Review of Optical Properties

of bulk ice

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What do we know about
scattering (λ_e) and absorption (λ_a) in the ice:

- depth dependence (dust peaks, bubbles)
- wavelength dependence
- Scattering model ($\langle \cos\theta \rangle$)

How do we know this:

- data from in-situ light sources (pulsed, DC)
- independent fit methods (MC timing fits, fluence analysis)
- empirical models, Mie scattering calculations,...

Light scattering in AMANDA

What is "mean cosine theta"?

Use **Mie**[a] **scattering** theory to calculate scattering

- Mie scattering is general case for scattering off particles
- Particle size $\ll \lambda \Rightarrow$ Rayleigh scattering ($\propto r^6$)
- Particle size $\gg \lambda \Rightarrow$ geometric scattering ($\propto r^2$)
- Bubbles: $\begin{cases} \text{AMANDA-A:} & O(r) \gg O(\lambda) \\ \text{below:} & \text{shrink, convert to air hydrate crystals} \end{cases}$
- Dust in AMANDA: $O(r) \sim O(\lambda)$

[...some algebra...]

The Henyey-Greenstein approximation:

$$\frac{d\sigma}{d(\cos\theta)}(\lambda) = \frac{1-g(\lambda)^2}{(1+g(\lambda)^2-2g(\lambda)\cos\theta)^{\frac{3}{2}}}$$

$$g(\lambda) = \langle \cos\theta \rangle$$

scattering is forward peaked (isotropic) when $g > (=)\ 0$

Effective scattering length $\lambda_e = \frac{\lambda_s}{1-g}$

[a] Gustav Mie, Germany, 1868-1957

What is dust?

Four components considered[a]:

- Insoluble mineral grains
- Sea salt crystals – negl. absorption, most scattering
- Acids – negl. absorption
- Soot – highly absorbing, least scattering

Mie calculations give estimate of $g(\lambda)$ (Yudong/Dima)

Scale Antarctic measurements to South Pole for input:

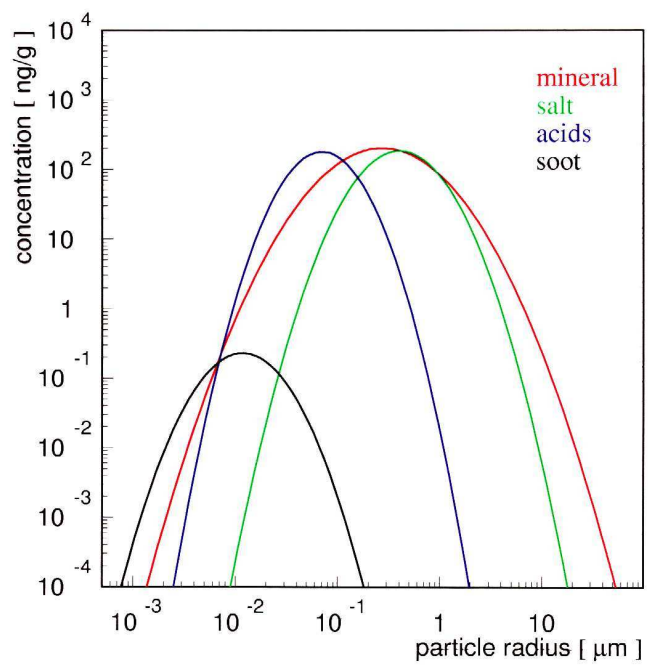
- size distributions (lognormal: modal r, σ)
- densities
- mass concentrations
- refractive indices

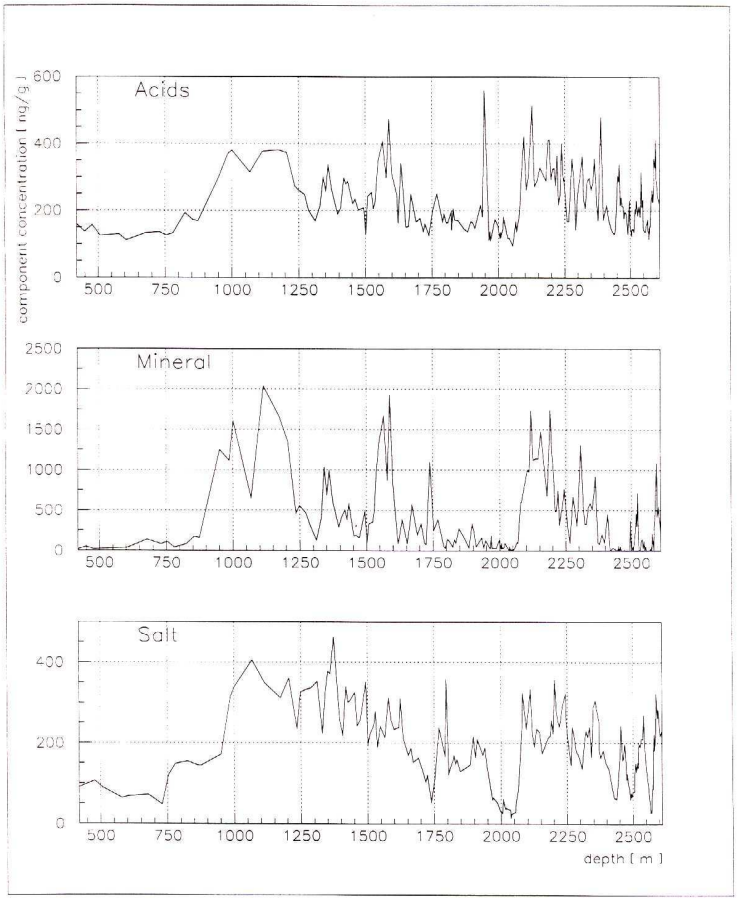
New best estimate of average for AMANDA ice:

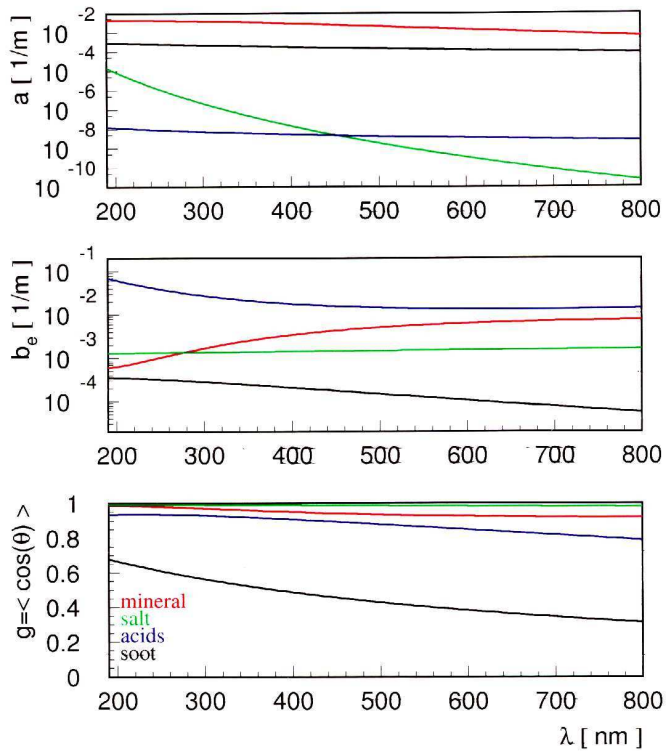
$g(400) = 0.94$

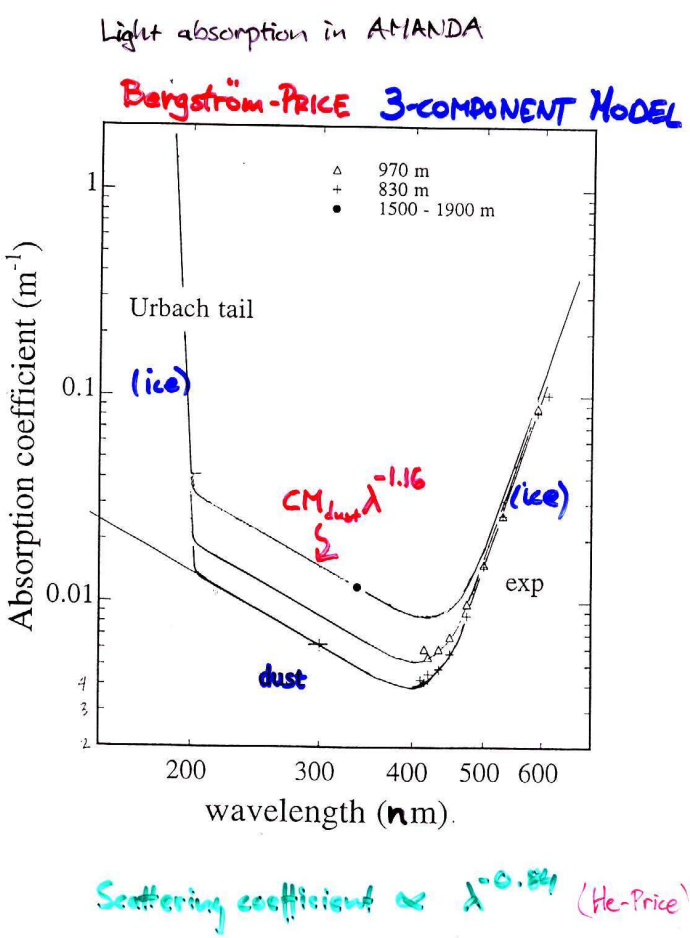
(updated concentrations, corrected summing)

