Title: Particle/Astro Observations

Speakers:

Collection: TRISEP 2023

Date: June 28, 2023 - 2:30 PM

URL: https://pirsa.org/23060085

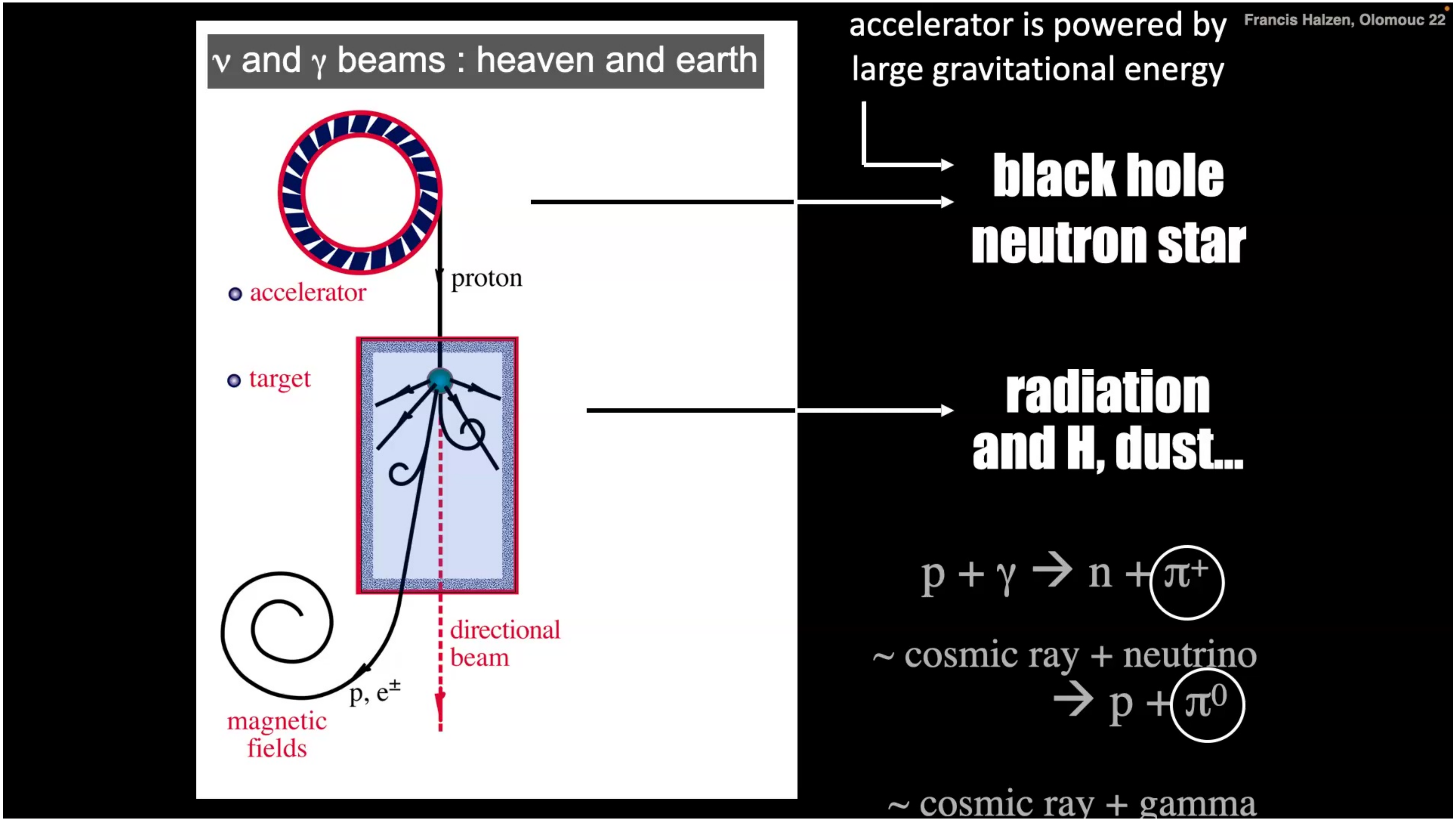
High-energy gamma-rays

TRISEP - June 2023

Many thanks to the broad particle astrophysics community for sharing materials online!

Content from: Jordan Goodman - U.Maryland; Francis Halzen - UW-Madison; Jörg R. Hörandel - RU Nijmegen, Nikhef, VU Brussel; Athina Meli - Univ. Athens; Elisa Resconi - TUM; Christian Stegmann - DESY; Yajie Yuan -Flatiron Institute

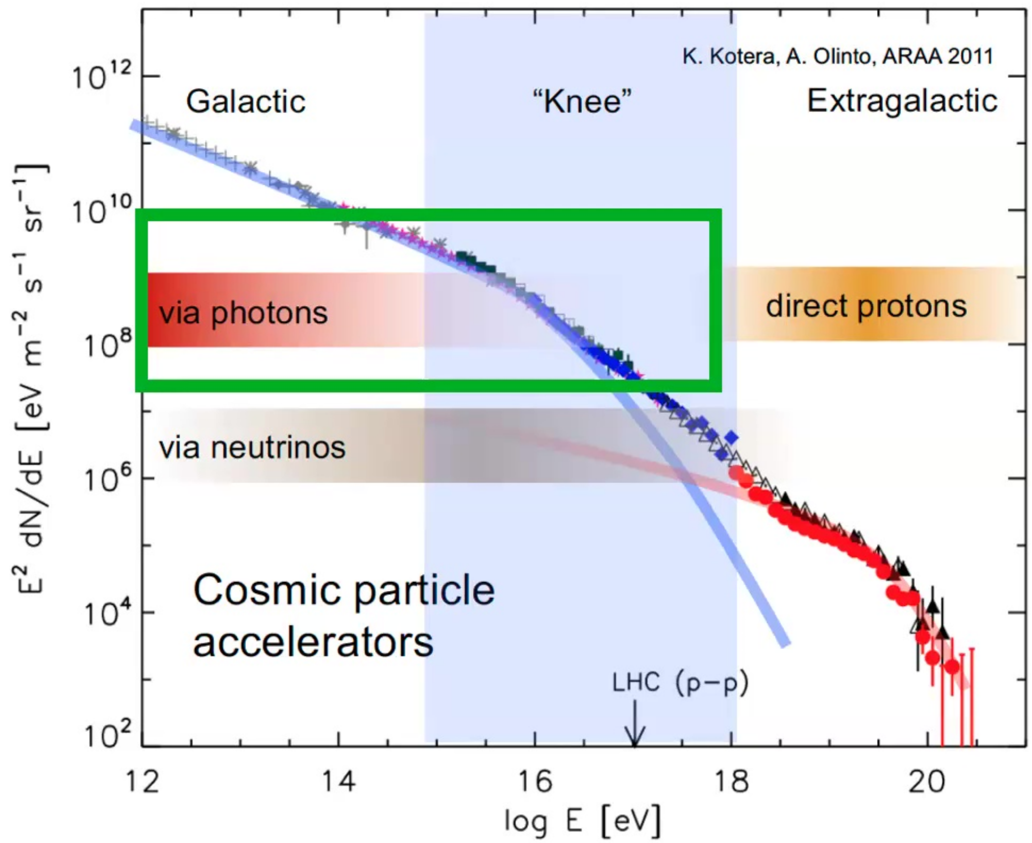
Jordan Goodman - Gamma ray astronomy with extensive air showers (https://agenda.astro.ru.nl/event/12/contributions/192/)
Jordan Goodman - Recent results from HAWC (https://agenda.astro.ru.nl/event/12/contributions/190/)
Jordan Goodman - Recent results from LHAASO and future arrays (https://agenda.astro.ru.nl/event/12/contributions/189/)
Francis Halzen - https://user-web.icecube.wisc.edu/~halzen/presentations/Olomouc22_Halzen.pptx
Jörg R. Hörandel - Historical introduction and basic properties of cosmic rays (https://agenda.astro.ru.nl/event/12/contributions/197/)
Athina Meli - http://wwwiexp.desy.de/groups/astroparticle/de/lehre/guest_seminar/meli.pdf
Elisa Resconi - https://campus.tum.de/tumonline/wblvangebot.wbshowlvoffer?ppersonnr=275352
Christian Stegmann - Ground-based gamma-ray astronomy with imaging air Cherenkov telescopes (3 lectures - https://agenda.astro.ru.nl/event/12/contributions/236/; https://agenda.astro.ru.nl/event/12/contributions/202/; https://agenda.astro.ru.nl/event/12/contributions/210/)
Yajie Yuan - https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&ved=2ahUKEwjAxO-a7-P_AhWVFlkFHTvhDoAQFnoECBAQAQ&url=https://confluence.slac.stanford.edu/download/attachments/223229391/ParticleAcceleration1.pdf?version=1&modificationDate=1496672393000&api=v2&usg=AOvVaw0BcCvH_wJNVD0UZyDbPVHP&opi=89978449

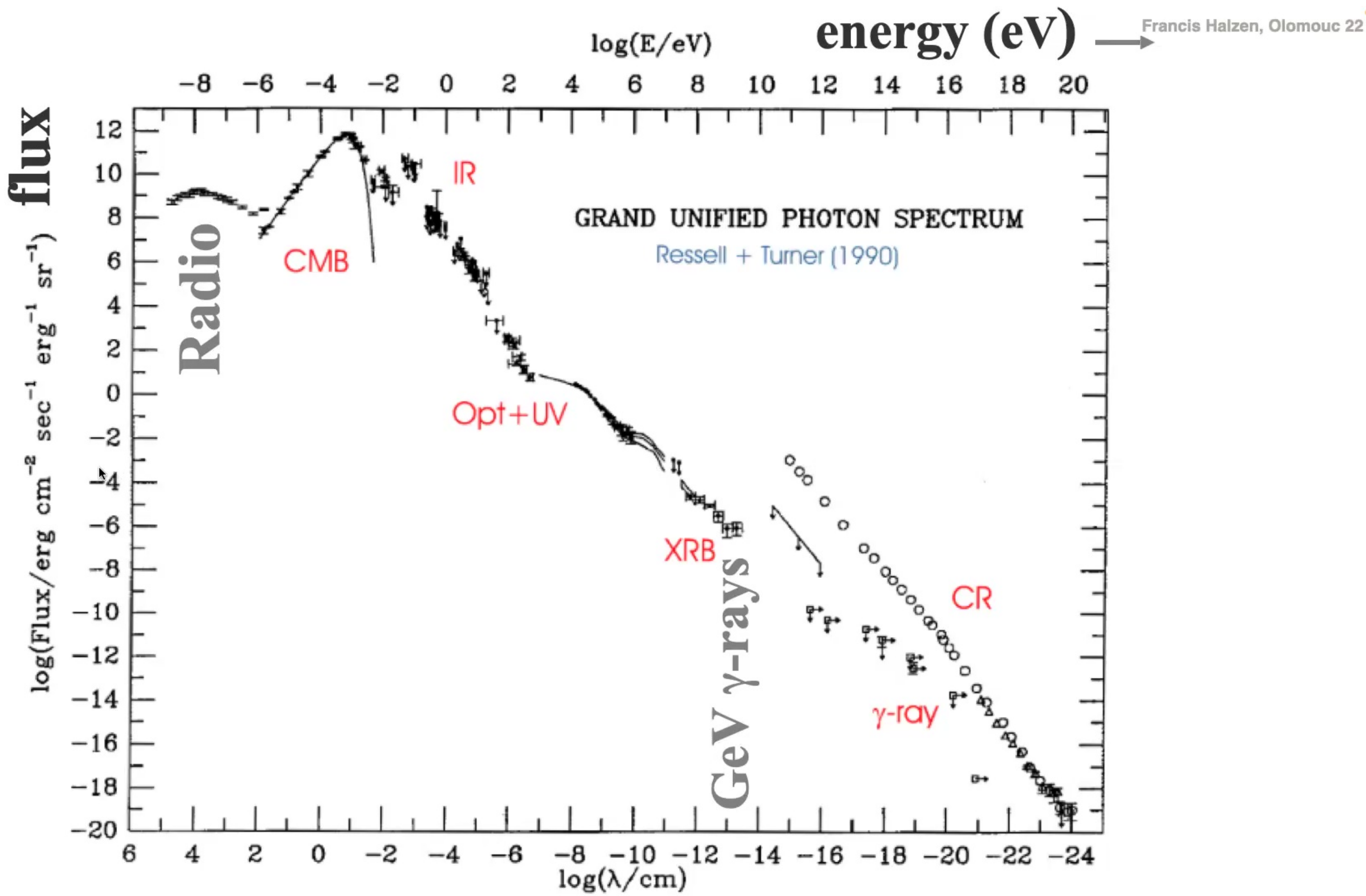


Francis Halzen, Olomouc 22
ν and γ beams : heaven and earth
accelerator
target
proton
magnetic fields
p, e±
directional beam
accelerator is powered by large gravitational energy
black hole
neutron star
radiation and H, dust...
p + γ → n + π+
~ cosmic ray + neutrino
→ p + π0
~ cosmic ray + gamma

Recap

We looked at cosmic rays and discussed possible sources and acceleration mechanisms at the most extreme energies in the Universe. Next we look at how to probe those objects to using other information (today TeV+ gamma-rays, Friday neutrinos) to try and resolve a now more than 100 year mystery.





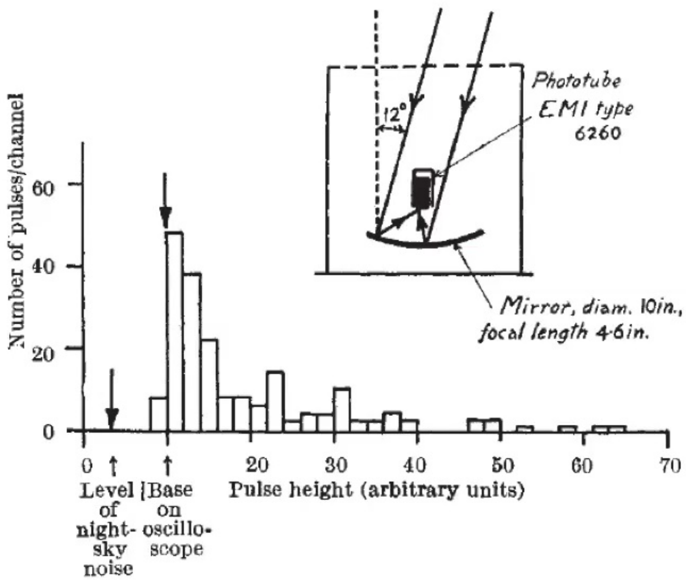
Francis Halzen, Olomouc 22
energy (eV)
log(E/eV)
flux
log(Flux/erg cm^-2 sec^-1 erg^-1 sr^-1)
GRAND UNIFIED PHOTON SPECTRUM
Ressell + Turner (1990)
Radio
CMB
IR
Opt+UV
XRB
GeV γ-rays
CR
γ-ray
log(λ/cm)

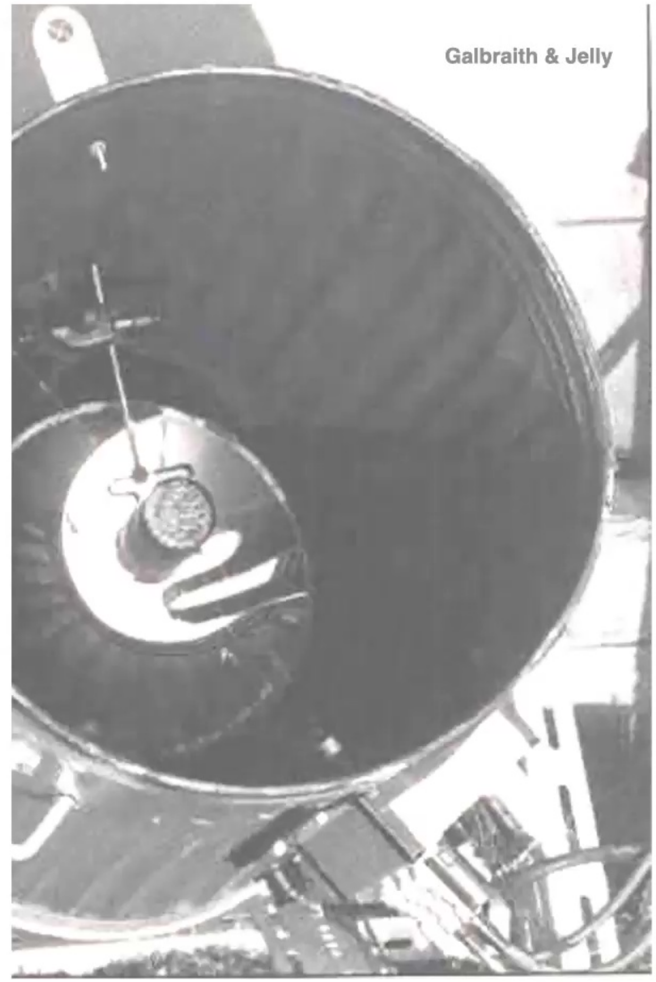
First observations of gamma-rays…

February 21, 1953 NATURE

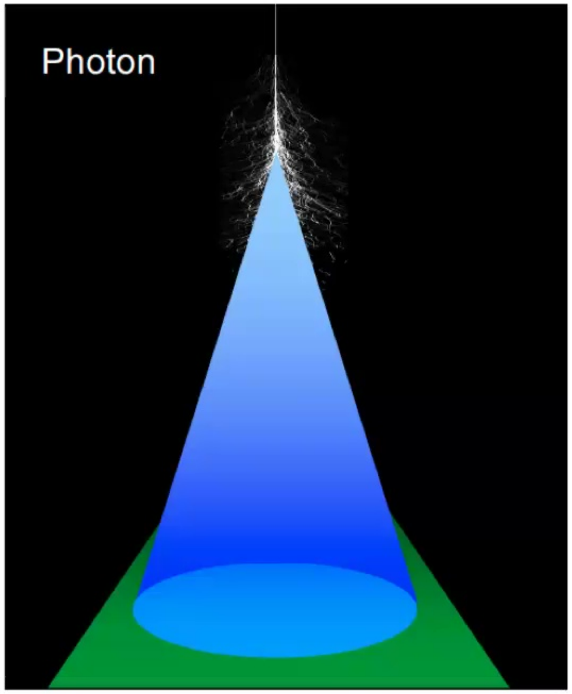
Light Pulses from the Night Sky associated with Cosmic Rays

In 1948, Blackett[1] suggested that a contribution approximately 10^{-4} of the mean light of the night-sky might be expected from Čerenkov radiation[2] produced in the atmosphere by the cosmic radiation. The purpose of this communication is to report the results of some preliminary experiments we have made using a photomultiplier, which revealed the

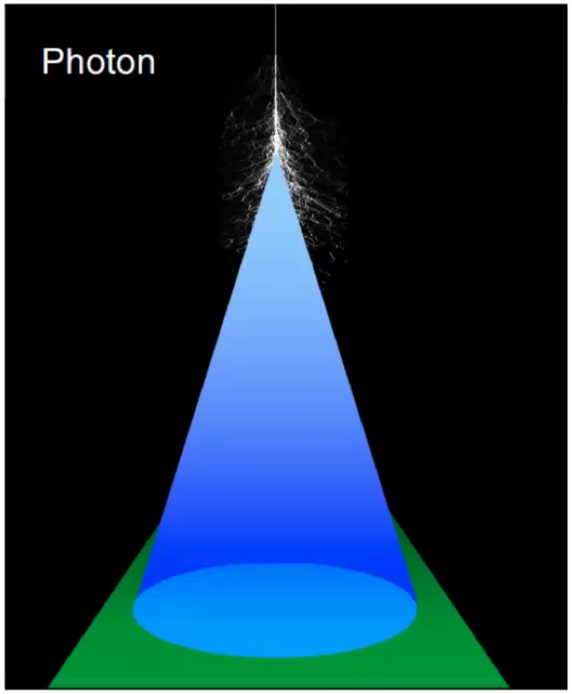


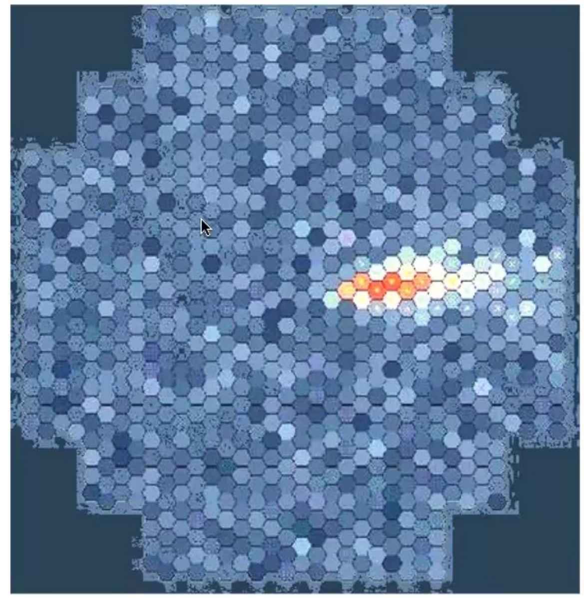


Detection principles…



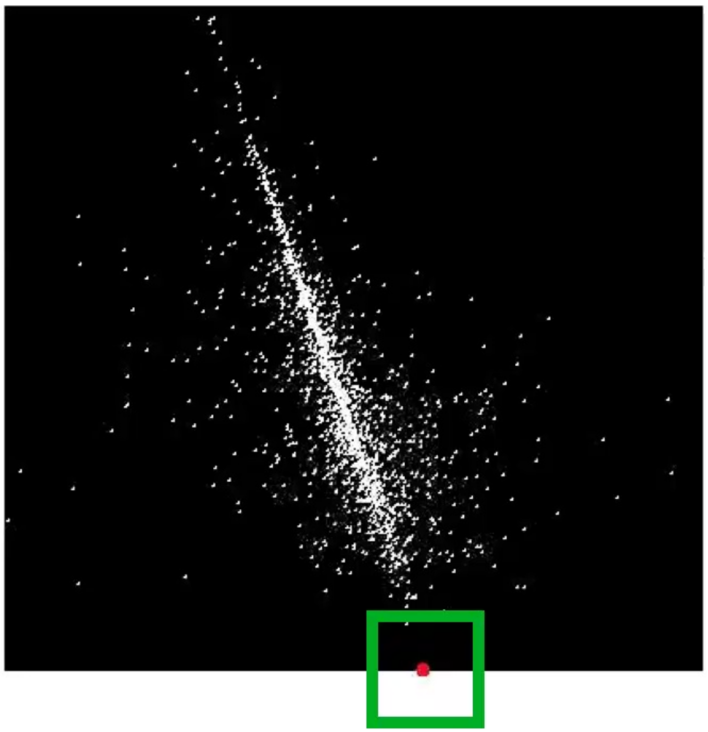
Detection principles…

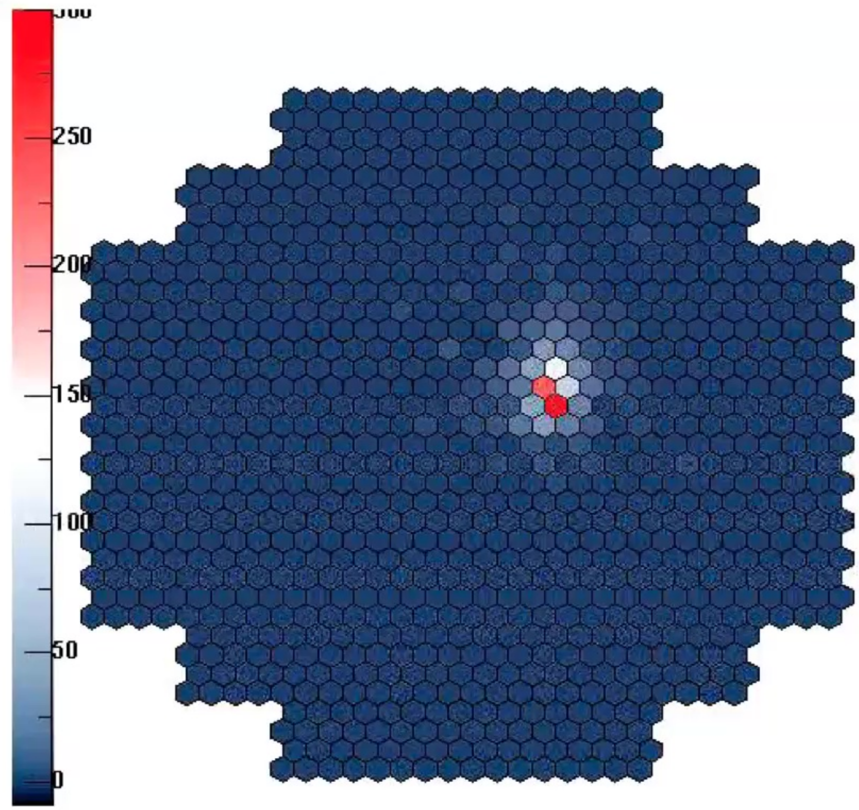




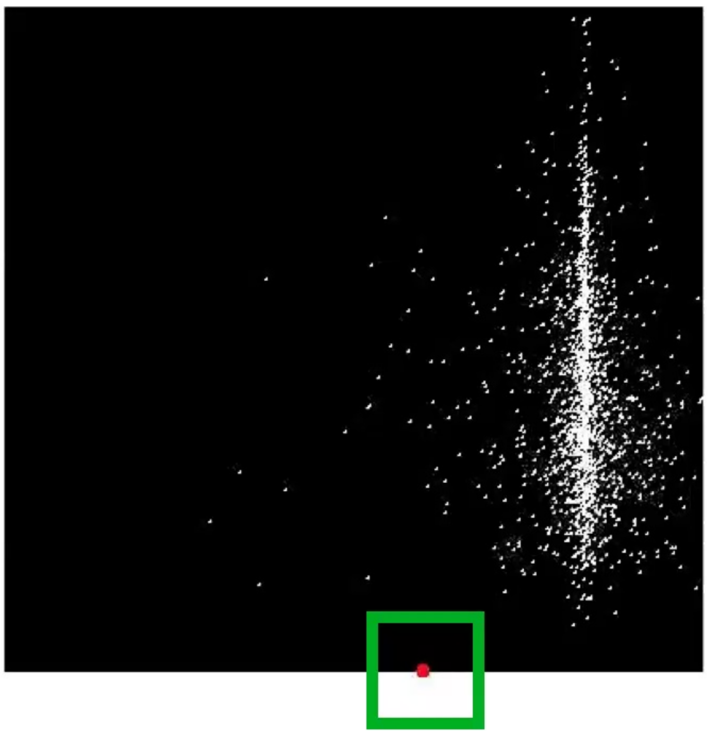
Intensity -> Energy
Orientation -> Direction
Shape -> Primary

