

# Multiple scattering effects of aerosols on light in the atmosphere

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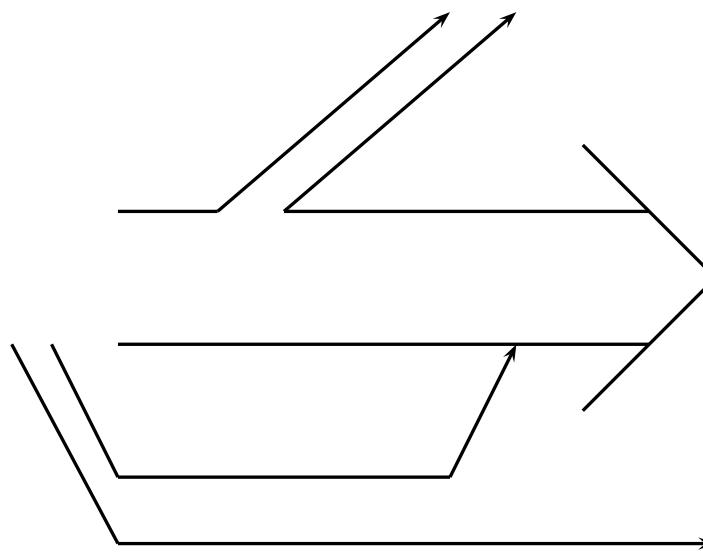


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# Scattering

- No absorption of fluorescence light for UV light from air showers  
=>Attenuation is just **scattering** out of the view of a detector.
- Photons can also be scattered back into the view of the detector.  
=>**Over-estimation** of energy
- Aerosols (their **concentration** and **size**) have an effect



- Two well known parameterisations used to model the percentage of multiply scattered light at fluorescence detectors.
  - Roberts<sup>[1]</sup> and Pekala<sup>[2]</sup>
  - Do NOT account for size of aerosols
  - Aerosol size changes significantly multiply scattered light collected at fluorescence detectors and should be taken into account.

[1] M D Roberts *J.Phys. G: Nucl. Part. Phys.* **31** (2005) 1291-1301

[2] J. Pekala, P. Homola, B. Wilczynska, H. Wilczynski, *Nucl. Instruments and Methods in Phys. Research A* **605** (2009) 388 – 398

# Outline

- Theory of scattering and simulation method.
- Global view :
  - General distribution of scattered photons in different atmospheres.
  - Indirect light detected at detectors across all space.
- Fluorescence detectors :
  - Study for isotropic sources.
  - Study for air showers.

# Outline

- **Theory of scattering and simulation method.**
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# Distribution of scatterers in the atmosphere

-> Attenuation length = Density

Molecules:

$$\Lambda_{\text{mol}}(h_{\text{agl}}) = \Lambda_{\text{mol}}^0 \exp\left(\frac{h_{\text{agl}} + 1412}{h_{\text{mol}}^0}\right)$$

Aerosols:

$$\Lambda_{\text{aer}}(h_{\text{agl}}) = \Lambda_{\text{aer}}^0 \exp\left(\frac{h_{\text{agl}}}{h_{\text{aer}}^0}\right)$$

$$\Lambda_{\text{mol}}^0 = 14.2 \text{ km}$$
$$h_{\text{mol}}^0 = 8.0 \text{ km}$$

ALWAYS !

$$\Lambda_{\text{aer}}^0 = 25.0 \text{ km}$$
$$h_{\text{aer}}^0 = 1.5 \text{ km}$$

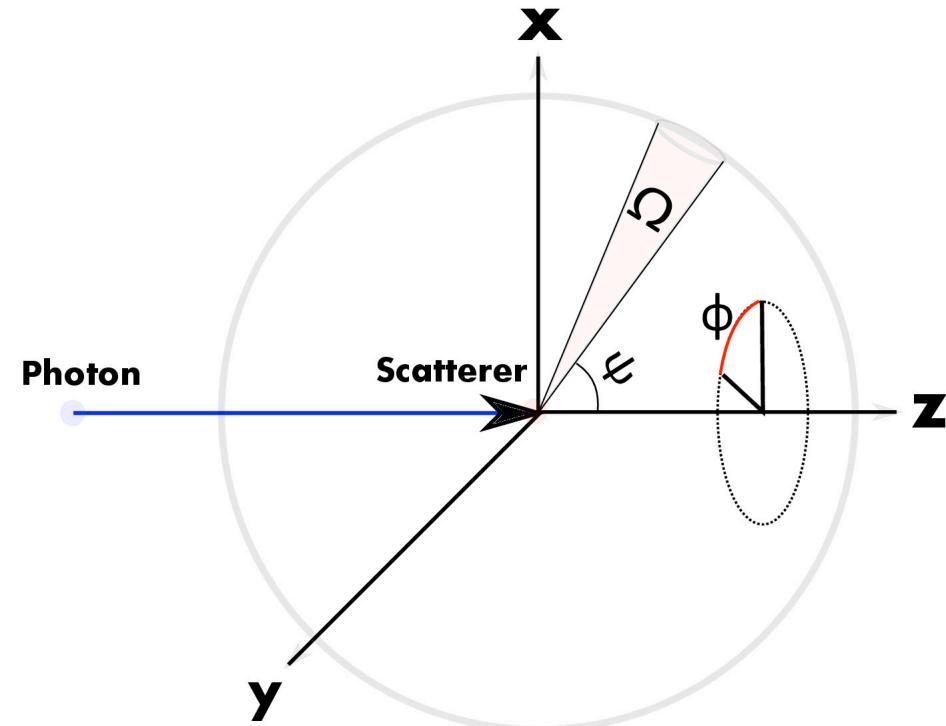
TYPICAL!

Is it scattered into or out of the view of  
the detector?

=> SCATTERING PHASE FUNCTION

# The Scattering Phase Function

- A normalised probability density function.
  - The integral over a solid angle is the probability of a photon being scattered within this range.



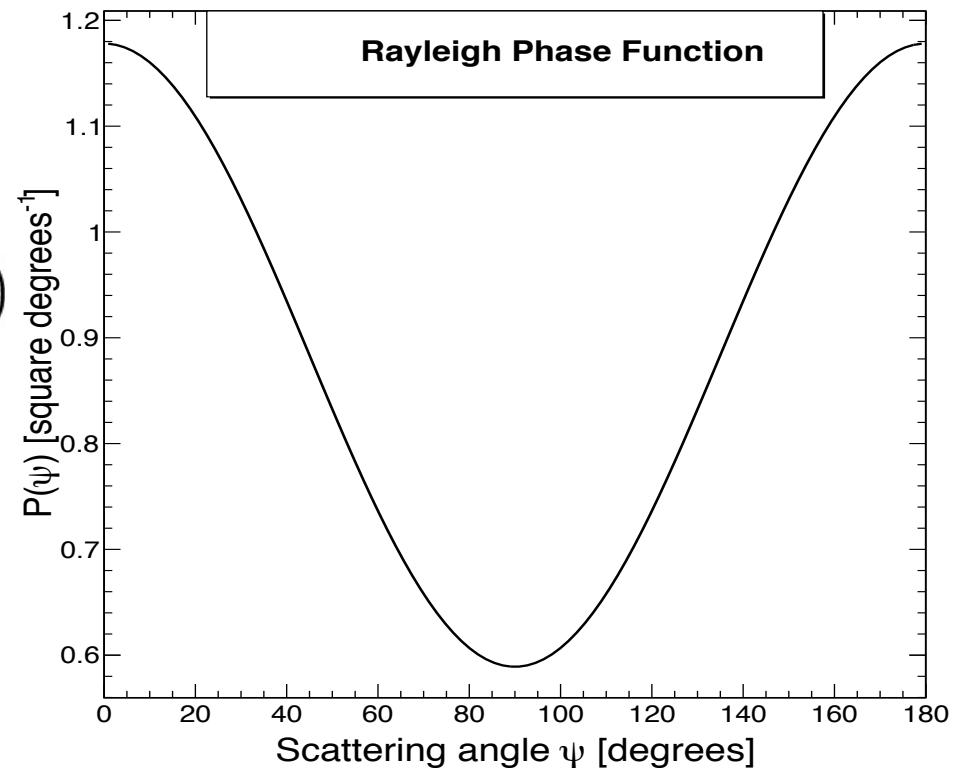
$$\iint P(\psi) \sin \psi \, d\psi d\phi$$

# Molecules vs. Aerosols

# Molecules

- Particles **smaller** than the wavelength of light
  - The **Rayleigh** Scattering Phase Function

$$P_{\text{mol}}(\psi) = \frac{3}{16\pi} (1 + \cos^2 \psi)$$



# Aerosols

- Particles **larger** than or comparable to the wavelength of light.
- More **anisotropic** scattering than molecules.
- Mie theory
  - Infinite series => Long computation times.  
⇒ Parameterisation used

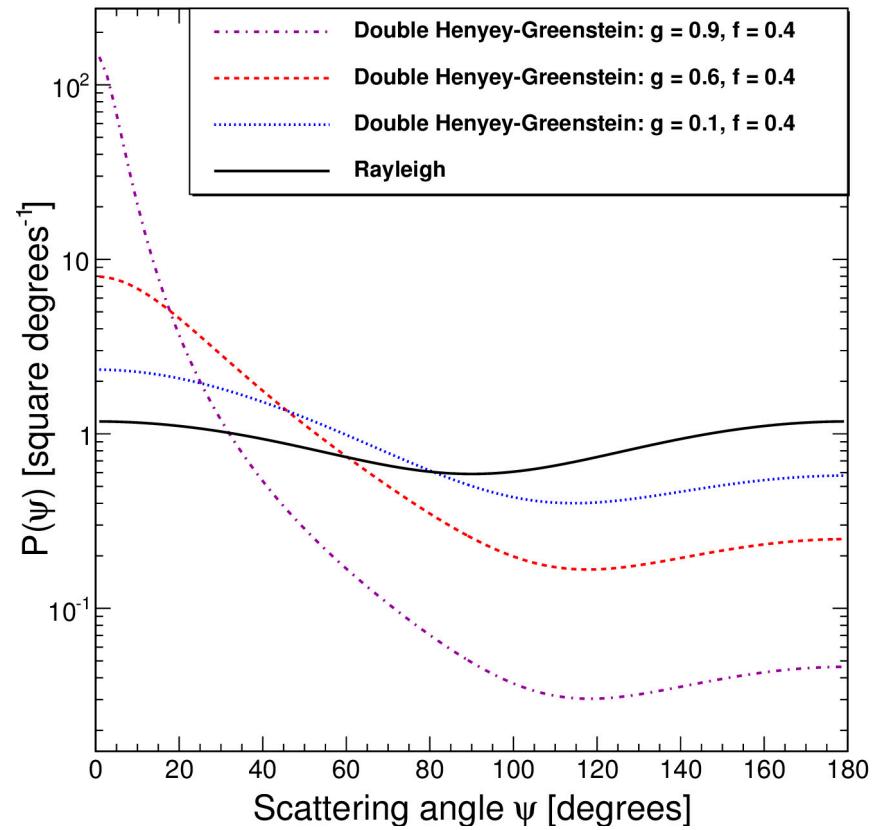
**Double Henyey-Greenstein function:**

$$P_{\text{aer}}(\psi|g, f) = \frac{1 - g^2}{4\pi} \left[ \frac{1}{(1 + g^2 - 2g \cos \psi)^{\frac{3}{2}}} + f \left( \frac{3 \cos^2 \psi - 1}{2(1 + g^2)^{\frac{3}{2}}} \right) \right]$$

# The Double-Henyey Greenstein Function

- $g$  - the asymmetry parameter.
  - Changes forward scattering peak
  - Causes greater anisotropy in scattering
  - Related to the size of aerosols (Ramsauer approach).

**f = 0.4 used**



$$P_{\text{aer}}(\psi|g, f) = \frac{1-g^2}{4\pi} \left[ \frac{1}{(1+g^2-2g \cos \psi)^{\frac{3}{2}}} + f \left( \frac{3 \cos^2 \psi - 1}{2(1+g^2)^{\frac{3}{2}}} \right) \right]$$

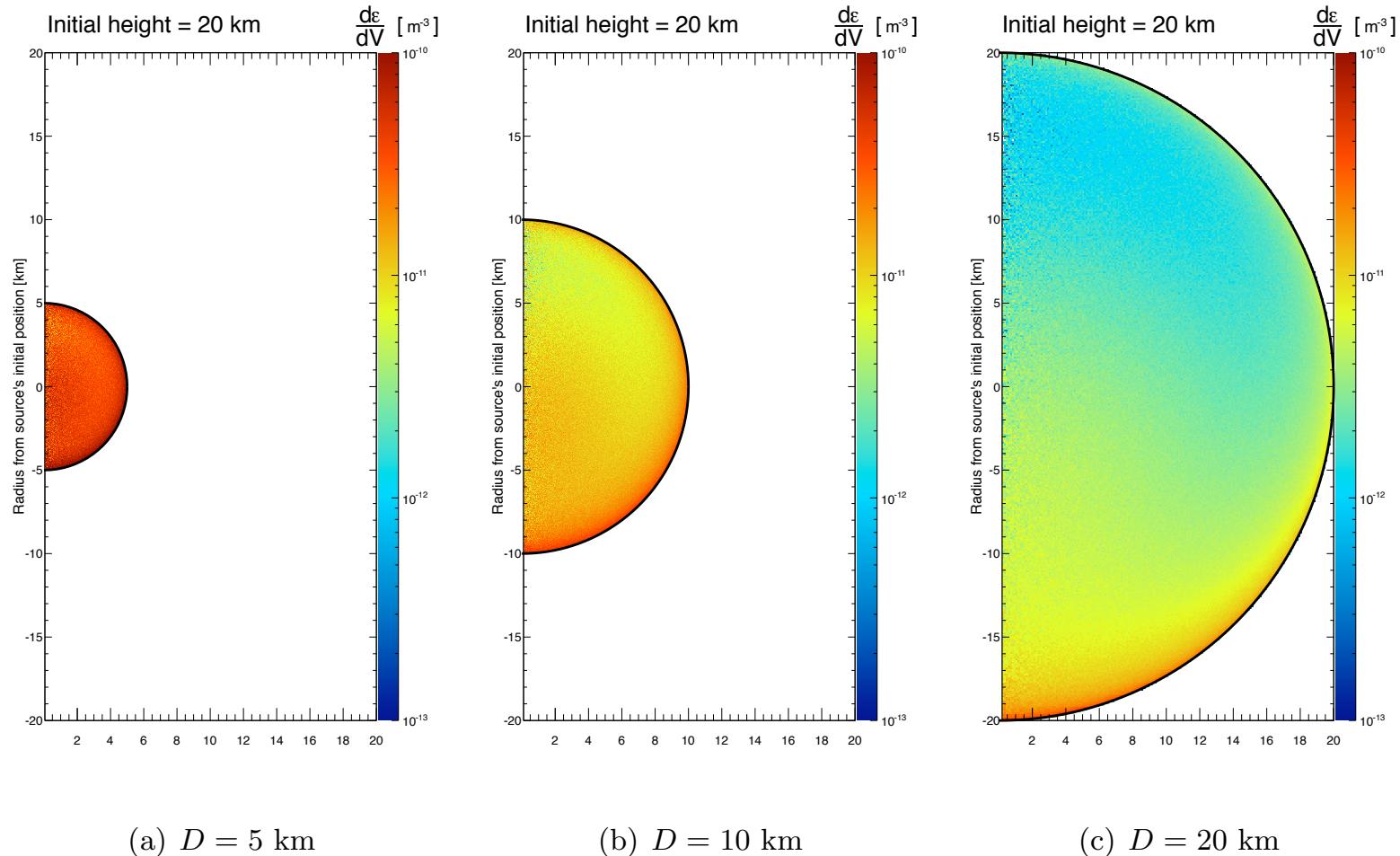
Simulation tracks every  
photon in space

-> The most accurate way!

