Search for Dark Matter in pp Collisions with CMS

Shin-Shan Eiko Yu
Department of Physics
National Central University, Taiwan

15 December 2020
Colloquium, Department of Physics
National Taiwan University

Outline

- Dark matter searches at colliders
  - Overview
  - Introduction to LHC and CMS
  - Experimental techniques
  - Interpretation of results
- Conclusion and outlook

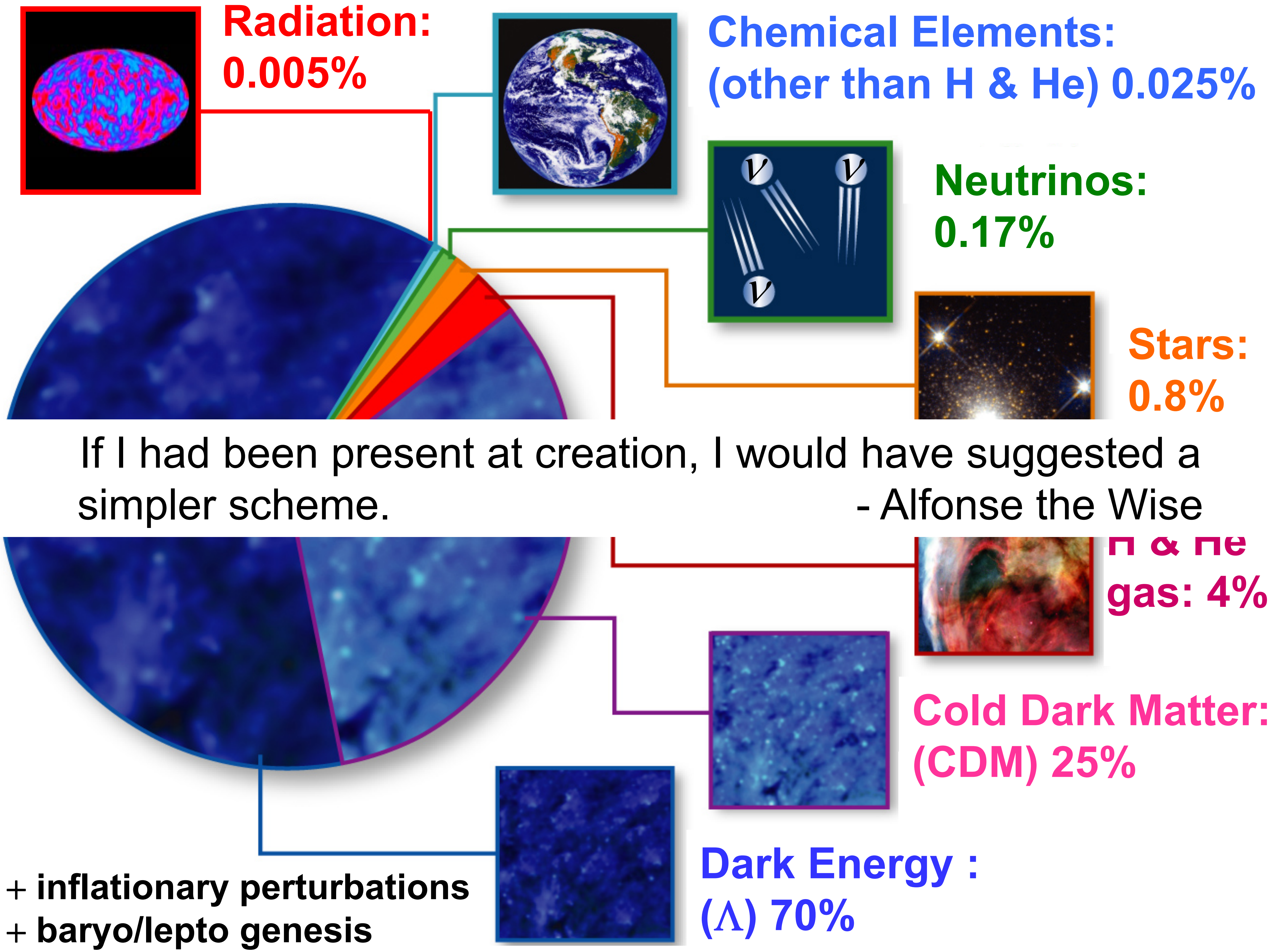
How Do You "See" an Object?

Reflection

Thermal Radiation

Visible for T=3800~7600 K

In our galaxy, besides visible stars, is there something else?



If I had been present at creation, I would have suggested a simpler scheme.

- Alfonse the Wise

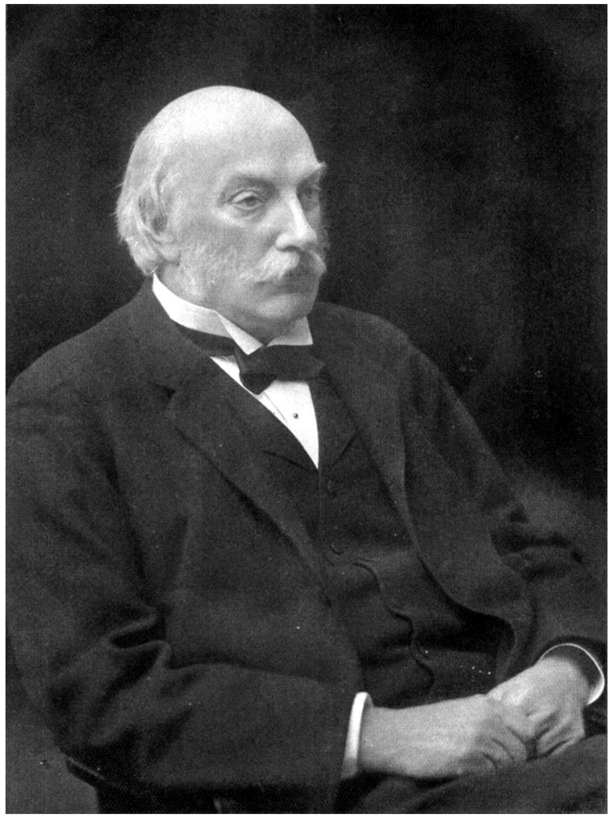
+ inflationary perturbations
+ baryo/lepto genesis

Rocky Kolb

What Is Dark Matter?

- “Dark Matter” is a temporary name

"Dark Matter" in Chemistry: Argon



Lord Rayleigh

Discovered in 1894

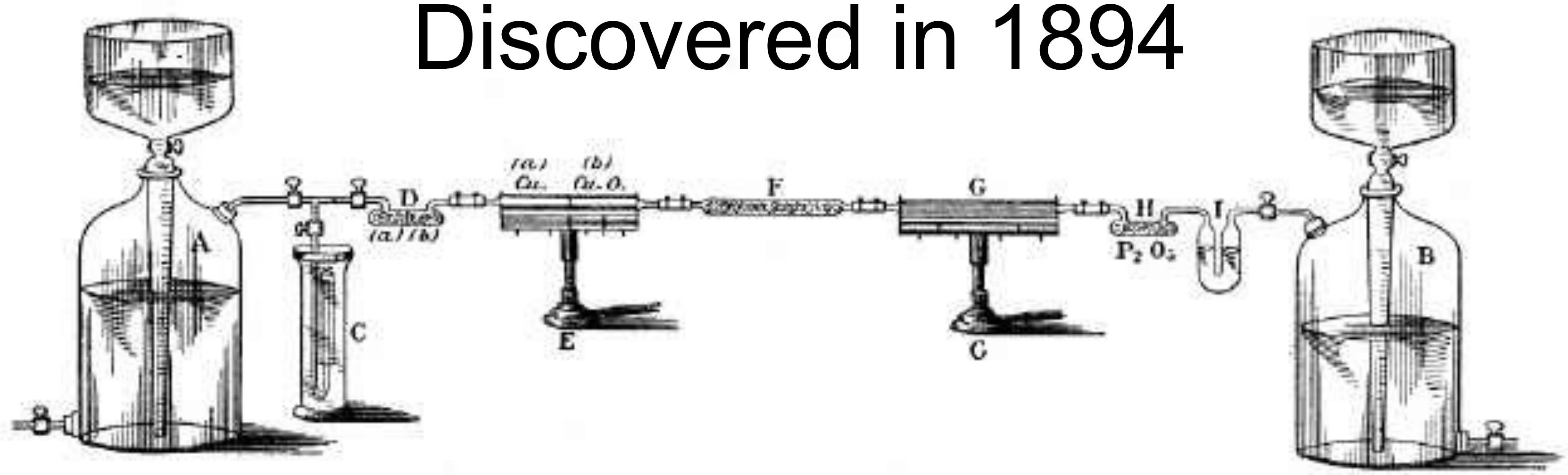
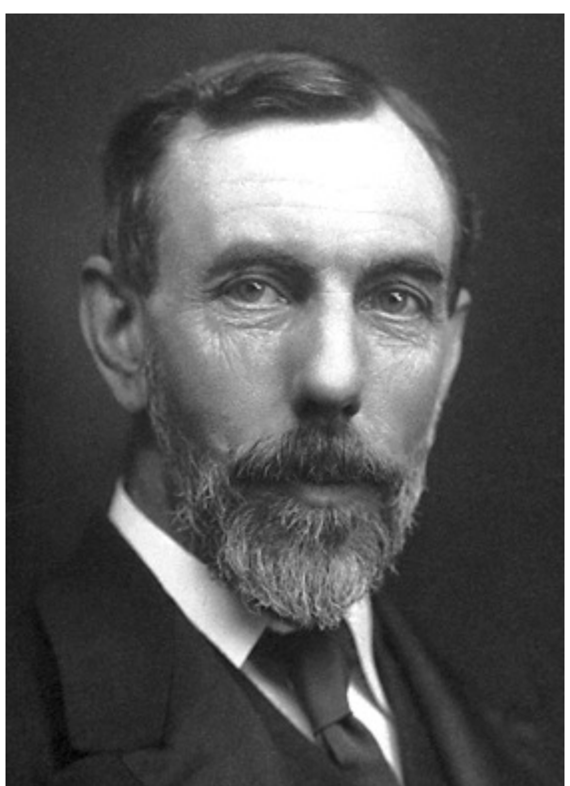


Fig. 1.



Sir William Ramsay

Nitrogen extracted from air is heavier than that extracted from the chemical reaction by 0.5%

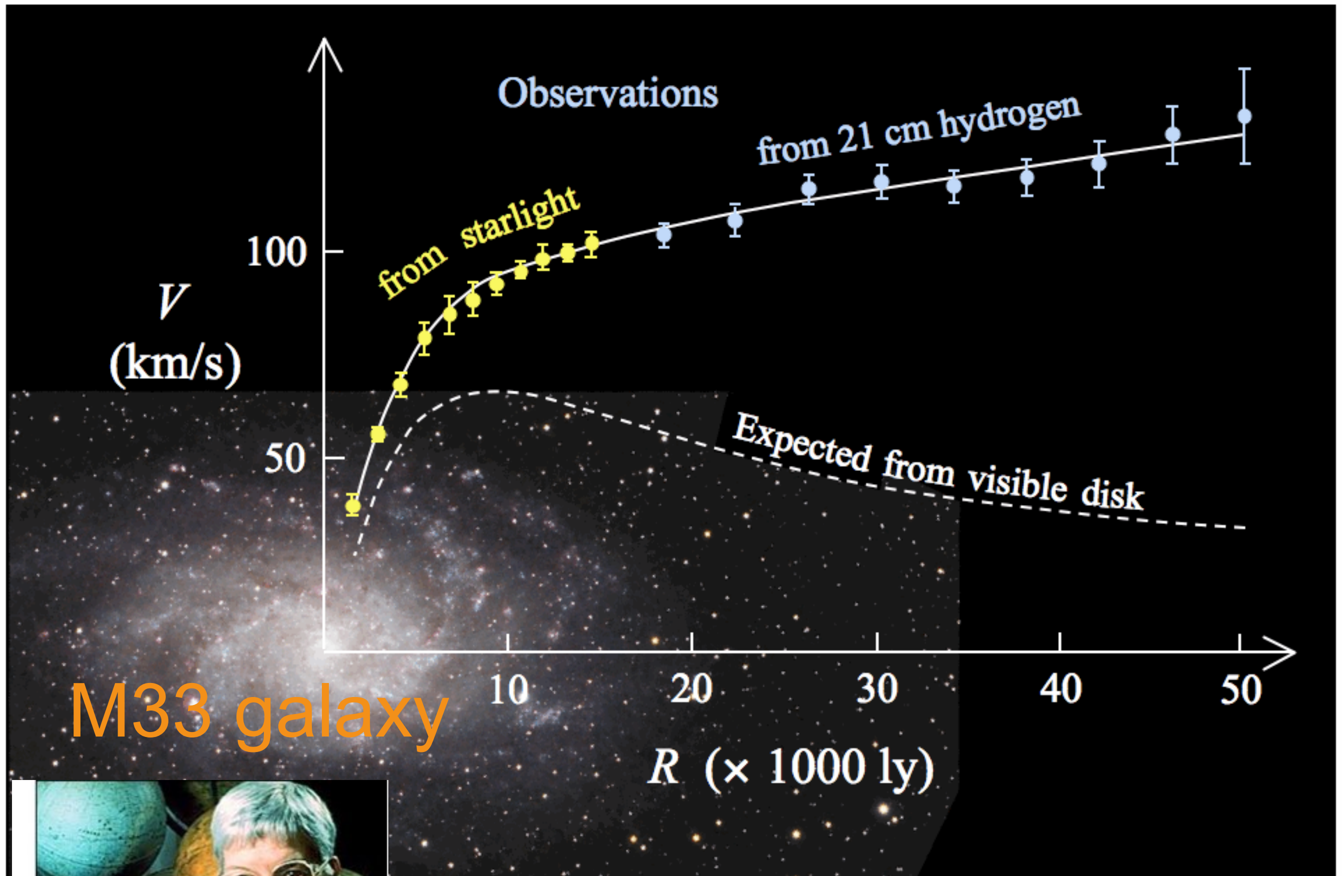
☞ New Unknown Gas: Argon

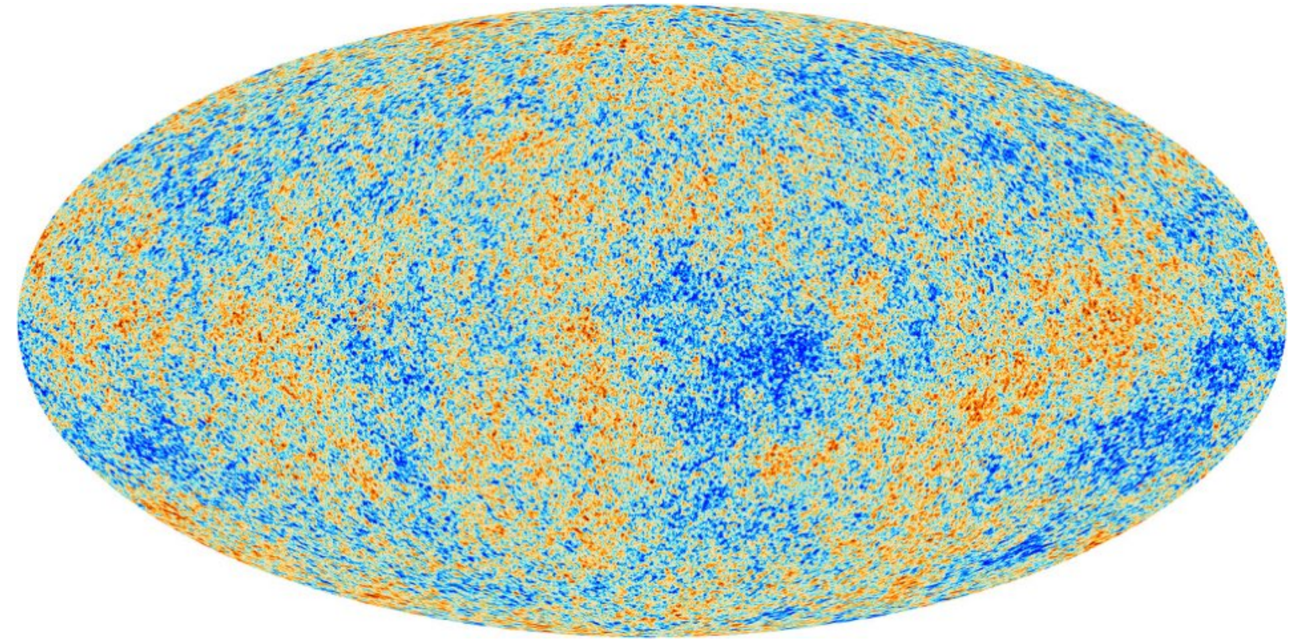
What Is Dark Matter?

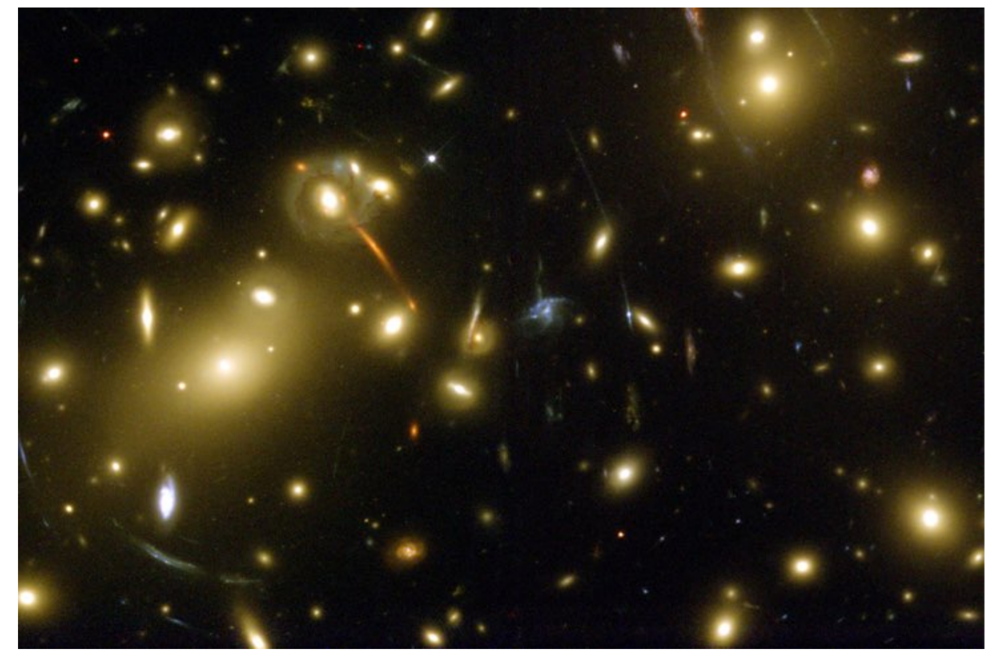
- “Dark Matter” is a temporary name

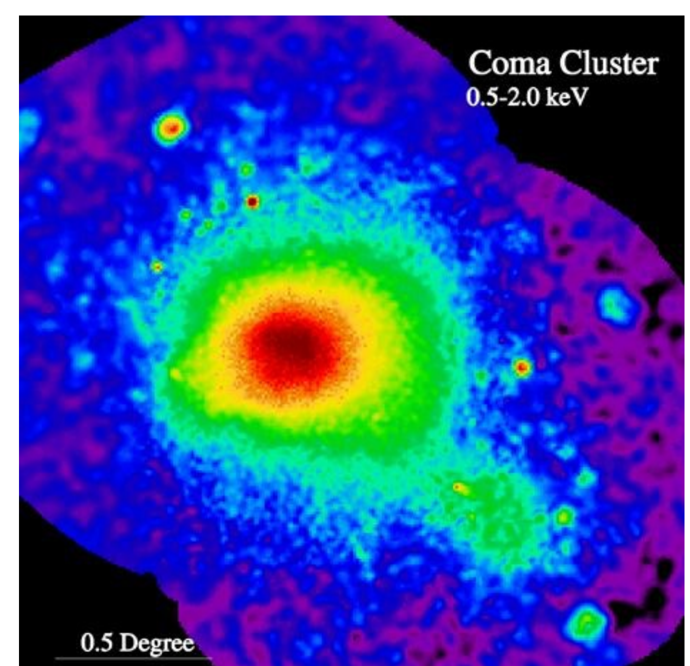
- Influenced by gravitational interaction and no other standard model (SM) interactions
- Interact weakly with normal matter →may need a new type of interaction

Why Dark Matter?

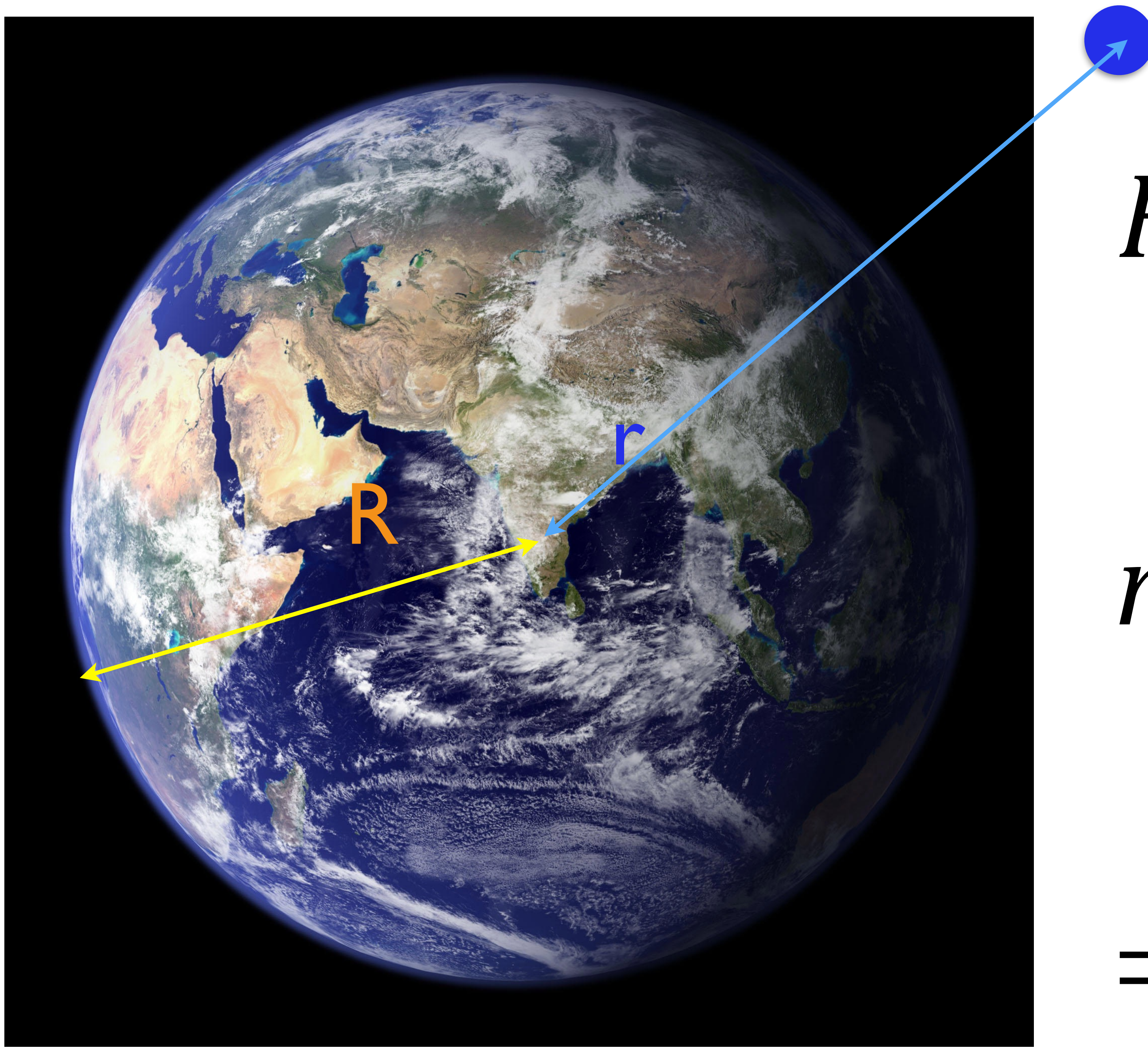








Reminder of Gravitation Law (Outside the Earth)