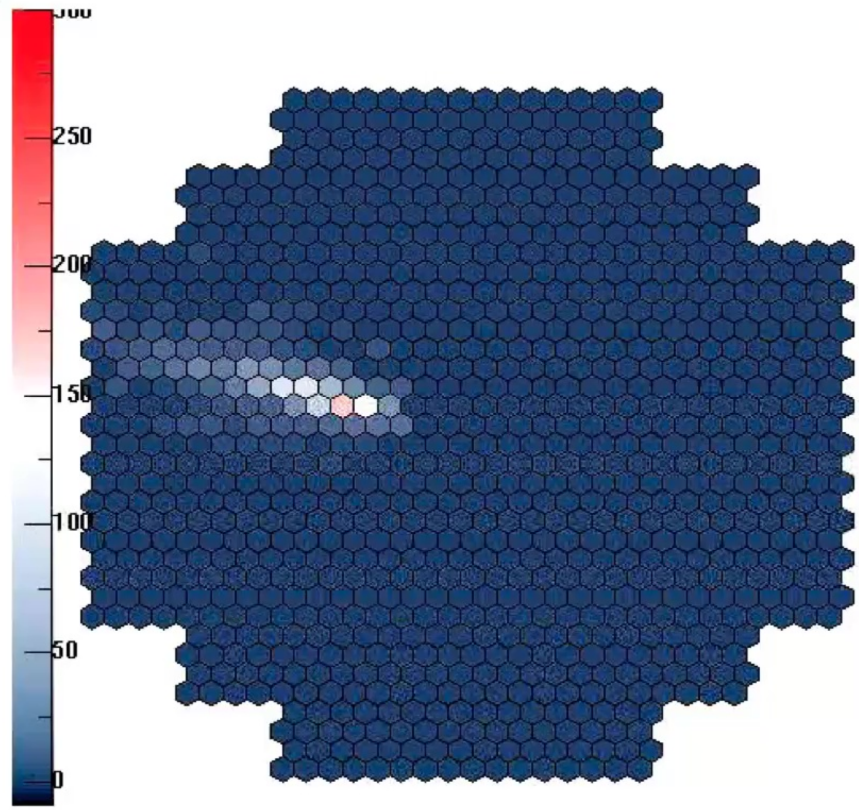
Detection principles…



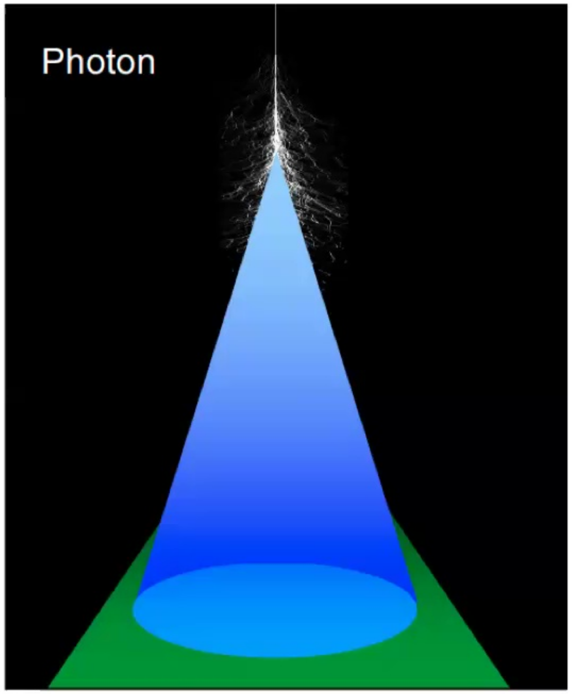


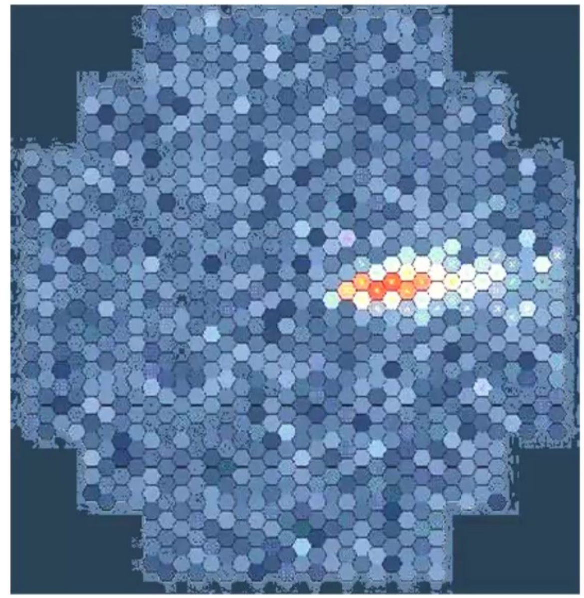
Detection principles…





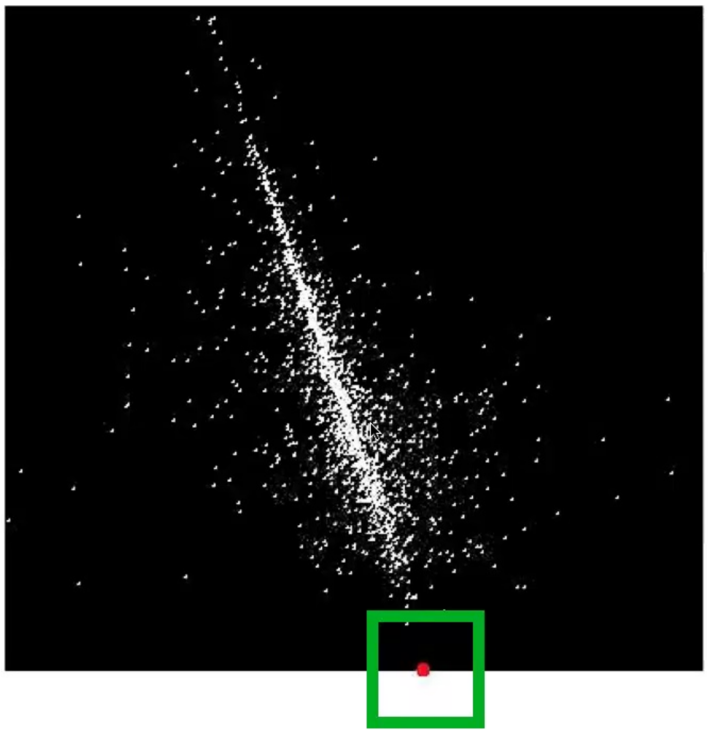
Detection principles…

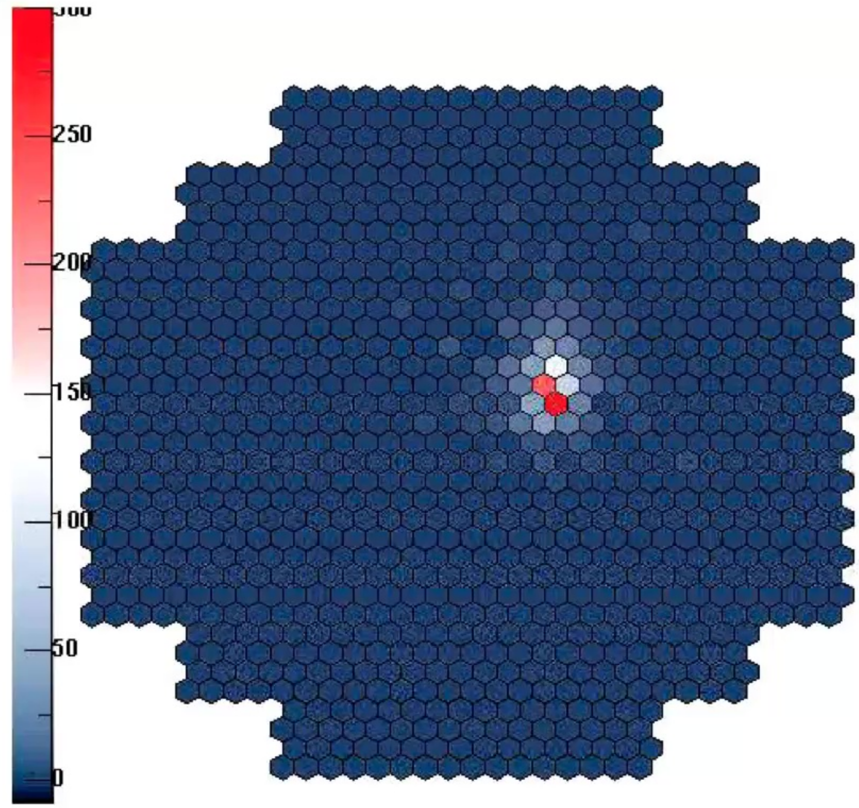




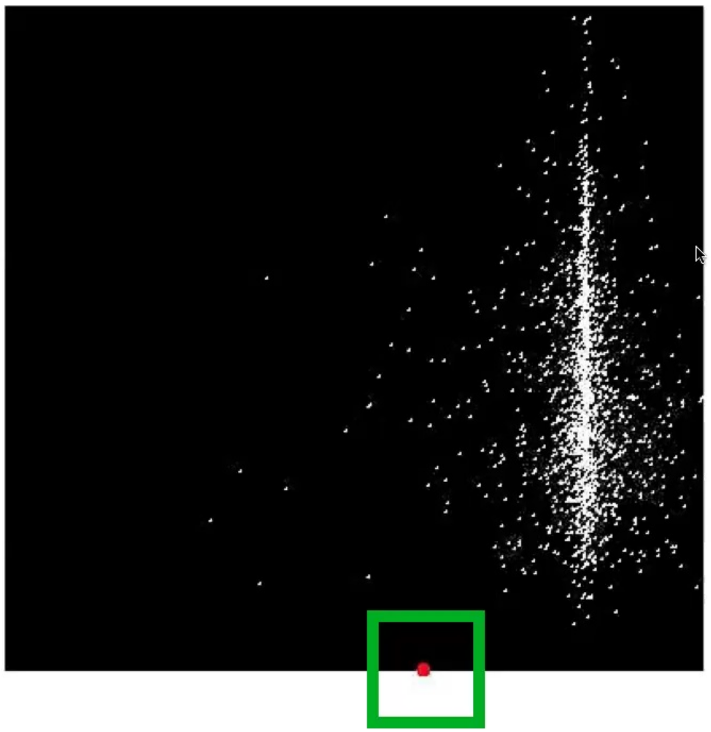
Intensity -> Energy
Orientation -> Direction
Shape -> Primary

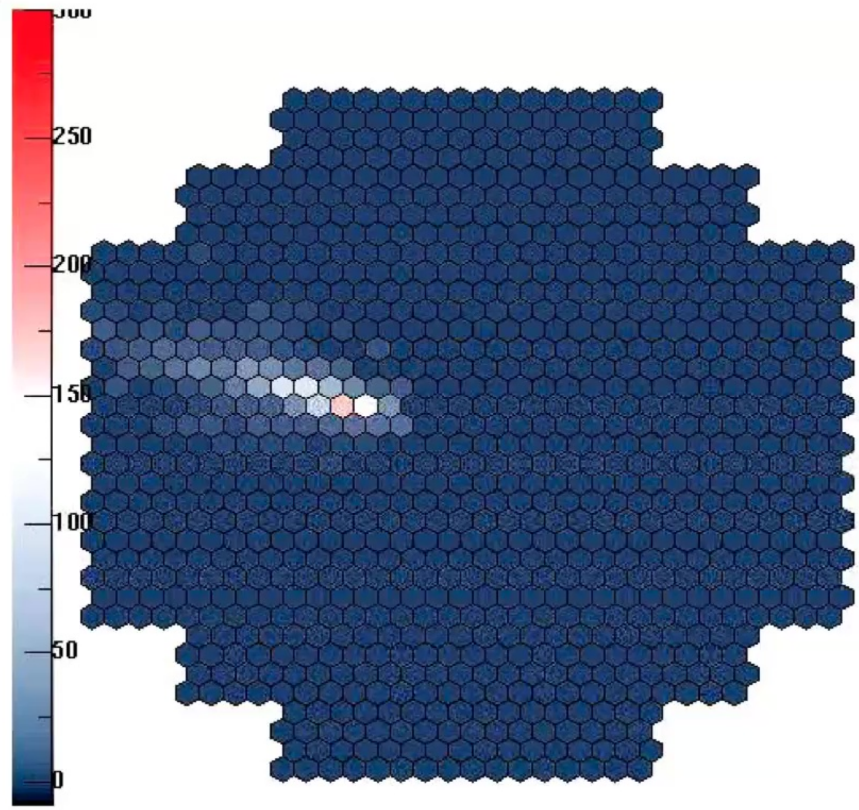
Detection principles...



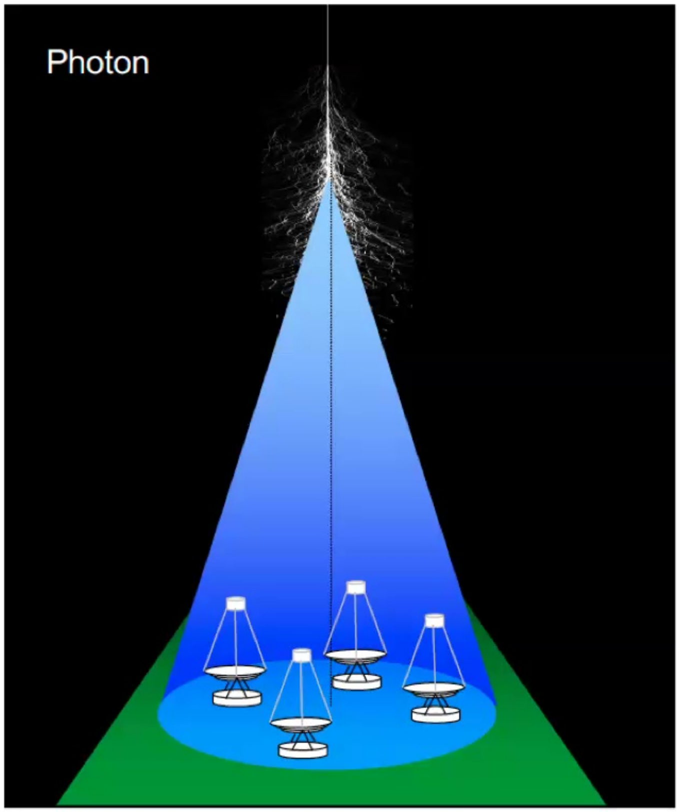


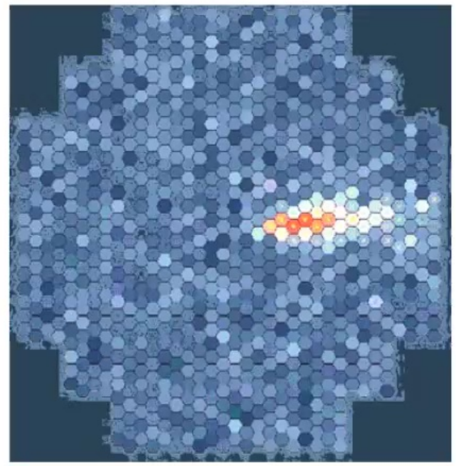
Detection principles…



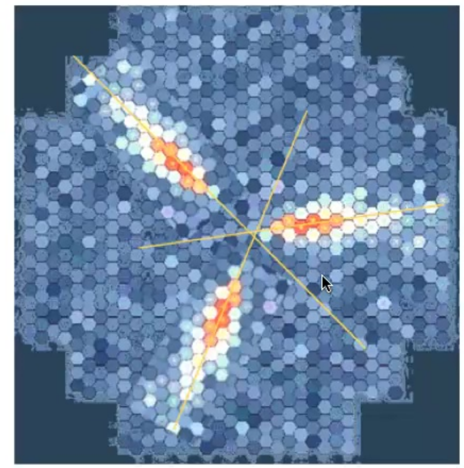


Detection principles…





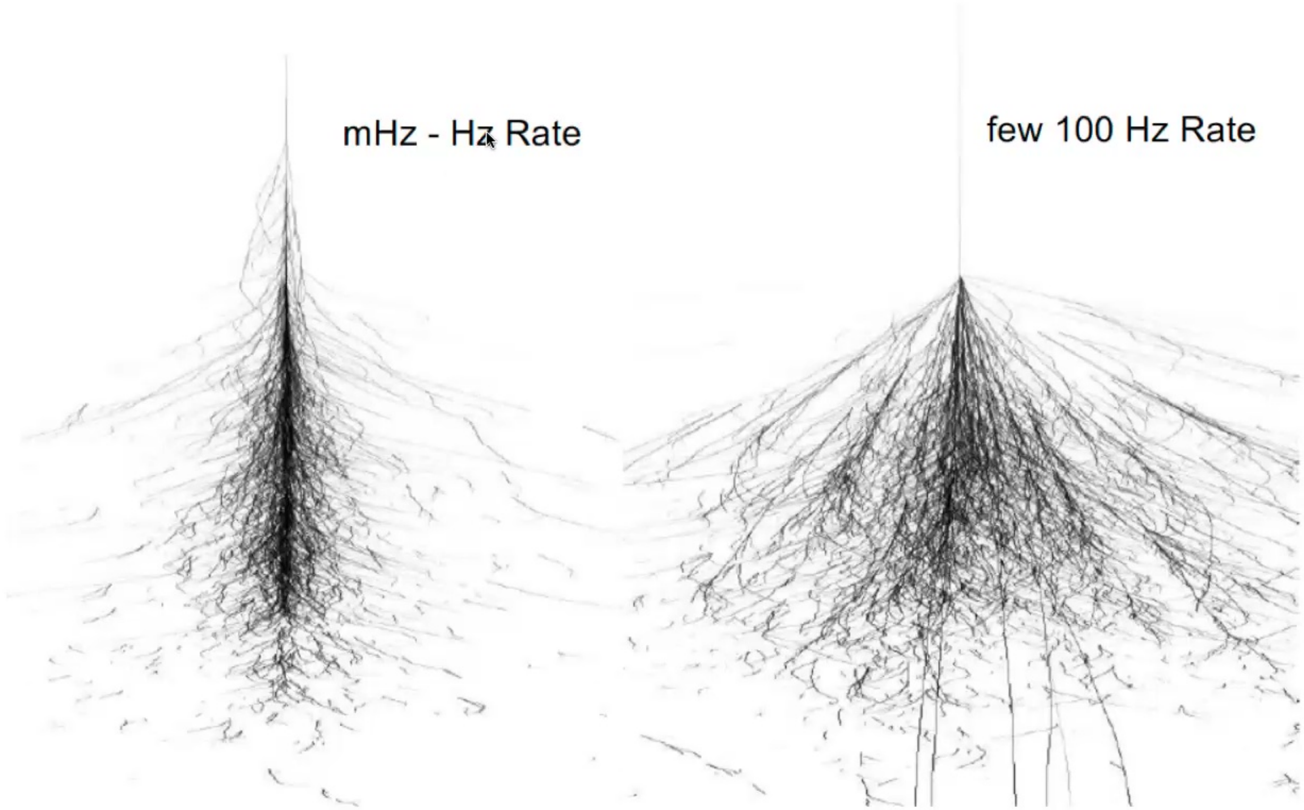
Single telescope event



3 telescope image in common camera plane

Intensity -> Energy
Orientation -> Direction
Shape -> Primary

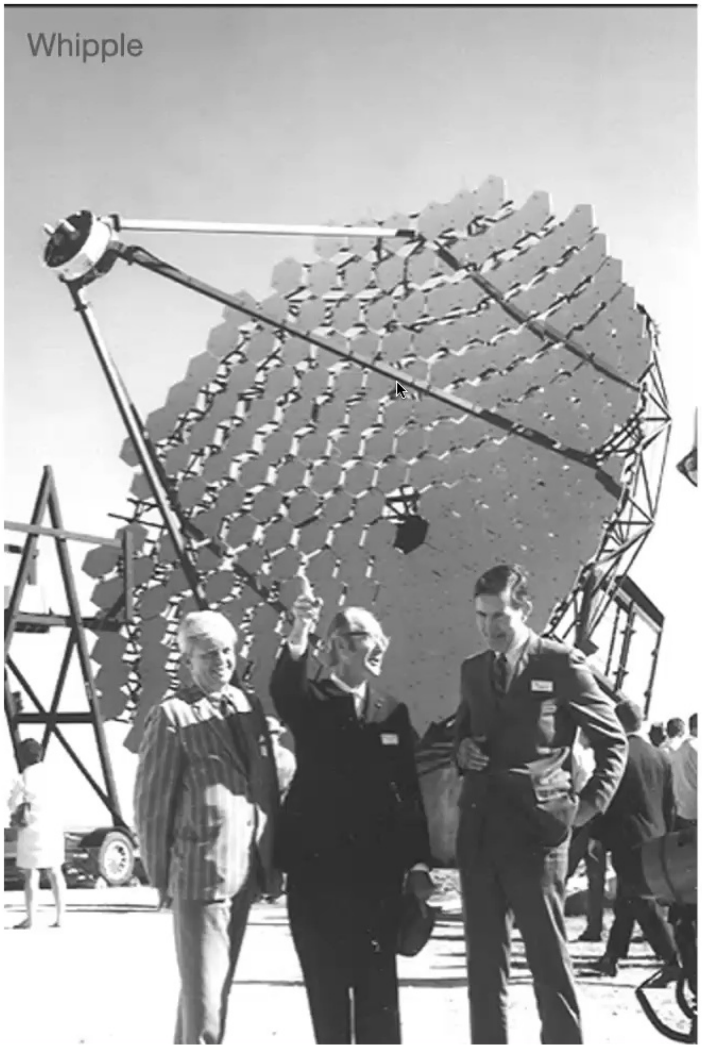
Distinguishing the gamma-ray signal from cosmic ray backgrounds



Gamma shower

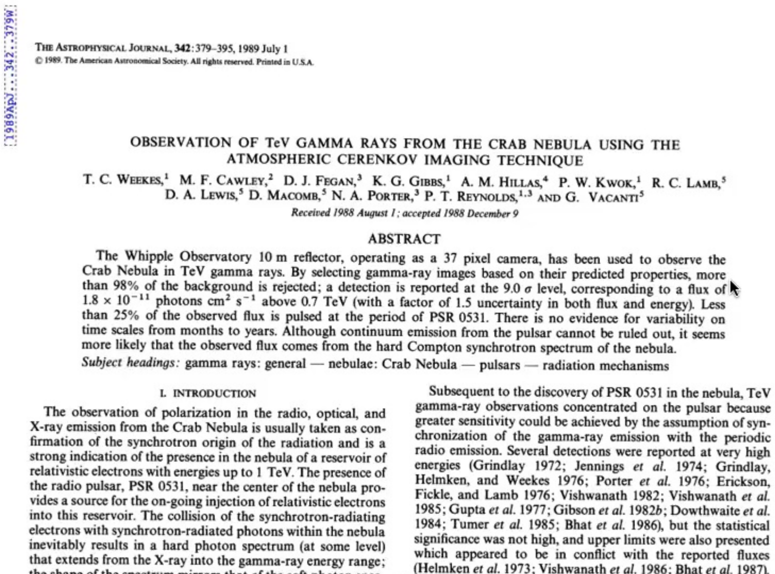
Hadronic shower

First detection of TeV gamma-rays



Crab Nebula (supernova remnant)

First detection of TeV gamma-rays



THE ASTROPHYSICAL JOURNAL, 342:379–395, 1989 July 1

OBSERVATION OF TeV GAMMA RAYS FROM THE CRAB NEBULA USING THE ATMOSPHERIC CERENKOV IMAGING TECHNIQUE

T. C. WEEKES,[1] M. F. CAWLEY,[2] D. J. FEGAN,[3] K. G. GIBBS,[1] A. M. HILLAS,[4] P. W. KWOK,[1] R. C. LAMB,[5] D. A. LEWIS,[5] D. MACOMB,[5] N. A. PORTER,[3] P. T. REYNOLDS,[1,3] AND G. VACANTI[5]

Received 1988 August 1; accepted 1988 December 9

ABSTRACT

The Whipple Observatory 10 m reflector, operating as a 37 pixel camera, has been used to observe the Crab Nebula in TeV gamma rays. By selecting gamma-ray images based on their predicted properties, more than 98% of the background is rejected; a detection is reported at the 9.0 σ level, corresponding to a flux of 1.8×10^{-11} photons cm^2 s^{-1} above 0.7 TeV (with a factor of 1.5 uncertainty in both flux and energy). Less than 25% of the observed flux is pulsed at the period of PSR 0531. There is no evidence for variability on time scales from months to years. Although continuum emission from the pulsar cannot be ruled out, it seems more likely that the observed flux comes from the hard Compton synchrotron spectrum of the nebula.

