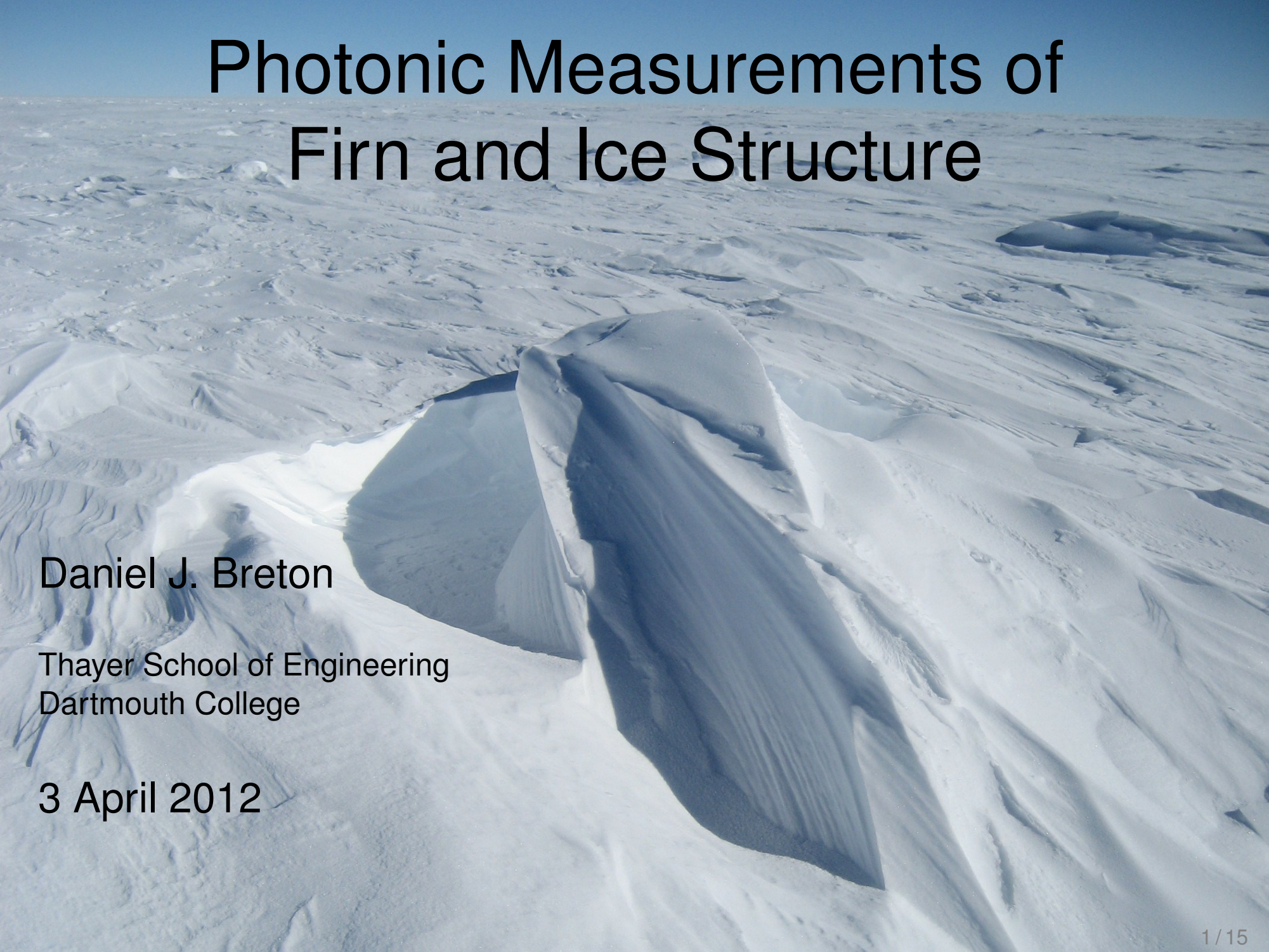
Photonic Measurements of Firn and Ice Structure



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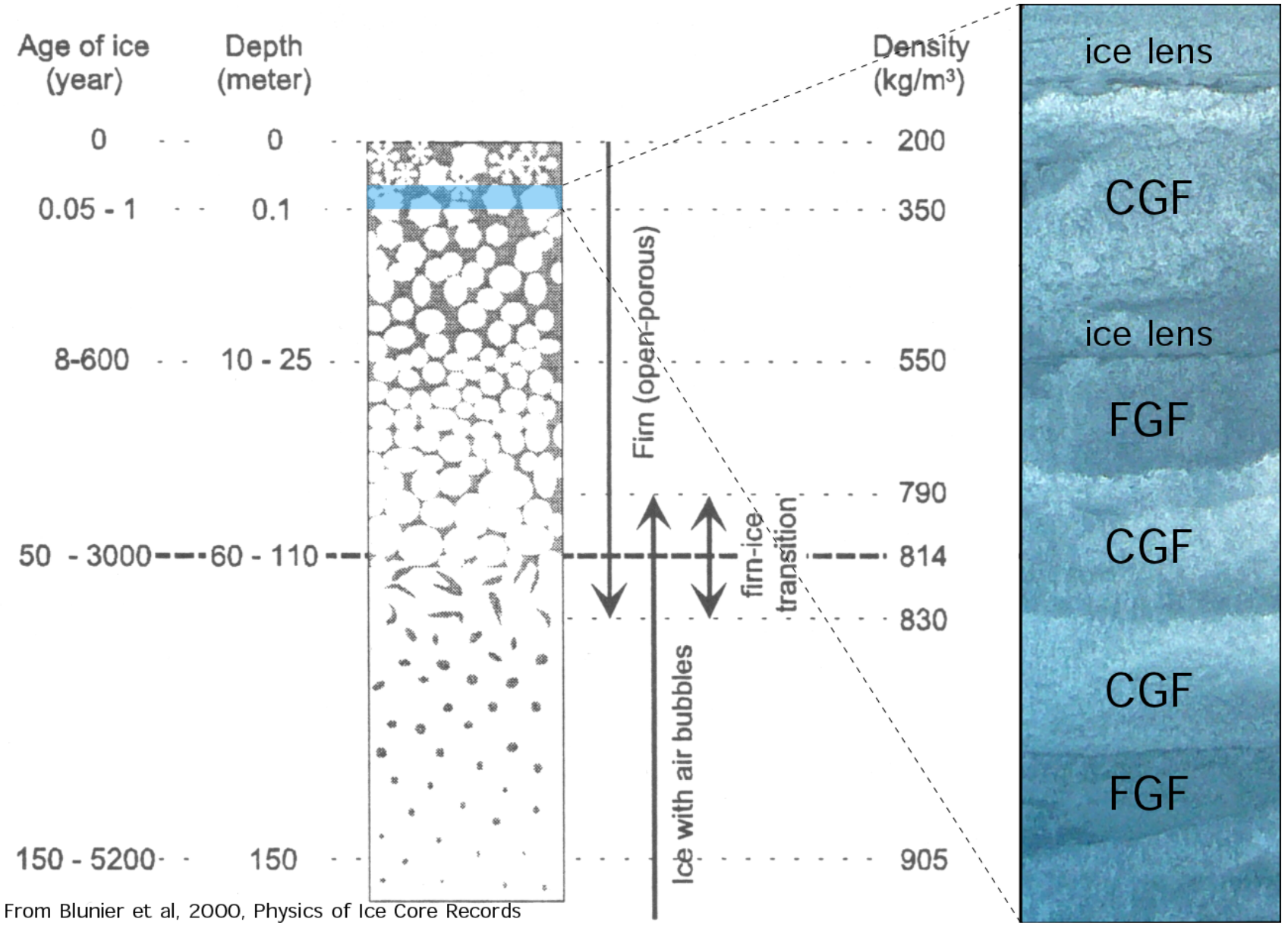
From snow to ice: firn densification