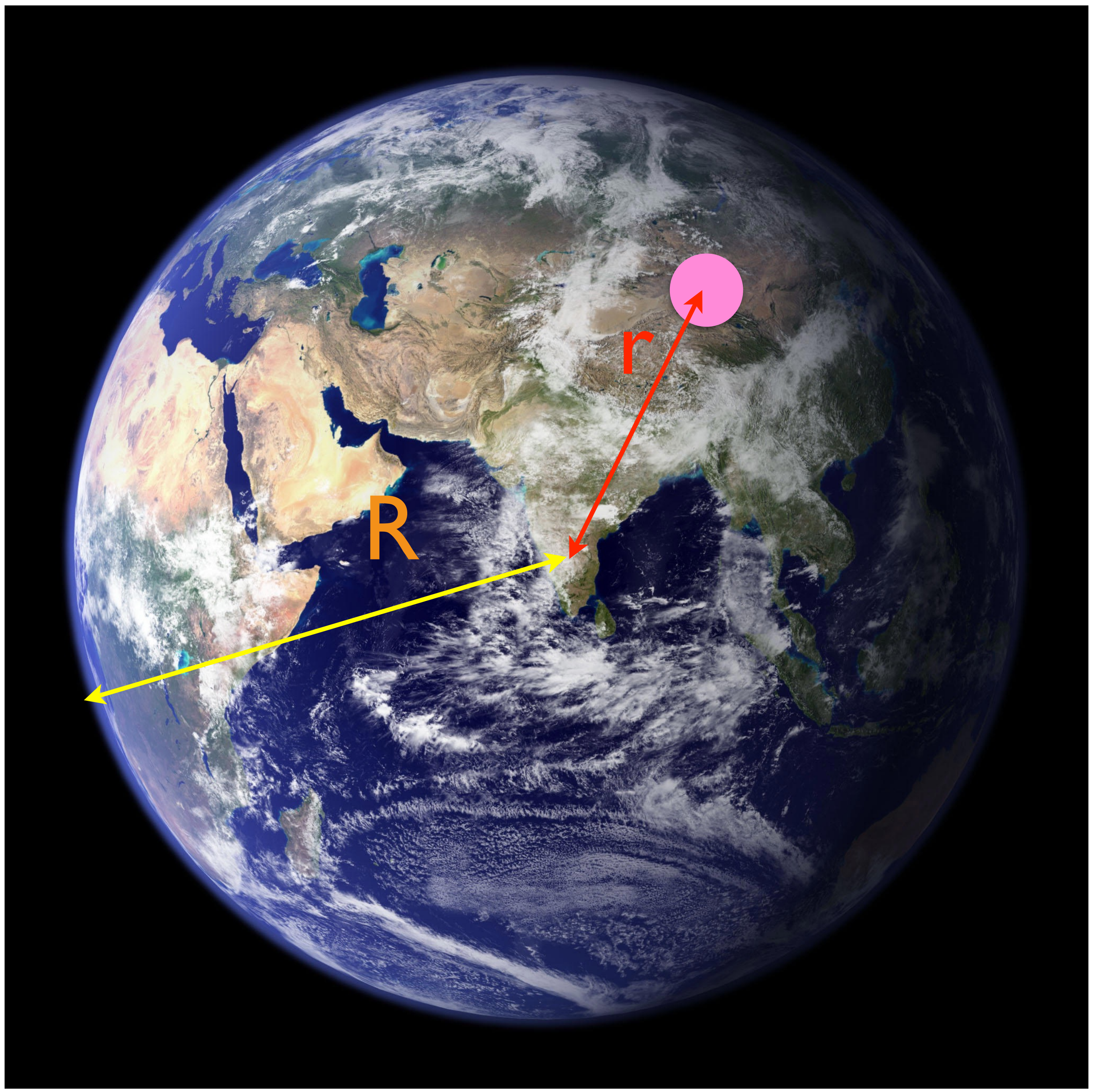


$$F\left(r > R\right) \propto \frac{M_{\text{total}}}{r^2}$$

$$m\frac{v^2_{\text{particle}}}{r} \propto \frac{M_{\text{total}}}{r^2}$$

$$\Rightarrow v_{\text{particle}} \propto \sqrt{\frac{M_{\text{total}}}{r}}$$

Reminder of Gravitation Law: Inside the Earth



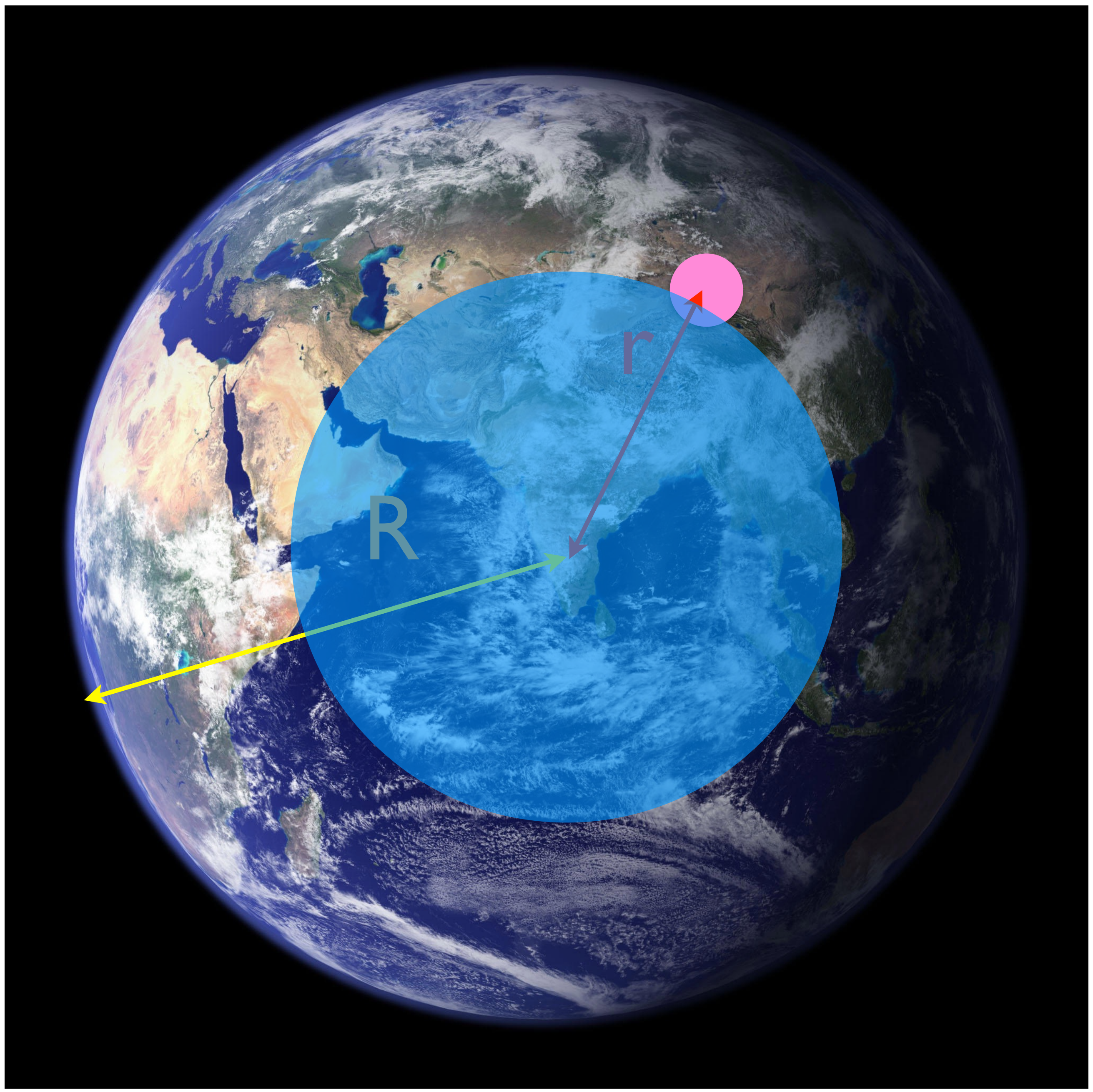
$$F(r<R) \propto \frac{M(r)}{r^2}$$

$$= \frac{\rho\left(\frac{4\pi}{3}r^3\right)}{r^2} = r$$

$$m\frac{v^2_{\text{particle}}}{r} \propto r$$

$$\Rightarrow v_{\text{particle}} \propto r$$

Reminder of Gravitation Law: Inside the Earth



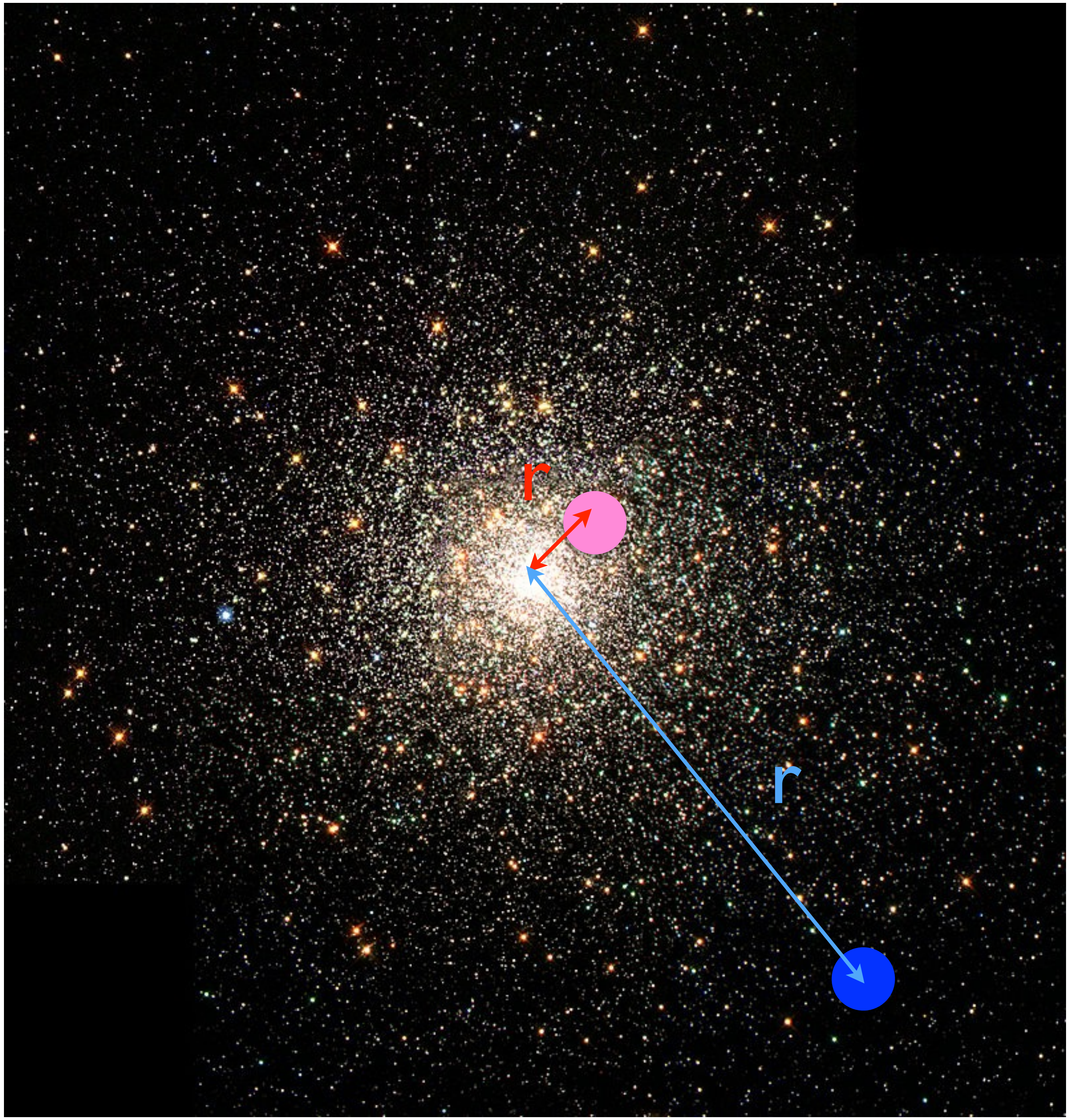
$$F(r<R) \propto \frac{M(r)}{r^2}$$

$$= \frac{\rho\left(\frac{4\pi}{3} r^3\right)}{r^2} = r$$

$$m\frac{v^2_{\text{particle}}}{r} \propto r$$

$$\Rightarrow v_{\text{particle}} \propto r$$

Extended to the Stars in a Galaxy

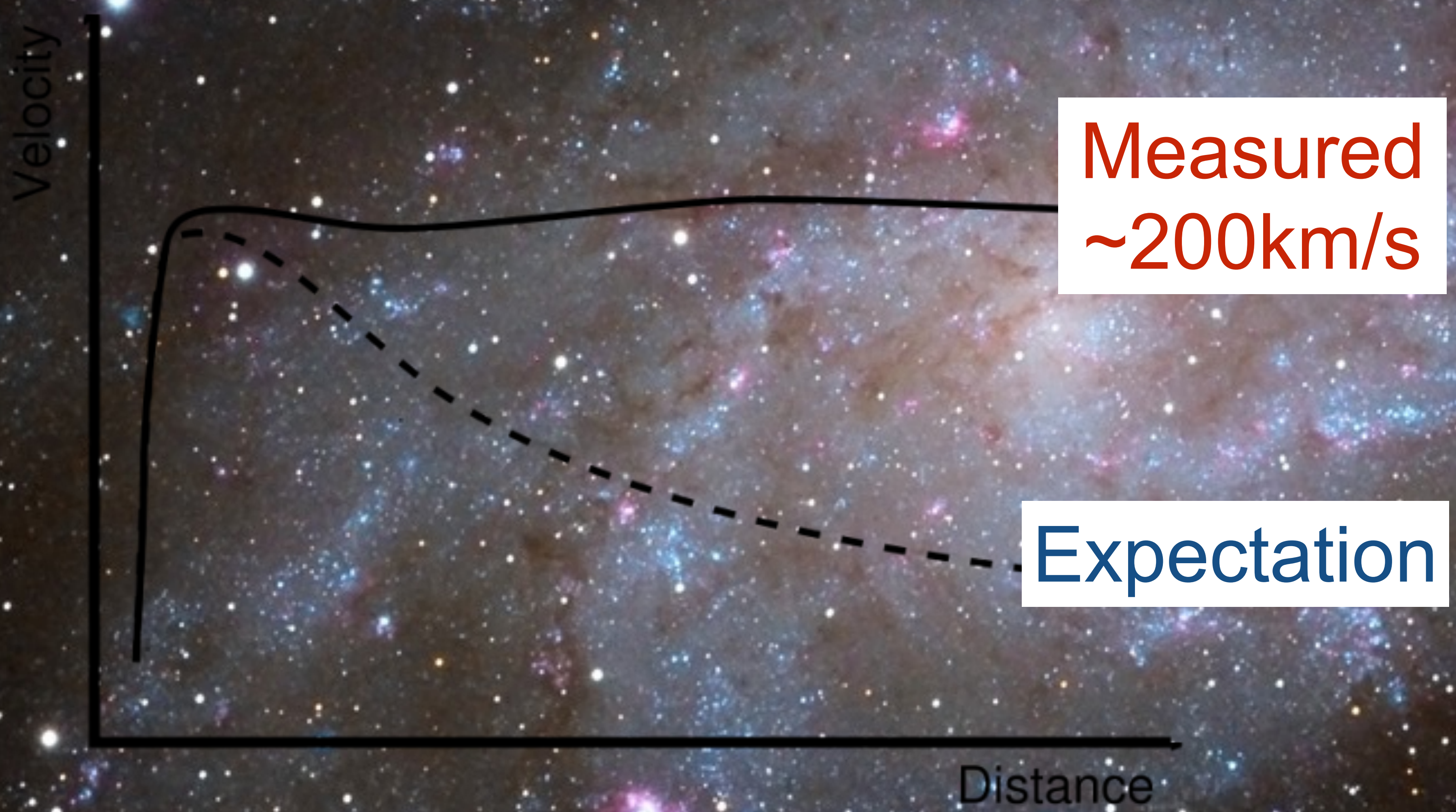


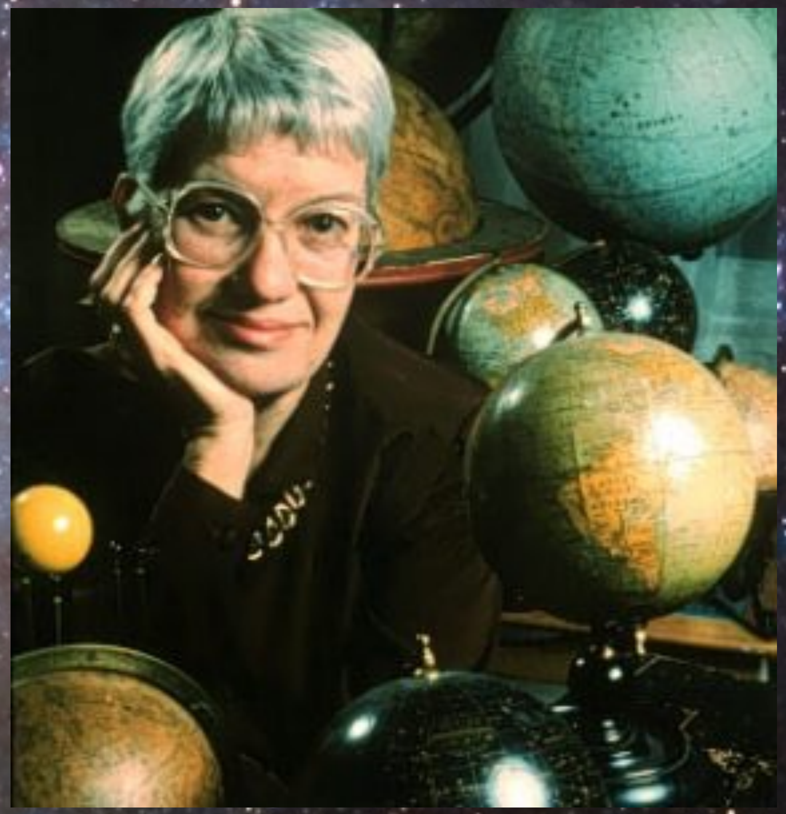
$$v \propto \sqrt{\frac{M(r)}{r}}$$

$$v(r<R) \propto r$$

$$v(r>R) \propto \frac{1}{\sqrt{r}}$$

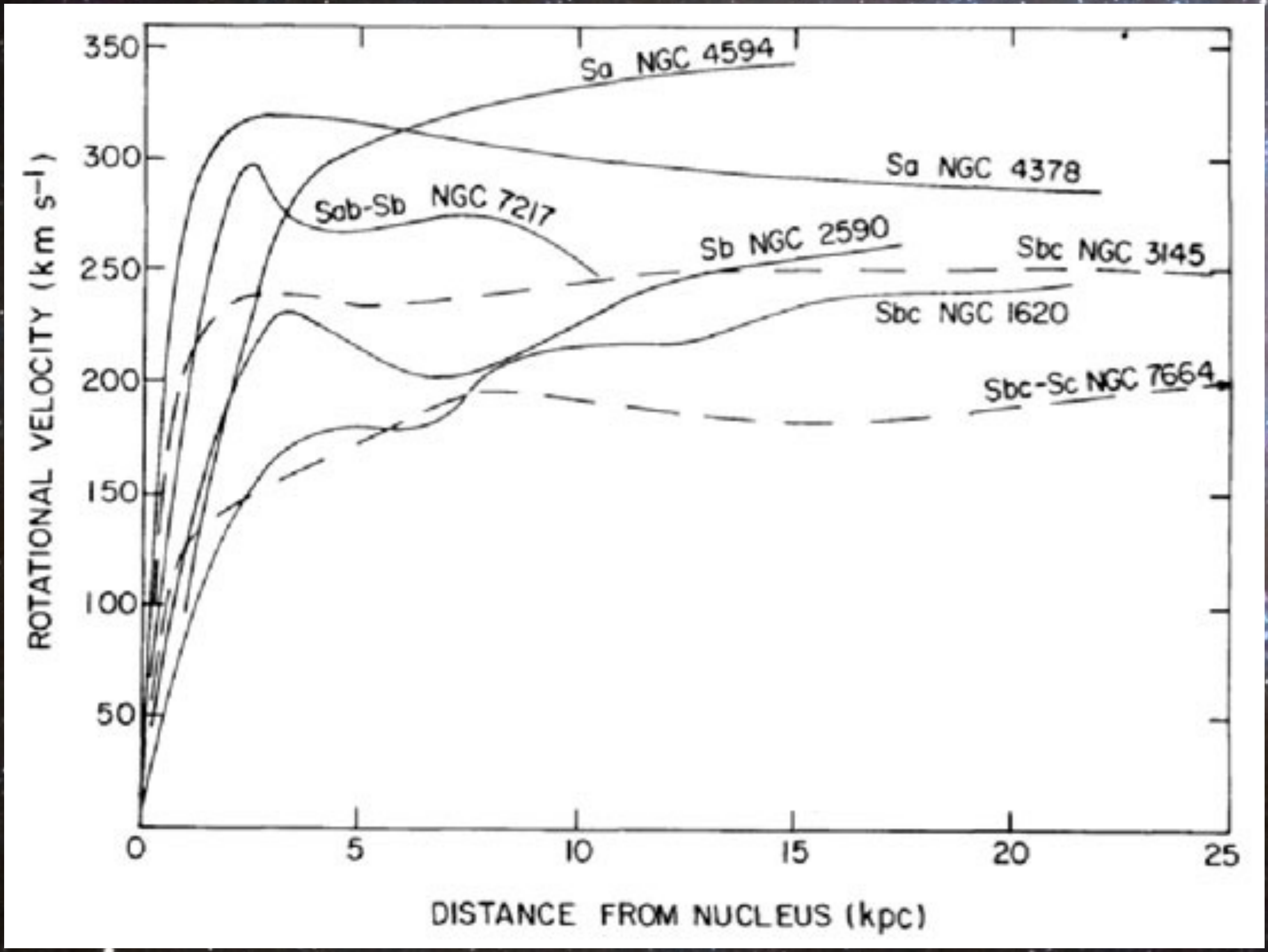
Rotational Curves

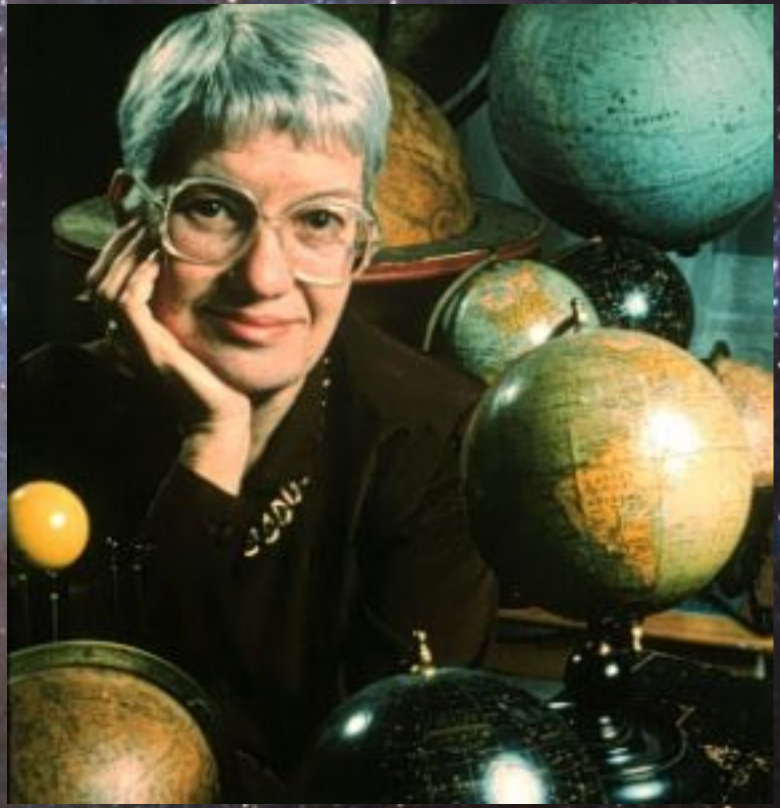




Vera Rubin
1928-2016

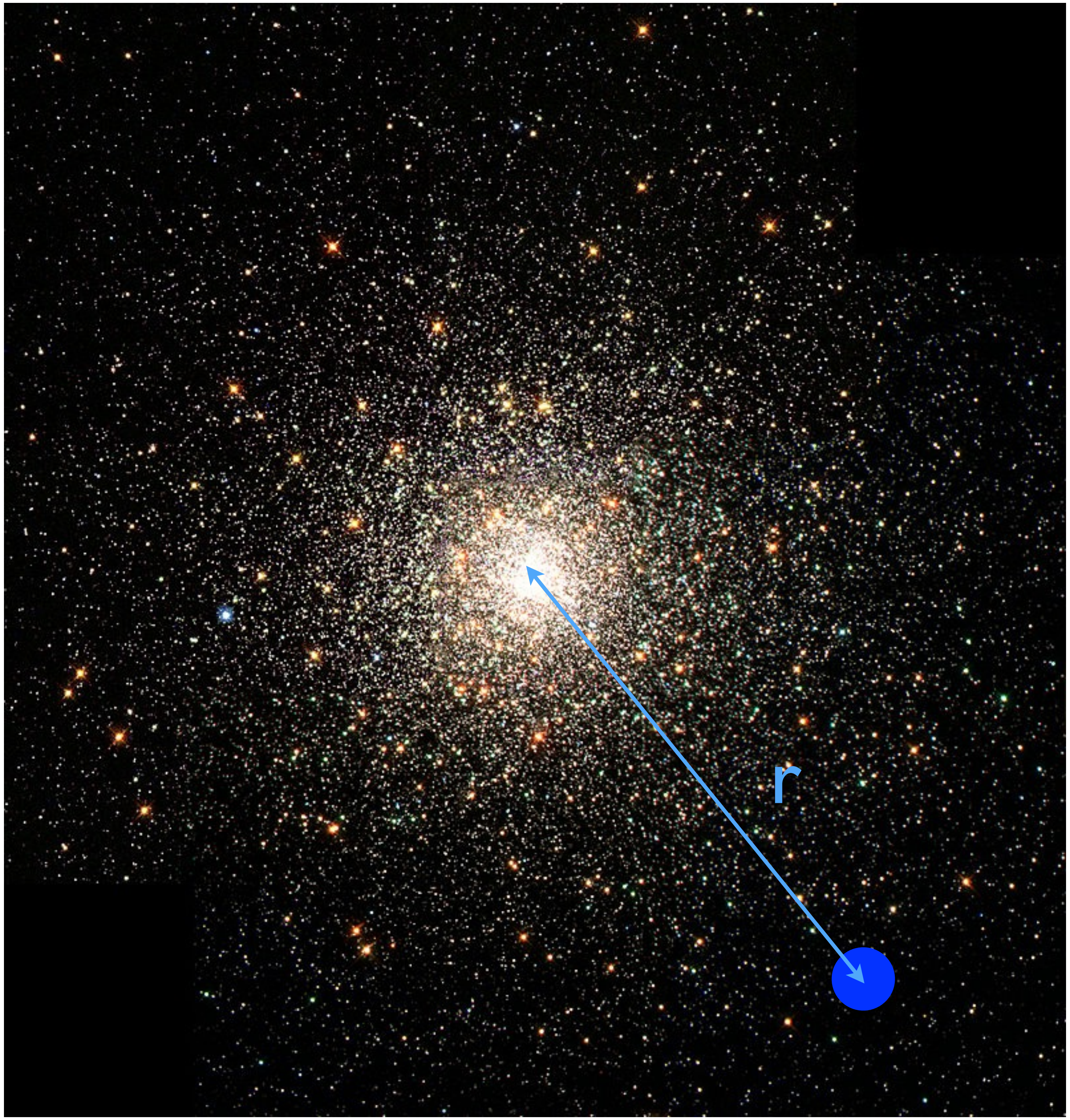
Rotational Curves





Vera Rubin
1928-2016

Extended to the Stars in a Galaxy

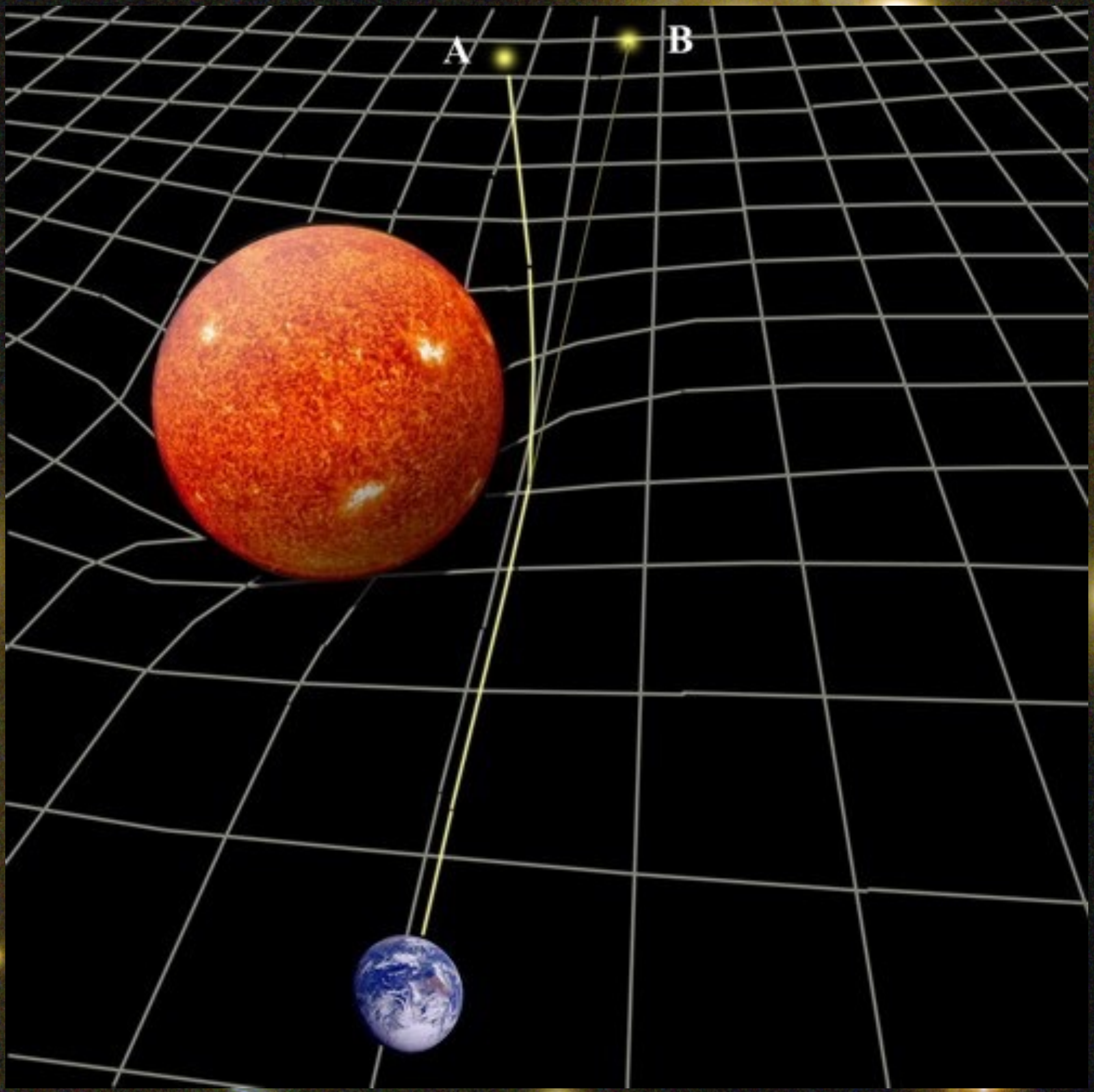


$$v_{\text{particle}}\left(r>R\right)\propto\sqrt{\frac{M_{\text{total}}}{r}}$$

$$v_{\text{particle}}\left(r>R\right)\propto\sqrt{\frac{M\left(r\right)}{r}}$$

$$\Rightarrow M\left(r\right)\propto r$$

Gravitation Lensing

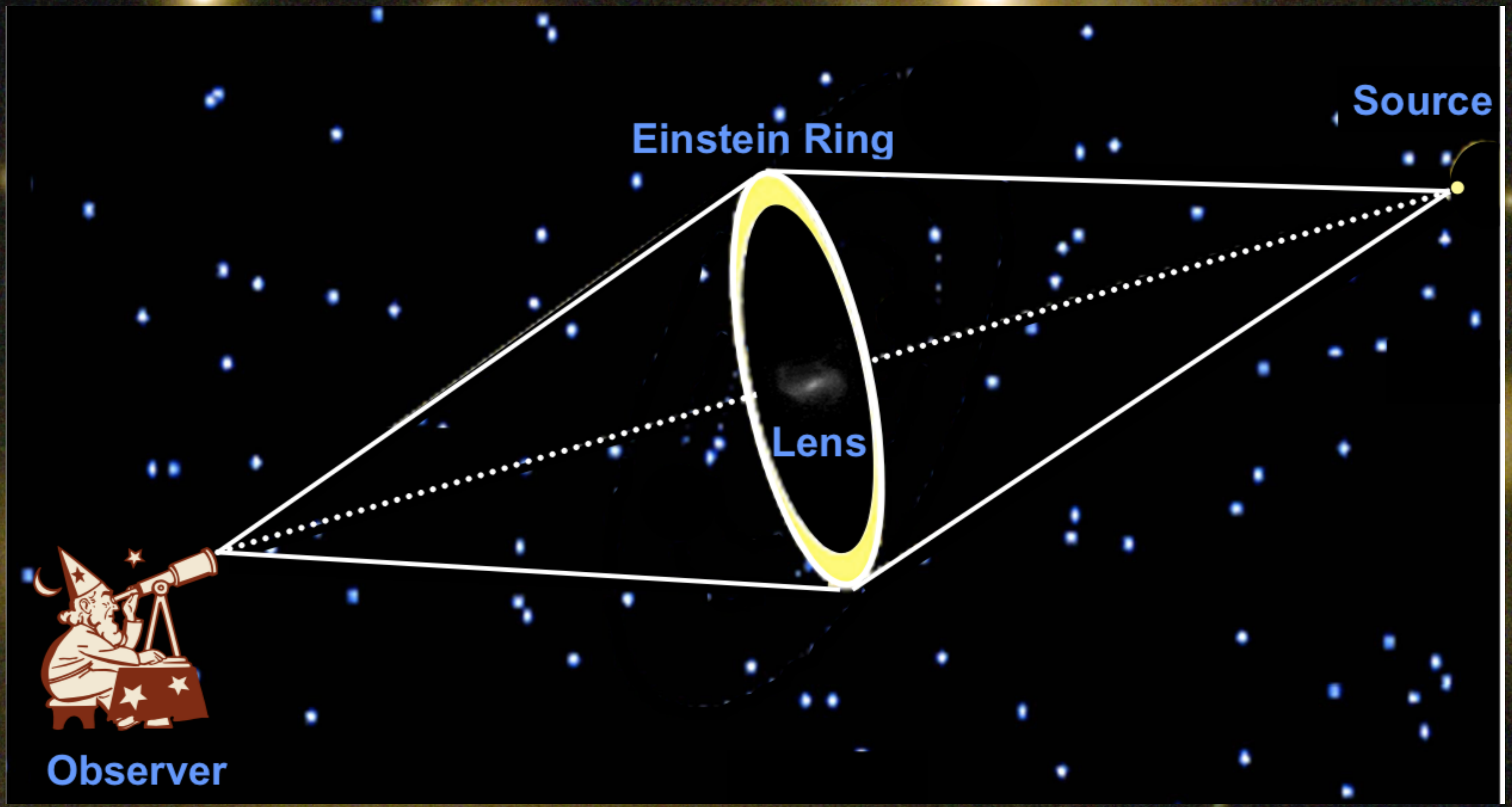


The size of the Einstein ring is related to the mass of the lensing

$$\theta \propto \sqrt{M_{\text{lense}}}$$

Abell 2218 Cluster

Gravitation Lensing

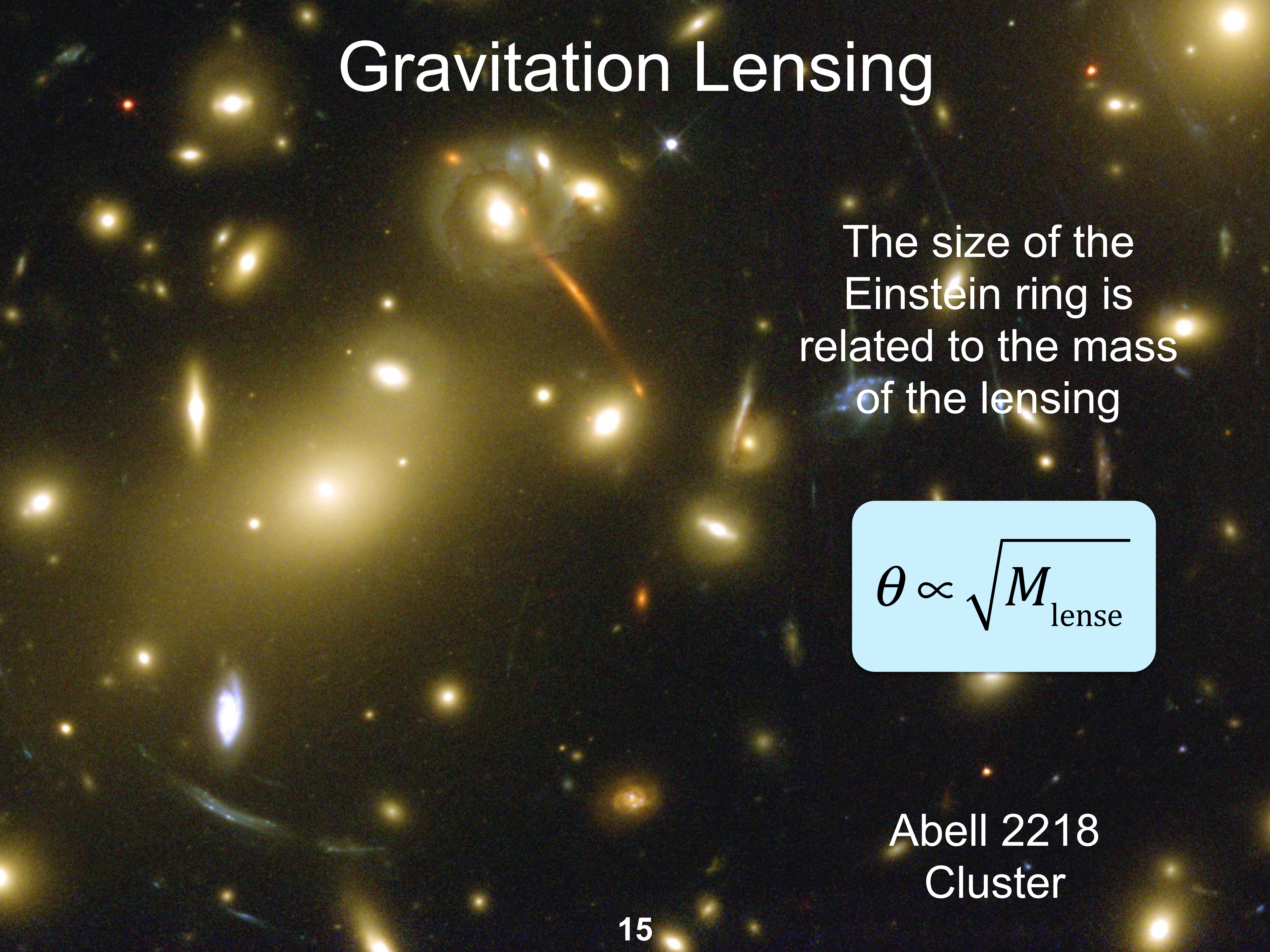


The size of the Einstein ring is related to the mass of the lensing

$$\theta \propto \sqrt{M_{\text{lense}}}$$

Abell 2218 Cluster

Gravitation Lensing

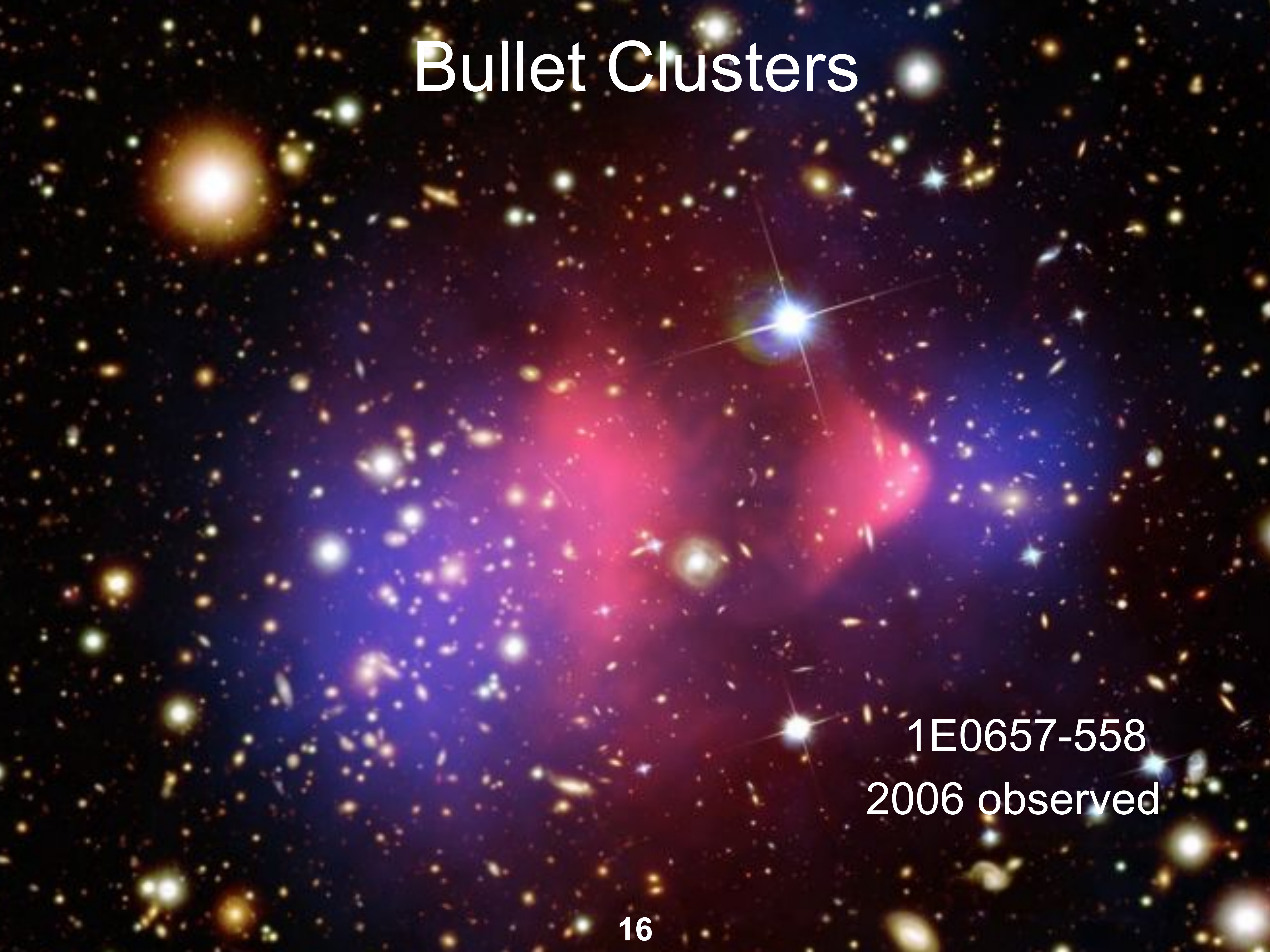


The size of the Einstein ring is related to the mass of the lensing

$$\theta \propto \sqrt{M_{\text{lense}}}$$

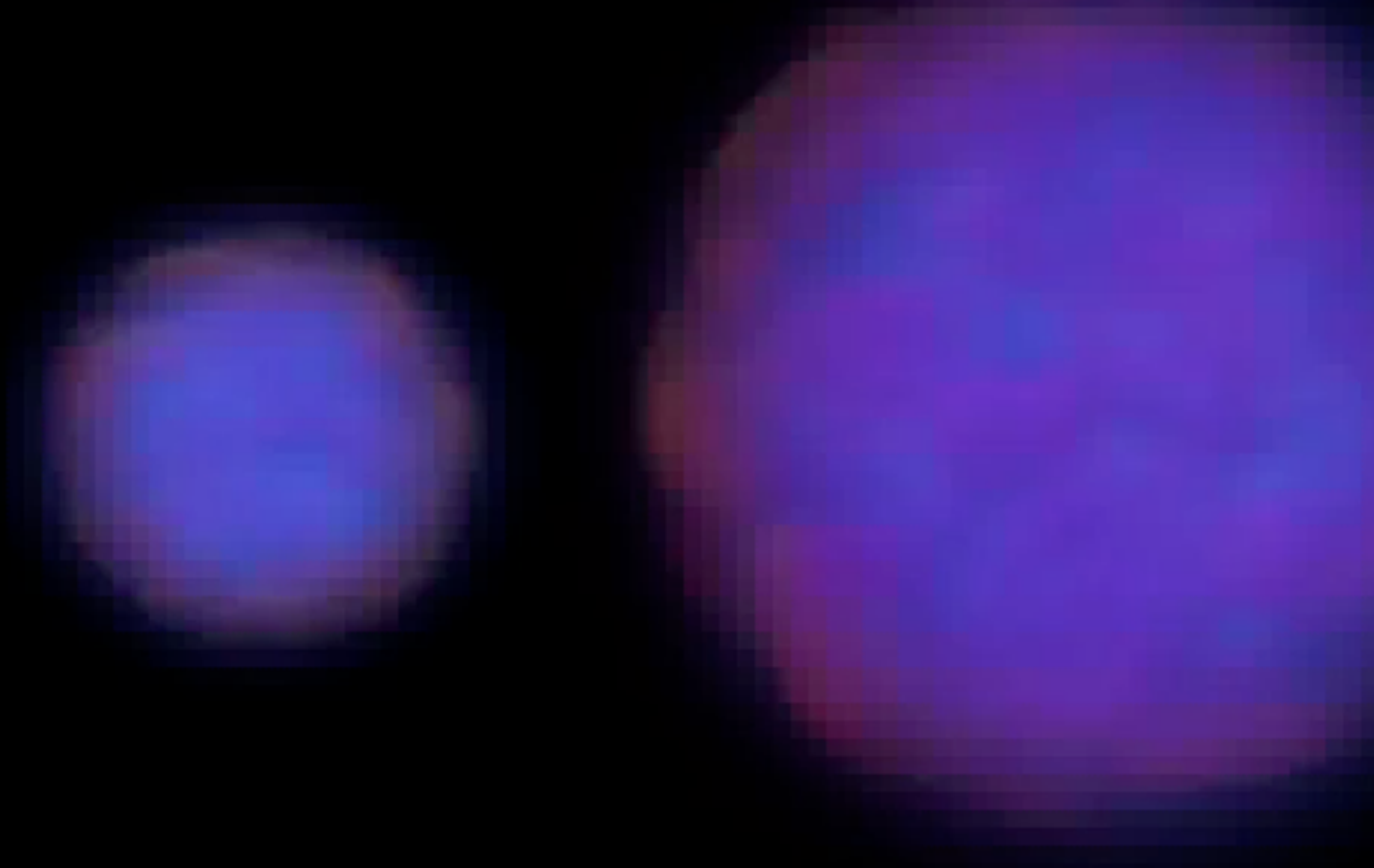
Abell 2218 Cluster

Bullet Clusters

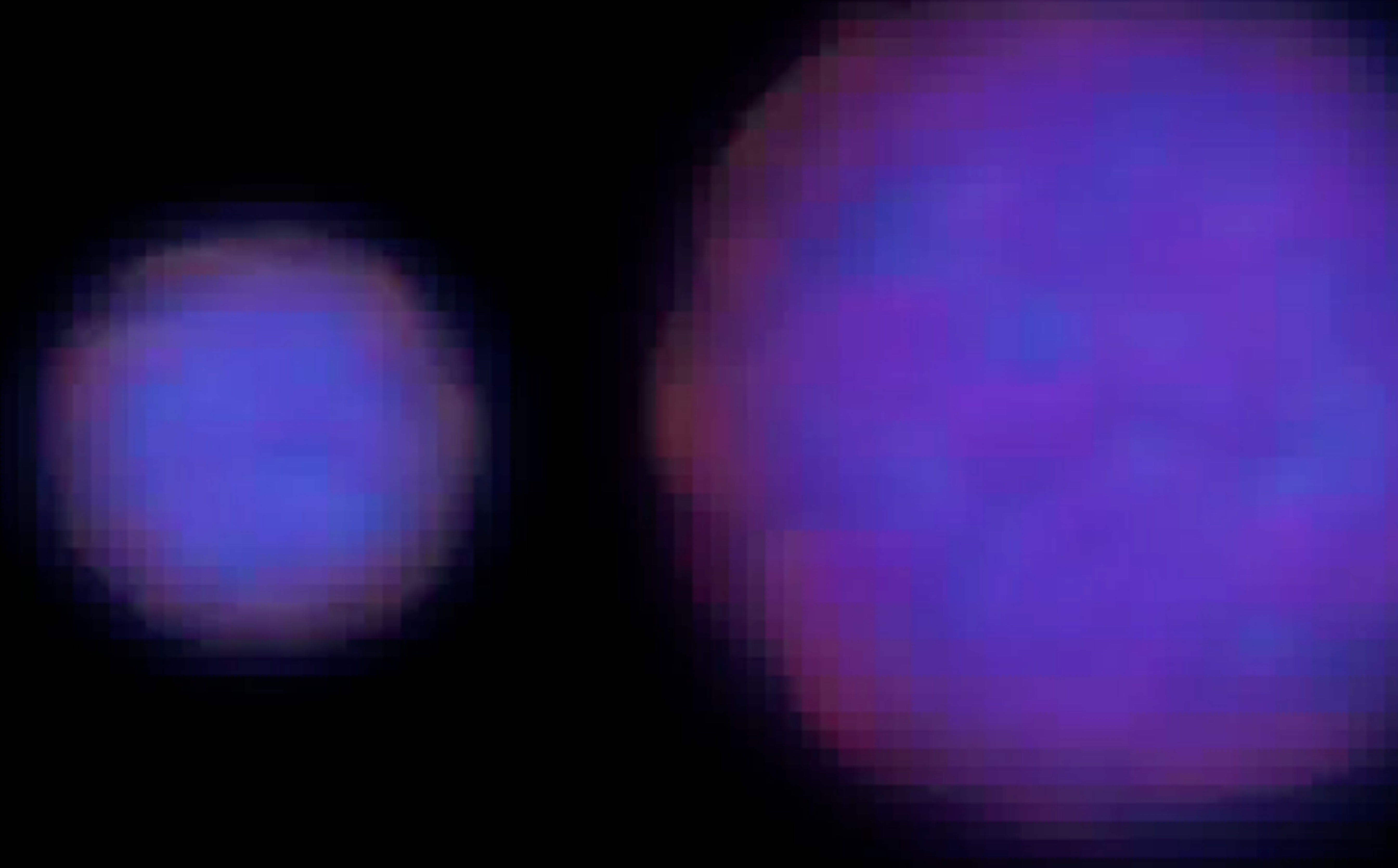


Bullet Clusters

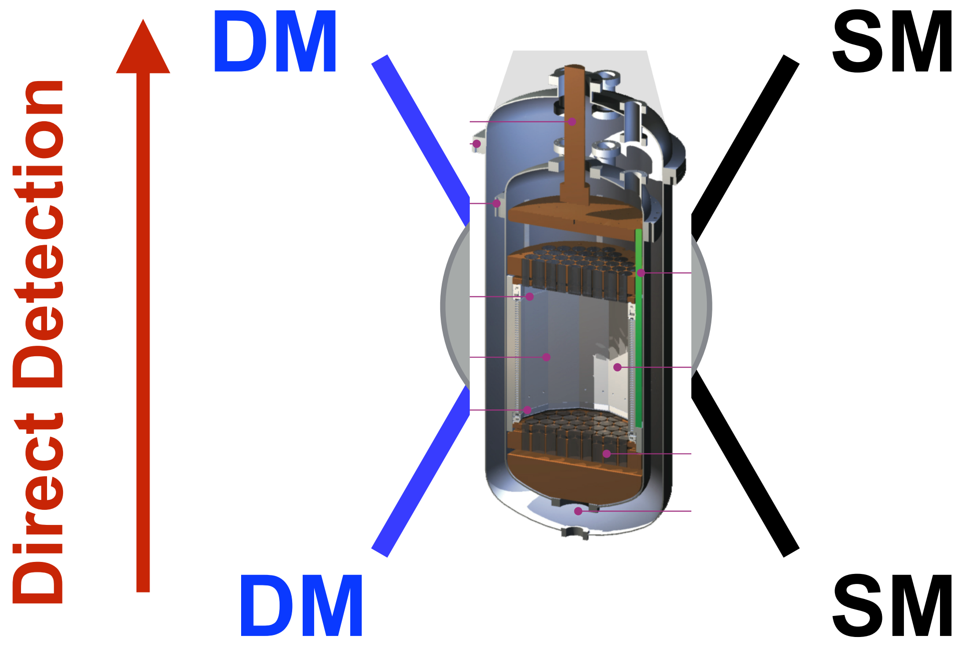
Bullet Clusters

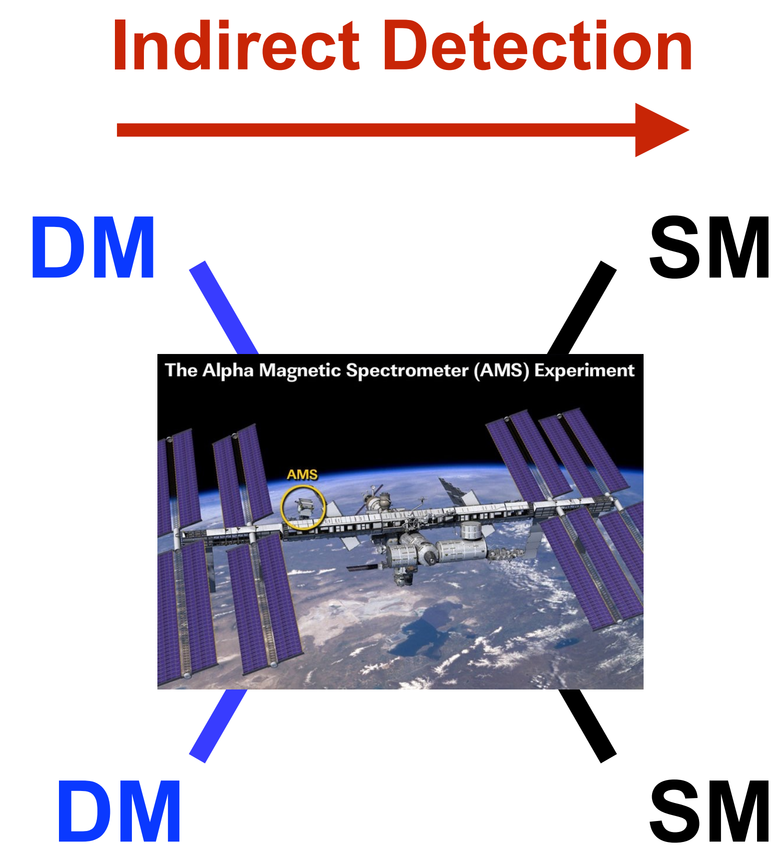


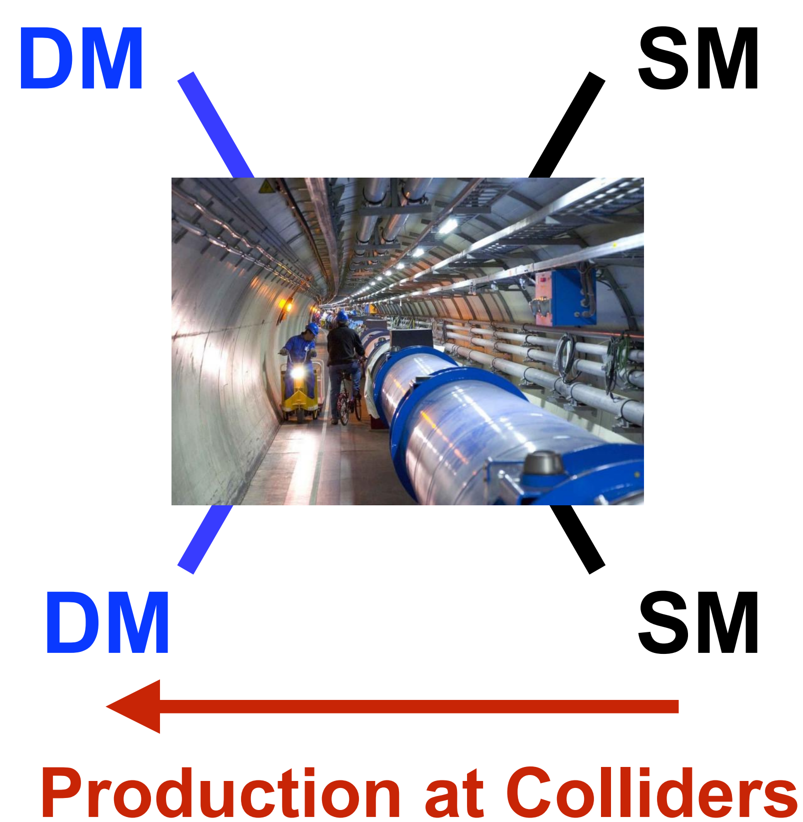
Bullet Clusters



Dark Matter Detection

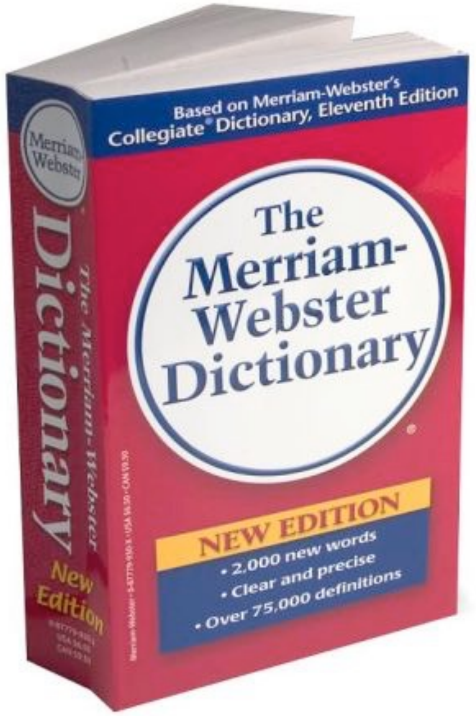






Introduction to LHC and CMS

- **CERN**
  - Conseil Européen pour la Recherche Nucléaire
