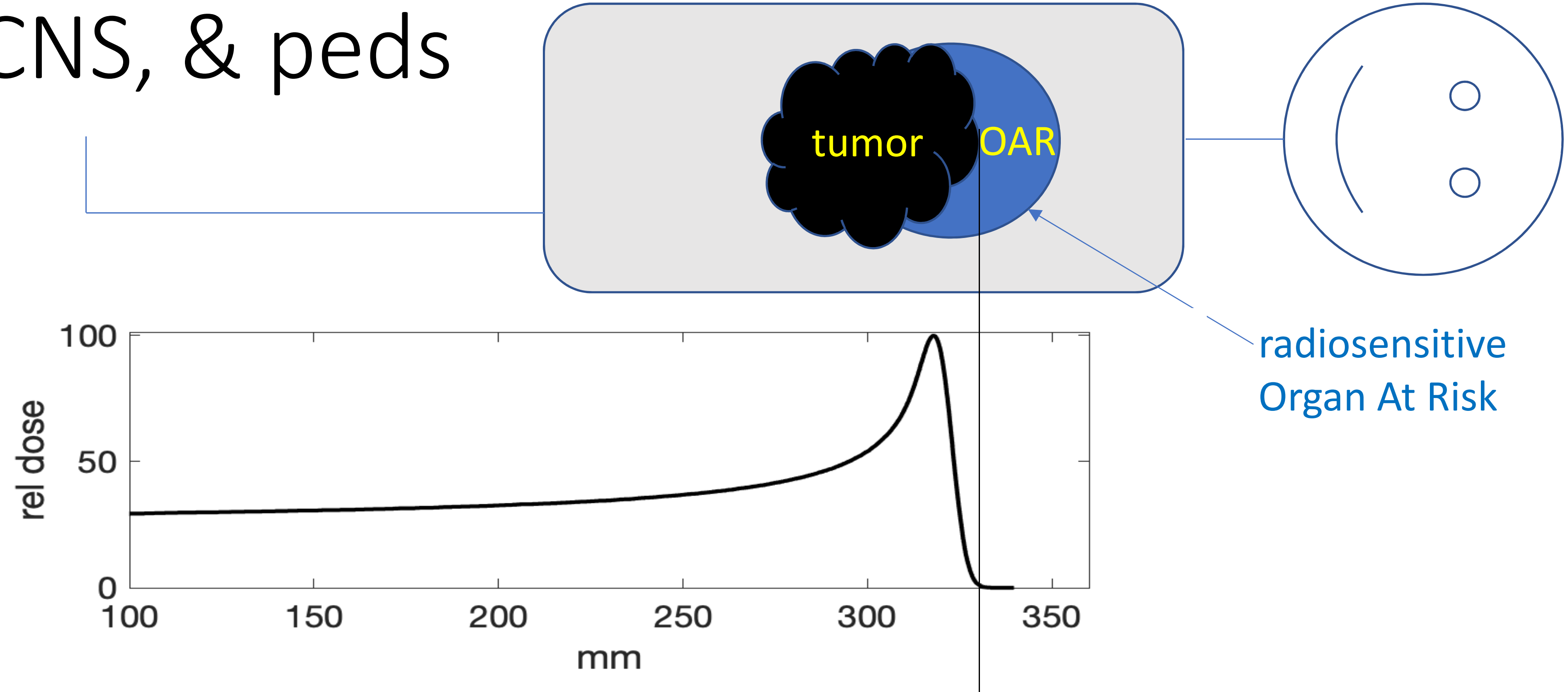
THERMOACOUSTIC RANGE VERIFICATION DESPITE ACOUSTIC HETEROGENEITY AND SOUNDSPEED ERRORS

S. K. Patch†, UW-Milwaukee & A.R.E.
B. Mustapha, Argonne National Laboratory
D. Santiago-Gonzalez , Argonne National Laboratory

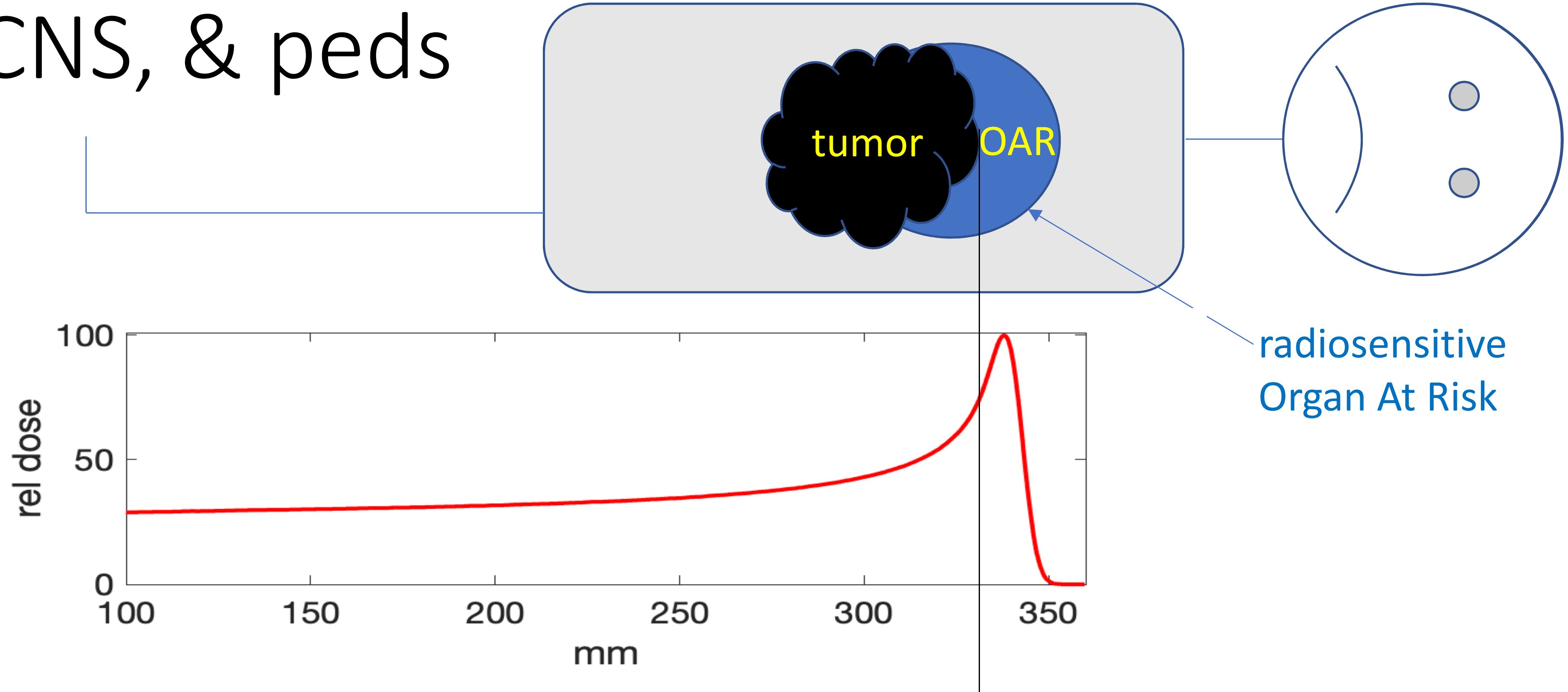
Particle therapy can minimize collateral damage

Amer Soc for Therapeutic Radiology & Oncology recommends particle therapy for (generally) brain, CNS, & peds



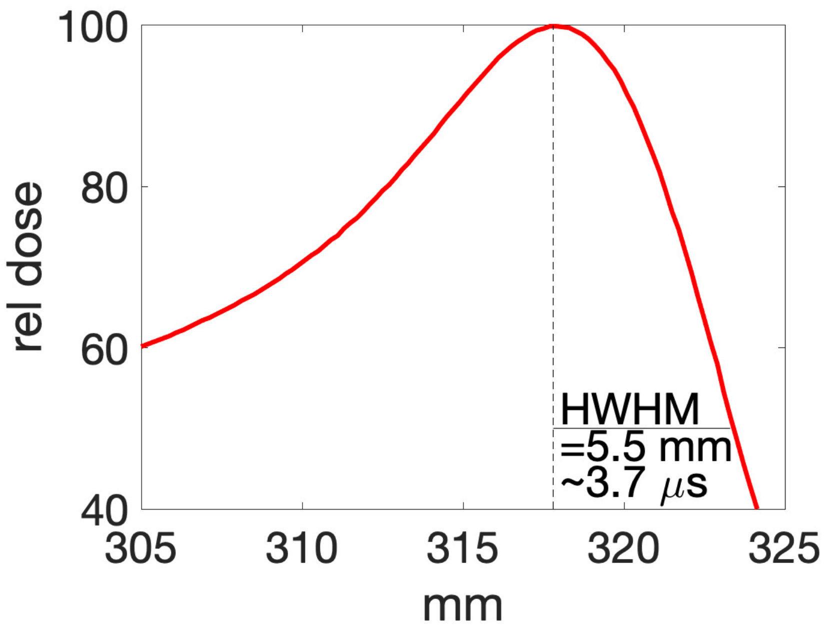
Particle therapy can *max*imize collateral damage

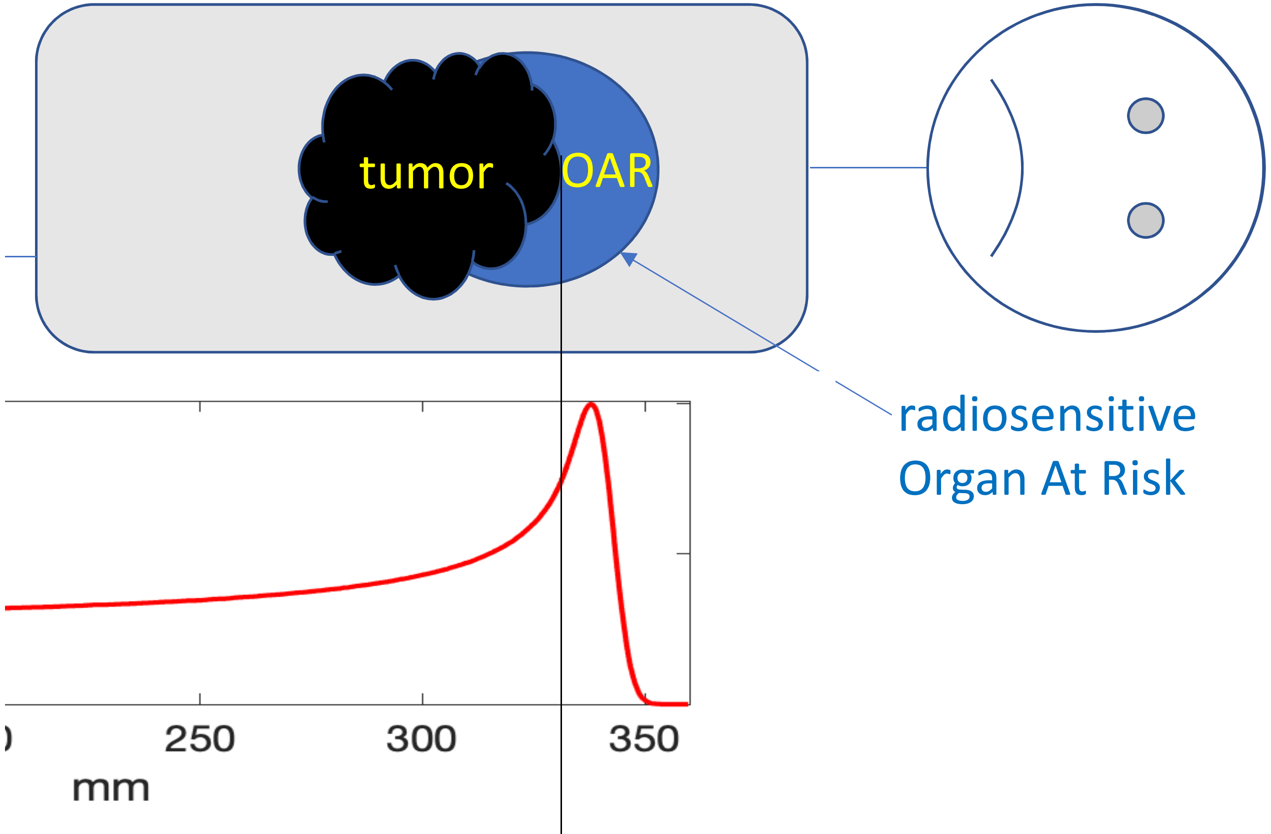
Amer Soc for Therapeutic Radiology & Oncology recommends particle therapy for (generally) brain, CNS, & peds