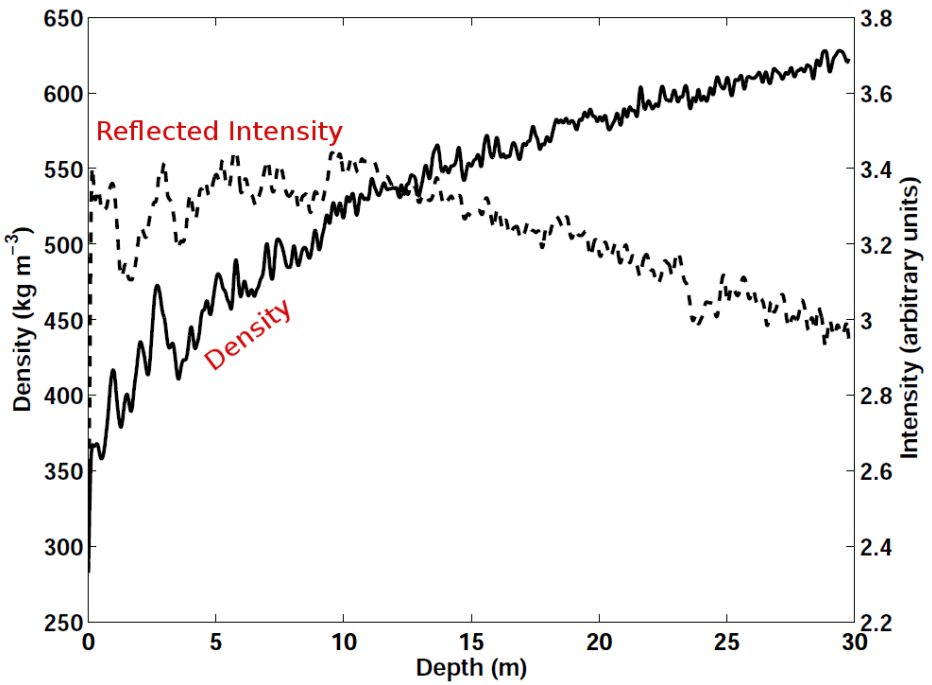


From Blunier et al, 2000, Physics of Ice Core Records

Observations of MDD: Hawley and Morris (2006)

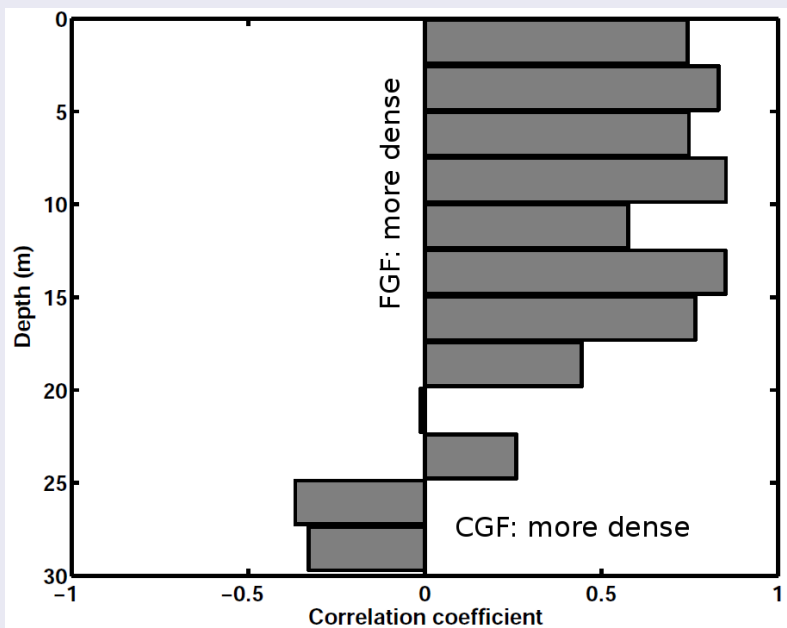
30 m core at Summit, Greenland

- Borehole wall optical reflectivity
- Neutron scattering density probe
- In-situ, but low resolution



