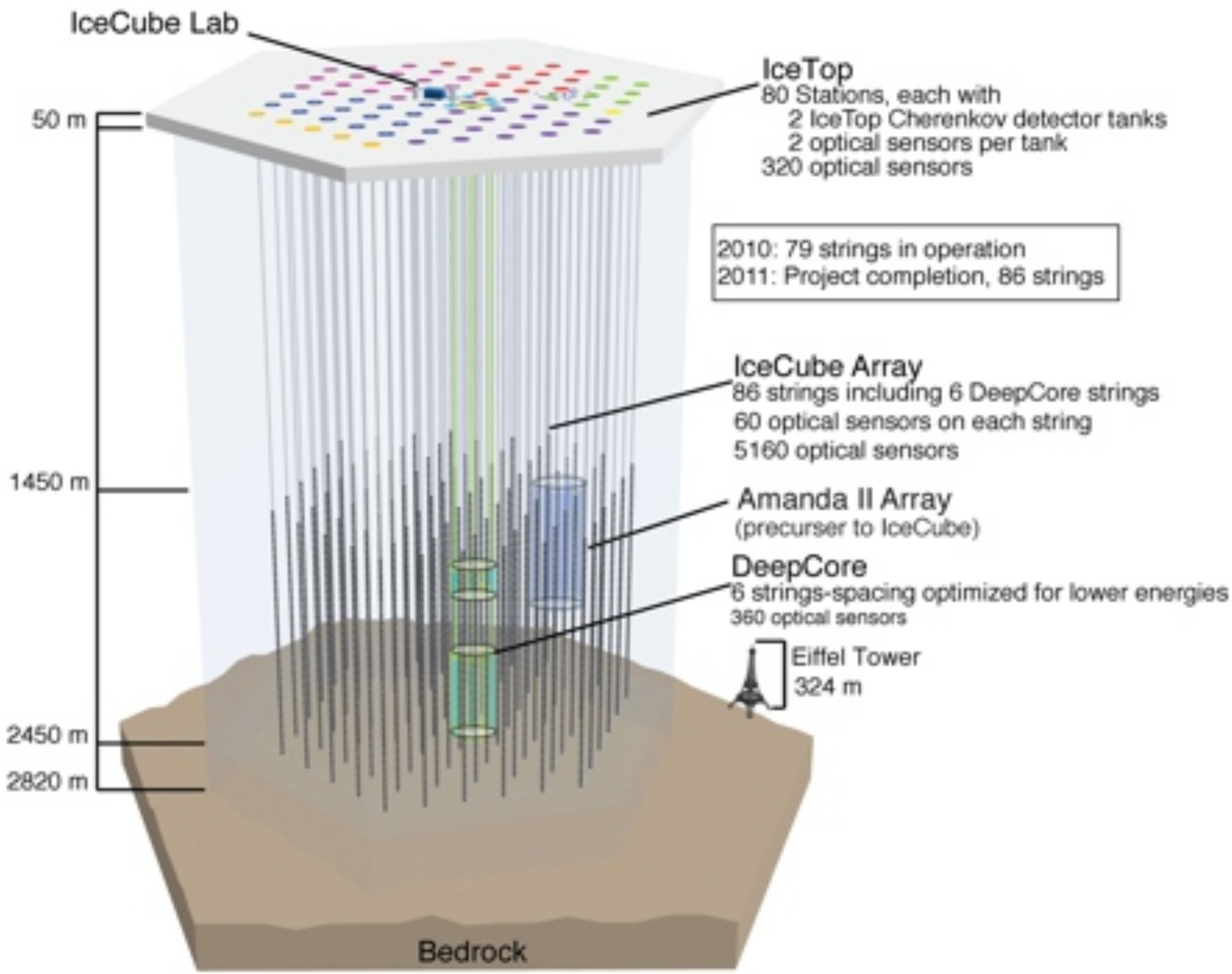
Modeling the South Pole Ice

Dmitry Chirkin, UW-Madison



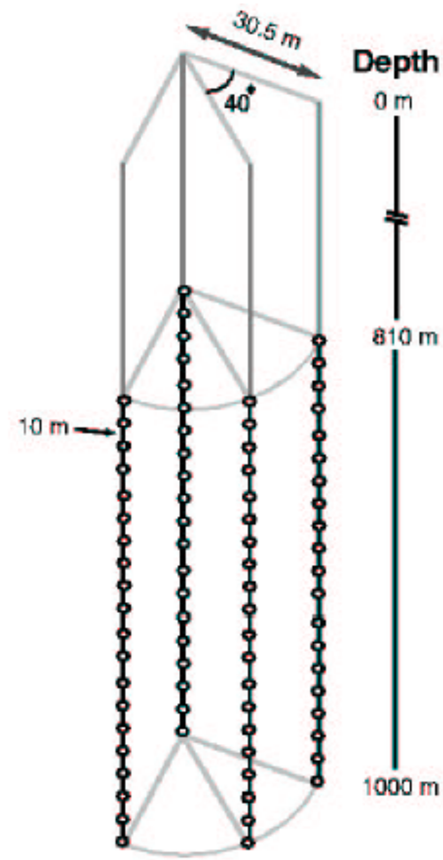


IceCube Lab
IceTop
80 Stations, each with
2 IceTop Cherenkov detector tanks
2 optical sensors per tank
320 optical sensors
2010: 79 strings in operation
2011: Project completion, 86 strings
IceCube Array
86 strings including 6 DeepCore strings
60 optical sensors on each string
5160 optical sensors
Amanda II Array
(precurser to IceCube)
DeepCore
6 strings-spacing optimized for lower energies
360 optical sensors
Eiffel Tower
324 m
50 m
1450 m
2450 m
2820 m
Bedrock

AMANDA-A: scattering on air bubbles!

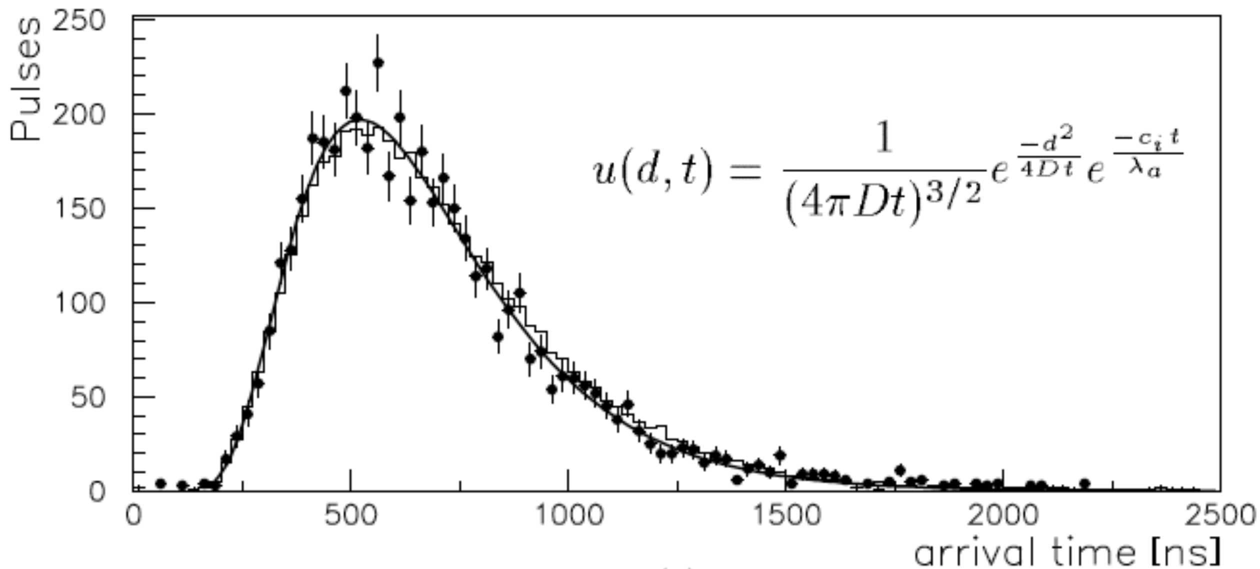
Optical Properties of the South Pole Ice at Depths Between 0.8 and 1 km

P. Askebjer*, S.W. Barwick†, L. Bergström*, A. Bouchta*, S. Carius‡, A. Coulthard§, K. Engel§, B. Erlandsson*, A. Goobar*, L. Gray§, A. Hallgren‡, F. Halzen§, P.O. Hulth*, J. Jacobsen§, S. Johansson*¶, V. Kandhadai§, I. Liubarsky§, D. Lowder||, T. Miller||**, P.C. Mock†, R. Morse§, R. Porrata†, P.B. Price||, A. Richards||, H. Rubinstein‡, E. Schneider†, Q. Sun*, S. Tilav§, C. Walck* & G. Yodh†

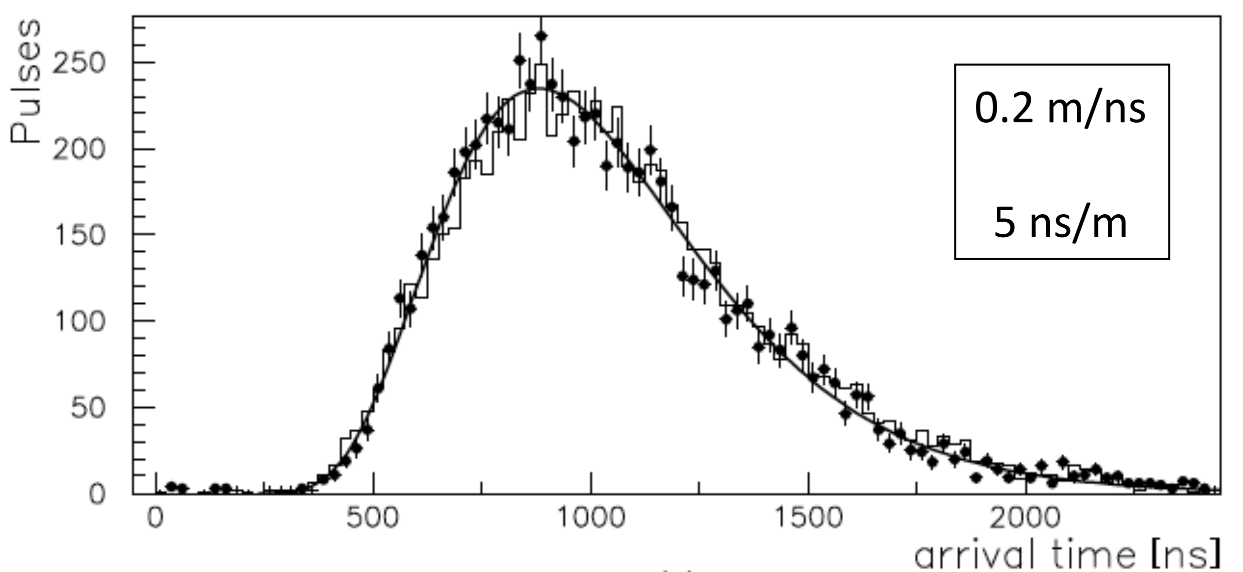
The optical properties of the ice at the geographical South Pole have been investigated at depths between 0.8 and 1 kilometers. The absorption and scattering lengths of visible light (~515 nm) have been measured *in situ* using the laser calibration setup of the AMANDA neutrino detector. The ice is intrinsically extremely transparent. The measured absorption length is 59 ± 3 meters, comparable with the quality of the ultra-pure water used in the IMB and Kamiokande proton-decay and neutrino experiments and more than two times longer than the best value reported for laboratory ice. Due to a residual density of air bubbles at these depths, the trajectories of photons in the medium are randomized. Assuming bubbles are smooth and spherical, the average distance between collisions at 1 km depth is about 25 cm. The measured inverse scattering length on bubbles decreases linearly with increasing depth in the volume of ice investigated.



