Basic Facts About Gravity Waves

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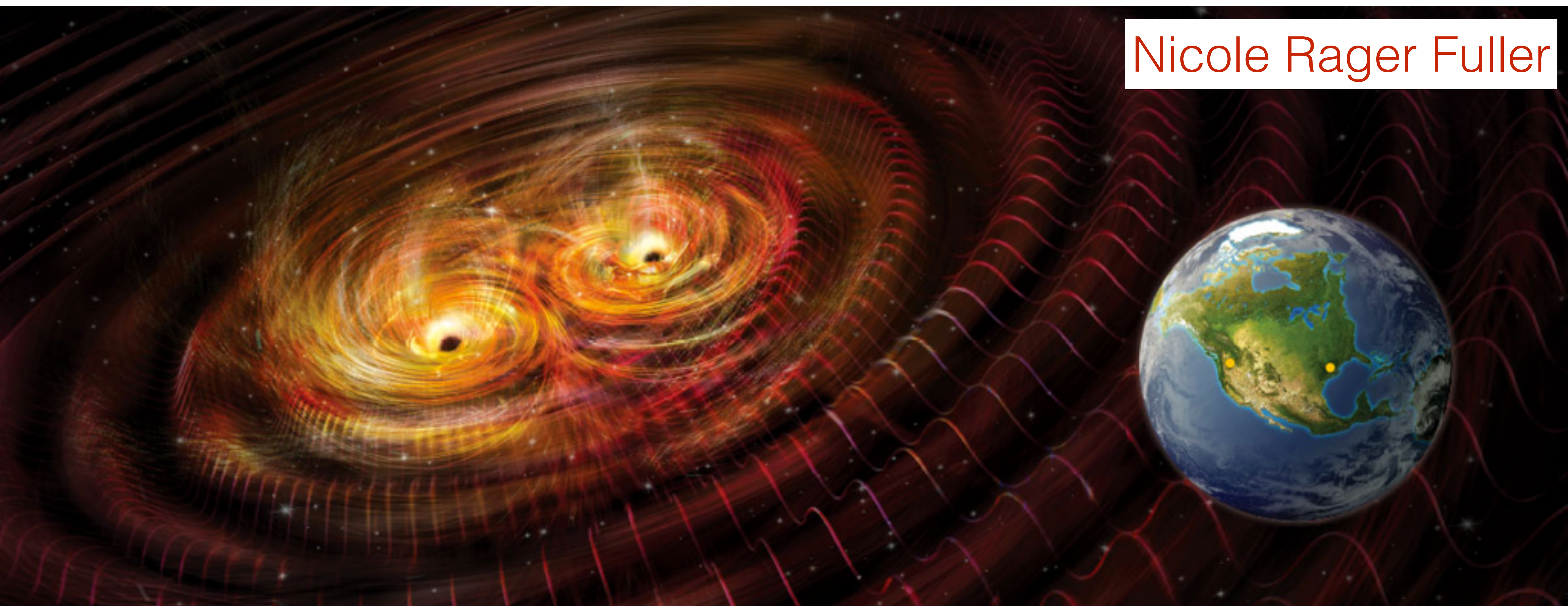
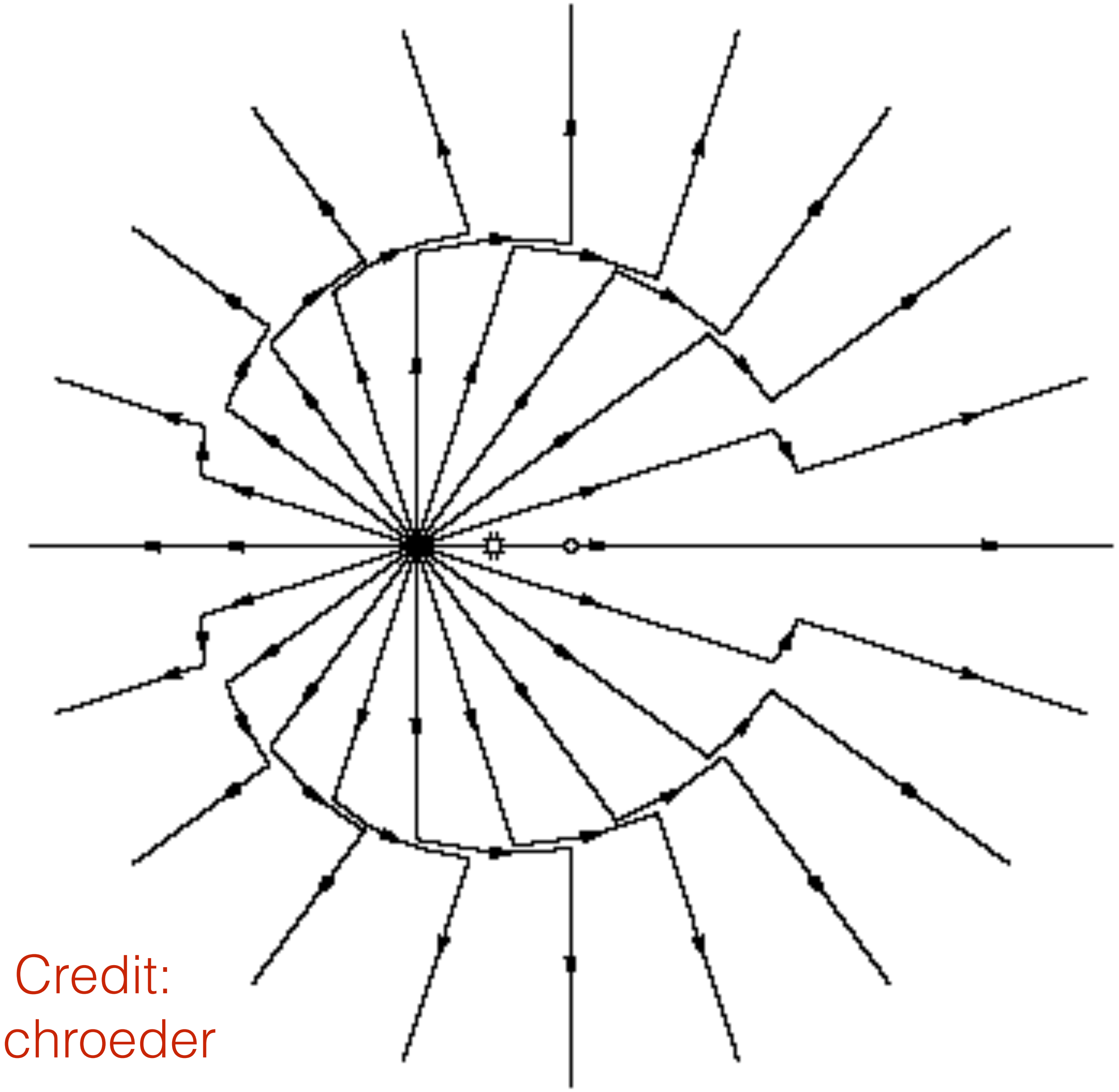
University of Oregon
Quarknet 2016



Talk Outline

- Pictorial Derivation of Radiation (Electromagnetic and Gravitational)
- Dimensional Analysis Explanation of Gravity Wave Properties - Intelligent Guessing of Physics Formulas



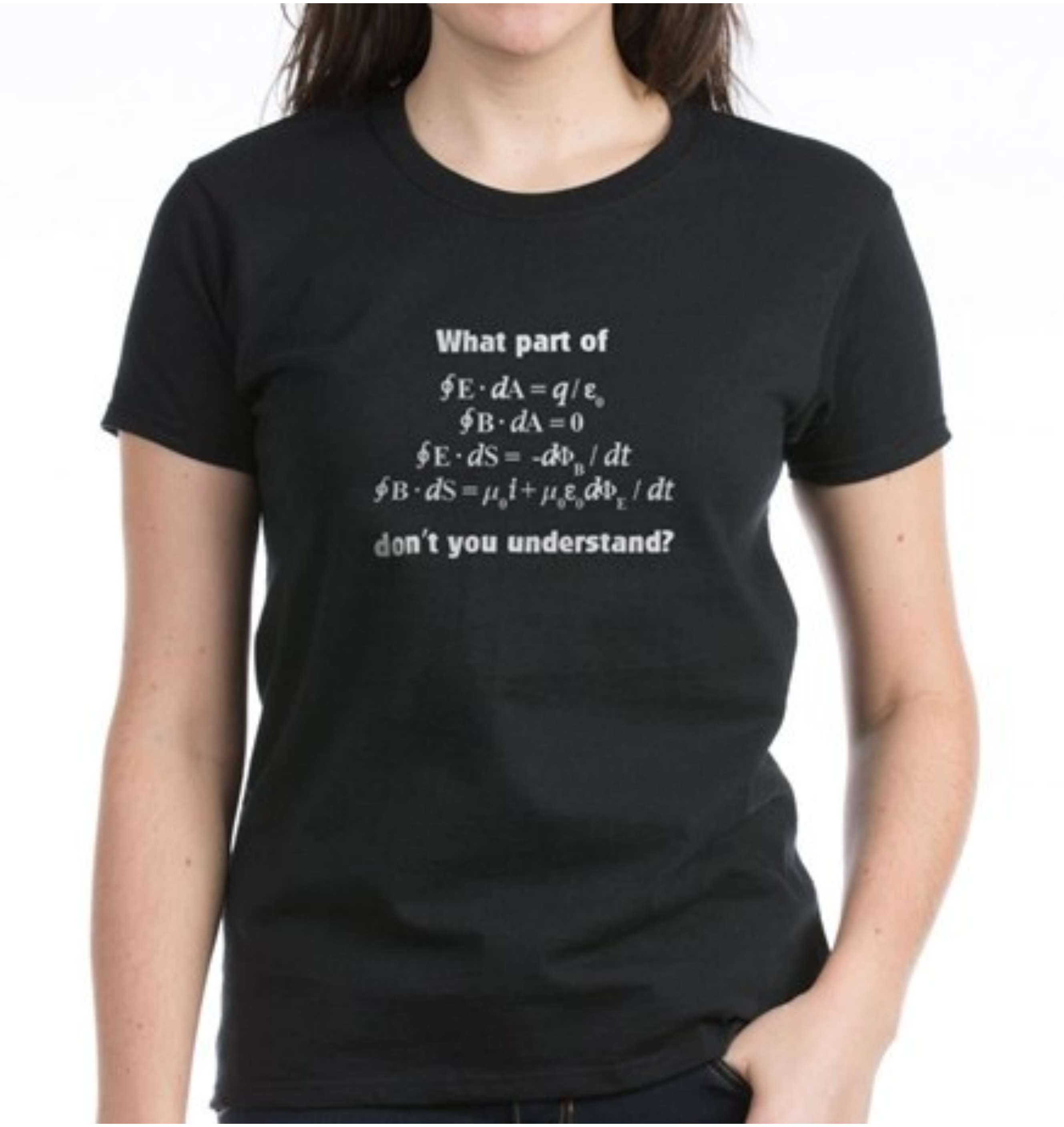
Credit: Schroeder

Topic 1

A Pictorial Derivation of Radiation

For Electromagnetism
see "Electricity and Magnetism" by Purcell
and discussion from Schroeder (link)

