Magnetic Resonance Imaging in Turbulent Flows

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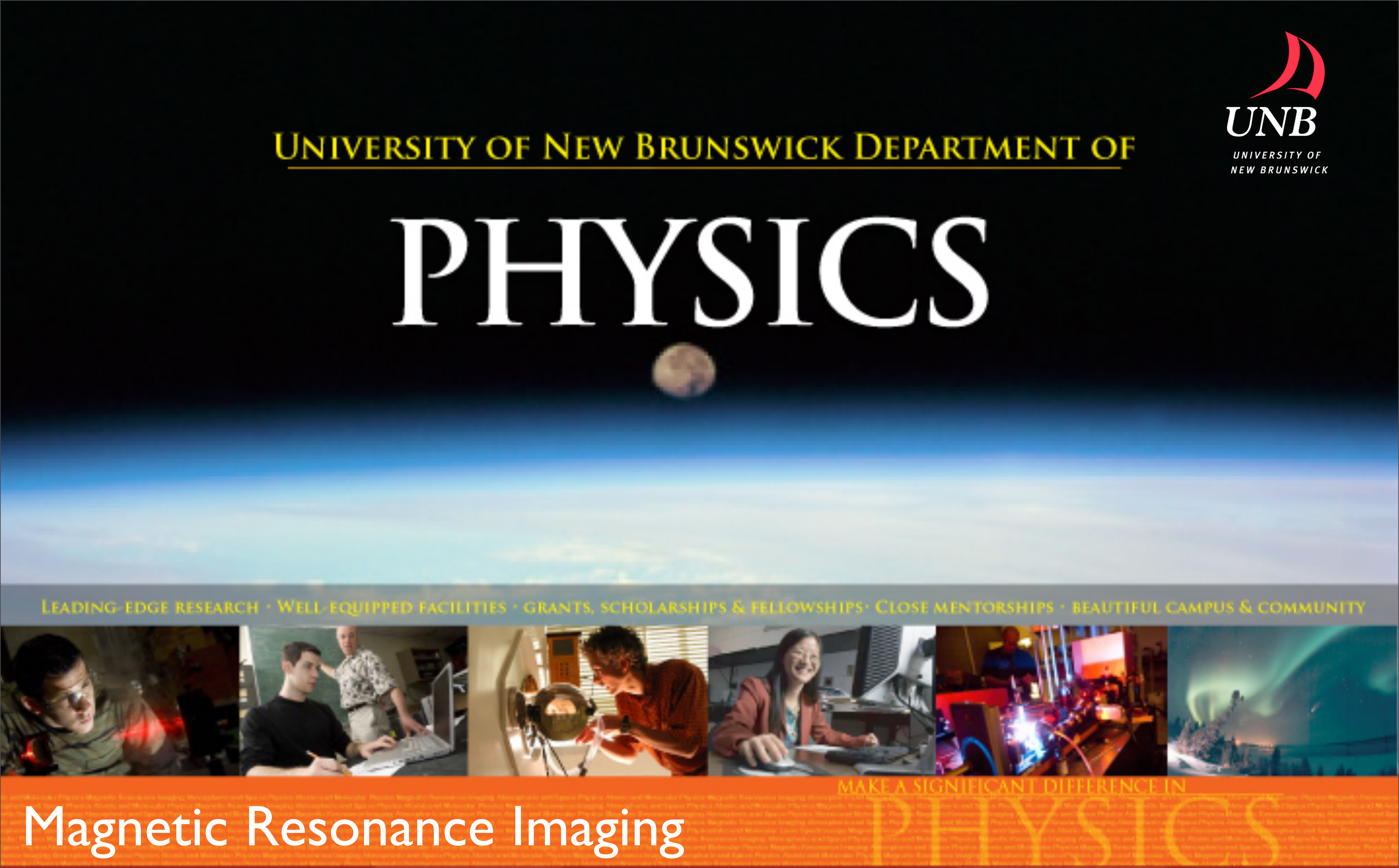


Magnetic Resonance Imaging

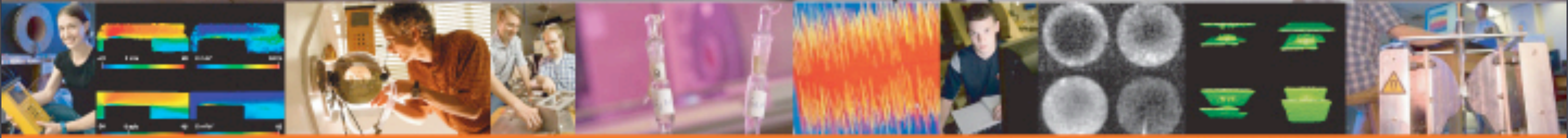
Atomic & Molecular Physics

Space & Atmospheric Physics

UNIVERSITY OF NEW BRUNSWICK DEPARTMENT OF PHYSICS

MAGNETIC RESONANCE IMAGING (MRI)

LEADING-EDGE RESEARCH · WELL-EQUIPPED FACILITIES · GRANTS, SCHOLARSHIPS & FELLOWSHIPS · CLOSE MENTORSHIPS · BEAUTIFUL CAMPUS & COMMUNITY



MAKE A SIGNIFICANT DIFFERENCE IN

PHYSICS

UNB
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The UNB MRI Centre

materials MRI (short signal lifetimes)

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materials MRI (short signal lifetimes)

The UNB MRI Centre

materials MRI (short signal lifetimes < 1ms)

single point ramped imaging with T_1 enhancement

(SPRITE)

motion-sensitised SPRITE

Why? Turbulent Flow.

Turbulence is still incompletely described.

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Many natural and engineering flows are turbulent.

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Many natural and engineering flows are turbulent.

We have collaborators who are interested in
- fish migration in rivers
- validation of CFD codes
- steam turbines
- cardiovascular flows

Why? MRI.

There are lots of ways to measure flow.

Magnetic resonance imaging is non-invasive (*cf.* particle imaging velocimetry, hot wire/film anemometry, laser doppler anemometry).

It is not point-by-point. (*cf.* HWA, some LDA, some ultrasound)

It doesn't care about optical opacity (*cf.* PIV, LDA)

Why not? MRI.

There are lots of ways to measure flow.

Magnetic resonance imaging is low resolution and/or slow.
(*cf.* LDA).

MRI does care about RF opacity
(*cf.* metal pipes can be a problem)

Why not? MRI.

There are lots of ways to measure flow.

Magnetic resonance imaging is low resolution and/or slow.
(*cf.* LDA).

MRI does care about RF opacity
(metal pipes can be a problem)

This is how it will end

MRI measures average propagators non-invasively, even in the dark.

SPRITE MRI can do it even when there are liquid/gas interfaces **or** just gas...
...and when the flow is “fast”.

The propagator contains information about average velocity **and** velocity fluctuation.

www.unb.ca/physics/mri

Order of Service

Magnetic Resonance Imaging (MRI)

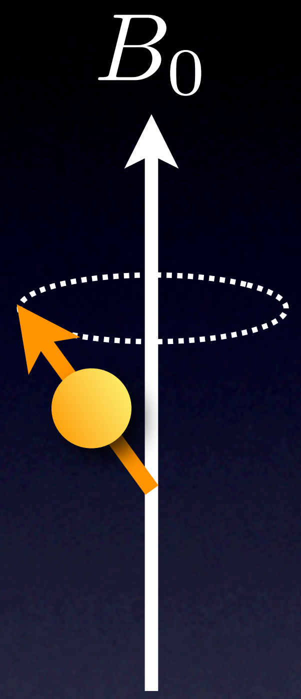
SPRITE MRI with motion sensitisation

Advantages of SPRITE MRI in subsonic gas flow

Advantages of SPRITE MRI in two-phase flow

Run for the hills

Magnetic Resonance Imaging



Nuclei with spin angular momentum, $\vec{J}$

... have a magnetic dipole moment $\vec{\mu} = \gamma \vec{J}$

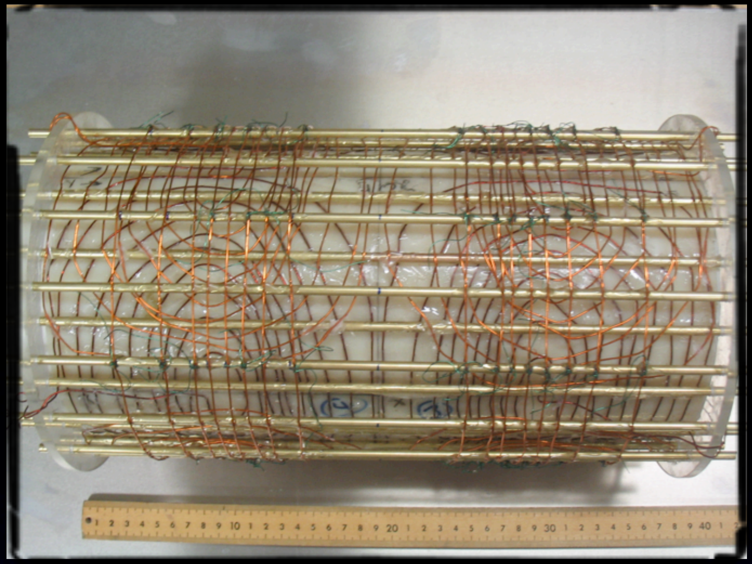
... and, by virtue of the two, precess around a static magnetic field at the Larmor frequency

$$\omega_L = \gamma B_0$$

In the presence of a magnetic field gradient the precession frequency depends on position

$$\omega\left(\vec{r}\right) = \gamma\left(B_0 + \vec{G}\cdot\vec{r}\right)$$

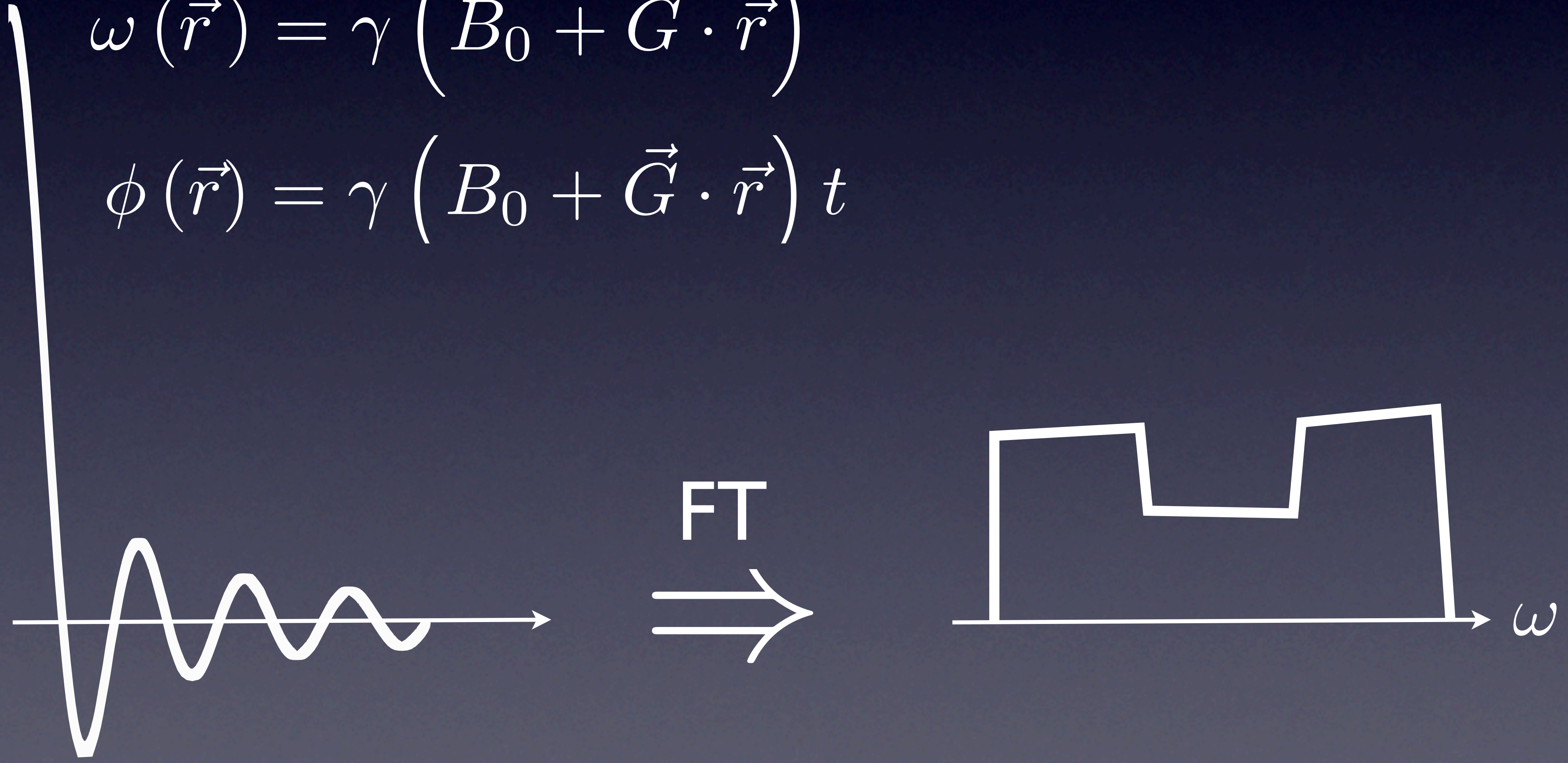
Spatial spectroscopy



In a magnetic field gradient
the precession frequency depends on position

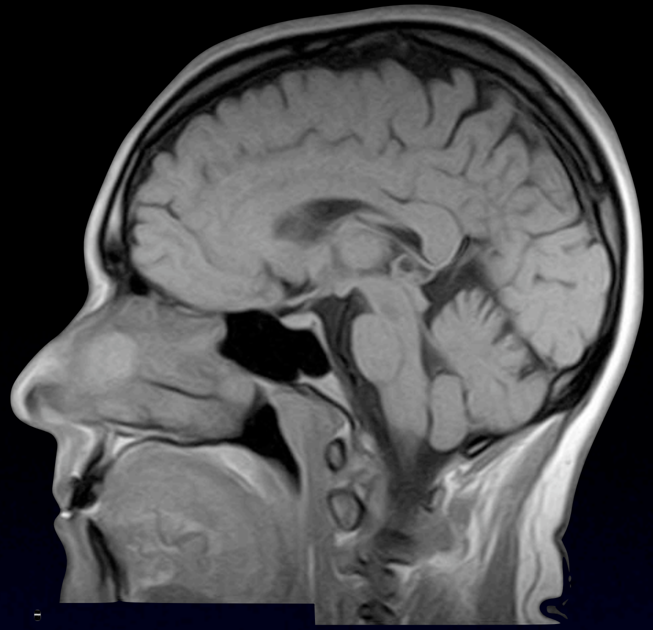
$$\omega\left(\vec{r}\right) = \gamma\left(B_0 + \vec{G}\cdot\vec{r}\right)$$

$$\phi\left(\vec{r}\right) = \gamma\left(B_0 + \vec{G}\cdot\vec{r}\right)t$$



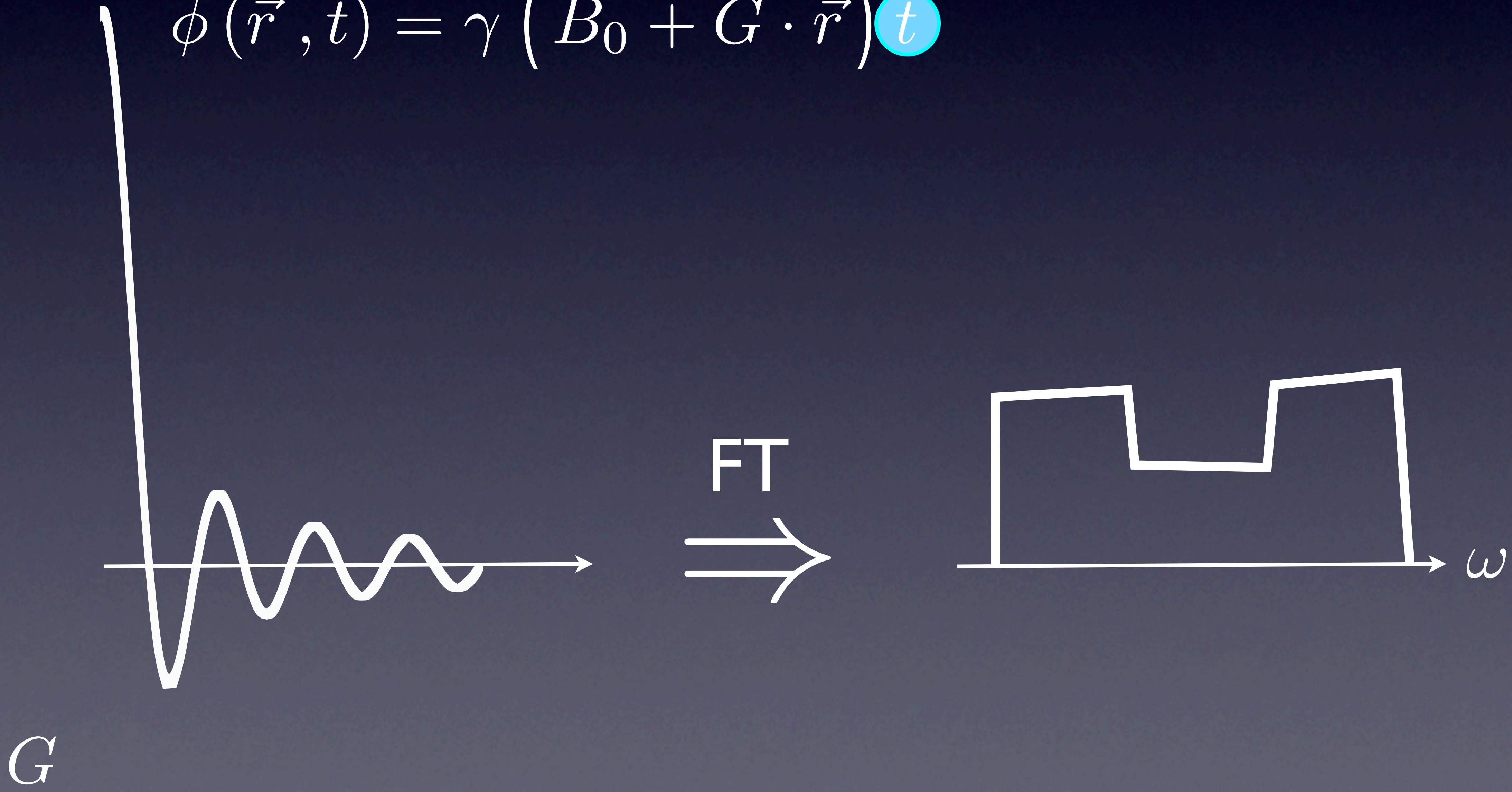
$$\xrightarrow{\text{FT}}$$

Spatial spectroscopy



How should we sample the signal?
If we sample as a time axis, then...

$$\phi\left(\vec{r},t\right) = \gamma\left(B_0 + \vec{G}\cdot\vec{r}\right)t$$



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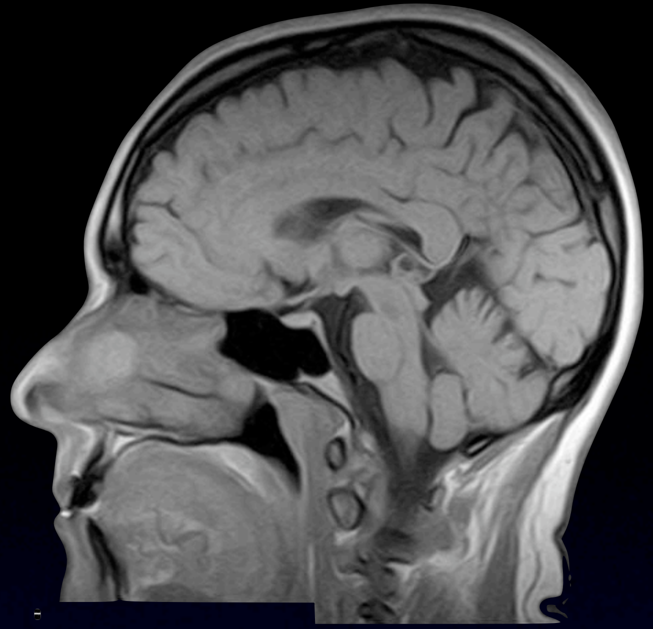

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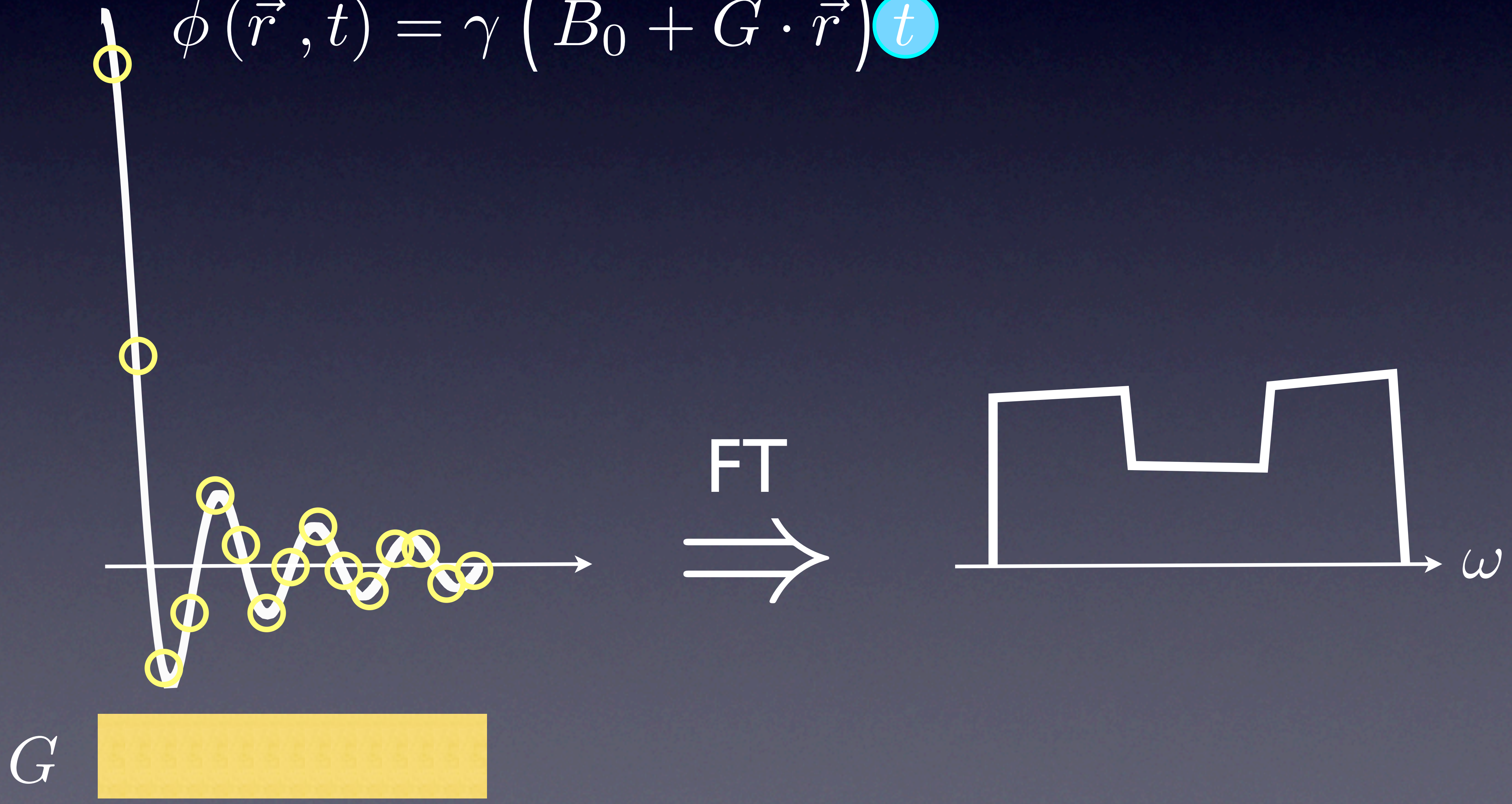

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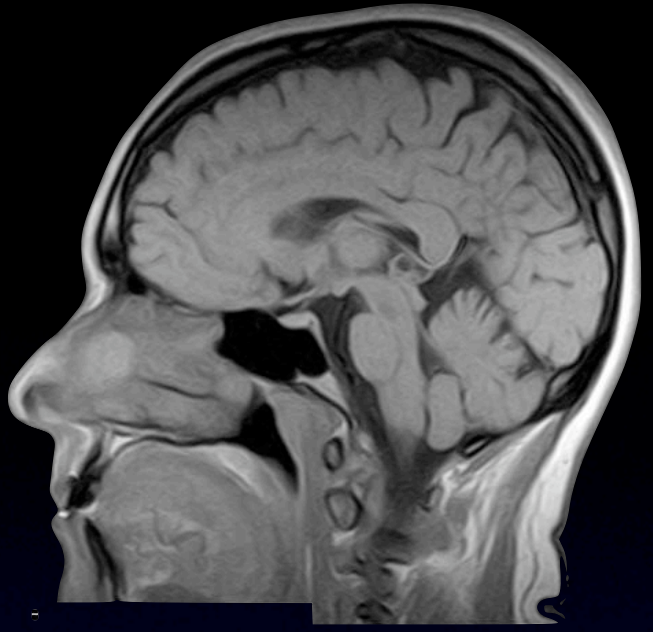

