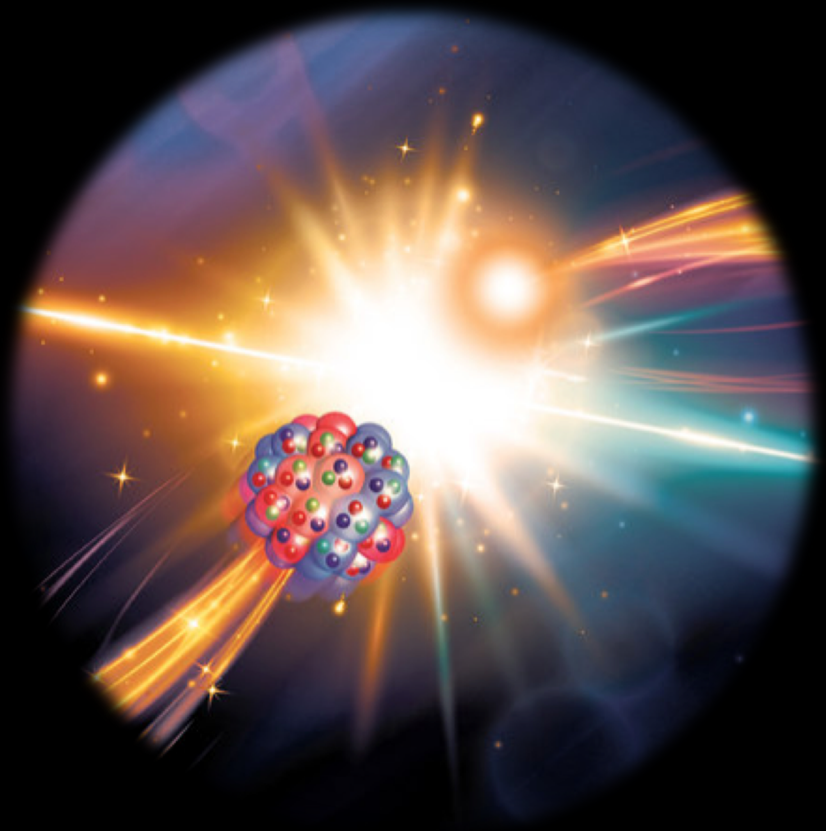
EIC Detector Technology Challenges

The R&D program



Inaugural Symposium of the Center for Frontiers in Nuclear Science

Stony Brook
November 29, 2018

Marcel Demarteau
demarteau@anl.gov

Argonne National Laboratory

Beautiful Theories in Physics

$$R_{\mu\nu} - \frac{1}{2} R\, g_{\mu\nu} + \Lambda\, g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

$$\begin{aligned}\mathcal{L} = &-\frac{1}{4} F_{\mu\nu} F^{\mu\nu} \\ &+ i \bar{\psi} \not{D} \psi + h.c \\ &+ \psi_i y_{ij} \psi_j \phi + h.c \\ &+ |D_\mu \phi|^2 - V(\phi)\end{aligned}$$

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Work a century in the making !

Beautiful Theories in Physics

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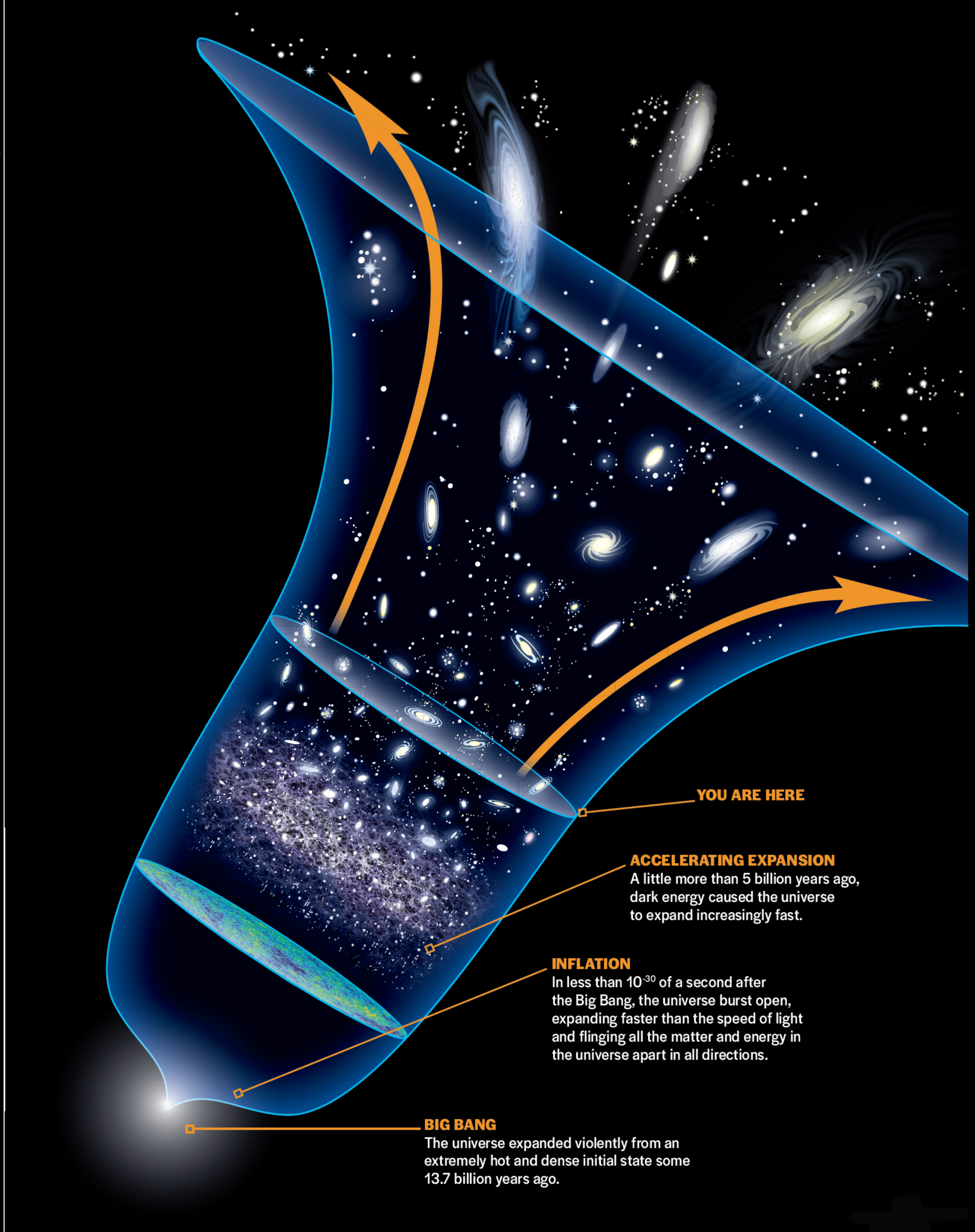
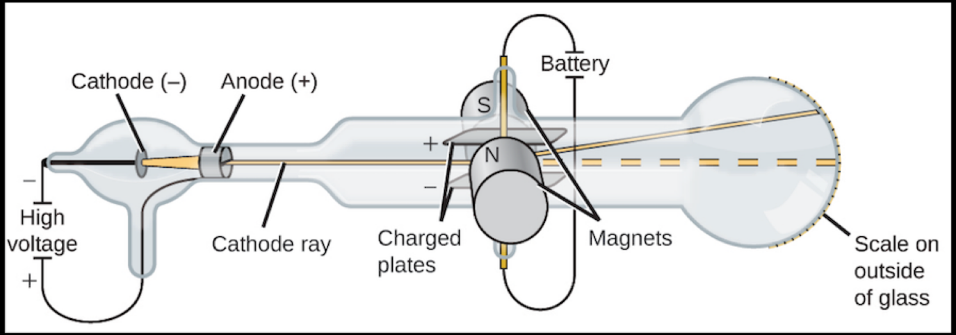
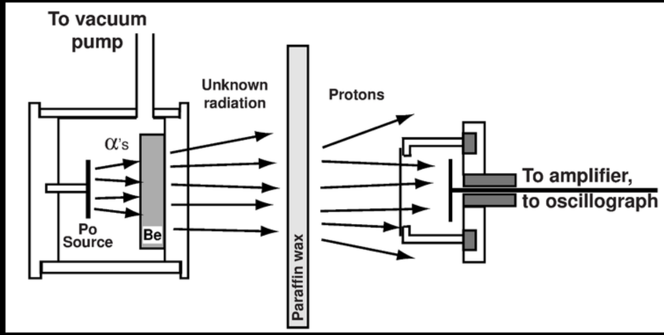


An amazing understanding at vastly different scales

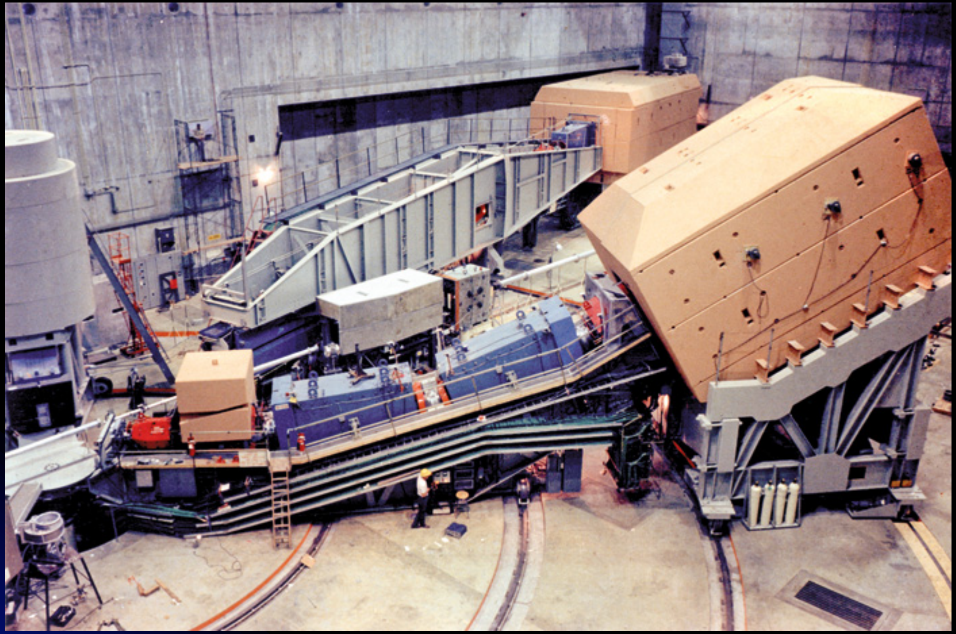
Building An Understanding Of The Universe



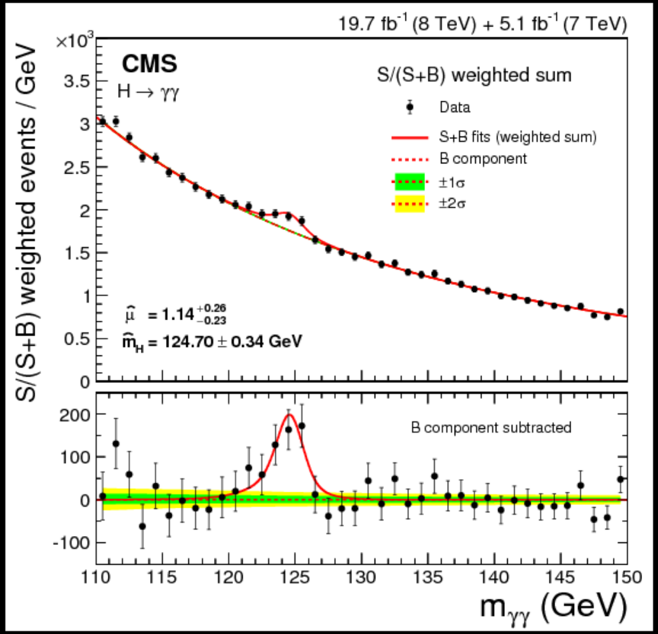
Discovery of the electron, J.J. Thompson (1897)



Discovery of the neutron, J. Chadwick (1932)



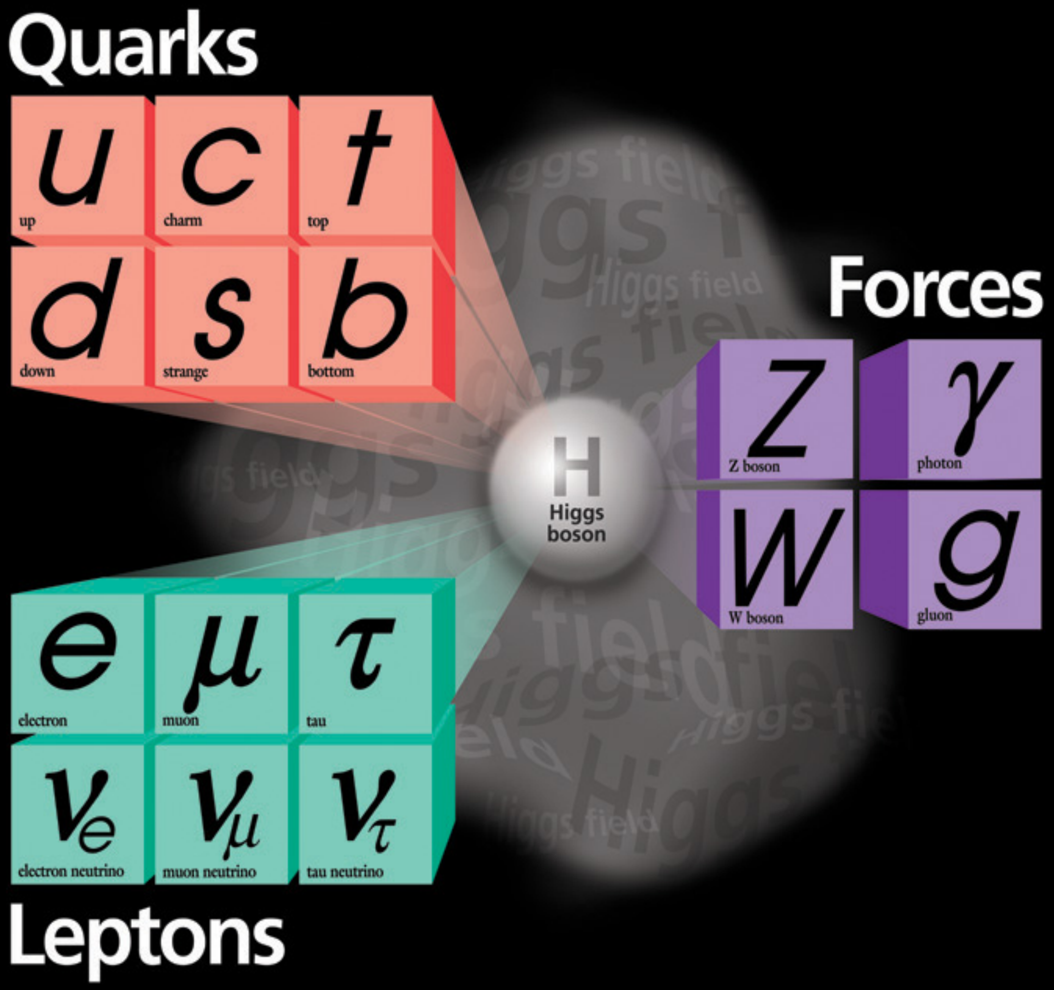
Discovery of quarks, Friedman, Kendall, Taylor (1969)



Discovery of Higgs boson, CERN (2012)