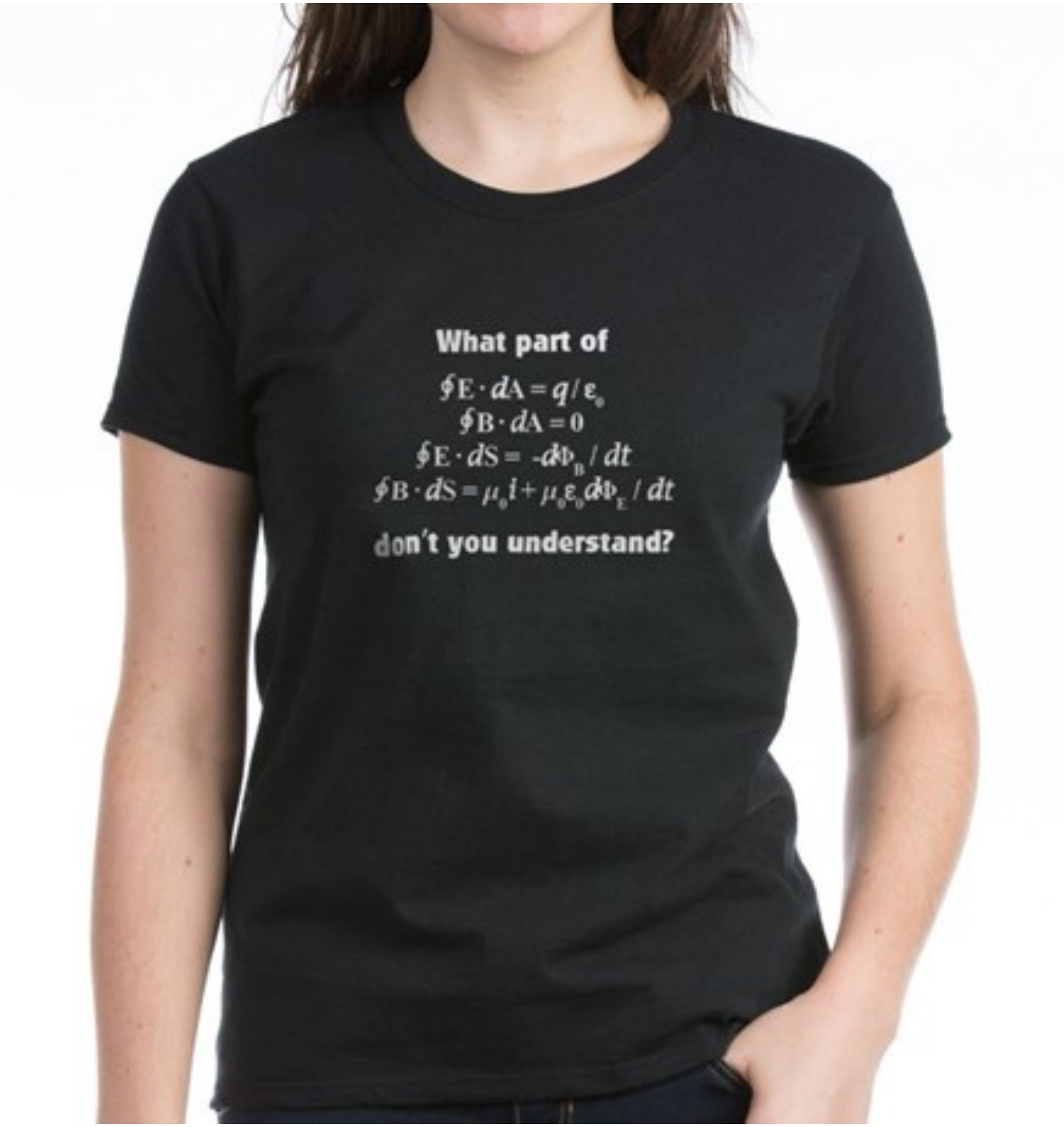
Radiation Argument



T-shirt by Extremely Smart

Standard derivation of electromagnetic radiation (aka light): Start with Maxwell's equations and calculate away

Radiation Argument



T-shirt by Extremely Smart

Standard derivation of electromagnetic radiation (aka light):
Start with Maxwell's equations and calculate away

It's unintuitive, complicated and obscures the physical mechanism

Graphical Argument

Just need a few facts

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1) No information can travel faster than light

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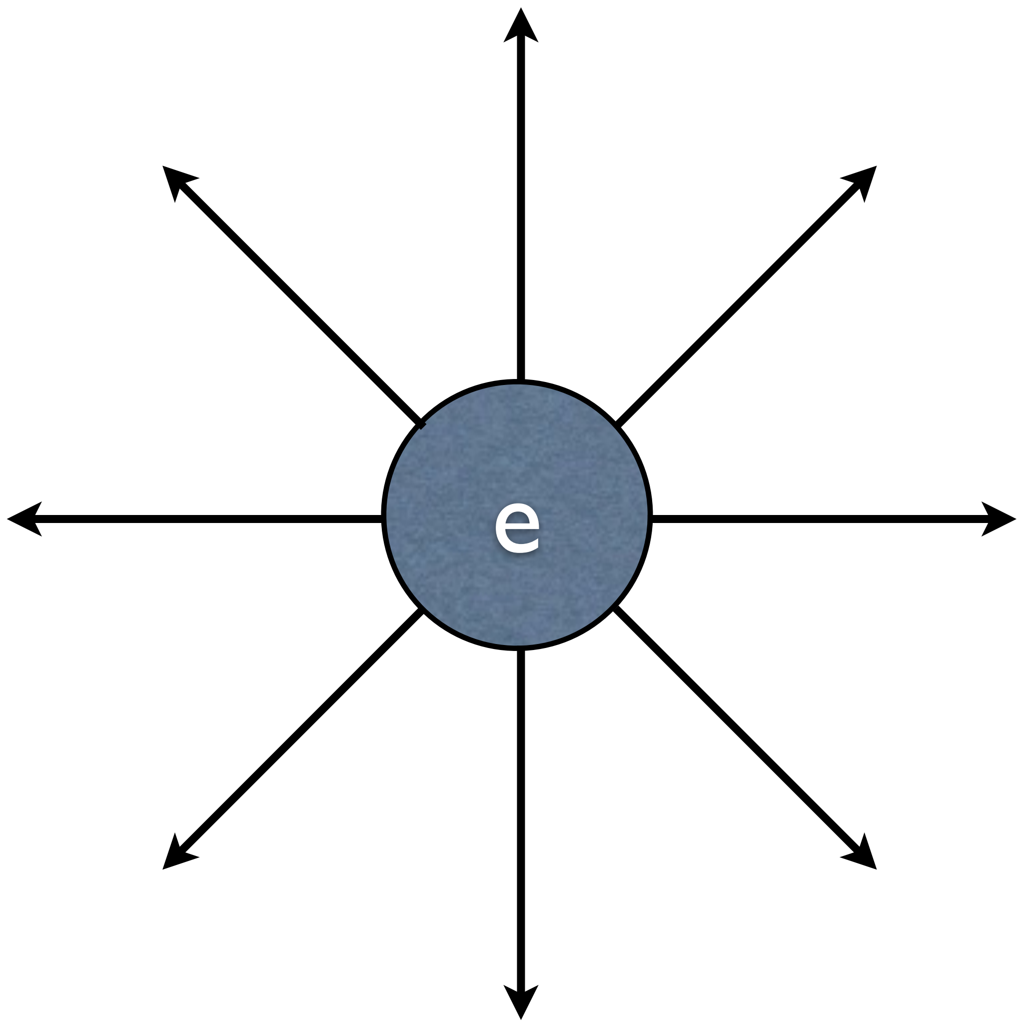
1) No information can travel faster than light

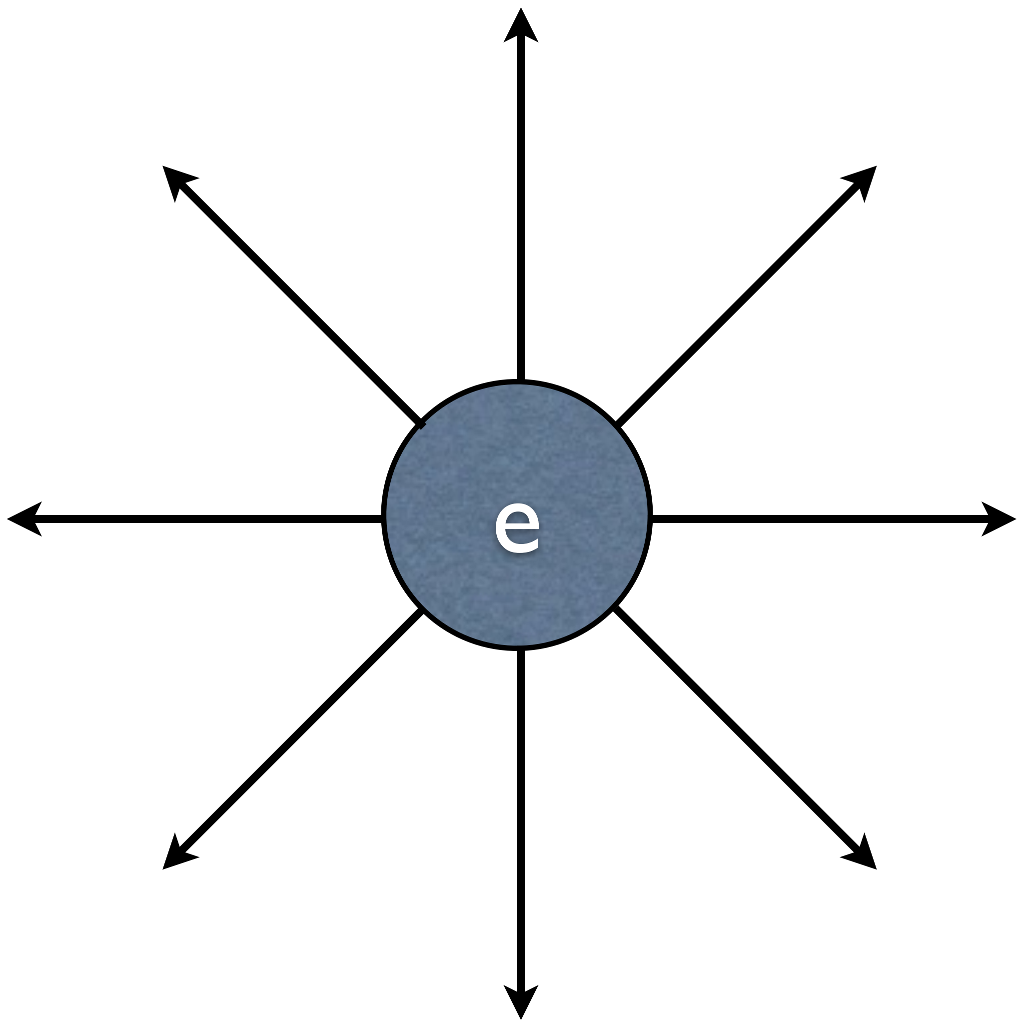
2) Behavior of electric field lines around an electric charge