  - European Council for Nuclear Research
  - Location of LHC and the experiments



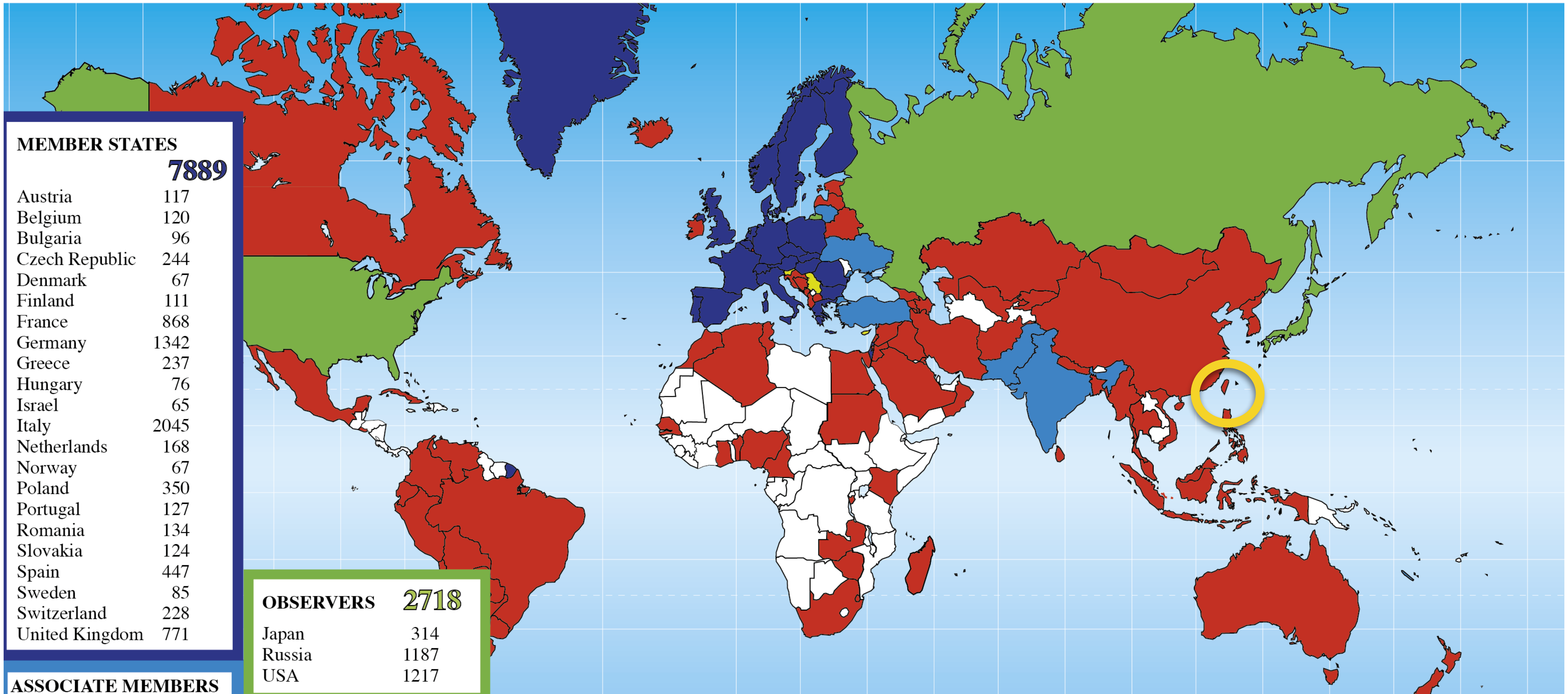
CERN

- Established by 12 European countries on 1954/09/29
- Origin of WWW
  - Tim Berners-Lee in 1989
- Director
  - Fabiola Gianotti

- 23 member states
- Yearly budget～10^9 CHF (= 3.2×10^{10} TWD)
  - Germany、UK、France、Italy
  - LHC cost ~ 4.3×10^9 CHF

Users Around the World

Distribution of All CERN Users by Nationality on 24 January 2018



MEMBER STATES 7889

Austria	117
Belgium	120
Bulgaria	96
Czech Republic	244
Denmark	67
Finland	111
France	868
Germany	1342
Greece	237
Hungary	76
Israel	65
Italy	2045
Netherlands	168
Norway	67
Poland	350
Portugal	127
Romania	134
Slovakia	124
Spain	447
Sweden	85
Switzerland	228
United Kingdom	771

OBSERVERS 2718

Japan	314
Russia	1187
USA	1217

ASSOCIATE MEMBERS 745

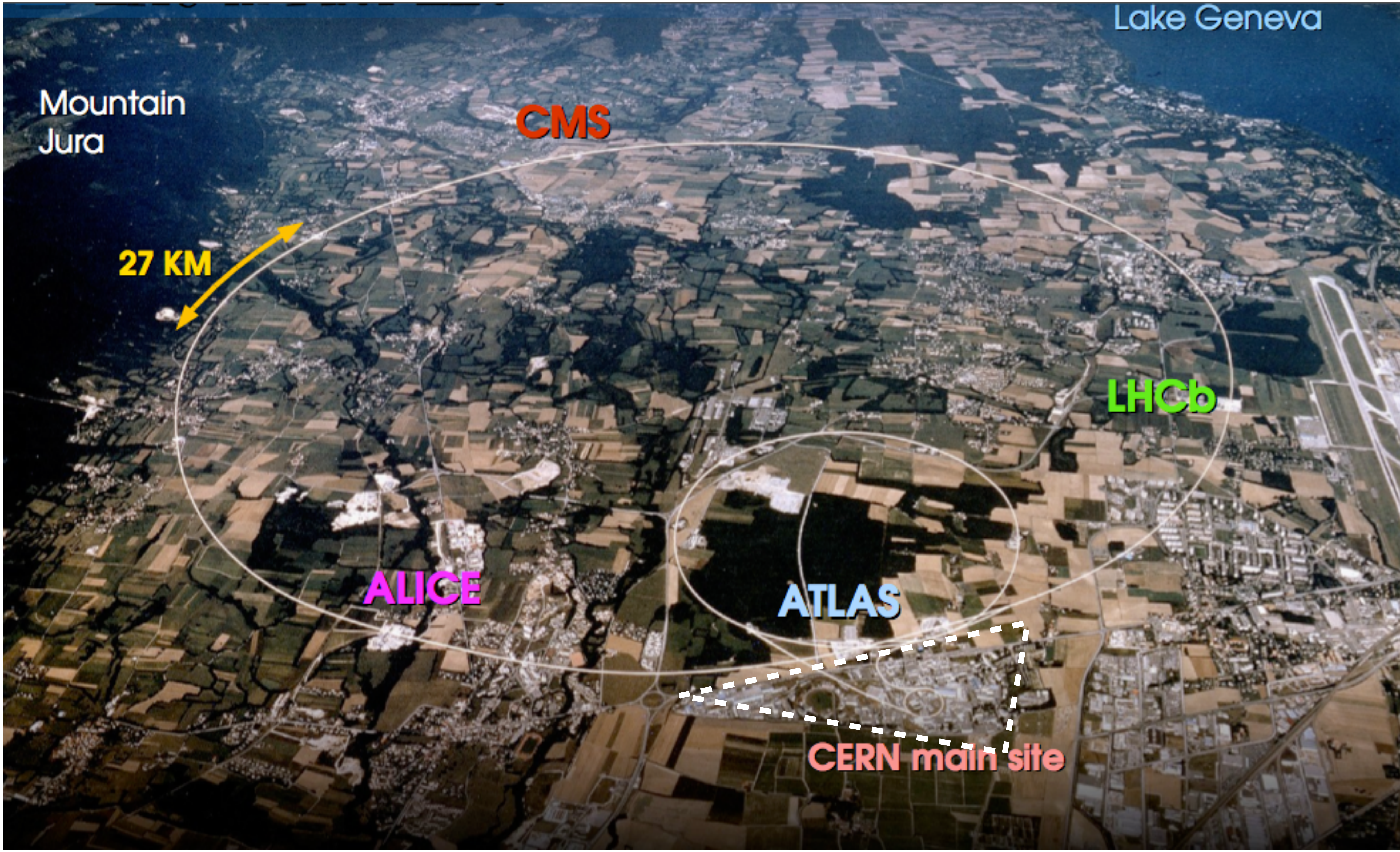
India	357
Lithuania	35
Pakistan	65
Turkey	173
Ukraine	115

ASSOCIATE MEMBERS IN THE PRE-STAGE TO MEMBERSHIP 118

Cyprus	26
Serbia	57
Slovenia	35

OTHERS 1872

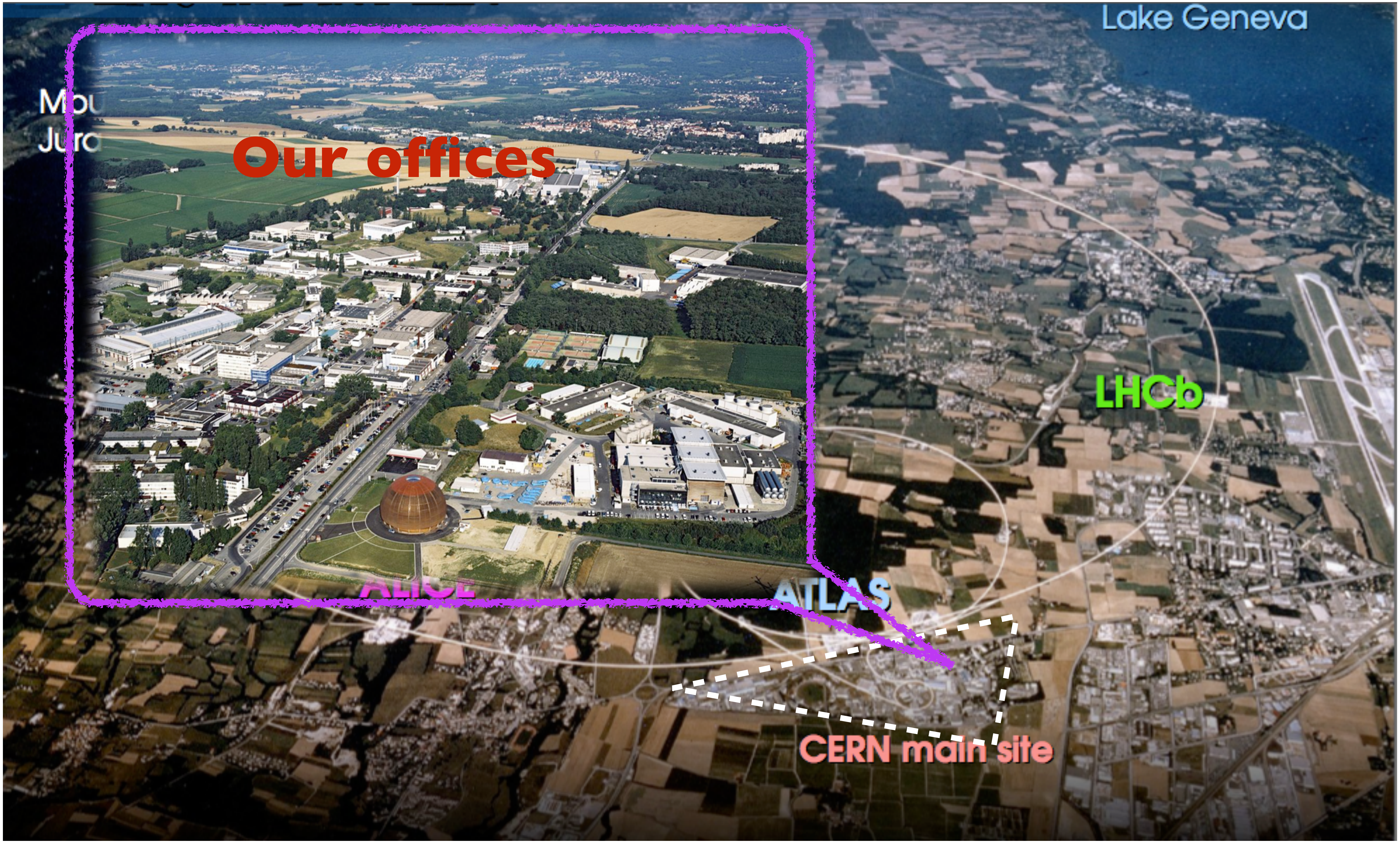
Afghanistan	1
Albania	3
Algeria	14
Argentina	27
Armenia	19
Australia	31
Azerbaijan	10
Bangladesh	11
Belarus	48
Benin	1
Bolivia	4
Bosnia & Herzegovina	2
Brazil	135
Burundi	1
Cameroon	1
Canada	161
Chile	20
China	510
Colombia	45
Croatia	41
Cuba	12
Ecuador	6
Egypt	31
El Salvador	1
Estonia	15
Georgia	46
Ghana	1
Hong Kong	1
Iceland	3
Indonesia	11
Iran	51
Iraq	1
Ireland	16
Jordan	1
Kazakhstan	5
Kenya	3
Korea Rep.	185
Kyrgyzstan	1
Latvia	2
Lebanon	23
Luxembourg	2
Madagascar	4
Malaysia	15
Malta	9
Mauritius	1
Mexico	82
Mongolia	2
Montenegro	11
Morocco	20
Myanmar	1
Nepal	10
New Zealand	5
Nigeria	3
North Korea	1
Oman	3
Palestine (O.T.).	7
Paraguay	2
Peru	7
Philippines	3
Saint Kitts and Nevis	1
Saudi Arabia	2
Senegal	1
Singapore	4
South Africa	56
Sri Lanka	6
Sudan	1
Swaziland	1
Syria	1
Taiwan	51
Thailand	22
T.F.Y.R.O.M.	2
Tunisia	5
Uruguay	1
Uzbekistan	4
Venezuela	10
Viet Nam	13
Zambia	1
Zimbabwe	2



LHC Birdview

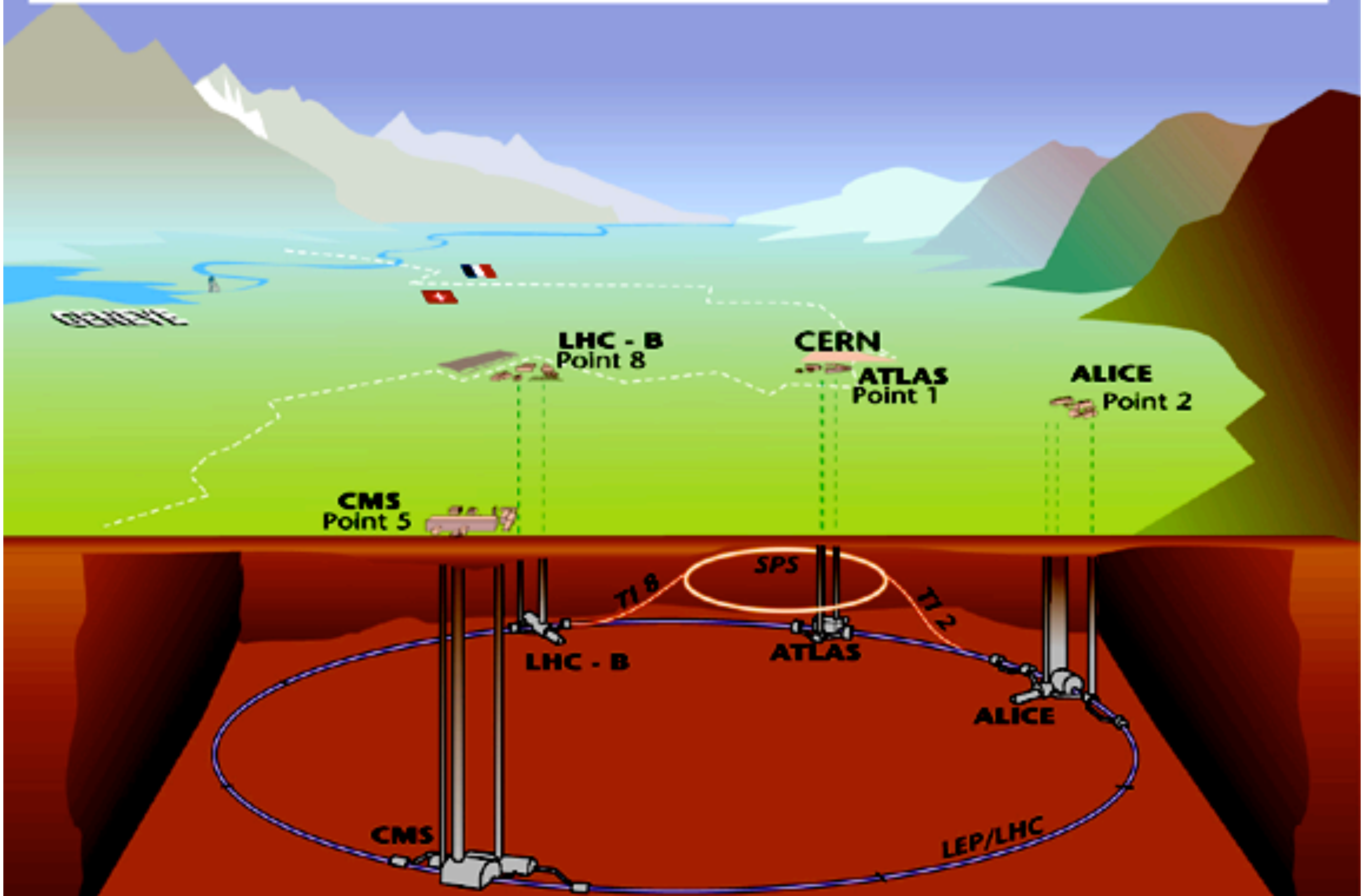
LHC Birdview

LHC Birdview



LHC Birdview

Overall view of the LHC experiments.



Tunnel circumference 26.7 km, tunnel diameter 3.8 m
Depth : ~ 50-175) m – tunnel is inclined by ~ 1.4%

LHC Tunnel

Magnetic dipole field: 8.3 Tesla
Beam-pipe pressure: 10^{-13} atm

1232 superconducting dipoles
Operating temperature: 1.9 K

LHC Tunnel

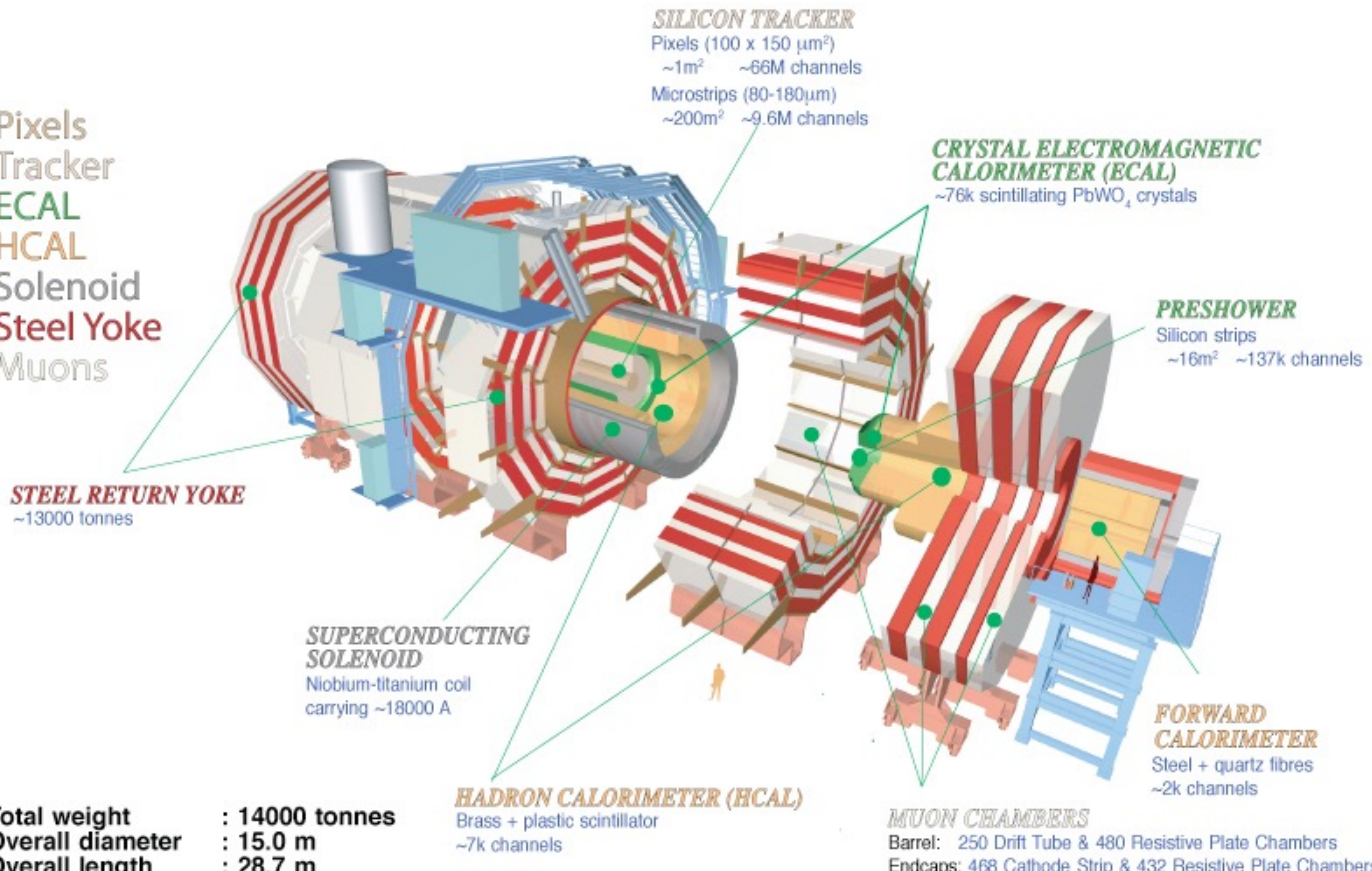
LHC Tunnel

Magnetic dipole field: 8.3 Tesla
Beam-pipe pressure: 10^{-13} atm

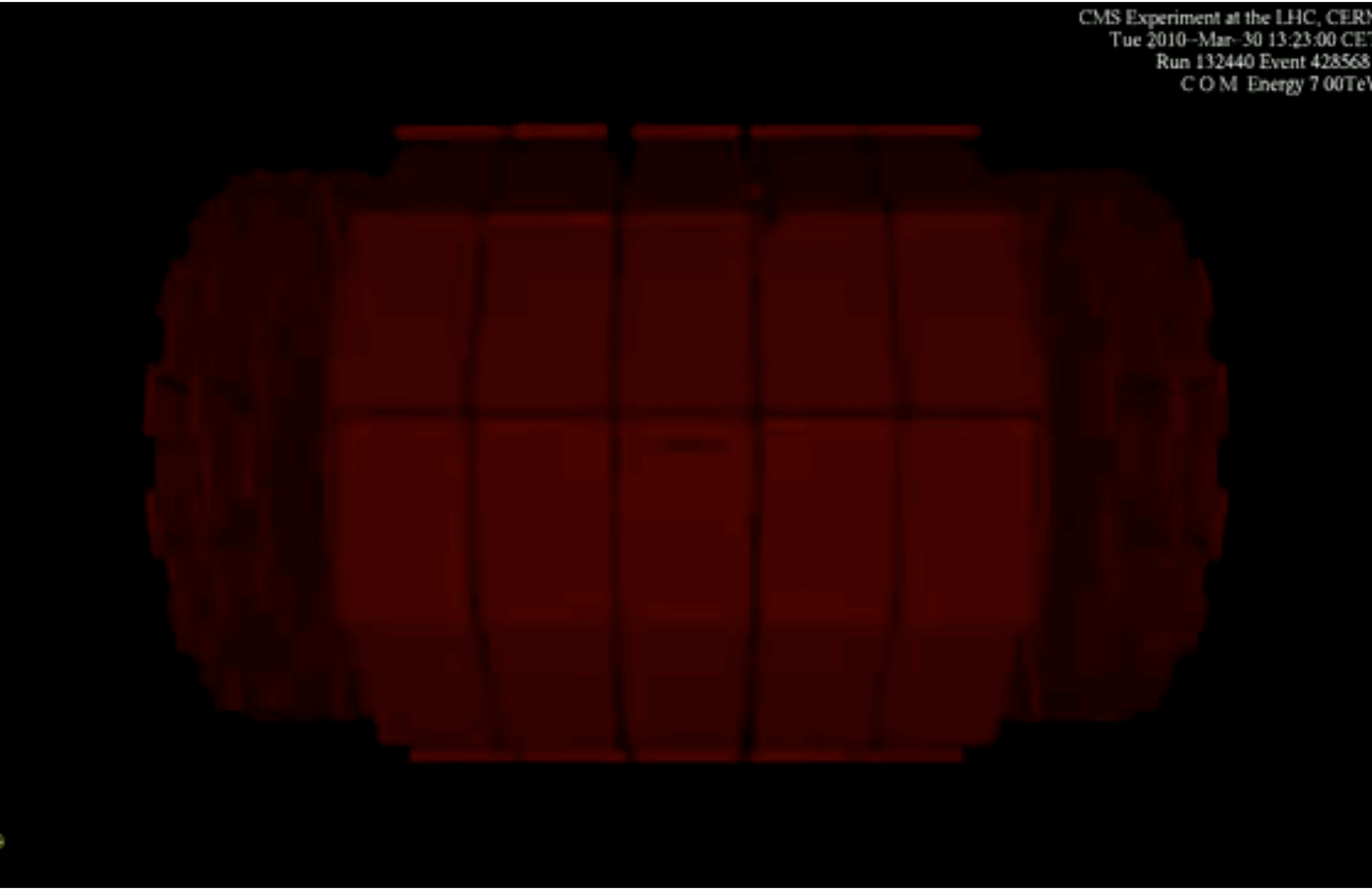
1232 superconducting dipoles
Operating temperature: 1.9 K

