

R. BRICEÑO, T. ROGERS

MAGNETS AND SYMMETRIES

ADMIN STUFF

Need links, just email python4physics@odu.edu

The screenshot shows an Apple Mail window with the following details:

From: Python 4 Physics
Subject: Automatic reply:
To: Briceno, Raul A.

Date: 5:19 PM

Message Content:

Thanks for your interest in Python4Physics.

Please visit our webpage at <https://sites.google.com/view/odu-nuc-th/service/p4p-2020>. In addition to providing links to our Dropbox folder, you will see our "Frequently Asked Questions" section. There we answer the many questions we have been receiving.

Slack chat with faculty and TAs: https://join.slack.com/t/python4physics/shared_invite/zt-ffgssu43-4x9_bCCLmGt8dou~Xwzycw. Note, to use Slack you must be at least 16yrs old [see <https://slack.com/terms-of-service>].

Livestreams link: https://vs.prod.odu.edu/bin/reyes_system/

Recordings link: <https://odu.edu/reyes/recordings>

Reyes - Python4Physics archive: https://vs.prod.odu.edu/bin/reyes_system/archives/6_python4Physics.php

Reyes - Python4Physics breakout sessions archive: https://vs.prod.odu.edu/bin/reyes_system/archives/6_python4Physics_breakouts.php

Dropbox link: <https://www.dropbox.com/sh/ur6mk8gzl22mq4l/AACRe9R4UlB-4bYAvJG2UI3aa?dl=0>

Briceno, Raul A.
(No Subject)
To: Python 4 Physics

5:19 PM

RB

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The screenshot shows a web browser window with the title "Nuclear & particle theory - P4P". The address bar displays the URL sites.google.com/view/odu-nuc-th/service/p4p-2020. The page content features a large, abstract background image of a particle collision event with many colored tracks. Overlaid on this image is the text "P4P 2020 - FAQS". At the top of the page, there are several navigation links: "Nuclear & particle theory", "ODU nuclear", "Faculty", "Postdocs & Students", "Past students & postdocs", and "Service". Below the background image, the main heading reads "PYTHON4PHYSICS (2020) COURSE DETAILS". A detailed paragraph explains the course broadcast information, mentioning REYES and the REYES website. A final sentence states that this page addresses frequently asked questions (FAQs) regarding the Python4Physics (2020) course.

PYTHON4PHYSICS (2020) COURSE DETAILS

As discussed in the main [Python4Physics page](#), this year's class is being broadcasted live via https://vs.prod.odu.edu/bin/reyes_system/. You can see us by going to the sessions labeled "Python4Physics" session Tuesdays and Thursday at 1pm (EDT). This platform allows for no limit to the number of participants. Slides and videos will be posted afterwards in the [REYES website](#).

In this page, we address the frequently asked questions (FAQs), regarding Python4Physics (2020).

ADMIN STUFF

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Dropbox for students, email us! Subject: “Dropbox access”

REVIEW

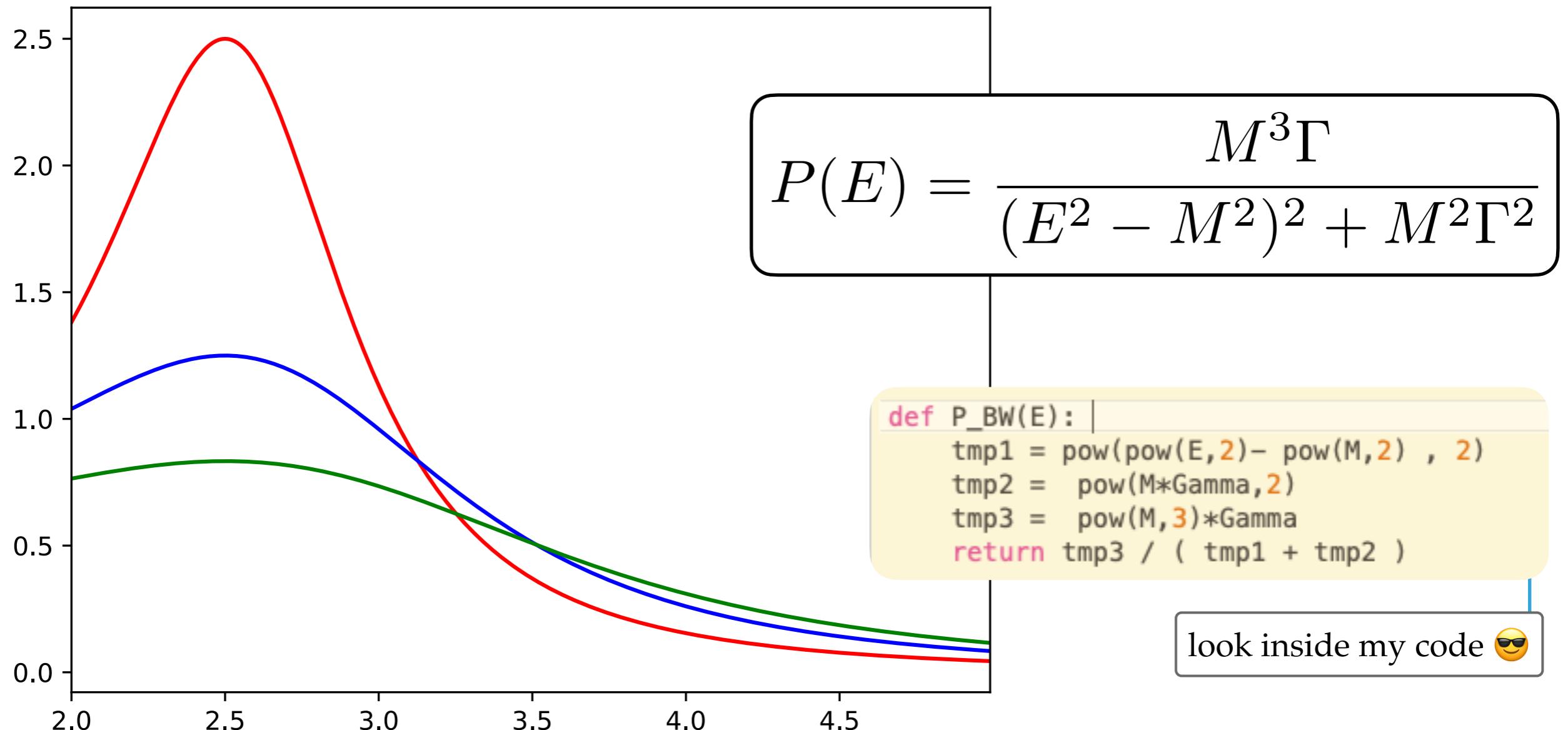


EXERCISE #1 - PLOTTING A BREIT-WIGNER

The three values of the decay width are $\Gamma = 1, 2, 3$.

Reproduce this plot, and figure out which color correspond to which value.

Hint: Develop some intuition. How does the distribution behave as a function of the width at its peak. Does it grow or decrease with the Γ ?



PYTHON ROUTINES FOR MINIMIZATION

scipy has many different routines for optimization and root finding: <https://docs.scipy.org/doc/scipy/reference/optimize.html>

Here is a simple one I use}

```
def chi2_BW(M_Gamma):
    M_Gamma = M_Gamma
    Pis = P_BW(M_Gamma,Xs)

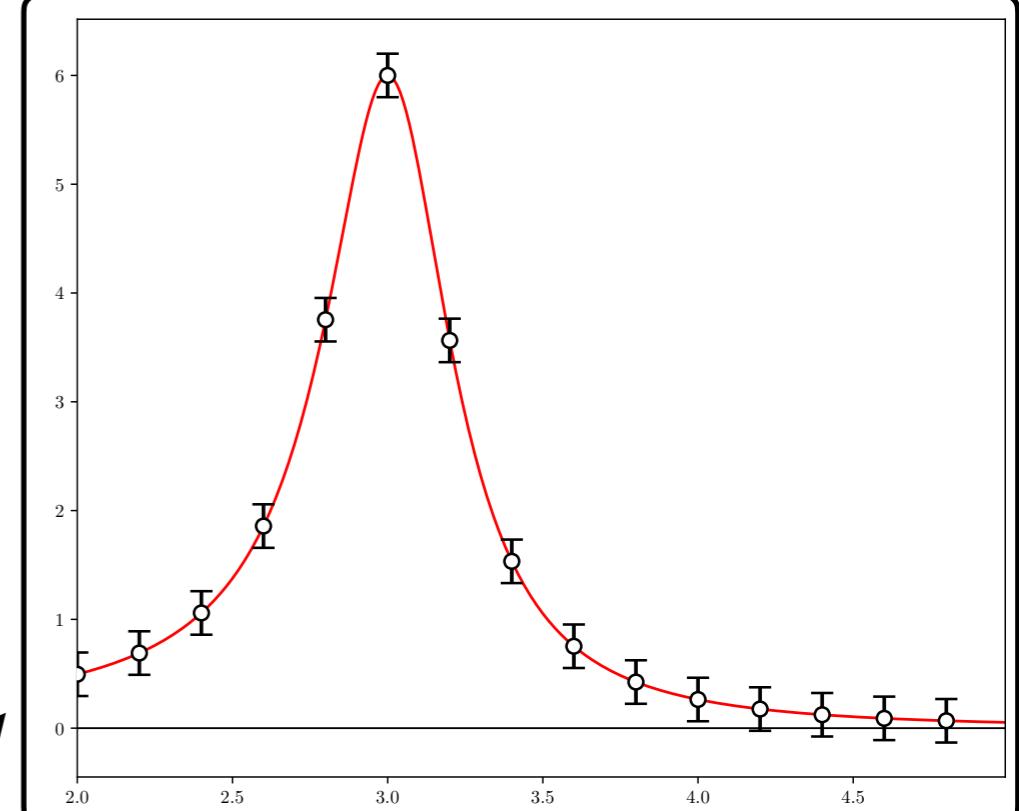
    chi20 = np.sum(pow((Pis-Ys)/sig,2))
    dof = len(sig)-2.0
    return chi20

def find_min_chi2_BW():
    M_Gamma_guess = [2.,1.0]
    """
    https://docs.scipy.org/doc/scipy/reference/generated/scipy.optimize.minimize.html
    """
    from scipy import optimize
    M_Gamma = optimize.minimize(chi2_BW, M_Gamma_guess, method='nelder-mead')
    print("M_Gamma",M_Gamma)
    return M_Gamma.x
```

minimum coincides
with $(M, \Gamma) = (3, 0.5)$

```
In [80]: import BW_plots
M_Gamma_final_simplex: (array([[2.99995863, 0.49998755],
[2.9999788 , 0.50007577],
[3.00004901, 0.49990999]]), array([2.17813848e-05, 3.02255241e-05, 5.72629601e-05]))
fun: 2.1781384810732297e-05
message: 'Optimization terminated successfully.'
    nfev: 103
    nit: 55
    status: 0
success: True
x: array([2.99995863, 0.49998755])
```

plotting the distribution
using the fitted values...



EXERCISE #2 - WARM UP...FIT A CONSTANT

Load the data in [Dropbox:/P4P_2020/project# 4/fitting_data/const_data.txt](#)

independent variable

average measurement

standard deviation

			const_data.txt
1	0.000000000000000e+00	9.995608073198061447e+02	2.010880856634203795e+00
2	1.000000000000000e+00	9.989000304105954910e+02	1.635795591692006834e+00
3	2.000000000000000e+00	9.990060216805485425e+02	2.196269491332777601e+00
4	3.000000000000000e+00	1.001145019684710974e+03	2.727748014799645127e+00
5	4.000000000000000e+00	1.000325729760938771e+03	3.133910015053178011e+00
6	5.000000000000000e+00	9.996966972703230567e+02	2.582352105425600453e+00
7	6.000000000000000e+00	1.001185862556614097e+03	3.610132155324399239e+00
8	7.000000000000000e+00	9.988642623323200951e+02	3.990053363012680876e+00
9	8.000000000000000e+00	1.000437143482329930e+03	4.138951037265467647e+00
10	9.000000000000000e+00	9.997121768891632883e+02	4.065402221831392993e+00
11	1.000000000000000e+01	9.998270261017927396e+02	4.065727850605284743e+00
12	1.100000000000000e+01	1.000965868351814720e+03	4.418148420465375814e+00
13	1.200000000000000e+01	9.995462363367937542e+02	2.086260784909980348e+00
14	1.300000000000000e+01	9.998277159350965348e+02	4.191409335069876008e+00
15	1.400000000000000e+01	9.997391408396299539e+02	2.868036357268816339e+00
16	1.500000000000000e+01	9.996997858726948607e+02	3.100581750743879539e+00
17	1.600000000000000e+01	9.994488473562142872e+02	4.001916818957766075e+00
18	1.700000000000000e+01	1.000306724780818513e+03	2.653736388738097141e+00
19	1.800000000000000e+01	9.985763846692332208e+02	2.203381851084773579e+00
20	1.900000000000000e+01	1.001307855283192339e+03	1.830367272051301120e+00
21	2.000000000000000e+01	9.994477788298243013e+02	3.733641562551535564e+00
22	2.100000000000000e+01	1.001323711961507342e+03	2.828454877578798765e+00
23	2.200000000000000e+01	9.989779317670313503e+02	2.992168487437034230e+00
24	2.300000000000000e+01	9.989108166430121400e+02	4.285277418619901191e+00
25	2.400000000000000e+01	9.996794307426688420e+02	2.803714930261759442e+00
26	2.500000000000000e+01	9.995316088565639348e+02	3.519255602155442642e+00
27	2.600000000000000e+01	1.001489465965241038e+03	4.293321083141394823e+00
28	2.700000000000000e+01	9.990306379092597808e+02	2.485797284494362103e+00
29	2.800000000000000e+01	9.992218459646275051e+02	2.108402591512725799e+00
30	2.900000000000000e+01	1.000751406739915751e+03	3.220350739074319790e+00
31	3.000000000000000e+01	1.000517685400707251e+03	3.036311141027919547e+00
32	3.100000000000000e+01	1.000653489026880834e+03	1.864845433477076986e+00
33	3.200000000000000e+01	9.99812085143717542e+02	3.700866594021734254e+00

to load, you can see
the following code

```
filename = 'const_data.txt'  
const_data = np.loadtxt(filename)  
print("shape(const_data) =", np.shape(const_data))  
Xs,Ys,sigs = const_data.T  
print("shape(Xs) =", np.shape(Xs))  
print("shape(Ys) =", np.shape(Ys))  
print("shape(sigs) =", np.shape(sigs))
```

