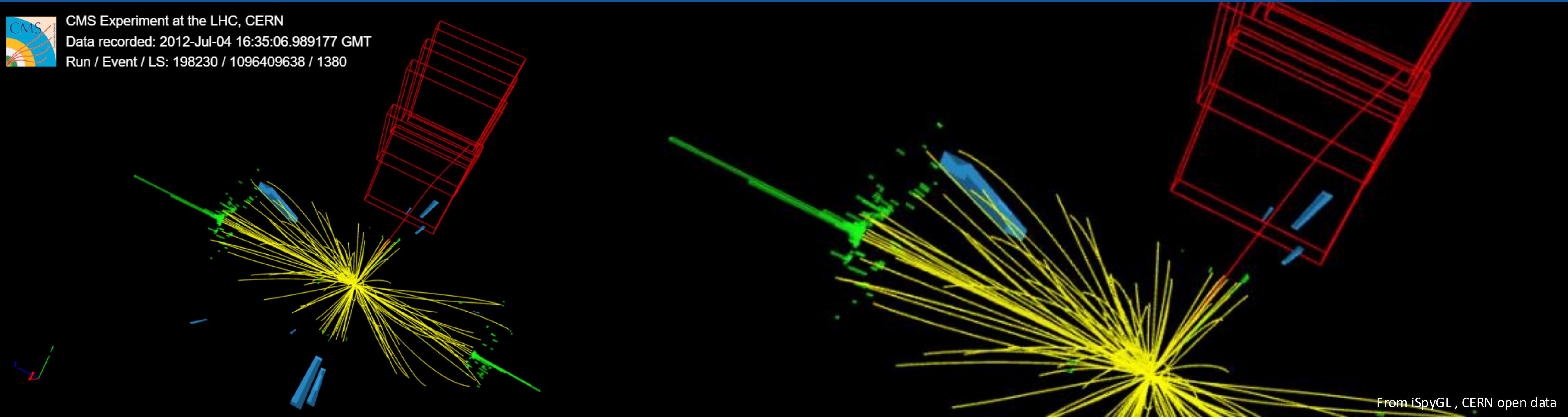
School of Physics

हैदराबाद विश्वविद्यालय
University of Hyderabad



Project update

$$‘Search\ for\ dark\ matter\ in\ the\ MonoHiggs\ to\ b\bar{b} + p_T^{miss}\ final\ state’$$

Name : *Prayag Yadav*
Program : *Integrated Masters of Science 9th Semester*
ID: *19IPMP03*
Project Supervisor: *Dr. Bhawna Gomber*

What is Dark matter? interact only via gravitational interactions

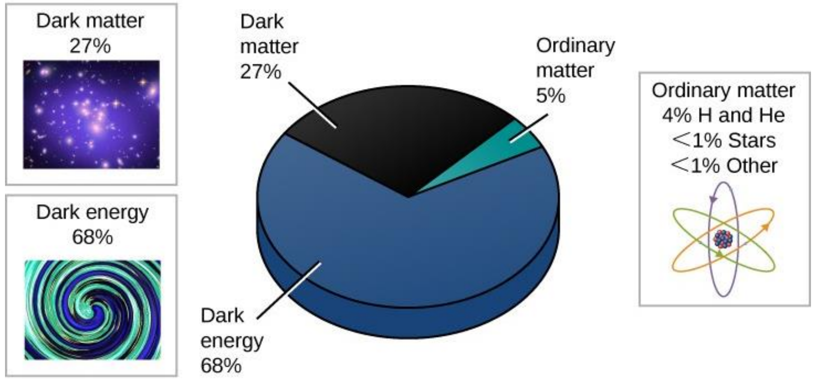
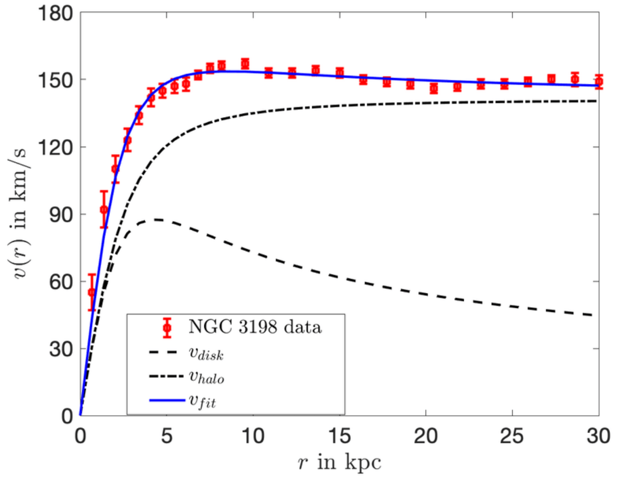
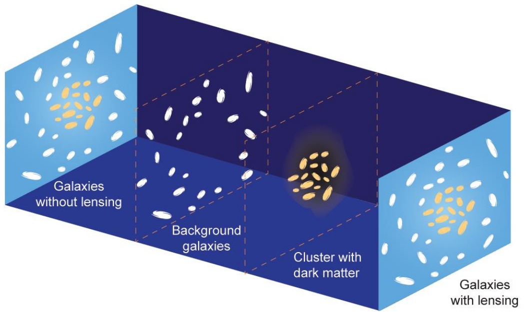


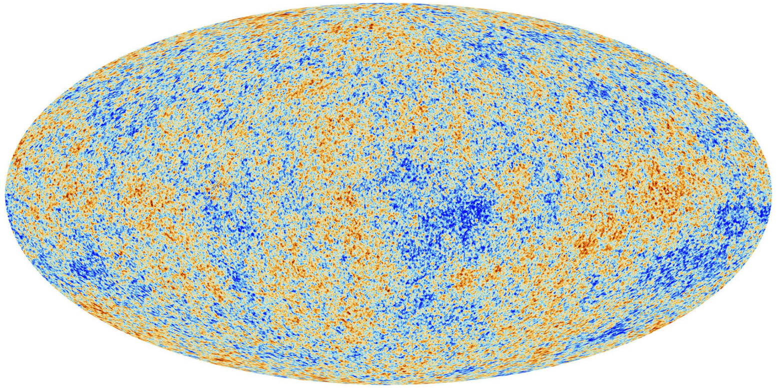
Image : https://courses.lumenlearning.com/suny-geneseo-astronomy/chapter/what-is-the-universe-really-made-of/



Venkataramani, Shankar & Newell, Alan. (2021). Pattern dark matter and galaxy scaling relations.



This Photo by NASA/SSU/Aurore Simonnet is licensed under CC BY-SA-NC



https://www.esa.int/Science_Exploration/Space_Science/Planck/Planck_reveals_an_almost_perfect_Universe

Evidences

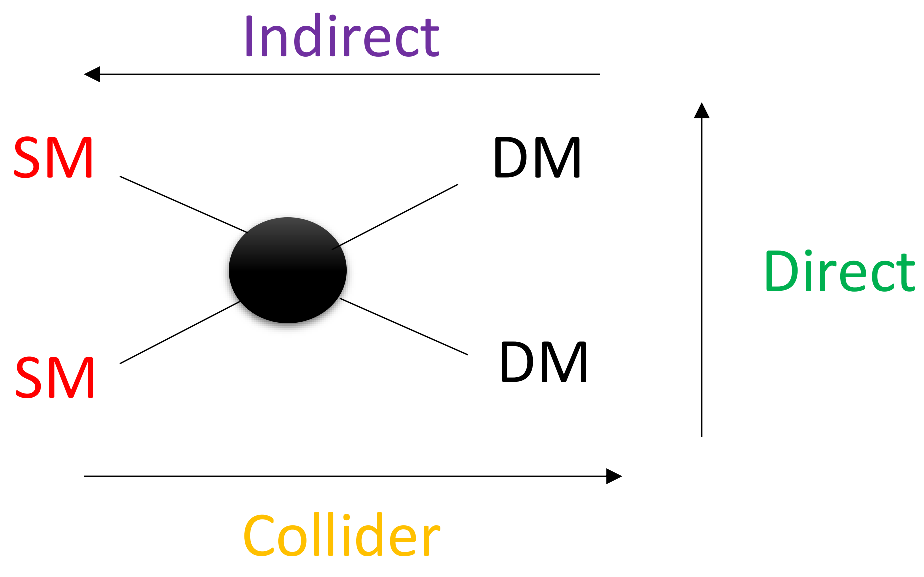
Astronomical Evidences

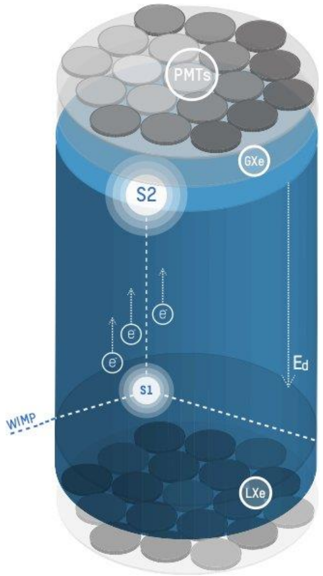
- Rotational Curves of Spiral Galaxies
- Gravitational Lensing

Cosmological Evidences

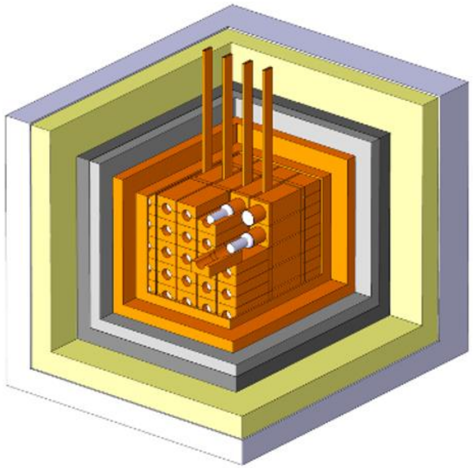
- CMB

Search for Dark Matter



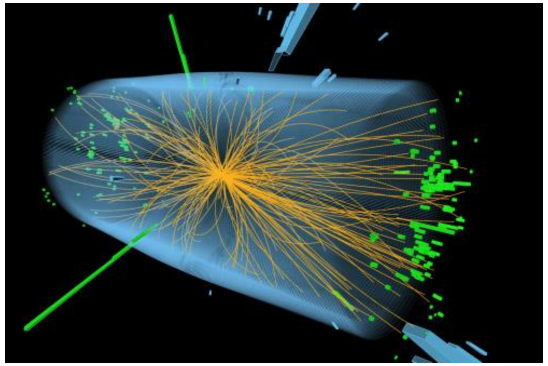


XENON Experiment

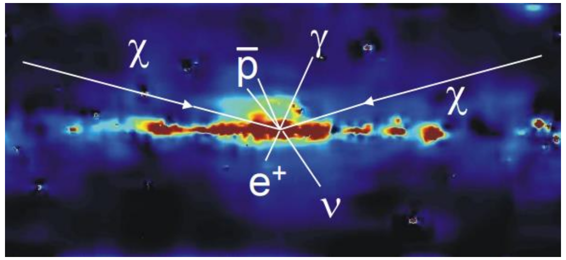


DAMA

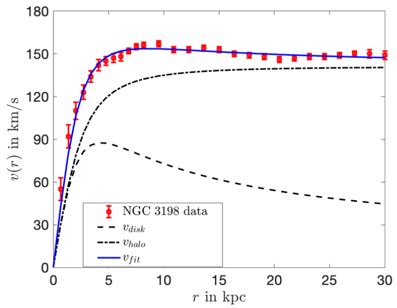
https://dama.web.roma2.infn.it/?page_id=64



Collider searches at CMS



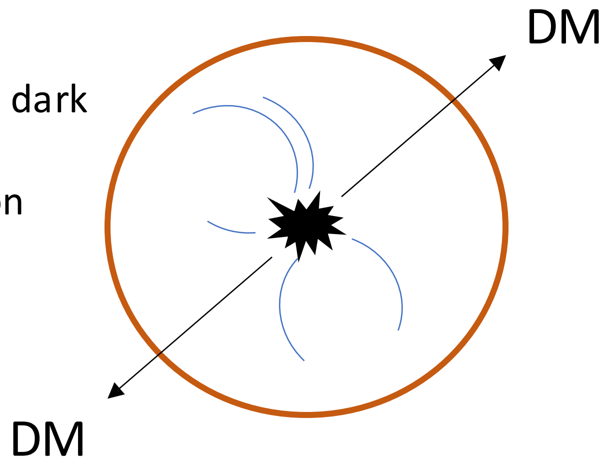
Gamma ray observations from the galaxy

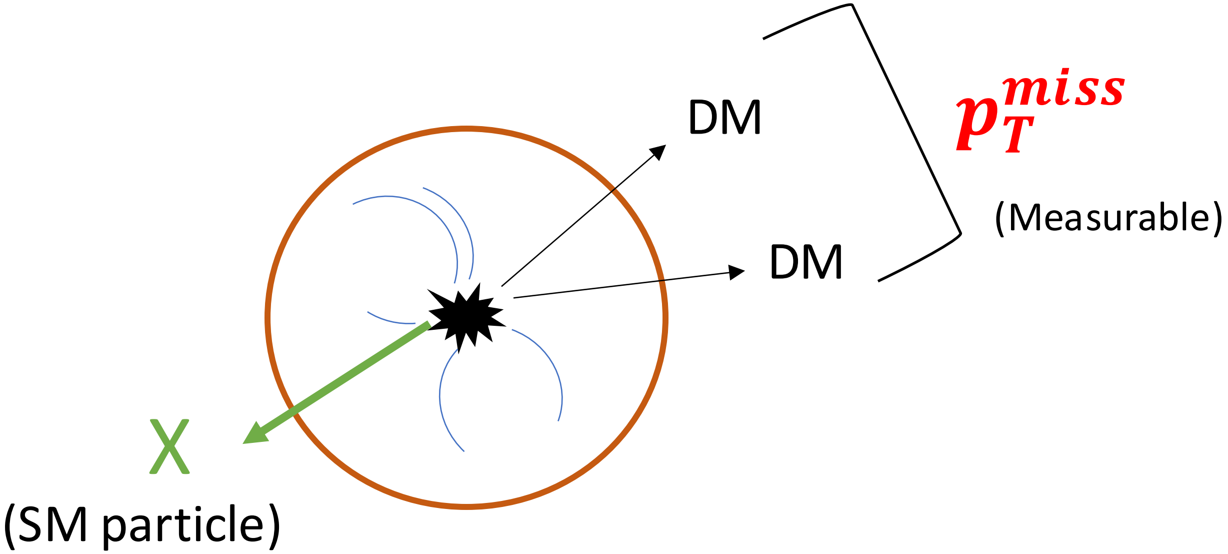


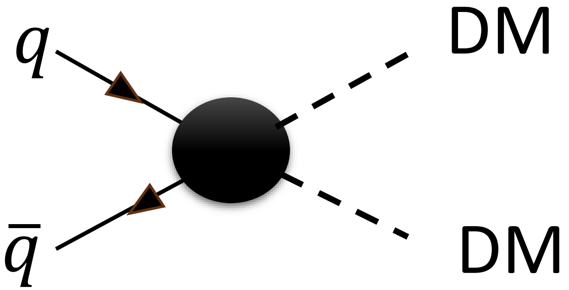
Rotation curves of galaxies

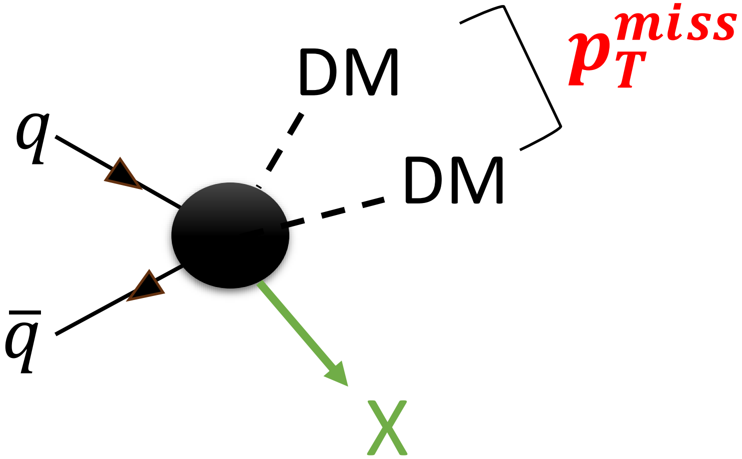
Collider Search: Mono-X Topology

Back to undetectable dark matter production









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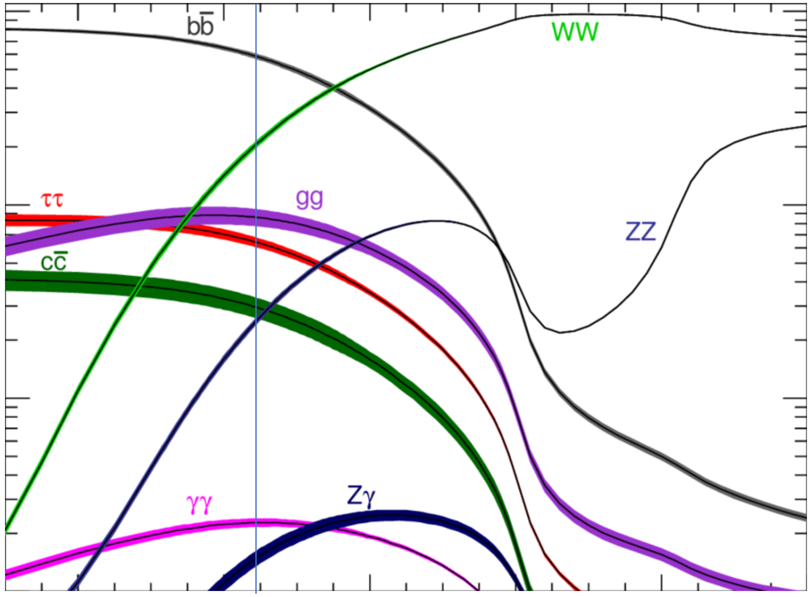
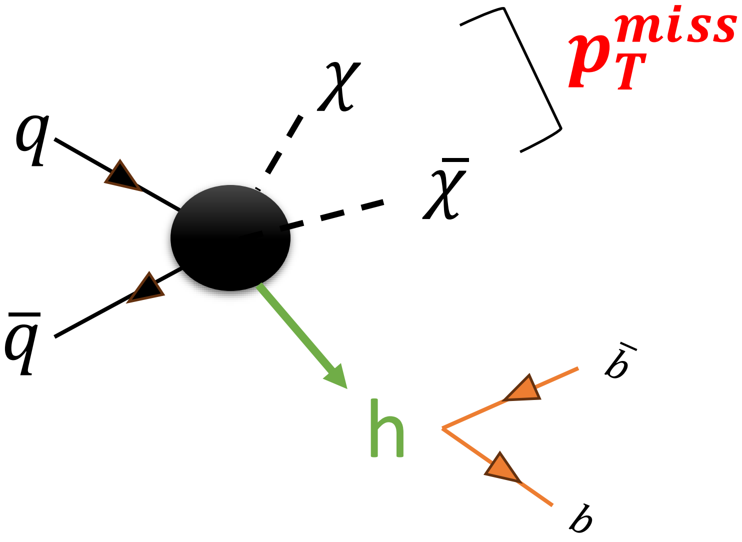
Mono Higgs Searches

1. No Initial State Radiation
2. More closely connected to DM production
3. Signal Signature has a high MET trail which helps to separate the signal from background.





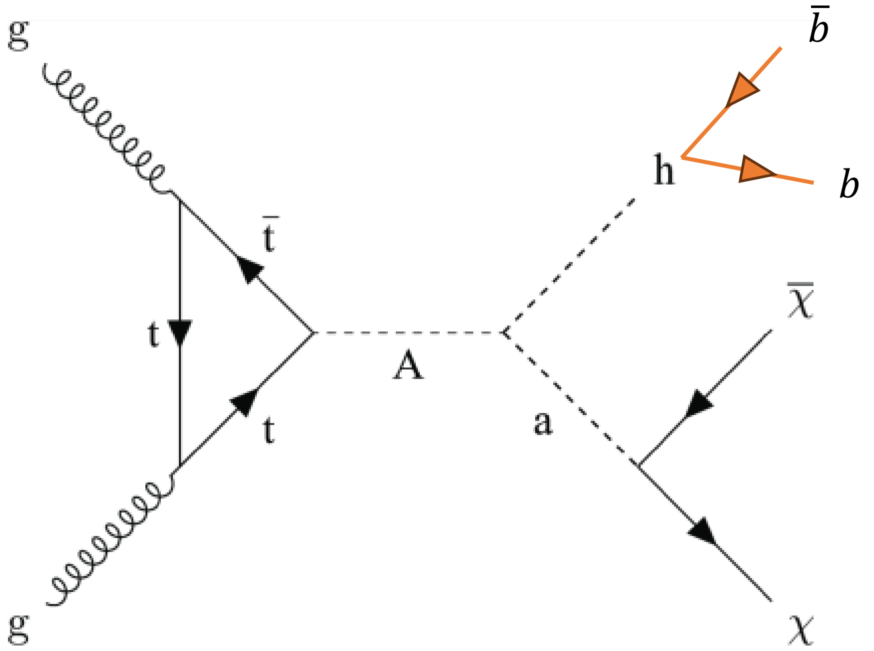
H(125)->bb branching ratio is ~ 57%

The 2HDMa Model

A supersymmetric model to explain dark matter

- The 2HDM Model proposes **five Higgs** :
  - Two neutral scalars (h and H)
  - Pseudoscalar A and
  - Charged Higgs(H^- and H^+ .)
- The 2HDMa model introduces a new pseudoscalar ‘a’ which mediates interaction between Dark particles χ and $\bar{\chi}$.

- The Higgs SM ‘h’ produced can decay through many channels.
- One of these channels is the **Higgs to two b-quarks**.
- These b quarks produce **jets** of particles.
- The Dark matter particles go undetected and lead to a **large missing momentum**.