Electric Field



An electric charge
sets up an electric field
that points radially outwards

Electric Field



An electric charge
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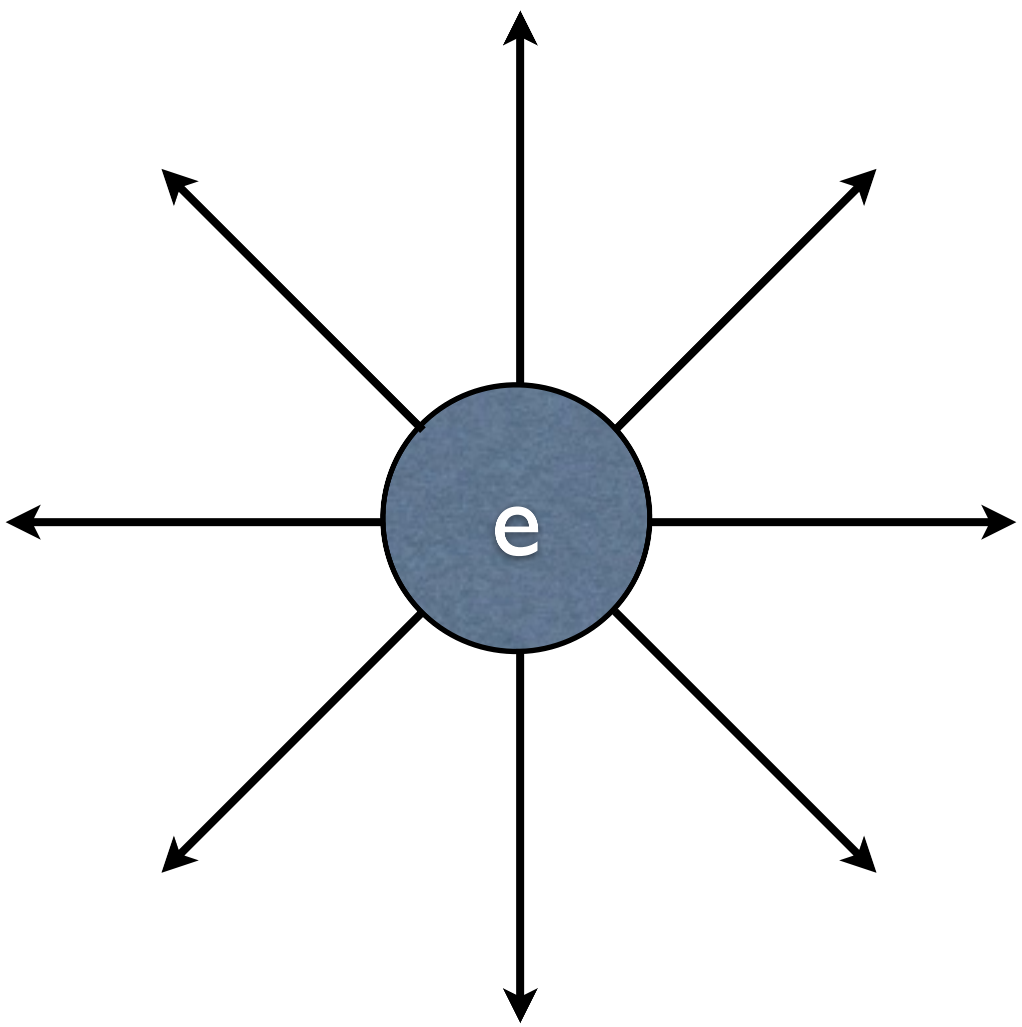
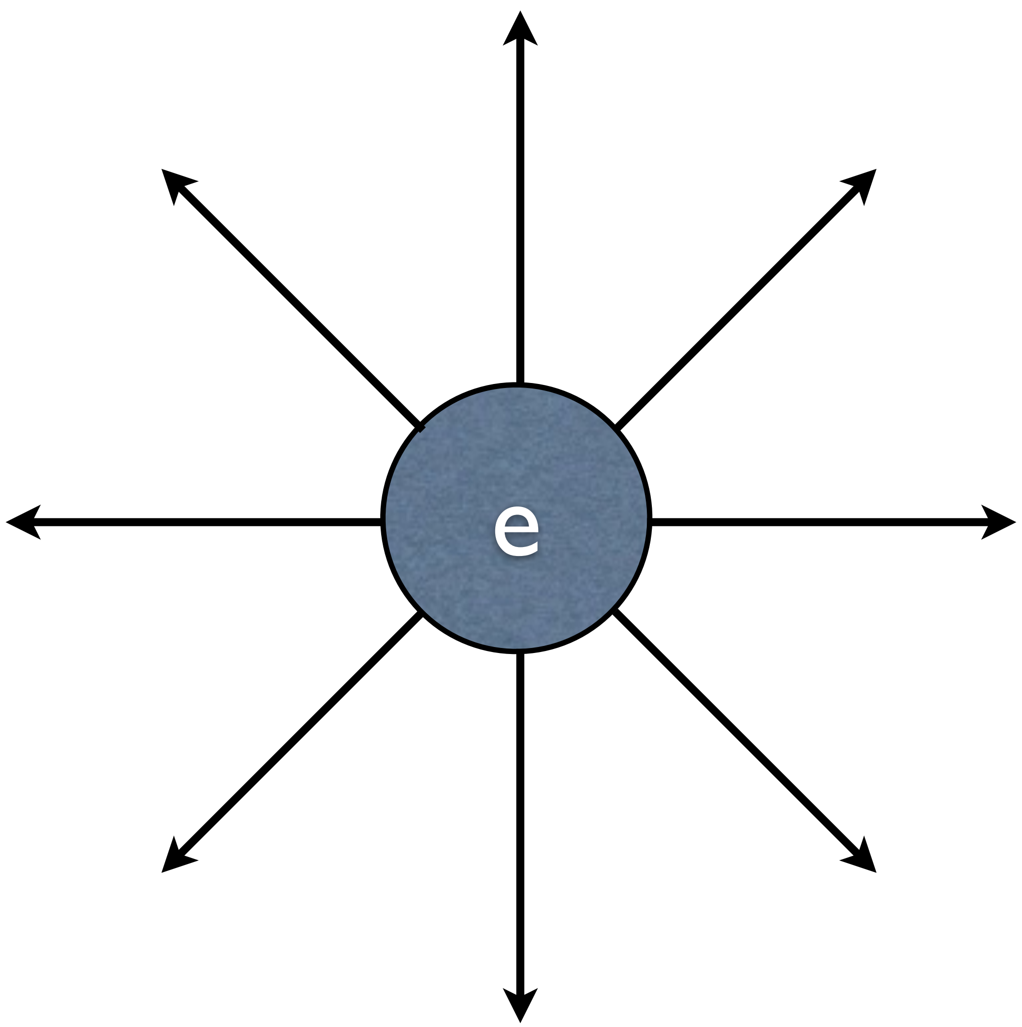
If you put another charge
somewhere, it feels a
force = charge x electric field

Speed of Light



If I'm far away and the charge disappears, I don't find out immediately (Sun disappearing example)

Speed of Light



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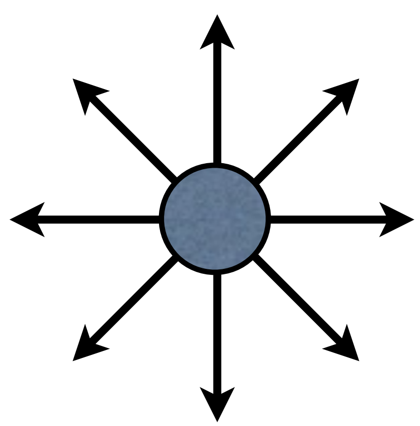
Information has to propagate out at the speed of light

Moving Charge

Imagine a charge moving at constant speed electric fields for a far observer "adjust" so that they point to charge

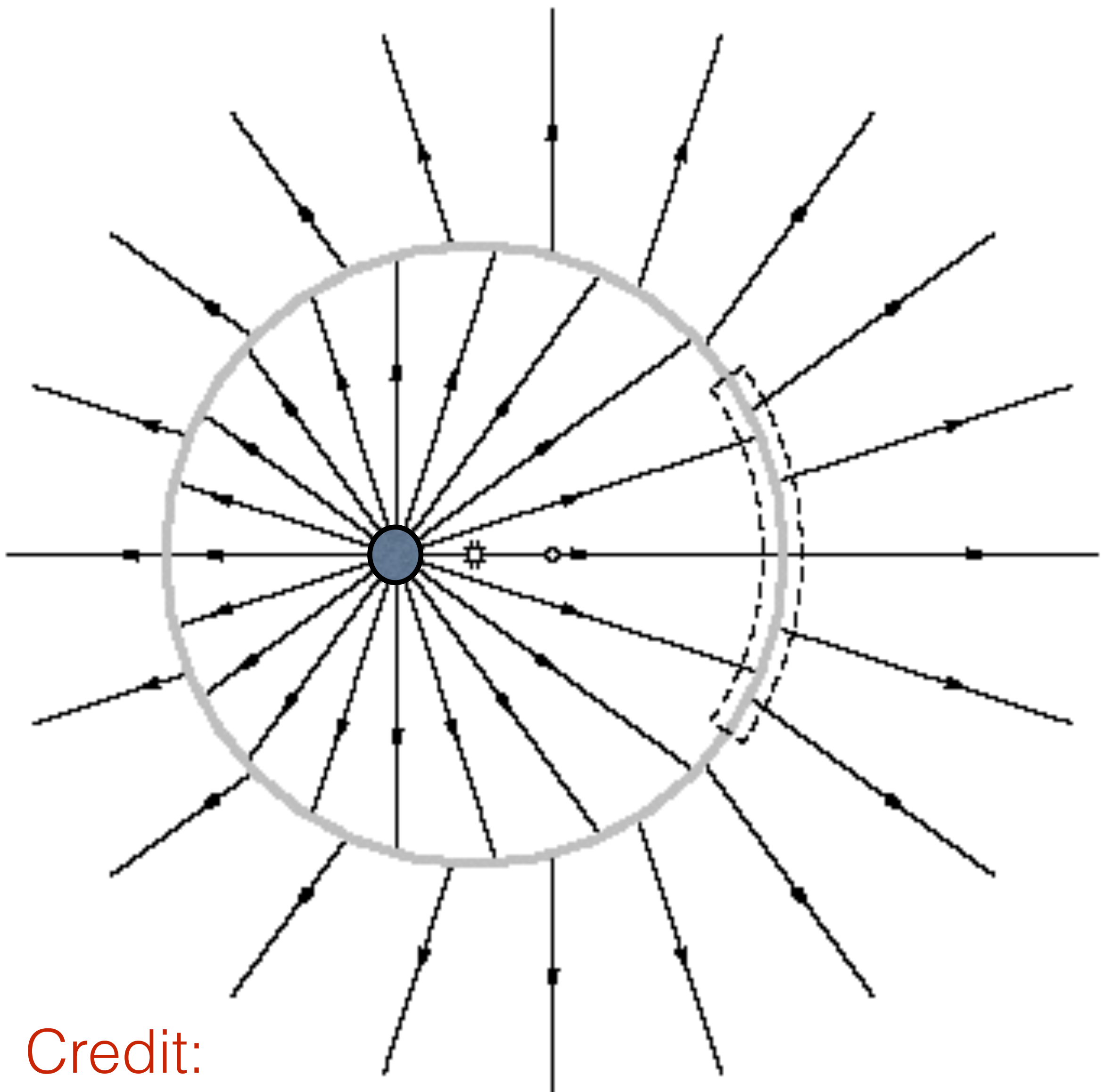


Moving Charge

Imagine a charge moving at constant speed
electric fields for a far observer "adjust" so that
they point to charge

However, imagine the charge bounces off a brick wall
For the far observer, electric field doesn't tell that
a bounce has occurred instantaneously