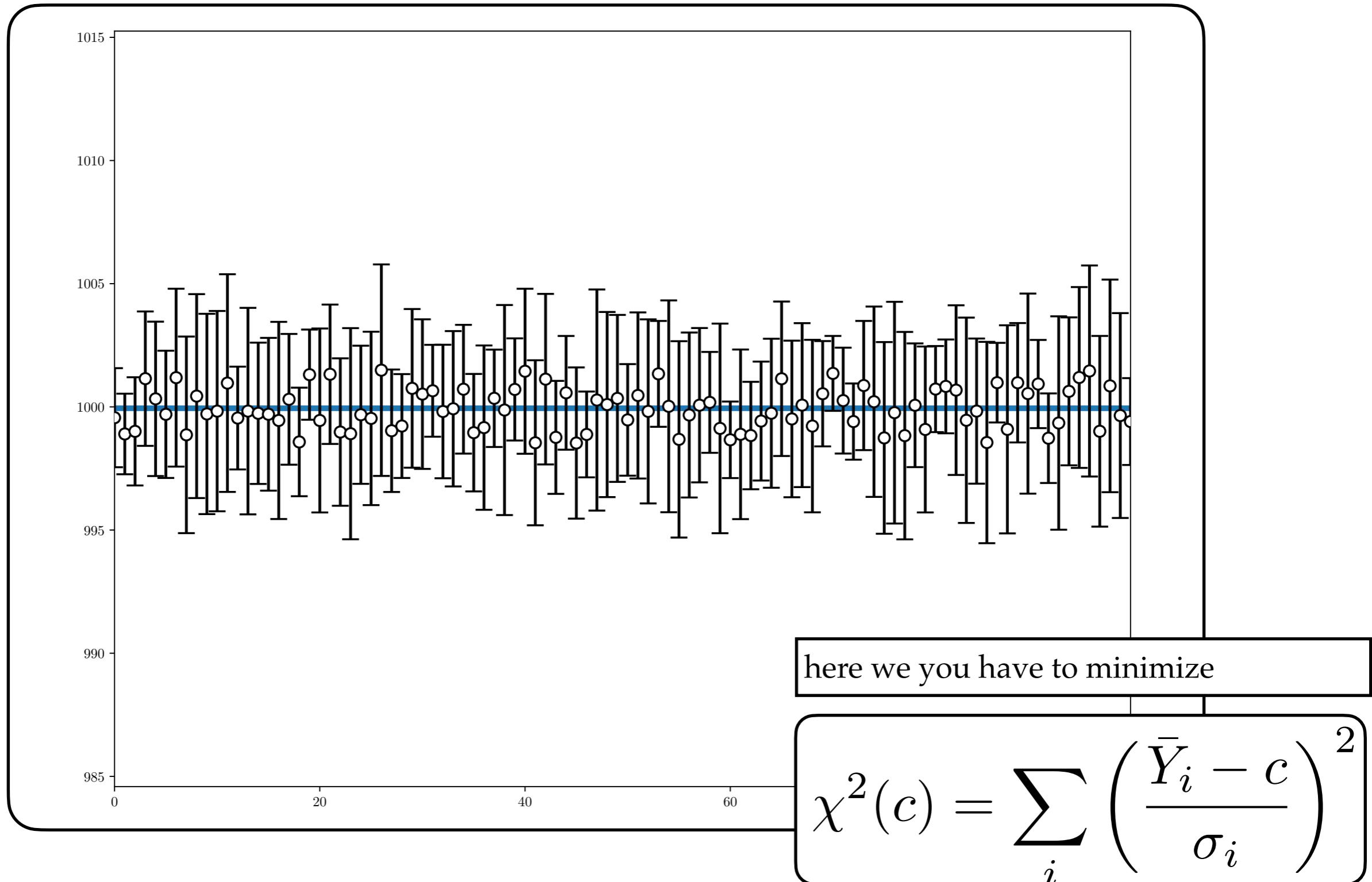
output...

```
shape(const_data) = (100, 3)  
shape(Xs) = (100, )  
shape(Ys) = (100, )  
shape(sigs) = (100, )
```

EXERCISE #2 - WARM UP...FIT A CONSTANT - WHAT TO EXPECT

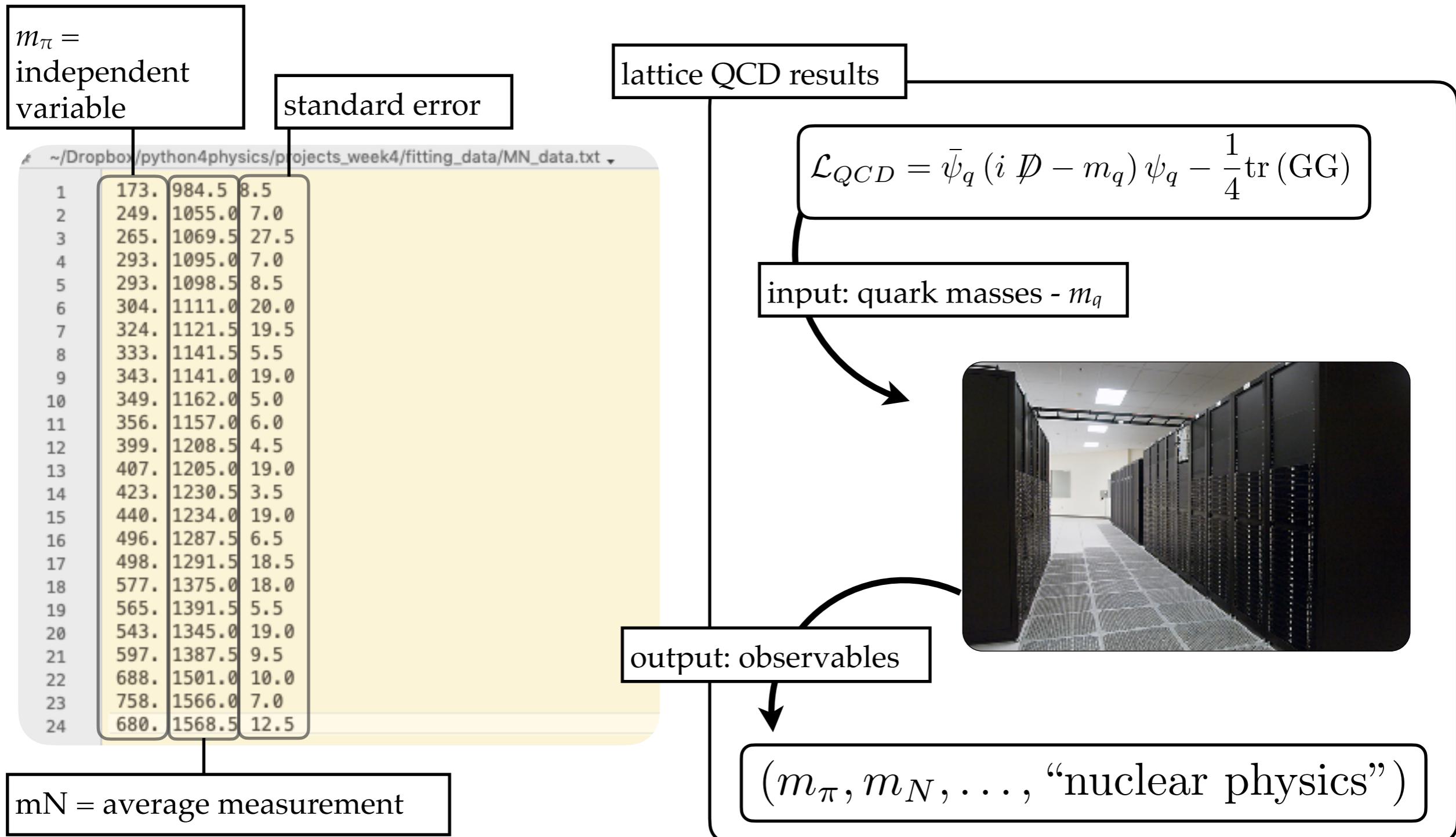
Load the data in Dropbox:/P4P_2020/project# 4/fitting_data/const_data.txt

Fit the data to a constant. Follow up, how does this constant compare to the average?



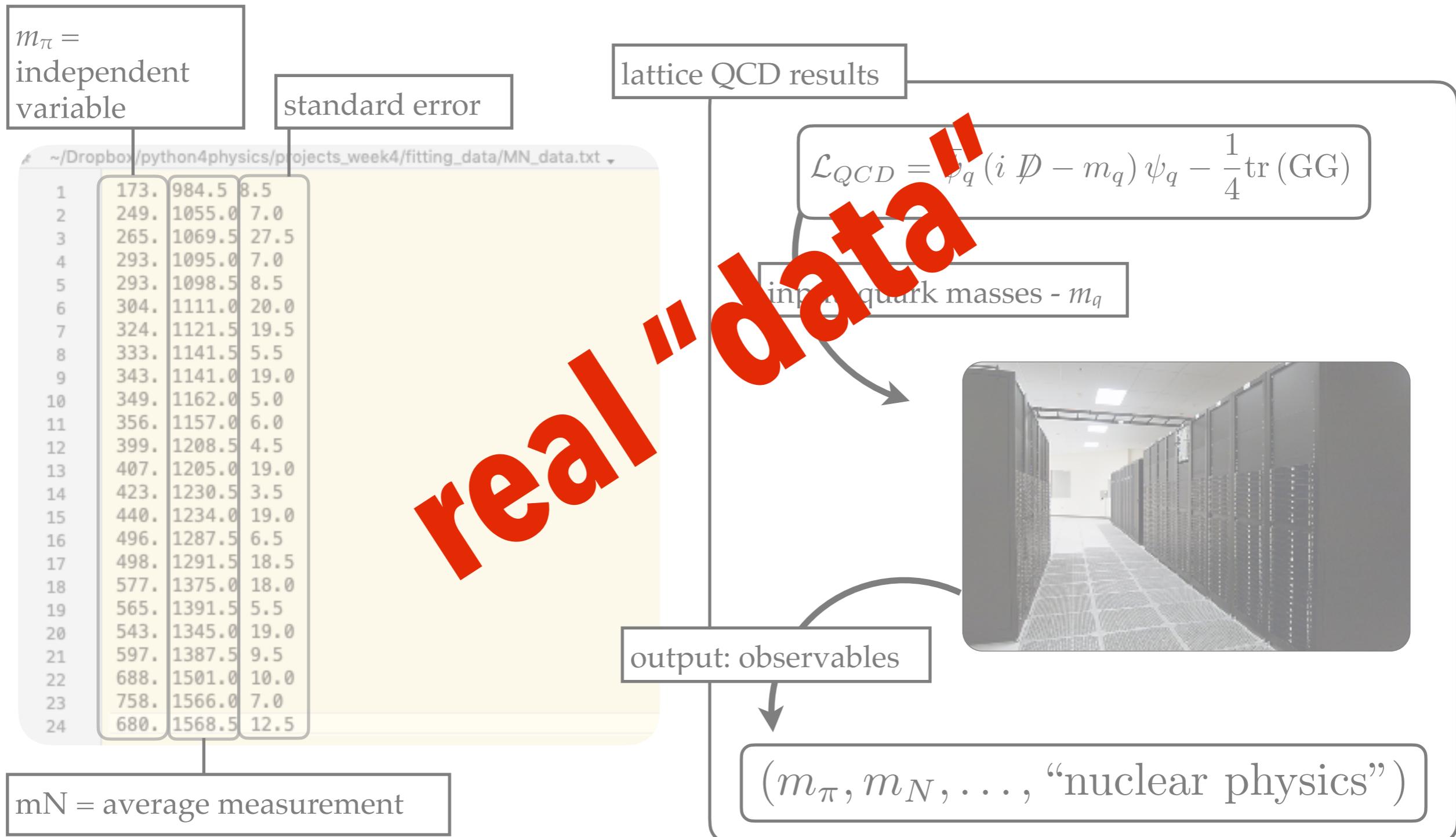
EXERCISE #3 - FIT A STRAIGHT LINE

Load the data in [Dropbox:/P4P_2020/project# 4/fitting_data/MN_data.txt](#)



EXERCISE #3 - FIT A STRAIGHT LINE

Load the data in [Dropbox:/P4P_2020/project# 4/fitting_data/MN_data.txt](#)

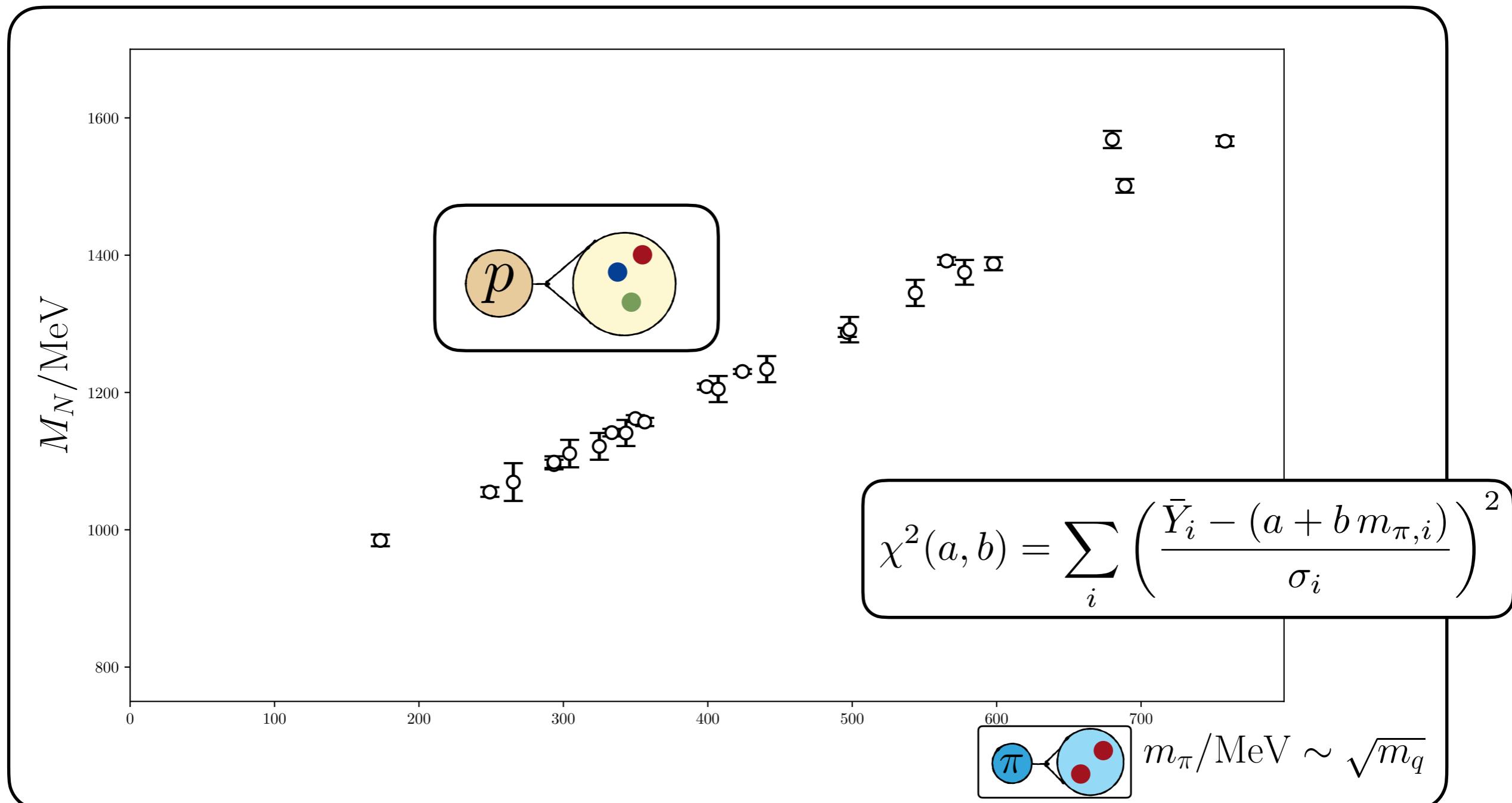


EXERCISE #3 - FIT A STRAIGHT LINE

Load the data in [Dropbox:/P4P_2020/project# 4/fitting_data/MN_data.txt](https://www.dropbox.com/s/1234567890/MN_data.txt?dl=1)

Fit to a straight line assuming $M_N = M_0 + m_\pi b$

M_0 is the value of the mass when the Higgs does not matter! Compare this to the physical nucleon mass. How much does the Higgs contribute to our mass?