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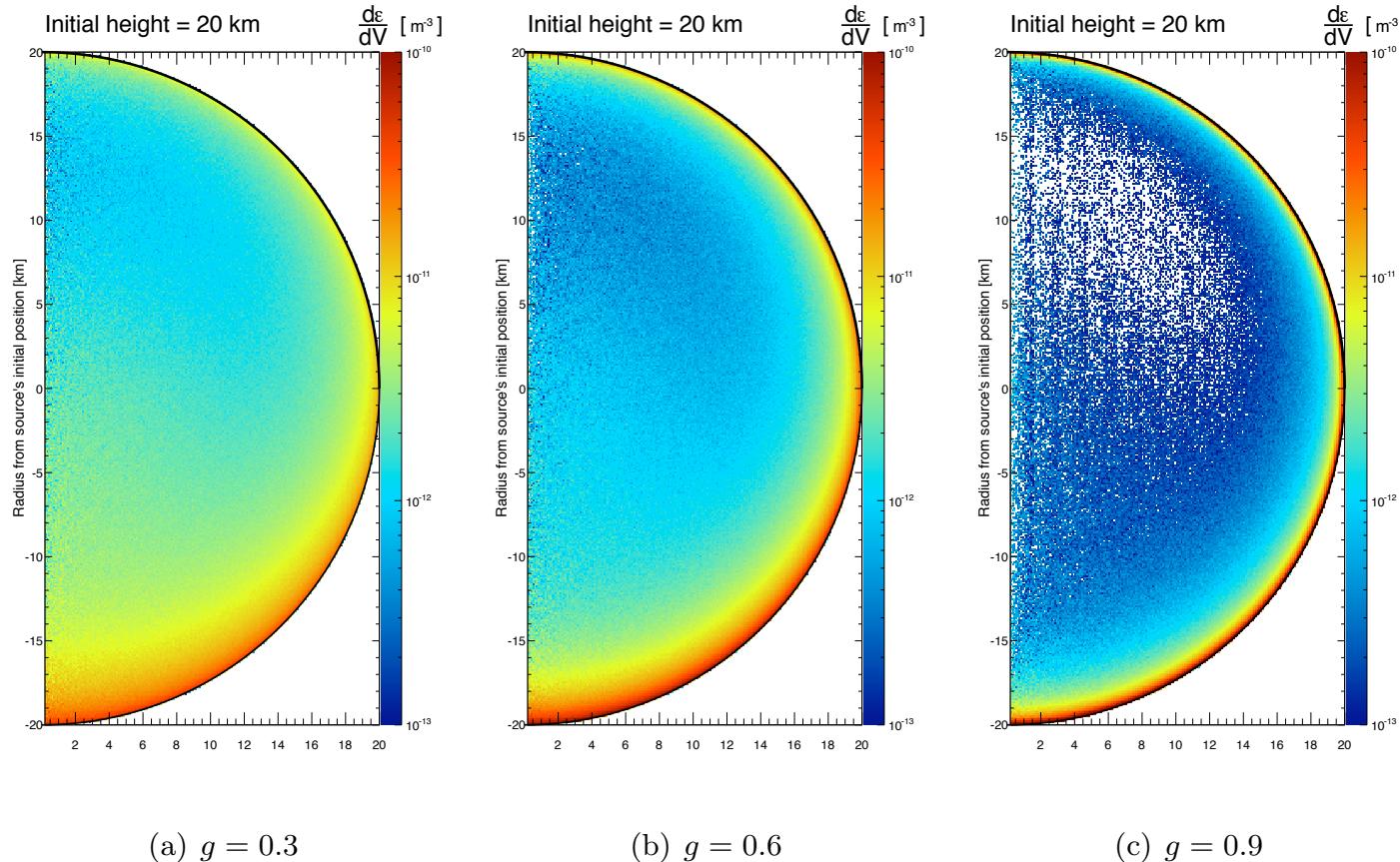
# Evolution of distribution of scattered photons with time



-> Difference in density at different heights

$$\Lambda_{\text{aer}}^0 = 25.0 \text{ km} \quad h_{\text{aer}}^0 = 1.5 \text{ km}$$

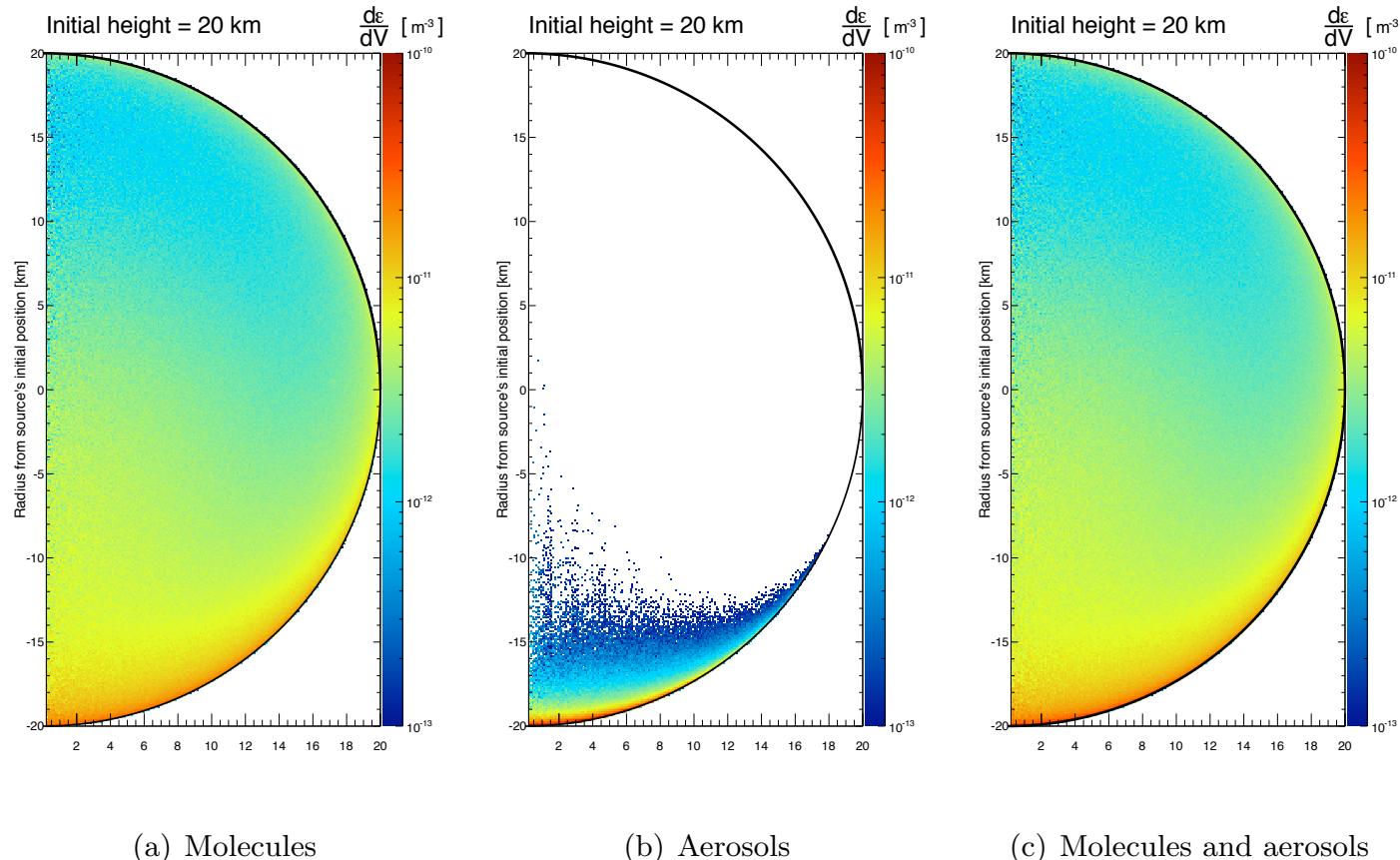
# Effect of changing the scattering phase function



- Unrealistic density of aerosols.
  - Accumulation of scattered photons before direct photons for high  $g$ .
- => Scattered photons have high component of velocity along direct photon motion.

$$\Lambda_{\text{aer}}^0 = 14.2 \text{ km} \quad h_{\text{aer}}^0 = 8.0 \text{ km} \text{ (same density as molecules)}$$

# Relative effects of aerosols and molecules



- Higher density of molecules => molecules dominate.
  - Does NOT mean aerosols can be overlooked

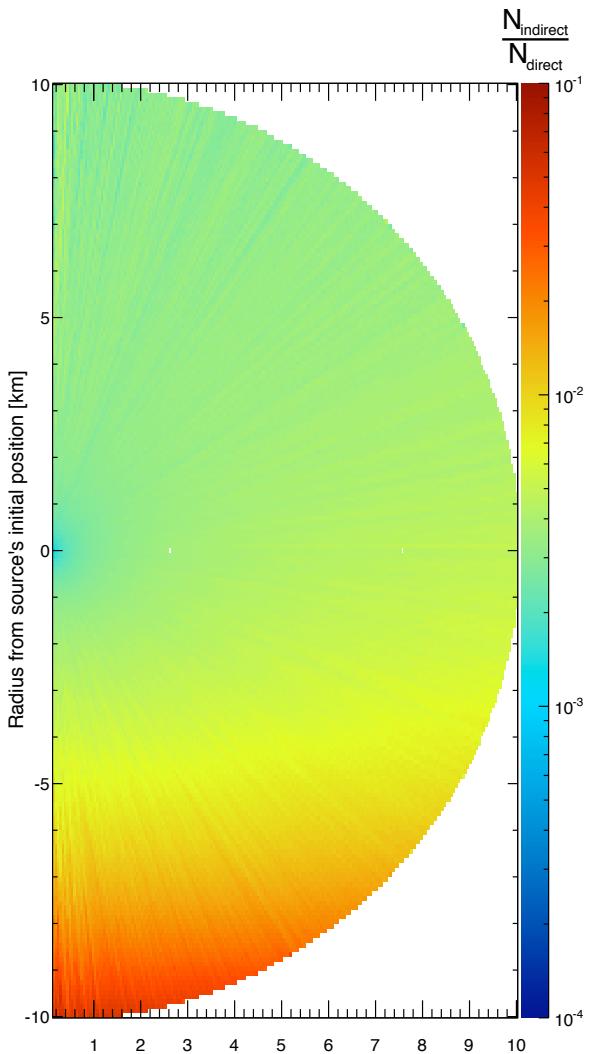
$$g = 0.6 \quad \Lambda_{aer}^0 = 25.0 \text{ km} \quad h_{aer}^0 = 1.5 \text{ km}$$

# Outline

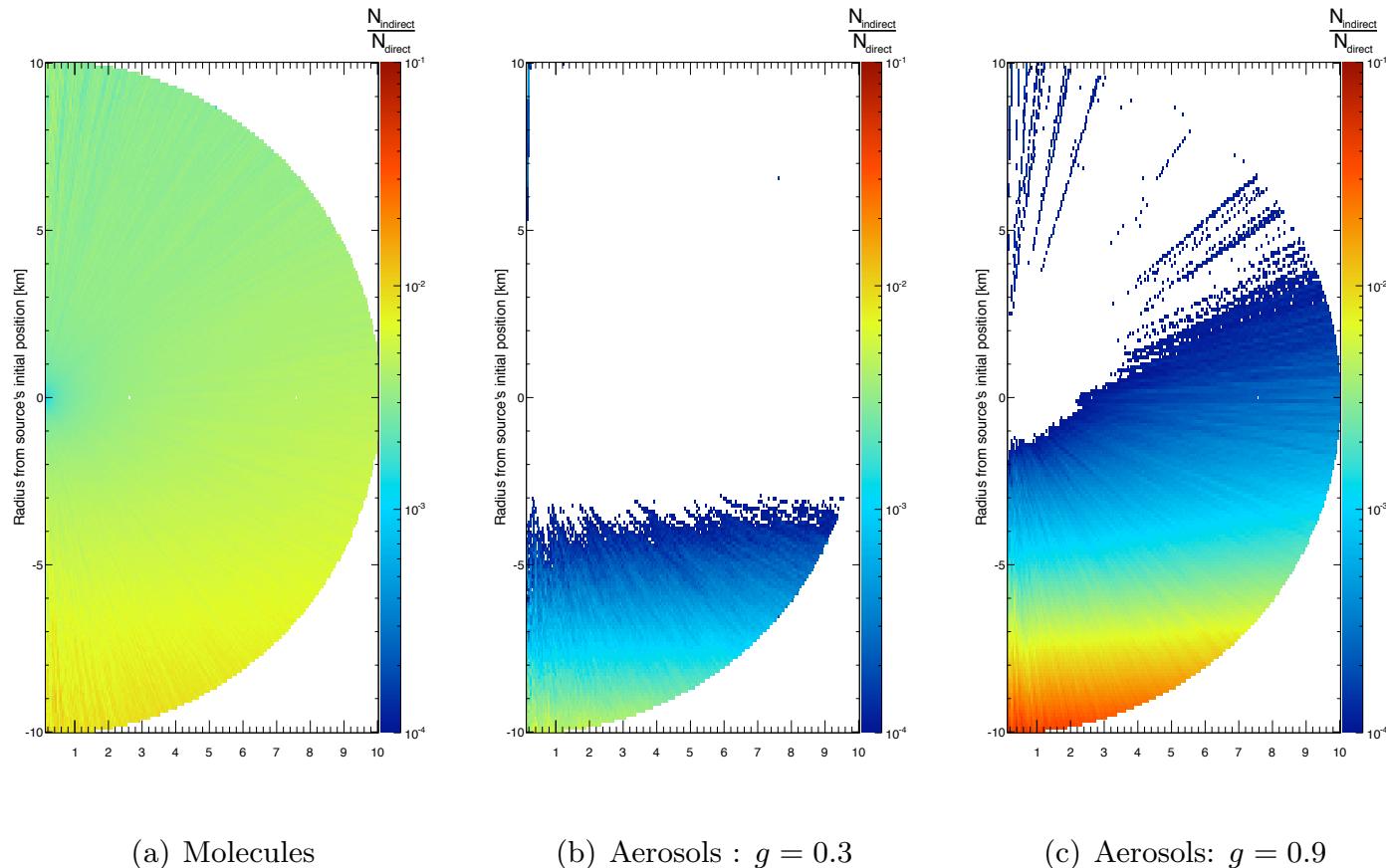
- Theory of scattering and simulation method.
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# Presentation of results

- Ratio  $N_{\text{indirect}}/N_{\text{direct}}$
- A histogram bin represents the ratio of **indirect** photons detected within a given integration **time**  $t_{\text{det}}$ .