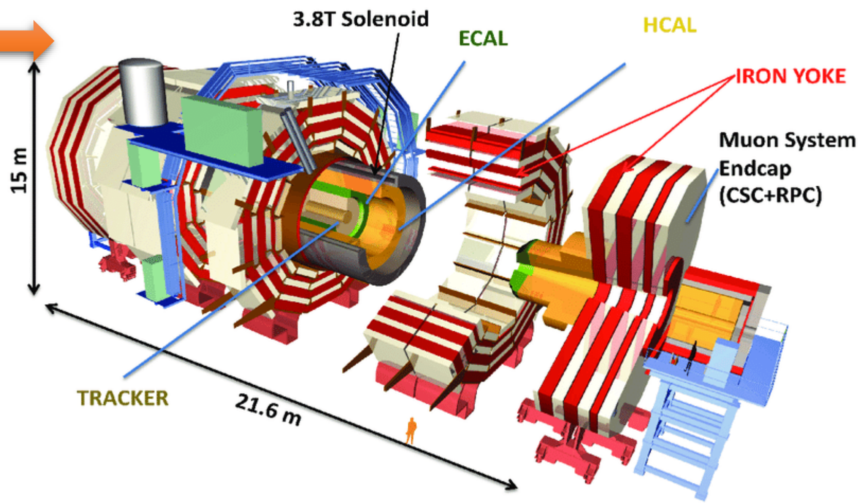


Final state: $H(\bar{b}b) + p_T^{miss}$

2HDM = Two Higgs Doublet Model

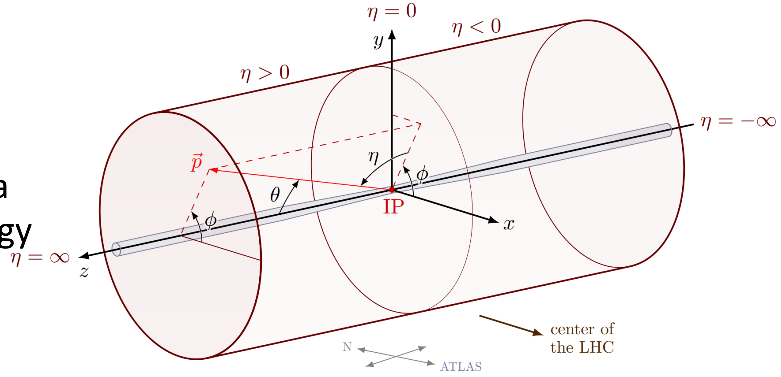
2HDMa = Two Higgs Doublet Model with a pseudoscalar mediator ‘a’

The Large Hadron Collider (LHC) and the Compact Muon Solenoid (CMS)



- Large Hadron Collider (LHC) regulated by the European Organization for Nuclear Research.(**CERN**)
- **Proton-Proton collisions** happen every 25ns 24/7 .
- Based at the French-Swiss border near **Geneva**.
- Two proton beams accelerated to a centre of mass energy of **13.6 TeV** are made to collide at four locations.
- Detectors surround these four interaction points; these detectors are **ALICE, ATLAS, CMS and LHCb** .

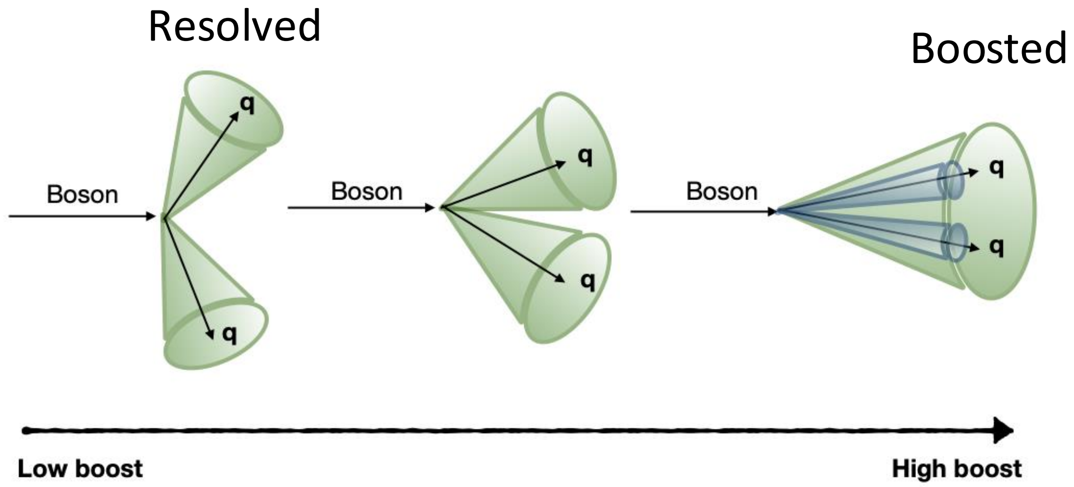
- **CMS** is a **general-purpose detector**
- CMS uses a **powerful solenoid magnet** which helped to design the detector in a "compact" form.
- Its located **100m underground** and provides a good charged particle identification and energy resolution.

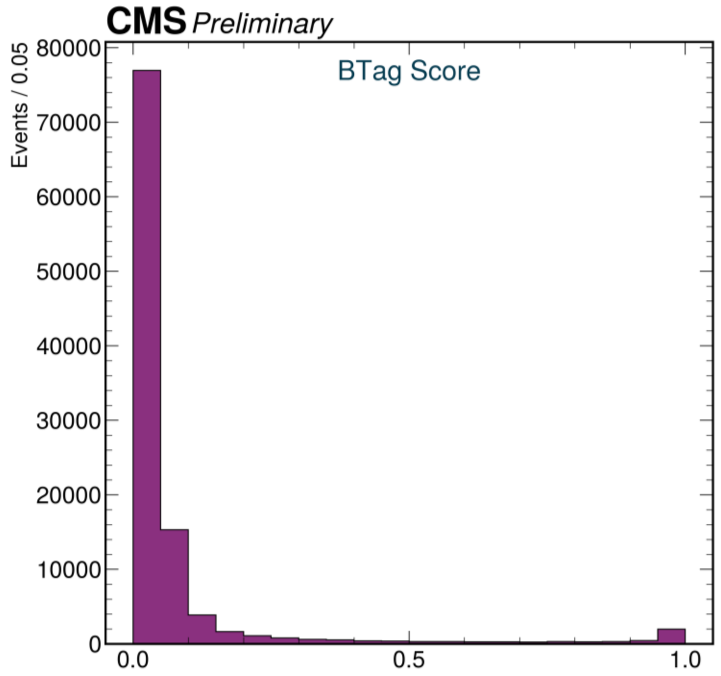


Focardi, Ettore. (2012). Status of the CMS Detector. Physics Procedia. 37. 119-127. 10.1016/j.phpro.2012.02.363.

Signal and Background

- The signal region can be divided into two regions depending upon the Lorentz **boost** the initial Higgs:
  - Resolved (two AK4Jets)
  - Boosted (one AK8 FatJet)
- These jets are classified using various Jet reconstruction algorithms depending upon their cone radii (ΔR) values.
- These jets are then **tagged** using **a deep learning model** which assigns flavours to the jets.
- **b-jets** are chosen using a "**score**" which determines the efficiency of the selection.





2018 DATA

1 Million events processed

Signal and Background

- The **backgrounds** which **mimic** the dijet and missing transverse energy **signal** are :
  - Z(νν)+jets
  - W+jets
  - Drell-Yan(DY)+jets
  - Top quark pair production (tt)
  - Single top production(ST)
  - The production of the single top quark association with W boson (tW)
  - Diboson (WW, WZ, ZZ)
  - The associated production of a Higgs Boson with vector bosons (WH and ZH)

- These backgrounds are **estimated by** using samples generated by **Monte Carlo simulation** of the reactions.
- In addition to background, the 2HDMa(or closely related ZprimeBaryonic) model is also available as a simulated sample.

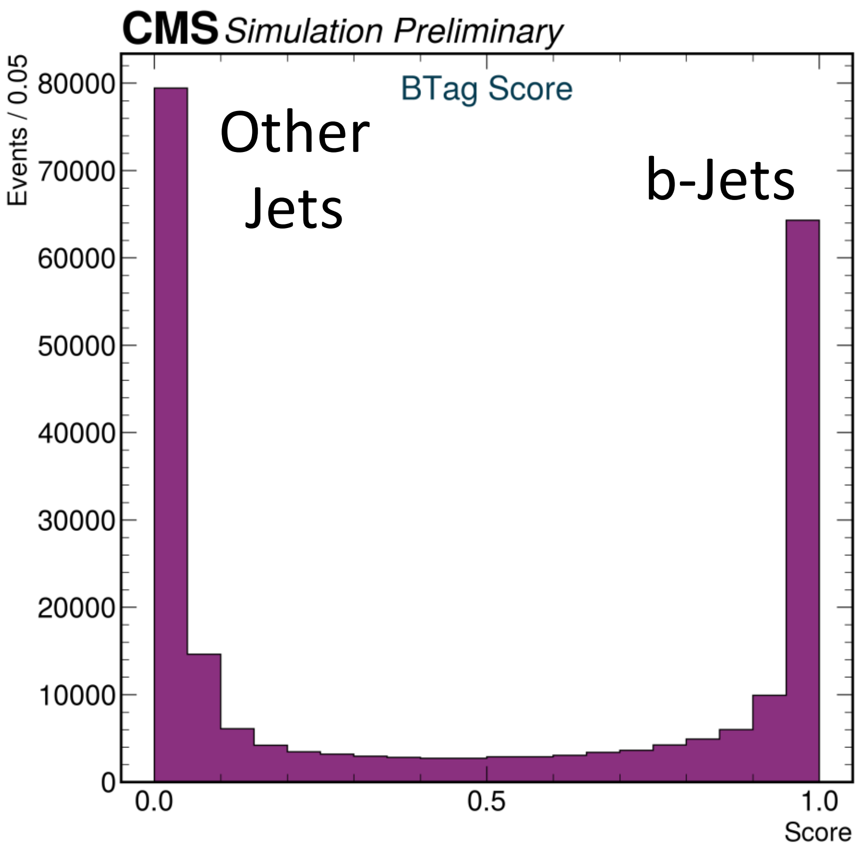
Analysis tools and Strategy

- Analysis tools like COFFEA are used. Various other tools in the python ecosystem are routinely employed.
- COFFEA is a **columnar analysis** tools which enables us to deploy **scalable** and **parallel** computing ready code for High Energy Physics.
- Run 2 data (2018,2017) of CMS is retrieved from the different CERN data tiers.
- The data is processed in various **compute clusters** available at the University of Wisconsin, Madison, USA.

The COFFEA Framework

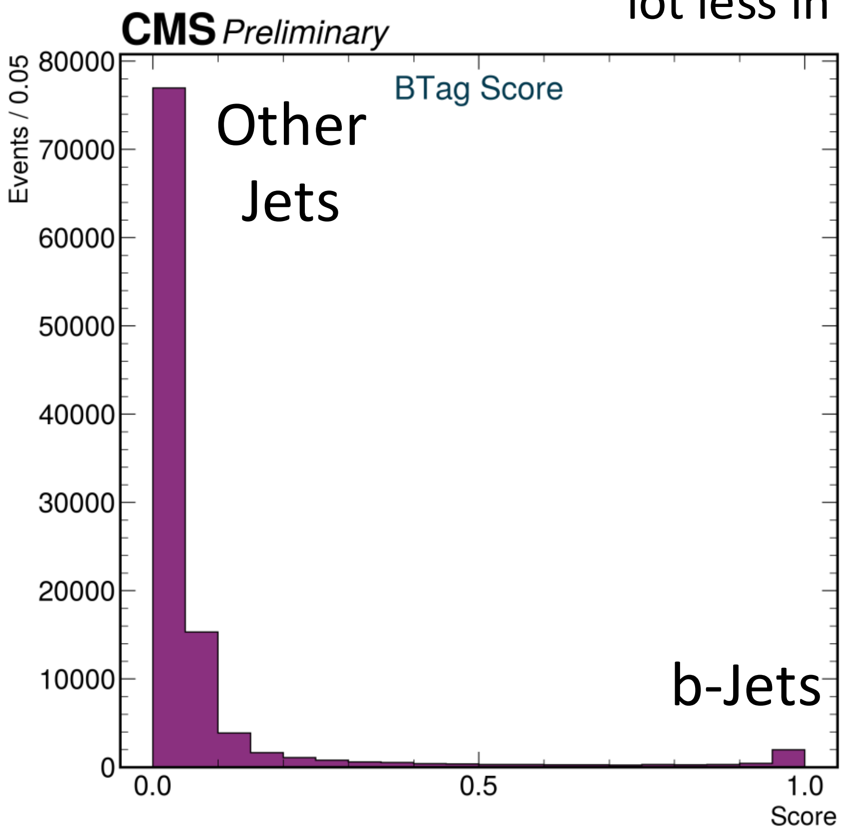
B-Tag Score of all the jets

1 Million events processed



Simulated Signal Sample

Number of b-jets are a lot less in actual data

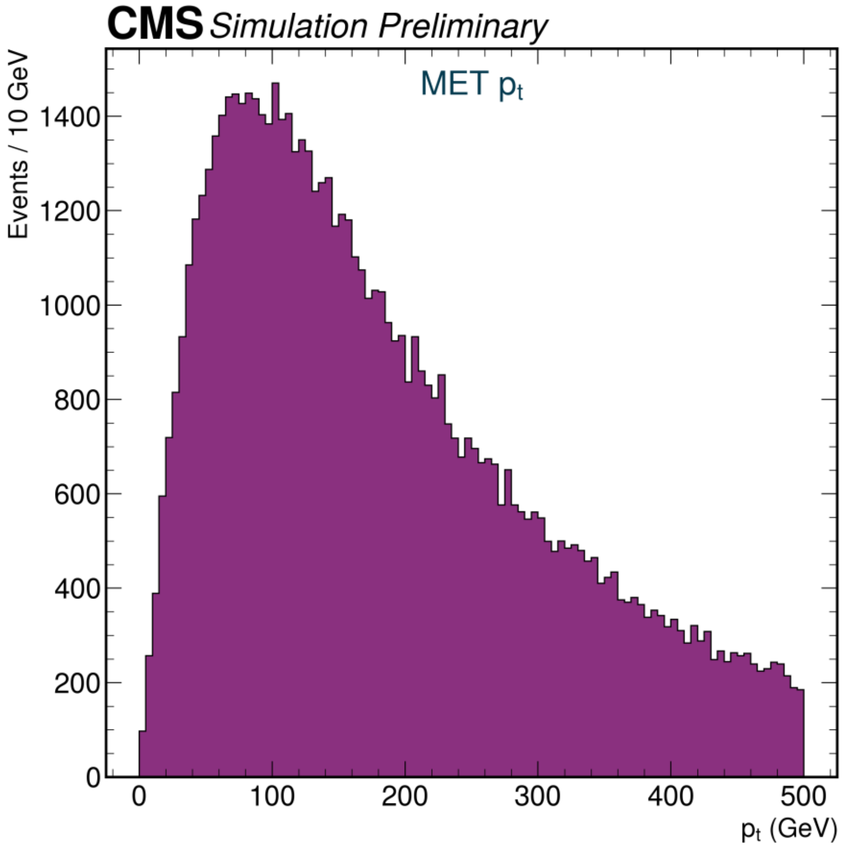


2018 Data from CMS

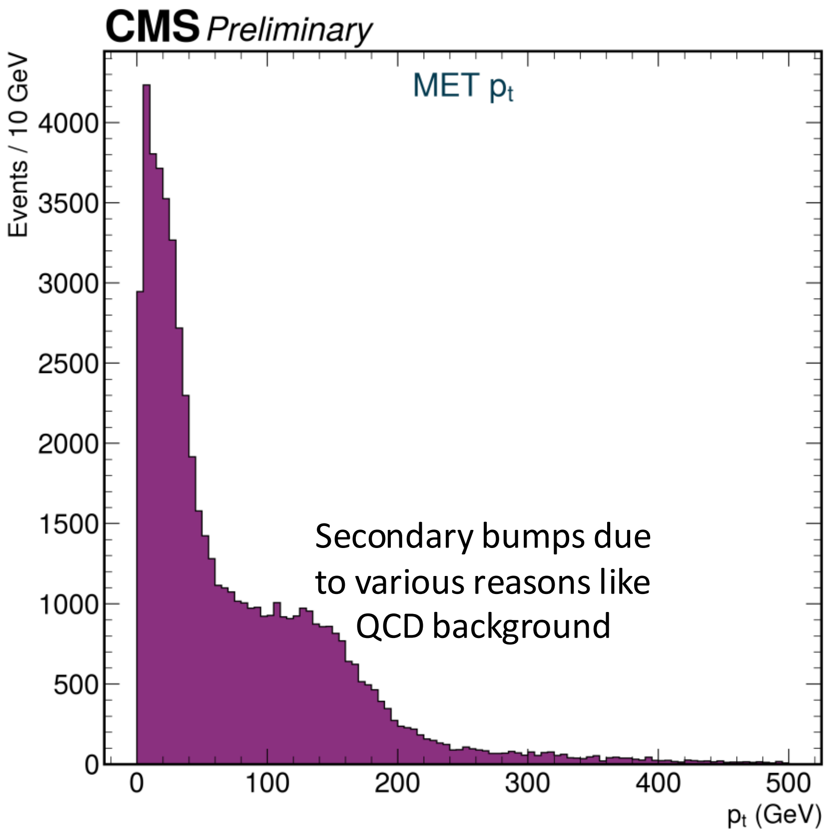
Missing transverse energy (MET) p_T^{miss}

1 Million events processed

No selections applied



Simulated Signal Sample



Secondary bumps due to various reasons like QCD background

2018 Data from CMS

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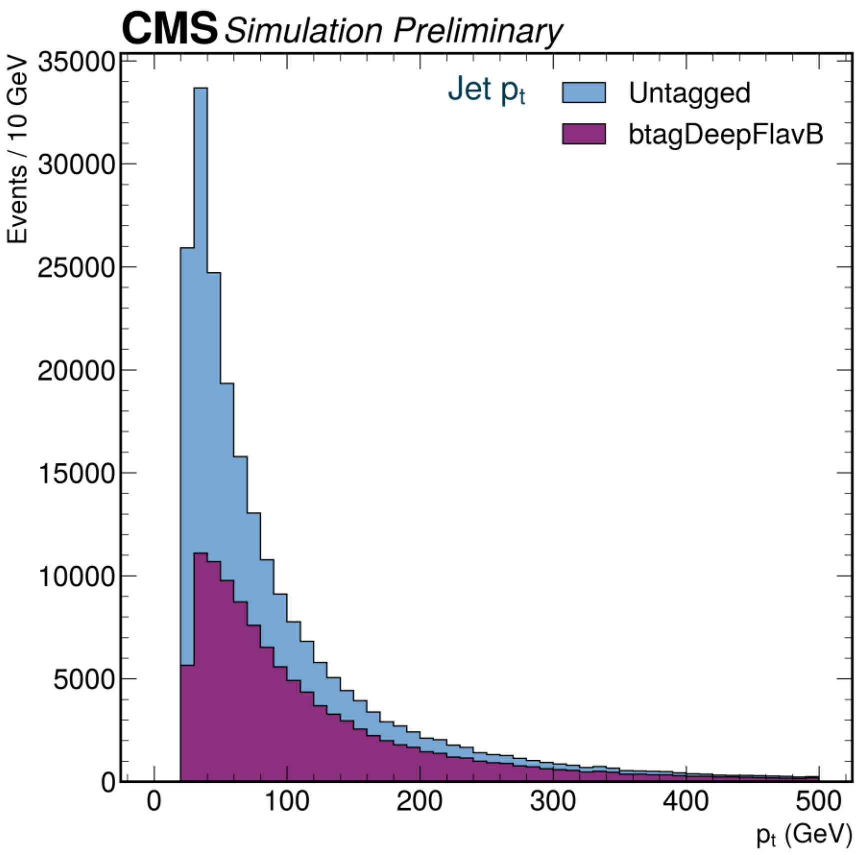
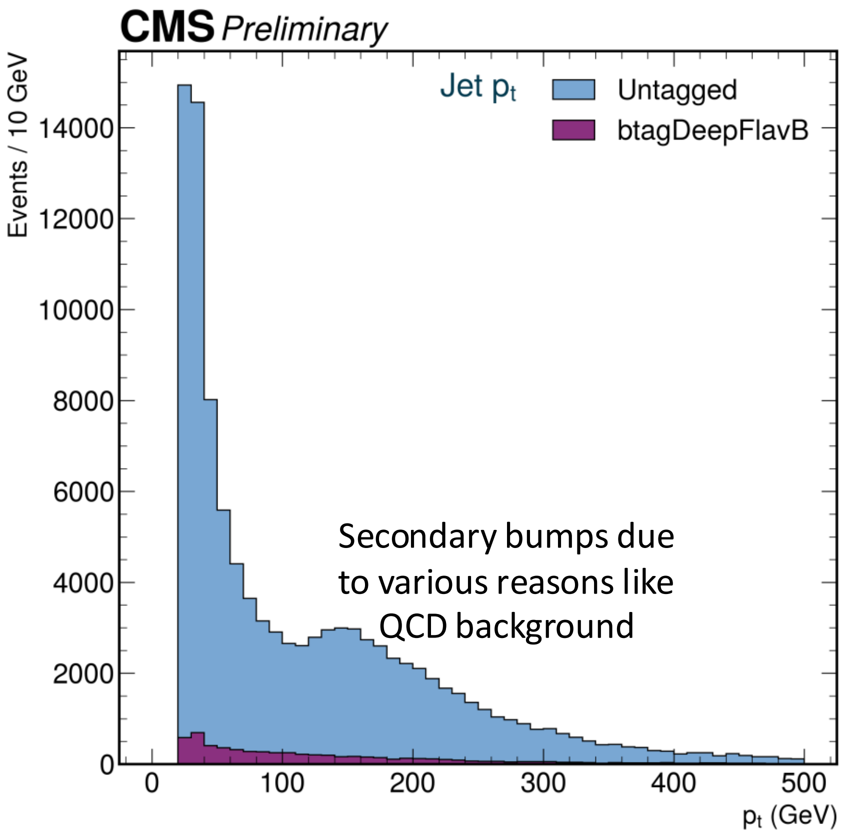
Jet p_T