Diffusive approximation

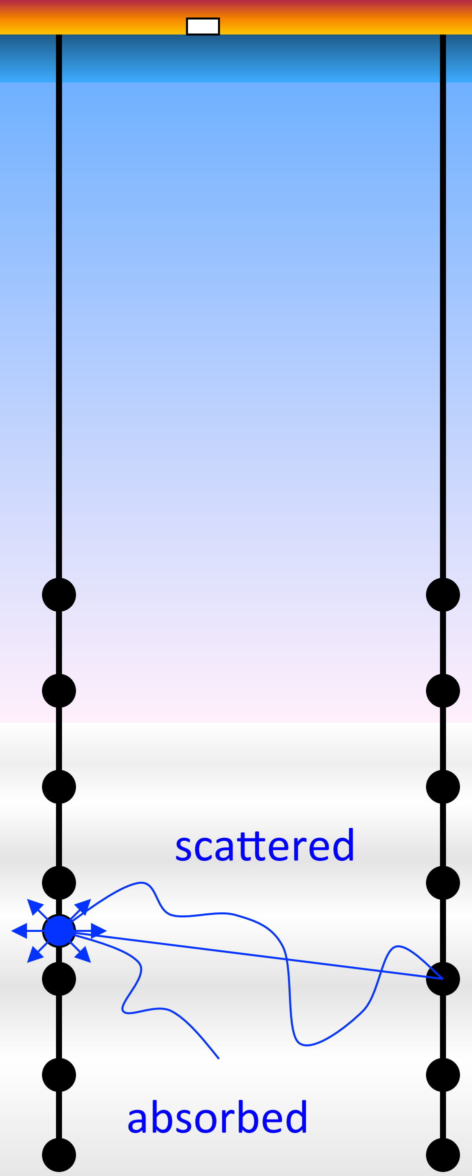


(a)

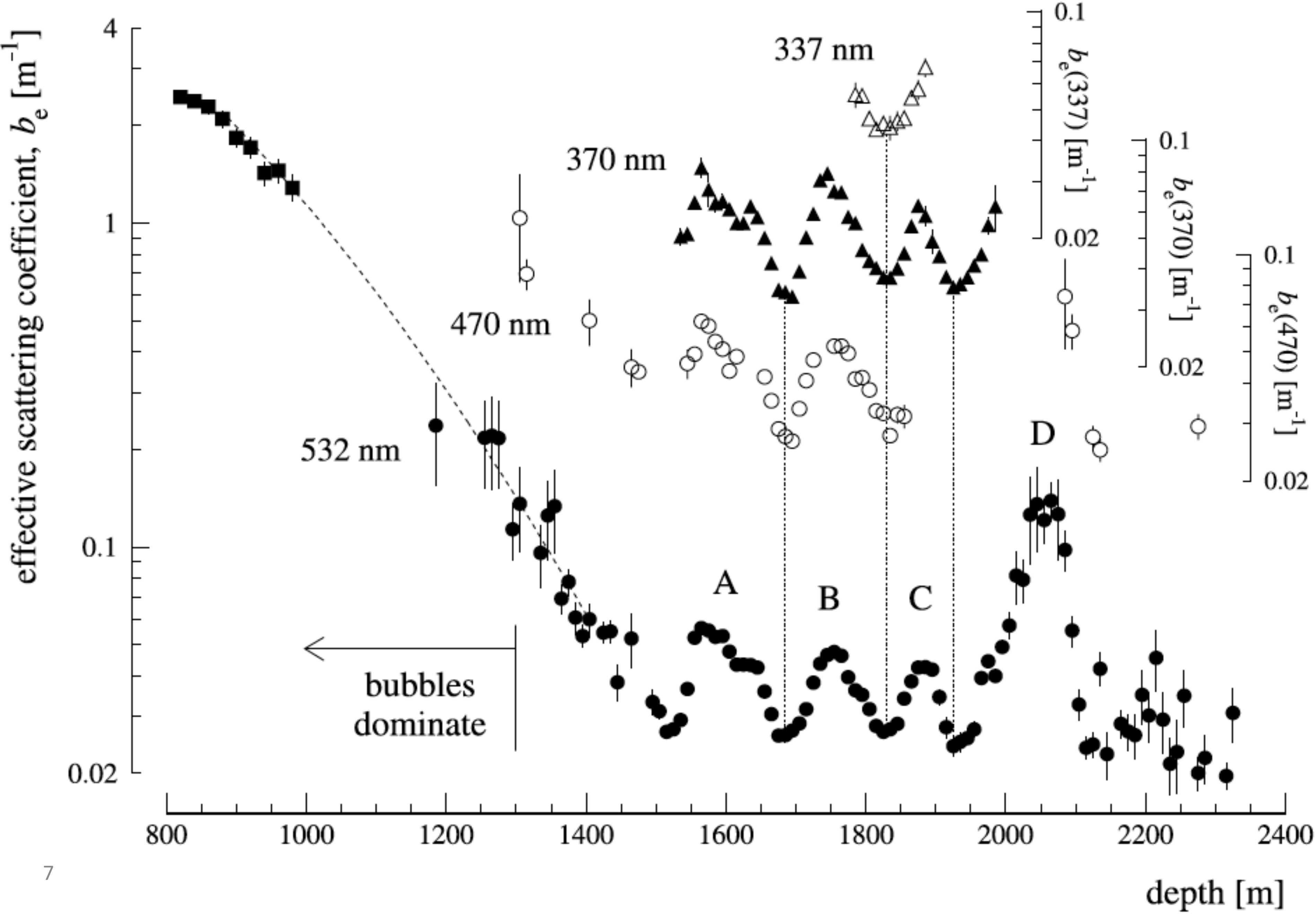


(b)

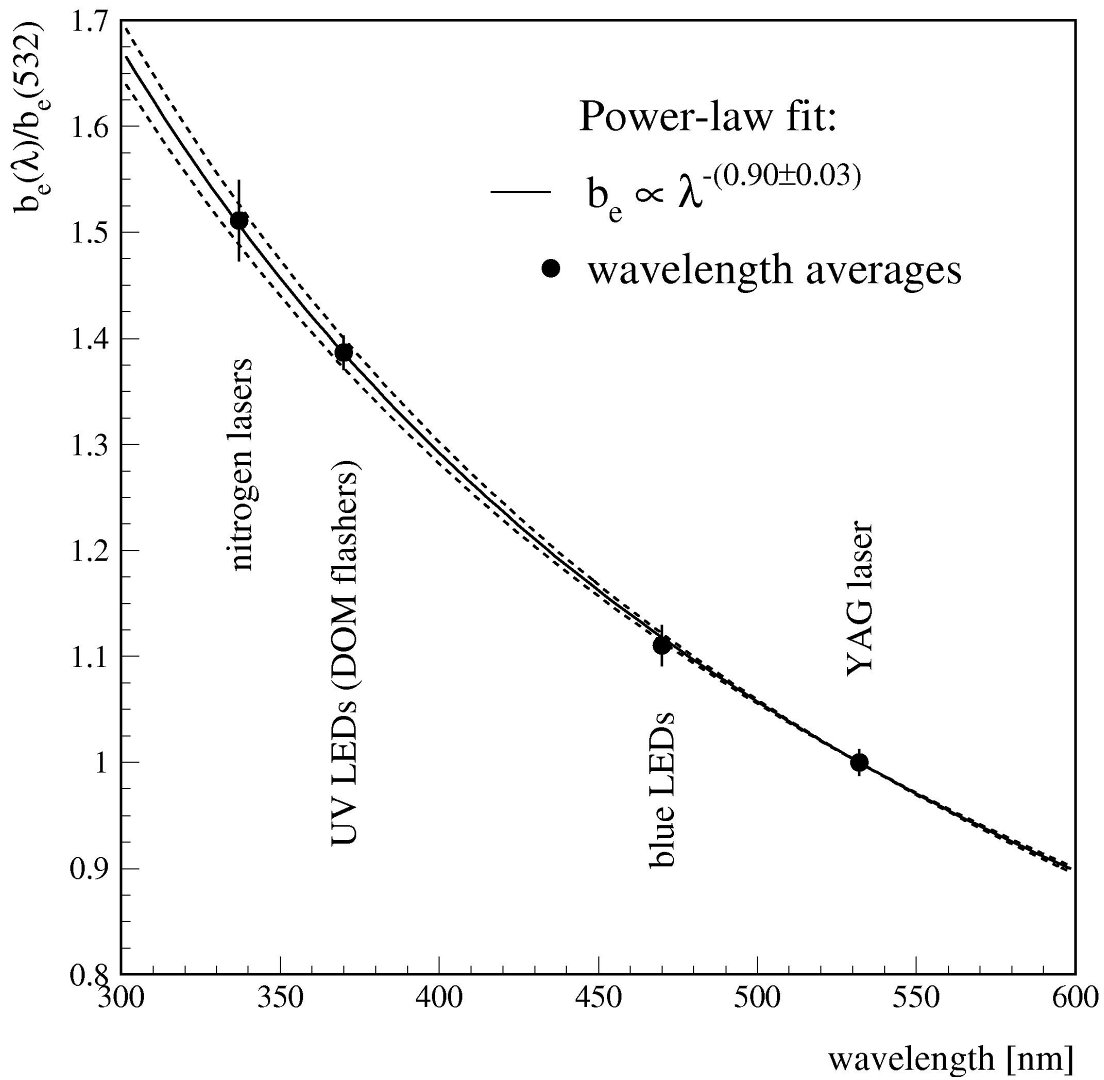
Measuring Scattering & Absorption



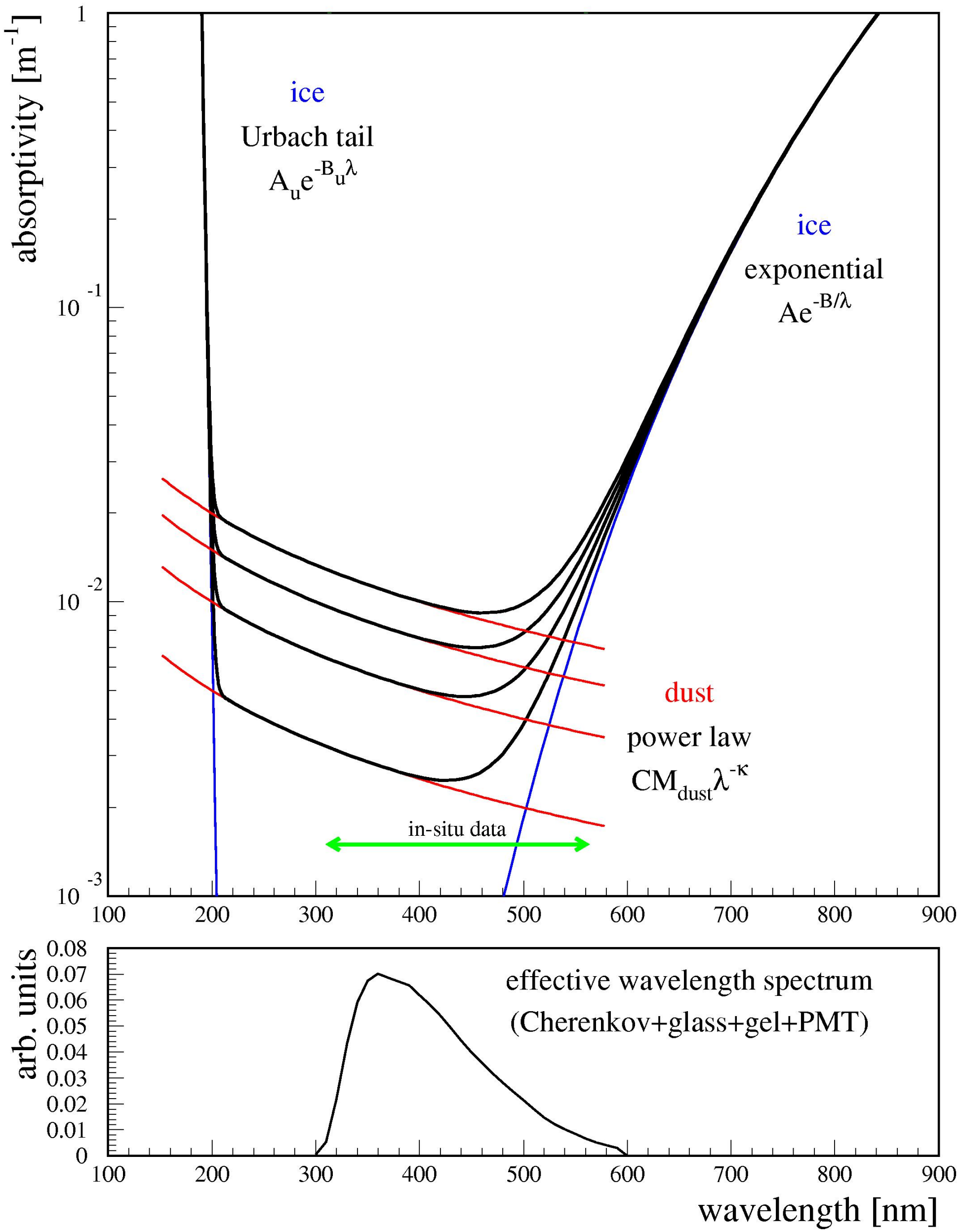
- Install **light sources** in the ice
- Use light sensors to:
  - Measure how long it takes for light to travel through ice
  - Measure how much light is delayed
  - Measure how much light does not arrive
- Use different wavelengths
- Do above at many different depths


effective scattering coefficient, b_e [m^{-1}]
4
1
0.1
0.02
337 nm
370 nm
470 nm
532 nm
$b_e(337)$ [m^{-1}]
$b_e(370)$ [m^{-1}]
$b_e(470)$ [m^{-1}]
0.1
0.02
A
B
C
D
bubbles dominate
800
1000
1200
1400
1600
1800
2000
2200
2400
depth [m]