# Short integration time – $t_{\text{det}} = 100 \text{ ns}$



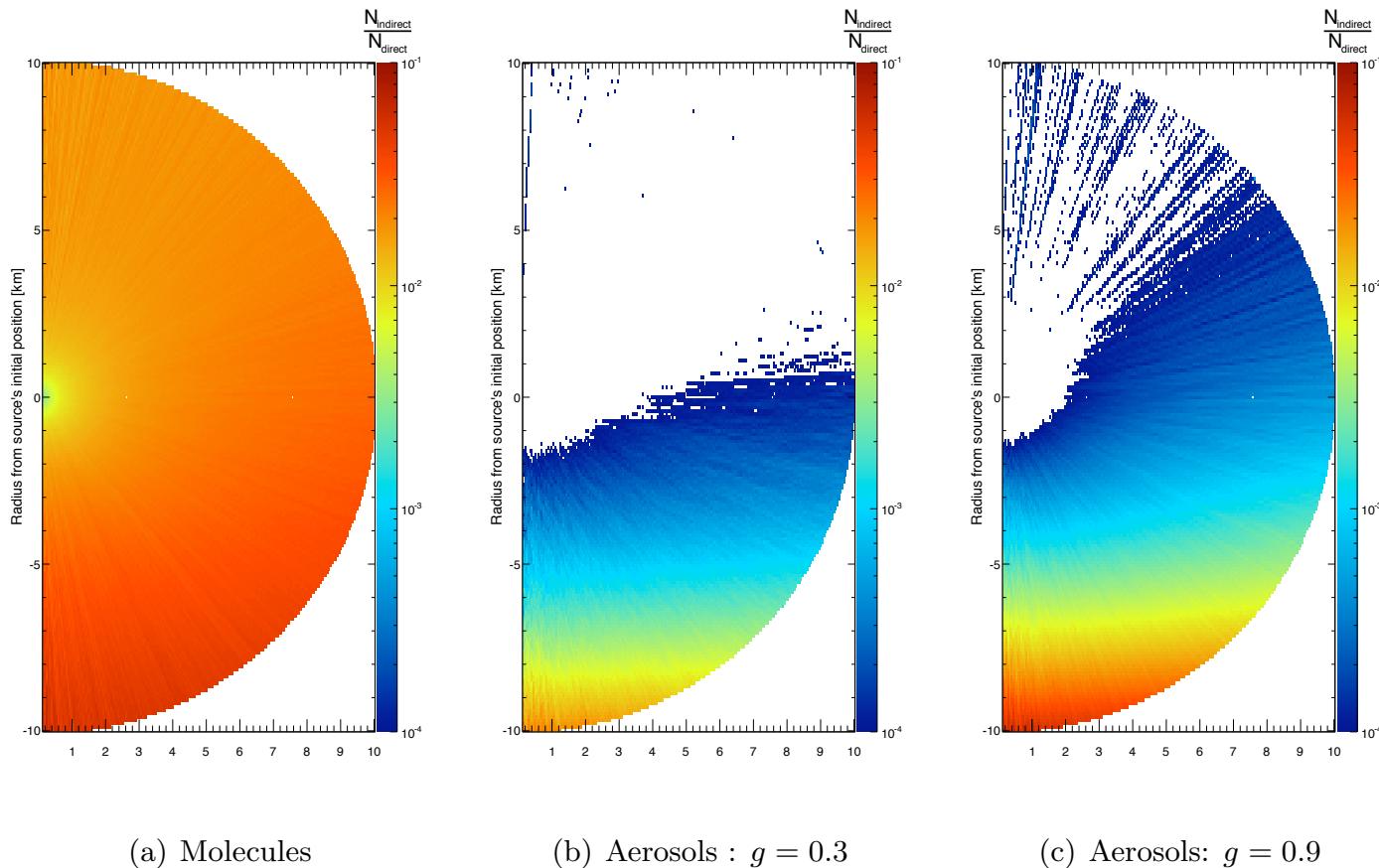
(a) Molecules

(b) Aerosols :  $g = 0.3$ (c) Aerosols:  $g = 0.9$ 

- High  $g \Rightarrow$  more indirect photons
- Scattering phase function more important than relative density of scatterers

$$\Lambda_{\text{aer}}^0 = 25.0 \text{ km} \quad h_{\text{aer}}^0 = 1.5 \text{ km}$$

# Longer integration time – $t_{\text{det}} = 1000 \text{ ns}$



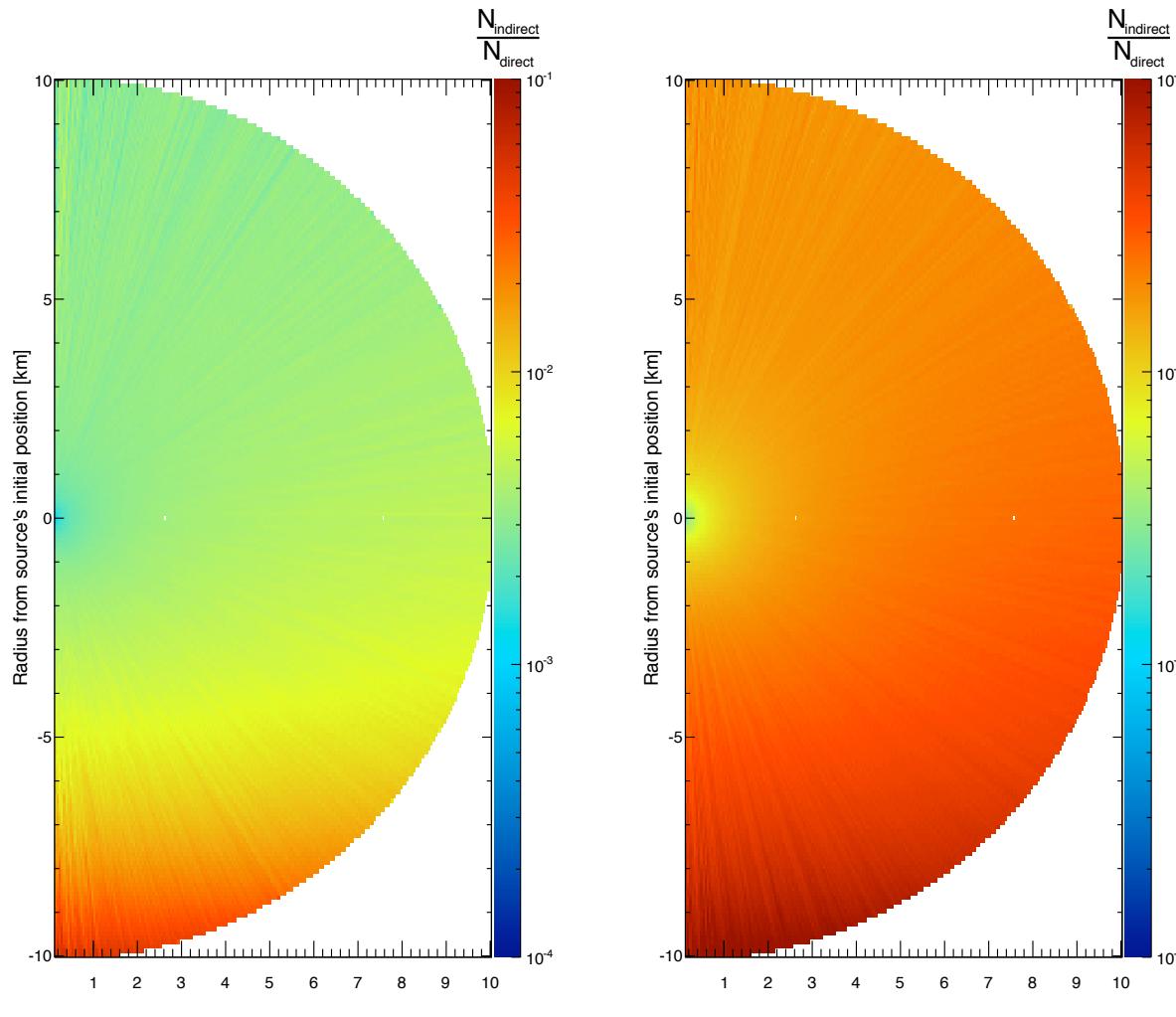
(a) Molecules

(b) Aerosols :  $g = 0.3$ (c) Aerosols:  $g = 0.9$ 

- No more indirect photons detected for high  $g$ .
- Many more indirect photons detected for molecules => molecules dominate.

$$\Lambda^0_{\text{aer}} = 25.0 \text{ km} \quad h^0_{\text{aer}} = 1.5 \text{ km}$$

# Relative effects of aerosols and molecules



(a)  $t_{\text{det}} = 100$  ns

**g = 0.9**

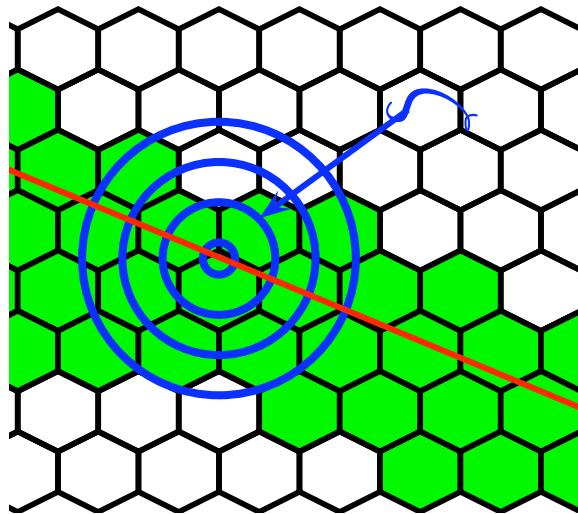
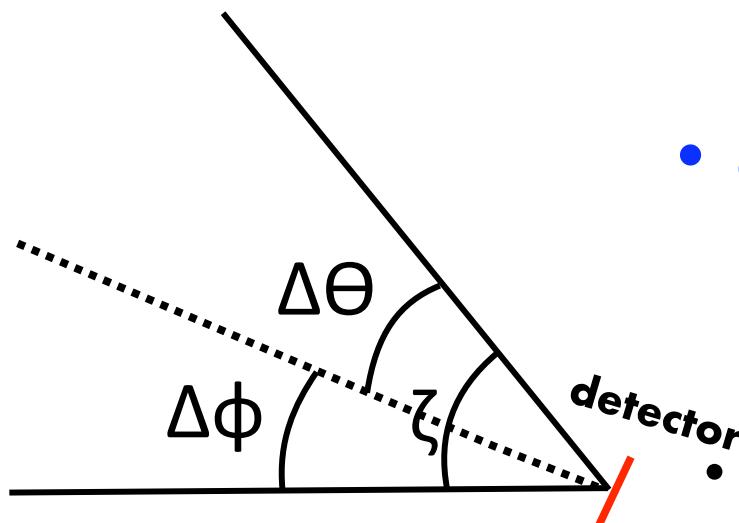
(b)  $t_{\text{det}} = 1000$  ns

$\Lambda^0_{\text{aer}} = 25.0 \text{ km}$     $h^0_{\text{aer}} = 1.5 \text{ km}$

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# Integration angle - $\zeta$



- $\zeta = \arccos(\cos(\Delta\theta)\cos(\Delta\phi))$

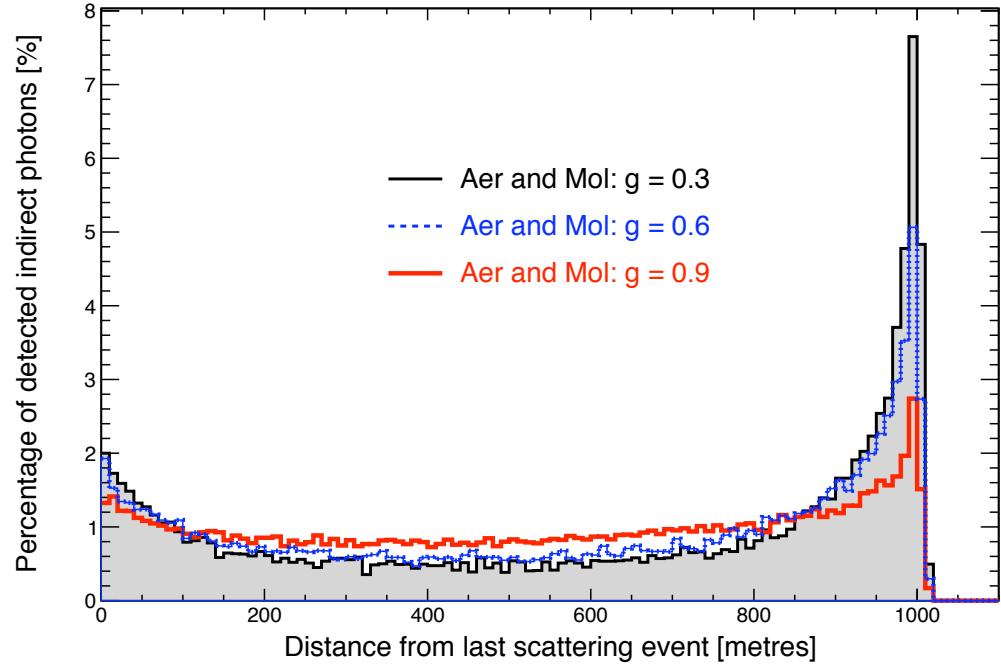
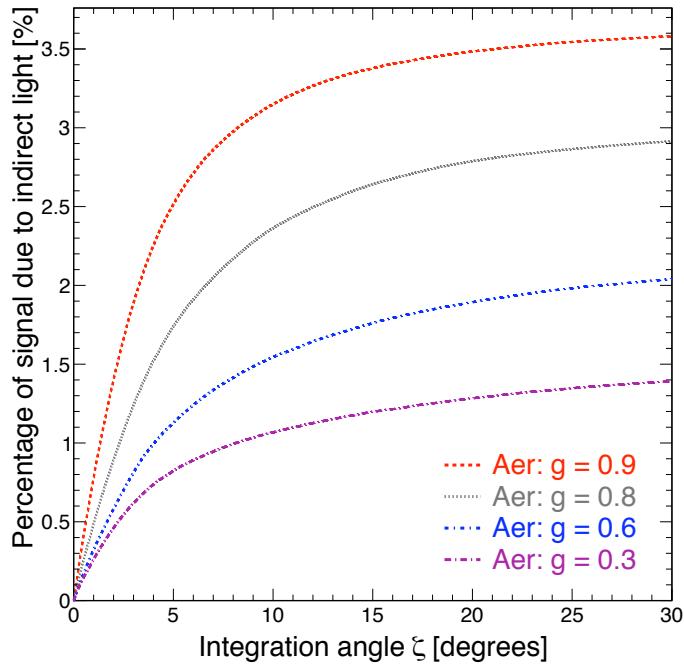
$\zeta = 1.5^\circ$  TYPICALLY.

- Relation between indirect light signal and integration angle  $\zeta$  is of interest for fluorescence detectors.

- It is over a specified  $\zeta$  range that light is accounted for.