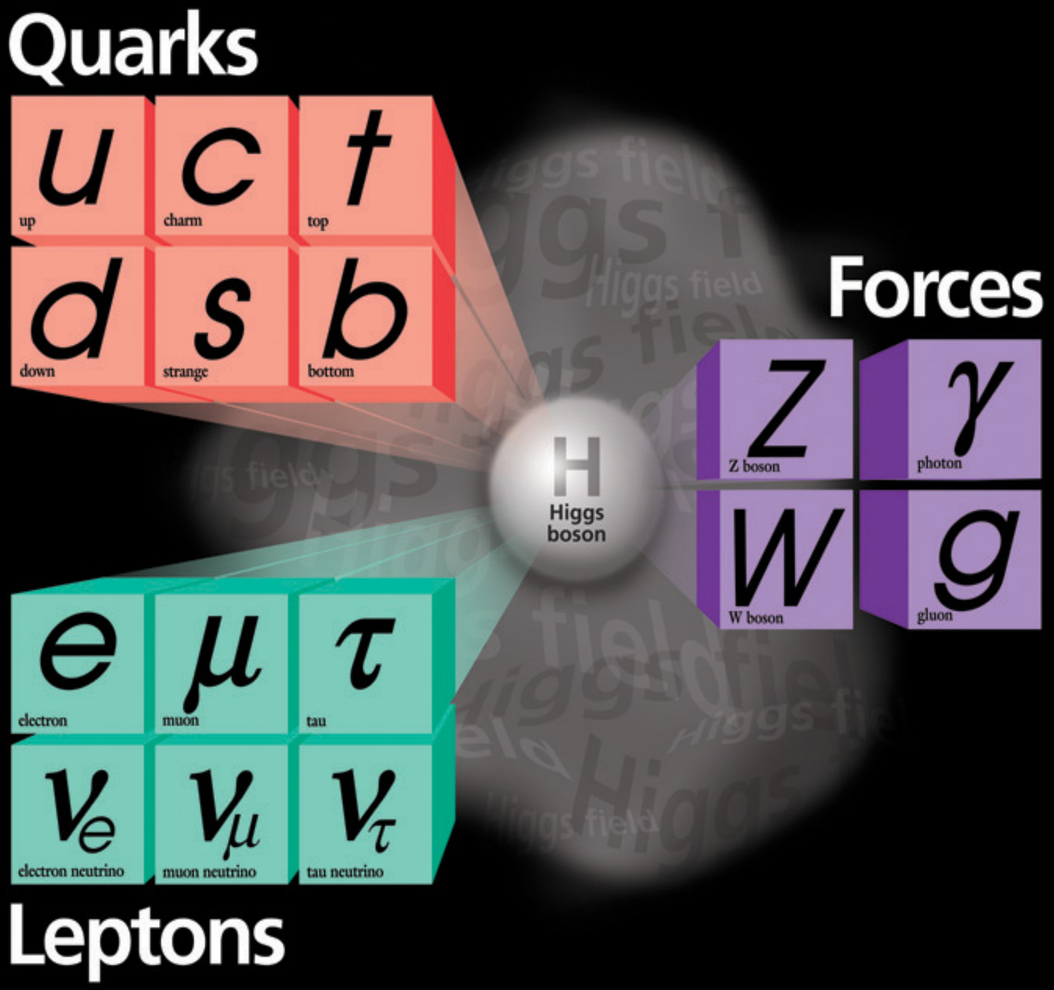
An Edifice Hundred Years In The Making

Particle Standard Model

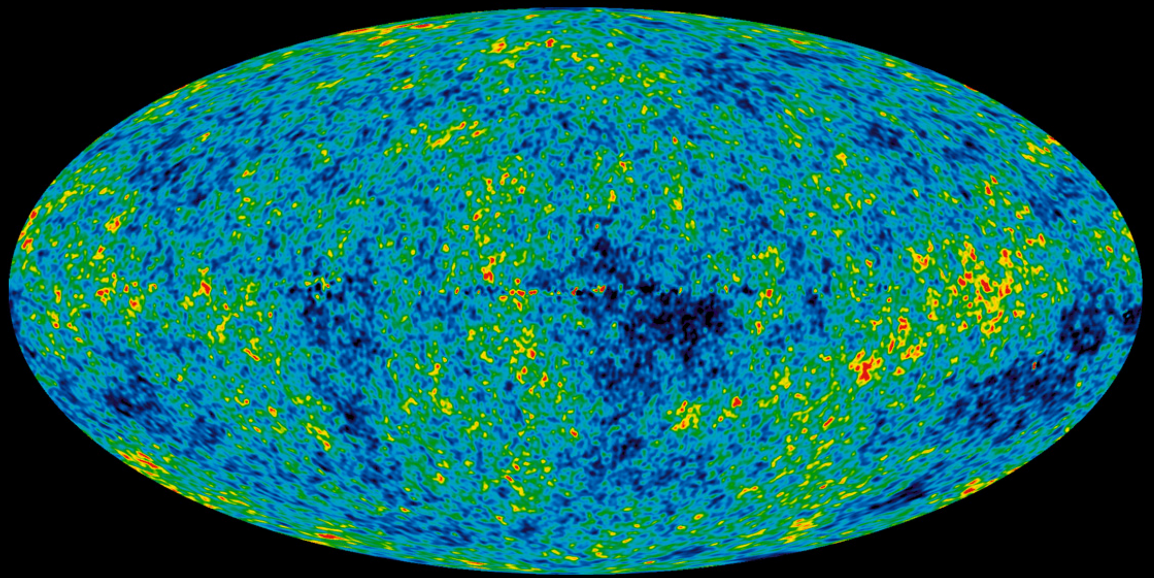


An Edifice Hundred Years In The Making

Particle Standard Model



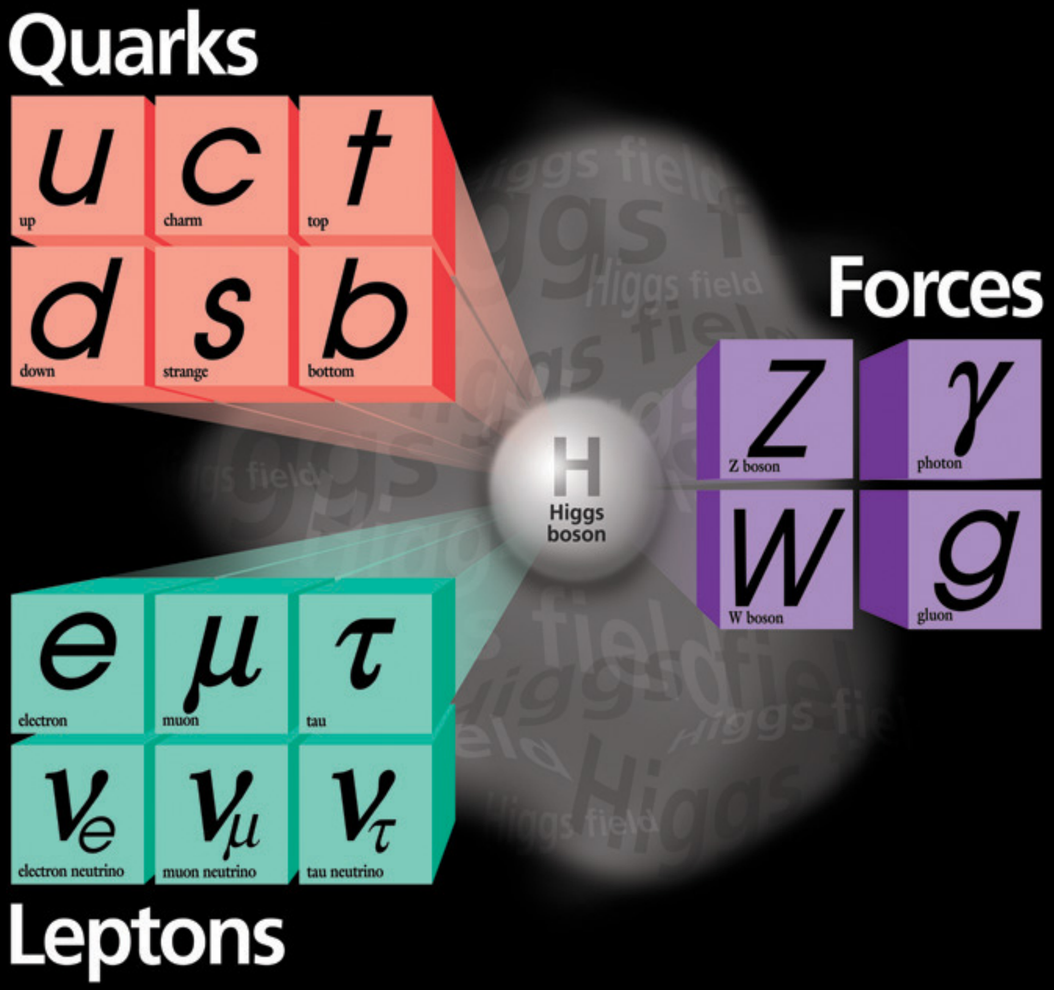
Cosmology Standard Model



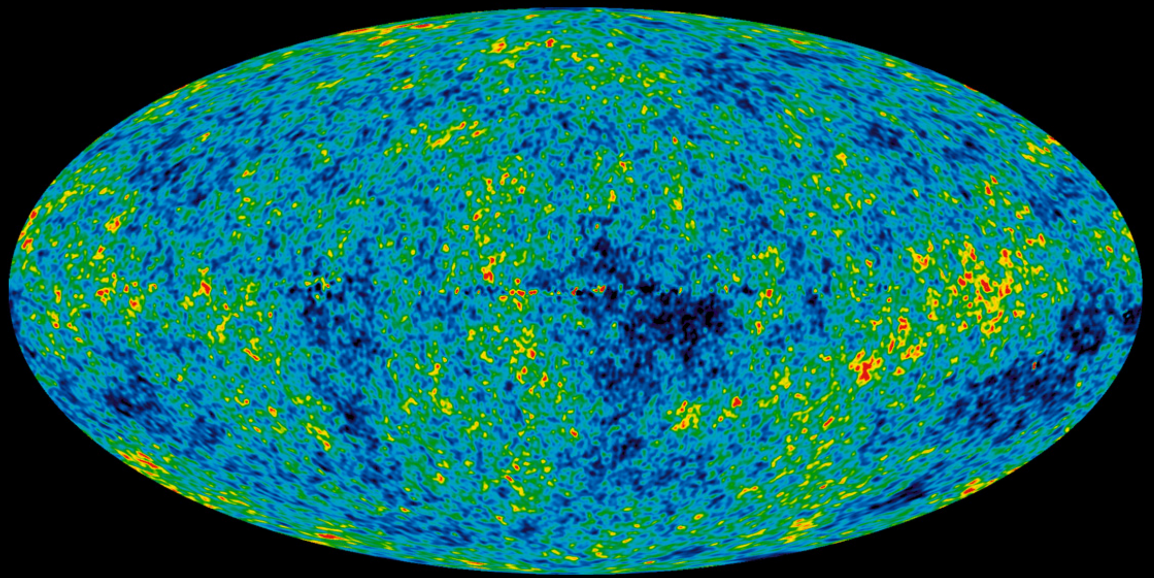
Λ_{CDM}

An Edifice Hundred Years In The Making

Particle Standard Model



Cosmology Standard Model

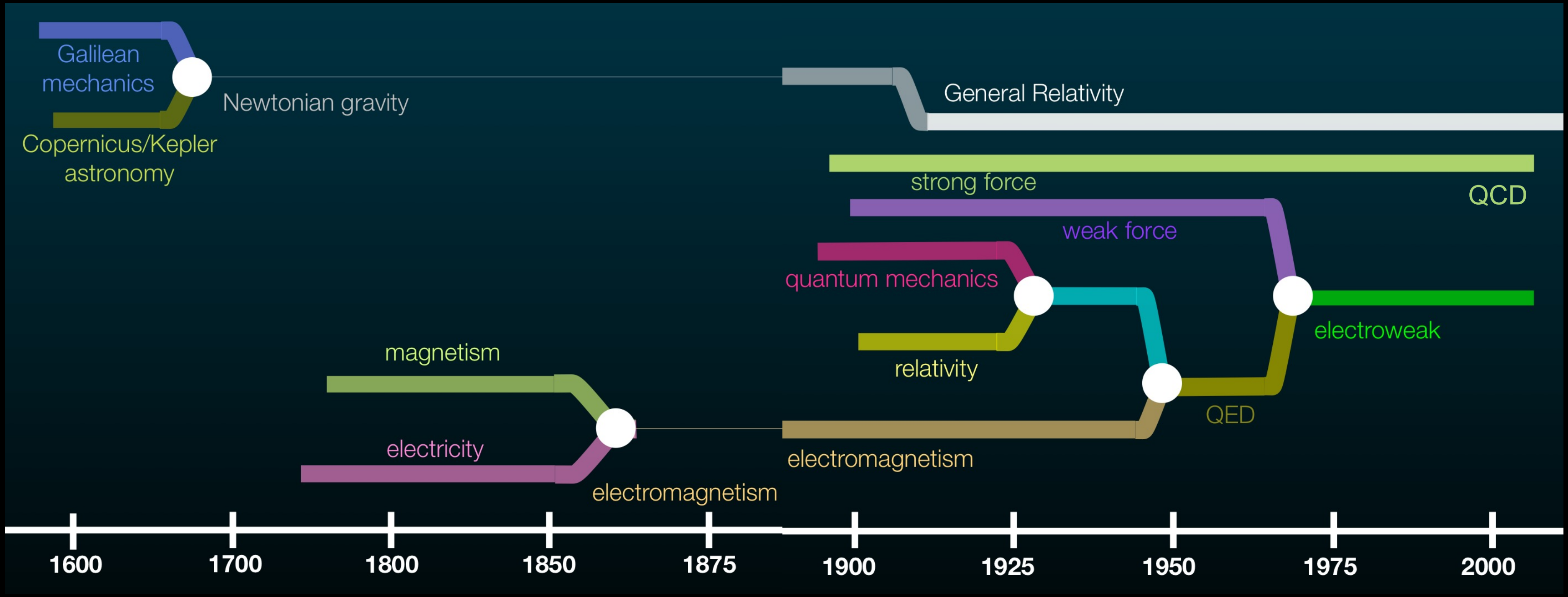


Λ_{CDM}

… it is highly predictive and has been rigorously tested in some cases to 1 part in 10 billion

Completing The Edifice

- These "Standard Models" are among the highest intellectual achievements



Completing The Edifice

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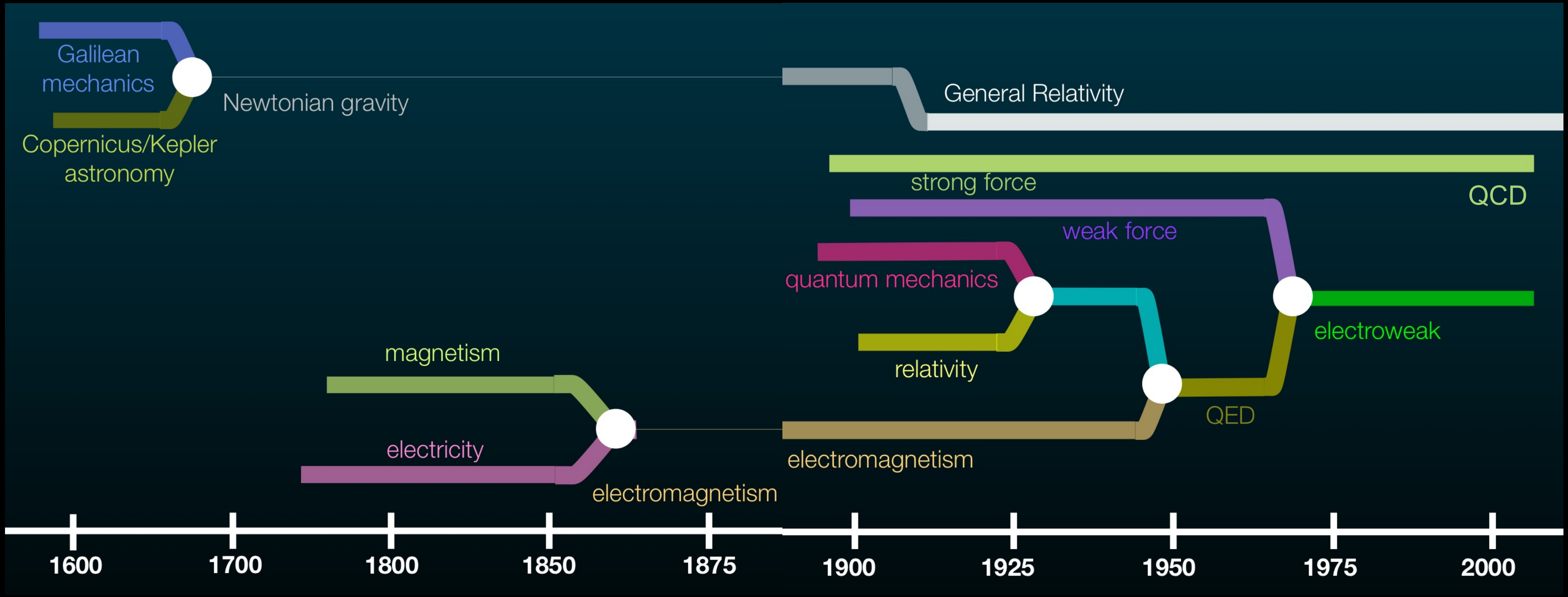
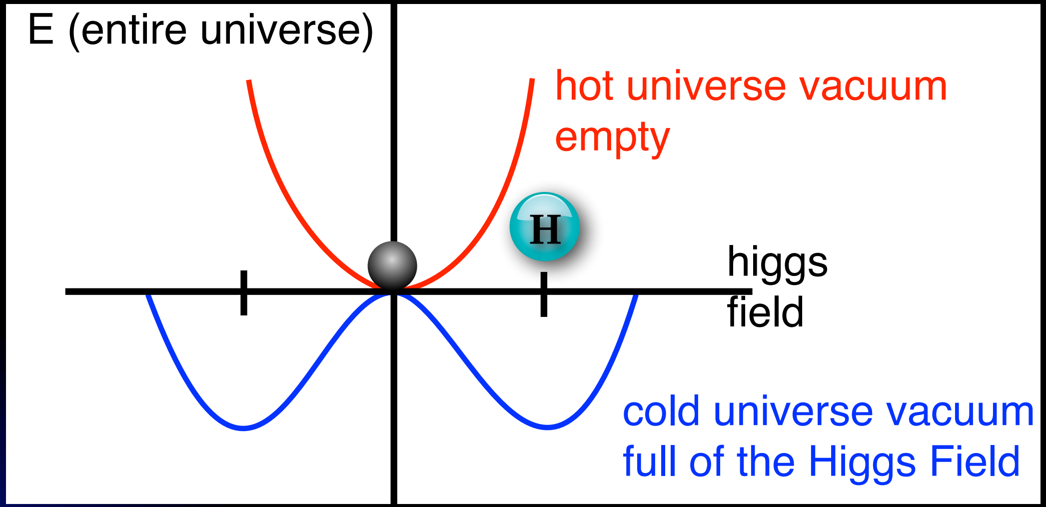


- The potential exists now to revolutionize our knowledge again.

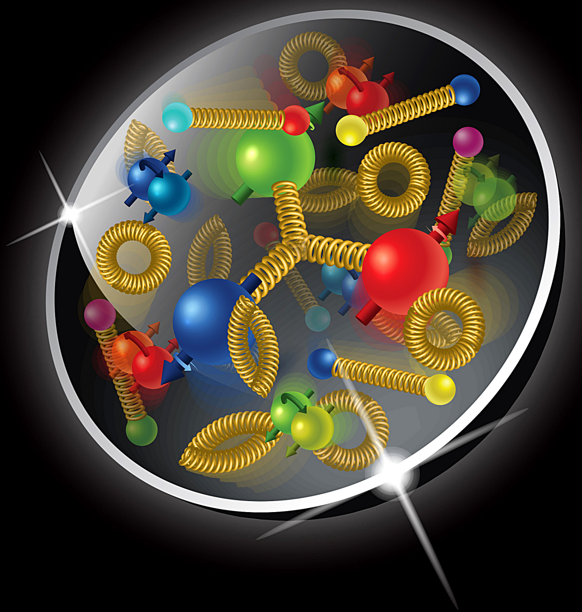
Mystery: The Higgs Boson

- Scalar particle
- Relation to inflationary field
- Self-interaction
- Composite particle ?
- How many are there ?



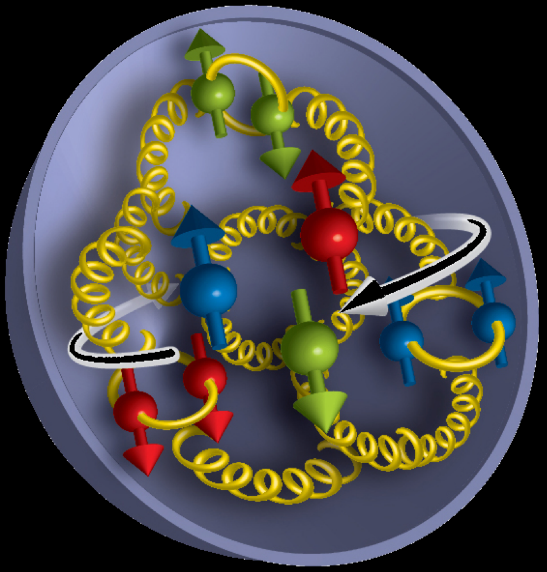
Mystery: The Proton

Proton Mass



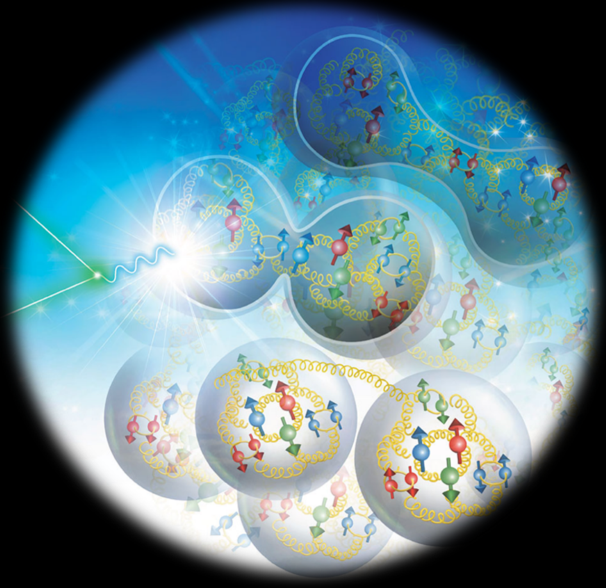
- Gluon Energy 55%
- Quark Energy 44%
- Quark Mass 1%

Proton Spin



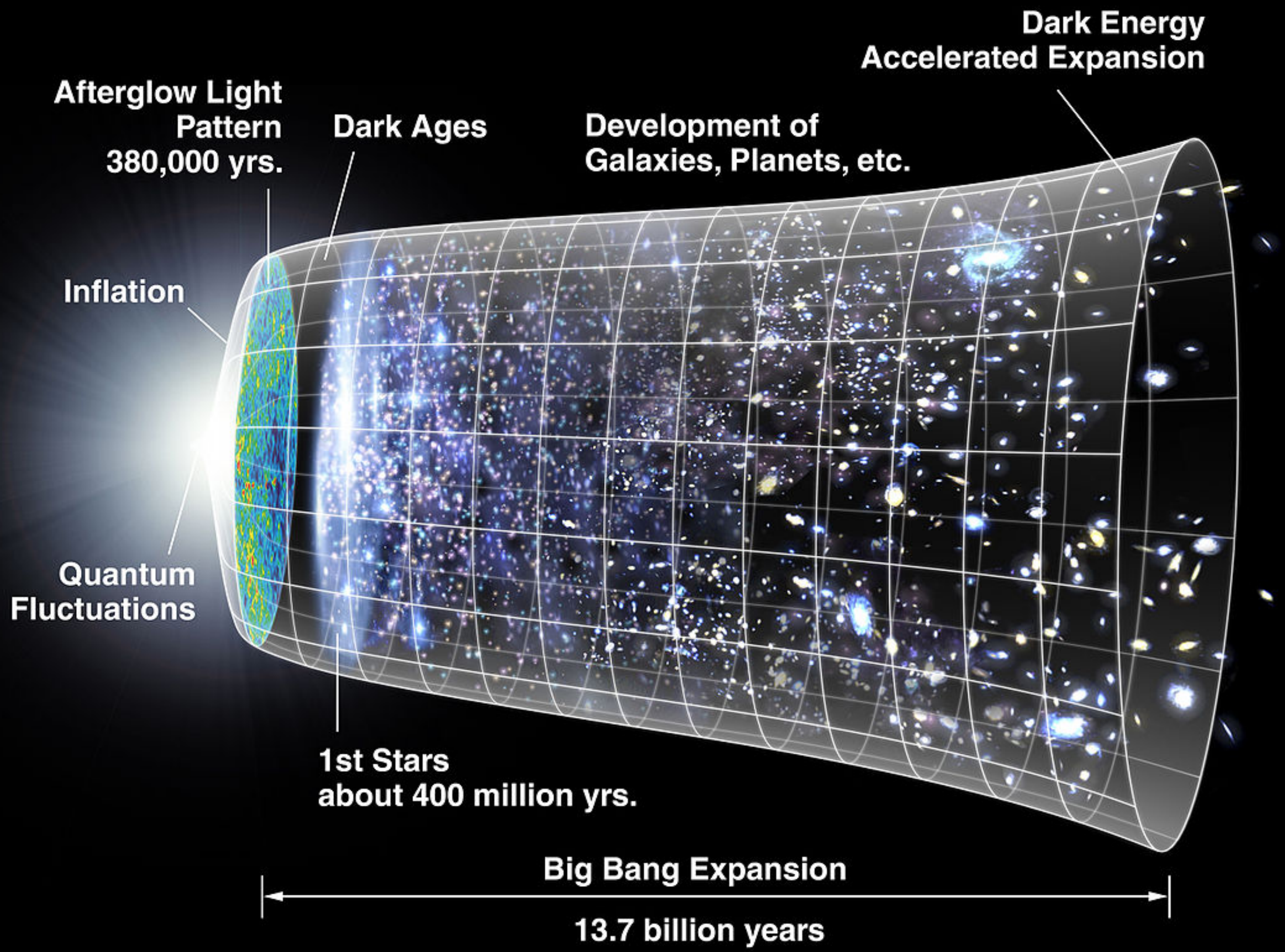
- Valence Quarks 1/3
- Gluons 1/3

Confinement



- Proton vs Nucleus Behavior

Mystery: Cosmic Inflation



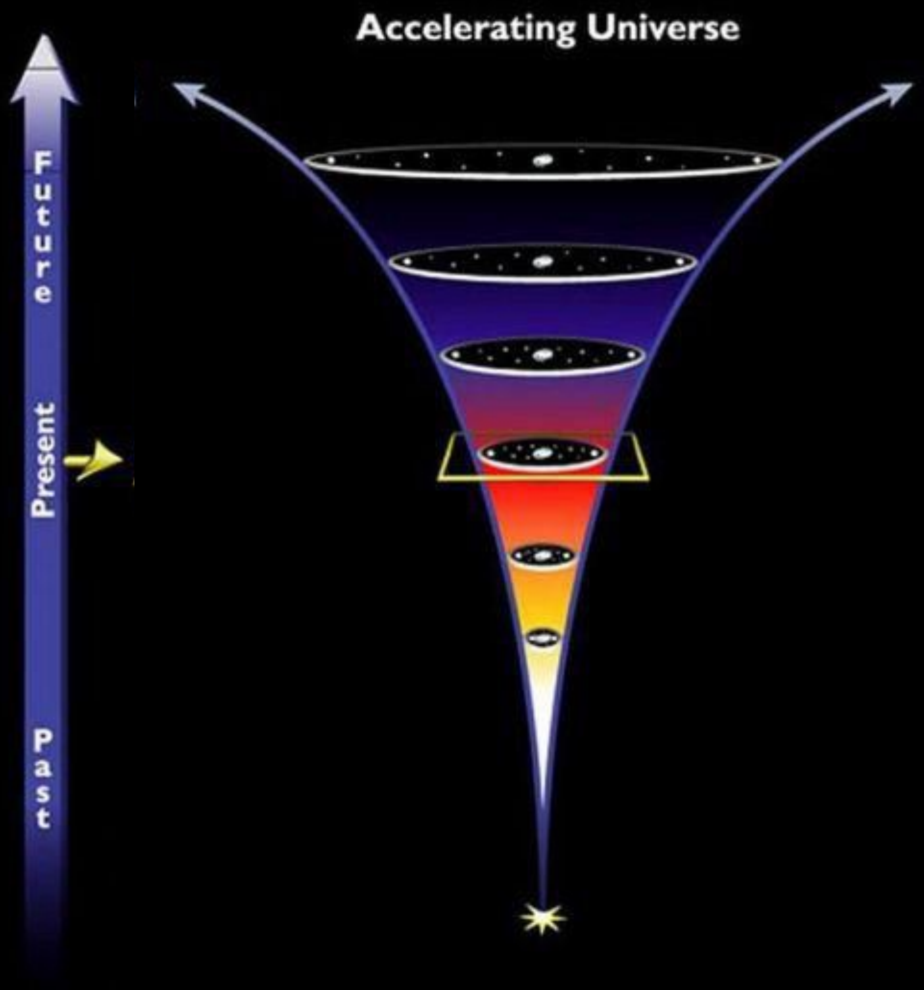
Relation of Field that Powered Inflation and the Higgs ?

Mystery: Dark Sector

Dark Matter

Mystery: Dark Sector

Dark Matter



Dark Energy

Mystery: Matter Asymmetry

10,000,000,001	10,000,000,000
Matter	Anti-Matter

Early Universe

Mystery: Matter Asymmetry

1 0

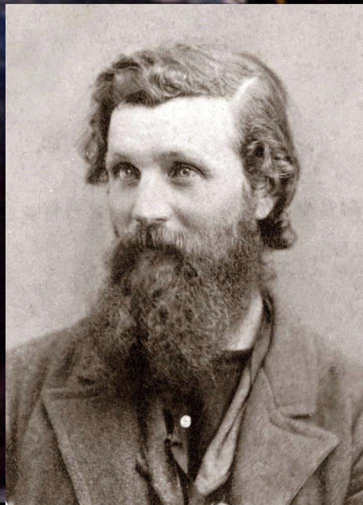
Matter Anti-Matter

Now

The Puzzle Of The Mysteries

When one tugs at a single thing in nature, he finds it hitched to the rest of the universe.

-- John Muir



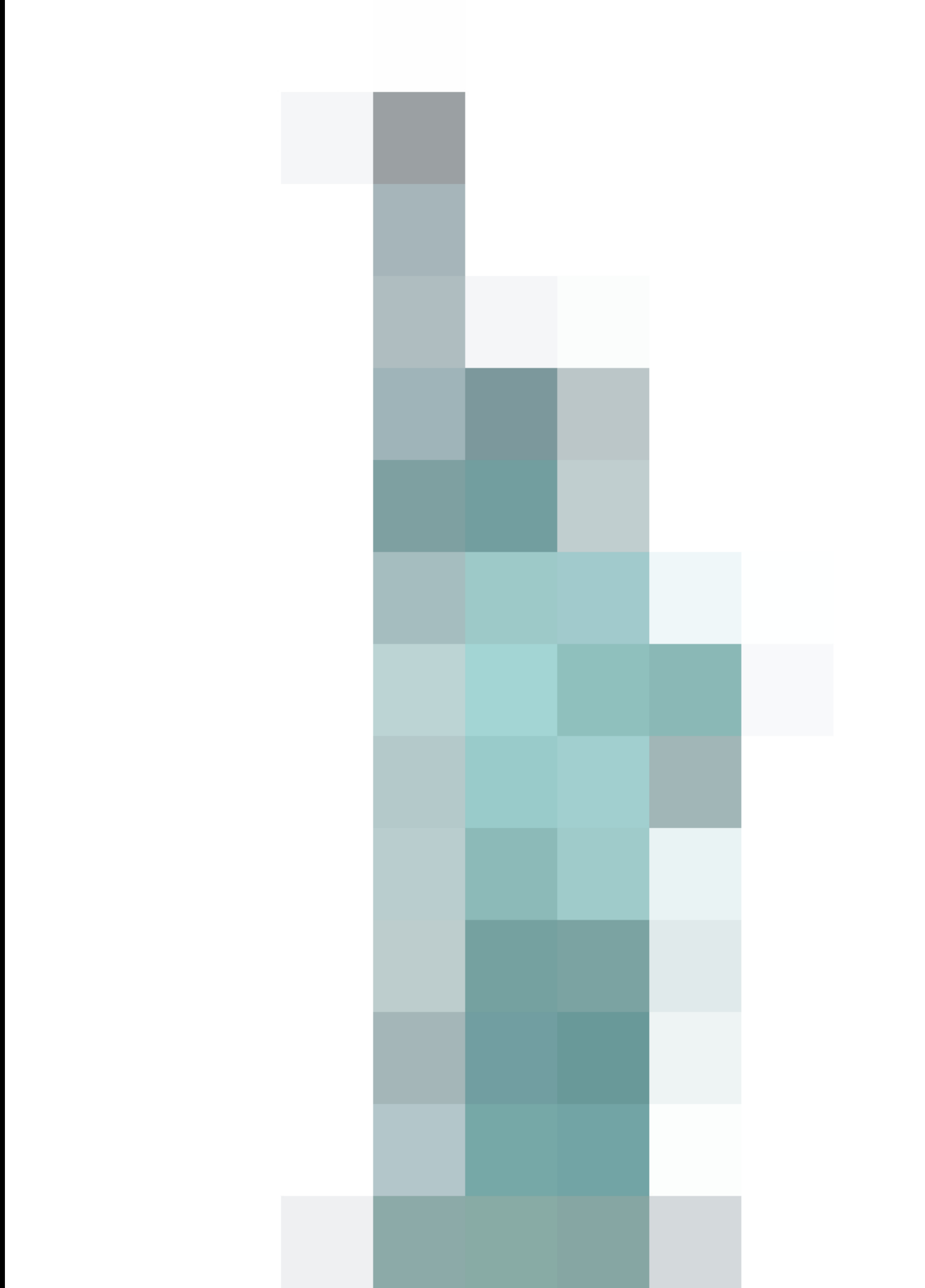
Gaining Clarity and Understanding

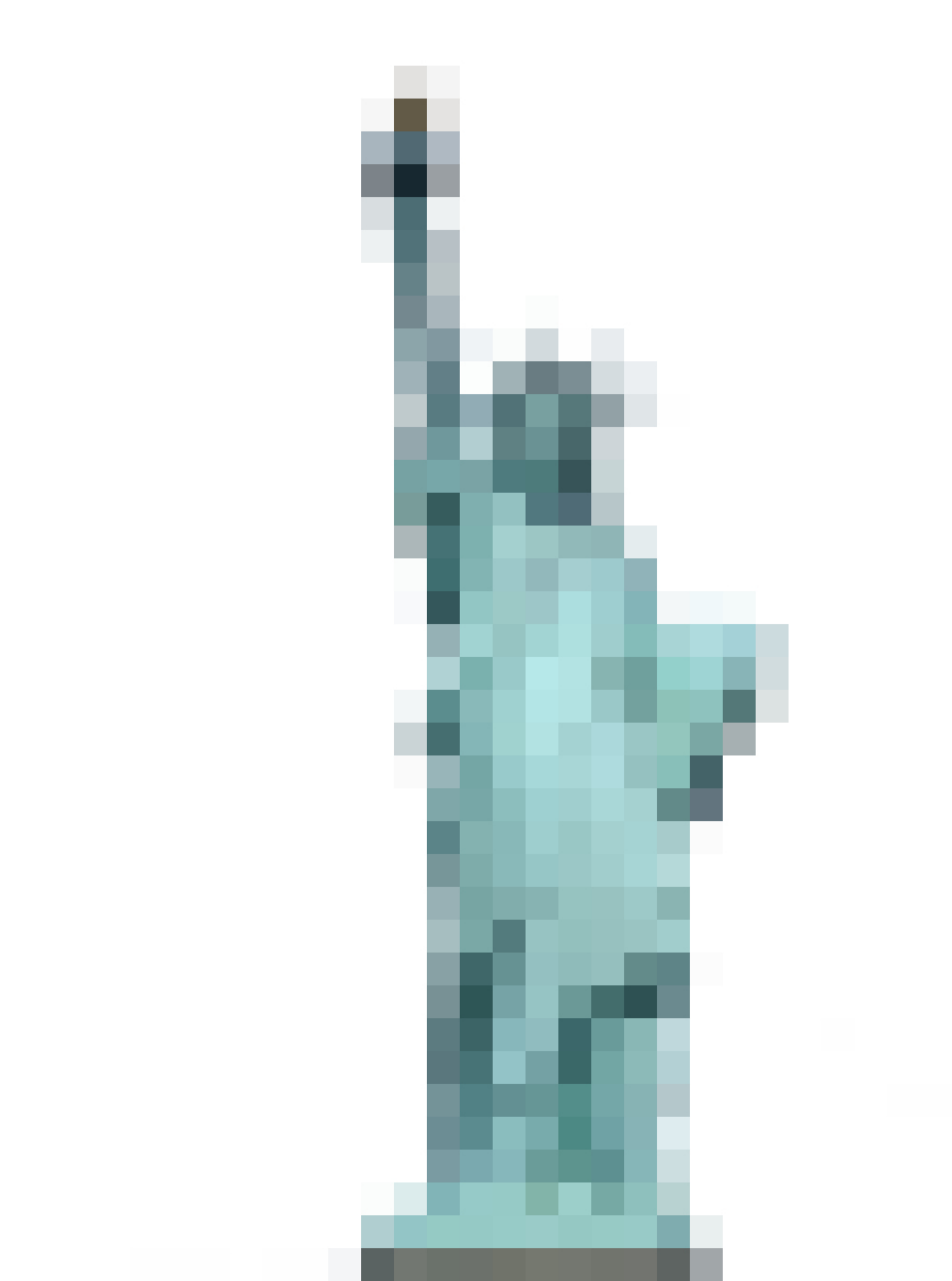
- Our approach and interpretation is driven by our
  - Experiences (perceptions)
  - Theory (top-down)
  - Data (bottom-up)