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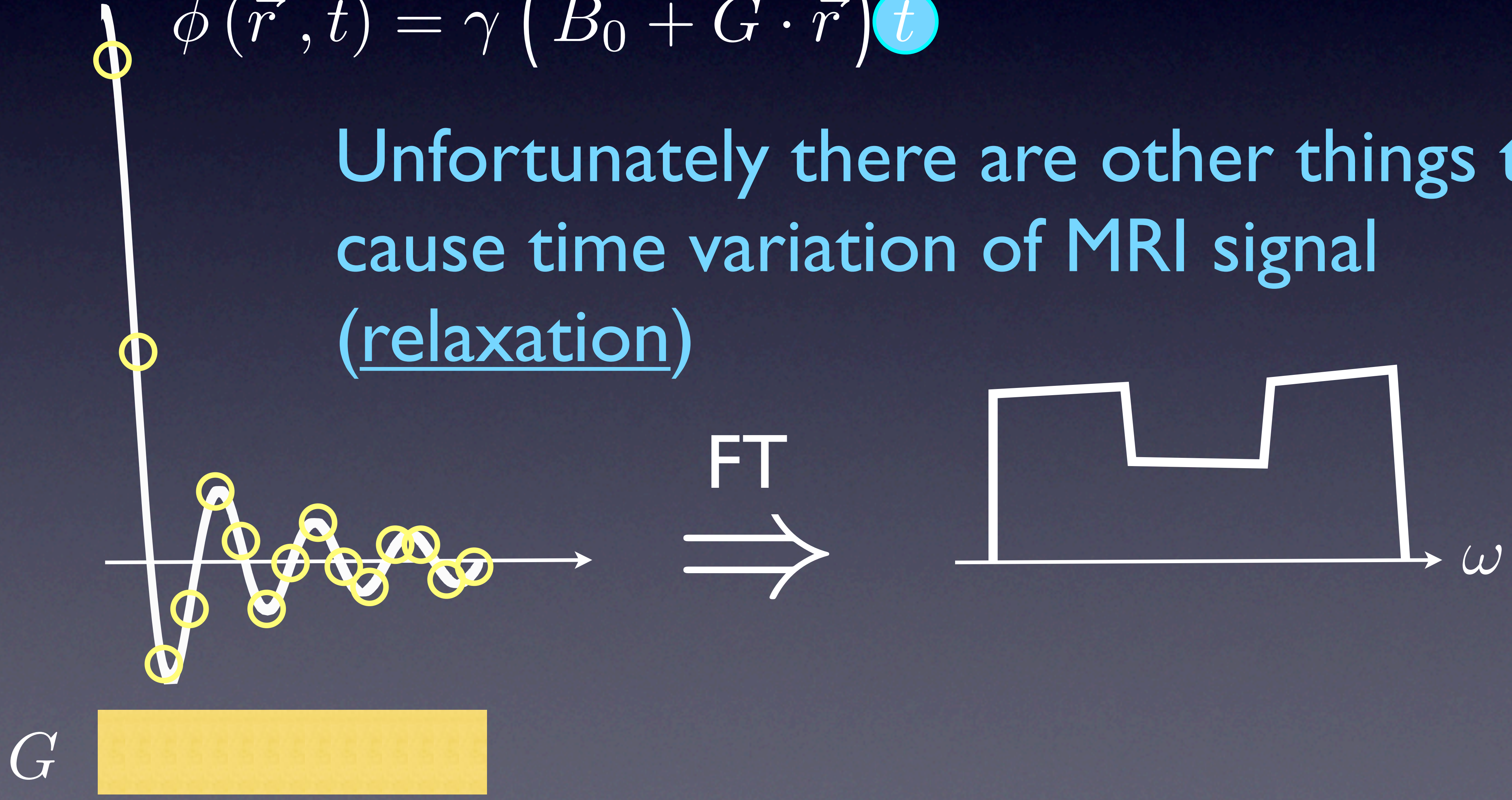
Unfortunately there are other things that cause time variation of MRI signal (relaxation)



Spatial spectroscopy

How should we sample the signal?

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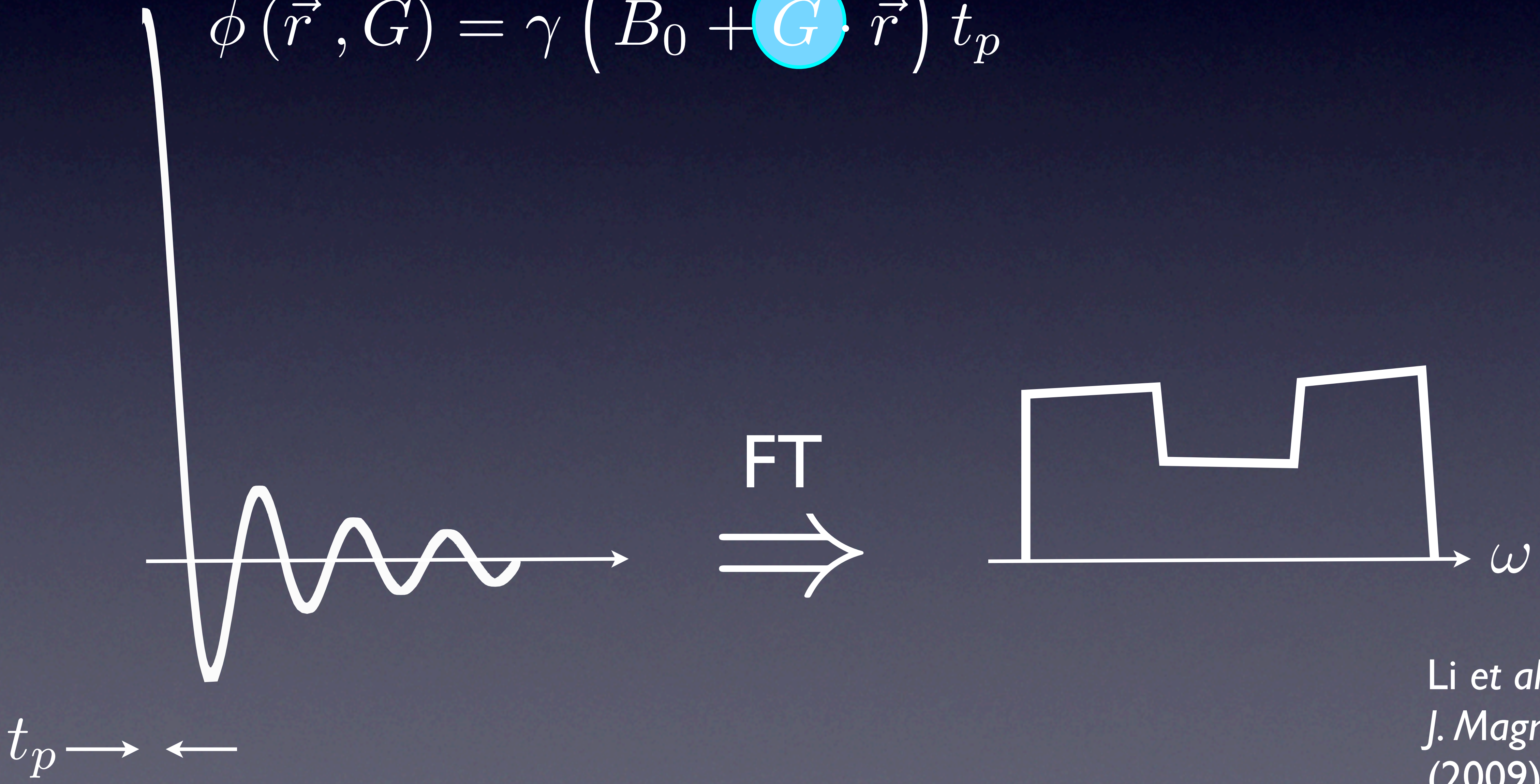
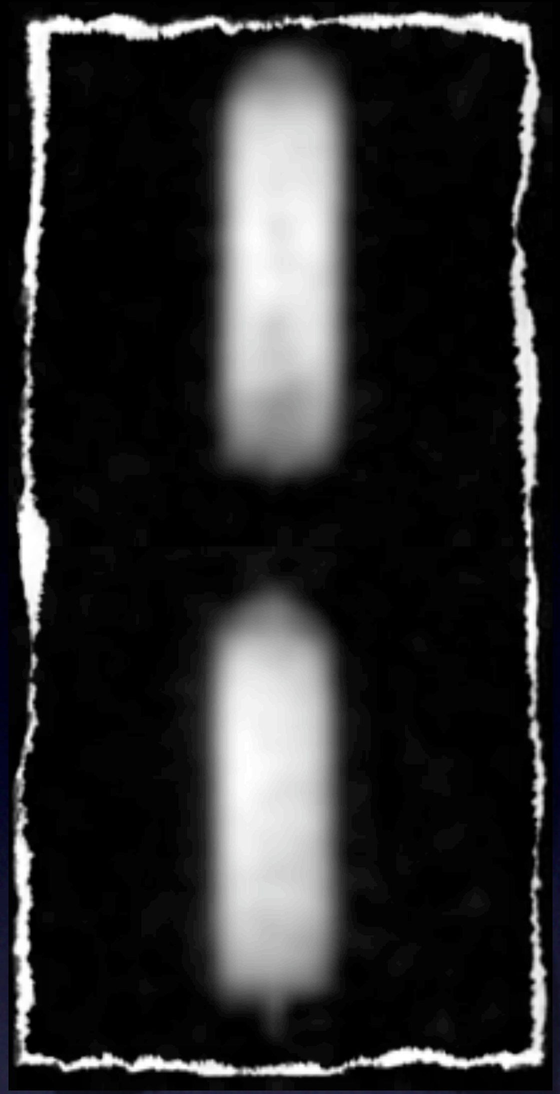
$$\phi\left(\vec{r}\,,\vec{G}\right)=\gamma\left(B_0+\vec{G}\cdot\vec{r}\right)t_p$$



Li *et al.*
J. Magn. Reson.
(2009) **197** 1

Spatial spectroscopy



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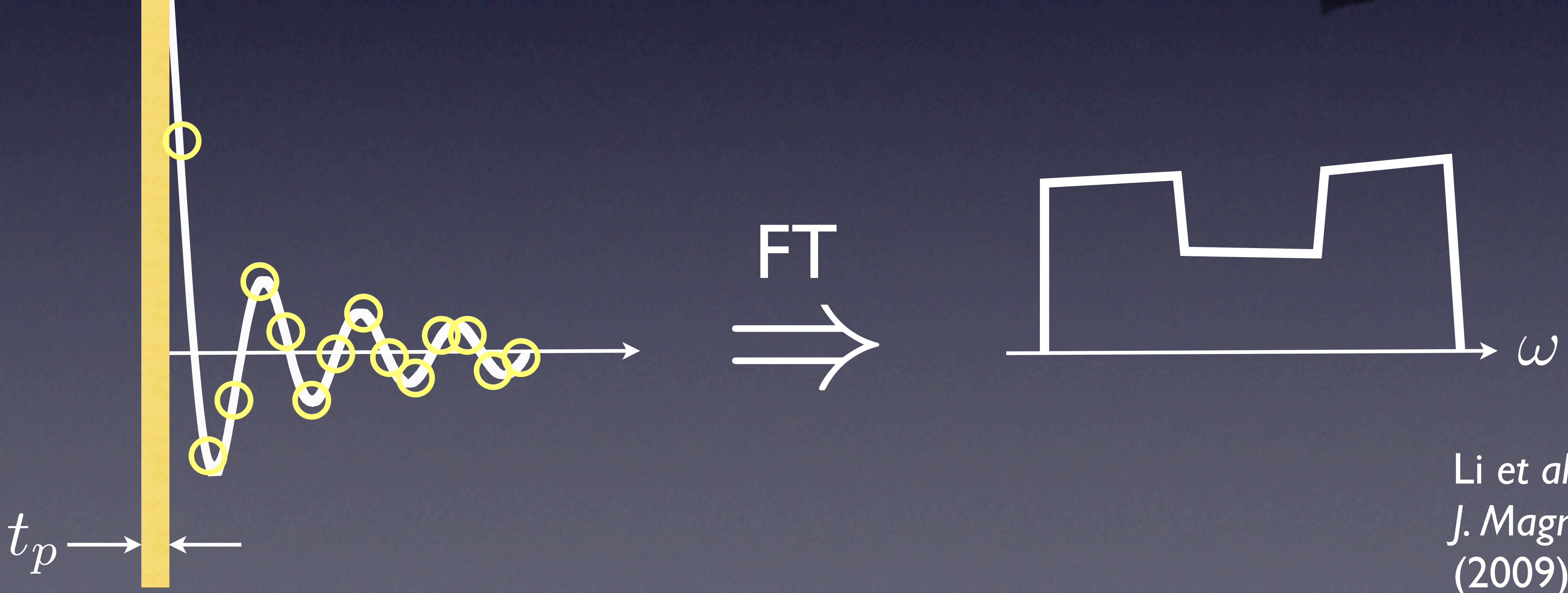

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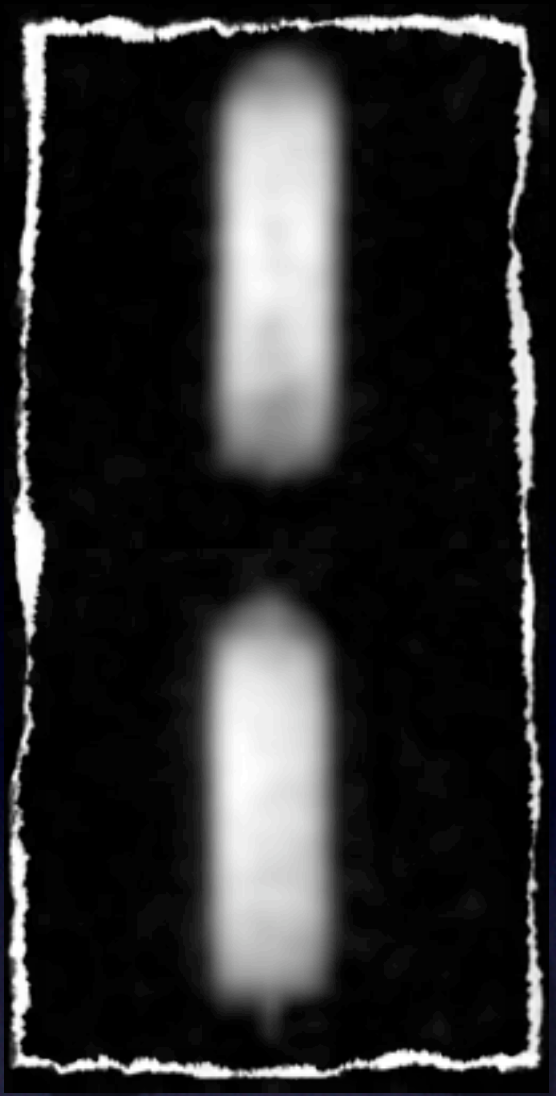

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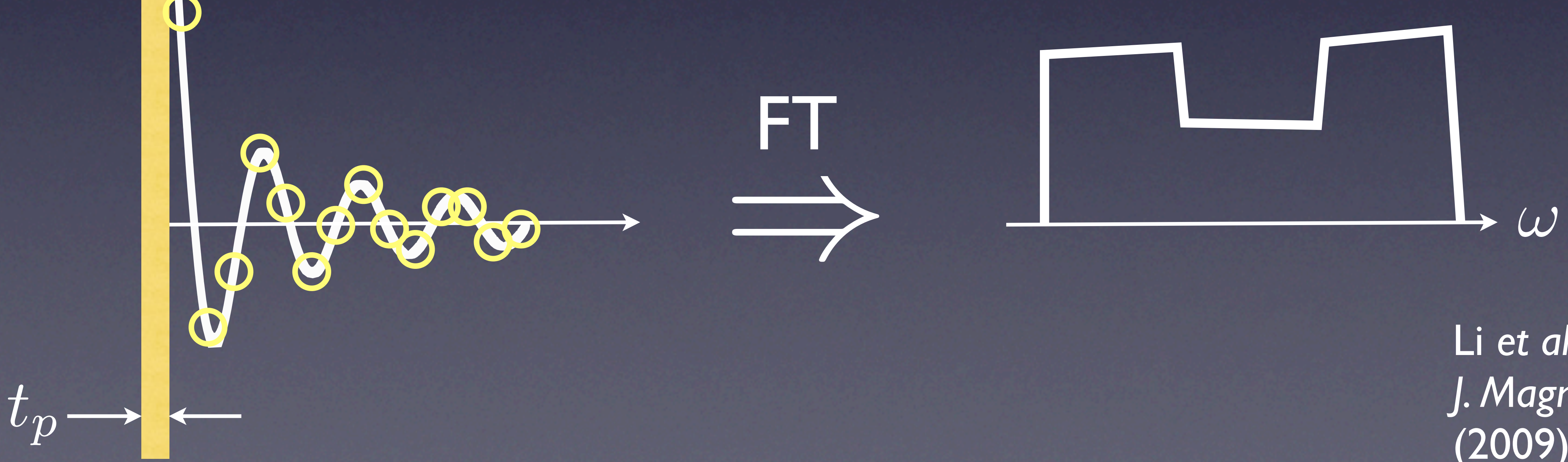

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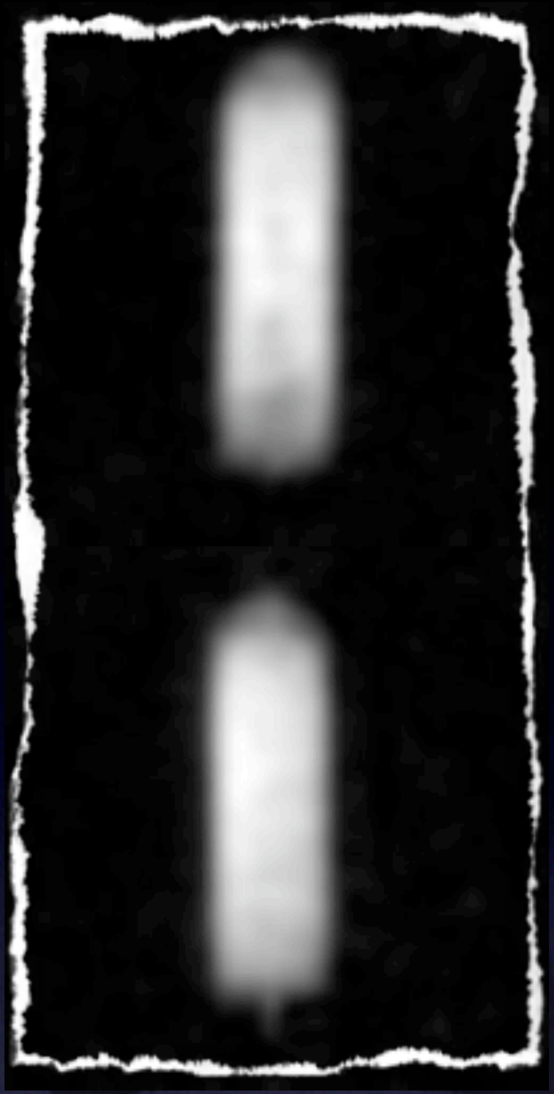

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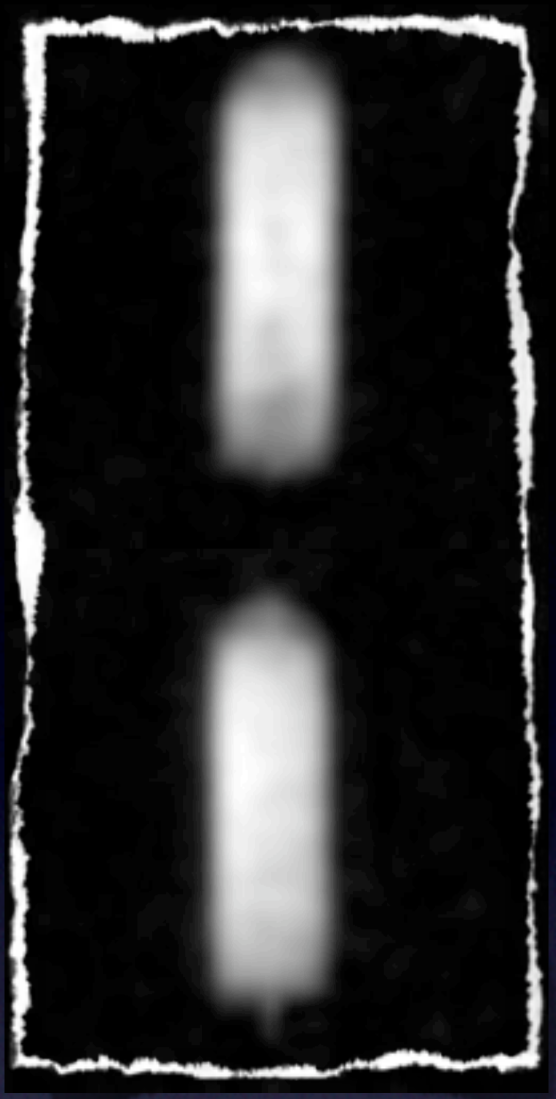

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Purely phase-encoded MRI

The encoding time t_p is short: this is good for short-lived signal....

... *and* for fast flow ($\gg$ 1 m/s)

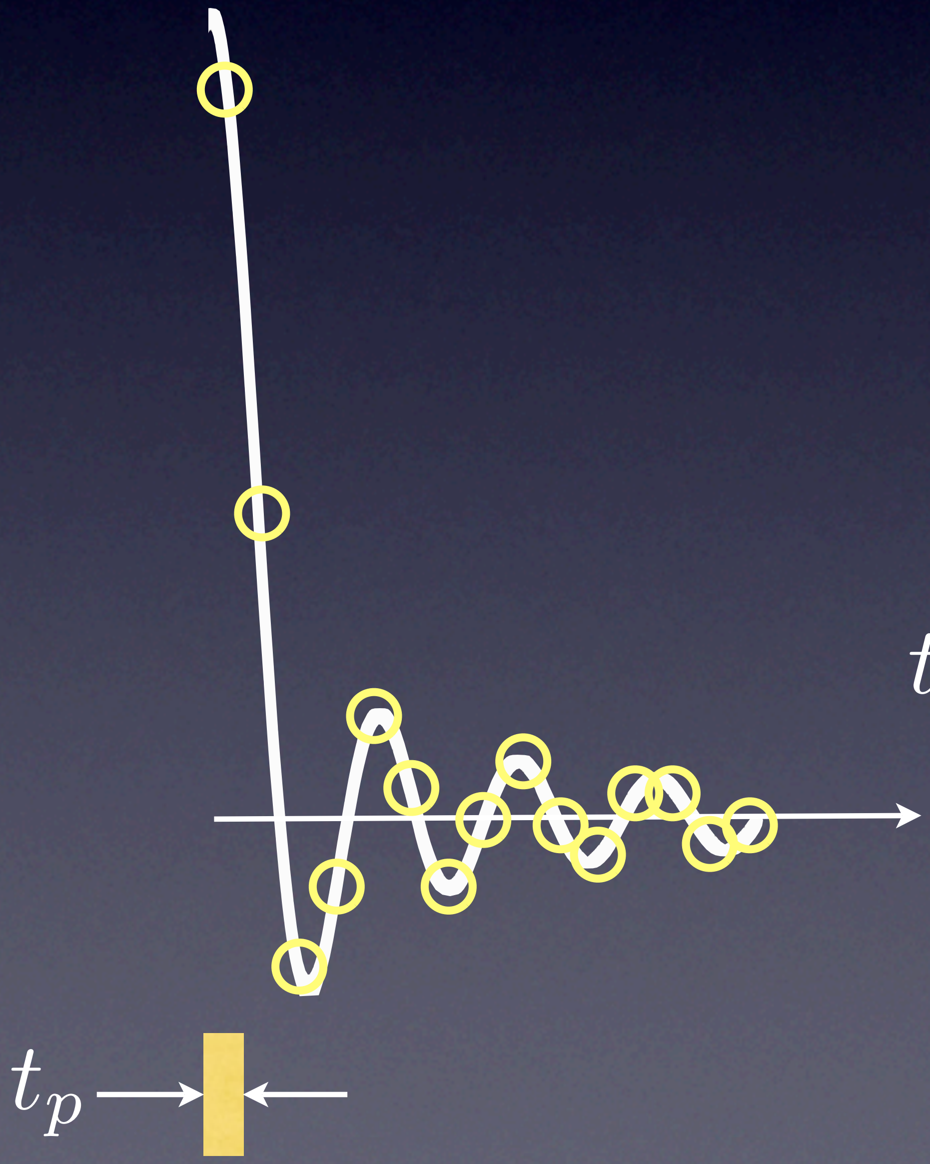
The encoding time t_p is constant: this is good for time-varying effects:

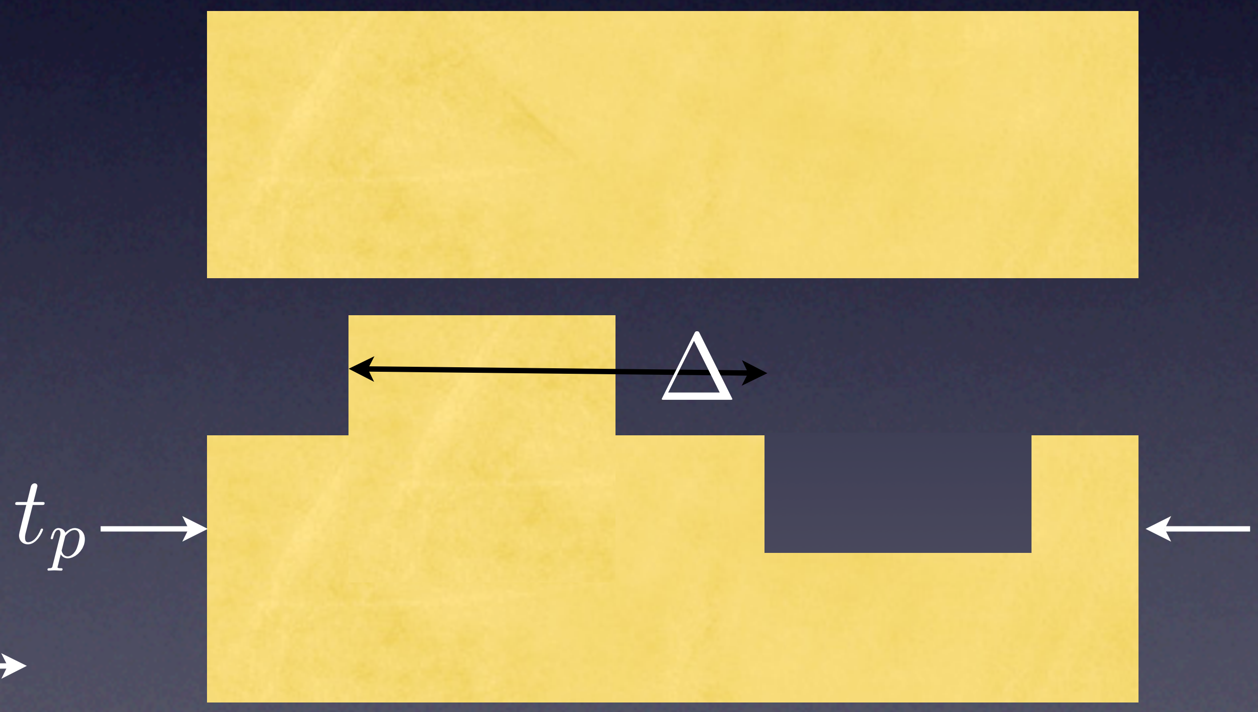
signal relaxation
magnetic susceptibility effect
turbulent flow

leading to quantitative imaging.