# 1)a) Changing the position in space of the isotropic source

$t_{\text{det}} = 100 \text{ ns}$

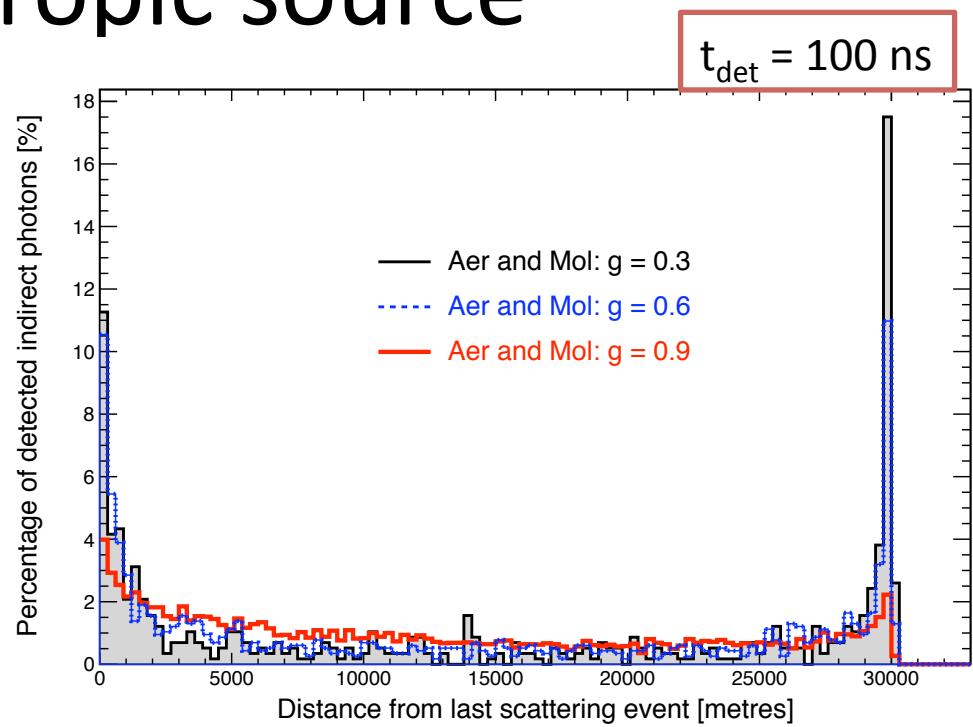
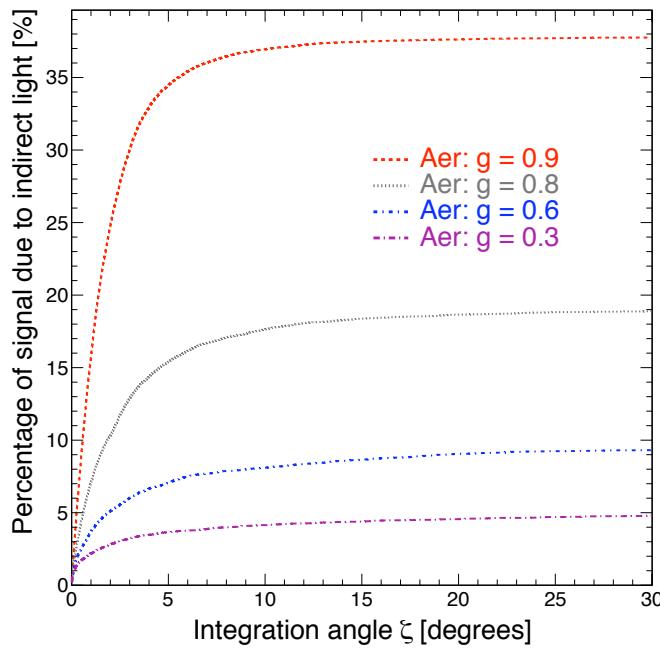


Distance to detector = 1 km Inclination angle =  $3^\circ$

-> Greater aerosol size => Greater signal

$\Lambda^0_{\text{aer}} = 25.0 \text{ km}$   $h^0_{\text{aer}} = 1.5 \text{ km}$

# 1)b) Changing the position in space of the isotropic source

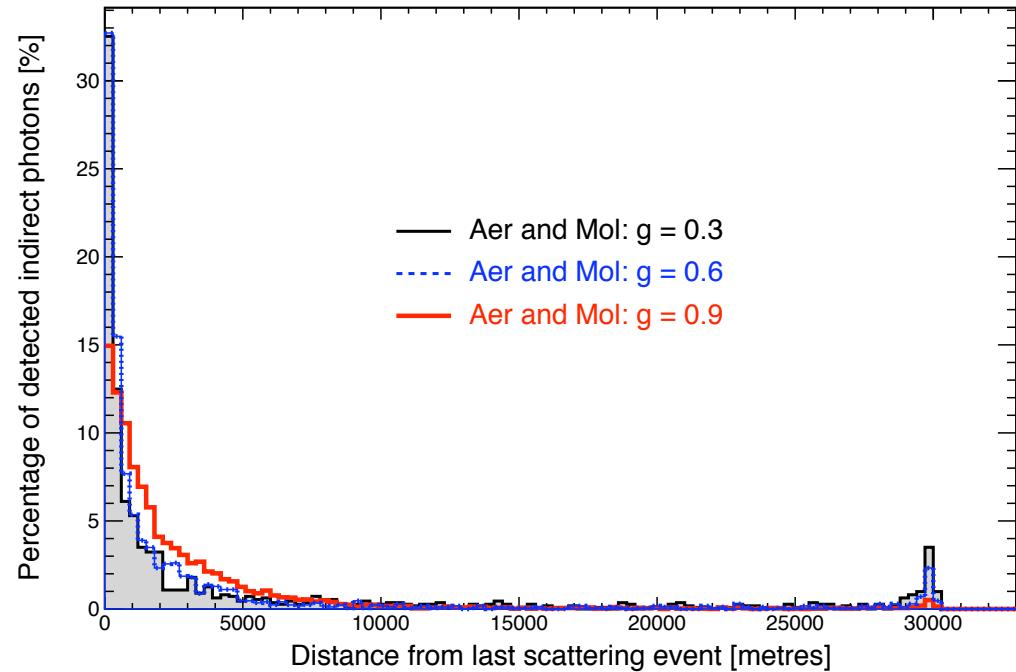
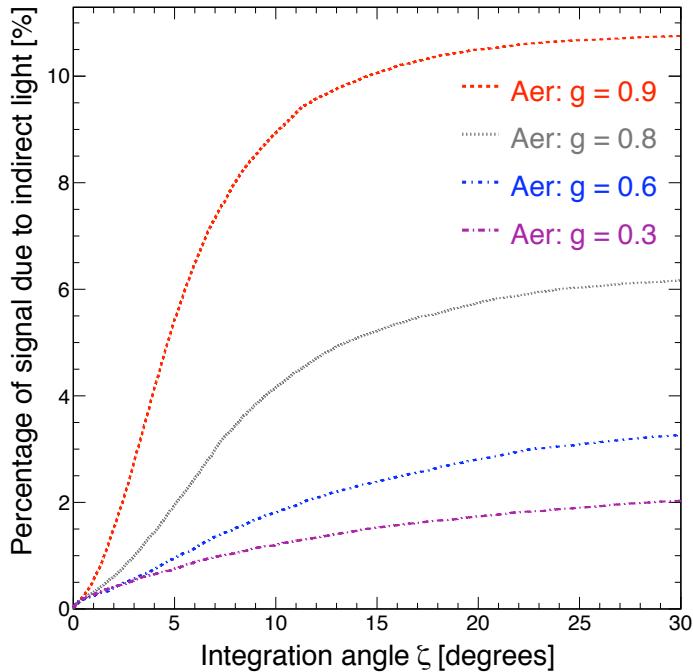


Distance to detector = 30 km, Inclination angle =  $3^\circ$

- Increasing distance to detector increases indirect signal and decreases direct signal.
    - Increasing distance to detector increases effect of aerosol size
- => High forward scattering peak means aerosol scattered photons are likely to be detected even at far distances.

$$\Lambda^0_{\text{aer}} = 25.0 \text{ km} \quad h^0_{\text{aer}} = 1.5 \text{ km}$$

# 1)c) Changing the position in space of the isotropic source

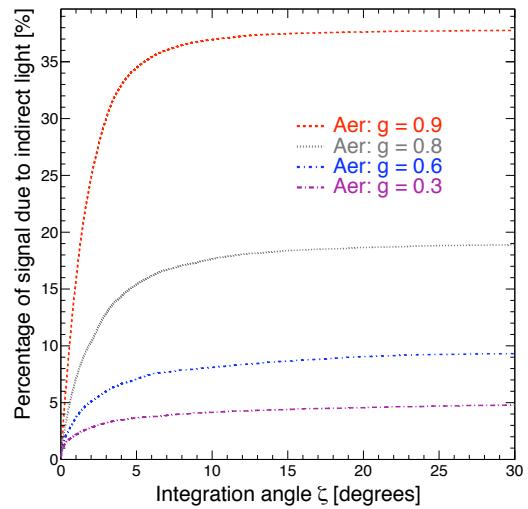
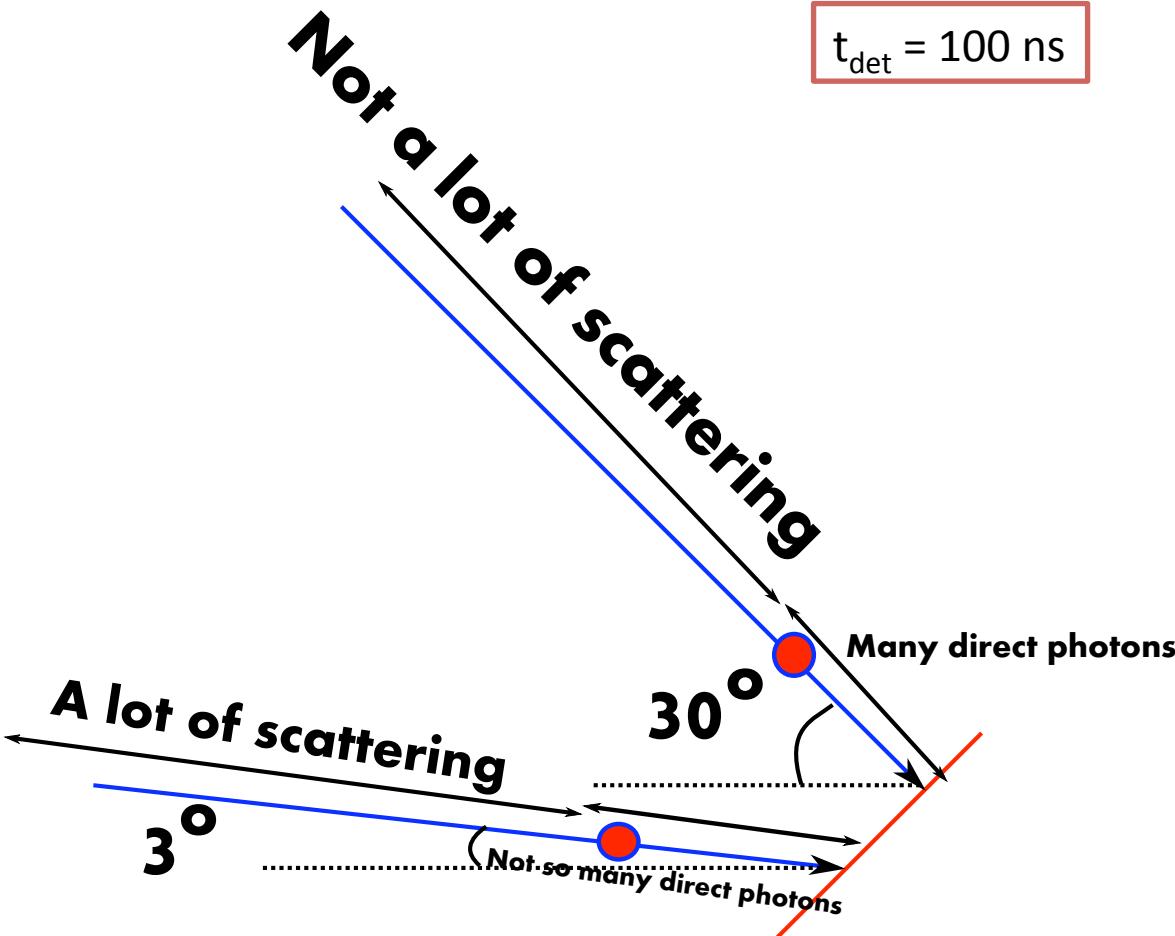


Distance to detector = 30 km Inclination angle = 30°

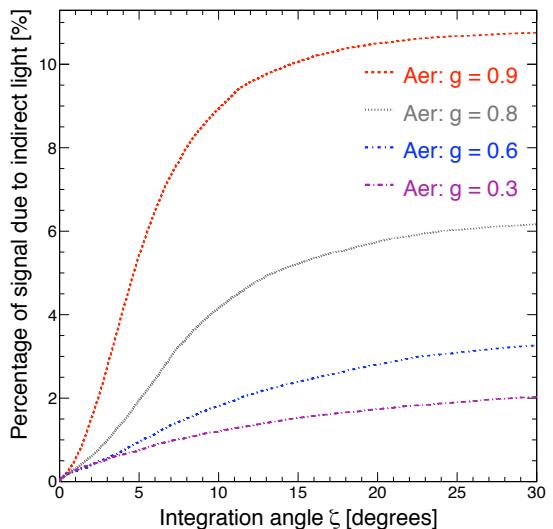
- Increasing inclination angle makes halo wider and decreases percentage of indirect light
- Photons are scattered nearer to detector due to increased density of scatterers near to detector

$$\Lambda_{\text{aer}}^0 = 25.0 \text{ km} \quad h_{\text{aer}}^0 = 1.5 \text{ km}$$