1 Million events processed

No selections applied



Simulated Signal Sample



Secondary bumps due to various reasons like QCD background

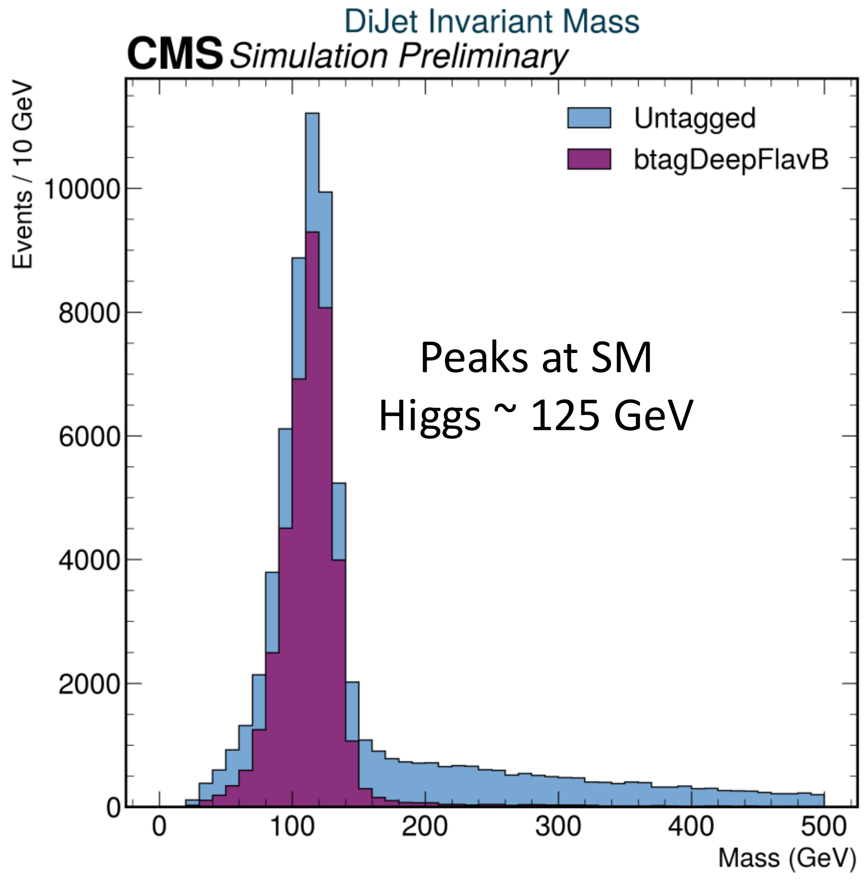
2018 Data from CMS

Dijet Invariant Mass

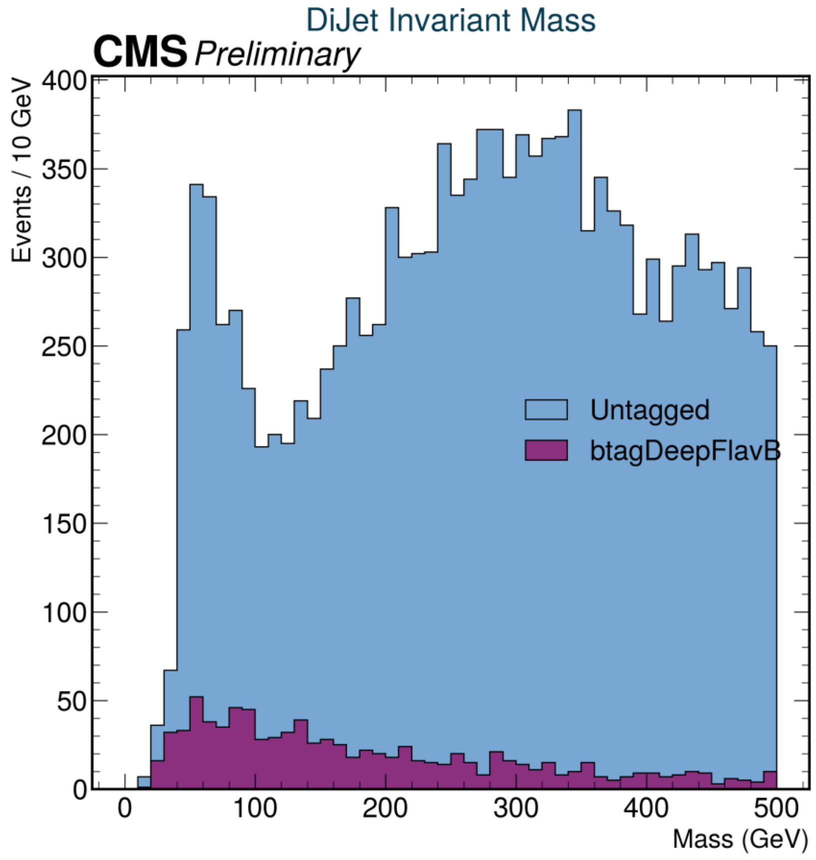
No selections applied

1 Million events processed

Lot of noise in data
as expected



Simulated Signal Sample



2018 Data from CMS

Current Status

- Apply selection criteria to remove backgrounds from data.
- Employing the event selections and object selections for signal region on data and monte-carlo samples.
- Estimating the various backgrounds by scaling each of them with their own cross section data, so that I can compare them.
- Performing control region studies(getting a hang of it)

Future Aspects

- Perform all or some part of control region studies with all the corrections, scaling, refactoring etc.
- Perform signal region studies if time permits.

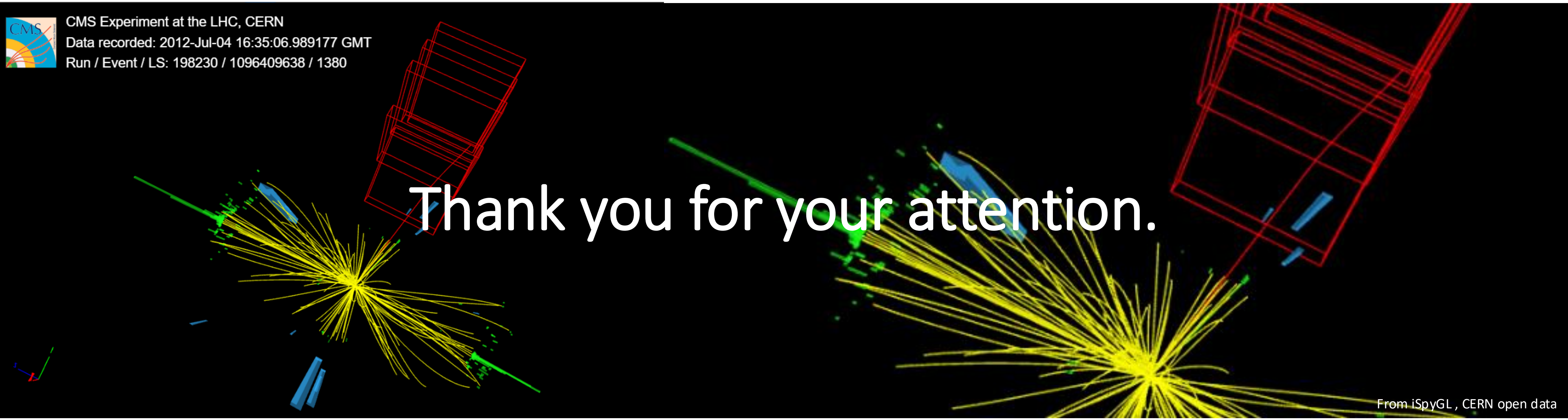
References

- *DARK MATTER SEARCH ON THE MONOHIGGS (H→bb) IN ATLAS EXPERIMENT - Dalia Maria Portillo on behalf of ATLAS*
- *Indirect detection of Dark Matter candidates in gamma-rays by Lars Bergström in 2007*
- *Teresa Marrodán Ūndagoitia, & Ludwig Rauch (2015). Dark matter direct-detection experiments. Journal of Physics G: Nuclear and Particle Physics, 43(1), 013001.*
- LHC Higgs Cross Section Working Group., Denner, A., Heinemeyer, S. *et al.* Standard model Higgs-boson branching ratios with uncertainties. *Eur. Phys. J. C* **71**, 1753 (2011). https://doi.org/10.1140/epjc/s10052-011-1753-8
- The CMS collaboration., Sirunyan, A.M., Tumasyan, A. et al. Search for associated production of dark matter with a Higgs boson decaying to $\bar{b}b$ or γγ at $\sqrt{s}$ = 13 TeV. J. High Energ. Phys. 2017, 180 (2017). https://doi.org/10.1007/JHEP10(2017)180

“No man should escape our universities without knowing how little he knows.”

— J. Robert Oppenheimer

Thank you for your attention.

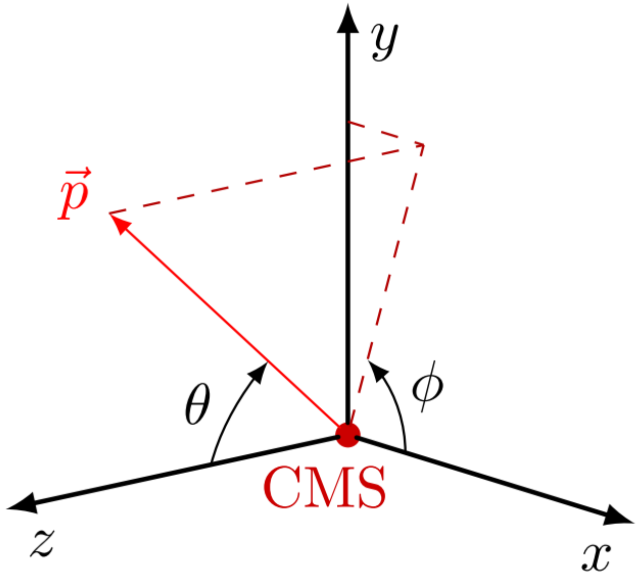


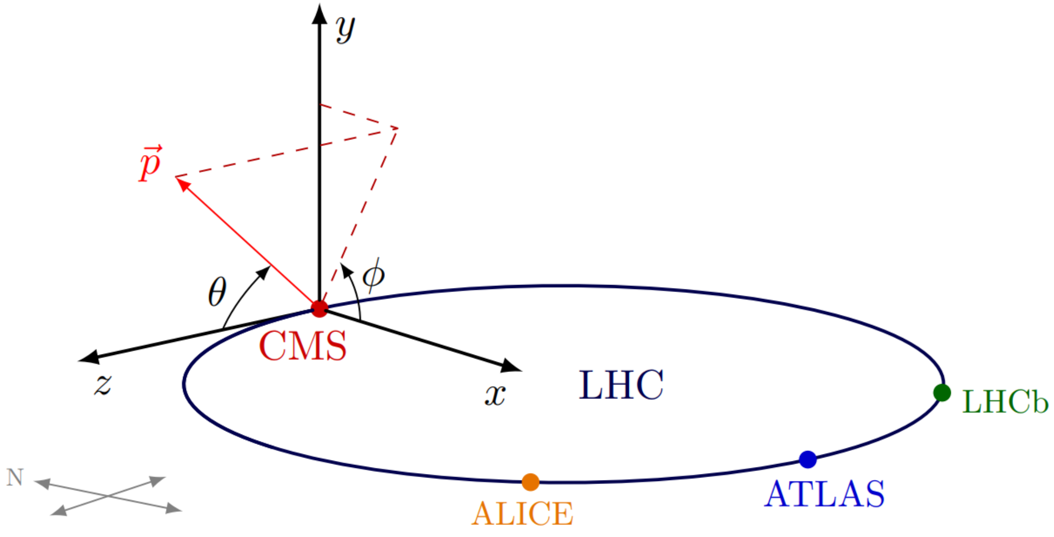
Backup Slides

The Coordinate System

- The Interaction point(IP) is the origin of the coordinate system.
- X direction points to the centre of the LHC ring
- Y direction points vertically upwards.
- Z direction points towards the western side of beam axis.
- The positive angle from the x axis is the azimuthal angle ϕ .
- The positive angle from the z axis is the polar angle θ.
- Pseudorapidity is defined as:

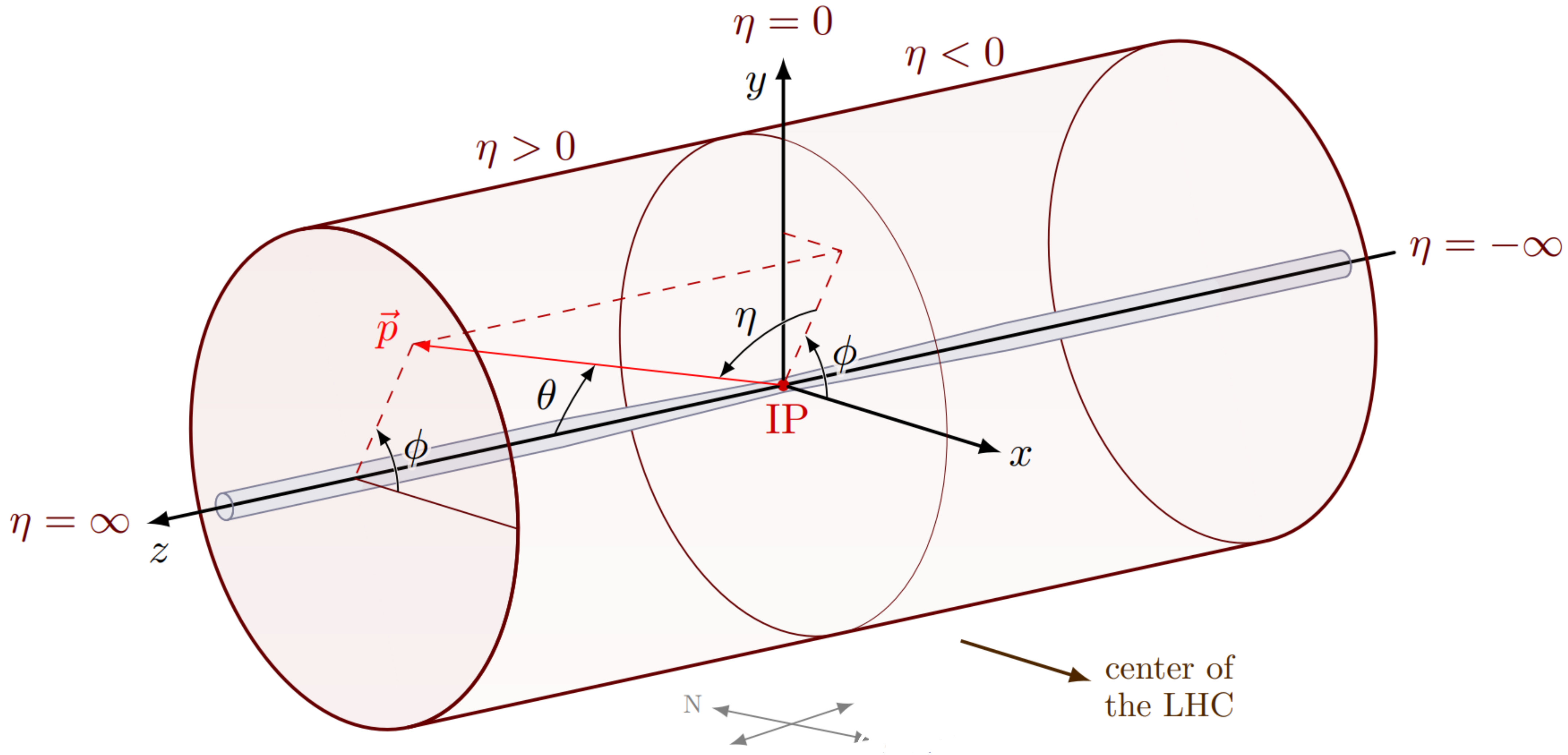
$$\eta = -ln\left(tan\left(\frac{\theta}{2}\right)\right)$$





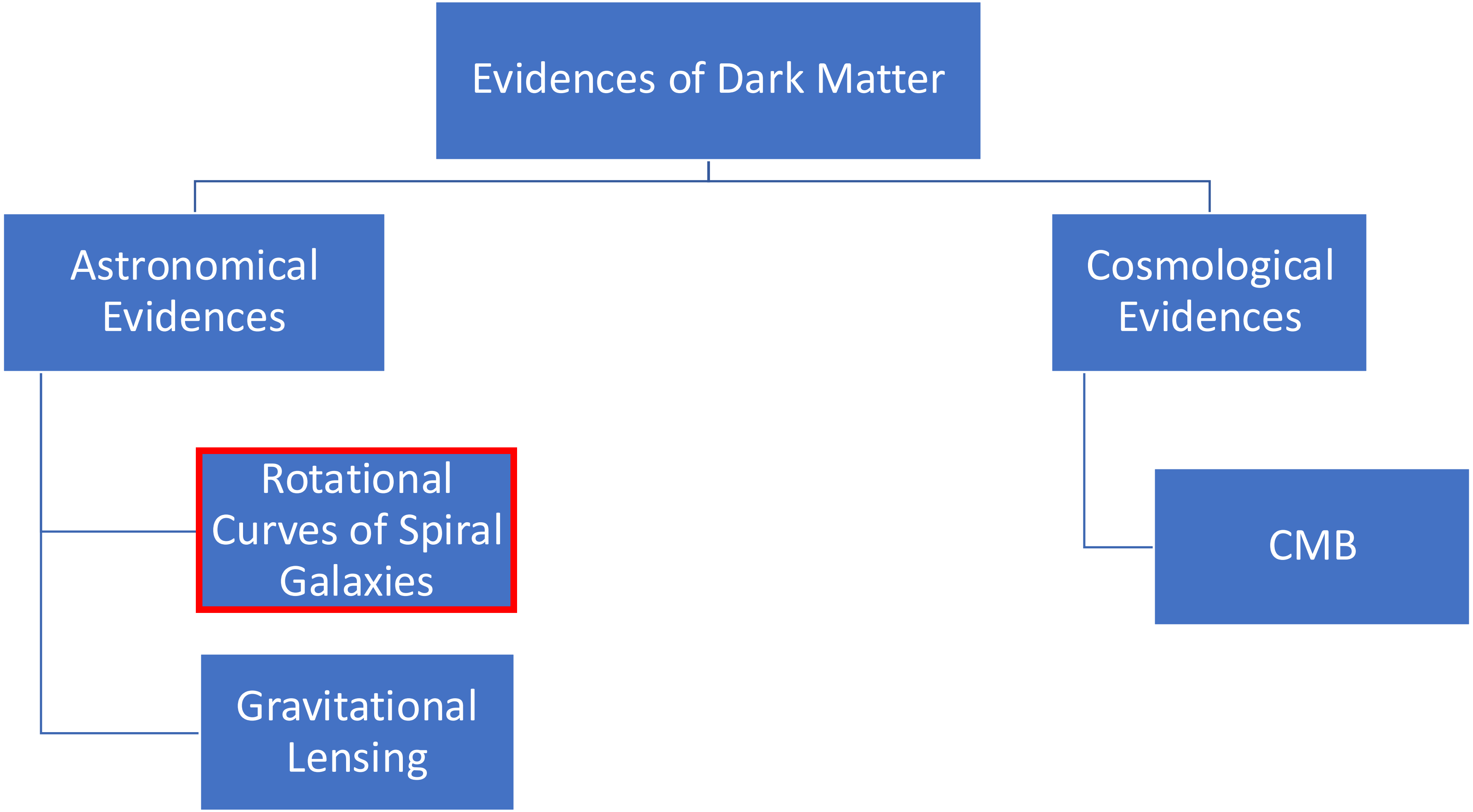
https://tikz.net/axis3d_cms/

The Coordinate System



https://tikz.net/axis3d_cms/

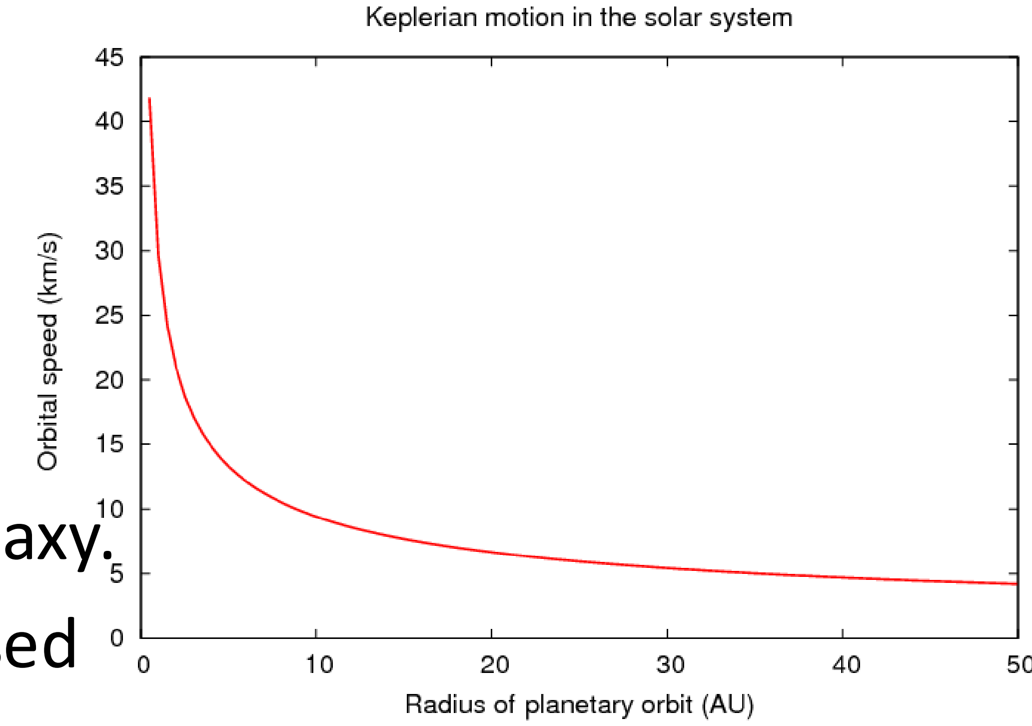
Evidences of Dark Matter



Rotation Curves : Expectation

From Kepler's law,

$$v(r) = \sqrt{\frac{GM(r)}{r}}$$



http://spiff.rit.edu/classes/phys443/lectures/gal_dark/gal_dark.html

is the velocity of a star in the galaxy.