Particle therapy can *max*imize collateral damage

Amer Soc for Therapeutic Radiology & Oncology recommends particle therapy for (generally) brain, CNS, & peds





Patient Positioning is Critical

Patient Positioning Systems (PPS) use “room coordinates”

Patient Positioning is Critical

Patient Positioning Systems (PPS) use absolute coordinates

Treatment Planning based upon x-ray CT (“CAT scan”)
- images reconstructed in absolute coordinates
- acquired days/weeks prior to treatment, repeated infrequently

Modality	Coordinates	Physical interpretation	cost / mass / scan time
X-ray CT	absolute	ρ, “density”	\$\$\$, 1 ton, seconds
MRI	quasi-absolute	H density + relaxation times	\$\$\$, 1 ton, minutes
PET	absolute (low res.)	*511 keV* emissions	\$\$\$, 1 ton, many minutes
ultrasound	relative to soundspeed	*Z*, acoustic impedance	*\$, 3 lbs, seconds*
thermoacoustic	relative to soundspeed	induced pressure = $\Gamma\rho$ dose	*\$, 4 lbs, seconds*

co-register

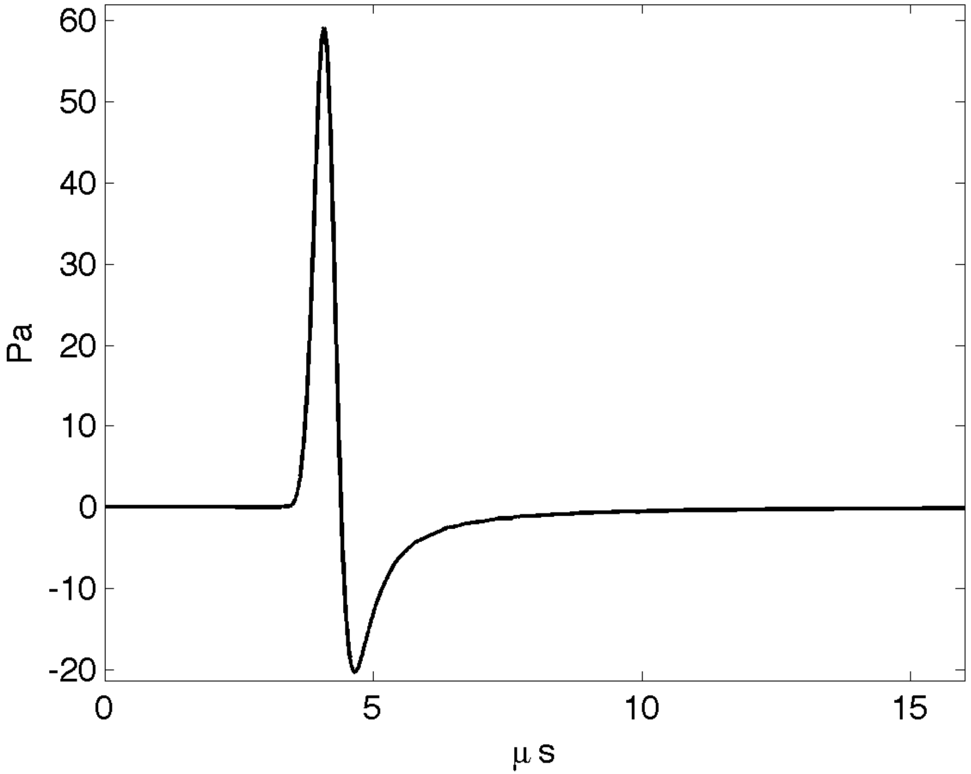
inher-ent

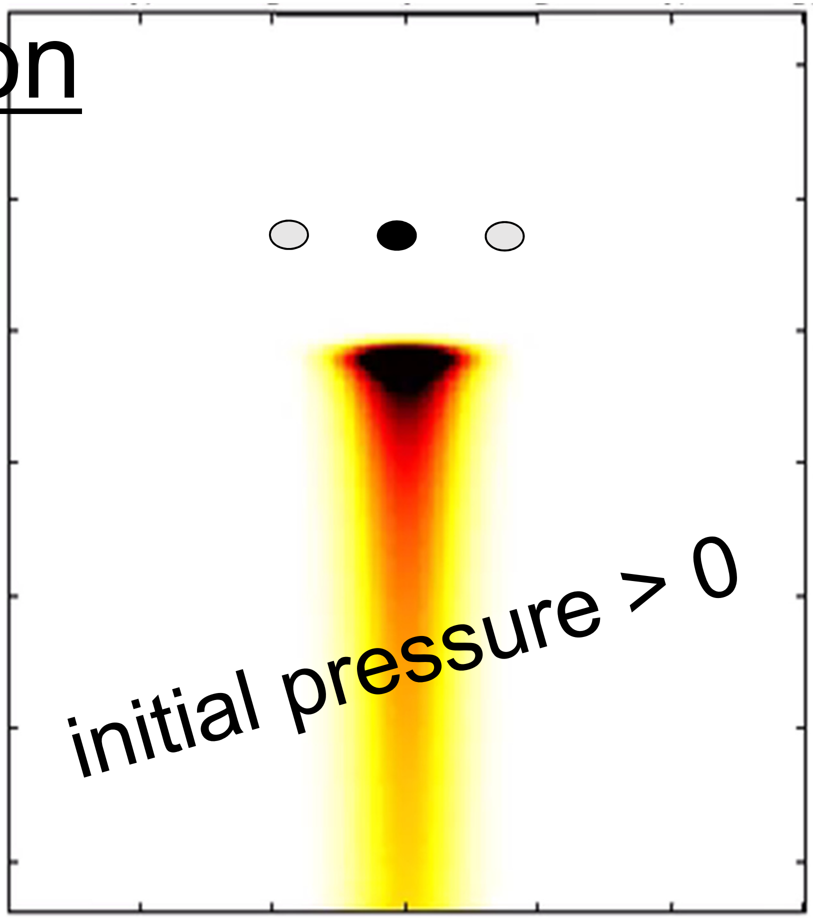
Thermoacoustic Signal Generation

$p_o(\mathbf{x}) = \Gamma\,\left({}^{E}/_{V}\right)(\mathbf{x})$ instantaneous deposition