# 1)d) Changing the position in space of the isotropic source

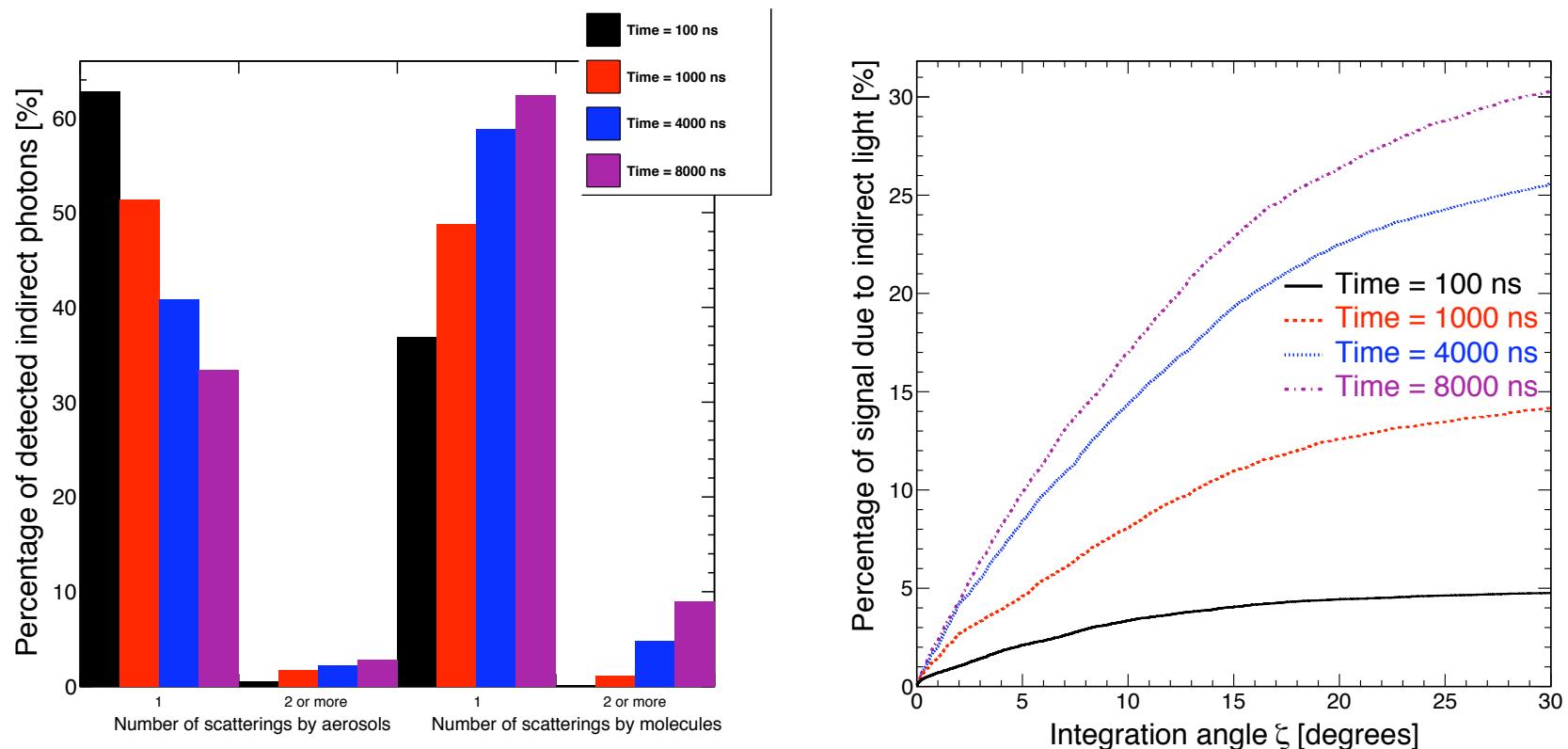


$D = 30 \text{ km}$  Inclination angle =  $3^\circ$



$D = 30 \text{ km}$  Inclination angle =  $30^\circ$

## 2) The effect of increasing integration time

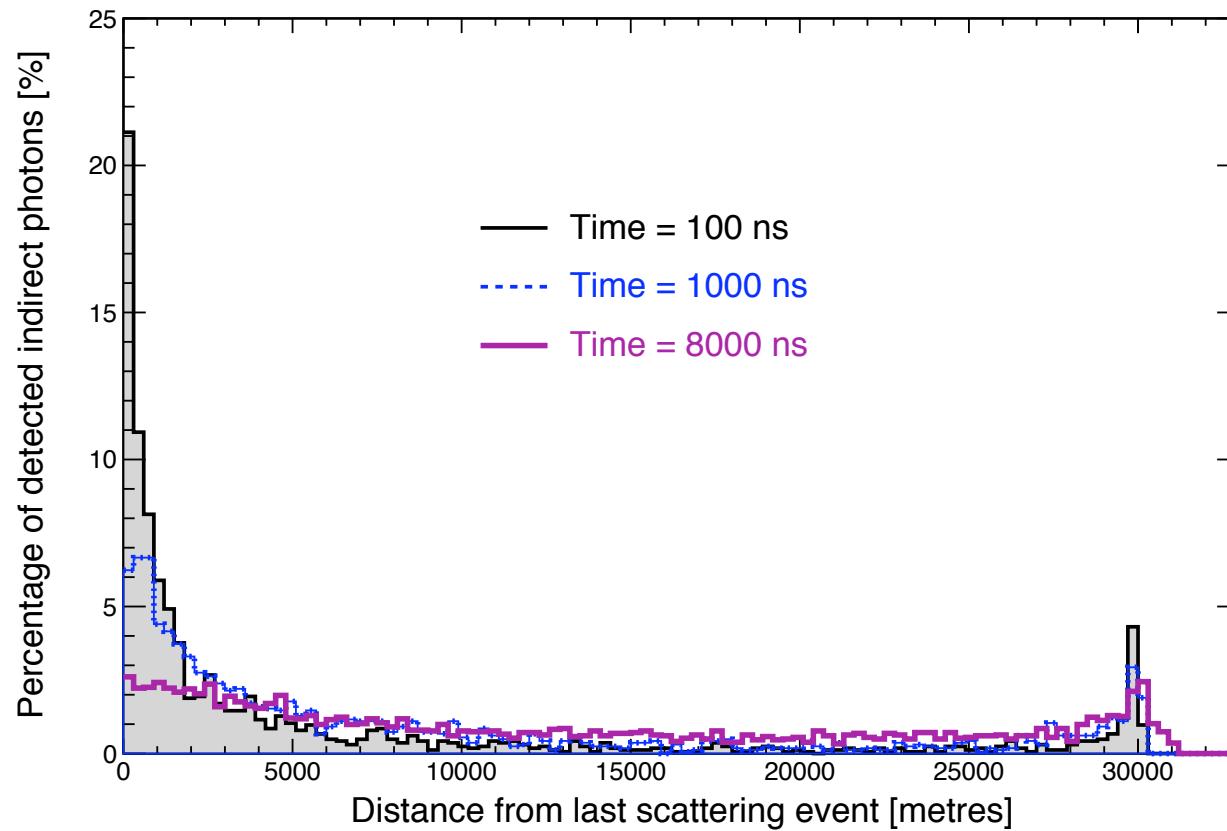


Distance to detector = 15 km Inclination angle = 15°

- More molecularly scattered photons are detected  
=> High forward scattering peak less important at higher time

$$g = 0.6 \quad \Lambda_{\text{aer}}^0 = 25.0 \text{ km} \quad h_{\text{aer}}^0 = 1.5 \text{ km}$$

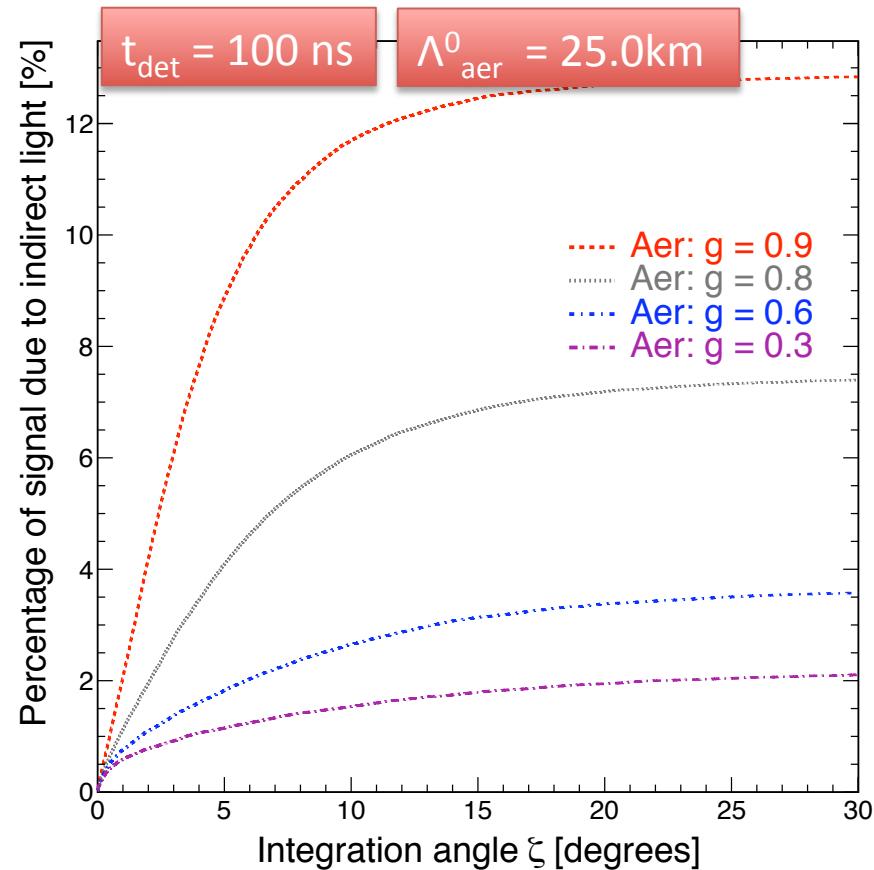
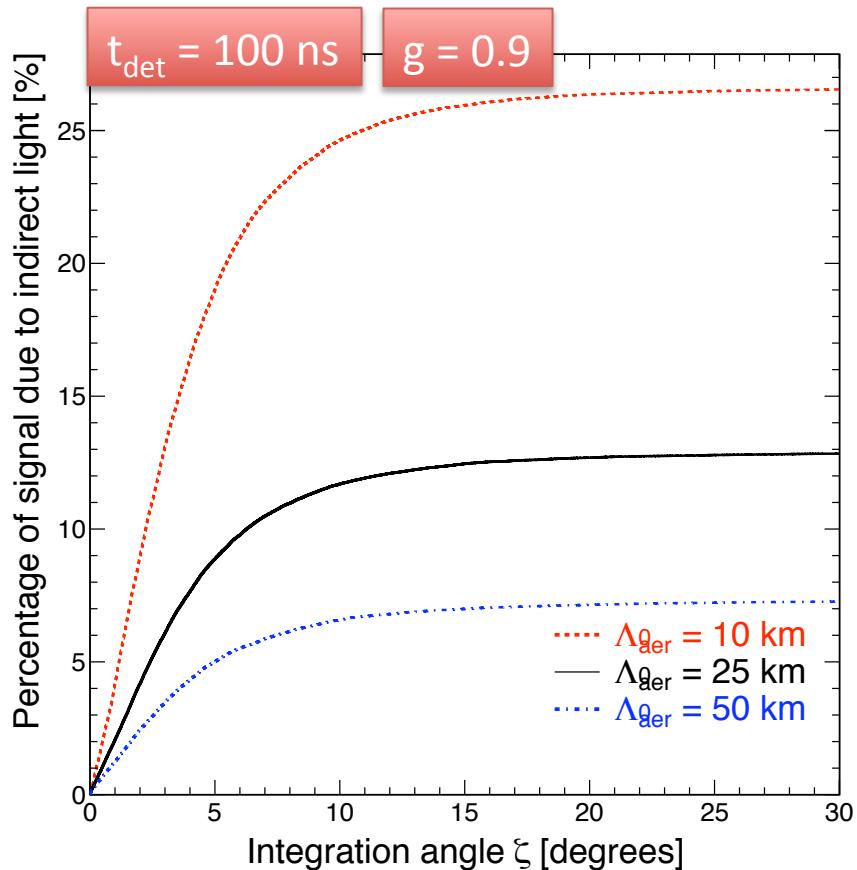
## 2) The effect of increasing integration time



Distance to detector = 15 km Inclination angle = 15°

$g = 0.6$ ,  $\Lambda_{\text{aer}}^0 = 25.0 \text{ km}$ ,  $h_{\text{aer}}^0 = 1.5 \text{ km}$

### 3) Effect of changing aerosol density ( $\Lambda^0_{\text{aer}}$ )

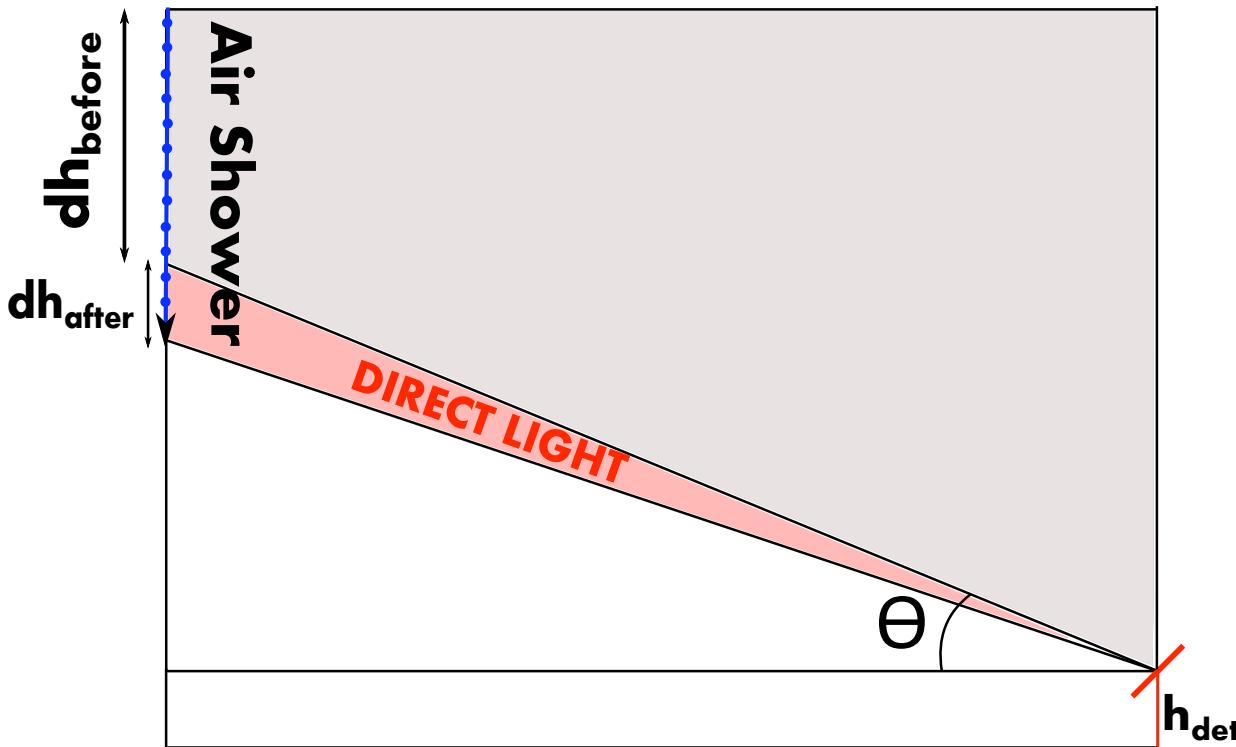


- Aerosol size should be considered with the same importance as aerosol density.

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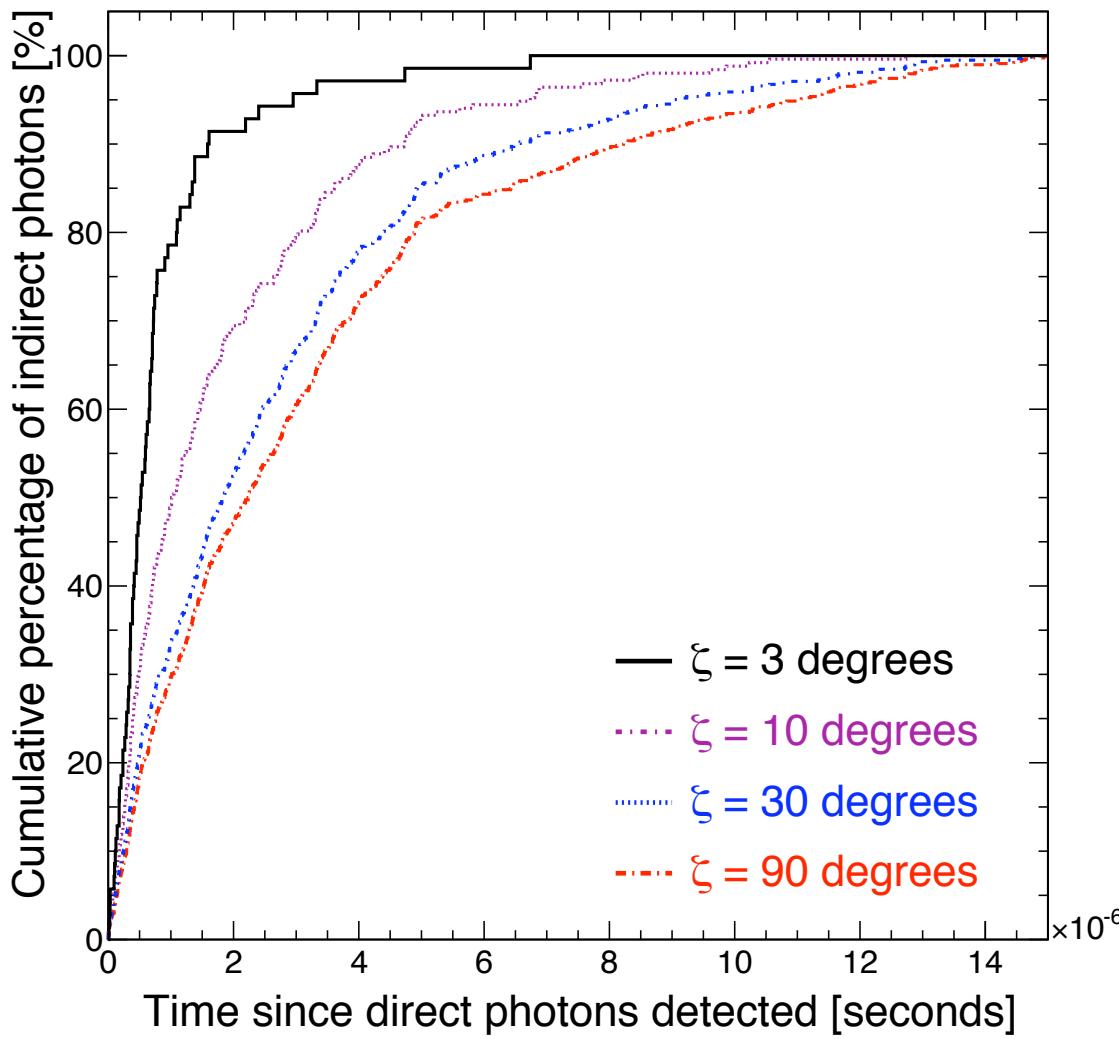
# Simulation approximations



- 'Pixel' left active for 100 ns
- Direct light calculated analytically
- Indirect light with simulation.