[a] He & Price, *J. Geophys. Res.*, **103** (1998) 17041









Available[a] data

• Interstring/YAG	532 nm	>500 sources	pulsed
• Nitrogen lasers	337 nm	4 sources	pulsed
• Blue LED modules	470 nm	10 sources	pulsed
• UV LED flashers	370 nm	41 sources	pulsed
• Rainbow module	340-540 nm	1 source	DC
• EUV module	313 nm	1 source	DC
• DESY DC sources	350,380,450 nm	3-4 sources	DC
• Muons			

Analysis methods

- Pulsed sources: MC fits to timing $\Rightarrow \lambda_c, \lambda_a$
- DC sources: Fluence analysis $\Rightarrow \lambda_{prop} = \sqrt{\lambda_e \lambda_a / 3}$
- Muons: Hit probability $\Rightarrow \lambda_{att} = f(\lambda_e, \lambda_a)$

Alternative parameters

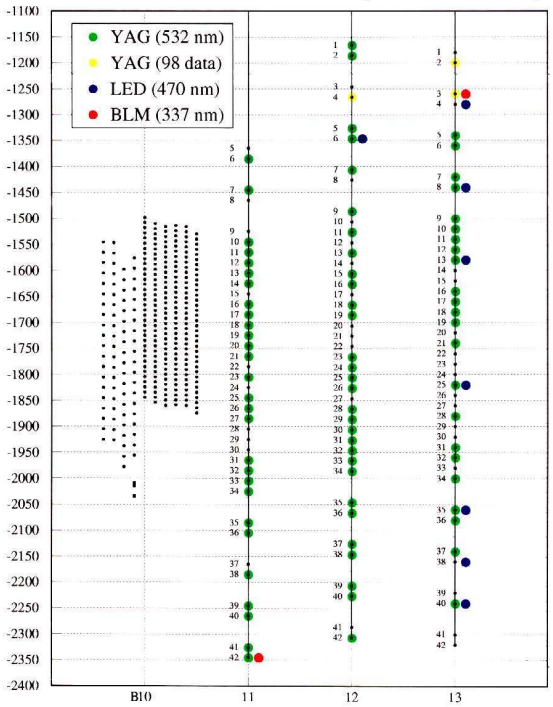
Absorption coefficient: $a = \frac{1}{\lambda_a}$

Scattering coefficient: $b_c = \frac{1}{\lambda_e}$

Propagation coefficient: $c = \frac{1}{\lambda_{prop}} = \sqrt{3ab_e}$

[a] not every source was used

Pulsed sources in AMANDA-II (data taken 1-2/99)



Extracting λ_e and λ_a from pulsed data

0. Record photon arrival times at distance d from source

If ($d \gg \lambda_e$) then

1. Analytical fit of random walk with absorption:
   $u(d,t) = \frac{1}{(4\pi Dt)^{3/2}} e^{-\frac{d^2}{4Dt}} e^{-\frac{c_i t}{\lambda_a}}; \quad D = \frac{c_i \lambda_e}{3}$

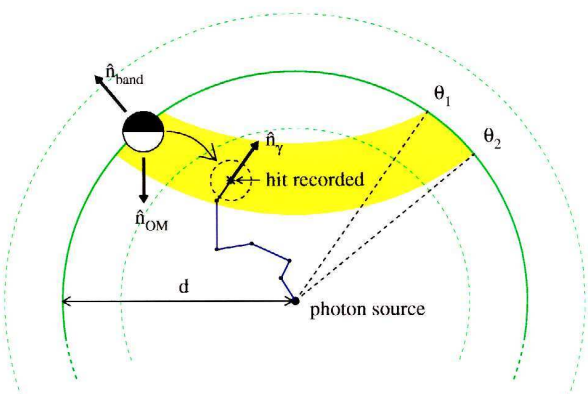
else

1. Produce MC timing distributions $t(d,\theta)$ at grid points in λ_e-λ_a space ($\langle \cos\theta \rangle = 0.8$).
2. Reduce (+calibrate) raw data to timing histograms. Use arbitrary start time, to be fitted ($t_{\rm shift}$).
3. Compare MC/data $\Rightarrow$ make 2-dimensional χ^2 grid.
4. Fit grid with paraboloid:

$$z = \frac{2.3}{1-\rho^2}\left(\frac{(x-\lambda_e)^2}{\sigma_e{}^2} + \frac{(y-\lambda_a)^2}{\sigma_a{}^2} + \frac{2\rho(x-\lambda_e)(y-\lambda_a)}{\sigma_e\sigma_a}\right) + \chi^2_{\rm min}$$

$\Rightarrow$ scattering: $\lambda_e \pm \sigma_e$
$\Rightarrow$ absorption: $\lambda_a \pm \sigma_a$
$\Rightarrow$ correlation: ρ
$\Rightarrow$ fit quality: $\chi^2_{\rm min}$

Photon propagation Monte Carlo



Hit probability at shell/band crossing:

$$P_{\rm hit} = \frac{\epsilon_{\rm PMT}\pi R^2_{\rm OM}\left(\frac{1-\hat{n}_\gamma\cdot\hat{n}_{\rm OM}}{2}\right)}{A_{\rm band}|\hat{n}_\gamma\cdot\hat{n}_{\rm band}|}\cdot e^{-\frac{t c_{\rm ice}}{\lambda_a}}$$

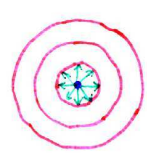
Timing distributions $t(d,\theta)$:

$$N(t) = \sum_{\rm hits[t,t+\delta t]} P_{\rm hit}$$

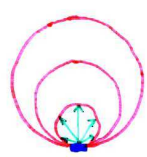
Photon propagation Monte Carlo (cont'd)

Source distribution depends on pulsed light source:

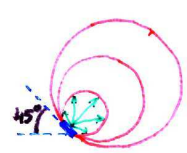
- isotropic for YAG laser (532 nm)

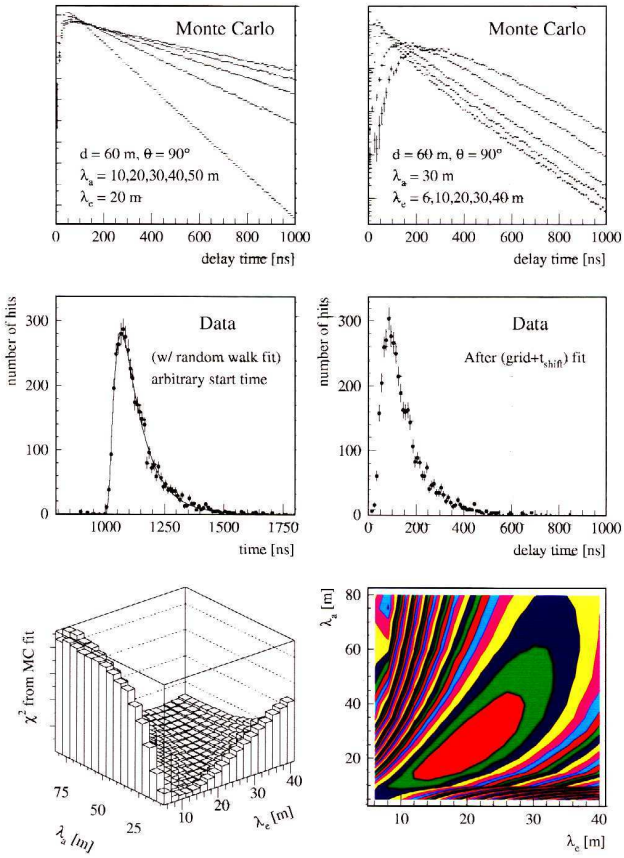


- $\cos\theta$ for nitrogen laser (337 nm) and blue LEDs (470 nm)



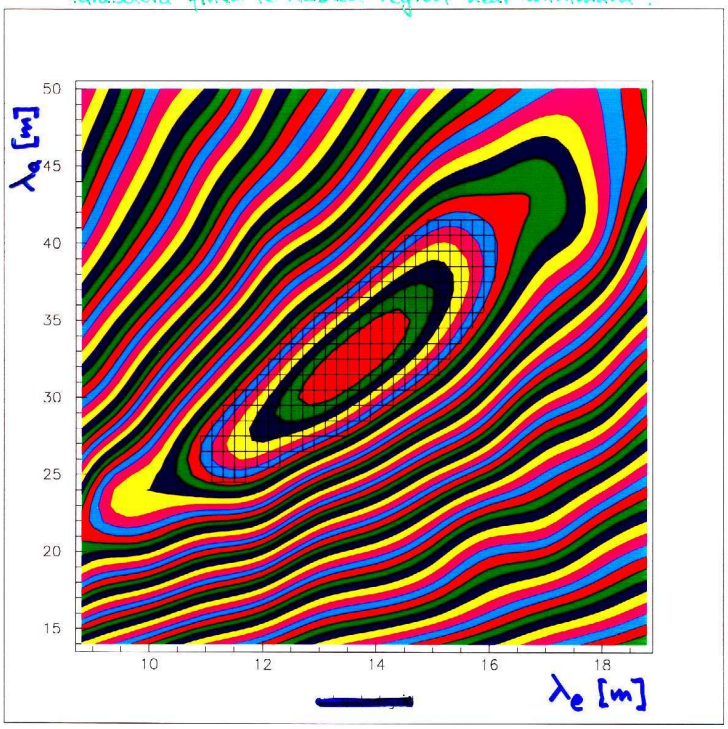
- tilted $\cos\theta$ for UV LED flashers (370 nm)