M(r) is the mass of the matter enclosed inside the disk of radius r.

G is the Universal Gravitational Constant

Major Feature: Orbital speed decreases as radius of orbit increases

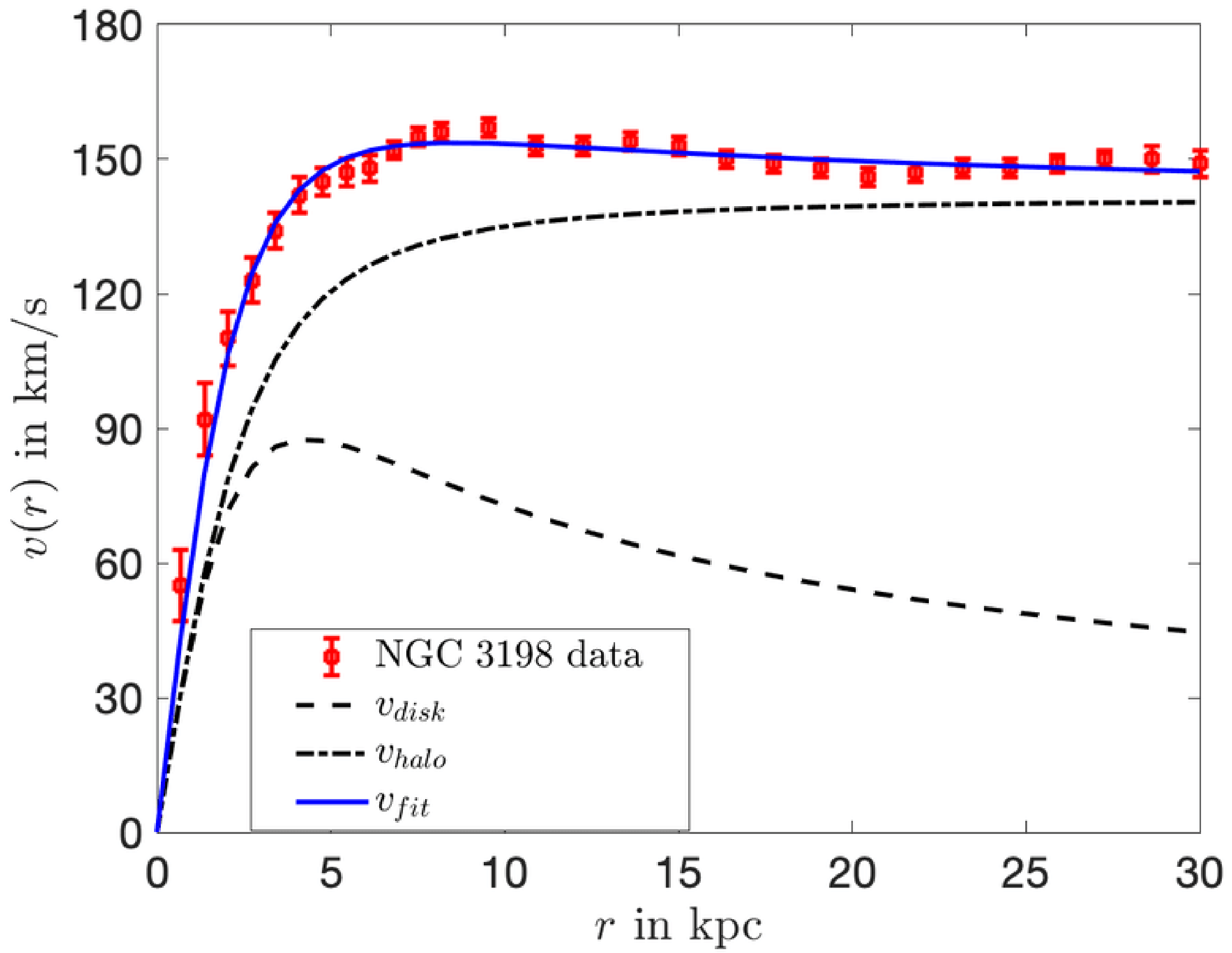
Rotation Curves : Reality

Reality is different

The Orbital speed curve almost becomes horizontal instead of decreasing

Solution : Probably extra mass in galaxy which increases as radius increases

This is the dark matter halo which needs to be considered.



Venkataramani, Shankar & Newell, Alan. (2021). Pattern dark matter and galaxy scaling relations.

Rotation Curves : Dark Matter to the rescue

- A dark matter halo engulfs the whole of our galaxy.
- Dark matter interacts only via gravity.
- The Rotation curve of galaxies can be accounted for if we have a dark matter halo profile given by

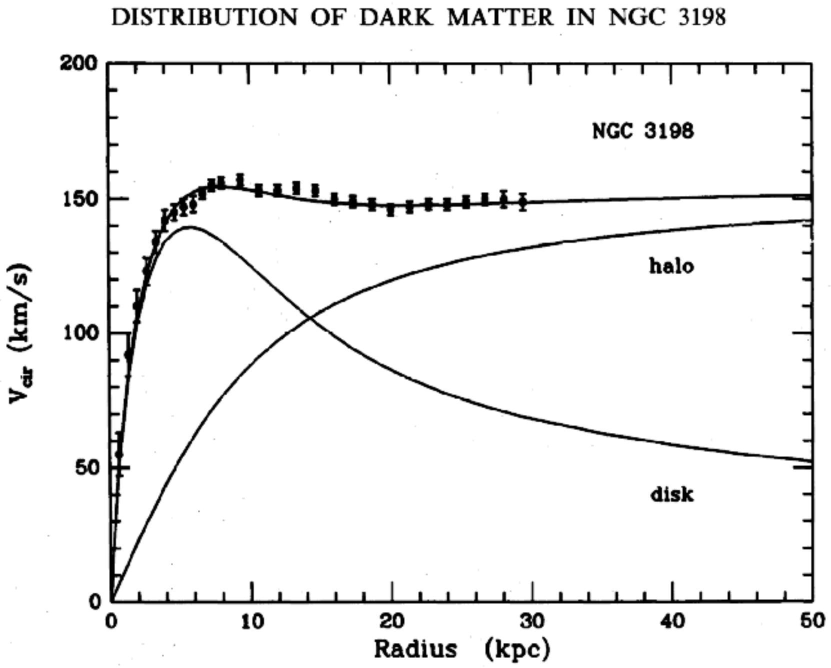
Navarro-Frenk-White (NFW) profile.

$$\rho(r) = \frac{\rho_0}{\frac{r}{R_s}\left(1 + \frac{r}{R_s}\right)^2}$$

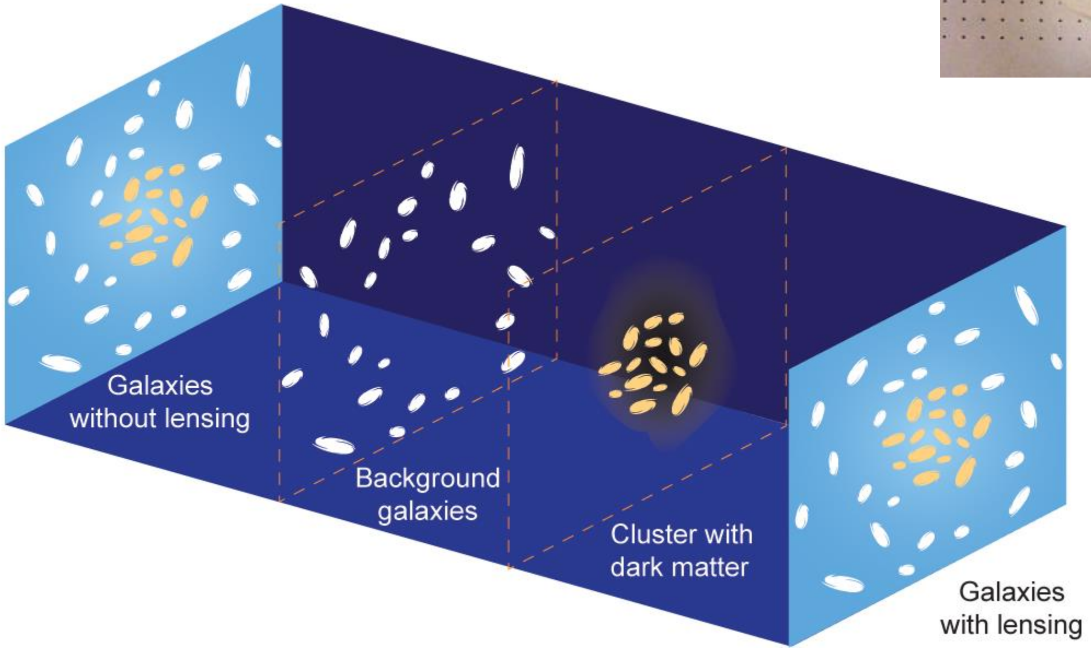
Which dictates the variation of density of the halo matter w.r.t. the distance r.

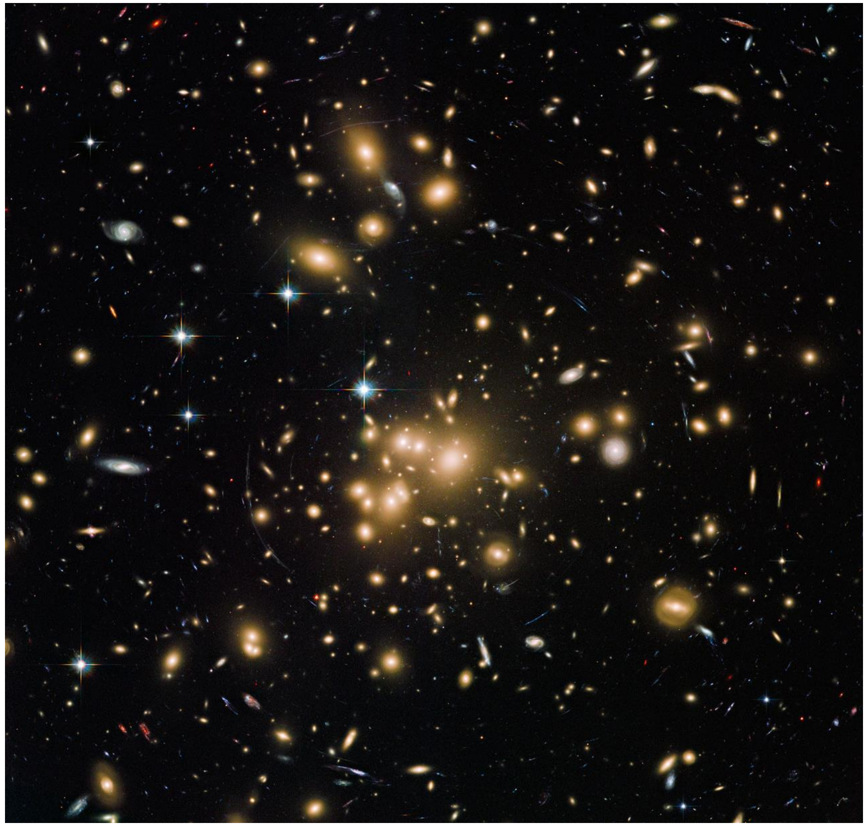
R_s and ρ_0 are fitted accordingly.

https://wwwmpa.mpa-garching.mpg.de/~swhite/picture.html



Gravitational lensing





Abell 1689

- Location: In the Virgo cluster
- ICRS : 13 11 31.882 -01 21 26.10
- Distance: 764Mpc

Heavy Distortion in the image due to gravity

Astronomical Evidences:
Rotational Curves of Spiral Galaxies

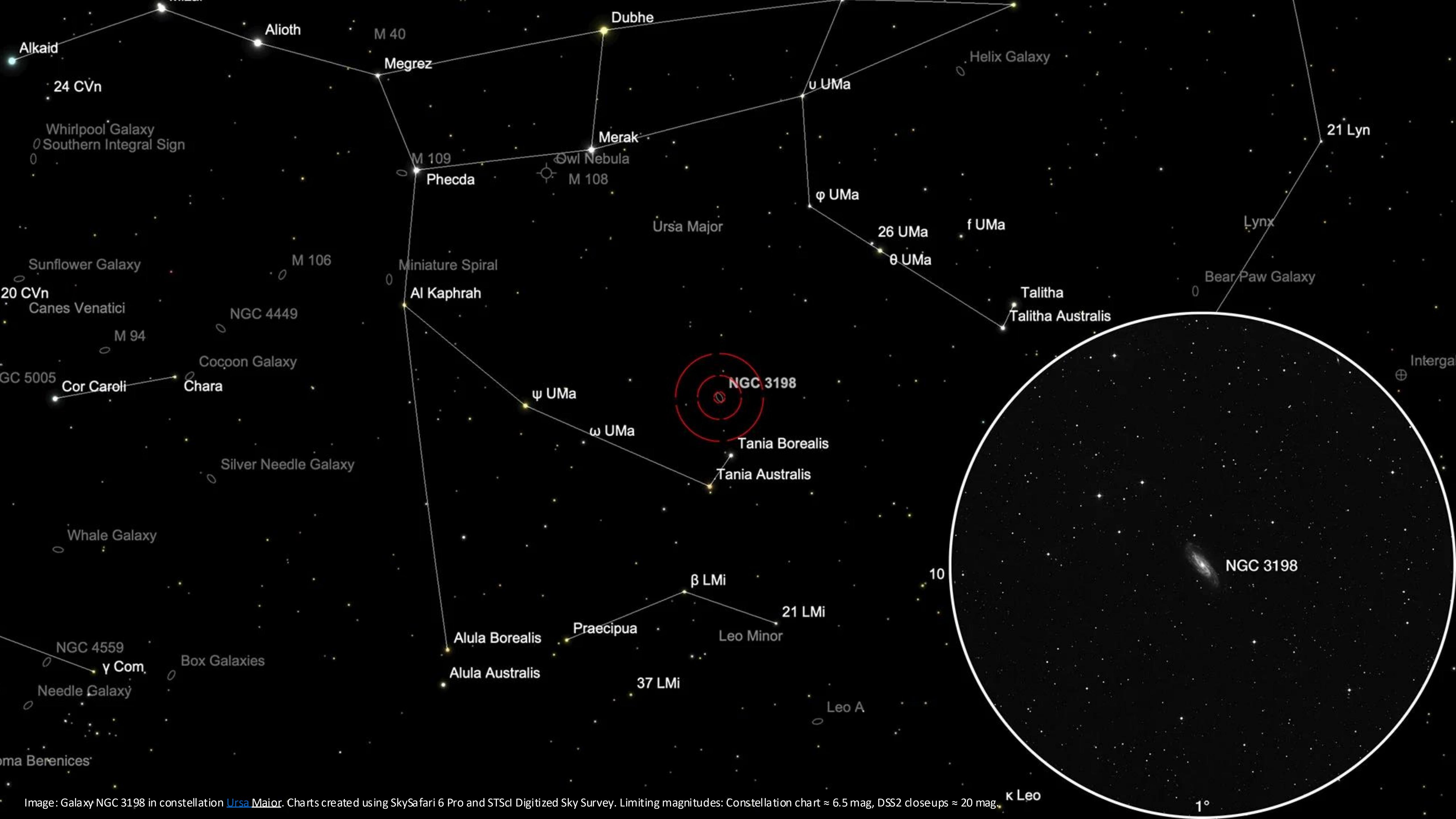
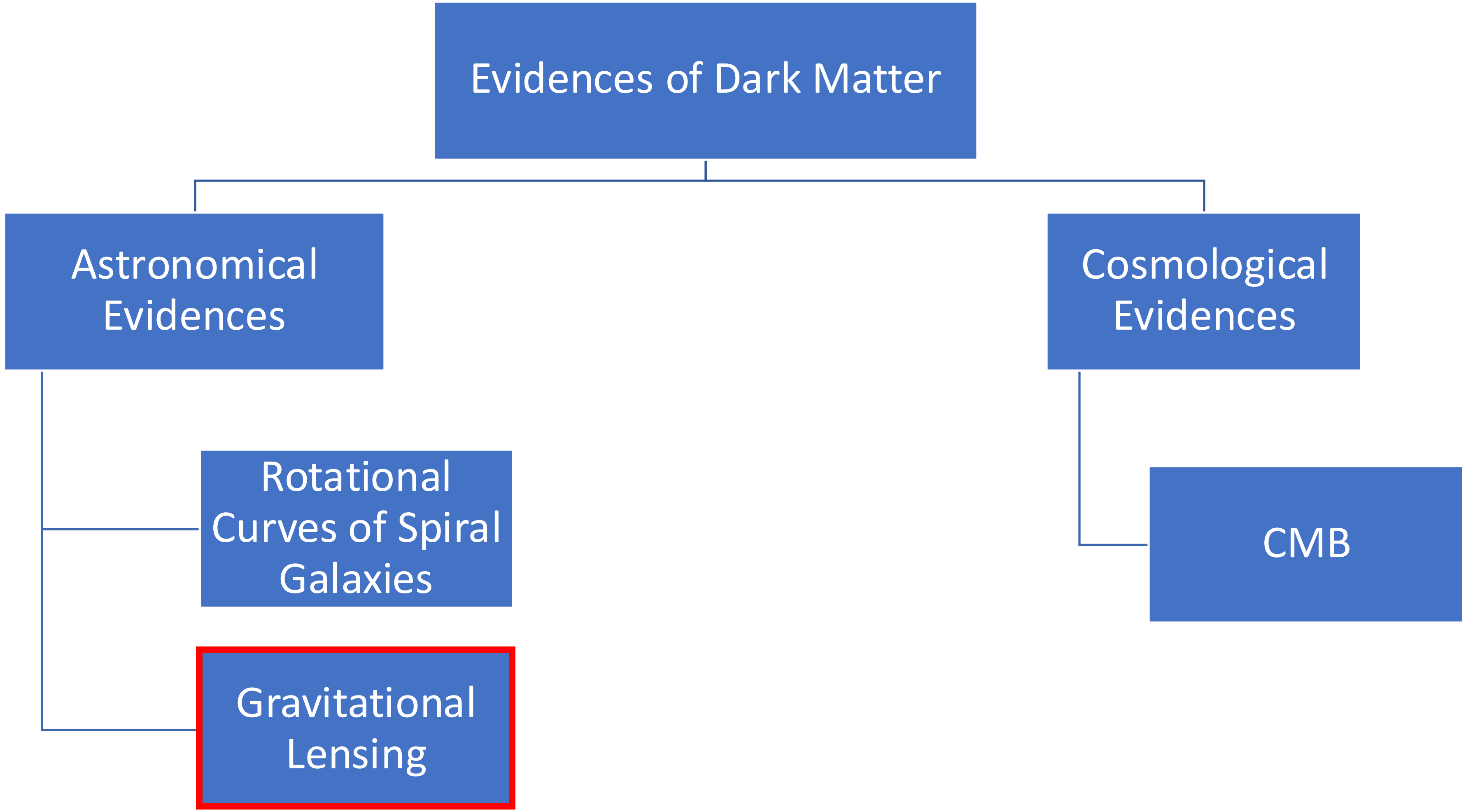


Image: Galaxy NGC 3198 in constellation Ursa Major. Charts created using SkySafari 6 Pro and STScI Digitized Sky Survey. Limiting magnitudes: Constellation chart ≈ 6.5 mag, DSS2 closeups ≈ 20 mag.