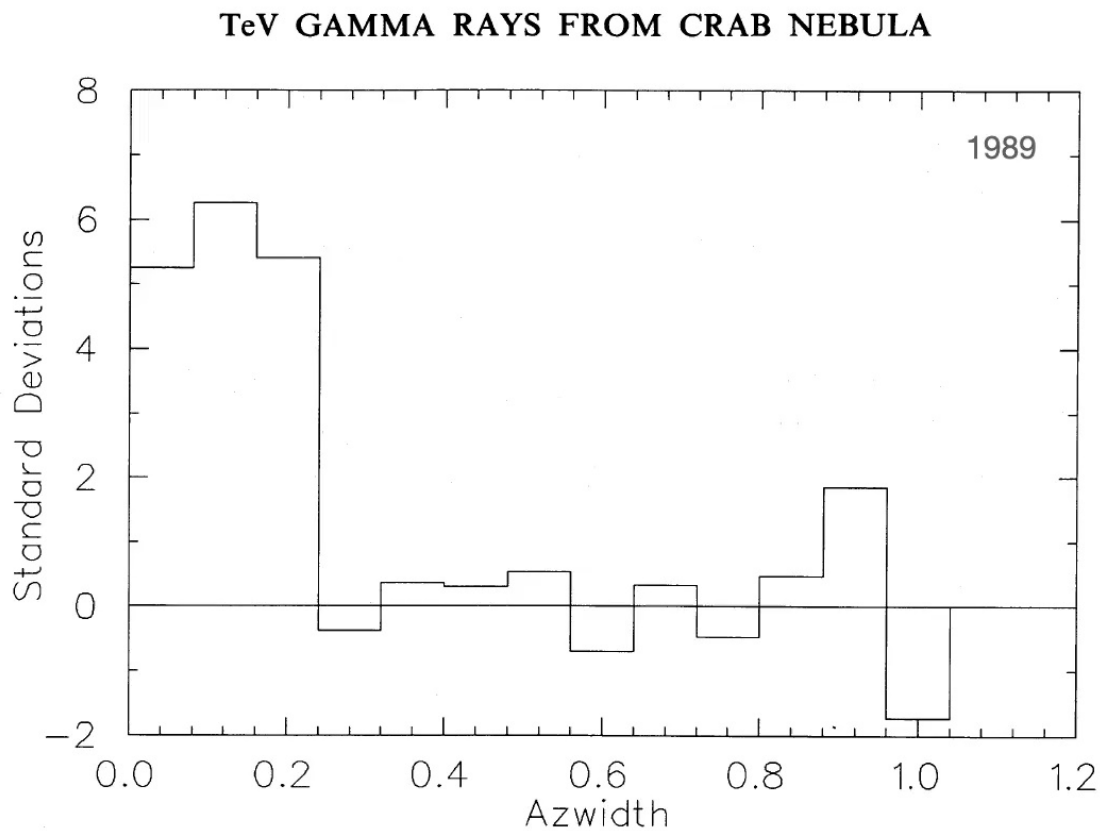
Subject headings: gamma rays: general — nebulae: Crab Nebula — pulsars — radiation mechanisms

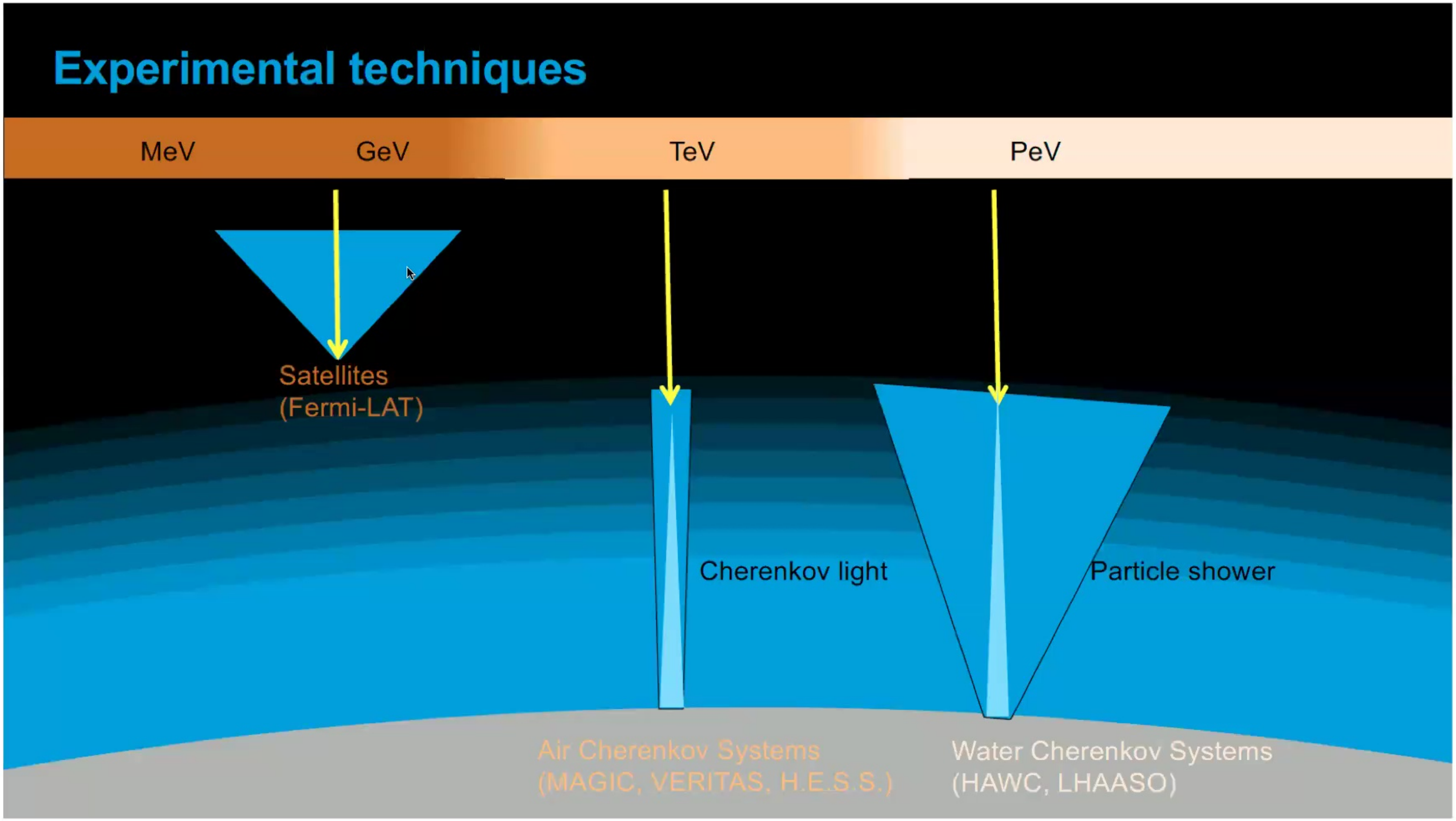
I. INTRODUCTION

The observation of polarization in the radio, optical, and X-ray emission from the Crab Nebula is usually taken as confirmation of the synchrotron origin of the radiation and is a strong indication of the presence in the nebula of a reservoir of relativistic electrons with energies up to 1 TeV. The presence of the radio pulsar, PSR 0531, near the center of the nebula provides a source for the on-going injection of relativistic electrons into this reservoir. The collision of the synchrotron-radiating electrons with synchrotron-radiated photons within the nebula inevitably results in a hard photon spectrum (at some level) that extends from the X-ray into the gamma-ray energy range;

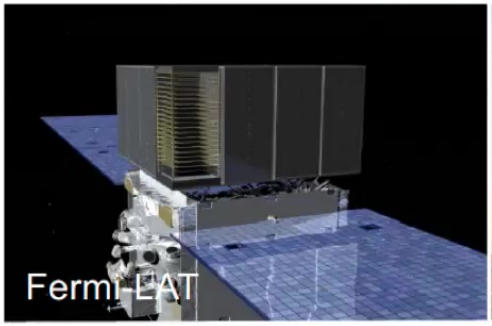
Subsequent to the discovery of PSR 0531 in the nebula, TeV gamma-ray observations concentrated on the pulsar because greater sensitivity could be achieved by the assumption of synchronization of the gamma-ray emission with the periodic radio emission. Several detections were reported at very high energies (Grindlay 1972; Jennings *et al.* 1974; Grindlay, Helmken, and Weekes 1976; Porter *et al.* 1976; Erickson, Fickle, and Lamb 1976; Vishwanath 1982; Vishwanath *et al.* 1985; Gupta *et al.* 1977; Gibson *et al.* 1982*b*; Dowthwaite *et al.* 1984; Tumer *et al.* 1985; Bhat *et al.* 1986), but the statistical significance was not high, and upper limits were also presented which appeared to be in conflict with the reported fluxes (Helmken *et al.* 1973; Vishwanath *et al.* 1986; Bhat *et al.* 1987).

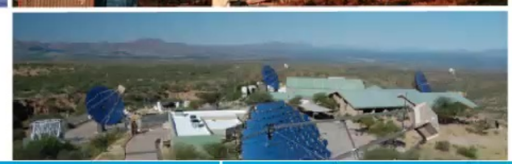
Crab Nebula (supernova remnant)




Experimental techniques
MeV
GeV
TeV
PeV
Satellites
(Fermi-LAT)
Cherenkov light
Particle shower
Air Cherenkov Systems
(MAGIC, VERITAS, H.E.S.S.)
Water Cherenkov Systems
(HAWC, LHAASO)

MeV	GeV	TeV	PeV

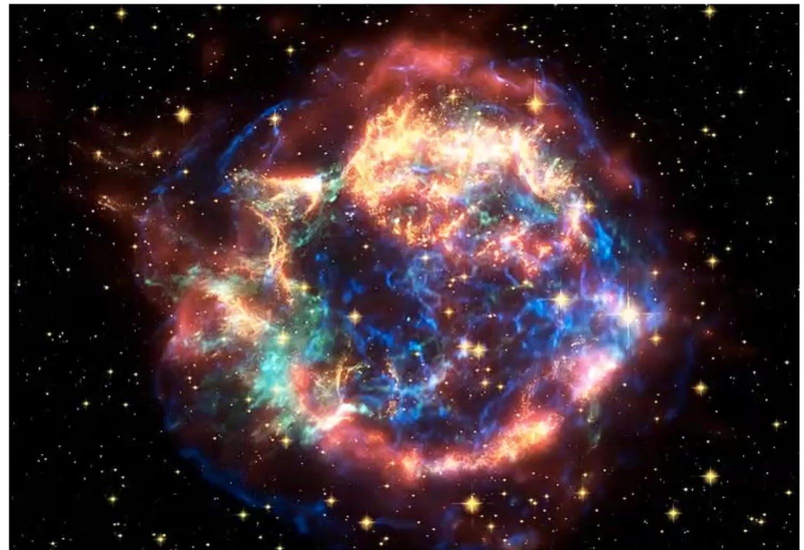


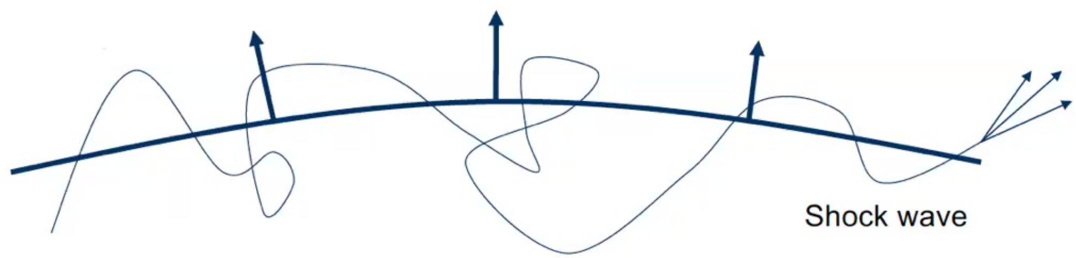


	Fermi LAT	IACTs	HAWC
Effective area	1 m^2	**10^5 m^2**	**10^5 m^2**
Field of view	**20% of the sky**	$3^o – 5^o$	**15% of the sky**
Energy res.	10%	**10%**	100% – 20%
Angular res.	$6^o – 0.3^o$	**0.1^o**	$1^o – 0.2^o$
Duty cycle	**Full year**	1400 h/year	**Full year**

Consider Supernova remnants:

- large energy release ~ O(e39 ergs/s) or ~10E_{CR}
- Acceleration in shock waves (see previous lecture)


O. Krause (Steward Obs.) et al. SSC, JPL, Caltech, NASA



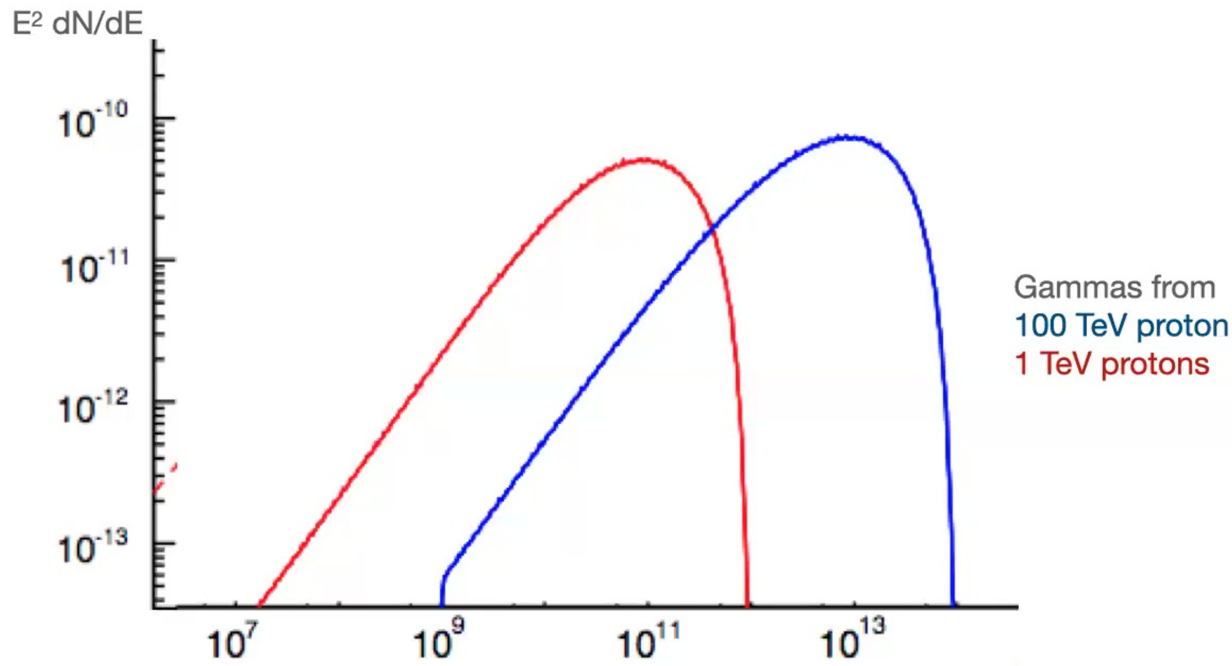
Gamma-ray production… via protons

- The gamma-ray spectrum follows the proton spectrum (roughly 1:10) with features smeared over approximately 1 decade in energy and appearing about a decade lower in energy

- A power law proton spectrum gives a power law gamma spectrum with the same index (+/- 0.2)

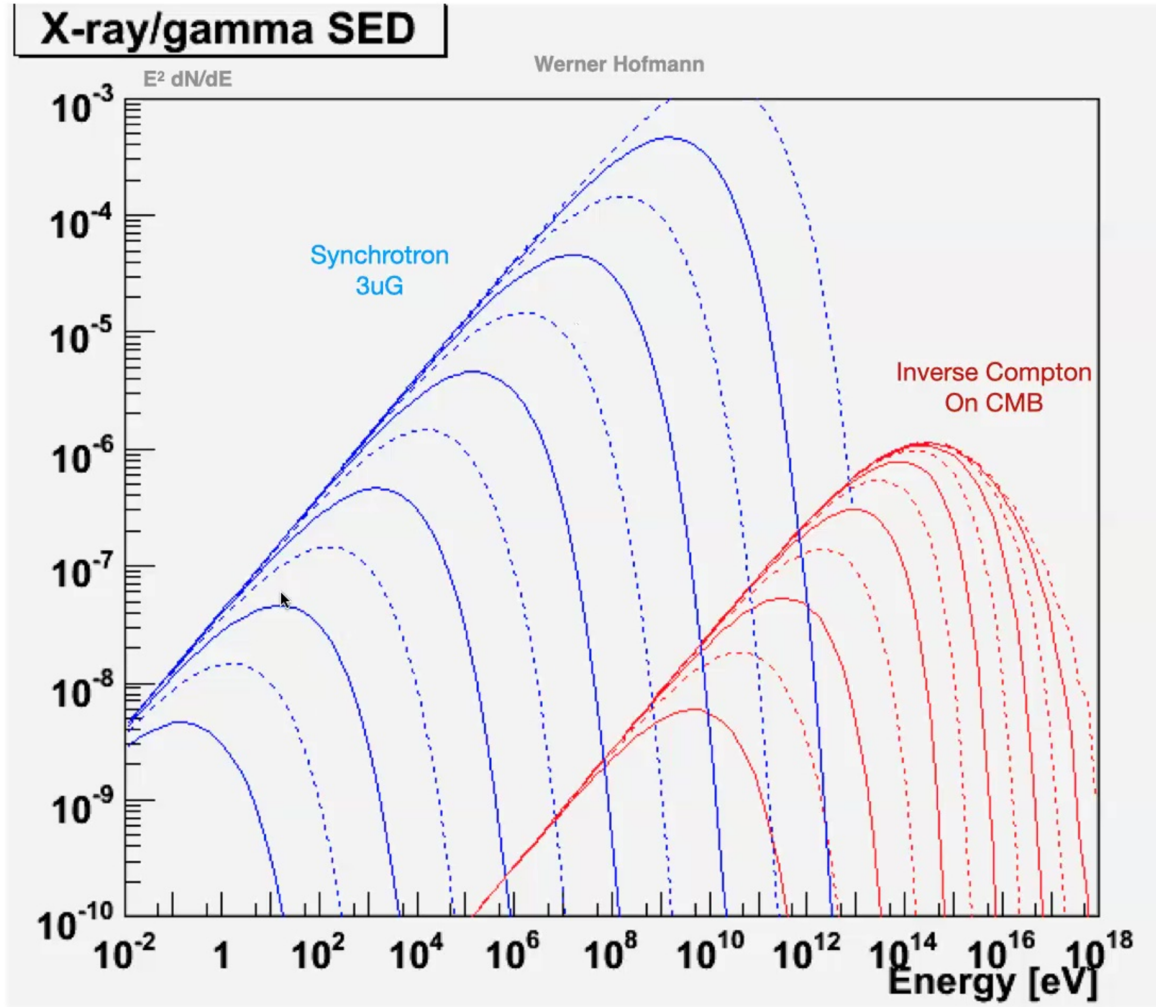
- The gamma-ray SED = proton SED x cross-section, convolved with p->gamma SED

Reference Kelner & Aharonian (arXiv:0803.0688)



Bremsstrahlung, Synchrotron Radiation, and Compton Scattering of High-Energy Electrons Traversing Dilute Gases

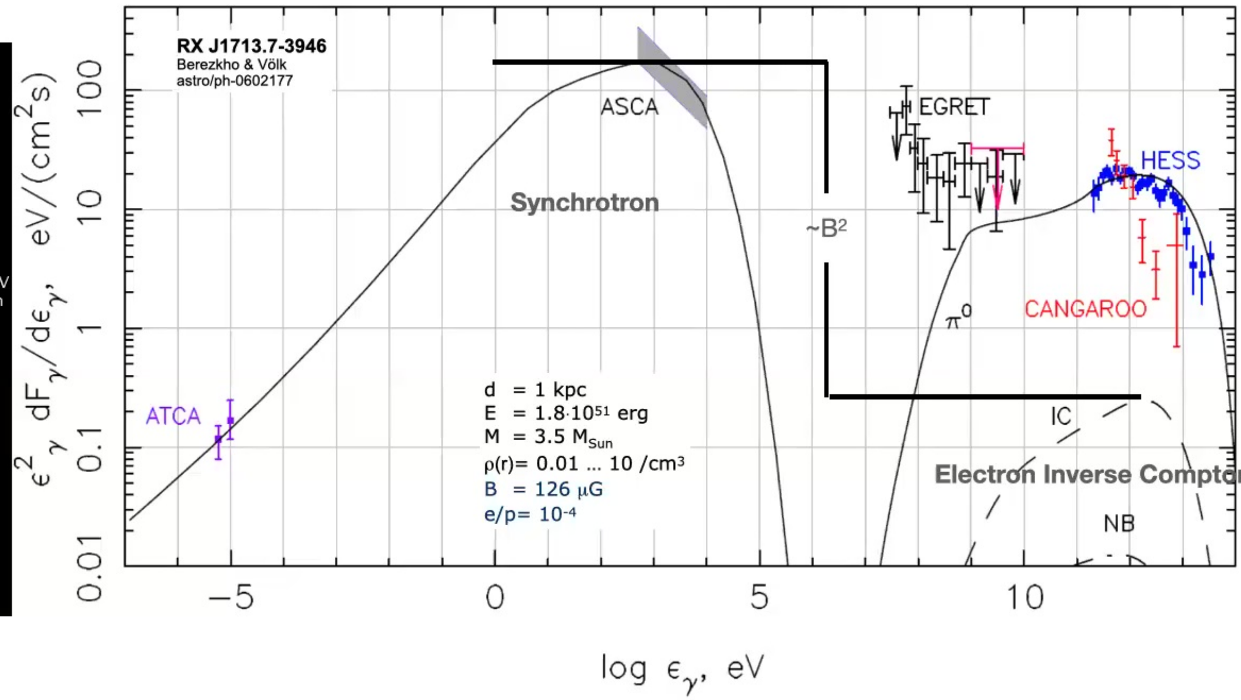
Blumenthal & Gould, Reviews of Modern Physics, vol. 42, pp. 237-271



Electron spectrum with index 2 and a varied cutoff energy

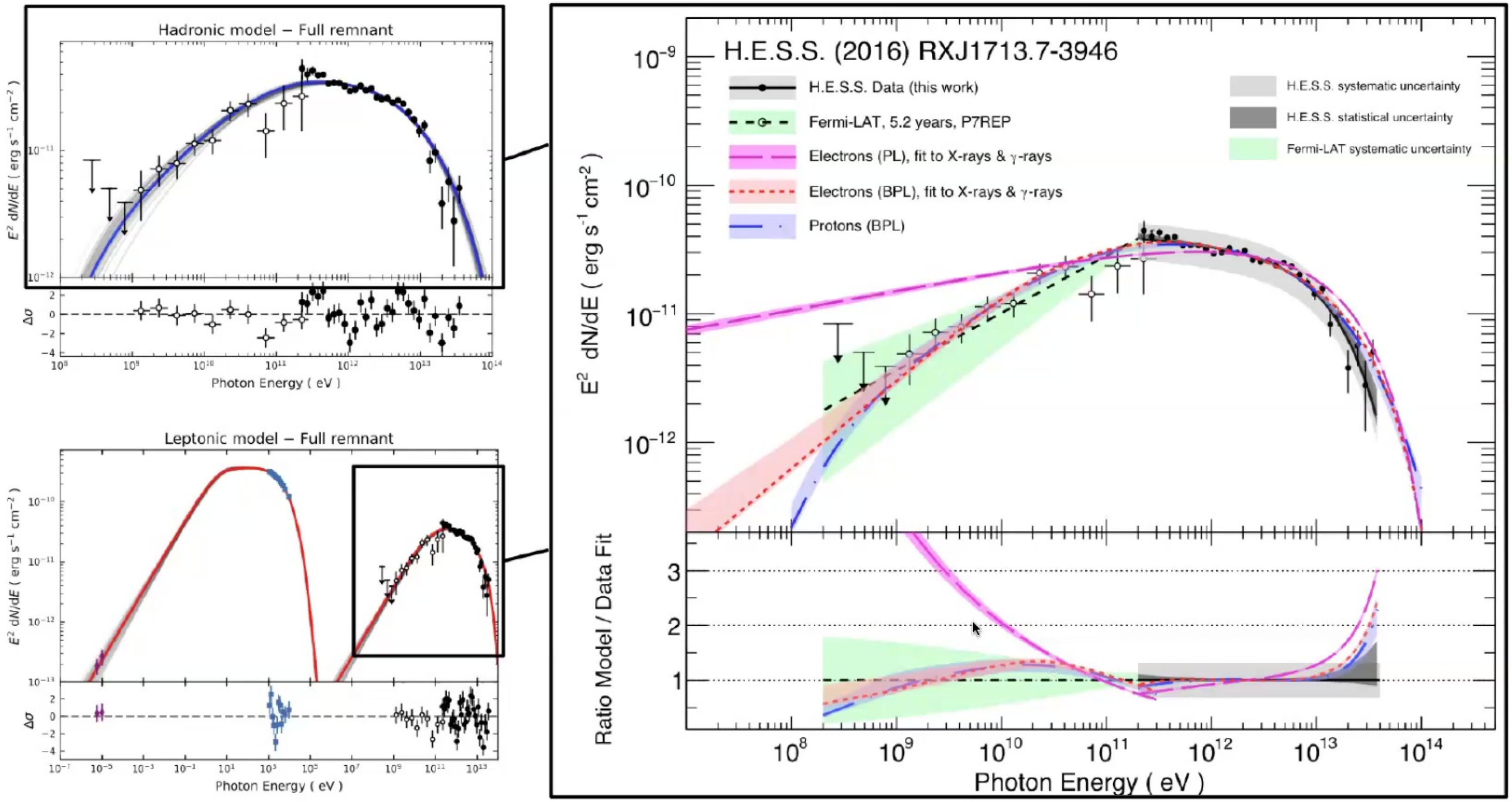
In this example the electron spectrum is flat

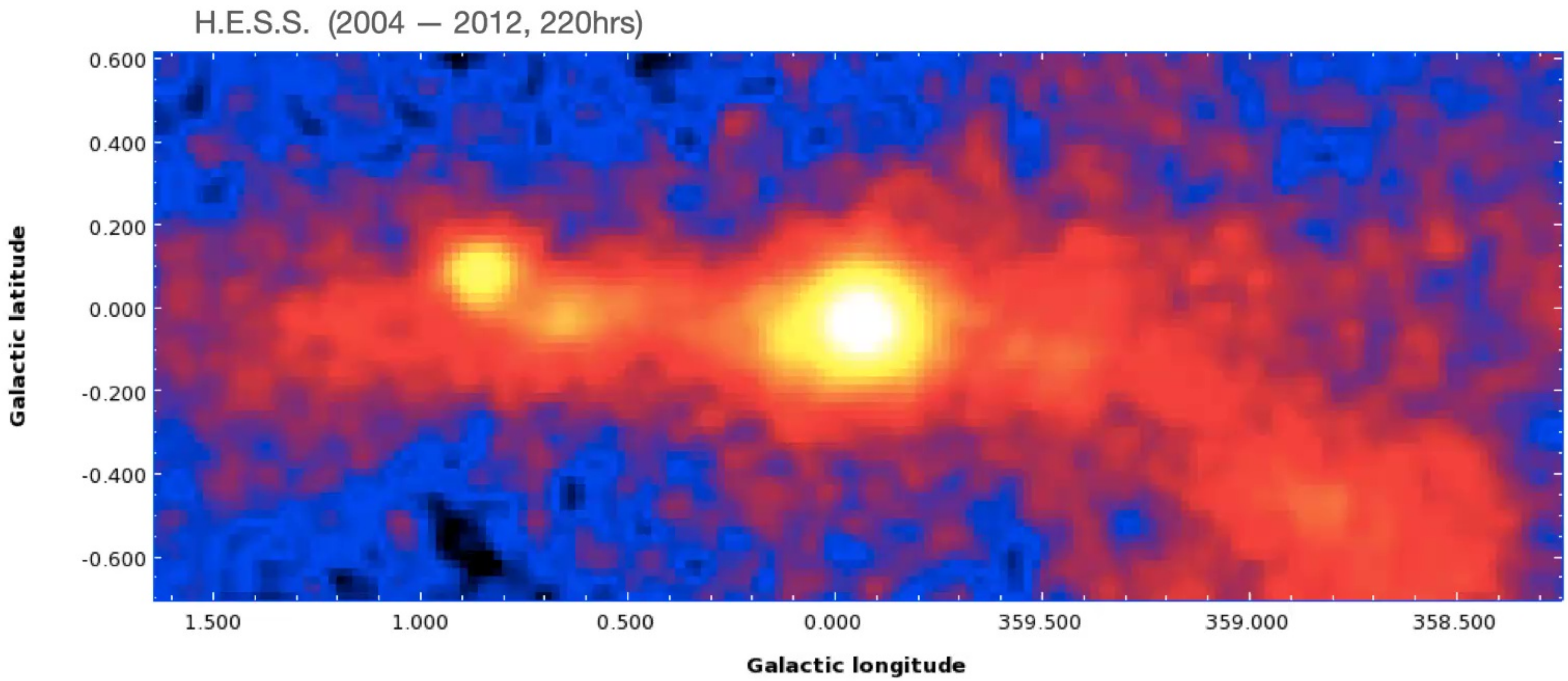
Spectra and radiation cooling

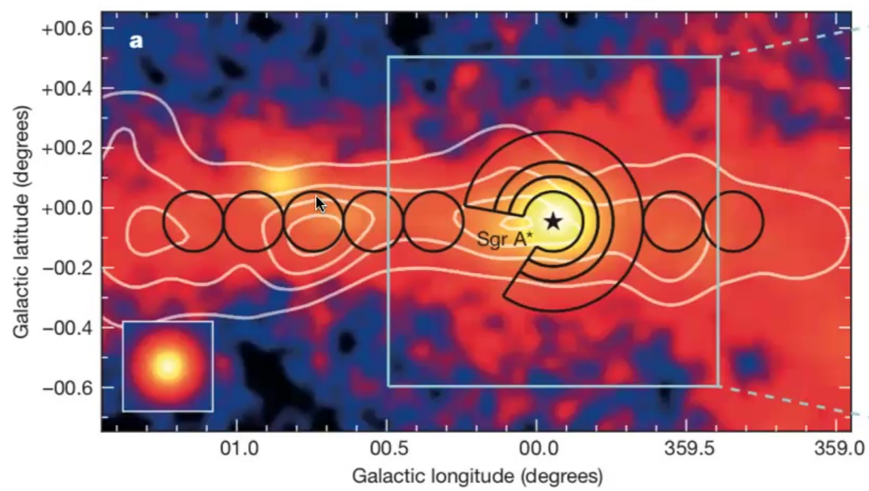


https://www.astro.umd.edu/~richard/ASTR480/Beckmann_Longair_Radiation3.pdf

Leptonic vs hadronic models



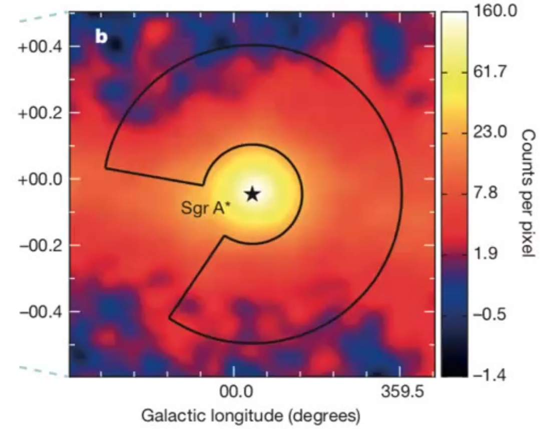

H.E.S.S. (2004 — 2012, 220hrs)
0.600
0.400
0.200
0.000
-0.200
-0.400
-0.600
Galactic latitude
1.500
1.000
0.500
0.000
359.500
359.000
358.500
Galactic longitude