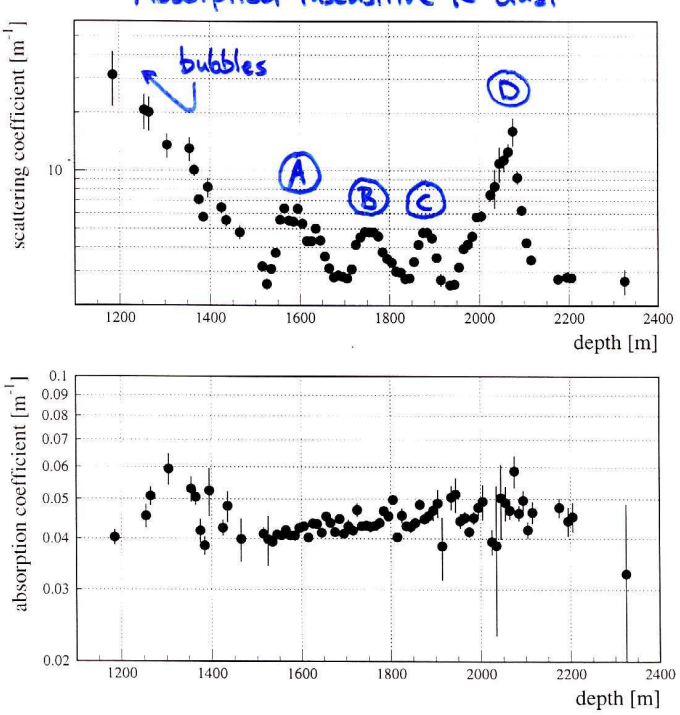
An example of a well-behaved grid

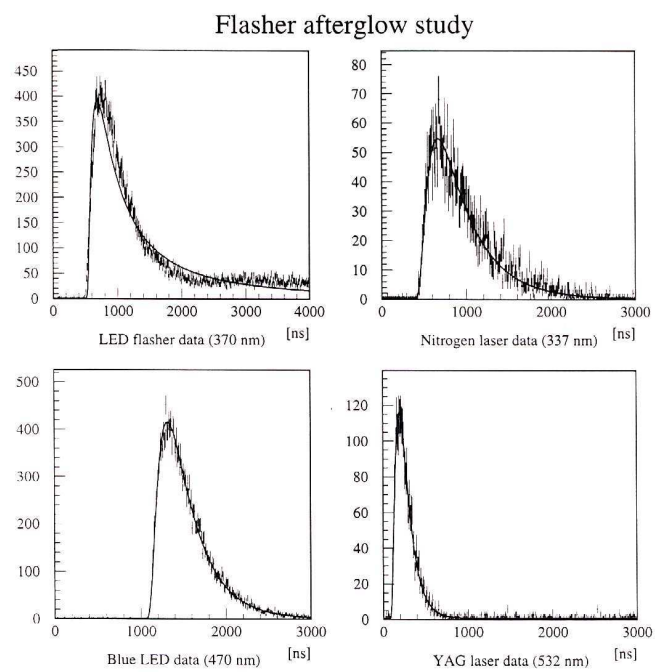
Paraboloid fitted to hashed region near minimum.



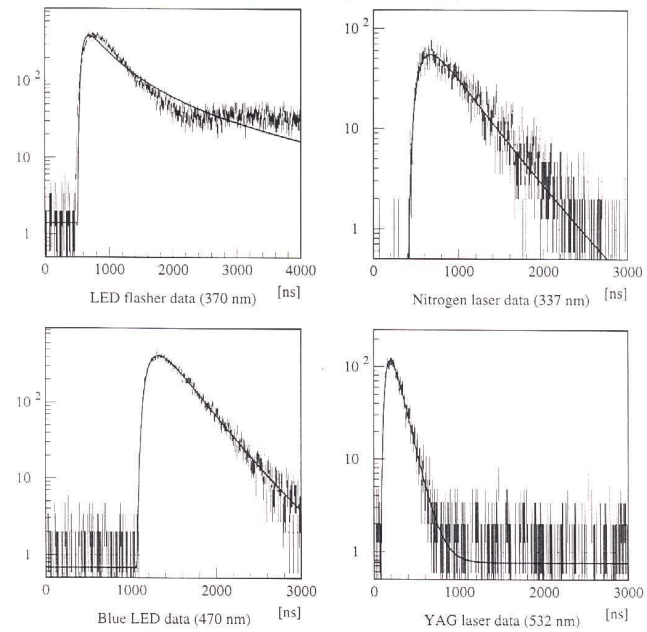
532 nm (YAG Laser)