- When we know the characteristics and context of what to expect a little data goes a long way (top-down dominates)

- When we do not know the characteristics and context of what to expect, a lot of high precision data is required (bottom-up dominates)

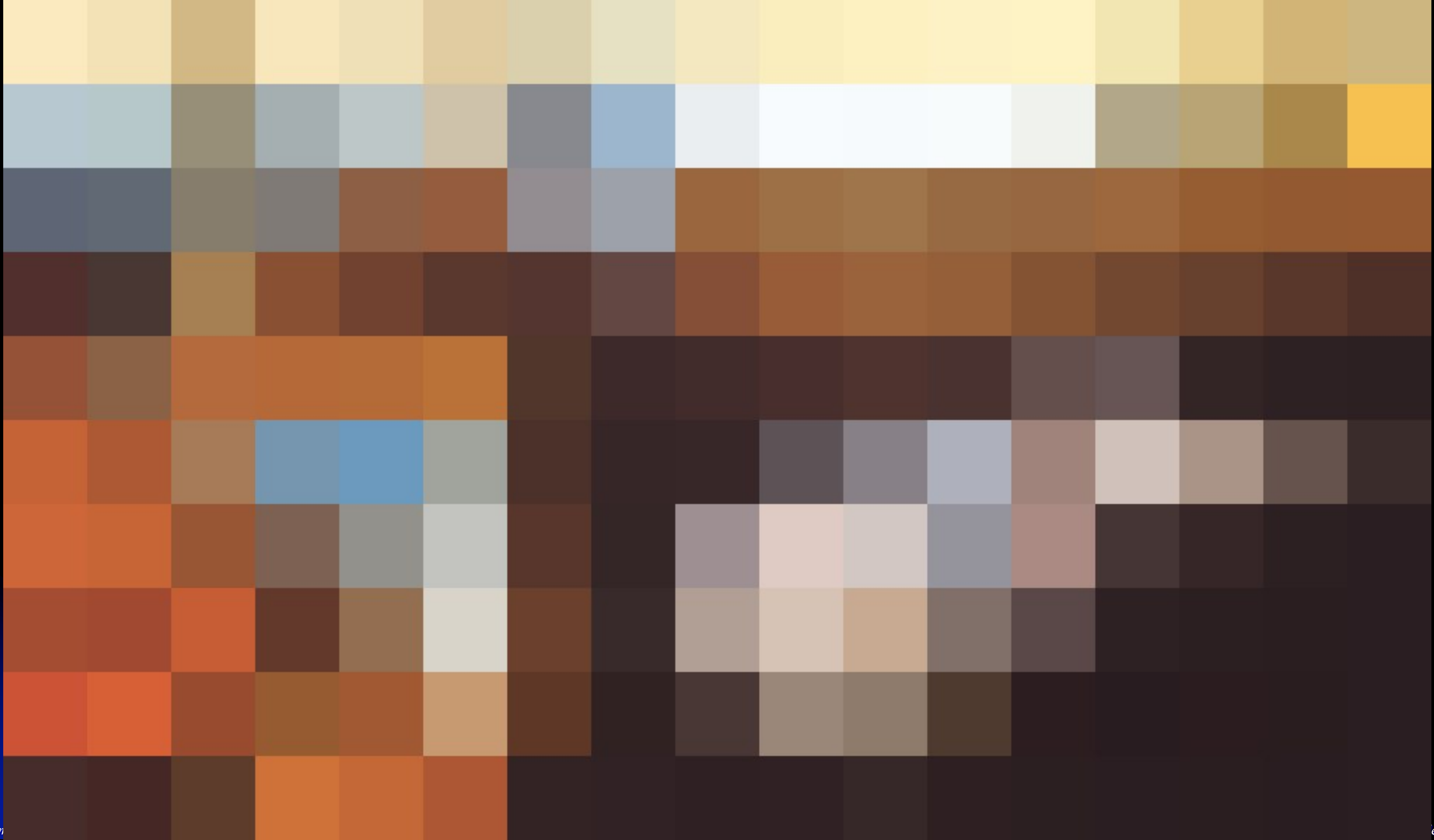
Adapted from Ian Shipsey

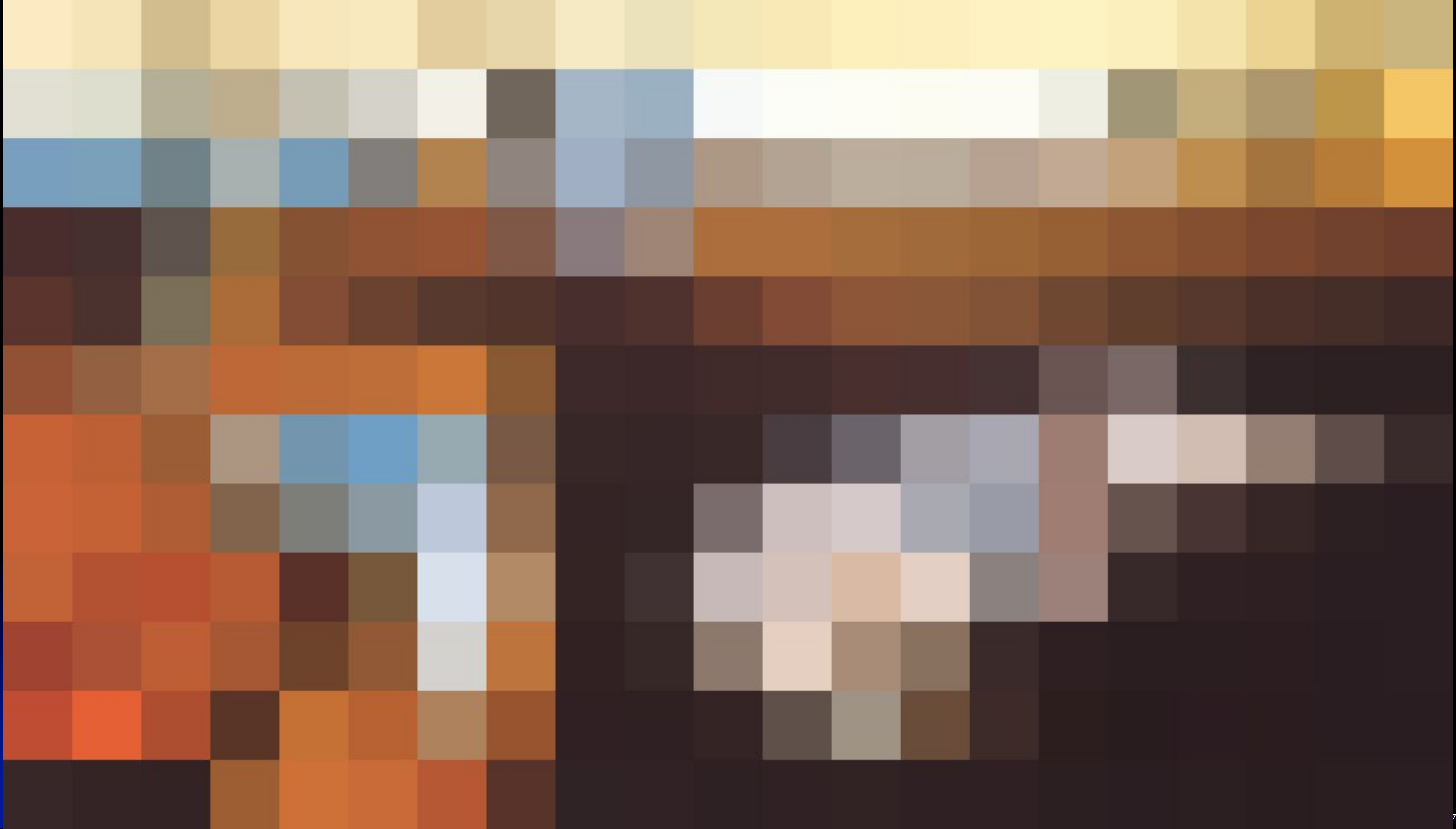


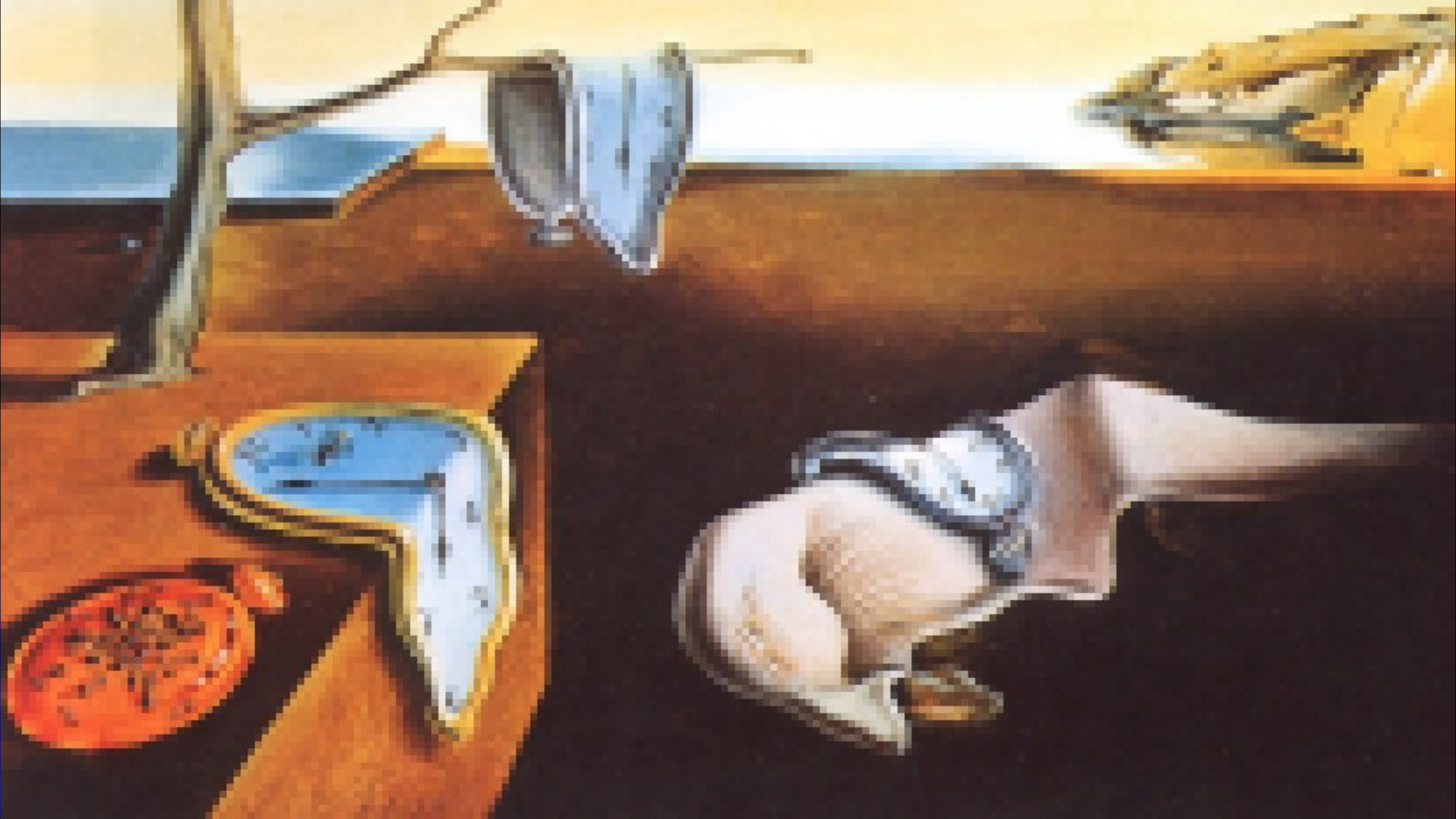


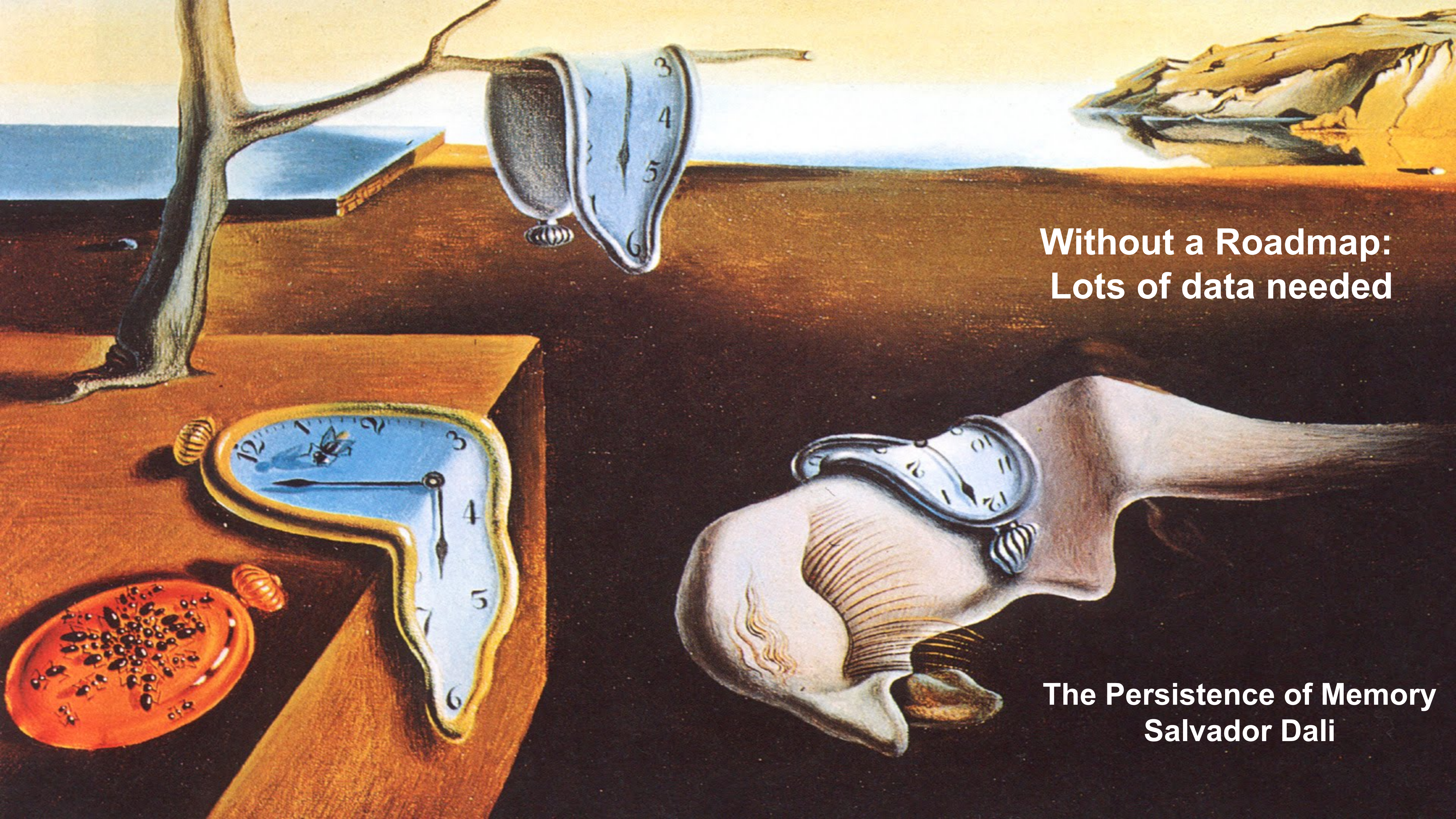
With a Roadmap:
Little data needed

Statue of Liberty
New York City









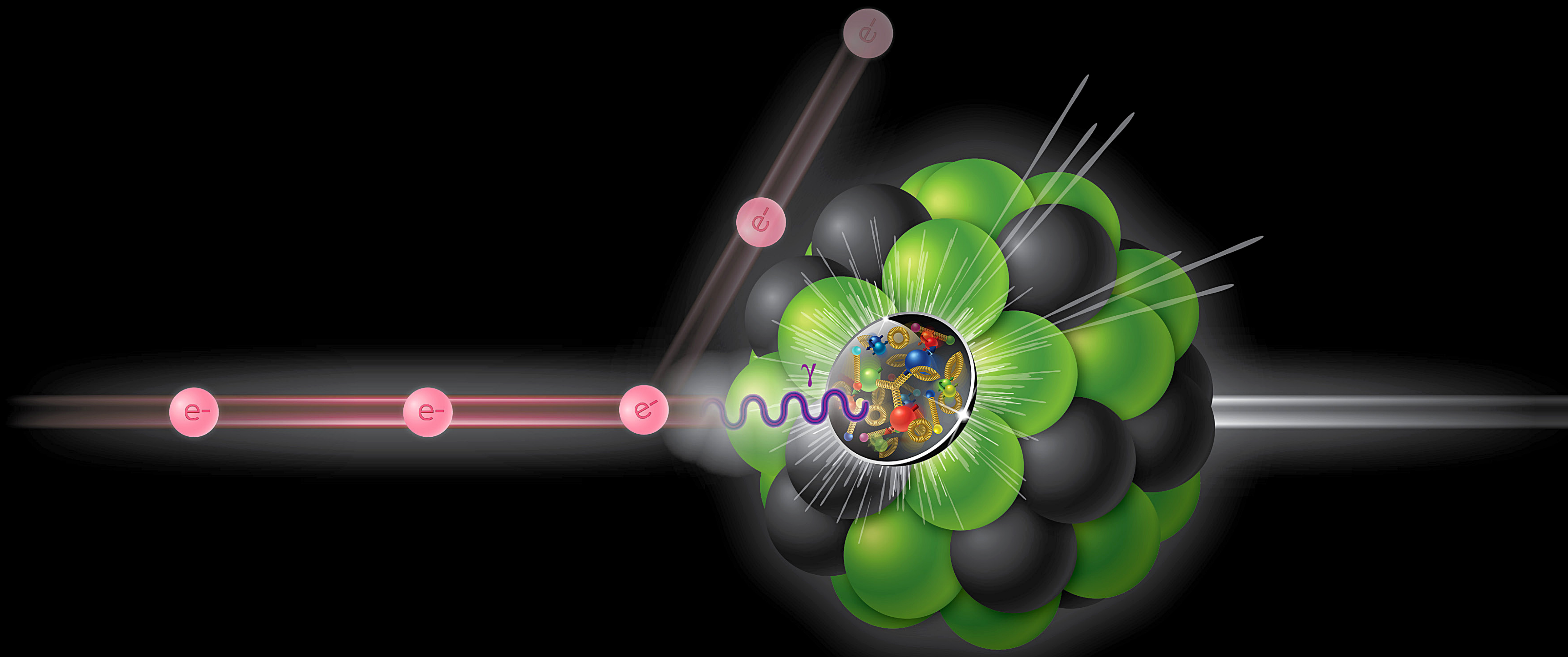
The Persistence of Memory
Salvador Dali

We are very much in a data driven era !

"New directions in science are launched by new tools much more often than by new concepts."

