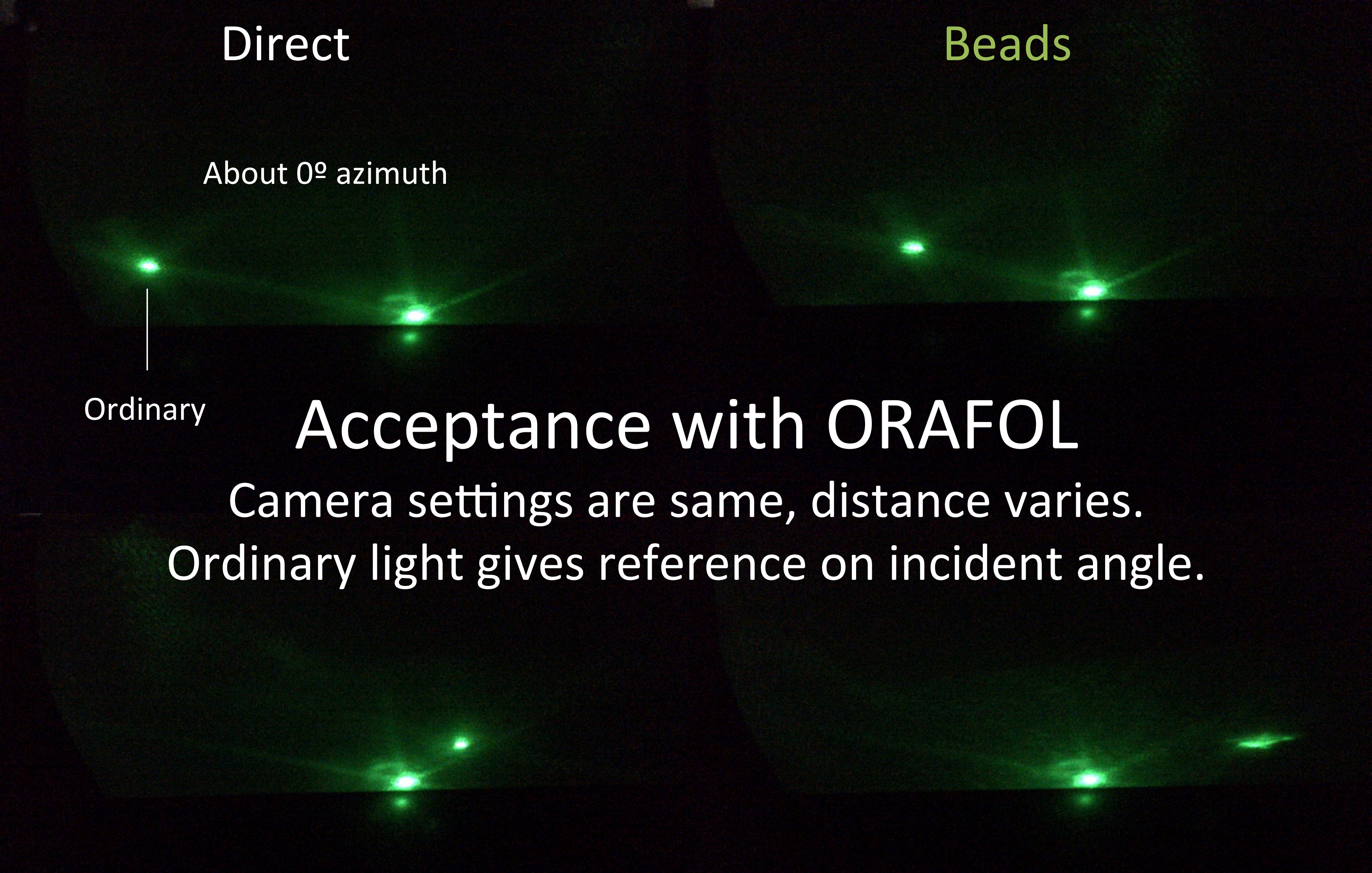


“Glass” beads

- Ideally spheres with refrective index ~2x of water. Hard to get? (ZrO_2 available as balls)
  2.2 Cubic zirconia (ZrO_2)
  2.4 Zinc oxide
  2.4 Diamond
  2.6 Rutile (TiO_2)
  2.7 Moissanite (SiC)
- Even with right material, spherical abberation remains.
- Can improve with two-layered approach, see BLITS satellite or Luneburg lens.
- Probably impractical for large-scale application.







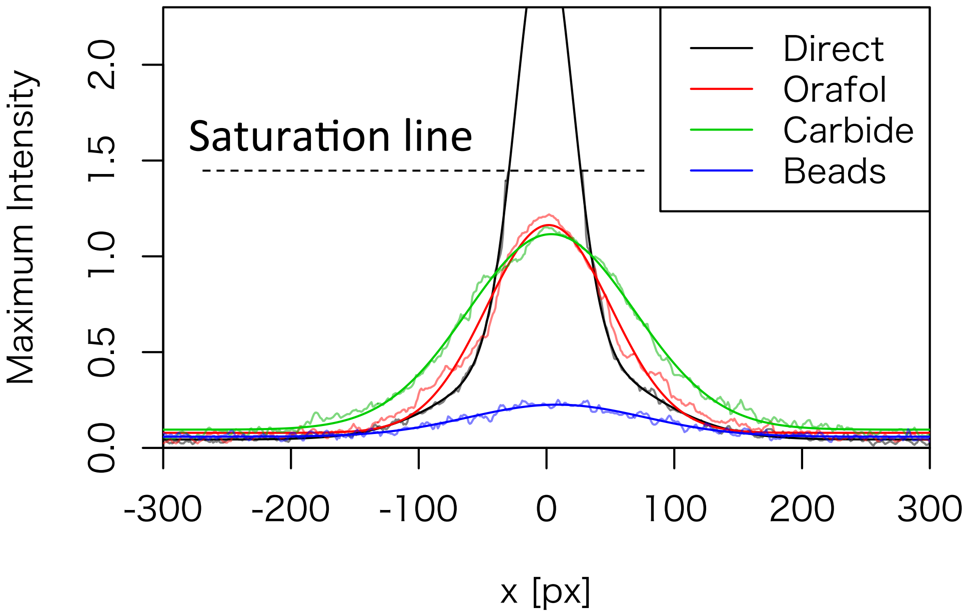
Acceptance with ORAFOL

Camera settings are same, distance varies.

Ordinary light gives reference on incident angle.

Acceptance is better than expected (almost up to 50º),
but double-reflection and mirror reflection is strong.

1D slice through retro-peak



Reflector	Spread
Orafol	0.5^o
Carbide	0.7^o
Beads	0.7^o

- Align retro-reflection peaks and fit by constant background + gaussian.
- *Direct* is fitted with two gaussians (glass used for beam splitter causes scattering)
- Spread approximated by subtracting *direct* spread in square, and assuming *Orafol* has 0.5^o (catalog value)

This seems to be more-or-less accurate.