Motion sensitisation

Notice that the gradient area is important in determining the phase.

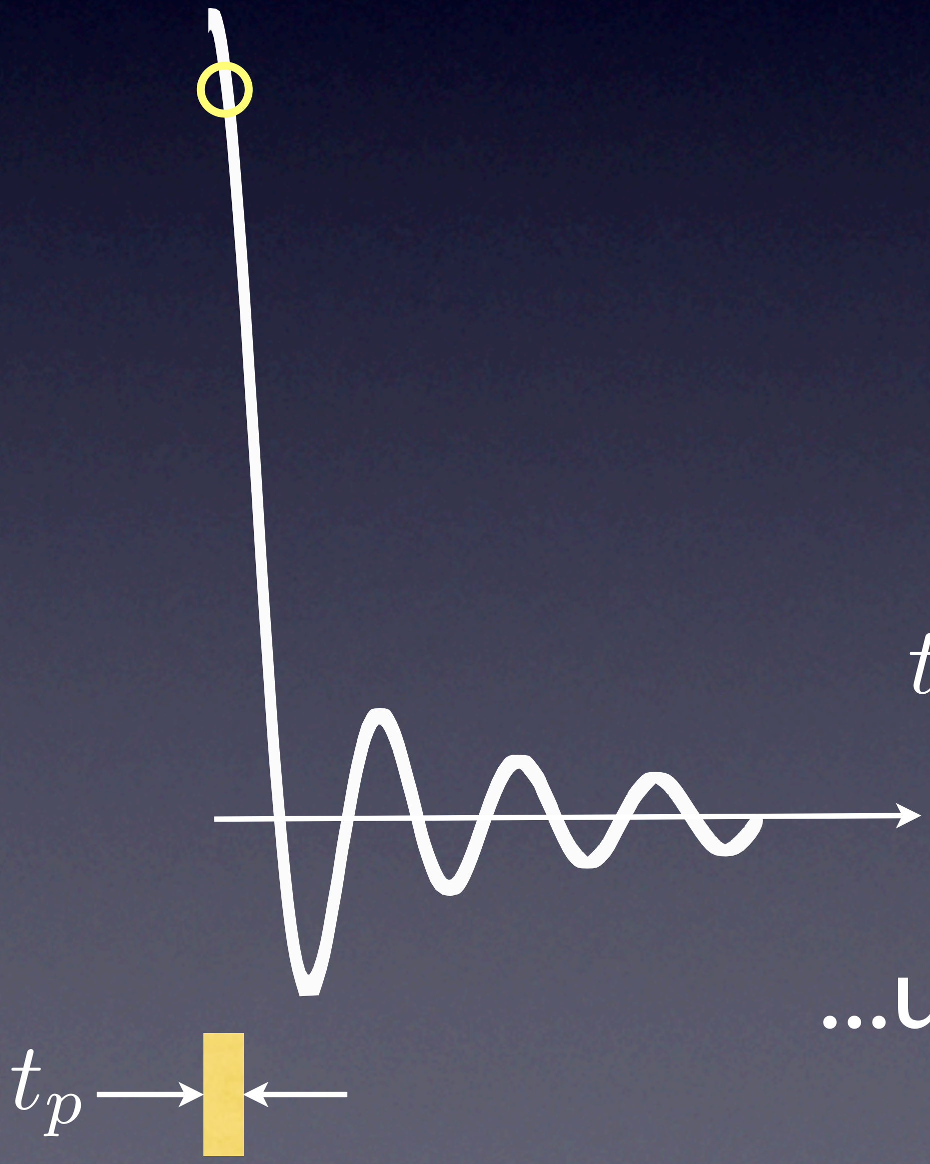


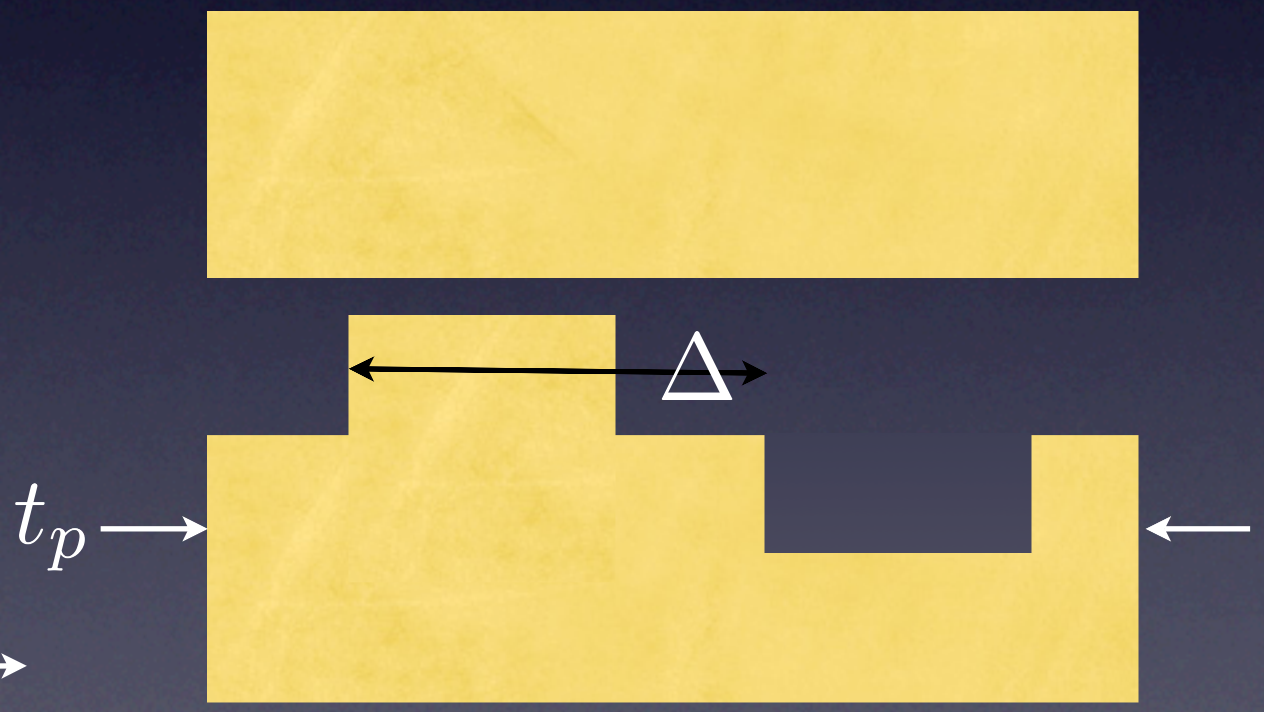


Motion sensitisation

Notice that the gradient area is important in determining the phase.

These two are the same...

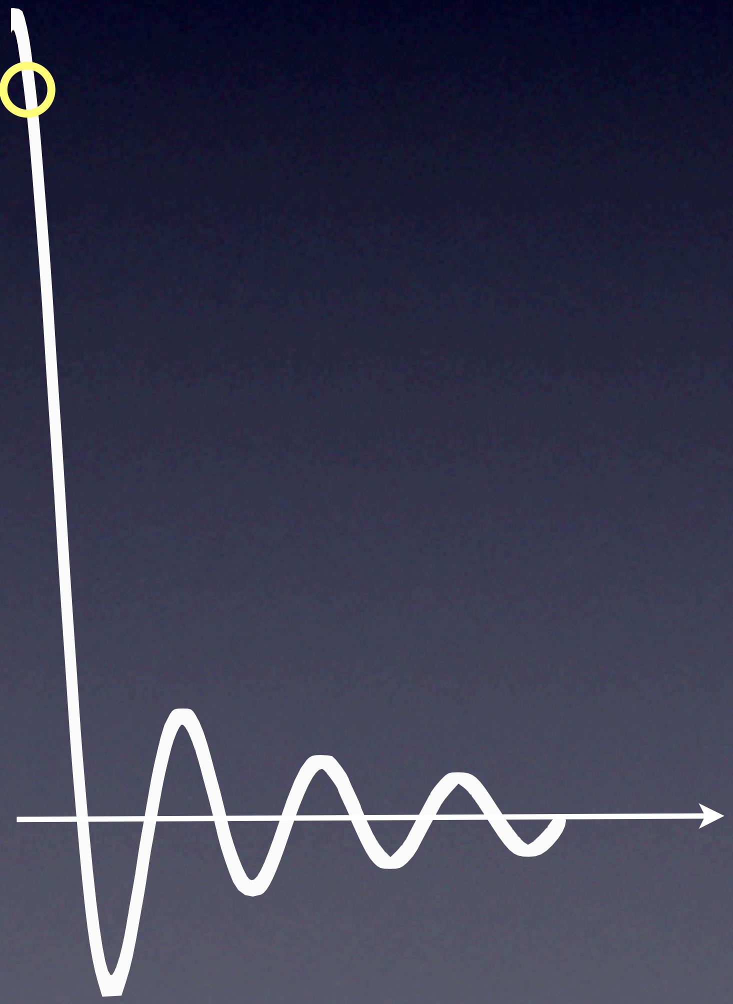


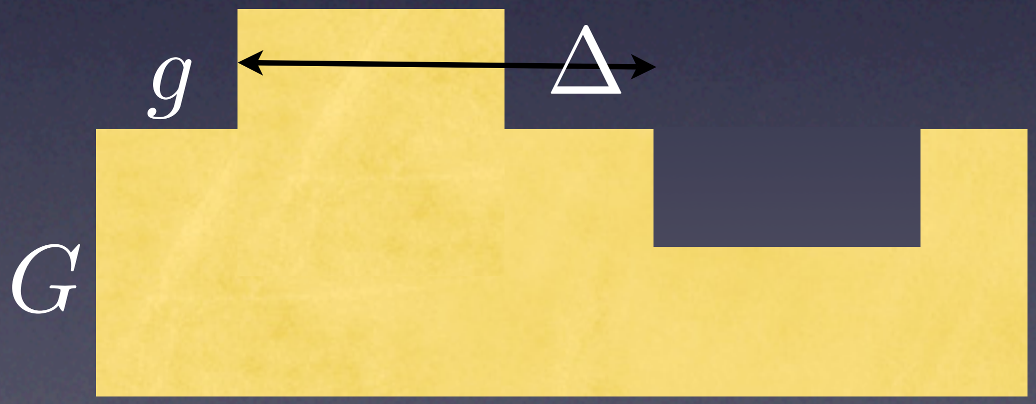


...unless there is motion during Δ .

Motion sensitisation

Increasing the step increases sensitivity to displacement.
We can Fourier transform along this dimension too.





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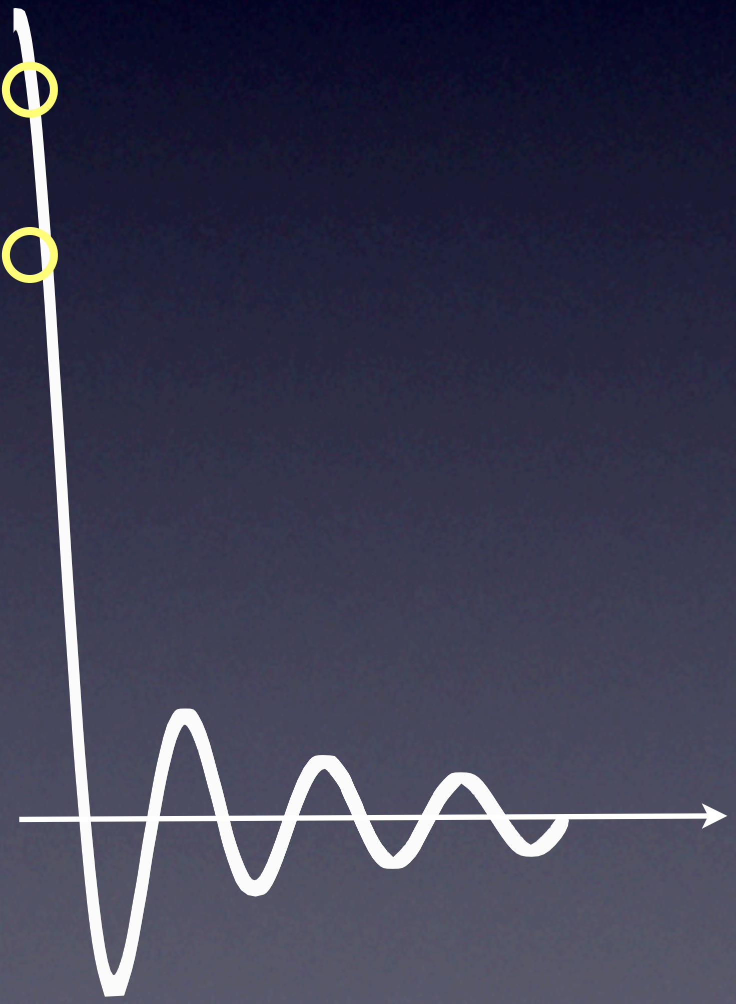

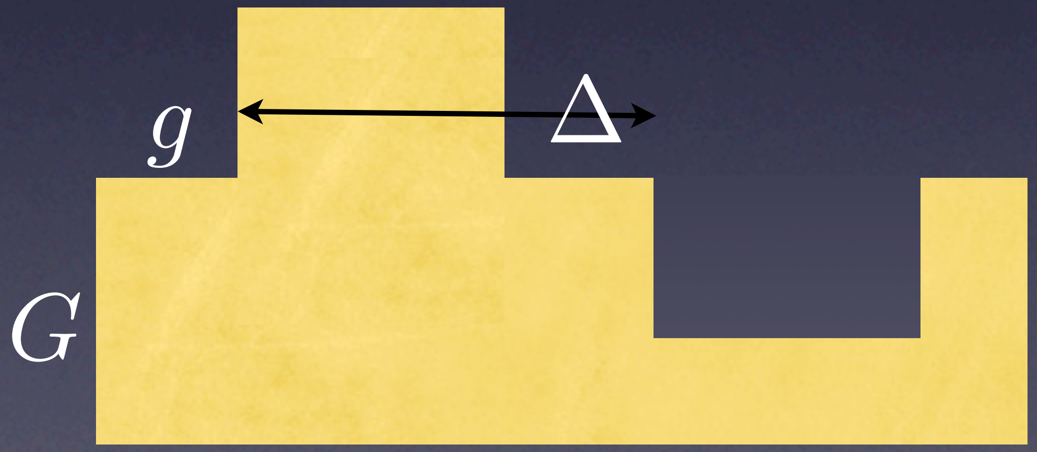

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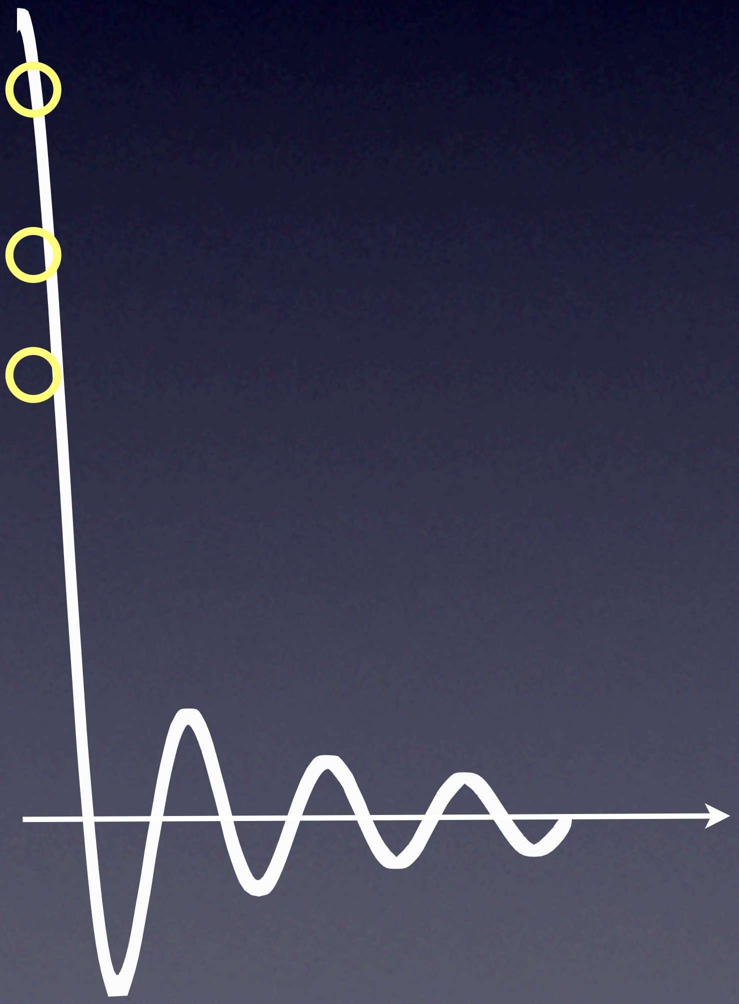

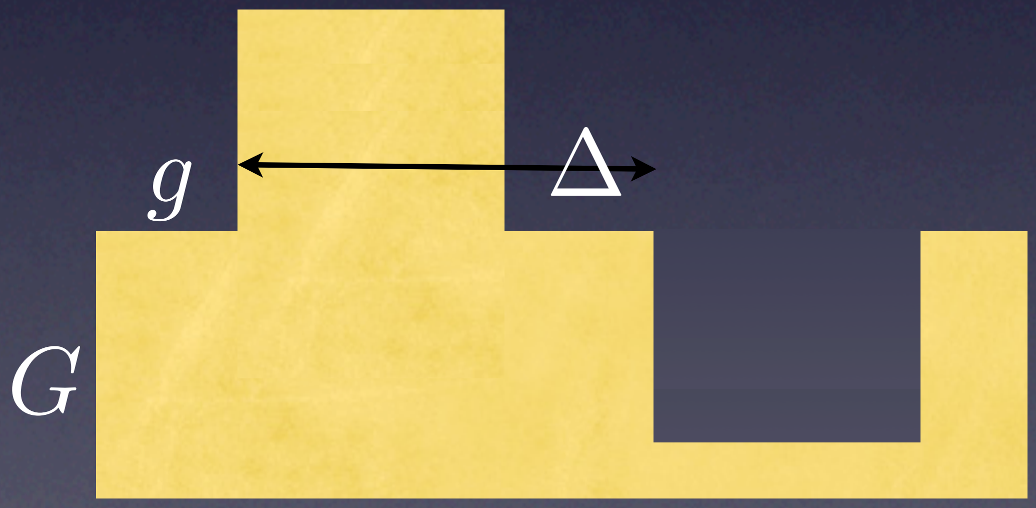

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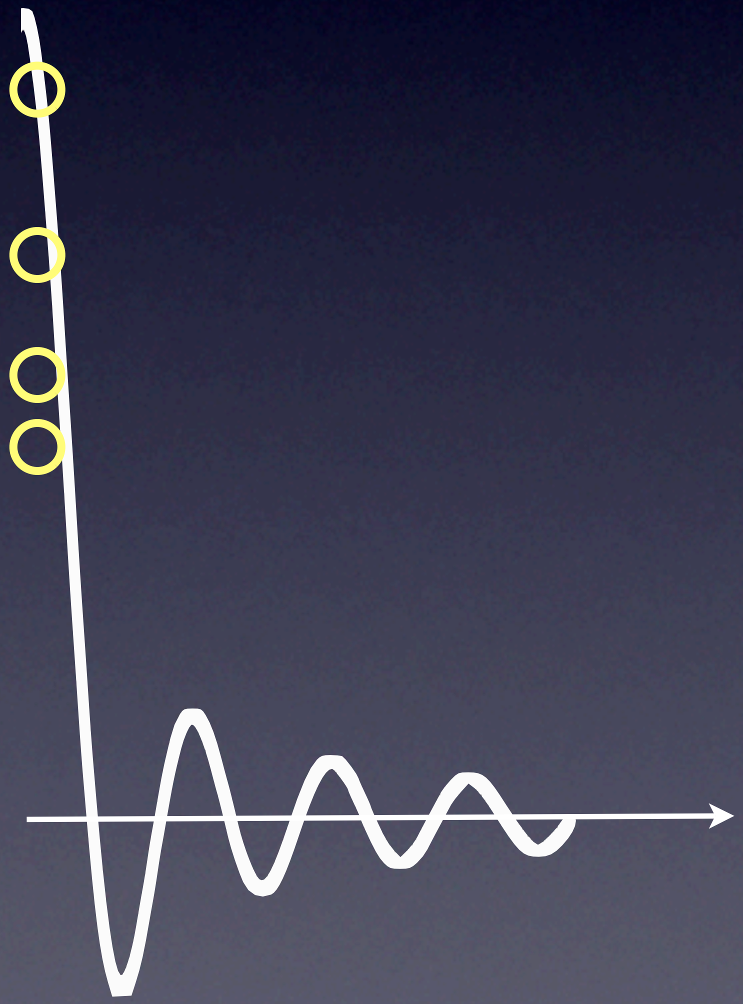