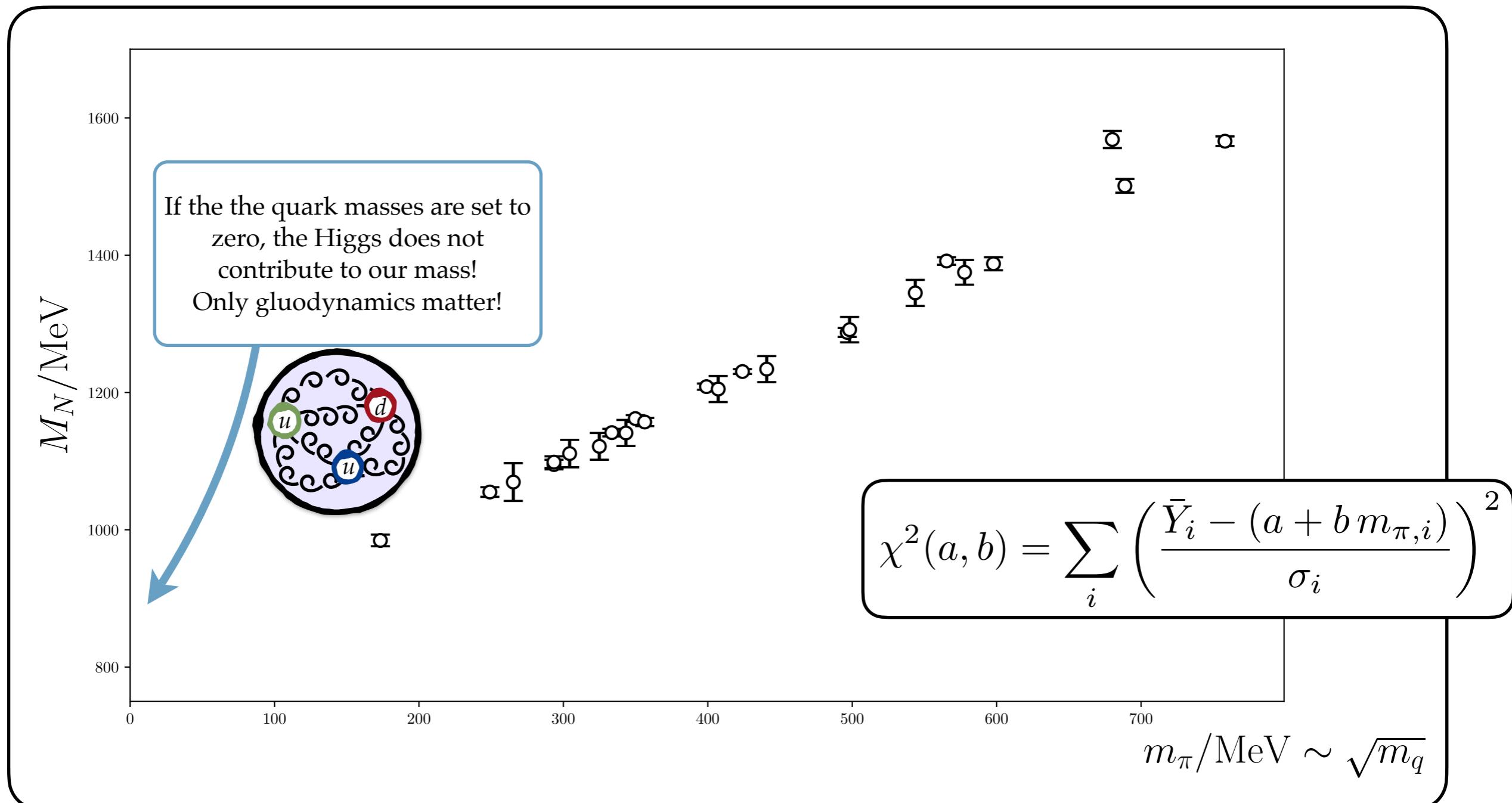


EXERCISE #3 - FIT A STRAIGHT LINE

Load the data in [Dropbox:/P4P_2020/project# 4/fitting_data/MN_data.txt](https://www.dropbox.com/s/1234567890123456/MN_data.txt?dl=1)

Fit to a straight line assuming $M_N = M_0 + m_\pi b$

M_0 is the value of the mass when the Higgs does not matter! Compare this to the physical nucleon mass. How much does the Higgs contribute to our mass?

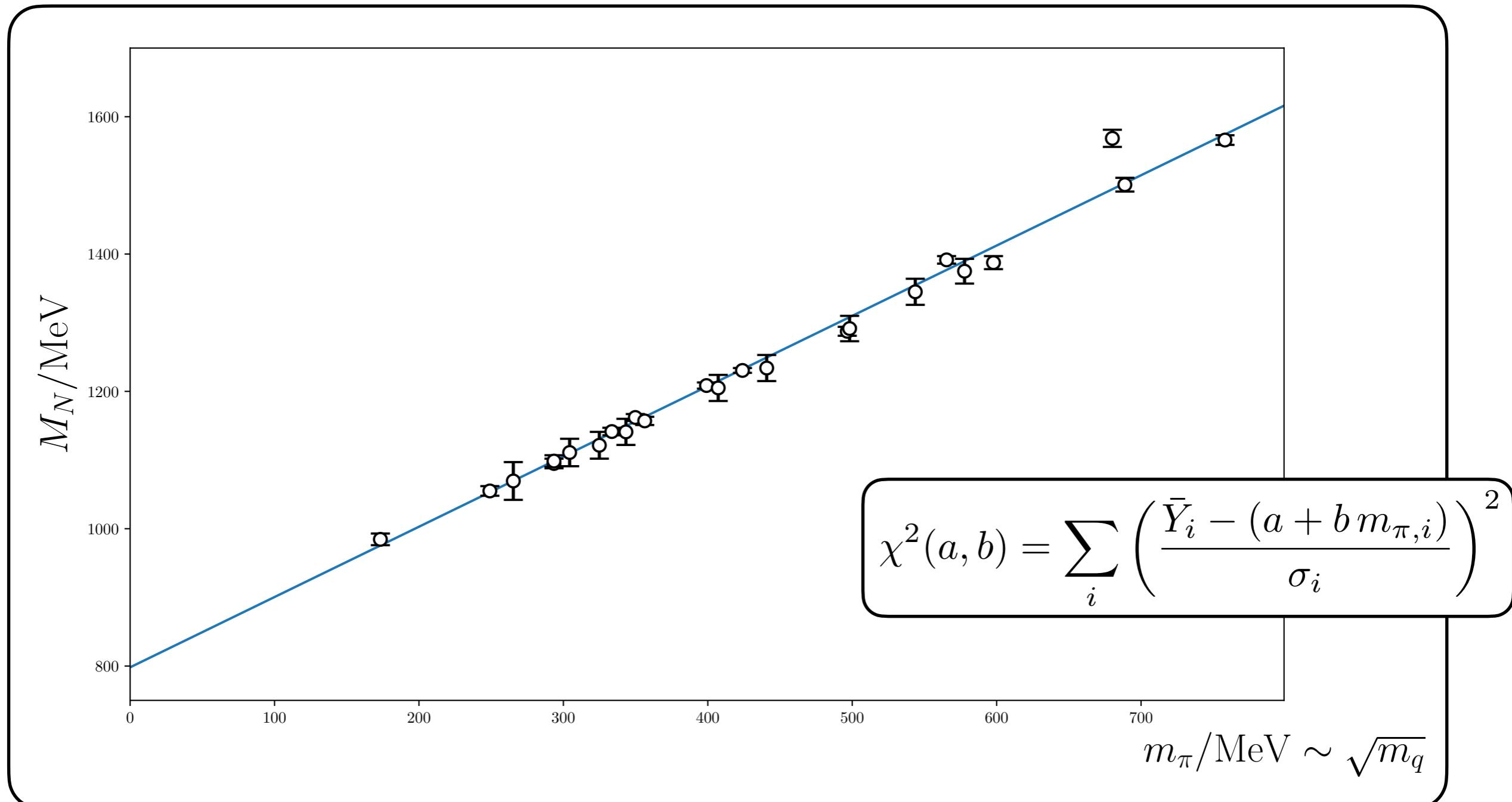


EXERCISE #3 - FIT A STRAIGHT LINE - WHAT TO EXPECT

Load the data in [Dropbox:/P4P_2020/project# 4/fitting_data/MN_data.txt](https://www.dropbox.com/s/1234567890123456/MN_data.txt?dl=1)

Fit to a straight line assuming $M_N = M_0 + m_\pi b$

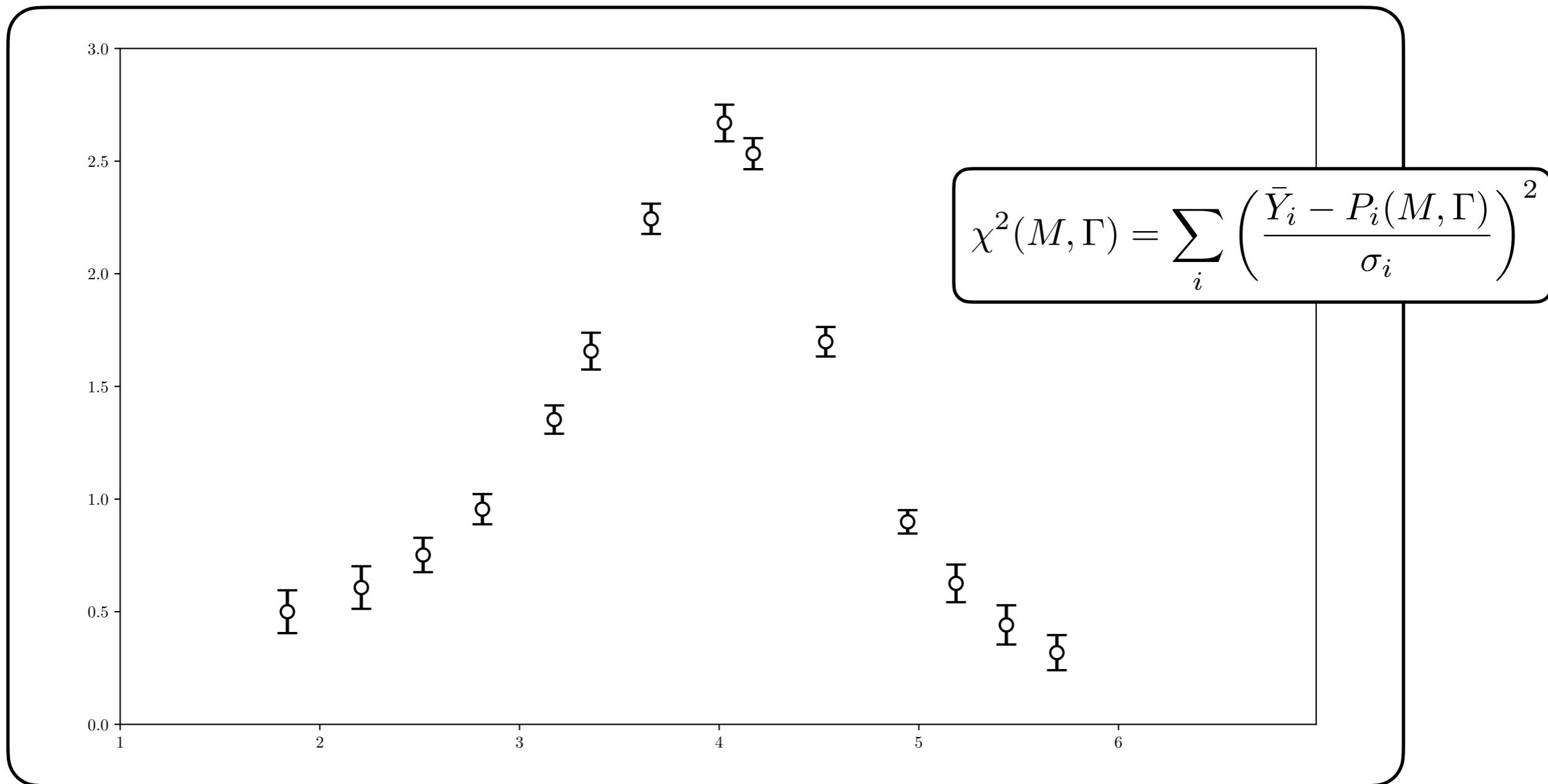
M_0 is the value of the mass when the Higgs does not matter! Compare this to the physical nucleon mass. How much does the Higgs contribute to our mass?



EXERCISE #4 - FIT A BREIT-WIGNER

Load the data in [Dropbox:/P4P_2020/project# 4/fitting_data/BW_data.txt](#)

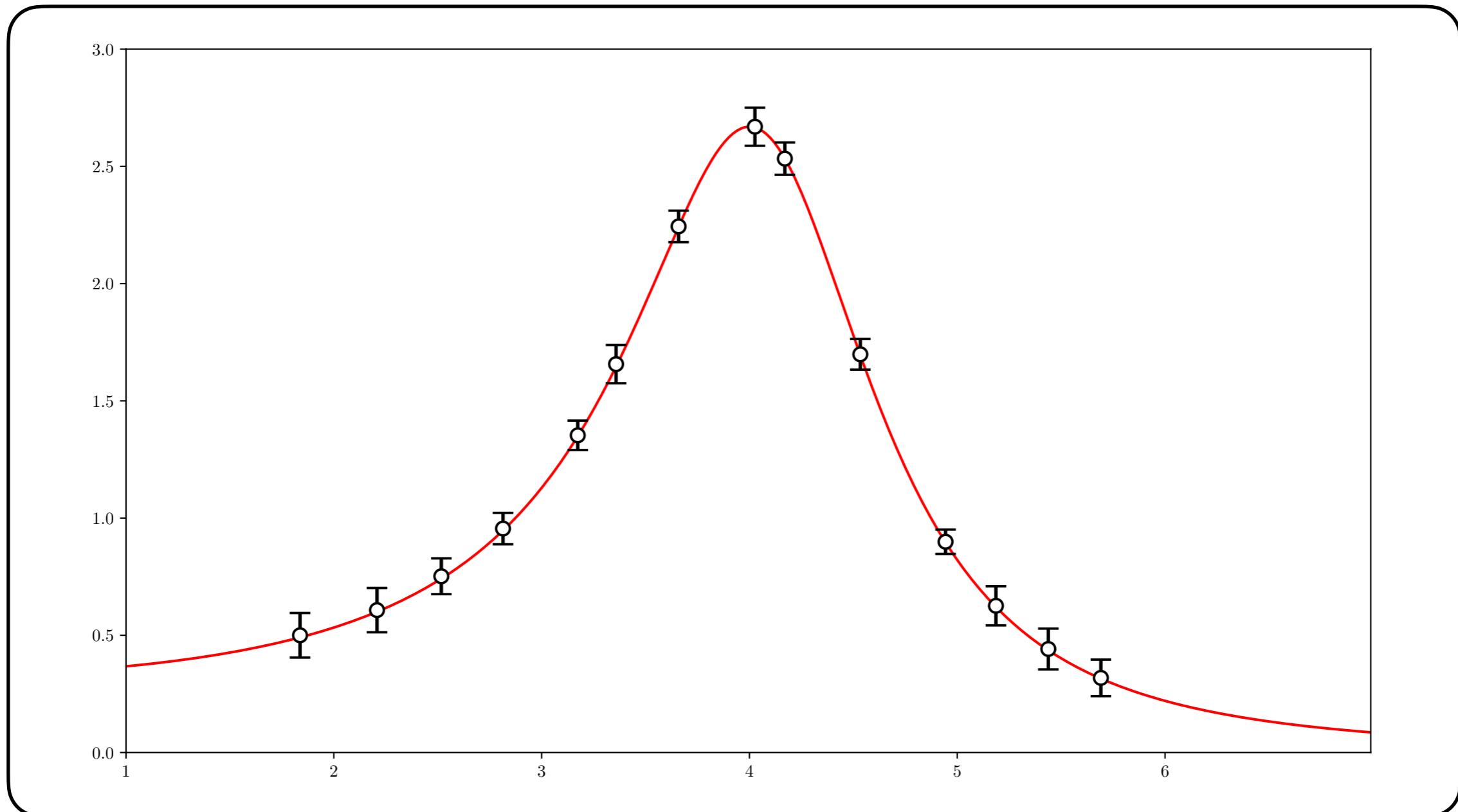
Fit to a Breit-Wigner. Determine the mass and width of the state



EXERCISE #4 - FIT A BREIT-WIGNER - WHAT TO EXPECT

Load the data in [Dropbox:/P4P_2020/project# 4/fitting_data/BW_data.txt](https://www.dropbox.com/s/1234567890123456/p4p_2020/project%204/fitting_data/BW_data.txt)

Fit to a Breit-Wigner. Determine the mass and width of the state



SUMMARY - EQUATIONS USED

Statistics:

$$\text{Goodness of fit: } \chi^2(\{c\}) = \sum_i \left(\frac{\bar{Y}_i - f(X_i, \{c\})}{\sigma_i} \right)^2$$

X_i = independent variables, Y_i = dependent variables, σ_i = errors in Y_i ,
 f = function of variables $\{c\}$, which represent the expected value.