- Four dust peaks
- Absorption insensitive to dust

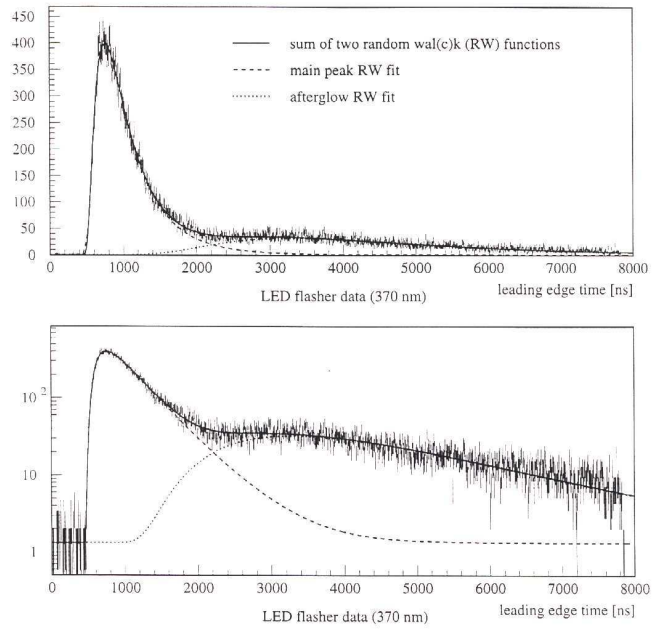




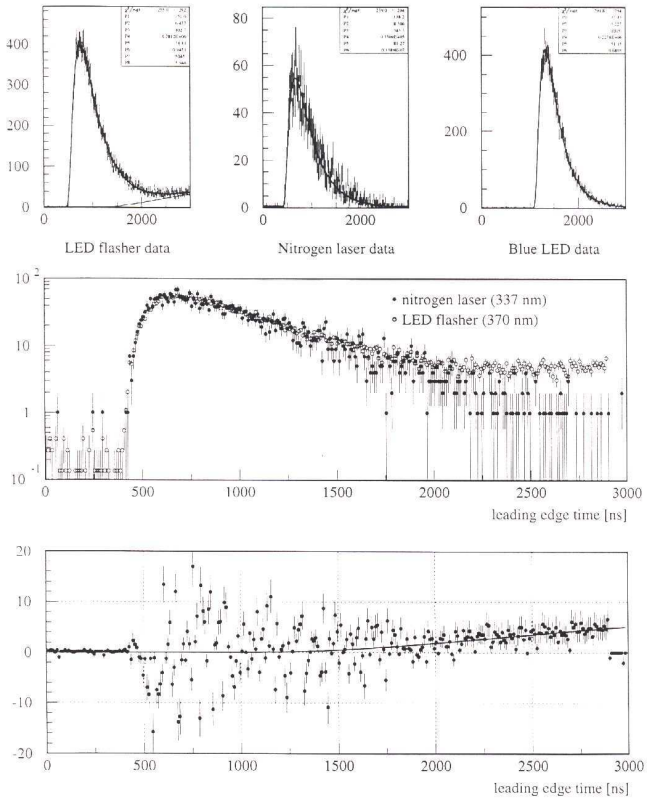
Flasher afterglow study



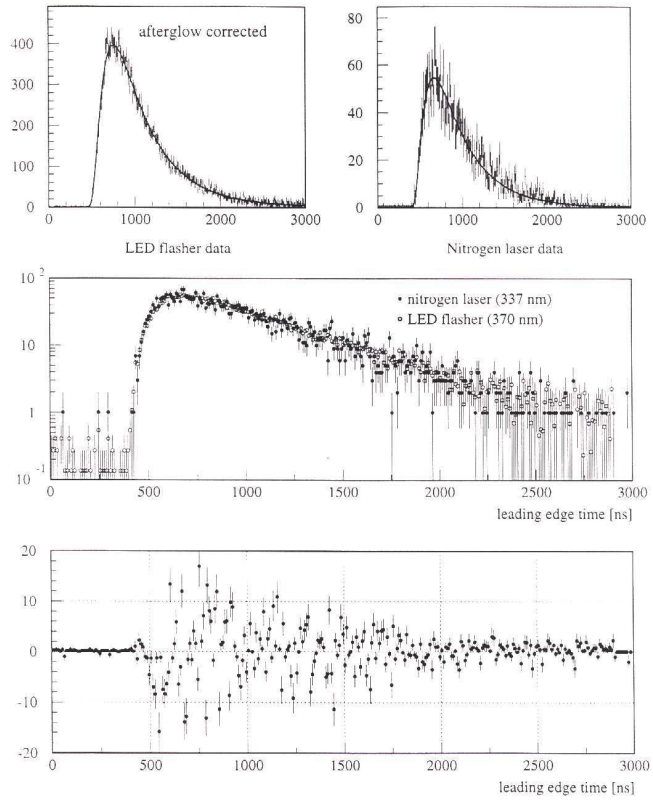
Flasher afterglow study



Flasher afterglow correction

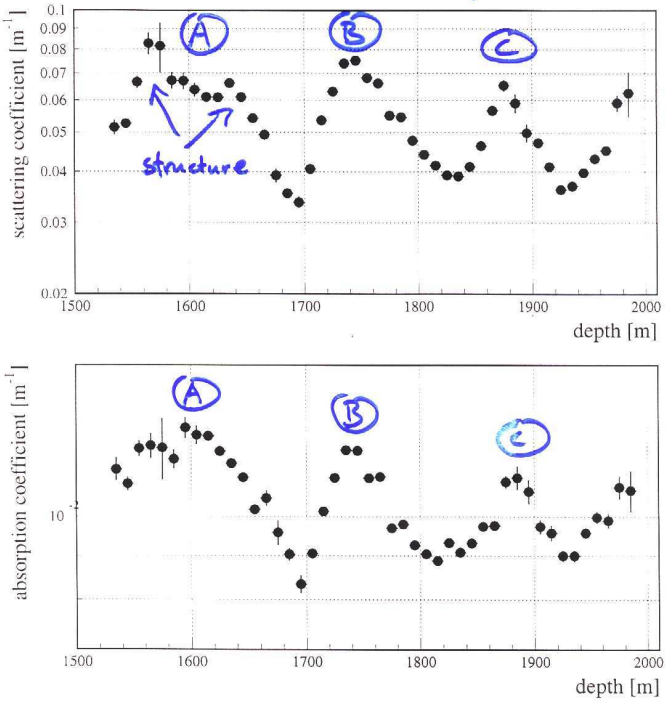


Flasher afterglow correction



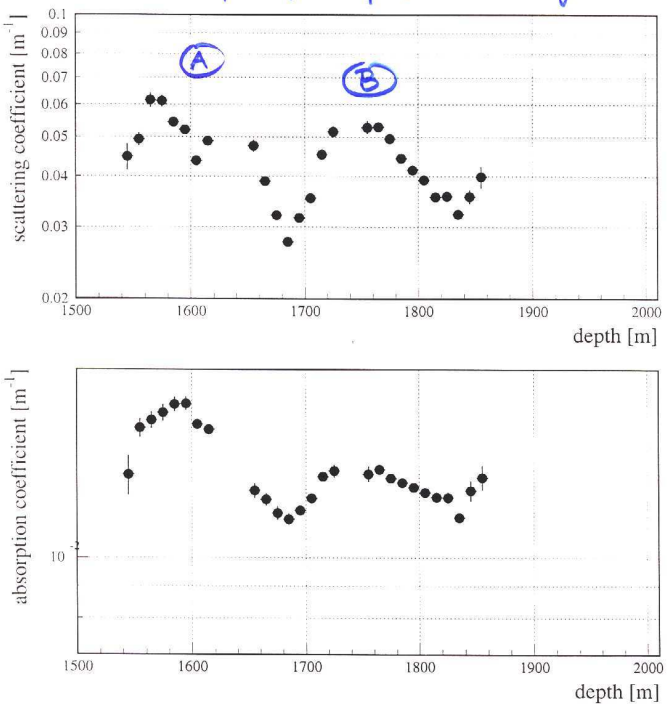
370 nm (DOM LED flashers)

- Dust peaks in scattering and absorption
- Peak (A) structure confirmed



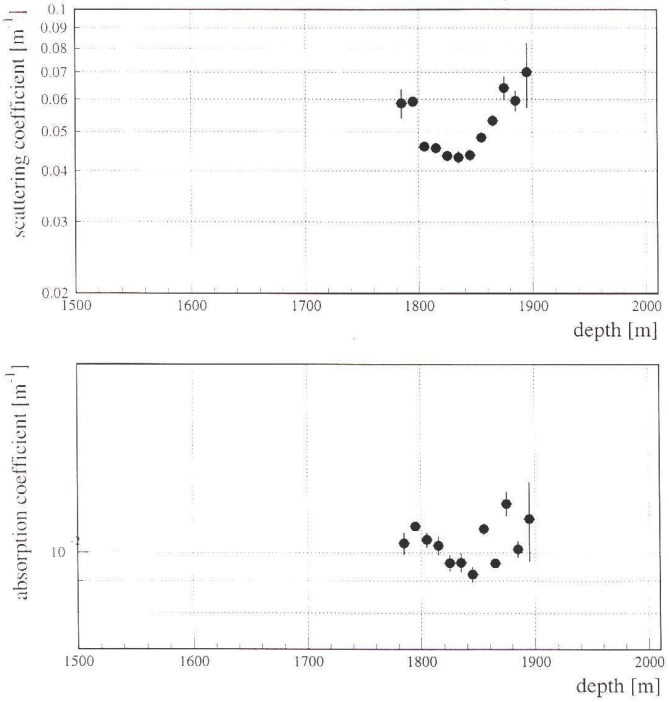
470 nm (blue LED flashers)

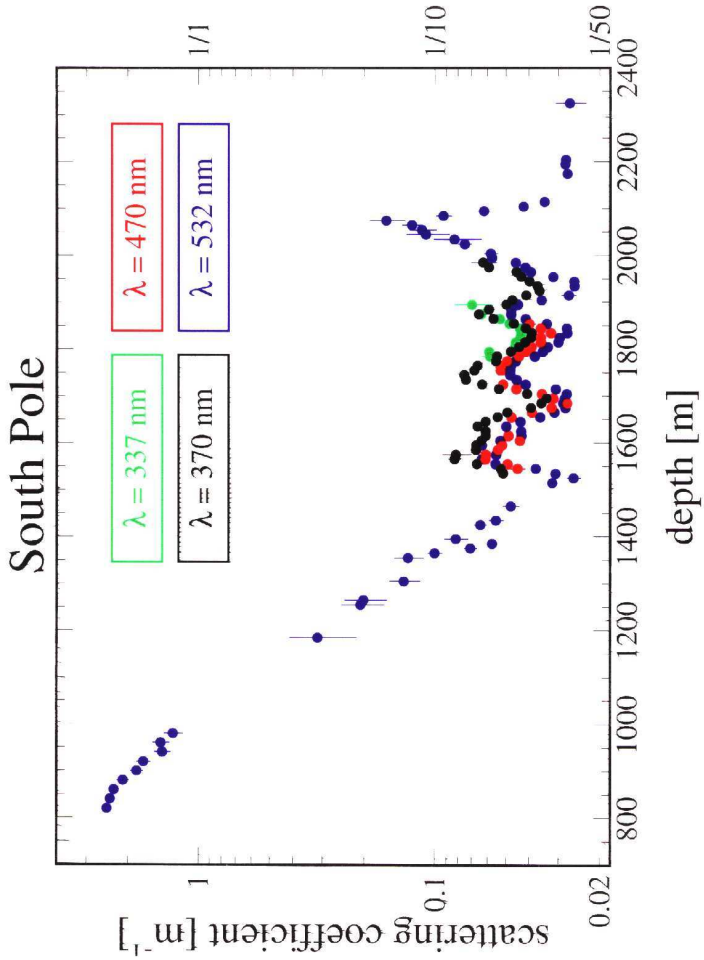
- Same structure in partial profile
- Dust peaks/valleys in scattering & absorption

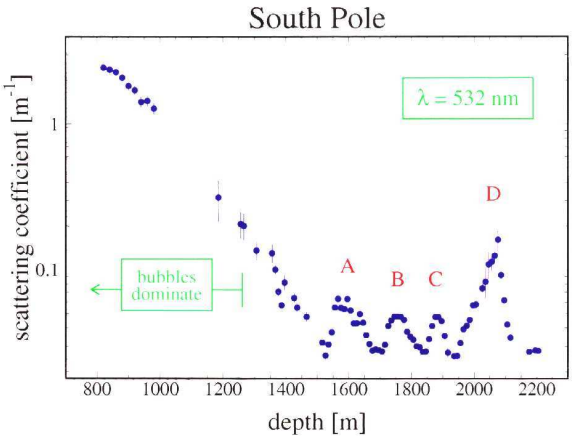


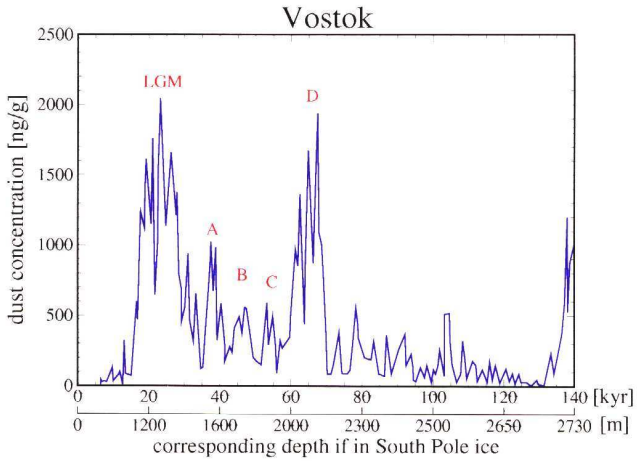
337 nm (nitrogen Laser Modules)