$\Gamma \sim 0.1$ in water, 0.2 in muscle and organ, 0.7 in fat

49 MeV: 4 pC instantaneously



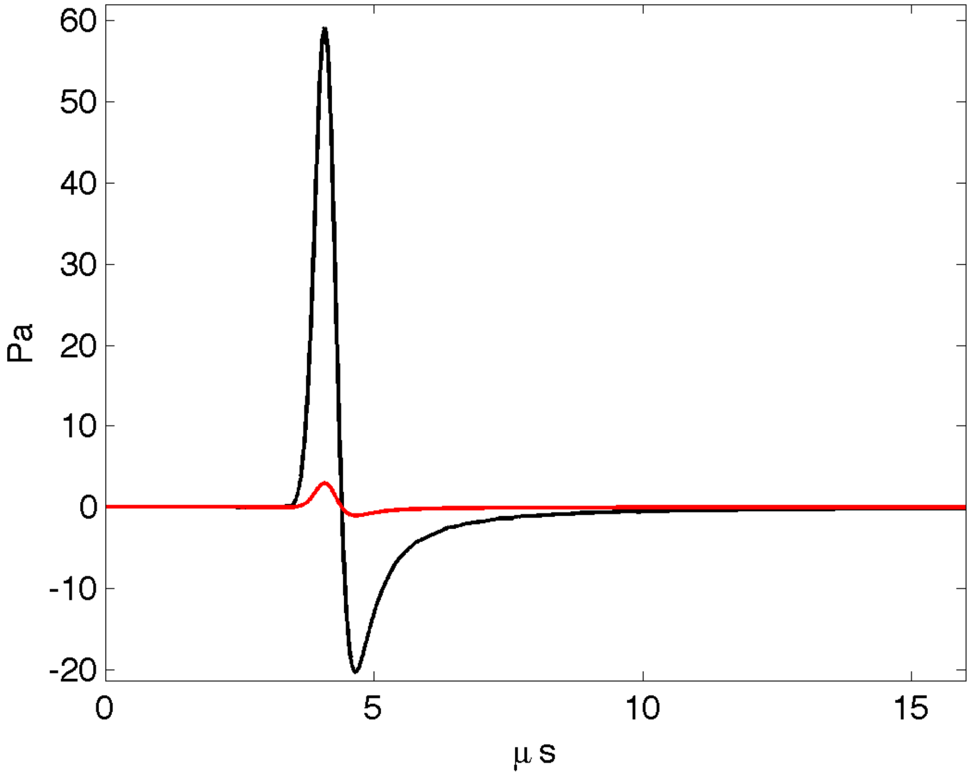


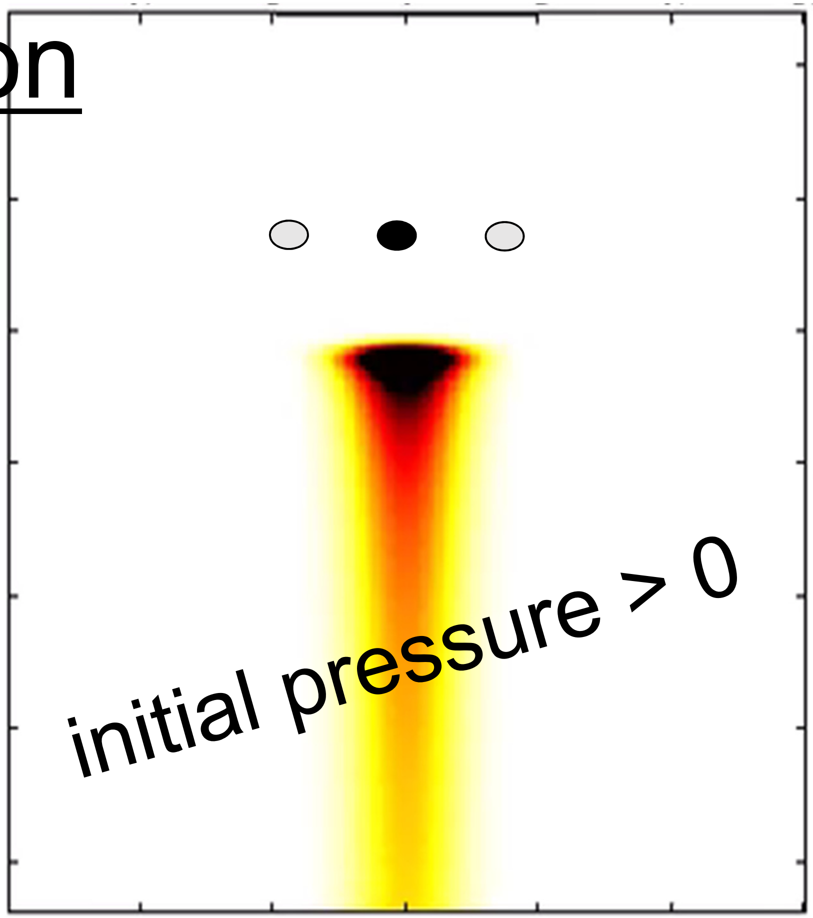
Thermoacoustic Signal Generation

$p_o(\mathbf{x}) = \Gamma\,({}^{E}/_{V})\,(\mathbf{x})$ instantaneous deposition

$\Gamma \sim 0.1$ in water, 0.2 in muscle and organ, 0.7 in fat

49 MeV: 4 pC in 2 μs



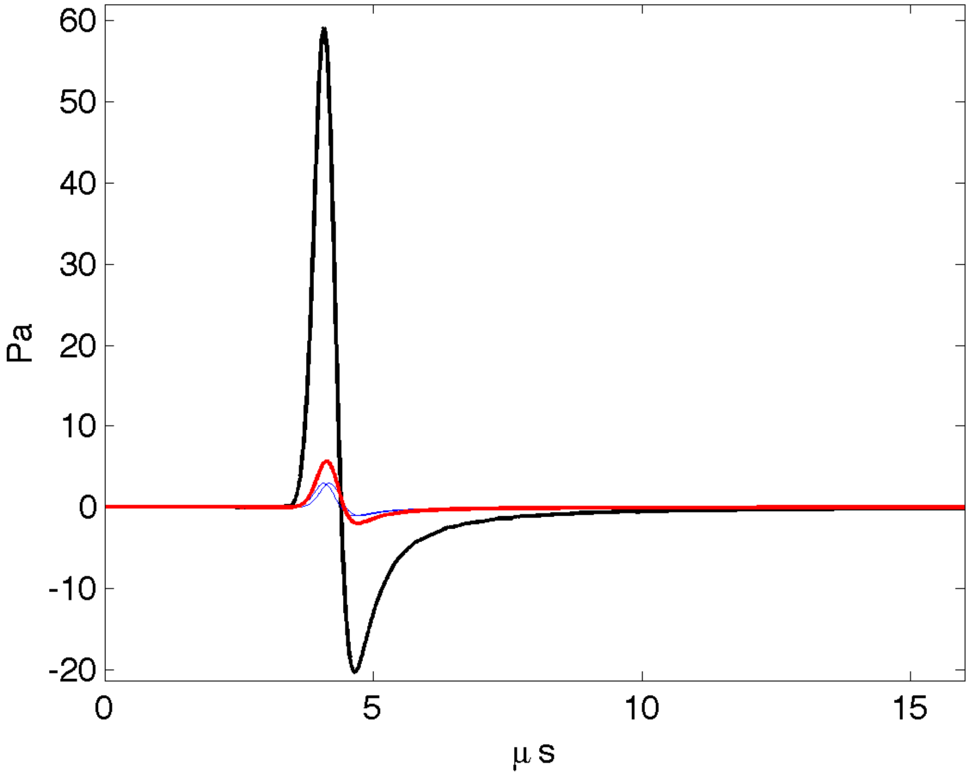


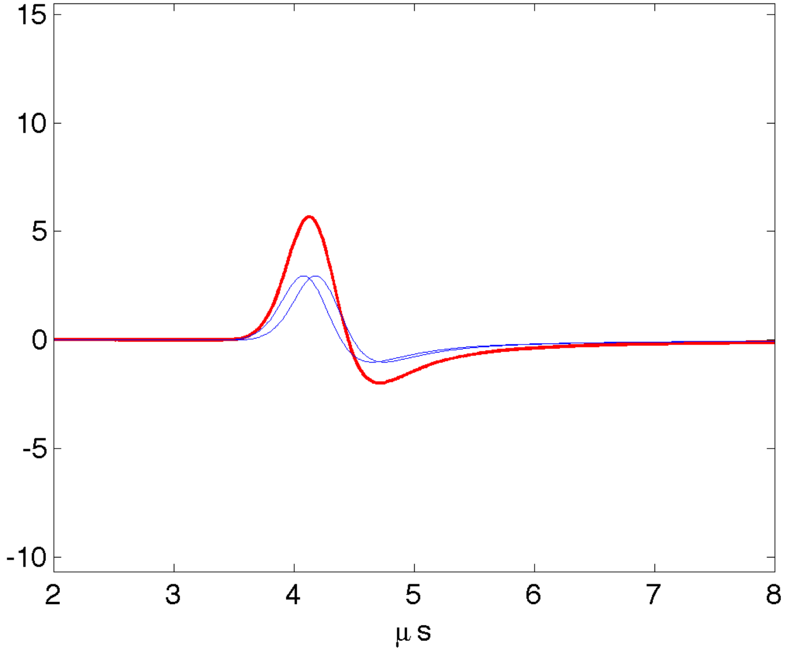
Thermoacoustic Signal Generation

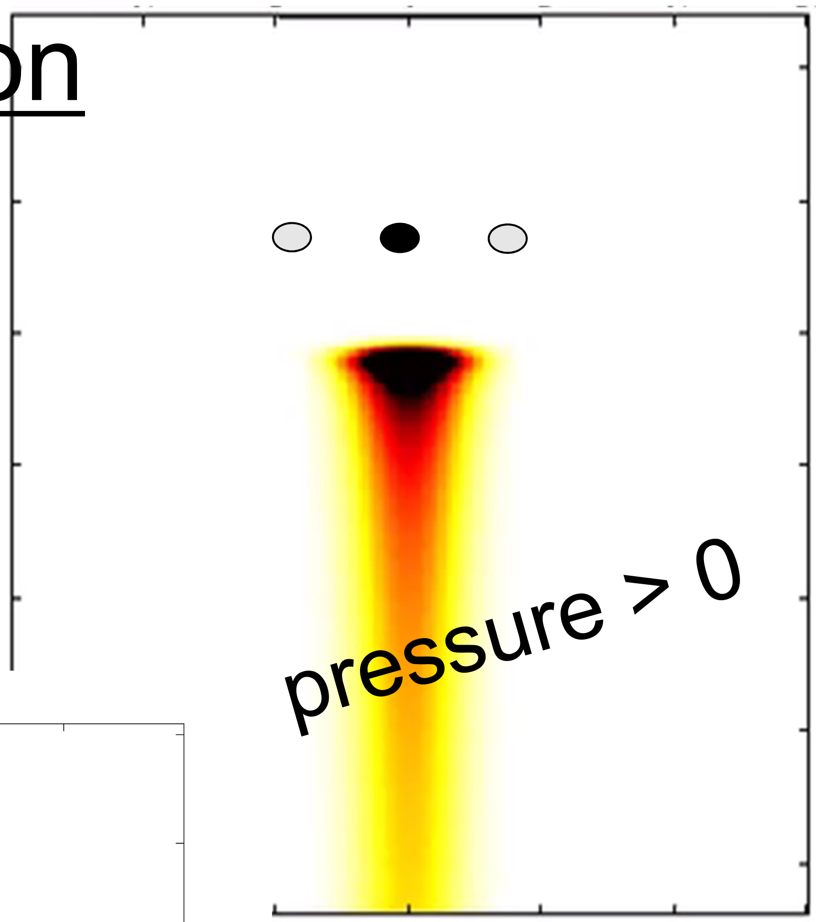
$p_o(\mathbf{x}) = \Gamma\,(E/V)\,(\mathbf{x})$ instantaneous deposition