Physics:

Breit-Wigner distribution as a function of energy (E):

$$P(E) = \frac{M^3 \Gamma}{(E^2 - M^2)^2 + M^2 \Gamma^2}$$

M, Γ are properties of a short-lived resonating particle.

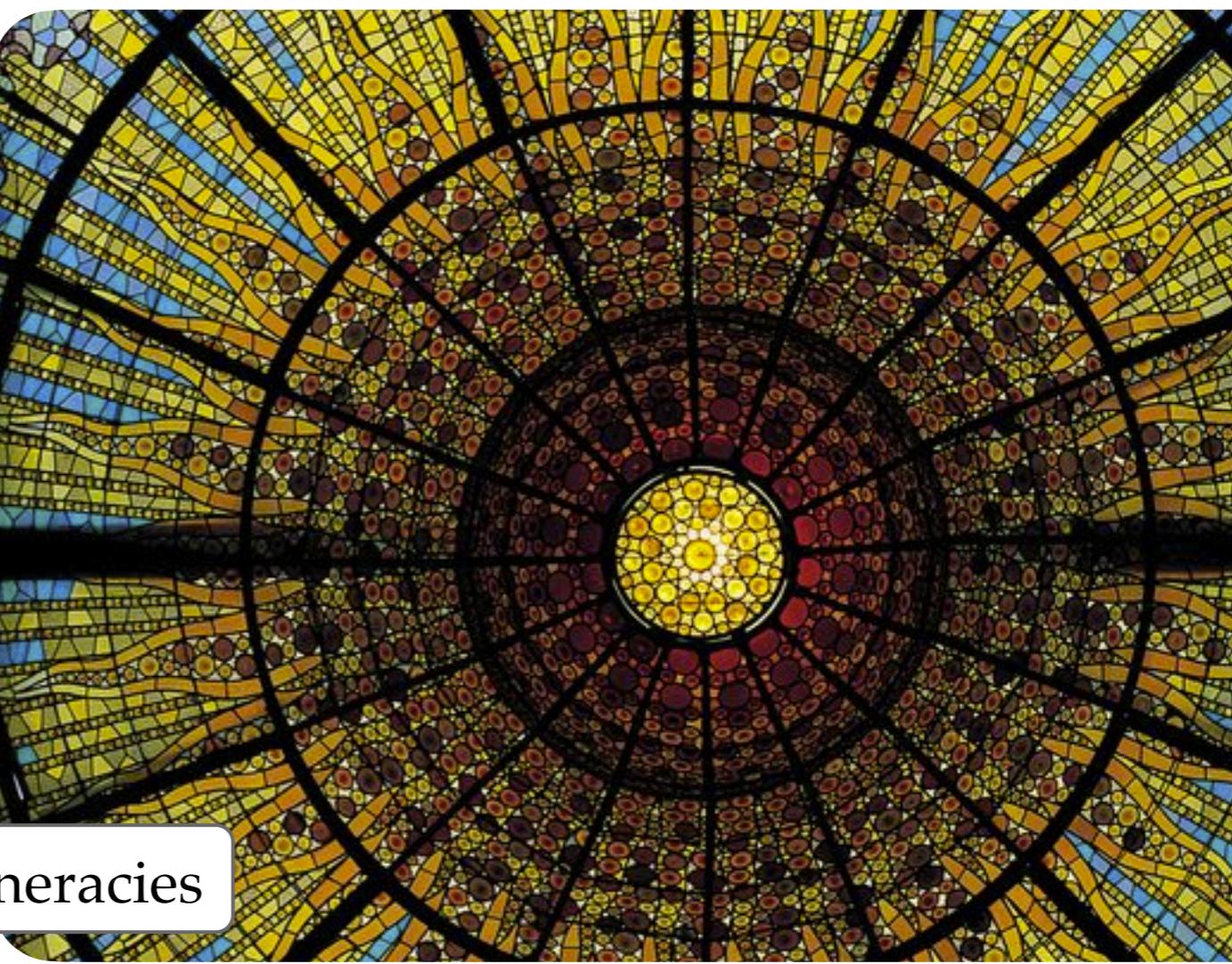
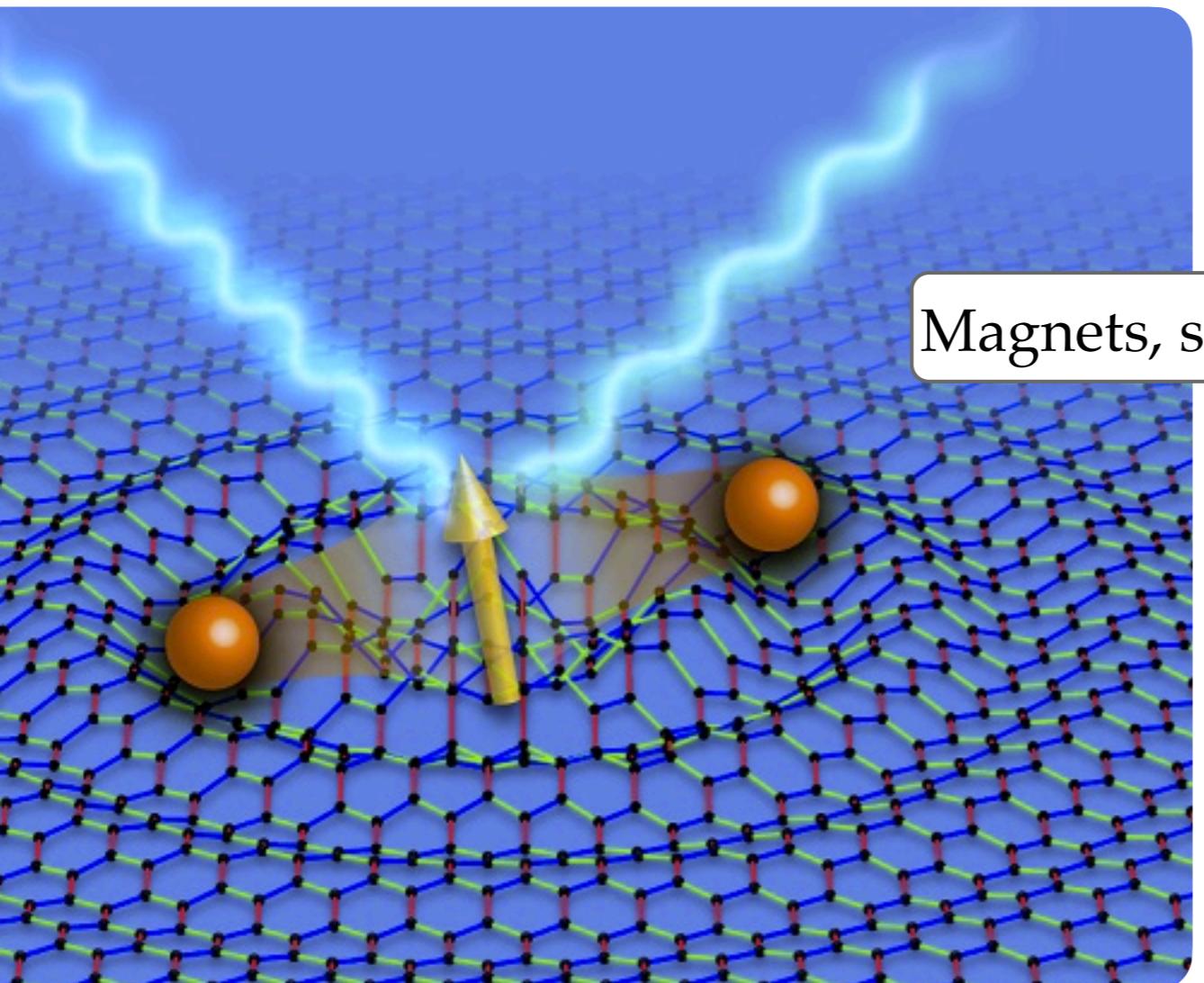
M = is the mass of the resonance

Γ = decay width of the resonance = $1 / (\text{lifetime of the resonance})$

OK, Let's
Dive in

A small, shaggy dog with light brown and white fur is captured mid-air, leaping out of a swimming pool. The dog is positioned in the center-right of the frame, with its front paws extended forward and its back legs pushing off. The swimming pool is a vibrant turquoise color, reflecting the clear blue sky above. In the background, there's a well-maintained lawn with a row of green hedges. To the right, two palm trees stand tall, and a white diving board is visible on the right edge of the pool. The overall scene is bright and sunny, suggesting a summer day.

OUTLINE FOR TODAY

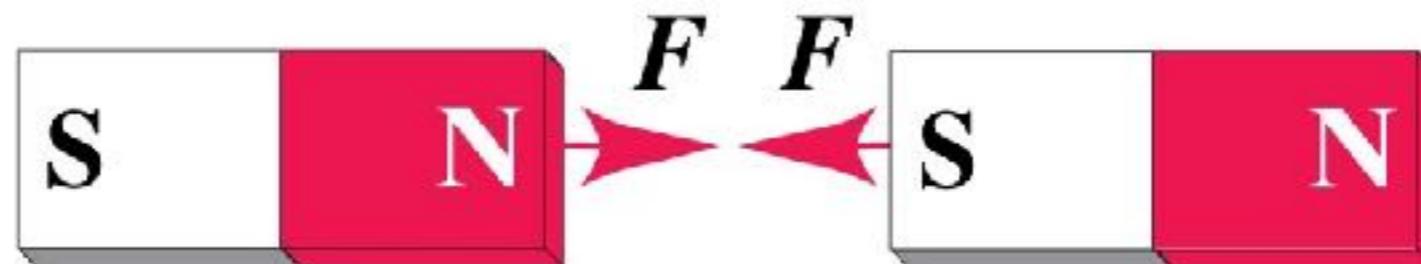


BAR MAGNET & IRON FILINGS



MAGNETS

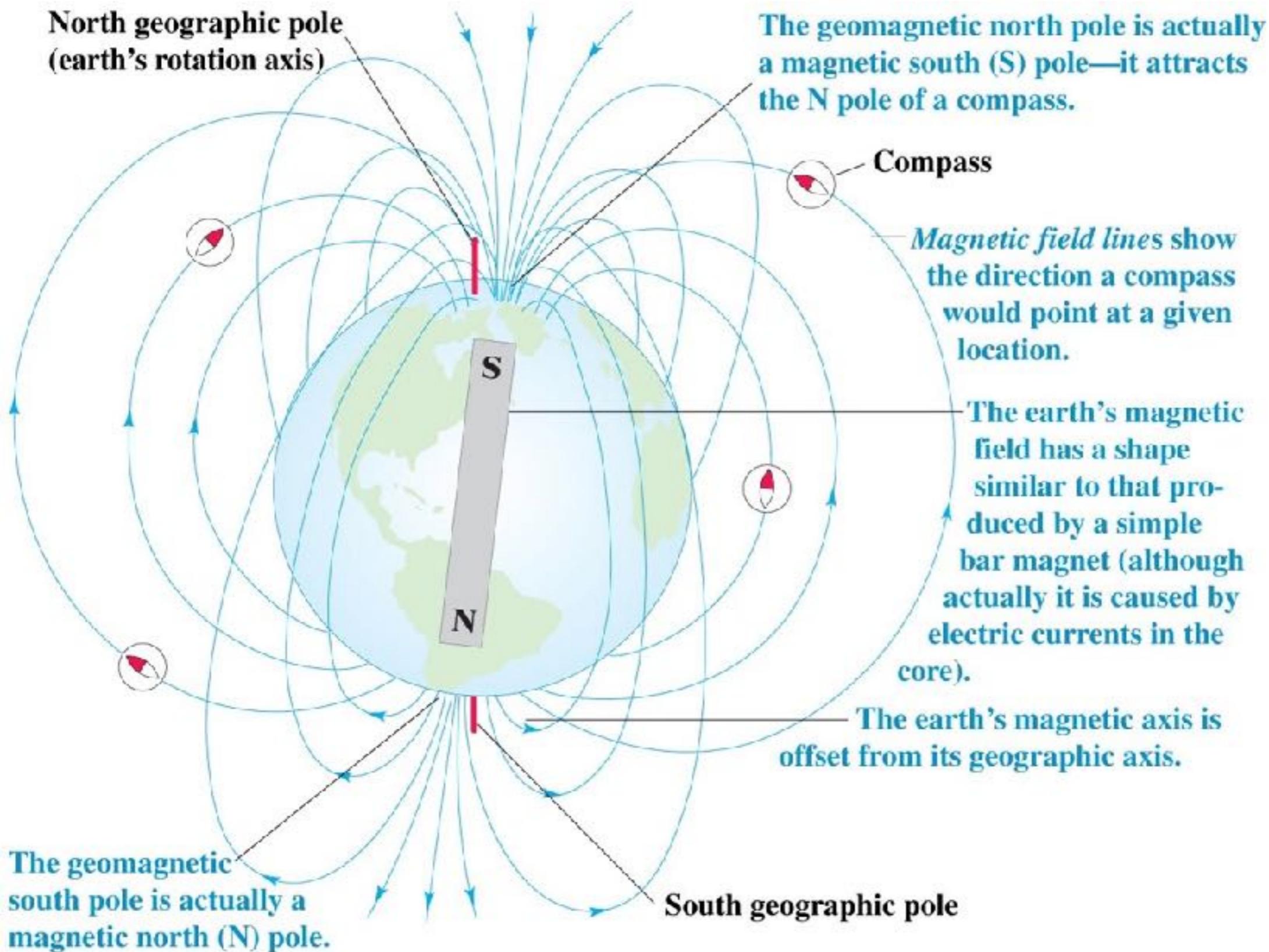
Unlike poles attract.