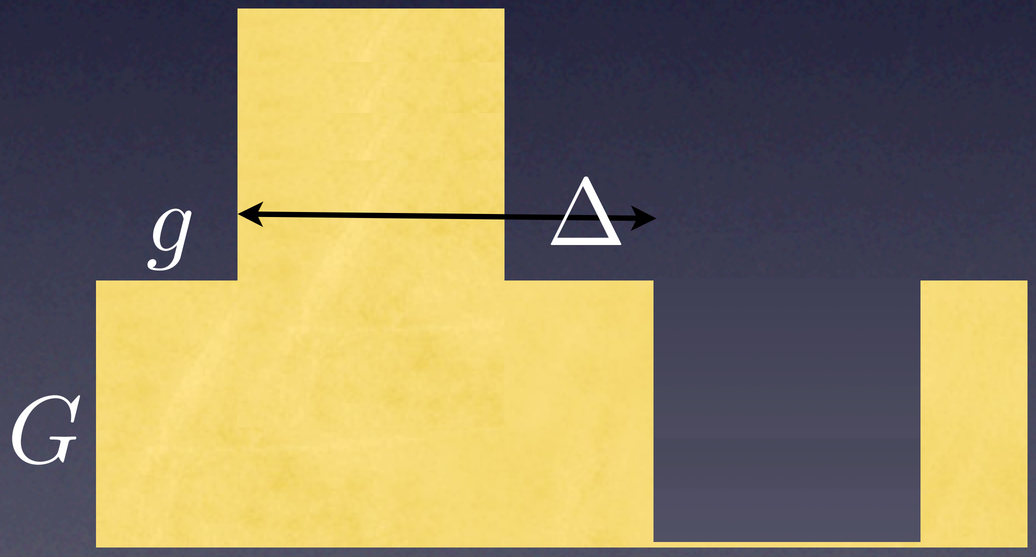

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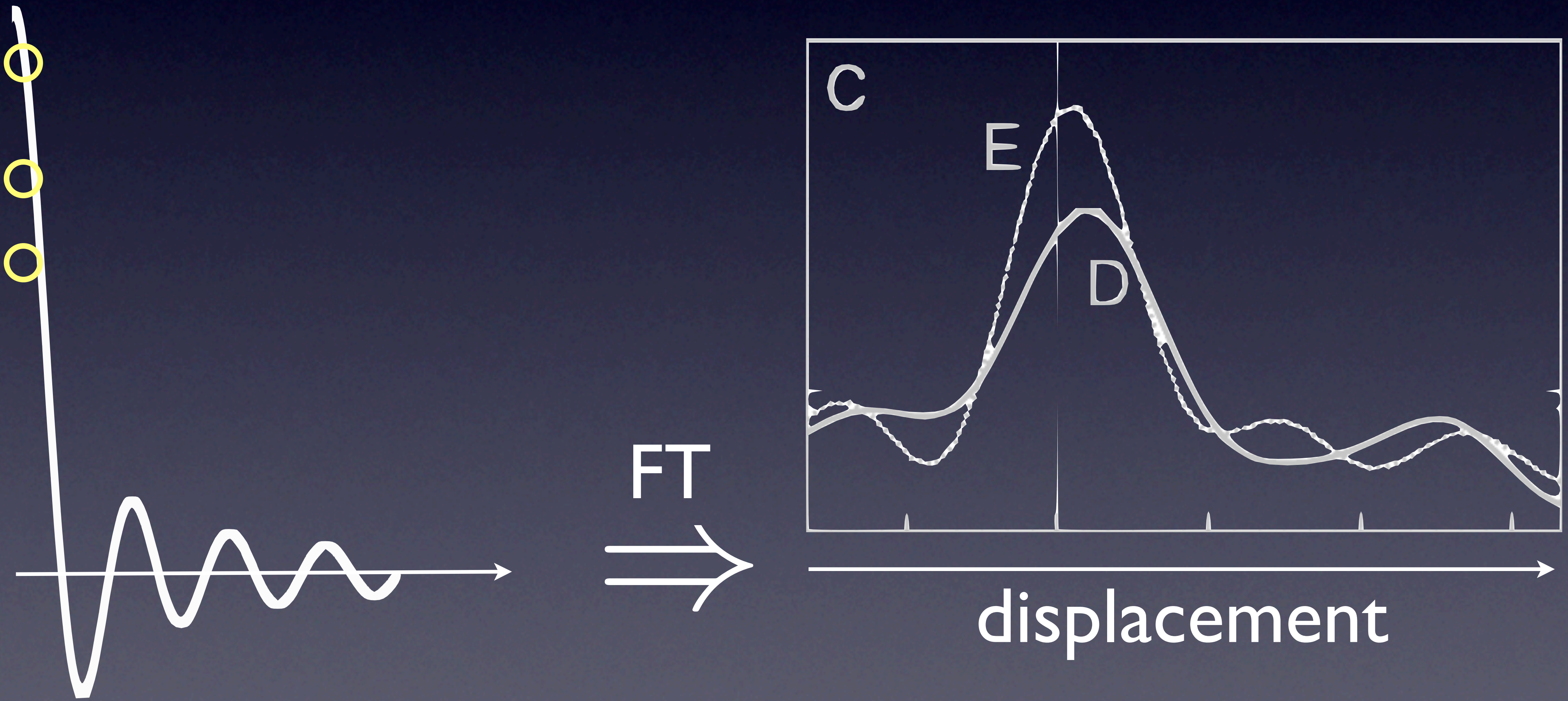

... giving an average propagator at every position.

Motion sensitisation

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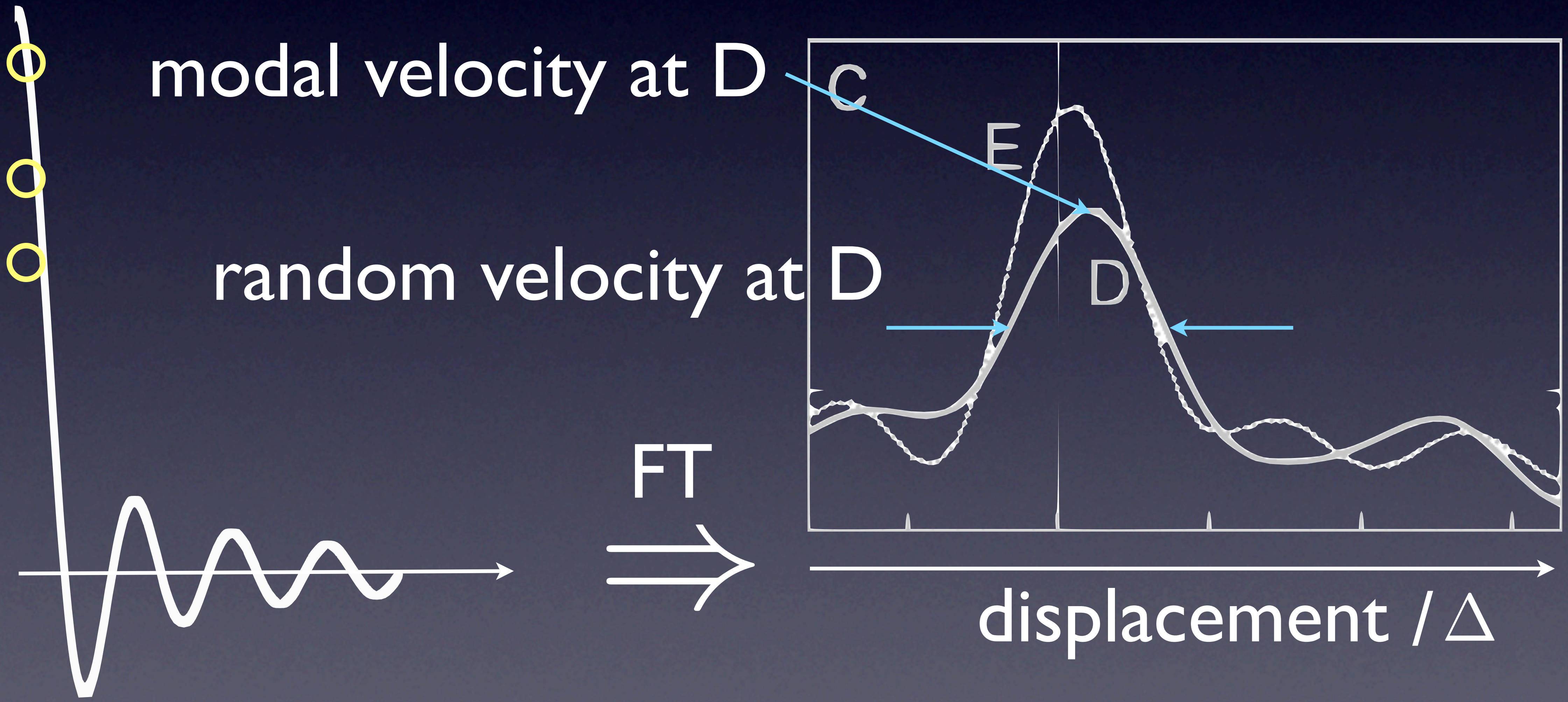


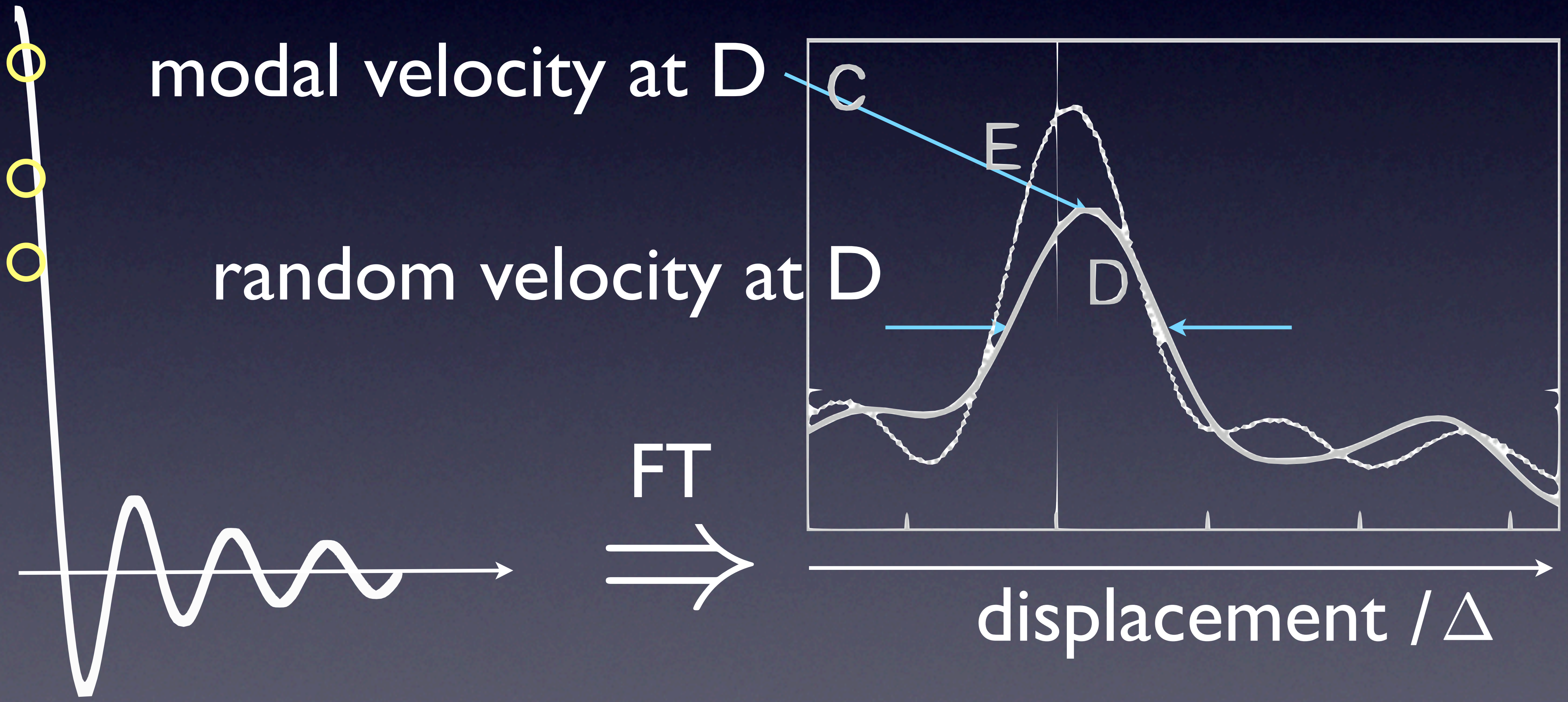
modal velocity at D

random velocity at D

... giving an <u>average propagator</u> at every position.

Motion sensitisation

Random displacements could be due to turbulence or diffusion or mechanical dispersion or cavitation.



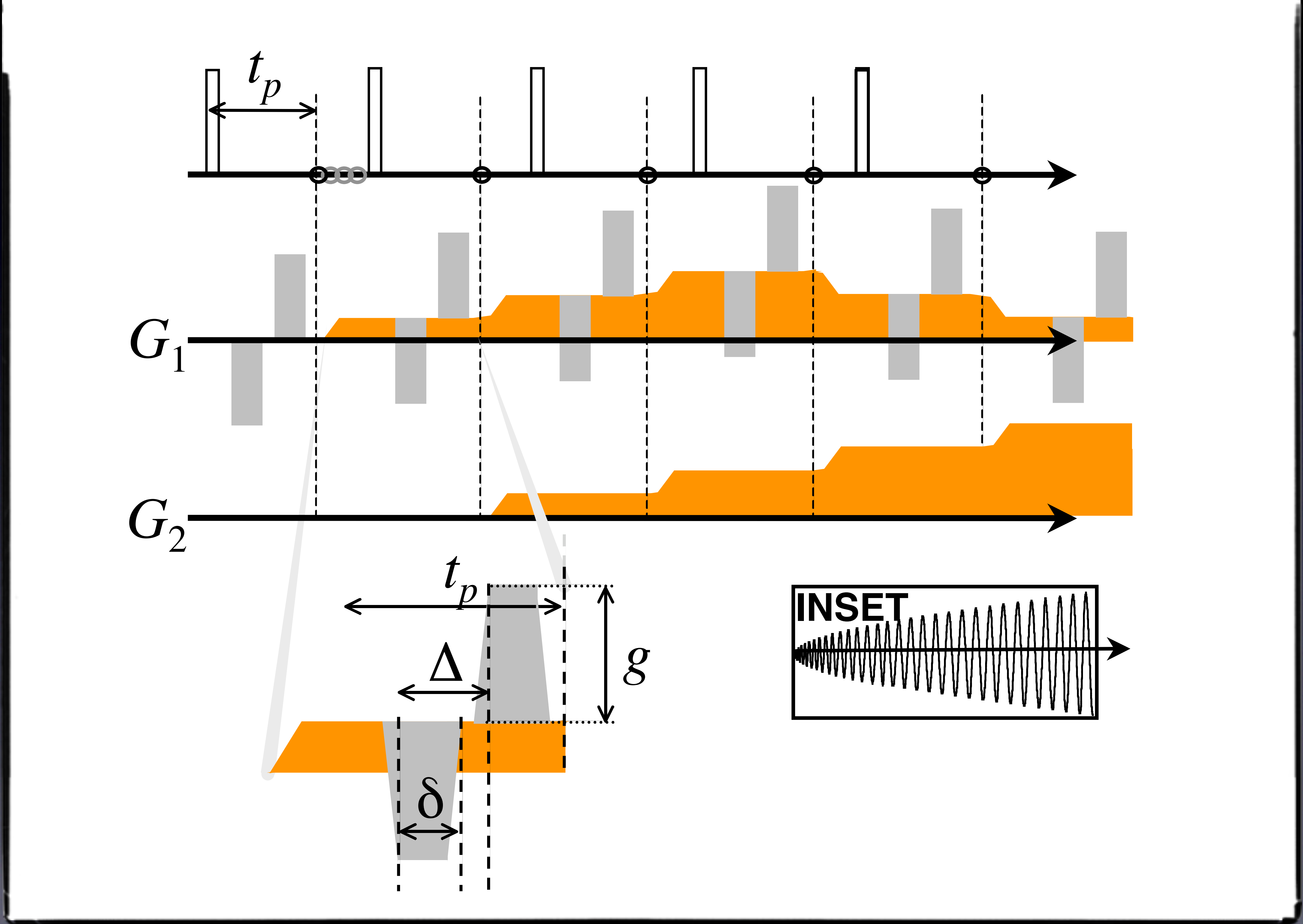
modal velocity at D

random velocity at D

FT

displacement / Δ

Motion sensitisation



Motion sensitisation

Recall that these data take several tens of minutes to acquire in total.

The measurements are highly time-averaged.

Motion sensitisation

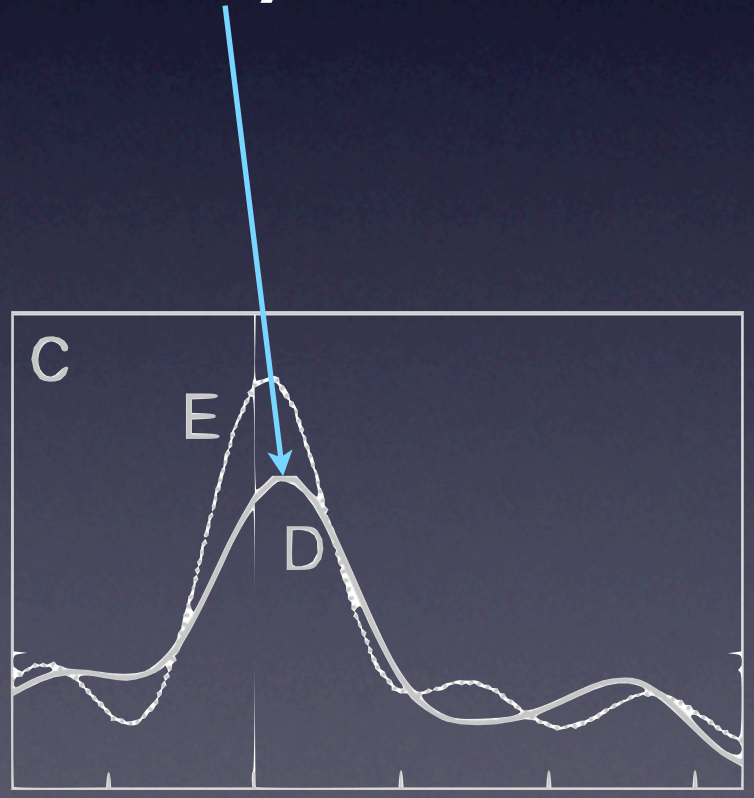
Recall that these data take several tens of minutes to acquire in total.

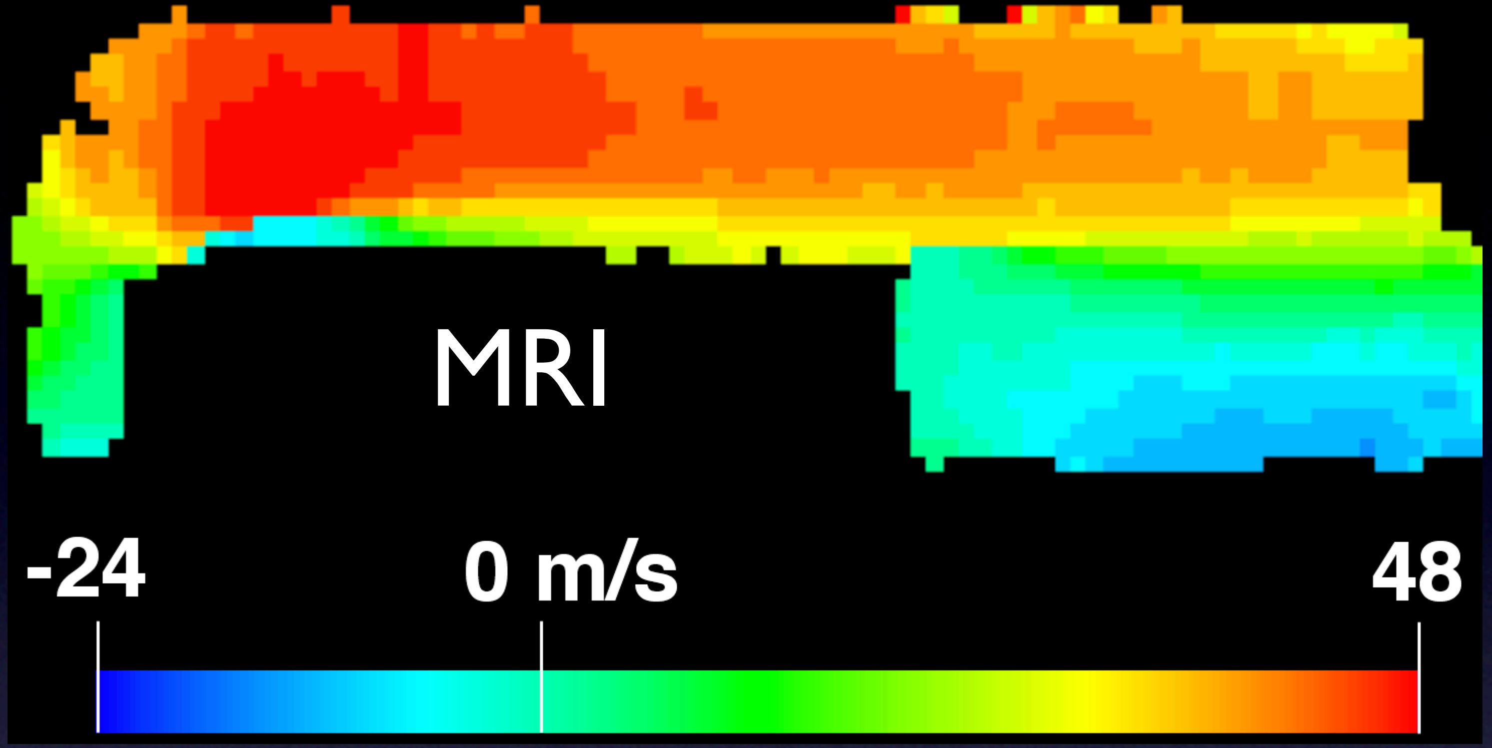
The measurements are highly time-averaged.

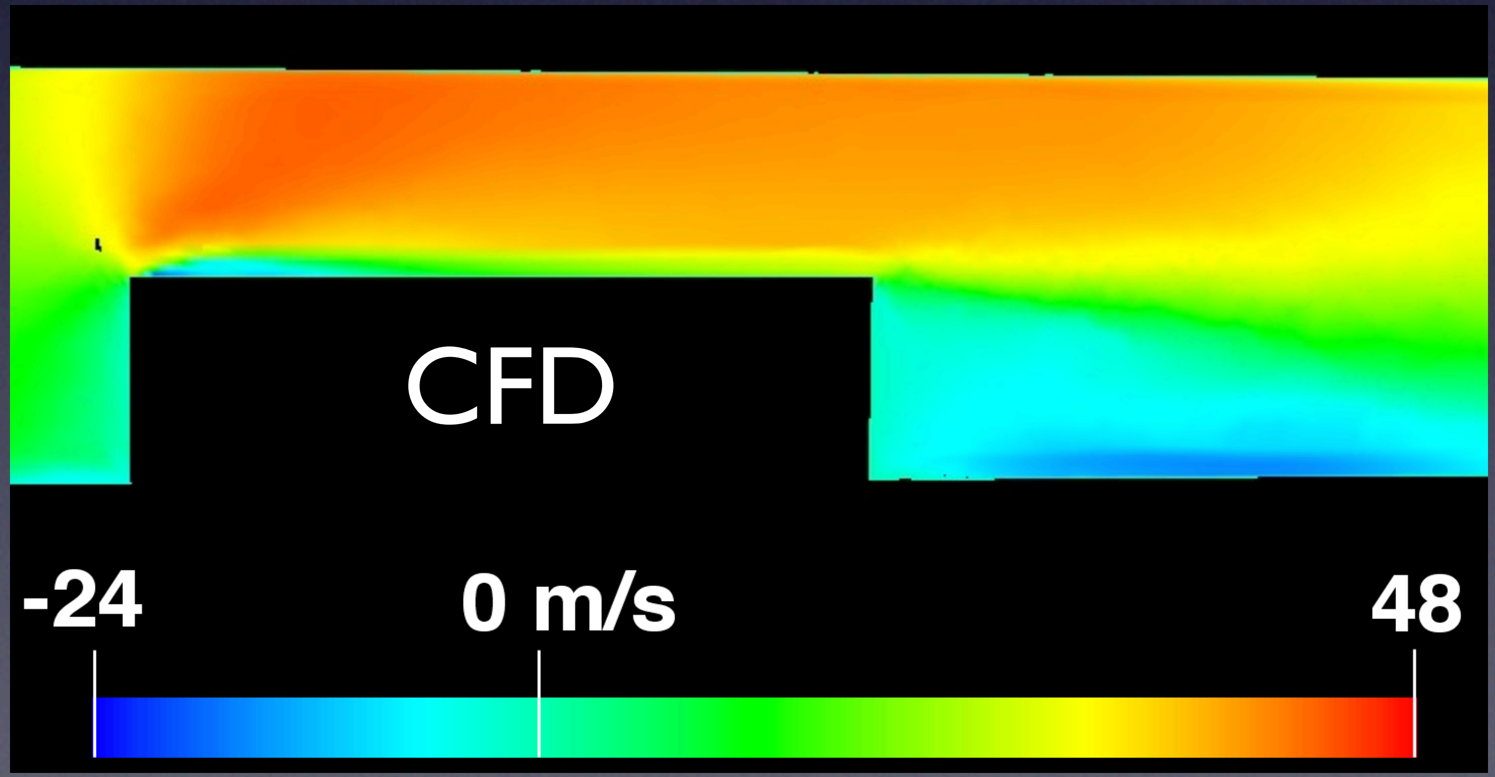
So all the statistics are done for you.

Subsonic gas

From the average propagator, we pick a modal velocity.