$\Gamma \sim 0.1$ in water, 0.2 in muscle and organ, 0.7 in fat

49 MeV: 4 pC in $2\ \mu s$





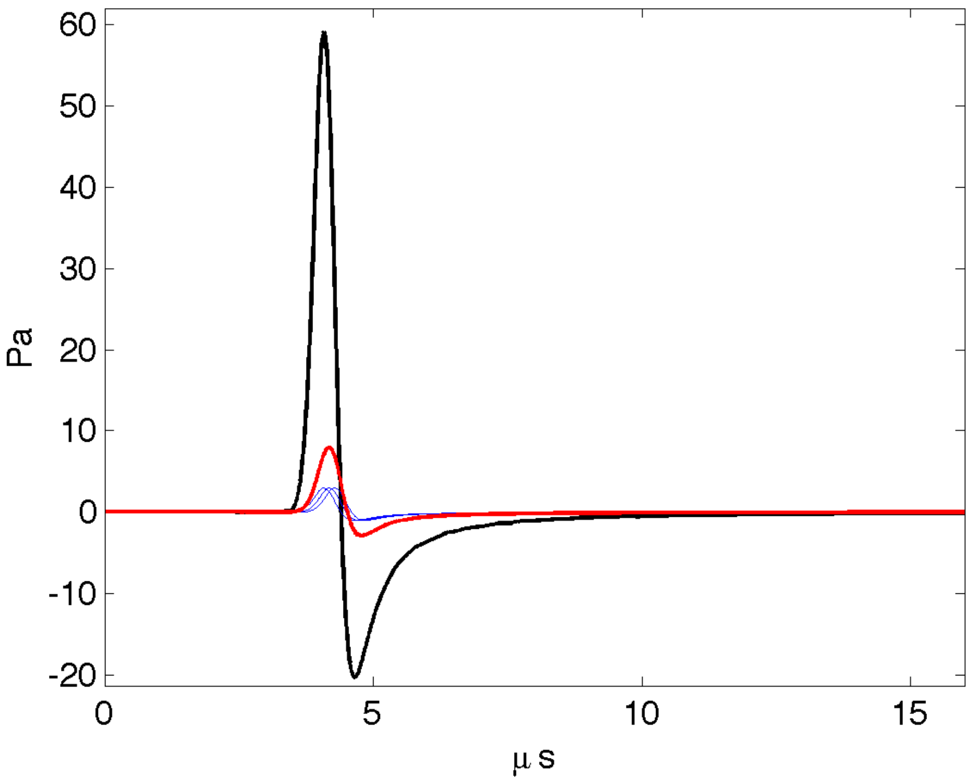


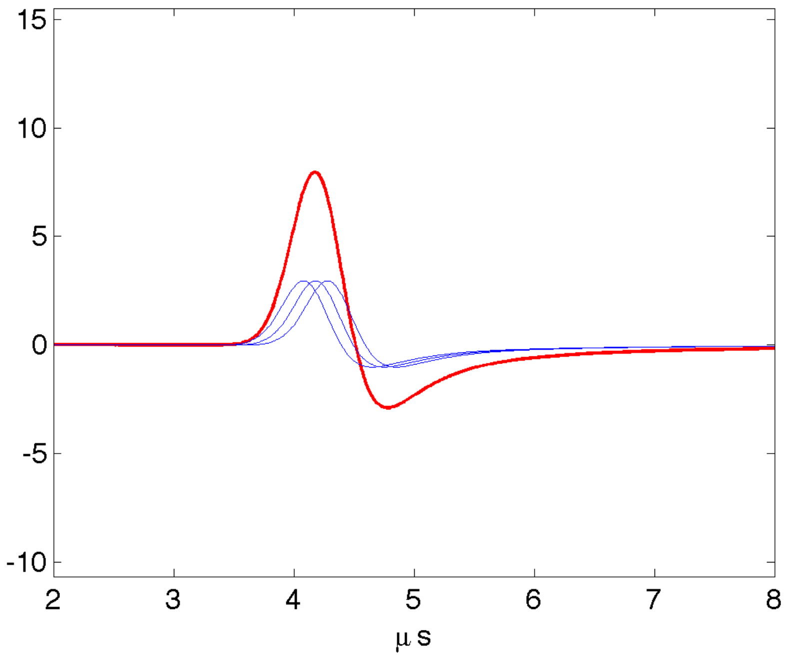
Thermoacoustic Signal Generation

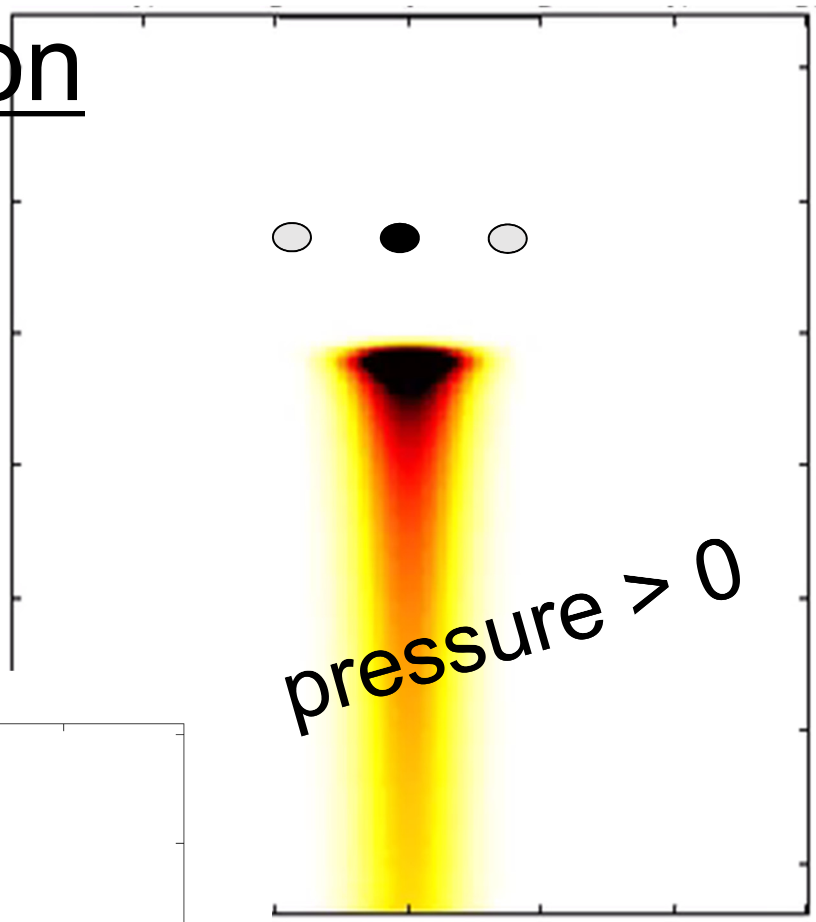
$p_o(\mathbf{x}) = \Gamma\,(^{E}/_{V})\,(\mathbf{x})$ instantaneous deposition

$\Gamma \sim 0.1$ in water, 0.2 in muscle and organ, 0.7 in fat

49 MeV: 4 pC in 2 μs



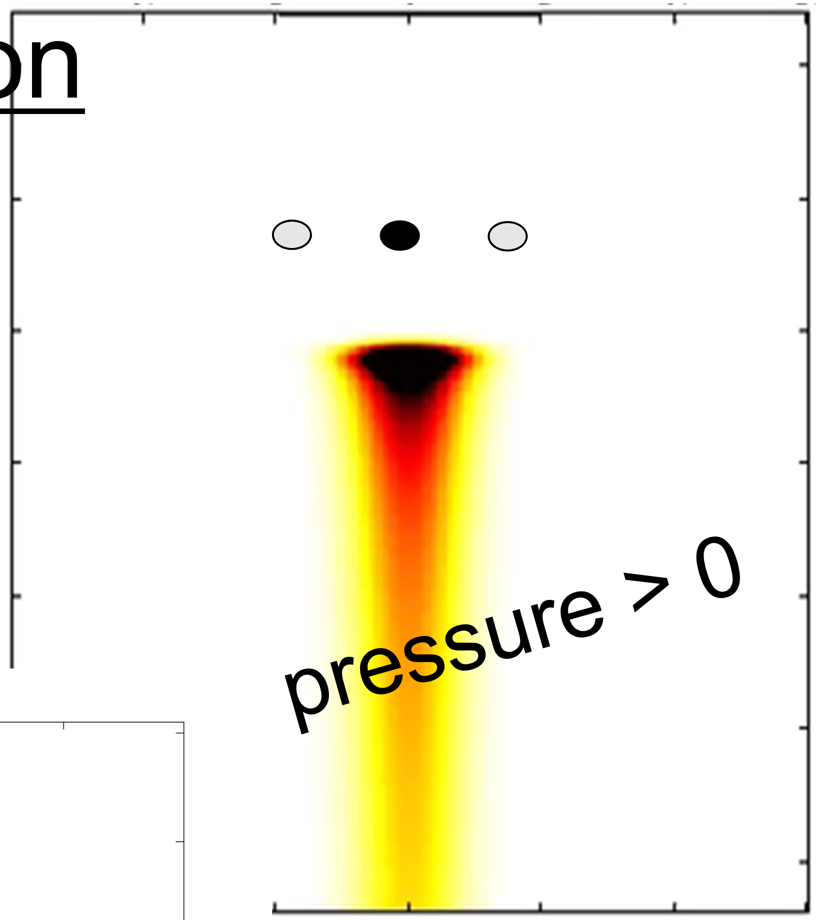




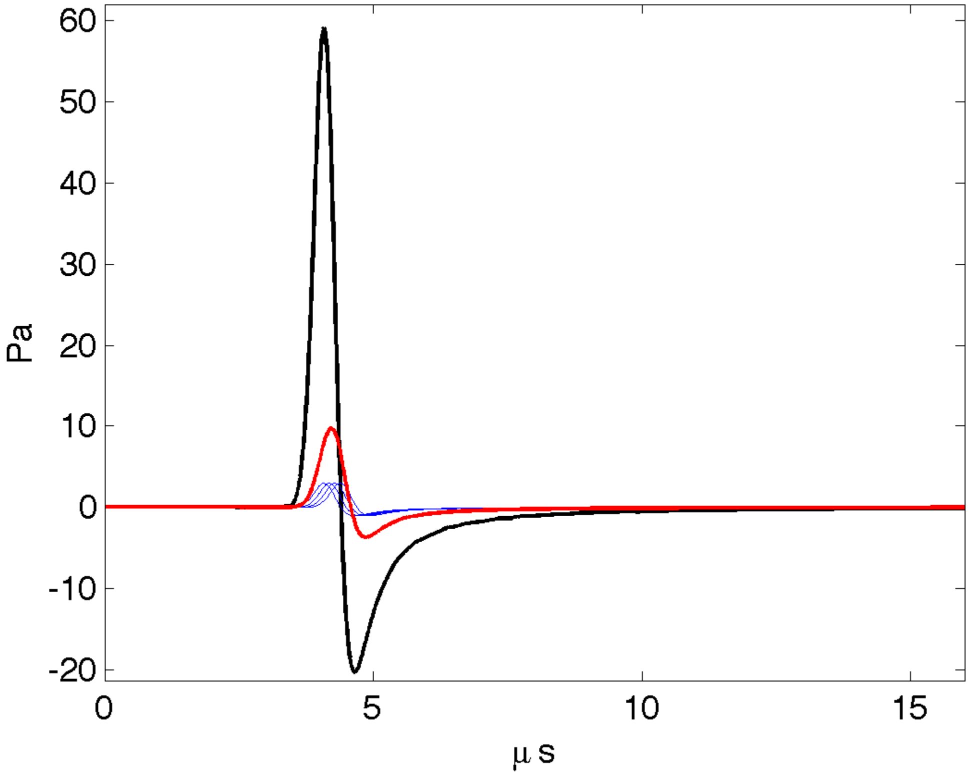
Thermoacoustic Signal Generation

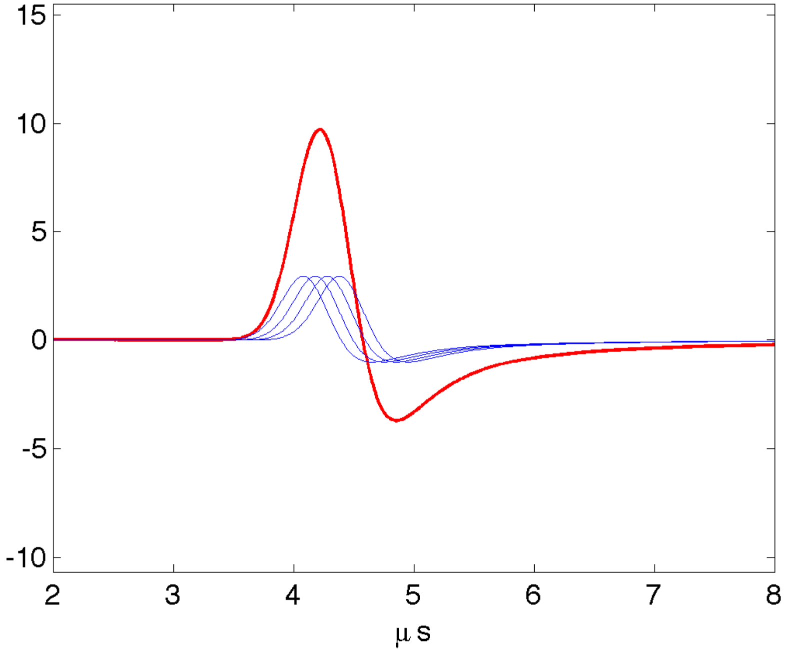
$p_o(\mathbf{x}) = \Gamma\,(E/V)\,(\mathbf{x})$ instantaneous deposition