Change in ρ-reflectivity correlation

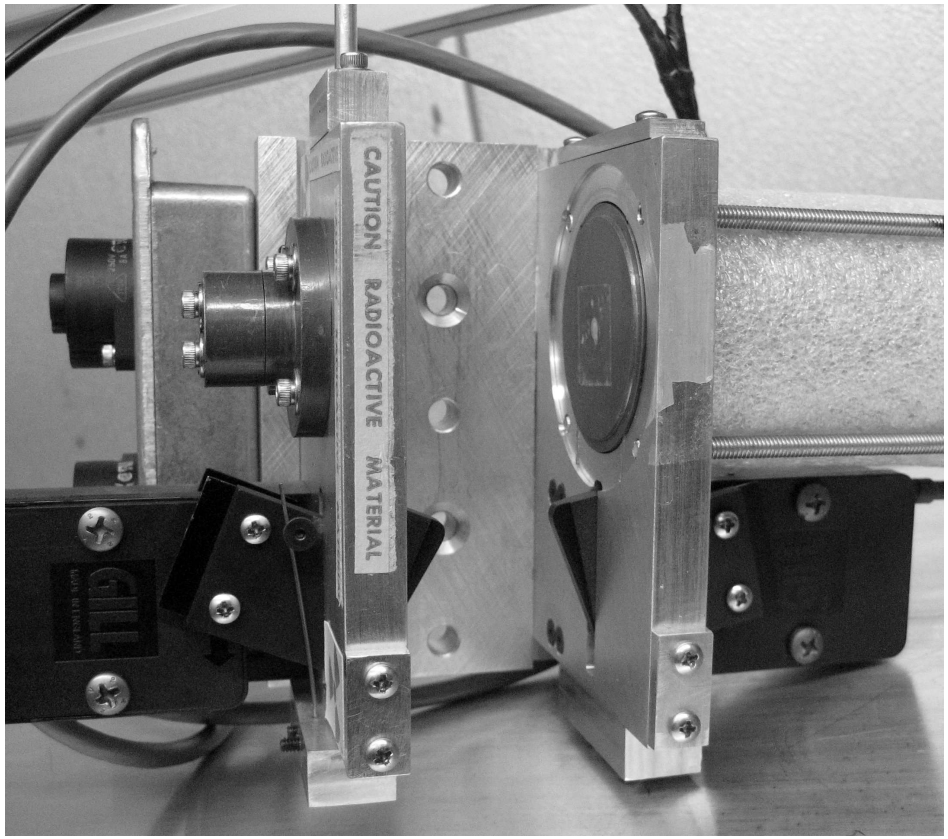
- Shift in correlation suggests density inversion...
- ... but not supported by subsequent chemistry data



Maine Automated Density Gauge Experiment

Overview

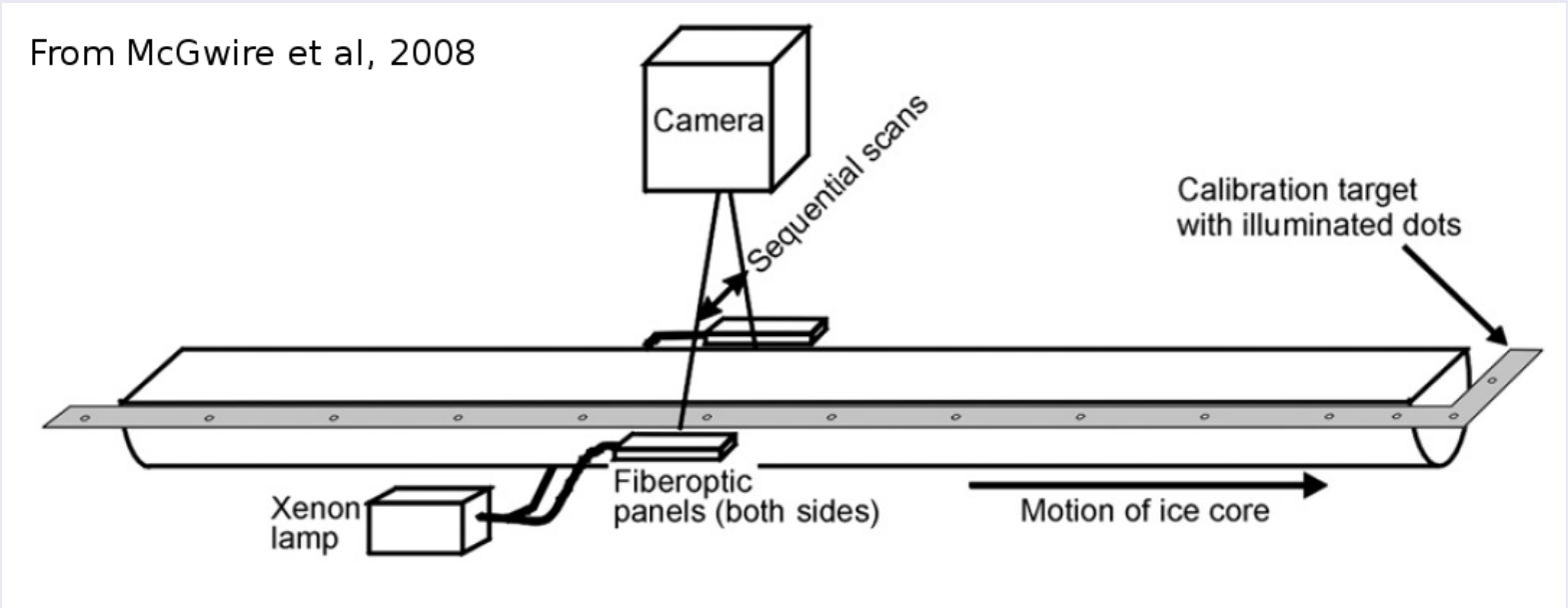
- low energy gamma-ray: optimized for 5-8 cm cores
- pulse mode: well defined nuclear counting uncertainty
- calipers: measure core diameter ± 0.1 mm
- $1-\sigma$ uncertainty: ± 4 kg m^{-3}
- high resolution: 3.3 mm
- throughput: ~ 1 m h^{-1}
- field-deployable, used for 2 seasons on U.S. ITASE traverse



MADGE sensor head

The NICL Optical Imaging System

A line-scan camera



- dark-field photography: camera perpendicular to illumination
- goal is archival photography, not firn/ice optics measurements
- image brightness: bulk density and scatterer size & shape

What do we see?