Image : NGC 3198: Galaxy in Ursa Major; 500 mm Cassegrain f/7.2; SBIG STL11K; 890-240-240-240 min LRGB; Bernese Highlands; © 2015 Radek Chromik

Evidences of Dark Matter

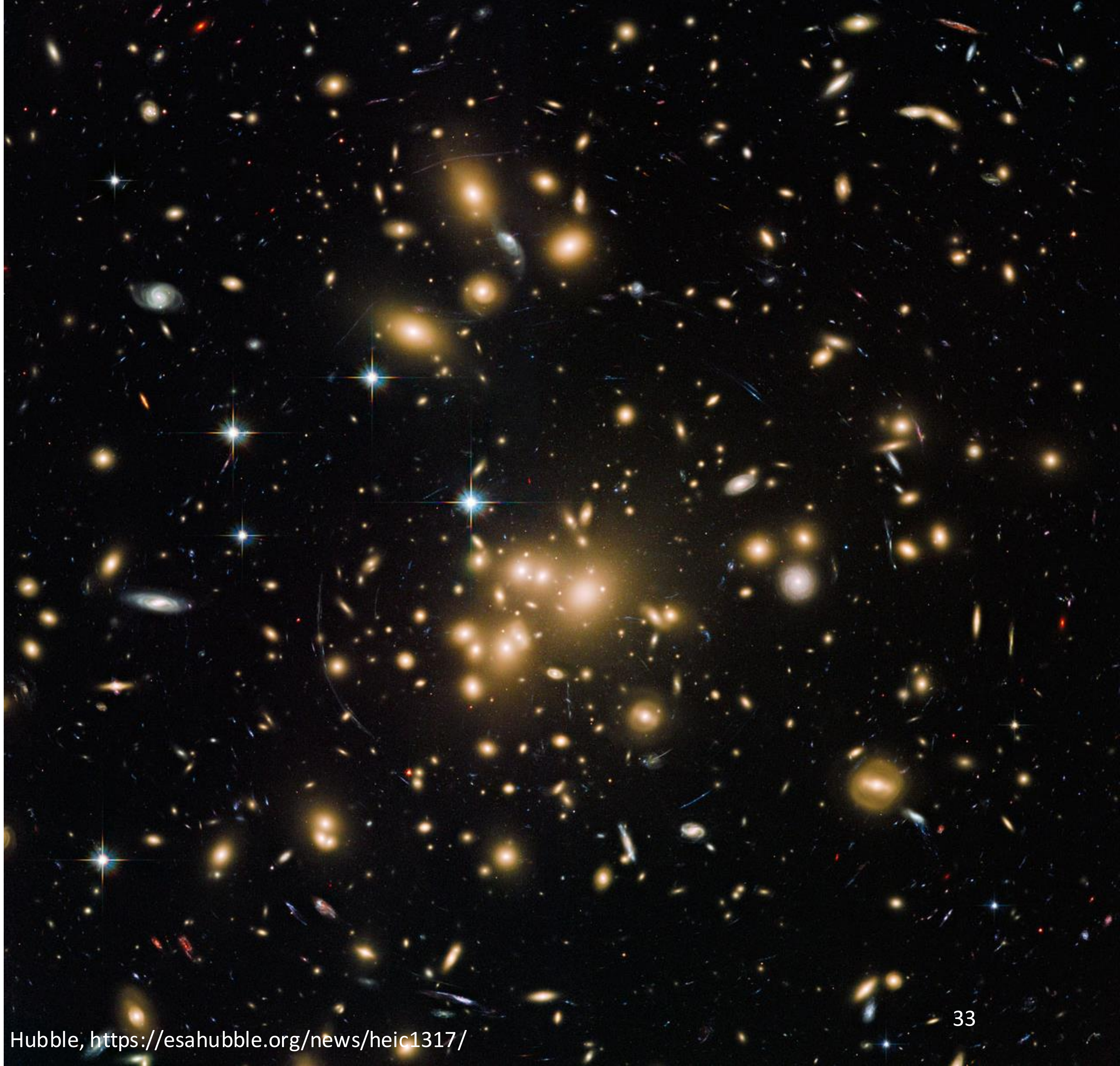


Astronomical Evidences: Gravitational Lensing

Gravitational Lensing: Abell 1689

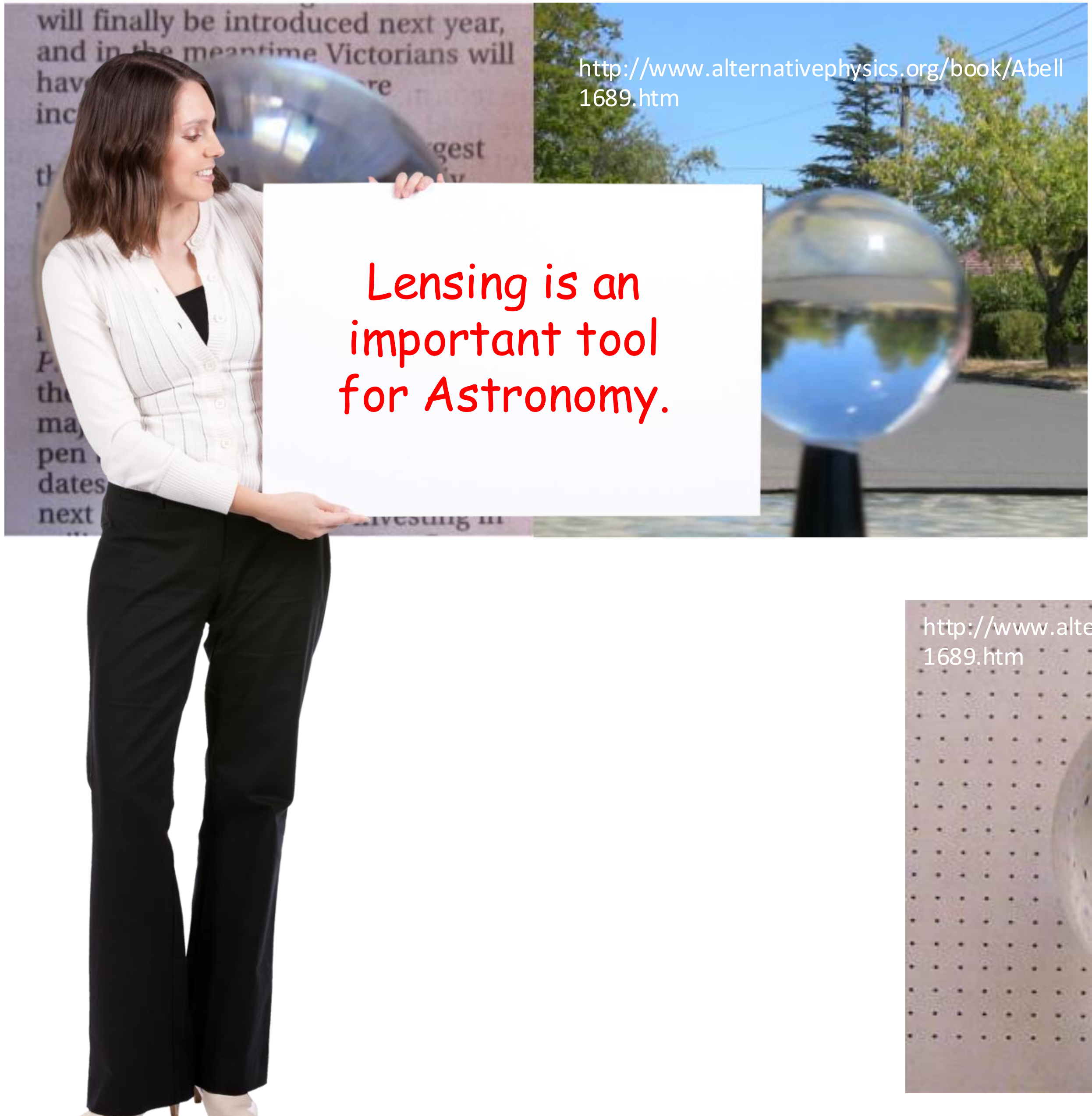
- Location: In the Virgo cluster
- ICRS : 13 11 31.882 -01 21 26.10
- Distance: 764Mpc

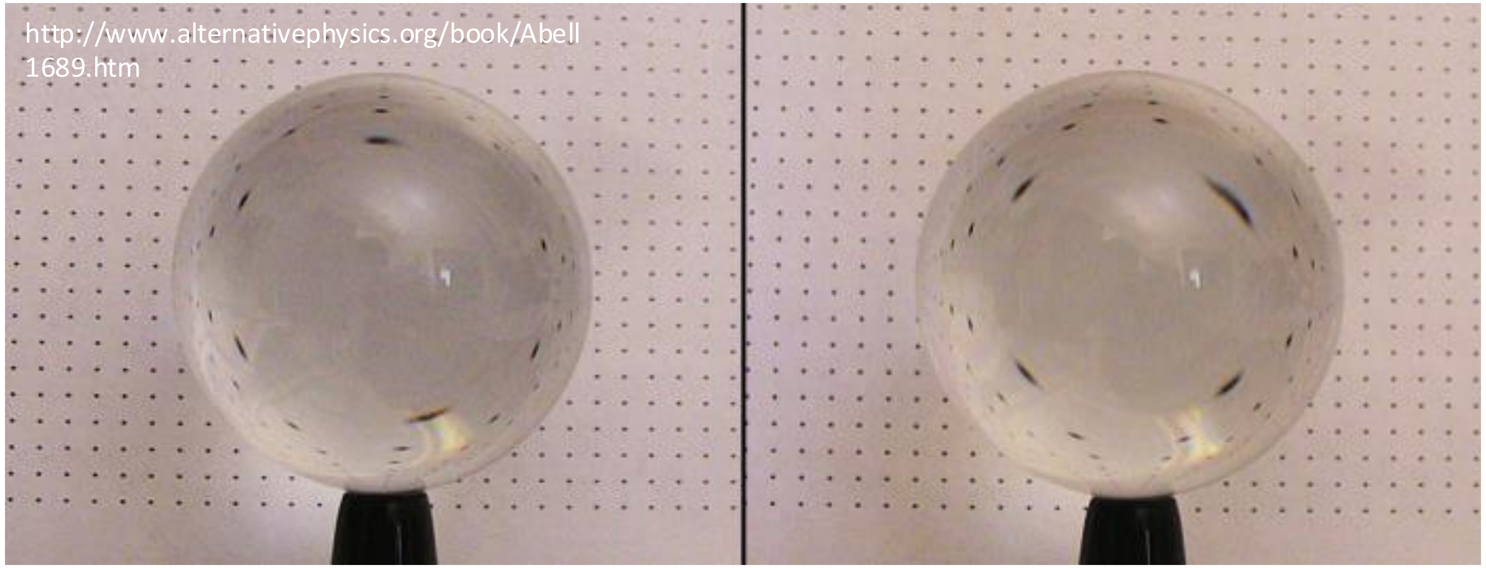
Heavy Distortion in the image due to gravity



Hubble, https://esahubble.org/news/heic1317/

But what is gravitational lensing?



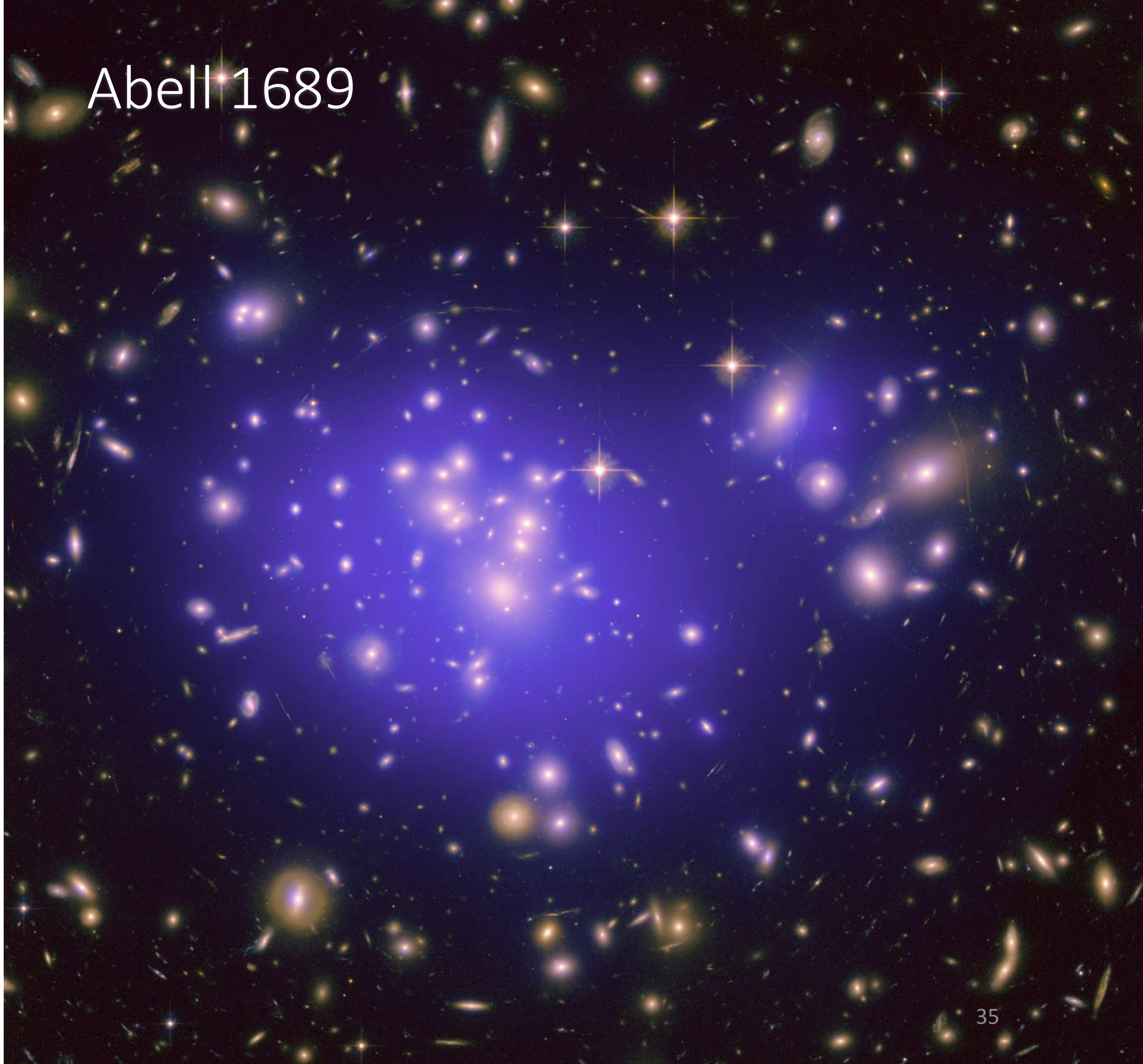


Gravitational Lensing:

By measuring the amount of lensing in each area element, a corresponding mass distribution can be calculated.

The blue overlay shows the mass distribution. The major contributor of this mass is dark matter.

Evidence that the cluster has an extra mass which interacts exclusively via gravity



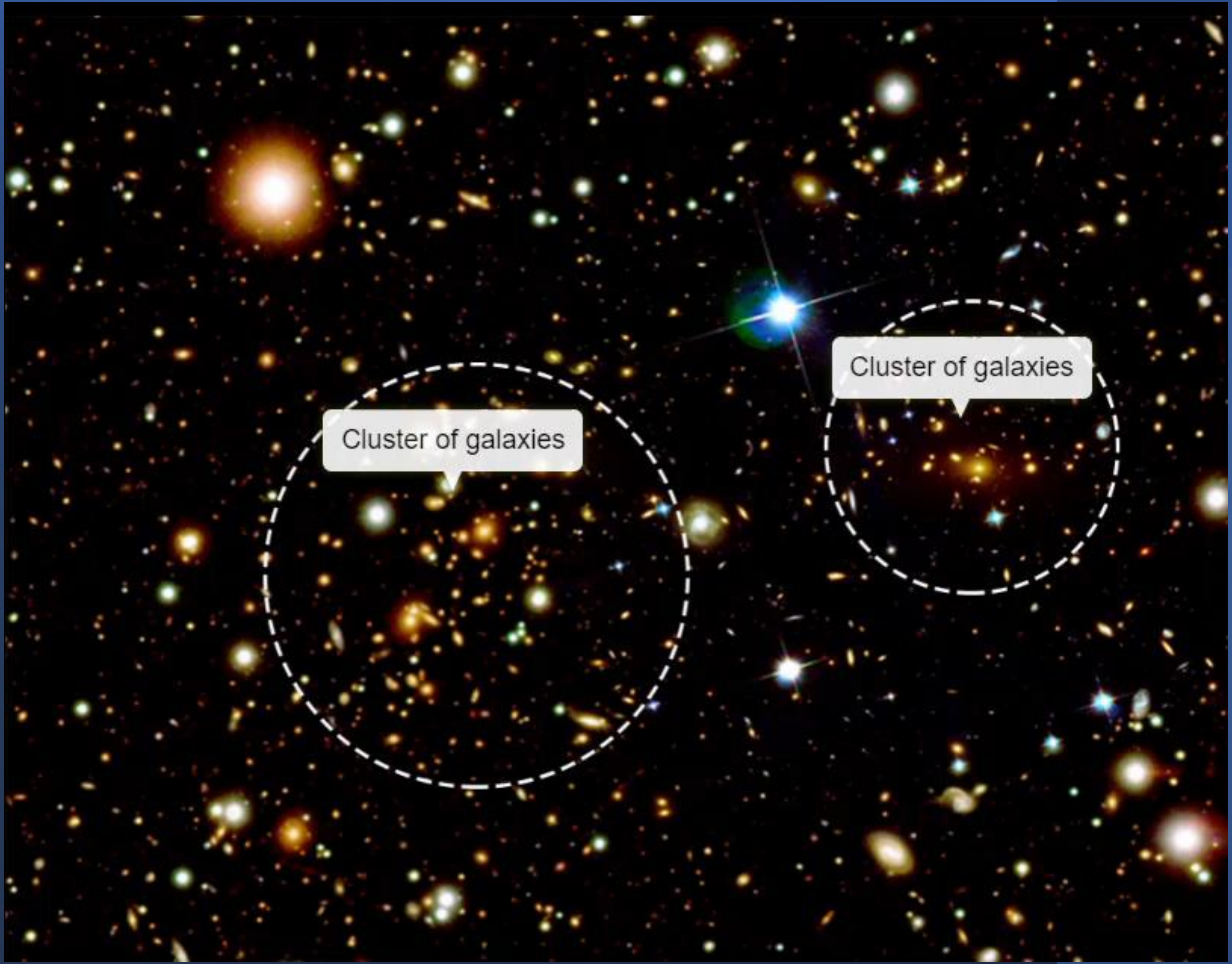
Gravitational Lensing: Bullet Cluster

- Location: In the Carina Constellation
- ICRS : 06 58 29.6 -55 56 39
- Distance: 1.141 Gpc (3.7 billion light-years)

A snapshot of two galaxy clusters colliding

Well photographed in
Visible(Hubble and Magellan Telescope at the University of Arizona),
Infrared () and
X-ray(Chandra) spectra.

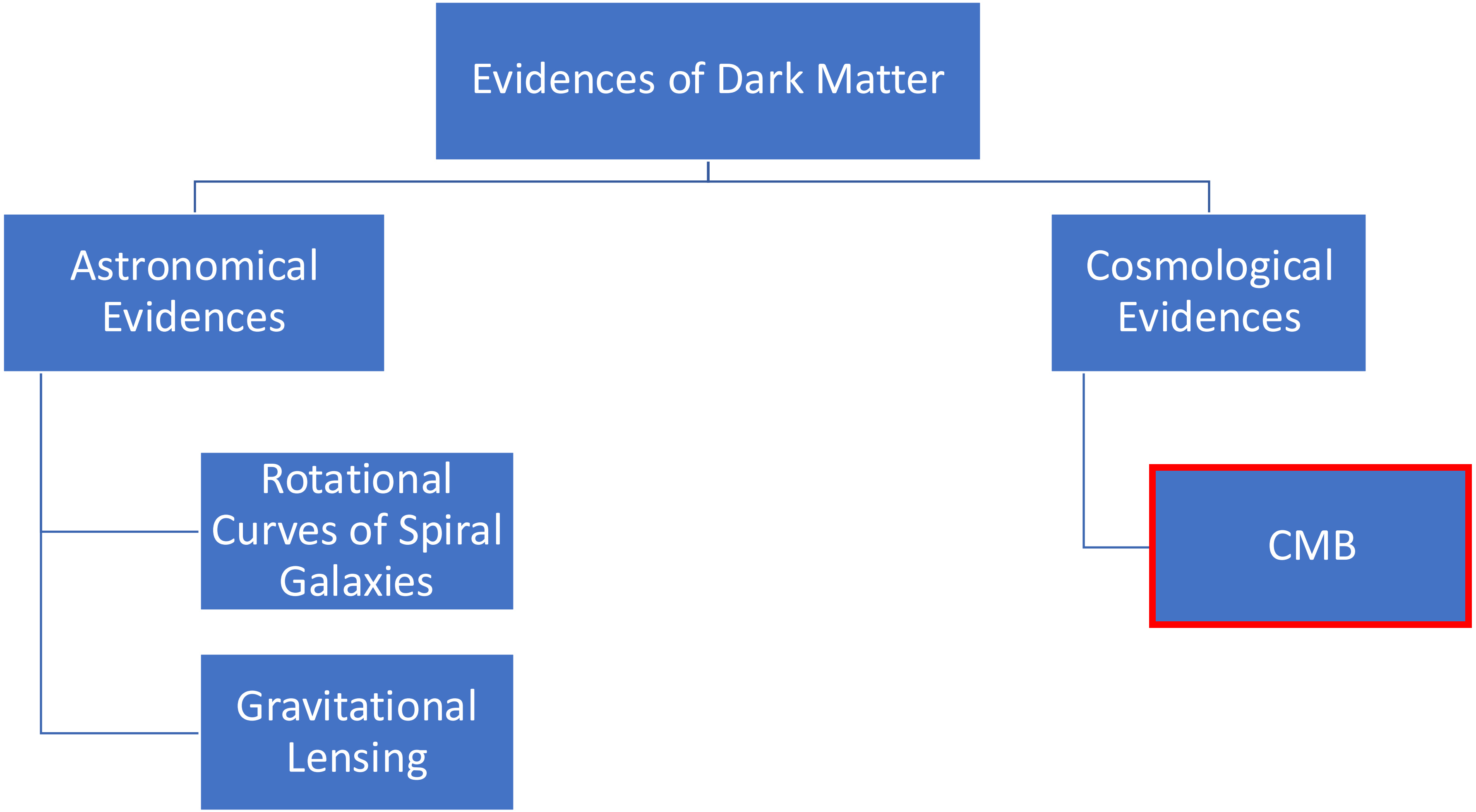
Image: Hubble : https://viewspace.org/interactives/unveiling_invisible_universe/dark_matter/bullet_cluster https://viewspace.org/interactives/unveiling_invisible_universe/dark_matter/bullet_cluster