$\Gamma \sim 0.1$ in water, 0.2 in muscle and organ, 0.7 in fat



49 MeV: 4 pC in 2 μs

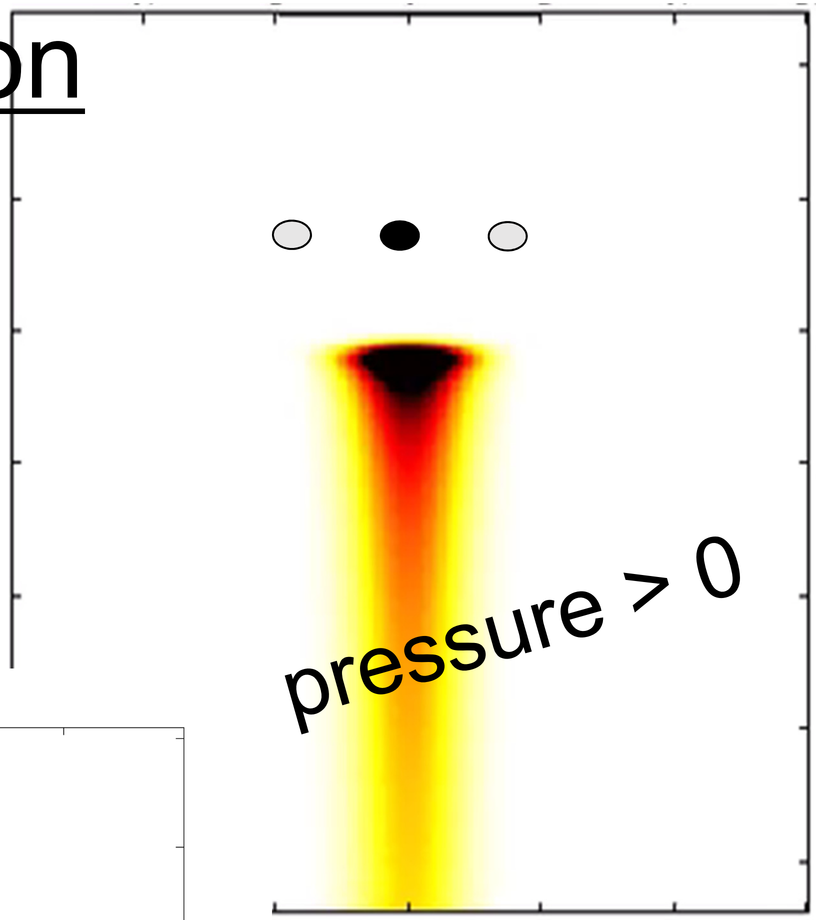




Thermoacoustic Signal Generation

$p_o(\mathbf{x}) = \Gamma \, ({}^{E}/_{V}) \, (\mathbf{x})$ instantaneous deposition

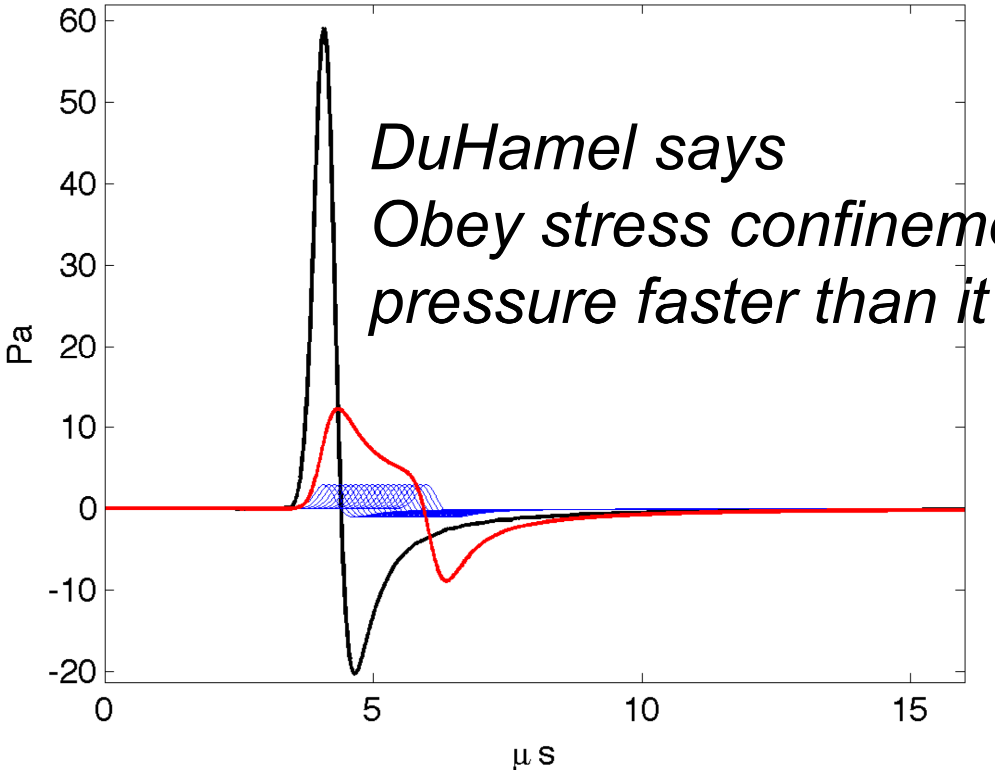
$\Gamma \sim 0.1$ in water, 0.2 in muscle and organ, 0.7 in fat



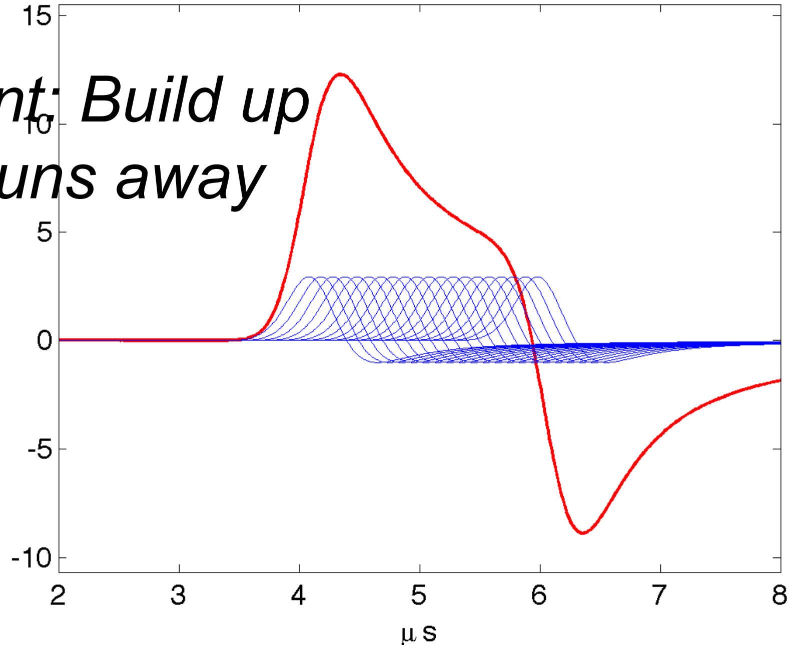
pressure > 0

2D-kwave sim

49 MeV: 4 pC in $2\ \mu s$



DuHamel says
Obey stress confinement: Build up pressure faster than it runs away



Thermoacoustics History

Emissions detected in fluids (in late 70's) : Sulak *et al,*
Askariyan, *et al*

Emissions detected in patients (mid '90s) : Hayakawa, *et al*

Recent resurgence (2013 – present) : Parodi, Jones/Avery, SKP

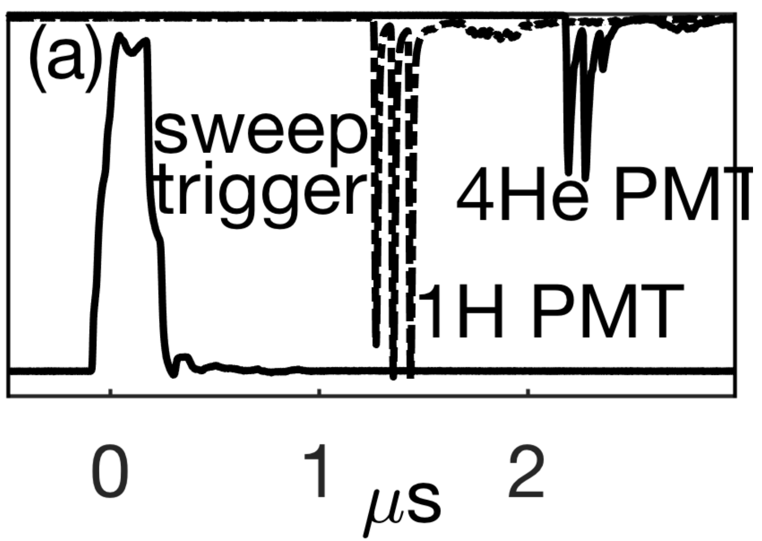
However, until recently primary criticism was errors (absolute) induced by soundspeed inhomogeneity.

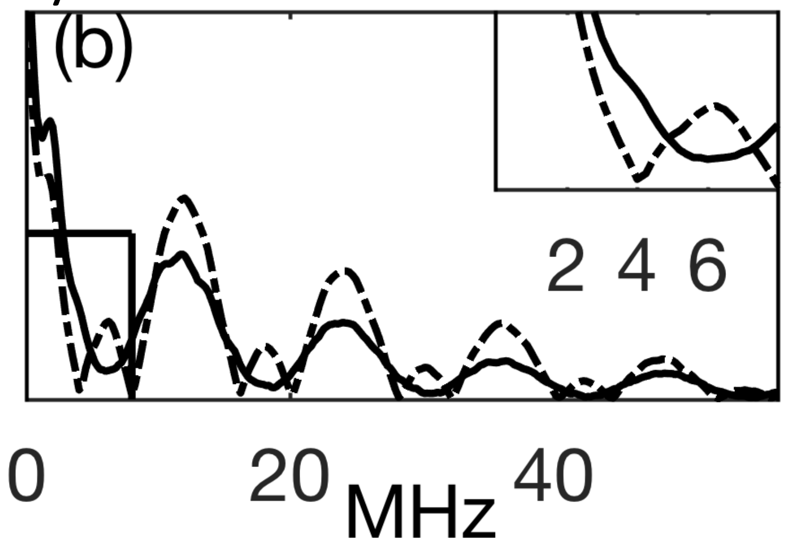
Synchrocyclotron pulse durations $\leq TOF \sim 2\,HWHM/v_s$