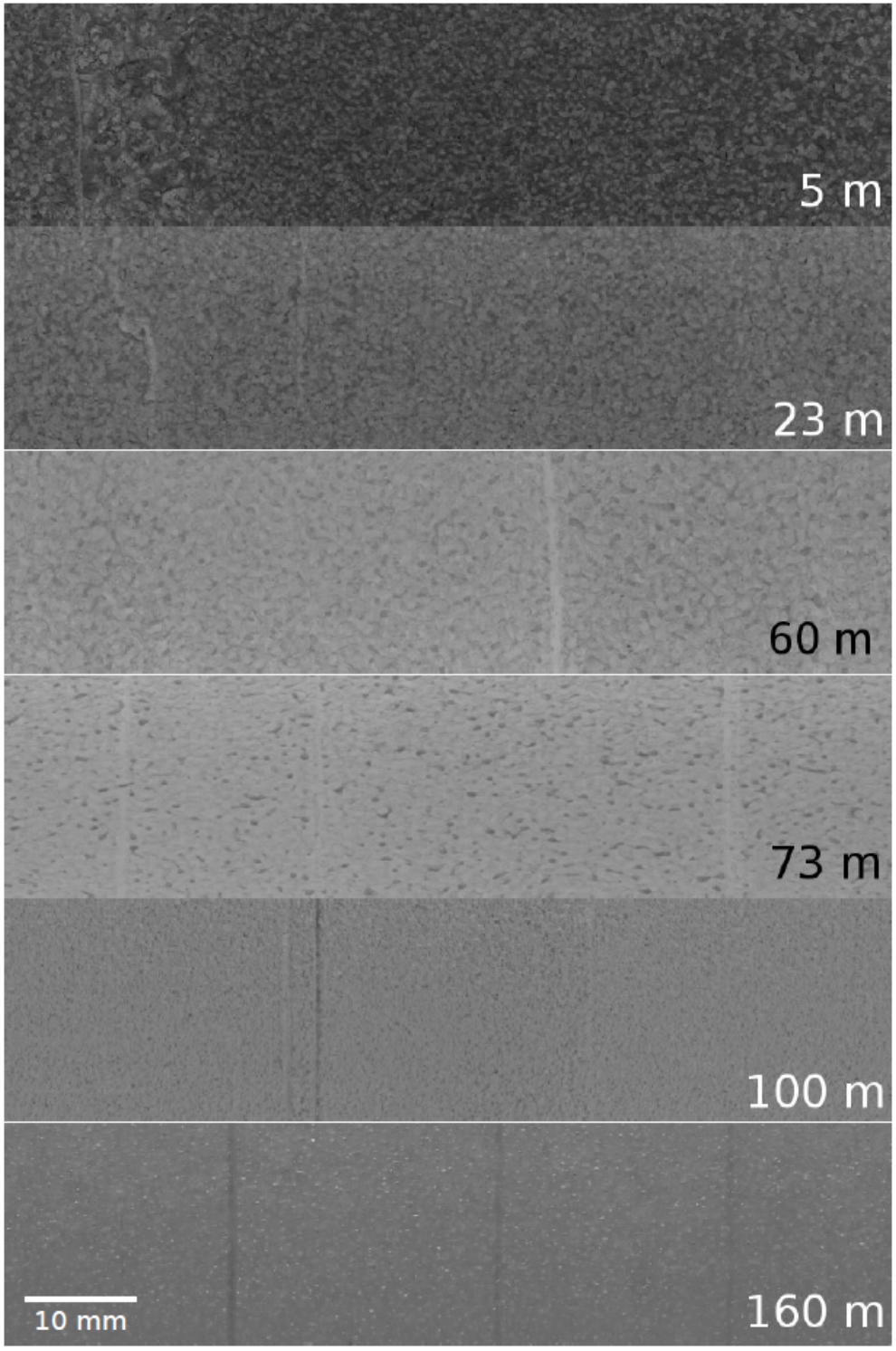
- variations in grain/bubble size
- ice lenses
- variations in brightness

How to measure?

- cross-core average
- mask core breaks

How to interpret?