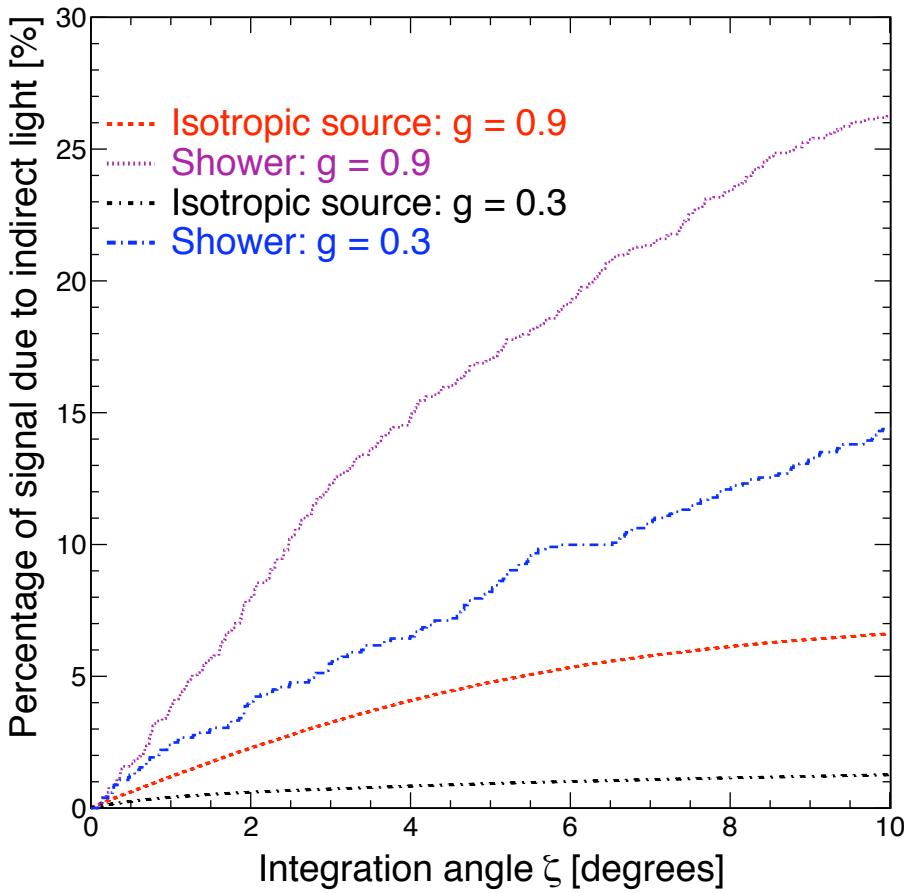
Approximation => 5000 ns after direct light from a source has been detected source no longer has an effect

# Validity of approximation

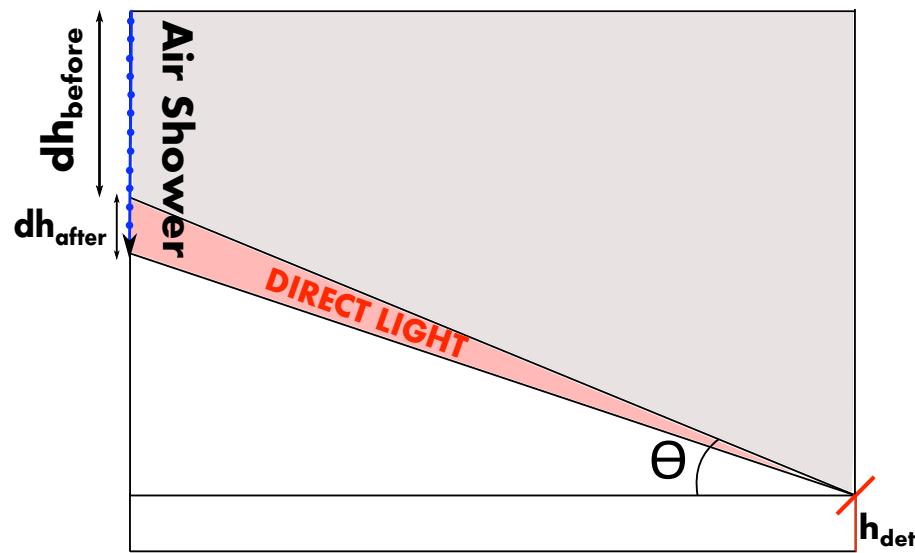


- Simulation ran for 15000 ns
- For smaller integration angles the majority of indirect photons arrive from sources that have had their direct light recently detected.
- $g = 0.3$  worst case scenario

# Comparison of air shower and isotropic source ( $t_{\text{det}} = 100 \text{ ns}$ )

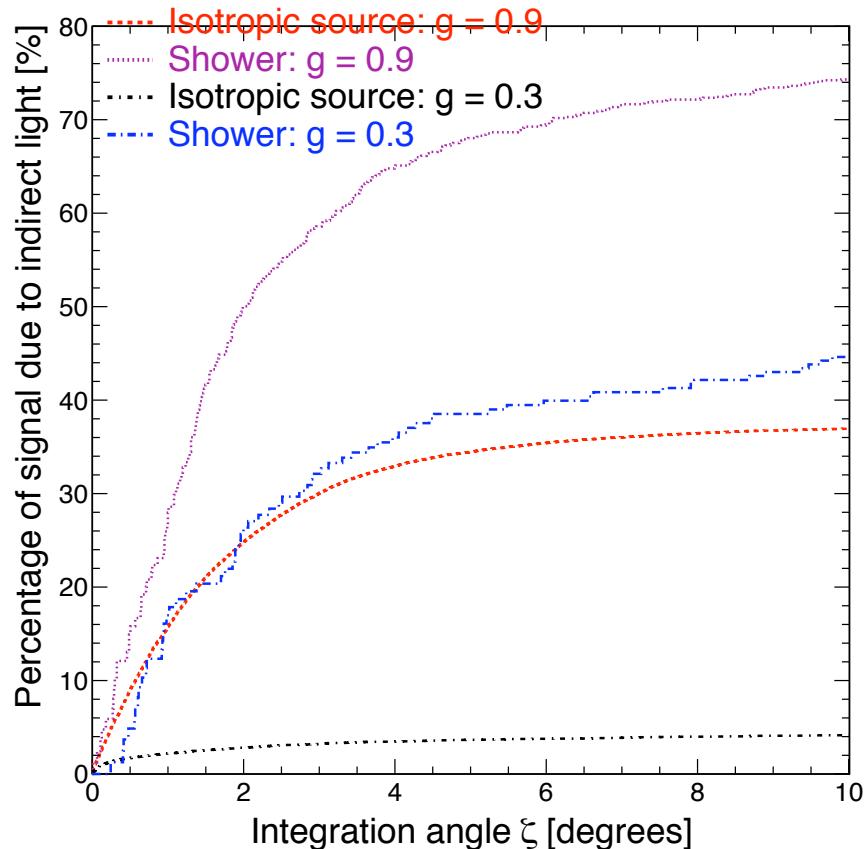


- More indirect light signal for the shower
- ⇒ Expected as where parts of the shower where only indirect light can be detected.
- Aerosol size still has an effect!

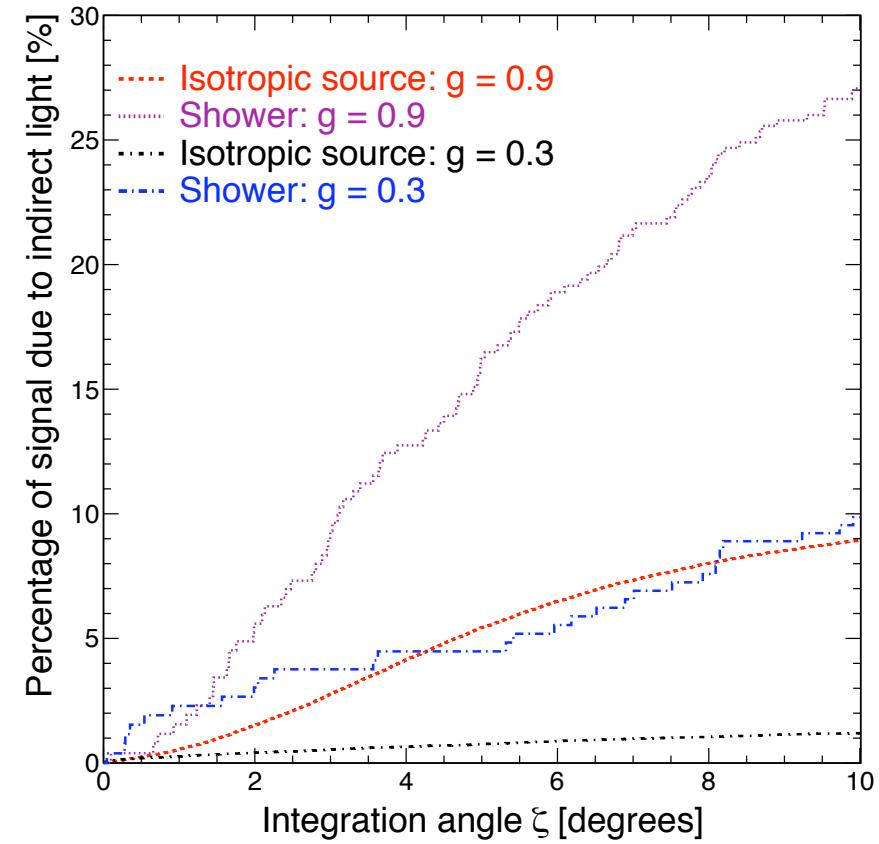


# Results for different geometries (Preliminary)

Distance to detector = 30 km, Inclination angle = 3°,



Distance to detector = 30 km, Inclination angle = 3°,



- Simulations continue to run.

# Conclusion

- Even in lower proportions, the high forward scattering peak of the aerosol phase function means aerosols effect greatly the percentage of signal due to indirect light at fluorescence detectors.
- Considering aerosol size is of equal importance as considering aerosol density .
- Multiply scattered light from air showers has an even greater effect than from isotropic sources (changing aerosol size from  $g=0.3$  to  $g=0.9$  can change percentage of signal due to indirect light by a factor of 2!)

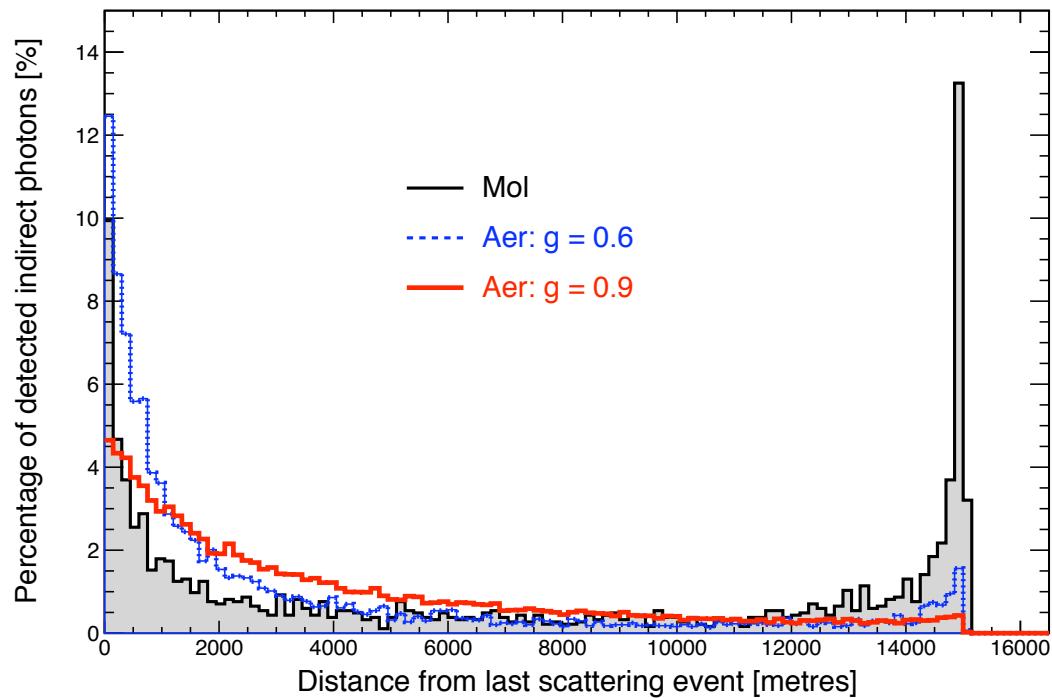
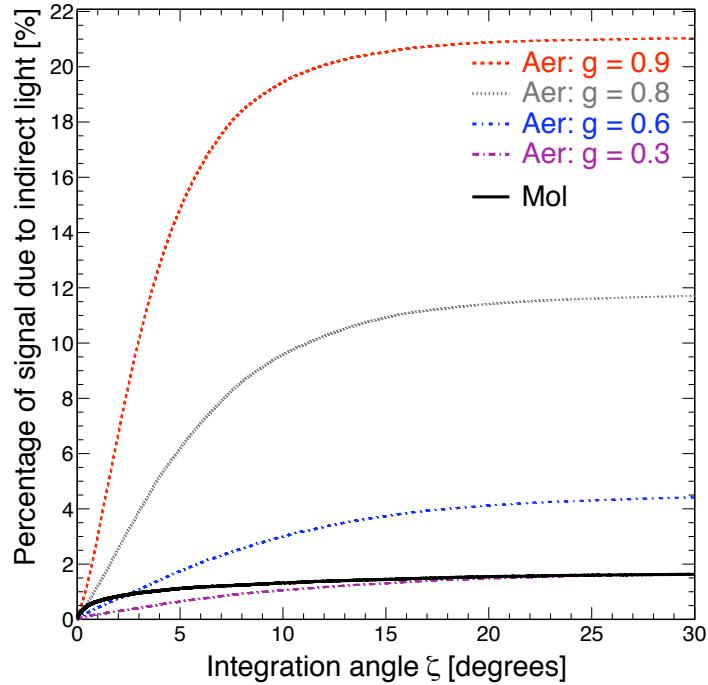
=> New parameterisation with aerosol size required.

Thank you for listening.

I invite any questions.