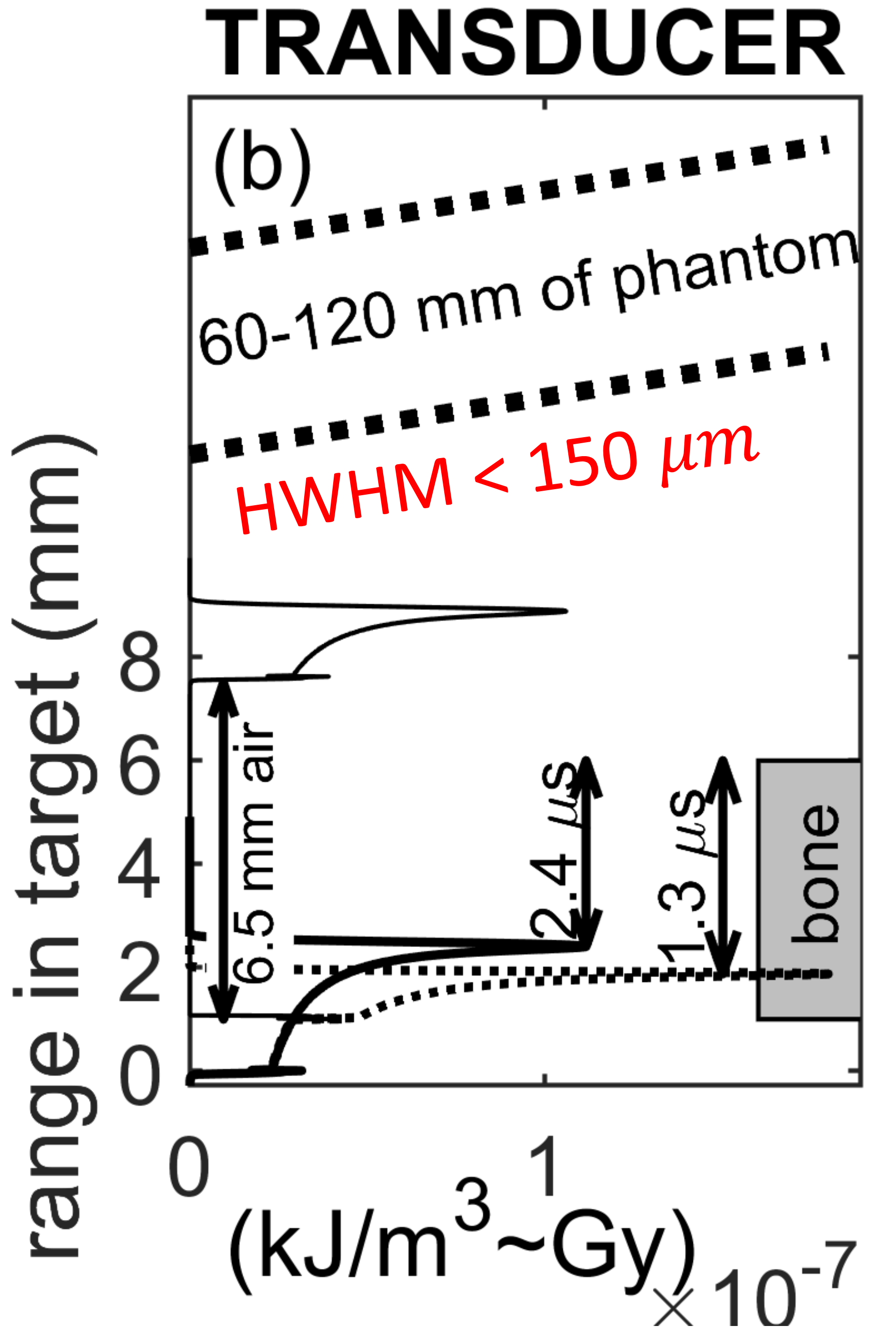
- $6\ \mu s$ Mevion@WUSTL;
- $4.5 - 5\ \mu s$ (IBA S2C2 @ Newport)

Thermoacoustics @ ATLAS

low E beams
- particle range < 2.5 mm
  - minimal straggle, sharp Bragg curve
    - fast delivery for stress confinement
      - bandwidth in ultrasound regime, detect TA emissions with 1-4 MHz ultrasound array