Subsonic gas

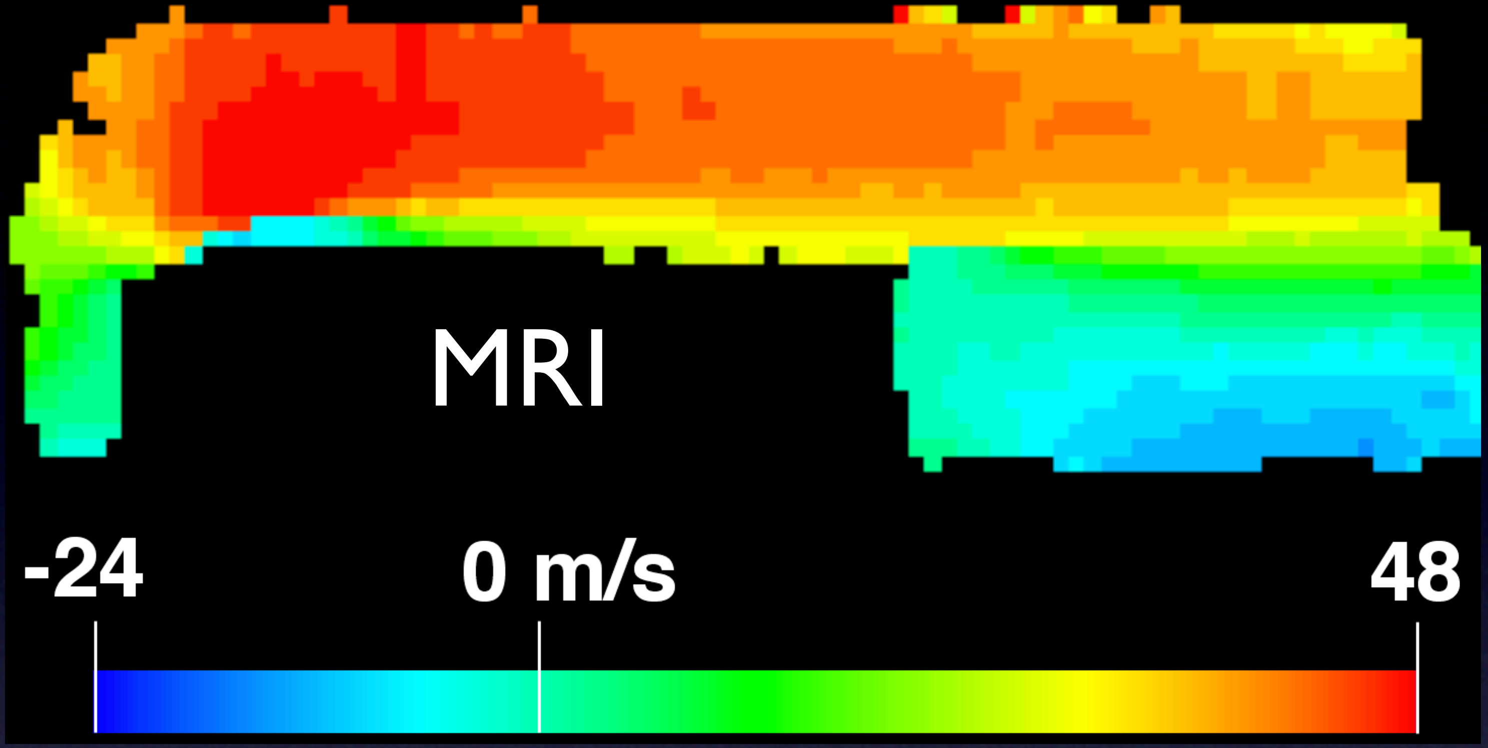
Flow of SF_6 gas

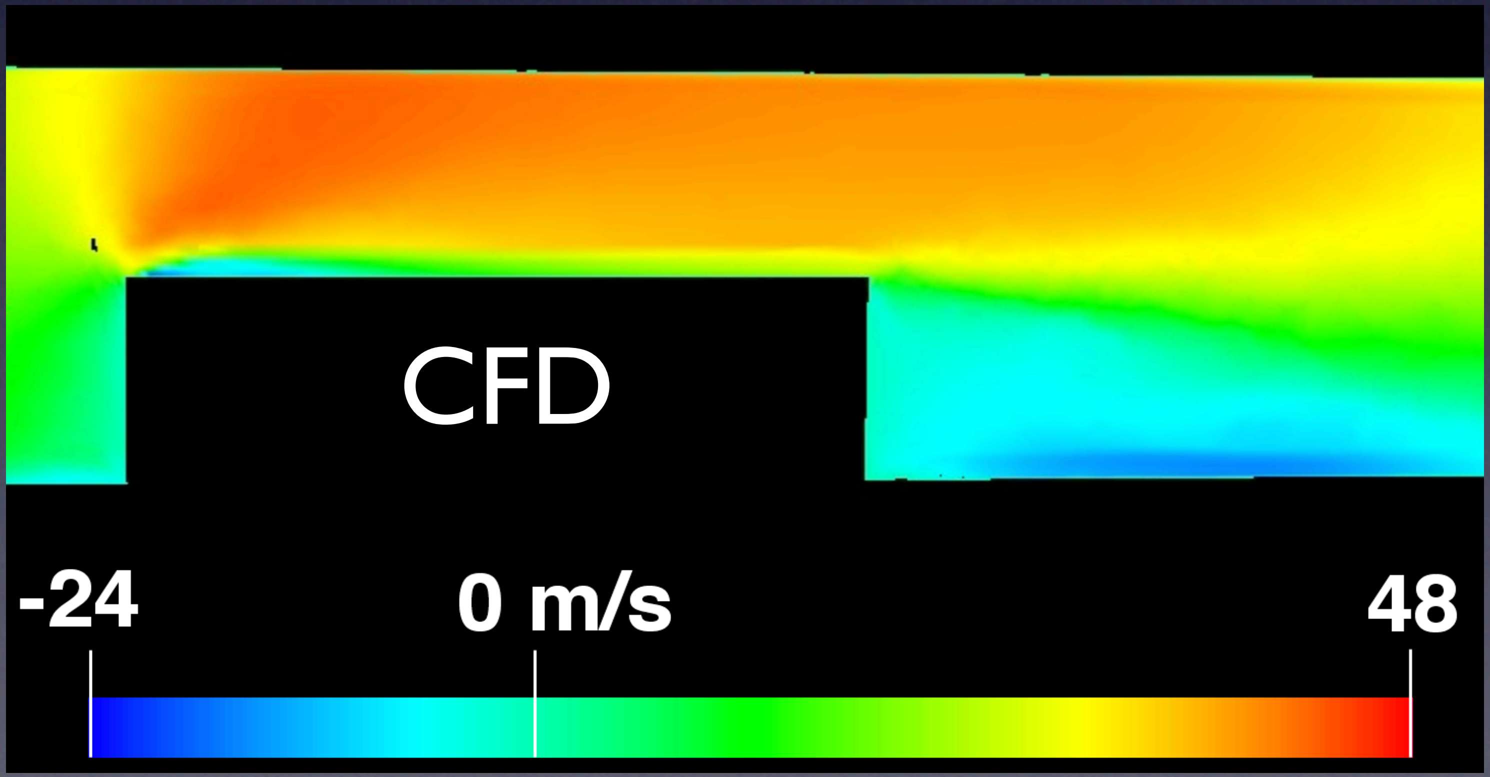
Mach 0.12

Re = 210,000

Modal velocities

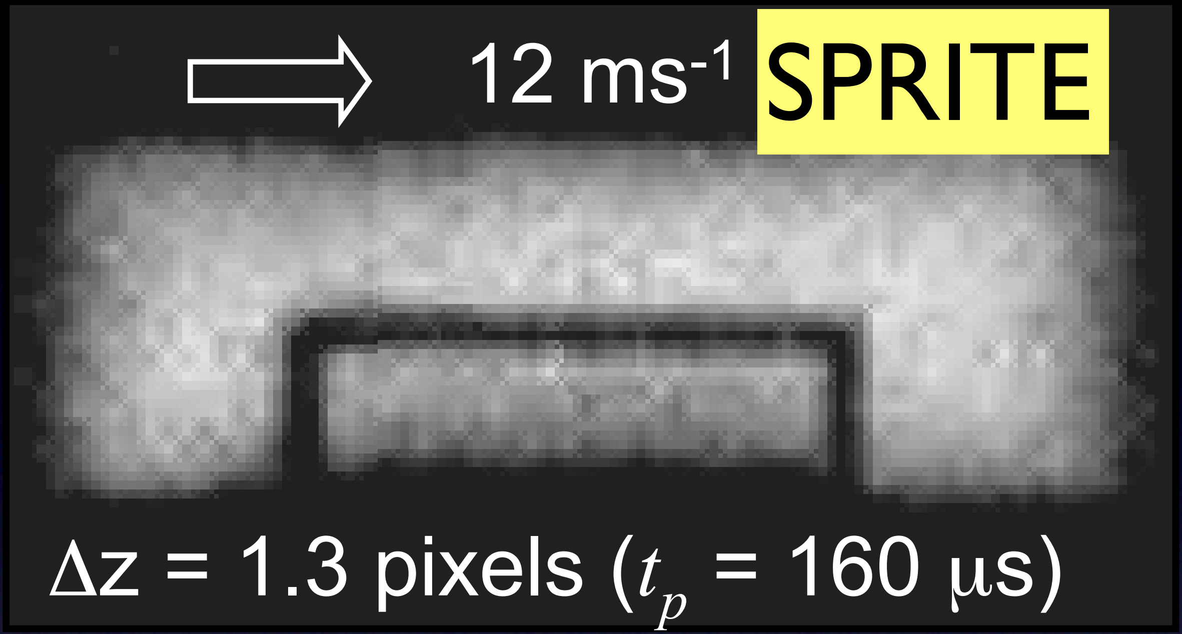
Only SPRITE could do this (among MRI).

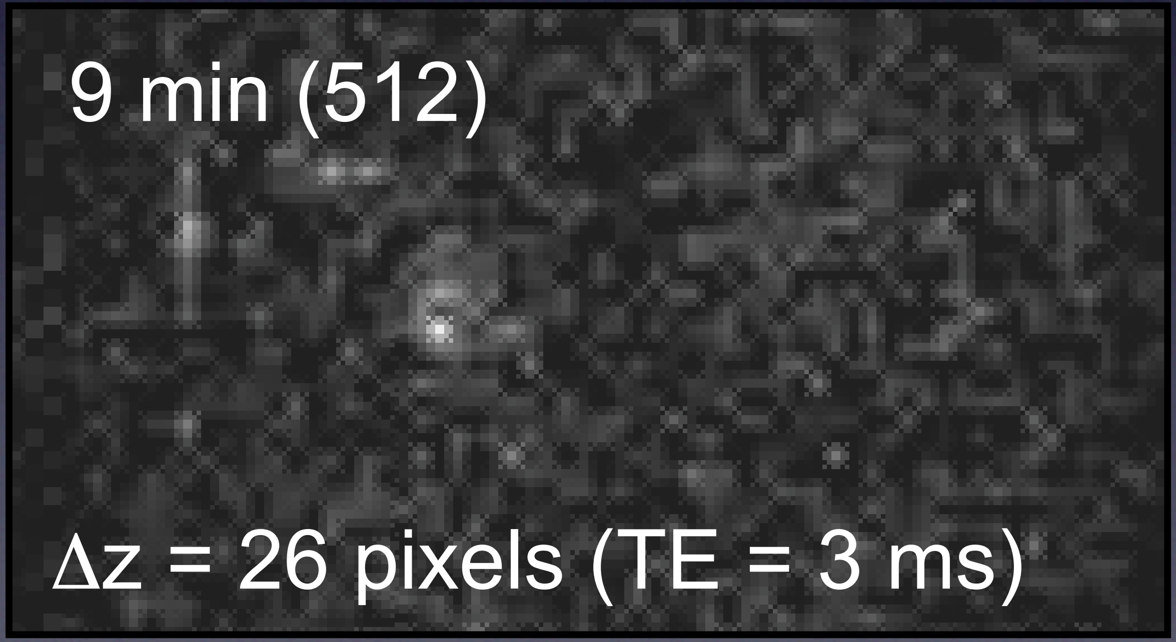




Subsonic gas

Flow faster than c. 1 m/s

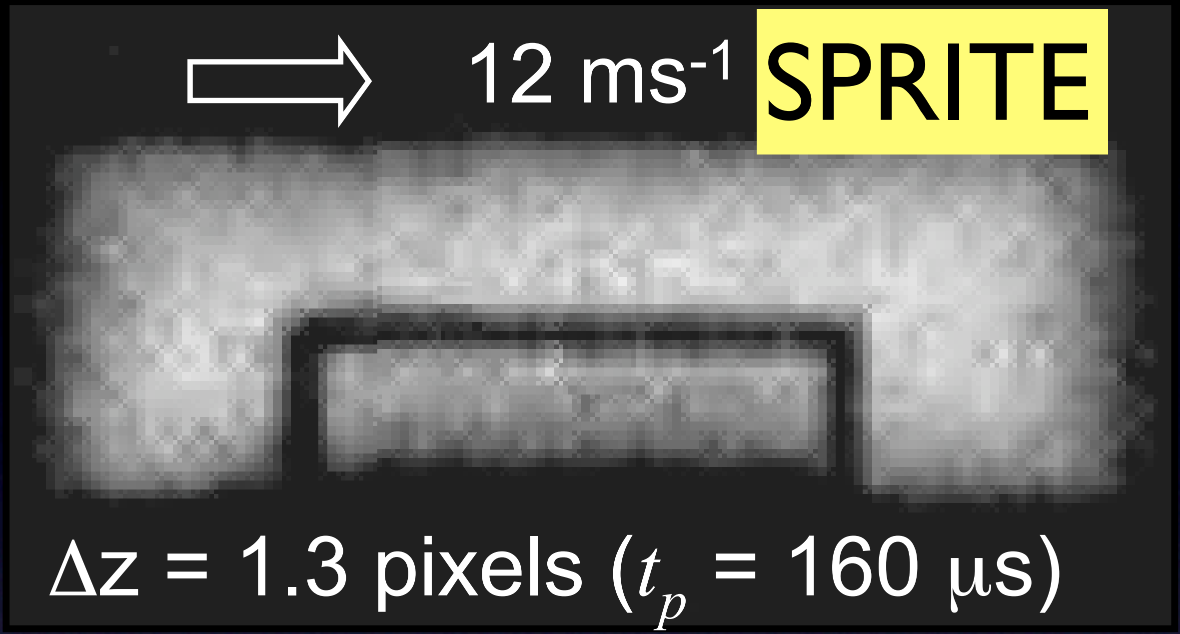




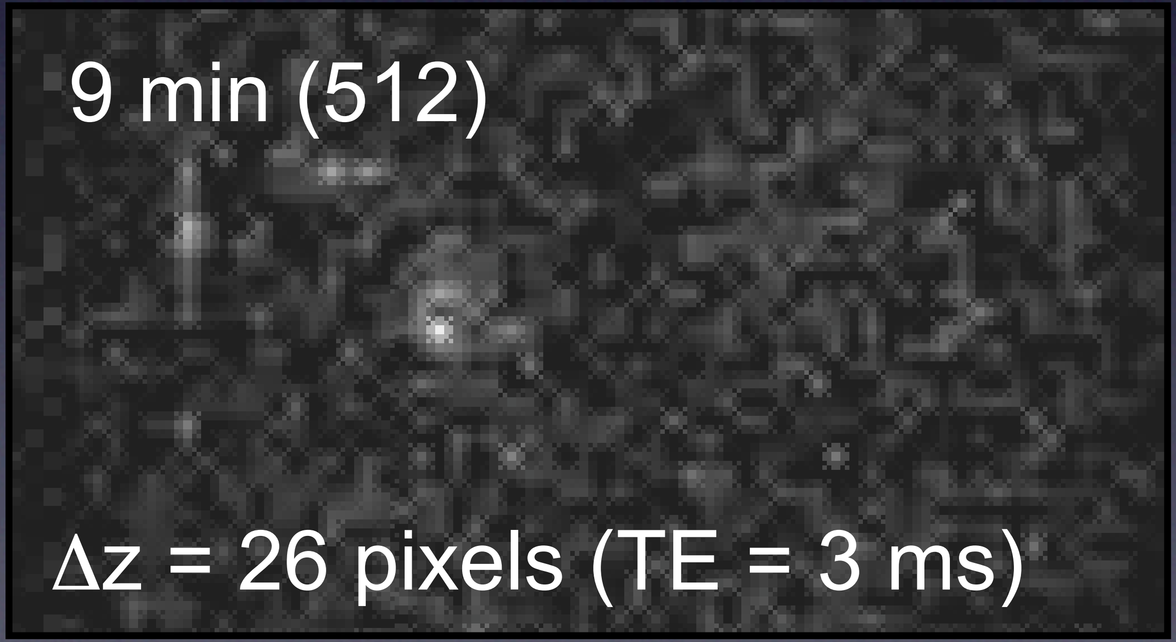
... can lead to complete signal loss in conventional MRI
... the gas leaves the probe during the measurement.

Subsonic gas

Random fluctuations in displacement also lead to extreme signal attenuation in conventional MRI.



In SPRITE MRI, short t_p controls the signal loss.



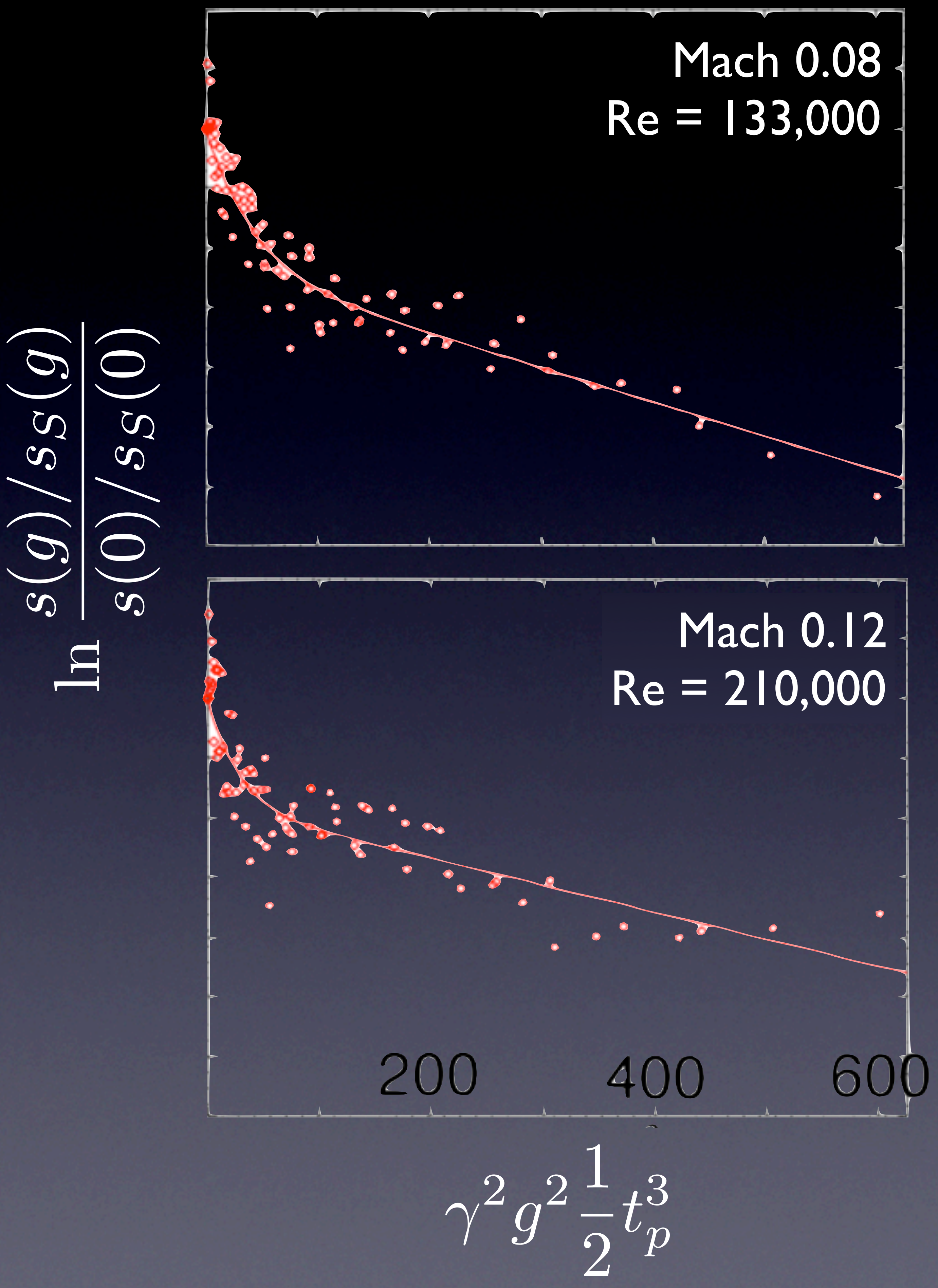
In fact, we <u>measure</u> the signal loss (width of propagator).

Subsonic gas

In fact, we measure the signal loss (width of average propagator).

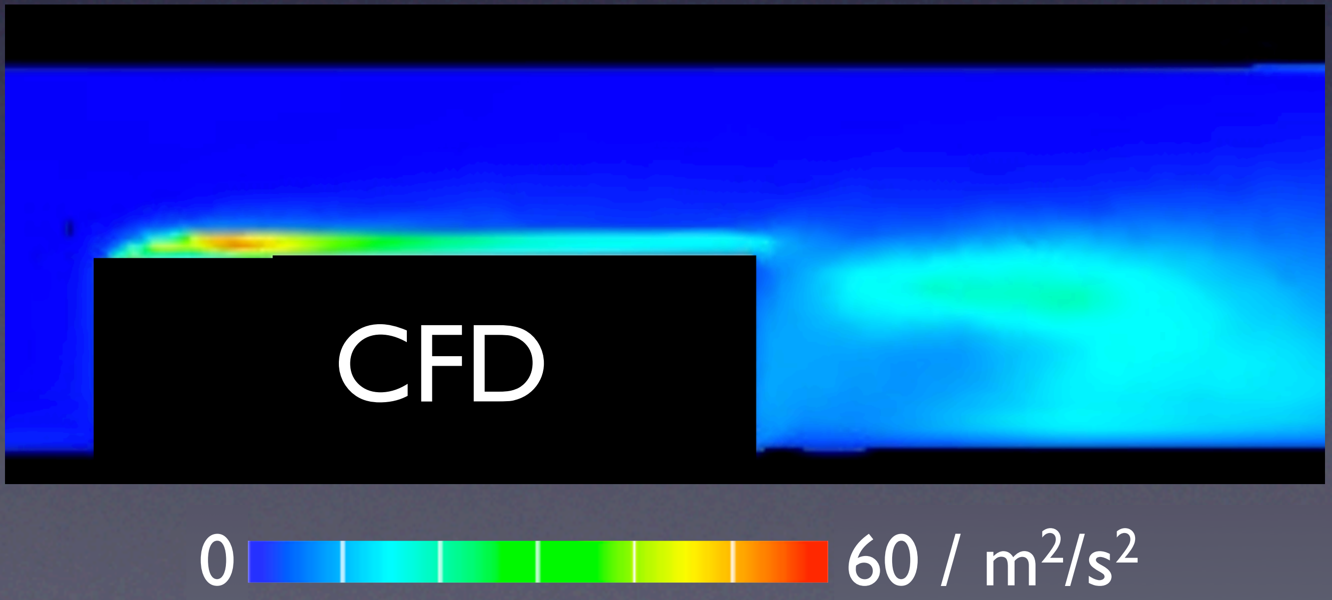
Slope is proportional to width...

... which we associate with [two] turbulent eddy diffusivity coefficients.