Like poles repel.



THE EARTH'S MAGNETIC FIELD



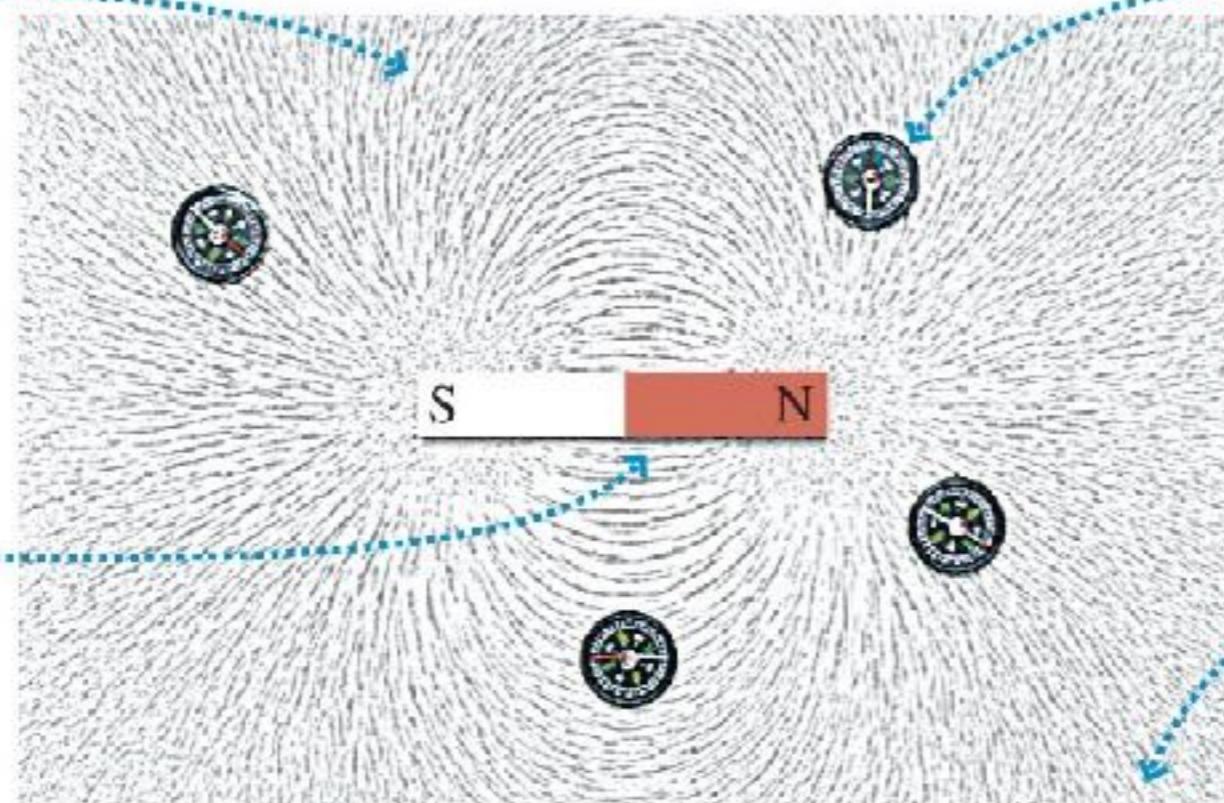
MAGNETIC FIELDS

Each iron filing acts
like a tiny compass
needle and rotates to
point in the direction
of the magnetic field.

Where the field is
strong, the torque
easily lines up the
filings.

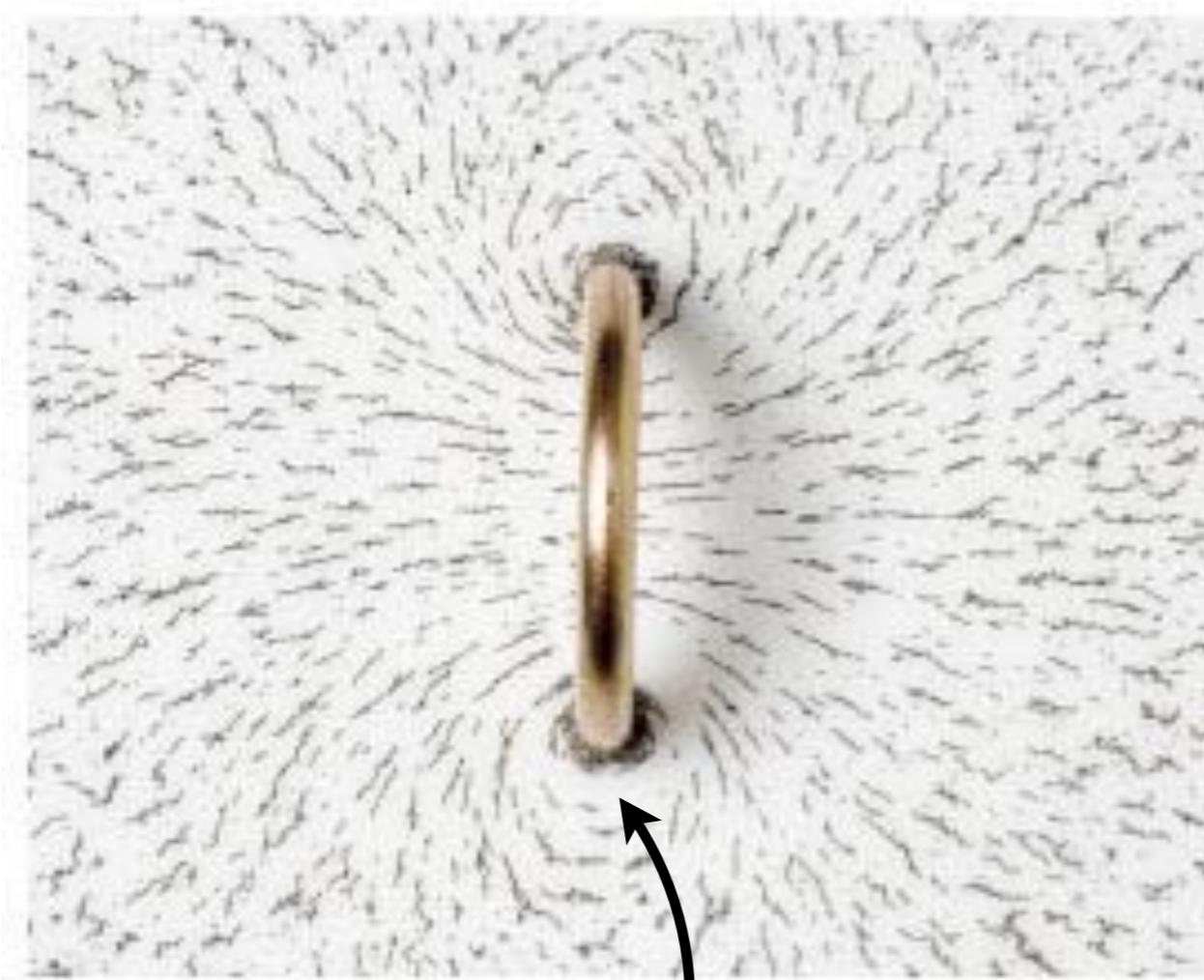
..... Since the poles of the
iron filings are not
labeled, a compass can
be used to check the
direction of the field.

Where the field is
weak, the torque barely
lines up the filings.



'ELECTRO'-MAGNETISM

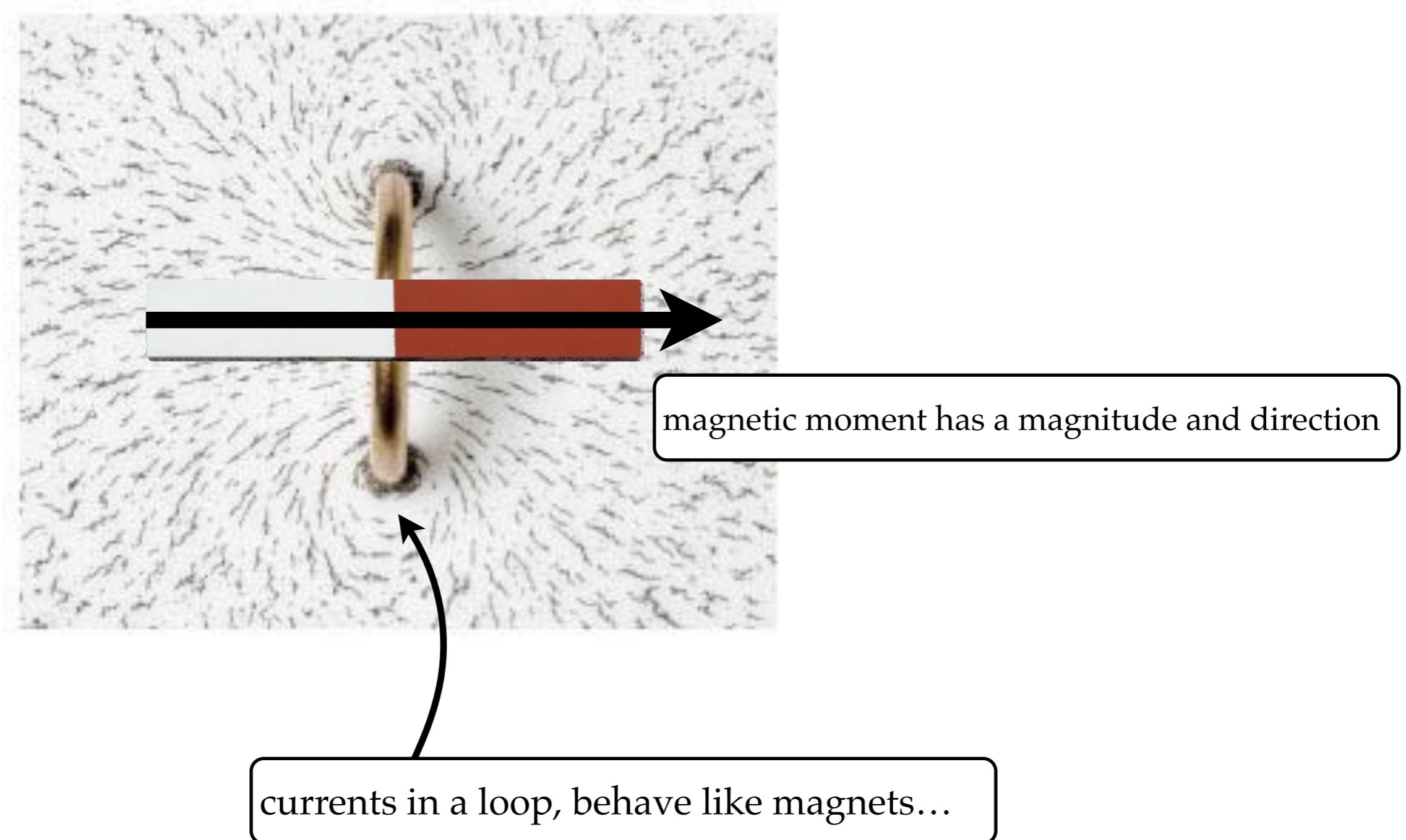
- is there a connection between electricity and magnetism ?
- a loop carrying a large current



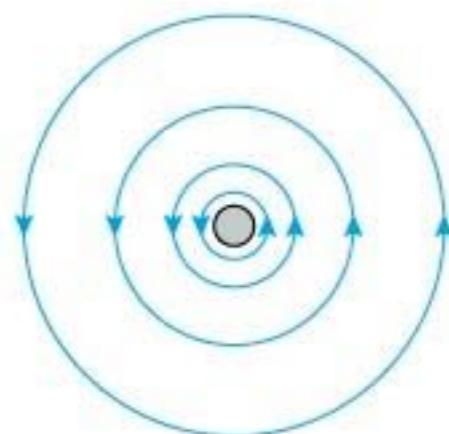
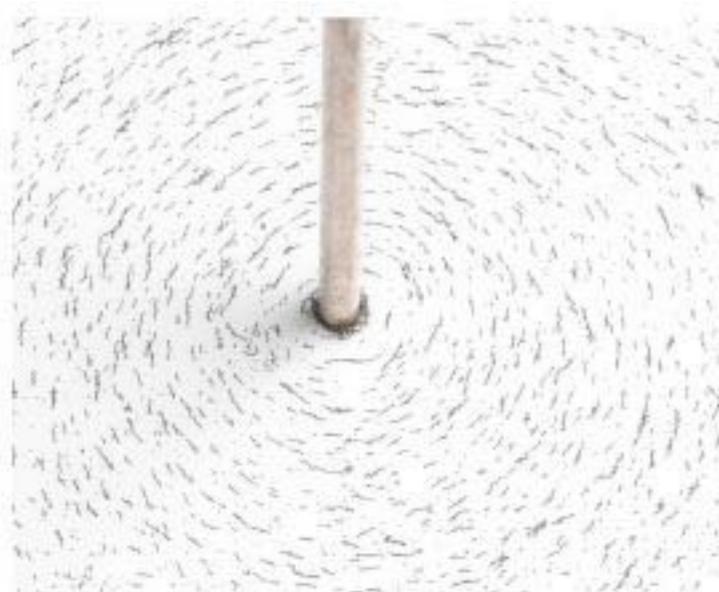
currents in a loop, behave like magnets...