Bouncing Electric Fields



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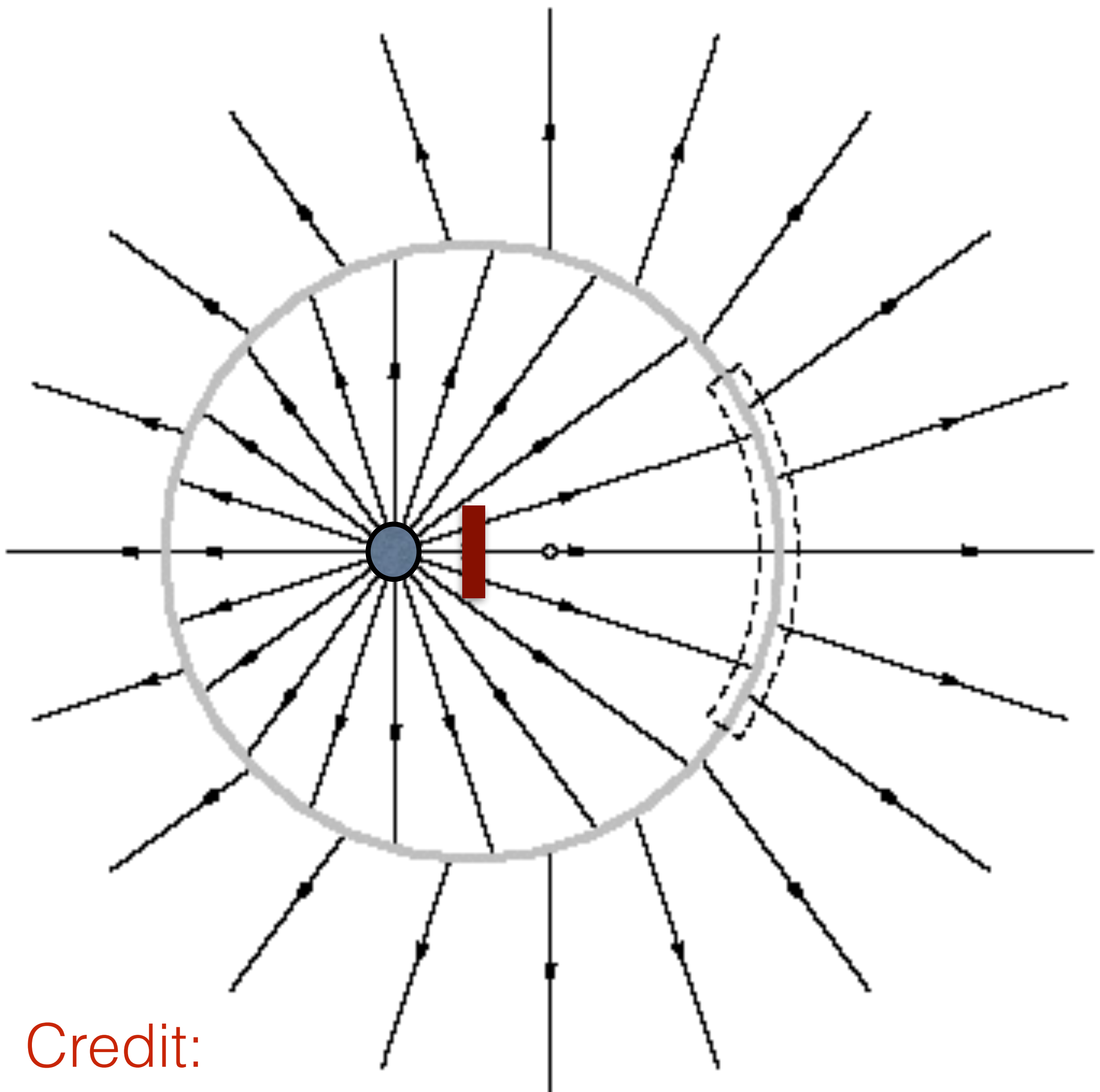
Bouncing Electric Fields



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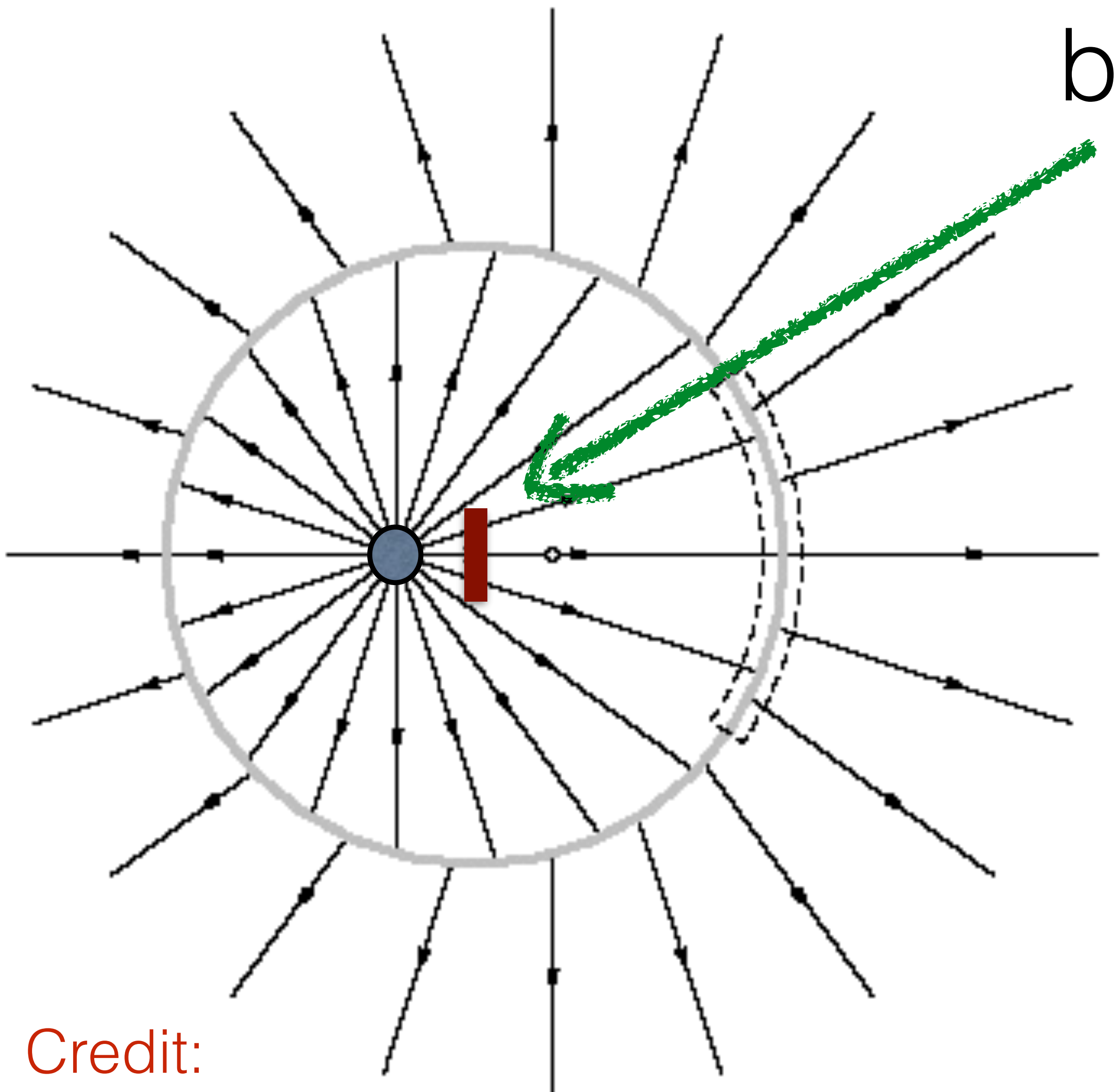

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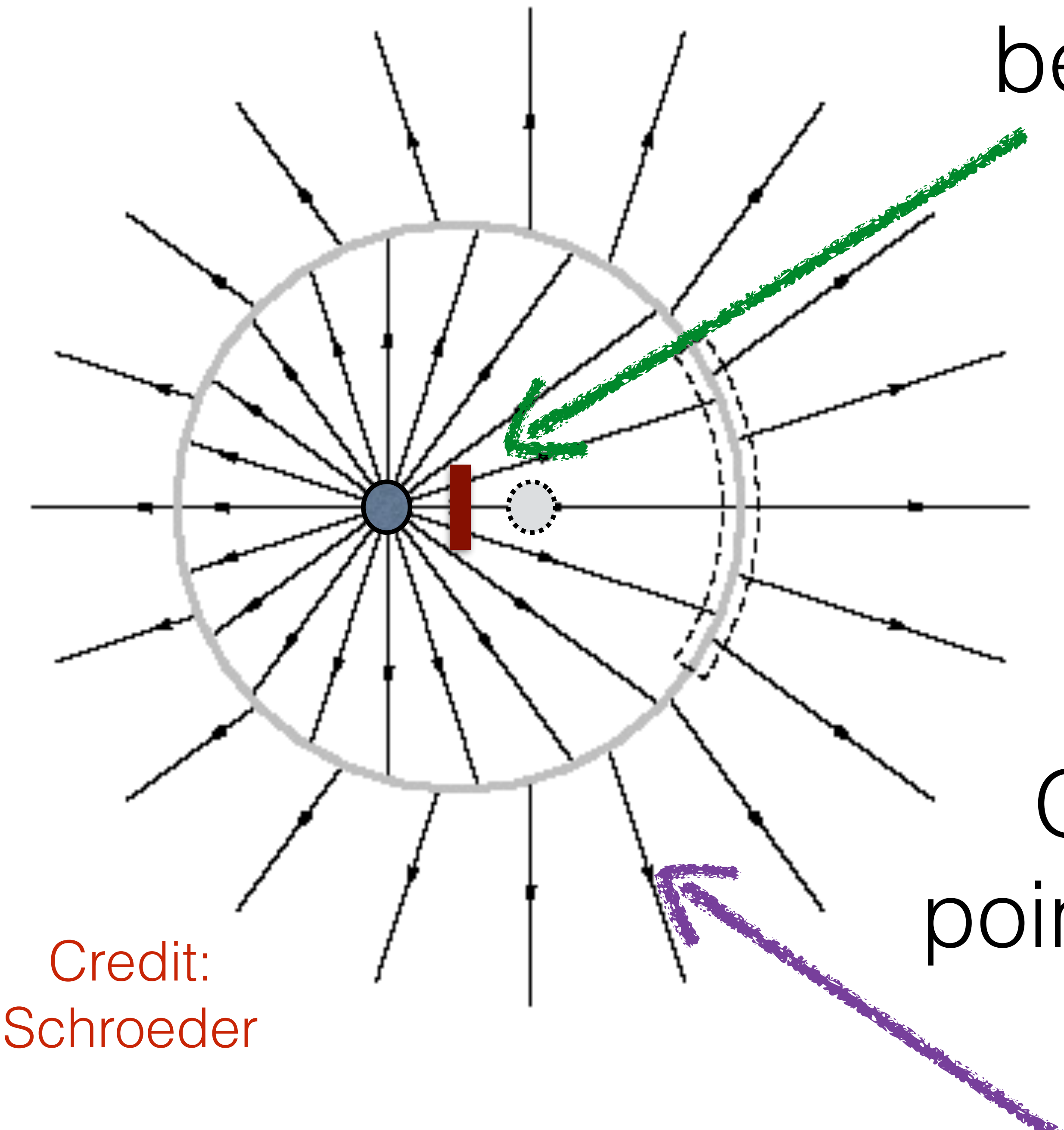
Inside circle, electric fields point to where charge is because they are close enough to receive the information of the bounce