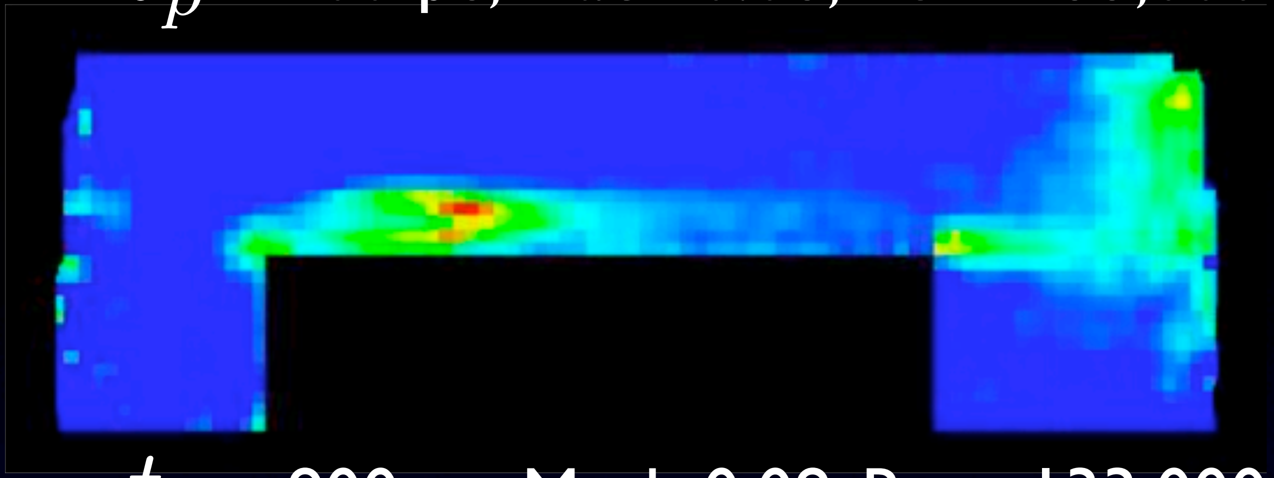


Subsonic gas

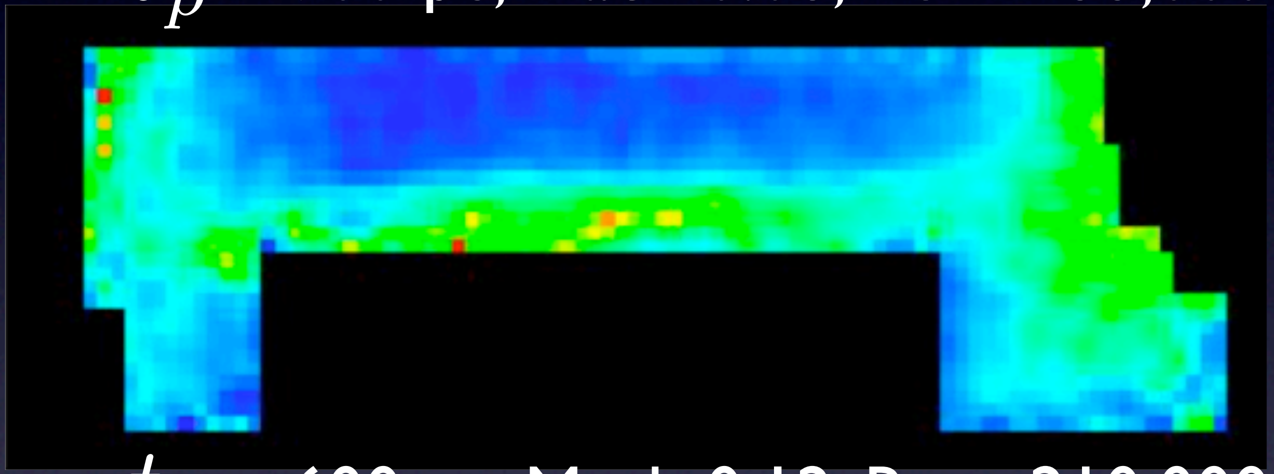
We can map D_t because it is constant with t_p



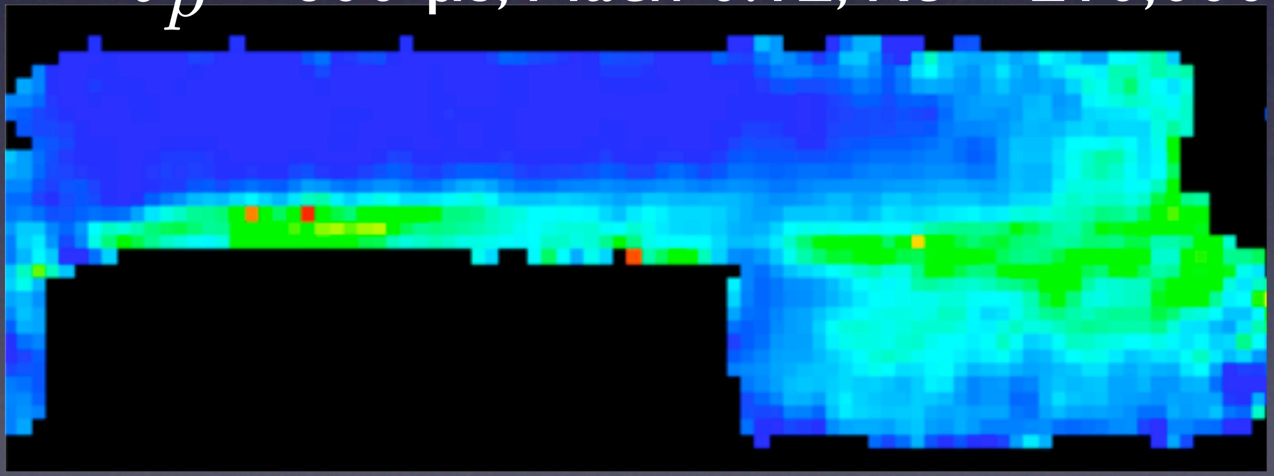
t_p = 400 μs, Mach 0.08, Re = 133,000



t_p = 900 μs, Mach 0.08, Re = 133,000



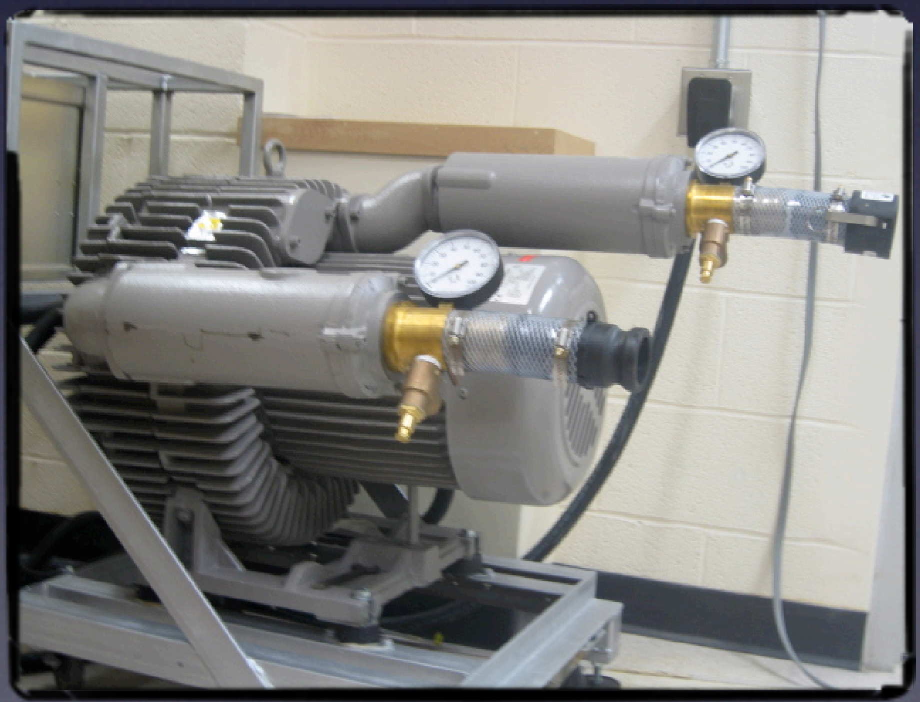
t_p = 600 μs, Mach 0.12, Re = 210,000



Slightly-less-subsonic gas

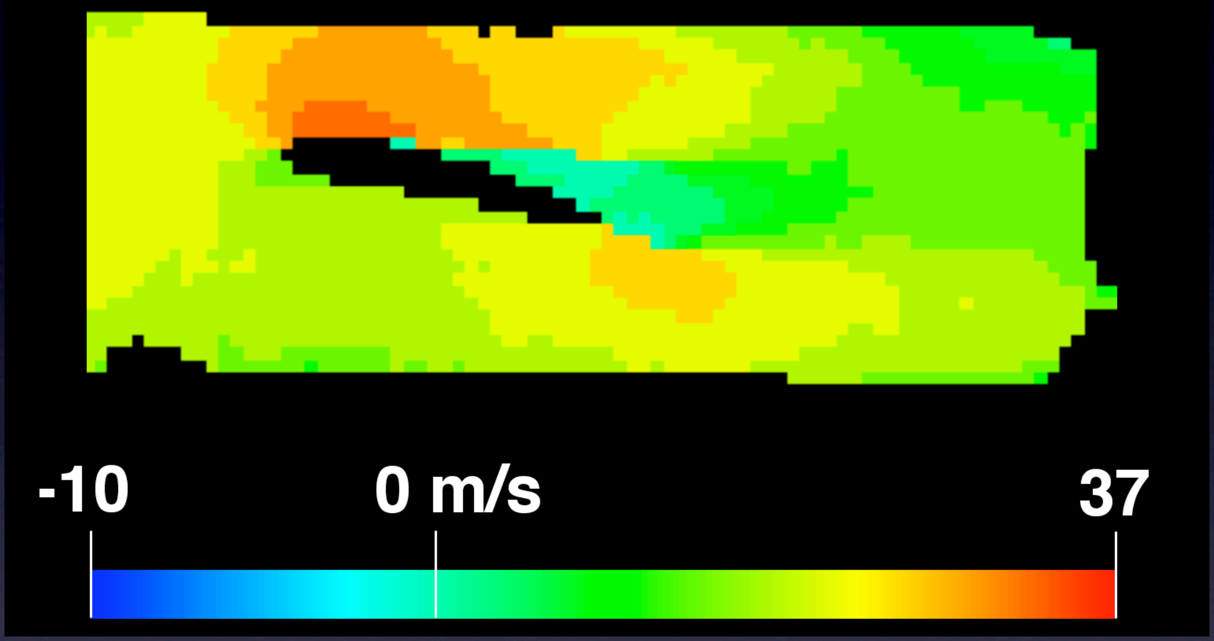
This arrangement can be used as an MRI wind tunnel.

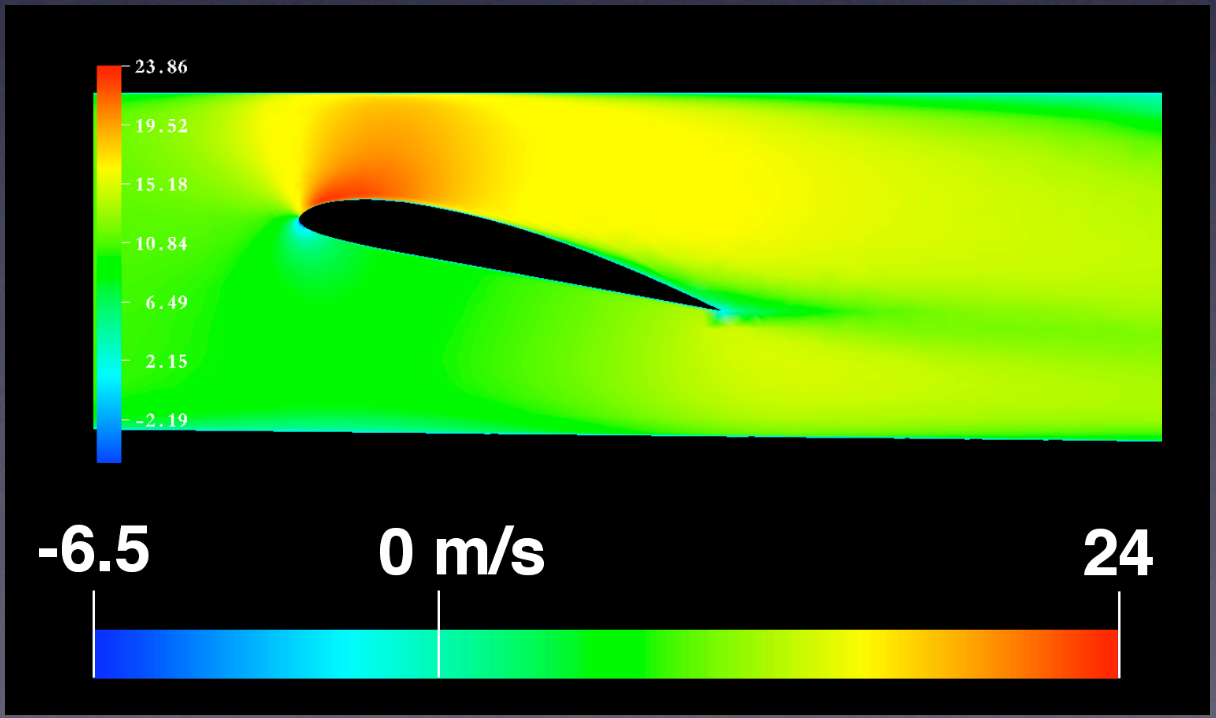
Current developments are towards Mach 1



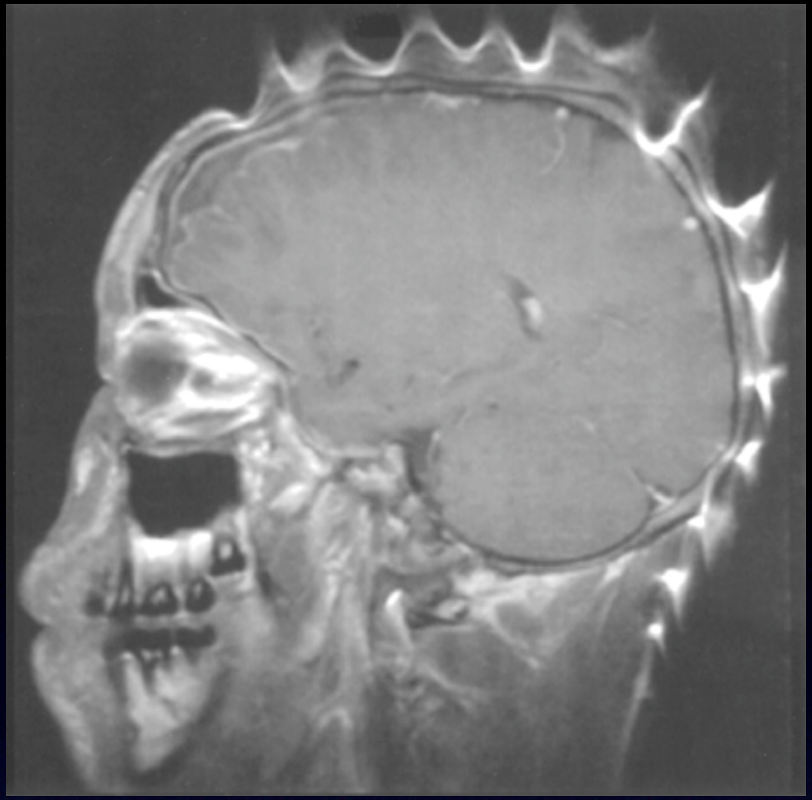
Newling *et al.* *Phys Rev. Lett.* (2004) **93** 154504

12 m/s Re 165 000 SF_6



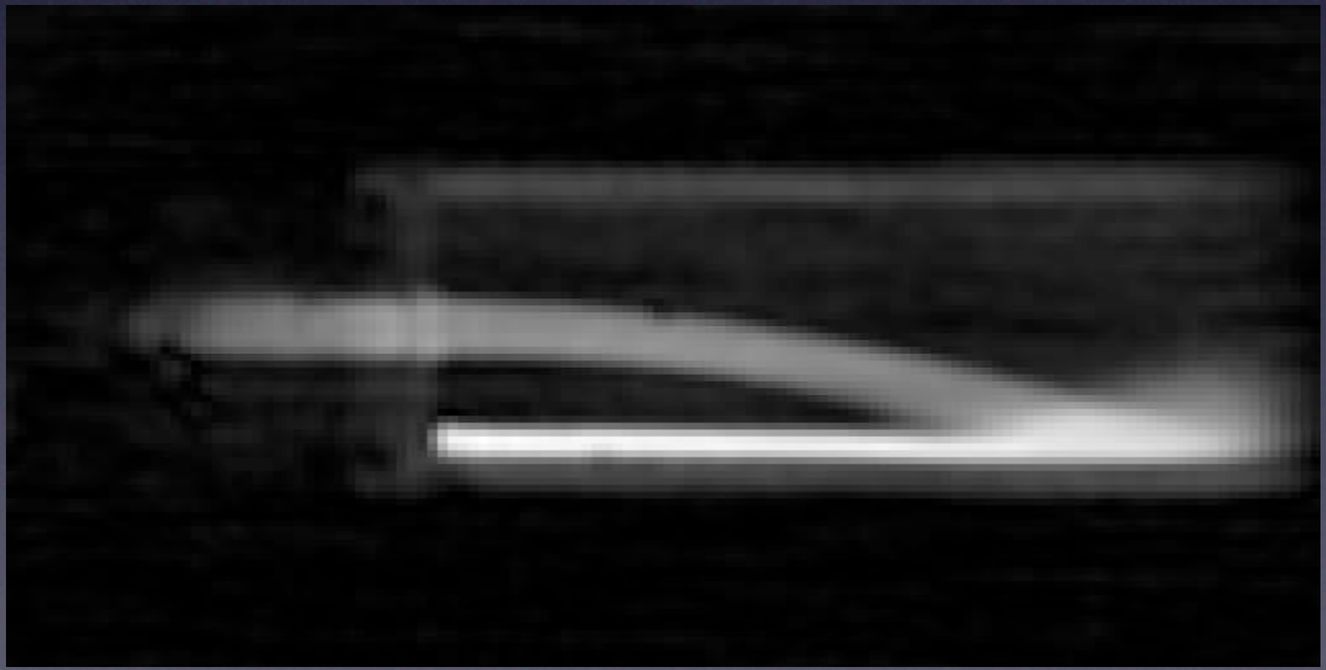


Two-phase flow



Another place where traditional MRI would not cope well...

... at the interface of air and water χ changes (artefacts)



McKinstry & Jarrett *Am. J. Roentgenology.* (2004) **182** 532

Two phase flow

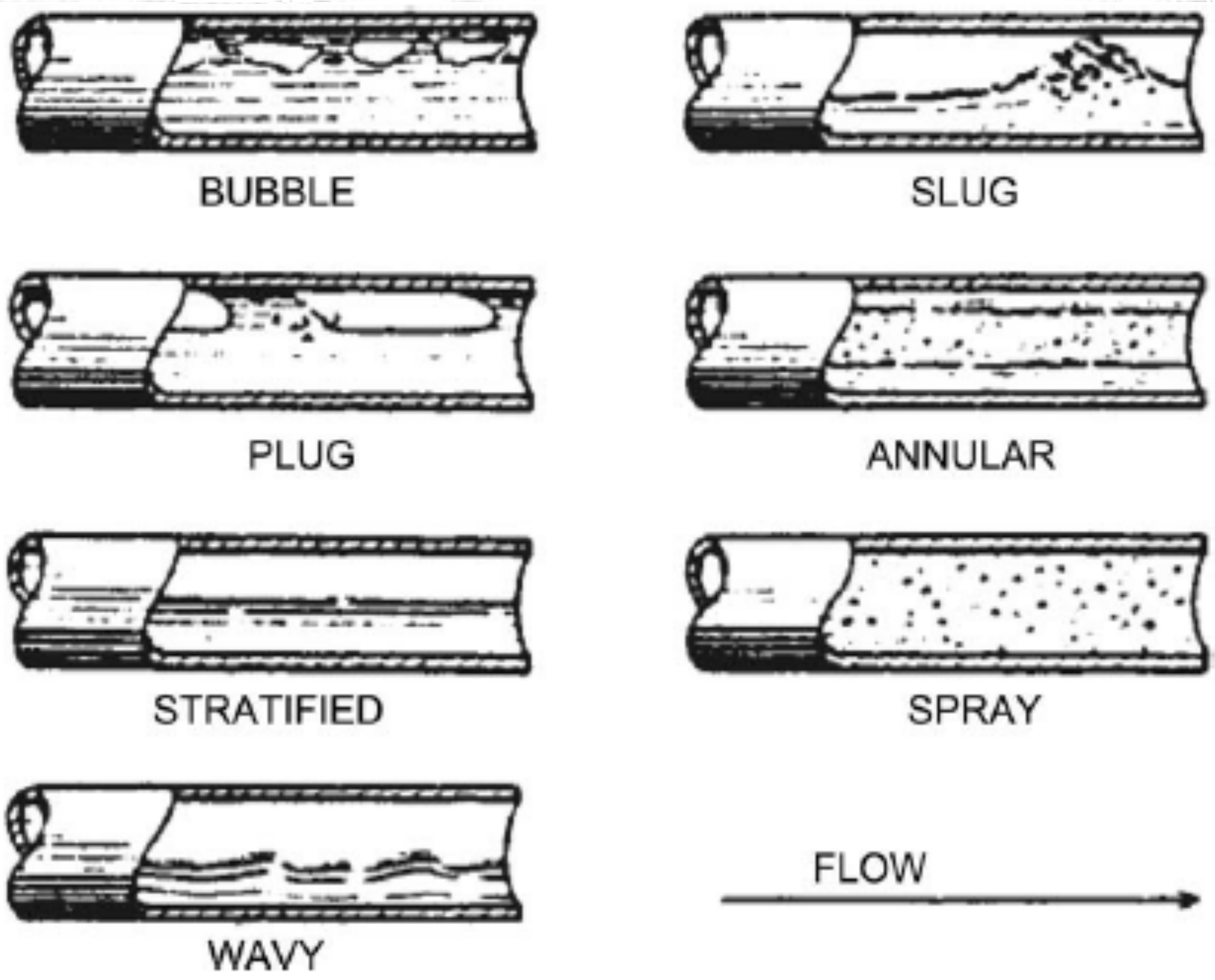
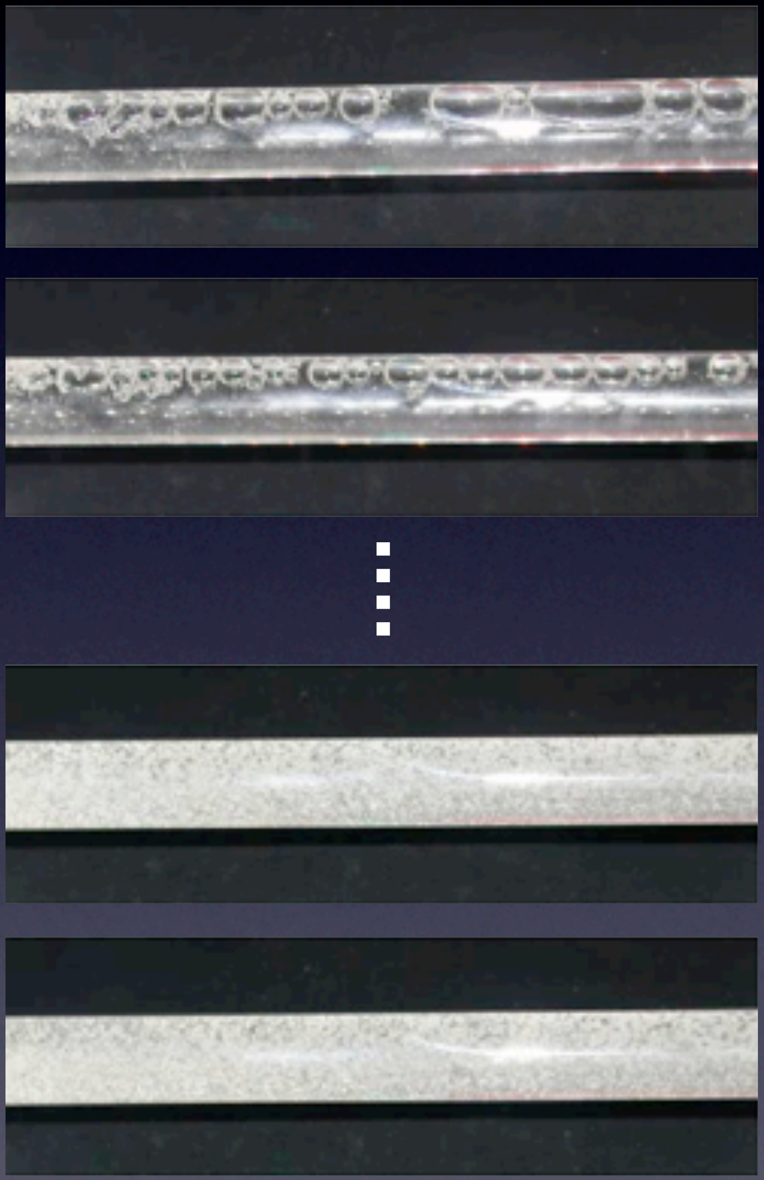
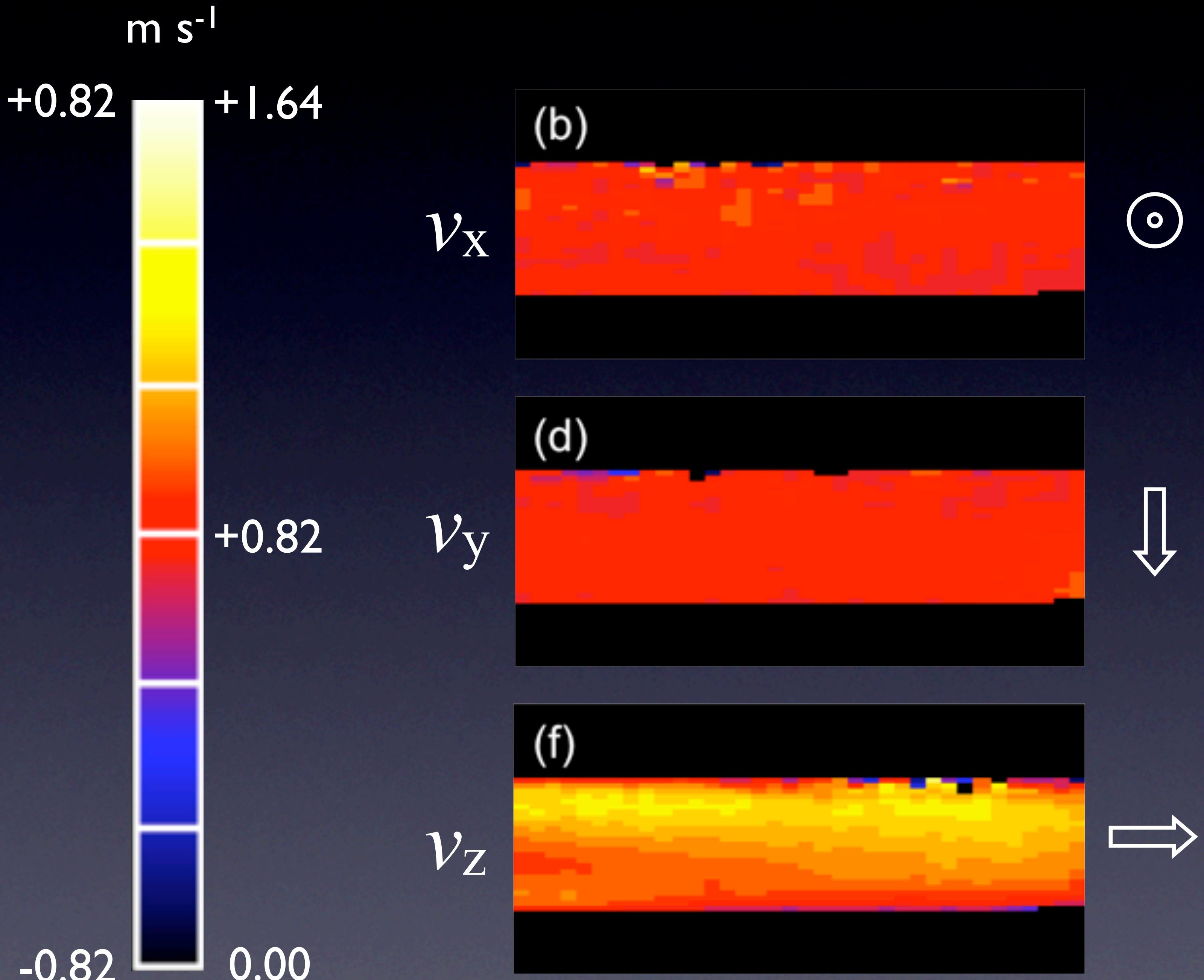


Fig. 1. Gas–liquid flow patterns in horizontal pipes (reproduced with permission, copyright American Institute of Chemical Engineers, from Alves [4]).