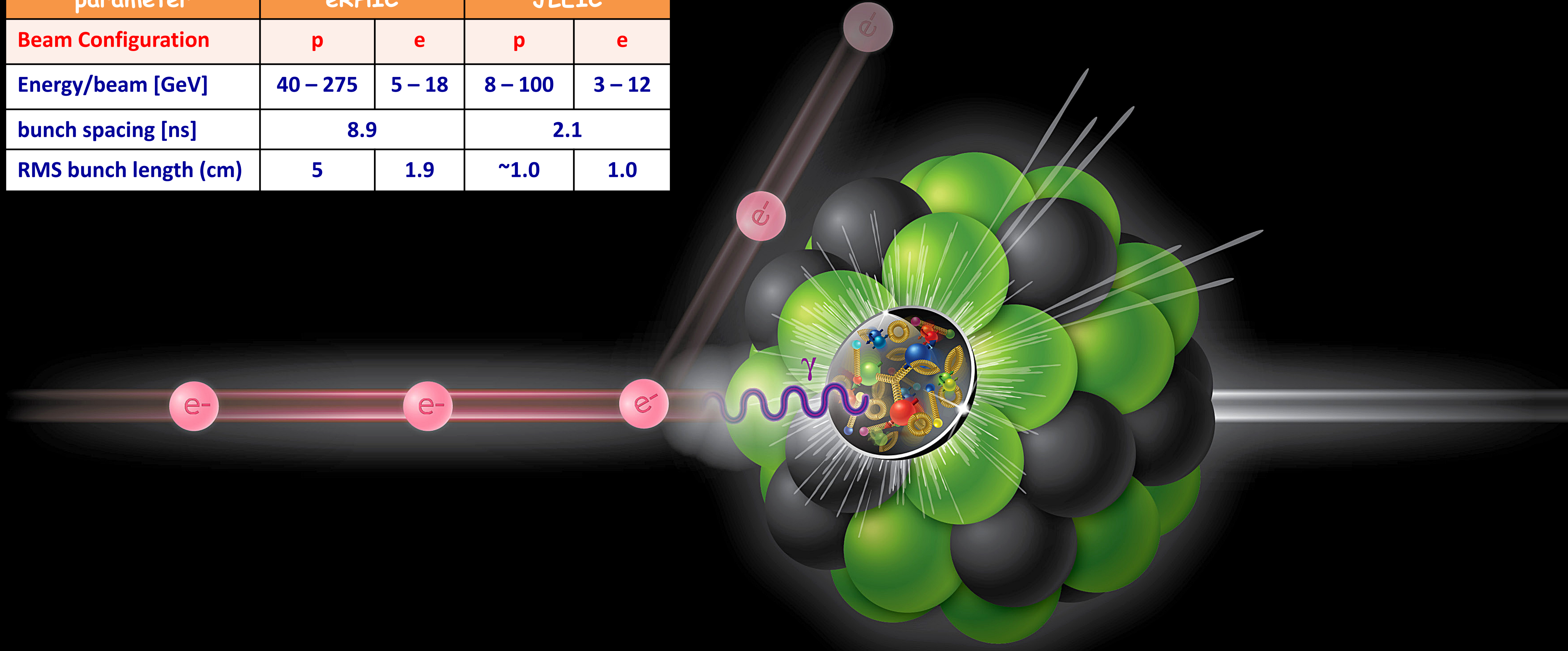
Freeman Dyson

New Tools: Electron Ion Collider

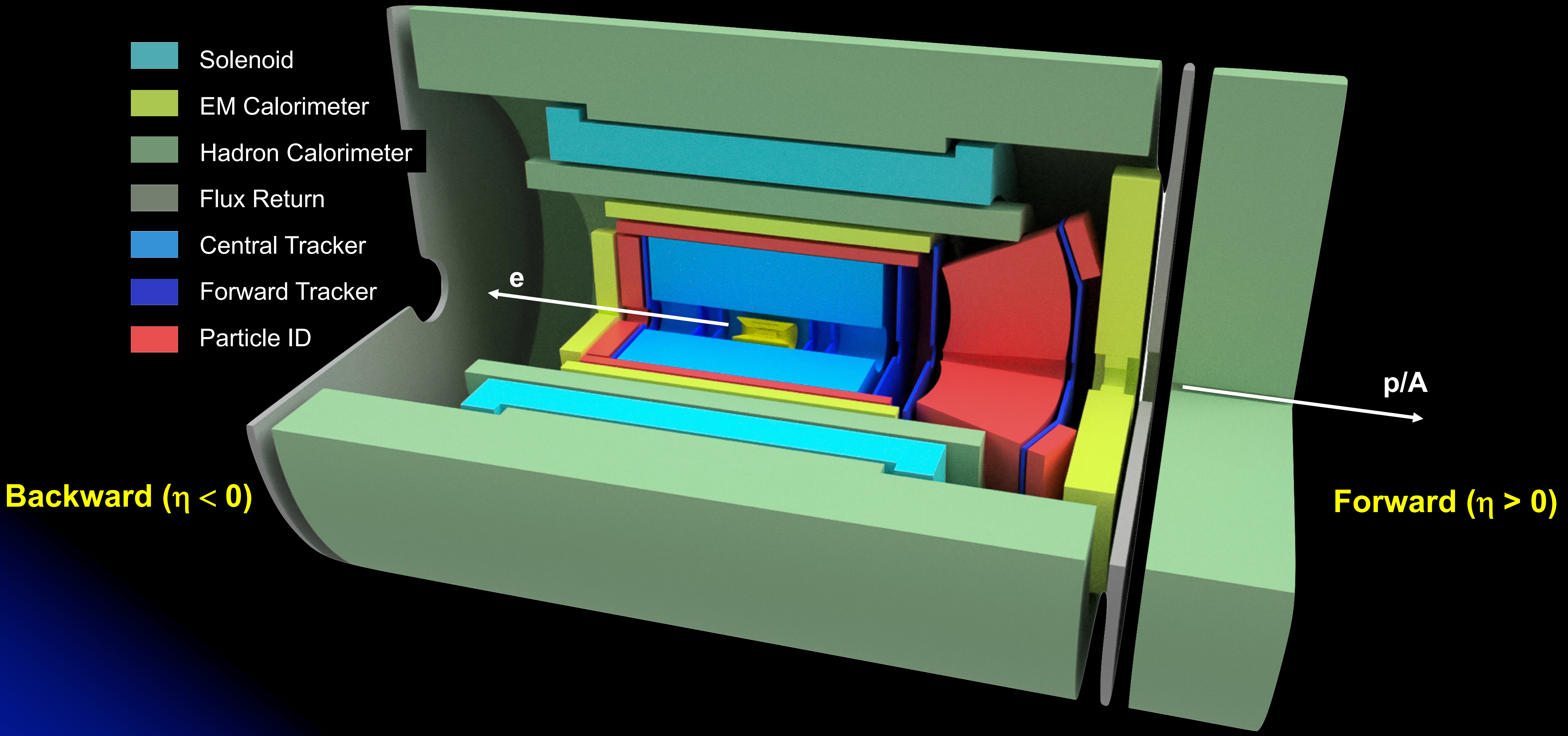


New Tools: Electron Ion Collider

parameter	eRHIC		JLEIC	
Beam Configuration	p	e	p	e
Energy/beam [GeV]	40 – 275	5 – 18	8 – 100	3 – 12
bunch spacing [ns]	8.9		2.1	
RMS bunch length (cm)	5	1.9	~1.0	1.0



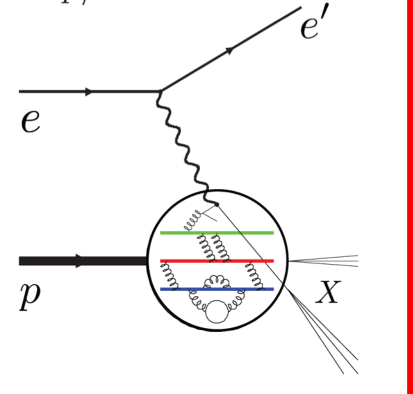
New Tools: Detectors



New Tools: Detectors

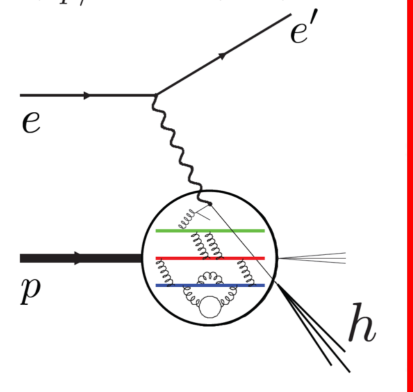
Inclusive DIS

$$e + p/A \rightarrow e' + X$$



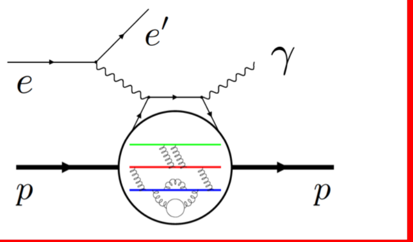
Semi-Inclusive DIS

$$e + p/A \rightarrow e' + h + X$$

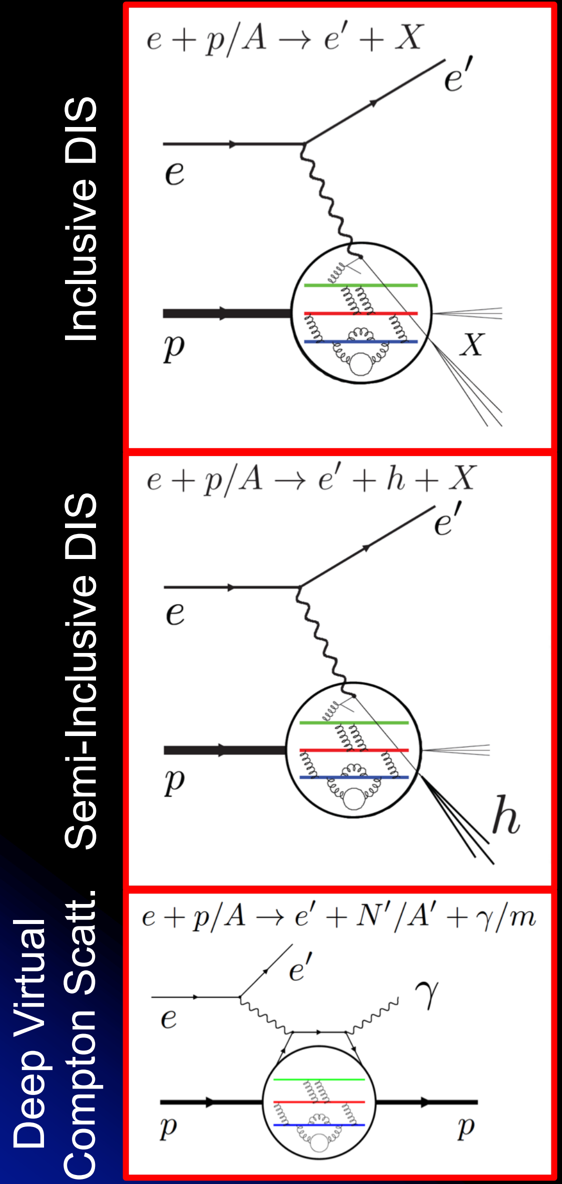


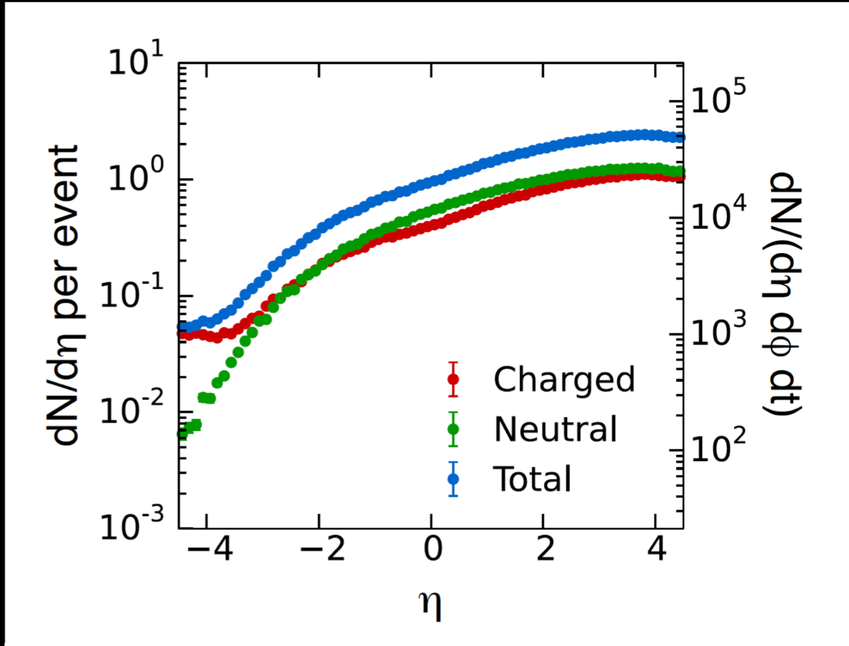
Deep Virtual Compton Scatt.

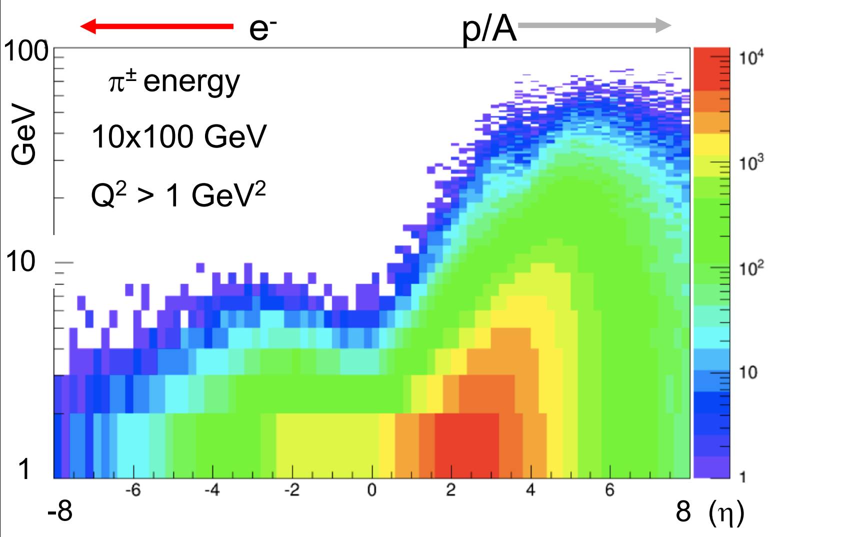
$$e + p/A \rightarrow e' + N'/A' + \gamma/m$$



New Tools: Detectors





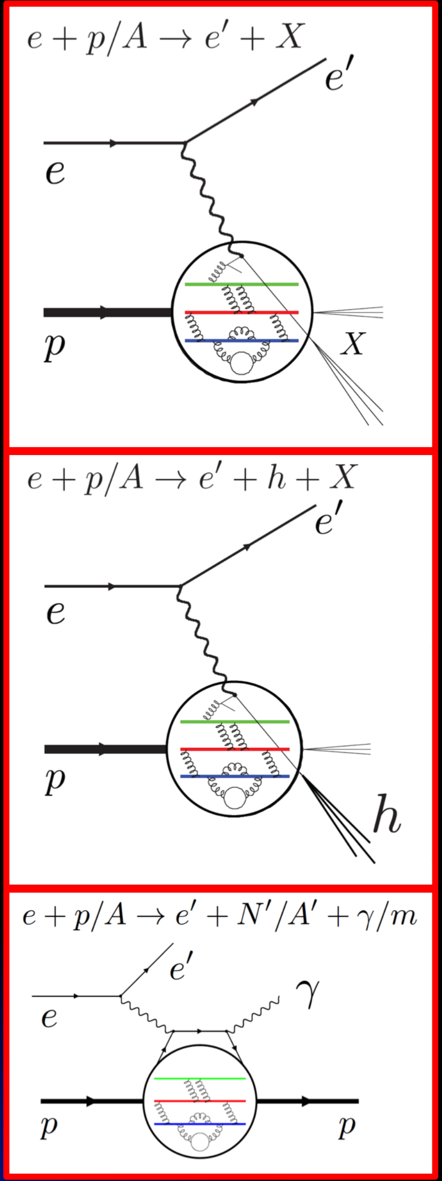


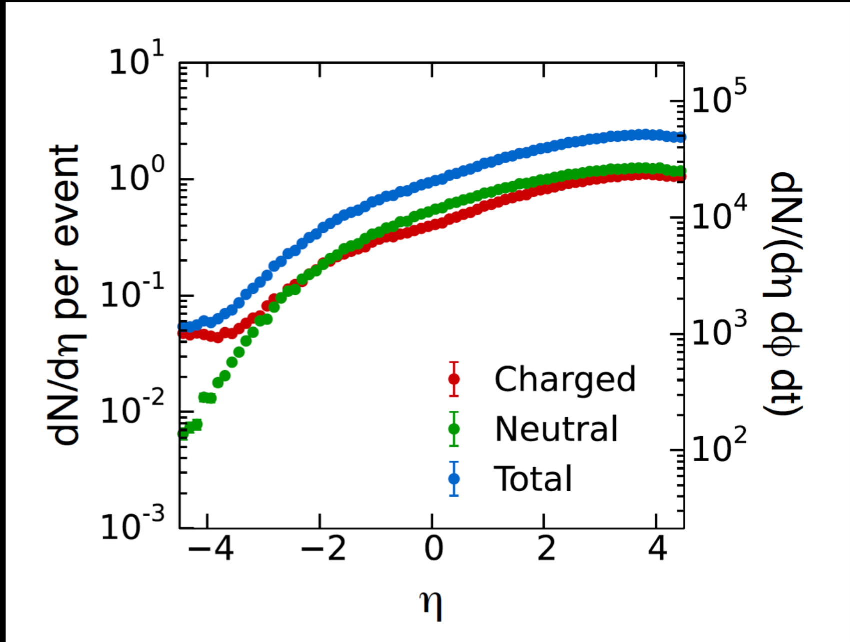
New Tools: Detectors

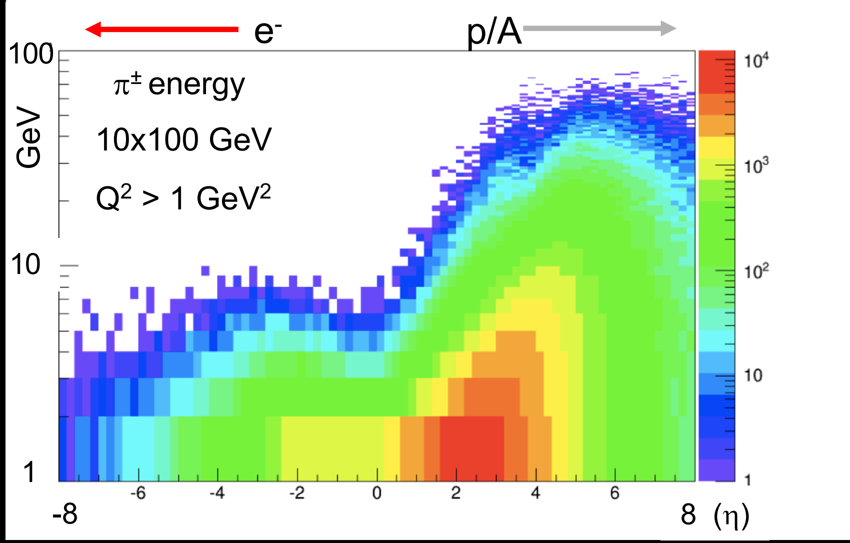
Inclusive DIS

Semi-Inclusive DIS

Deep Virtual Compton Scatt.





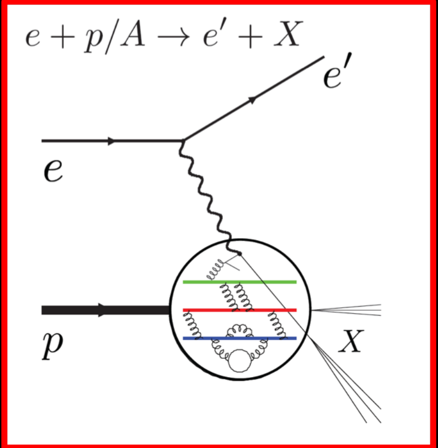


- Modest particle multiplicity
- Modest integrated radiation dose
- Relatively low momenta
- Different requirements for different regions
- Premium of forward direction

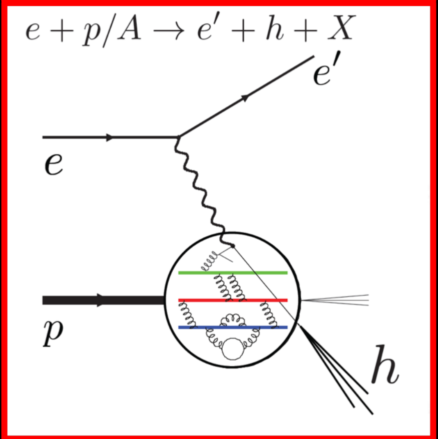
- Short bunch crossing (8.9/2.1 ns)
- Q^2 tagger, polarization measurement

New Tools: Detectors

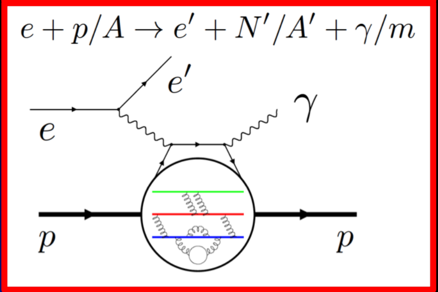
Inclusive DIS



Semi-Inclusive DIS



Deep Virtual Compton Scatt.



Physics Drivers

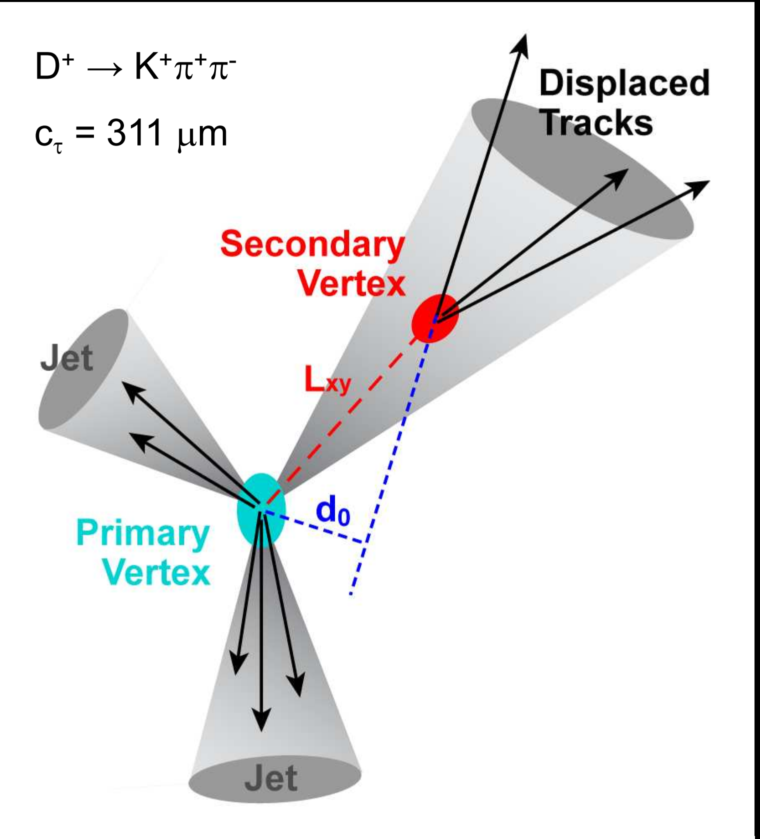
- Good momentum resolution (+ particle id)
  - $\sigma(p)/p = 0.05\%\, p \oplus 1\%$ (central)
  - $\sigma(p)/p = 0.1\%\, p \oplus 2\%$ (forward)
- Good impact parameter resolution (low mass)
  - $\sigma = 5 \oplus 15 / p \sin^{\frac{3}{2}} \vartheta$ (μm) (central)
- Excellent EM energy resolution
  - $\sigma = 10\% / \sqrt{E}$ (central)
  - $\sigma = 2\% / \sqrt{E}$ (forward)
- Good hadronic energy resolution
  - $\sigma = 50\% / \sqrt{E}$
- Excellent particle identification π/K/p
  - Forward η: up to ~50 GeV/c
  - Central η: up to ~5-8 GeV/c
  - Backward η: up to ~7 GeV/c

Vertexing and Flavor Tagging

- Measure point of origin of tracks as accurately as possible
  - Excellent impact parameter resolution
  - Good single hit resolution
  - Good primary vertex resolution

- Challenges:
  - Lowest possible mass budget
  - Low power, low occupancy
  - Best position resolution
  - Timing information for each hit
  - As close as possible to the interaction point
  - Radiation hard

- Silicon technology a prime candidate



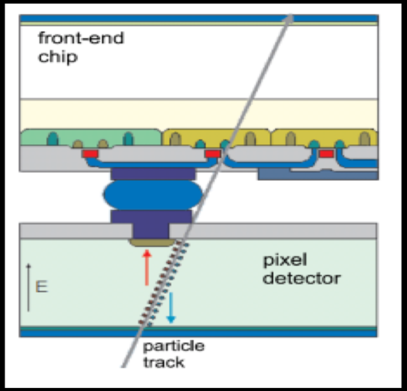
$$\sigma(d_0) = \sqrt{a^2 + b^2 \cdot \mathrm{GeV}^2/(p^2 \sin^3\theta)}$$

dominated by single-point resolution

multiple-scattering term => low material!