Bouncing Electric Fields



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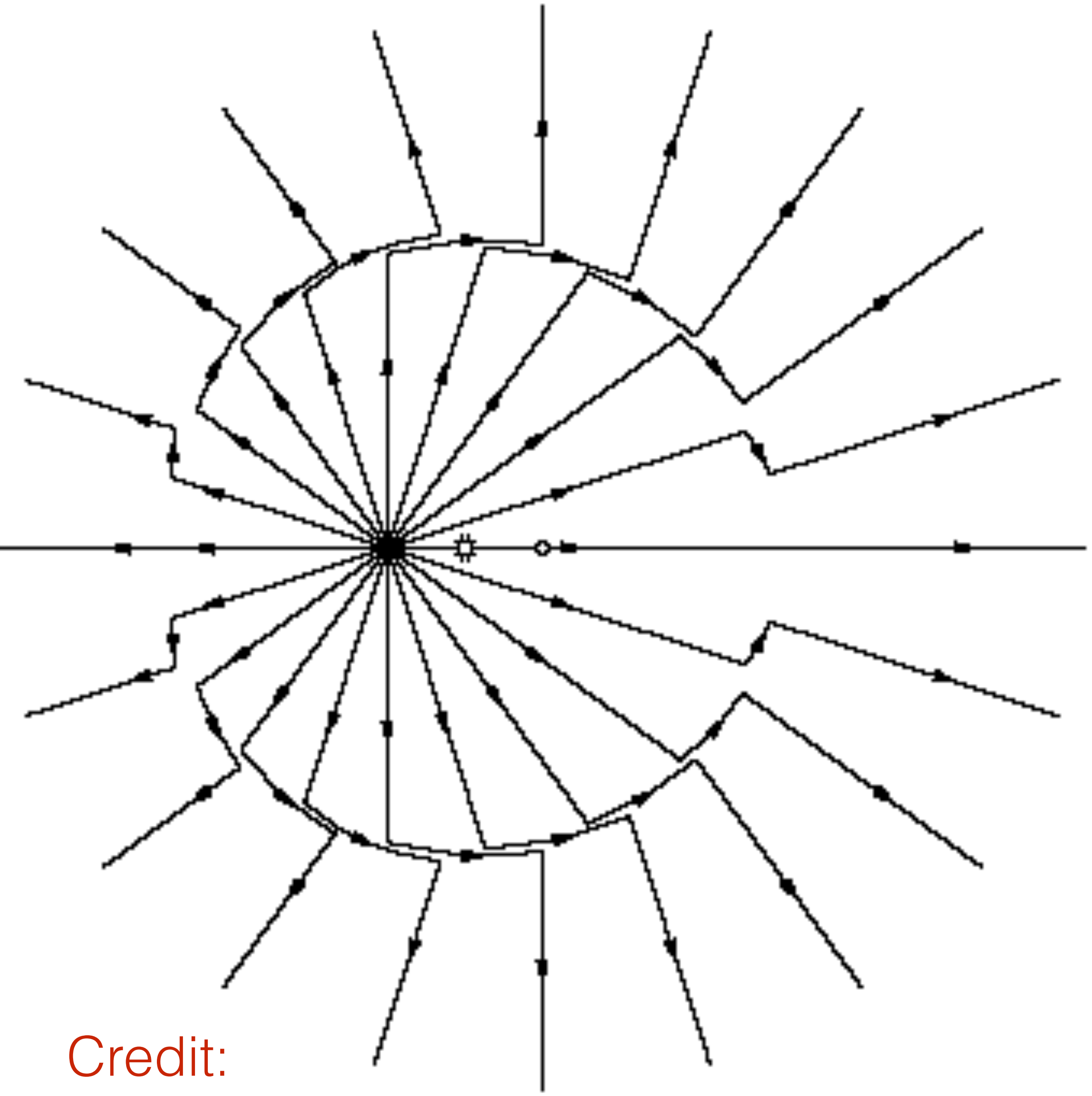
Inside circle, electric fields point to where charge is because they are close enough to receive the information of the bounce

Outside circle, electric fields point to where charge would have been w/o bounce, since it is too far to receive the information of the bounce

Radiation



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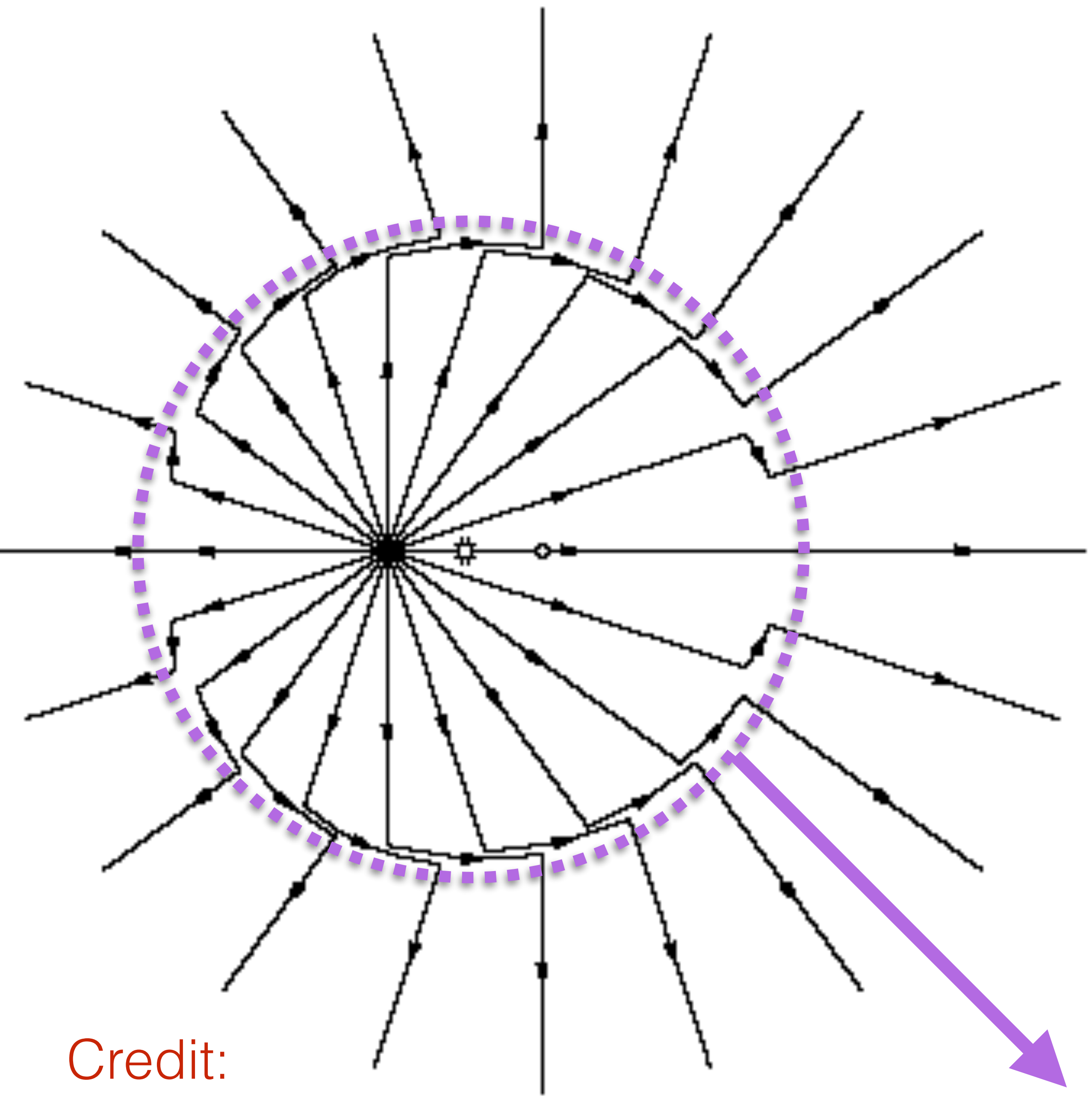
In circle, electric field has to "connect" the electric field of the two regions, the one aware of bounce and one oblivious

Radiation



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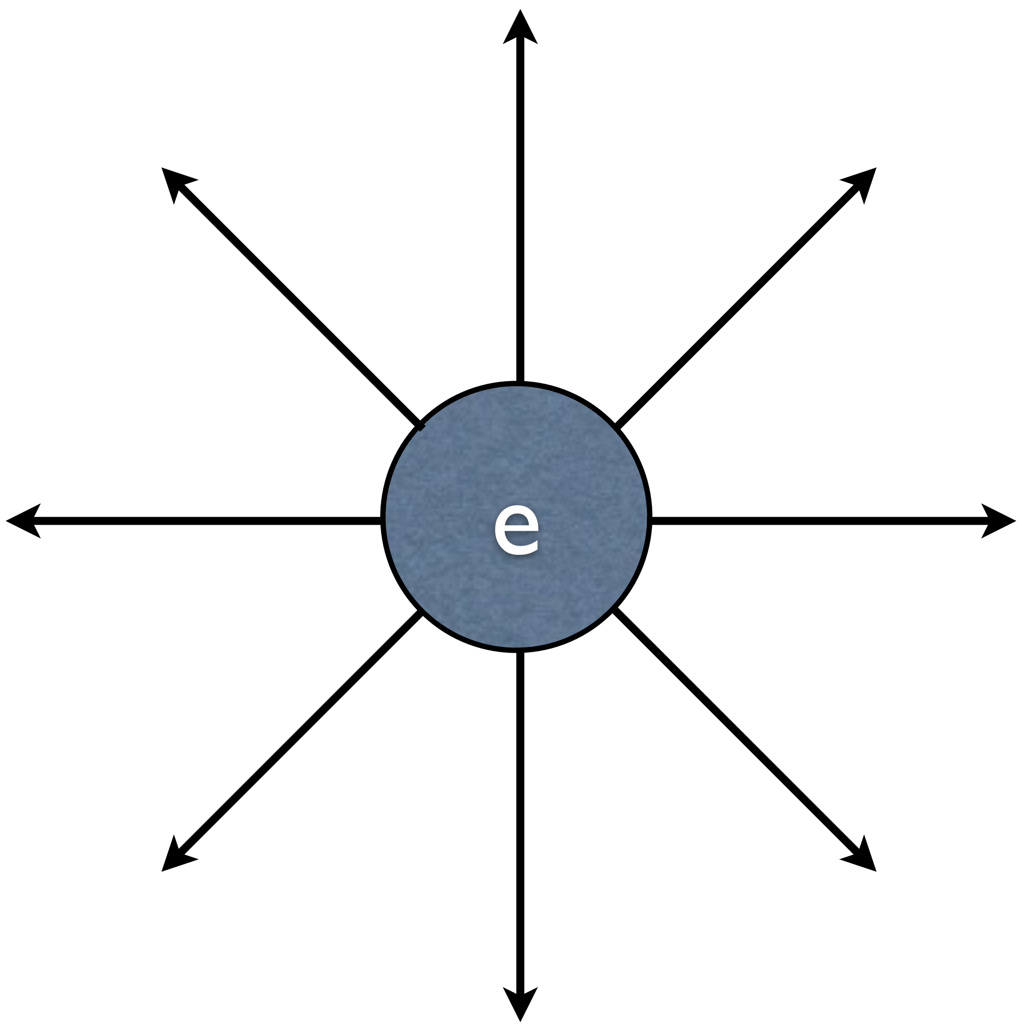
In circle, electric field has to "connect" the electric field of the two regions, the one aware of bounce and one oblivious