Sankey *et al. J. Magn. Reson.* (2009) **199** 126

Two-phase flow





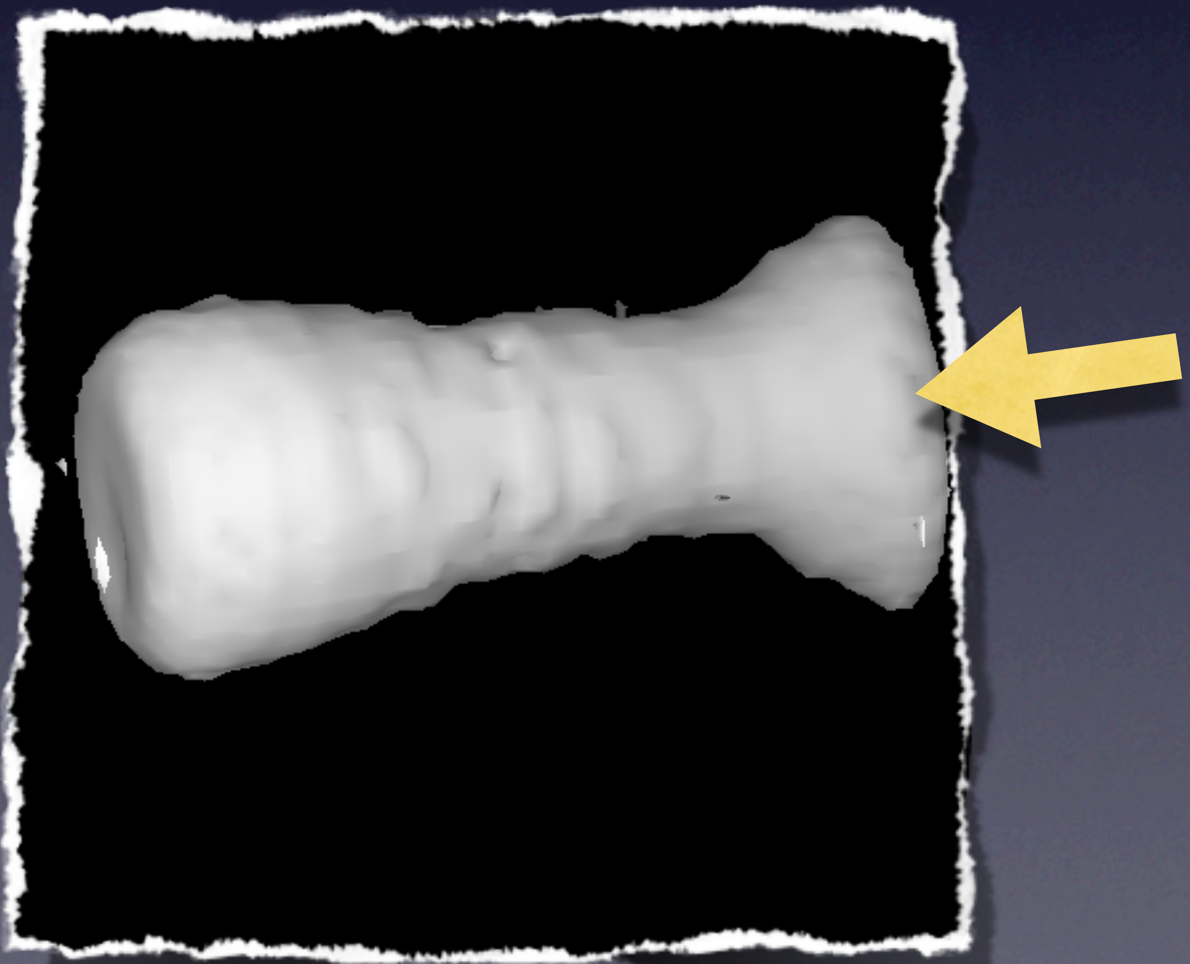
1 m/s Re 14 500 $GdCl_3$ (aq.)

e.g. t_p = 1.3 ms

Sankey *et al. J. Magn. Reson.* (2009) **199** 126

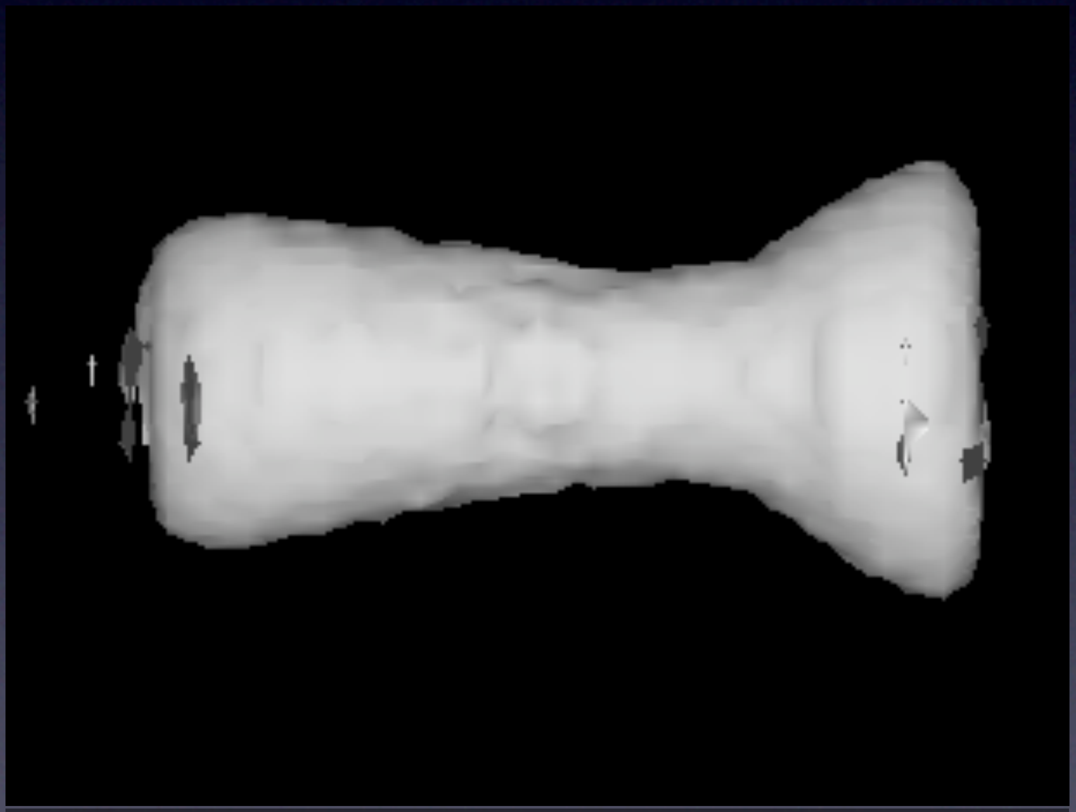
Two-phase flow

Latest measurements are in hydrodynamic cavitation: the formation of bubbles in a flow field.



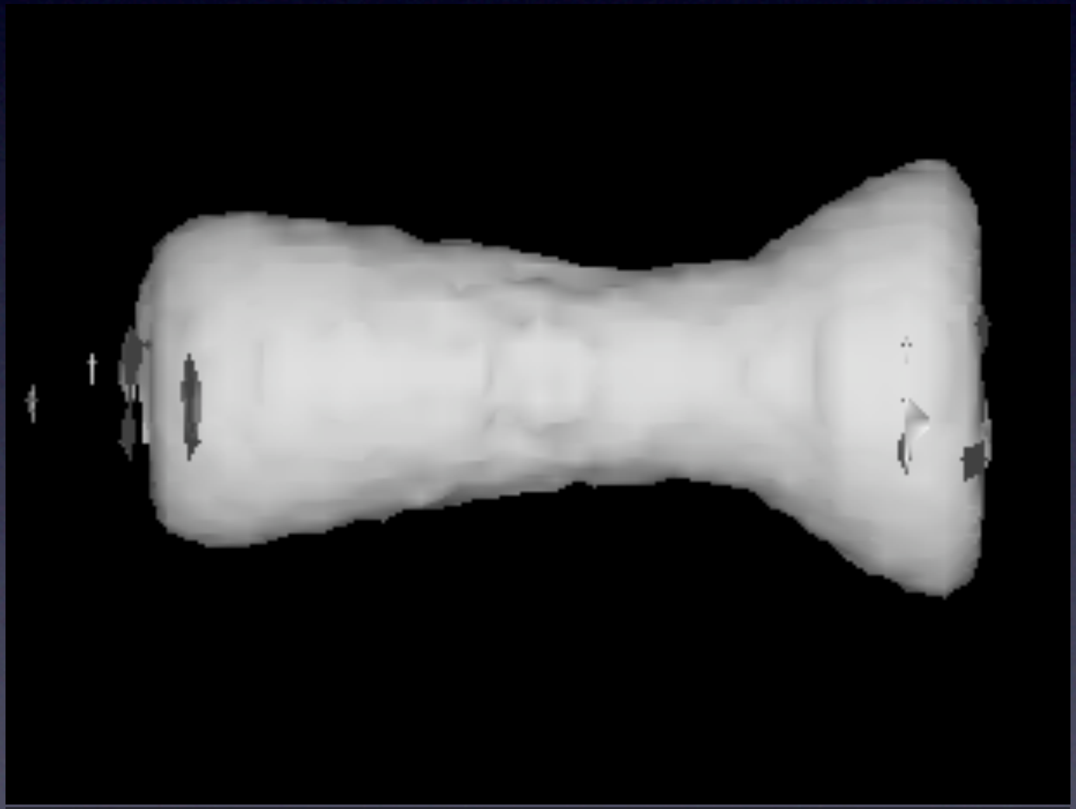
Hydrodynamic Cavitation

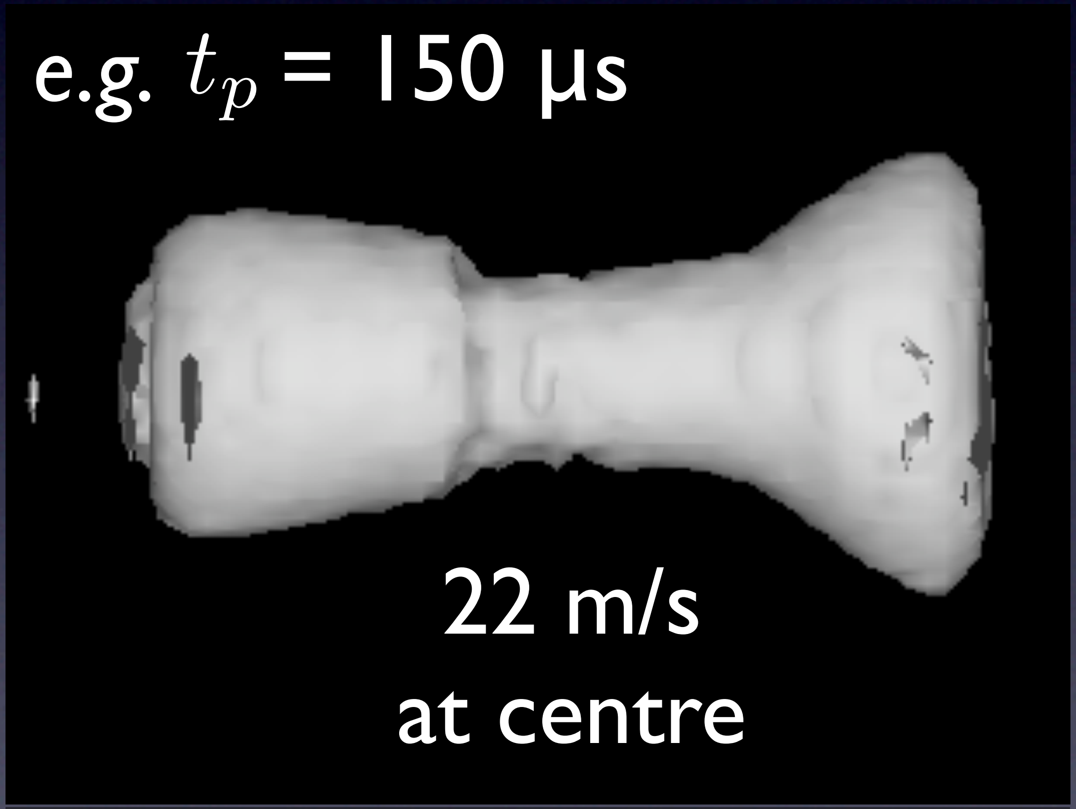
The formation of bubbles in a flow field.



Hydrodynamic Cavitation

The formation of bubbles in a flow field.



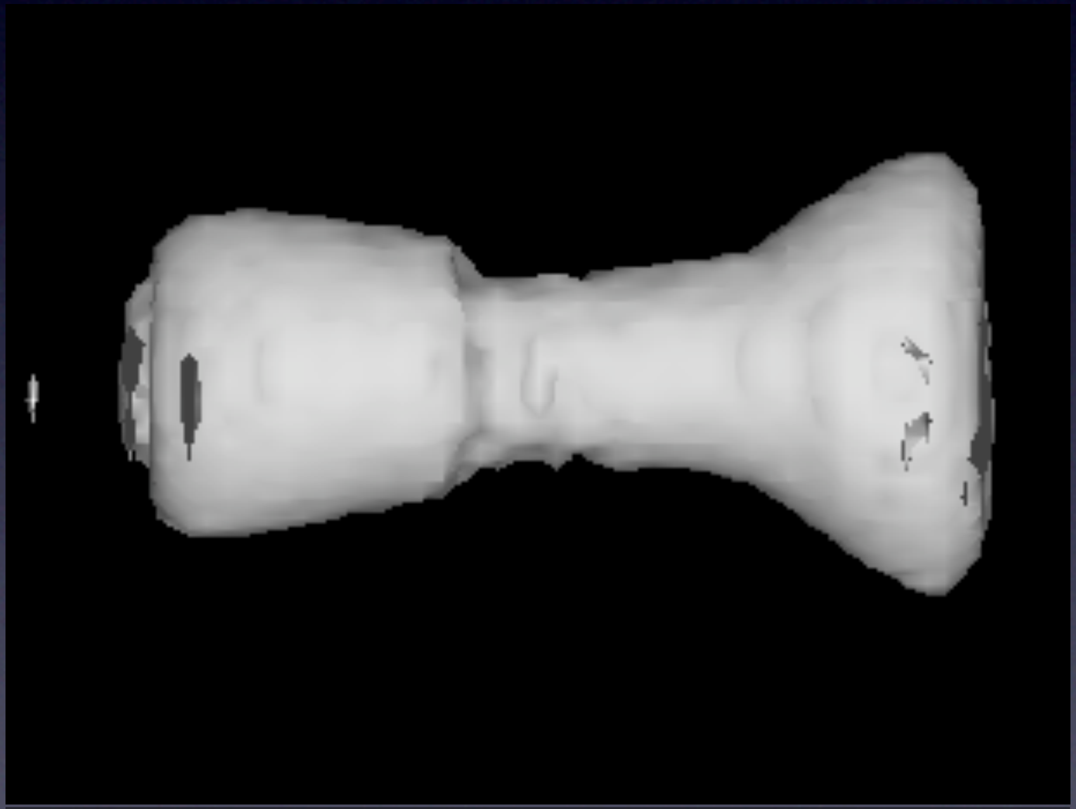


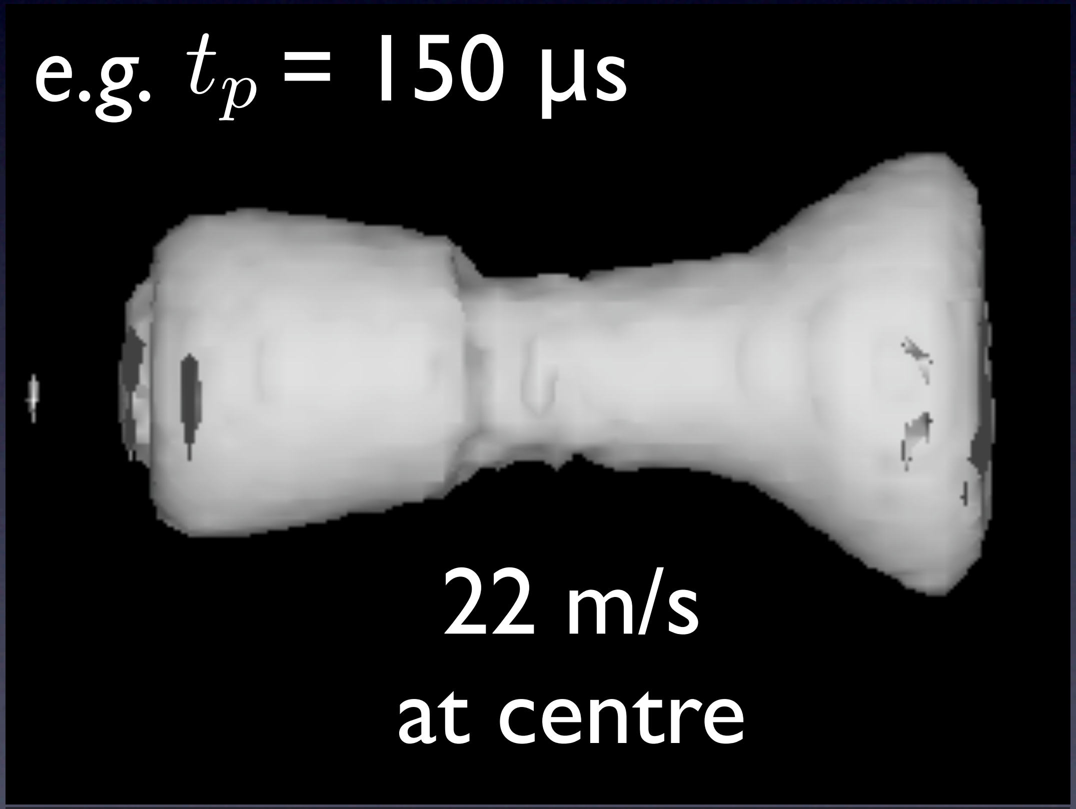
e.g. t_p = 150 µs

22 m/s
at centre

Hydrodynamic Cavitation

The formation of bubbles in a flow field.





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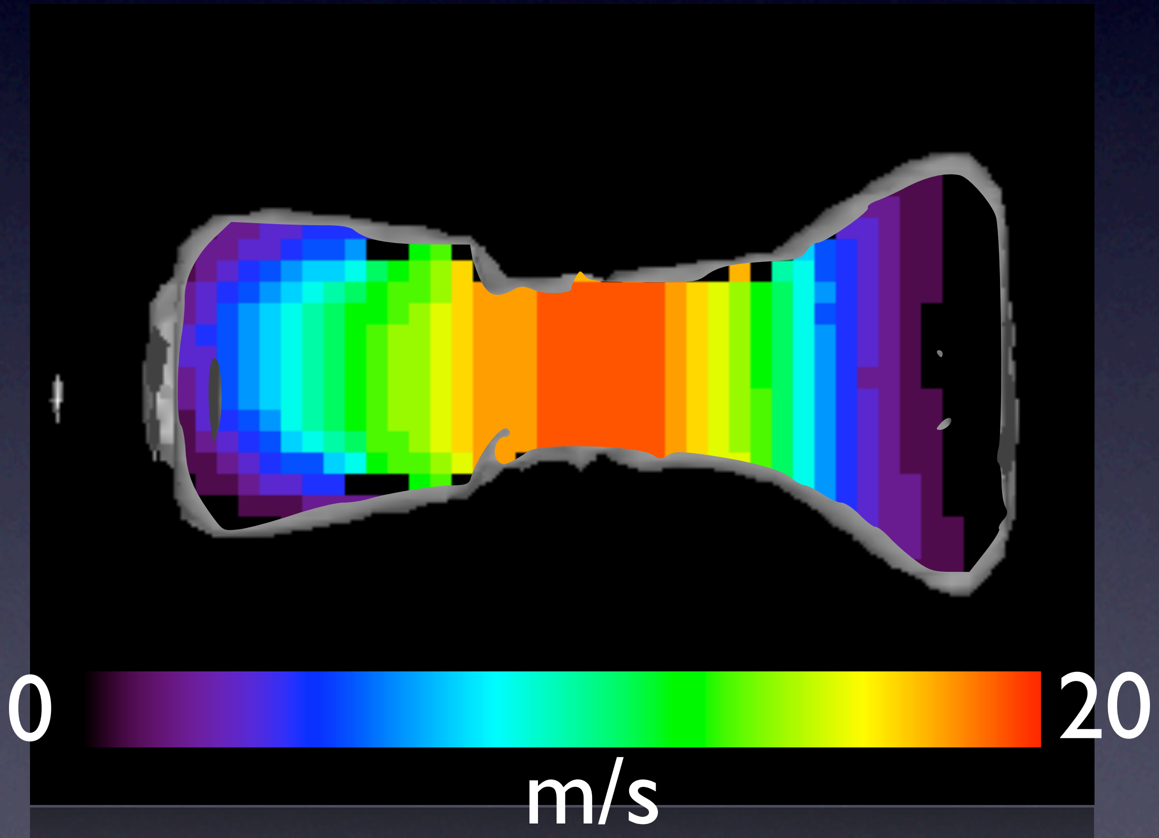
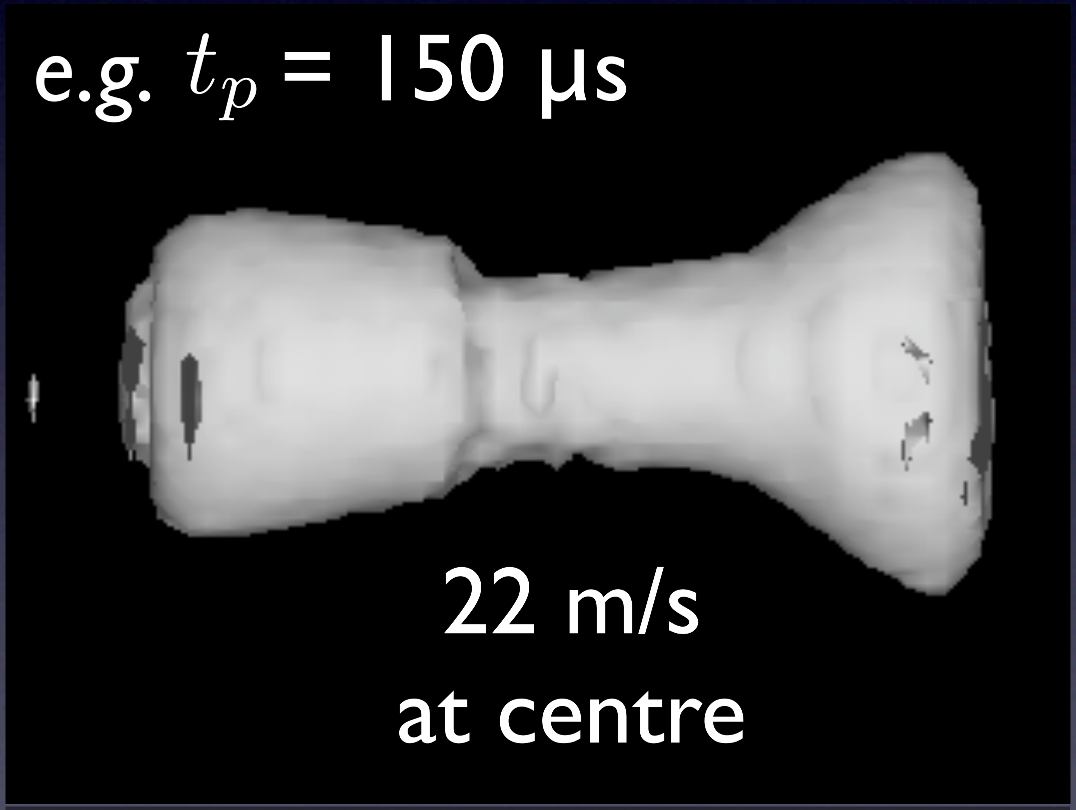