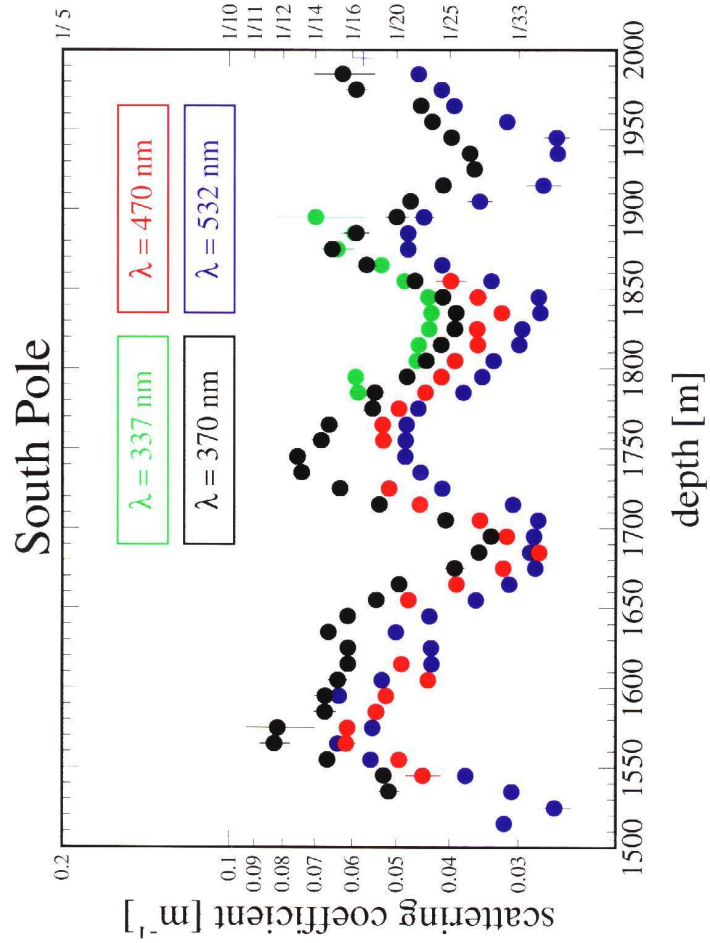
- Both LMs at same depth
- Data covers one dust valley

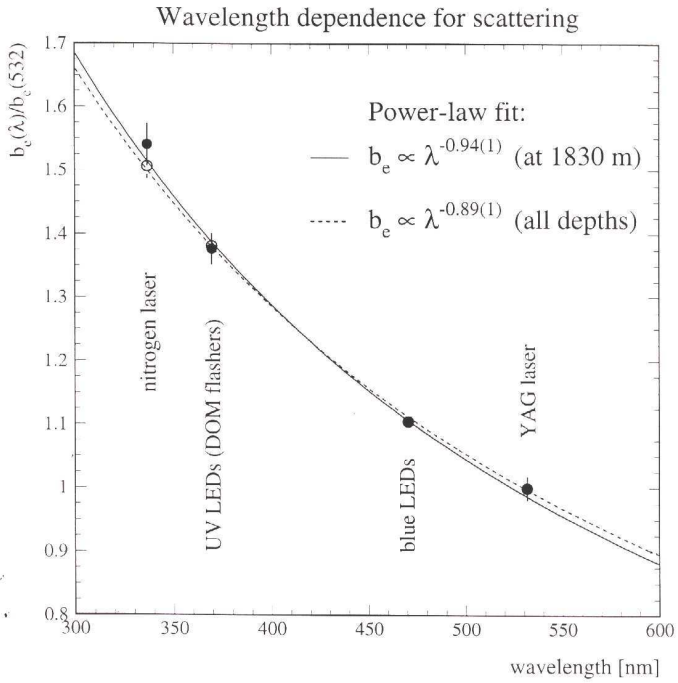


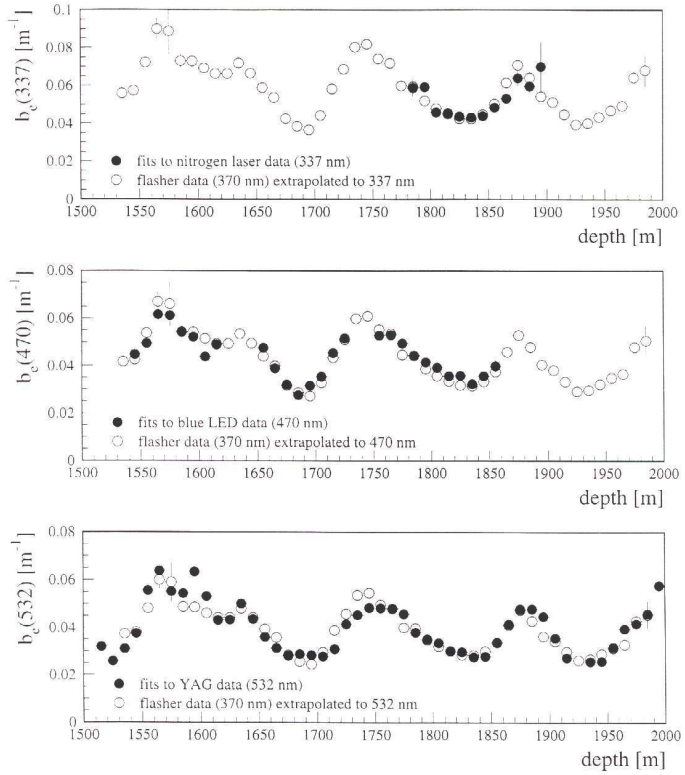


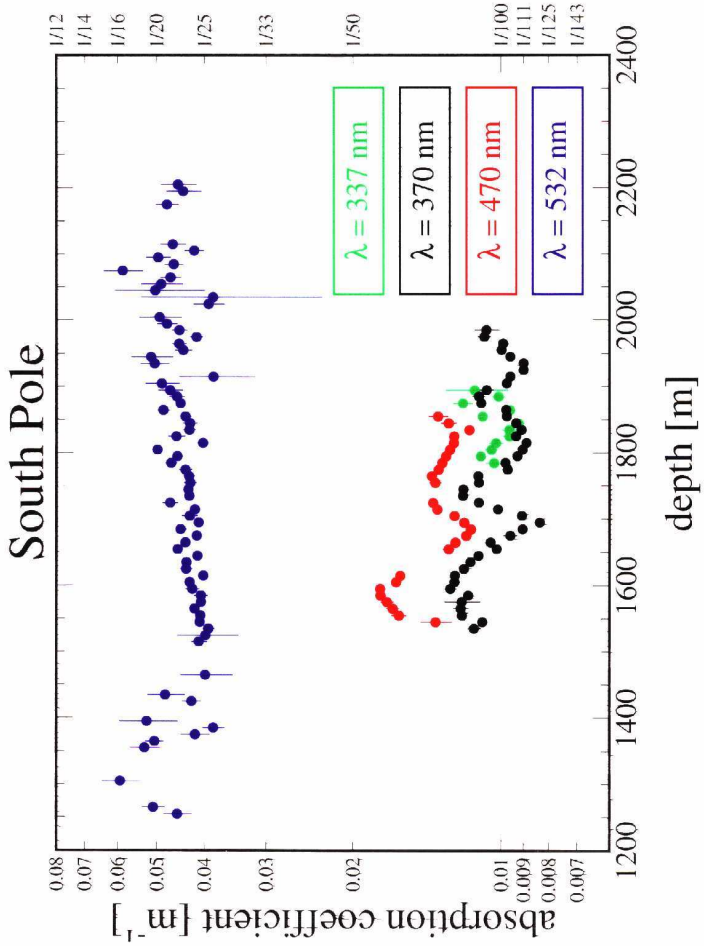

South Pole
λ = 532 nm
bubbles dominate
A
B
C
D
scattering coefficient [m^{-1}]
depth [m]

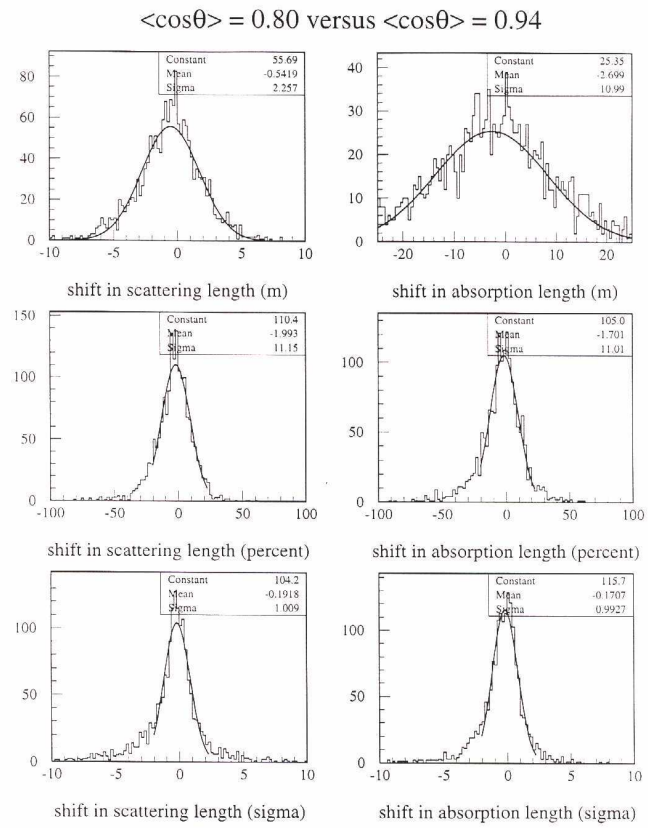

Vostok
LGM
A
B
C
D
dust concentration [ng/g]
[kyr]
corresponding depth if in South Pole ice
[m]