- not reflectivity
- not transmission
- need a model

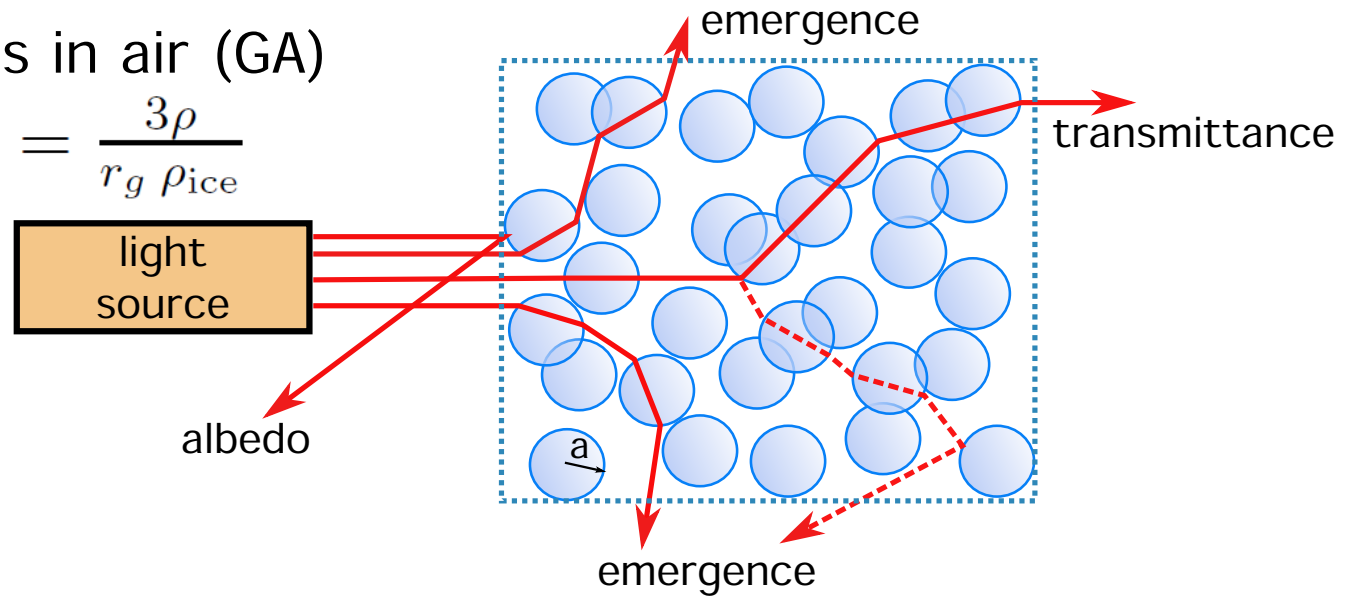


Geometric (ray-tracing) optics model of firn

The spherical cow, revisited

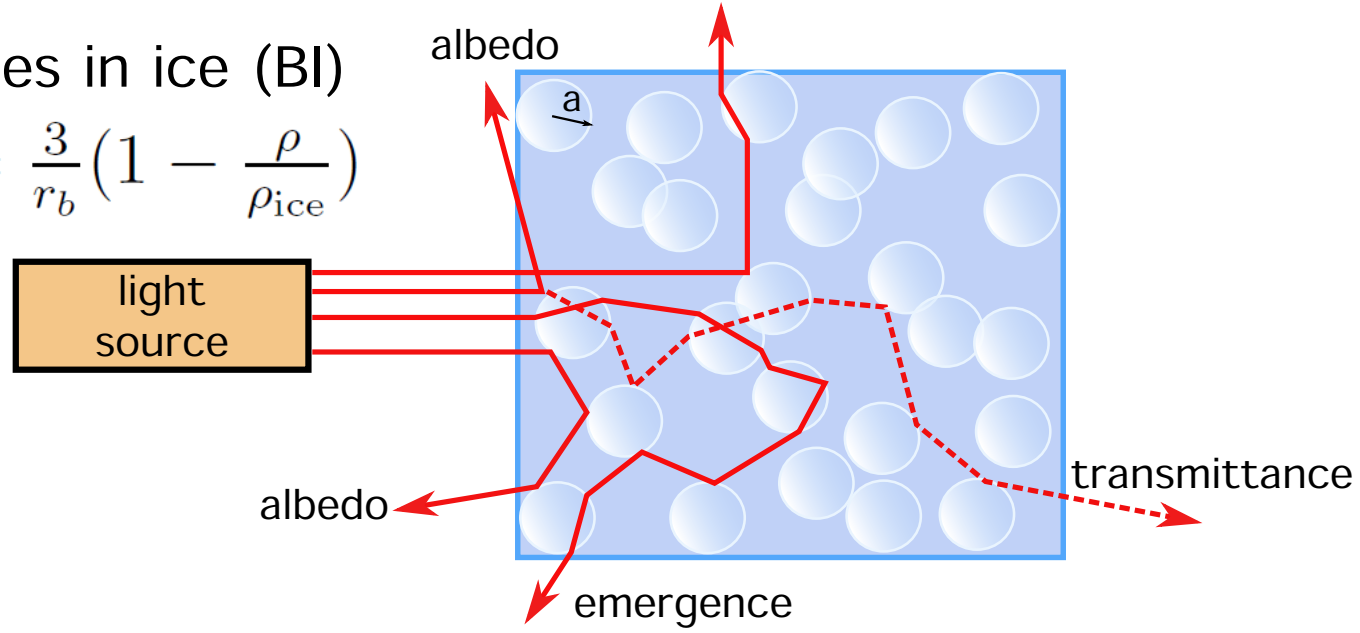
ice grains in air (GA)

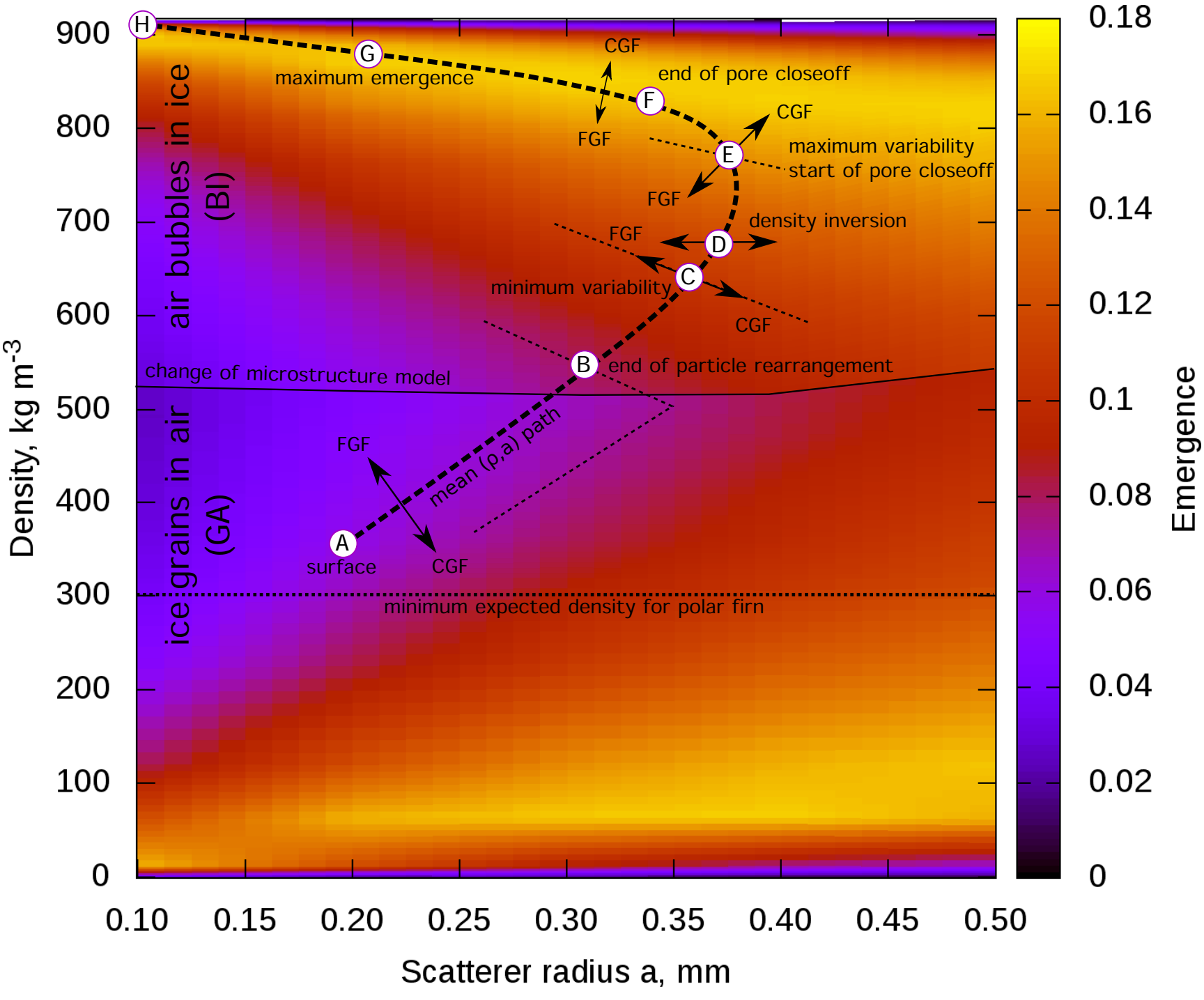
$$\mathrm{SSA}_v = \frac{3\rho}{r_g\,\rho_{\mathrm{ice}}}$$