X-RAY IN PINK

Dark Matter in Blue

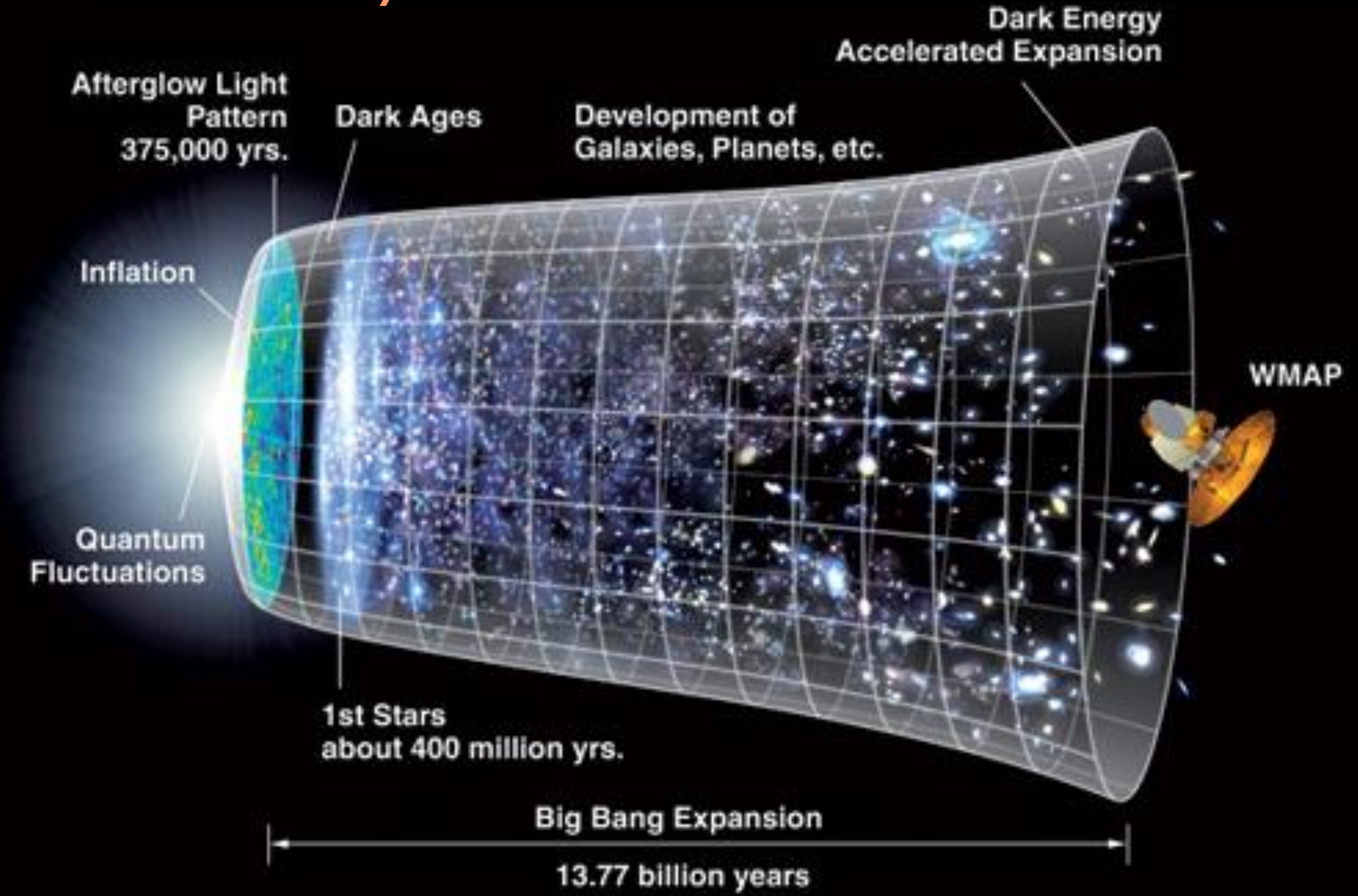
Evidences of Dark Matter



Cosmological Evidence: Cosmic Microwave Background

CMB: wave

This early light reaches to us redshifted to microwave regime and follows the black body curve



Cosmic Microwave Background

Cosmic Background Explorer (COBE)

2.725 Kelvin

An accidental discovery in 1965 by Arno Penzias and Robert Wilson

Has small variations depending upon the area of the sky where we look at

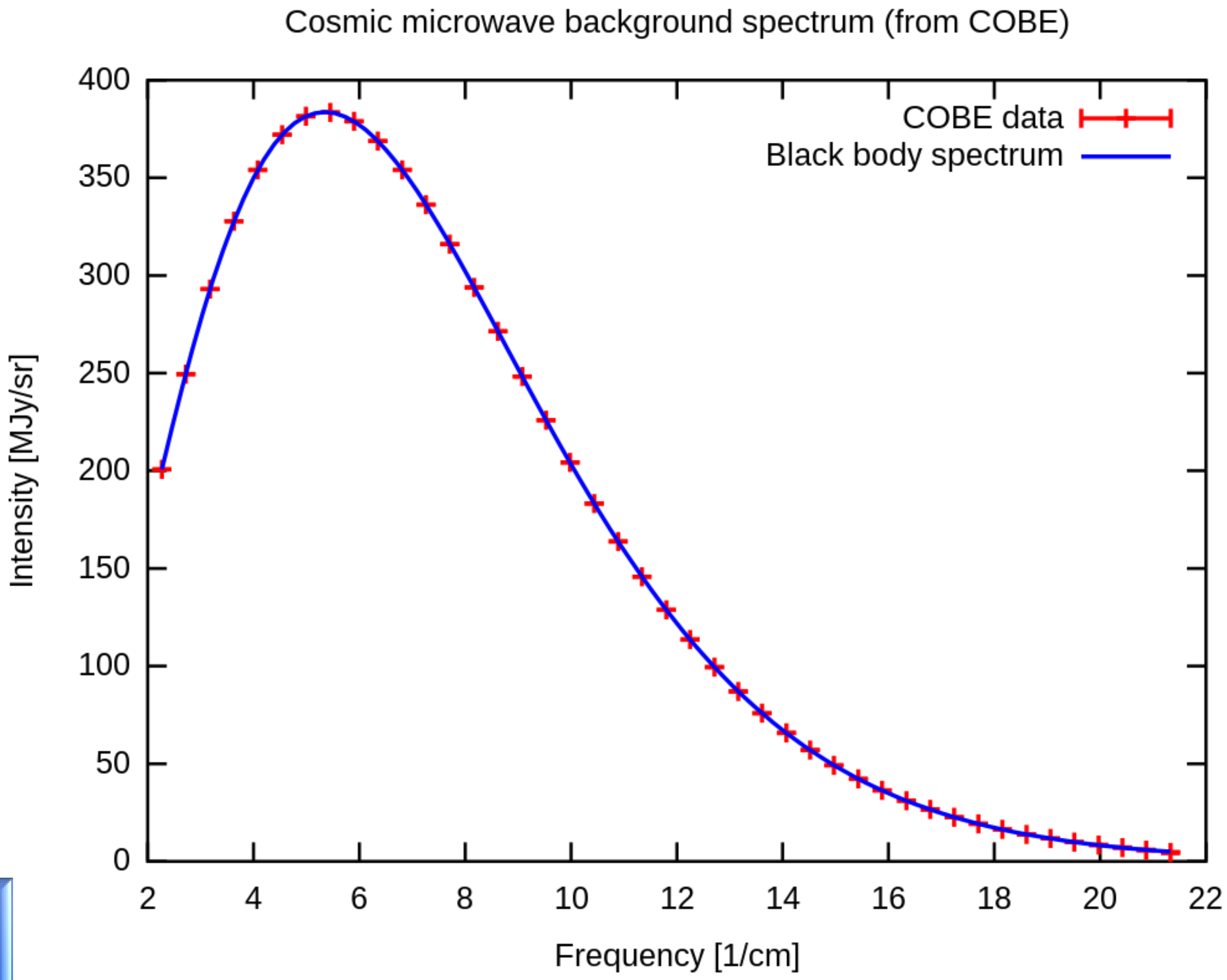


Image: Spectrum measured by the FIRAS instrument on the COBE,

Planck Probe

Operated from 2009 to 2013

Image by Mike Peel: Model of the Planck Satellite. Photographed at the Royal Astronomical Society's National Annual Meeting 2009

Cosmic Microwave Background

Penzias and Wilson

COBE

Wilkinson Microwave Anisotropy Probe (WMAP)

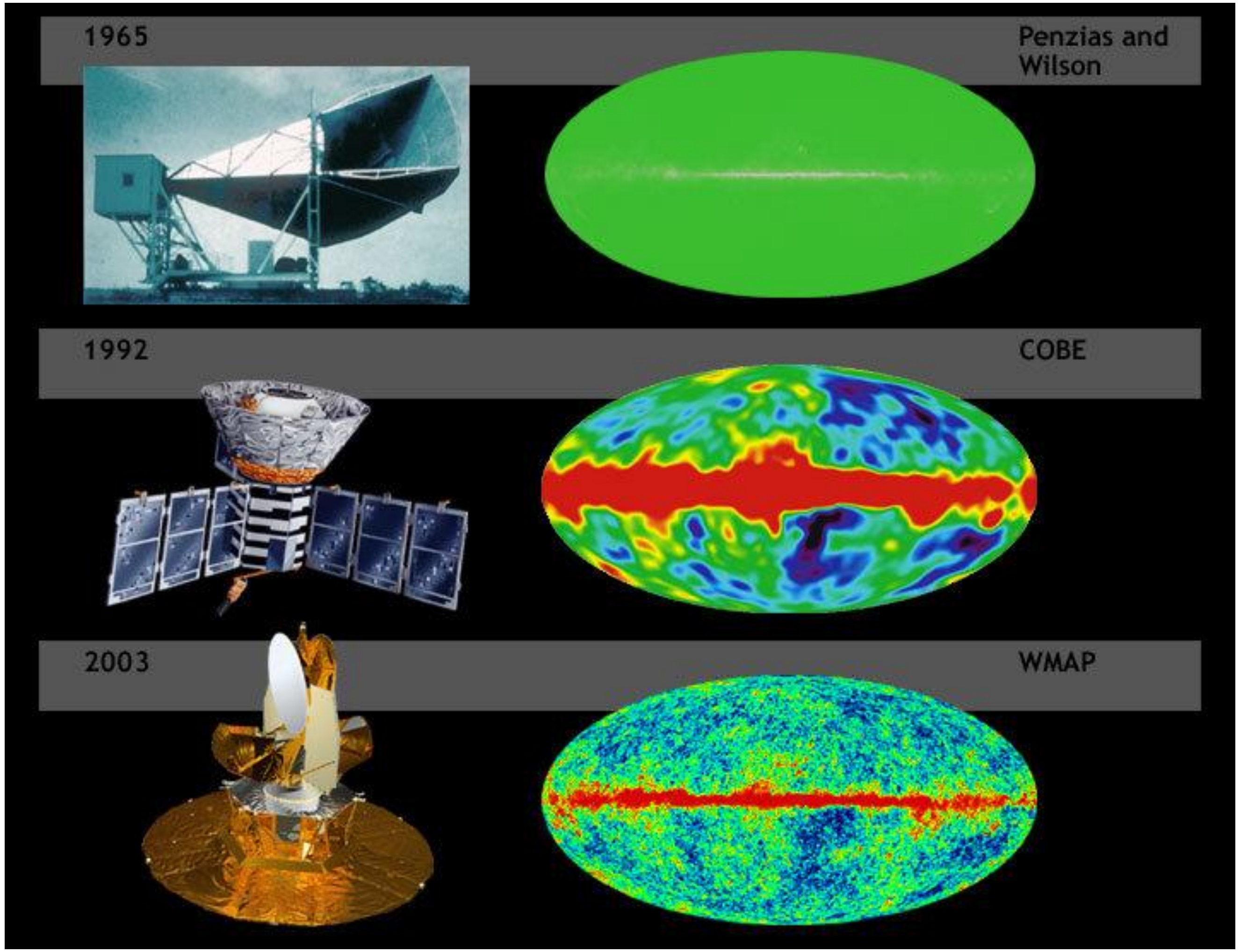
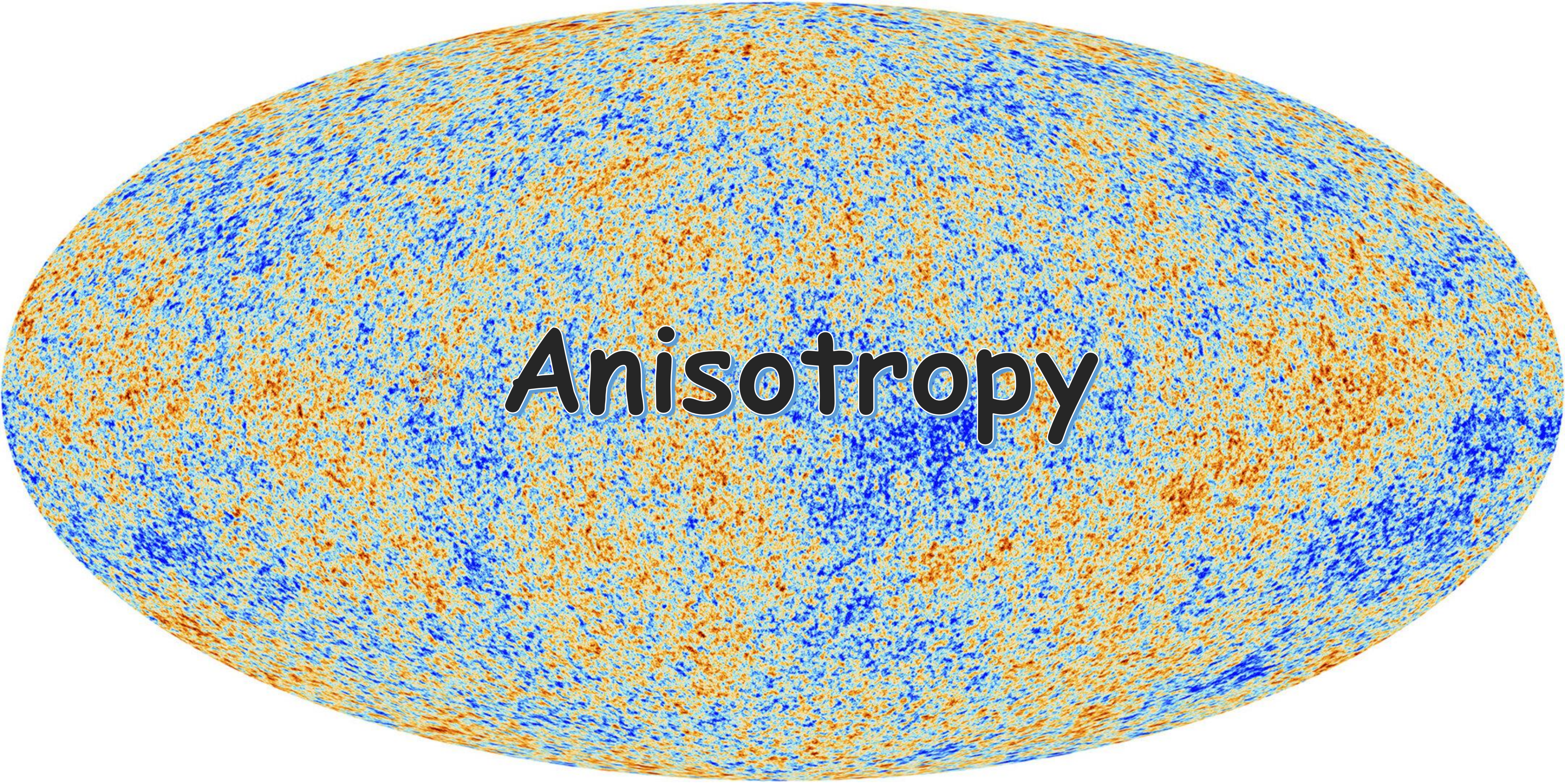
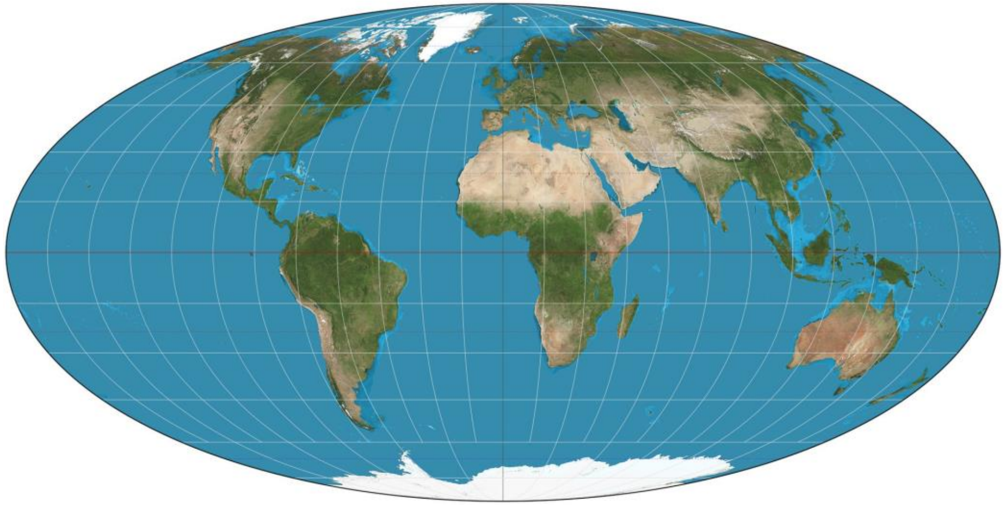


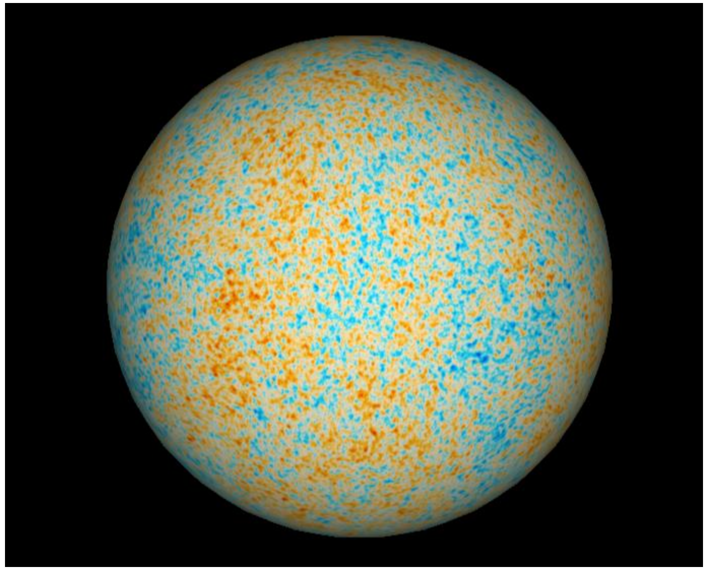
Image: http://map.gsfc.nasa.gov/m_ig/030644/030644.html

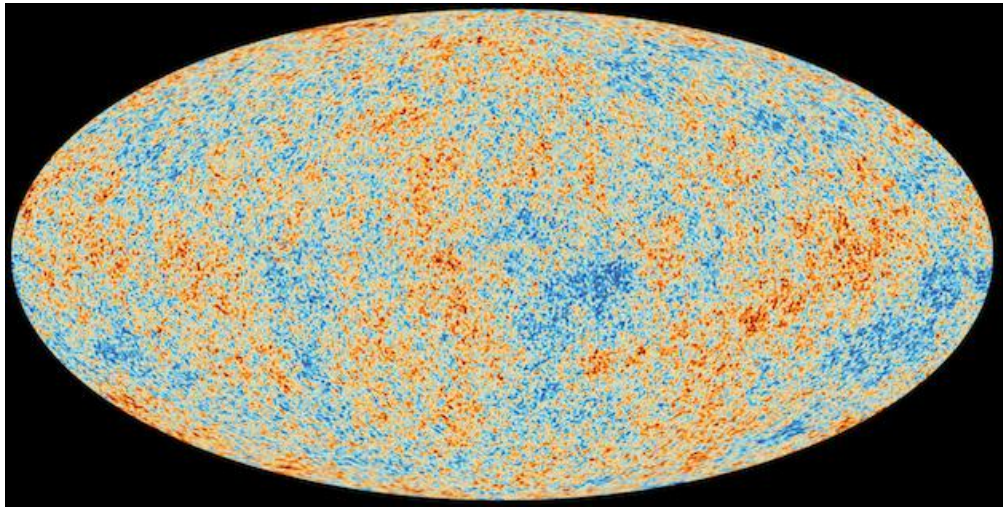
Planck Probe



Cosmic Microwave Background: Mollweide Projection







The CMS Detector

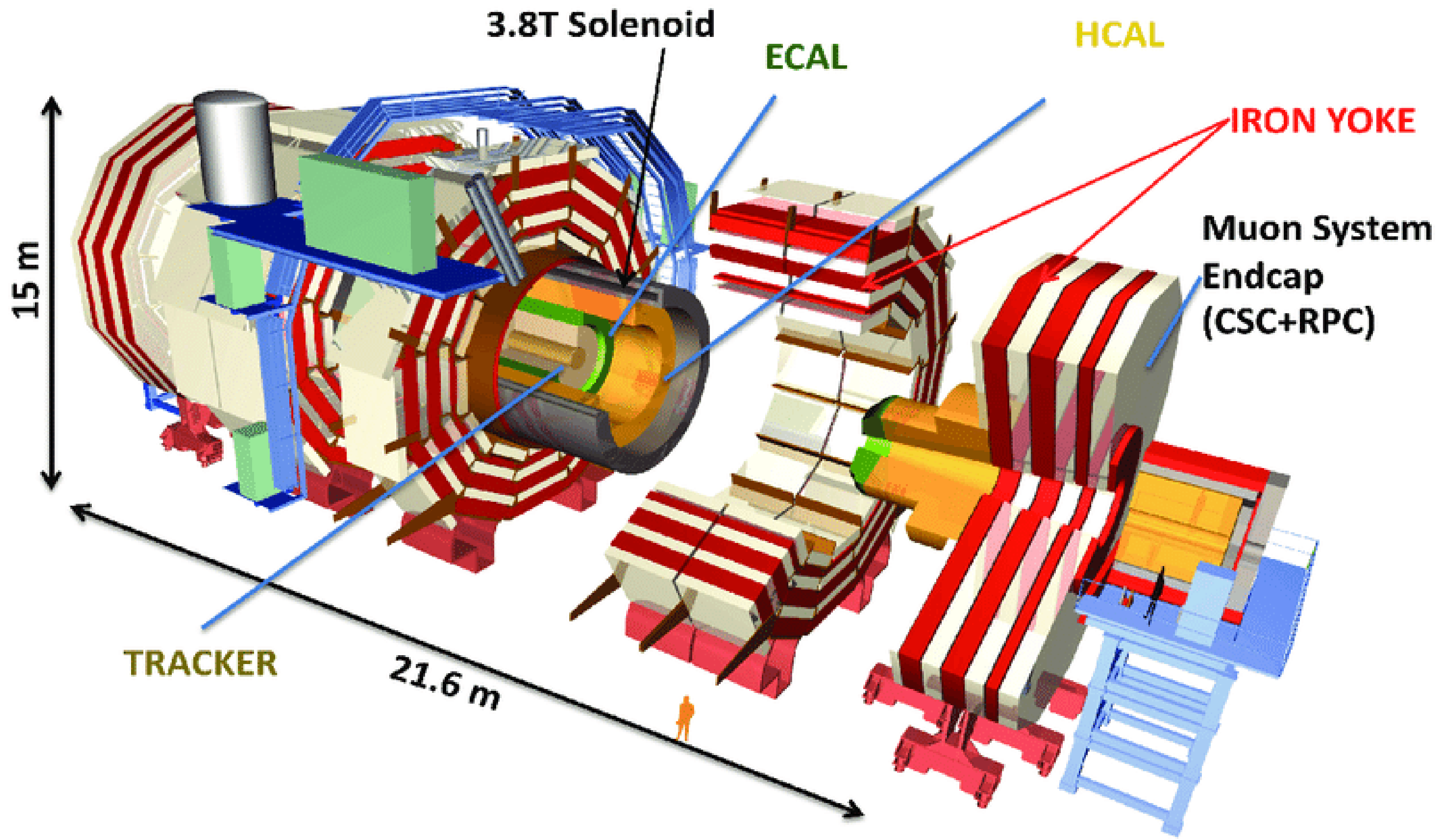


Fig : Schematic Representation of the CMS detector

Focardi, Ettore. (2012). Status of the CMS Detector. Physics Procedia. 37. 119-127. 10.1016/j.phpro.2012.02.363.