Wavelength dependence of scattering



3-component model of absorption

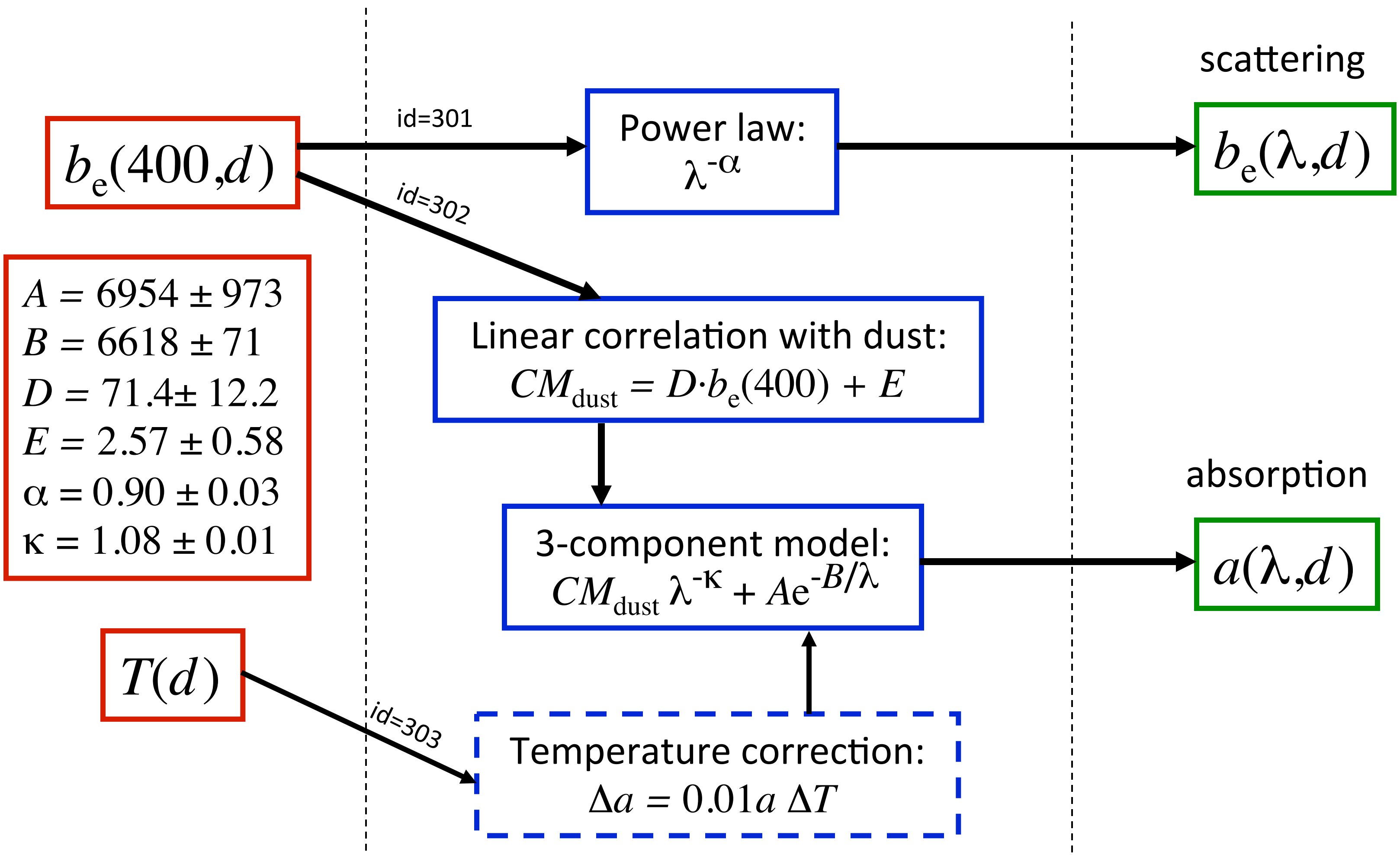


Ice extremely transparent between 200 nm and 500 nm

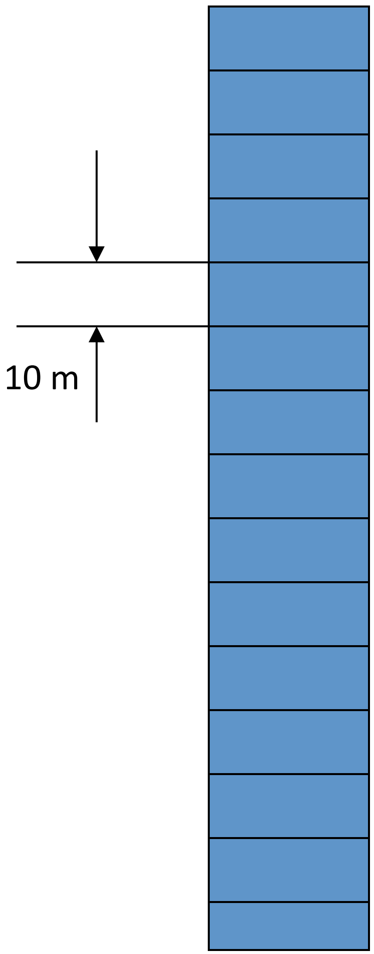
Absorption determined by dust concentration in this range

Wavelength dependence of dust absorption follows power law

A 6-parameter Plug-n-Play Ice Model

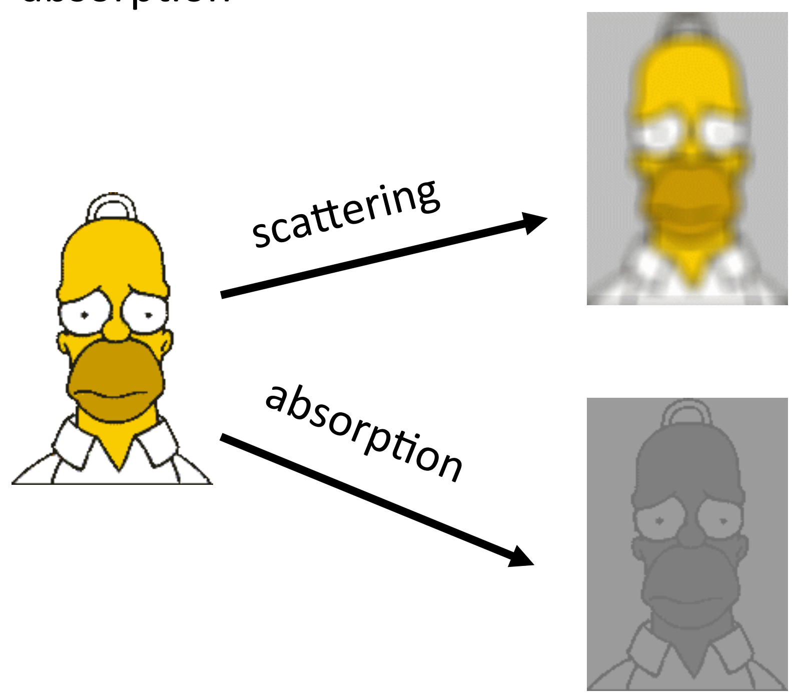


Ice layer parametrization



In each 10-meter layer define:

- scattering
- absorption

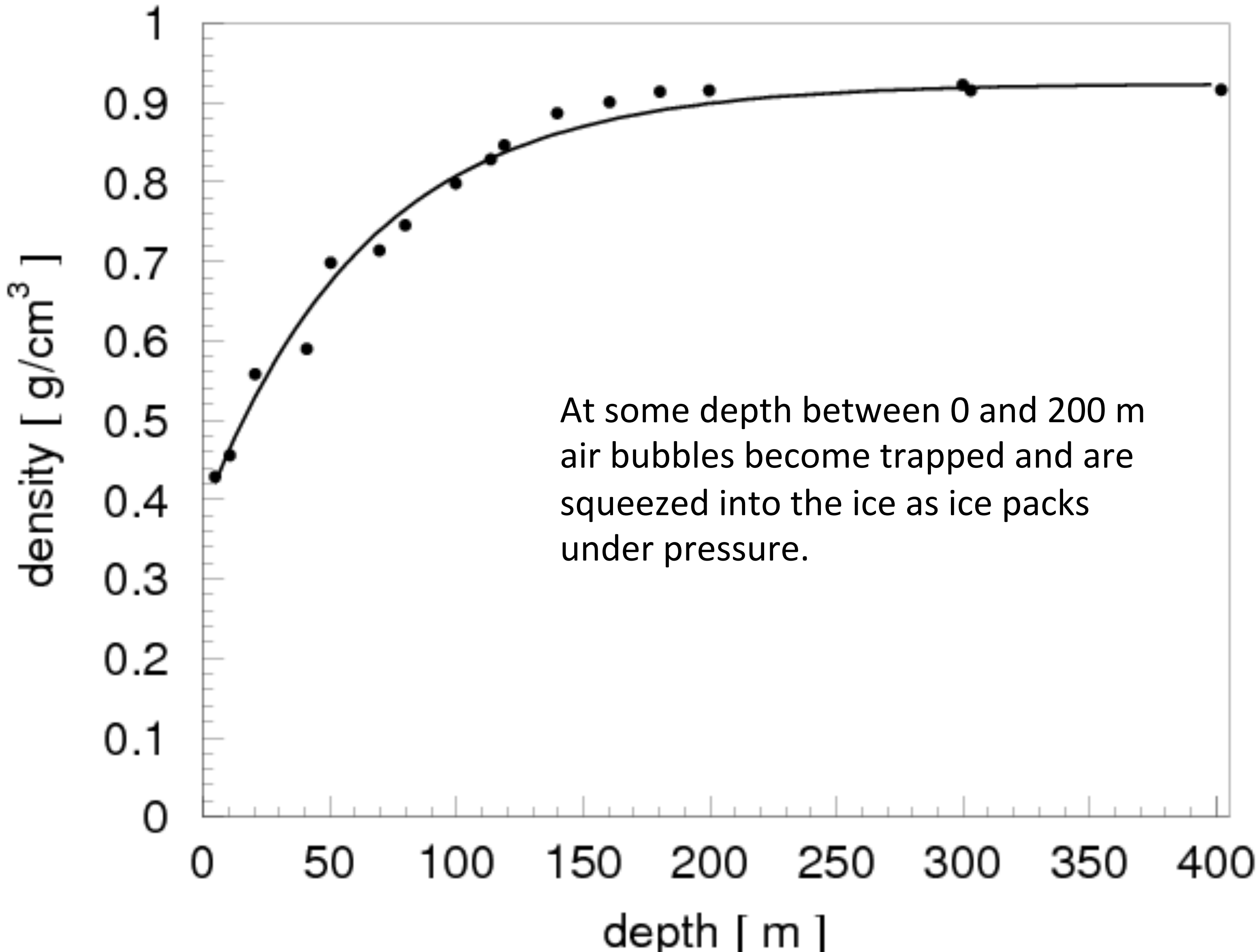


Source is blurred

Source is dimmer

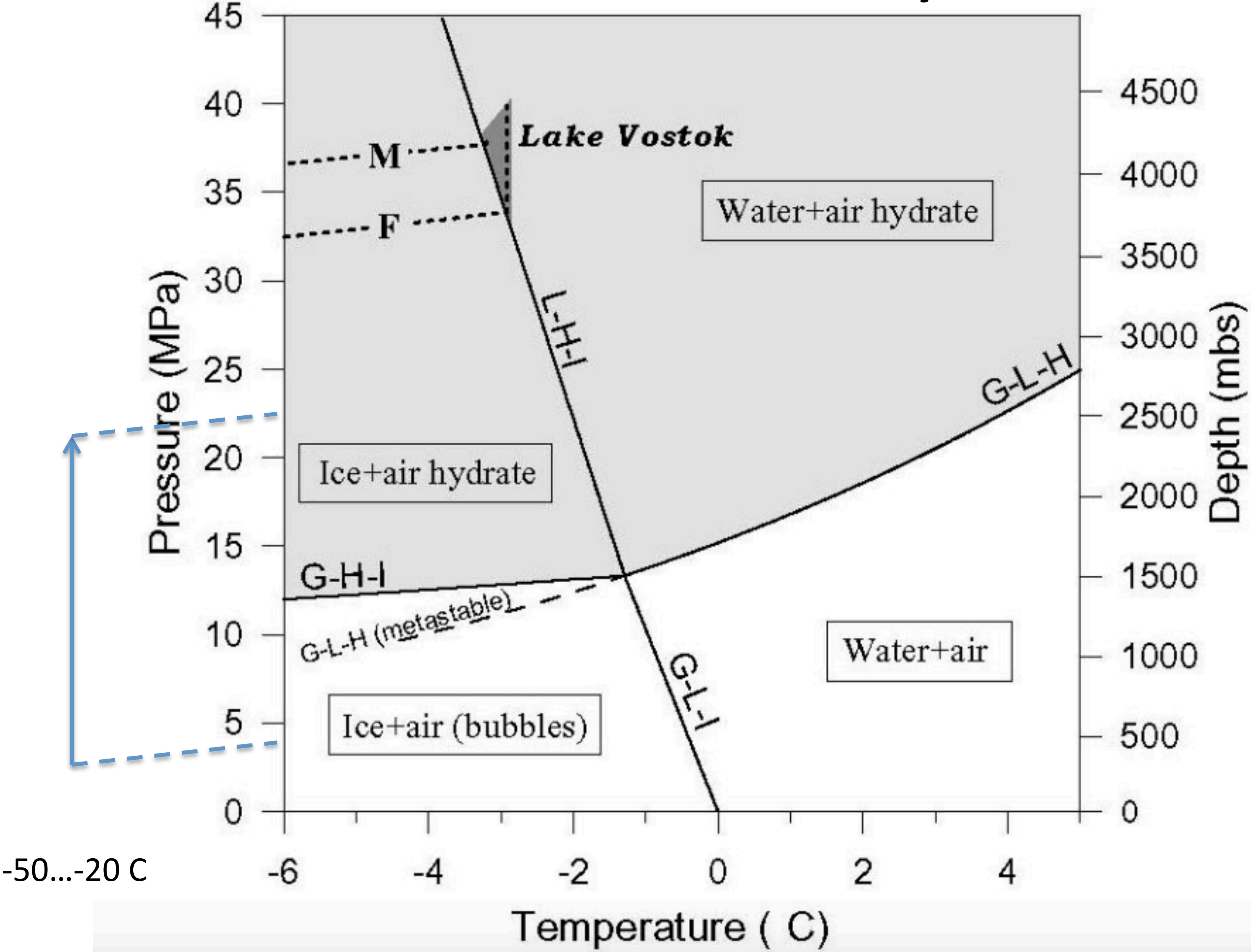
a = inverse absorption length ($1/\lambda_{abs}$)
b = inverse scattering length ($1/\lambda_{sca}$)