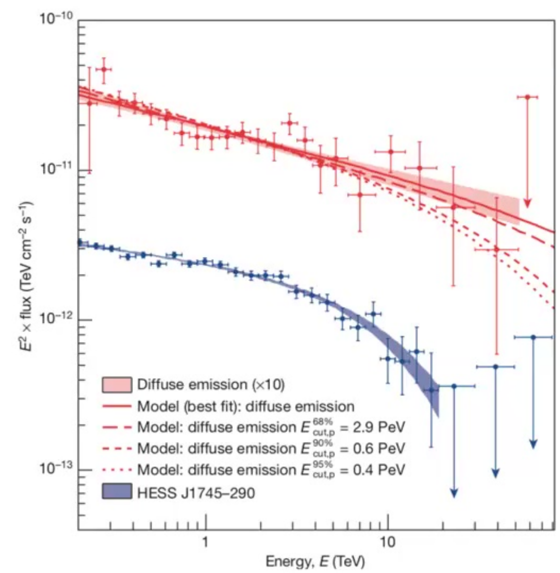


- Correlation with molecular clouds
  → pp interaction target mass (M)
- Gamma-ray luminosity ($\mathscr{L}$) in several regions
  → CR density ~$\mathscr{L}/M$
- CR radial distribution
  - Homogeneous → impulsive injection of CRs and diffusive propagation
  - $1/r^2$→ Wind-driven propagation
  - $1/r$ → continuous injection and diffusive propagation
- Central accelerator located within 10 pc and injecting CRs continuously for > 1kyrs

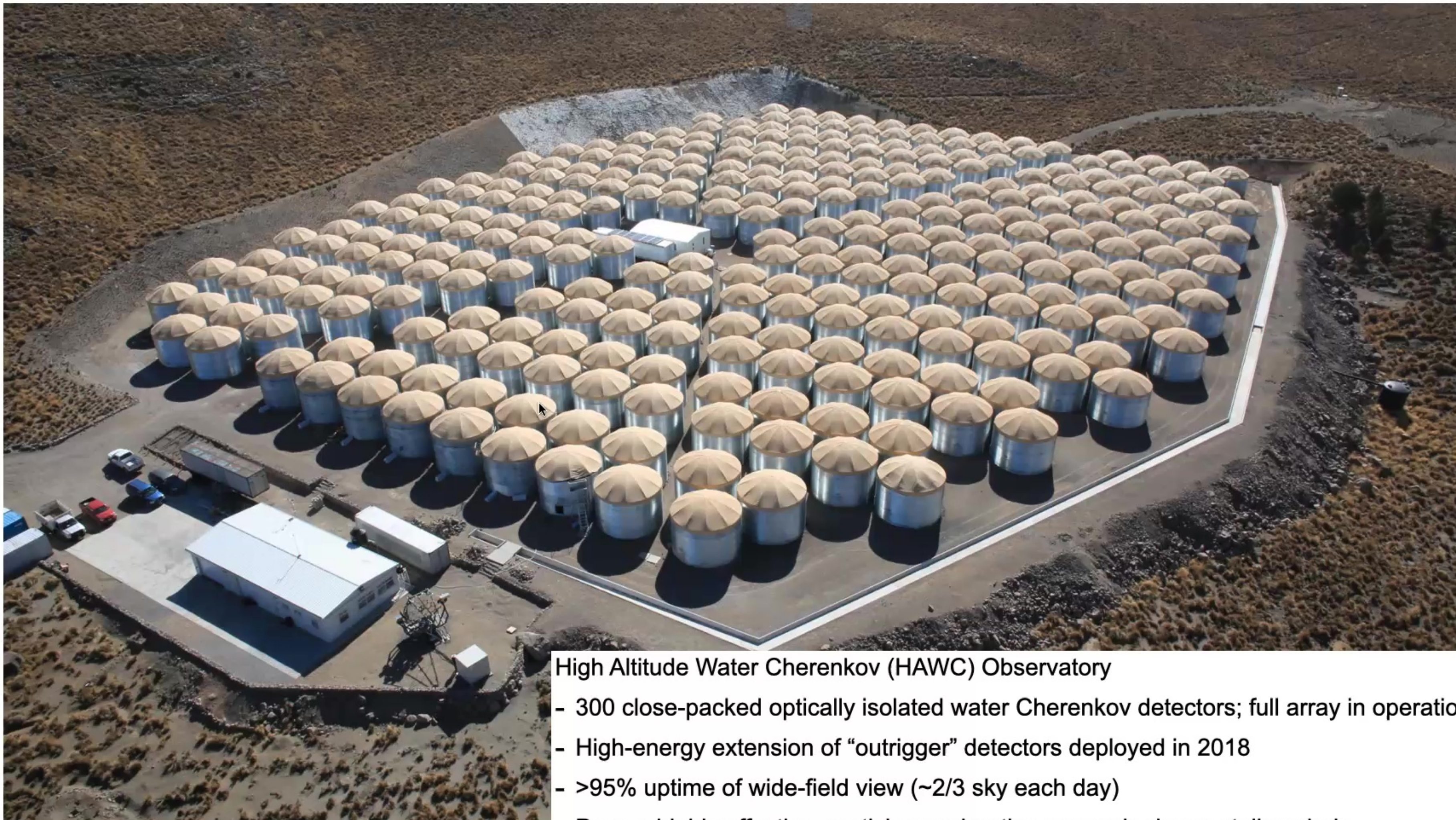
- Diffuse gamma-ray spectrum
  - $E^{-2.3}$ up to 50 TeV w/o cutoff
- Assume central source of protons
  - fit resulting gamma-ray spectrum to HESS data
- Proton injection spectrum:
  - $E^{-2.2}$ power law from GeV to few PeV
  - Cut-off
    0.6 PeV at 90% CL
    2.9 PeV at 68% CL

- **A cosmic PeVatron!**
  Nature 531 (2016) 476



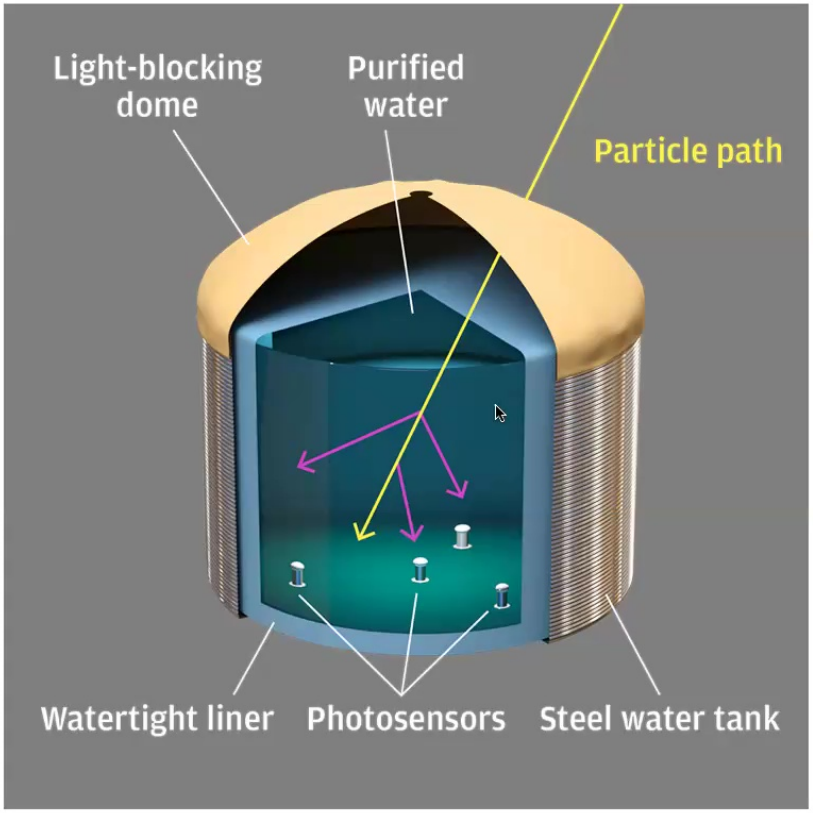


Detection of VHE gamma-rays



High Altitude Water Cherenkov (HAWC) Observatory

- 300 close-packed optically isolated water Cherenkov detectors; full array in operation since 2015
- High-energy extension of “outrigger” detectors deployed in 2018
- >95% uptime of wide-field view (~2/3 sky each day)
- Proves highly effective particle acceleration occurs in dense stellar winds



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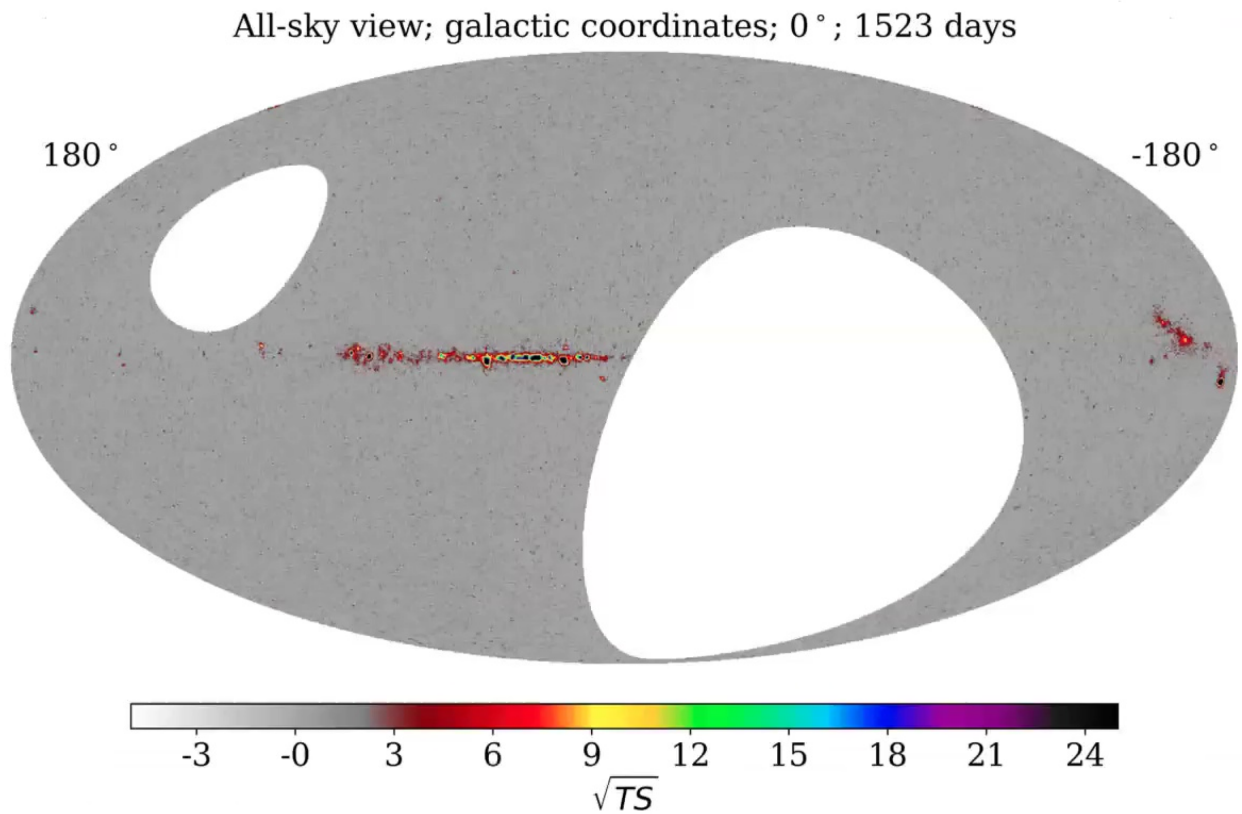
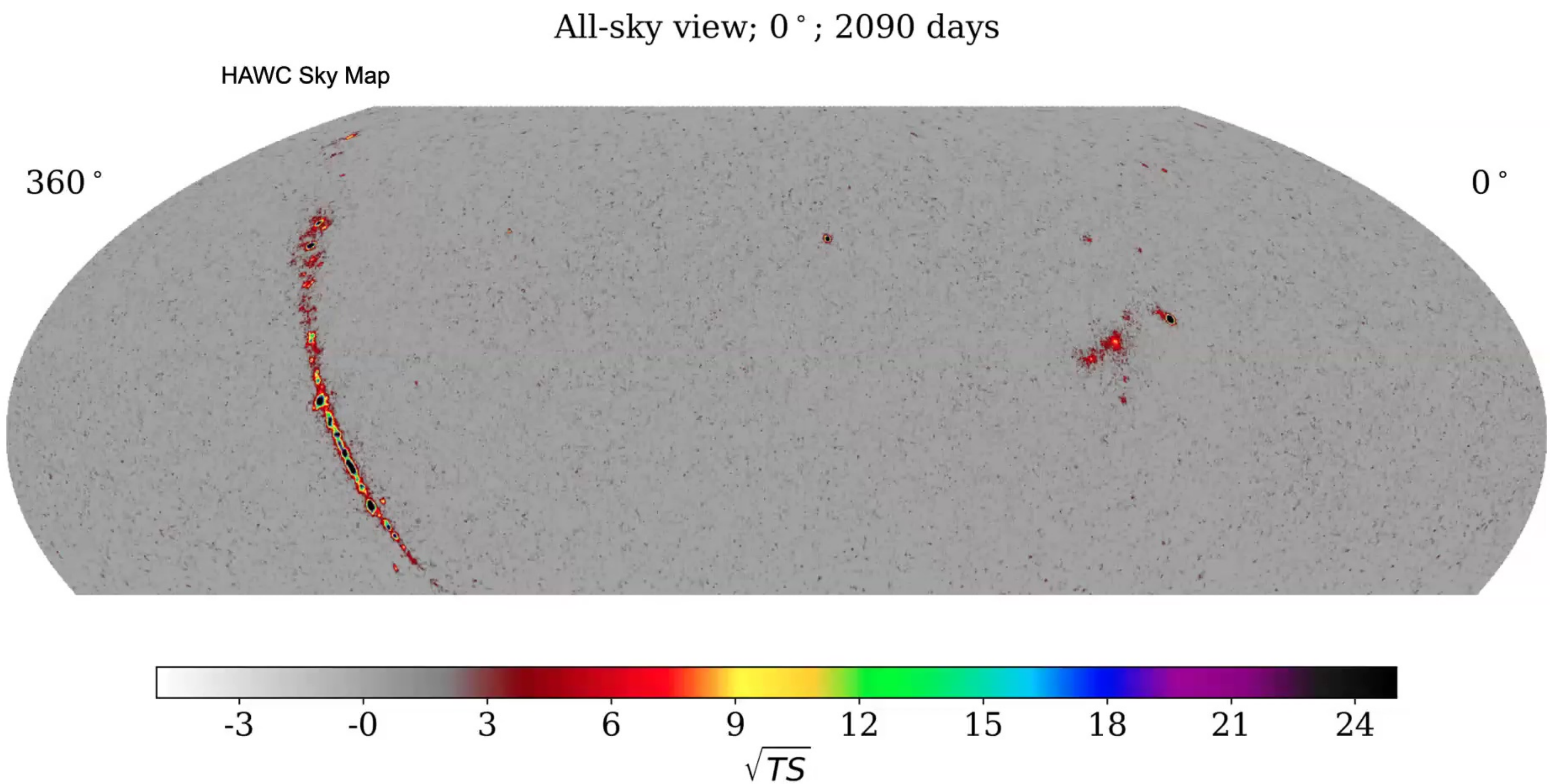
Jordan Goodman, Erice

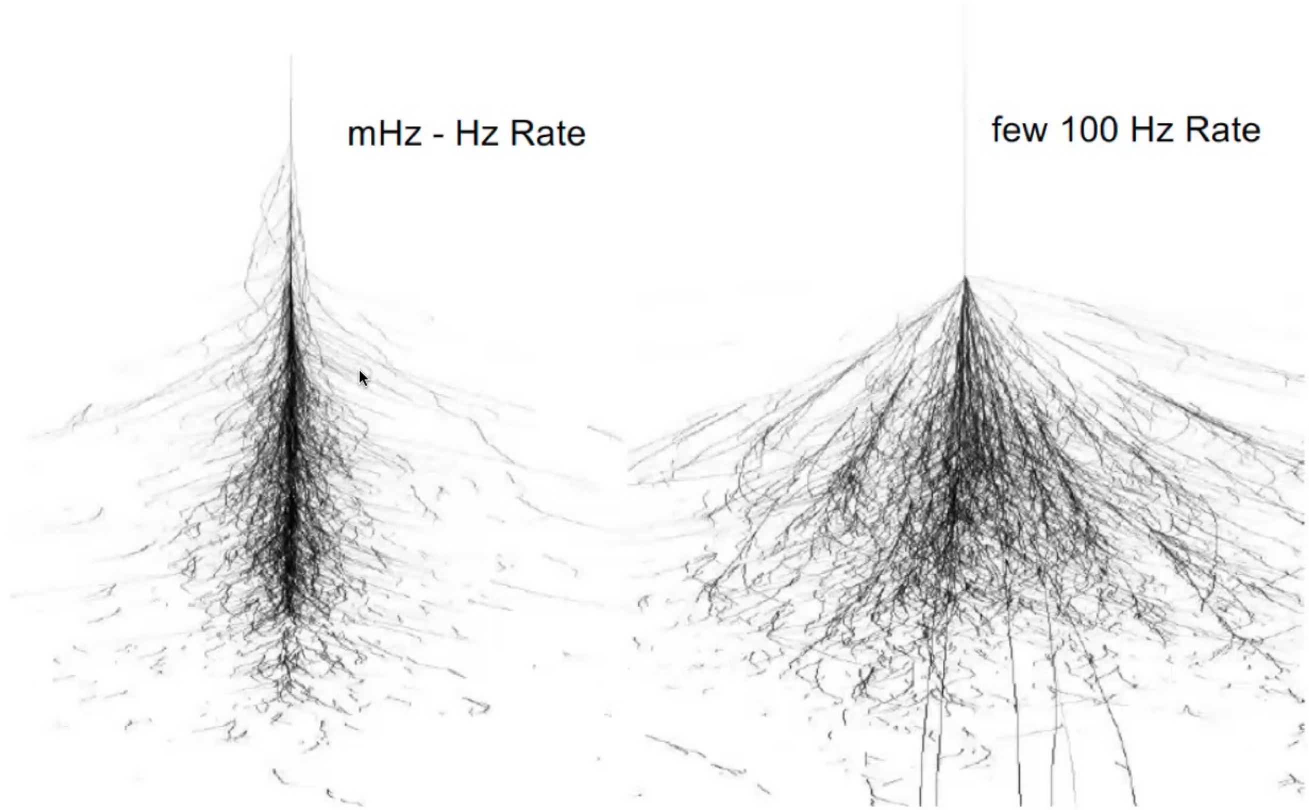
HAWC Sky Map




All-sky view; 0 °; 2090 days
HAWC Sky Map
360 °
0 °
-3
-0
3
6
9
12
15
18
21
24
√TS

Detection principles…

Distinguishing the gamma-ray signal from cosmic ray backgrounds



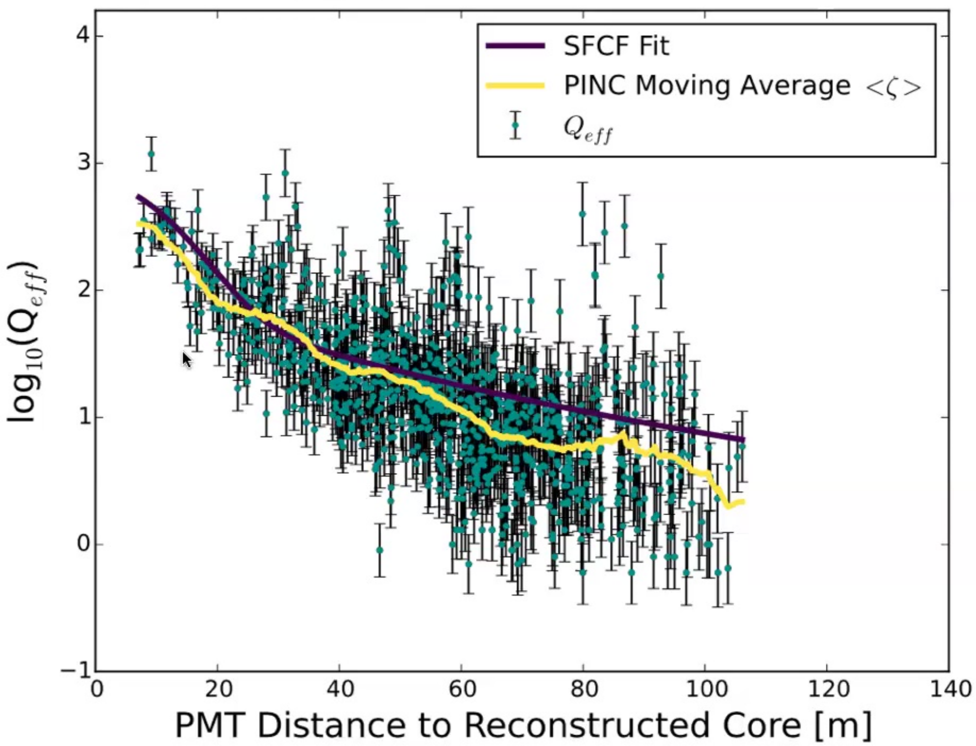
Gamma shower

Hadronic shower

HAWC event reconstruction

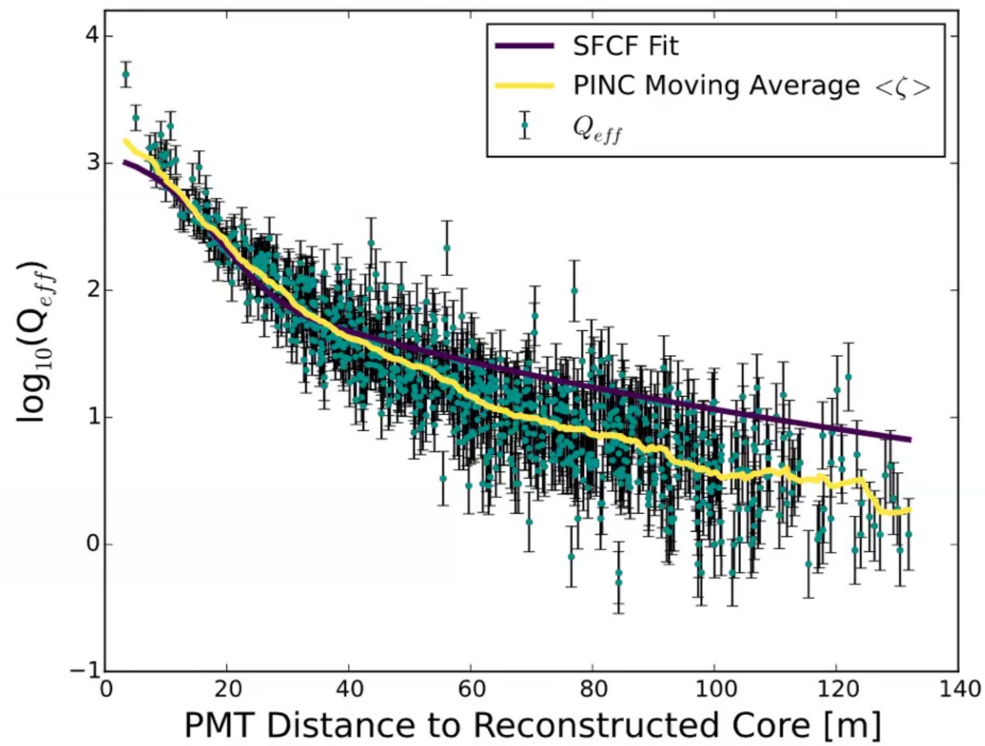
- measurement of time and light level in each PMT
- Reconstruct direction, location, energy and background rejection

Hadron-like (clumpy)



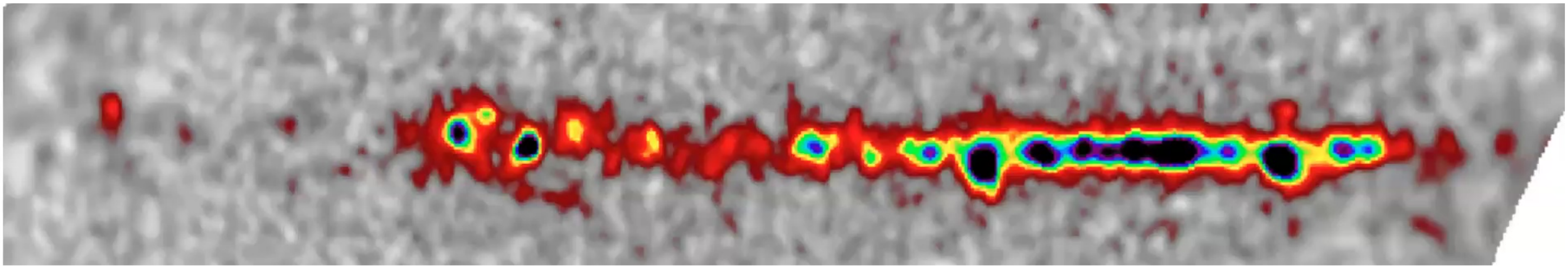
Gamma-like (smooth)

ApJ 843 (2017), 39.