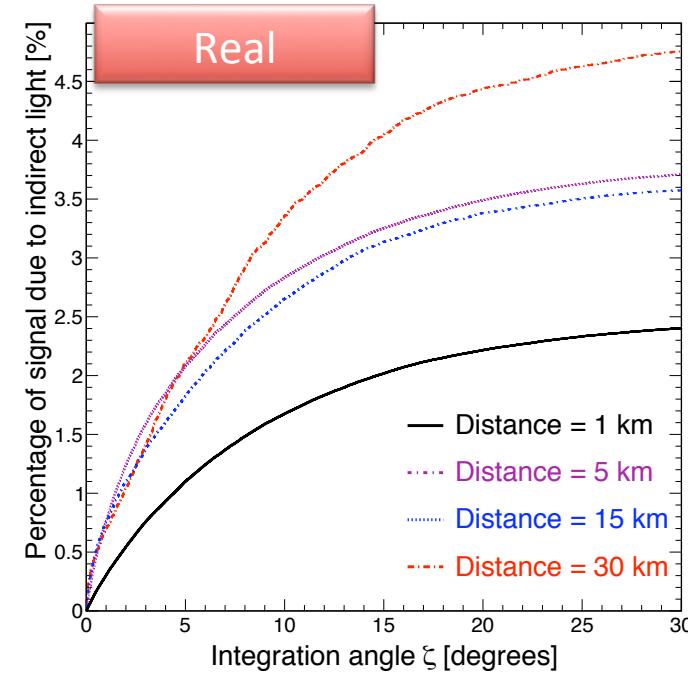
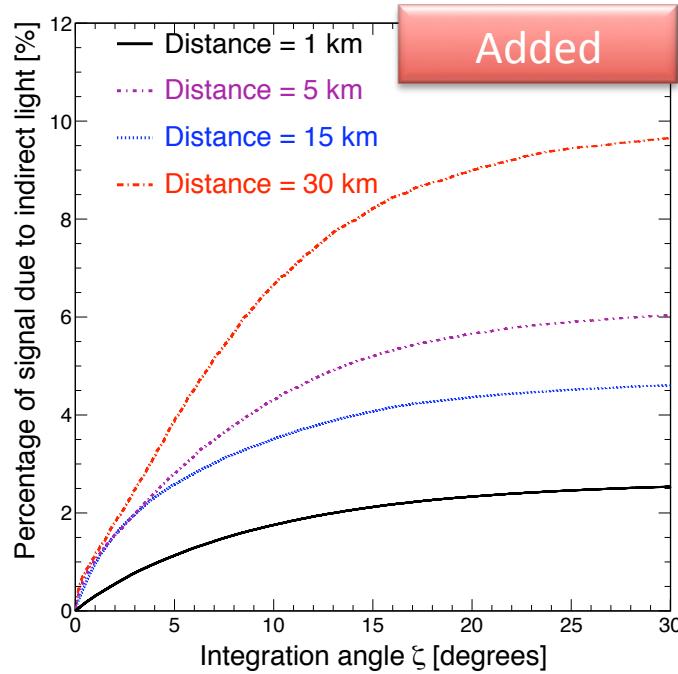
# Back-up Slides

# Effect of the scattering phase function – $t_{\text{det}} = 100 \text{ ns}$



- High  $g$  – high percentage of signal due to indirect light.
  - Increasing  $g$  makes halo narrower
- Aerosol scattering events are detected from many distances  
=> Even in a much lower density, aerosols dominate effects

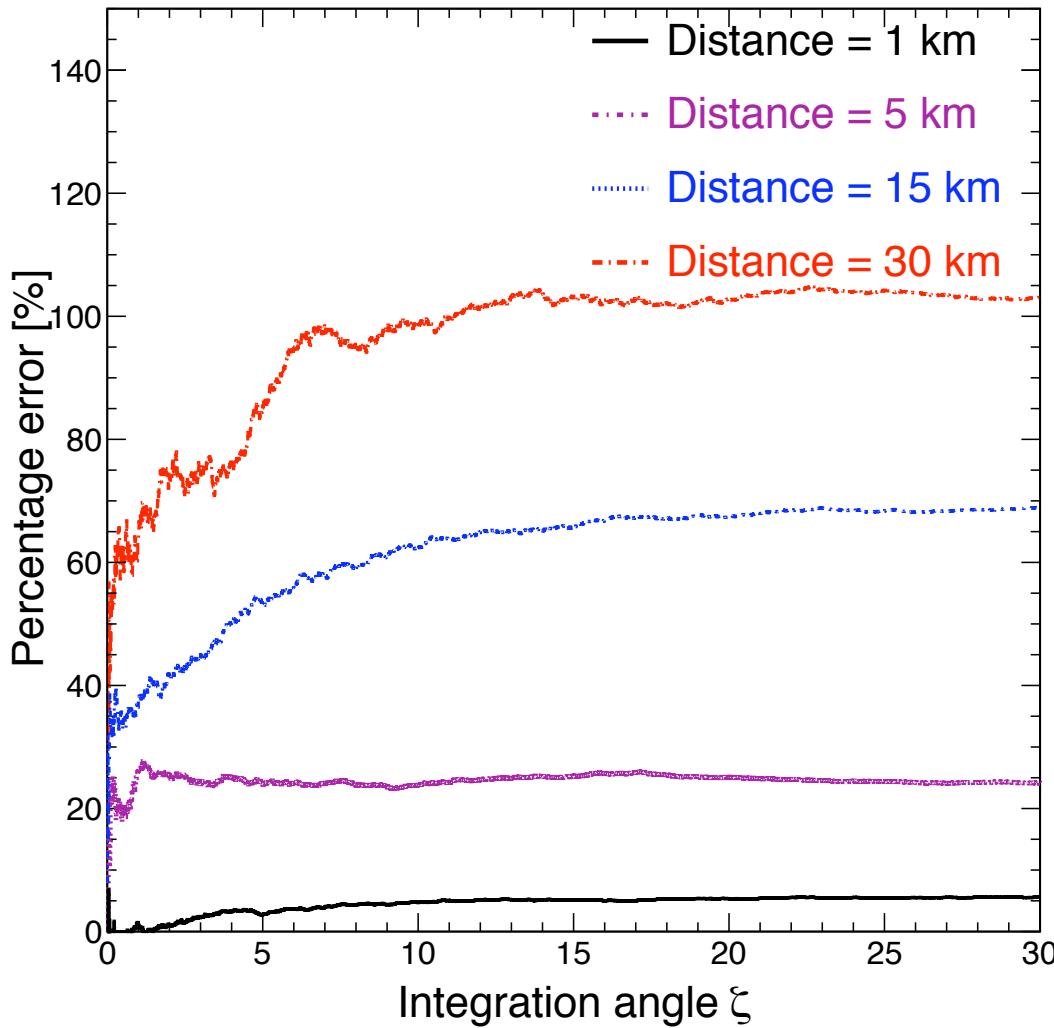
# The effect of molecules and aerosols being simultaneously present



$$g = 0.6 ; \text{ inclination angle} = 15^\circ ; \Lambda_{\text{aer}}^0 = 25.0 \text{ km} ; h_{\text{aer}}^0 = 1.5 \text{ km}$$

- Molecules decrease the effect aerosols have on the amount of indirect light detected

# The effect of molecules and aerosols being simultaneously present

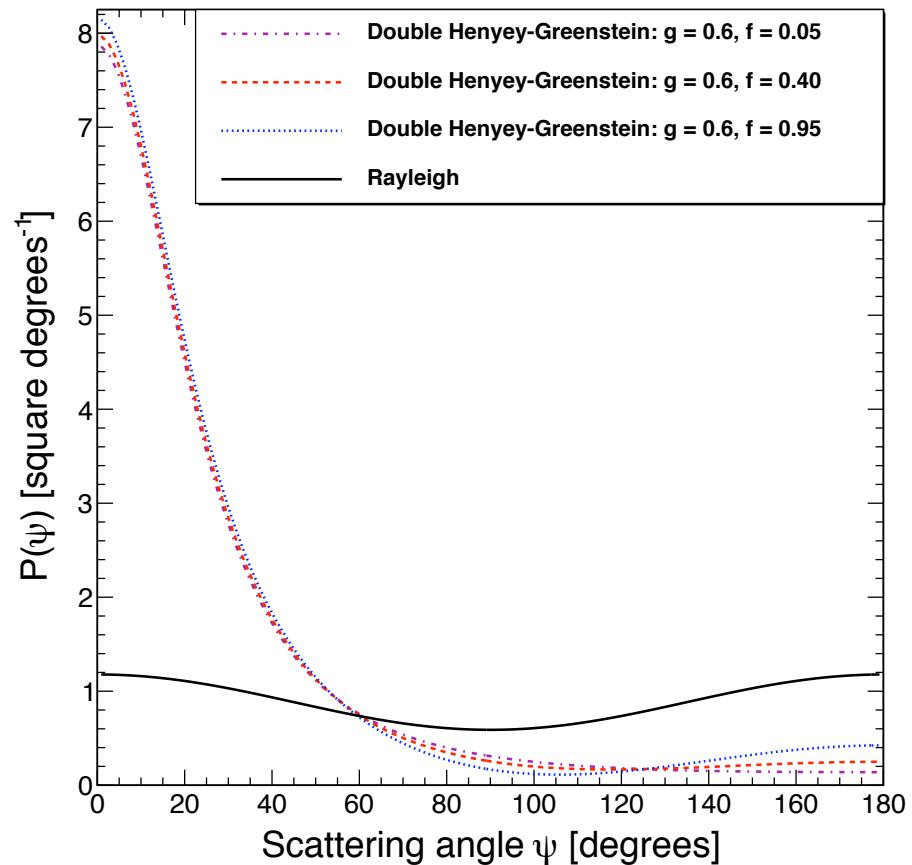


- Error is greater for larger distances => molecules attenuate indirect photons caused by aerosol scattering that would have been detected.
- Molecules **decrease** overall indirect light signal!
  - =>**Scatterers do not automatically increase the amount of indirect light detected!**

# The Double-Henyey Greenstein Function

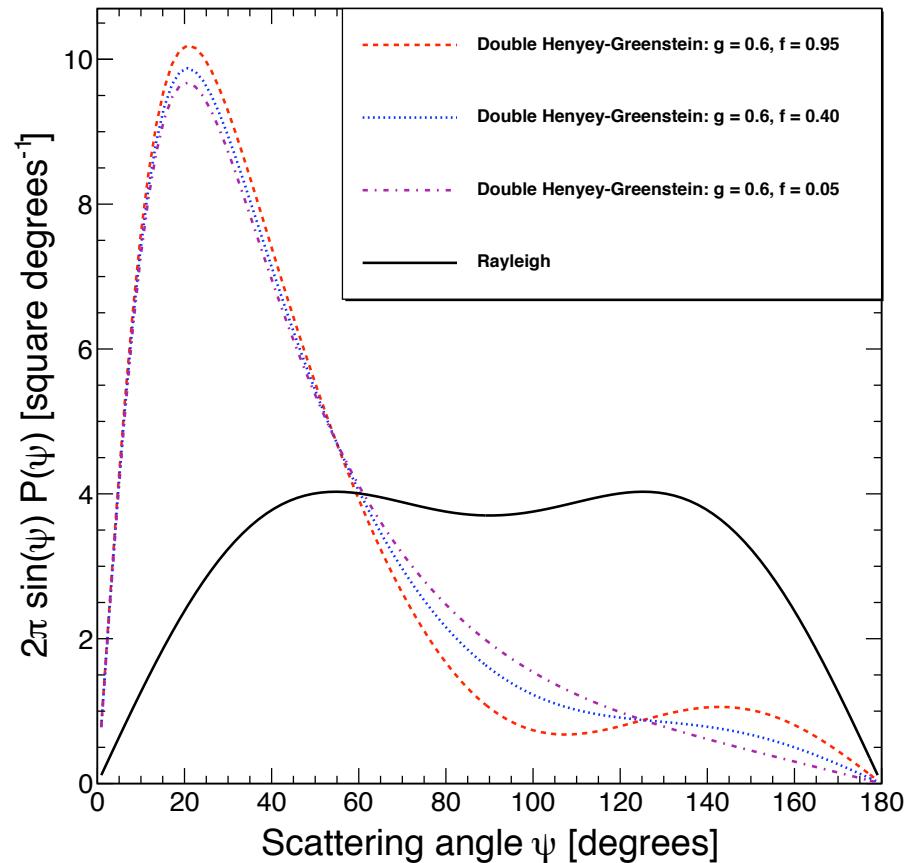
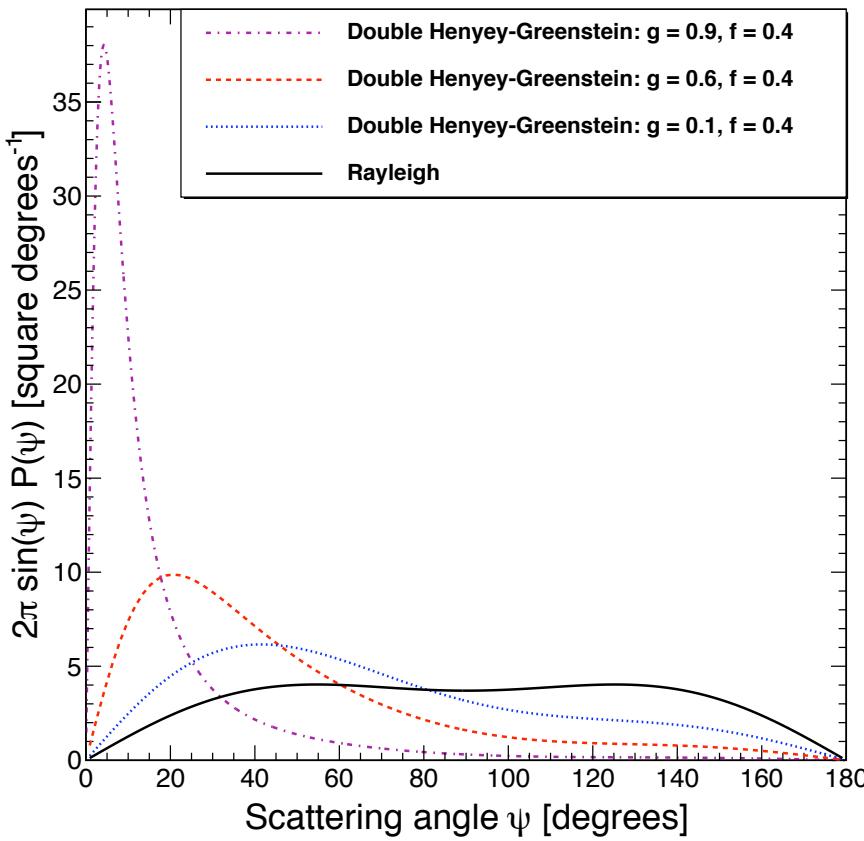
- $f$  – backward scattering parameter
    - Much less influence on phase function.
- ⇒ Effects on detected light negligible.