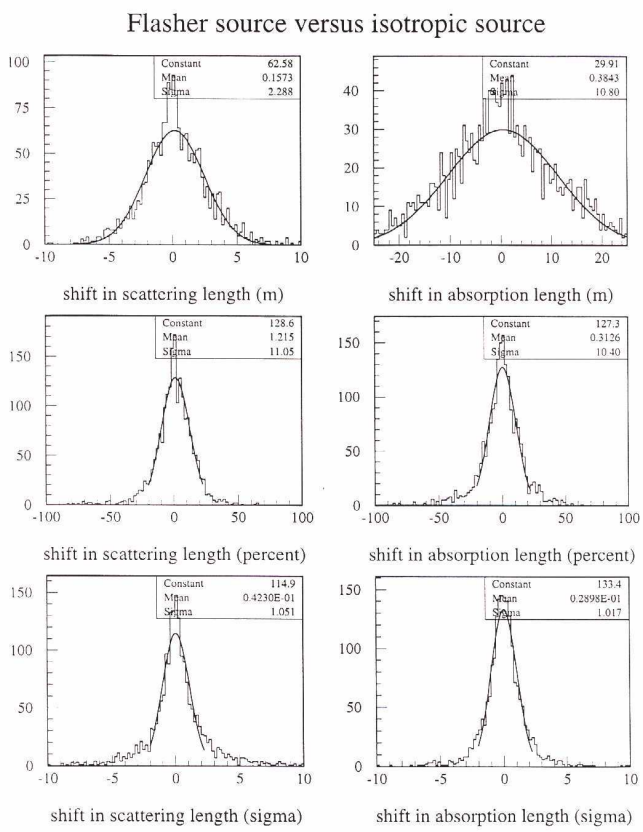

South Pole
λ = 470 nm
λ = 532 nm
λ = 337 nm
λ = 370 nm
scattering coefficient [m^{-1}]
depth [m]

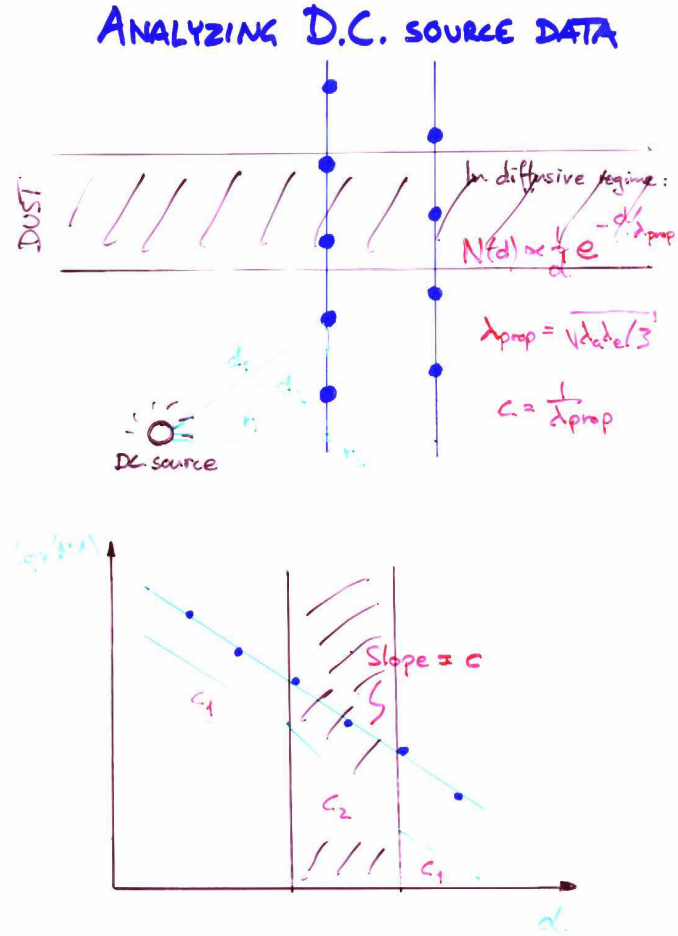

Wavelength dependence for scattering
Power-law fit:
$b_e \propto \lambda^{-0.94(1)}$ (at 1830 m)
$b_e \propto \lambda^{-0.89(1)}$ (all depths)
nitrogen laser
UV LEDs (DOM flashers)
blue LEDs
YAG laser
$b_e(\lambda)/b_e(532)$
wavelength [nm]


$b_e(337)$ [m^{-1}]
fits to nitrogen laser data (337 nm)
flasher data (370 nm) extrapolated to 337 nm
$b_e(470)$ [m^{-1}]
fits to blue LED data (470 nm)
flasher data (370 nm) extrapolated to 470 nm
$b_e(532)$ [m^{-1}]
fits to YAG data (532 nm)
flasher data (370 nm) extrapolated to 532 nm
depth [m]

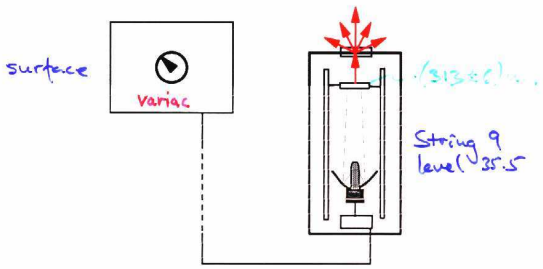

South Pole
λ = 337 nm
λ = 370 nm
λ = 470 nm
λ = 532 nm
depth [m]
absorption coefficient [m⁻¹]

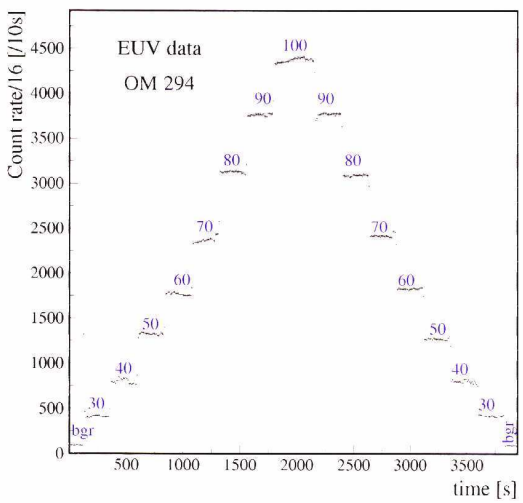

<cosθ> = 0.80 versus <cosθ> = 0.94
shift in scattering length (m)
shift in absorption length (m)
shift in scattering length (percent)
shift in absorption length (percent)
shift in scattering length (sigma)
shift in absorption length (sigma)


Flasher source versus isotropic source
shift in scattering length (m)
shift in absorption length (m)
shift in scattering length (percent)
shift in absorption length (percent)
shift in scattering length (sigma)
shift in absorption length (sigma)