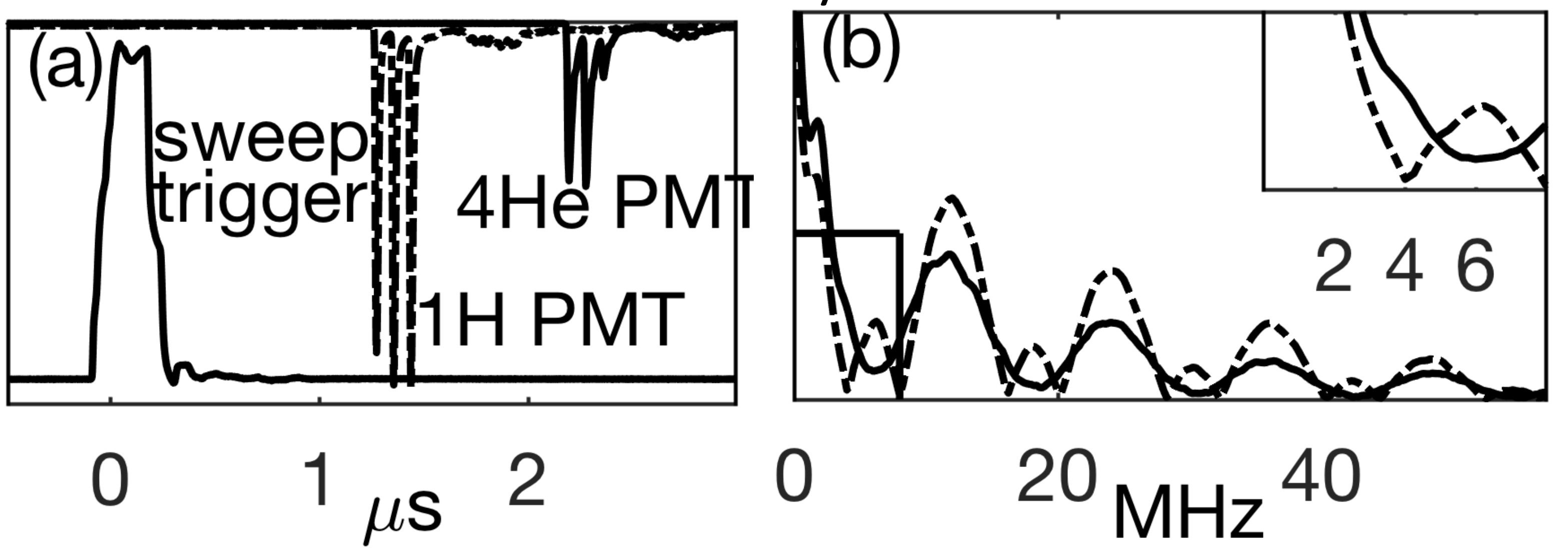


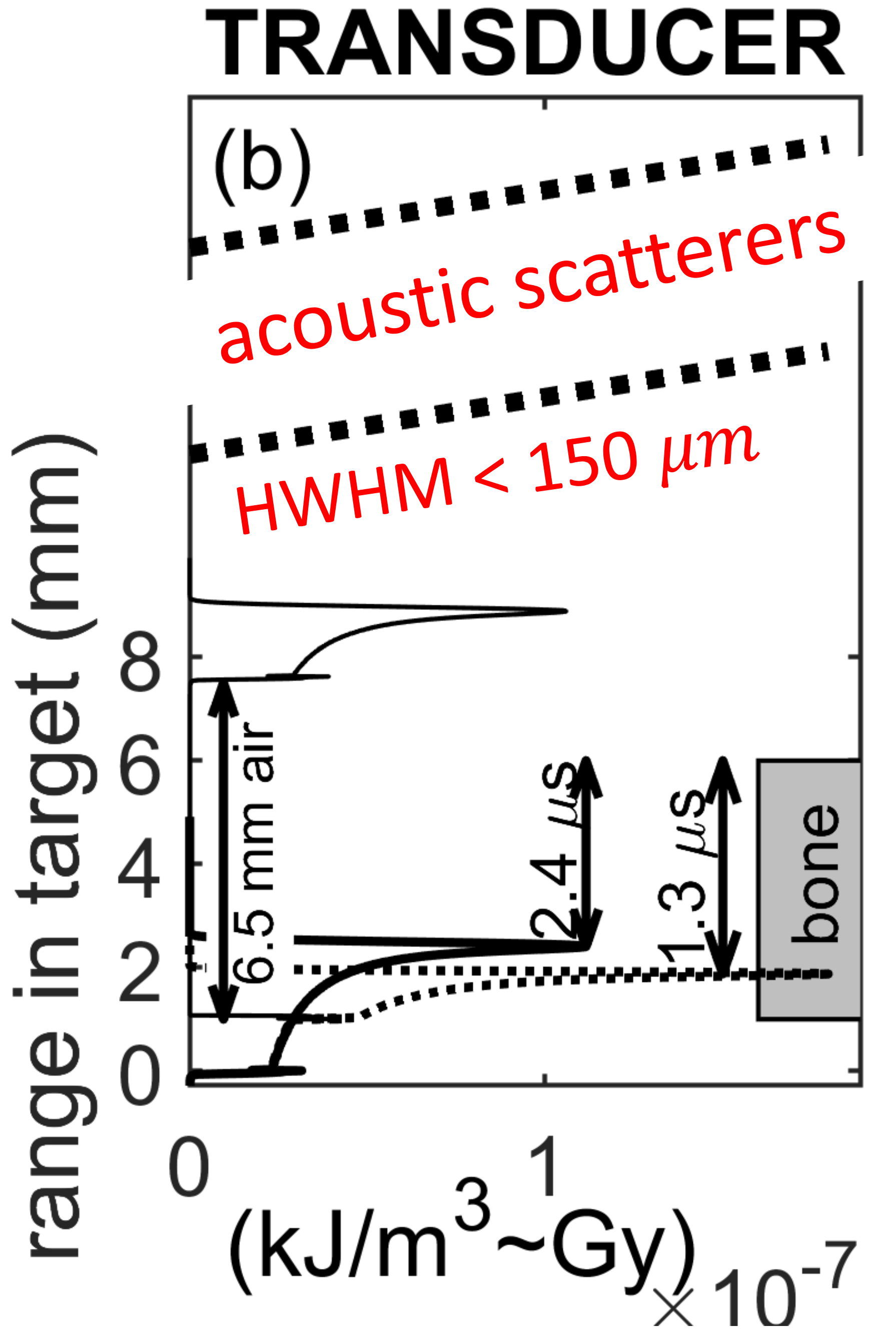




Thermoacoustics @ ATLAS

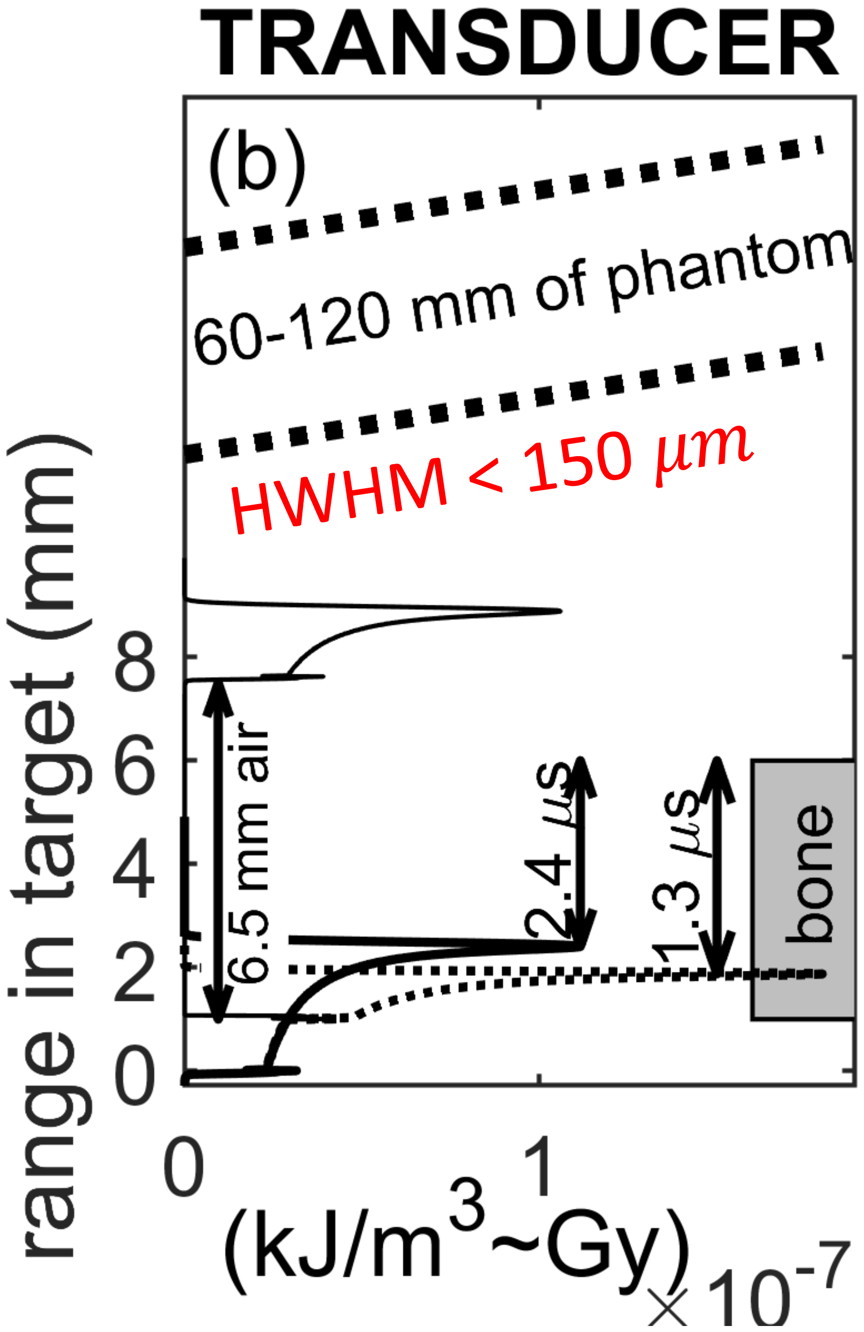
low E beams
- particle range < 2.5 mm
  - minimal straggle, sharp Bragg curve
    - fast delivery for stress confinement
      - bandwidth in ultrasound regime, detect TA emissions with 1-4 MHz ultrasound array





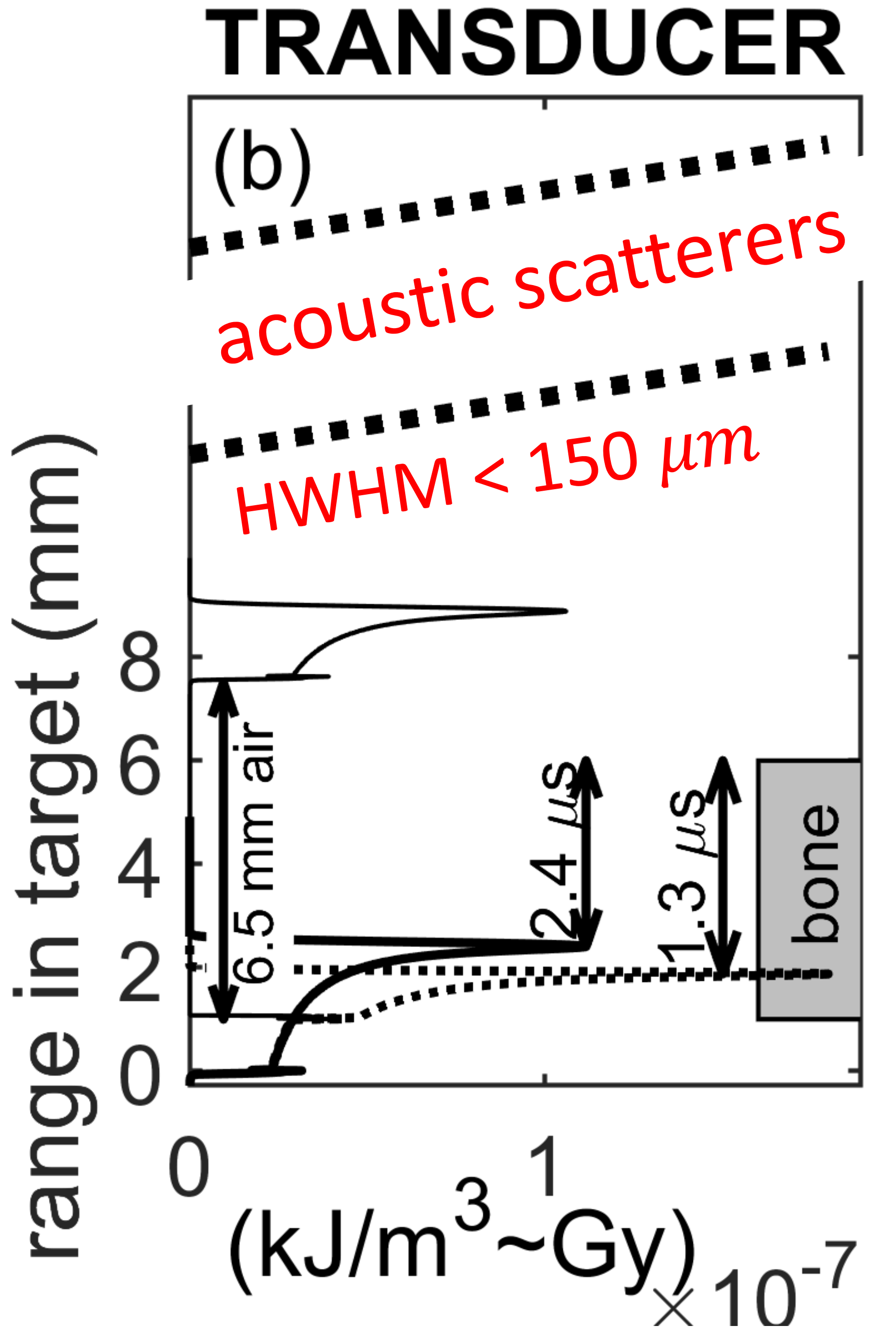
Thermoacoustics @ ATLAS

60 MeV 4He
- Ti foil vacuum exit window
- acrylic tape liquid entry window
- 165 pA *average* current, 100 Hz PRF
- FWHM: 3.9 mm horiz. / 6.9 mm vert.
- safflower oil target
- CIRS bone and in-house gelatin



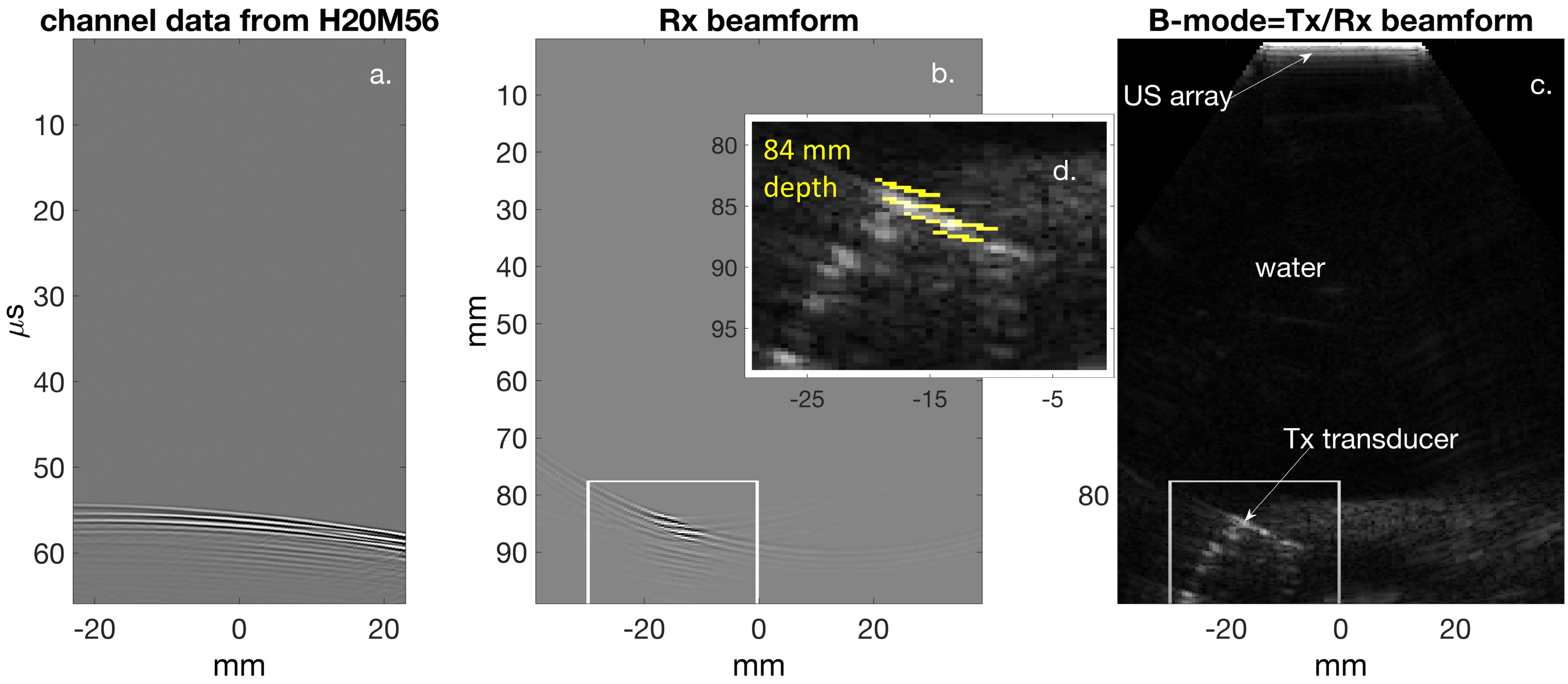
Thermoacoustics @ ATLAS

60 MeV 4He
- Ti foil vacuum exit window
- acrylic tape liquid entry window
- 165 pA *average* current, 100 Hz PRF
- FWHM: 3.9 mm horiz. / 6.9 mm vert.
- safflower oil target
- CIRS bone and in-house gelatin