Trapped air bubbles

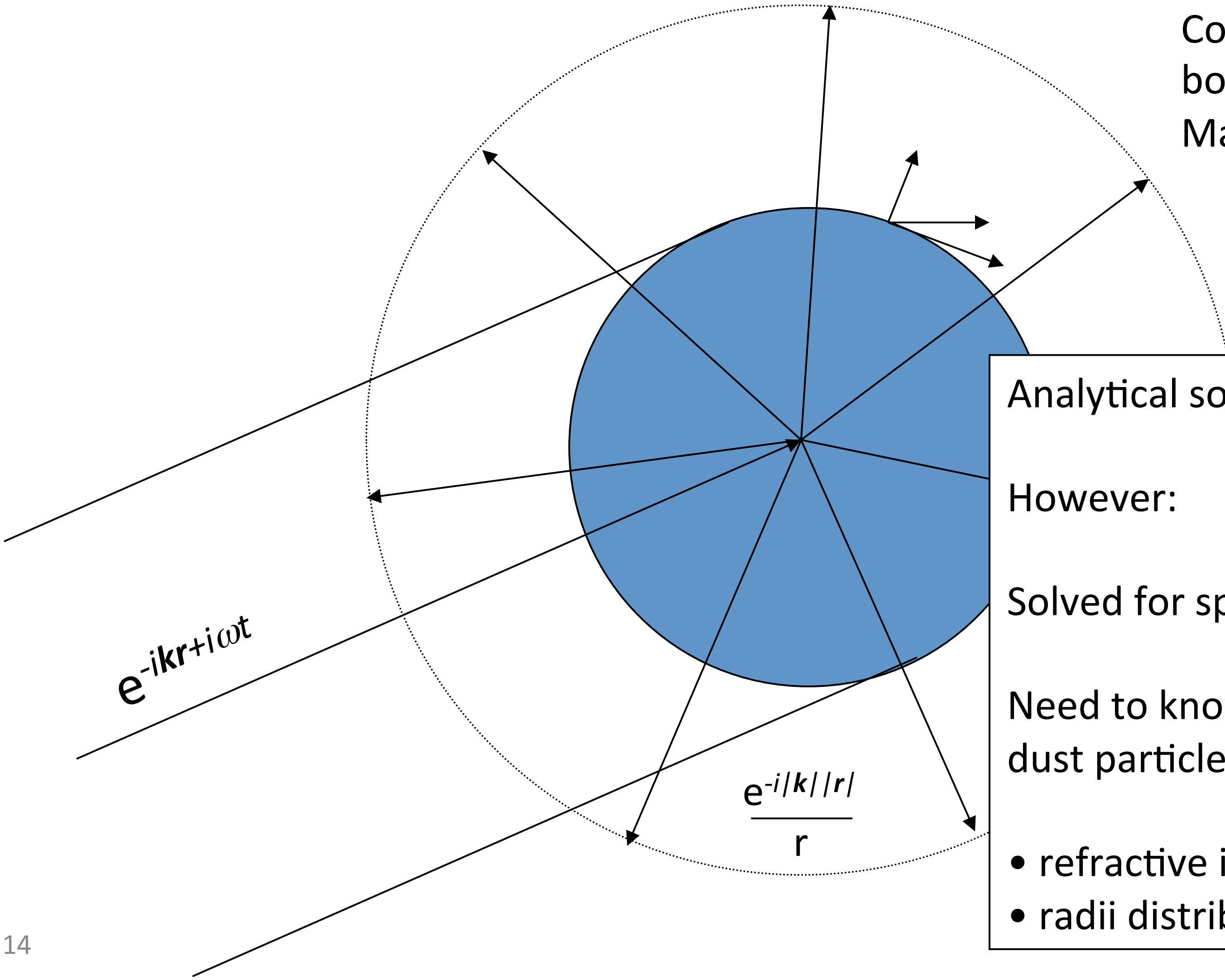


At some depth between 0 and 200 m air bubbles become trapped and are squeezed into the ice as ice packs under pressure.

Conversion into air hydrates



Mie scattering theory



Continuity in E, H: boundary conditions in Maxwell equations

Analytical solution!

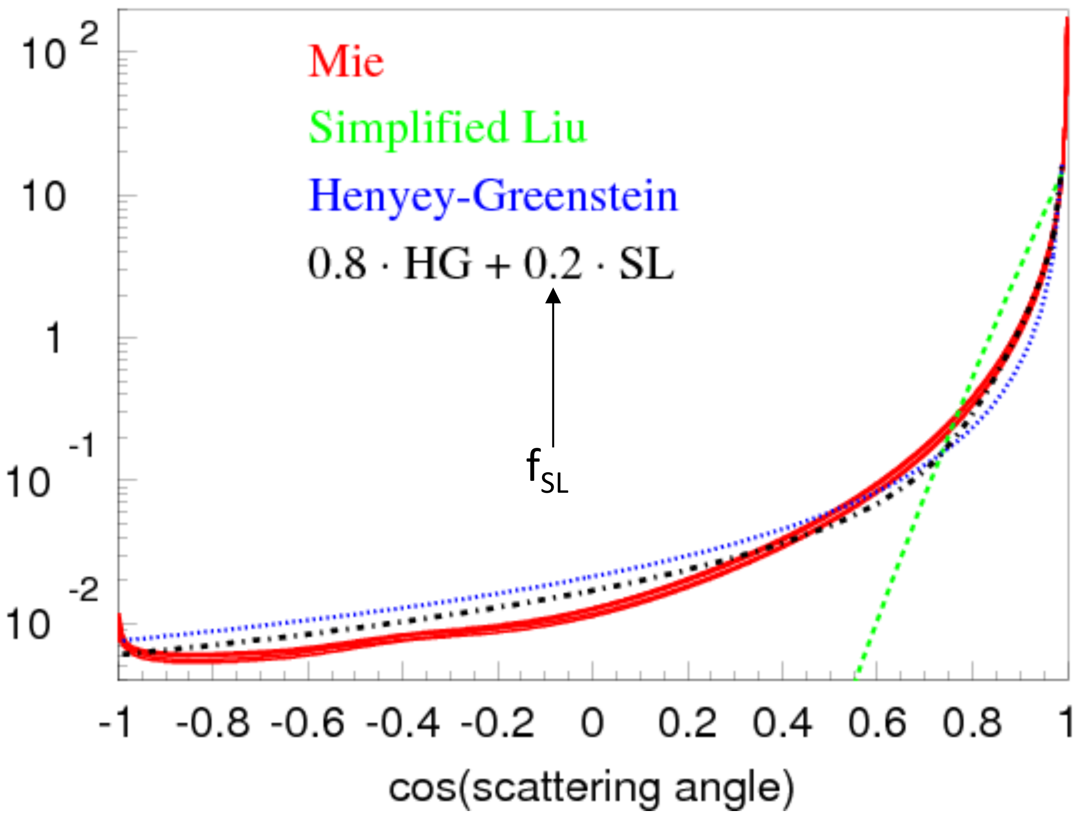
However:

Solved for spherical particles

Need to know the properties of dust particles:

- refractive index (Re and Im)
- radii distributions

Approximation to Mie scattering



Simplified Liu:

$$p(\cos\theta) \sim (1+\cos\theta)^{\alpha}, \quad \text{with} \quad \alpha = \frac{2g}{1-g}$$

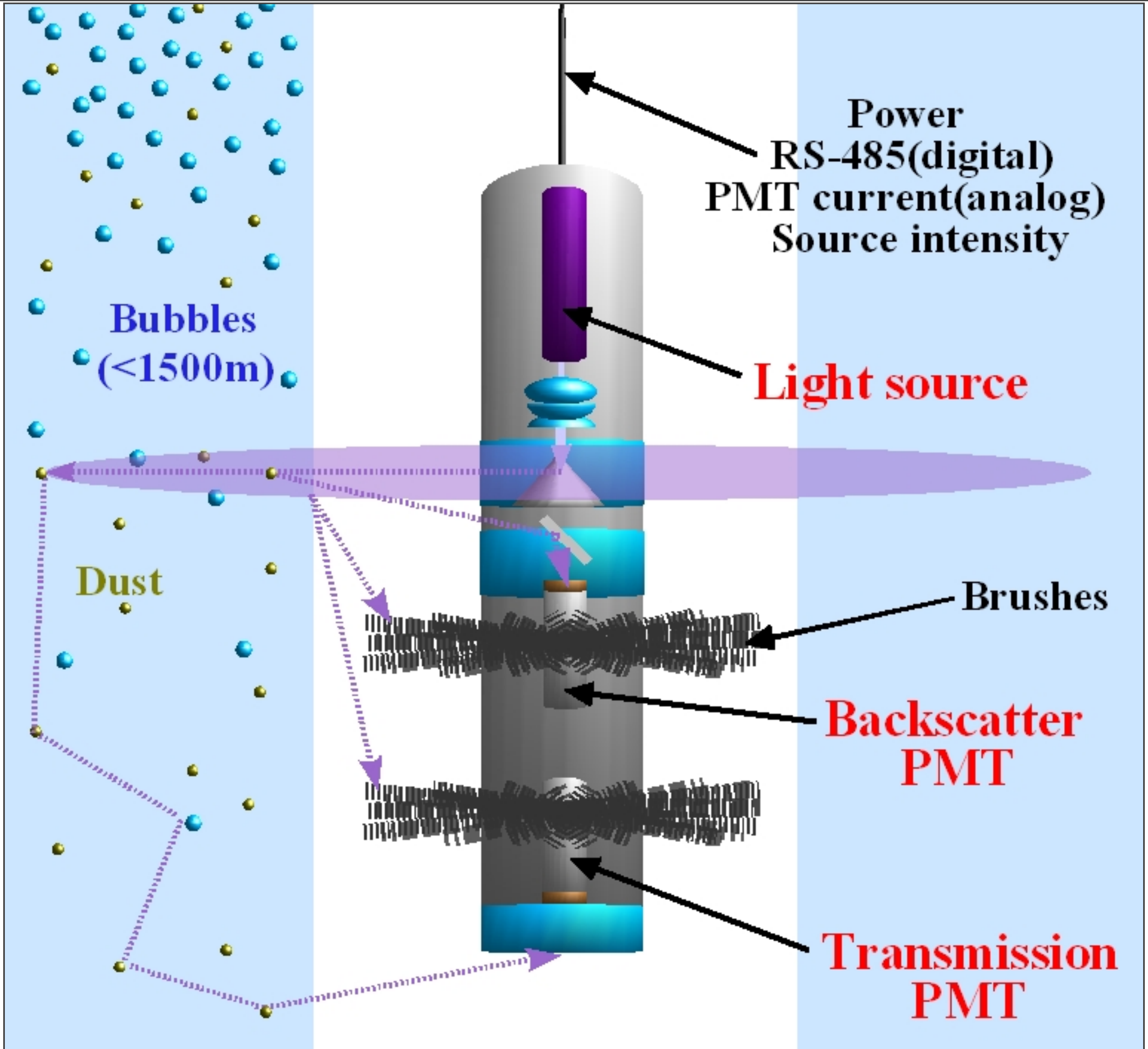
Henyey-Greenstein:

$$p(\cos\theta) = \frac{1}{2}\frac{1-g^2}{[1+g^2-2g\cdot\cos\theta]^{3/2}}$$

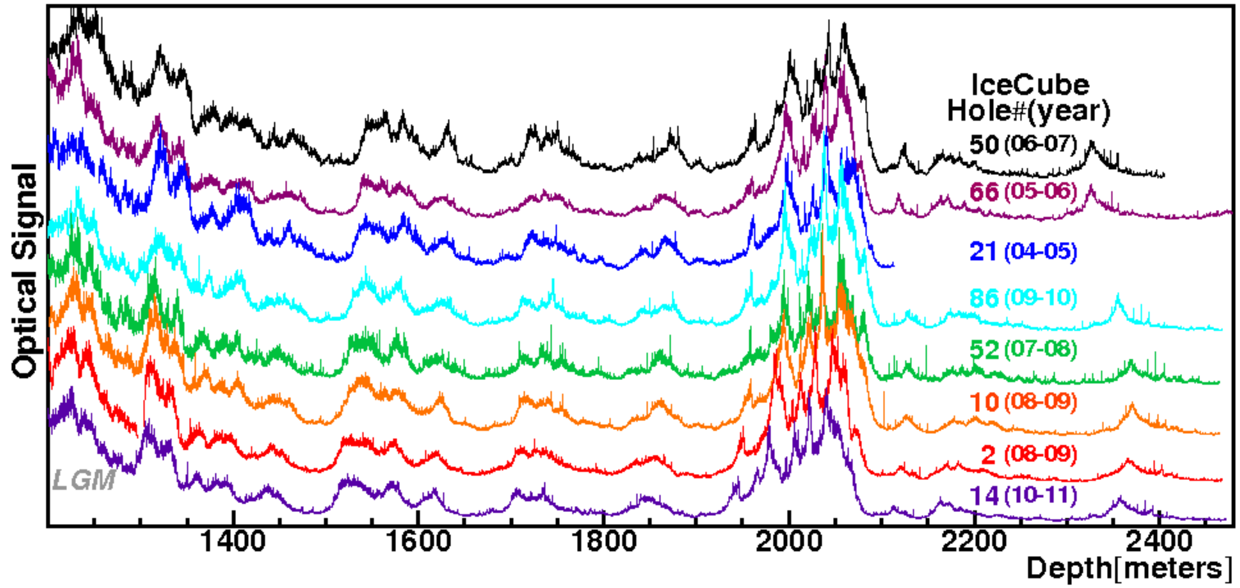
Mie:

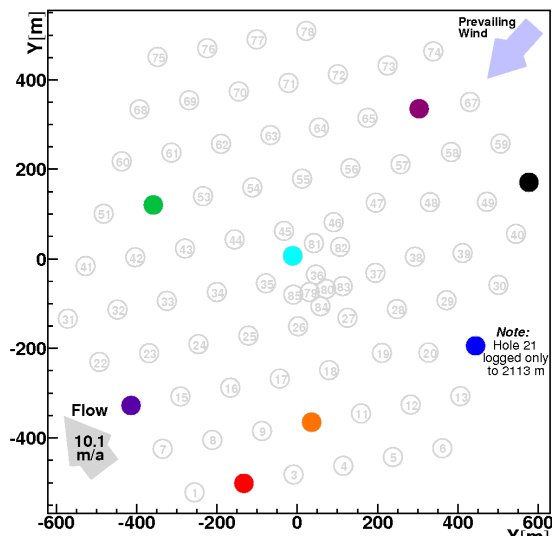
Describes scattering on acid, mineral, salt, and soot with concentrations and radii at SP