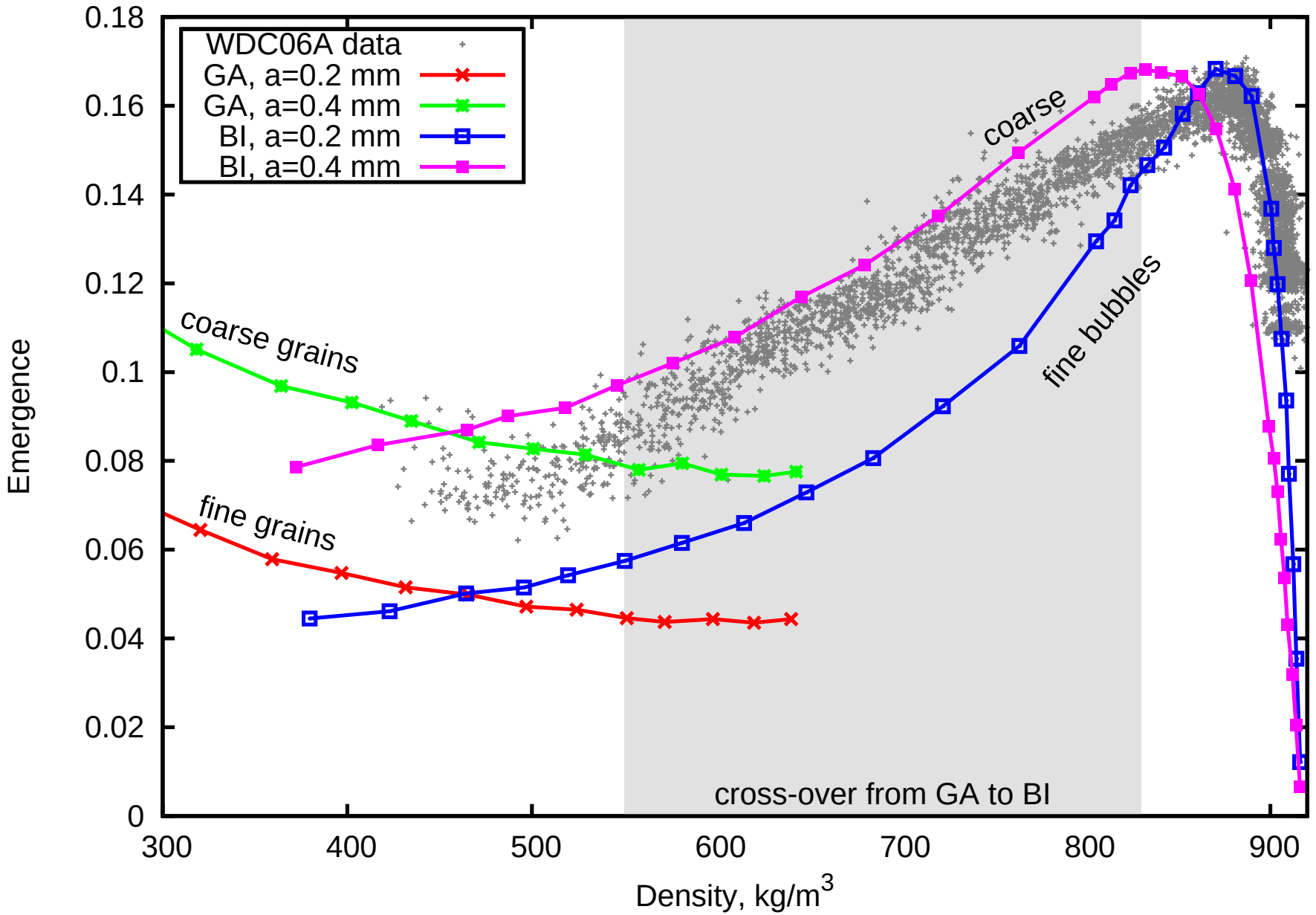
air bubbles in ice (BI)

$$\mathrm{SSA}_v = \frac{3}{r_b}\left(1 - \frac{\rho}{\rho_{\mathrm{ice}}}\right)$$

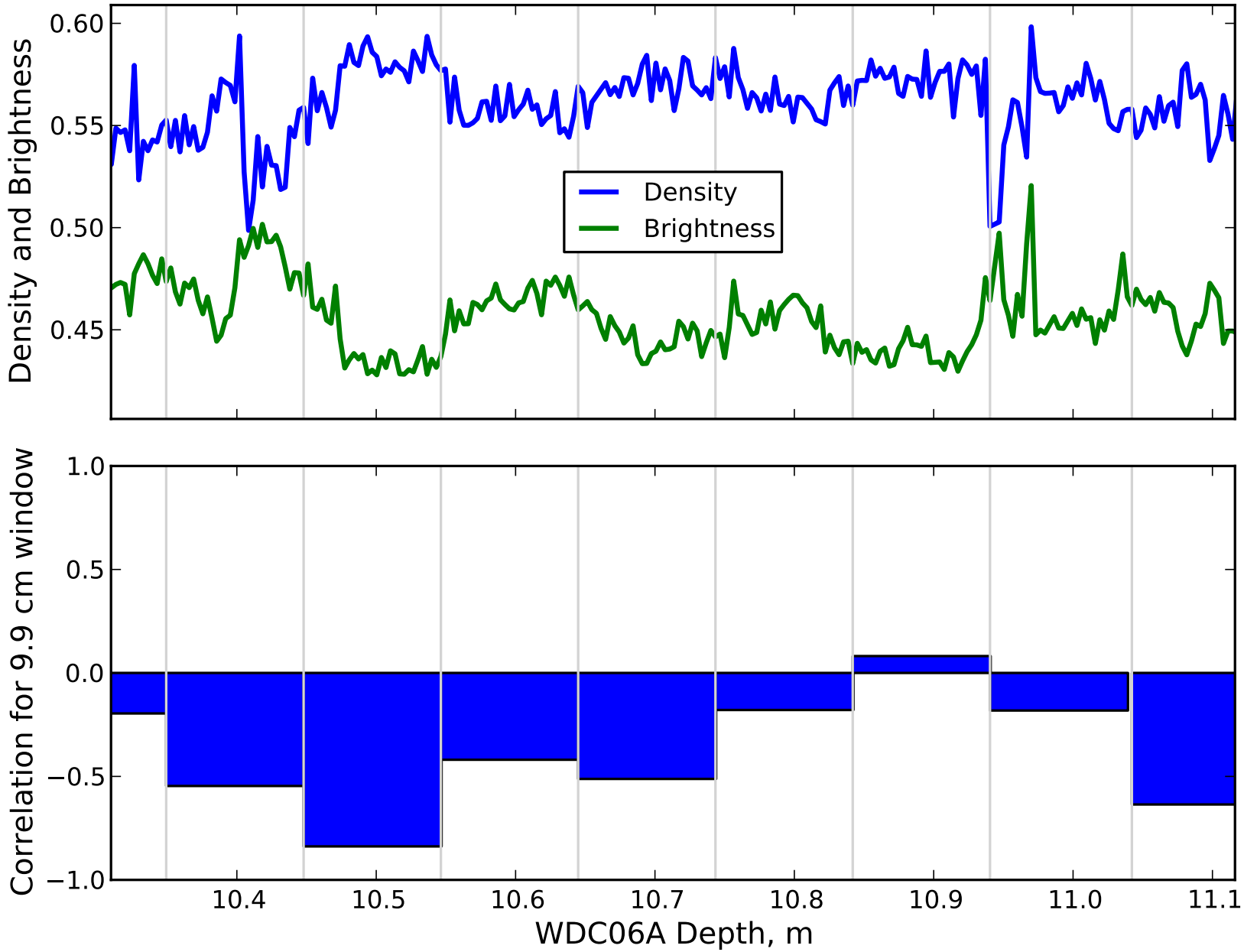



H
G
maximum emergence
CGF
end of pore closeoff
F
FGF
CGF
maximum variability
start of pore closeoff
E
FGF
density inversion
FGF
D
C
minimum variability
CGF
B
end of particle rearrangement
change of microstructure model
air bubbles in ice
(BI)
ice grains in air
(GA)
FGF
mean (ρ,a) path
A
surface
CGF
minimum expected density for polar firn
Density, kg m-3
Scatterer radius a, mm
Emergence
0
100
200
300
400
500
600
700
800
900
0.10
0.15
0.20
0.25
0.30
0.35
0.40
0.45
0.50
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0.18