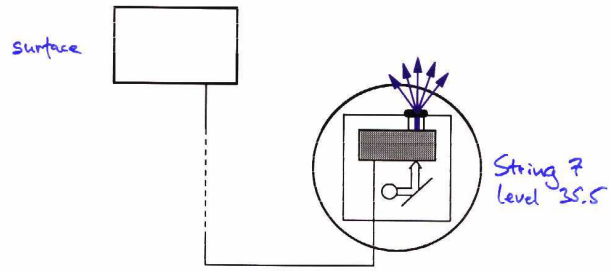

ANALYZING D.C. SOURCE DATA
DUST
In diffusive regime:
DC source
Slope = c

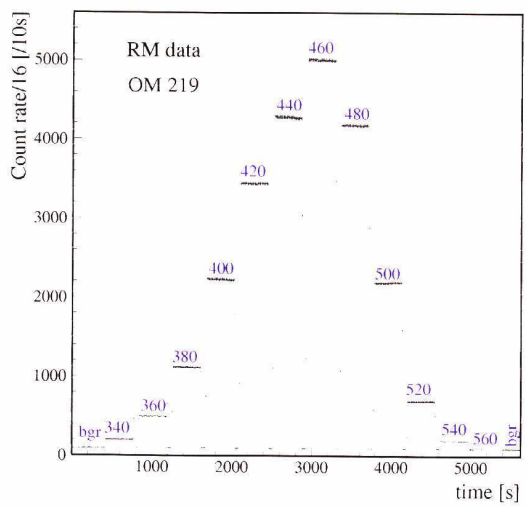
The Extreme UltraViolet (EUV) Module

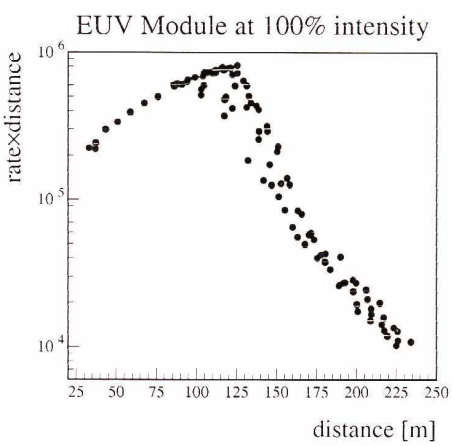


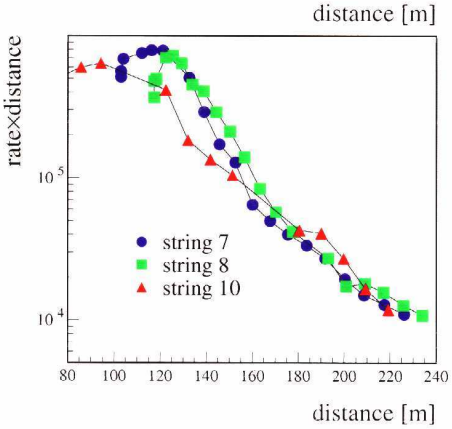


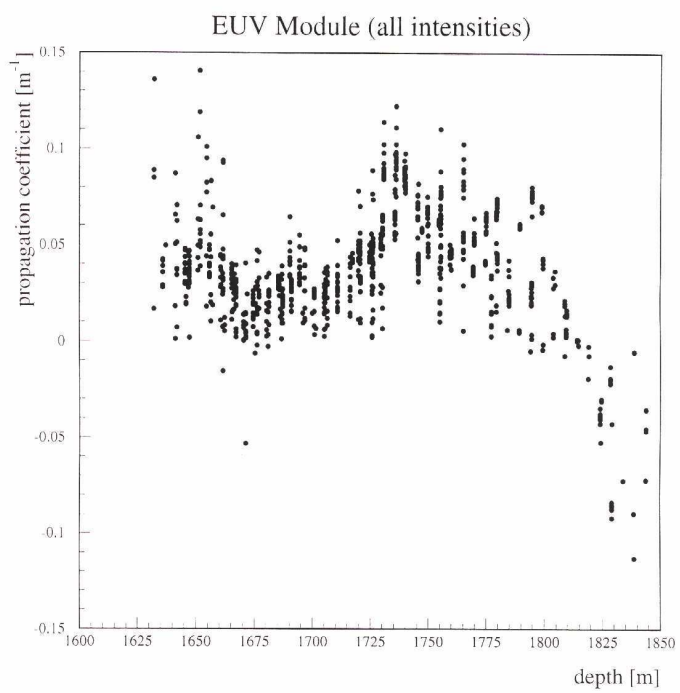
THE RAINBOW MODULE

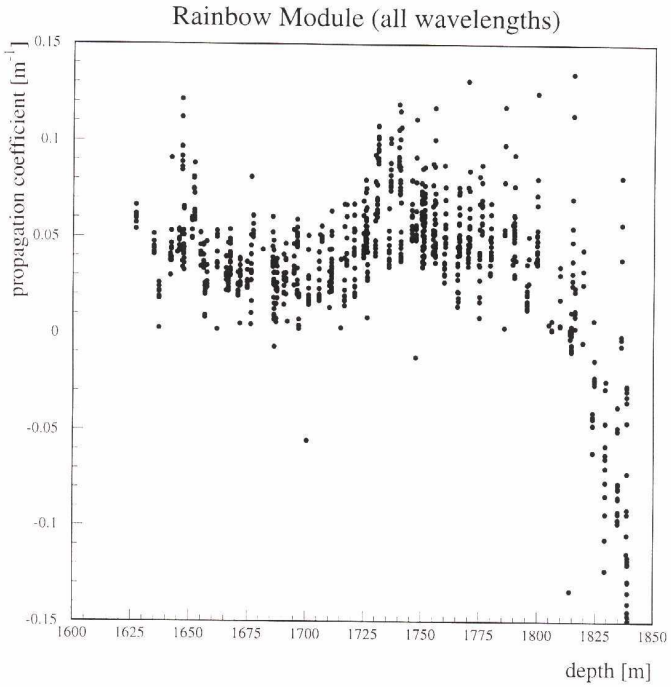


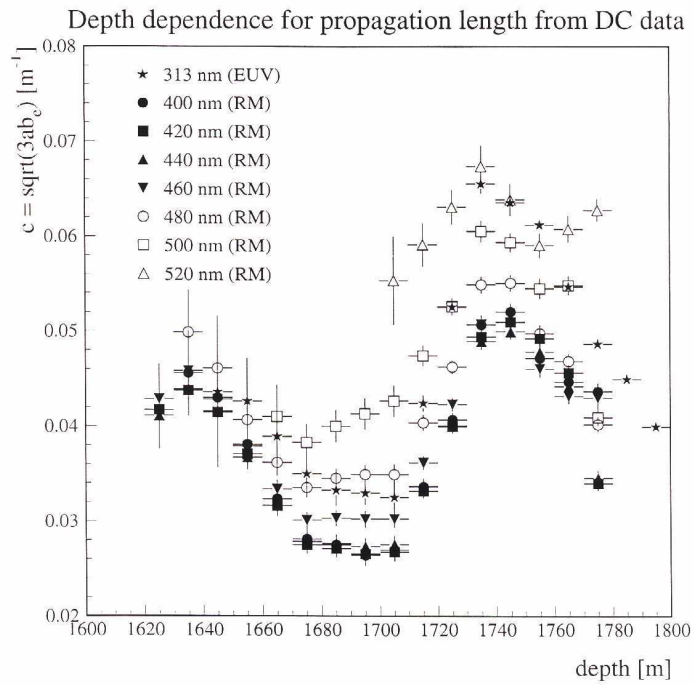


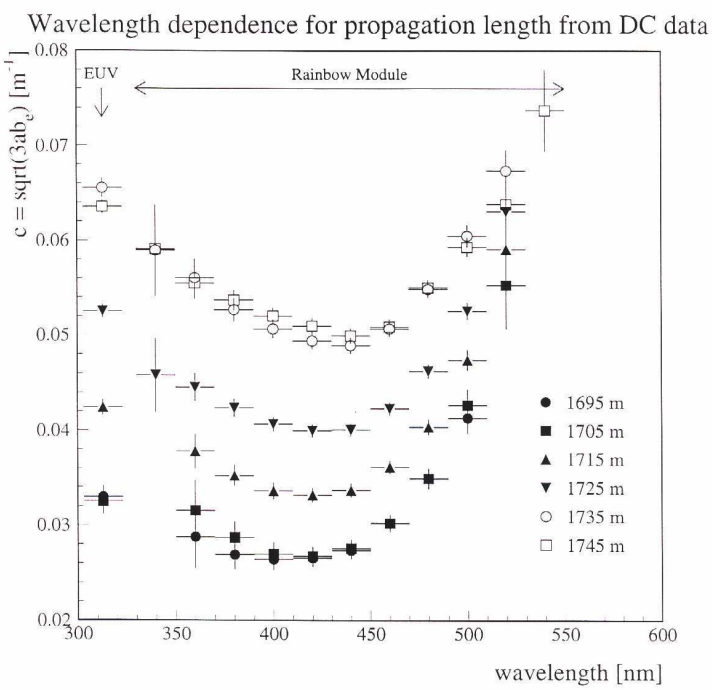


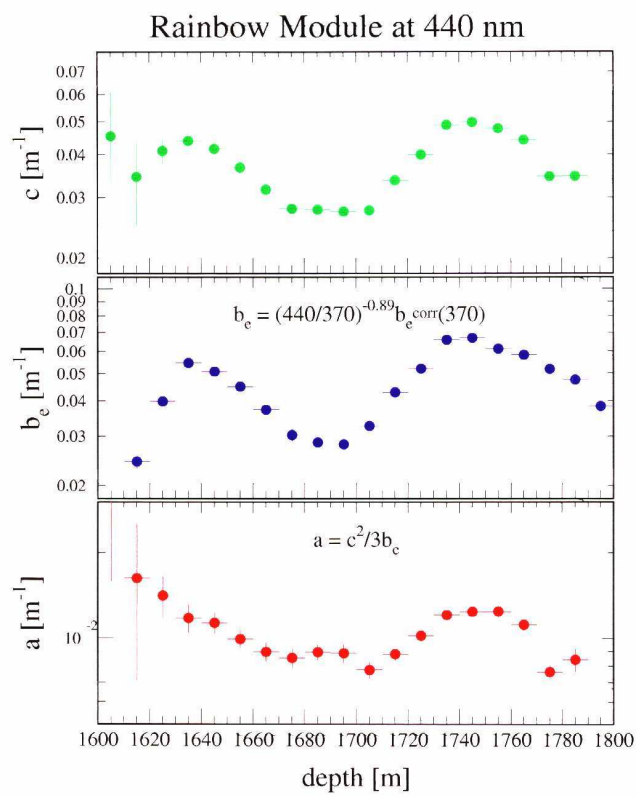


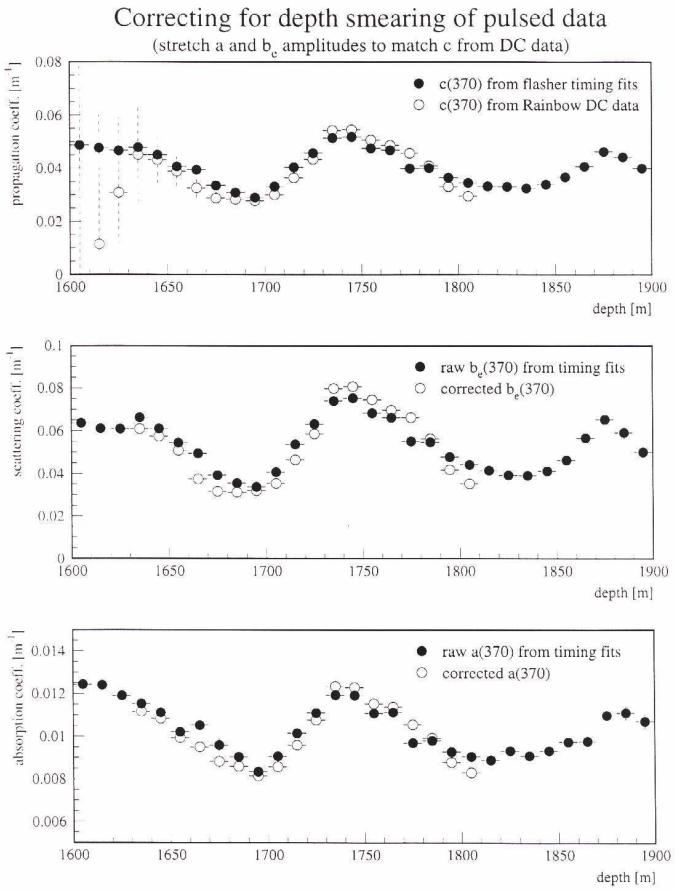


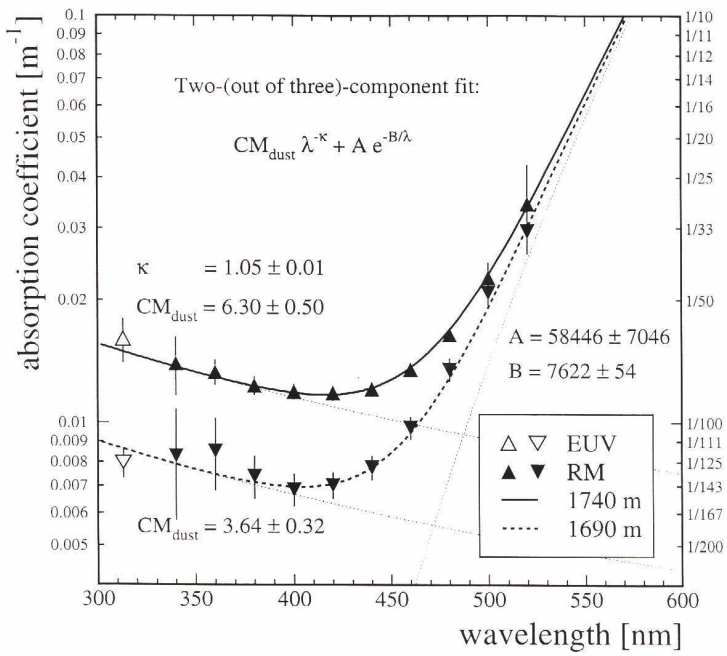

Rainbow Module (all wavelengths)
propagation coefficient [m^{-1}]
depth [m]

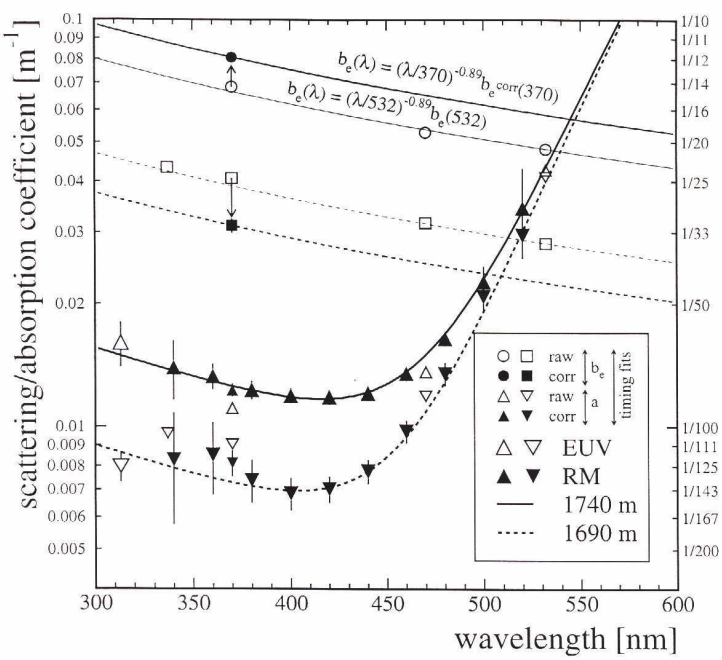

Depth dependence for propagation length from DC data
c = sqrt(3ab$_e$) [m^{-1}]
313 nm (EUV)
400 nm (RM)
420 nm (RM)
440 nm (RM)
460 nm (RM)
480 nm (RM)
500 nm (RM)
520 nm (RM)
depth [m]

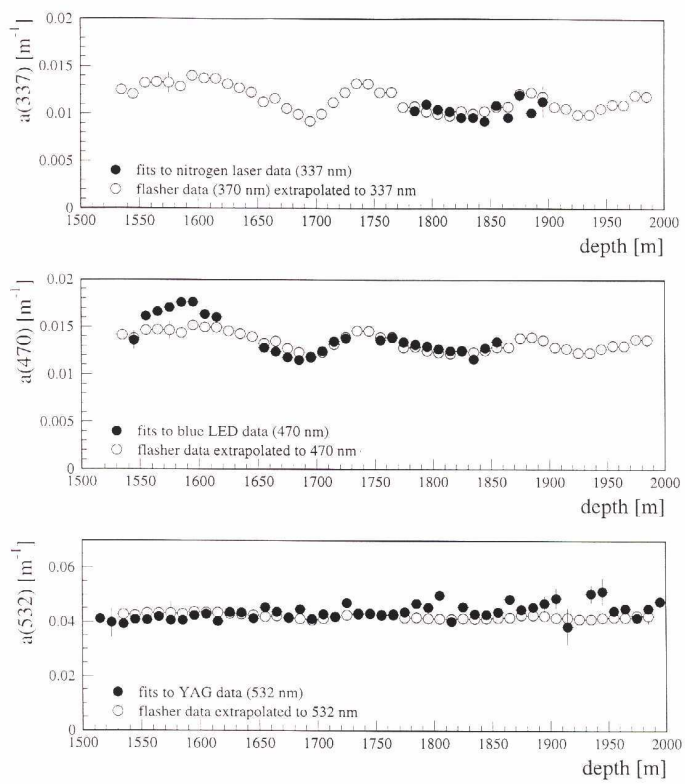

Wavelength dependence for propagation length from DC data
c = sqrt(3ab$_e$) [m^{-1}]
EUV
Rainbow Module
1695 m
1705 m
1715 m
1725 m
1735 m
1745 m
wavelength [nm]

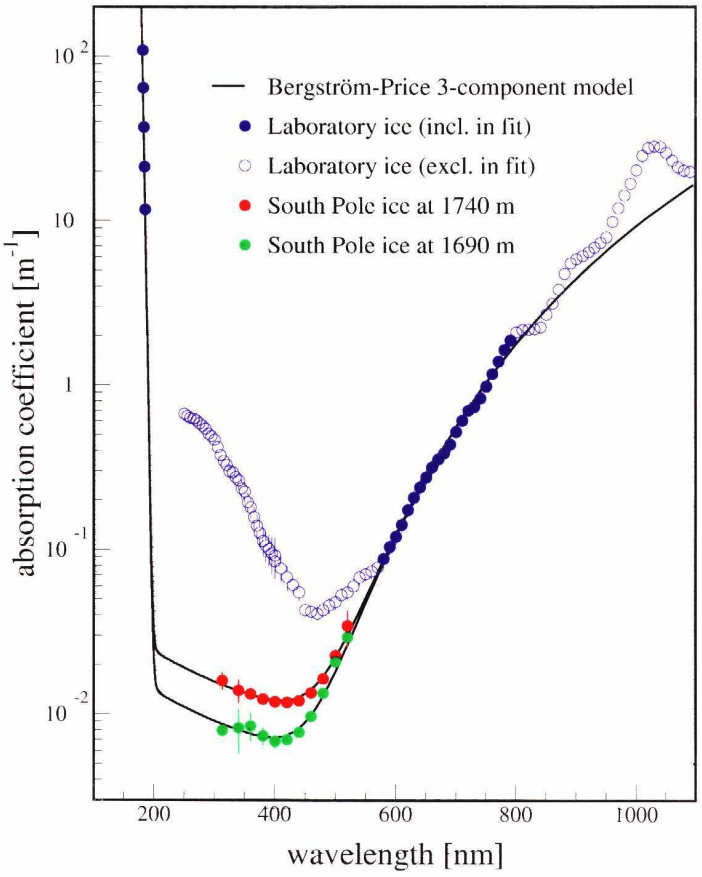

Rainbow Module at 440 nm
c [m^{-1}]
b$_e$ = (440/370)$^{-0.89}$b$_e$^{corr}(370)
b$_e$ [m^{-1}]
a = c^2/3b$_e$
a [m^{-1}]
depth [m]


Correcting for depth smearing of pulsed data