'ELECTRO'-MAGNETISM

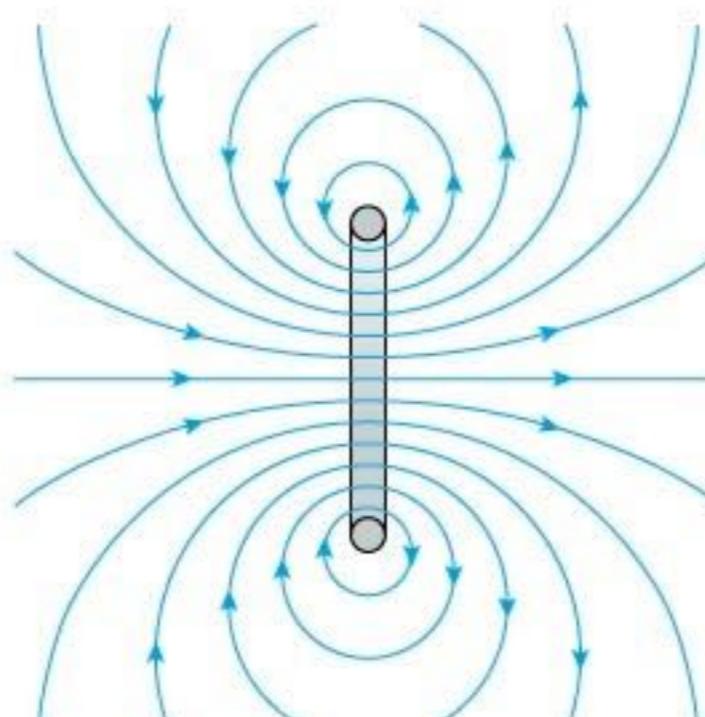
- is there a connection between electricity and magnetism ?
- a loop carrying a large current



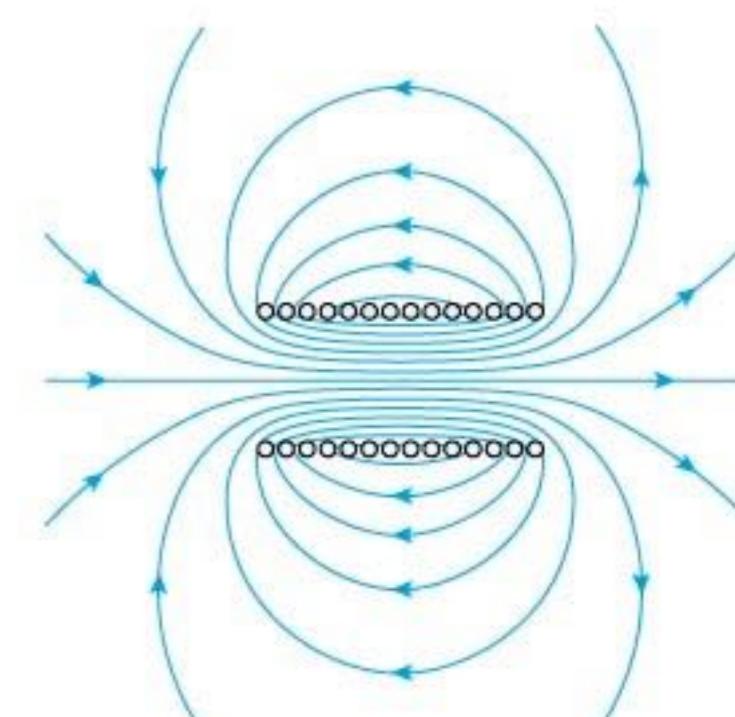
MAGNETIC FIELDS



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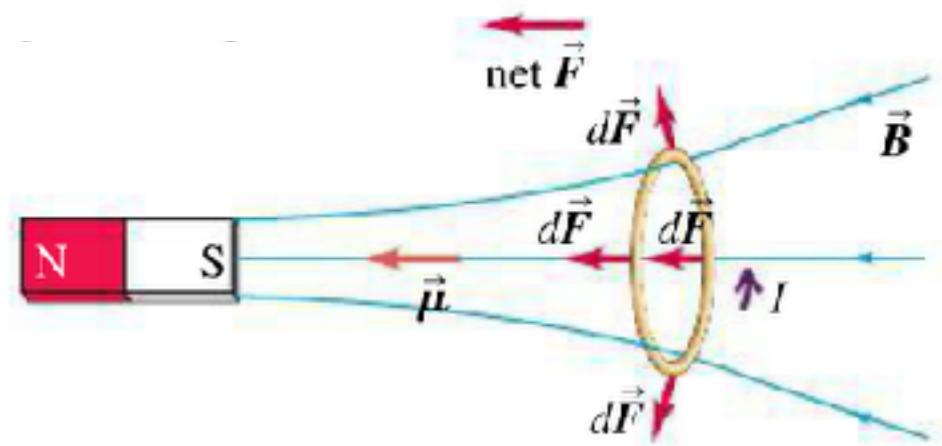
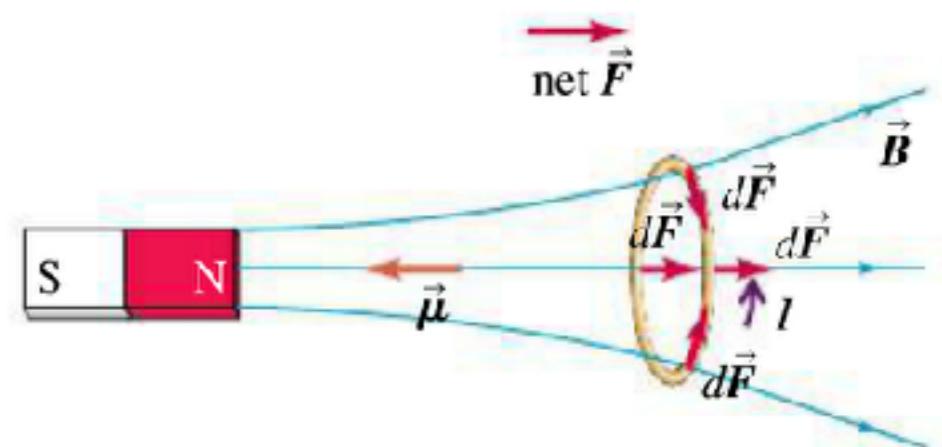
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MAGNETIC DIPOLES IN NON-UNIFORM FIELDS

If the magnetic moment of a dipole is anti-aligned with a field, it will experience a force towards where there is a lower density.

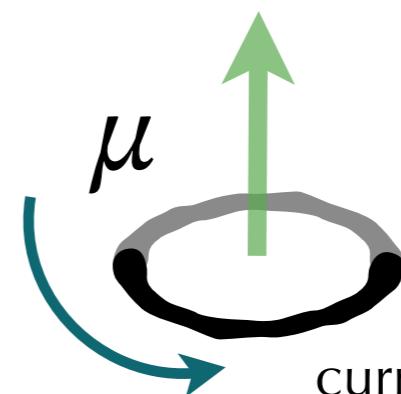
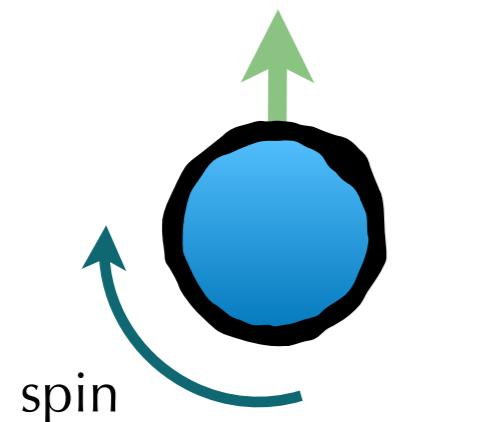
Conversely, if the moment is aligned with the field, it will experience a force towards the higher density.

In other words, they behave like magnets!



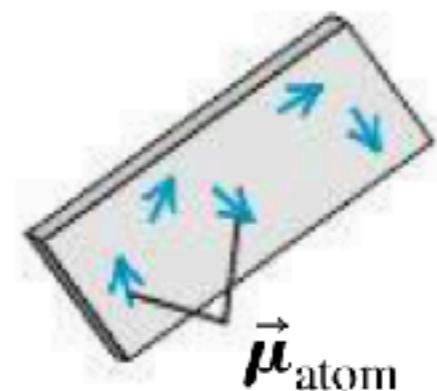
MAGNETIC DIPOLES IN NON-UNIFORM FIELDS

This then allows us to paint a microscopic picture of magnets. If we think of electrons as little spheres spinning about their axis, this would result in a current and consequently a magnetic dipole

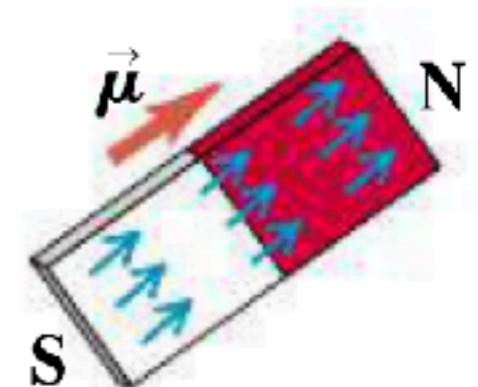


current [remember, electrons are negatively charged]

So, unmagnetized material is made of magnetic moments there are not aligned in any direction



Magnetized material is that where the moments have been aligned by an external field, and then persist to be aligned due to their internal interactions



ISING MODEL - PART 1

To understand spins inside material, it is useful to construct a simple model. The most famous of which is the **Ising model** [https://en.wikipedia.org/wiki/Ising_model], named after **Ernst Ising**.

Ising solved the simplest version of this model in 1-dimension (1D), which we consider here.

In the Ising model, spins are fixed. They can either **point up (+1)** or **down (-1)**. Spin inside material can either *align* or *anti-align*.

Depending on the material, certain alignment of spins, it might be favorable or dis-favorable for spins to align. This would manifest itself in the energy stored or the energy required to put the systems into a given configuration.



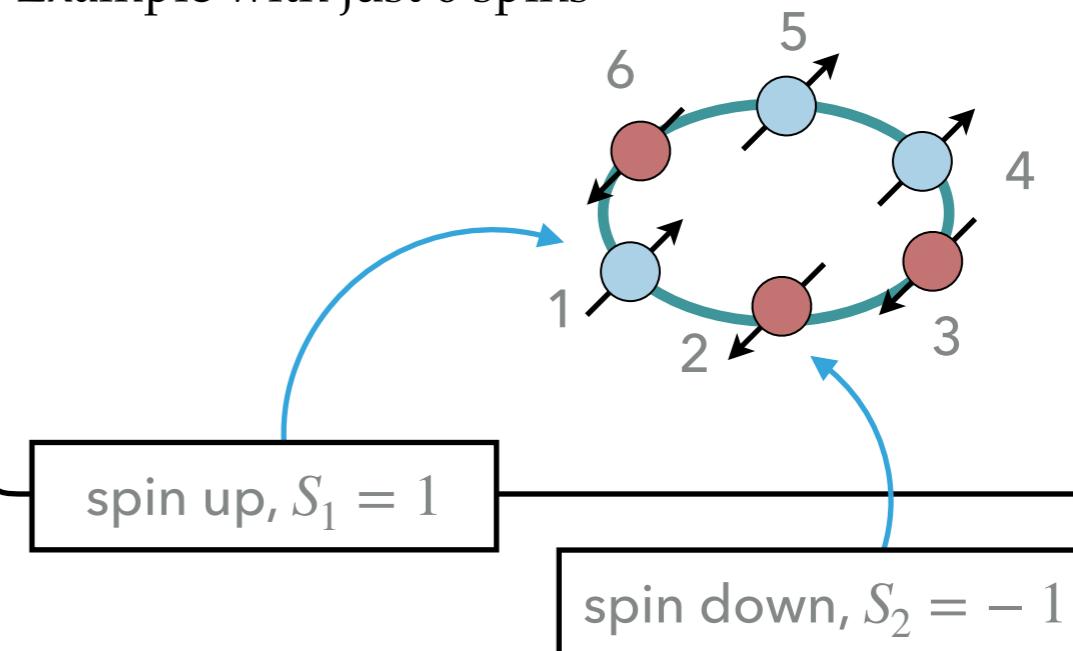
Ernst Ising [1900-1998]

ISING MODEL - PART 2

Consider N spins in a ring.

Enumerate the spin from 1 to N , as shown on the example to the right for $N=6$. Let i be a number satisfying $1 \leq i \leq N$. Then, we will label the value of the spin for that element in the ring as S_i .

Example with just 6 spins



In the example, we have $N = 6$, and the following values for the individual spins $S_1 = 1$, $S_2 = -1$, $S_3 = -1$, $S_4 = 1$, $S_5 = 1$, $S_6 = -1$.

ISING MODEL - PART 3

With this, we can make a fairly general model for the energy of a given configuration of spins:

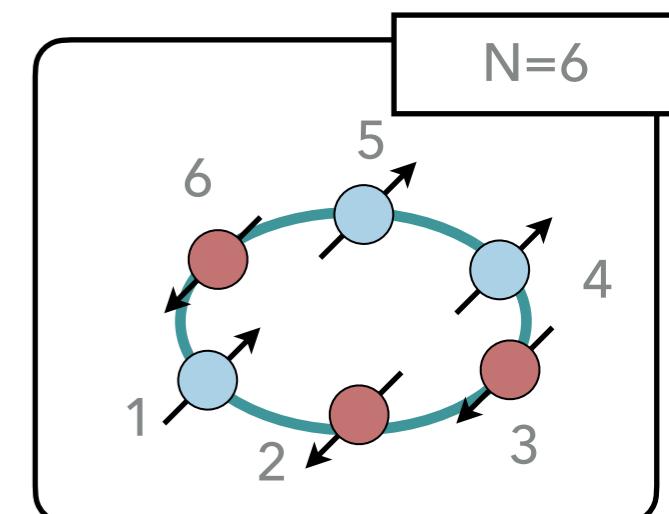
$$E(a, b, c) = a \sum_{i=1}^N S_i S_{i+1} + b \sum_{i=1}^N S_i S_{i+2} + c \sum_{i=1}^N S_i$$

a, b, c are constants that depend on the properties of the system. Here, we will consider different scenarios where we choose different values for these.

To understand this, we can consider a value for i , then the first term, $S_i S_{i+1}$, means that one must multiply the two values of the spin together. For this to make sense, we need to define $N + 1 = 1, N + 2 = 2$. This is referred to as “*periodic boundary conditions*”.

For example, here are the numbers for the example shown in the figure:

i	$i + 1$	$i + 2$	S_i	S_{i+1}	S_{i+2}	$S_i S_{i+1}$	$S_i S_{i+2}$
1	2	3	1	-1	-1	-1	-1
2	3	4	-1	-1	1	1	-1
3	4	5	-1	1	1	-1	-1
4	5	6	1	1	-1	1	-1
5	6	1	1	-1	1	-1	1
6	1	2	-1	1	-1	-1	1

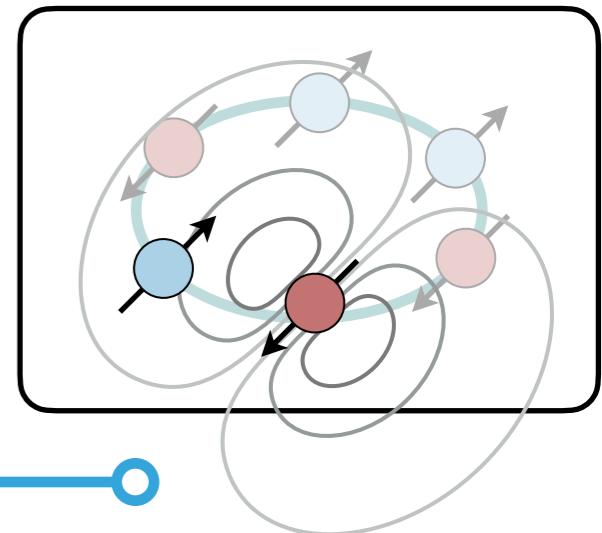


ISING MODEL - PHYSICS INTUITION

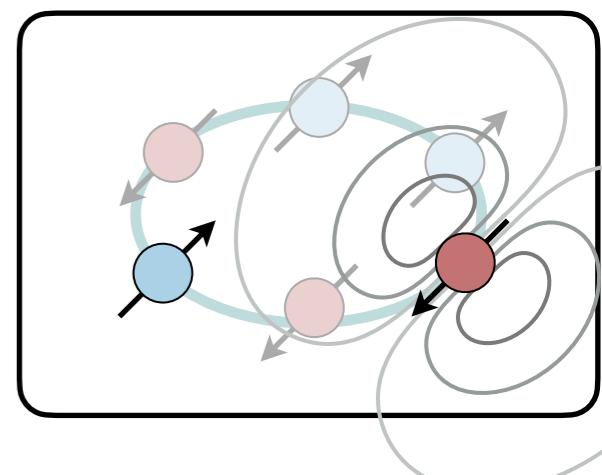
Let us gain from intuition for the physics of these terms,

Nearest neighbors: First, let us consider the first term, $E_a = a \sum_i S_i S_{i+1}$. This term tells us that each spin experiences the field generated by its closest neighbor.

The strength with which this contributes to the energy, depends on the values of a and the spins.