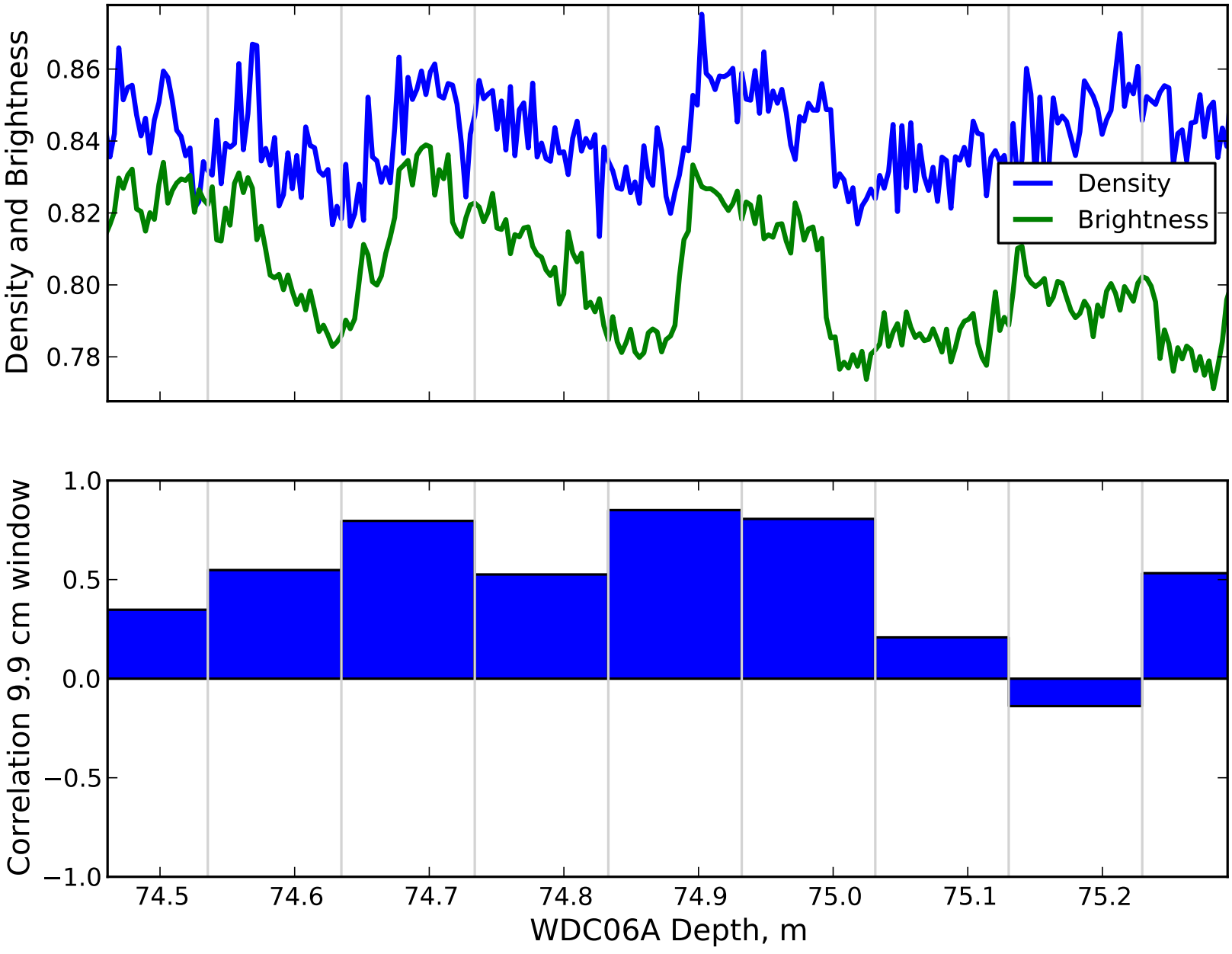
Comparison of modeled and measured emergence