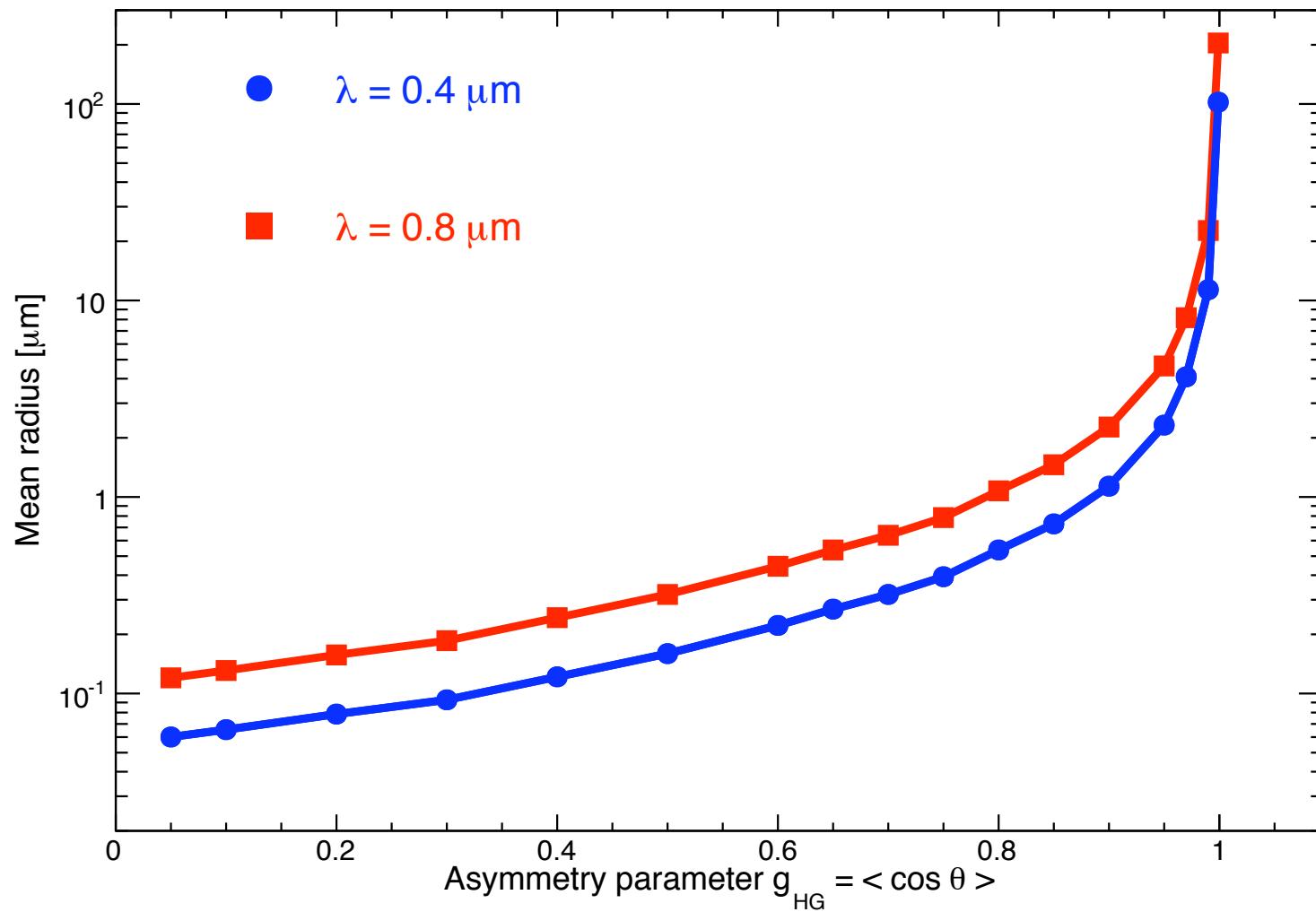
**f = 0.4 used**



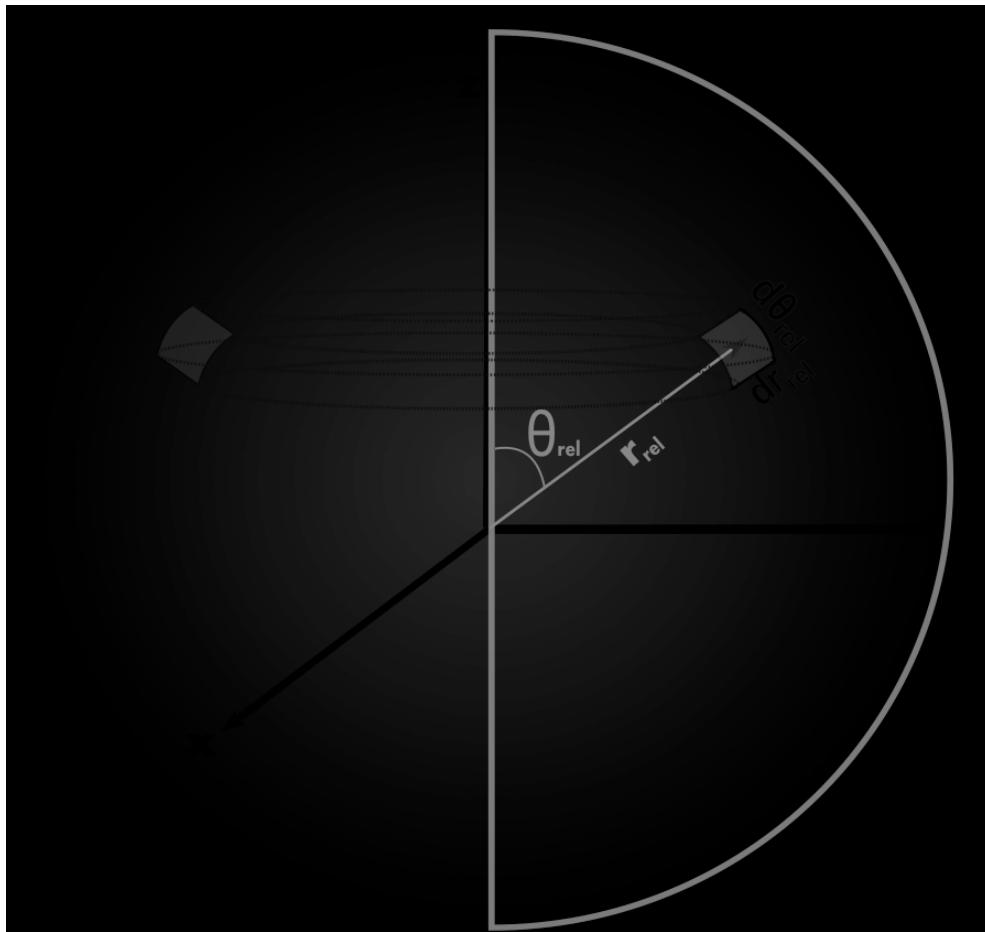
# Generating polar scattering angles from scattering phase functions

$$\begin{cases} \mathcal{P}_{\text{aer}}(\psi) = 2\pi P_{\text{aer}}(\psi) \sin \psi \\ \mathcal{P}_{\text{mol}}(\psi) = 2\pi P_{\text{mol}}(\psi) \sin \psi \end{cases}$$

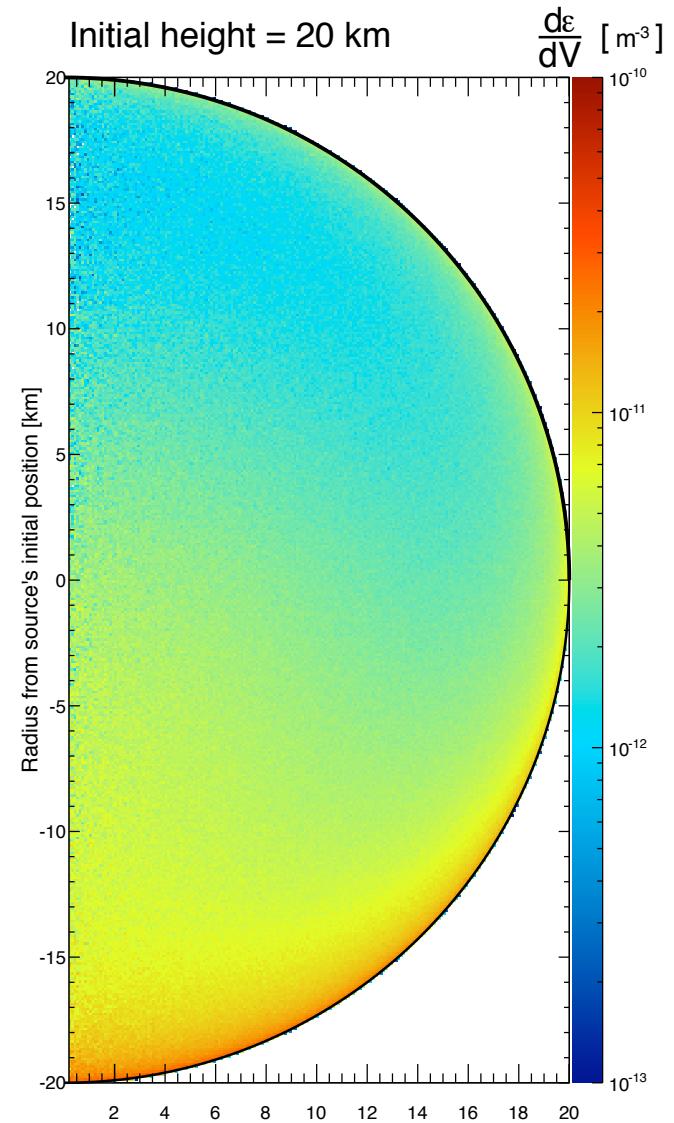




# Presentation of results

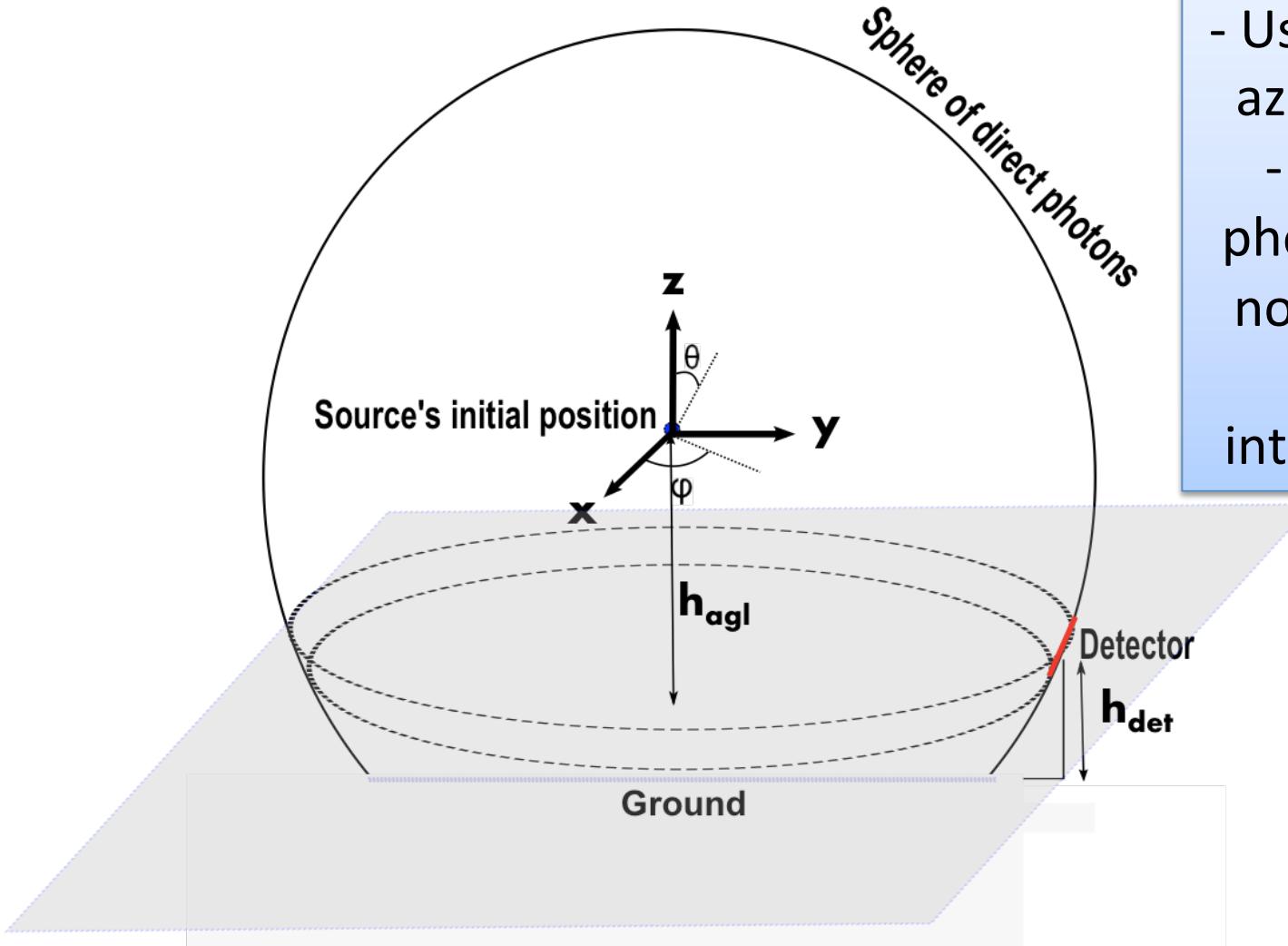


$$dV = r_{\text{rel}}^2 \sin(\theta_{\text{rel}}) d\theta_{\text{rel}} dr_{\text{rel}}$$



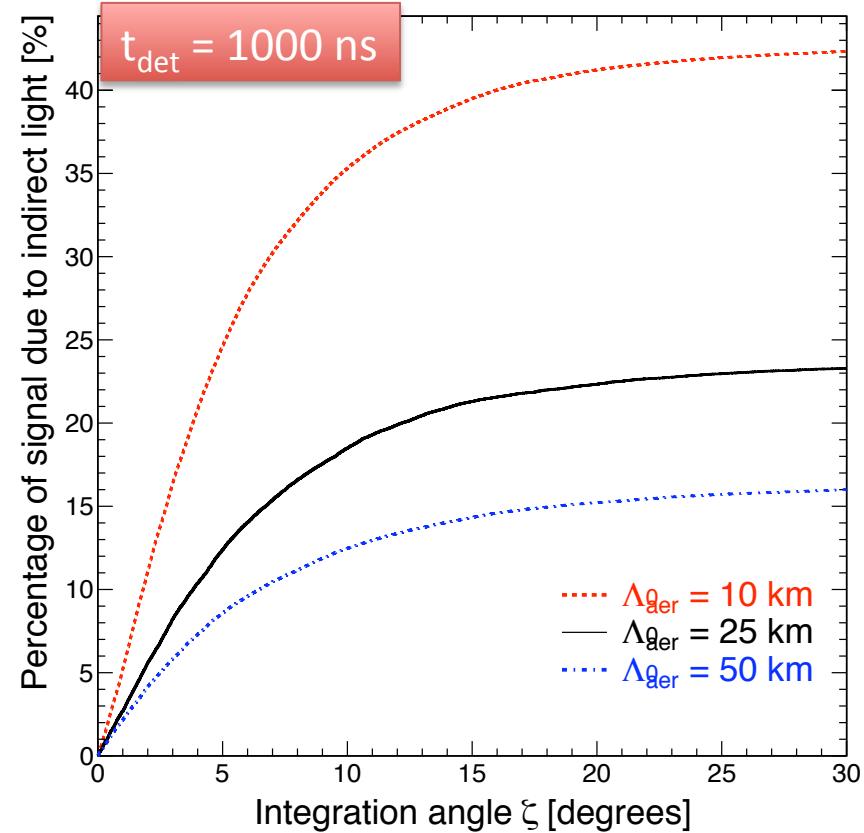
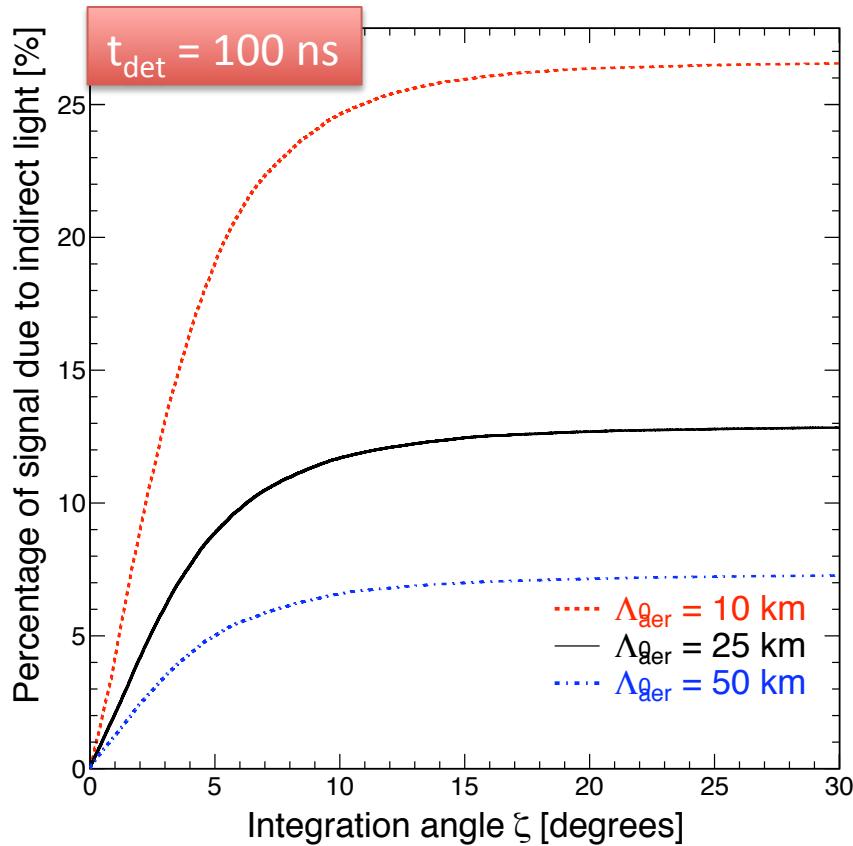
Molecules only  $\Lambda^0_{\text{mol}} = 14.2 \text{ km}$   $h^0_{\text{mol}} = 8.0 \text{ km}$

# Simulation Method



- Use symmetry in azimuthal angle
  - Stop tracing photons that can not be detected for a given integration time.

### 3) Effect of changing aerosol density ( $\Lambda^0_{\text{aer}}$ )



- Changing  $\Lambda^0_{\text{aer}}$  changes indirect signal proportionally