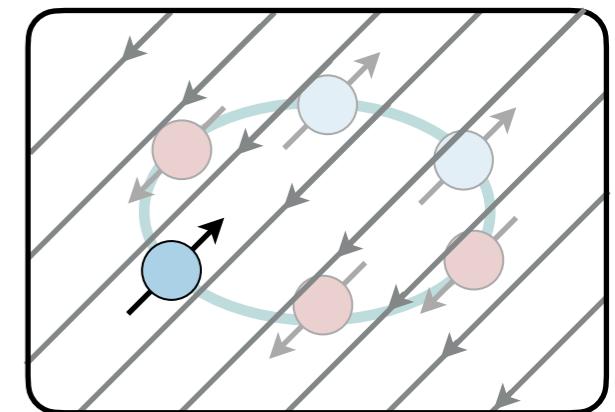


Next-to-nearest neighbors: next, we consider the second term, $E_b = b \sum_i S_i S_{i+2}$. This is similar to the one above, except now a given spin is feeling the field generated by a spin that is two slots away. Again, the strength of this effect on the energy of the system depends on a given variable b and the spins.



ISING MODEL - PHYSICS INTUITION

Background field: Lastly, we have the term $\Delta E_c = c \sum_i S_i$. This accounts for the possibility that there might be an external field, say from the earth or a big magnet, and these spins feel the effect from it. Again, this depends on the value of c considered.



SYMMETRIES - PART 1

In what follows, we will be determining the energies for the Ising model for a variety of different scenarios, but before we do, let's introduce some concepts. These are symmetry and degeneracy.

Symmetry: Symmetry is one of the most powerful concepts in physics. It has guided some of the major insights in physics in the last century.



Emmy Noether

"She was described by Pavel Alexandrov, Albert Einstein, Jean Dieudonné, Hermann Weyl and Norbert Wiener as the most important woman in the history of mathematics."

"Noether's theorem explains the connection between symmetry and conservation laws."

Simply put, one the most important Mathematical physicist of the 20th century.



F. Ortega-Gama

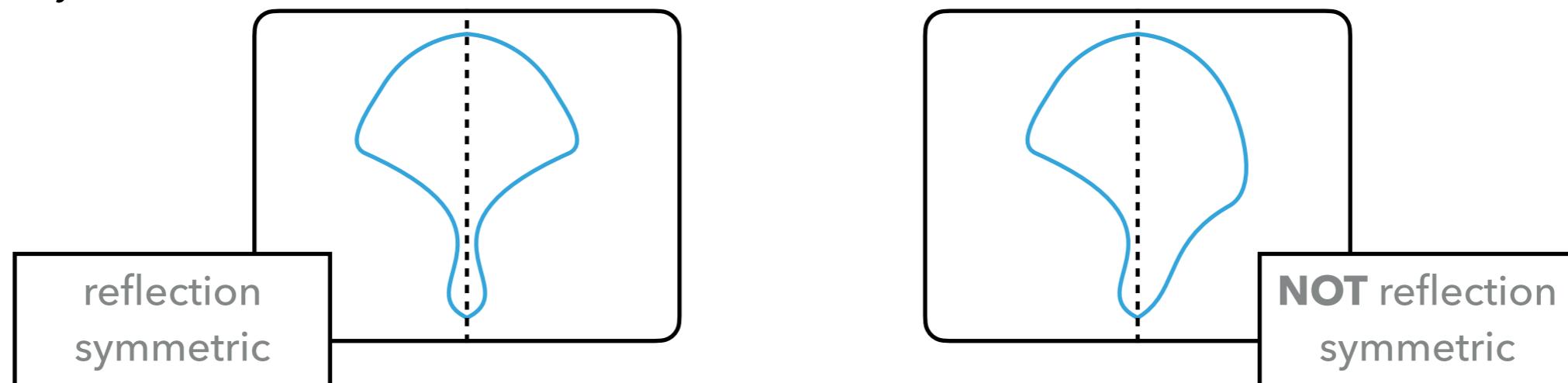
Student - William & Mary
Symmetries and how to use them in physics 07/24

SYMMETRIES - PART 1

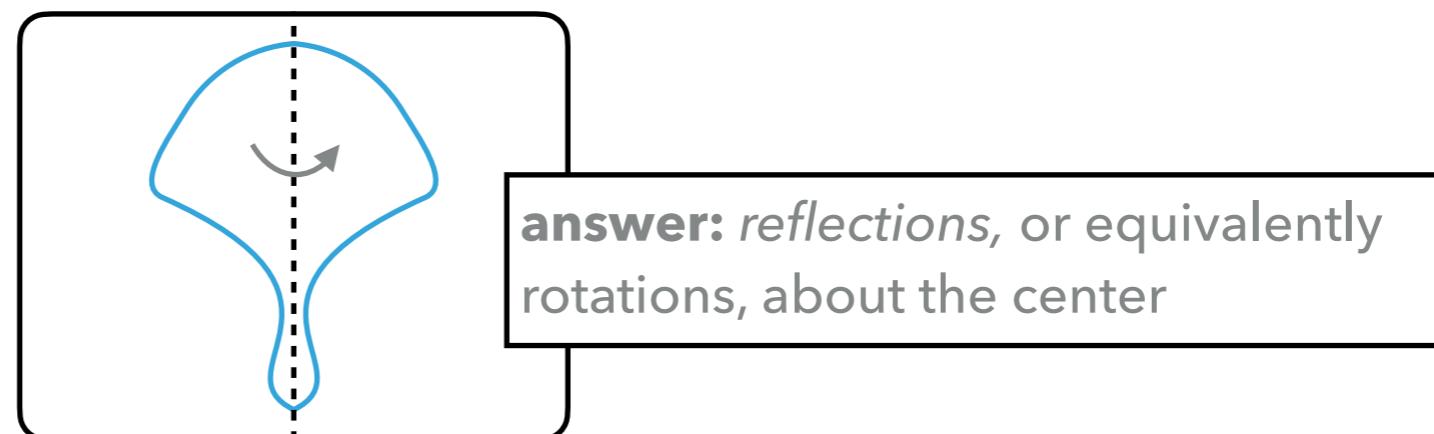
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Symmetry: Symmetry is one of the most powerful concepts in physics. It has guided some of the major insights in physics in the last century.

One can intuitively understand symmetry by considering, for example, objects that are reflection symmetric and those that are not.



Equivalently, one can ask the question: "*What actions (or transformations) leave the system invariant (or unchanged)?*"



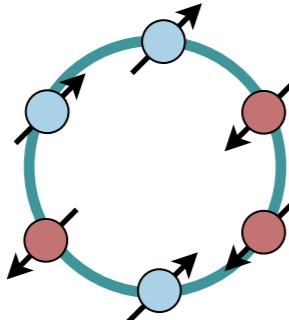
SYMMETRIES - PART 2

So what symmetries does our systems of spins have?

To answer this question, let us start with a simpler case where there is no external field, namely $c = 0$. In this case, the energy of the system of spins simplifies to...

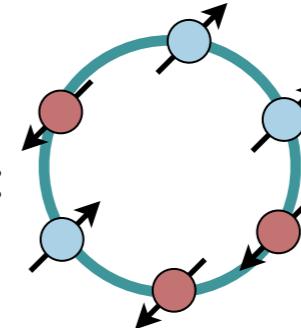
$$E(a, b, 0) = a \sum_{i=1}^N S_i S_{i+1} + b \sum_{i=1}^N S_i S_{i+2}$$

So now, let us again consider some arbitrary arrange of spins:

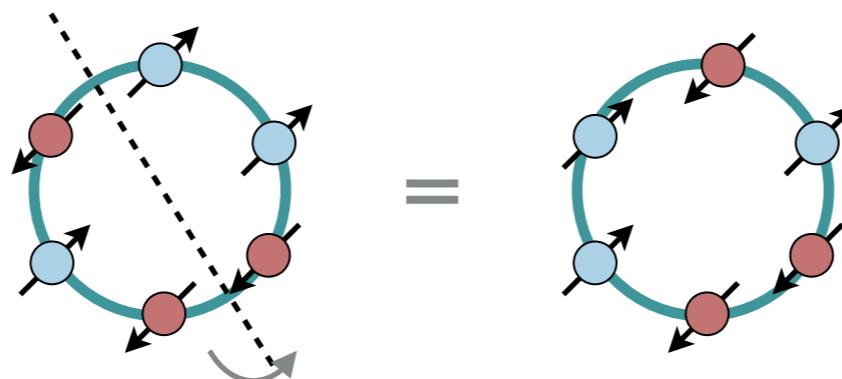


Rotations:

How many distinct rotations can we have? 🤔

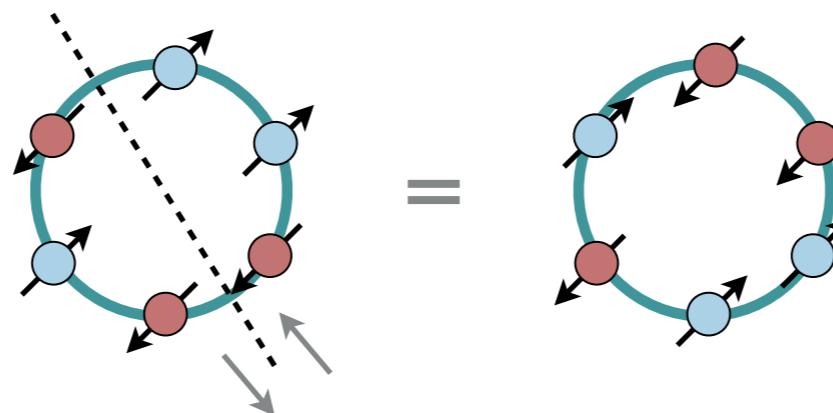


Reflections about any axis:



SYMMETRIES - PART 3

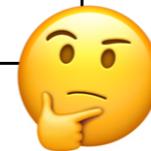
Reflections about the plane. In other words, flipping over all the spins...



Is this symmetry still present if we introduce an external field or equivalently, if c is not zero? 🤔

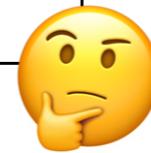
WARM UP QUESTION

Q: If I have N aligned in a ring, in how many different possible ways can they be aligned?



WARM UP QUESTION

Q: If I have N aligned in a ring, in how many different possible ways can they be aligned?



A:
$$2 \cdot \underbrace{2 \cdot 2 \cdots 2}_N = 2^N$$

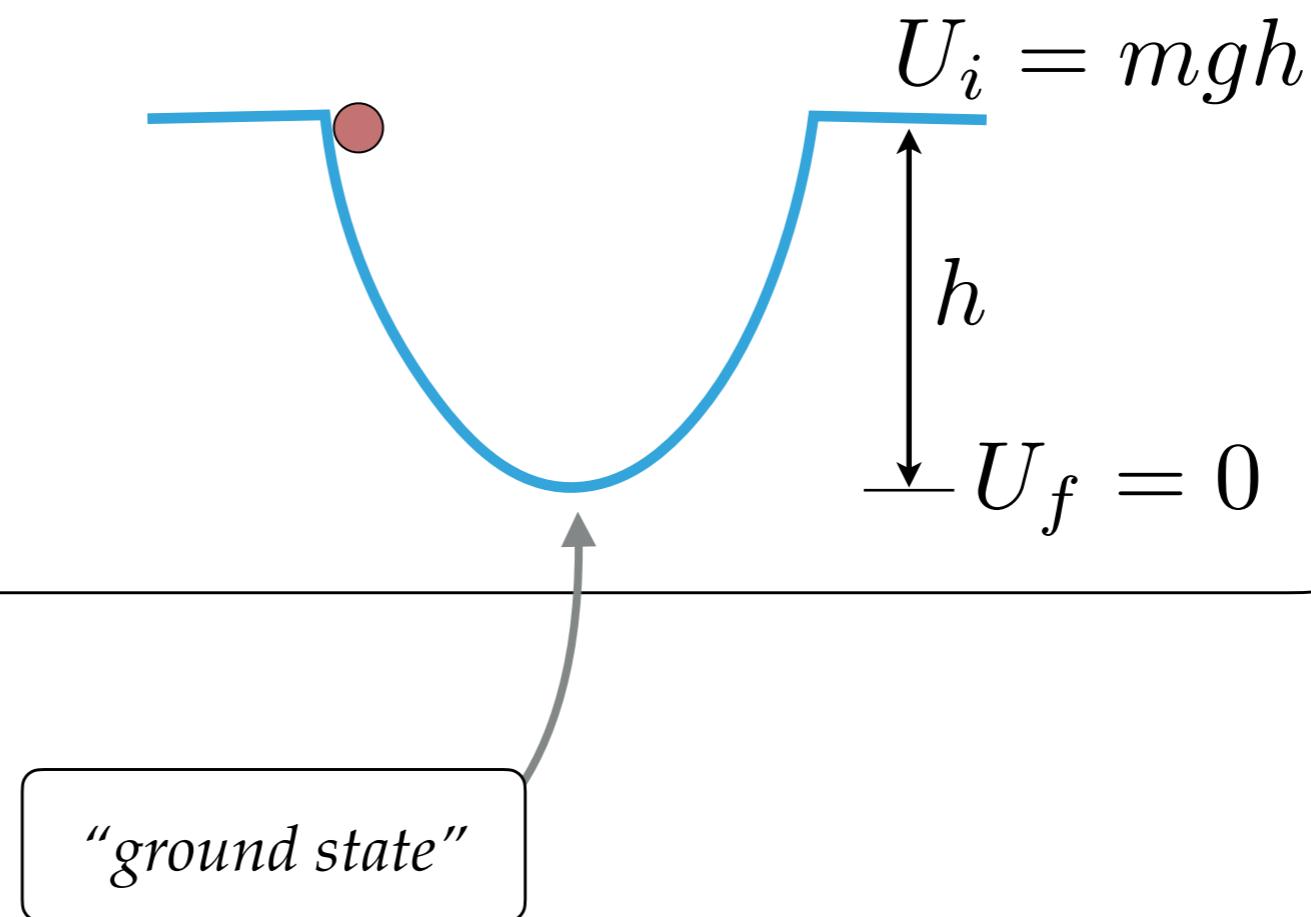
example: consider $N = 3$, implies that there should be $2^3 = 8$ distinct configurations. Each configuration is referred to as “state”

$$(\uparrow, \uparrow, \uparrow), \quad (\uparrow, \uparrow, \downarrow), \quad (\uparrow, \downarrow, \uparrow), \quad (\uparrow, \downarrow, \downarrow), \\ (\downarrow, \uparrow, \uparrow), \quad (\downarrow, \uparrow, \downarrow), \quad (\downarrow, \downarrow, \uparrow), \quad (\downarrow, \downarrow, \downarrow)$$

GROUND STATE VS EXCITED STATES

If left alone, nature always wants to minimize the energy budget of a system. In other words, particles always want to arrange themselves in the most energetically favorable way.

qualitative example: it is useful to keep in mind a ball in the presence of the gravity. It wants to always roll down the hill, where the potential energy is at its minimum.

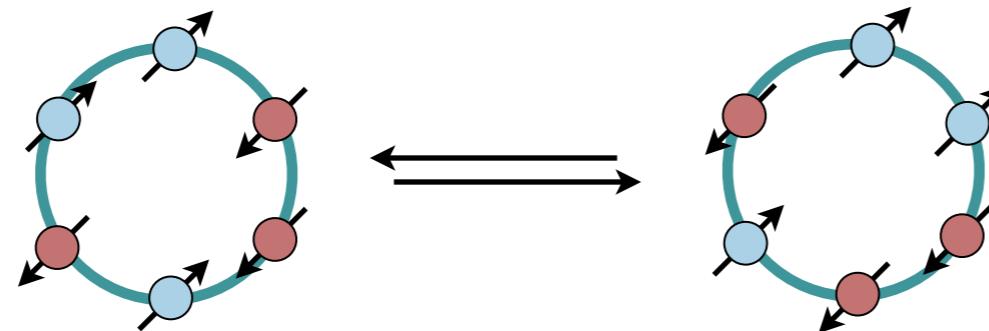


DEGENERACIES

The fact that the system has these symmetries, implies that different spin combinations would have the same energies. In quantum mechanics, this is known as a “*degeneracy*”

https://en.wikipedia.org/wiki/Degenerate_energy_levels

example: these two states are degenerate for all possible values of a, b, c



Q: how are these two states related?