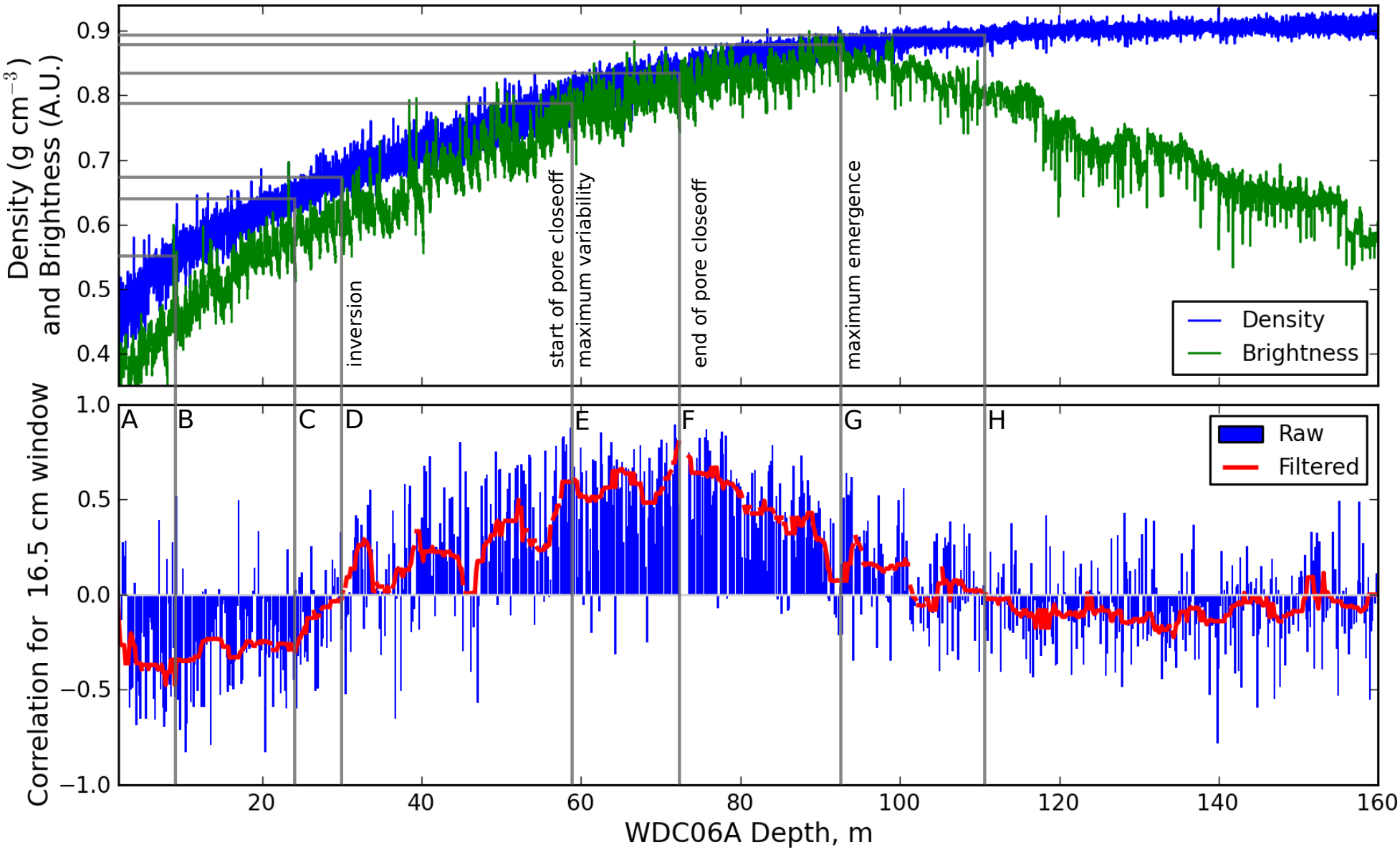
Shallow variability in WDC06A



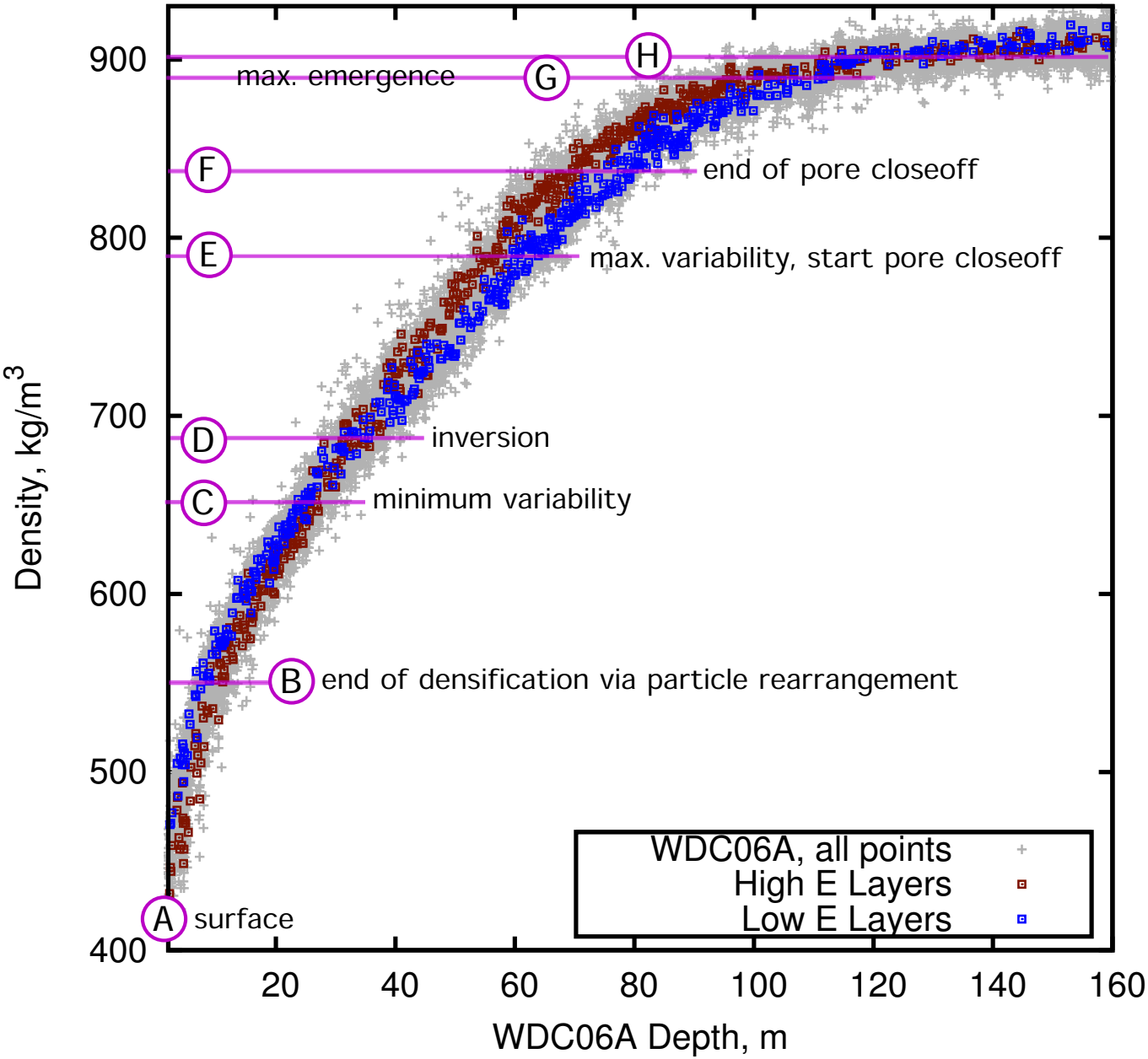
Deep variability in WDC06A



WDC06A overall optical scattering data



Evidence of MDD and density inversion in WDC06A



What is it good for?

Firn Optics & Density Profiles

- Can determine average scatterer size from density and optical scattering data
- High (mm-scale) resolution, non-destructive firn and ice microstructure data
  - In-situ XCT not possible
  - In-situ optical scattering has been done...
  - ...need high resolution, in-situ density probe

Applications

- Improved the utility of line-scan images
- Alternative to XCT for MDD studies
- Field-deployable technique for rapidly quantifying grain size: ground truthing for RADAR-based remote sensing

Acknowledgments

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- Karl Kreutz, Bess Koffman, WAIS Divide Project
- Photon Modelers and Measurers
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  - NICL: K. McGwire, G. Hargreaves