Hybrid Pixel Chips

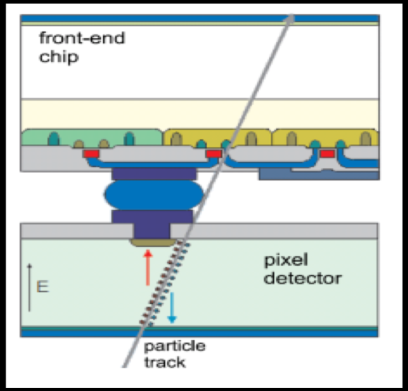
Hybrid Pixel



- Q collection by drift

Depleted Monolithic Active Pixel Sensors

Hybrid Pixel



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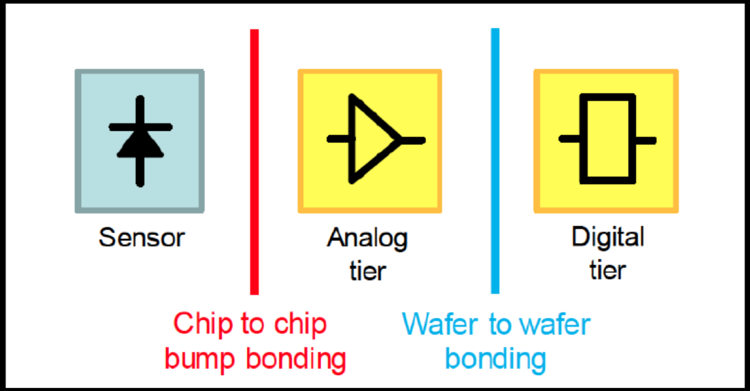
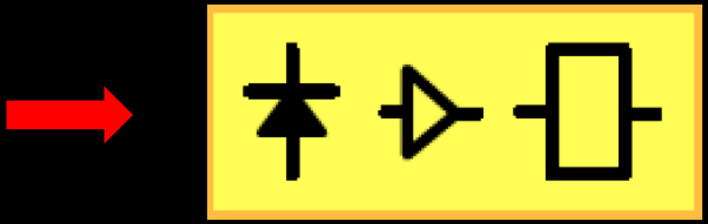


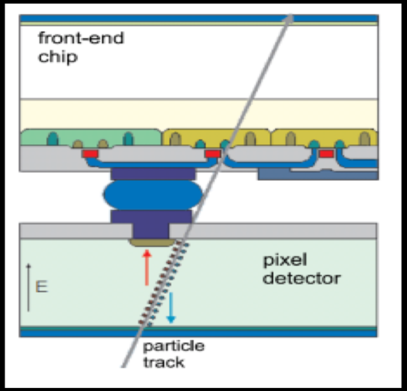
- Separate functionalities

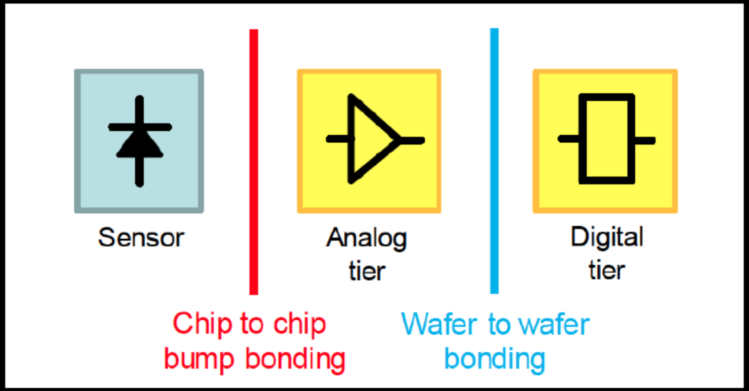


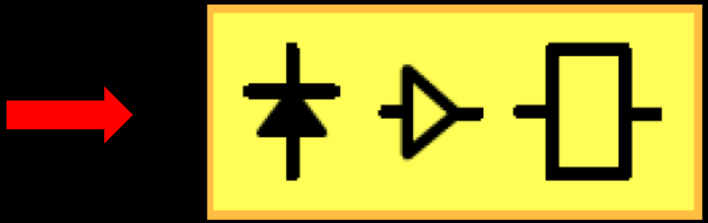
- Integrated functionalities

Depleted Monolithic Active Pixel Sensors

Hybrid Pixel

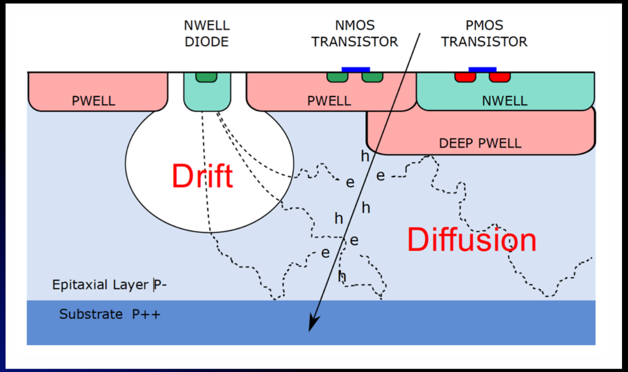




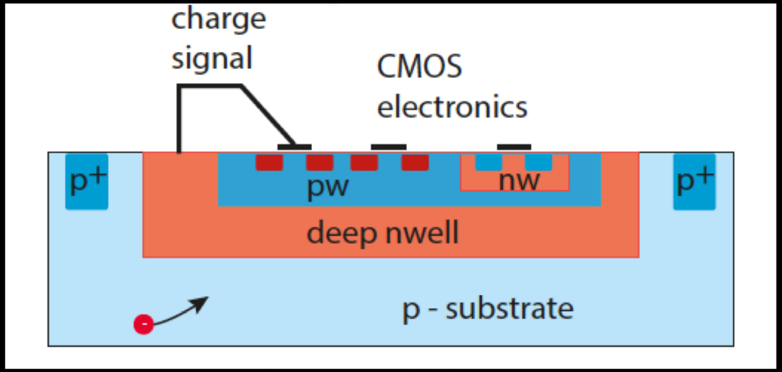


- Q collection by drift
- Separate functionalities
- Integrated functionalities

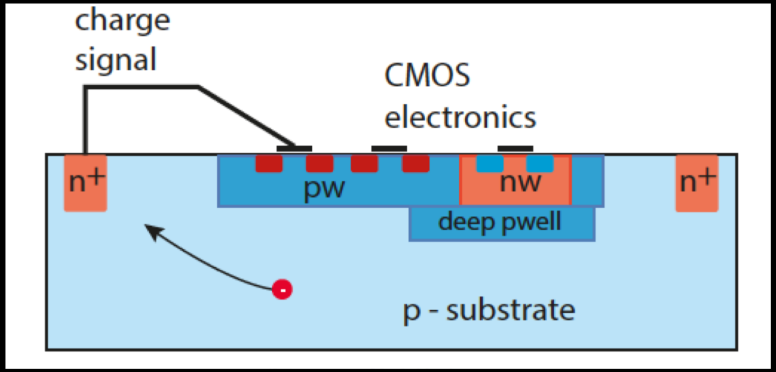
CMOS-MAPS



Depleted CMOS



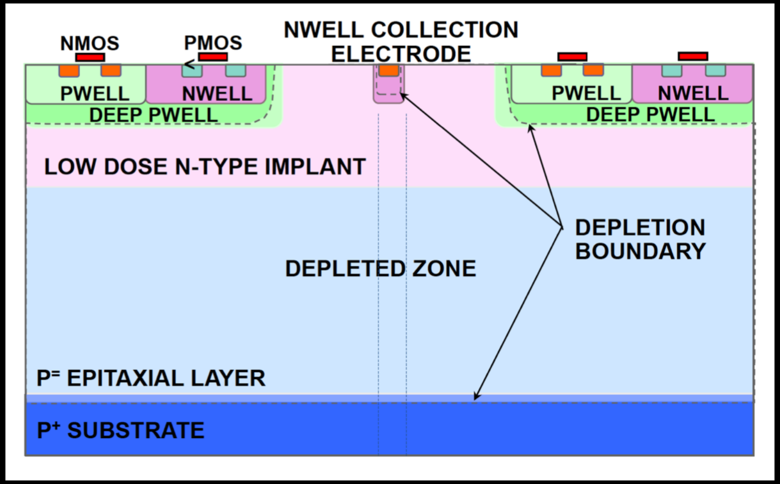
Depleted CMOS

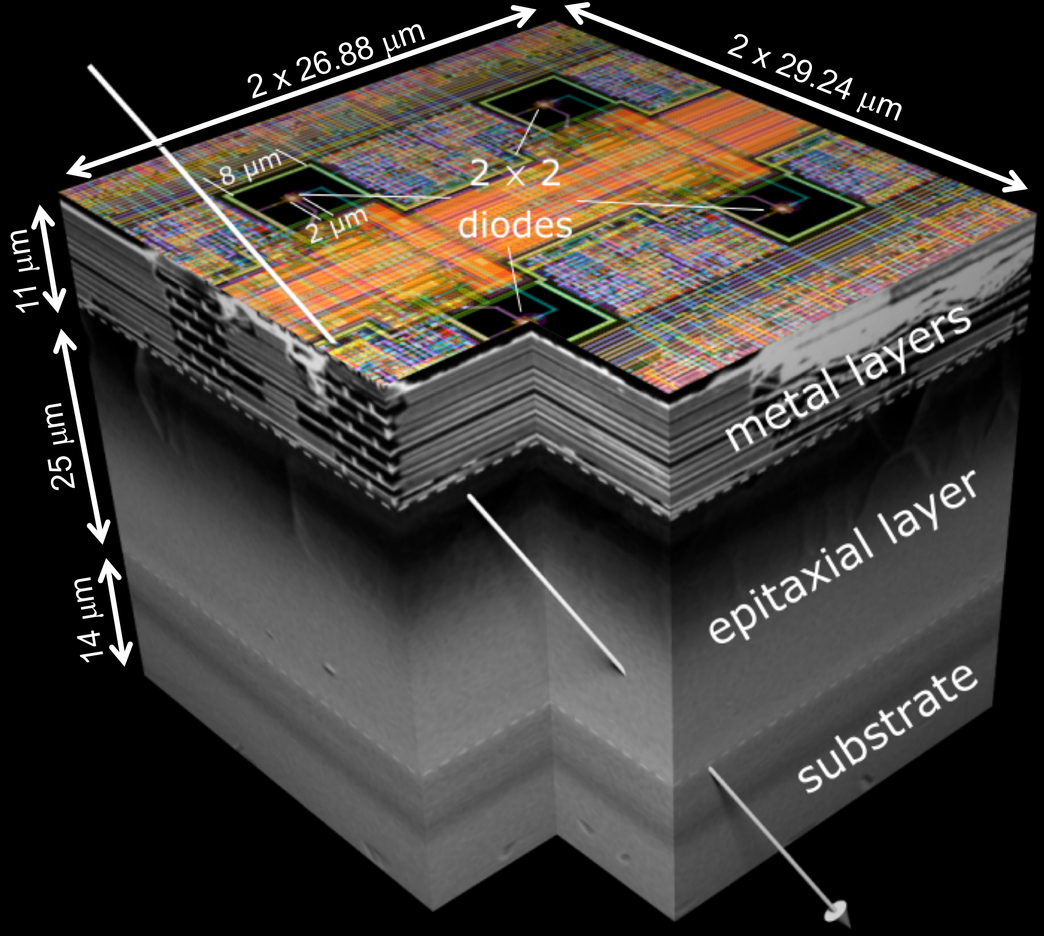


- Charge collection by drift and diffusion
- Large Fill Factor, collection by drift
- Small Fill Factor, collection by drift

Depleted CMOS Pixel Chips

- Pixel design in modified Tower-Jazz process
- Low noise, high collection speed
- Epitaxial layer only 25 μm thick → Q < 2000 e
- Radiation hardness to be studied



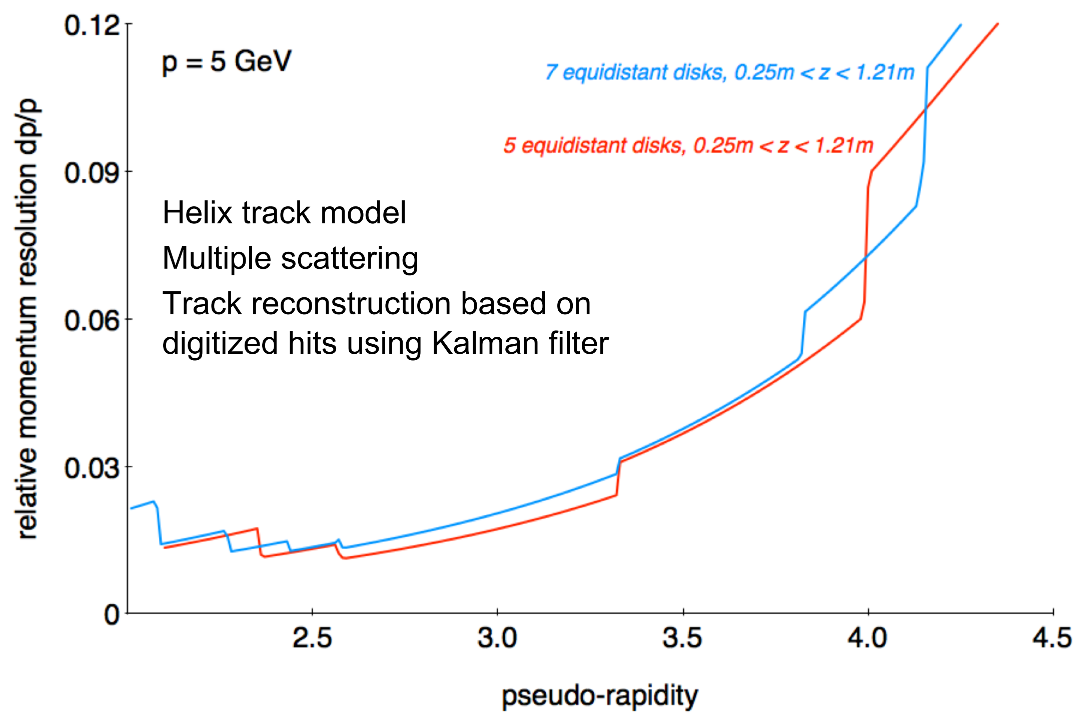


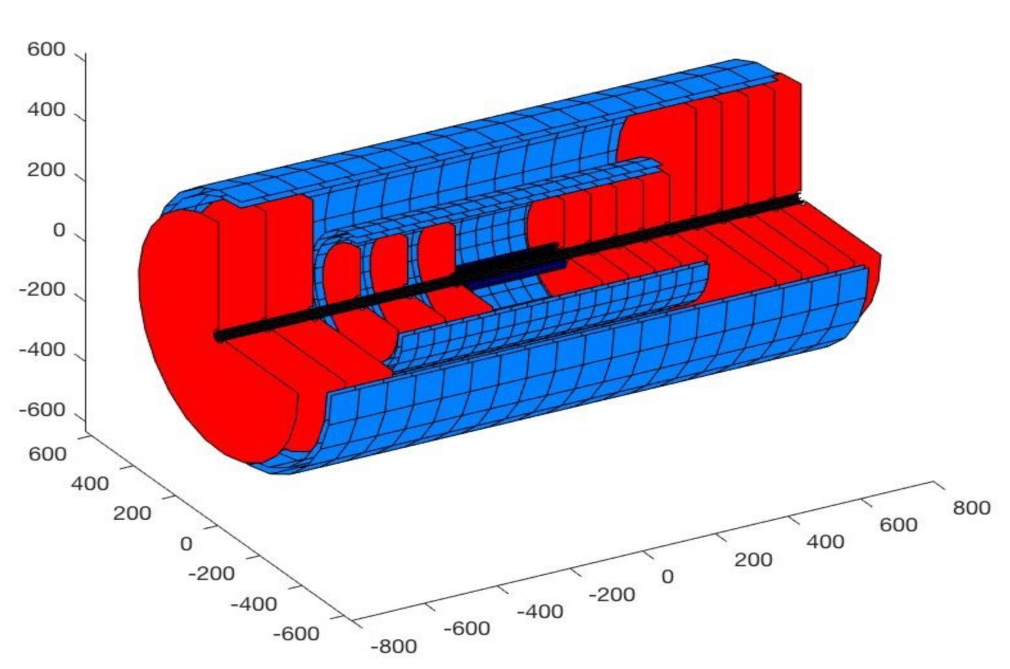
ALPIDE (ALICE)

- Tremendous progress in CMOS pixel designs
  - Power < 40mW/cm^2
  - Integration time <4μs
  - Low material budget (~ 0.3% X_0 per layer)
  - Moderate radiation hardness (~Mrad, 10^{13} 1MeV n_{eq}/cm^2)

All Silicon Tracking

- All silicon pixel tracking becoming possible



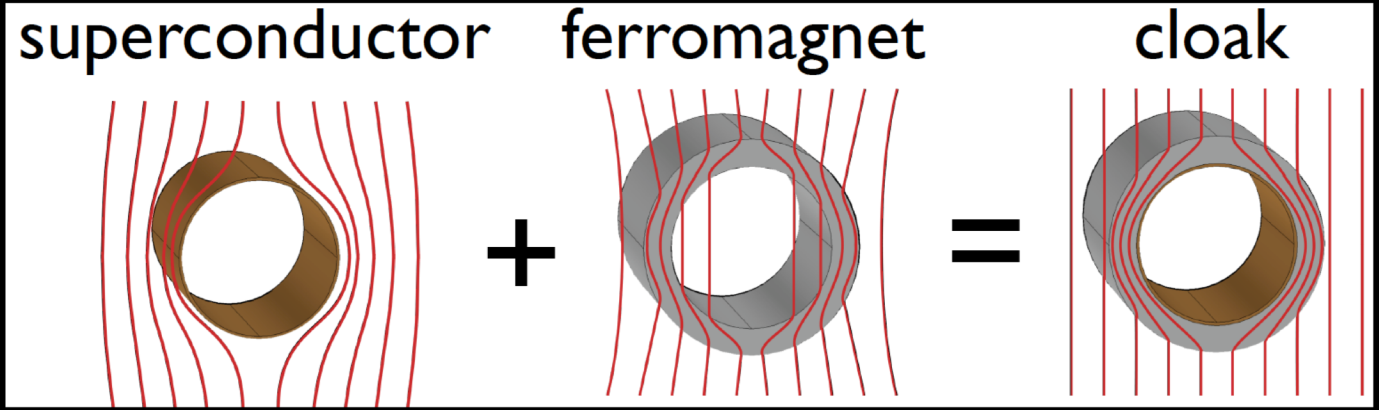


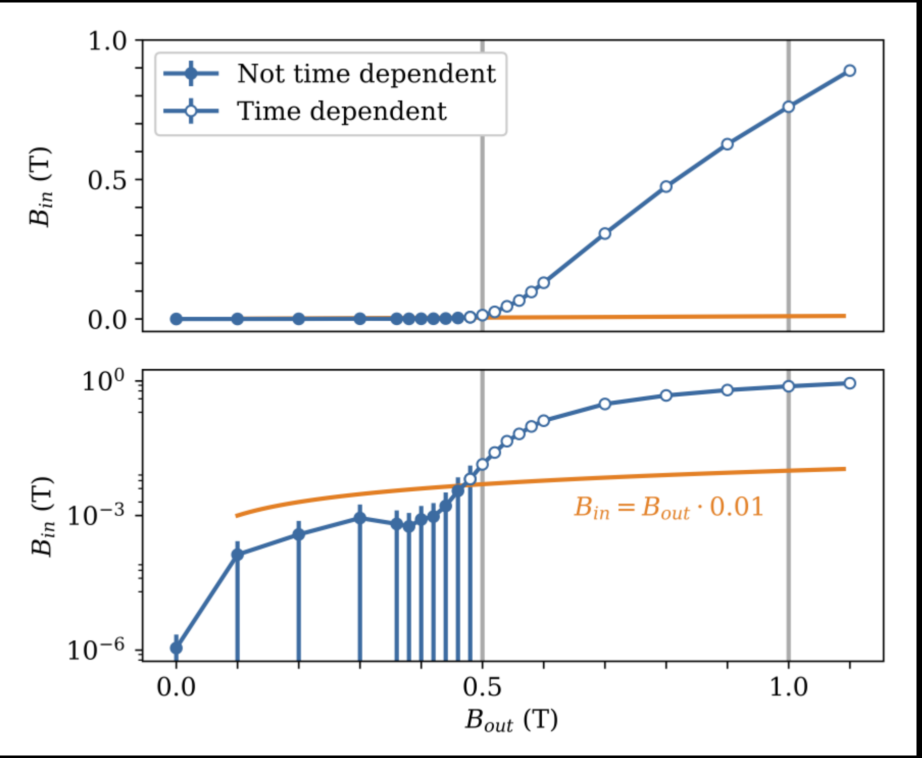
Hypothetical all-Si tracker in a 3T Solenoidal field.

- Configuration: 20μm pixels, 18 mm inner radii and 185 mm outer radii disks;
- Material budget: 0.3% X_0 beam-pipe, 0.3% X_0 for each disk
- Disks are equidistant in z; nominal collision vertex

Magnetic Cloak

- The integral of the B-field along the particle pathlength is limited in the forward region. Dipole fields with shielded areas would be desirable





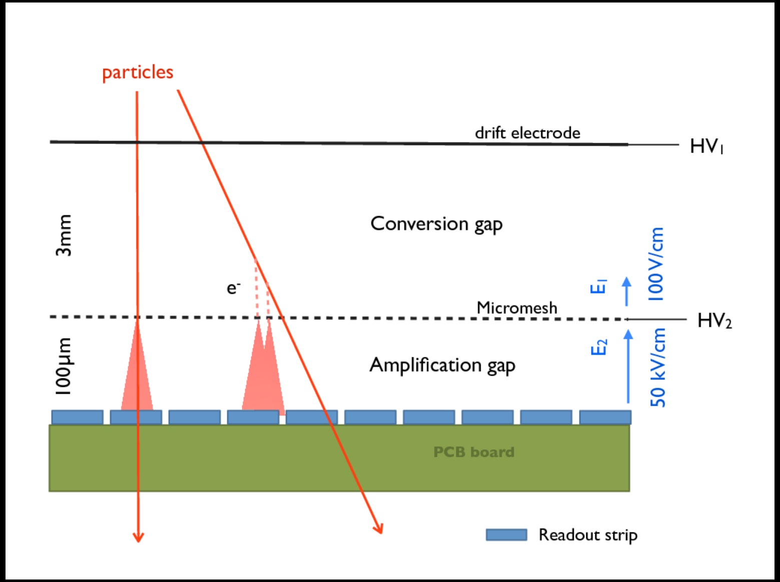
- Shield a 0.5 T field with a 10 cm SC cylinder with a multi-layer shield

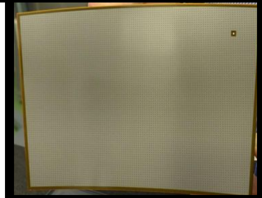
- Demonstrated magnetic field cloaking with 99% field shielding and 90% reduced field distortions next to the shield at 0.45 T

Micro-Pattern Gas Detector Tracking

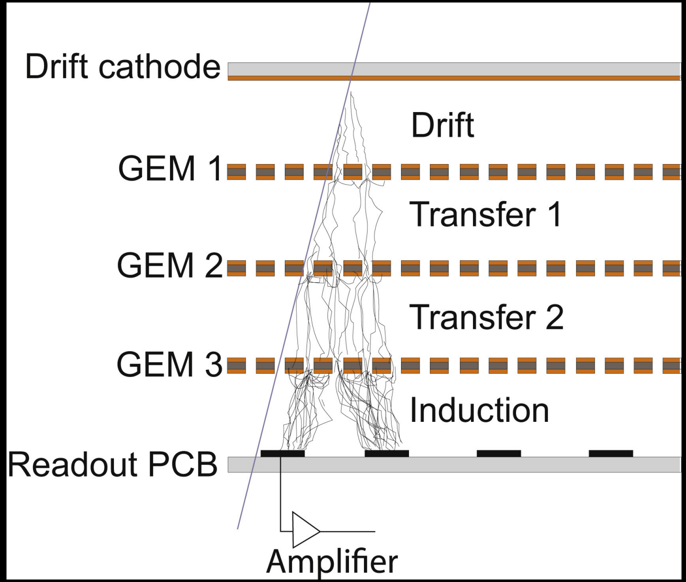
- Micro-Pattern Gas Detector (MPGD) based tracking detectors hold the promise of providing robust and cost-effective tracking detectors.

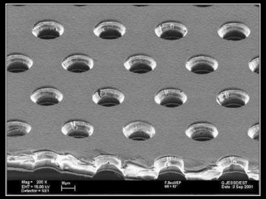
Micromesh Gas Detector (MicroMegas)





Gas Electron Multiplier (GEM)





- Note: if entrance is covered with appropriate photocathode, can also be used for photodetection

Micro-Pattern Gas Detector Tracking

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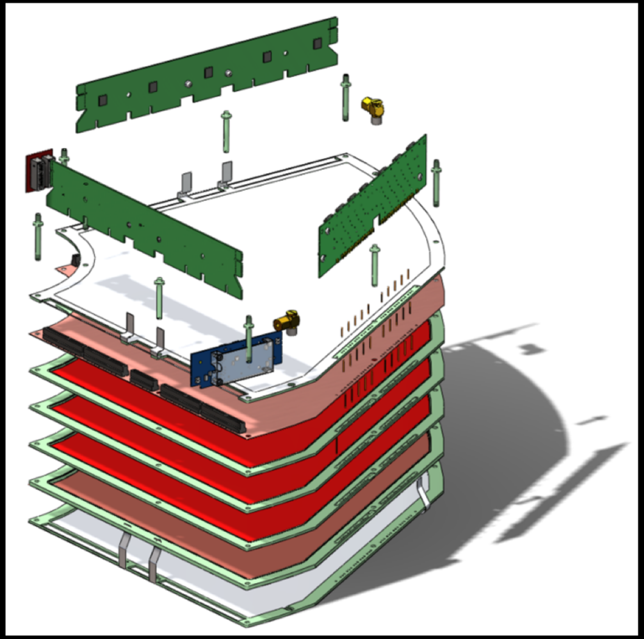
Micromesh Gas Detector (MicroMegas)

MicroMegas-based curved barrel tracking system being developed

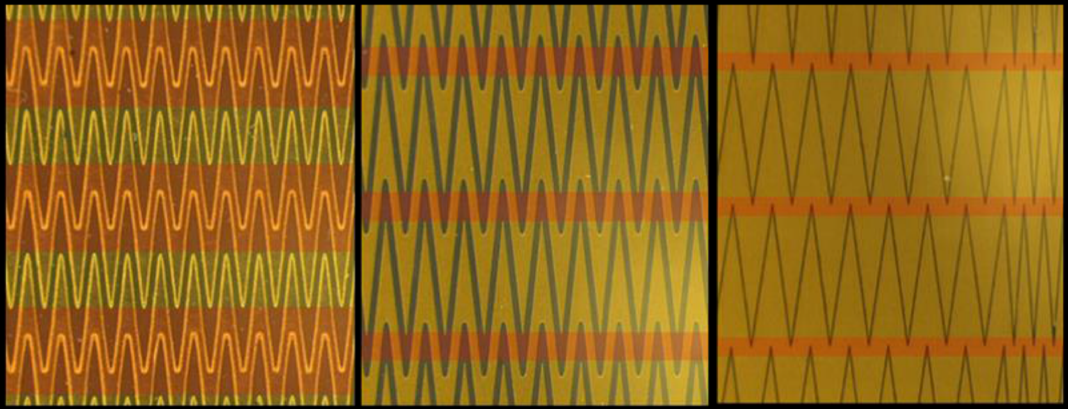
Gas Electron Multiplier (GEM)