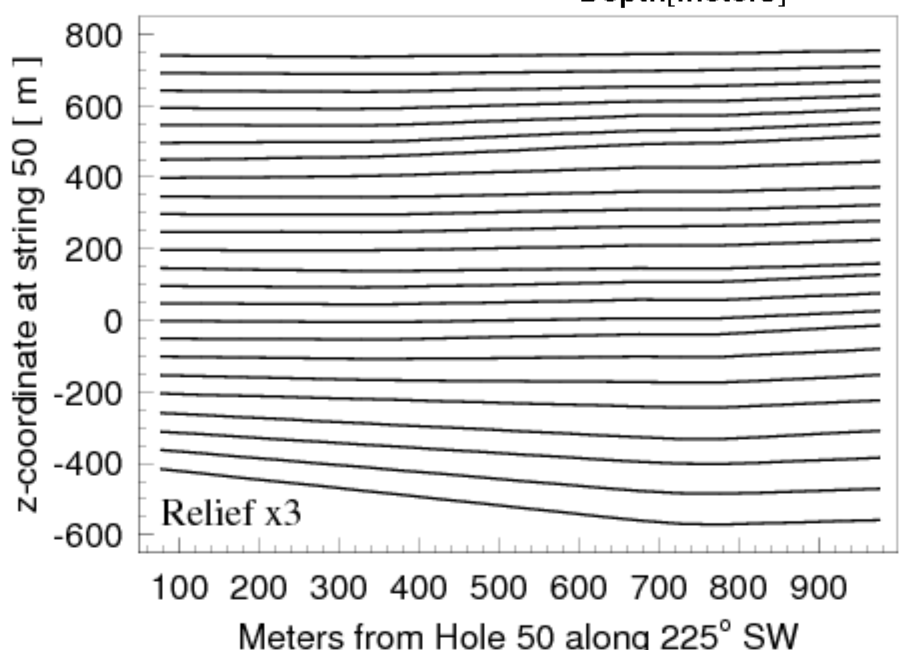
Dust logger


Power
RS-485(digital)
PMT current(analog)
Source intensity
Bubbles
(<1500m)
Light source
Dust
Brushes
Backscatter
PMT
Transmission
PMT

Dust logger discovers ice tilt

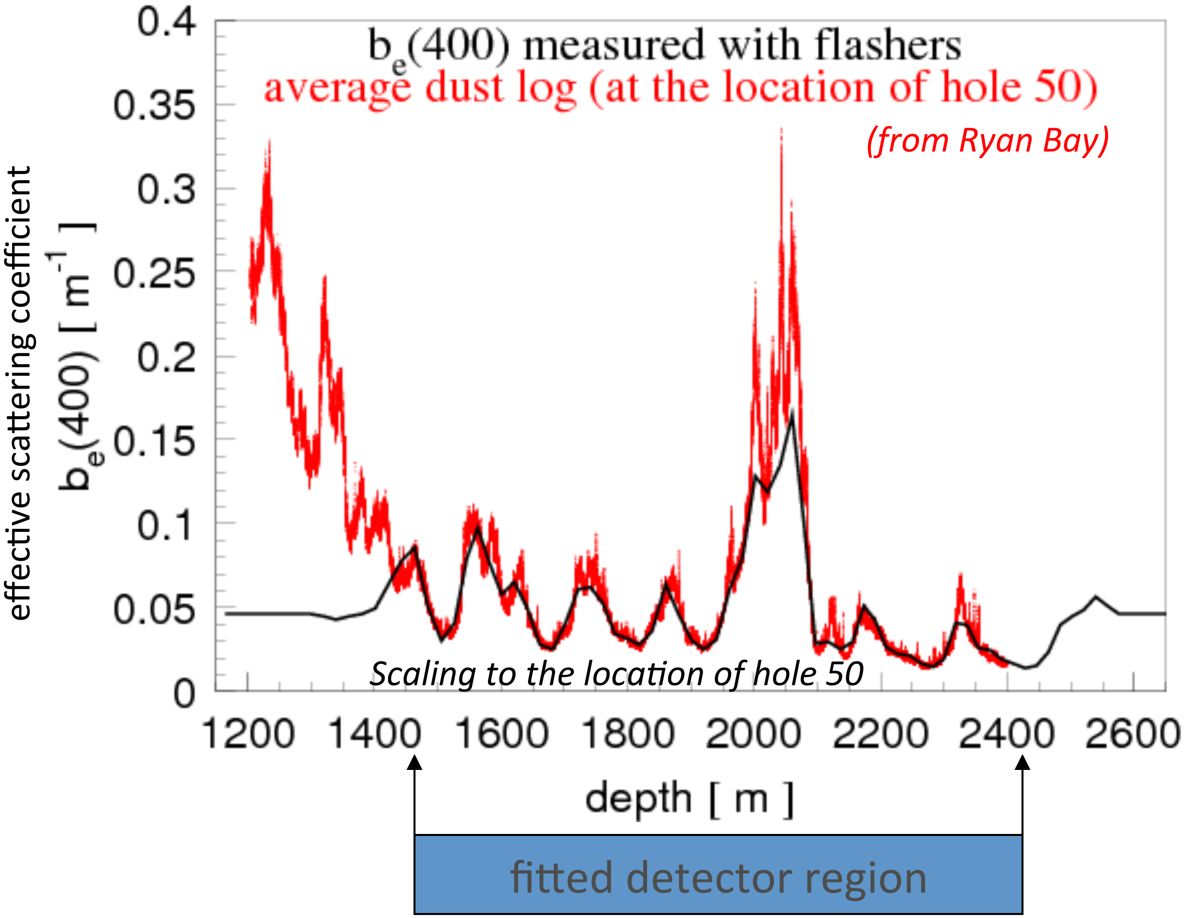


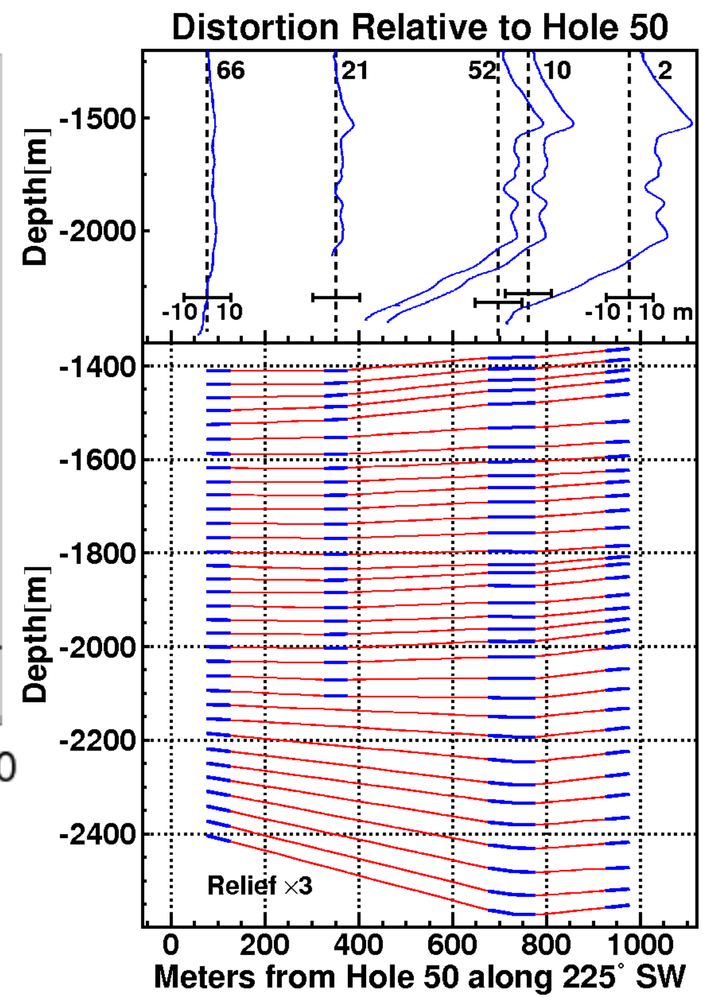




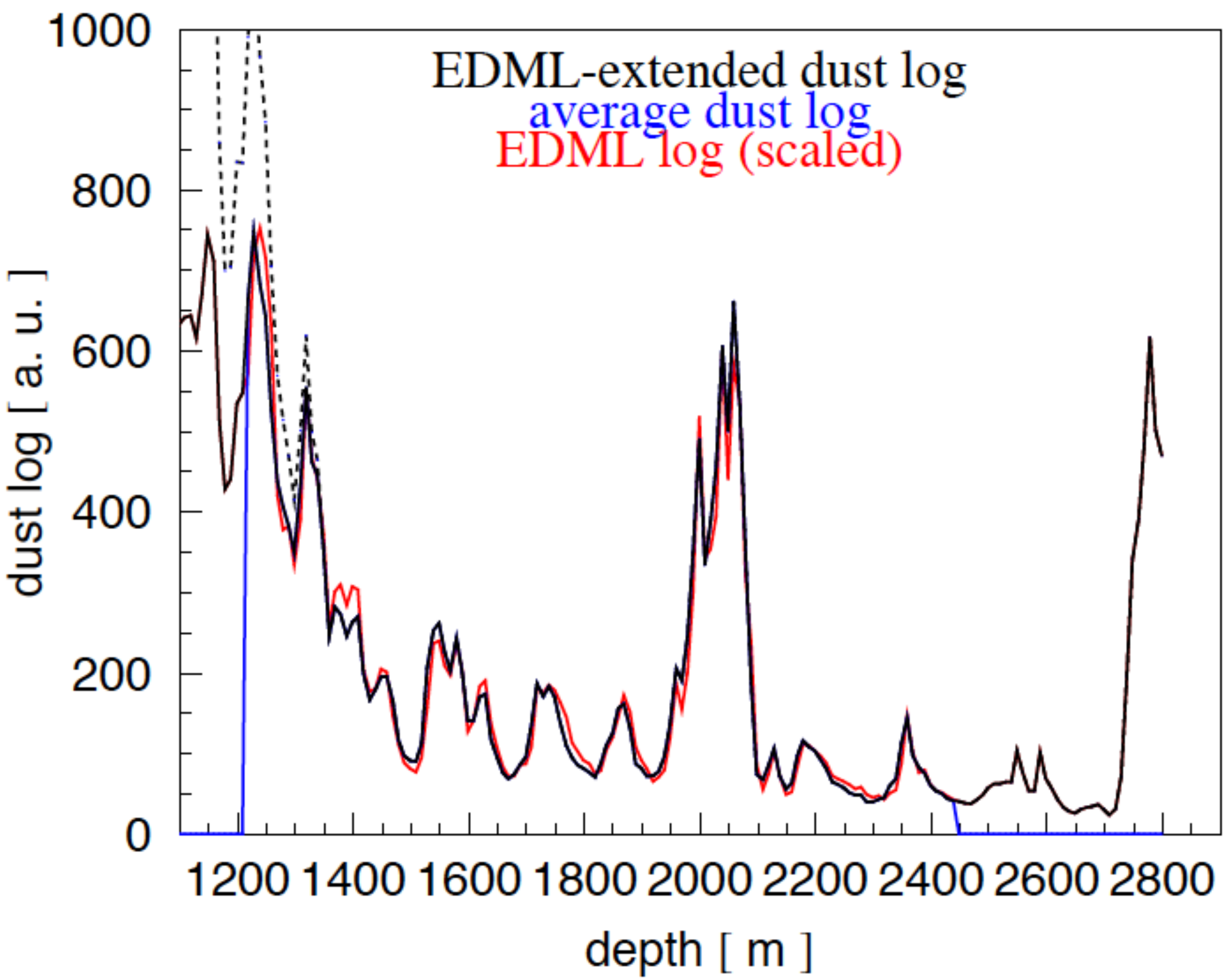
Measured with dust loggers (Ryan Bay)