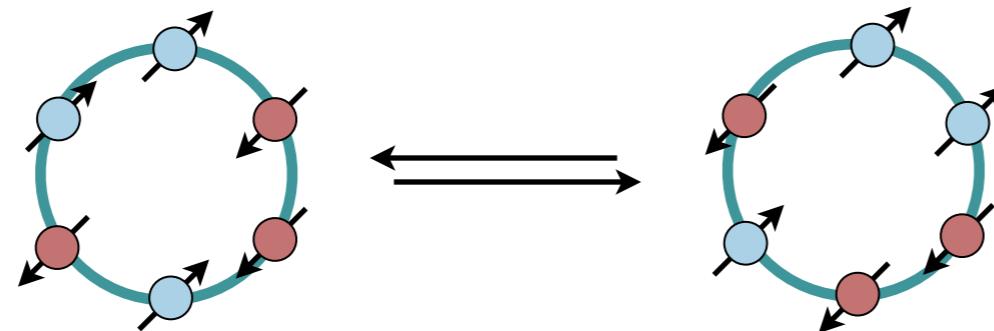
$$E(a, b, c) = a \sum_{i=1}^N S_i S_{i+1} + b \sum_{i=1}^N S_i S_{i+2} + c \sum_{i=1}^N S_i$$

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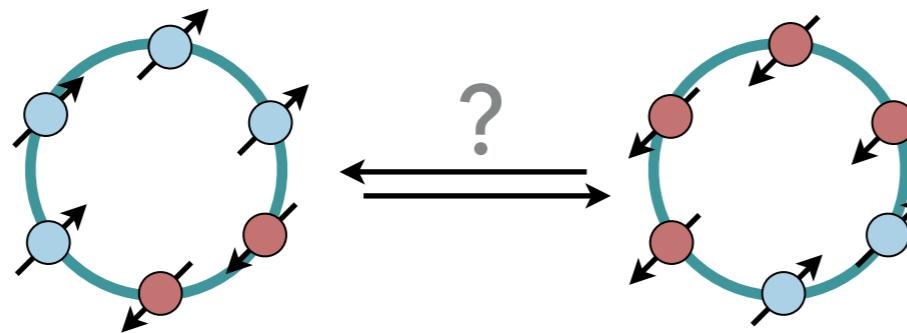
A: a rotation



$$E(a, b, c) = a \sum_{i=1}^N S_i S_{i+1} + b \sum_{i=1}^N S_i S_{i+2} + c \sum_{i=1}^N S_i$$

WARM UP QUESTION

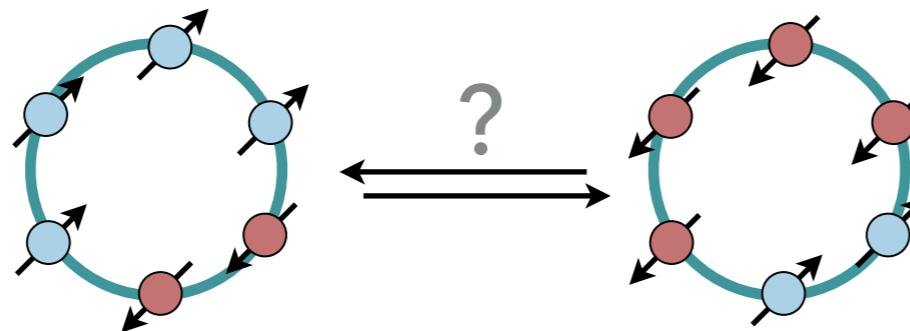
Q: are these two states always degenerate for all values of a, b, c ?



$$E(a, b, c) = a \sum_{i=1}^N S_i S_{i+1} + b \sum_{i=1}^N S_i S_{i+2} + c \sum_{i=1}^N S_i$$

WARM UP QUESTION

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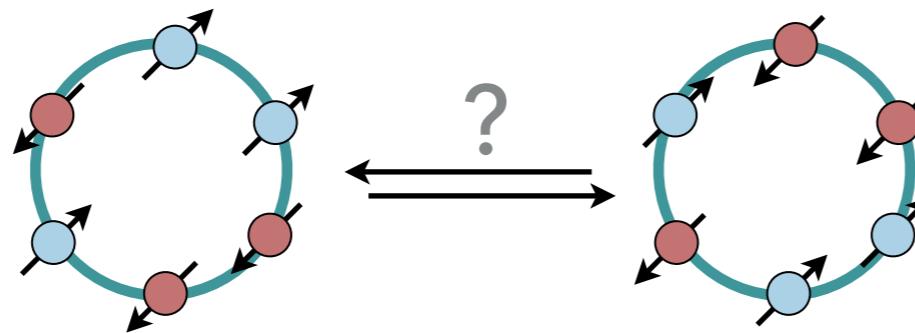


A: only when $c = 0$

$$E(a, b, c) = a \sum_{i=1}^N S_i S_{i+1} + b \sum_{i=1}^N S_i S_{i+2} + c \sum_{i=1}^N S_i$$

WARM UP QUESTION

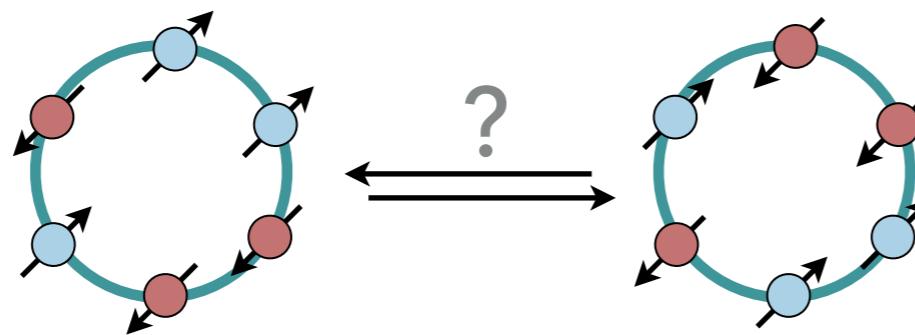
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WARM UP QUESTION

Q: are these two states always degenerate for all values of a, b, c ?



A: yes, because $\sum_i S_i = 0$

$$E(a, b, c) = a \sum_{i=1}^N S_i S_{i+1} + b \sum_{i=1}^N S_i S_{i+2} + c \sum_{i=1}^N S_i$$

EXERCISE #1

Write a function for the energy of N spins in a loop, as a function a, b, c .

$$E(a, b, c) = a \sum_{i=1}^N S_i S_{i+1} + b \sum_{i=1}^N S_i S_{i+2} + c \sum_{i=1}^N S_i$$

```
def rotate_vec(vec0):
    """
    this piece of code rotates an array (vec0)
    by one to the left
    """
    N=len(vec0)
    tmp = np.zeros(N)

    tmp[0:N-1]=vec0[1:N]
    tmp[N-1]=vec0[0]

    return tmp

def Eising(St,a,b,c):
    "rotate the spins by one"
    Stp1 = rotate_vec(St)
    "rotate the spins by two"
    Stp2 = rotate_vec(Stp1)

    "nearest neighbors"
    dEa = a * sum(St * Stp1)
    "next-to-nearest neighbors"
    dEb = b * sum(St * Stp2)
    "background field"
    dEc = c * sum(St)

    return dEa + dEb + dEc
```

look inside my code 😎

EXERCISE #2

Write code to list all possible configurations for N spins.

```
def ising_lists(N):
    """
    if we N possible spins,
    we have 2^N possible states

    we will put these into lists,
    starting with a single spin that is
    either up or down
    """
    TOT=[[1],[-1]]

    for n in range(N-1):

        "tmp0 is a place holder for some of the states"
        |
        Nt = len(TOT)
        for j0 in range(Nt):
            state1 = TOT[j0] [:]
            state2 = TOT[j0] [:]

            "we add 1 to the first one"
            state1.append(1)
            "we add -1 to the first one"
            state2.append(-1)

            TOT[j0]=state1
            TOT.append(state2)

    return TOT
```

look inside my code 😎

EXERCISE #3-6

Find the *ground state energy* and *degeneracy* for the following values of the parameters.

Exercise #3: $N = 3, a = 5, b = 1, c = 0.01$

Exercise #4: $N = 10, a = -5, b = 1, c = 0$

Exercise #5: $N = 10, a = -5, b = 1, c = 0.01$

Exercise #6: $N = 10, a = -5, b = 1, c = -0.01$

how do we make sense of
these three results?

Exercise #7: $N = 15, a = 15, b = -0.2, c = 0.02$

EXERCISE #8

Consider a system with $N=10$ spins. This can have $2^{10} = 1,024$ distinct states.

Consider $a = 1, b = 0.1$.

Q1: What is(are) the ground state(s) when $c = 0$ and its energy?

Q2: What is(are) the ground state(s) when $c = -\infty$ and its energy?

$$E(a, b, c) = a \sum_{i=1}^N S_i S_{i+1} + b \sum_{i=1}^N S_i S_{i+2} + c \sum_{i=1}^N S_i$$

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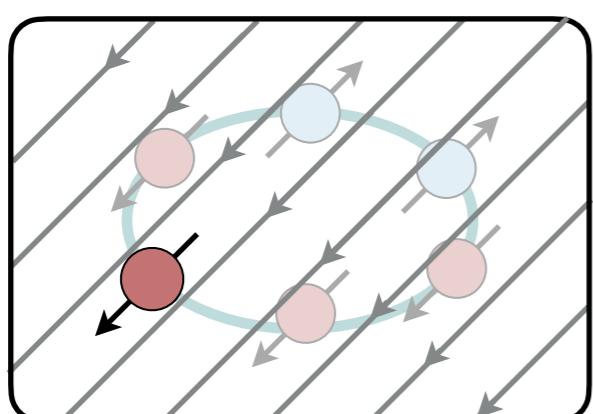
$$\begin{aligned} &(\uparrow, \downarrow, \uparrow, \downarrow, \uparrow, \downarrow, \uparrow, \downarrow, \uparrow, \downarrow) \\ &(\downarrow, \uparrow, \downarrow, \uparrow, \downarrow, \uparrow, \downarrow, \uparrow, \downarrow, \uparrow) \end{aligned}$$

check numerically and find the energy of the system

Q2: What is(are) the ground state(s) when $c = -\infty$ and its energy?

$$(\uparrow, \uparrow, \uparrow, \uparrow, \uparrow, \uparrow, \uparrow, \uparrow, \uparrow, \uparrow)$$

check numerically by making c increasingly large and negative.



makes sense, the stronger the background field, the more the spins want to align with it...

$$E(a, b, c) = a \sum_{i=1}^N S_i S_{i+1} + b \sum_{i=1}^N S_i S_{i+2} + c \sum_{i=1}^N S_i$$

EXERCISE #8

Consider a system with $N=10$ spins. This can have $2^{10} = 1,024$ distinct states.

Consider $a = 1, b = 0.1$.

Vary c continuously from 0 to -3.

Q3: At what value of c are these no longer the ground state?

$$\left\{ \begin{array}{l} (\uparrow, \downarrow, \uparrow, \downarrow, \uparrow, \downarrow, \uparrow, \downarrow, \uparrow, \downarrow) \\ (\downarrow, \uparrow, \downarrow, \uparrow, \downarrow, \uparrow, \downarrow, \uparrow, \downarrow, \uparrow) \end{array} \right.$$

Q4: At what value of c is this the ground state? [note, these two do not have to be the same values for c]

SUMMARY - CONCEPTS COVERED

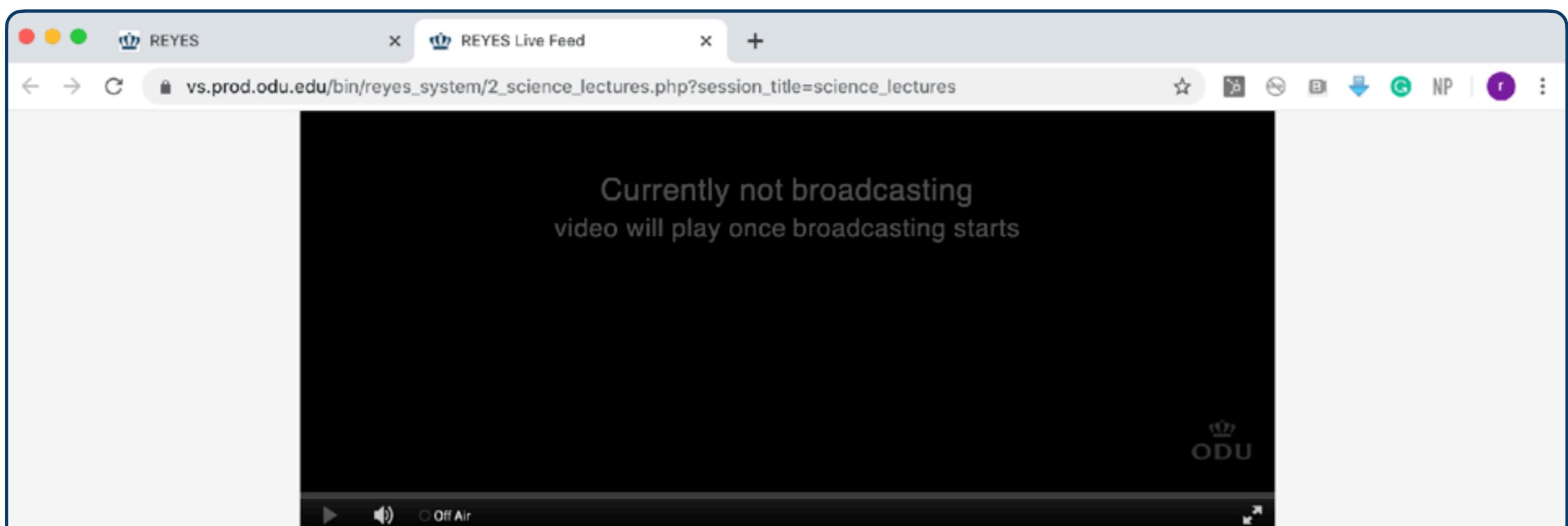
The Ising model and its energy:

$$E(a, b, c) = a \sum_{i=1}^N S_i S_{i+1} + b \sum_{i=1}^N S_i S_{i+2} + c \sum_{i=1}^N S_i$$

a, b, c are constants that depend on the properties of the system

Symmetry, degeneracy, ground state and ground state energy.

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We want to hear your thoughts!



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OLD DOMINION UNIVERSITY IDEA FUSION

Remote Experience for Young Engineers & Scientists (REYES)

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What is your gender?

Female
 Male

Fee My ethnicity is:

Asian or Asian American, including Chinese, Japanese, and others
 Black or African American
 Black Haitian and Caribbean Islander

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Your Feedback?



POTENTIAL PROJECTS

Next week we will introduce numerical limit, which will allow us to introduce derivatives. Also, we might introduce discrete Fourier transforms.

Neither one of these will require you having taken calculation.