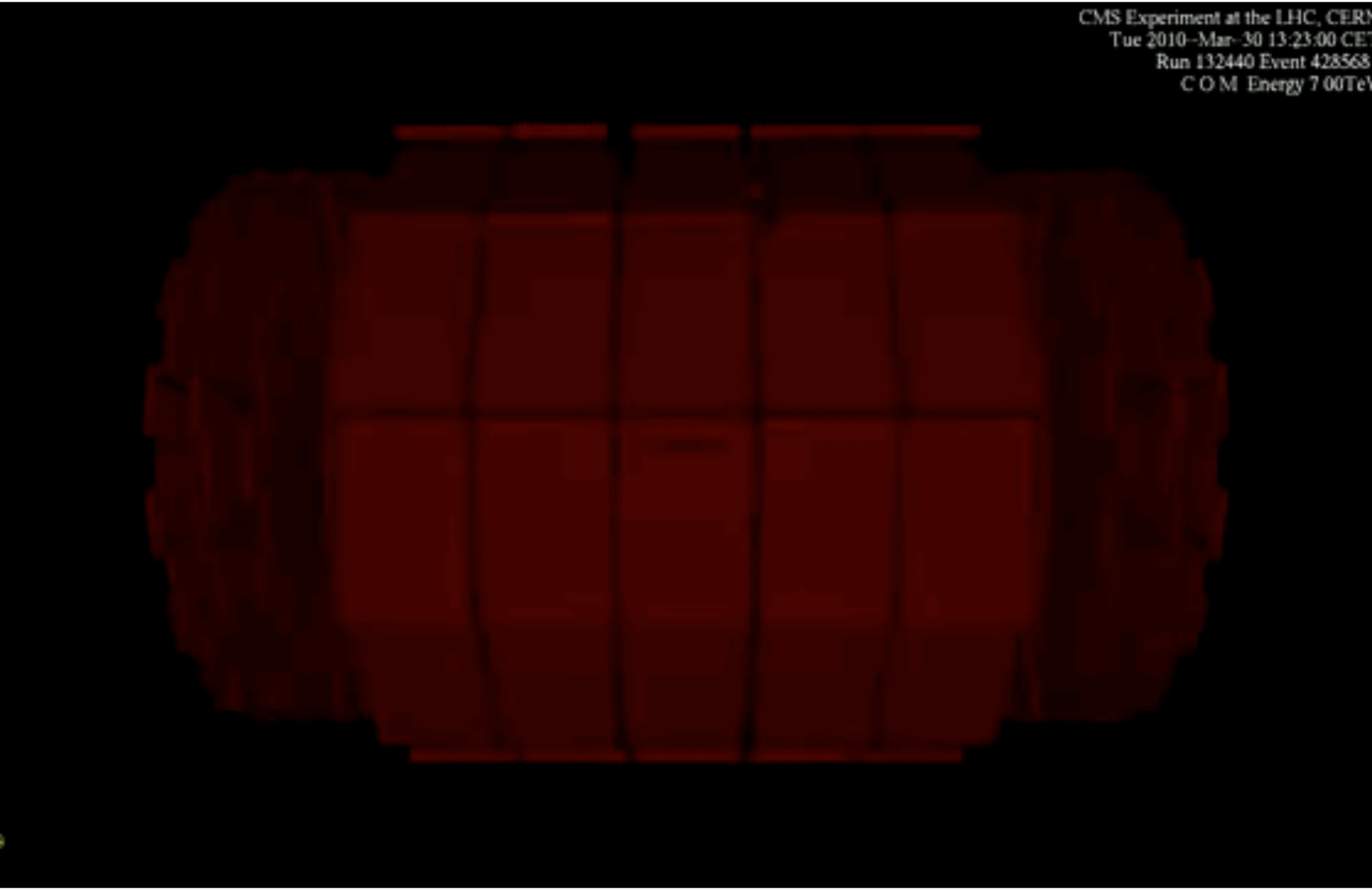
CMS Detector Sketch

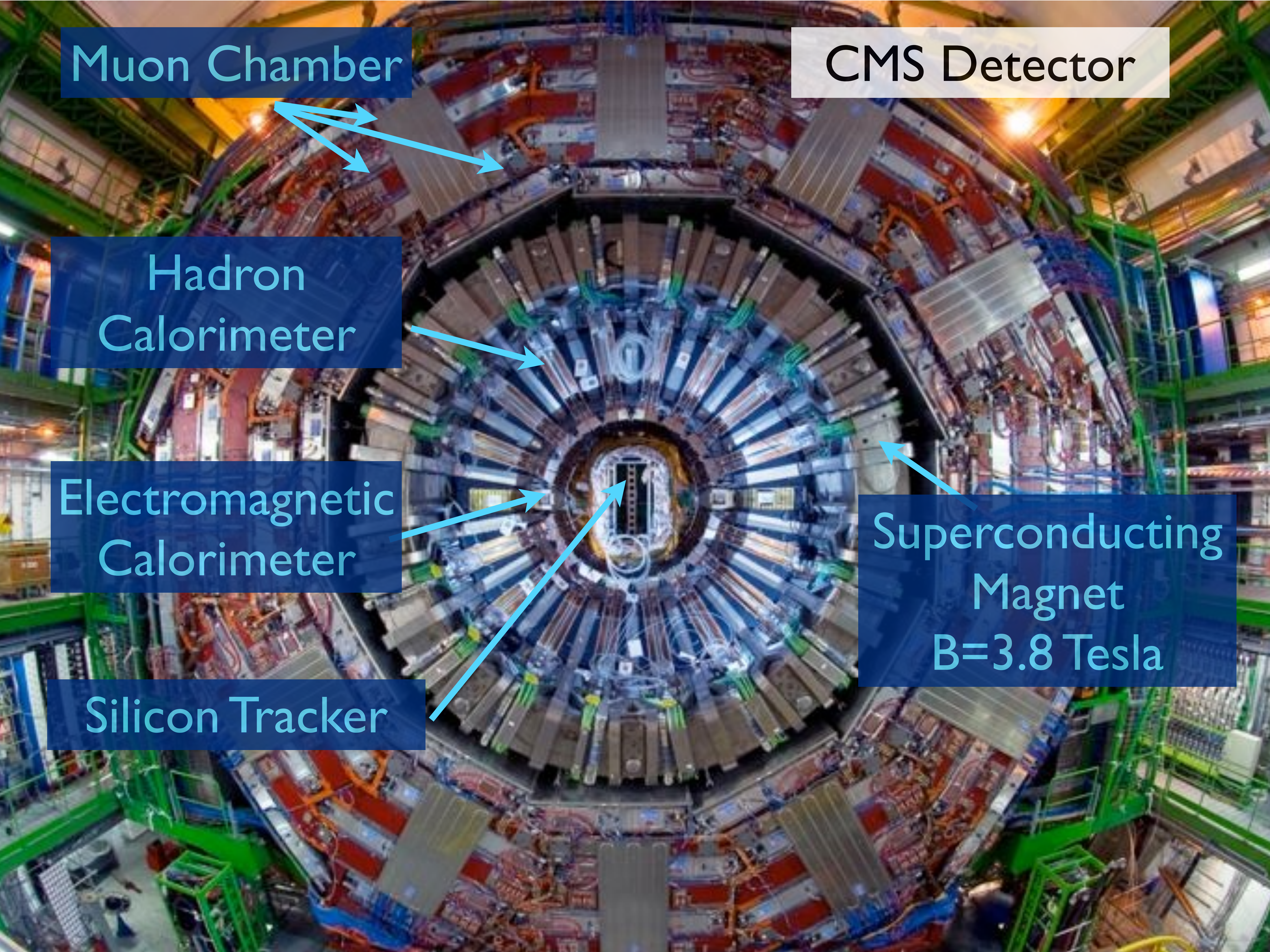
Pixels
Tracker
ECAL
HCAL
Solenoid
Steel Yoke
Muons

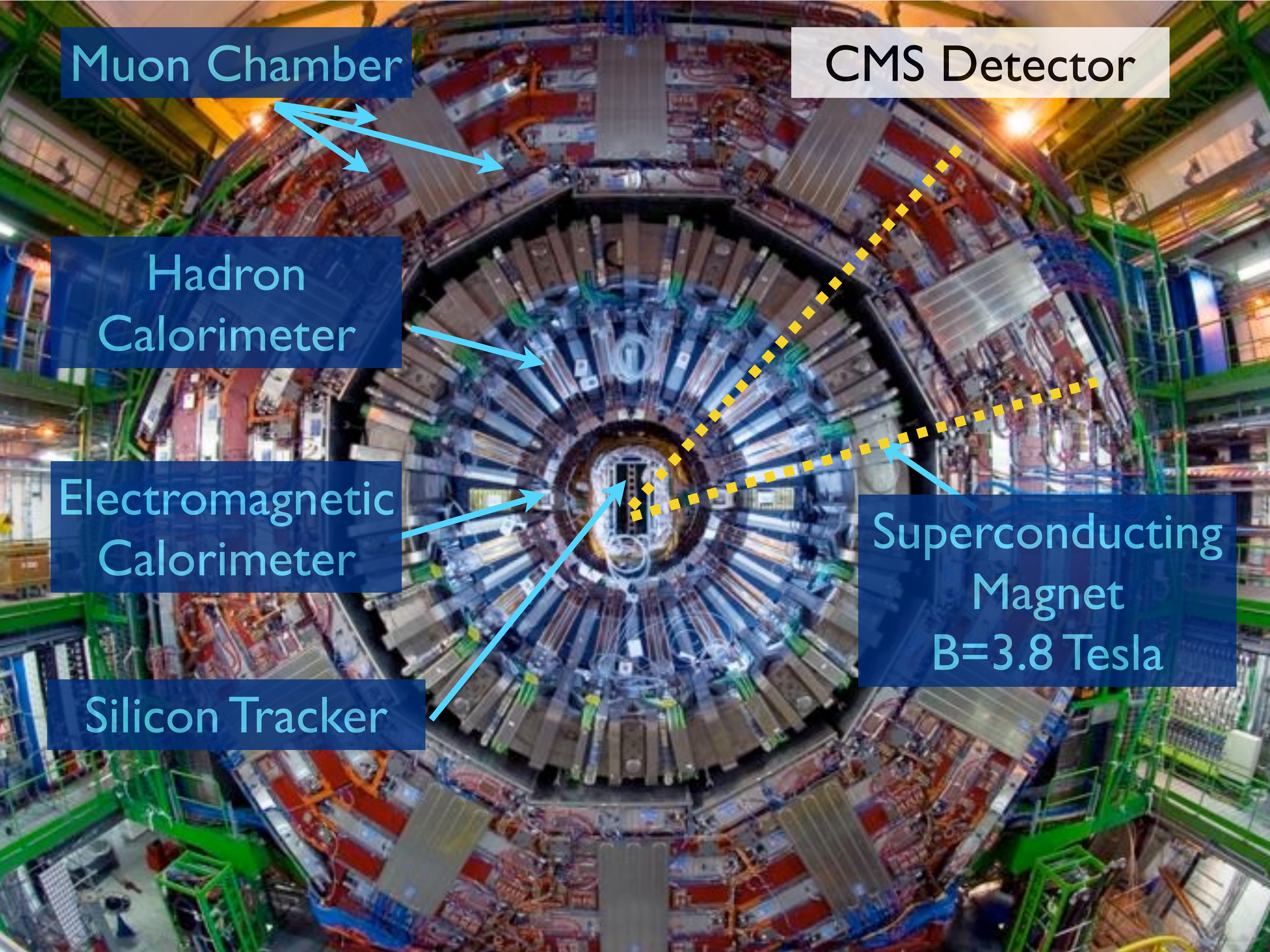


Total weight	**: 14000 tonnes**
Overall diameter	**: 15.0 m**
Overall length	**: 28.7 m**
Magnetic field	**: 3.8 T**

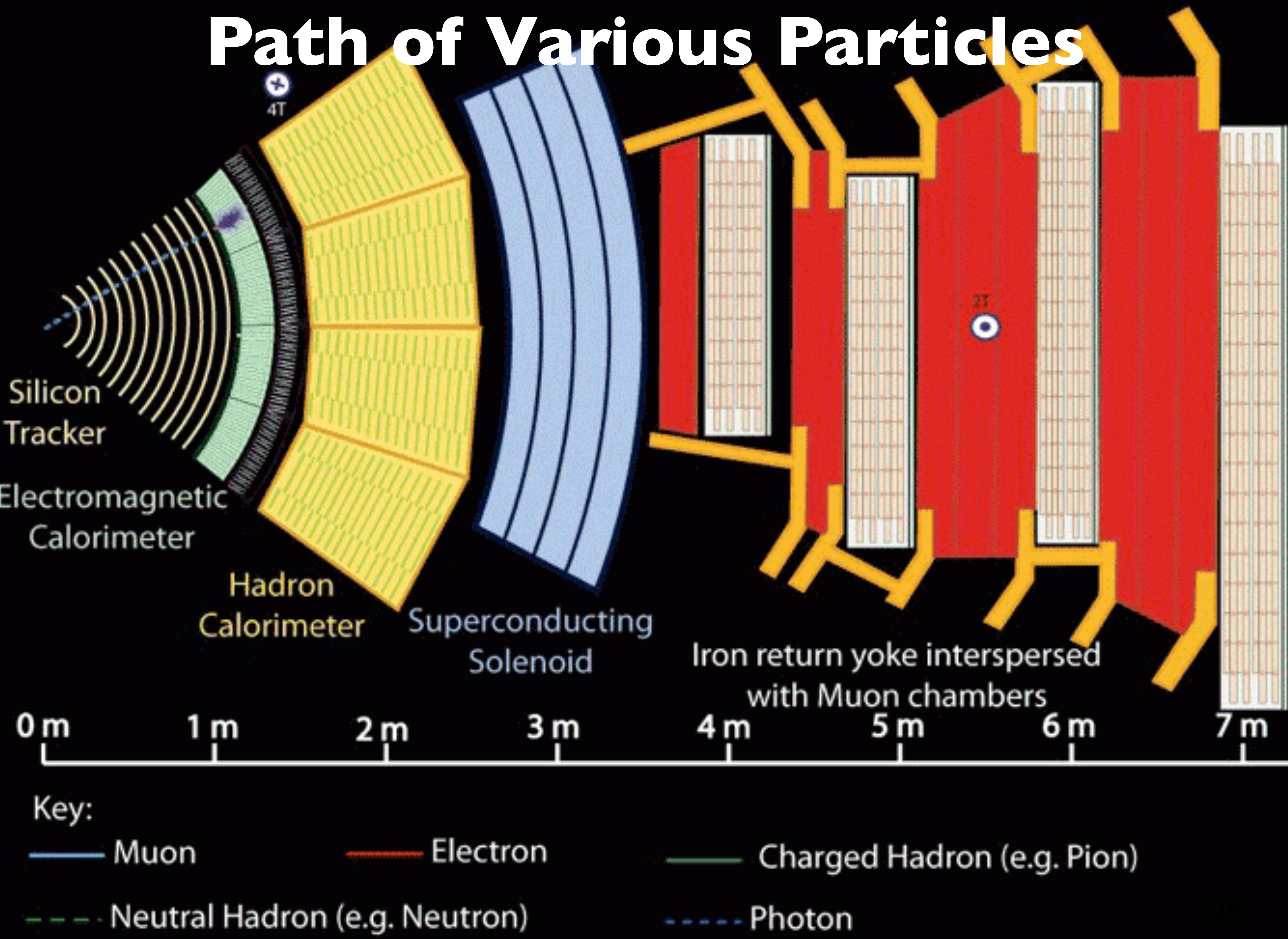

CMS Experiment at the LHC, CERN
Tue 2010–Mar–30 13:23:00 CET
Run 132440 Event 428568
C O M Energy 7 00TeV


CMS Experiment at the LHC, CERN
Tue 2010-Mar-30 13:23:00 CE
Run 132440 Event 428568
C O M Energy 7 00TeV

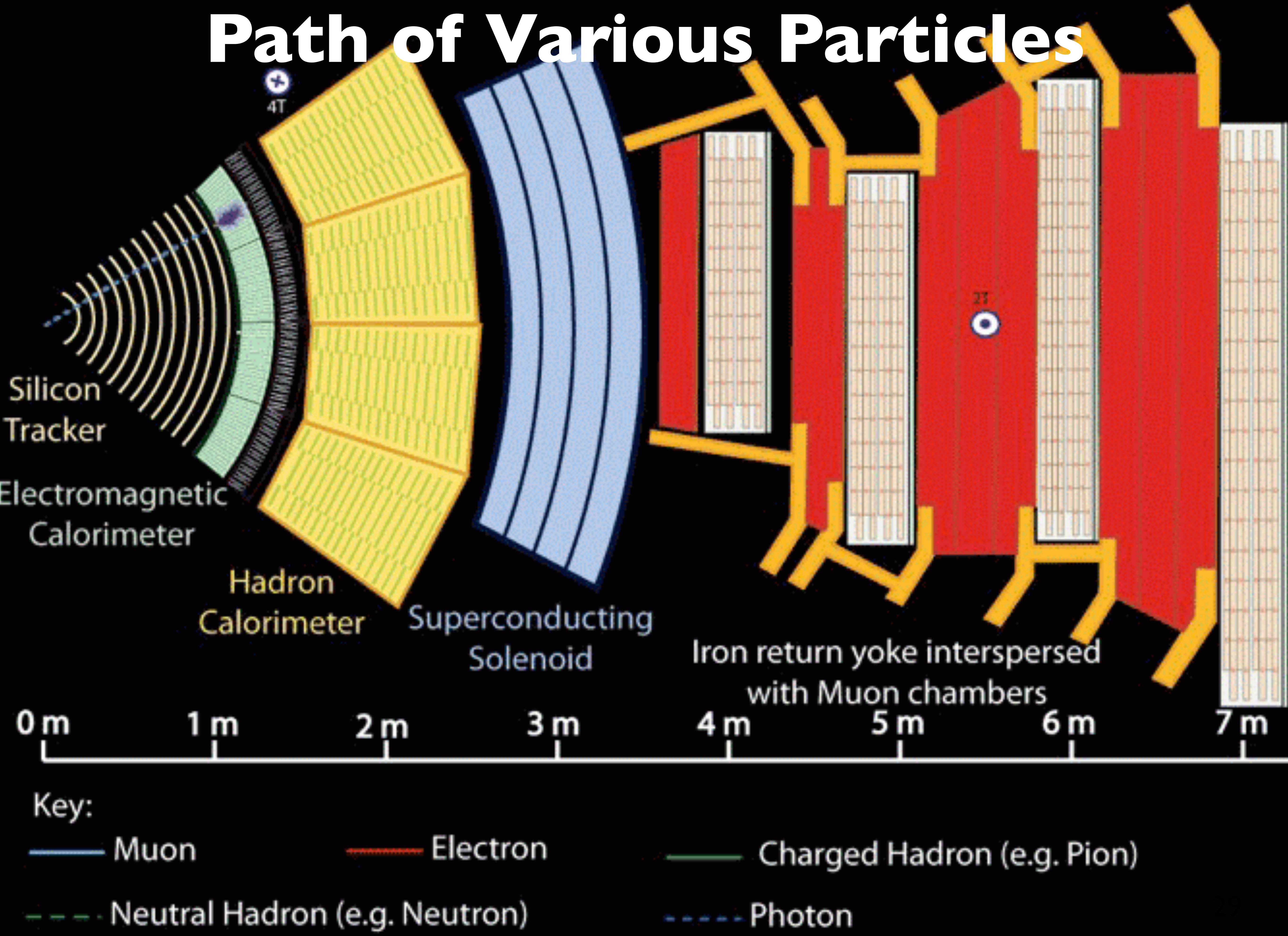

Muon Chamber
CMS Detector
Hadron Calorimeter
Electromagnetic Calorimeter
Superconducting Magnet B=3.8 Tesla
Silicon Tracker


Muon Chamber
CMS Detector
Hadron Calorimeter
Electromagnetic Calorimeter
Silicon Tracker
Superconducting Magnet
B=3.8 Tesla

Path of Various Particles

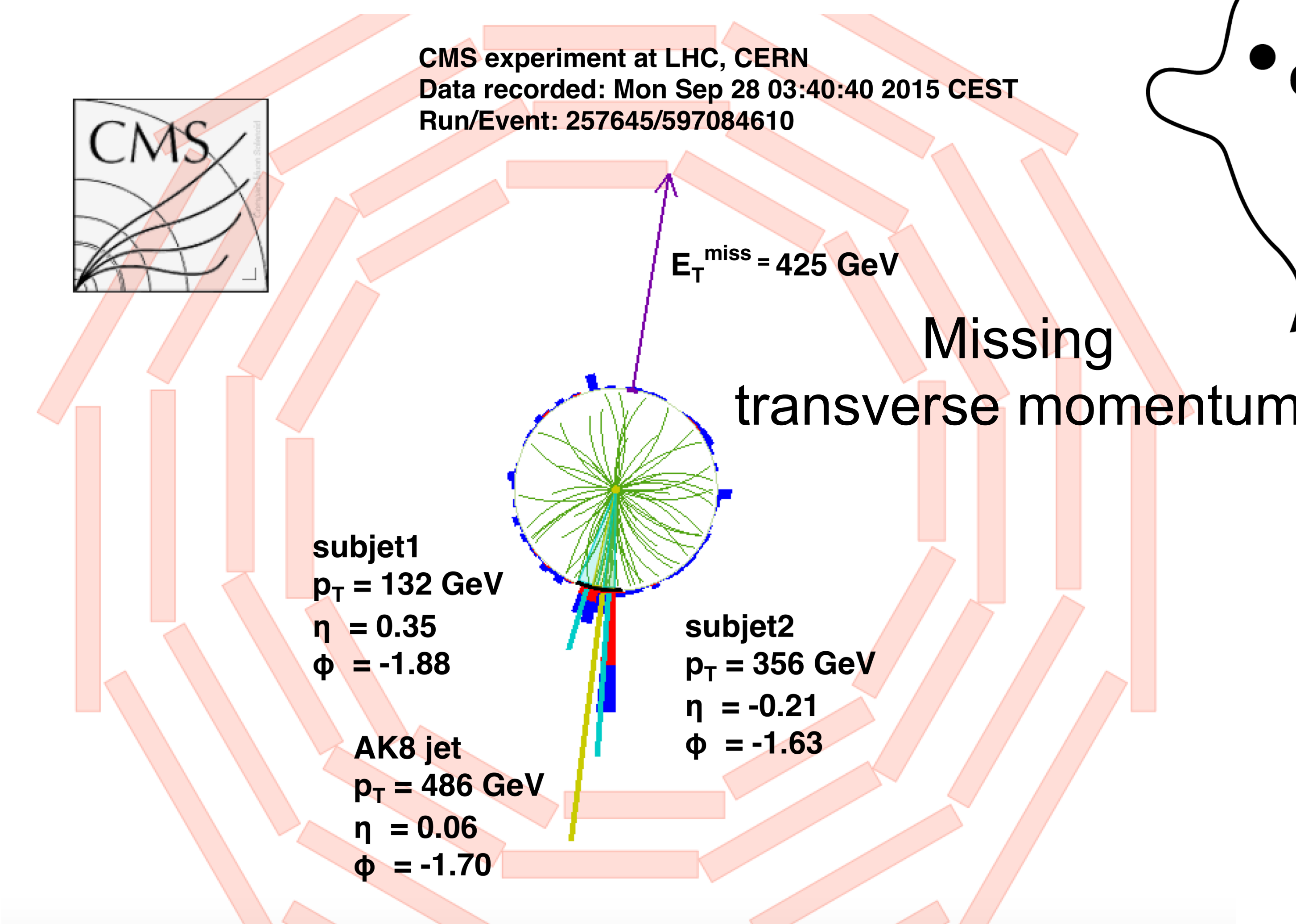


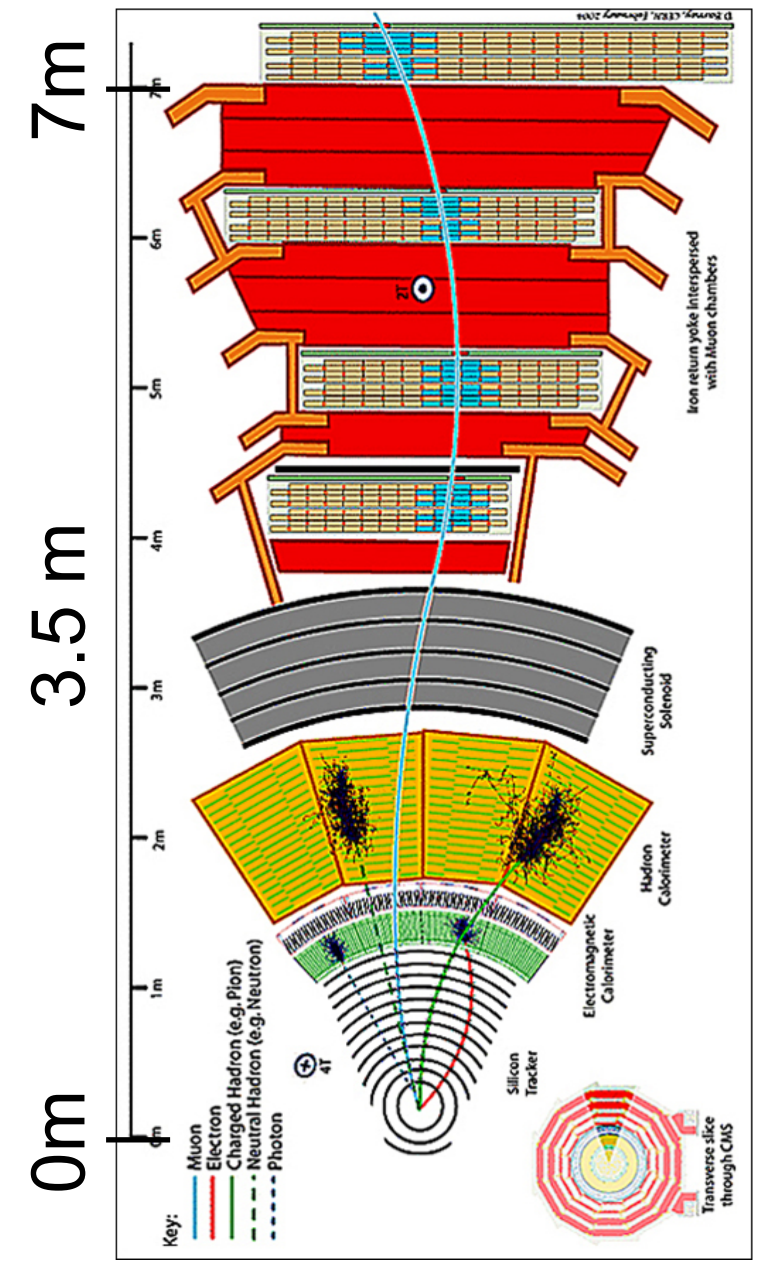
Path of Various Particles



What Is Dark Matter at Colliders?

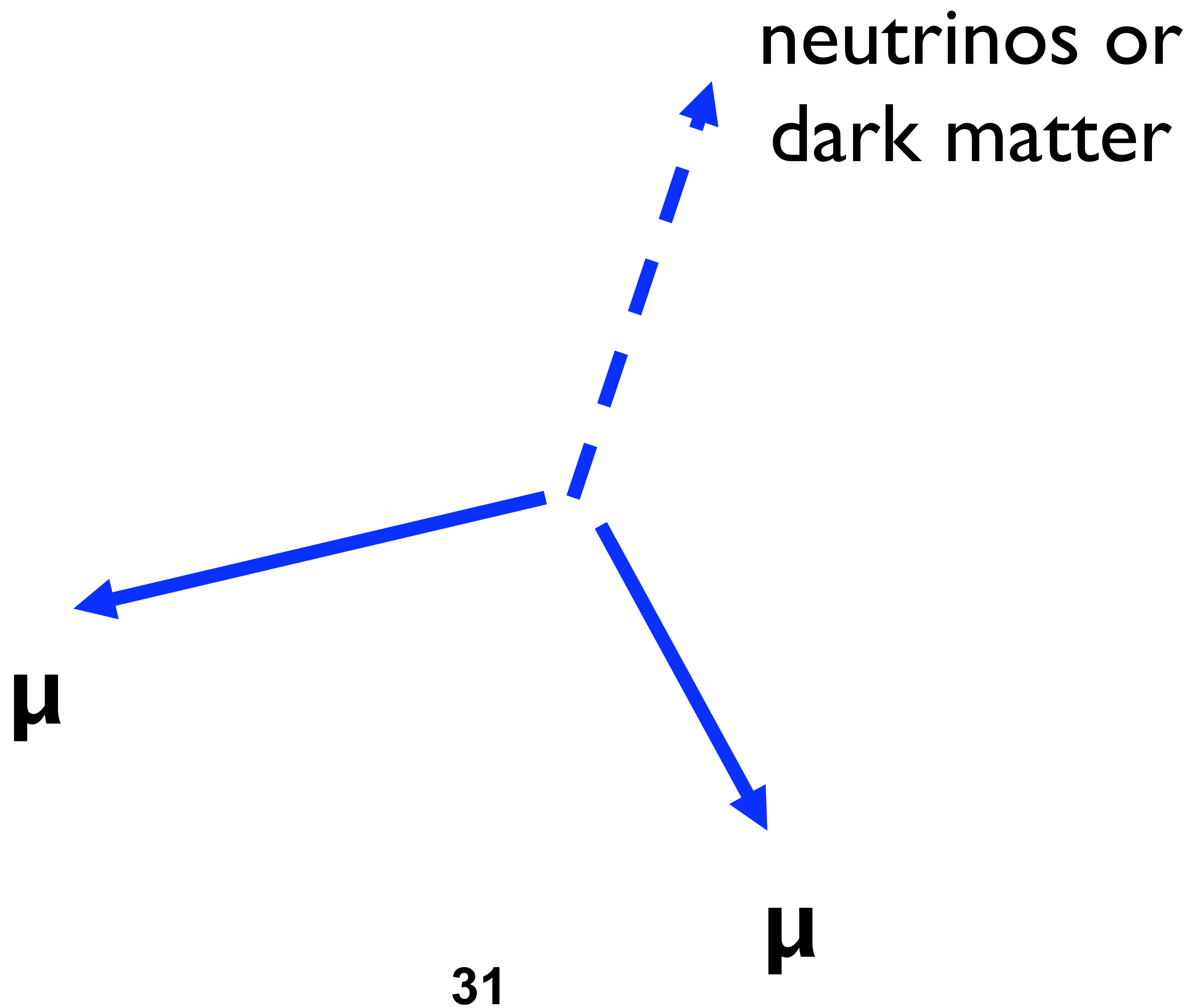
- Neutral, weakly-interactive, massive, and stable on the distance-scales of tens of meters
  - Dark matter appears as missing transverse momentum in collider detectors





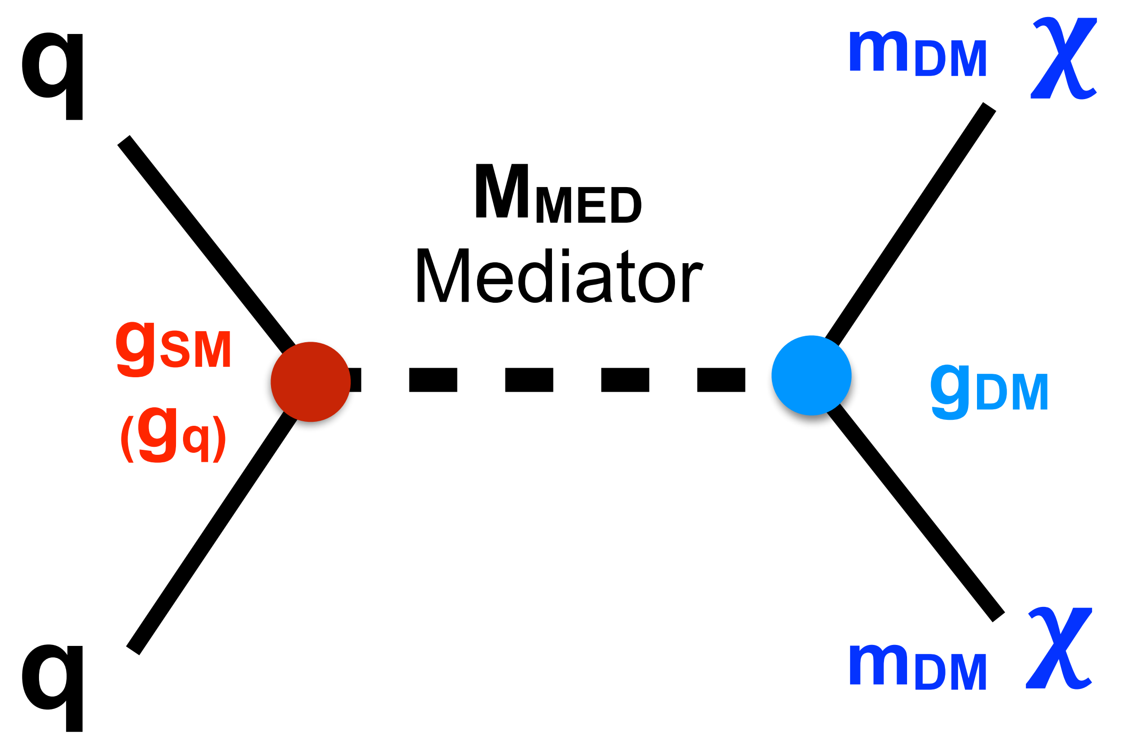
Missing Transverse Momentum

- The negative of the total transverse momentum of all observed particles in the detector



Simplified Models for Direct DM Production

- Mediator has minimal decay width
- Minimal set of parameters
  - coupling structure, M_{MED}, m_{DM}, g_{SM} (g_q), g_{DM}



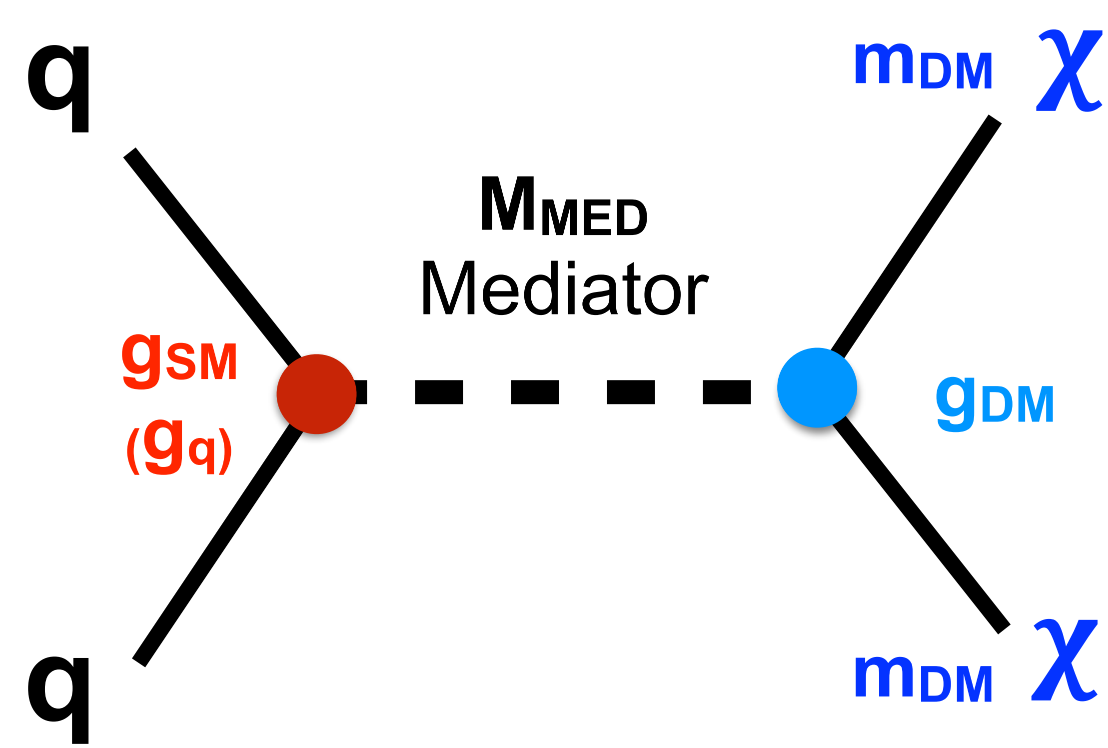
Simplified Models for Direct DM Production