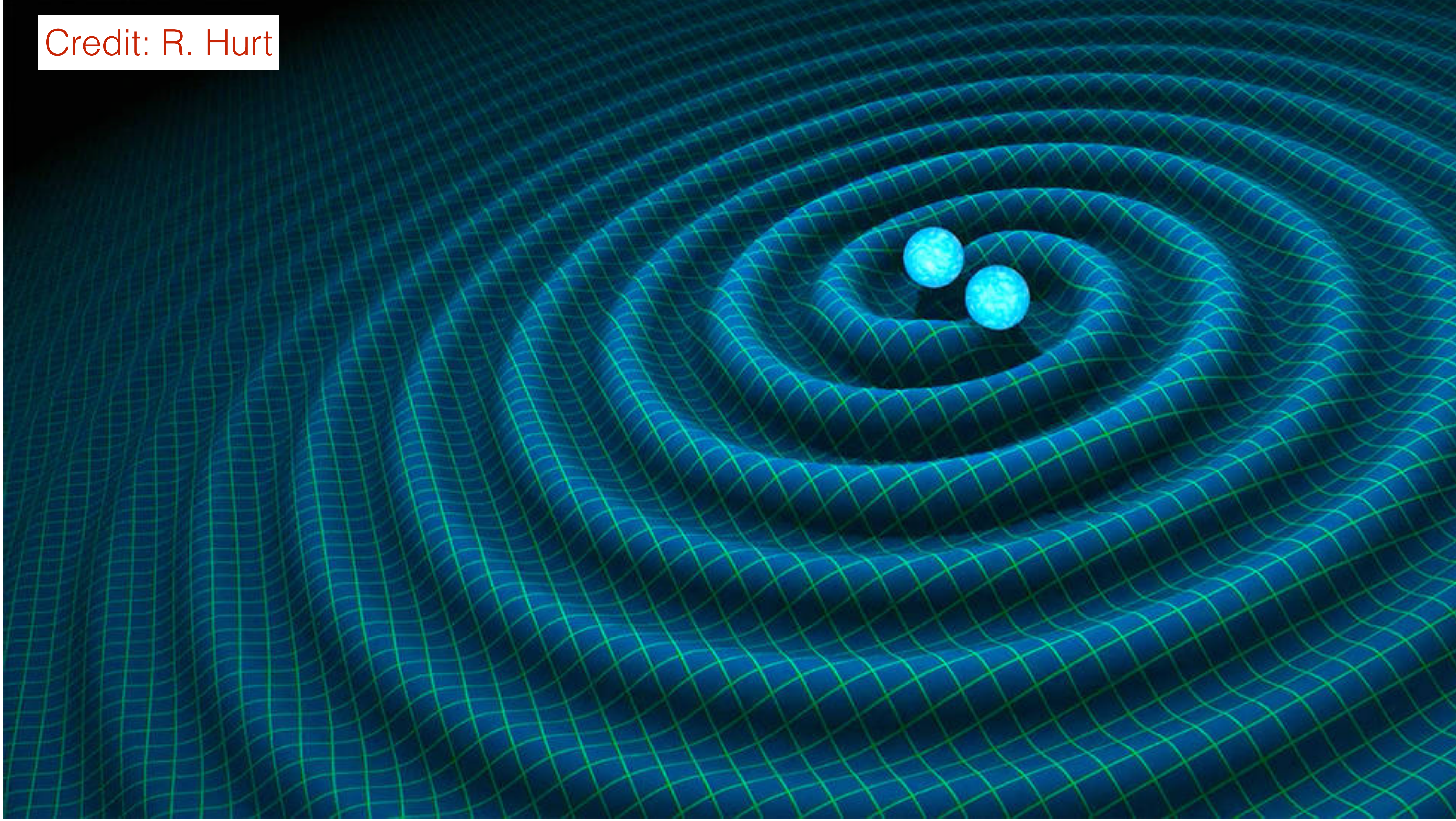
This circle expands at speed of light and it is this "connecting" electric field that is the electromagnetic radiation

Gravitational Waves (Radiation)



Gravitational field
instead of electric field
rest of argument applies

(Caveat: technical aspects
are not quite captured)



Topic 2

Dimensional Analysis Explanation of Gravity Wave Properties

Quick Quiz: Which of These Can Be Correct?

distance = speed x time

distance = speed x time^2

Quick Quiz: Which of These <u>Can Be</u> Correct?

✔ distance = speed x time

✘ distance = speed x time^2

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We know second is impossible, since units don't work out (distance not measured in meters x second)

Dimensional Analysis

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General strategy

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Identify what variables answer can depend upon

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Find combinations of variables that give correct units of final answer

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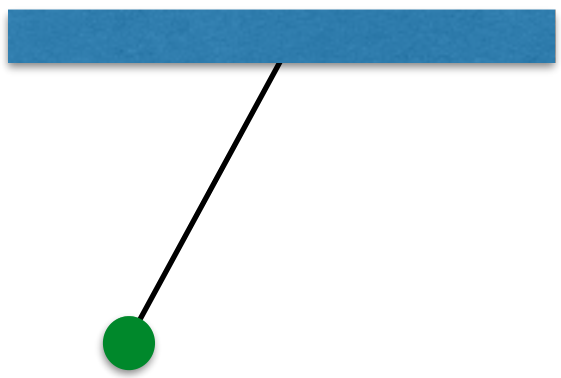
General strategy

Identify what variables answer can depend upon

Find combinations of variables that give correct units of final answer

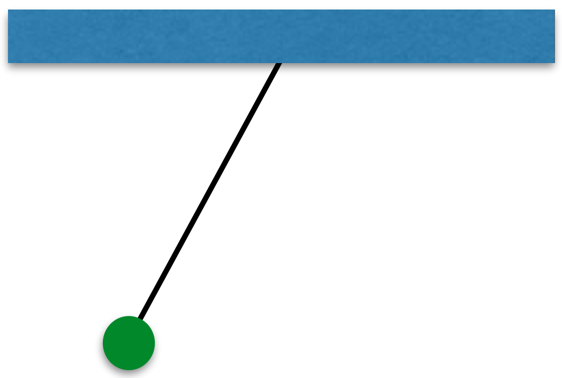
If only a single answer is correct, then that has to be the answer (or you missed a variable)

Pendulum Example



What is the period T of a pendulum?

Pendulum Example

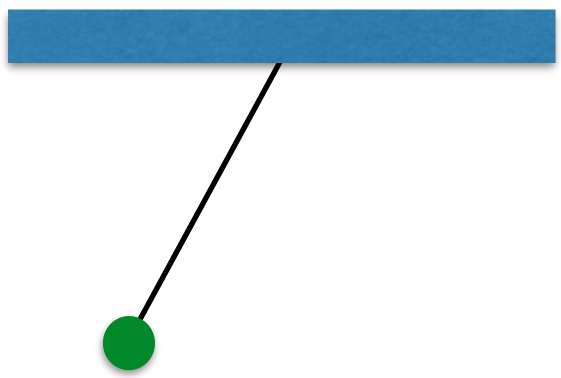


What is the period T of a pendulum?

Variables

d = length of string, m = mass of bob, g = acceleration due to gravity

Pendulum Example



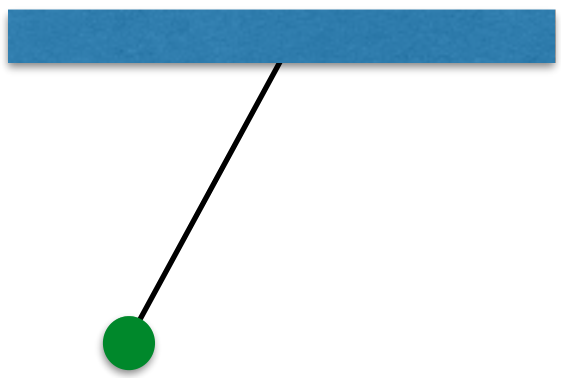
What is the period T of a pendulum?

Variables

d = length of string, m = mass of bob, g = acceleration due to gravity

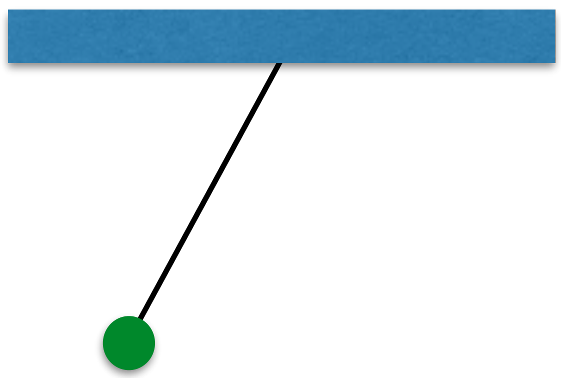
Units of variables are [d]=meters, [m]=kilograms [g] = meters/seconds^2, while [T] = seconds

Pendulum Example (cont.)



Use different powers for each variable and multiply by a dimensionless constant out front, $T = \text{number} \times d^{p1} \times m^{p2} \times g^{p3}$

Pendulum Example (cont.)



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$[d]^{p1} \times [m]^{p2} \times [g]^{p3} = \text{meters}^{p1+p3} \times \text{kilograms}^{p2} \times \text{seconds}^{-2p3}$

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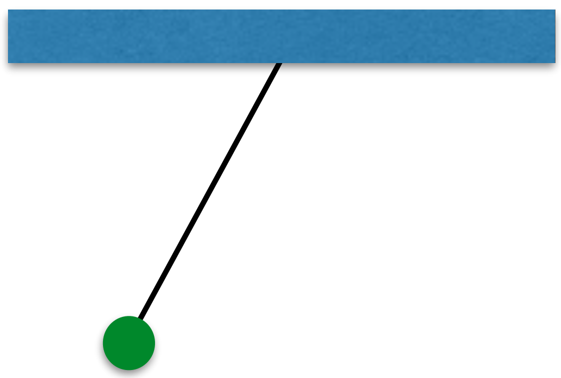

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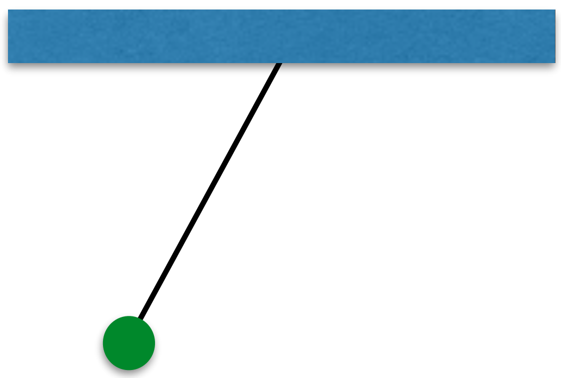
To get $[T]$ = seconds
need $p2 = 0$
$p1 = -p3$
$p3 = -1/2$

Pendulum Example (cont.)