- The CMS detector is a general-purpose detector, installed 100m underground at point 5 of LHC (near Cessy, France).
- It is designed to produce:

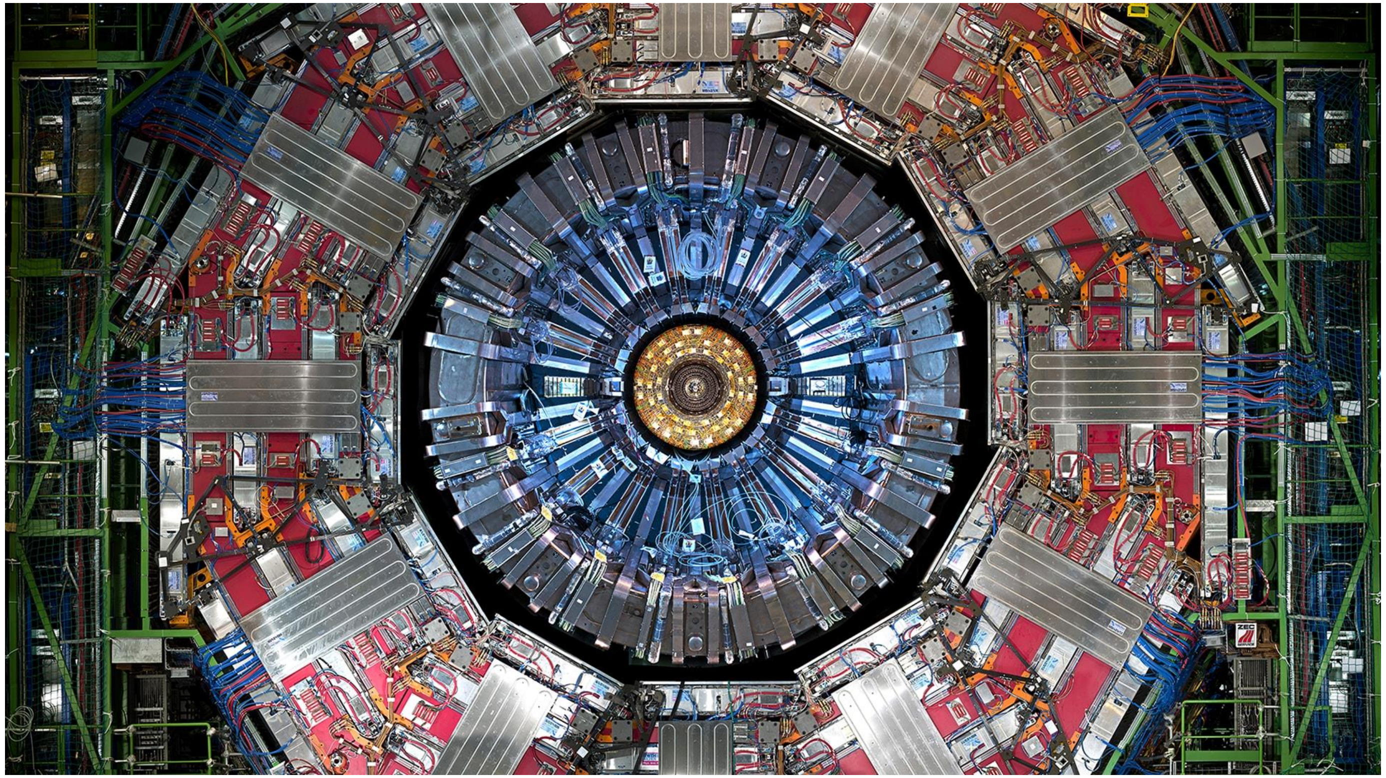
i. good muon identification and momentum resolution
ii. good charged particle momentum resolution and reconstruction efficiency
iii. good electromagnetic energy resolution, good diphoton and dielectron mass resolution and
iv. good missing-transverse-energy and dijet-mass resolution.

- CMS uses a powerful solenoid magnet which helped to design the detector in a “compact” form.

Solenoid magnets

- Precise measurement of charged particles over all the possible energies can be only achieved by presence of very strong magnetic field. This magnetic field is generated in the solenoid magnets of CMS detector

- The solenoid magnets of the CMS utilizes a 4 layered winding made from a stable reinforced Nb-Ti conductor.
- The flux is returned by a 10,000 tons Iron yoke of 5 wheels and two end caps that consist of 3 disks each.



Source: https://cms.cern/detector/identifying-tracks

Solenoid magnets

- For a charged particle the momentum of the particle is given by

$$\mathbf{p = \gamma mv = qBr}$$

where q is the charge of the particle, m is the mass of the particle and r is the bending radius of the particle.

- The transverse momentum depends on both the magnetic field and the solenoid radius

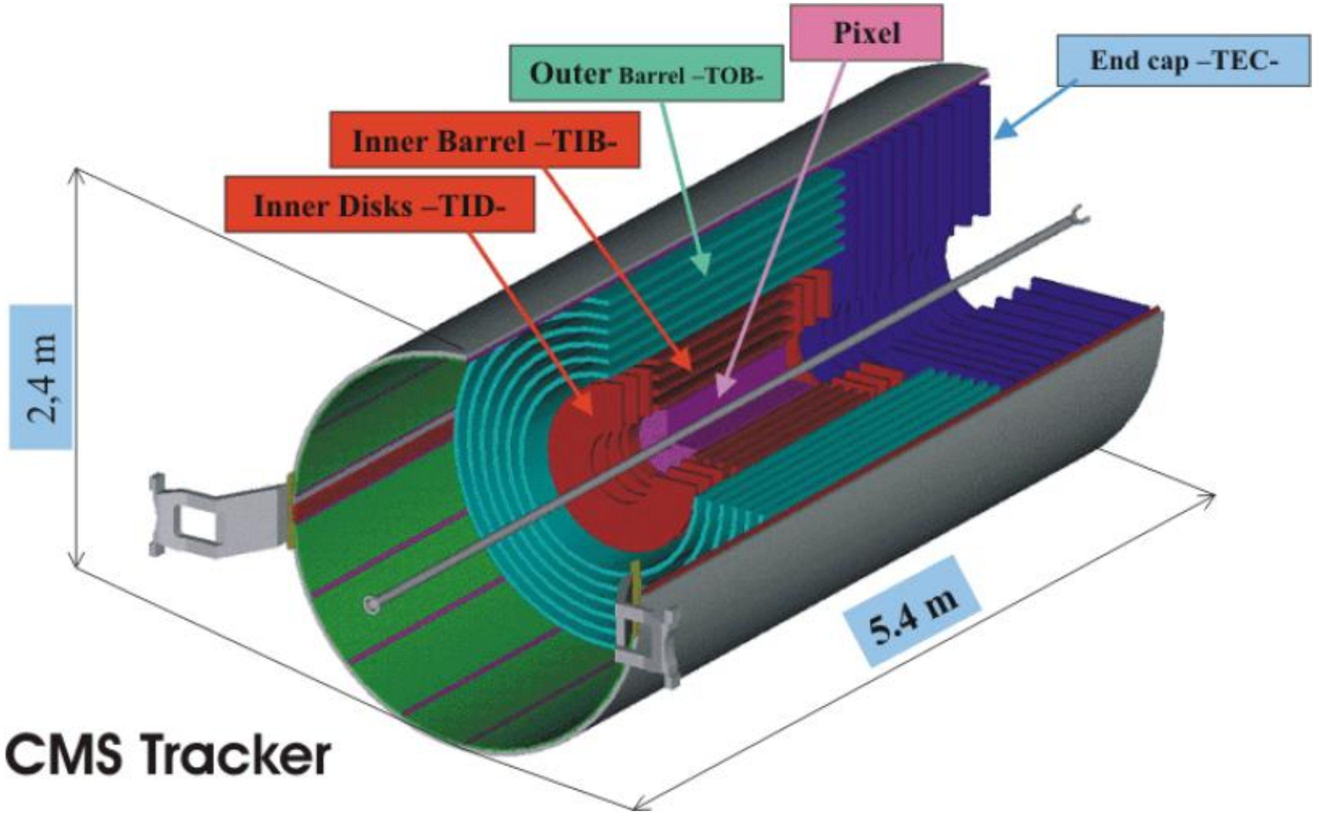
$$\boldsymbol{\frac{dp}{p} \alpha \frac{p}{BL^2}}$$

Where L is the path length in the magnetic field.

- The solenoid magnet of CMS is a 6m diameter solenoid which produces a field of 3.8T

Inner tracking system

- The tracker is the innermost sub-detector of the CMS. It is designed to provide a precise and efficient trajectories of all charged particles. It also helps in accurate reconstruction of secondary vertices.
- The inner tracking system of CMS detector is 5.8m length and a diameter of 2.5m and surrounds the interaction point of LHC



Gumus, Kazim & Akchurin, Nural. (2023). Search For New Physics In The Compact Muon Solenoid (CMS) Experiment And The Response Of The CMS Calorimeters To Particles And Jets. 10.2172/936638.

Inner tracking system

- At LHC there will be on average of 1000 particles from 20 overlapping p-p interactions that happens across the tracker per bunch i.e., of 25ns.

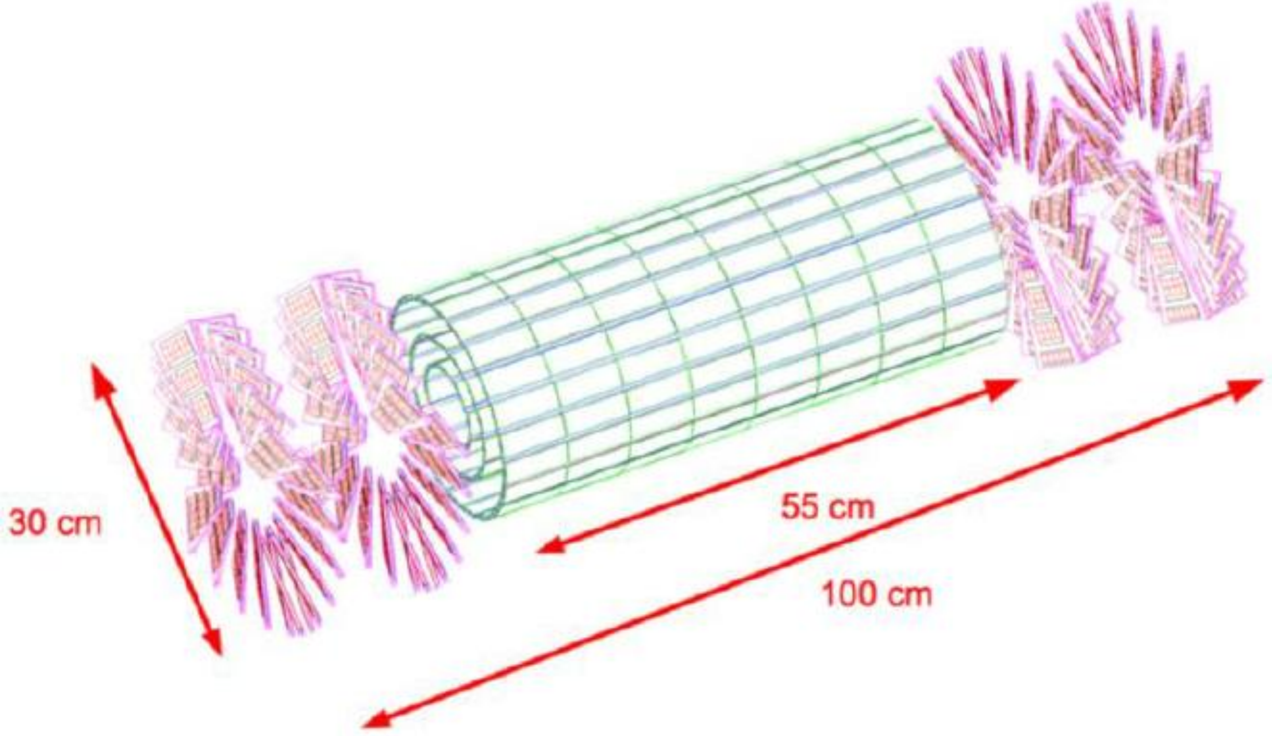
- For proper detection the detector needs to have a high granularity and fast response such that the trajectories can be identified.

- The inner tracking system has 2 parts

i. Pixel detector
ii. Silicon strip chambers

Pixel Detector

- This is located nearest to the interaction point and faces a very large particle flux in this region.
- It tracks the interactions so precisely and provides a precise tracking points in terms of r,θ,ϕ directions.
- The layout consist of 3 Barrel layers(BPIX) with two end cap disks (FPIX).



Karancsi, János. (2014). Operational Experience with the CMS Pixel Detector. Journal of Instrumentation. 10. 10.1088/1748-0221/10/05/C05016.

Pixel Detector

- BPIX is 53cm long and located at the mean radii of 4.4cm, 7.3cm and 10.2cm. The two end caps (FPIX) extending from 6cm to 15cm in radius and placed at 34.5cm and 64.5cm

- BPIX(FPIX) contains 48million(18million) pixels covering a total area of 0.78(0.28)m^2.

- The psuedorapidity range covered is from -2.5 < η < 2.5.

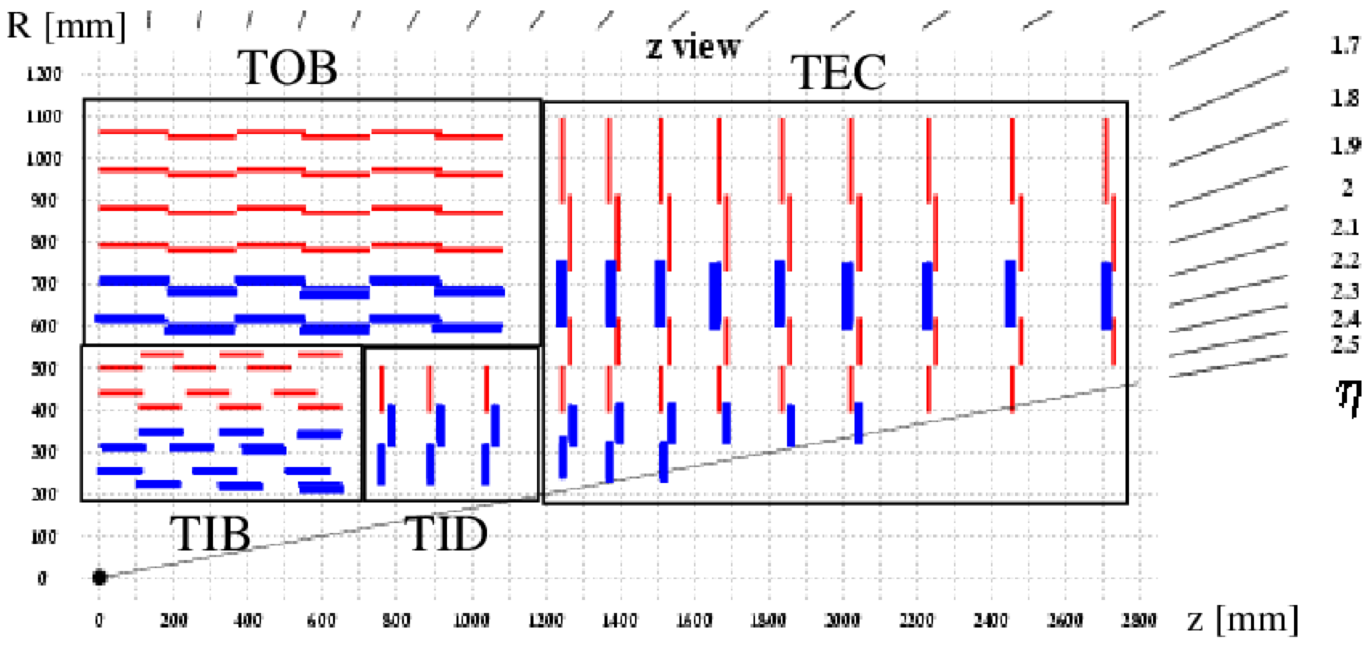
Silicon Strip Tracker (SST)

- Outside the Pixel detector the particle flux is so small hence Silicon micro strip detectors are used. The silicon strip tracker consist of 3 different sub systems

i. Tracker inner barrel and disks(TIB/TID).

ii. Tracker outer barrel system(TOB)

iii. Tracker end caps(+TEC, -TEC)



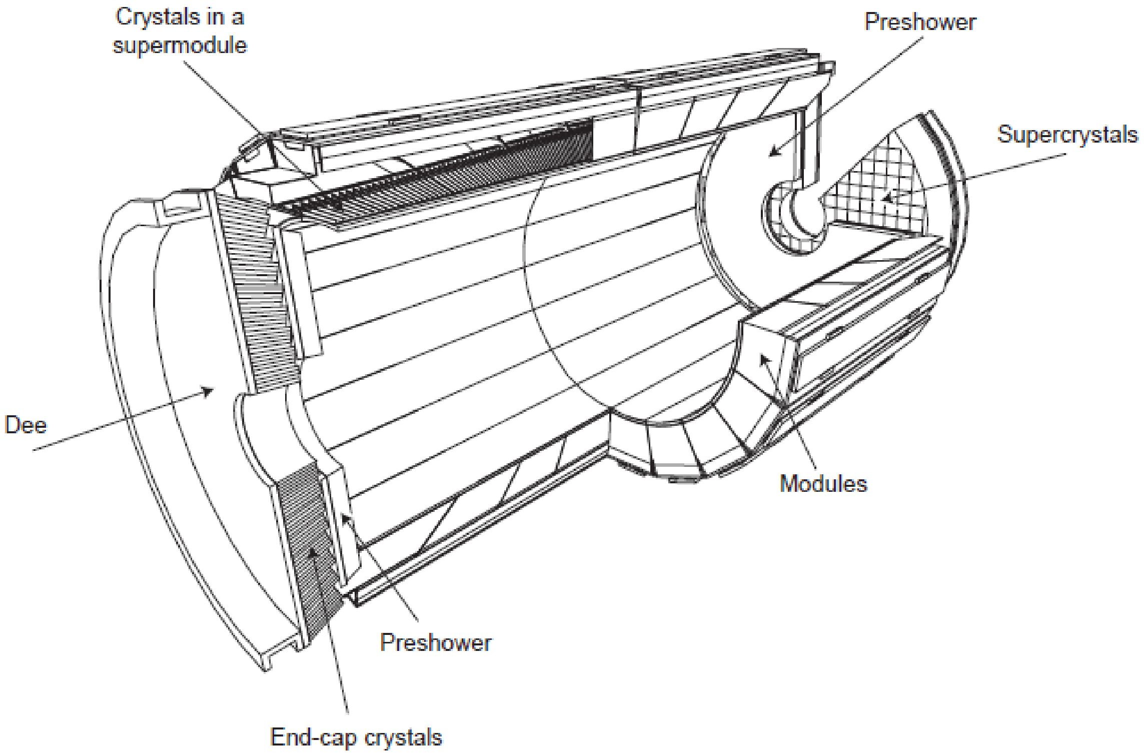
Brauer, Richard and K Klein. “The CMS Silicon Strip Tracker 2 . 1 Layout of the CMS Silicon Strip Tracker.”

Silicon Strip Tracker (SST)

- Tracker inner barrel extends in a radius of 55 cm, and has 4 barrel layers and 3 disks at each end with a position resolution of 23µm for inner two layers and 35 µm in outer two layers.
- The TIBs are surrounded by TOB which consist of 6 barrel layers with a resolution of 53 µm for first four layers and 35 µm for outer two layers. It extends up to z=118cm and beyond this range the tracker end caps takes over.
- Tracker end caps provides an additional coverage up to $\eta<2.5$. Each TEC provides nine ϕ measurements for each trajectory and extends up to z=282cm.
- In addition to first two layers of TIB/TID and TOB as well as rings 1,2 and 5 of TEC, carry a second micro-strip module with sensor in both sides with an angle of 100mrad to provide measurement of second coordinate z or r in the barrel and discs.

Electromagnetic Calorimeter

- It is a hermitic homogenous calorimeter made of 61200 lead tungstate ($PbWO_4$) mounted in a central barrel part accompanied by 7324 crystals in each of two end caps. A preshower detector is installed at the face of the two end caps
- Avalanche photo diodes(APDs) are used in the barrel and vacuum photo triodes (VPTs) are used in end caps



Bartoloni, Alessandro & Baccaro, S & Barone, L & Cavallari, Francesca & Dafinei, Ioan & Re, D & Diemoz, M & Marco, E & Grassi, M & Longo, E & Meridiani, Paolo & Micheli, Fiorenza & Organtini, G & Nourbakhsh, S & Paramatti, Riccardo & Pellegrino, Fabio & Rahatlou, S & Rovelli, Tiziano & Sigamani, Michael & Soffi, Livia. (2013). The CMS ECAL barrel HV system. Journal of Instrumentation. 8. C02039. 10.1088/1748-0221/8/02/C02039.