Features of Mediators

	spin 0	spin 1
Charge Q	$Q_{med} = 0$ for s-channel	
Mass m	unknown	
Dark sector bosons similar to	H [1609.09079]	γ, Z, Z'
Lorentz structure	scalar 1 pseudosc. γ_5	vector γ^μ axial v. $\gamma^\mu \gamma_5$
Coupling "g"	$\propto$ mass	$\propto$ charge
Consequences	$m_b \gg m_d$	$Q_b = Q_d$

Tae Min Hong, LHCP 2017

- Mediator has minimal decay width
- Minimal set of parameters
  - coupling structure, M_{MED}, m_{DM}, g_{SM} (g_q), g_{DM}



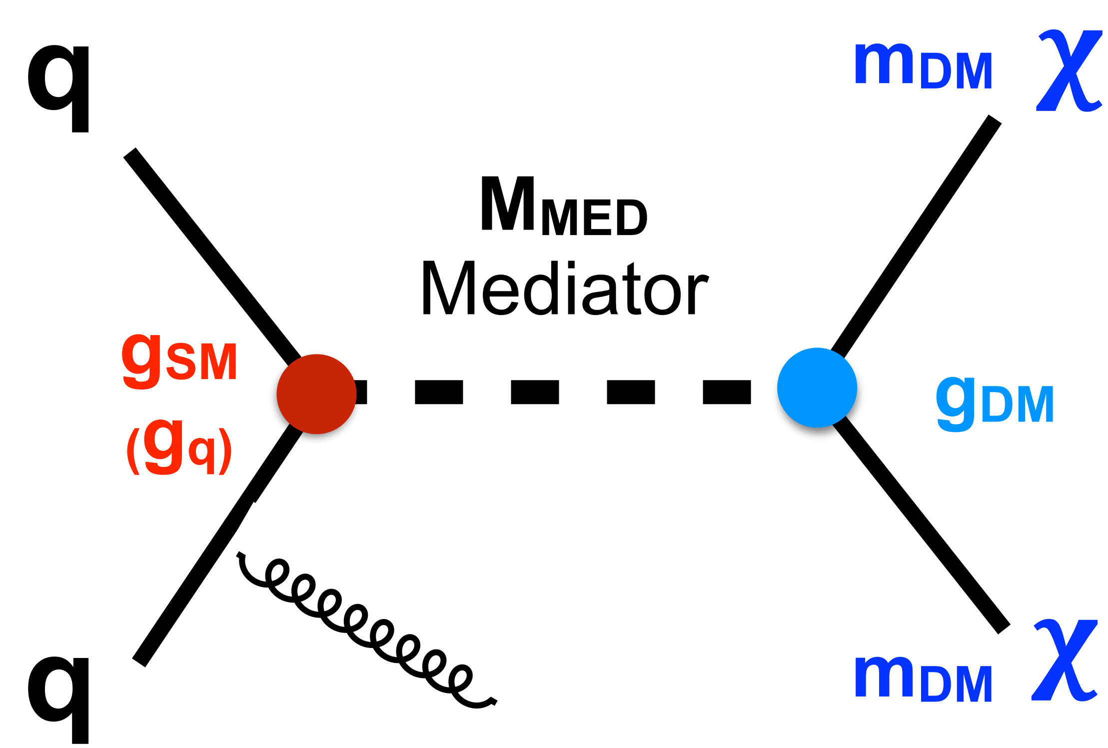
Simplified Models for Direct DM Production

Features of Mediators

	spin 0	spin 1
Charge Q	$Q_{med} = 0$ for s-channel	
Mass m	unknown	
Dark sector bosons similar to	H [1609.09079]	γ, Z, Z'
Lorentz structure	scalar 1 pseudosc. γ_5	vector γ^μ axial v. $\gamma^\mu \gamma_5$
Coupling "g"	$\propto$ mass	$\propto$ charge
Consequences	$m_b \gg m_d$	$Q_b = Q_d$

Tae Min Hong, LHCP 2017

- Mediator has minimal decay width
- Minimal set of parameters
  - coupling structure, M_{MED}, m_{DM}, g_{SM} (g_q), g_{DM}



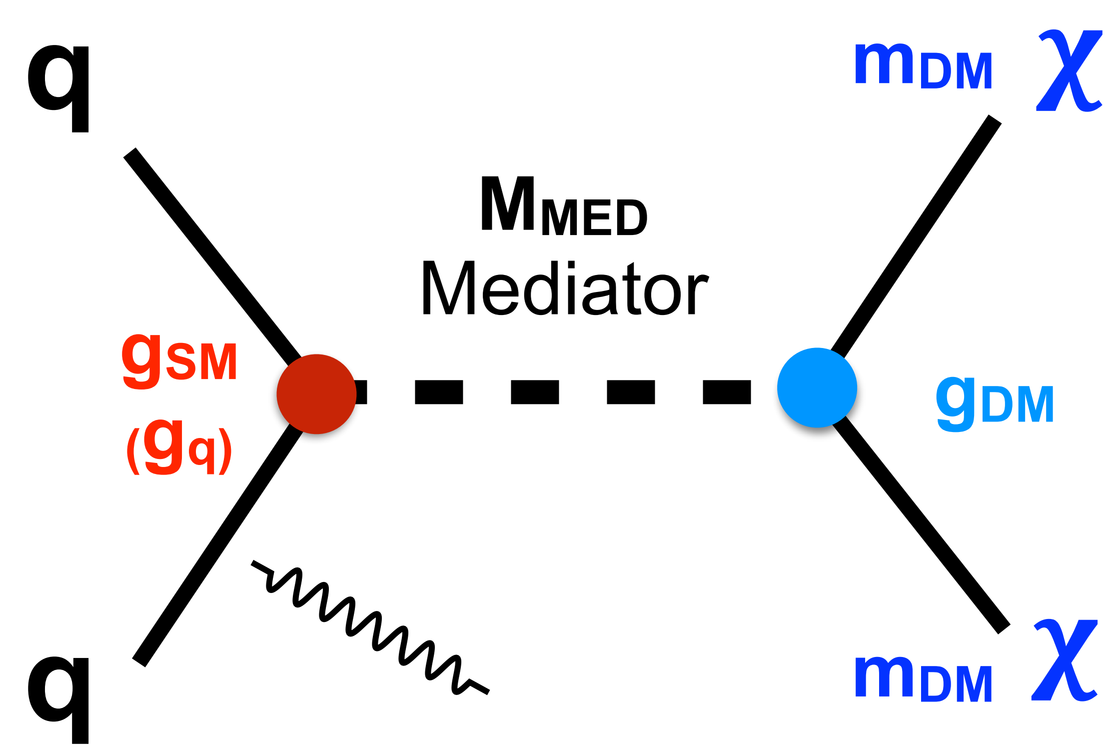
Simplified Models for Direct DM Production

Features of Mediators

	spin 0	spin 1
Charge Q	$Q_{med} = 0$ for s-channel	
Mass m	unknown	
Dark sector bosons similar to	H [1609.09079]	γ, Z, Z'
Lorentz structure	scalar 1 pseudosc. γ_5	vector γ^μ axial v. $\gamma^\mu \gamma_5$
Coupling "g"	$\propto$ mass	$\propto$ charge
Consequences	$m_b \gg m_d$	$Q_b = Q_d$

Tae Min Hong, LHCP 2017

- Mediator has minimal decay width
- Minimal set of parameters
  - coupling structure, M_{MED}, m_{DM}, g_{SM} (g_q), g_{DM}



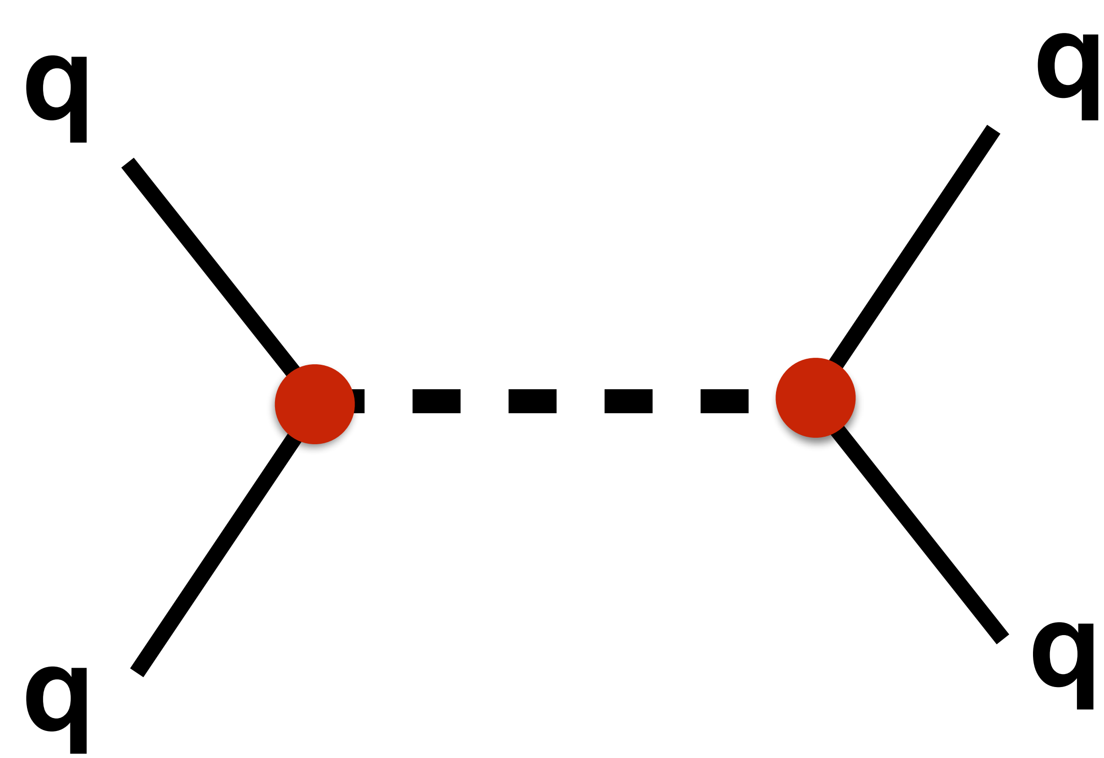
Simplified Models for Direct DM Production

Features of Mediators

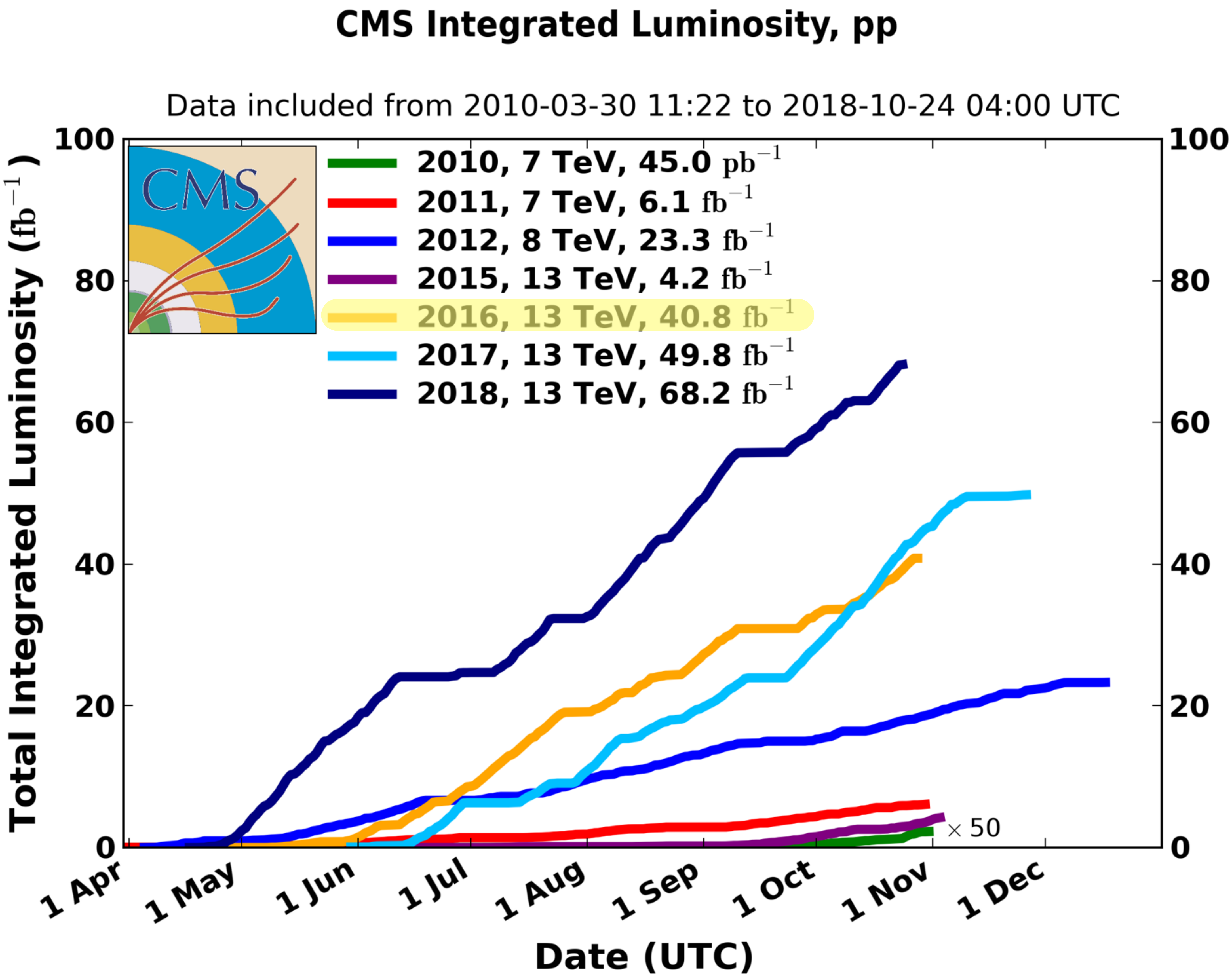
	spin 0	spin 1
Charge Q	$Q_{med} = 0$ for s-channel	
Mass m	unknown	
Dark sector bosons similar to	H [1609.09079]	γ, Z, Z'
Lorentz structure	scalar 1 pseudosc. γ_5	vector γ^μ axial v. $\gamma^\mu \gamma_5$
Coupling "g"	$\propto$ mass	$\propto$ charge
Consequences	$m_b \gg m_d$	$Q_b = Q_d$

Tae Min Hong, LHCP 2017

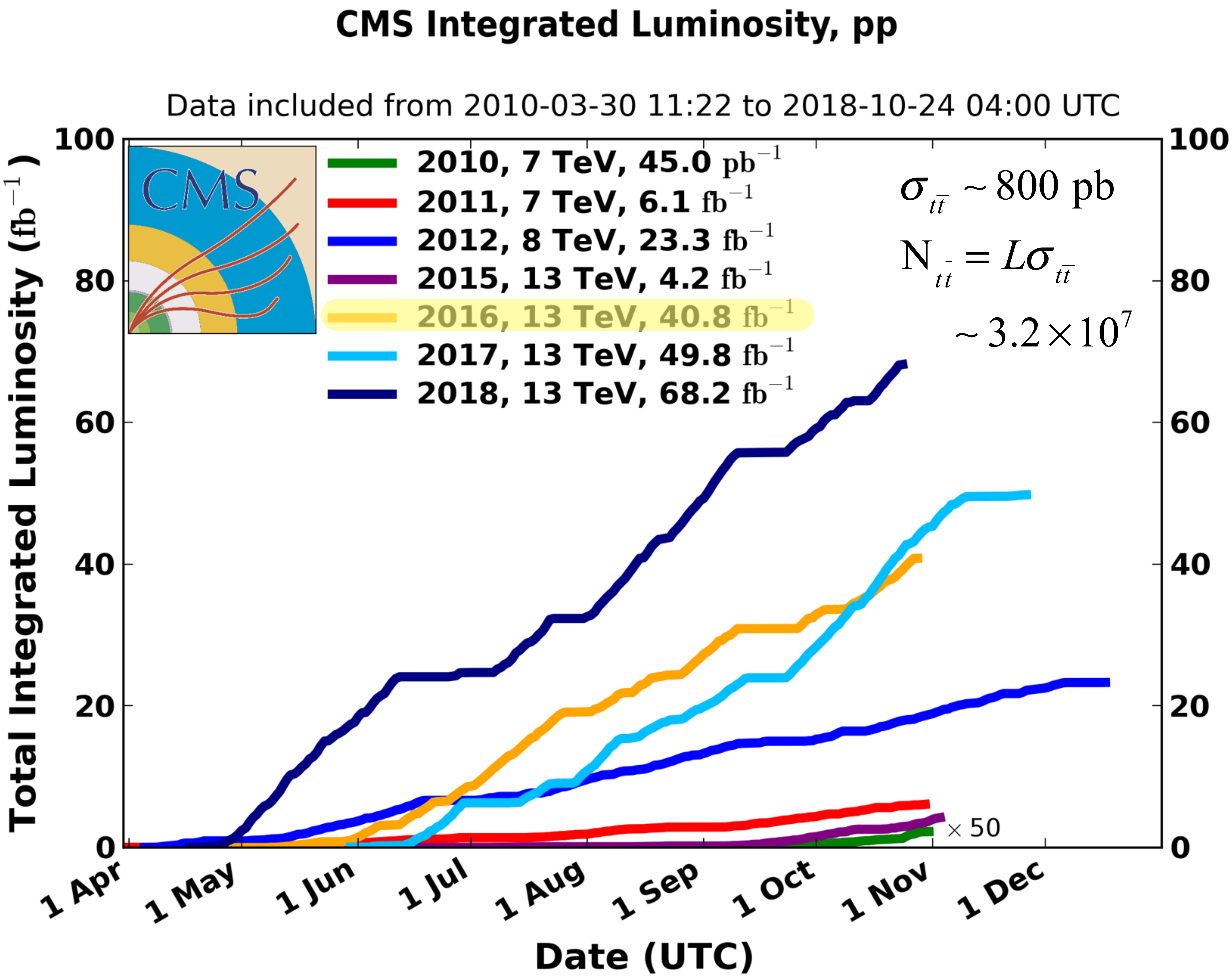
- Mediator has minimal decay width
- Minimal set of parameters
  - coupling structure, M_{MED}, m_{DM}, g_{SM} (g_q), g_{DM}



Amount of Data We Use



Amount of Data We Use

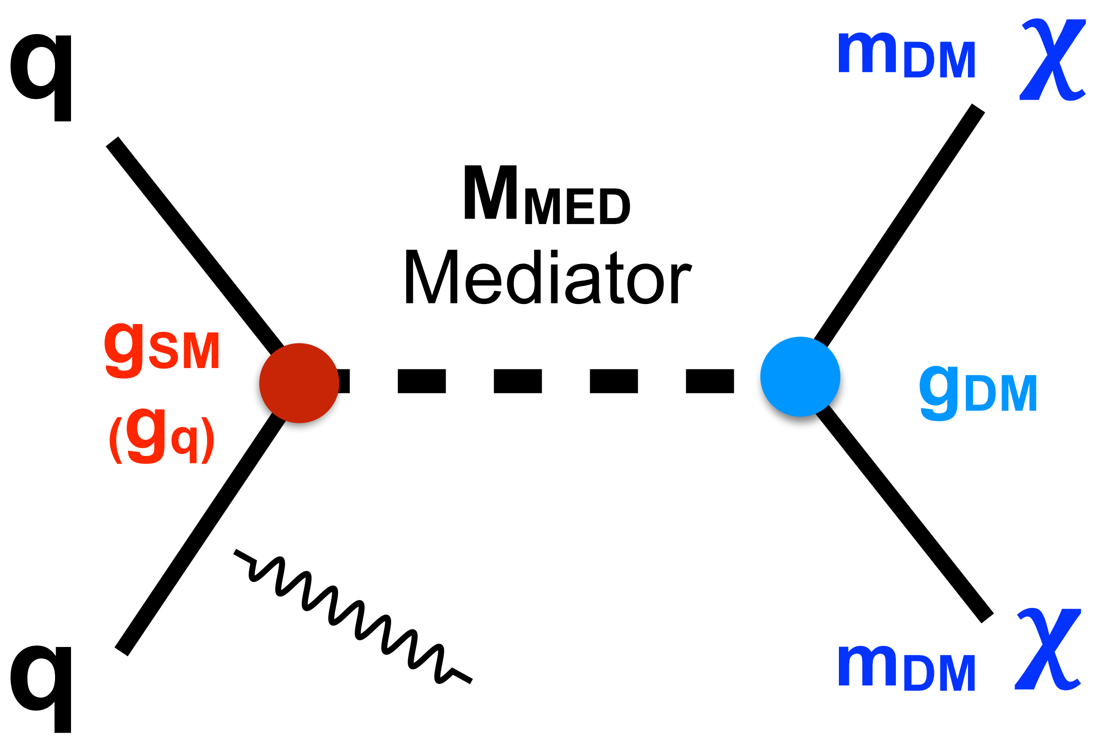


$$\sigma_{t\bar{t}} \sim 800 \text{ pb}$$

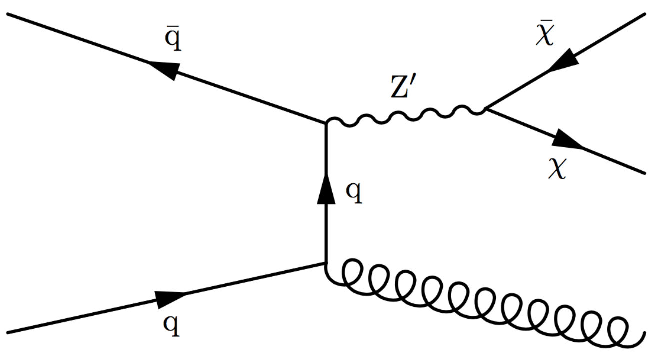
$$N_{t\bar{t}} = L\sigma_{t\bar{t}}$$

$$\sim 3.2\times 10^{7}$$

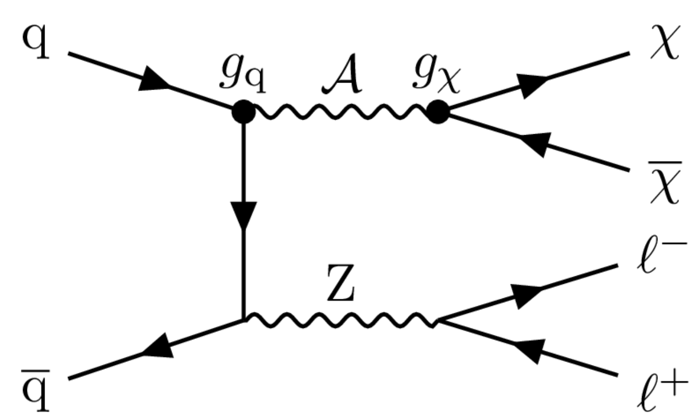
DM Searches with Missing Transverse Momentum Signatures



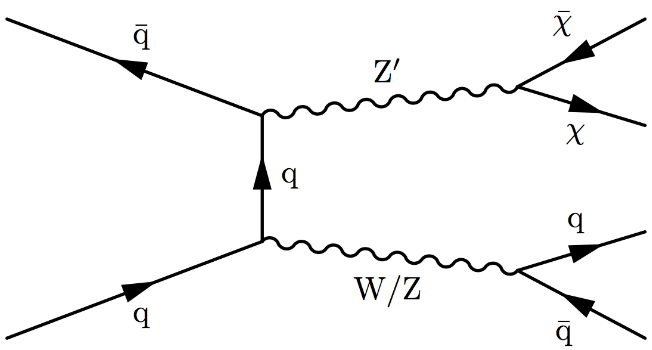
Mono-X Diagrams of Direct DM Production



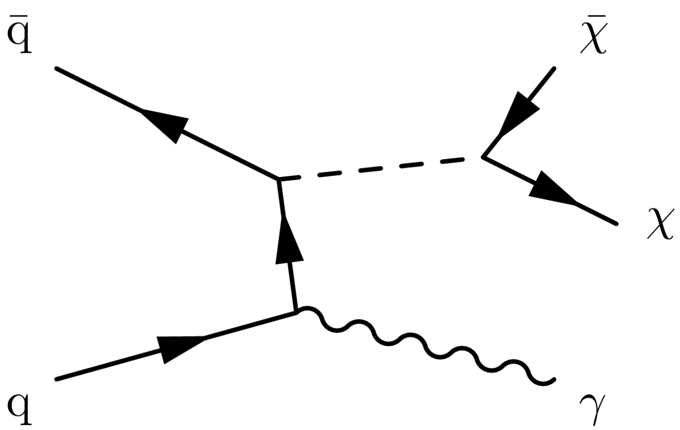
Mono-jet



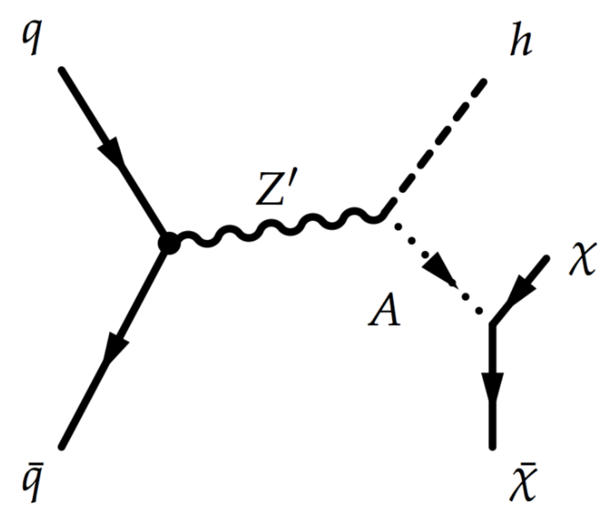
Mono-Z(leptonic)



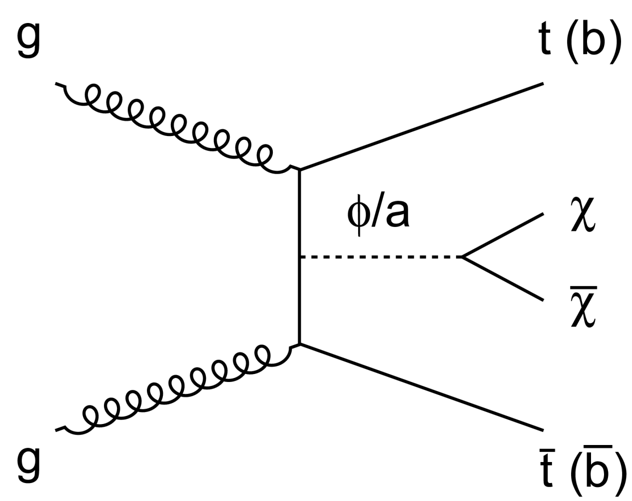
Mono-W/Z(hadronic)



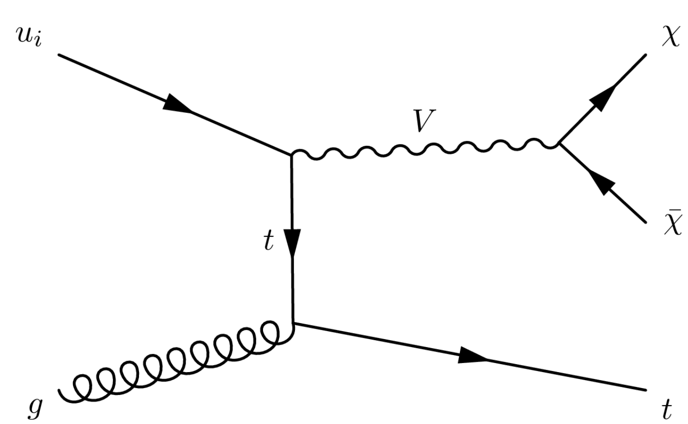
Mono-photon



Mono-h (bb, $\gamma\gamma$)



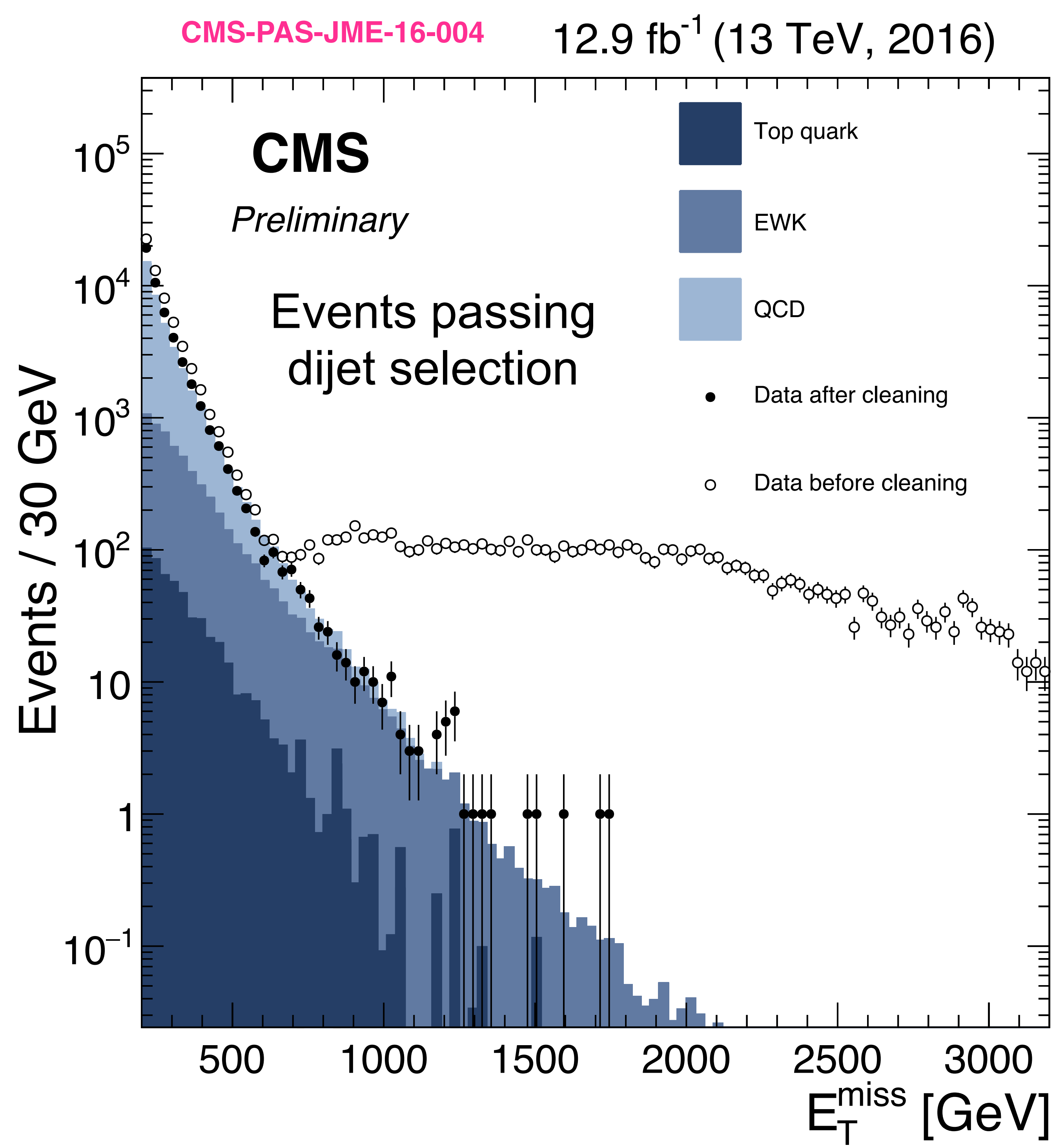
Mono-tt/bb



Mono-top

Challenges of Missing Transverse Momentum

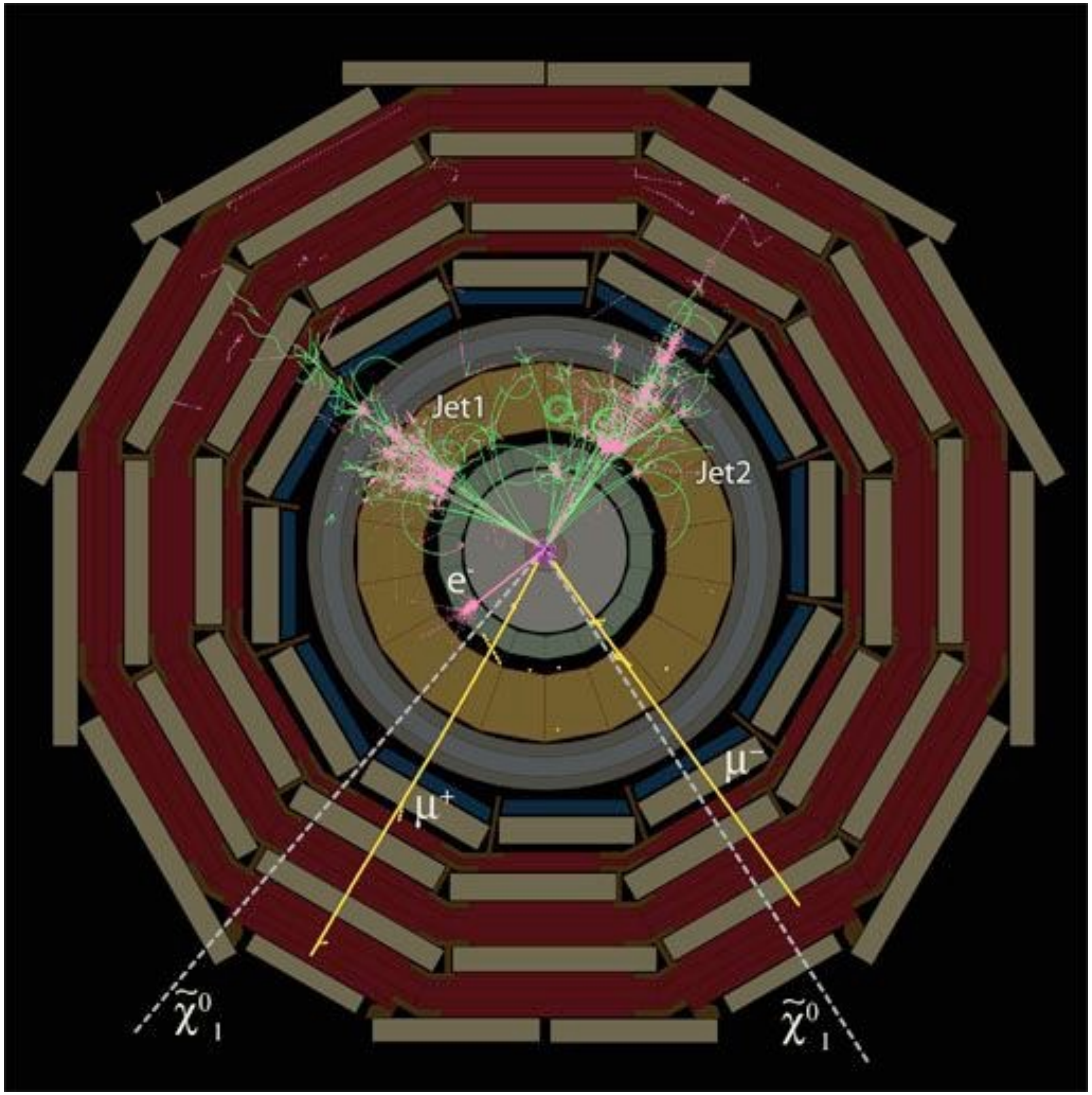
- Anomalous high MET can be due to:
  - Particles striking sensors in the ECAL photodetectors
  - Beam halo
  - Dead cells in ECAL or HCAL
  - Noise in ECAL or HCAL