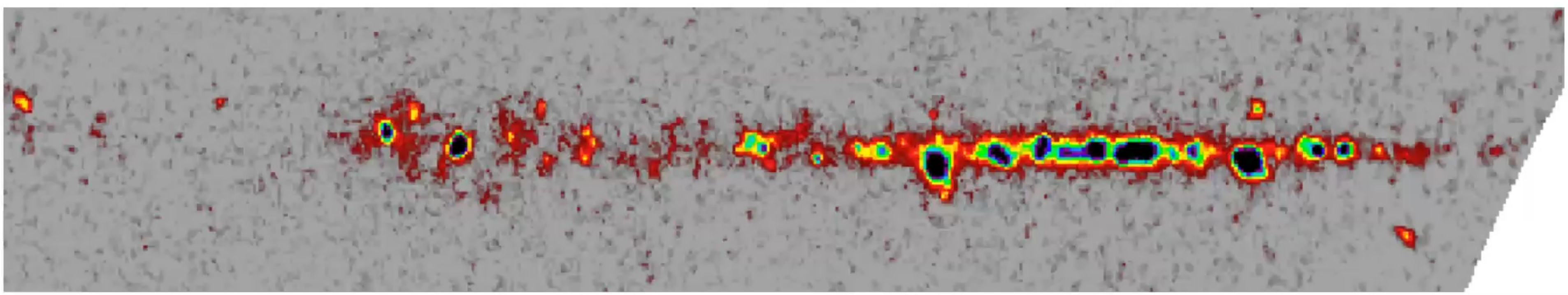


Detection of VHE gamma-rays

HAWC Pass 4 (1523d)



HAWC Pass 5 (2090d; improved reconstructions)

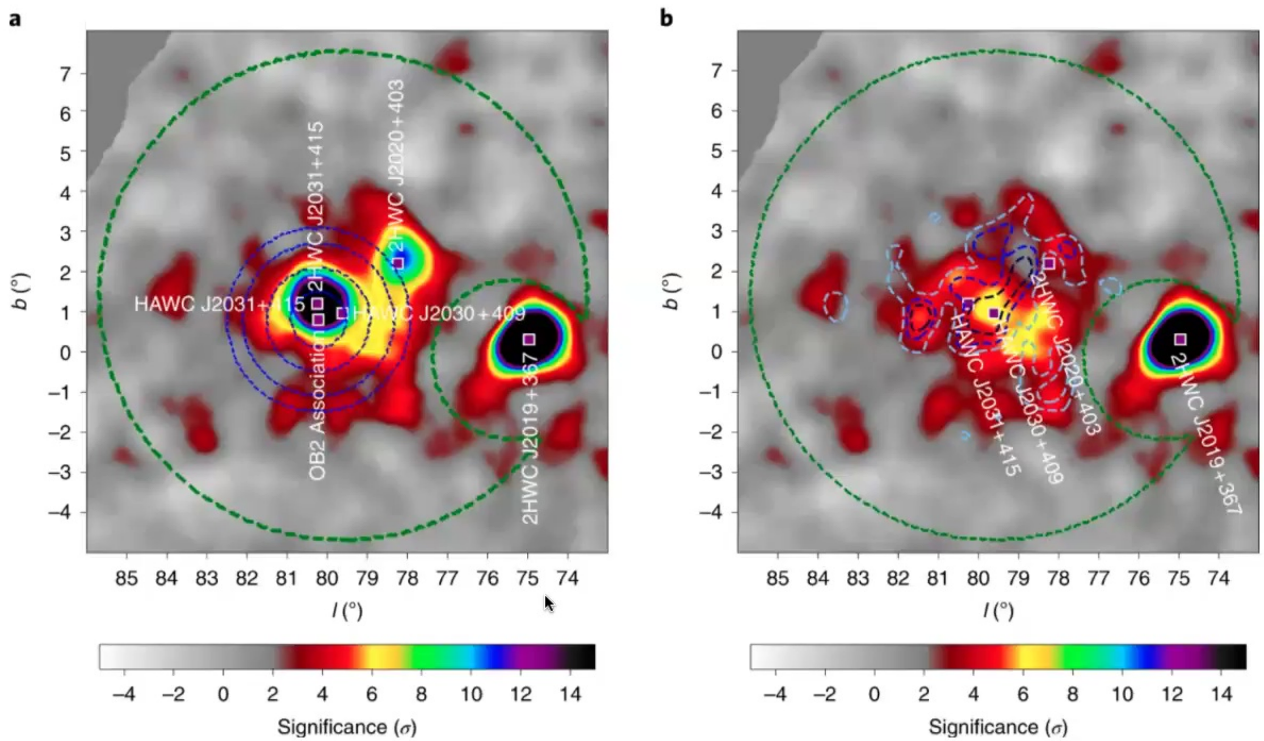


Sources of PeV cosmic rays?

- Supernova remnants do not show evidence of particle acceleration beyond 100s TeV; can Star forming regions?
  - Candidate in Cygnus region :The Cocoon”
  - Home to some of the most massive and luminous stars known
  - Hidden behind a massive dust cloud (Cygnus Rift)
  - Two massive stars orbiting tightly cause stellar winds to collide producing X-rays
  - These can influence star formation and possibly accelerate particles.
  - Observed 100 TeV gamma-rays coming from the super-bubble region of the star formation. These are likely produced by PeV accelerated cosmic rays that originate in the enclosed region.
  - Measured flux likely originates from hadronic interactions.

Fig. 1: Significance map of the Cocoon region before and after subtraction of the known sources at the region.

From: HAWC observations of the acceleration of very-high-energy cosmic rays in the Cygnus Cocoon



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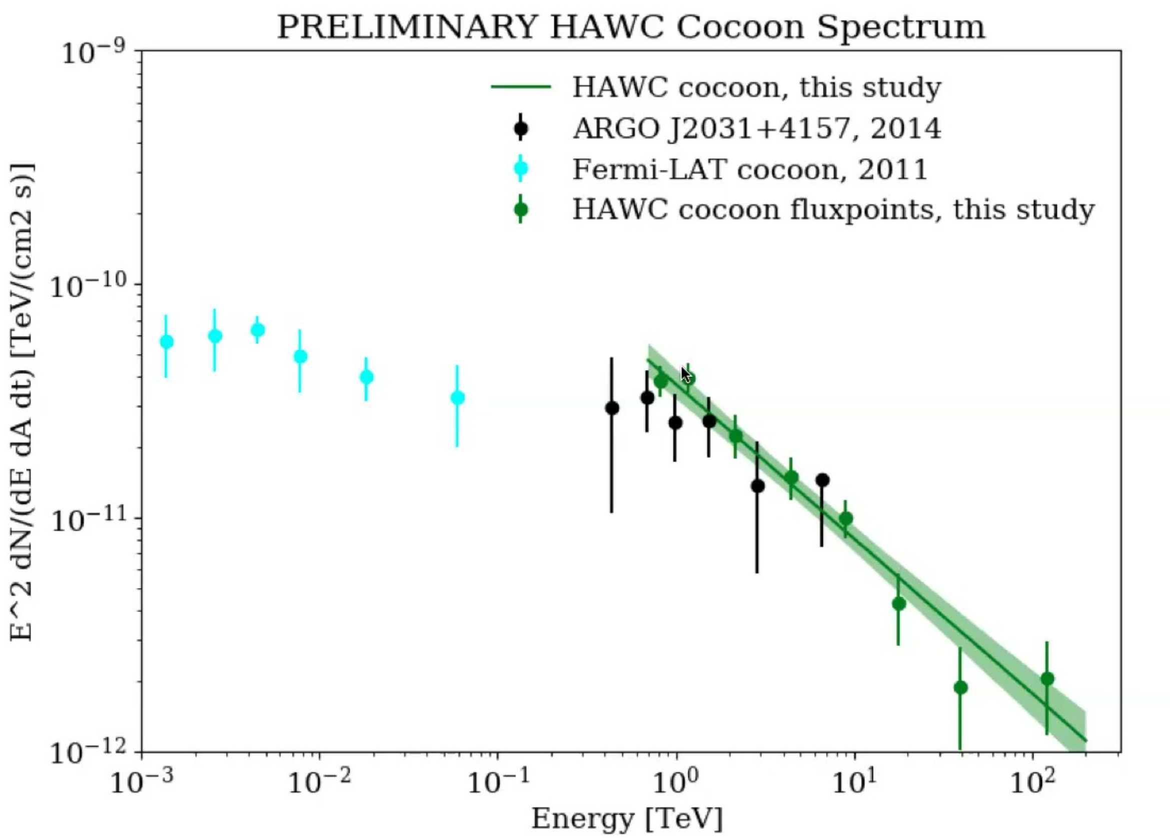

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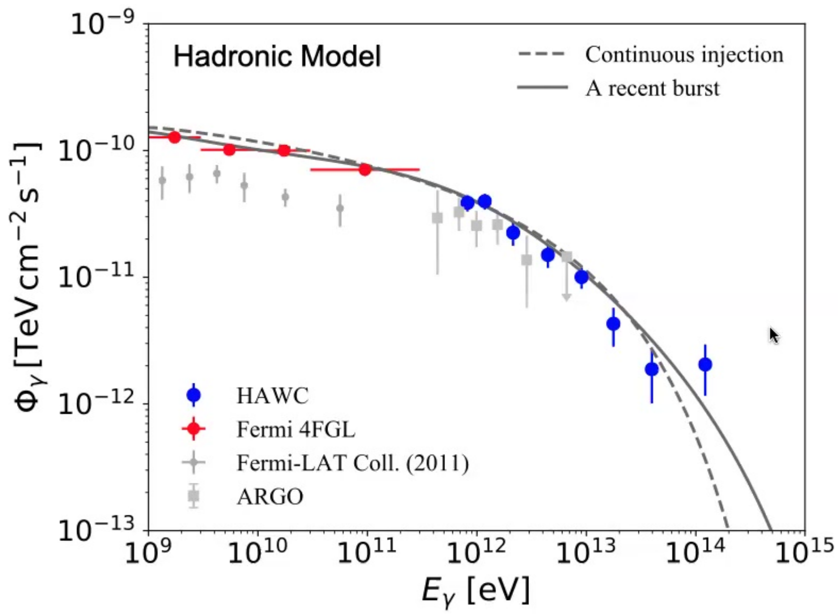
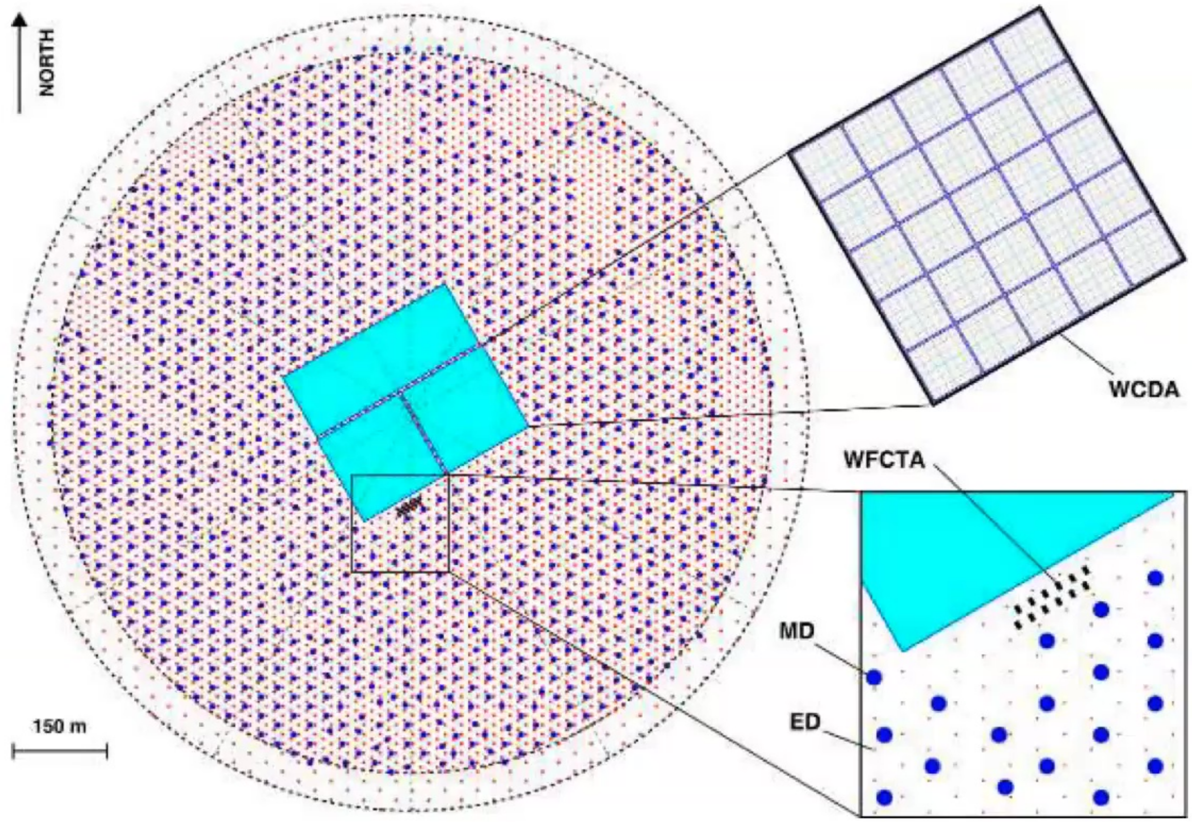


The Large High Altitude Air Shower Observatory (LHAASO)

The Large High Altitude Air Shower Observatory (LHAASO)

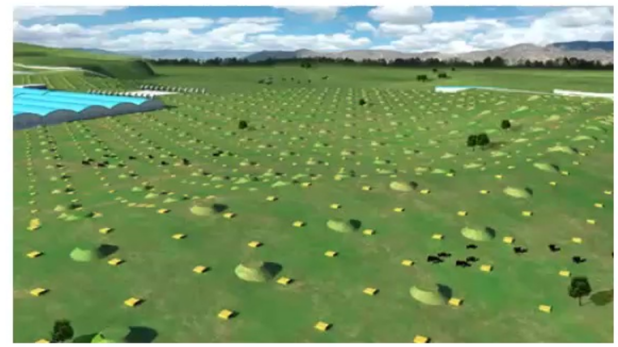
- 5242 Electron Detectors (ED)s
  - 1 m^2 each
  - 15 m spacing
- 1188 Muon Detectors (MD)s
  - 36 m^2 each
  - 30 m spacing
- 3120 Water Cherenkov Det. WCDs
  - 25 m^2 each
- 18 Wide Field Cherenkov Telescopes WFCTs



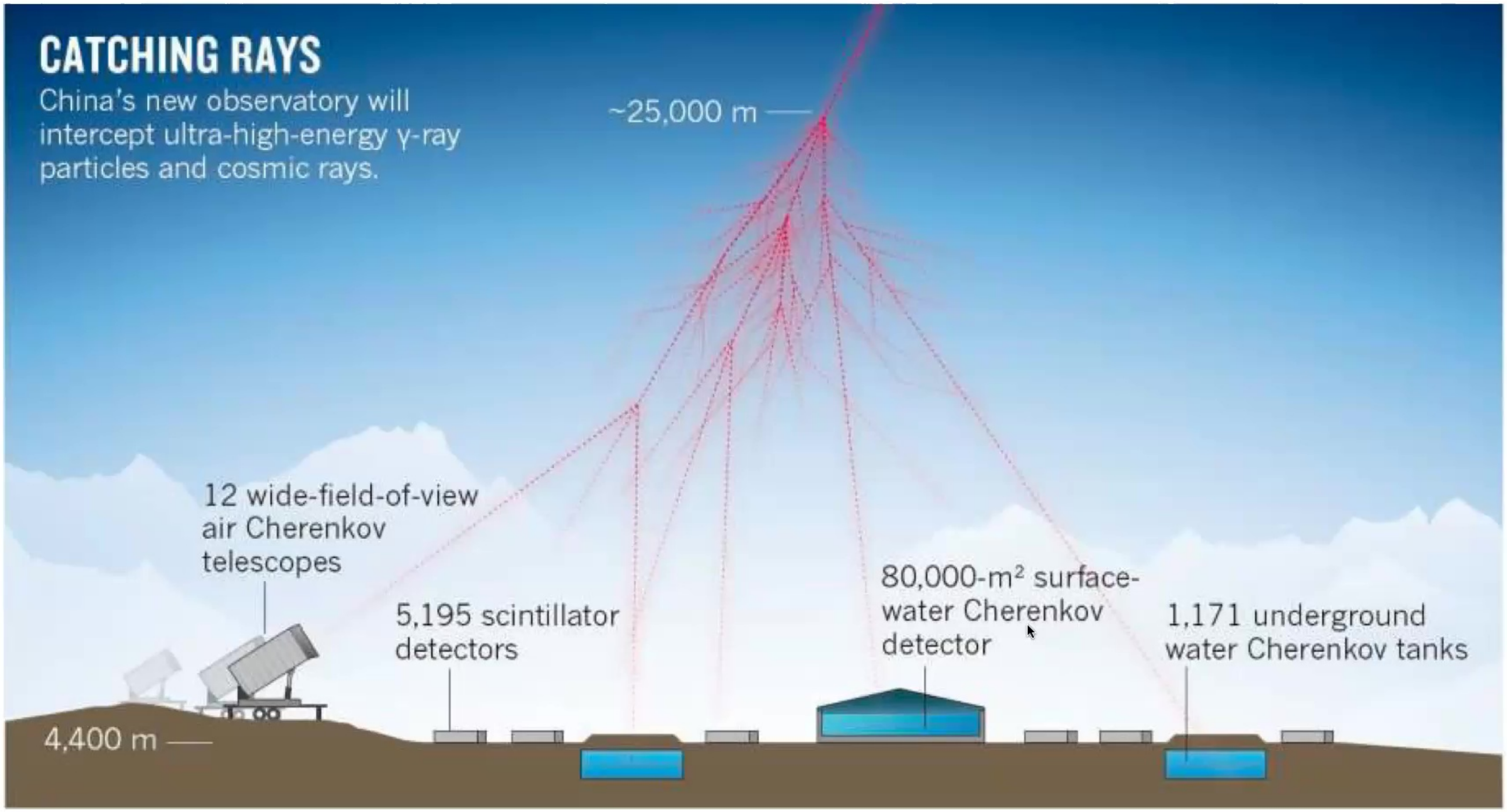
Detection of UHE gamma-rays

The Large High Altitude Air Shower Observatory (LHAASO)

- TeV gamma-ray survey → WCDA (100 GeV-30 TeV)
  - AGN, GRB, survey new source, …
- >20 TeV gamma-ray survey →KM2A (10TeV-1PeV)
  - SNR, PWN, Superbubble, diffuse around 100TeV, …
- Individual nuclei spectra →WFCTA (10TeV to EeV)
  - Different configures
  - Combined with WCDA, WCDA++, KM2A
- Benefit regions:
  - Anisotropy, Solar physics, dark matter, EBL, IGMF, Lorentz invariance, hadronic interaction, …

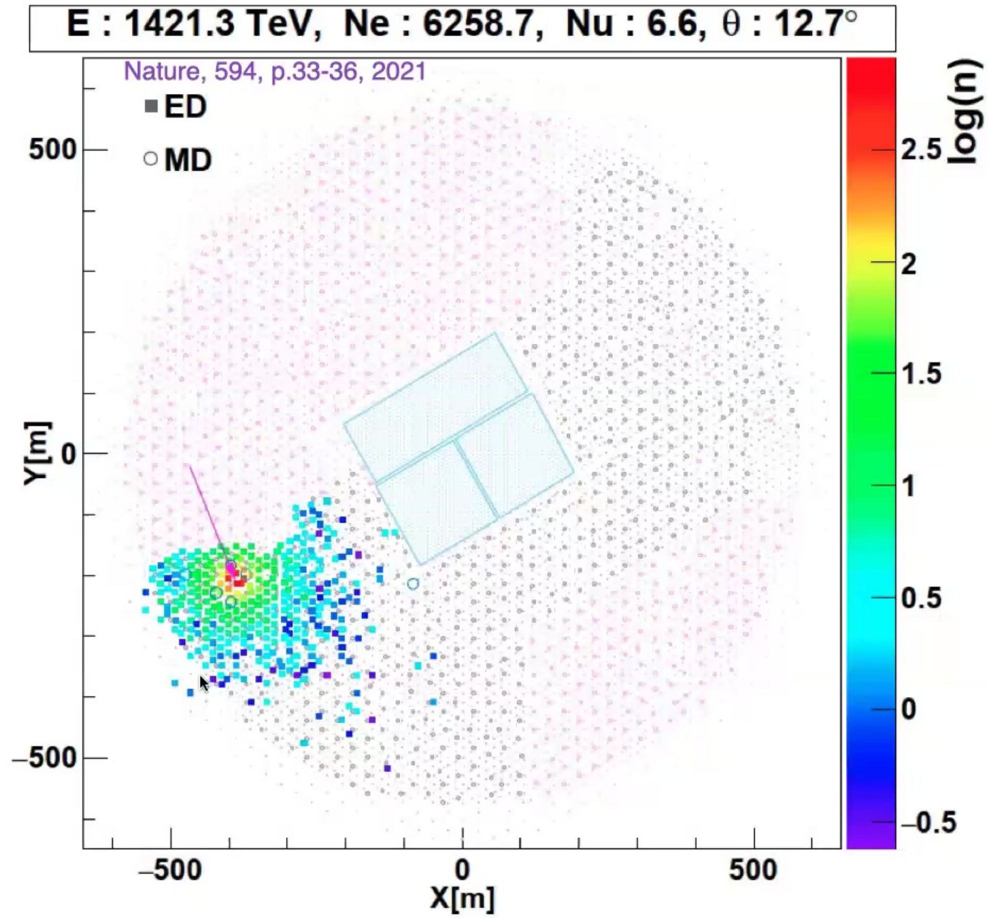


The Large High Altitude Air Shower Observatory (LHAASO)



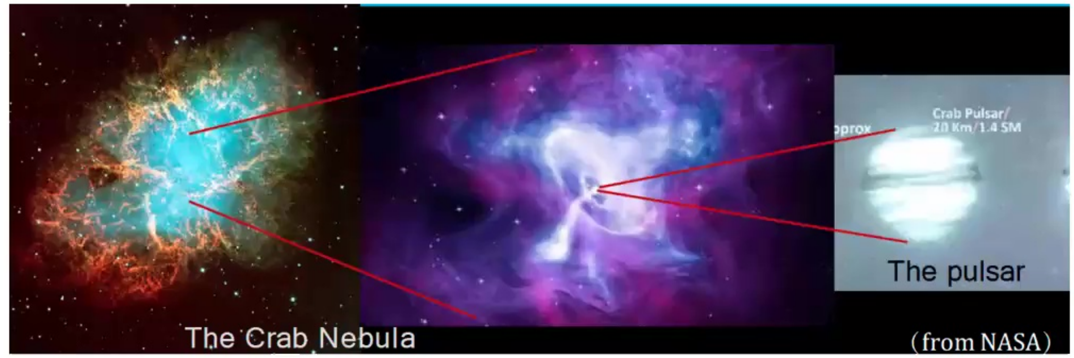
The Large High Altitude Air Shower Observatory (LHAASO)

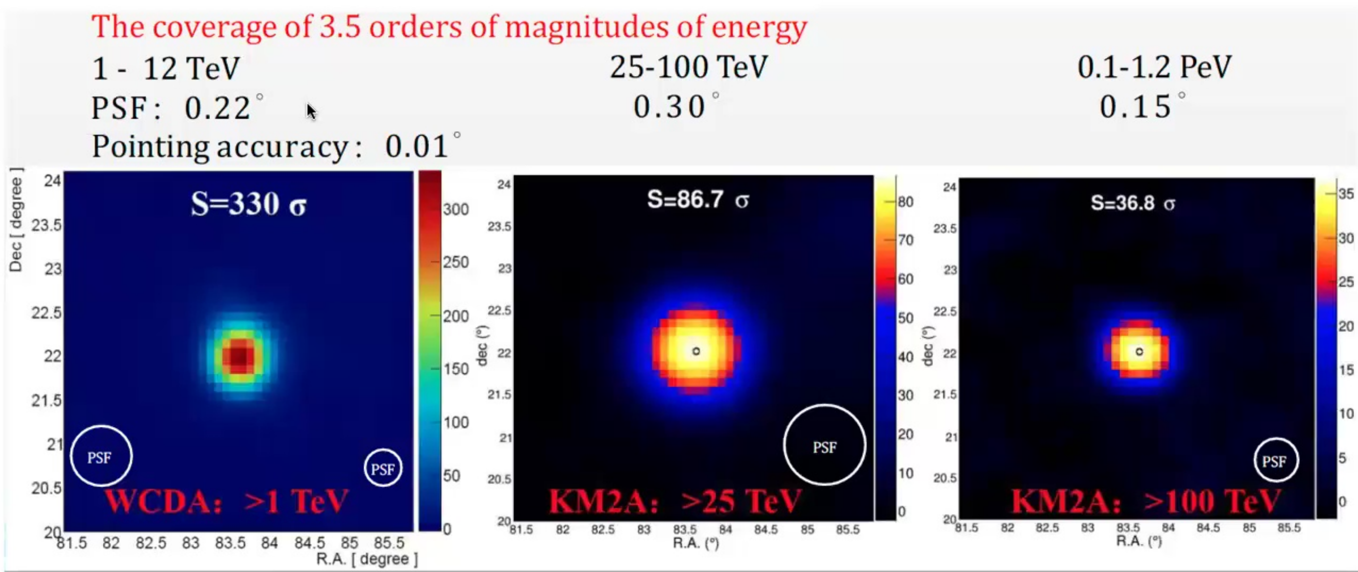
Observation of a 1.4 PeV photon from the Cygnus direction.
(chance probability 0.03%)



The Large High Altitude Air Shower Observatory (LHAASO)