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$T = \text{number} \times \sqrt{d/g}$

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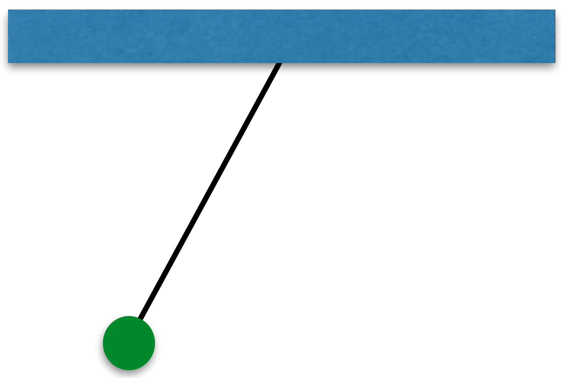

Use different powers for each variable and multiply by a dimensionless constant out front, T = number x d^{p1} x m^{p2} x g^{p3}

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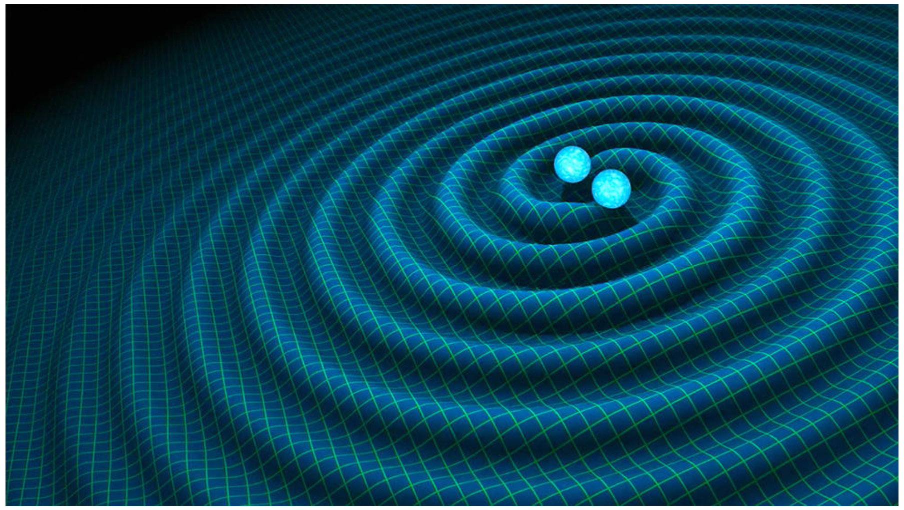
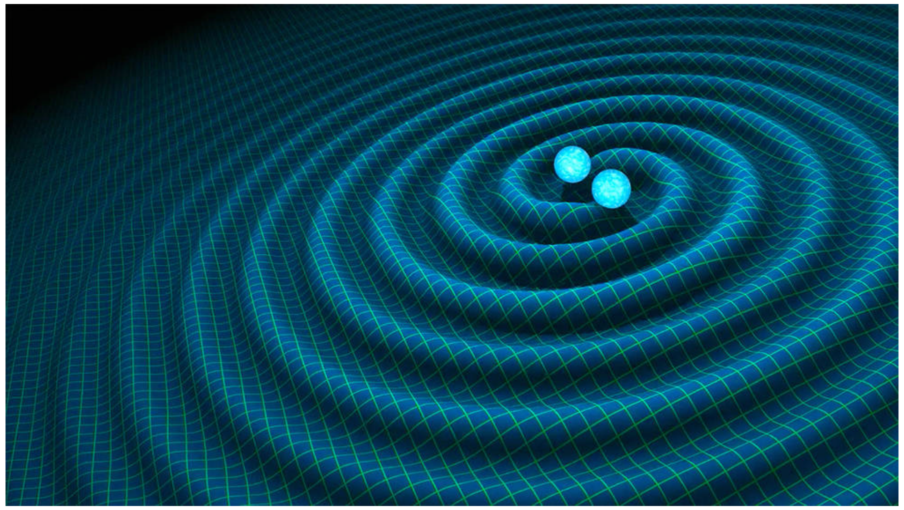
Note: physics calculation gives number = 2π

Properties of Gravitational Waves



Properties of Gravitational Waves

Why are GWs so hard to detect?



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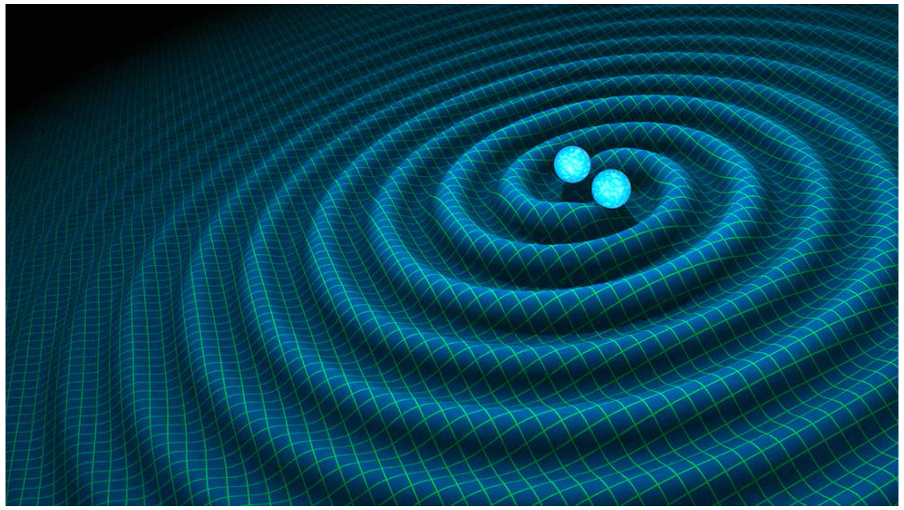
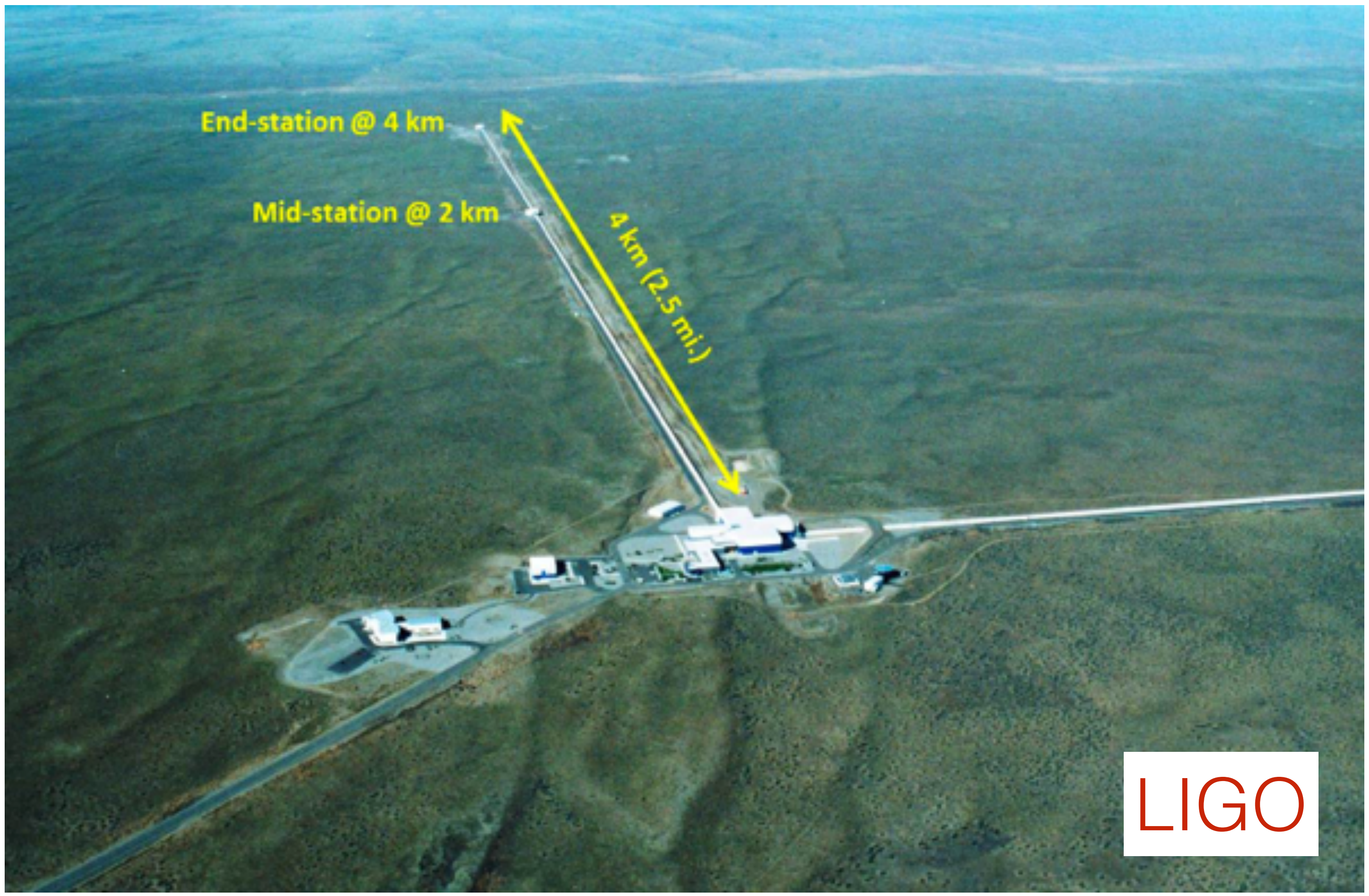


Why can we listen to them?

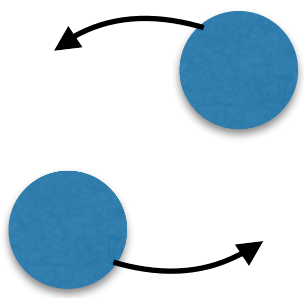
Straining to Hear a Gravity Wave



Current Sensitivity is "arms" changing by $h = \delta L/L \sim 10^{-22}$ so $\delta L \sim 4\text{x}10^{-19}$ m

Strain

h is dimensionless



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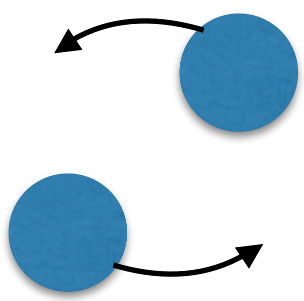

Variables

M = Mass of Black Holes
d = distance to Black Holes
c = speed of light
G = Newton's Gravitational constant

Strain

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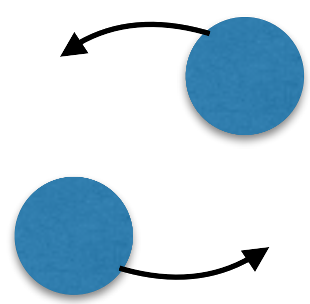

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Units

[M] = kg, [d] = m

[c] = m/s

[G] = $m^3/(kg\ s^2)$

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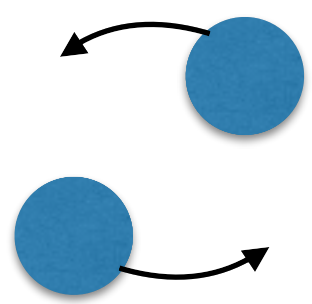

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Dimensionless Quantity

$G\ M/(d\ c^2)$
h = number x (GM/dc^2)
(Caveat: power)

Strain for Dec. Event

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$M \sim 10\ M_{Sun} = 2 \times 10^{31}$ kg

$d = 1.4$ billion lyrs $= 10^{25}$ m

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Small, but mass compensates for long distance