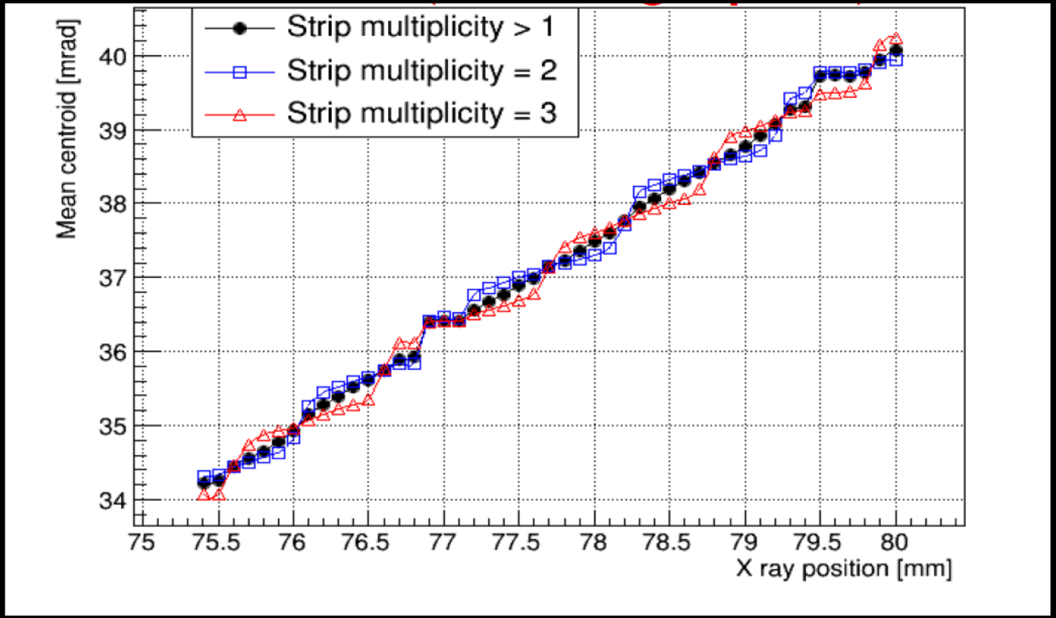


Forward/Backward tracking system based on triple-GEM TPC being developed

Micro-Pattern Gas Detector Readout

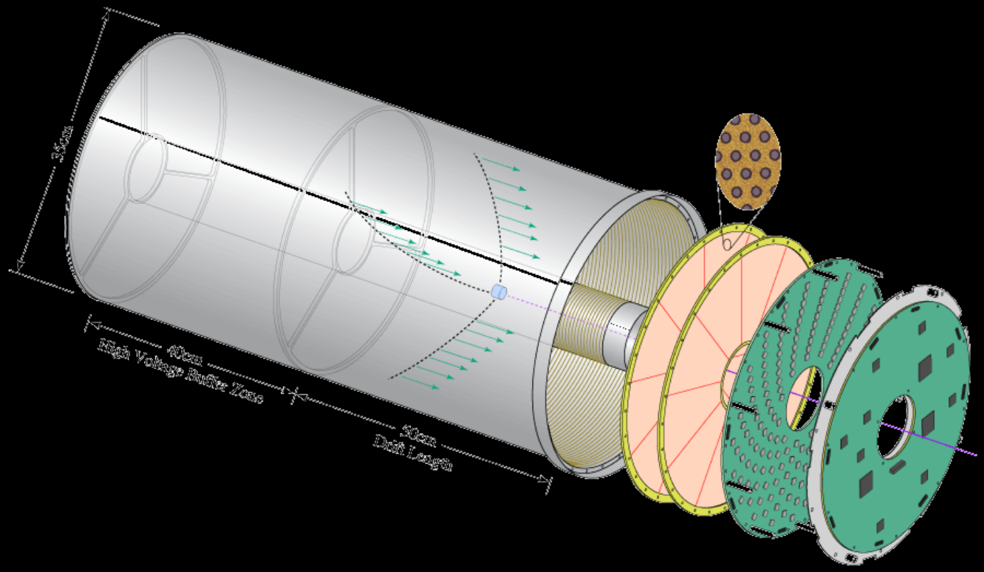
- Readout of electron cloud from the gain stage of MPGDs for optimal position resolution and low channel count
- Many readout variants being studied by the community:
  - Wires
  - Strips and Cross strips
  - CMOS integrated circuits
- Zig-Zag readout pattern tested with 3-stage GEM detector
- Optimization of the zigzag pad readout pattern parameters
- Good linearity of source and reconstructed position
- Spatial resolution better than 70 μm
- Room for optimization for charge sharing, interleaving, small transverse diffusion, etc





Cherenkov Time Projection Chamber

- Combine the functions of a Time Projection Chamber for charged particle tracking and a Cherenkov detector for electron identification in the same volume



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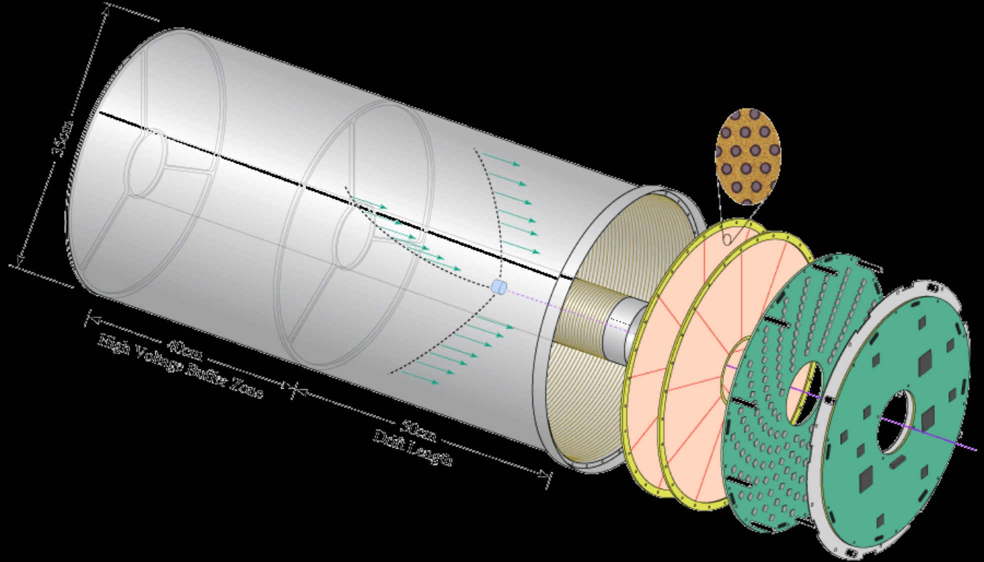
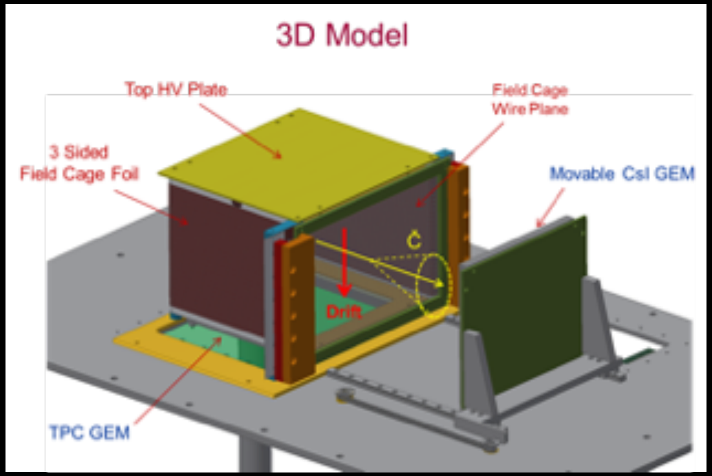
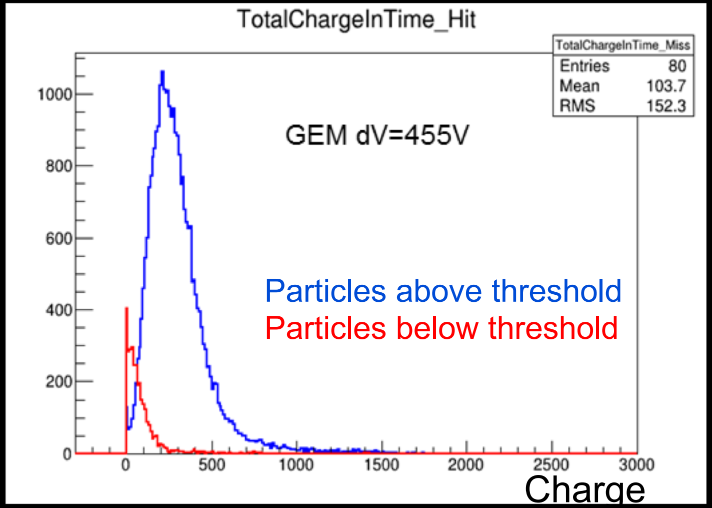




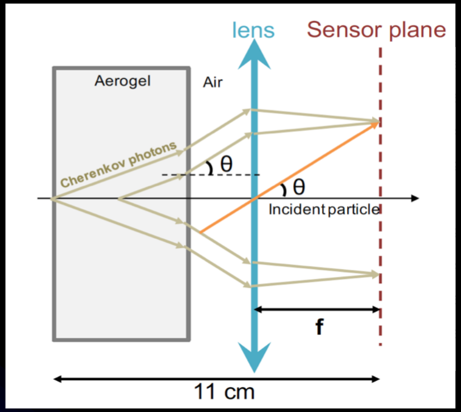


- Prototype:
  - TPC: 10cm drift + 10x10cm^2 4-GEM
  - Cherenkov: 3.3x3.3cm^2 pad array + 10x10cm^2 4-GEM
  - Common Gas: CF_4 (vdrift = 7.5cm/μs)
- Successful demonstration of proof of principle

Particle Identification

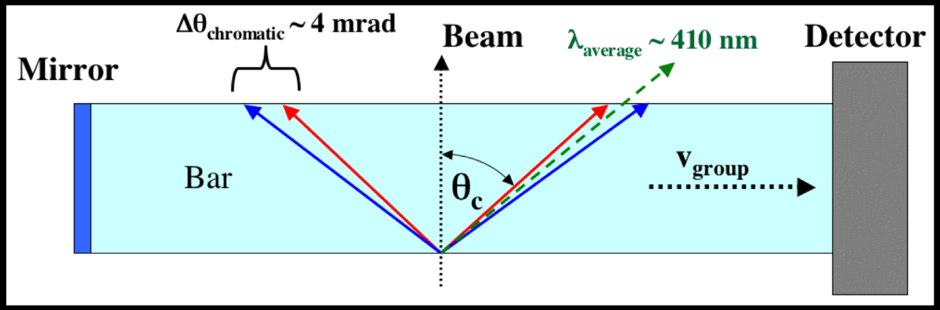
- Particle identification (PID) is crucial for an EIC with many challenges:
  - Large momentum range; requirements vary over rapidity
  - Compact detector, limited space; few photons; photodetectors in B-field
  - …
- There are also opportunities due to recent photodetector developments, such as pixel size, UV-sensitivity, photodetector materials and processing, …

Backward



- Modular RICH
- p < 7 GeV/c

Central

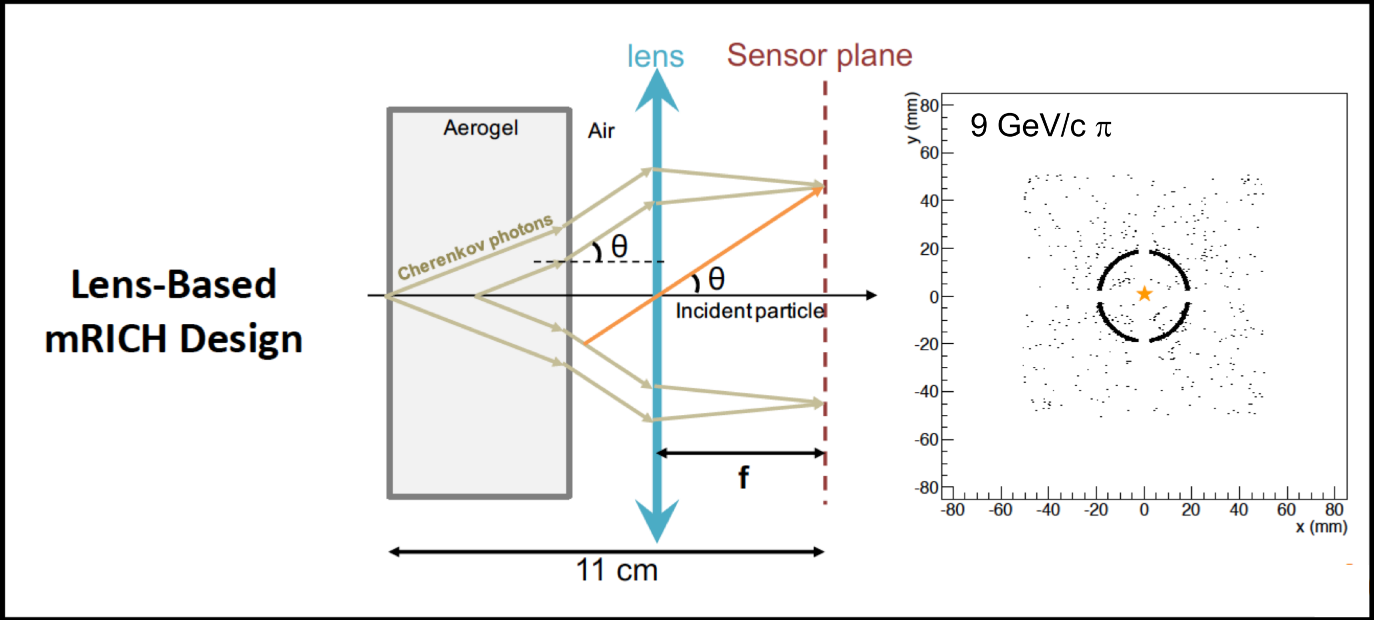


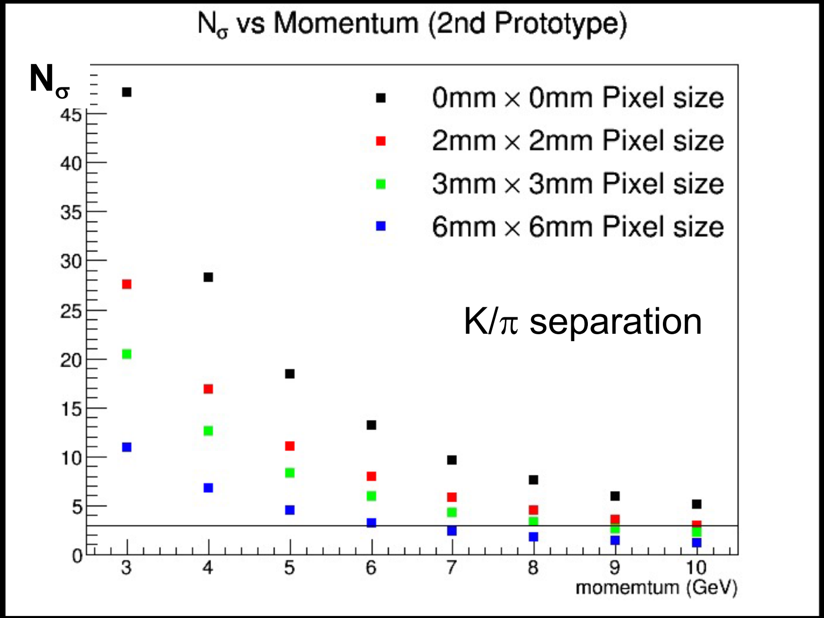
- DIRC
- p < 6 GeV/c

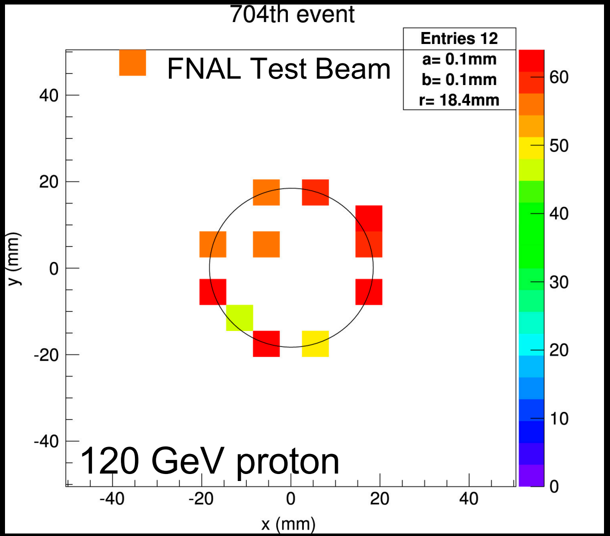
Forward

- Dual Radiator RICH
- p > 10 GeV/c

PID: Modular Ring Imaging Cherenkov

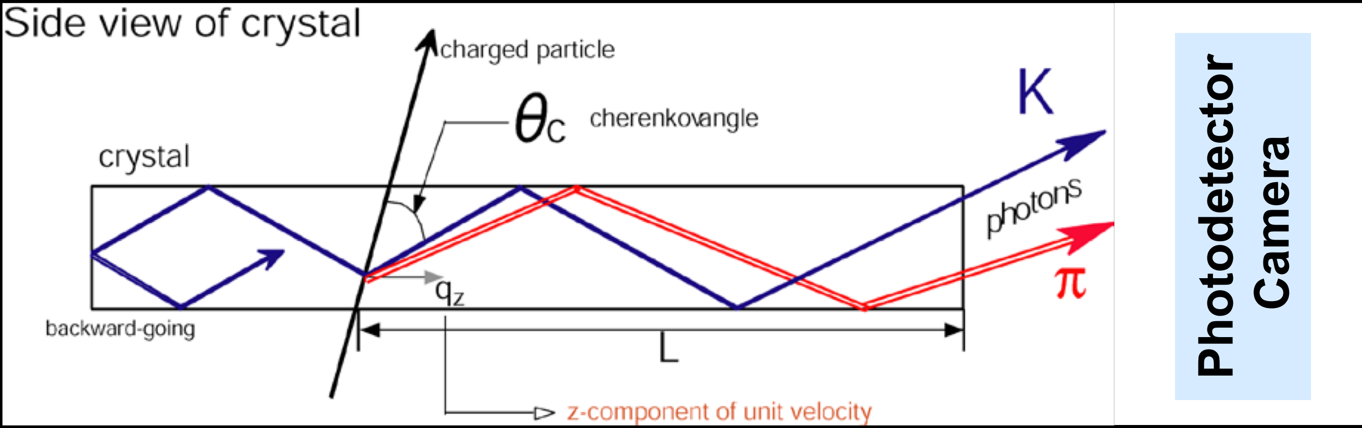


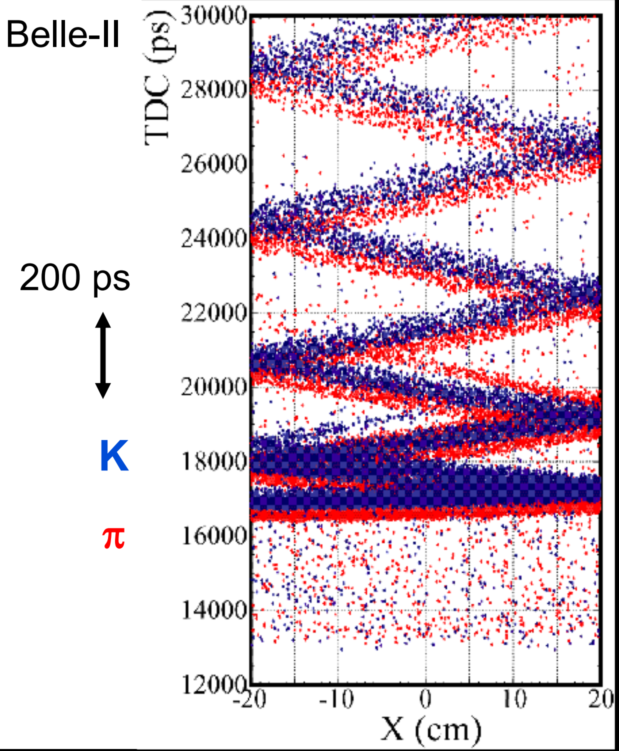




- Lens-based design allows for more compact detector compared to proximity focusing
  - First use of lens-based detector (rad. hardness)
  - Smaller, but sharper ring; few photons !
    120 GeV Proton: R=19.1 mm, N_γ = 11.0 +/- 2.9, $N_{\gamma det}$ = 5.9 +/- 1.8
  - Requires good position resolution for ring reconstruction

PID: Detection of Internally Reflected Cherenkov light





Simulation 2GeV/c, θ=90 deg

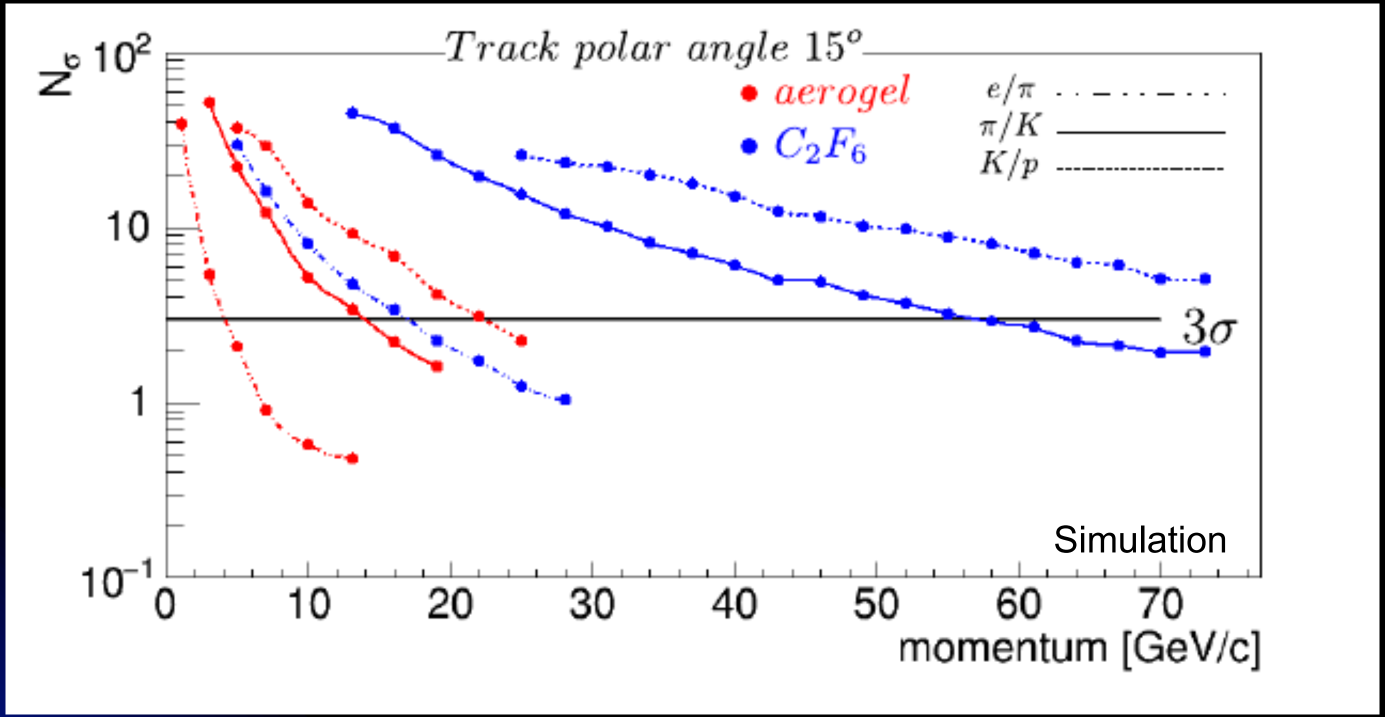
Different opening angle for the same momentum →

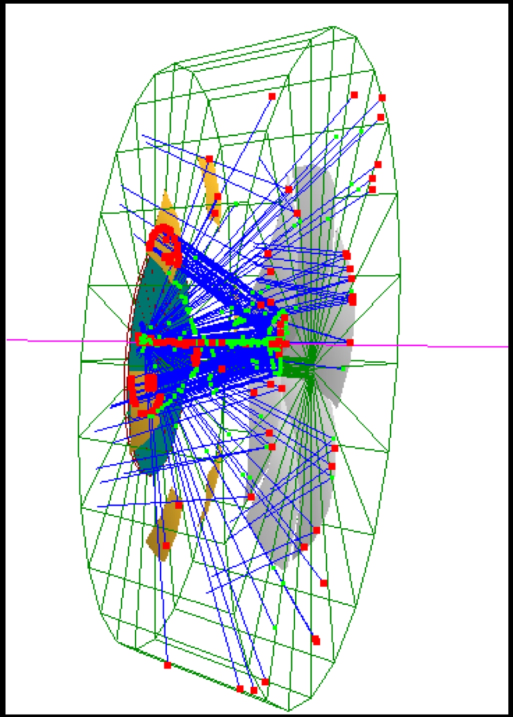
Different propagation length (=propagation time)

- Highly pixelated photodetectors required with exceedingly good timing resolution (<100ps) in magnetic field
- Compact focusing camera system
- Extension of PID to higher momenta desired