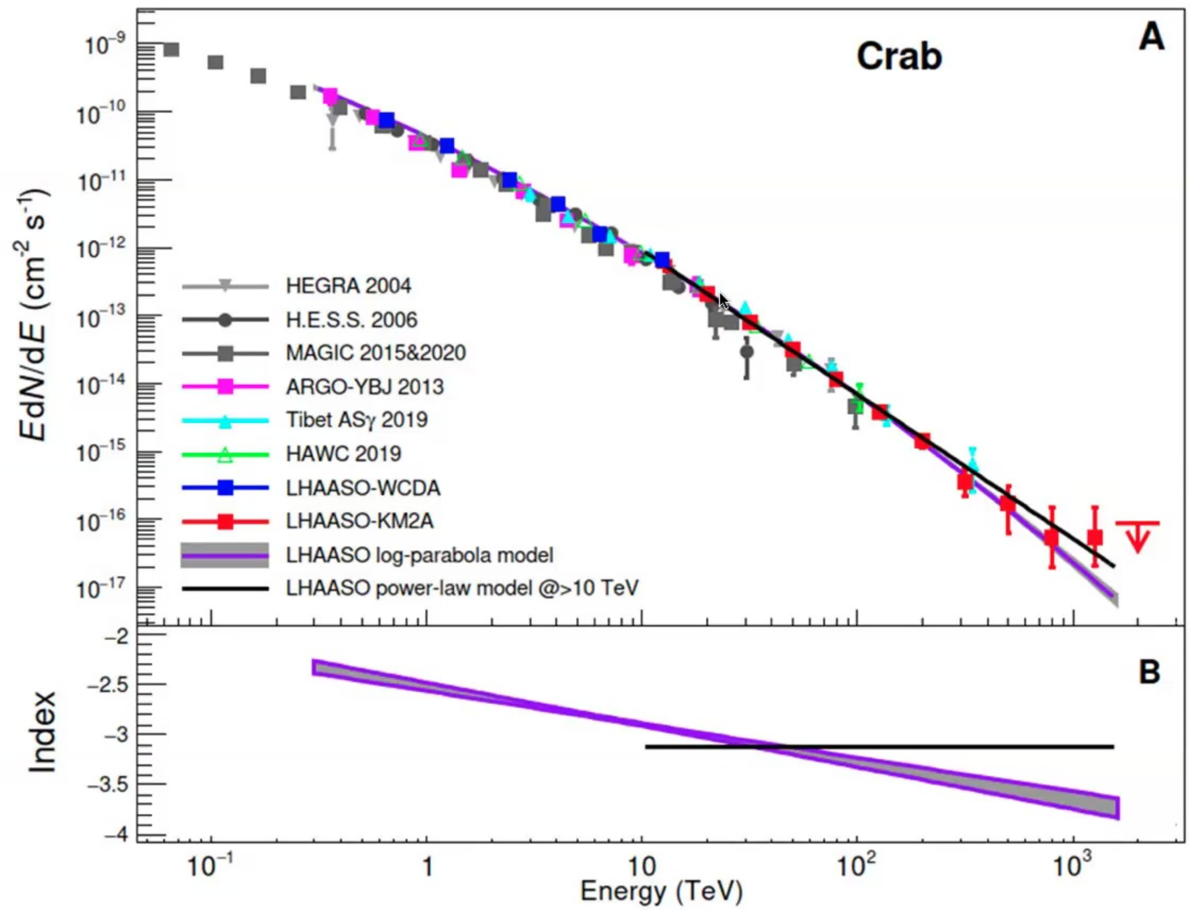
Observation of the gamma-ray “standard candle”





The Large High Altitude Air Shower Observatory (LHAASO)

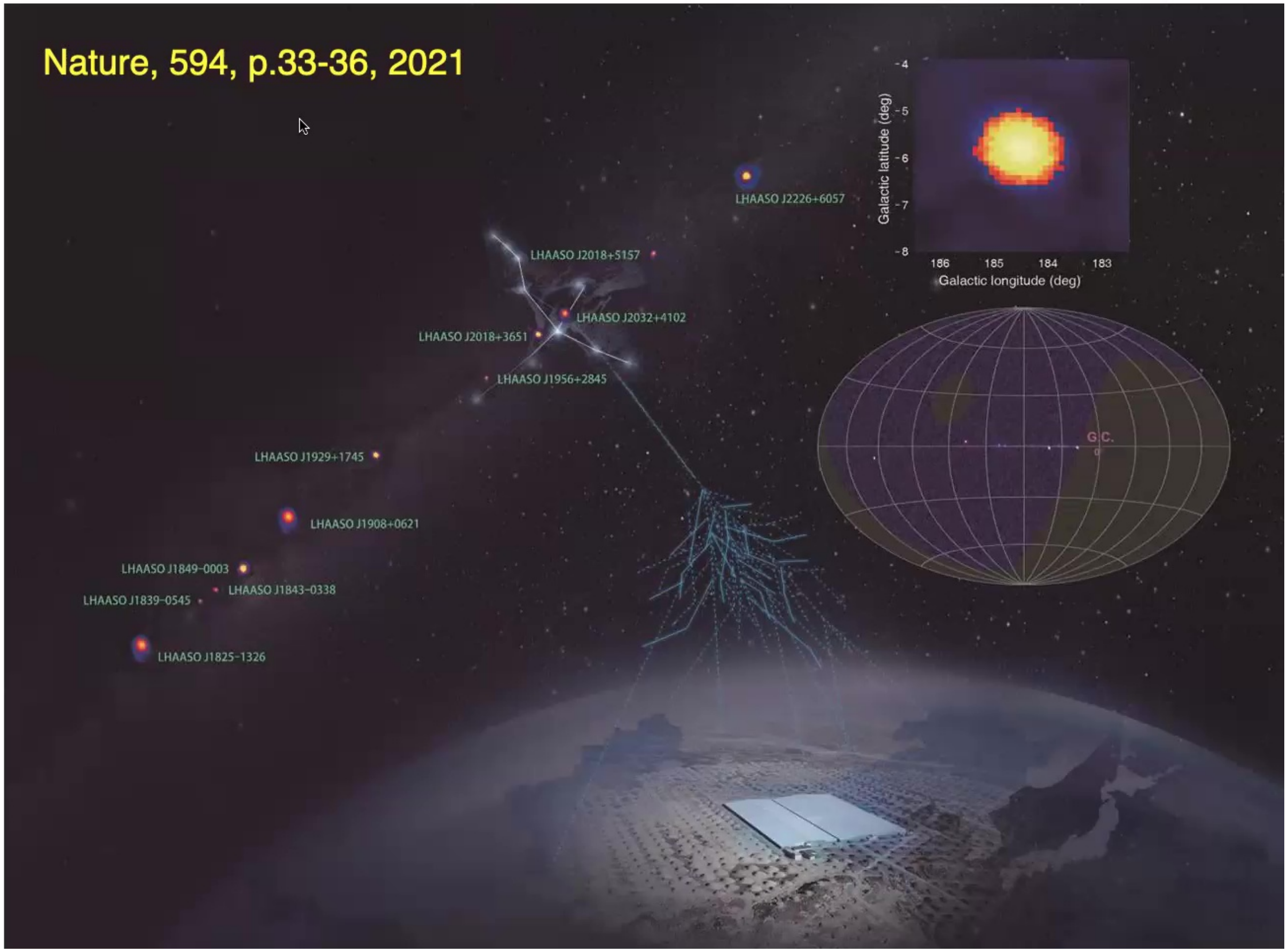
- Covering 3.5 decades of energy
- Agreeing with other experiments below 100 TeV
- Self cross-checking between WCDA & KM2A
- LHAASO-KM2A:
  - Unique UHE SED
  - A PeVatron without ambiguity
  - Clear origin: a well-known PWN
- An extreme e-accelerator:
  - 2.3 PeV electrons
  - in ~0.025 pc compact region
  - accelerating efficiency of 15% (1000× better than SNR shock waves)



The Large High Altitude Air Shower Observatory (LHAASO)

12 (Galactic) PeVatrons discovered at significance > 7sigma!

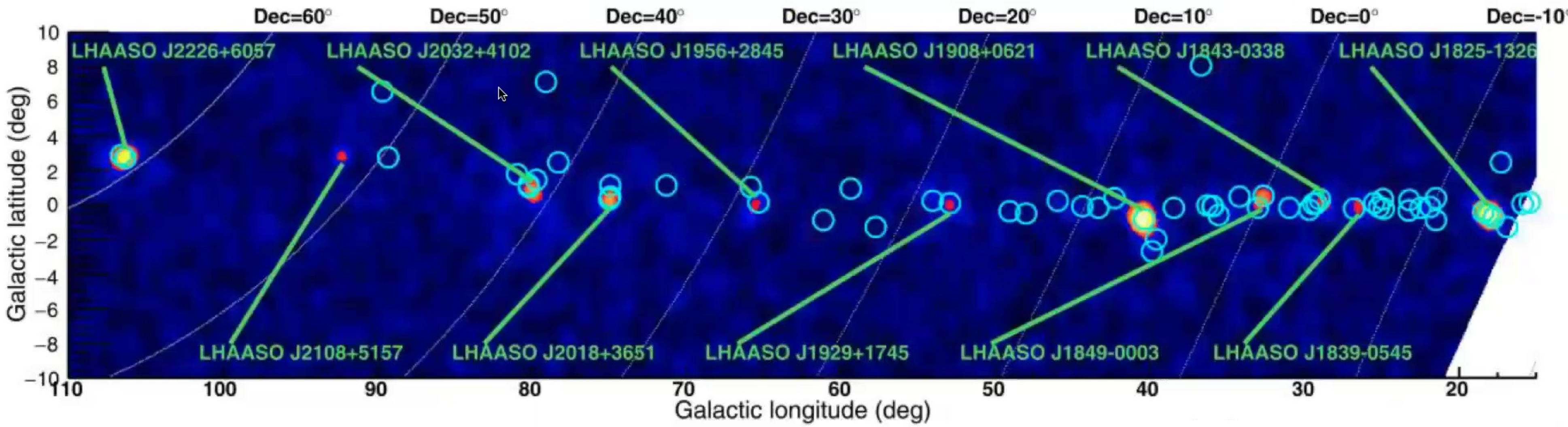
Multiple sources types…



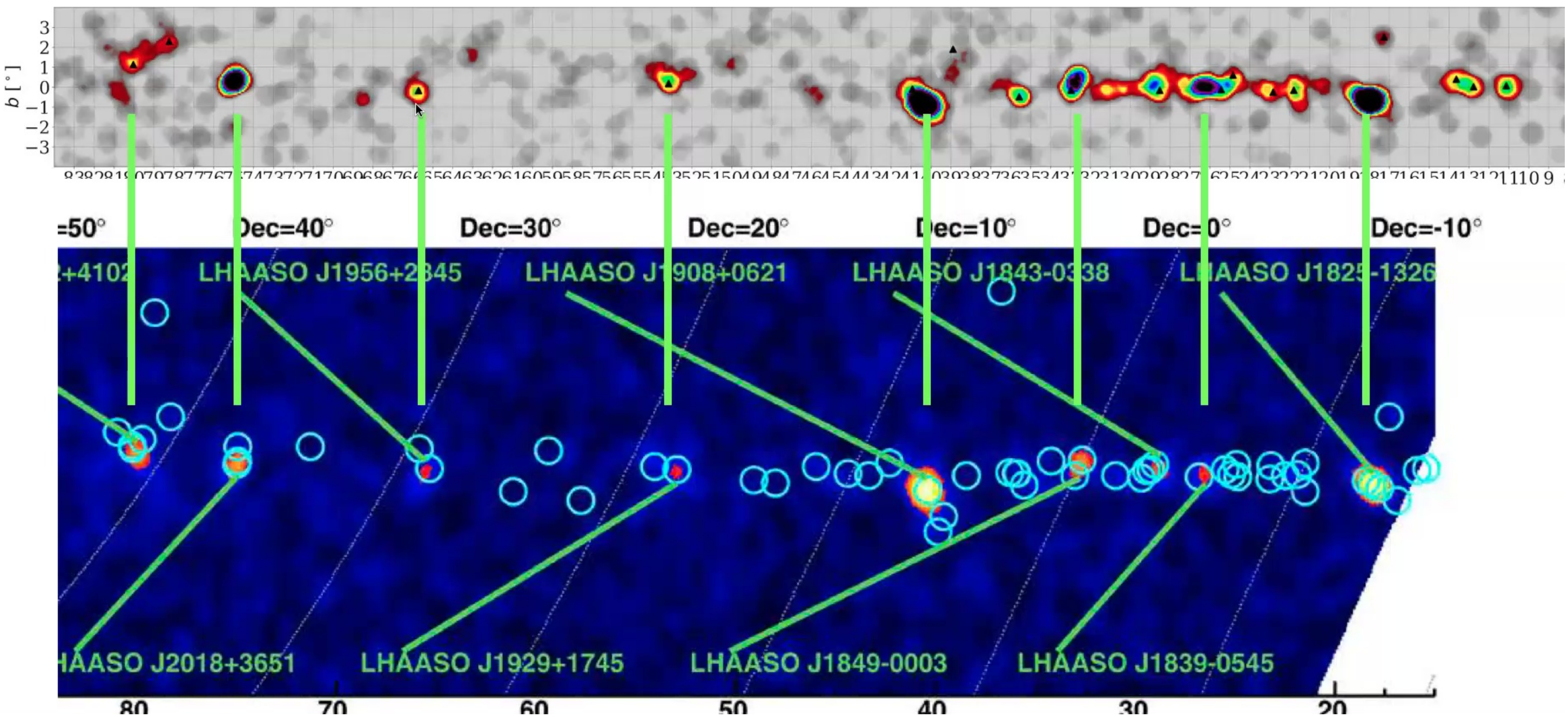
Jordan Goodman, Erice

The Large High Altitude Air Shower Observatory (LHAASO)

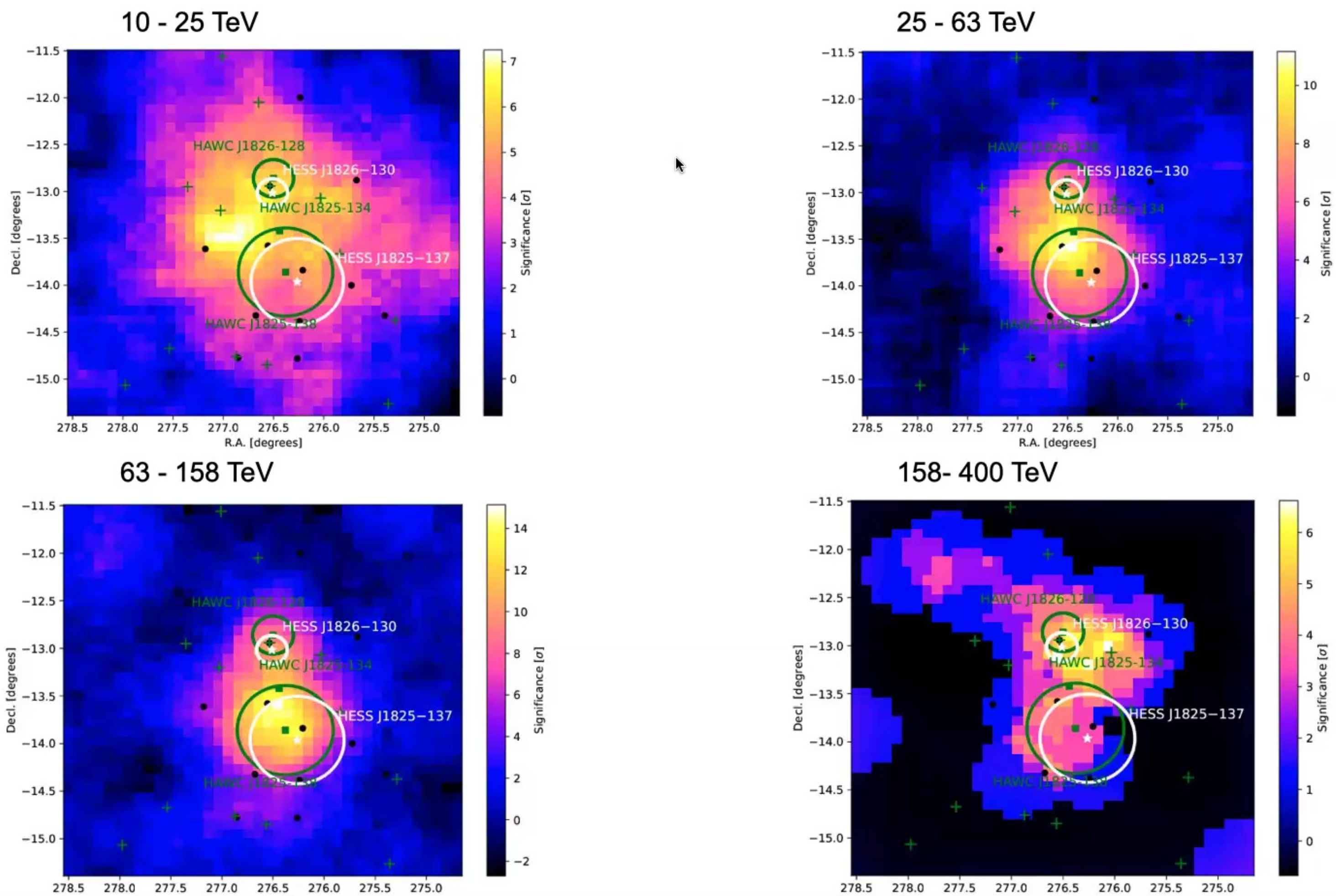
0.1 — 1 PeV sky map



The Large High Altitude Air Shower Observatory (LHAASO)



Energy dependent morphology of a source … J1825-134



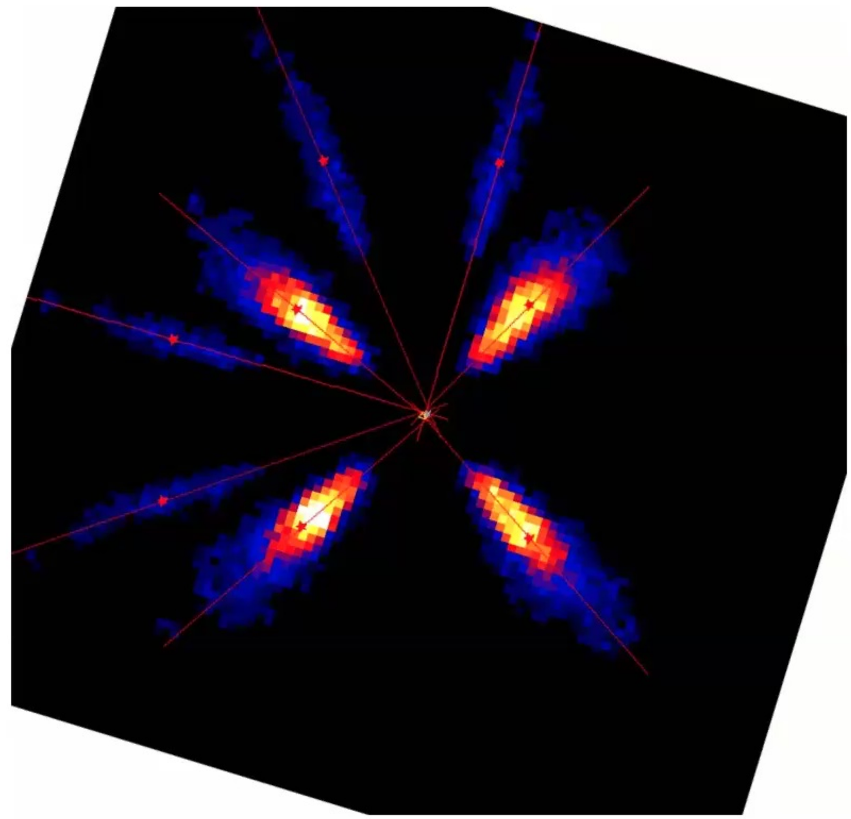
High-energy gamma rays

IACTs

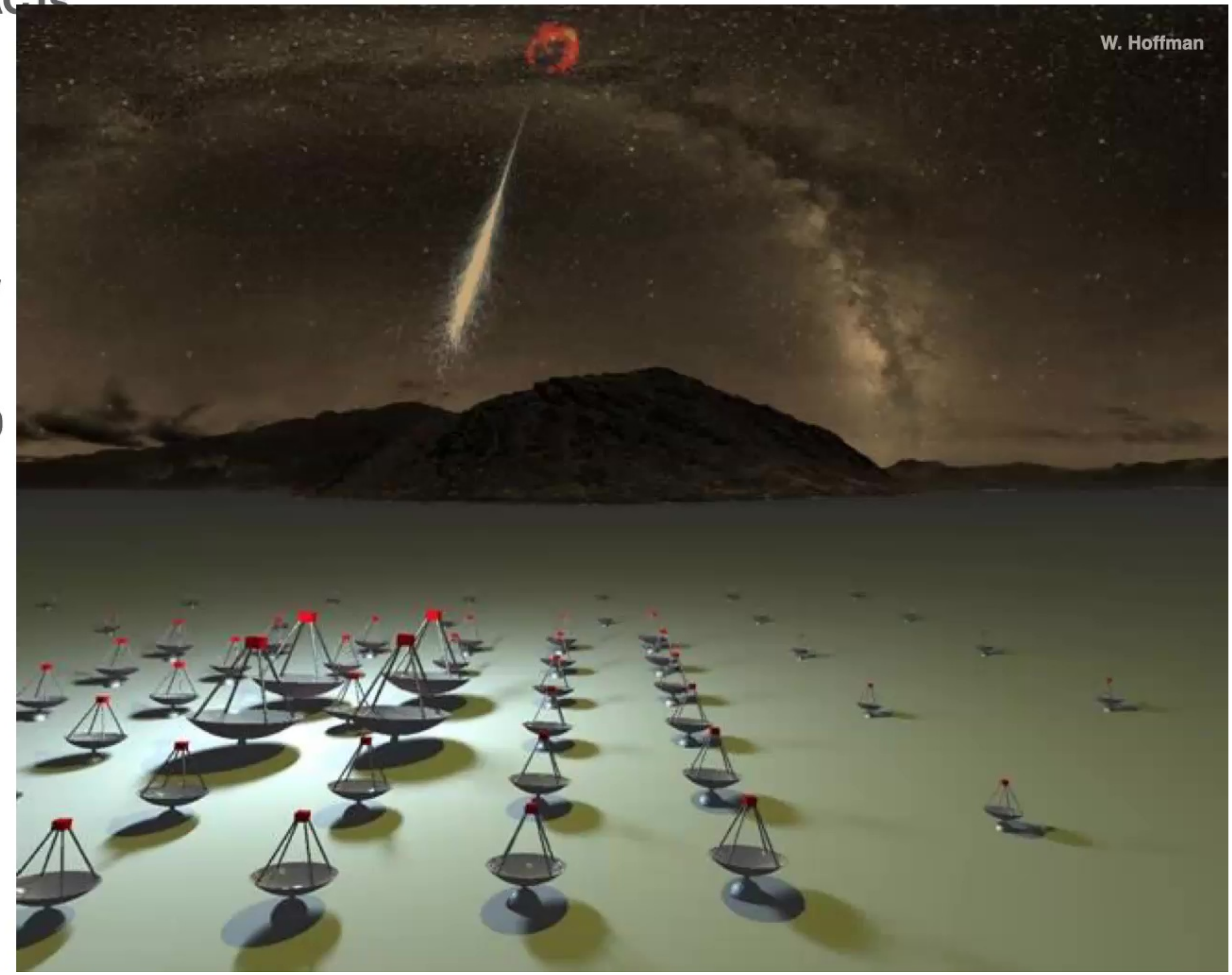
- Statistics (more events)
  - Larger collection areas provide more photons = better spectra, images and fainter sources

- Improved event quality
  - More precise measurements of atmospheric cascades and thus primary gamma rays
  - Improved angular resolution
  - Improved background rejection power

-> More telescopes!



High-energy gamma rays … IACTs



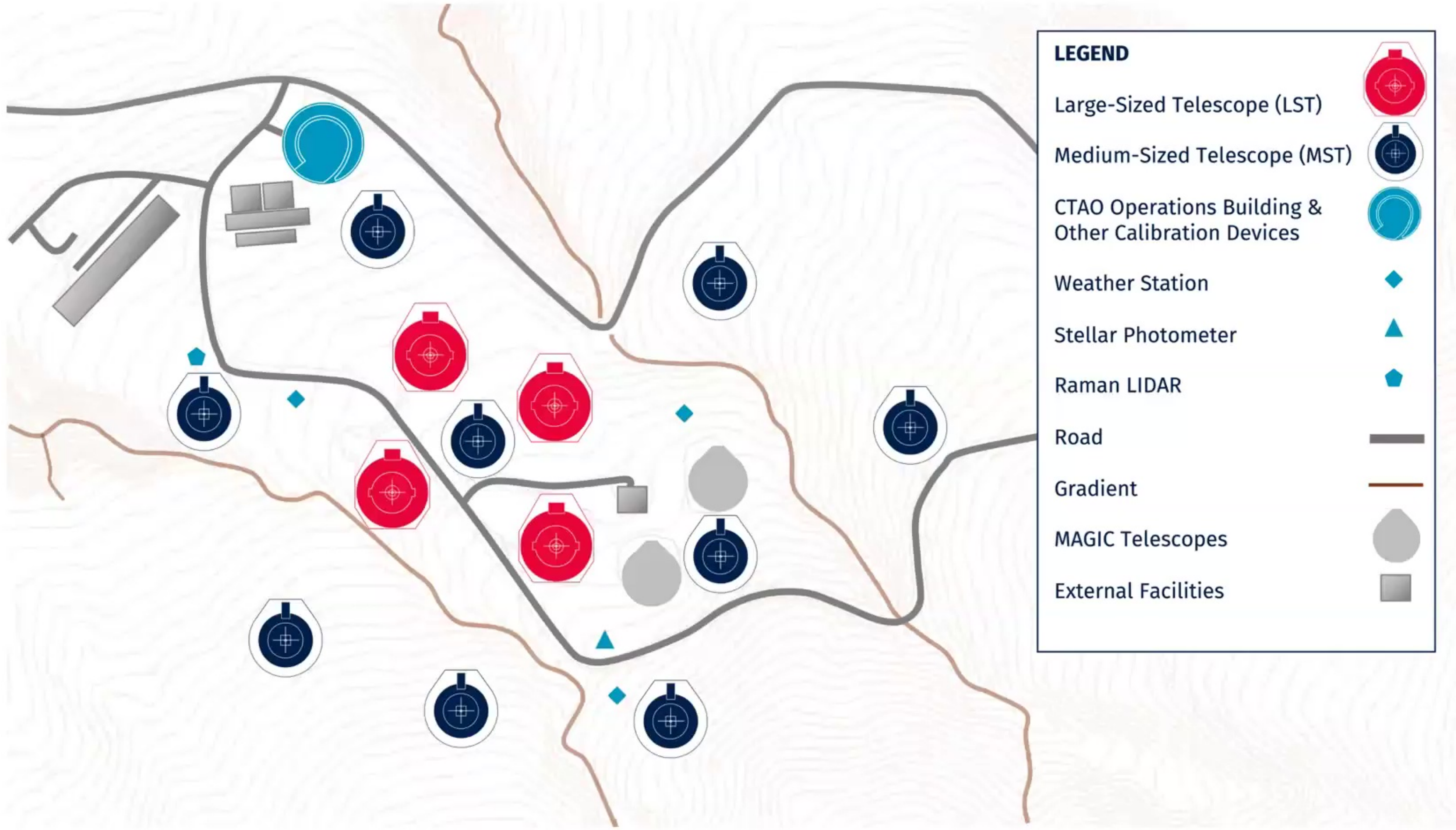
Cherenkov Telescope Array (CTA)

International project of ~1200 scientists and 70 institutes

Utilizes large, medium and small telescopes to realize a low (10 GeV threshold), medium (100 GeV - 10 TeV), and high-energy section (10-square-km area at multi-TeV)