Correlation of fitted optical properties with dust logger data

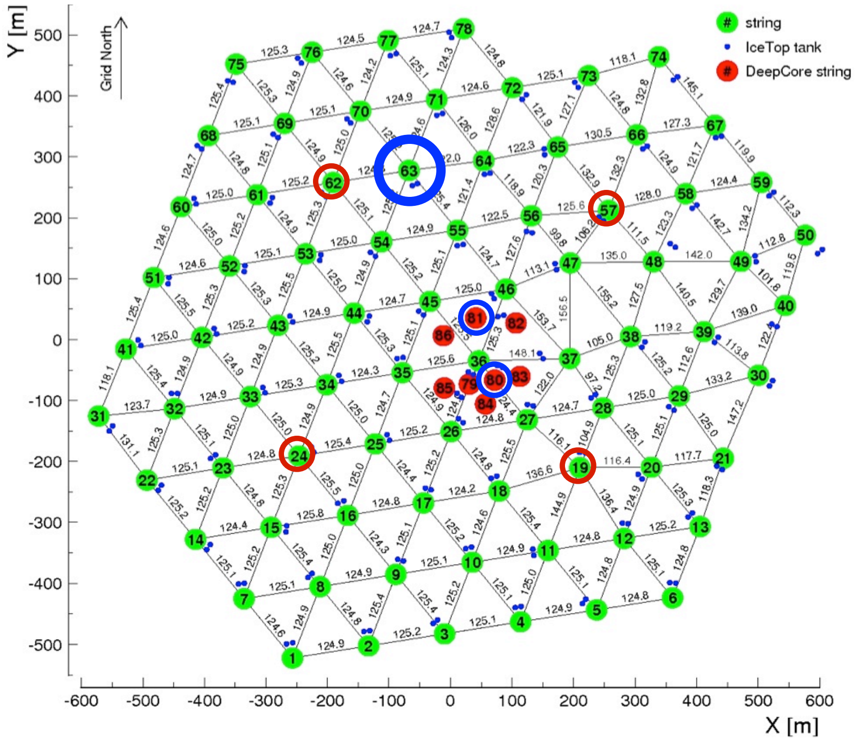


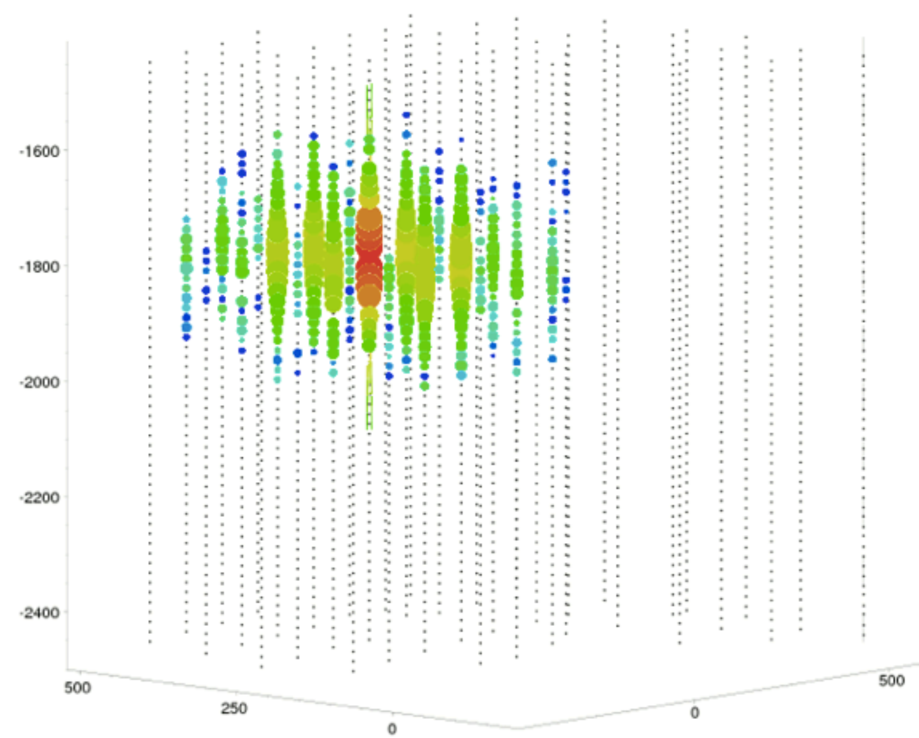


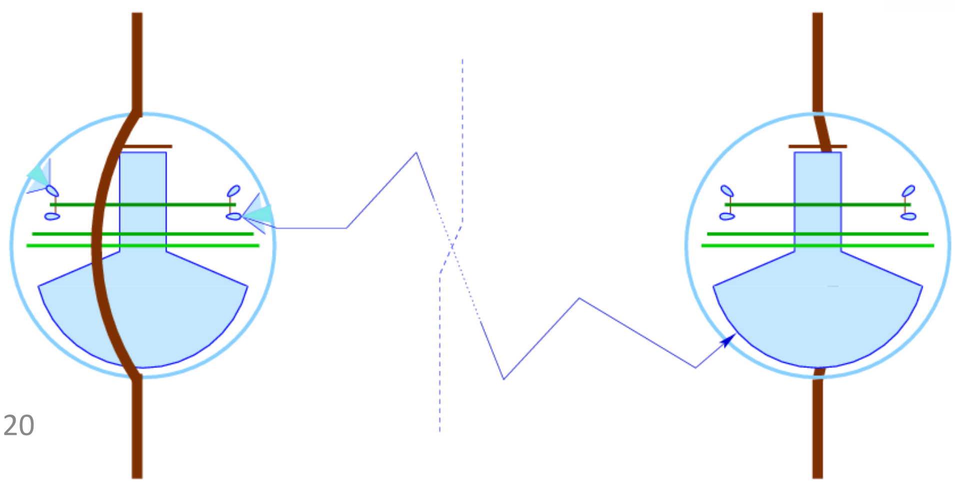
Merged dust log

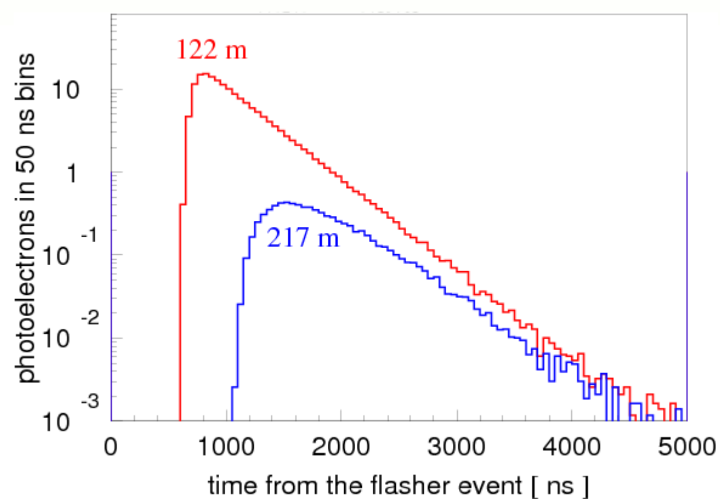


SPICE model fit

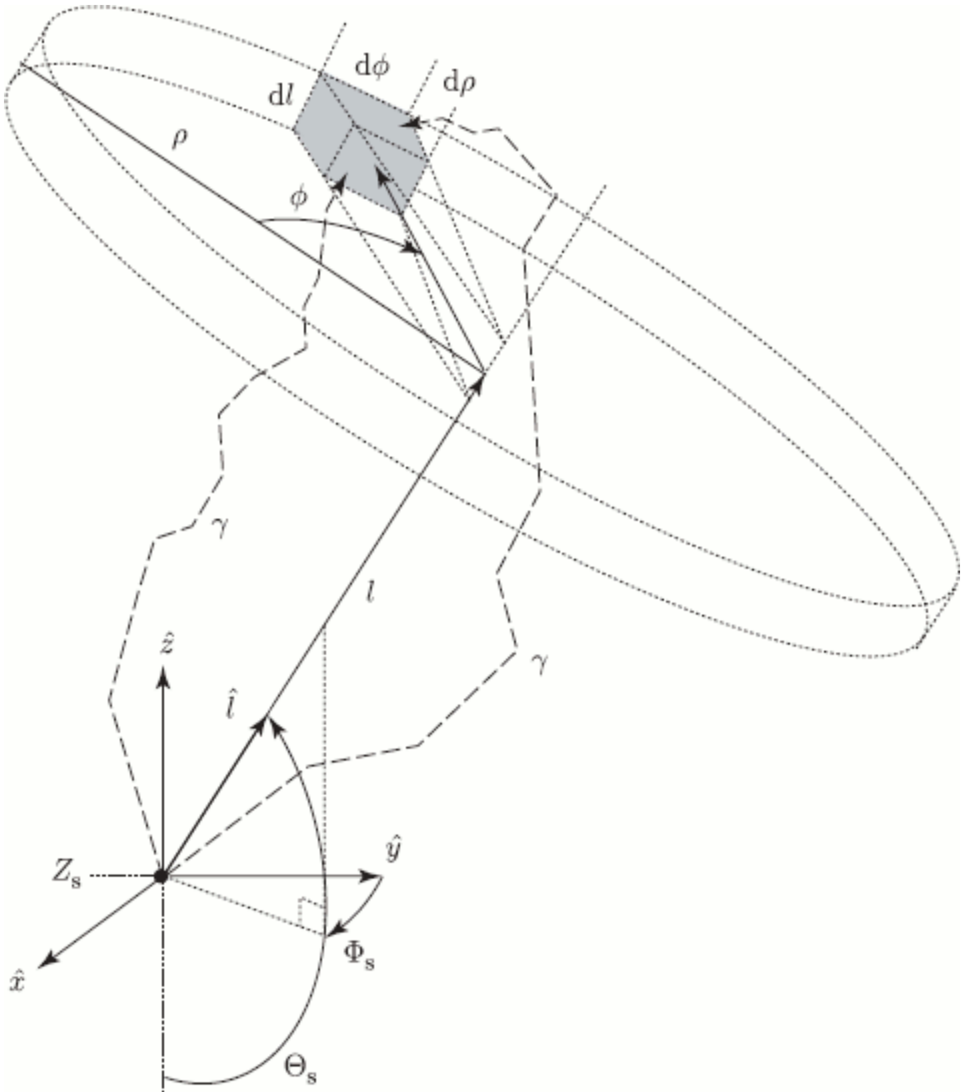








Photon tracking with tables



• First, run photonics to fill space with photons, tabulate the result

• Create such tables for nominal light sources: cascade and uniform half-muon

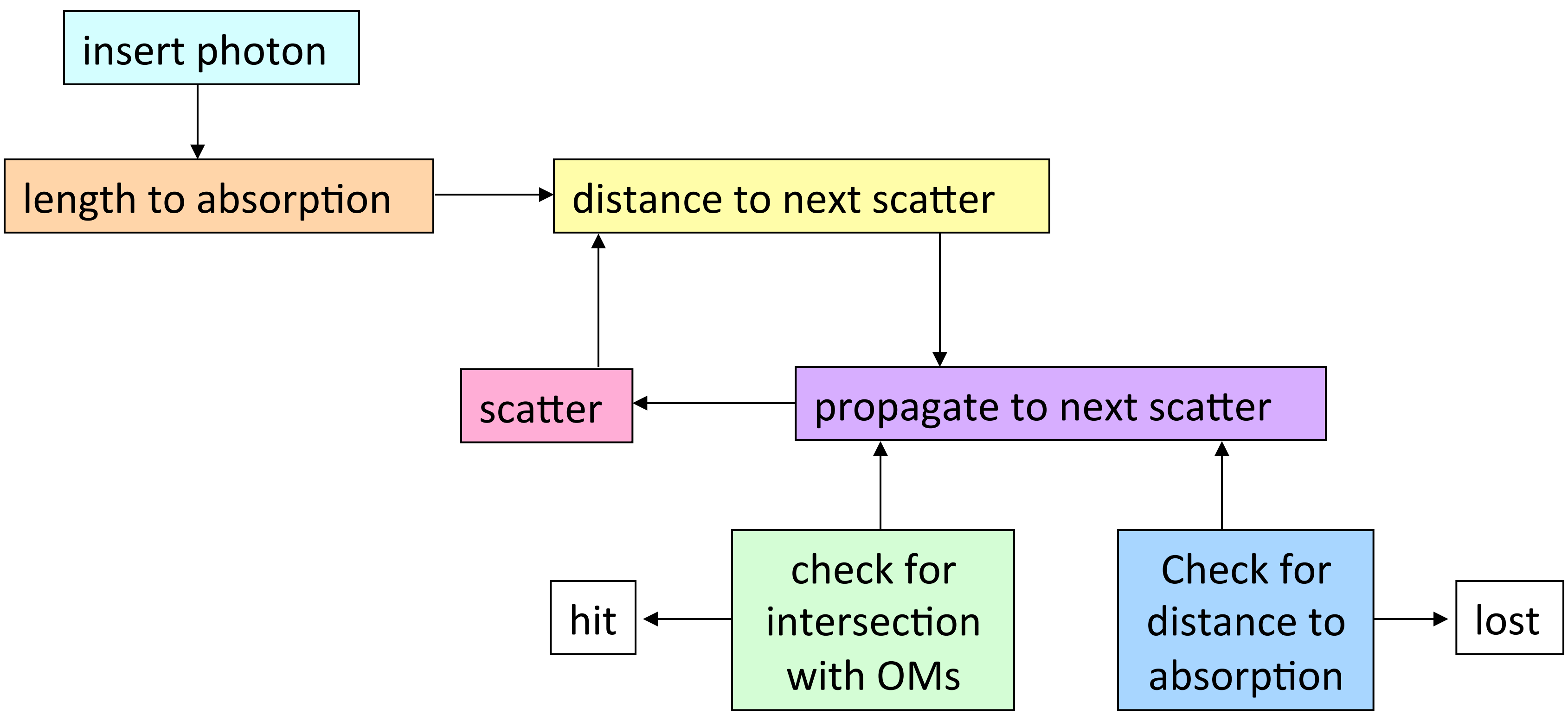
• Simulate photon propagation by looking up photon density in tabulated distributions

→ Table generation is slow
→ Simulation suffers from a wide range of binning artifacts
→ Simulation is also slow! (most time is spent loading the tables)