PID: Dual Ring Imaging Cherenkov Detector

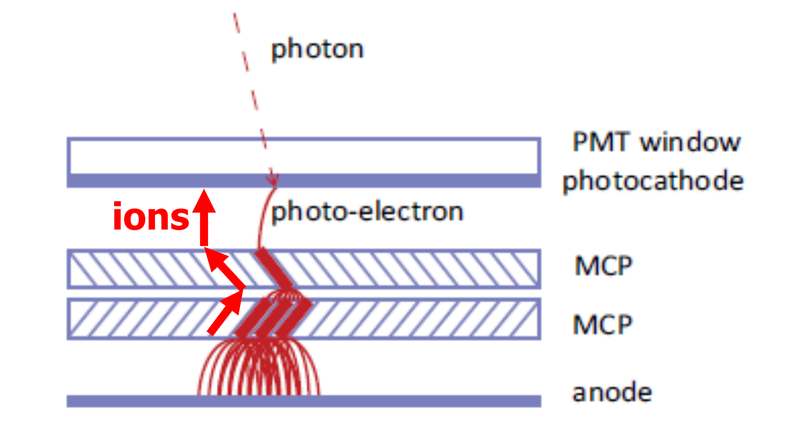
- EIC would be the first dual-radiator RICH developed for use with solenoidal detector
- Combination of C_2F_6 gas and n=1.02 aerogel leaves no gaps in coverage
- Outward-reflecting mirrors reduce backgrounds and (UV) scattering in aerogel
- Required sophisticated 3D focusing to reduce photosensor area

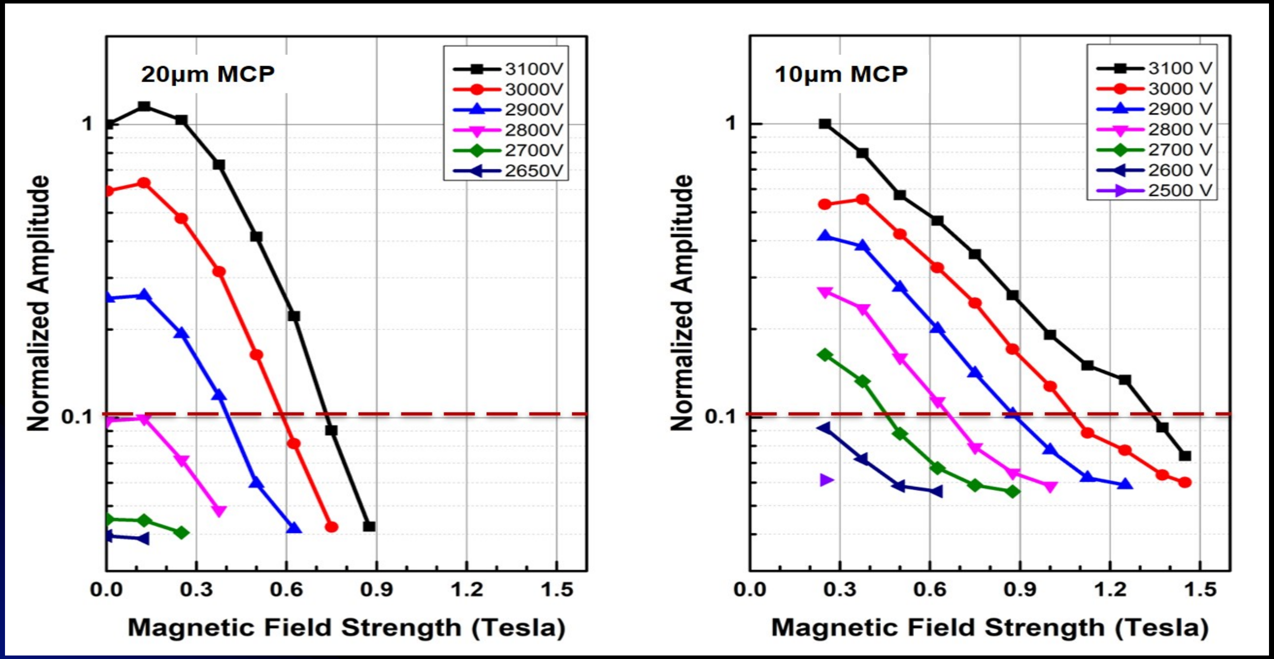


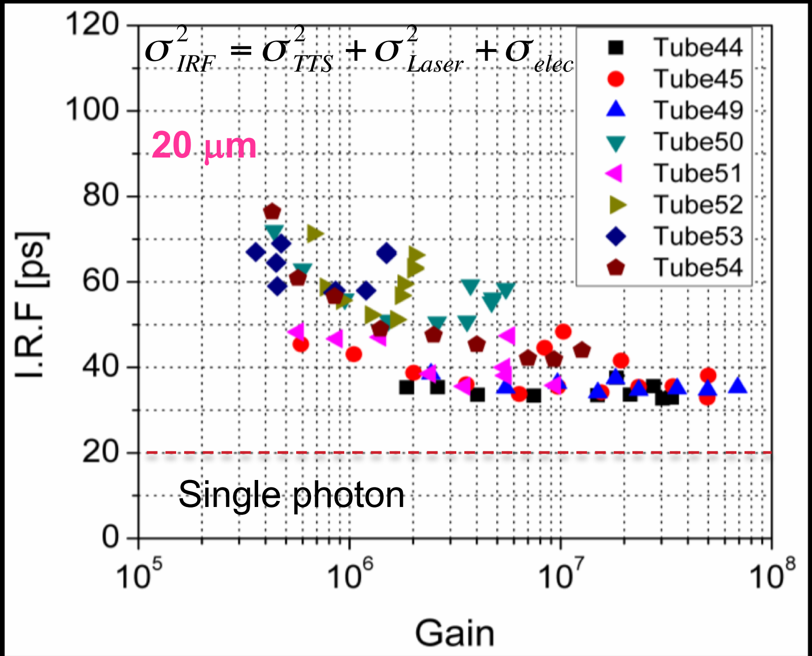


Micro-Channel Plate Photodetectors

- To date, Micro-Channel Plate (MCP) photodetectors have the best timing resolution, but B-field sensitivity
- Two main issues:
  - Very expensive
  - Not tolerant to magnetic fields
- Photodetectors: Arguably one of the key R&D issues





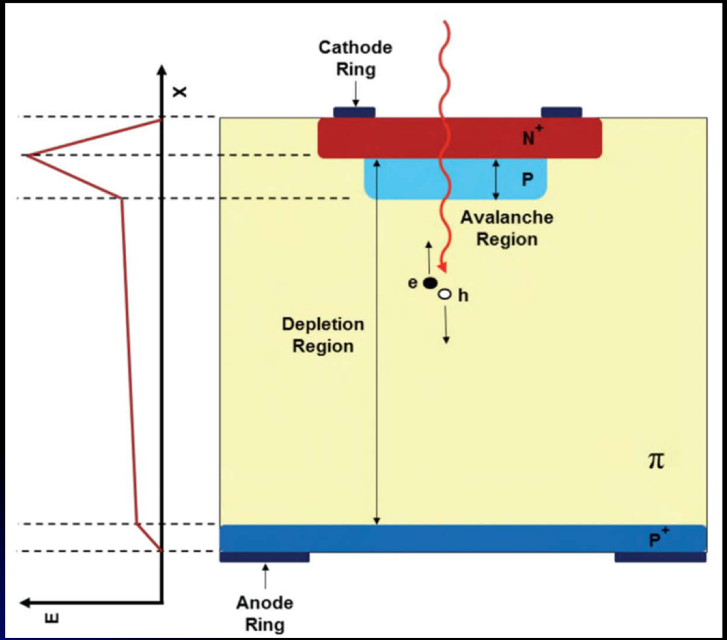


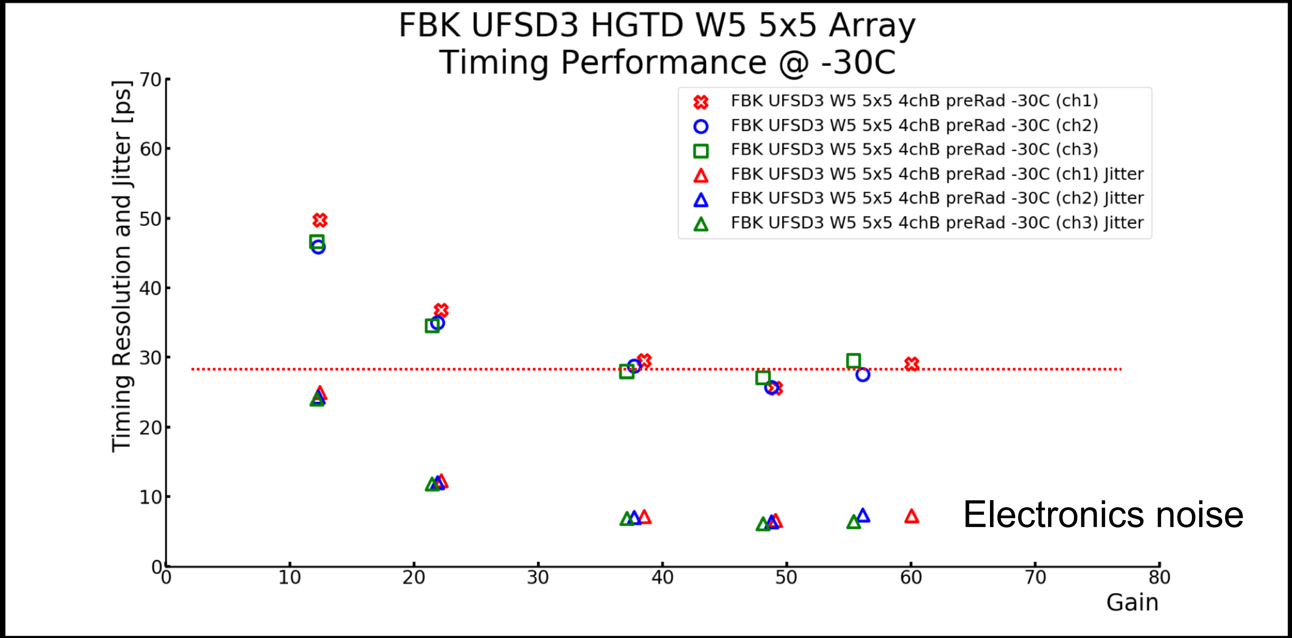
I.R.F = Instrument Response Function

Time-Of-Flight Detection

- Time-Of-Flight (TOF) detectors can be powerful particle identification detectors at low momenta
- Development of Low-Gain Avalanche Diodes (LGAD)
  - Additional doping layer before collection diode
  - Charge multiplication with moderate gain: 10 – 50

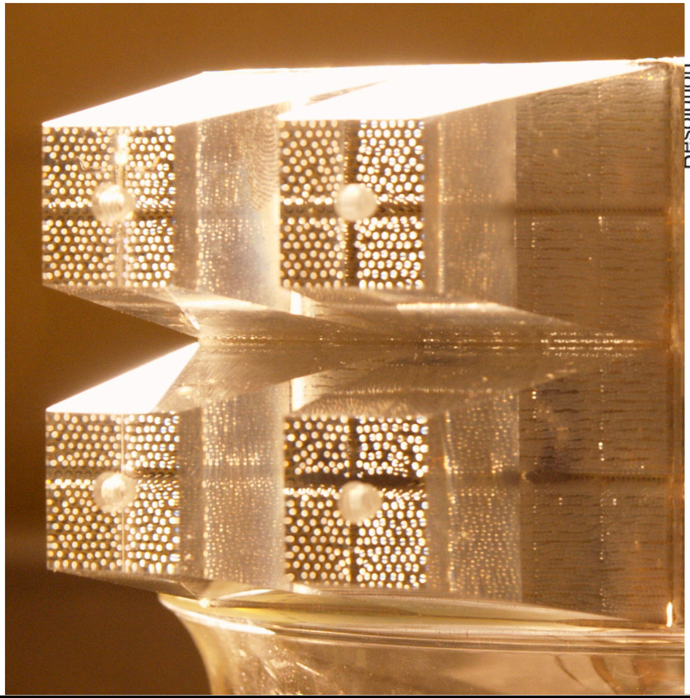
- Demonstrator LGAD device
  - LGAD sensors: 2x4 cm^2
  - Pixel size: 1.3x1.3 mm^2
- Confirmed intrinsic time resolution ~ 30ps with 50 μm thick LGADs;
- Overall time resolution ~50ps

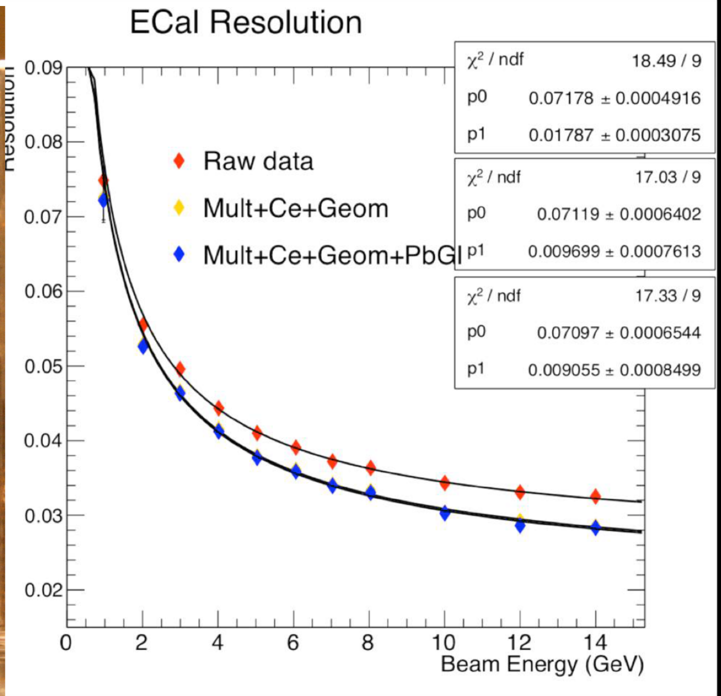




Calorimetry

- Develop cost-effective, flexible techniques to build compact sampling calorimeters that meet the EIC physics requirements using new technologies
- Tungsten powder scintillating fiber (Spacal) calorimeter with square fibers, each block readout with 4 SiPMs
- Many test beam campaigns



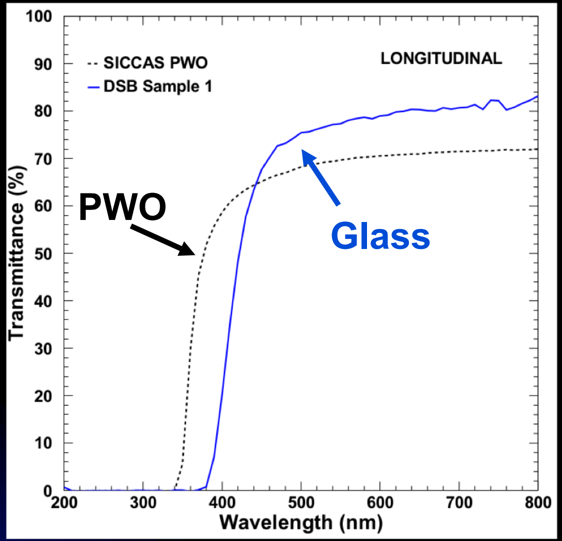


- Energy resolution of 7%/√E, with 1% constant term at 10°, 2.9% at 4°
- Study of radiation hardness of SiPM (non-uniform damage)
- Study of improvements in uniformity of response

Crystal Calorimetry

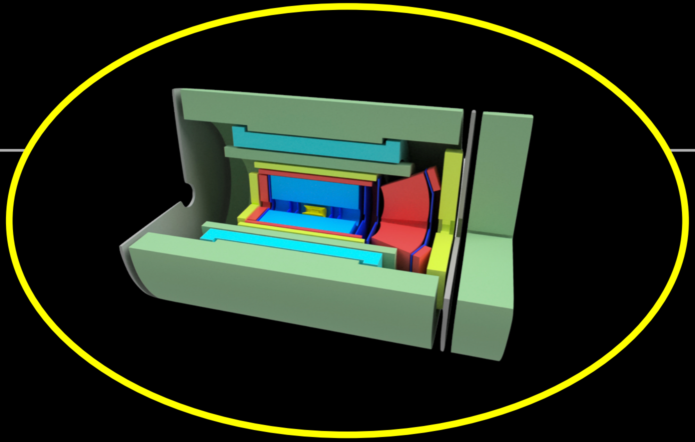
- Crystal calorimetry provides the best energy resolution for EM showers
- Crystals, however, are expensive, limited number of vendors, production difficulties, …
- Is glass calorimetry an option?
- Nano-sized particles of $BaSi_2O_5$
  - Improve scintillation
  - Allows doping with Gd, Yb, Ce, …

Material/ Parameter	$PbWO_4$	Sample 1	Sample 2	Sample 3	Sample 4
Luminescence (nm)	420	440	440	440	440
Relative light output (compared to $PbWO_4$)	1	35	16	23	11

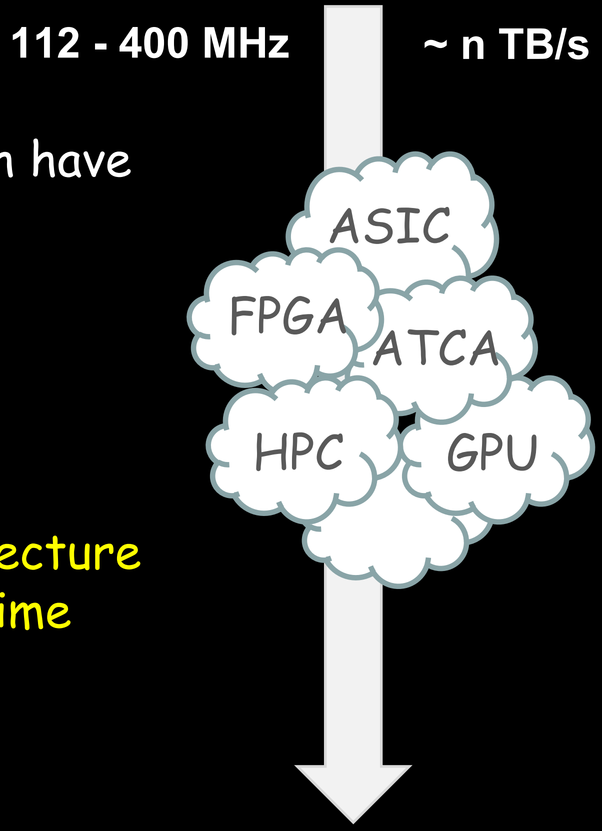


Material	Density (g/cm^3)	X_0 (cm)	Emission peak (nm)	Cutoff (nm)	Zeff
$(BaO*2SiO_2)$:Ce glass	3.7	3.6	440, 460	310	51
DSB:Ce	3.8	3.5	440, 460	310	51
$(BaO*2SiO_2)$:Ce glass loaded with Gd	4.7-5.4	2.2	440, 460	318	58

Data Acquisition



Larger detectors
Higher granularity
More data

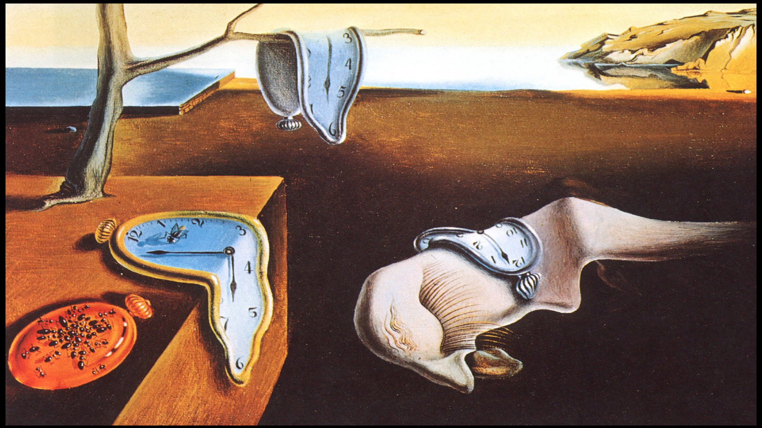


- Tracking and calorimeter each have substantial raw data rates
- Large capacity event-building network required
- Conventional triggered architecture most likely replaced by real-time processing architecture

- Early days, but interesting R&D required for most efficient data acquisition architecture, preferably based on commercial devices

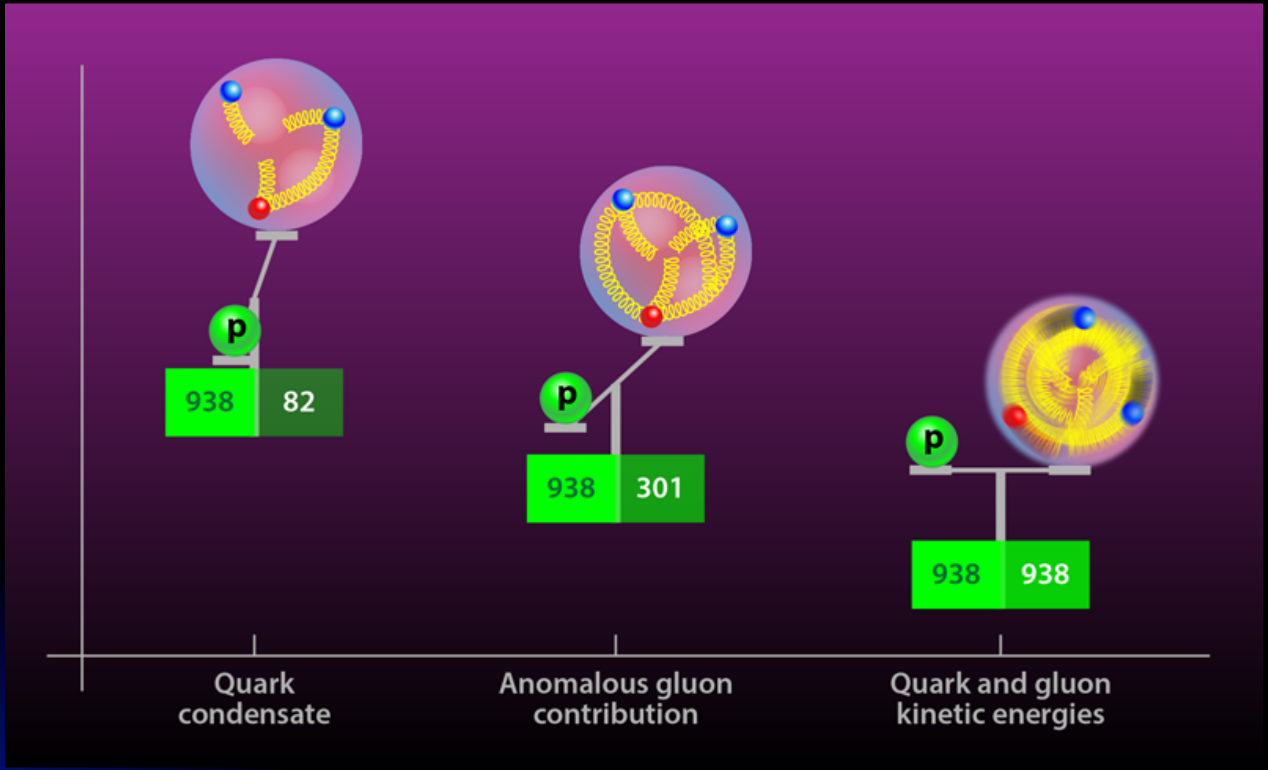
Conclusions

- An Electron-Ion Collider will contribute profoundly to the understanding of matter and be an important component in our suite of tools to again revolutionize our knowledge in the next decades.
- To mine the vast amount of data to expose the fundamental laws of Nature, highly sensitive instruments are needed.
- The future ain't what it used to be! Up to the challenge?



Proton Mass

- Four contributions to the proton mass:
  - Quark condensate (~9%)
  - Quark energy (~32%)
  - Gluonic field strength energy (~37%)
  - Anomalous gluonic contribution (~23%)



Y.-B. Yang, J. Liang, Y.-J. Bi, Y. Chen, T. Draper, K.-F. Liu, and Z. Liu, “Proton mass decomposition from the QCD energy momentum tensor,” Phys. Rev. Lett. 121, 212001 (2018).