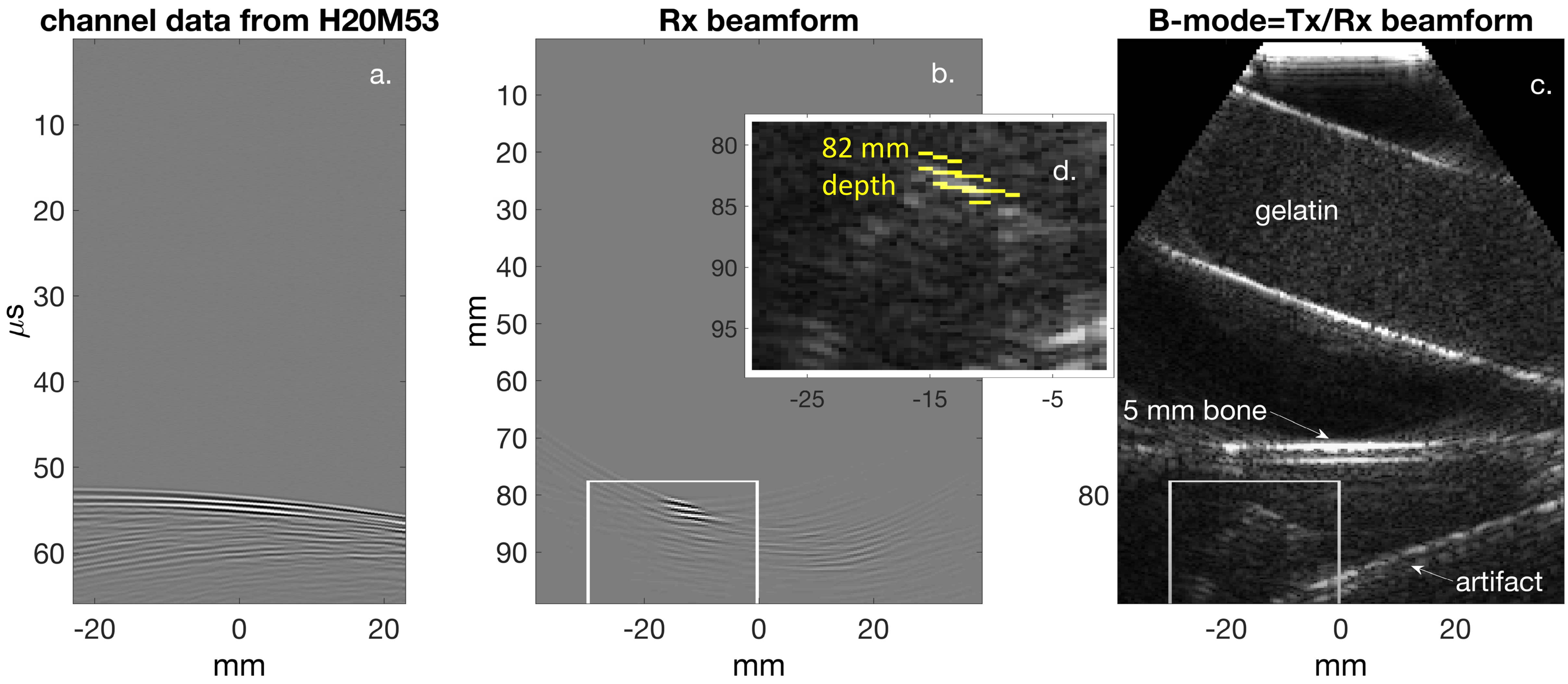
Spatial variations deform US; shift thermoacoustic

Benchtop Prep with “visible” acoustic source



Spatial variations deform US; shift thermoacoustic

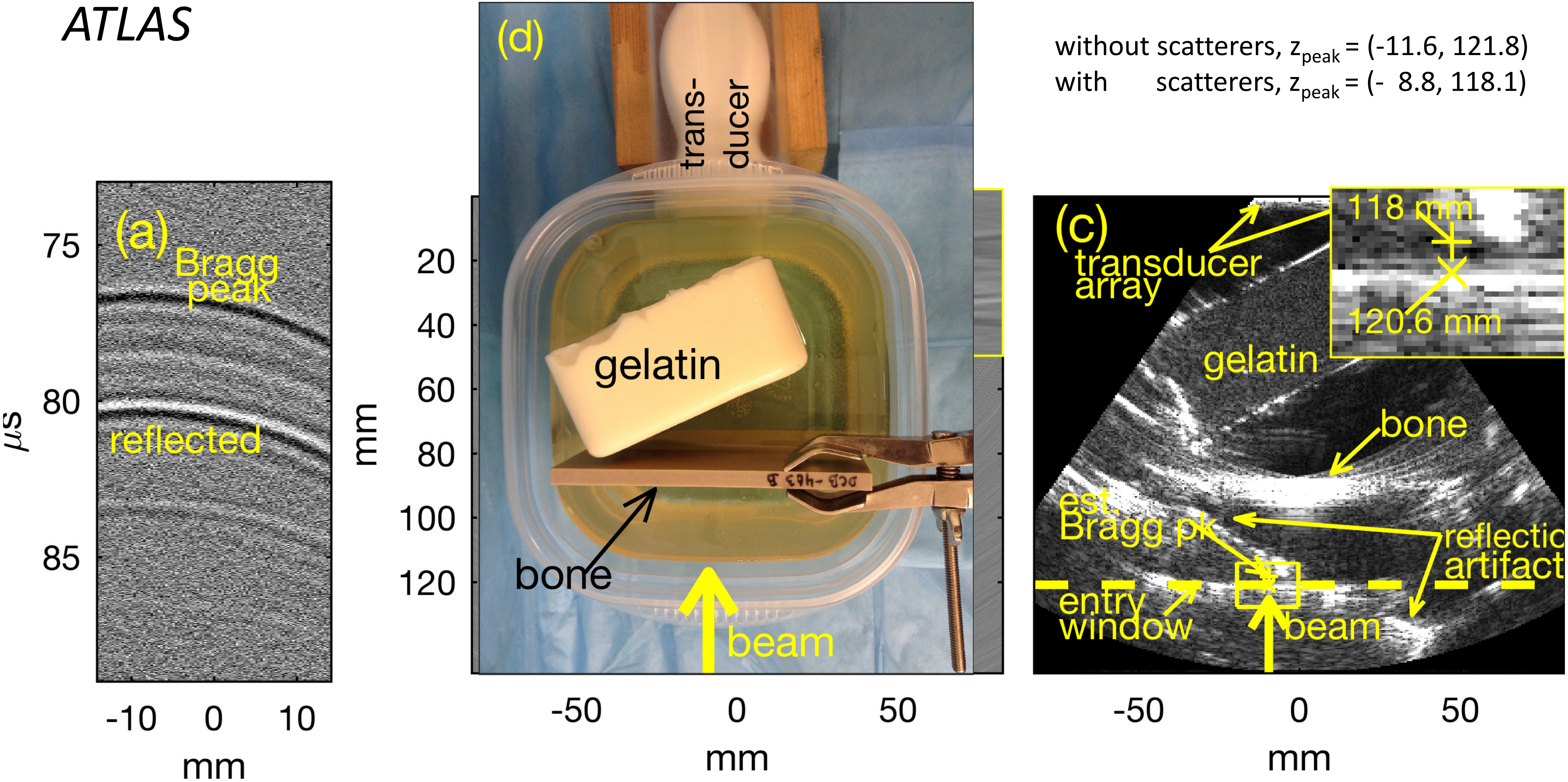
Benchtop Prep with “visible” acoustic source + acoustic scatterers



Spatial variations deform US; shift thermoacoustic

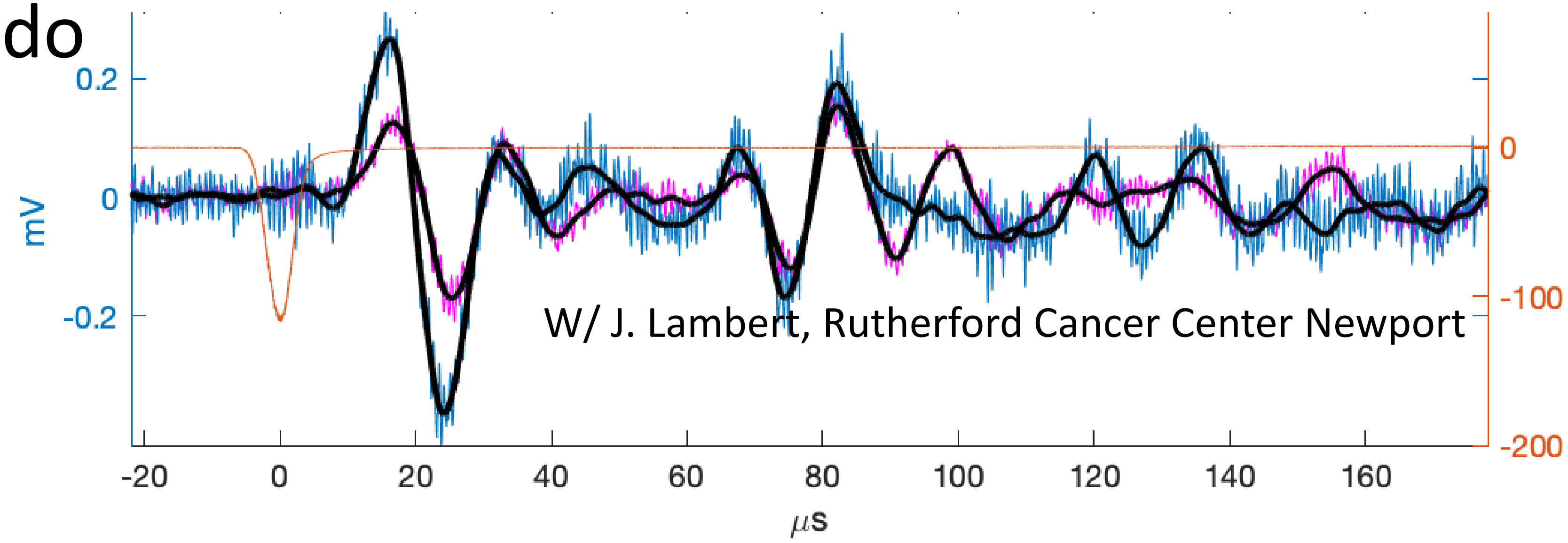
ATLAS

without scatterers, z_{peak} = (-11.6, 121.8)
with scatterers, z_{peak} = (- 8.8, 118.1)



Conclusions

- Thermoacoustic range verification is robust to acoustic heterogeneity *relative to ultrasound image*
- CT-ultrasound co-registration is a solved problem, sold by most major vendors
- preliminary measurements w/IBA S2C2 encouraging, but lots of work still to do



W/ J. Lambert, Rutherford Cancer Center Newport