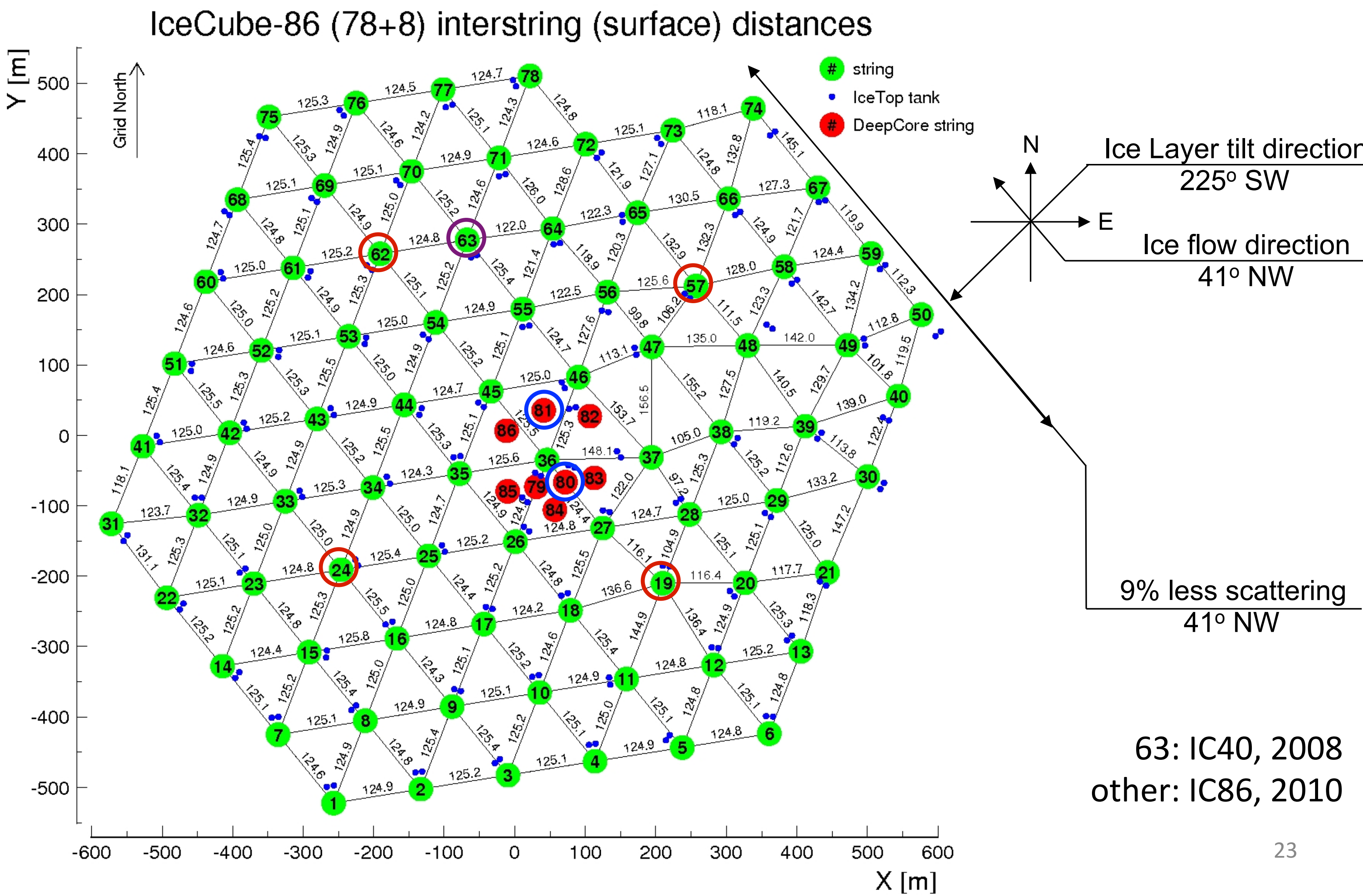
Direct photon tracking

photon propagation code (ppc) or OpenCL simulation (clsim)