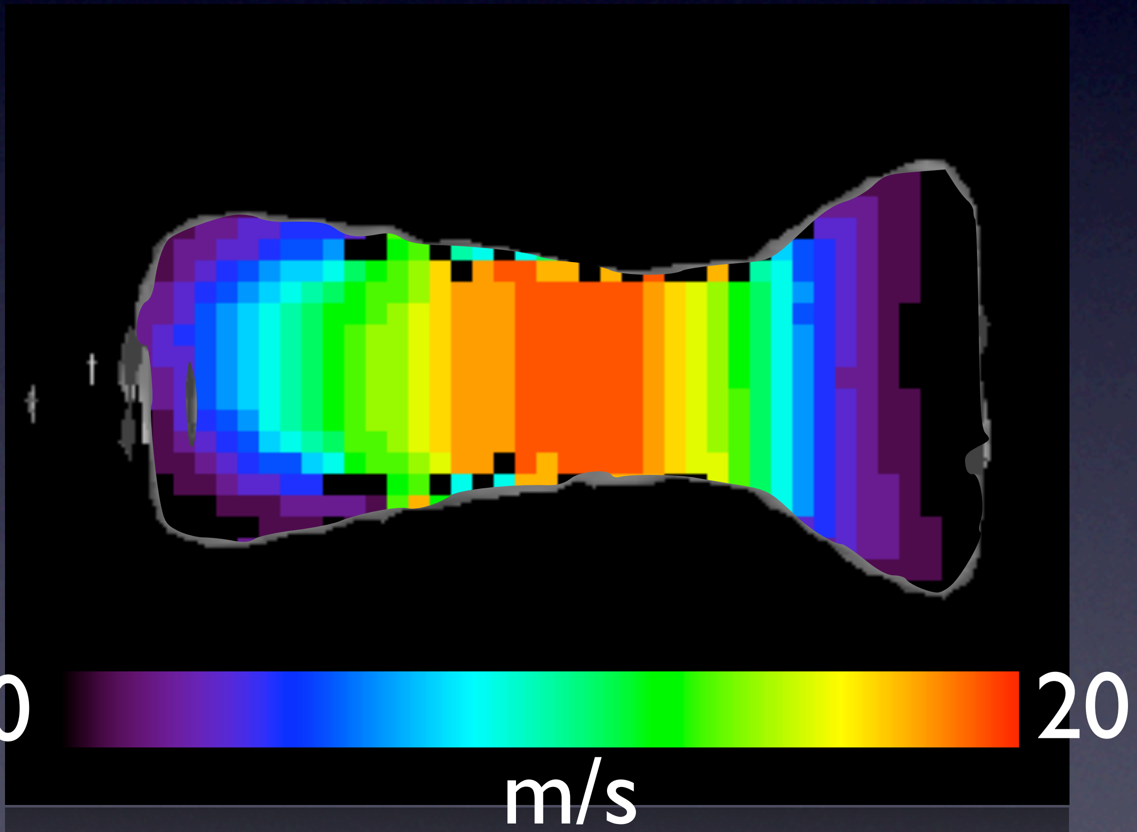


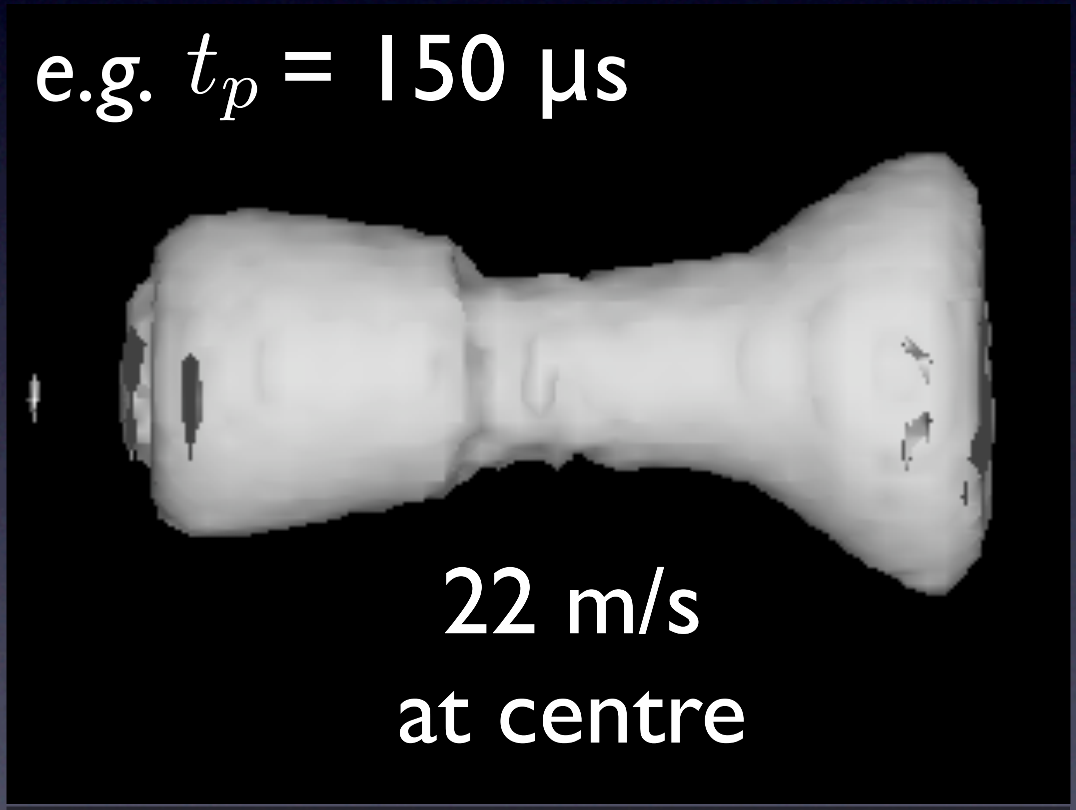
e.g. t_p = 150 µs

22 m/s
at centre

Hydrodynamic Cavitation

Only SPRITE could do this (among MRI),



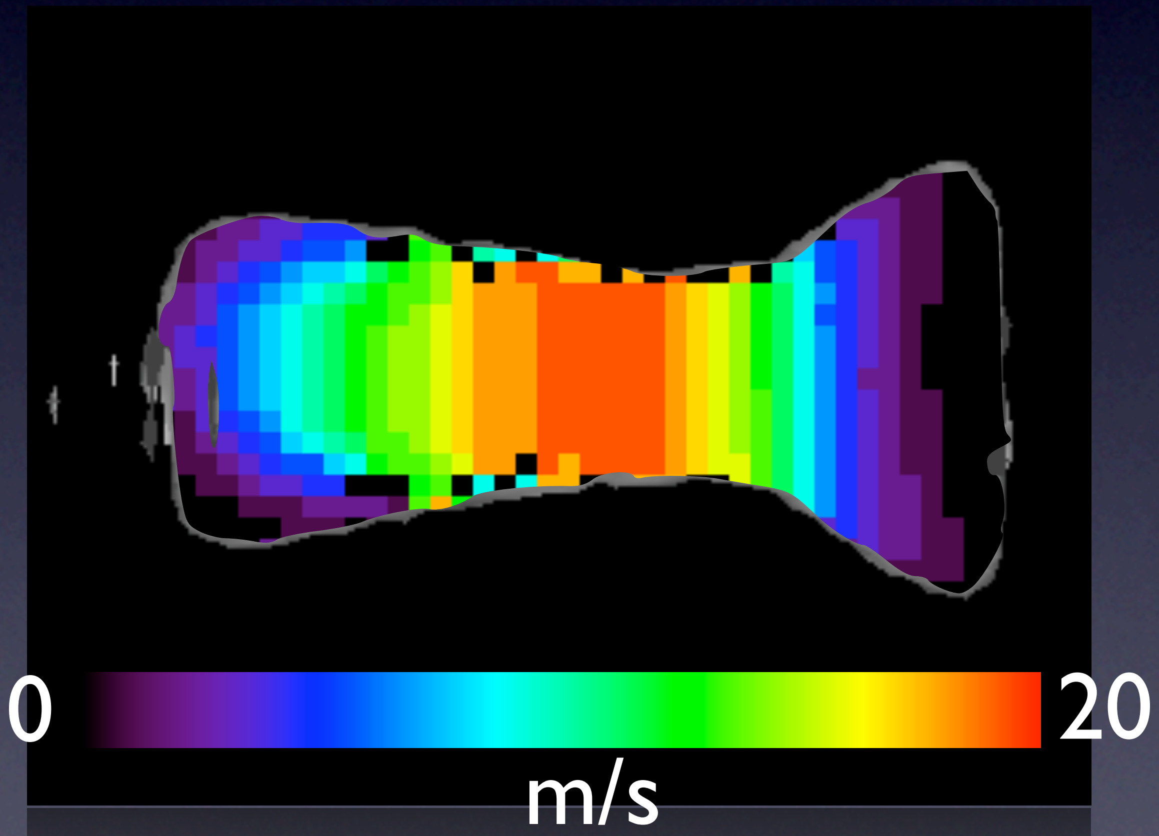

e.g. t_p = 150 µs

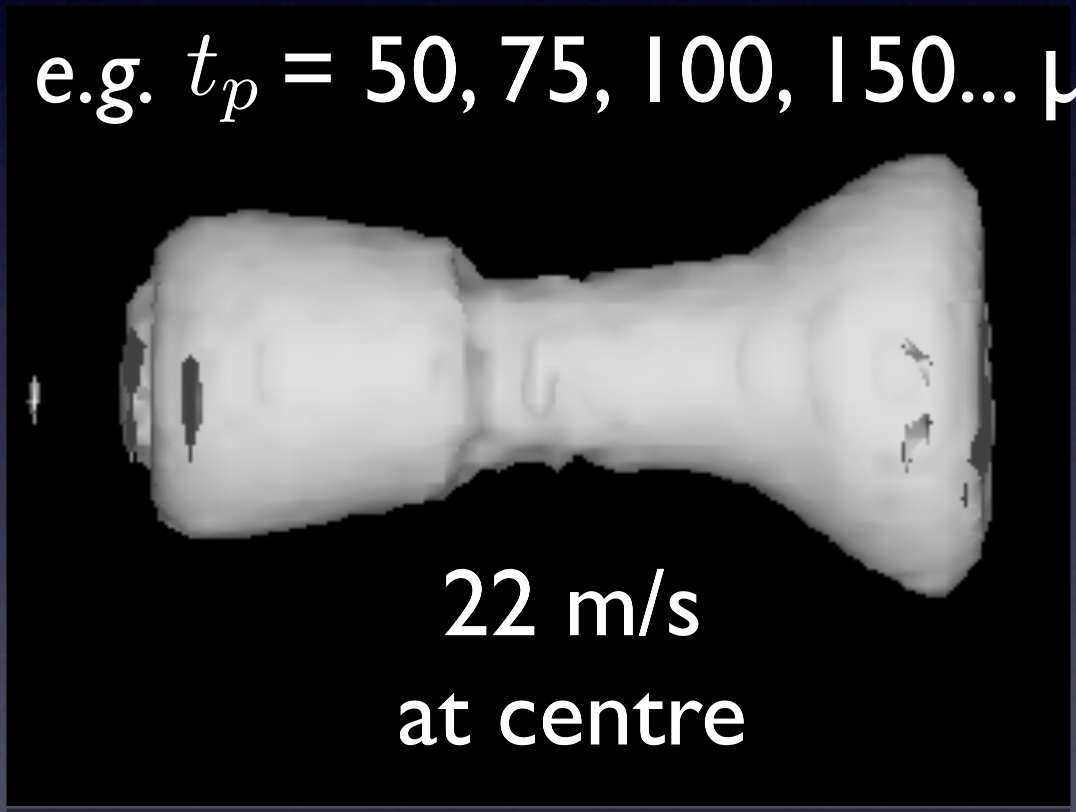
22 m/s
at centre

because t_p is short **and** constant.

Hydrodynamic Cavitation

Only SPRITE could do this (among MRI),





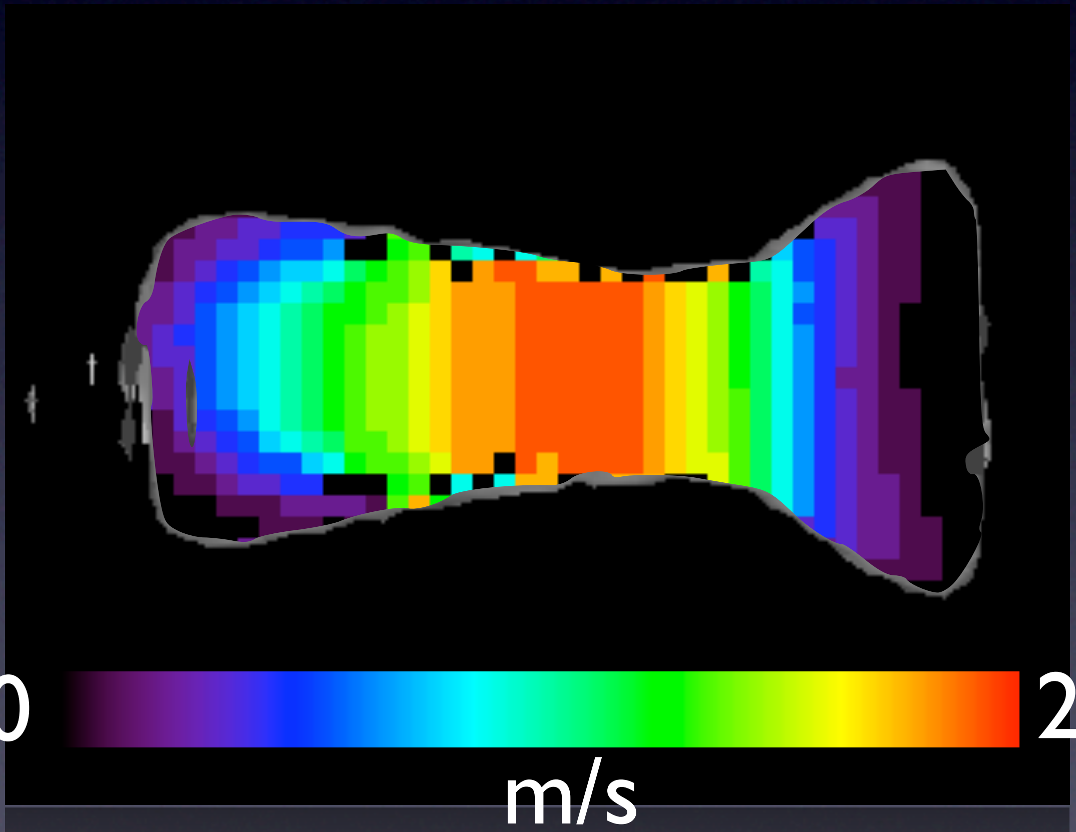
e.g. t_p = 50, 75, 100, 150... μs

22 m/s
at centre

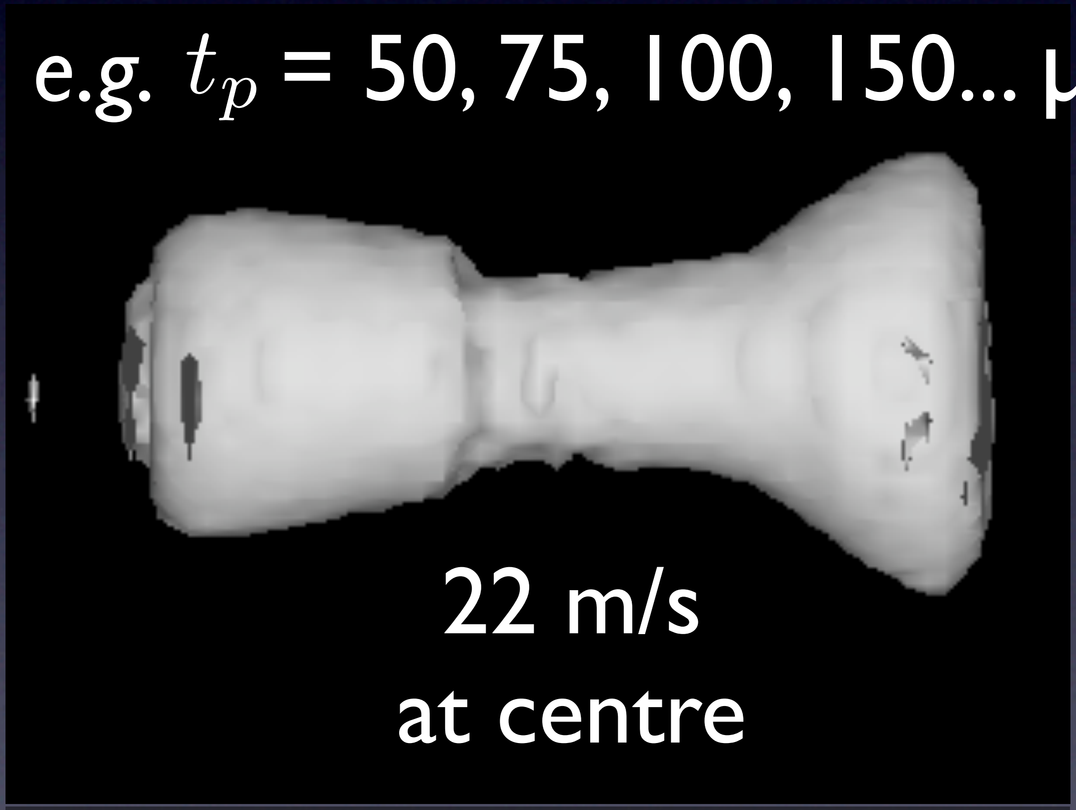
because t_p is short **and** constant.

Hydrodynamic Cavitation

Multiple t_p data allow us to fit the decay and back extrapolate to t_p = 0 s, giving volume fraction.



e.g. t_p = 50, 75, 100, 150... μs

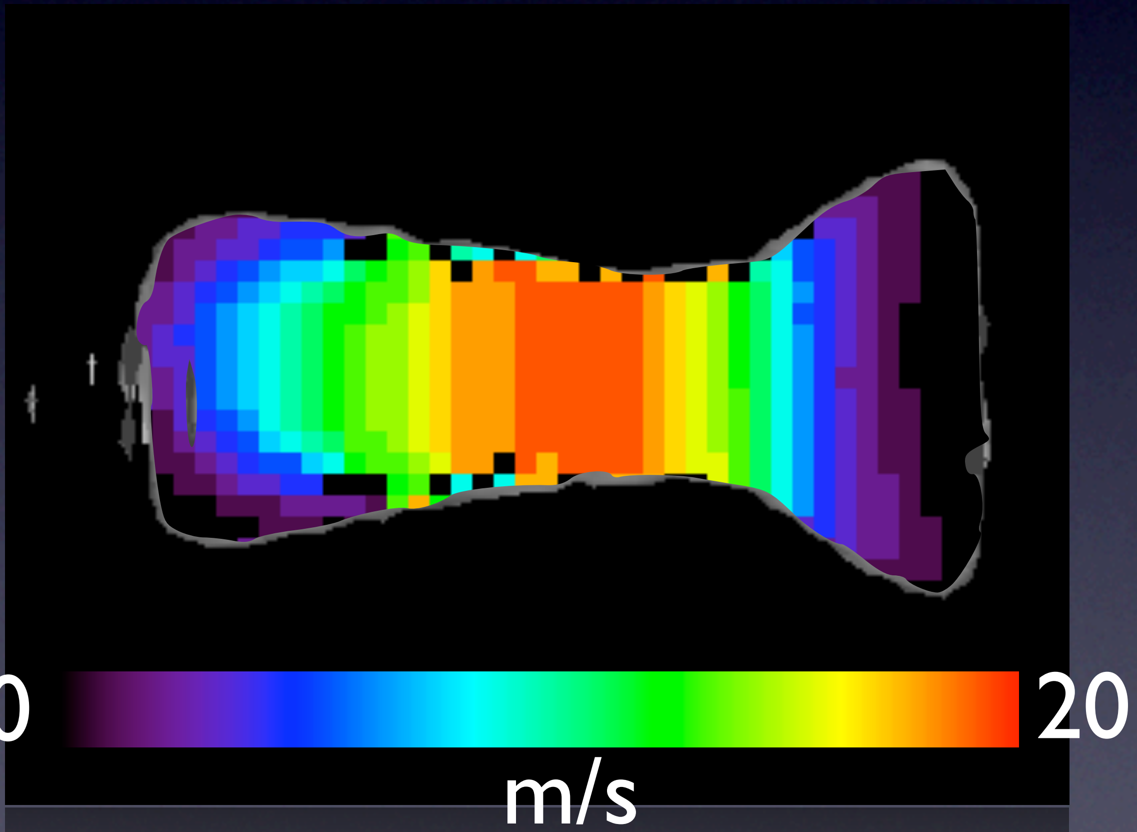


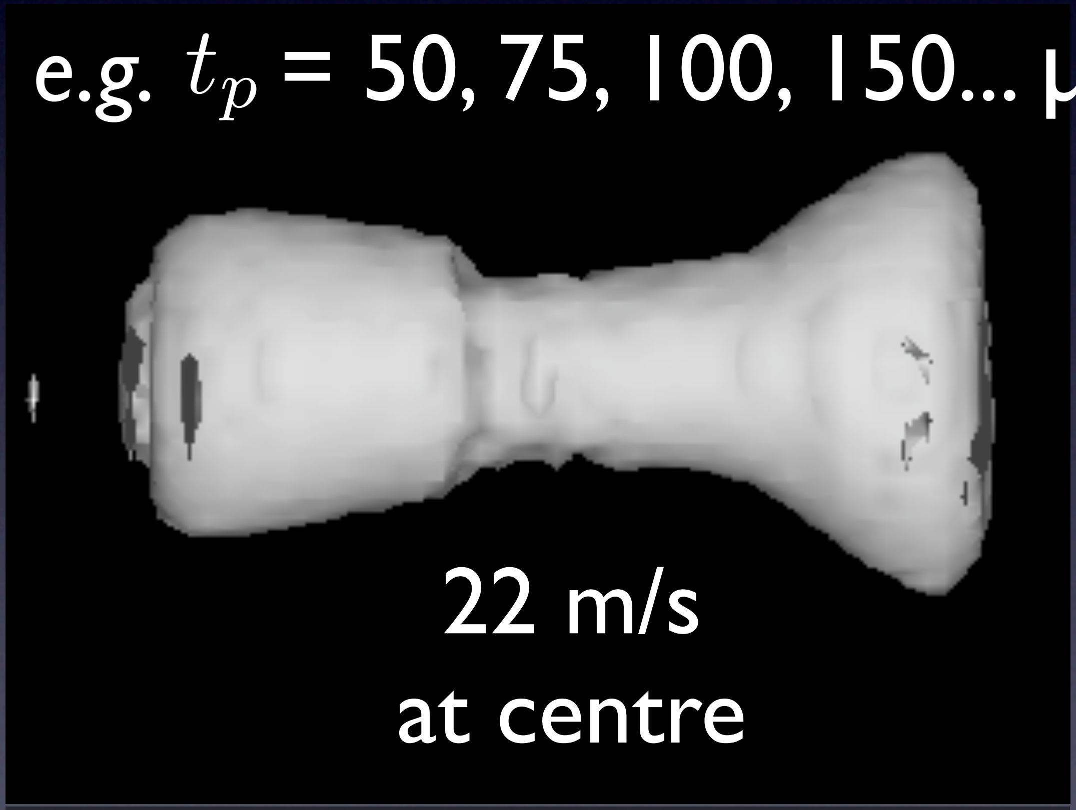
22 m/s
at centre

The decay is potentially also informative.

Hydrodynamic Cavitation

Multiple t_p data allow us to fit the decay and back extrapolate to t_p = 0 s, giving volume fraction.





e.g. t_p = 50, 75, 100, 150... µs

22 m/s
at centre

Mastikhin *et al. Phys. Rev. E* (2008) **199** 78-6-066316

Reminder

www.unb.ca/physics/mri

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MRI measures average propagators non-invasively, even in the dark.

SPRITE MRI can do it even when there are liquid/gas interfaces (two-phase flow) **or** just gas (subsonic flow) ... and when the flow is fast.

The propagator contains information about average velocity **and** velocity fluctuation.

Thanks to Rod, Murray, 2(Brian)

NSERC
CRSNG

Harrison McCain
Foundation