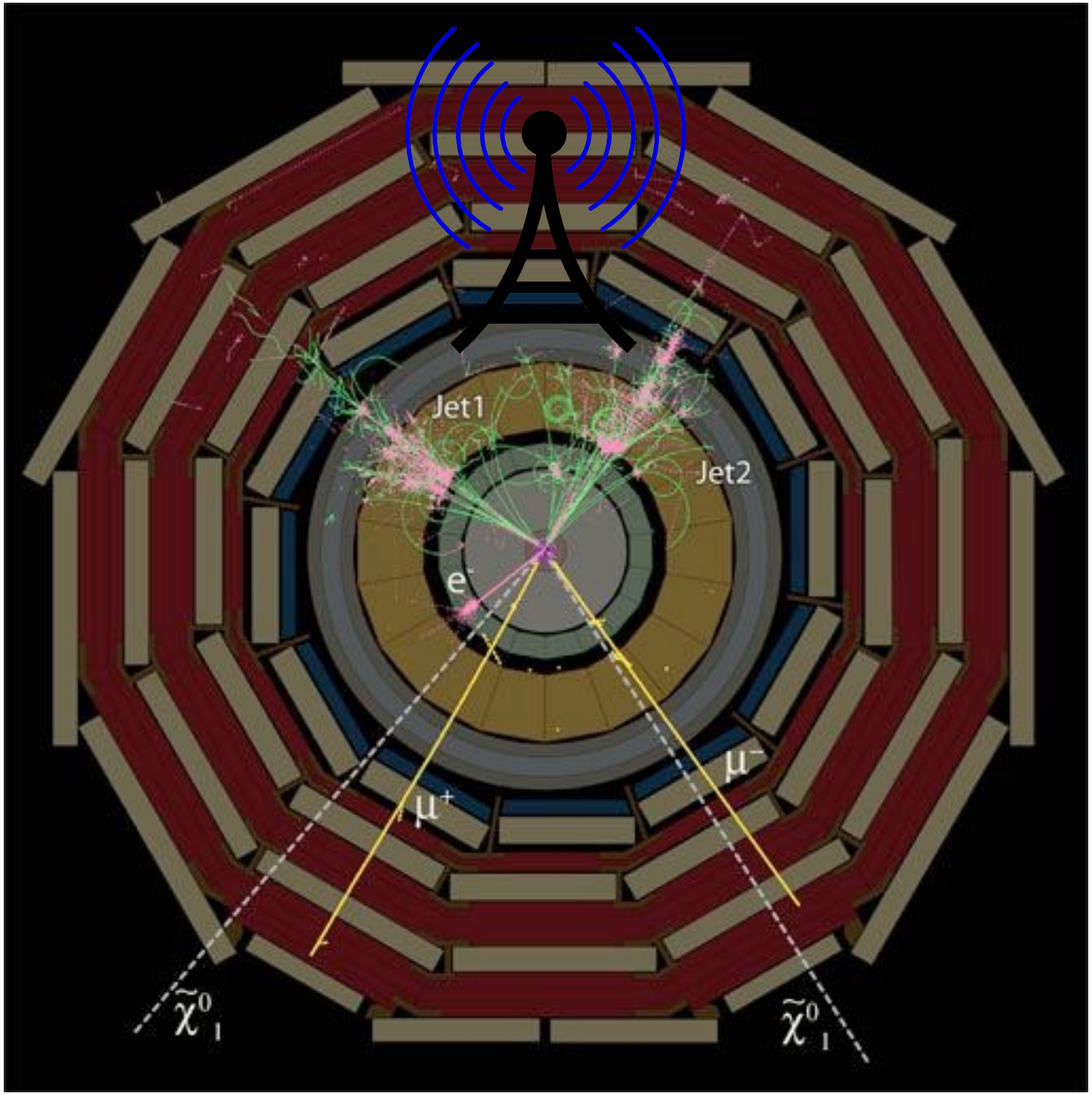
Raman Khurana

Ching-Wei Chen

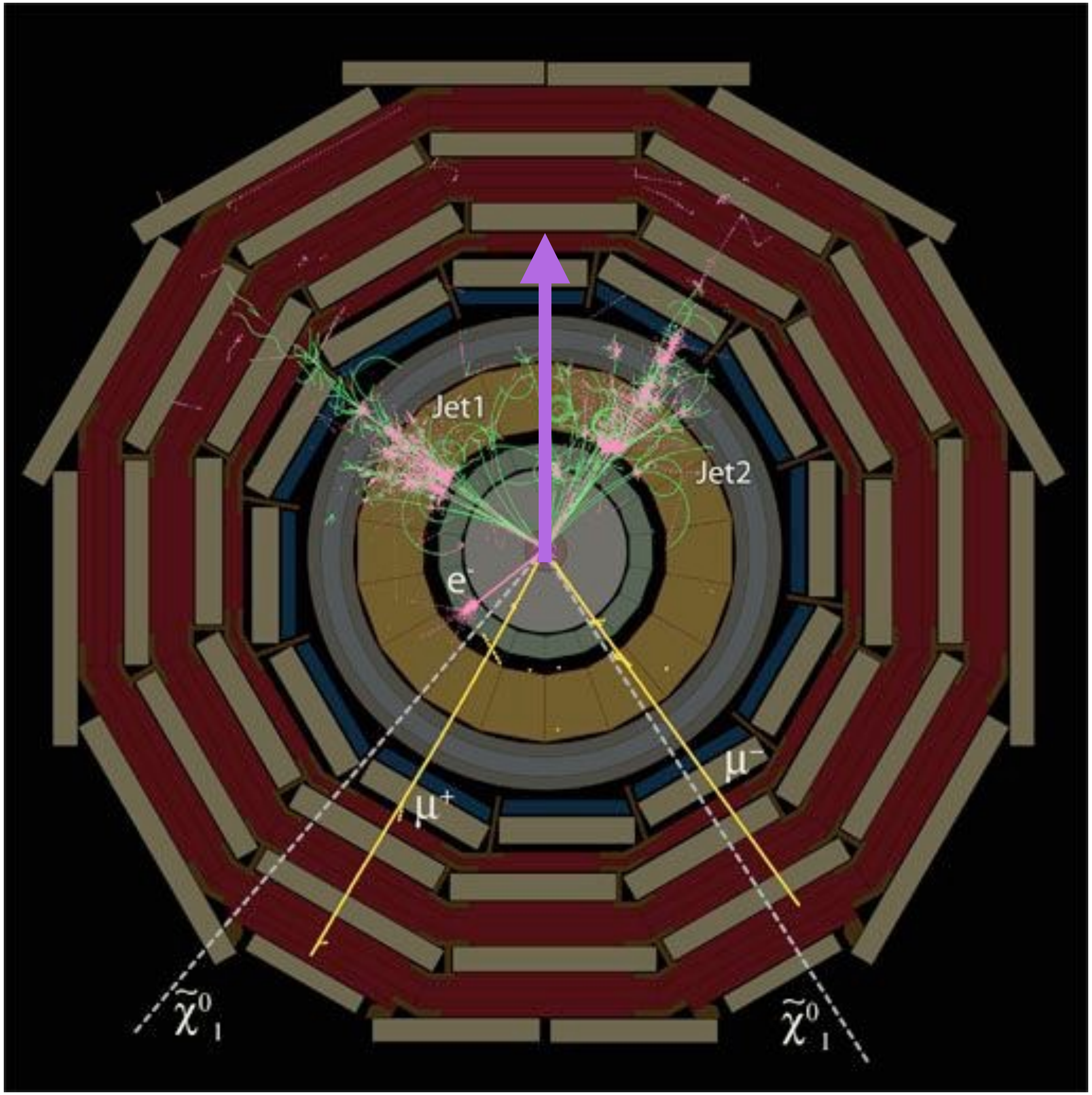
Fake Missing Transverse Momentum: Noise



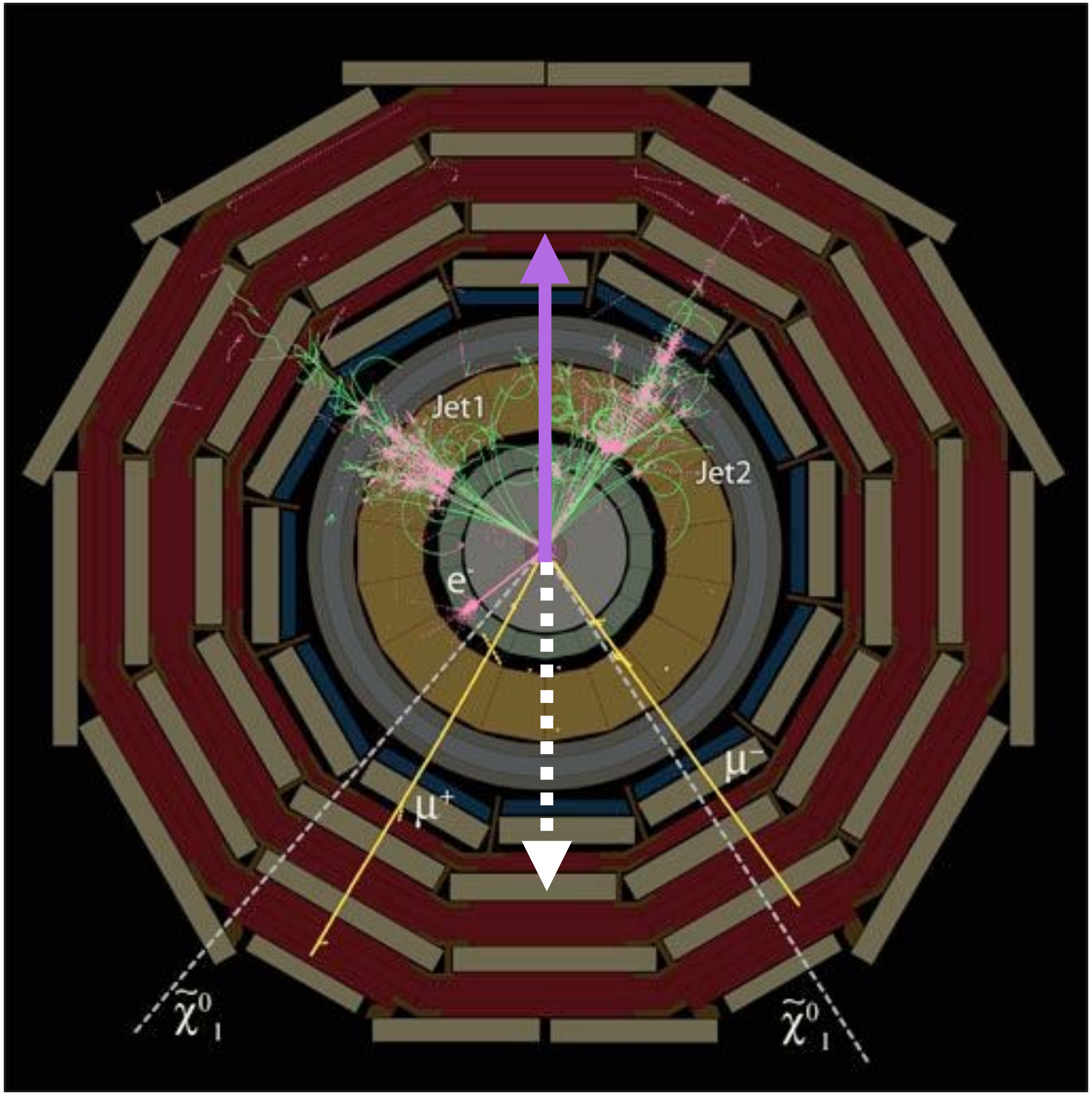
Fake Missing Transverse Momentum: Noise



Fake Missing Transverse Momentum: Noise

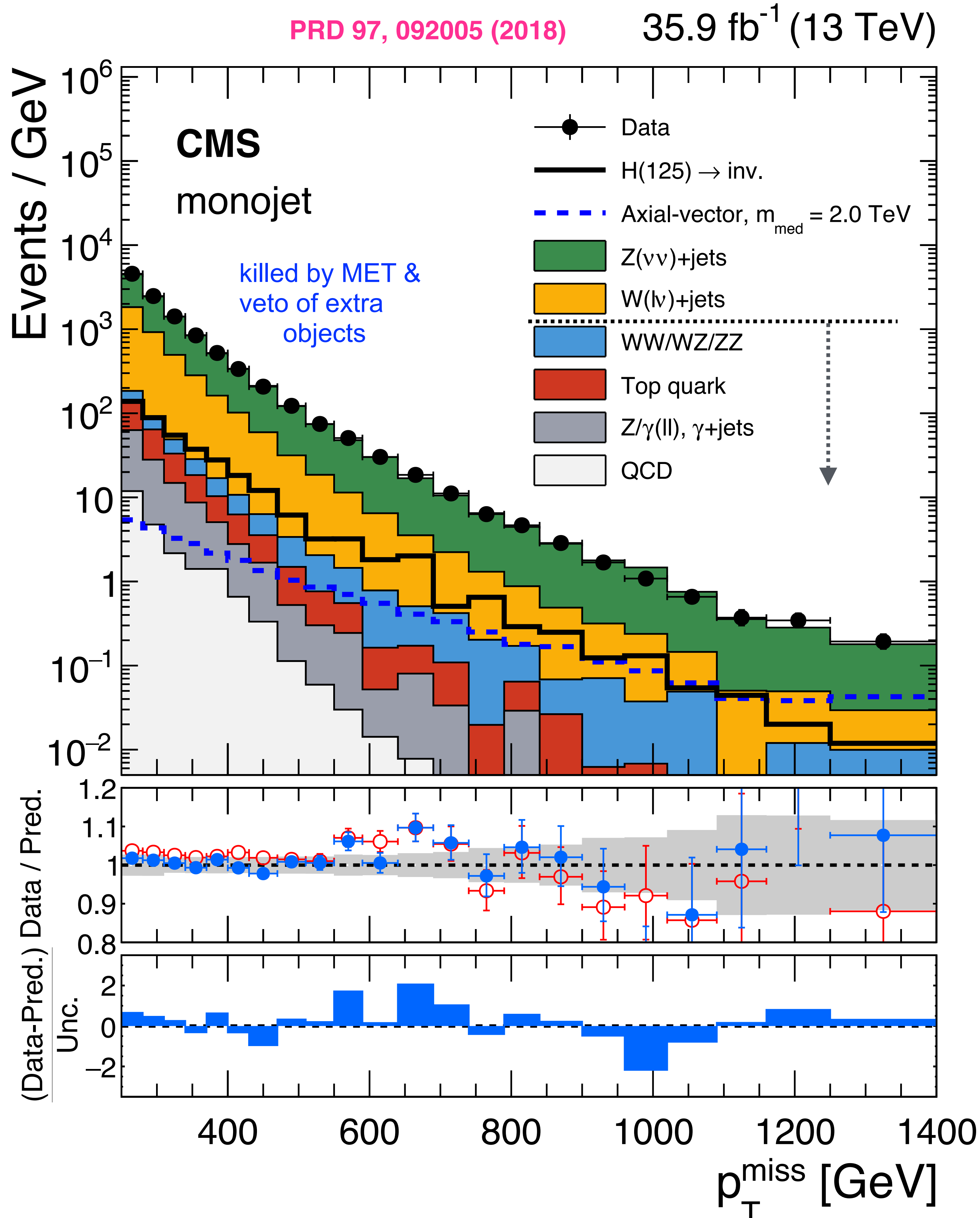


Fake Missing Transverse Momentum: Noise

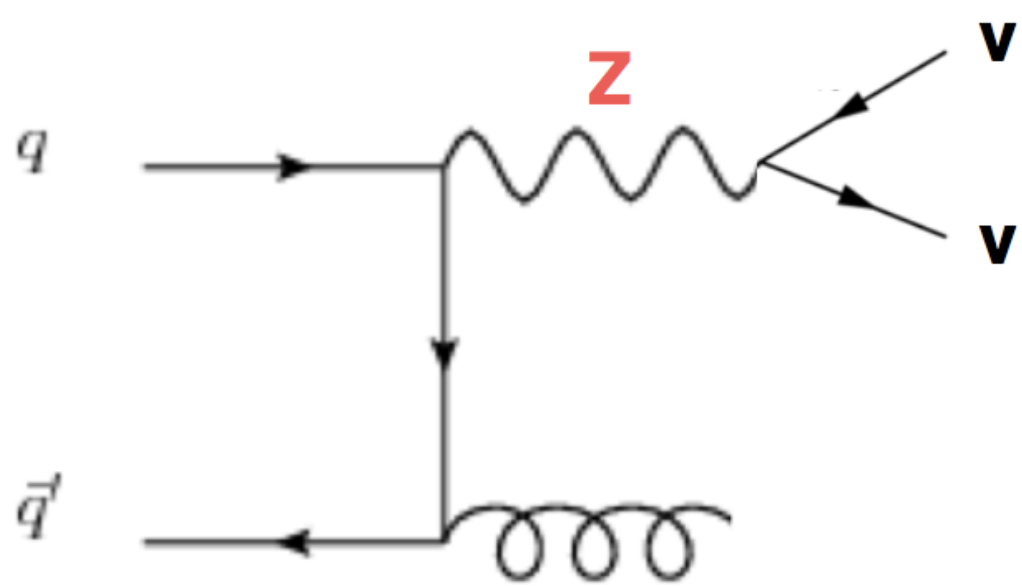


Mono-X Searches in Hadronic Final State

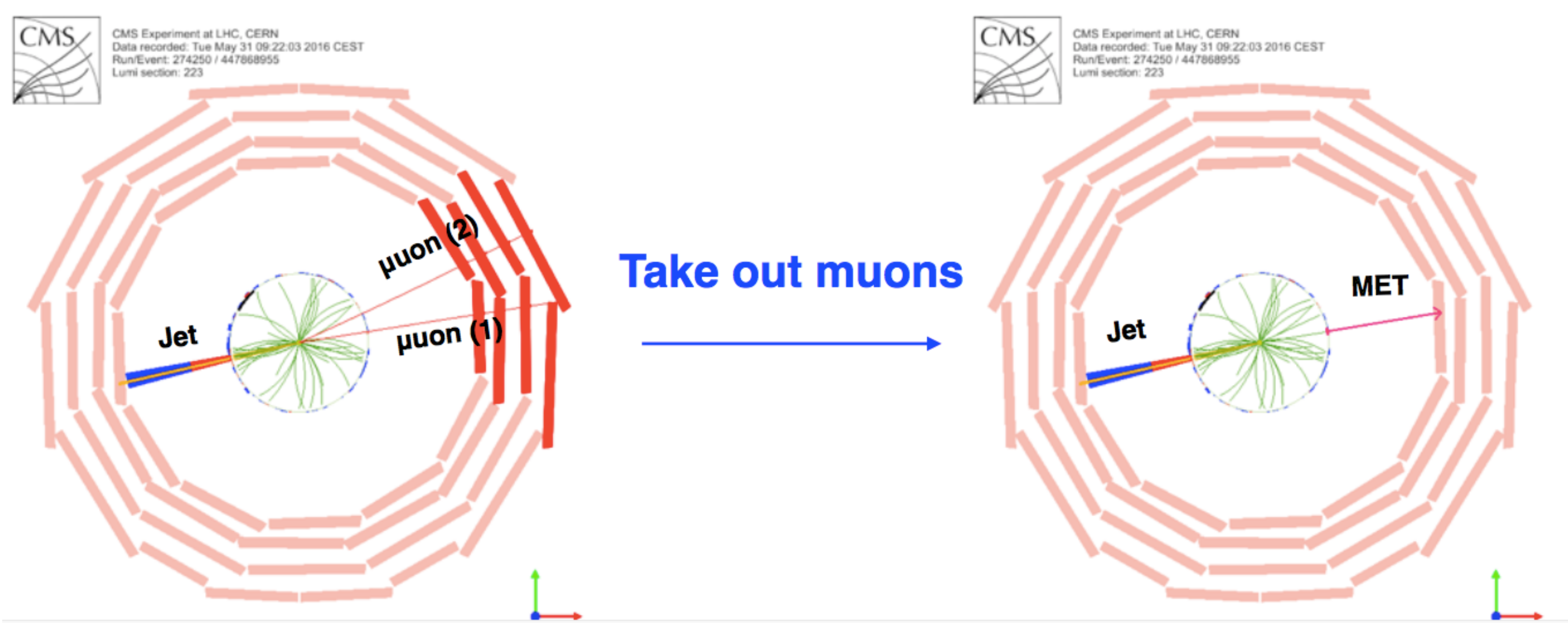
- Rely on MET triggers (offline MET cut ≳200 GeV)
- Major background from Z(→$\nu\nu$)+jets, W(→lν)+jets



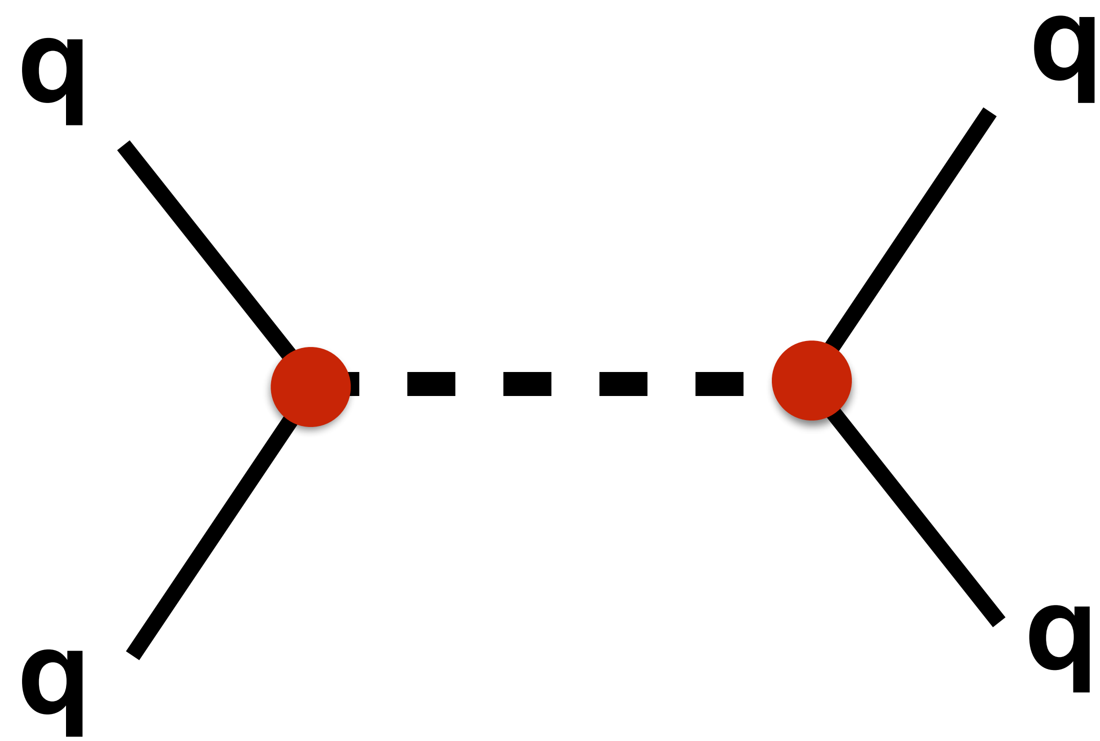
Estimation of Z+Jets Background



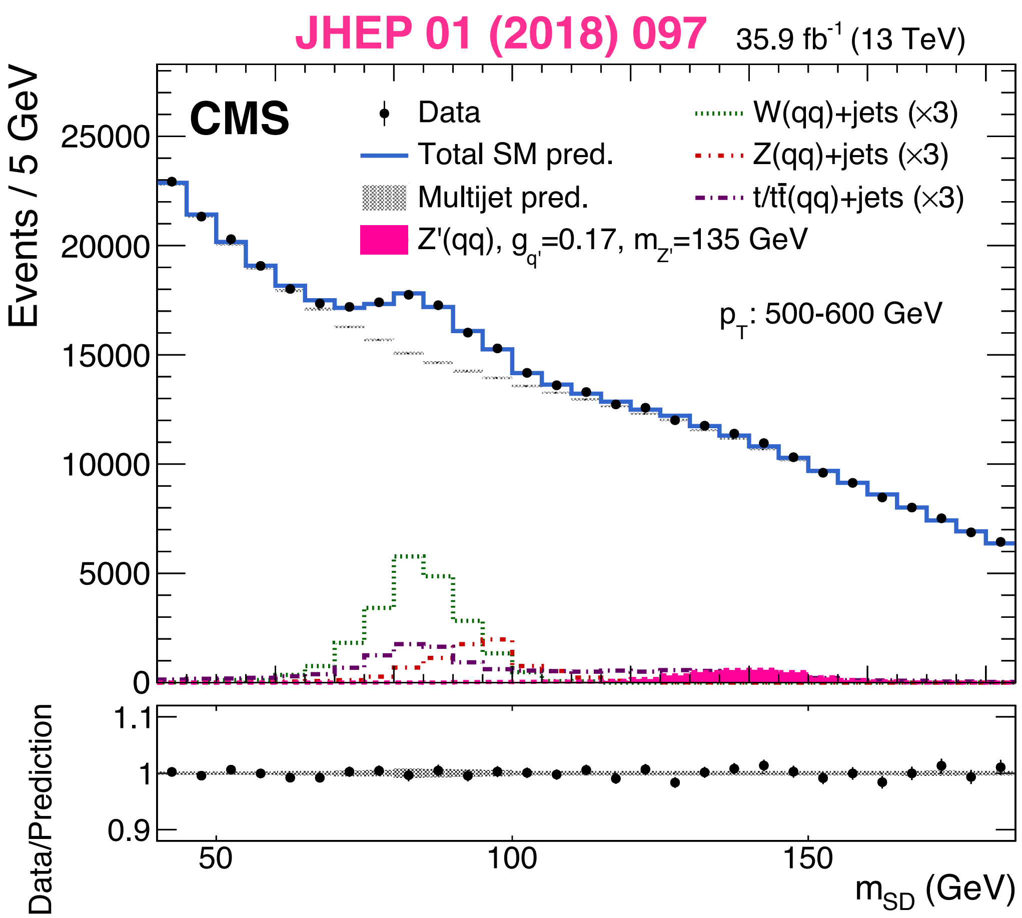
If we remove the muons from a Z→μμ event, it mimics a Z→νν event



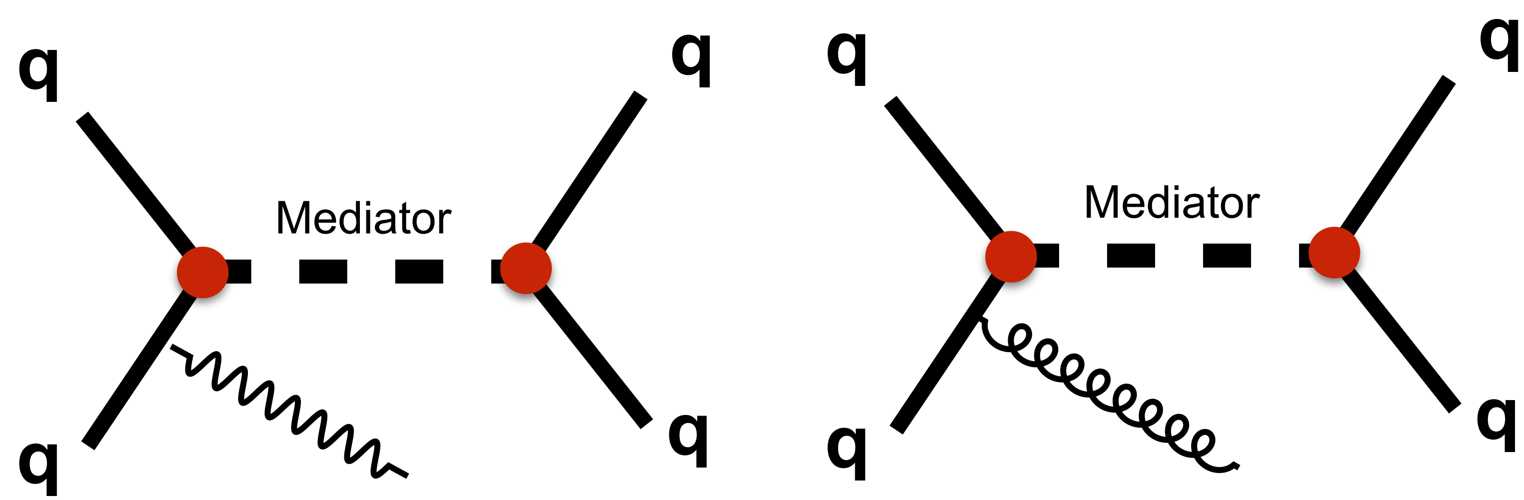
Searches for Visible Mediator Decays

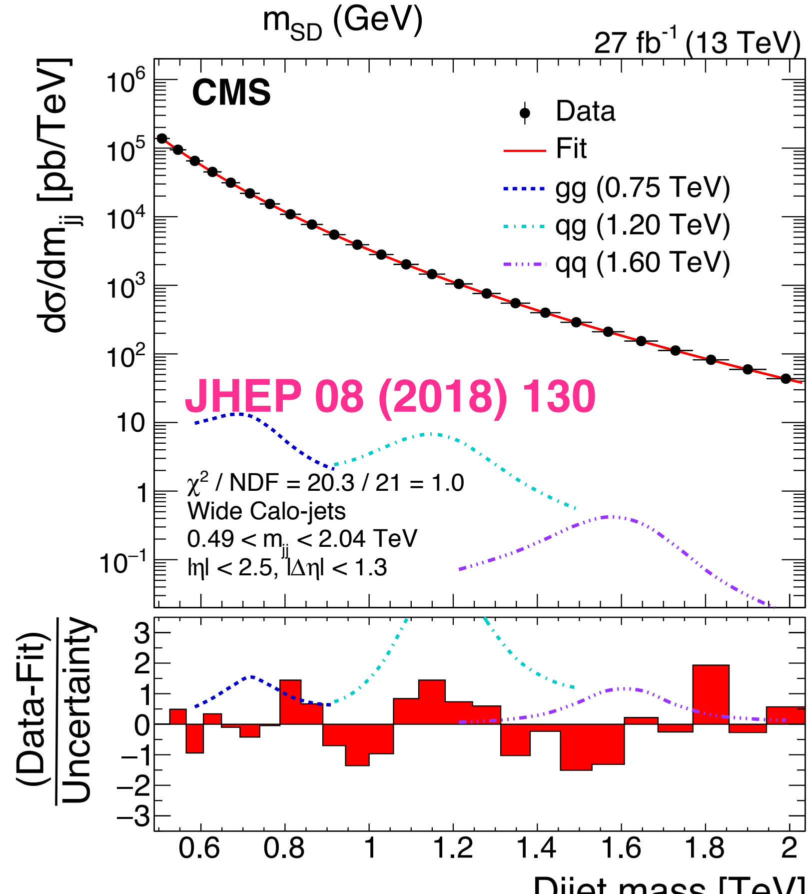


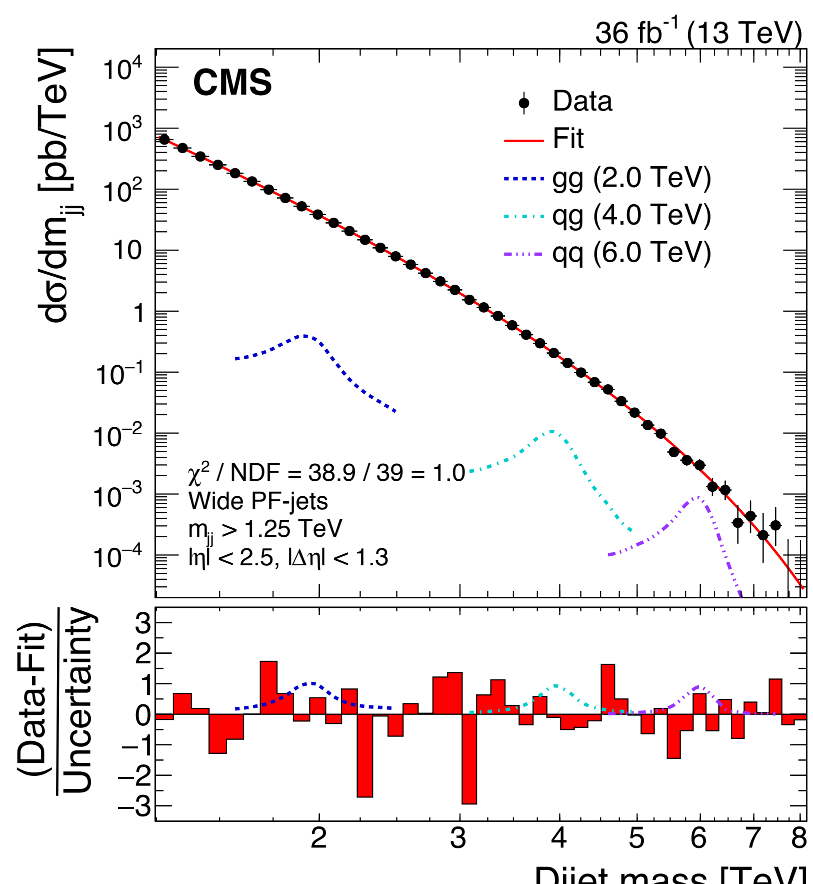
Visible Mediator Searches



- high-p_T/H_T trigger for large-Mjj, ISR γ/jet tag or data with only trigger-level objects (data scouting) for small-Mjj

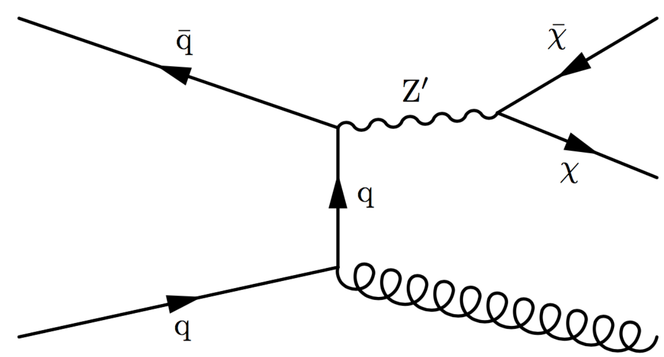




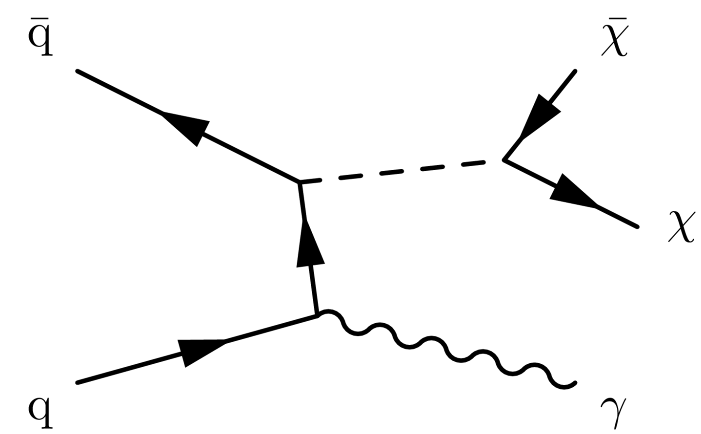


Result Interpretation

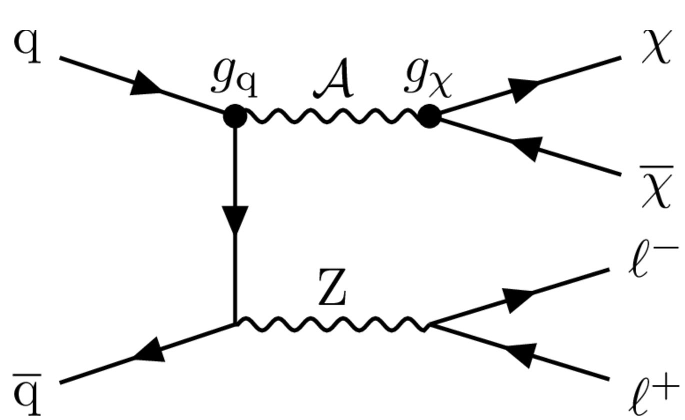
Mono-X With Vector/Axial Mediators



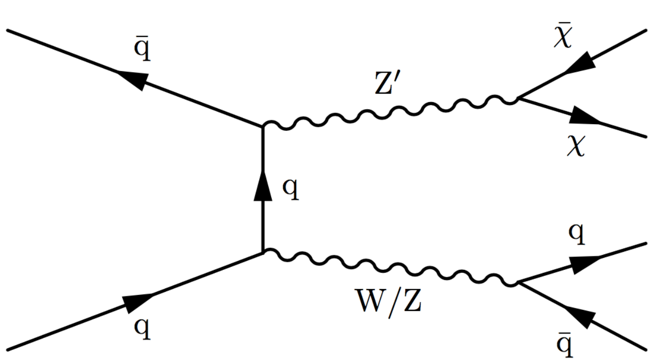
Mono-jet



Mono-photon

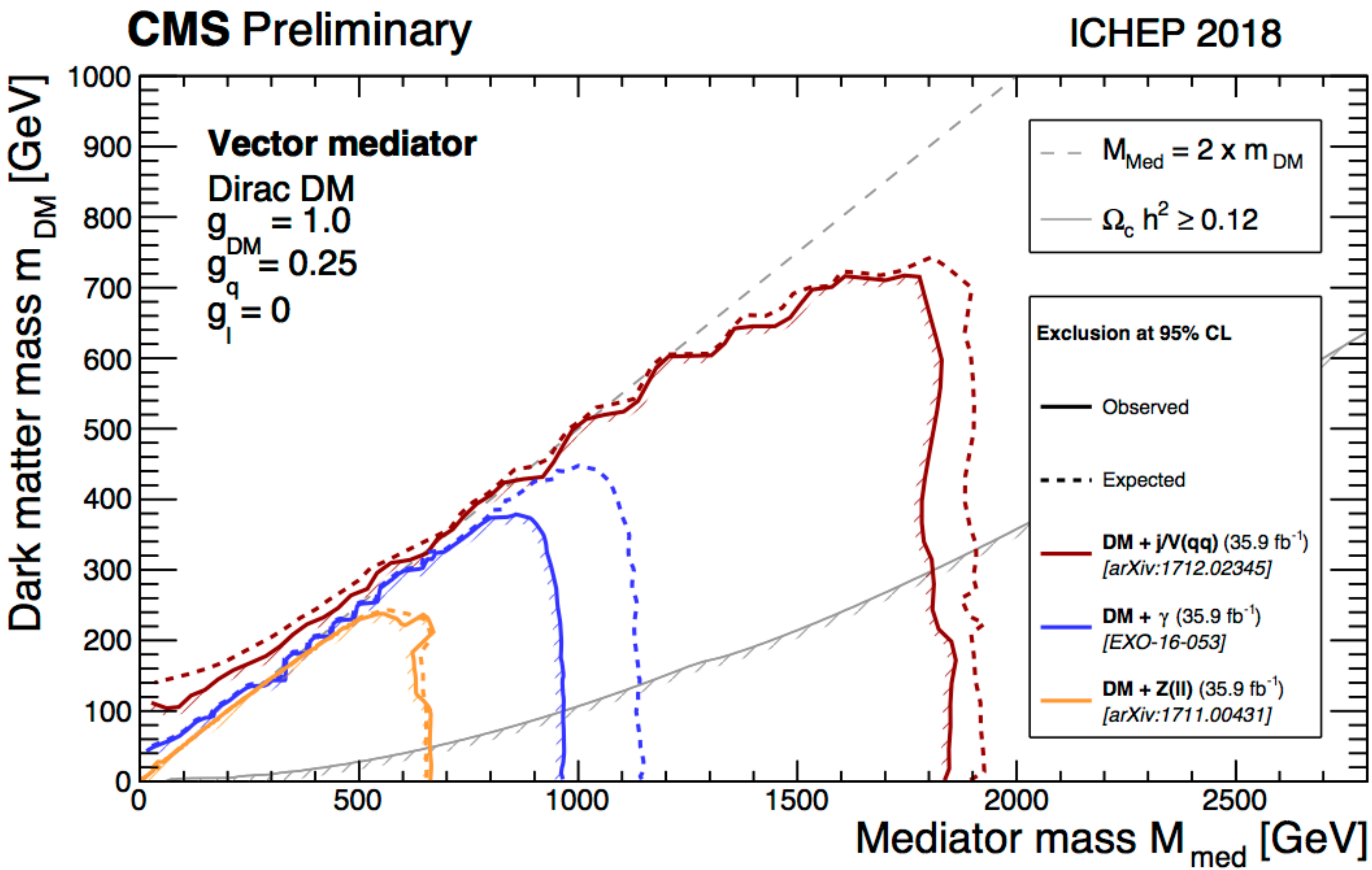


Mono-Z(leptonic)