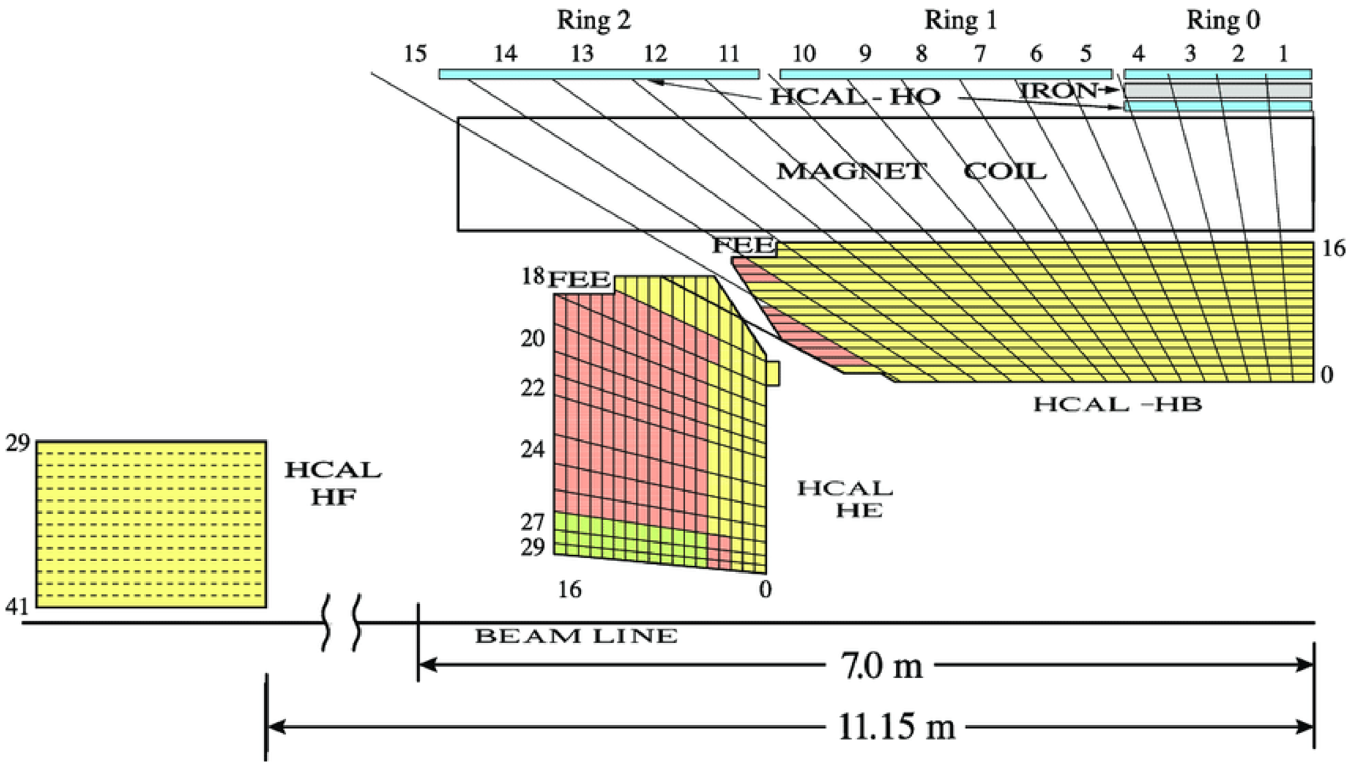
Electromagnetic Calorimeter

- The choice of crystals are very important aspect since for precise measurements the leakage outside of the crystals should be minimized which will be minimized by choosing a high-density crystal (8.28 $^{g}/_{m^2}$)with small Moliere radius(2.2cm) and short radiation length (0.89cm).
- The scintillation decay time is in the order of bunch crossing time i.e.., about 80% of light is emitted in 25ns.
- The crystal emits blue-green scintillation light with a peak of 420-430nm.
- The barrel part of ECAL covers a psuedorapidity range of $|\eta| < 1.479$
- The crystals have a tapered shape, slightly varying with the position in η.
- The crystals are contained in a thin-walled alveolar structure (sub module) which is 0.1mm thick and made of an aluminum layer facing the crystal and two layers of glass fiber-epoxy resin.
- The end caps cover the rapidity of $1.479 < |\eta| < 3.0$ and the longitudinal distance

between interaction point and end cap envelope is 315.4cm.

Hadronic Calorimeter

- It consist of hadron calorimeter barrel and hadron end caps which are located outside the ECAL.
- The hadron calorimeter barrel is located outside extent of ECAL (R=1.77m) and inner extent of magnetic coil(R=2.95m)
- The outer hadron calorimeter or tail catcher is placed outside the solenoid contemplating barrel calorimeter. Beyond $|\eta| = 3$, the forward calorimeter (HF)is placed at 11.2m from interaction point and a psuedorapidity up to $|\eta|=5.2$



Chatrchyan, S. & Nedelec, Patrick & Sillou, Daniel & Besancon, M. & Chipaux, Remi & Dejardin, M. & Denegri, D. & Descamps, J. & Fabbro, B. & Faure, J.L. & Ferri, Frederick & Ganjour, S. & Gentit, F & Givernaud, A. & Gras, Philippe & Monchenault, G & Jarry, P & Lemaire, M & Locci, E. & Romaniuk, Ryszard. (2010). Performance of the CMS Hadron Calorimeter with Cosmic Ray Muons and LHC Beam Data. Journal of Instrumentation. 5. T03012.

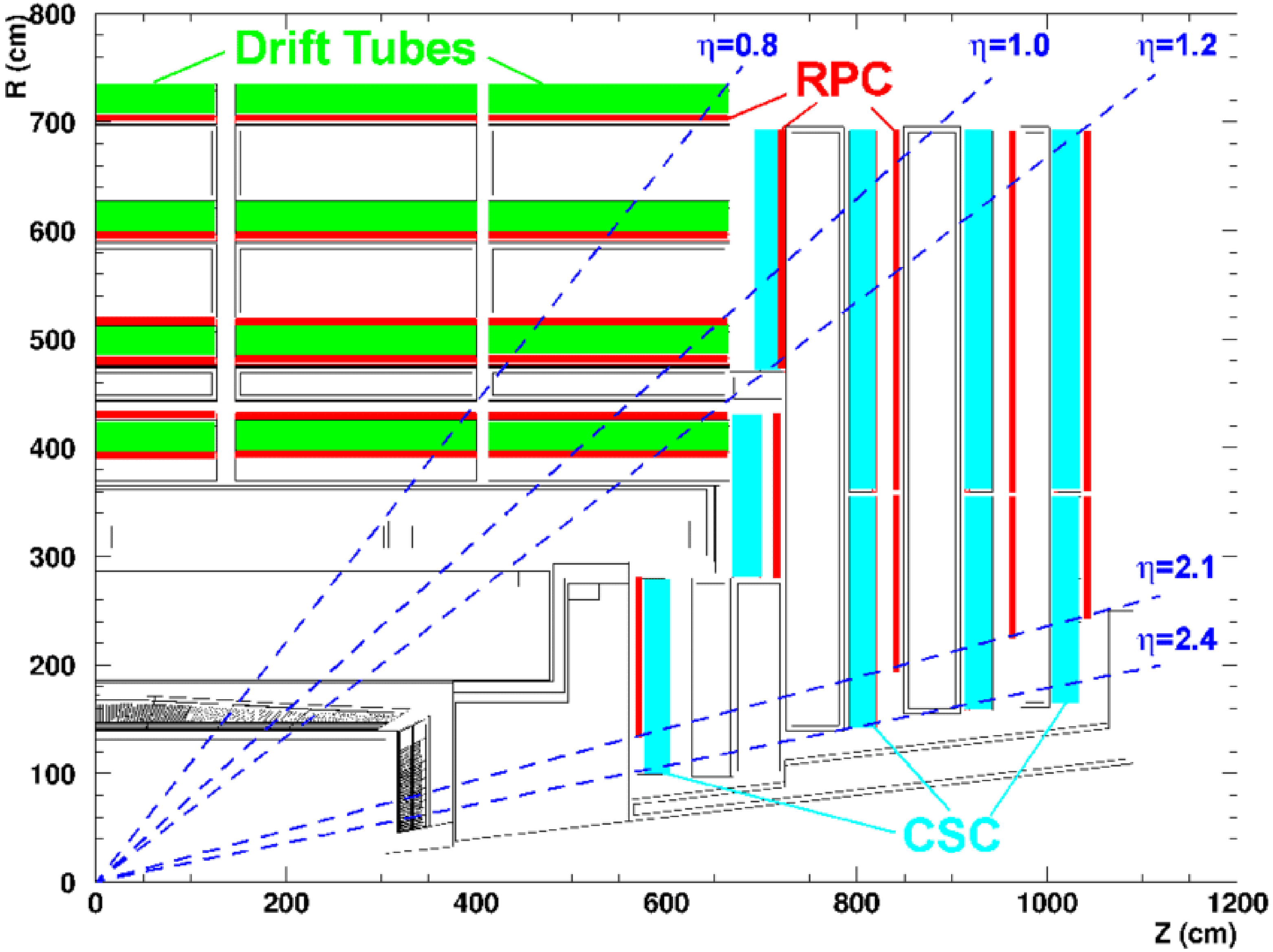
Hadronic Calorimeter

- HB consist of 36 azimuthal identical wedges covering a psuedorapidity of $|\eta|<3$ and each wedge is divided into 16 azimuthal plates, fitted in such a way that there is no projective dead material
- The first and last layer is made up of stainless steel for stability and all other layers are made in brass.
- The end cap sector covers $1.3 < |\eta| < 3.0$ and uses wavelength shifting fibers as an active medium
- These light is then analyzed by hybrid photo diodes(HPDs).

The Muon System

- The CMS Muon system is designed to provide a good muon identification and momentum resolution with good trigger capabilities.
- The muon system is made to work in the range : $|\eta| < 2.4$
- The detectors are placed in between the return yoke which provides magnetic field to the detectors and also stop hadrons.
- The Muon System comprises of : 4 layers of Drift tubes , end cap cathode strip chambers and resistive plate chambers.
- The Drift tubes are composed of drift tube cells filled with 85% Argon and 15% CO_2.
- Each DT chamber is made of two or three super-layers(SL) where each super-layer is made of four layers of drift cells staggered by half a cell.
- Cathode Strip Chambers, installed at the endcaps, are multi-wire proportional chambers consisting of six planes of anode wires interleaved among seven cathode panels.
- Resistive Plate Chambers (RPC) are gaseous parallel plate detectors. They provide a very fast response time, required for efficient triggering.

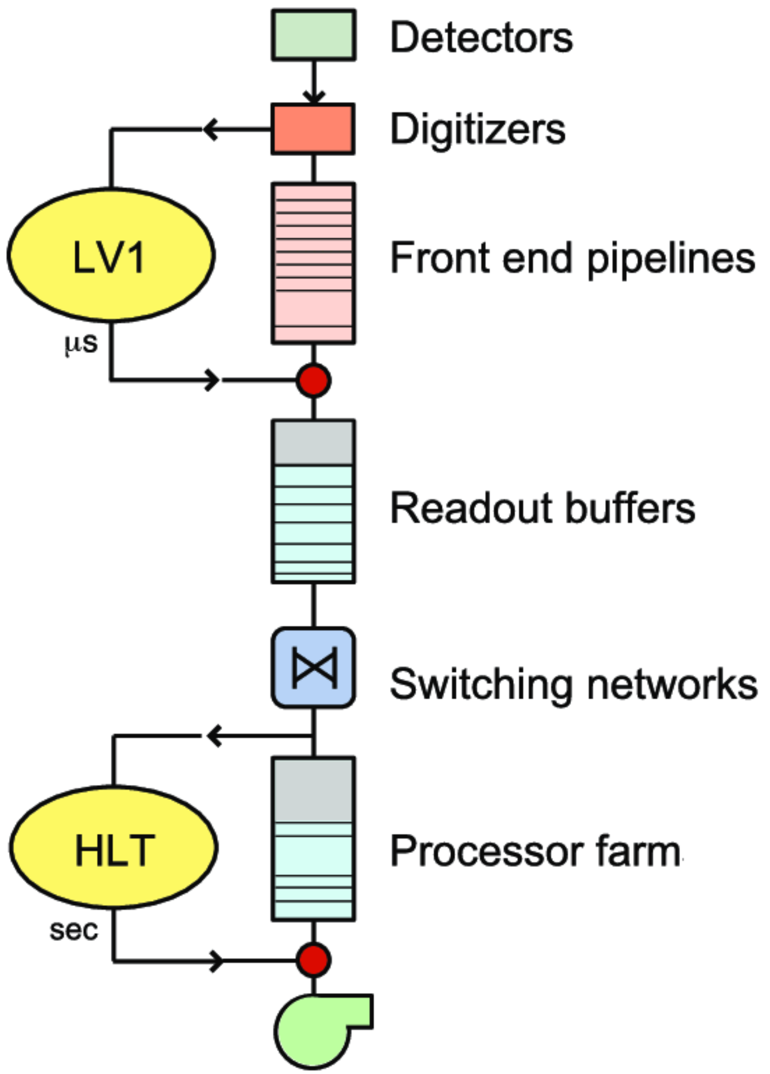
The Muon System



Kalinowski, Artur & Krolikowski, Jan. (2023). Search for the heavy, neutral MSSM Higgs particles in the $H/A -> \tau \tau -> \mu + X$ channel in the CMS detector at the LHC.

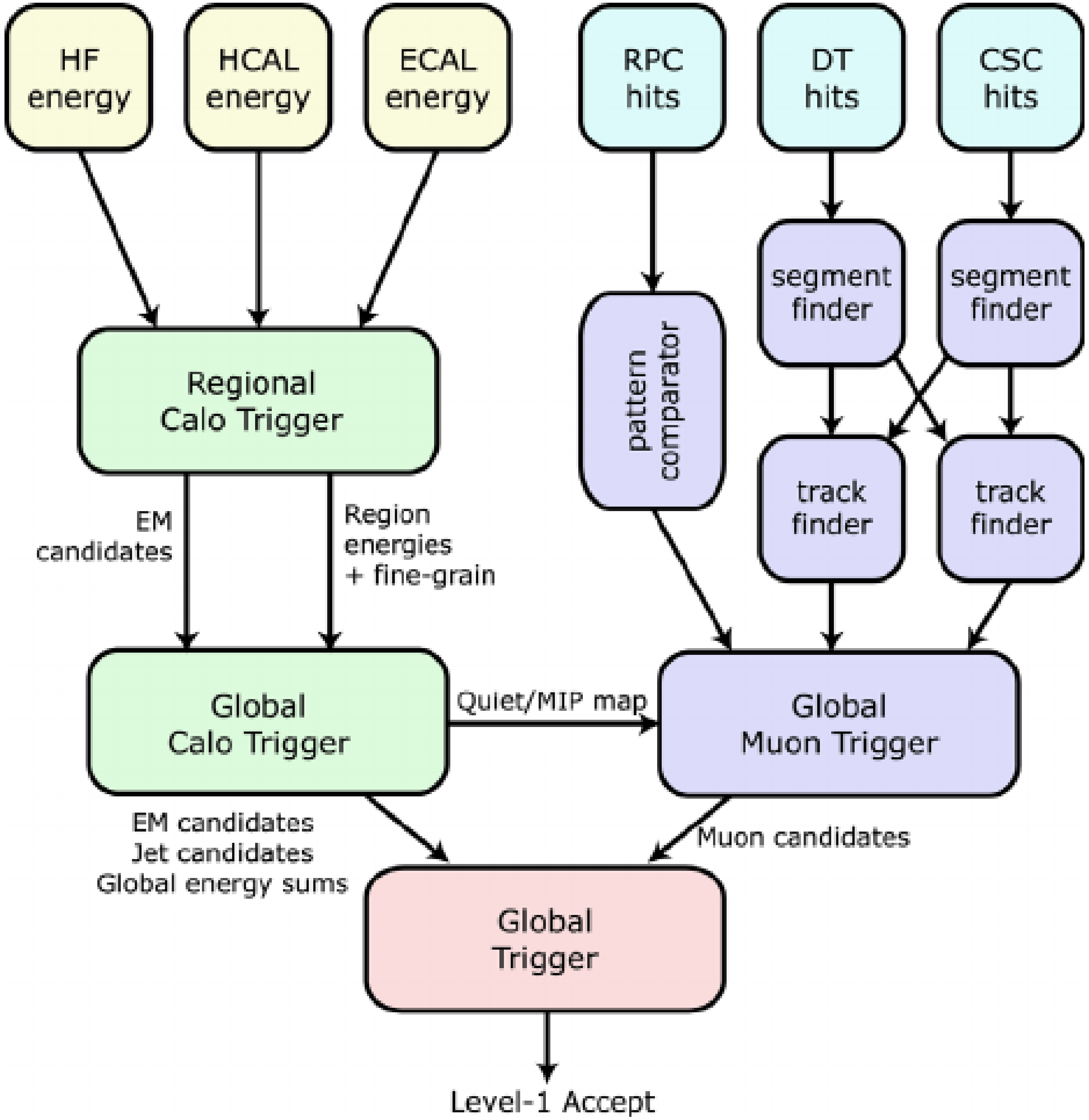
The Trigger System and Data Acquisition

- LHC produces a large interaction rates (Bunch crossing rate: 40 MHz)
- Each recorded event has a size around 1 MB; This makes it impossible to store all the data from the pp collisions at the designed bunch crossing rate.
- The Trigger system, is designed to select the best events from the collisions in real time.
- The Trigger Systems consists of : Level 1 trigger (L1 Trigger) and High Level Trigger(HLT).

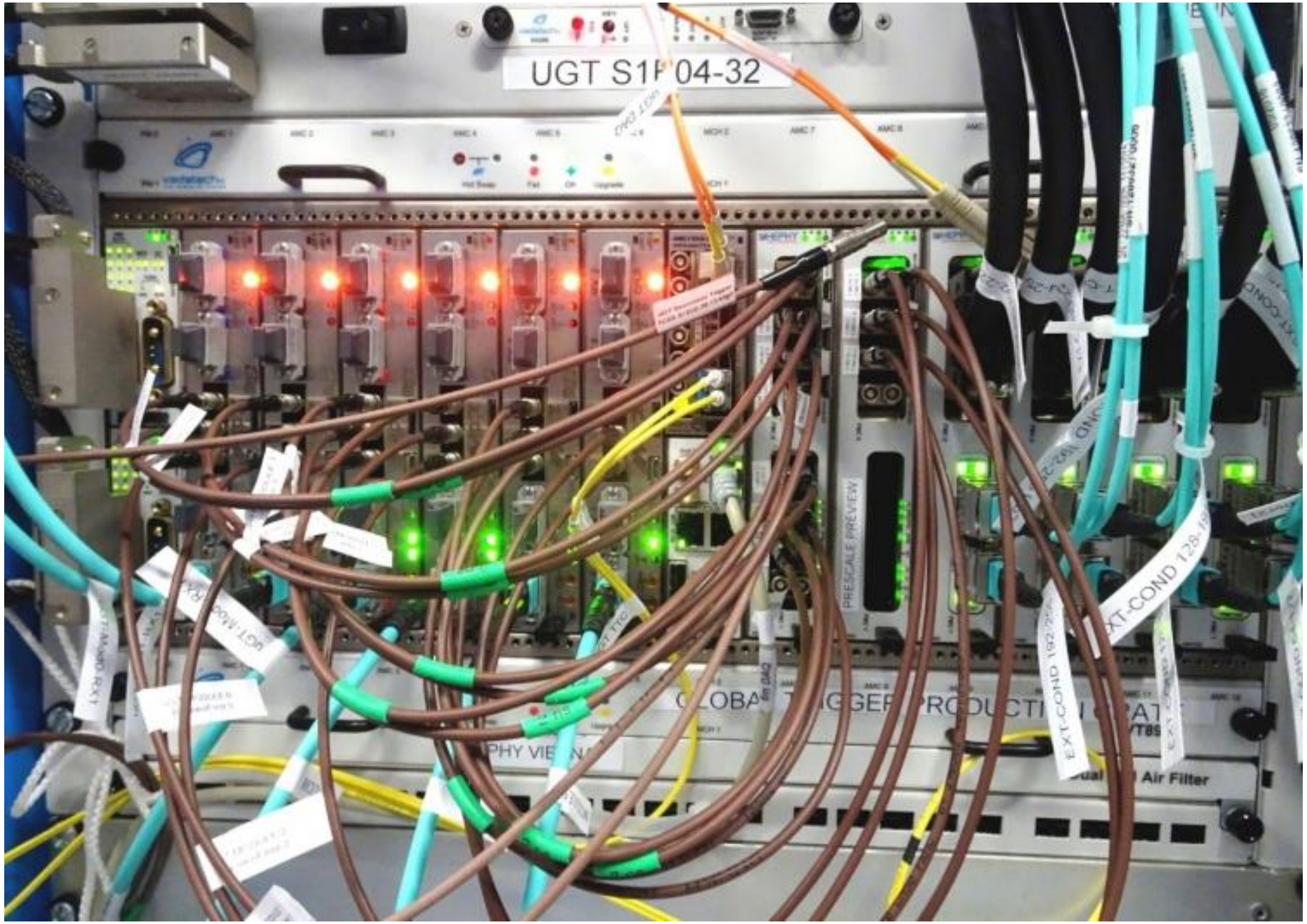


L1 Trigger

- The Level 1 trigger is a hardware based processing system which employs the use of programmable electronics like FPGAs extensively.
- The L1 trigger reduces the input crossing rate of 40MHz to an output rate of 100KHz.
- The L1 trigger follows a hierarchy as shown in the figure. The Global Trigger takes input from two , subsystems: **Calorimeter trigger** and **Muon trigger system**.
- The raw data from detector elements first reaches the "trigger primitives". These are represented in the top of the diagram.
- The regional detectors combine the information from trigger primitives to create ranked objects. For example, an e/γ candidate has deposits energy in narrow η . The RCT identifies and sorts such objects.



L1 Trigger



- The Global Calorimeter and Global Muon Trigger, sort the trigger objects from Regional Triggers into a ranking and feed to the Global Trigger.
- The Global Trigger takes the topology of the detector and other factors into consideration. It takes into account, various physics criteria to make a decision to keep an event or not.

High Level Trigger

- HLT is a software based processing system which employs commercial microprocessor based farms for trigger. The trigger farm is composed of about 2000 PCs.
- HLT takes information from L1 at 100 kHz and makes selections to produce a final rate of about 800Hz.
- HLT is much slower than L1 and has to account for possible failures of computing nodes.
- HLT builds one full event from the event fragments it gets as input.
- HLT is also responsible for Jet Reconstruction.

An HLT rack

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