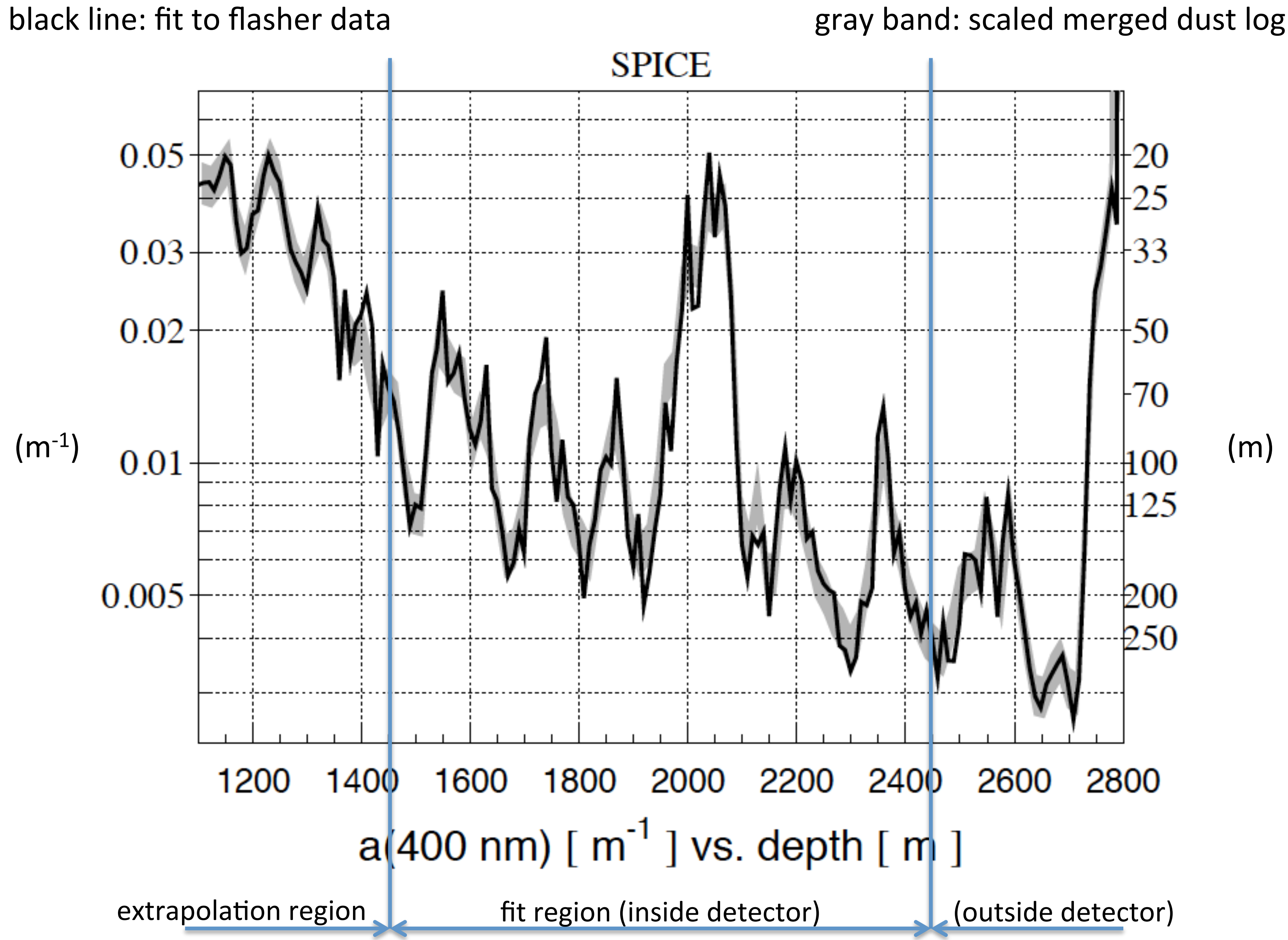
propagate photons directly when needed



7 (1+6) strings of flasher data

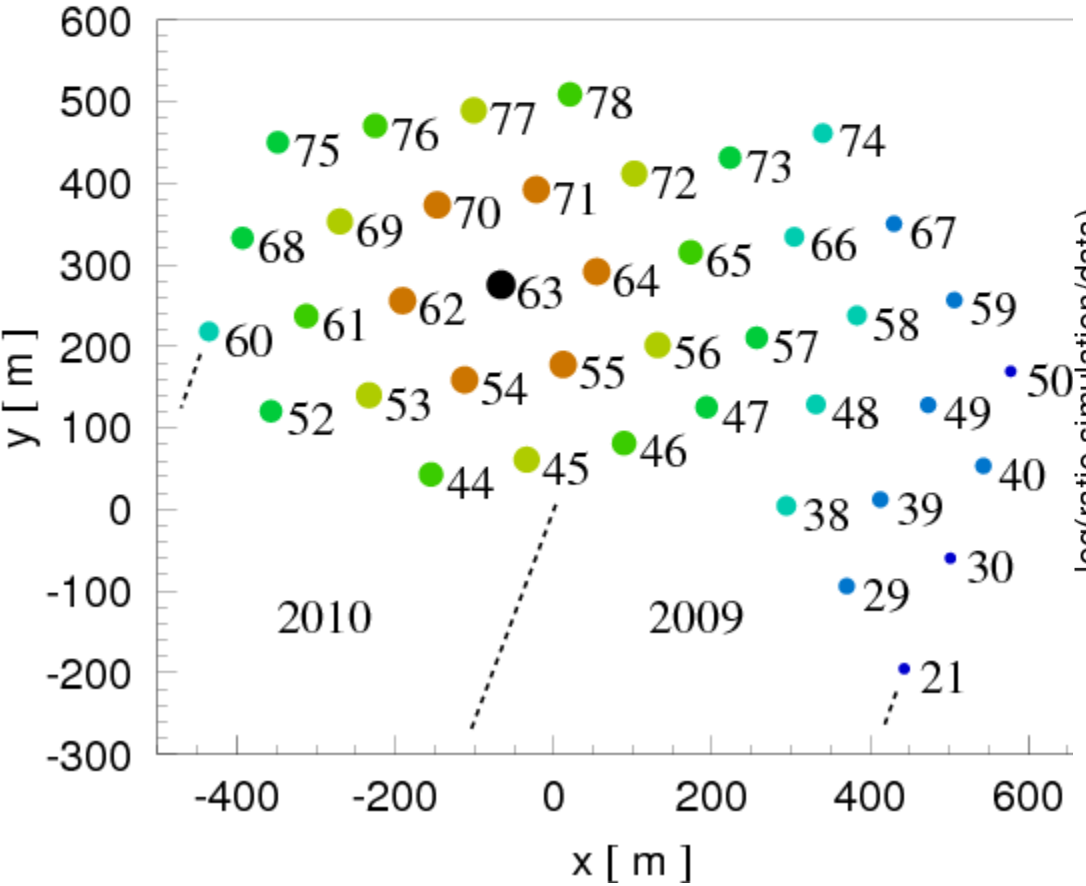


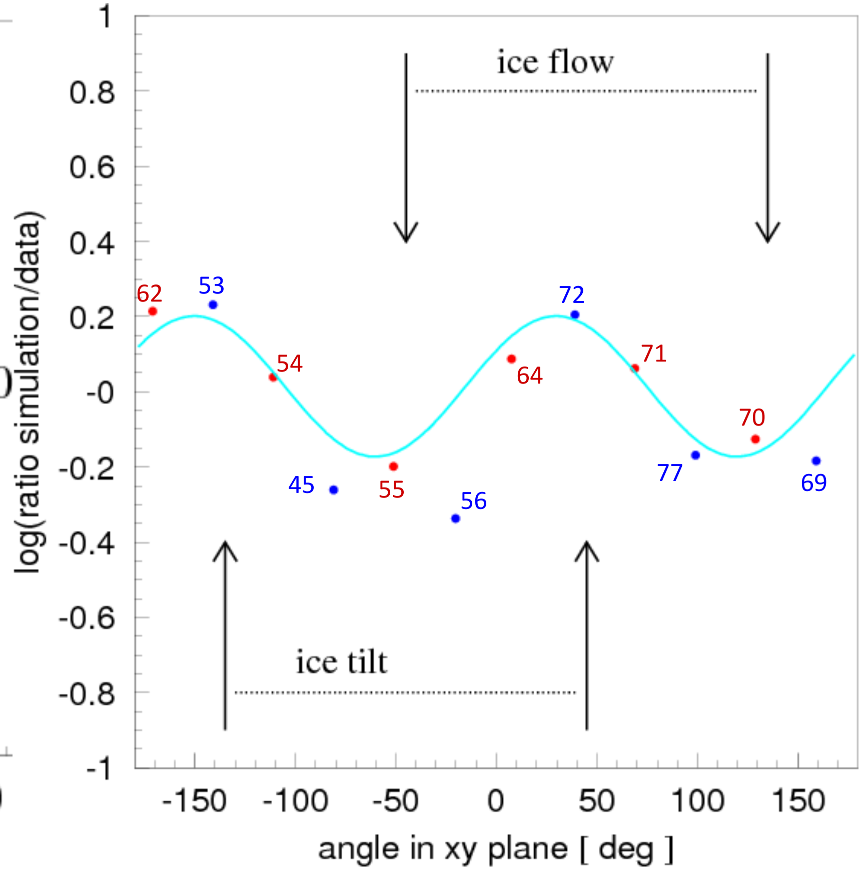
63: IC40, 2008
other: IC86, 2010



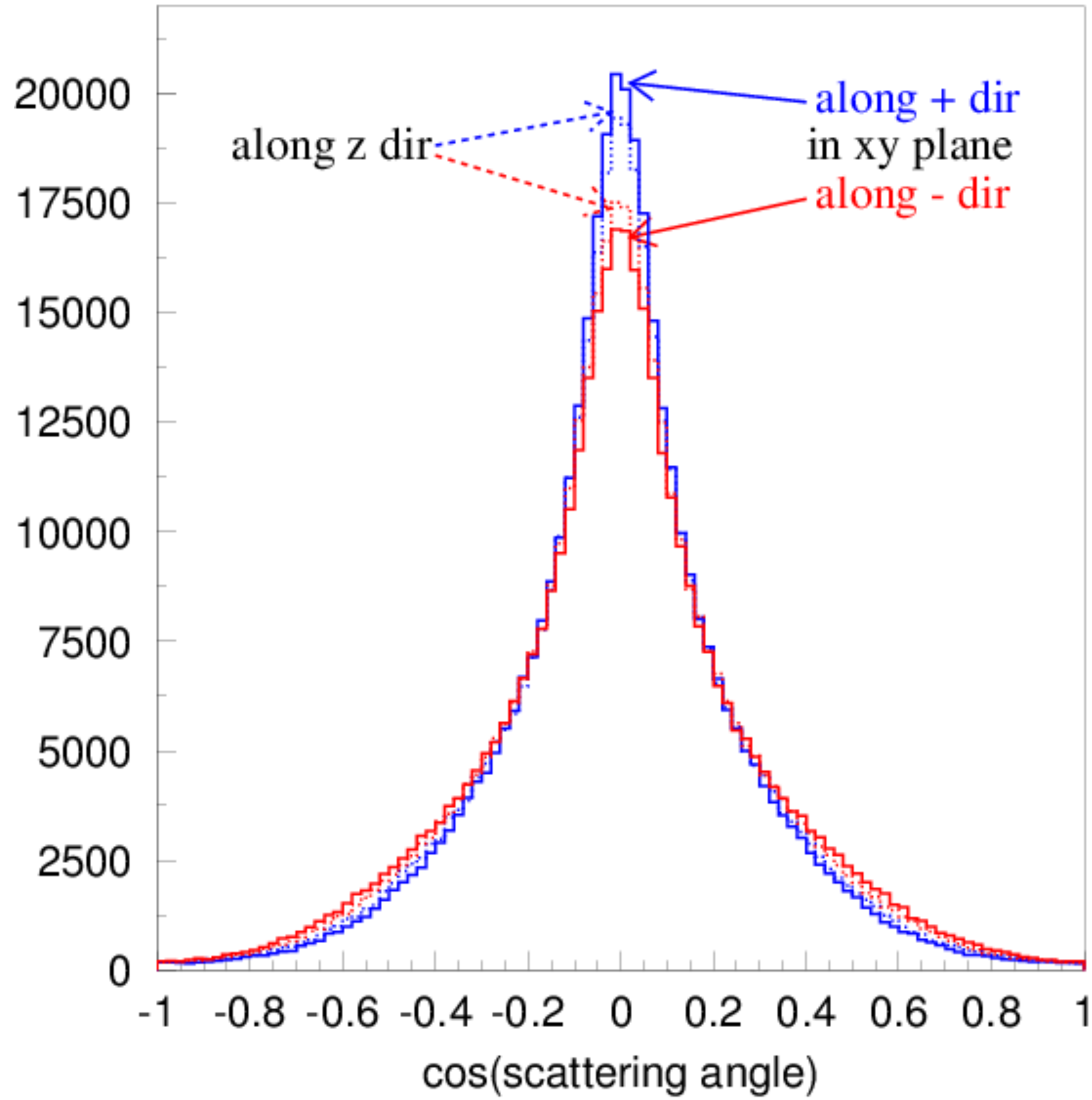
black line: fit to flasher data
gray band: scaled merged dust log
SPICE
0.05
0.03
0.02
0.01
0.005
(m-1)
20
25
33
50
70
100
125
200
250
(m)
1200
1400
1600
1800
2000
2200
2400
2600
2800
a(400 nm) [m-1] vs. depth [m]
extrapolation region
fit region (inside detector)
(outside detector)

Ice anisotropy





Scattering example (5% anisotropy)



Hole ice cameras

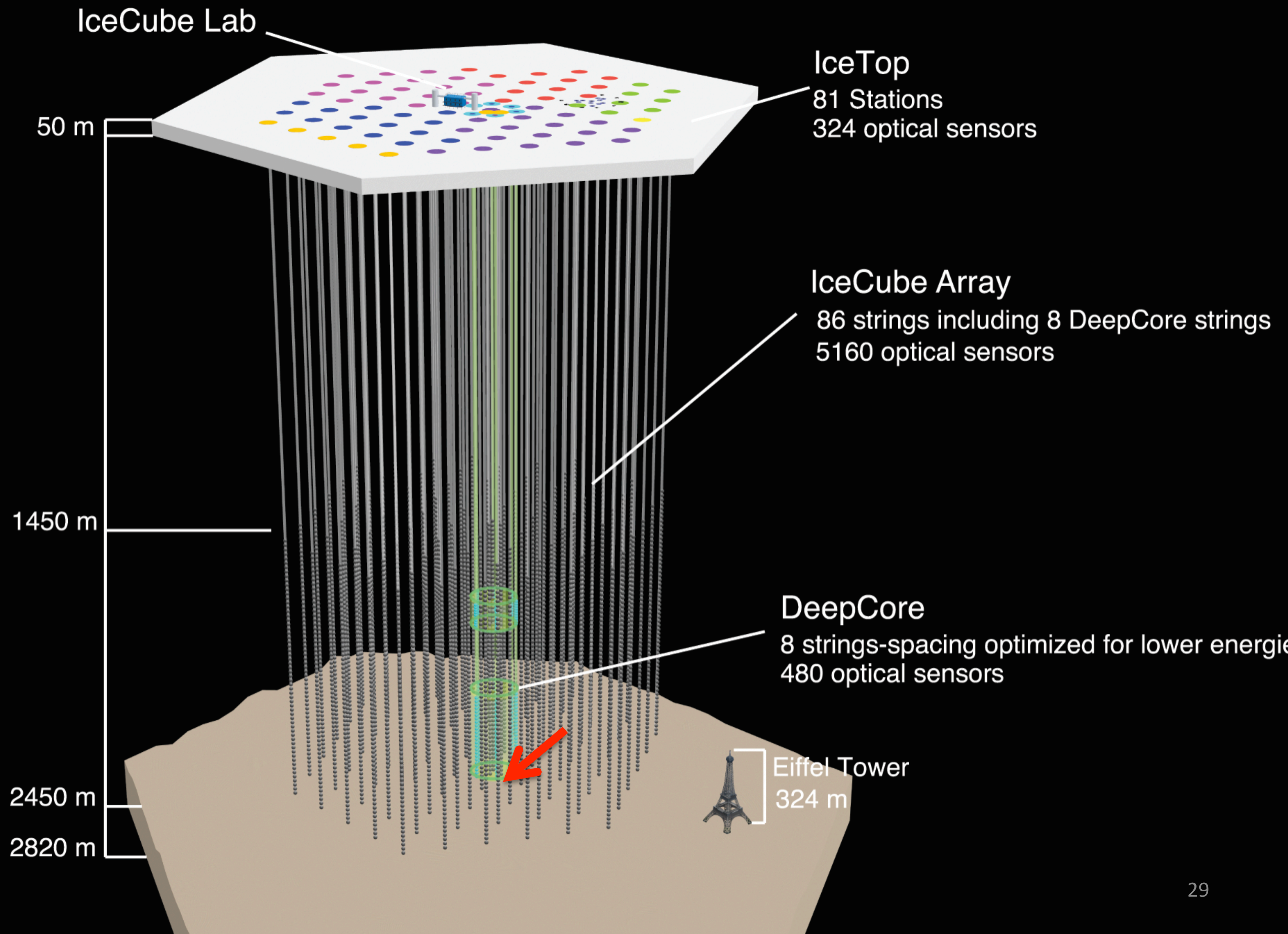
AMANDA:

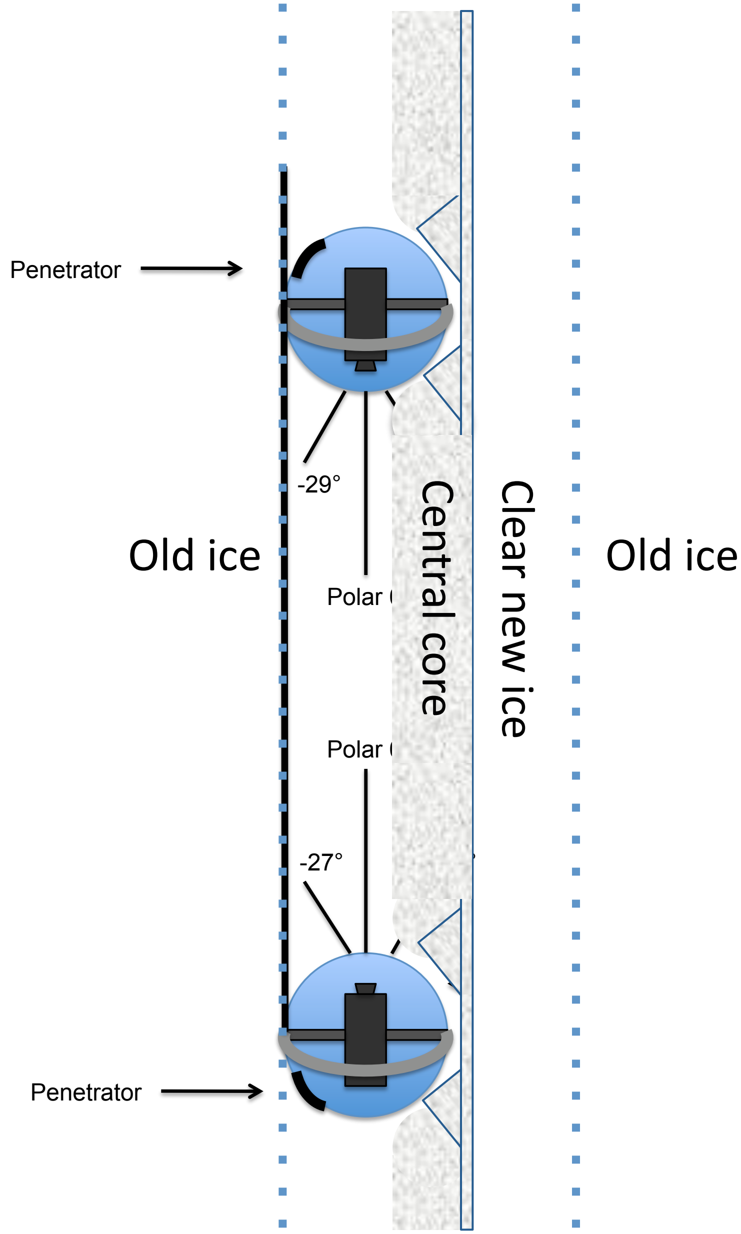
Swedish camera deployed in 1998 in AMANDA hole 13

IceCube:

Bubble camera deployed in the 2006/7 season with string 57

Swedish camera deployed in the 2010/11 season with the last string (80)


IceCube Lab
IceTop
81 Stations
324 optical sensors
50 m
IceCube Array
86 strings including 8 DeepCore strings
5160 optical sensors
1450 m
DeepCore
8 strings-spacing optimized for lower energie
480 optical sensors
Eiffel Tower
324 m
2450 m
2820 m


Penetrator
-29°
Old ice
Polar
Central core
Clear new ice
Old ice
Polar
-27°
Penetrator

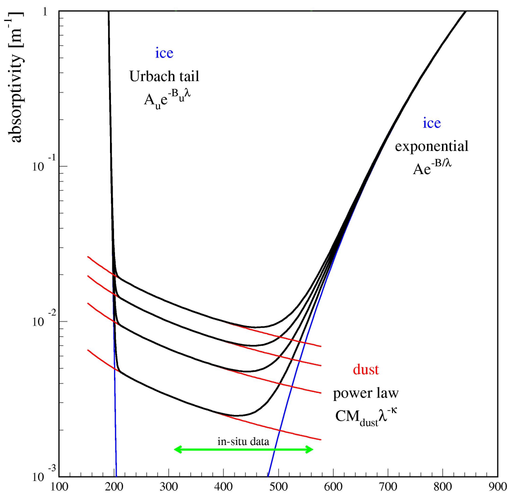
4

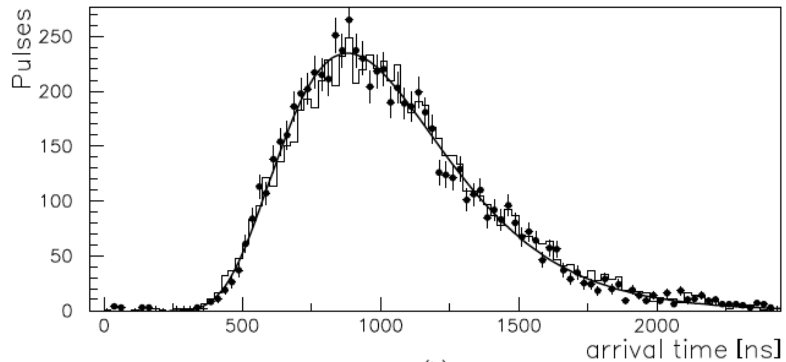

U -19 902 29 255 1 50 1.4
01:07:22 04/03/11 234 2094 9


L -5 2702 9 1 50 1.4
02:44:40 18/02/11 -2 829 29

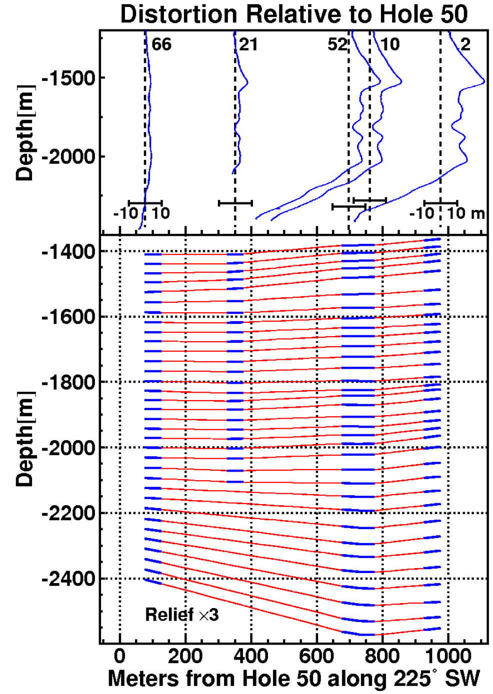
Things we learned

Dust/impurities

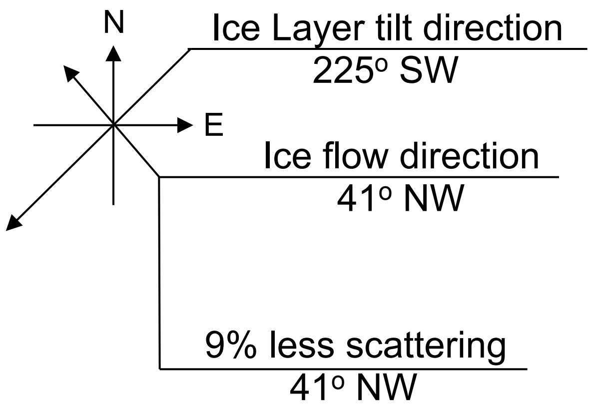




Air bubbles/hydrates



Hole ice



Ice anisotropy

Ice tilt