(stretch a and b_e amplitudes to match c from DC data)
propagation coeff. [m^{-1}]
c(370) from flasher timing fits
c(370) from Rainbow DC data
depth [m]
scattering coeff. [m^{-1}]
raw b_e(370) from timing fits
corrected b_e(370)
depth [m]
absorption coeff. [m^{-1}]
raw a(370) from timing fits
corrected a(370)
depth [m]


Two-(out of three)-component fit:
$CM_{dust}\,\lambda^{-\kappa} + A\,e^{-B/\lambda}$
$\kappa = 1.05 \pm 0.01$
$CM_{dust} = 6.30 \pm 0.50$
$A = 58446 \pm 7046$
$B = 7622 \pm 54$
$CM_{dust} = 3.64 \pm 0.32$
EUV
RM
1740 m
1690 m
absorption coefficient [m^{-1}]
wavelength [nm]


$b_e(\lambda) = (\lambda/370)^{-0.89} b_e^{corr}(370)$
$b_e(\lambda) = (\lambda/532)^{-0.89} b_e(532)$
raw
corr
raw
corr
b_e
a
timing fits
EUV
RM
1740 m
1690 m
scattering/absorption coefficient [m^{-1}]
wavelength [nm]


a(337) [m^{-1}]
fits to nitrogen laser data (337 nm)
flasher data (370 nm) extrapolated to 337 nm
depth [m]
a(470) [m^{-1}]
fits to blue LED data (470 nm)
flasher data extrapolated to 470 nm
depth [m]
a(532) [m^{-1}]
fits to YAG data (532 nm)
flasher data extrapolated to 532 nm
depth [m]


Bergström-Price 3-component model
Laboratory ice (incl. in fit)
Laboratory ice (excl. in fit)
South Pole ice at 1740 m
South Pole ice at 1690 m
absorption coefficient [m^{-1}]
wavelength [nm]
10^2
10
1
10^{-1}
10^{-2}
200
400
600
800
1000