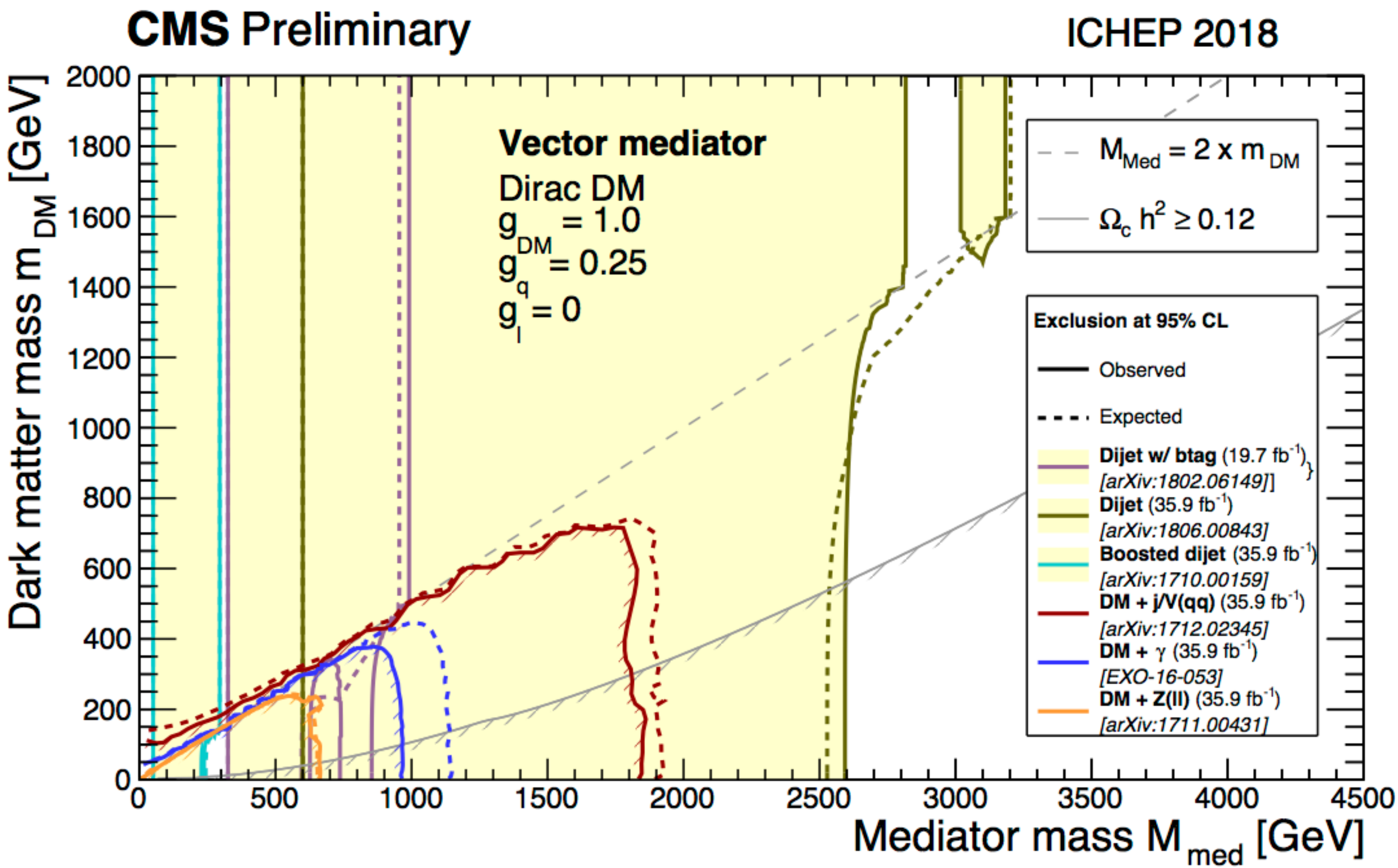


Mono-W/Z(hadronic)

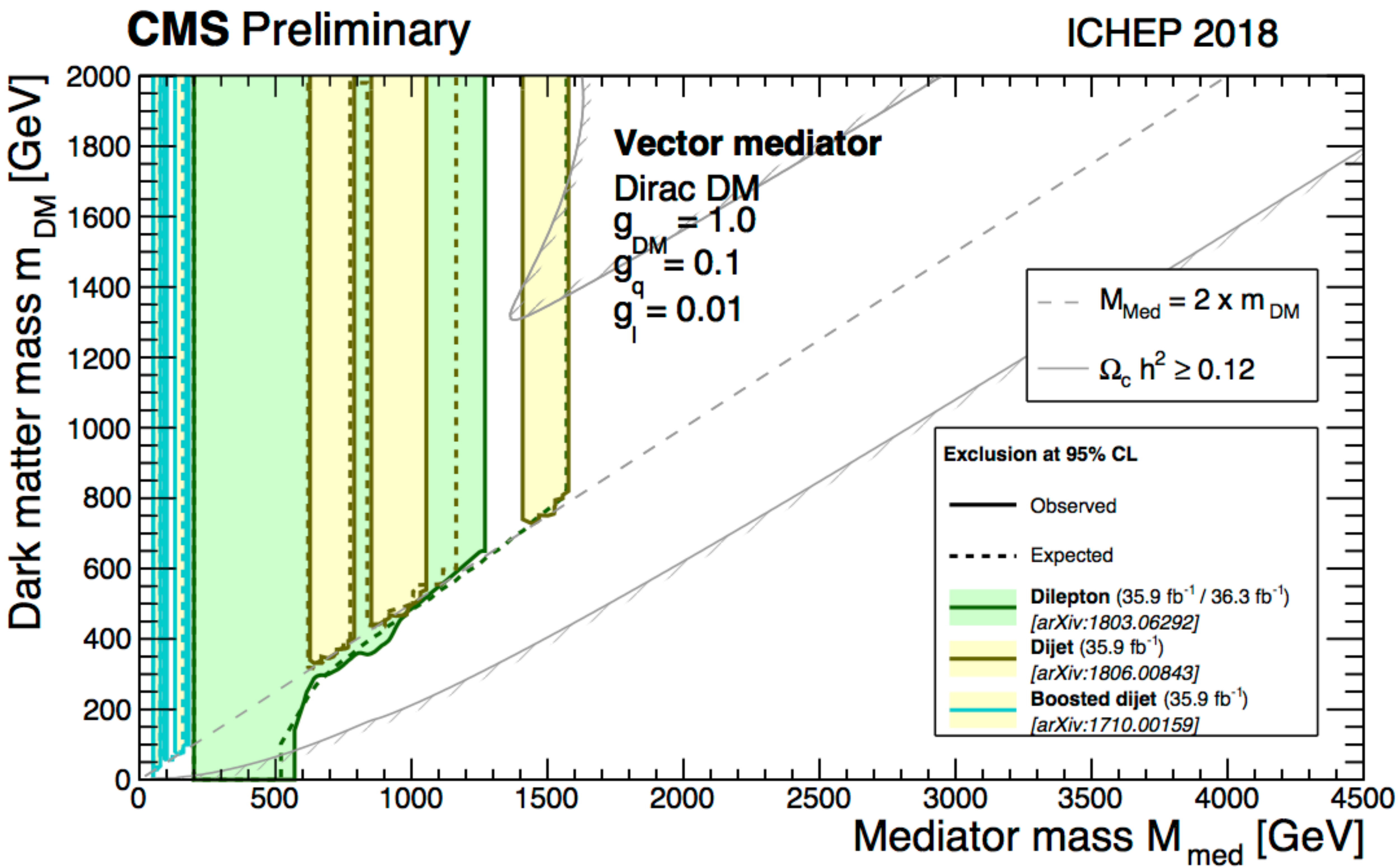
Collider Results Only (Vector Mediator)-Mono-X



Collider Results Only (Vector Mediator)

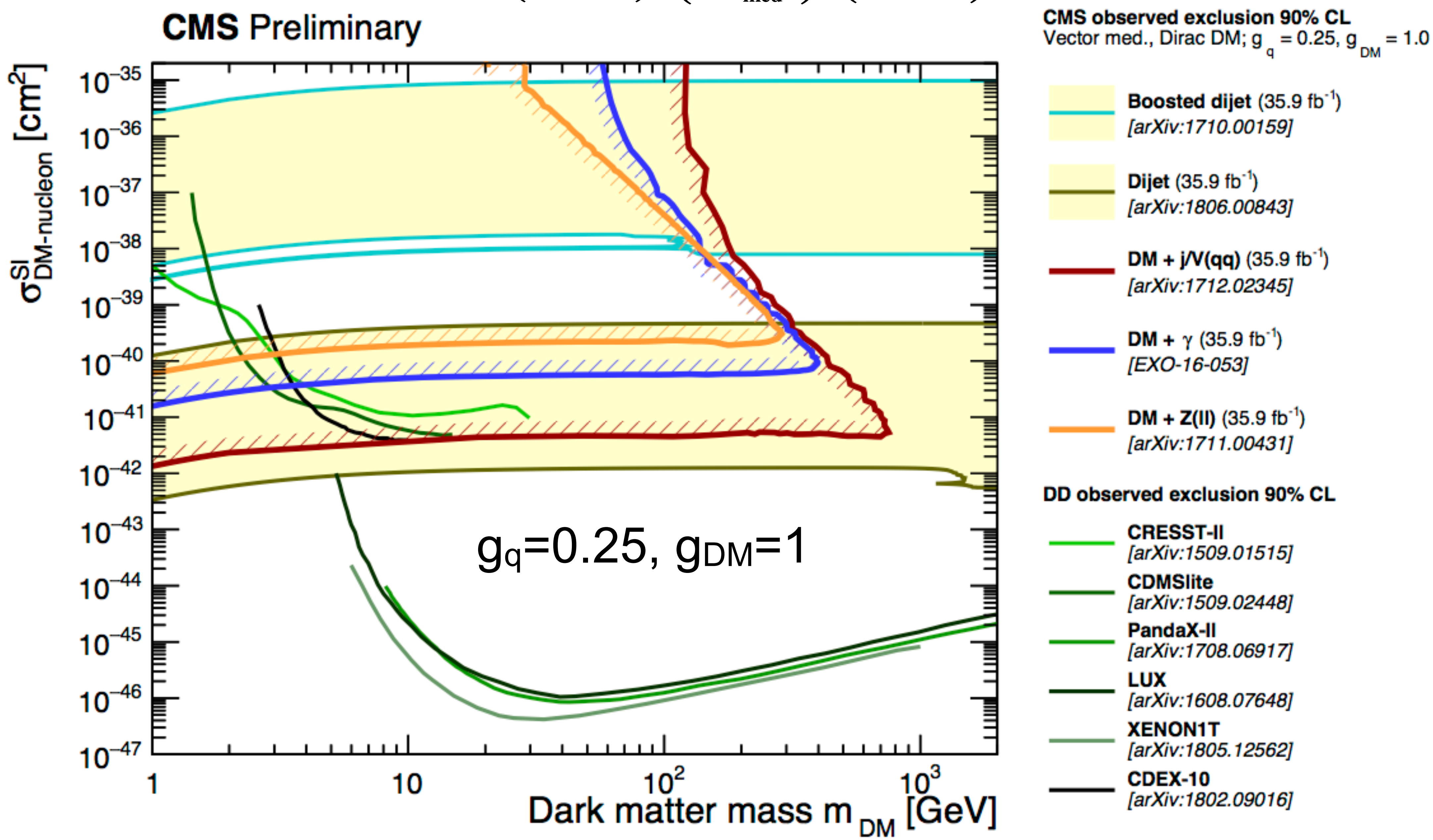


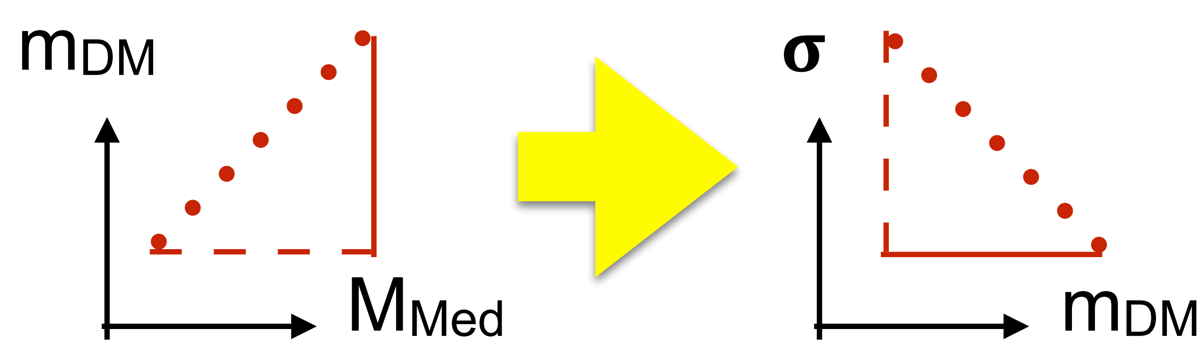
If We Use Different Parameter Values



Collider v.s. Non-Collider Experiments (SI)

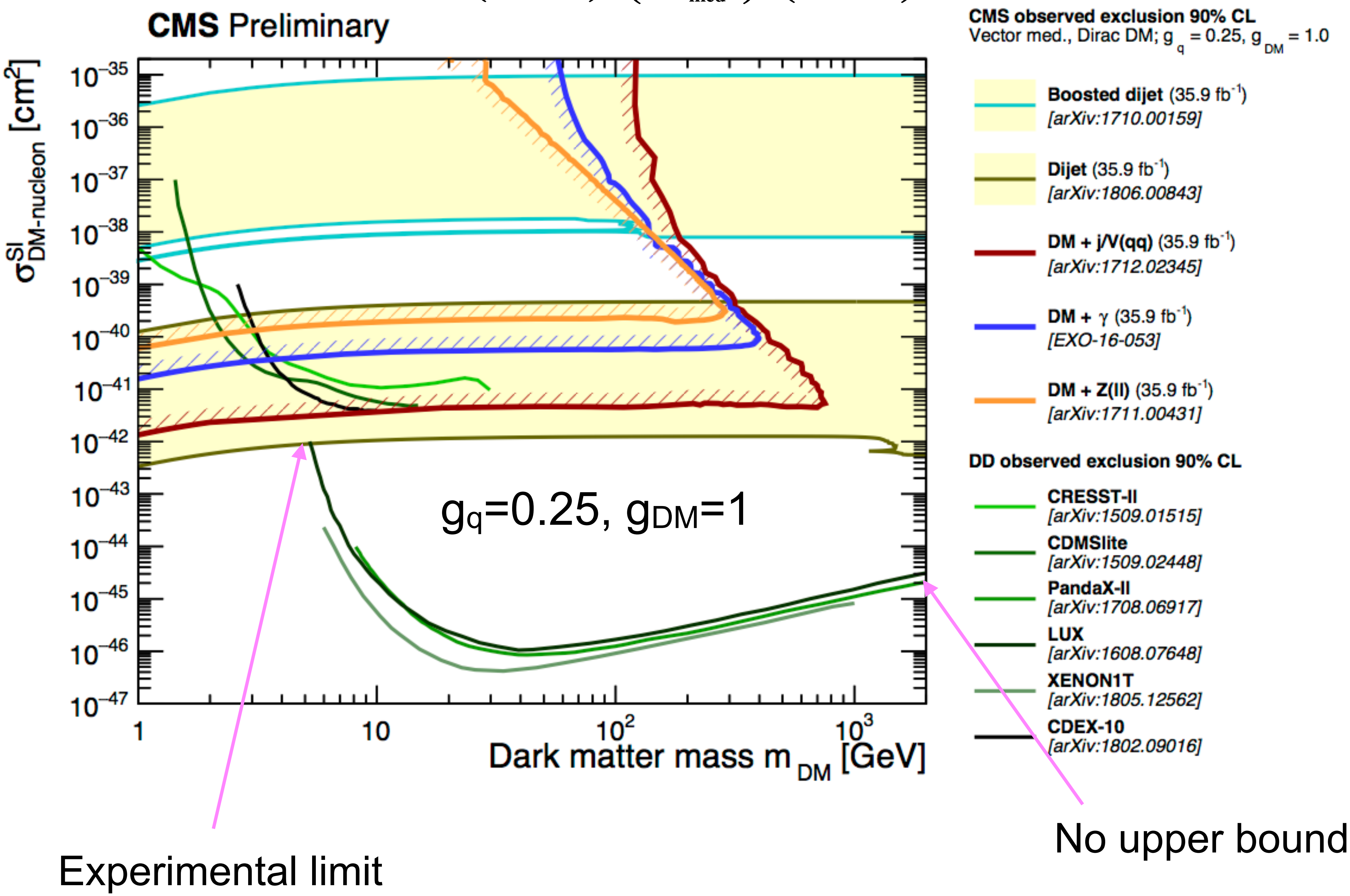
$$\sigma_{\rm SI}^{\rm vector} \simeq 6.9\times10^{-41}\,{\rm cm}^2 \left(\frac{g_q g_{\rm DM}}{0.25}\right)^2 \left(\frac{1\ {\rm TeV}}{M_{\rm med}}\right)^4 \left(\frac{\mu_{n\chi}}{1\ {\rm GeV}}\right)^2$$





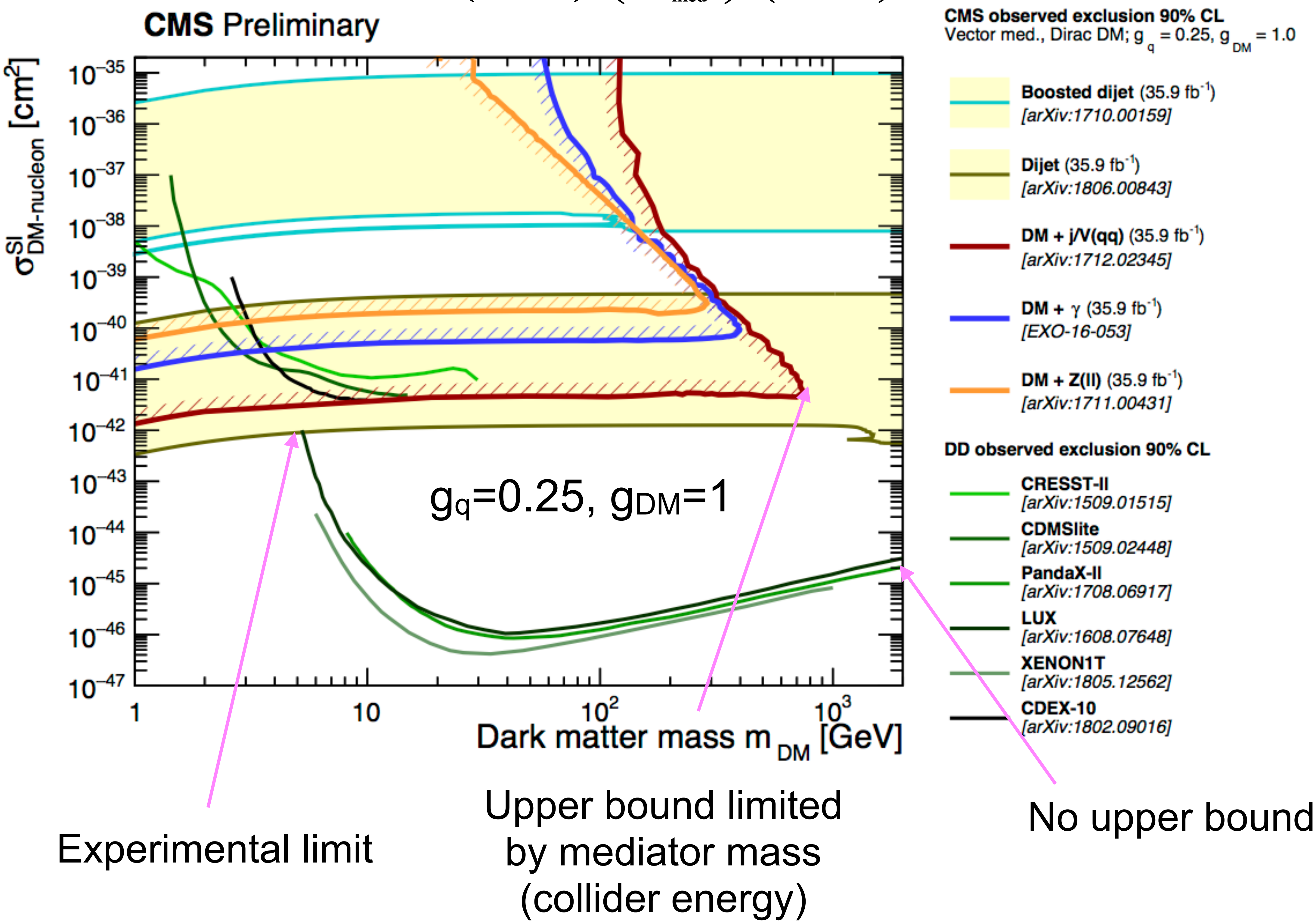
Collider v.s. Non-Collider Experiments (SI)

$$\sigma_{\mathrm{SI}}^{\mathrm{vector}} \simeq 6.9\times10^{-41}\,\mathrm{cm}^2 \left(\frac{g_q g_{\mathrm{DM}}}{0.25}\right)^2 \left(\frac{1\ \mathrm{TeV}}{M_{\mathrm{med}}}\right)^4 \left(\frac{\mu_{n\chi}}{1\ \mathrm{GeV}}\right)^2$$



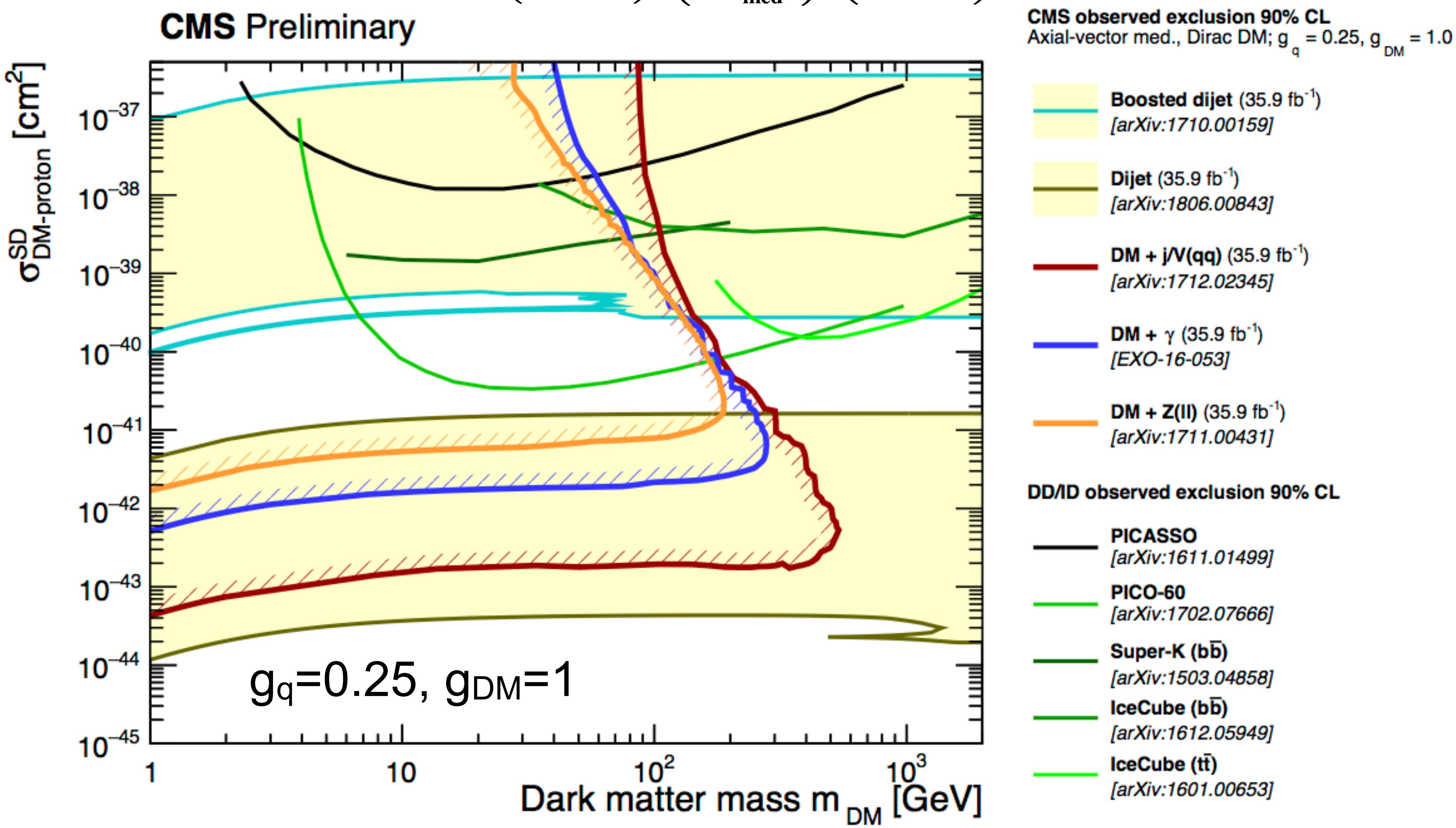
Collider v.s. Non-Collider Experiments (SI)

$$\sigma_{SI}^{vector} \simeq 6.9\times10^{-41}\,\mathrm{cm}^2 \left(\frac{g_q g_{DM}}{0.25}\right)^2 \left(\frac{1\ \mathrm{TeV}}{M_{med}}\right)^4 \left(\frac{\mu_{n\chi}}{1\ \mathrm{GeV}}\right)^2$$



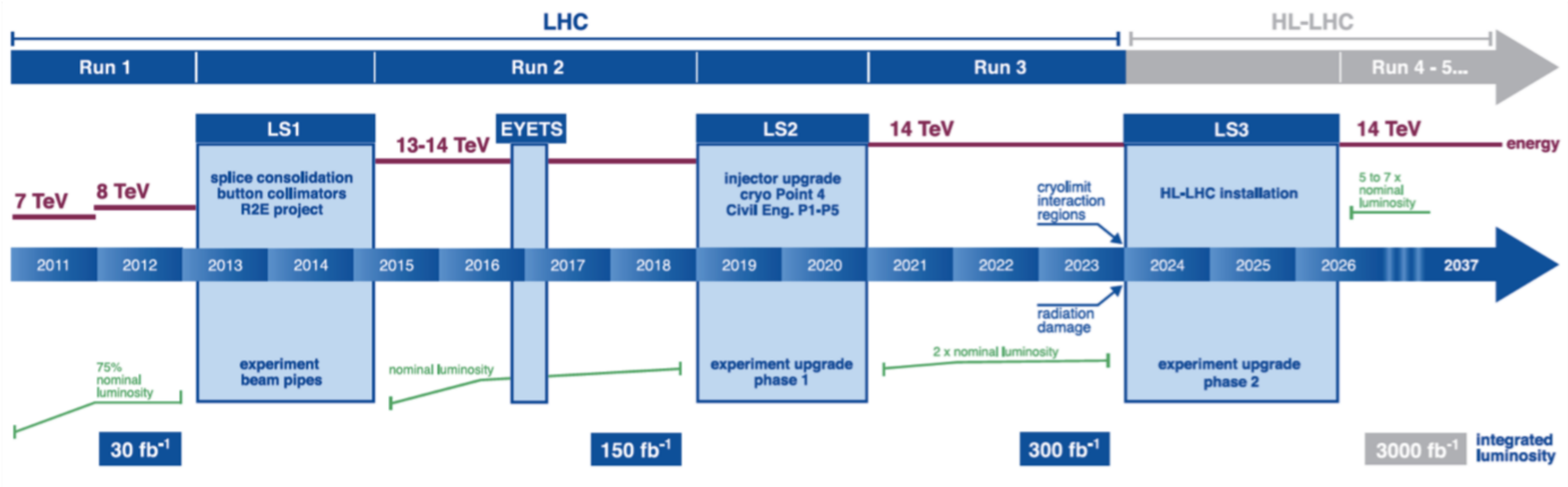
Collider v.s. Non-Collider Experiments (SD)

$$\sigma_{\rm SD}^{\rm axial} \simeq 2.4\times10^{-42}\,{\rm cm}^2 \left(\frac{g_q g_{\rm DM}}{0.25}\right)^2 \left(\frac{1\ {\rm TeV}}{M_{\rm med}}\right)^4 \left(\frac{\mu_{n\chi}}{1\ {\rm GeV}}\right)^2$$

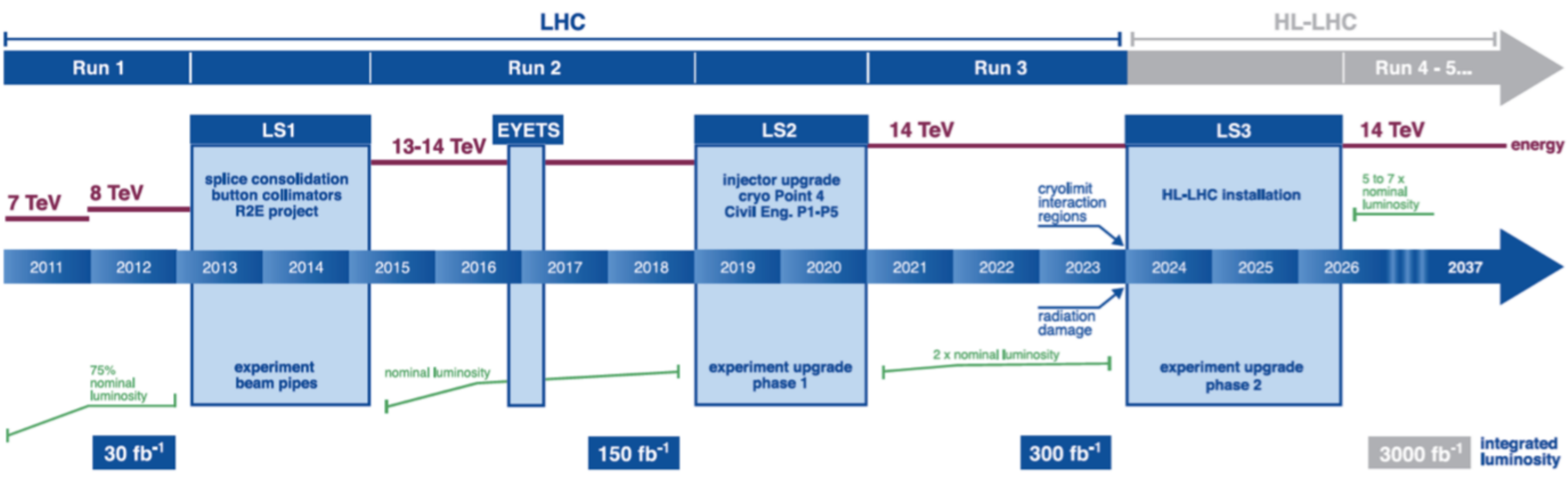


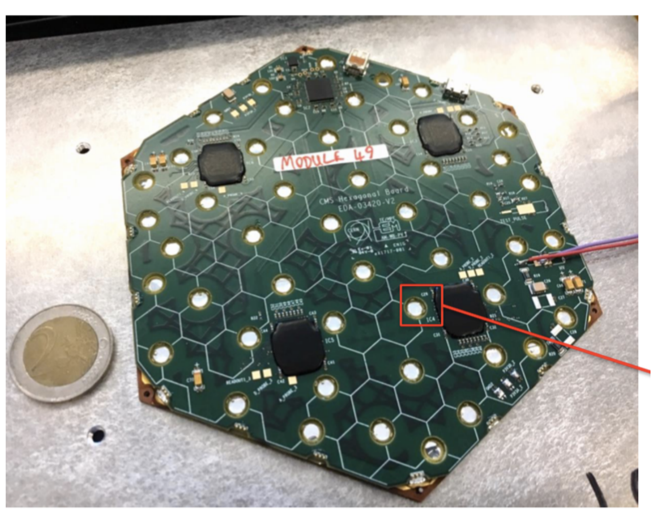
For the model parameters considered here, collider experiments can probe SD cross sections 2-3 orders of magnitude smaller than the non-collider experiments.