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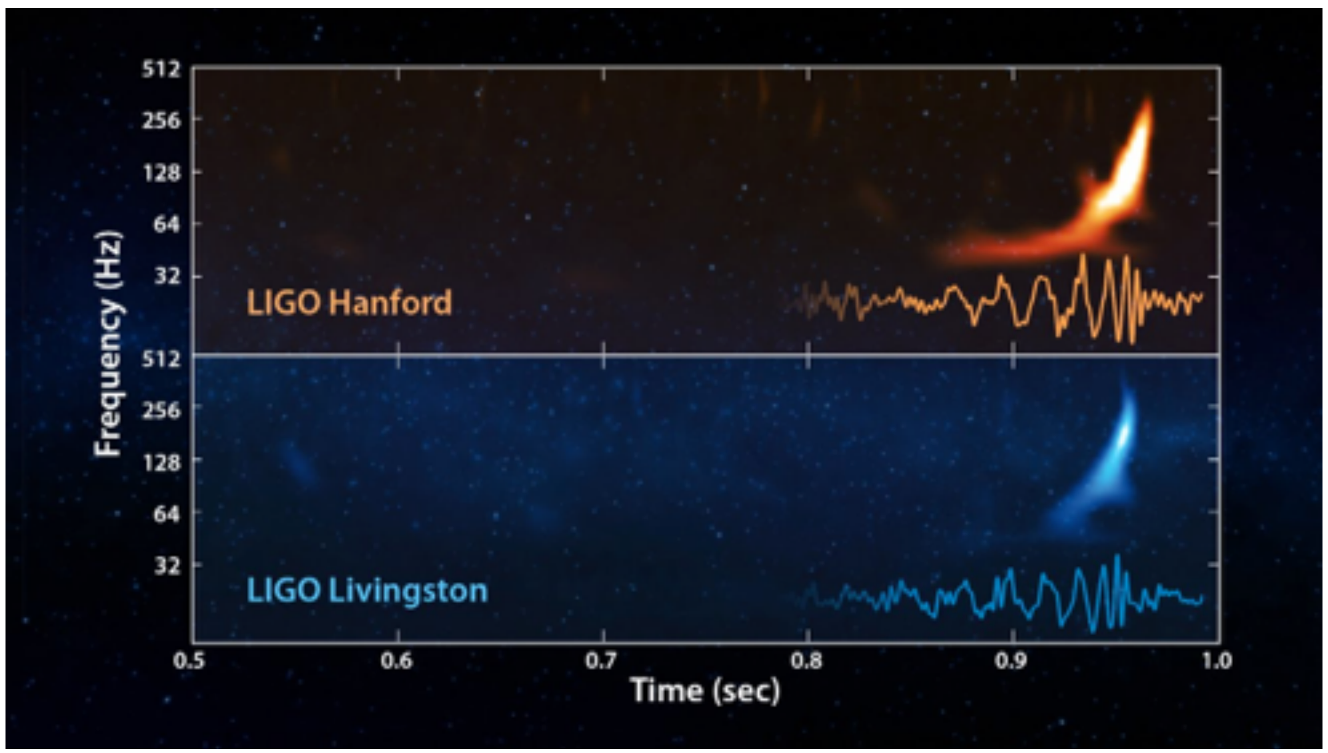
Small, but mass compensates for long distance

Earth-based GWs are too small because velocities are small

Frequency

Gravity wave frequencies are almost listenable
(~ 100 Hz) (Youtube link)



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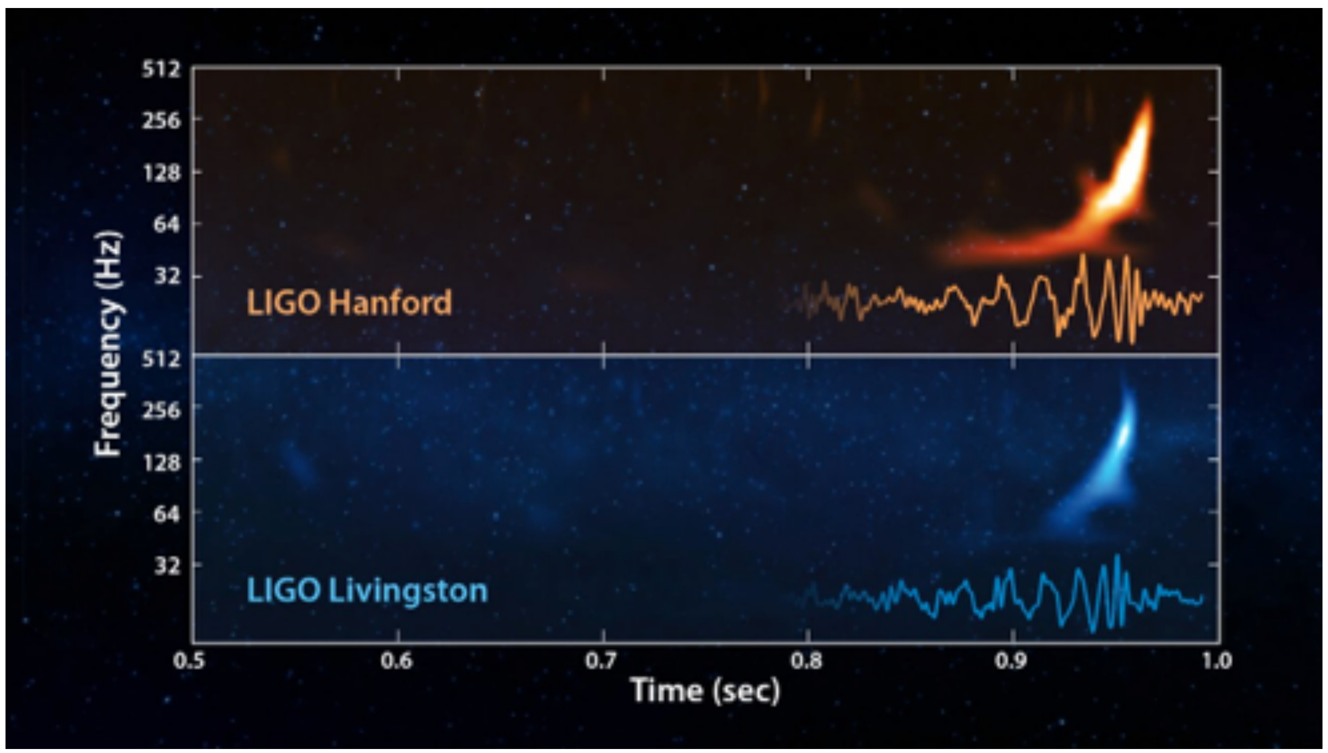

$[f]$ = Hz = 1/seconds

$f \sim c^3/(GM) \sim 27{,}000$ Hz

Actual $f = (1/2\pi)\, v^3/(GM)$

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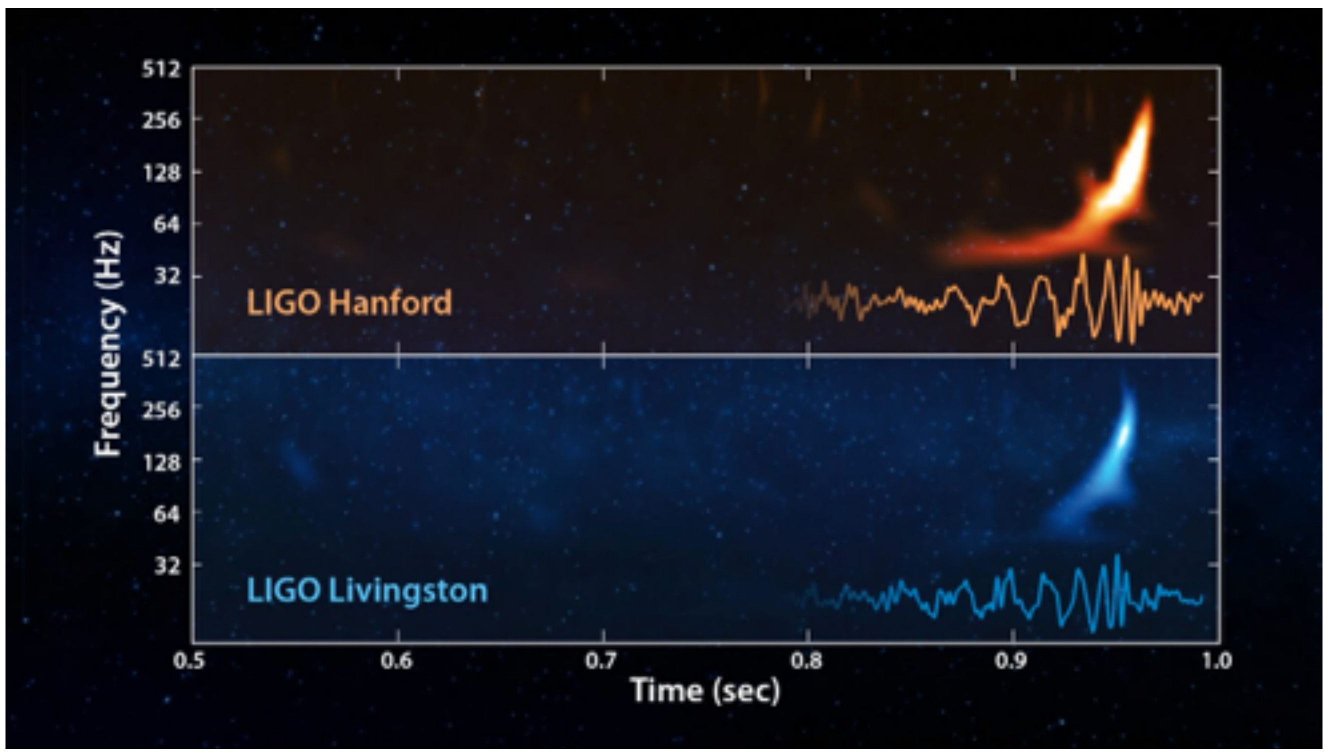


[f] = Hz = 1/seconds

f ~ $c^3/(GM)$ ~ 27,000 Hz

Actual f = $(1/2\pi)\, v^3/(GM)$

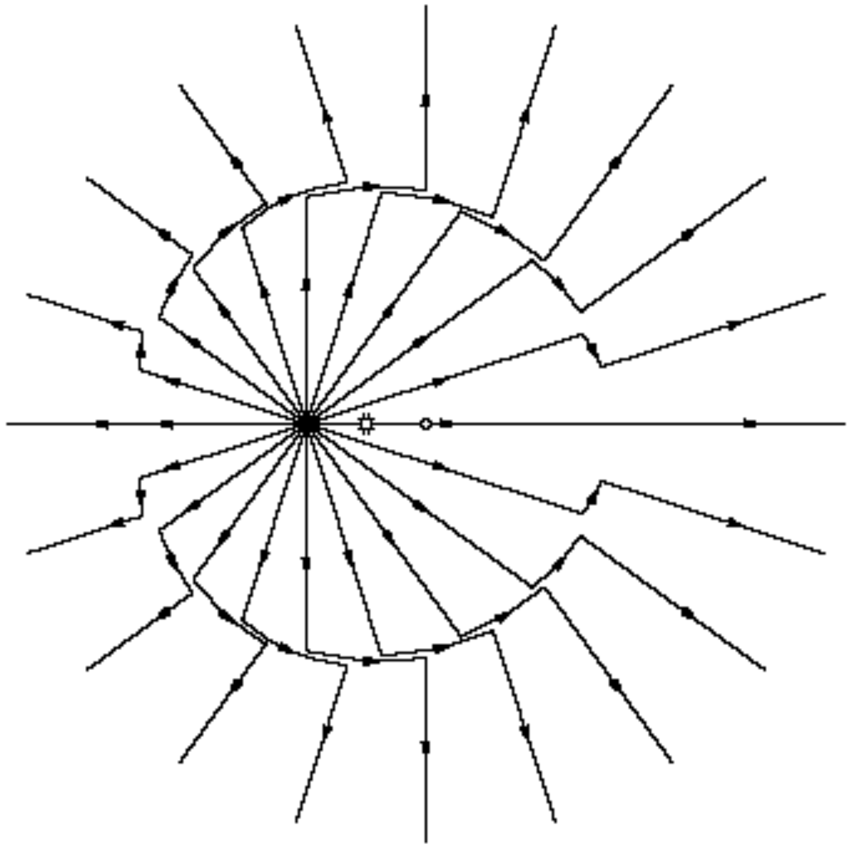
Other properties you can try to do

Radius of Black Hole Event Horizon

Amount of energy emitted

Conclusions

- Pictorial Derivation of Radiation - No Information Traveling Faster than Speed of Light



- Dimensional Analysis Applied to Gravity Wave Properties - Get Physics Formulas Without Memorization or Physics