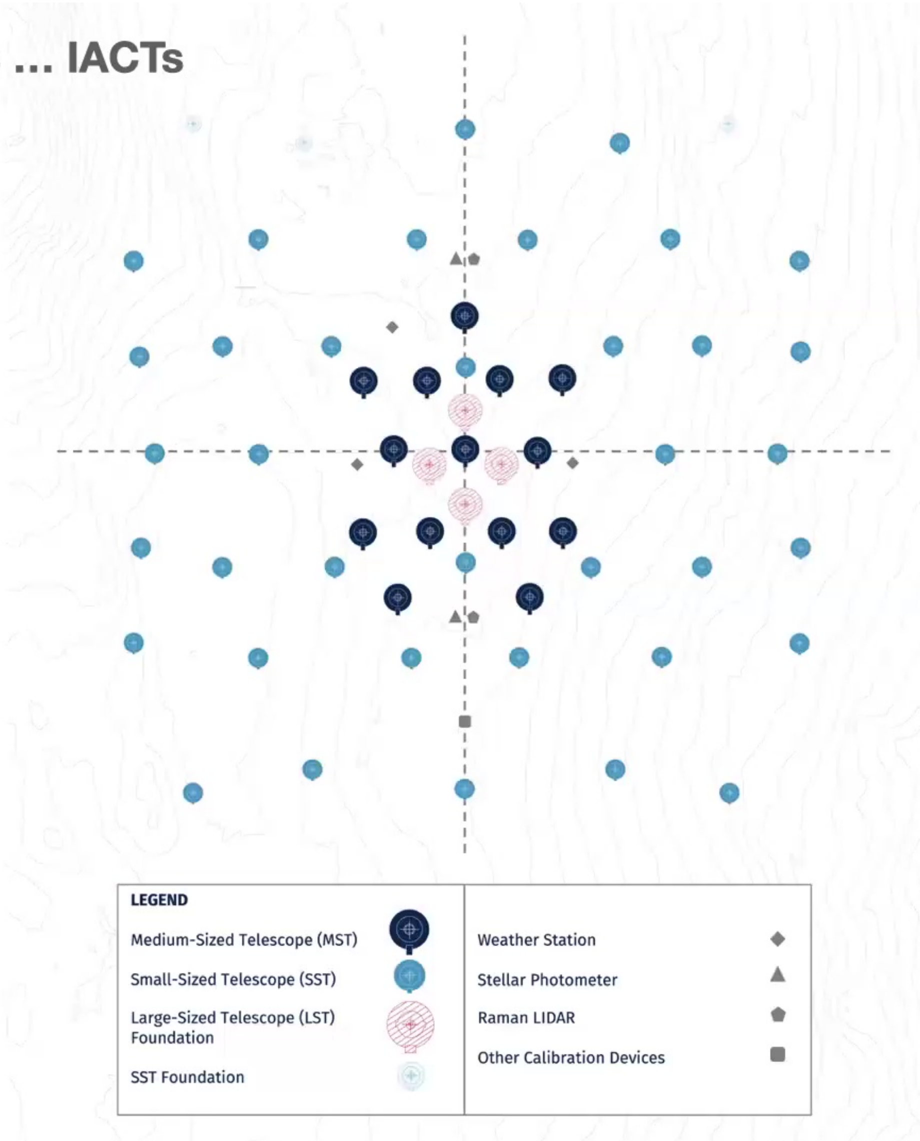
High-energy gamma rays … IACTs

La Palma



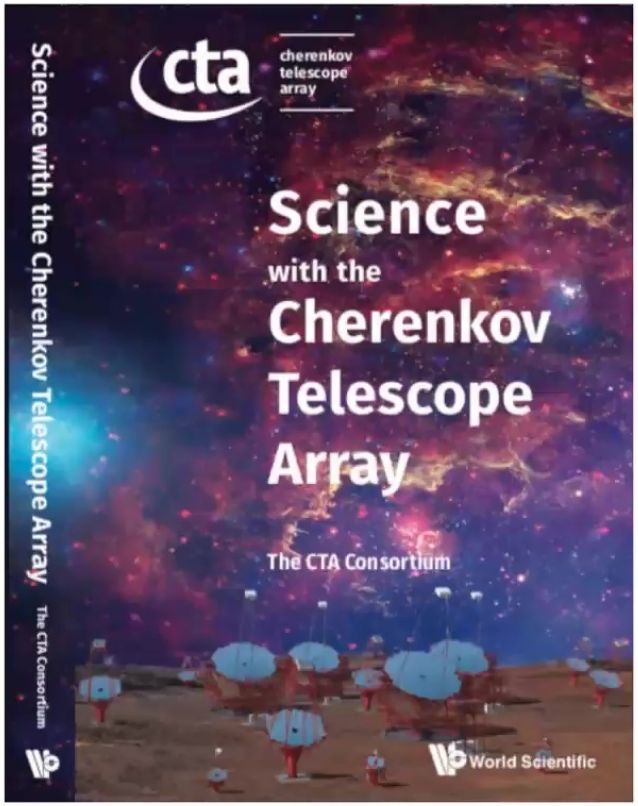
High-energy gamma rays … IACTs

Chile

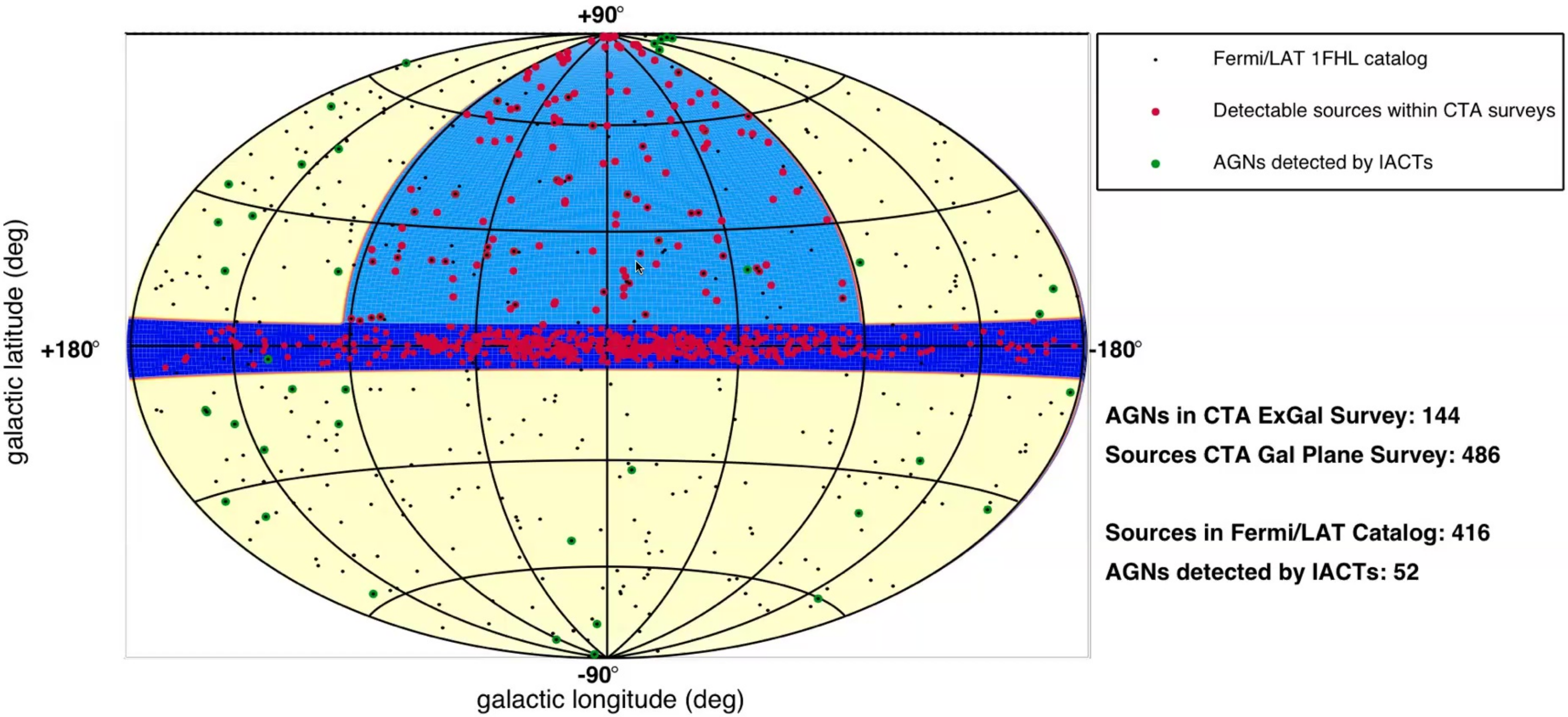


Science drivers for CTA

- **Theme 1: Cosmic Particle Acceleration**
  - How and where are particles accelerated?
  - How do they propagate?
  - What is their impact on the environment?
- **Theme 2: Probing Extreme Environments**
  - Processes close to neutron stars and black holes?
  - Processes in relativistic jets, winds and explosions?
  - Exploring cosmic voids
- **Theme 3: Physics Frontiers – beyond the SM**
  - What is the nature of Dark Matter? How it is distributed?
  - Is the speed of light a constant for high energy particles?
  - Do axion-like particles exist?