Contributions To Resolution

$$\sigma_t^2 = \sigma_{\text{Time Walk}}^2 + \sigma_{\text{Landau Noise}}^2 + \sigma_{\text{Distortion}}^2 + \sigma_{\text{Jitter}}^2 + \sigma_{\text{TDC}}^2$$

Contribution from RO electronics

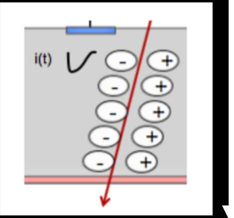
→ Sophisticated ASIC design

Dependence on signal noise

→ Minimized with fast signals and large S/N

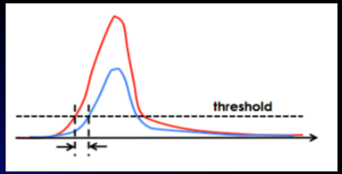
Dependence on drift velocity

→ Minimize with uniform electric fields



Varying density of e-hole pairs along path

→ Minimized by decreasing sensor thickness



Dependence on signal size

→ Minimize using Time over Threshold and Amplitude measurement

Micro-Channel Plate Photodetectors

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- Two main issues:
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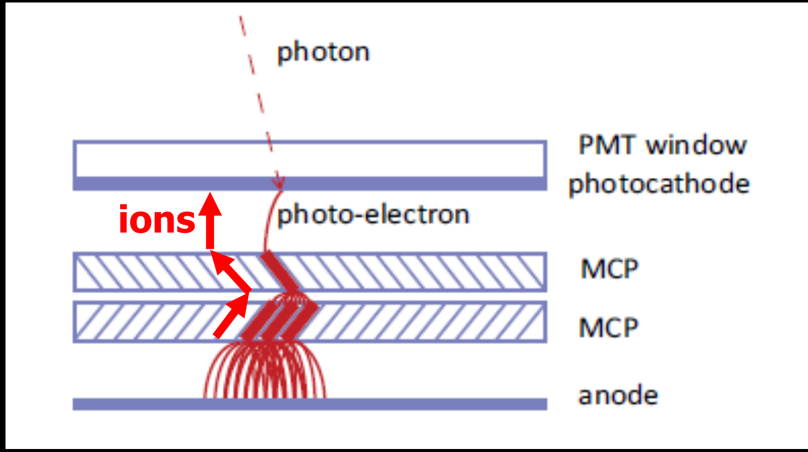
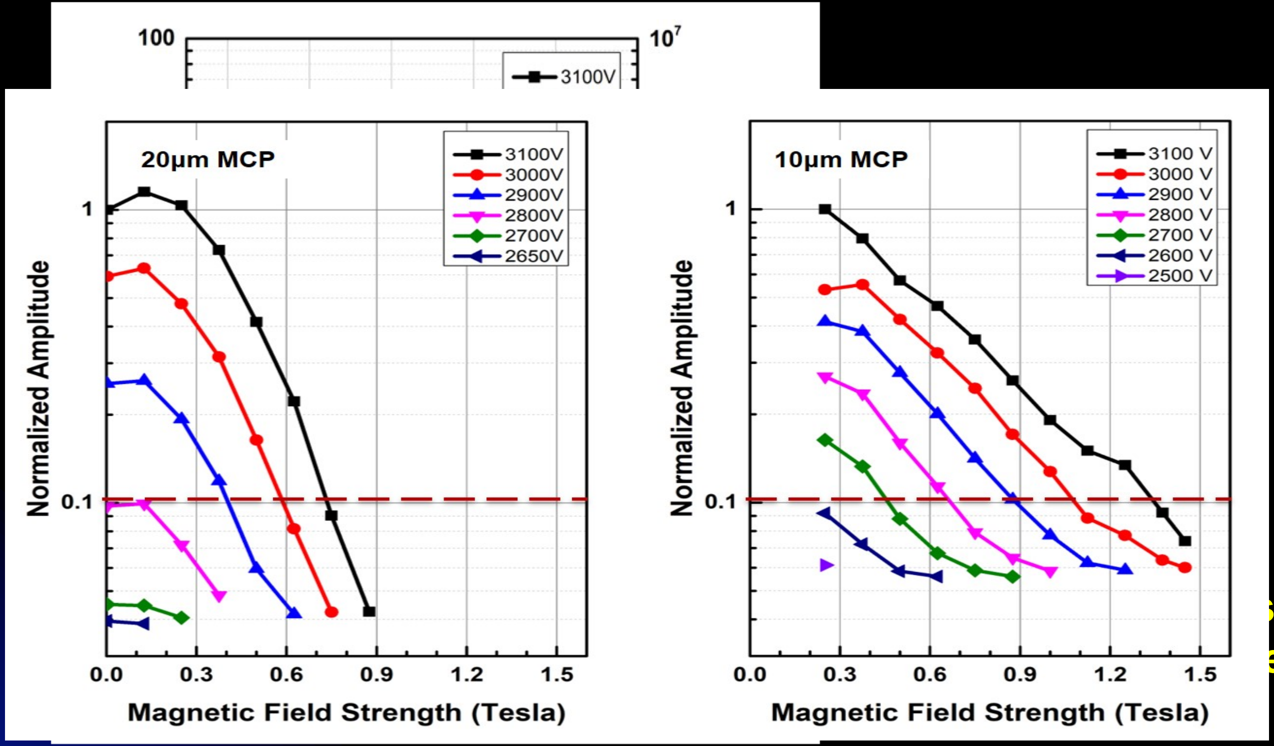
  - Not tolerant to magnetic fields





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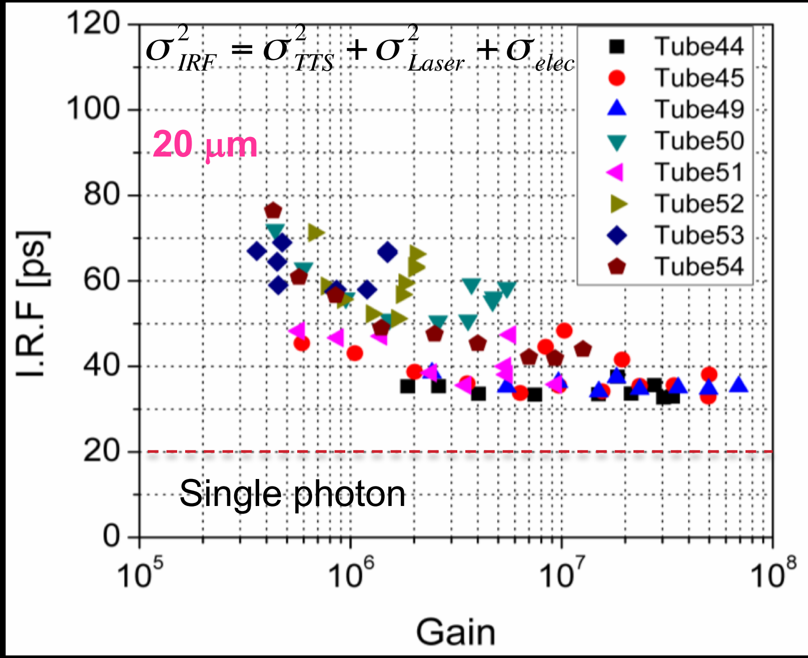
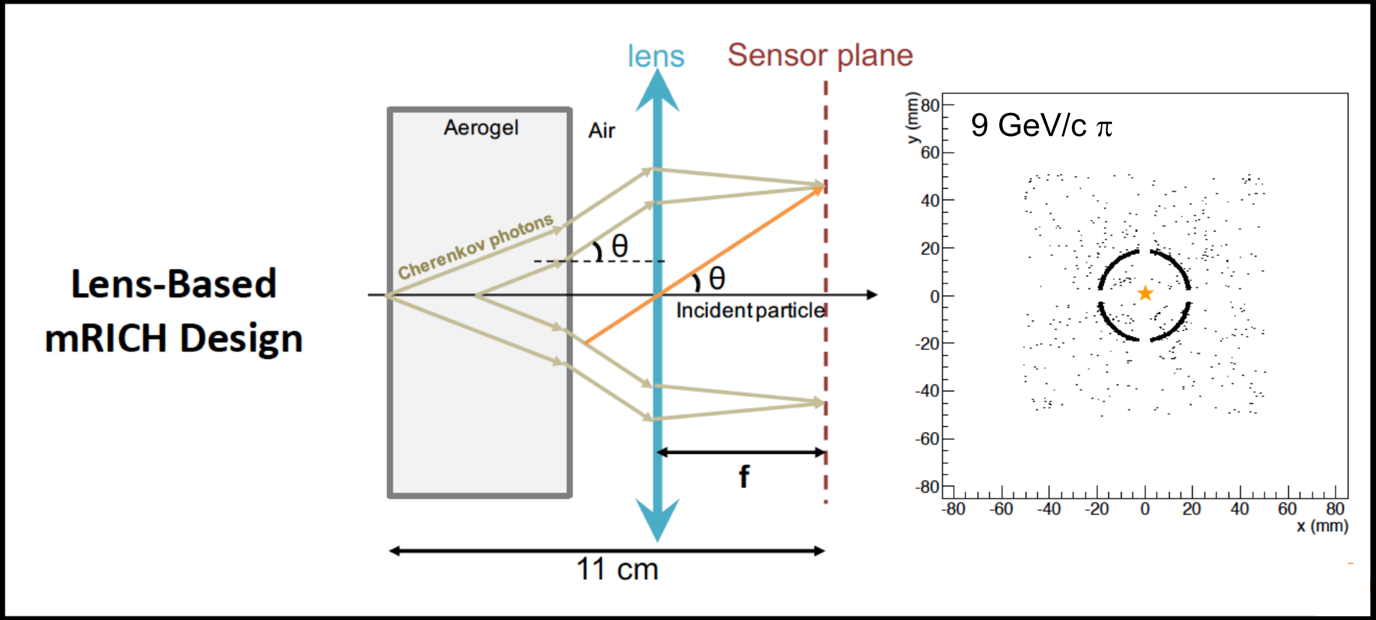
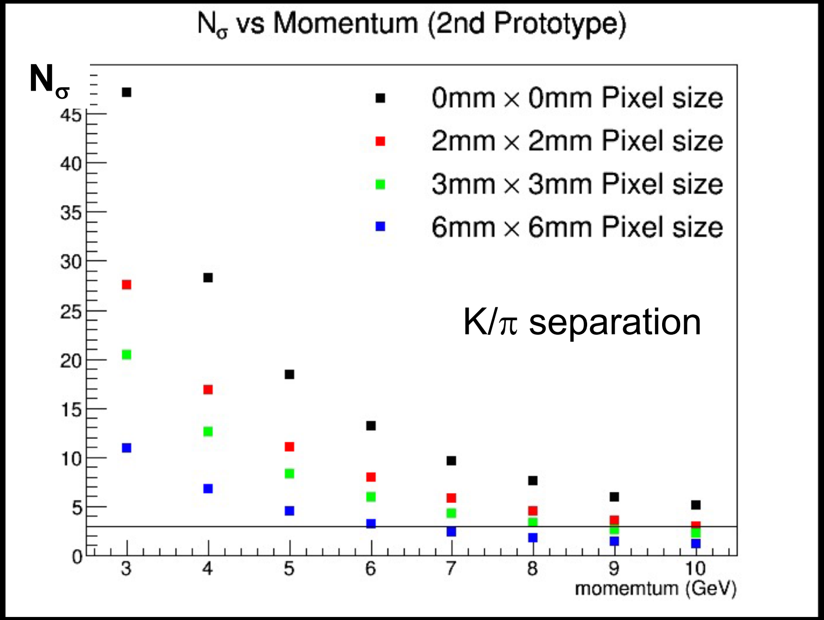


I.R.F = Instrument Response Function

PID: Modular Ring Imaging Cherenkov





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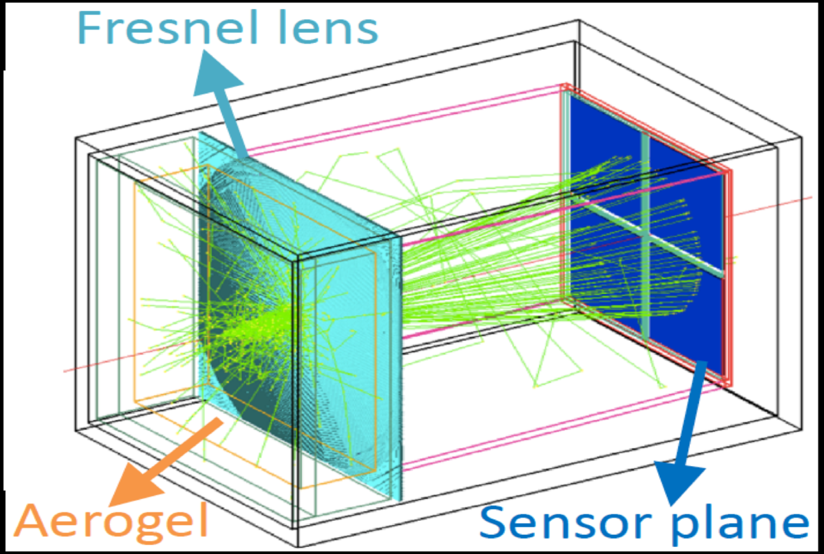
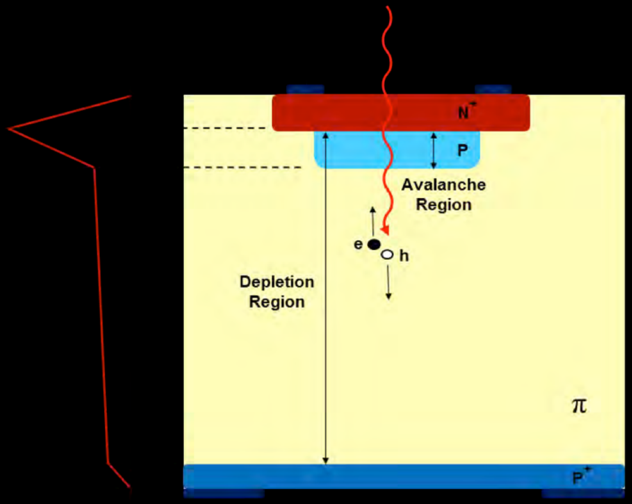


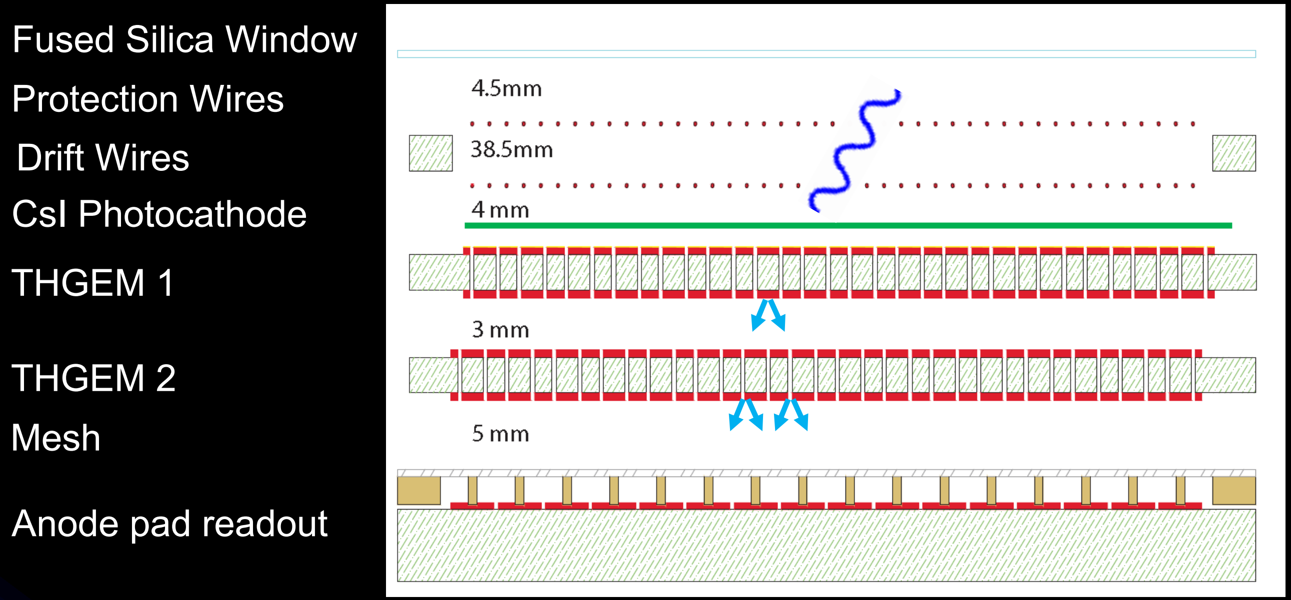
Time-of-Flight

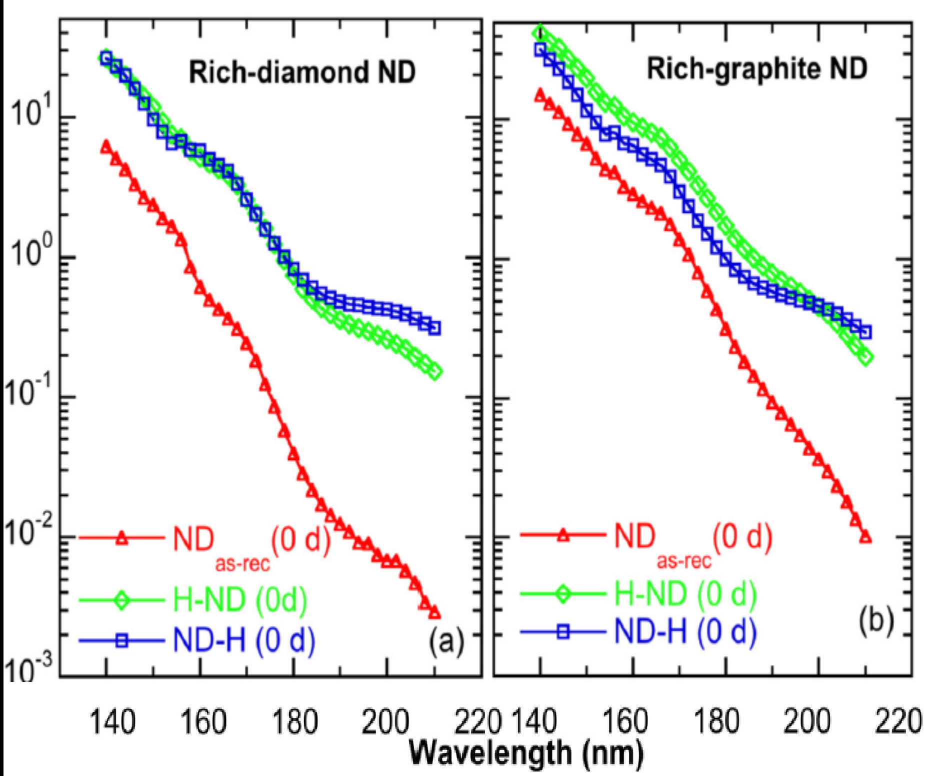
- Precisely measure hit timing in silicon detector
- Low Gain Avalanche Detectors (LGAD):
  - add an extra doping layer to create avalanche
  - maximize the slew rate, dV/dt;
  - E ~ 300 kV/cm, closed to breakdown voltage



MPGD-based Photon Detection

- Particle Identification over large momentum range is crucial for EIC physics
- Developing MPGDs as Ring Imaging Cherenkov (RICH) detector

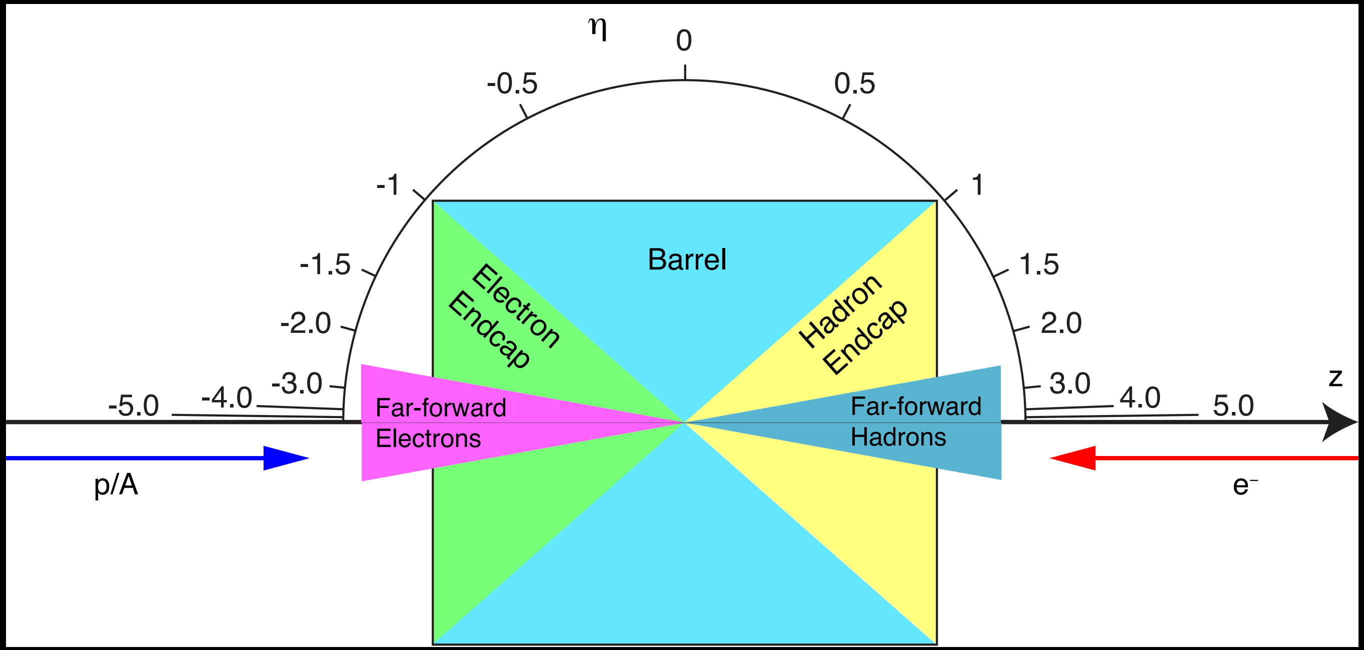


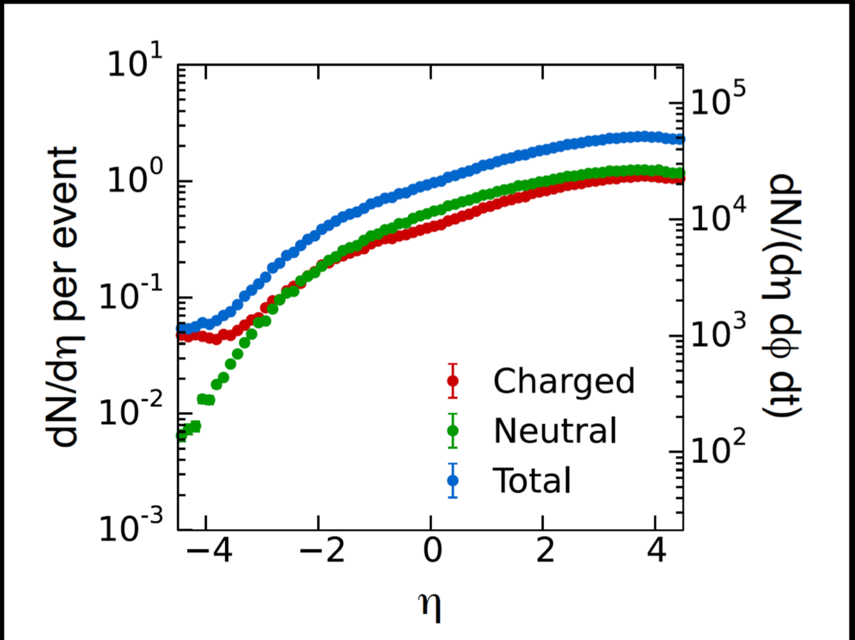


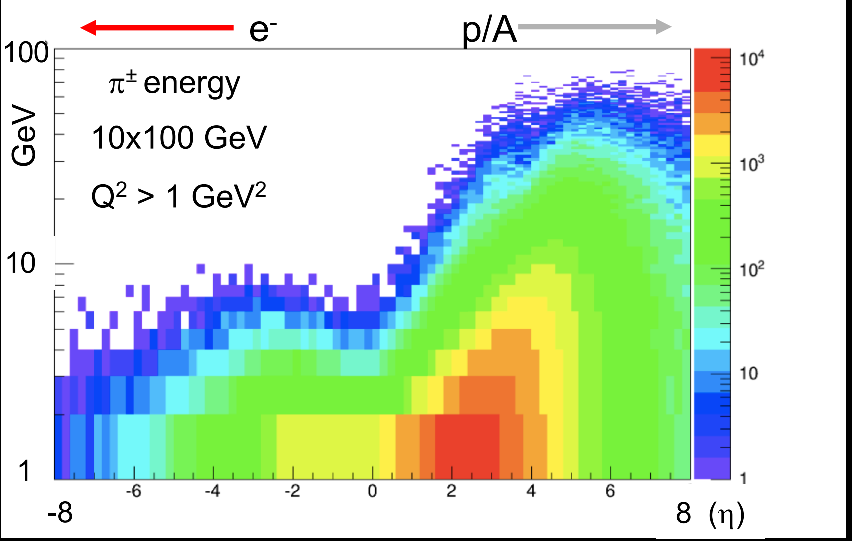
L.Velardi, A.Valentini, G.Cicala, Diamond & Related Materials 76 (2017) 1

- Possibility to develop nano-diamond based photocathodes (CsI vacuum process, ageing)
- Peak QE is 47% !

New Tools: Detectors







parameter	eRHIC		JLEIC	
Beam Configuration	p	e	p	e
Energy/beam [GeV]	40 – 275	5 – 18	8 – 100	3 – 12
bunch spacing [ns]	8.9		2.1	
bunch intensity [10^{10}]	6	15	0.98	3.7
RMS bunch length (cm)	5	1.9	~1.0	1.0
Polarization (%)	80	70	80	80

Detector Requirements

Physics Drivers

- Good momentum resolution

  $\sigma(p)/p = 0.05\%\, p \oplus 1\%$ (central)

  $\sigma(p)/p = 0.1\%\, p \oplus 2\%$ (forward)

- Good impact parameter resolution

  $\sigma = 5 \oplus 15 / p \sin^{\frac{3}{2}} \vartheta$ (μm) (central)

- Excellent EM energy resolution

  $\sigma = 10\% / \sqrt{E}$ (central)

  $\sigma = 2\% / \sqrt{E}$ (forward)

- Good hadronic energy resolution

  $\sigma = 50\% / \sqrt{E}$

- Low Q^2 tagger, precise pol. measurement
- Excellent particle identification π/K/p
  - Forward η: up to ~50 GeV/c
  - Central η: up to ~5-8 GeV/c
  - Backward η: up to ~7 GeV/c

Accelerator Drivers

- Interaction region layout affects:
  - Low Q^2 tagger
  - Compton polarimeter
- Low pile-up, modest multiplicities
- Short bunch crossing time
- Modest radiation hardness
- Forward region radiation hard EM calorimetry

Environment and requirements very different from multi-purpose LHC experiments