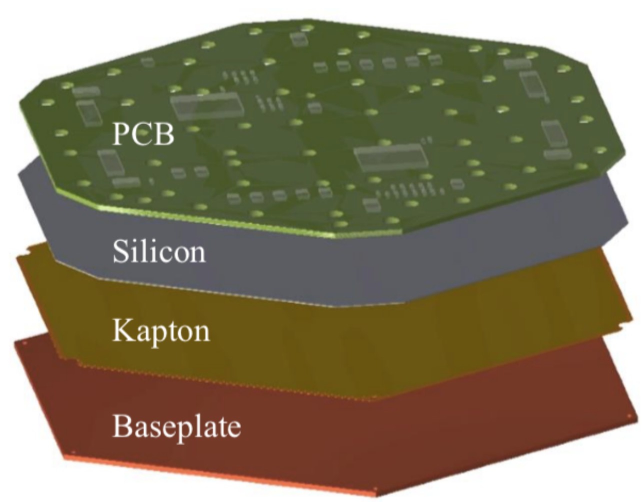
CMS Phase-2 Upgrade

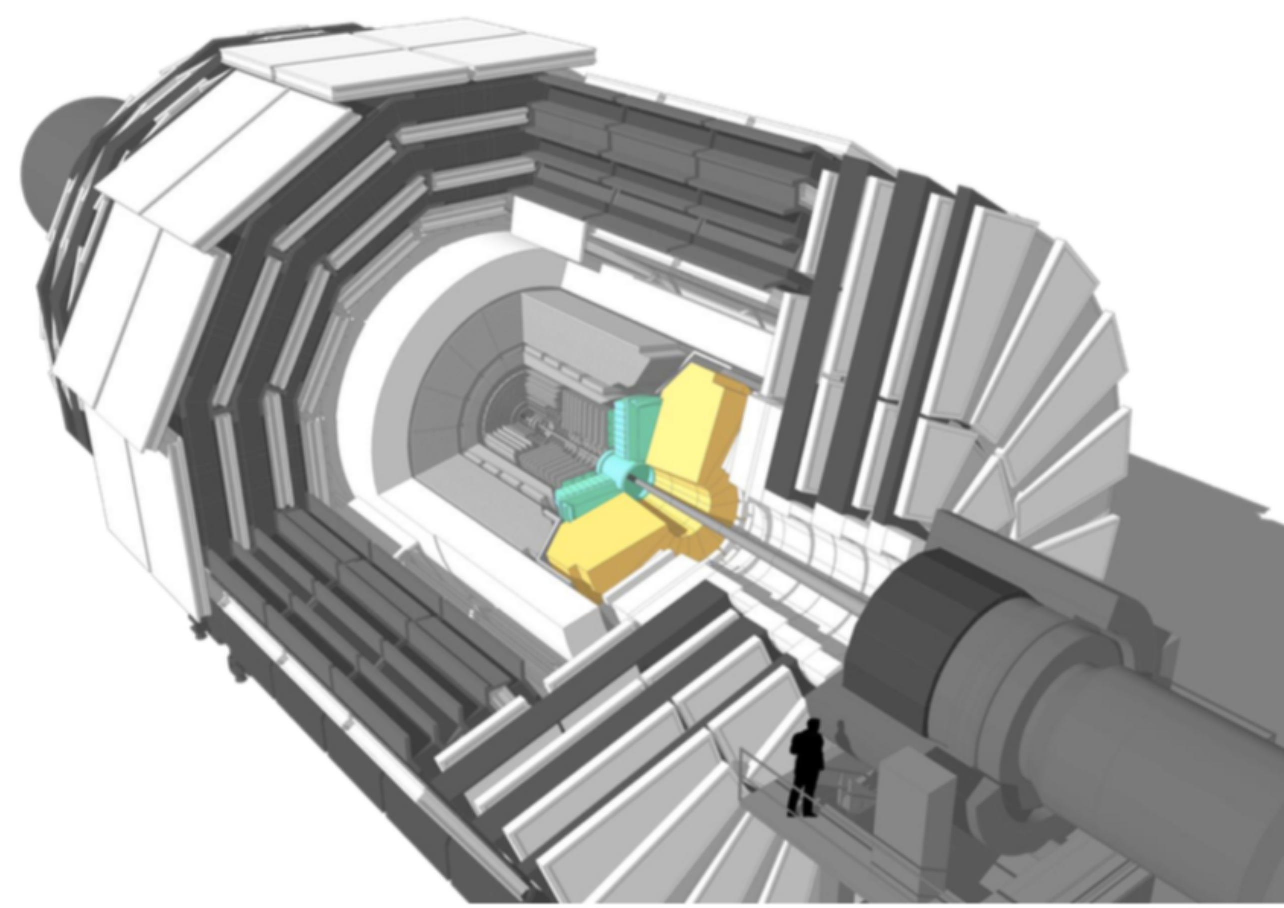


CMS Phase-2 Upgrade

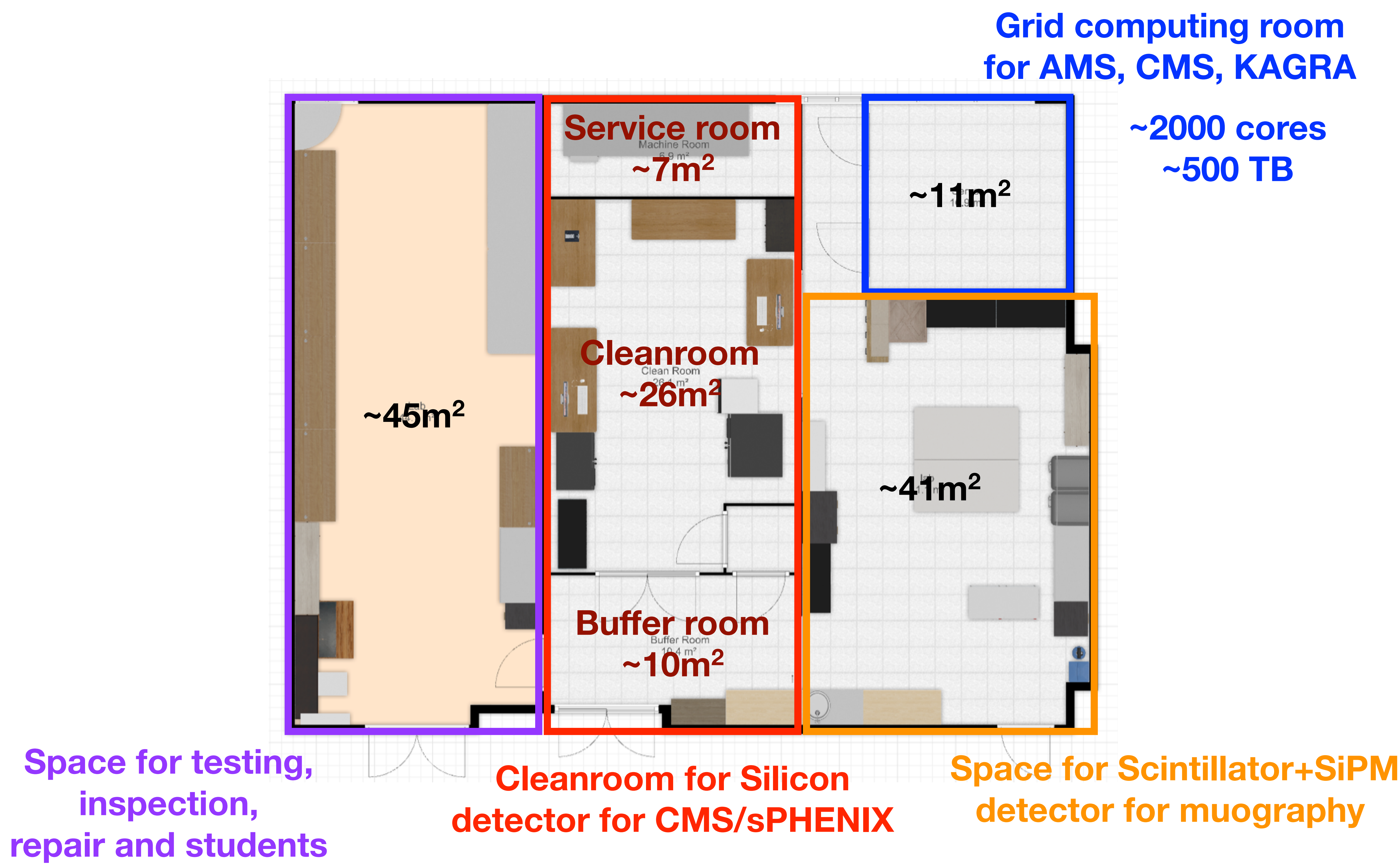








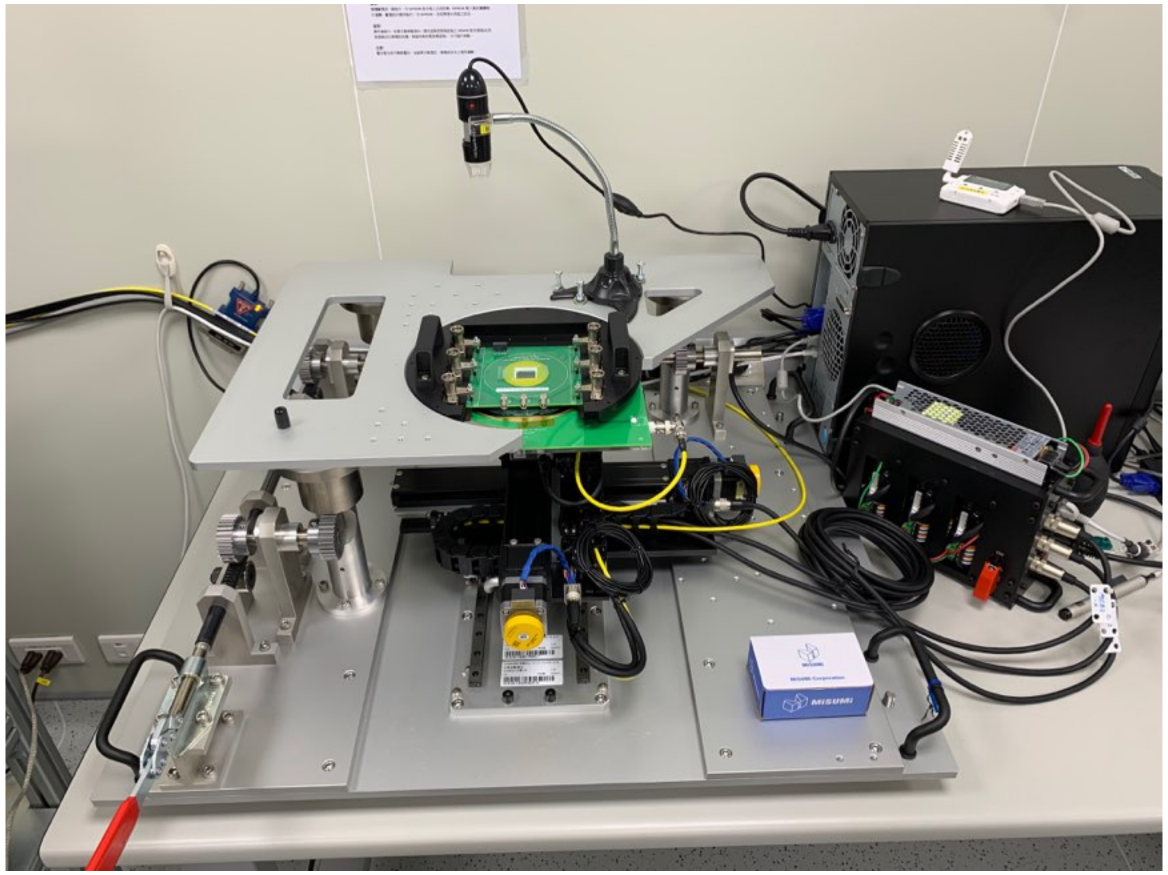
The Detector Lab @ NCU

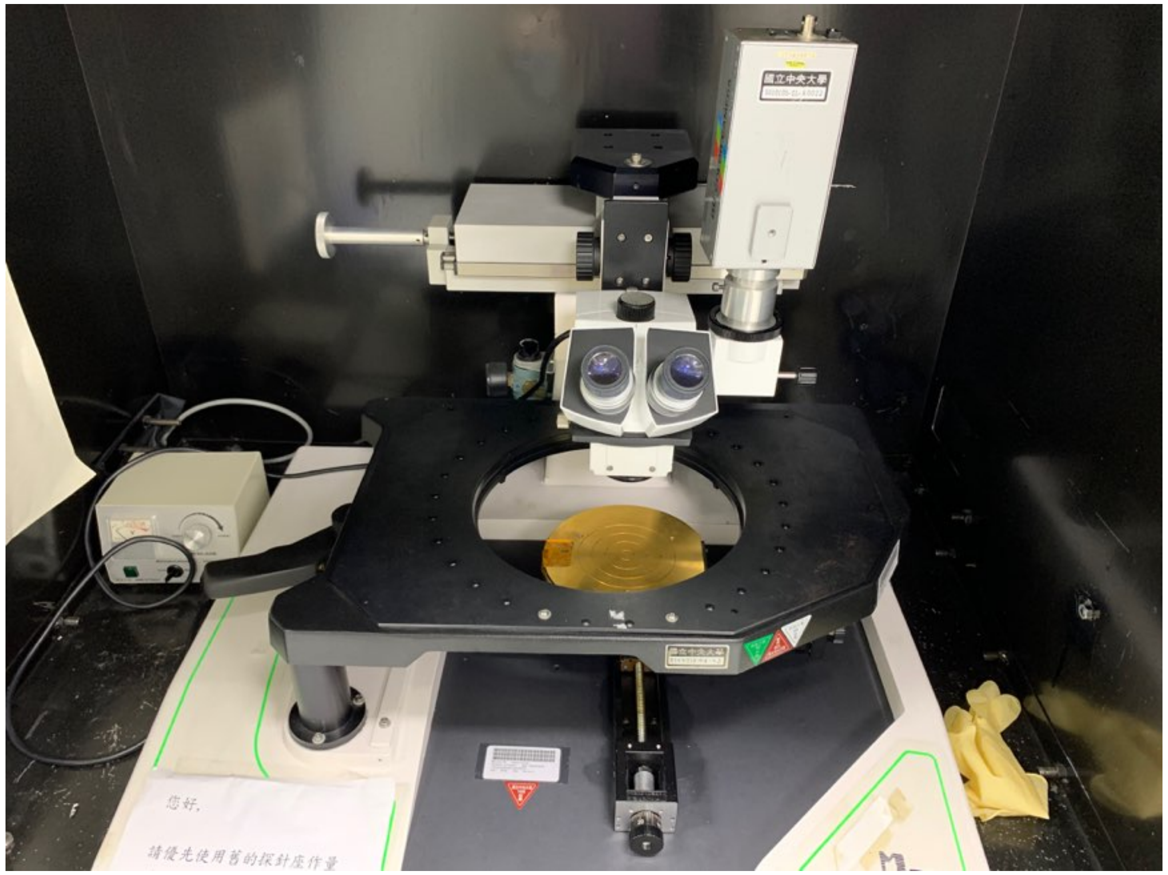


Cleanroom

- cleanroom： ~26m^2
- service + buffer room： ~17m^2
- **class 1000** with temperature and humidity controlled at 22℃ and relative humidity (RH) 55% all year round
  - fully operation with pressured dry-air service

Probe Stations

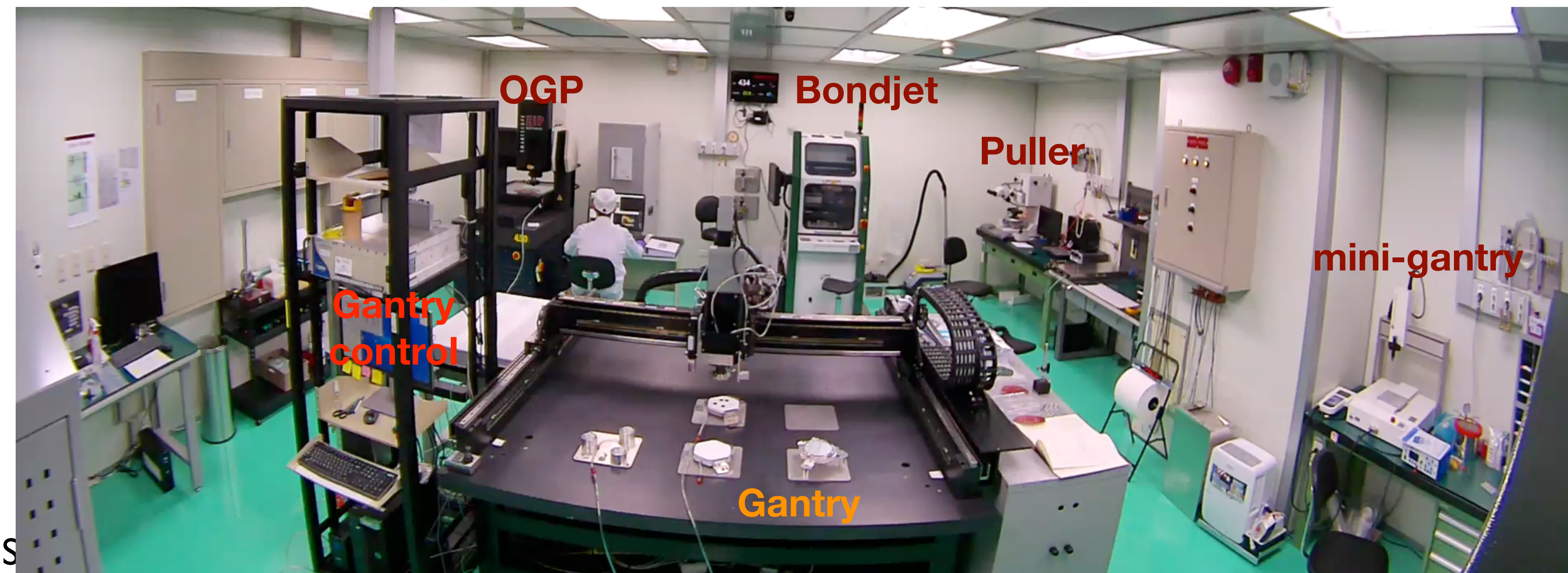




- left： self-designed 8-inch probe station used for the large pad silicon sensors
- right： 4-inch probe station used for PHOBOS and CMS Preshower (being upgraded for sPHENIX)
- A new 8-inch MPI probe station was installed in mid-November for CMS HGCal and sPHENIX

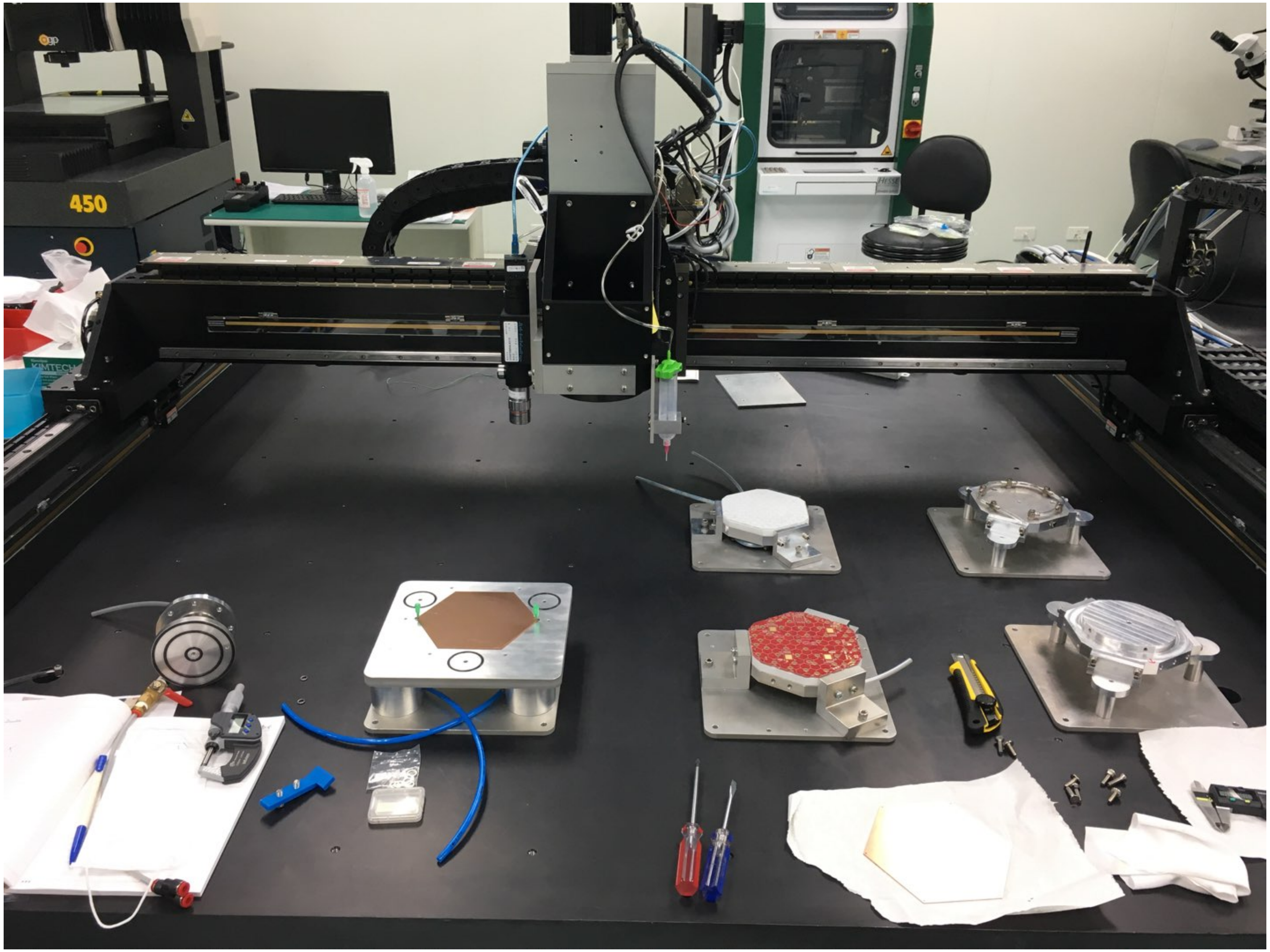
Cleanroom Equipments at NTU

- Aerotech 1.25x1.25 m^2 robotic gantry with Labview control.
- OGP optical 3d measurement
- Hesse BJ820 automatic Bondjet and DAGE 4000 Bondtester(puller)
- Manual probe station and picoprobes (not visible in this pic)
- glue dispensers, mini-gantry, microscope, degassing chamber, Keithley 2410 and tools …

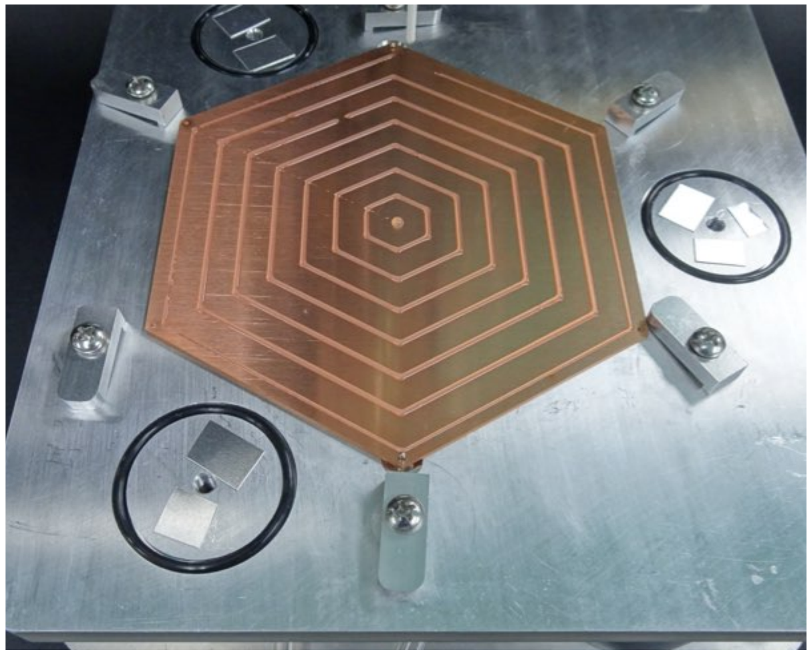


S

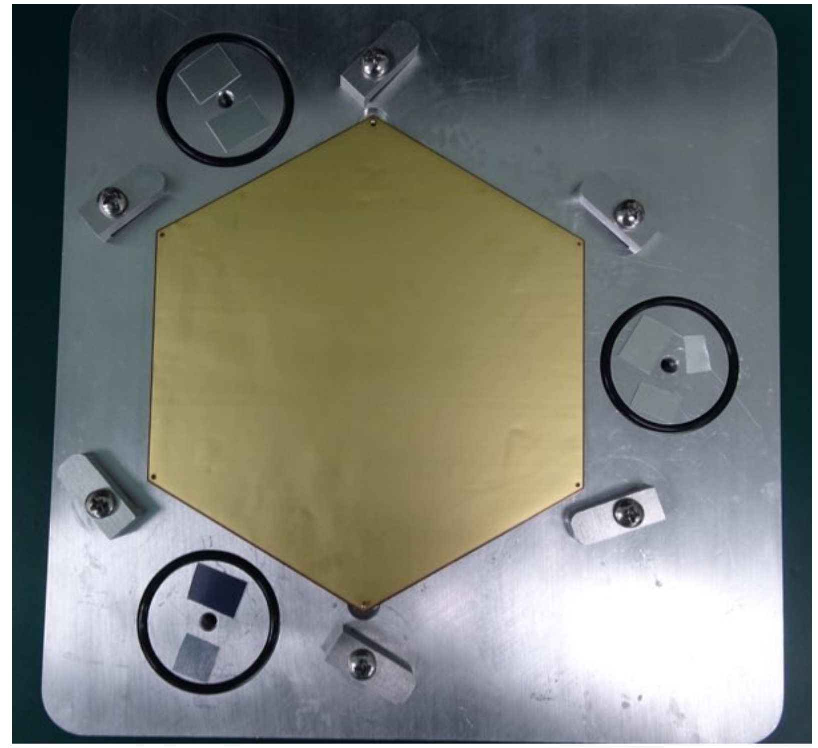
A set of jigs and tooling for 6-inch HGCal module assembly



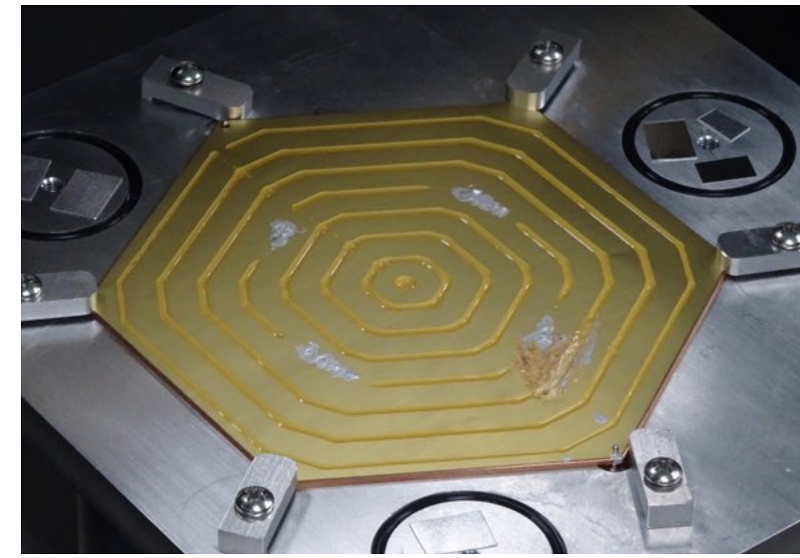
1. Deposit epoxy on Cu baseplate



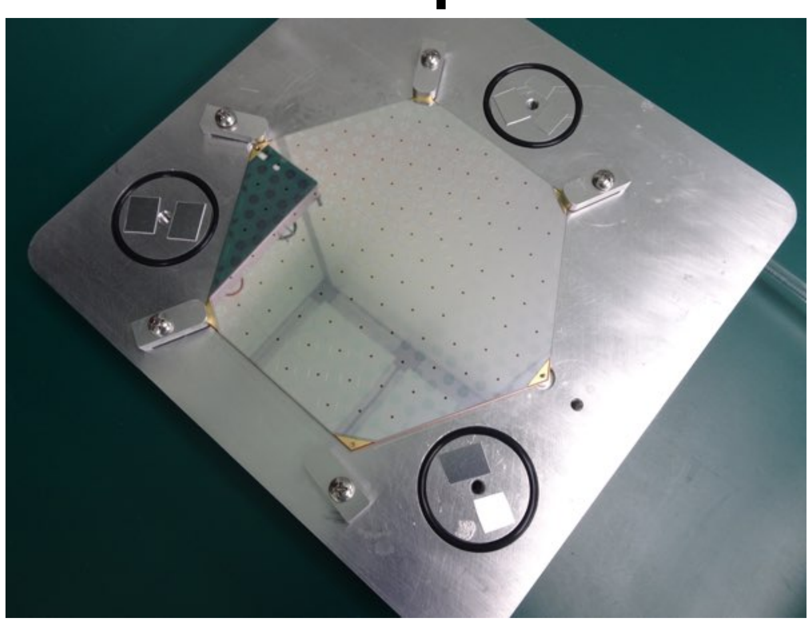
2. Place gold-plated Kapton film



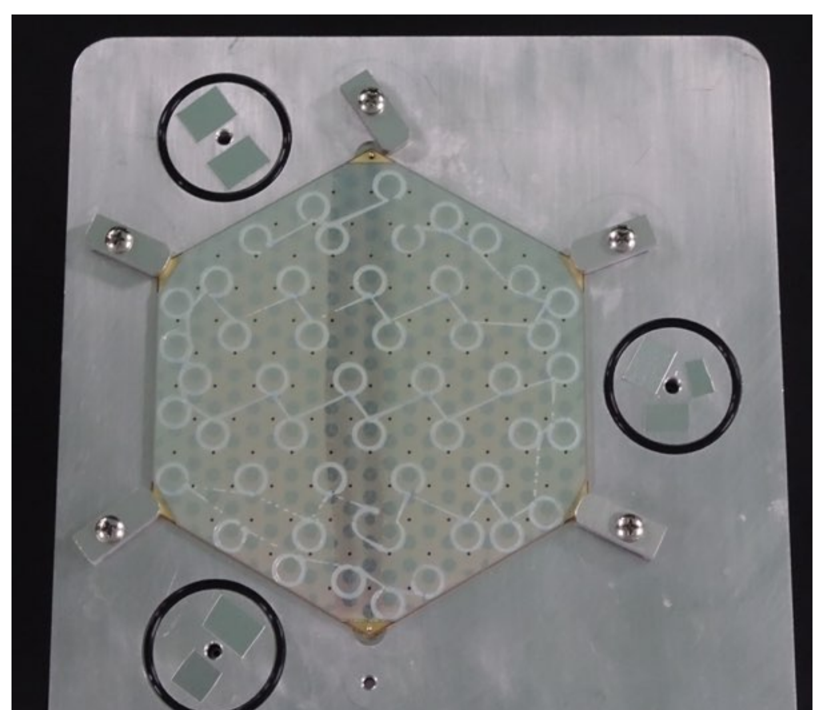
3. Deposit epoxy and silver epoxy on Kapton



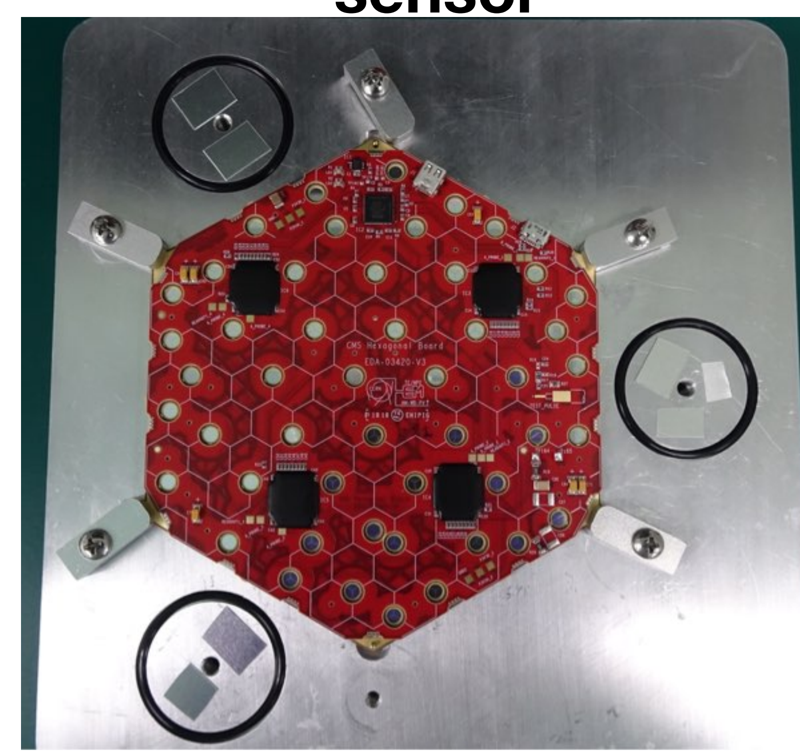
4. Place sensor on top of Kapton



5. Deposit epoxy on sensor, avoiding opening bond pads

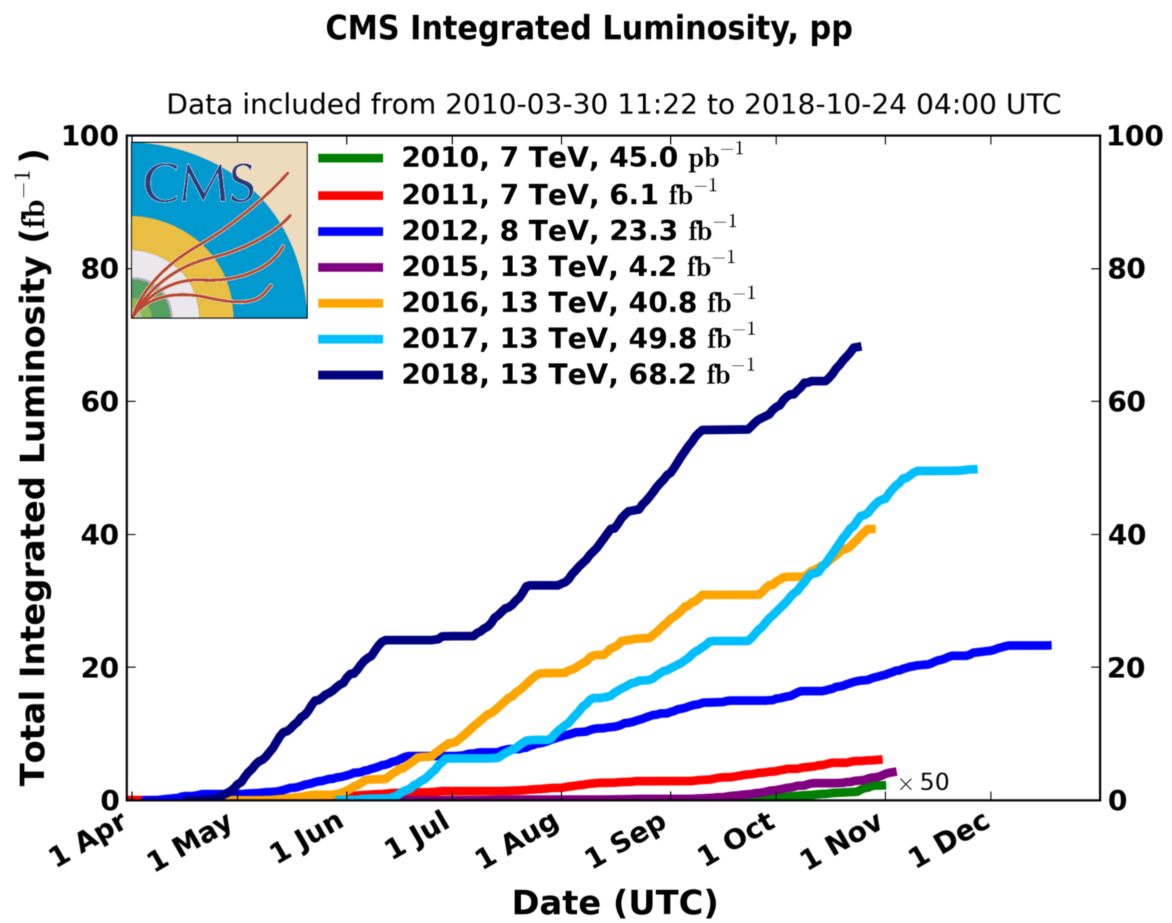


6. Place PCB on top of sensor



Conclusion and Outlook

- CMS has an extensive dark matter program, including both searches for mediators and searches in mono-X channels
- 137 fb^{-1} of full Run II data are yet to be analyzed



- Moving towards more advanced/sophisticated models
  - t-channel production
  - spin-2 mediators, long-lived mediators or intermediate "dark" particles
- Detector upgrade going on and Taiwan (NCU/NTU) is playing a major role in the endcap calorimeter