High-energy gamma rays … IACTs



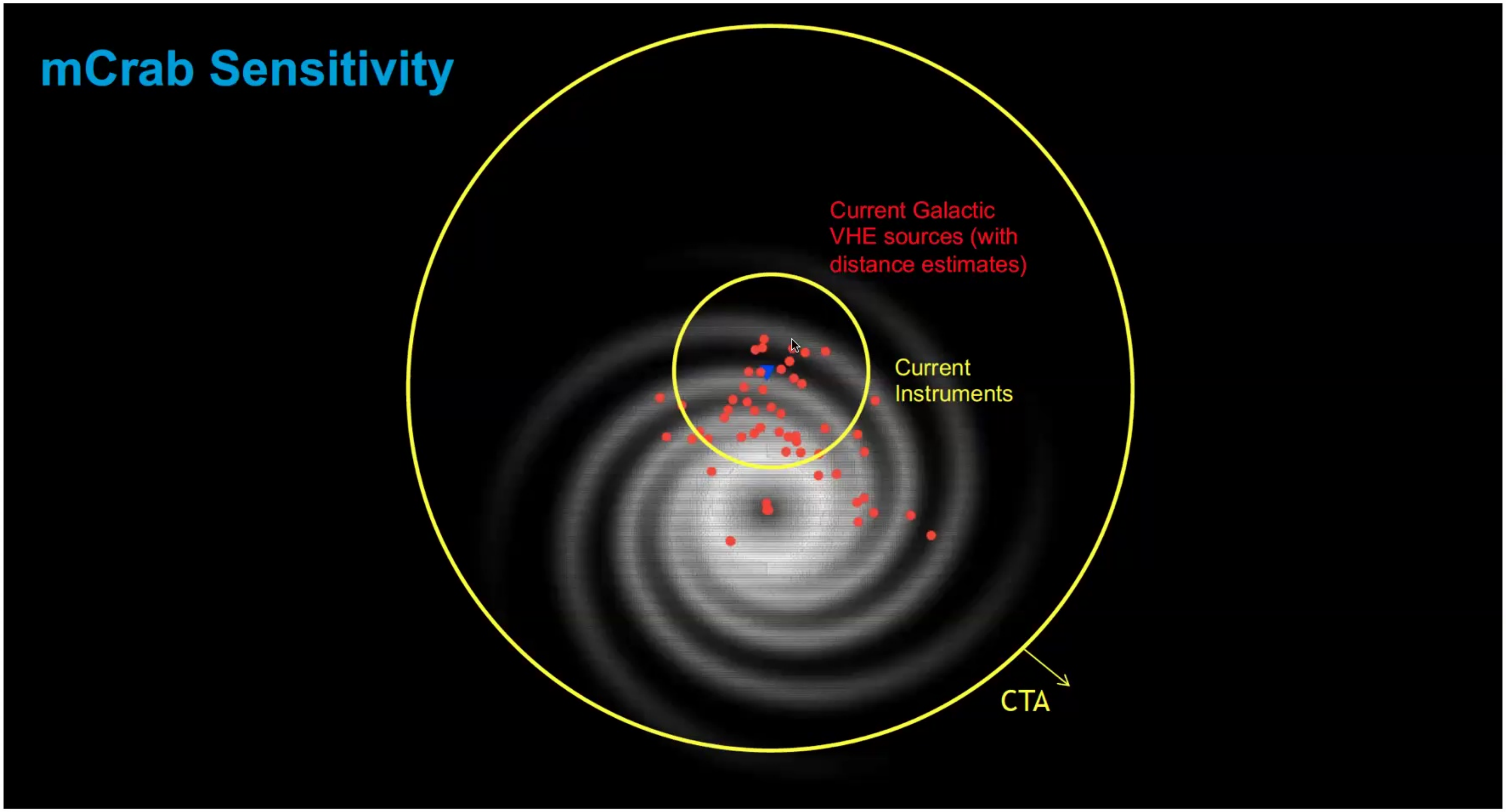
AGNs in CTA ExGal Survey: 144

Sources CTA Gal Plane Survey: 486

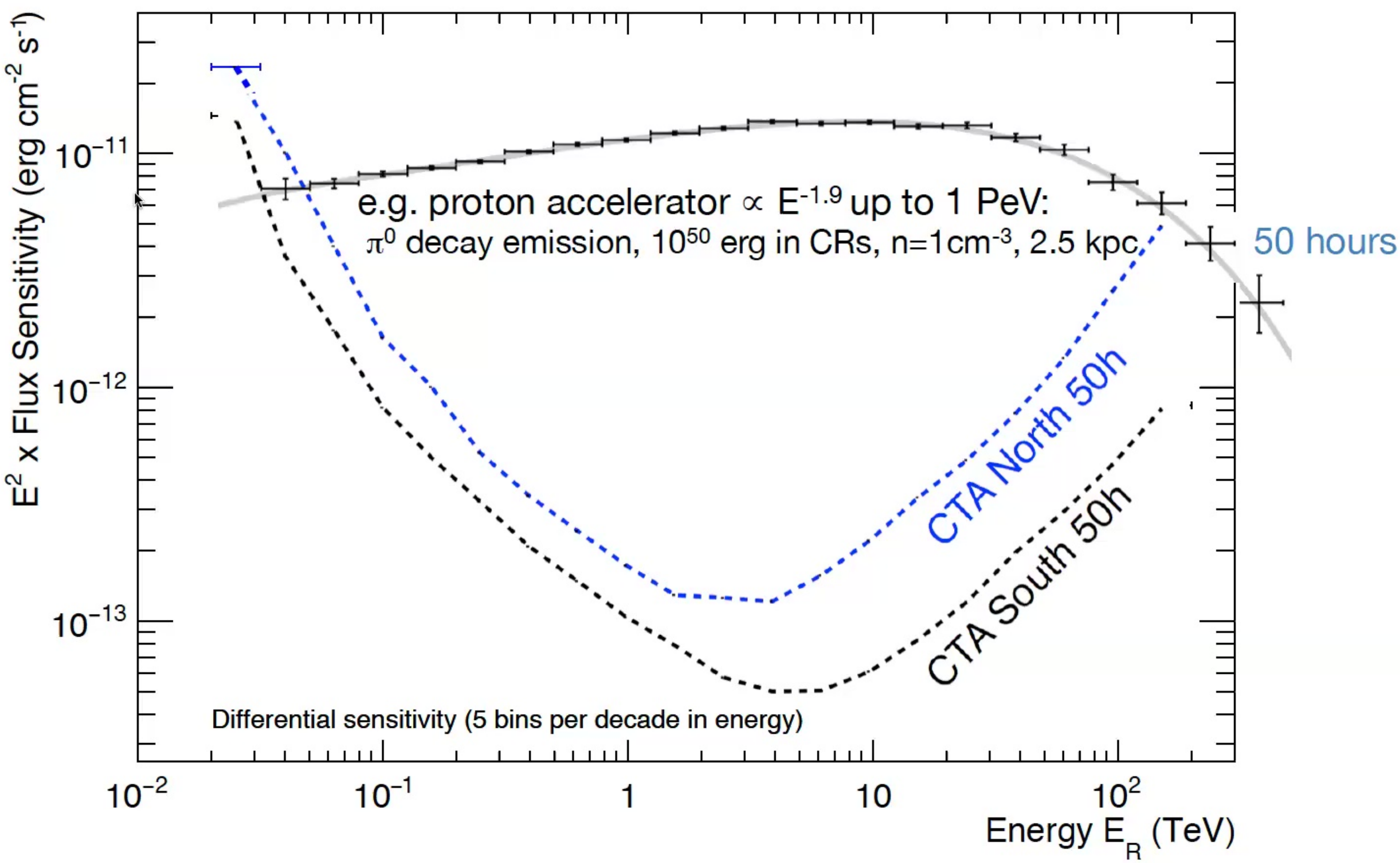
Sources in Fermi/LAT Catalog: 416

AGNs detected by IACTs: 52

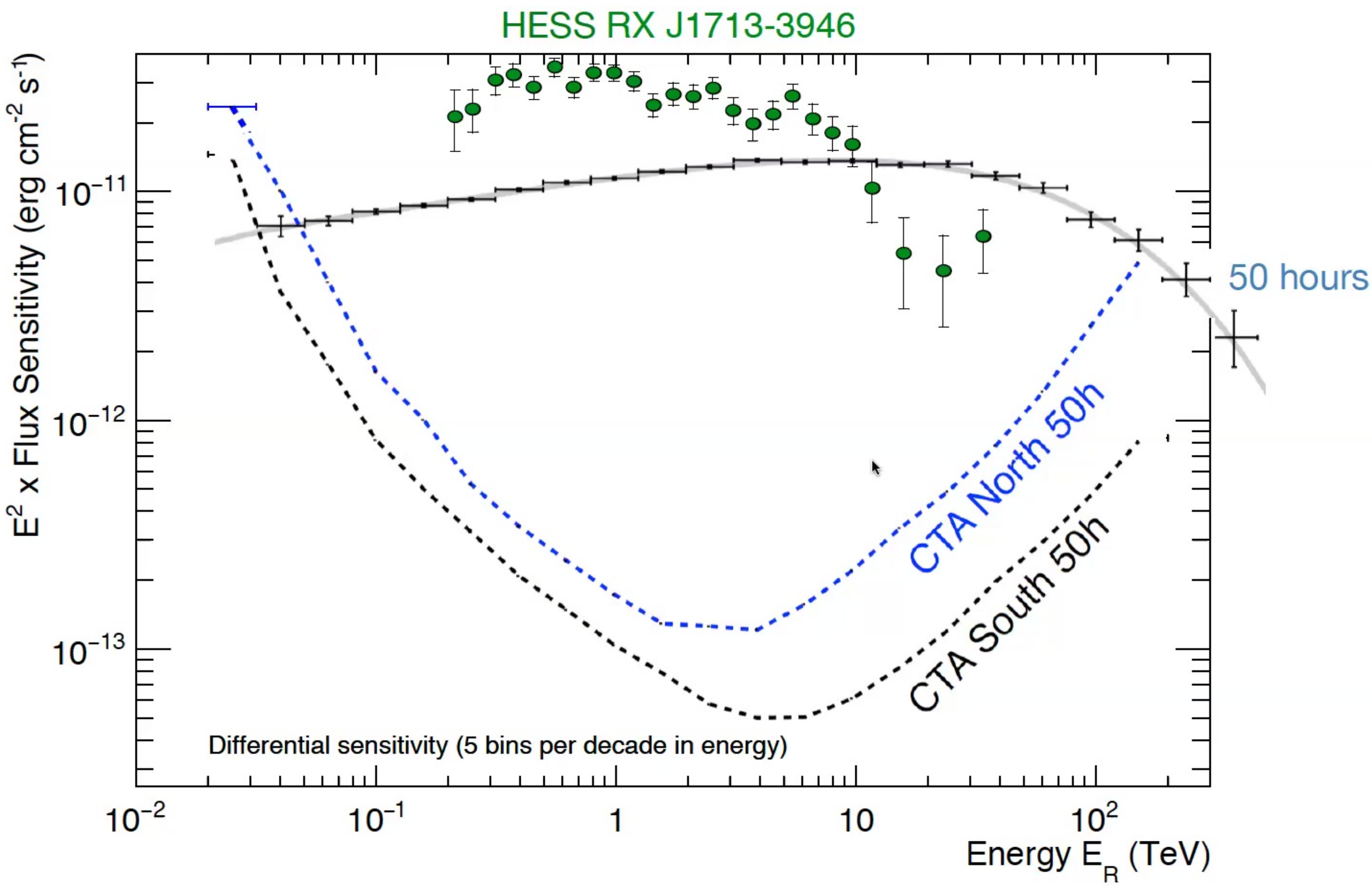
High-energy gamma rays … IACTs



High-energy gamma rays … IACTs

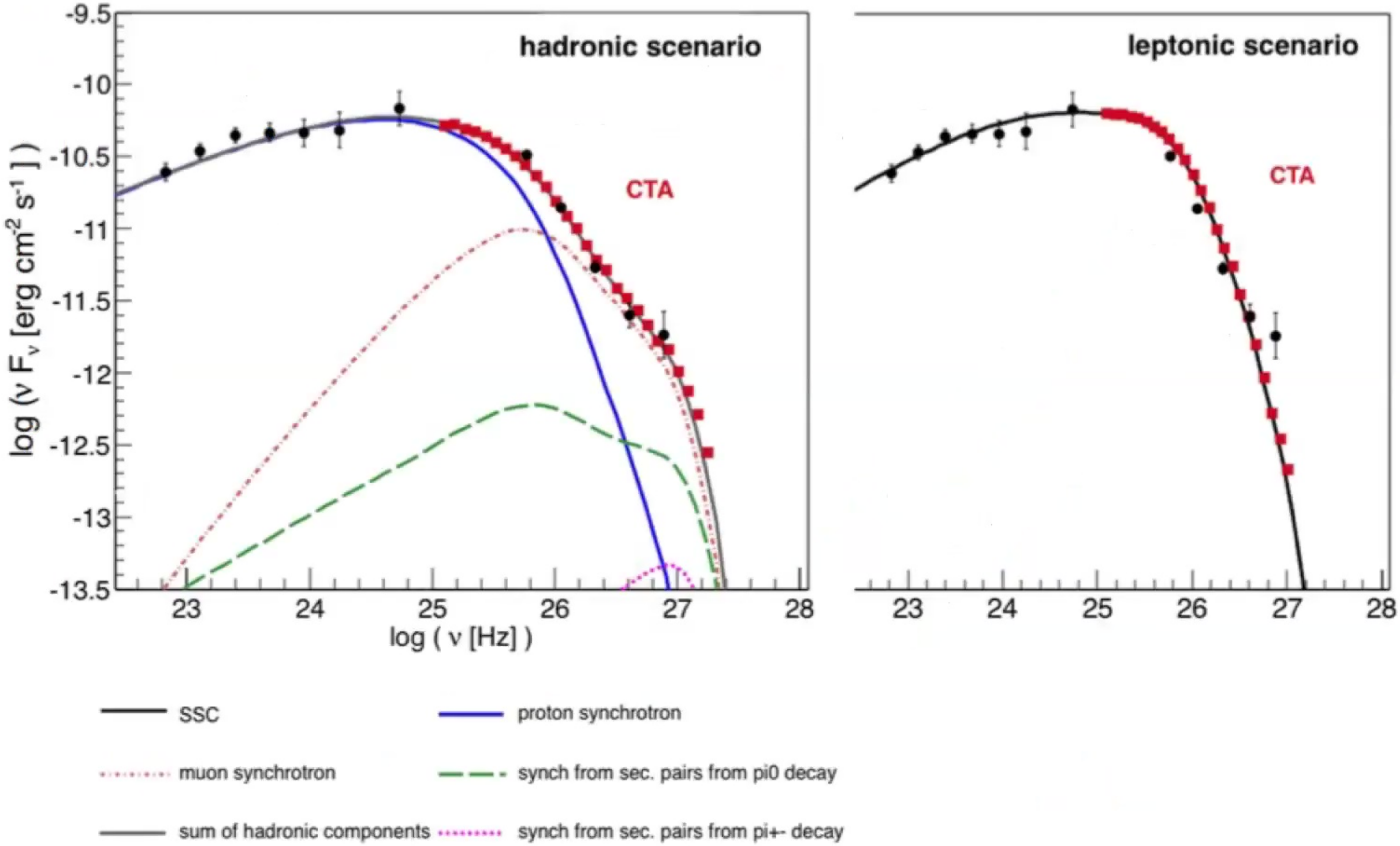


High-energy gamma rays … IACTs



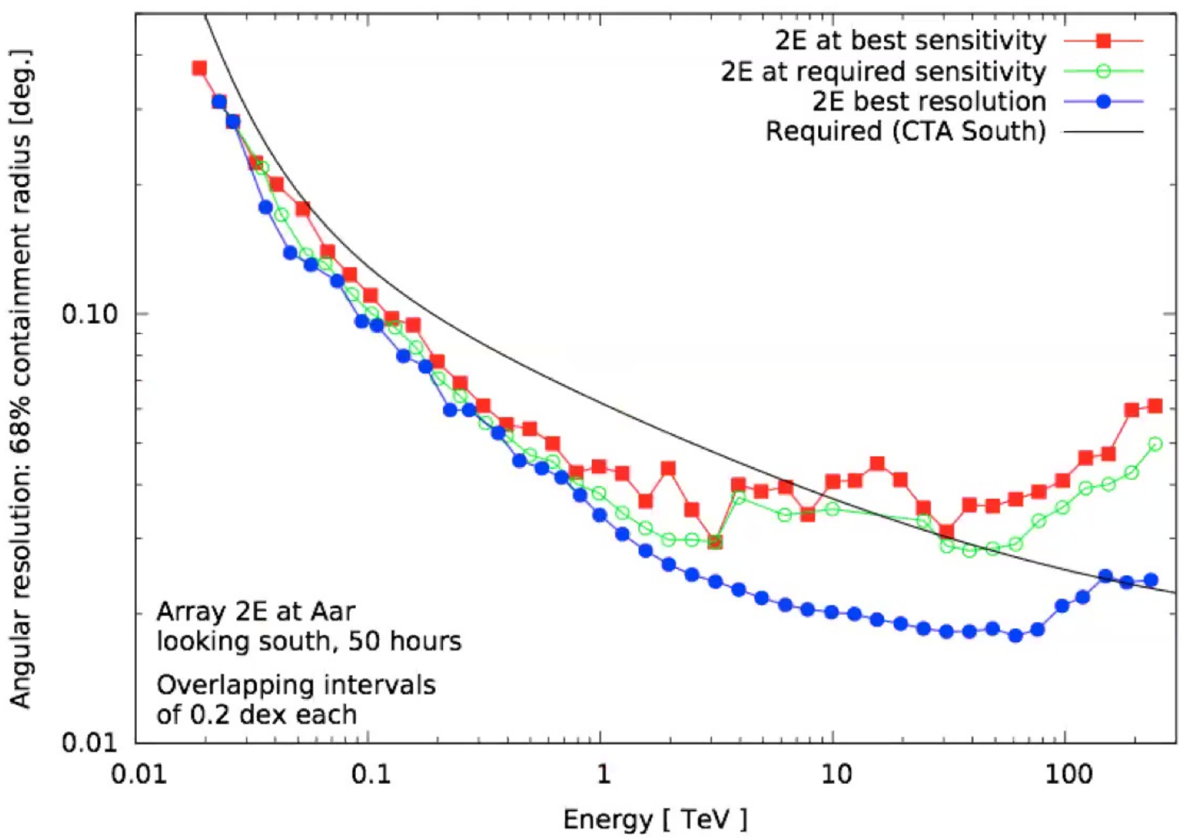
High-energy gamma rays … IACTs

Acceleration mechanisms



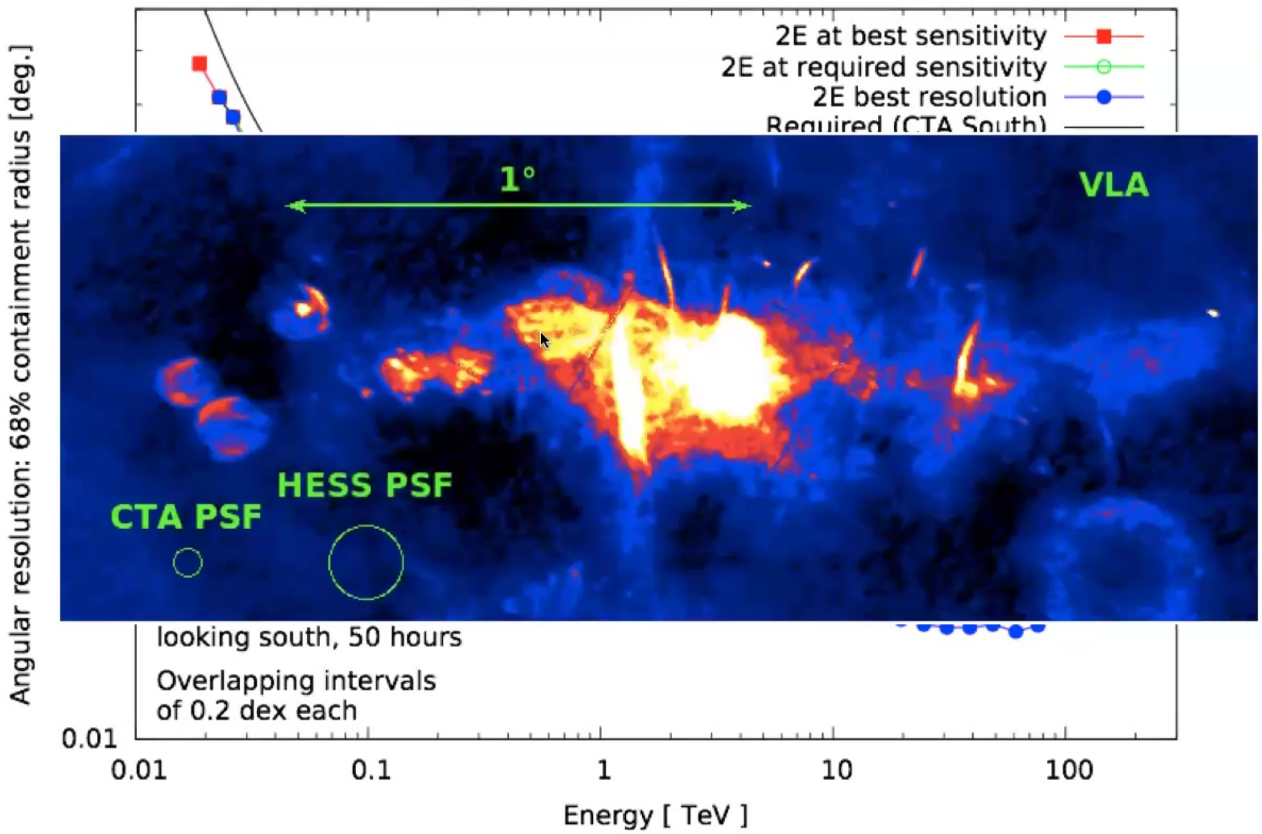
High-energy gamma rays … IACTs

Angular Resolution



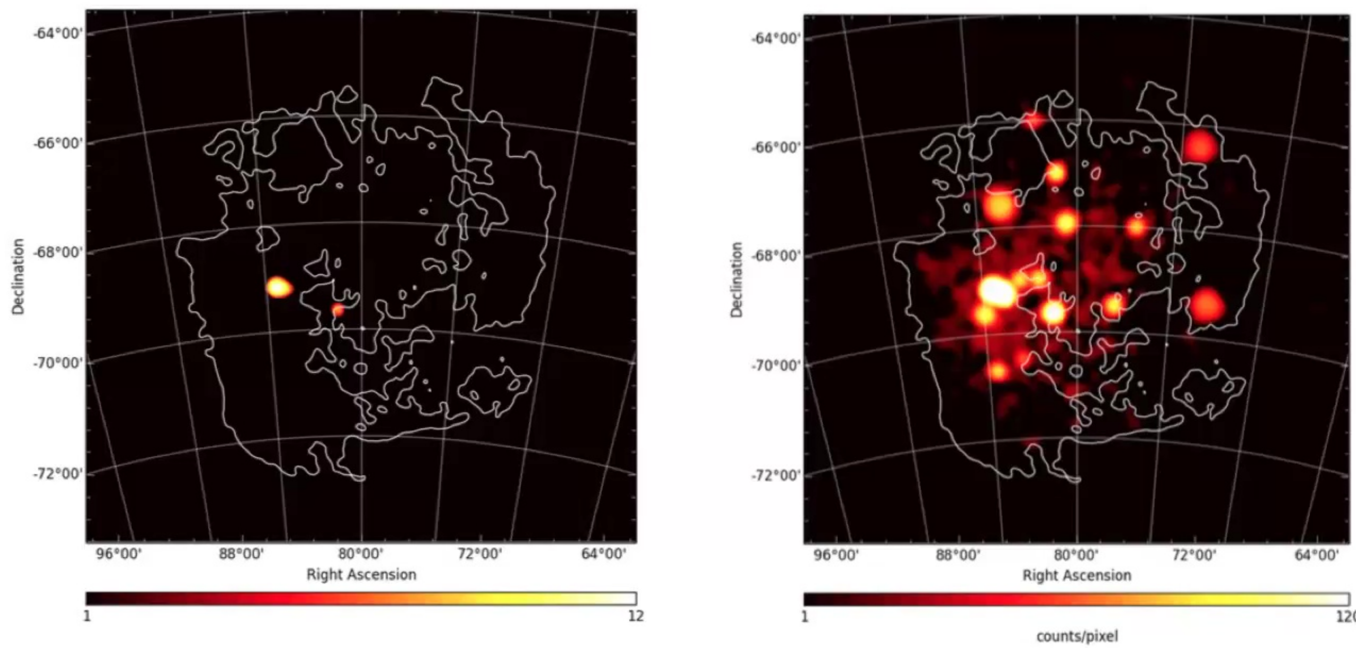
High-energy gamma rays … IACTs

Angular Resolution



High-energy gamma rays … IACTs

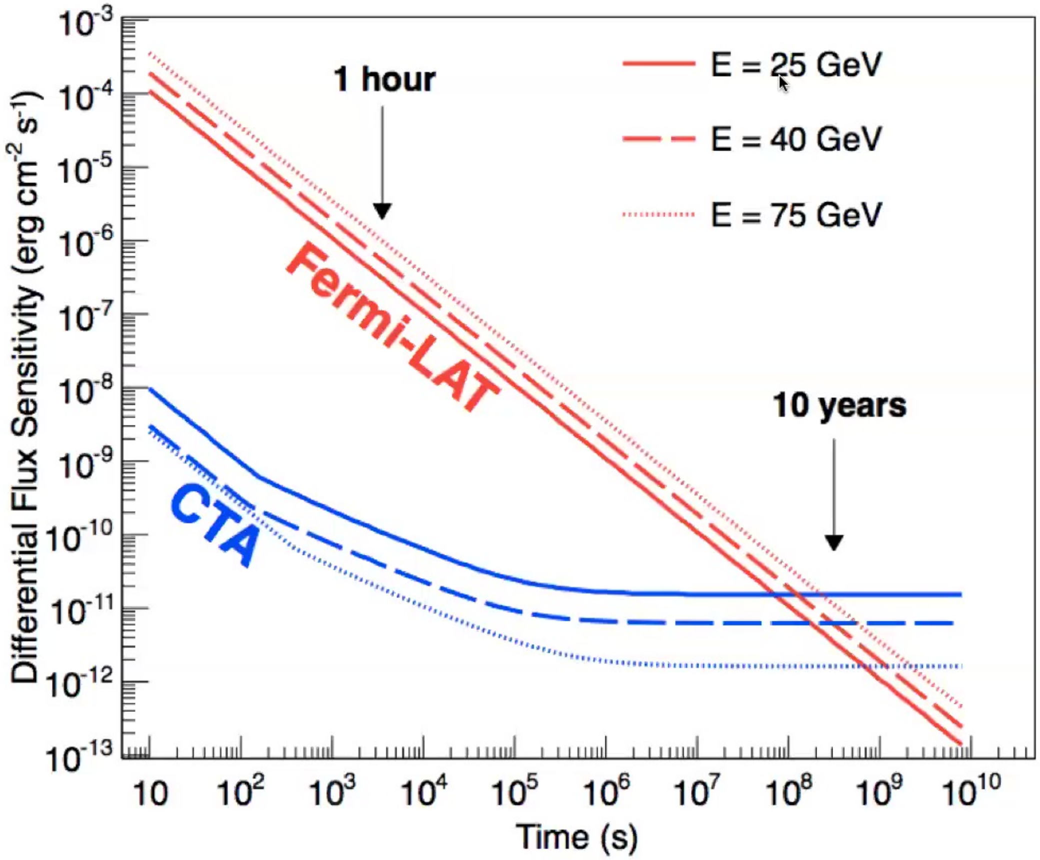
Eg. Large Magellanic Could survey



~10% of the Milky Way star formation in 2% of the volume hosts extreme accelerators

High-energy gamma rays … IACTs

CTA transient sensitivity

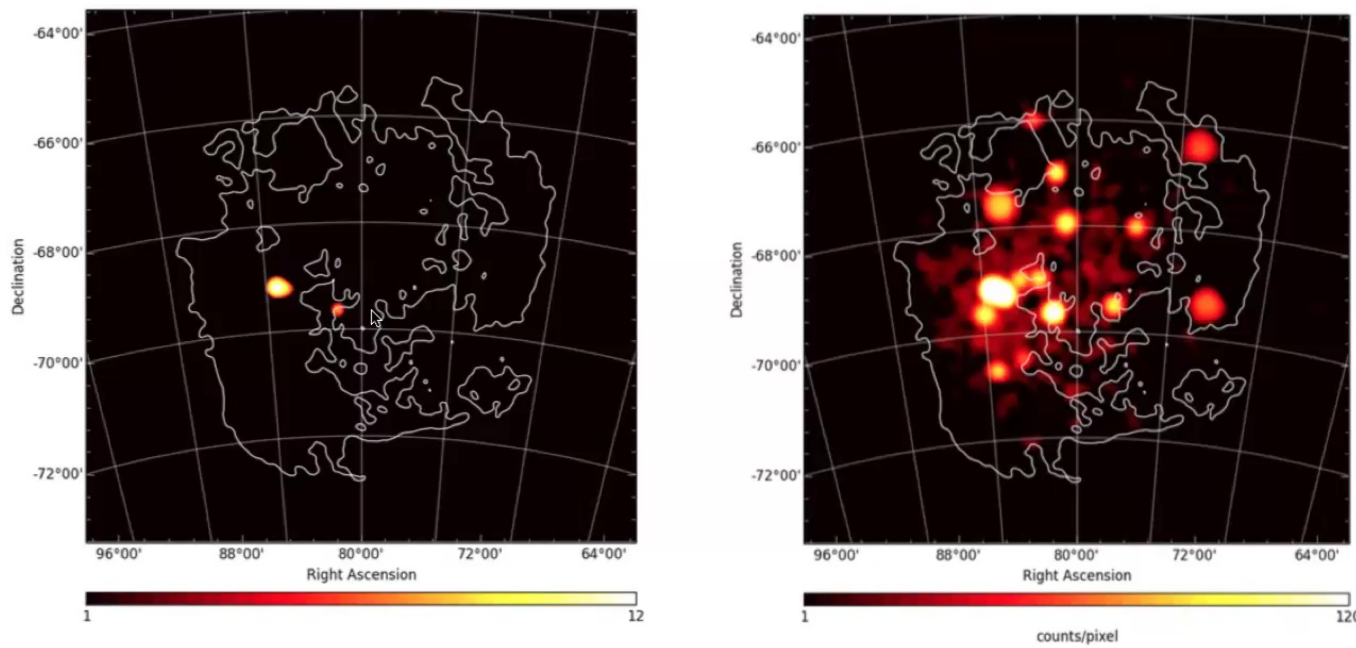


High-energy gamma rays … IACTs

La Palma - first large telescope

High-energy gamma rays … IACTs

Eg. Large Magellanic Could survey



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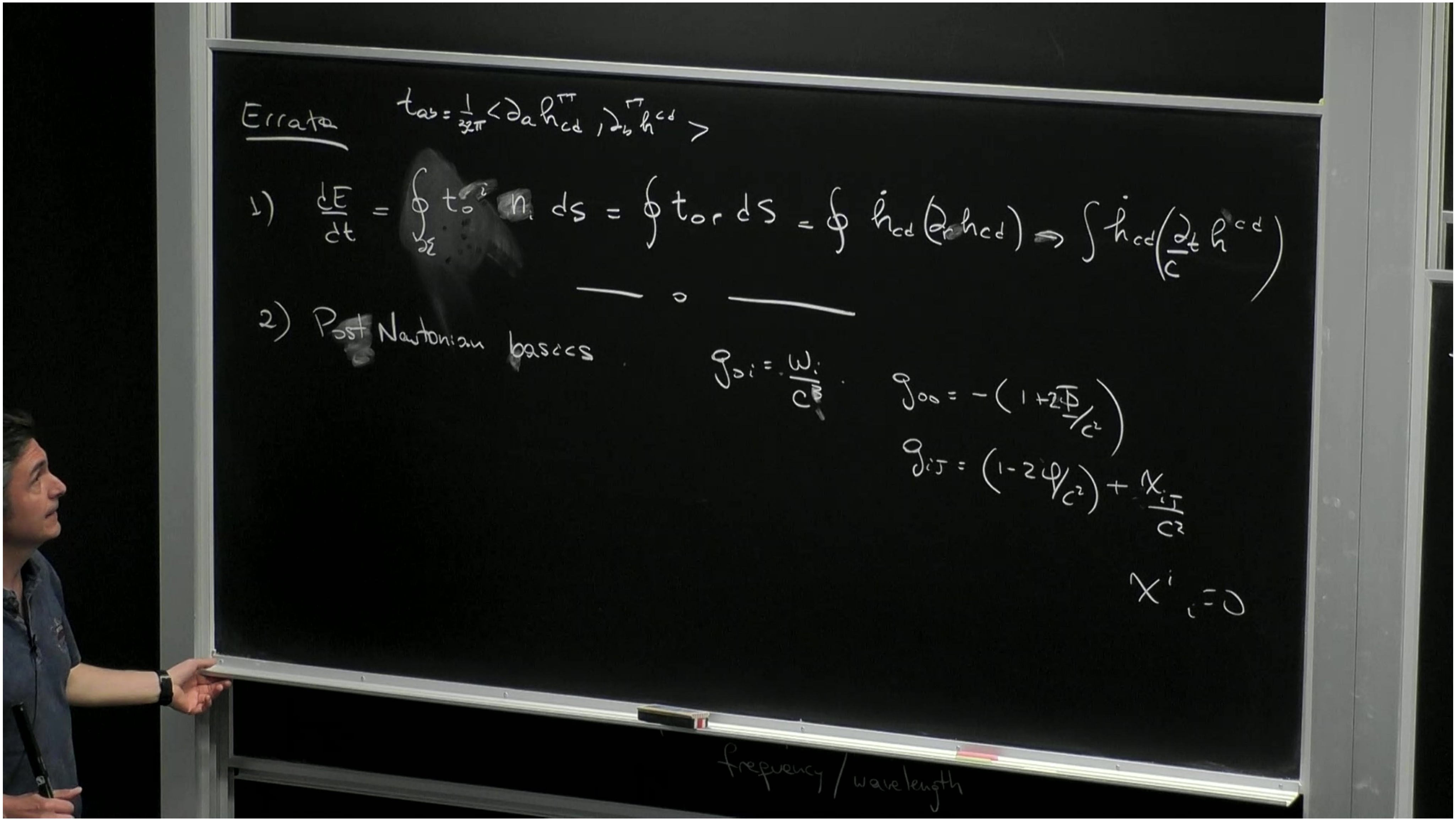
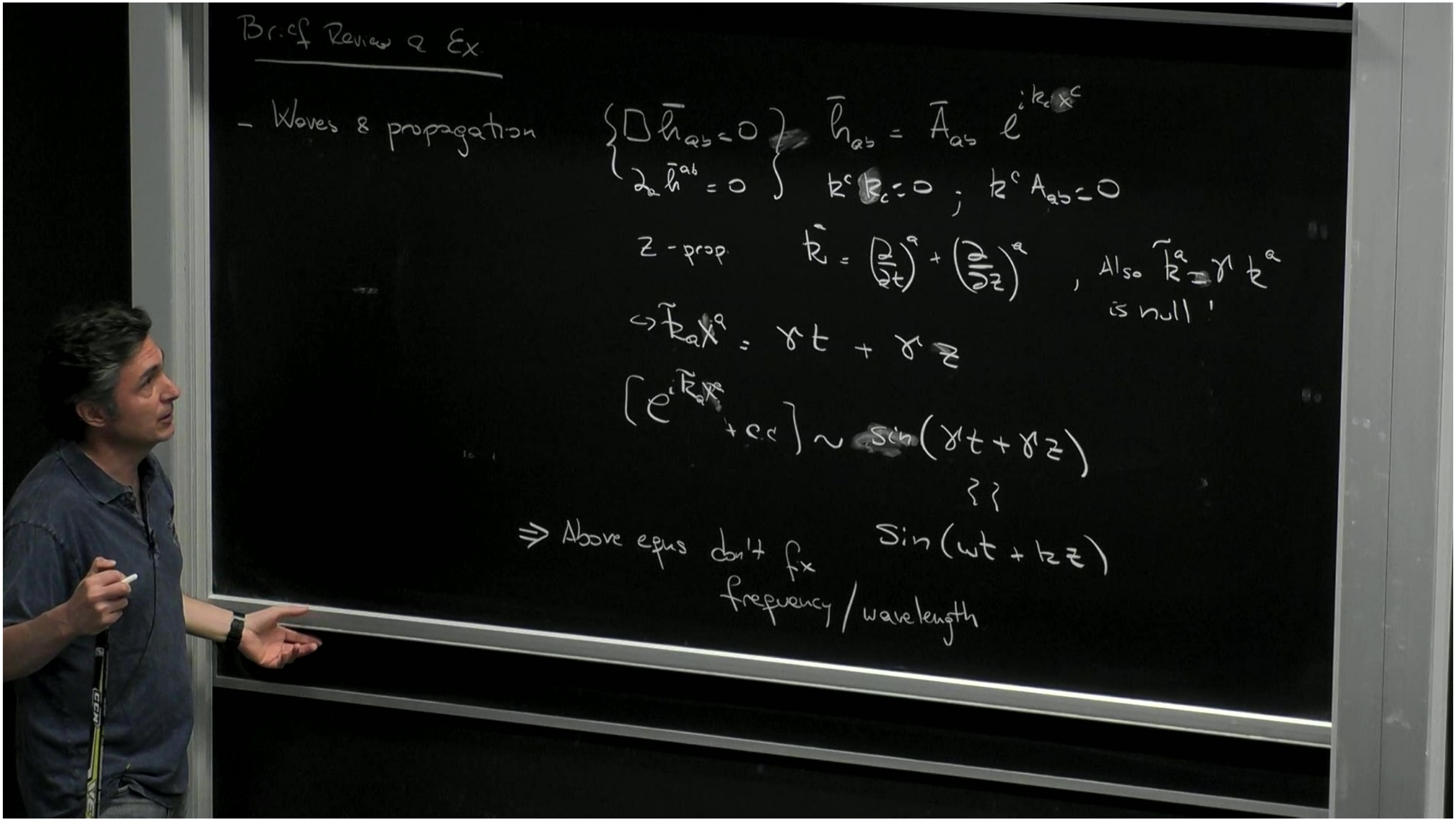
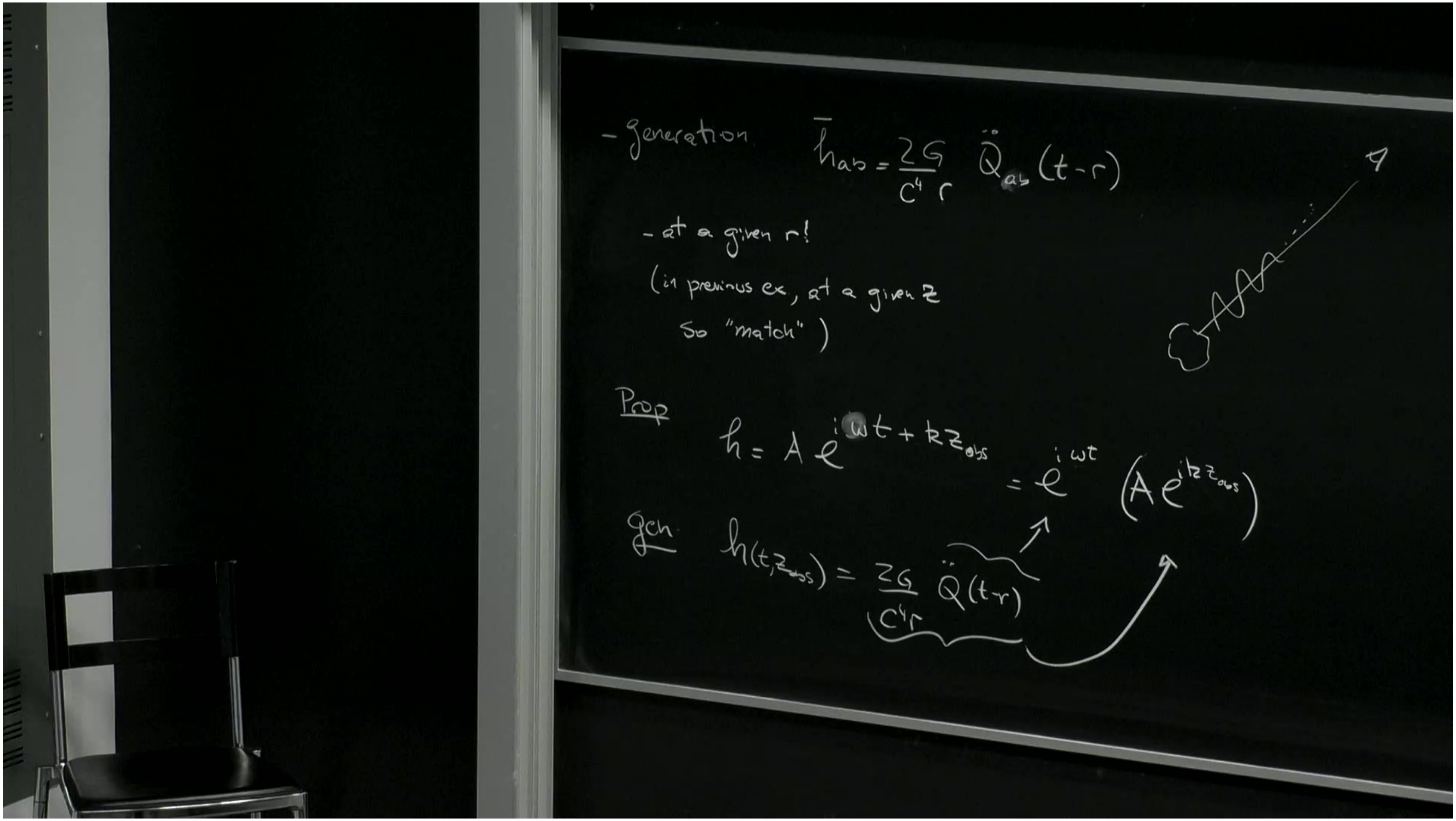
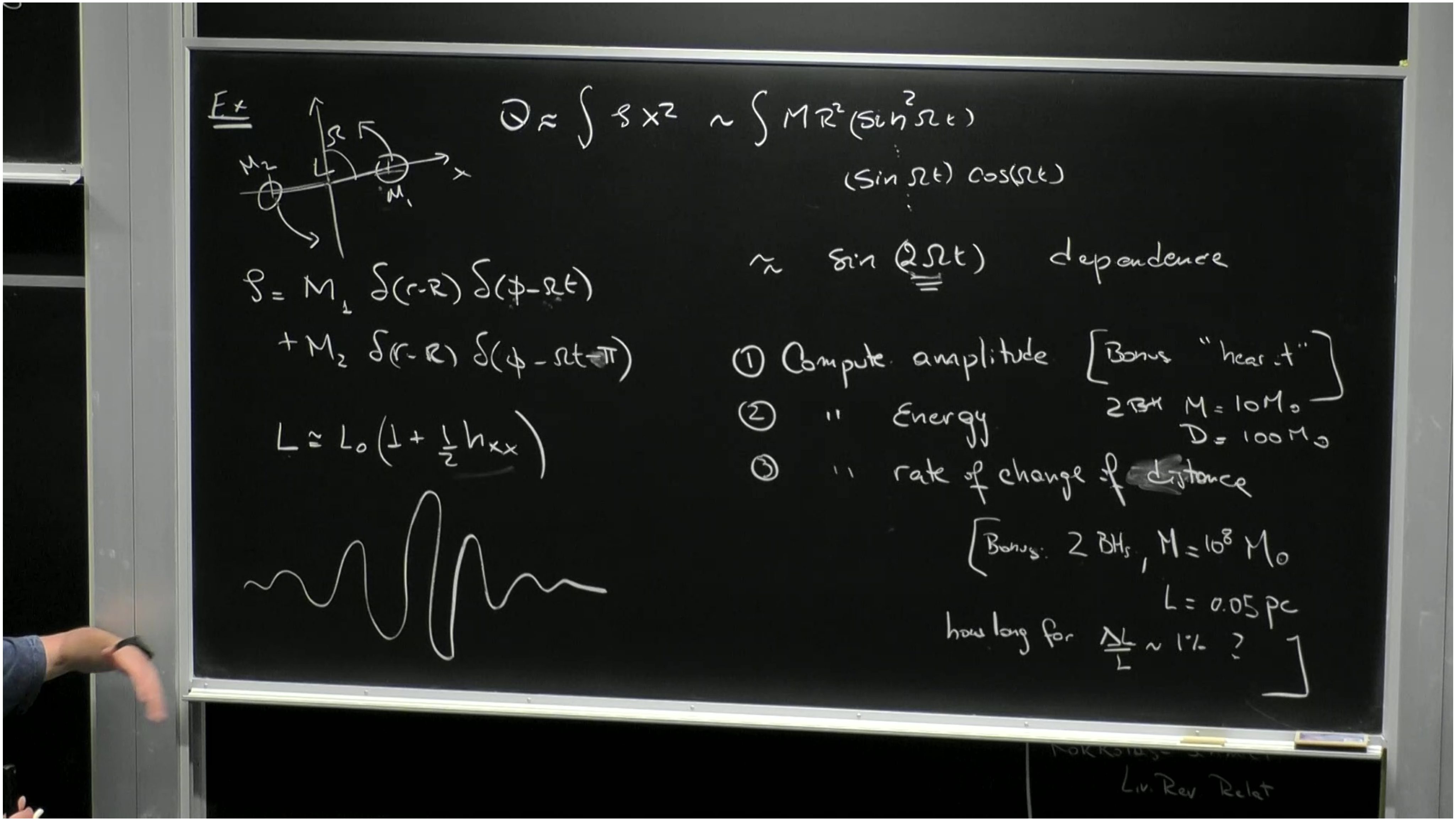
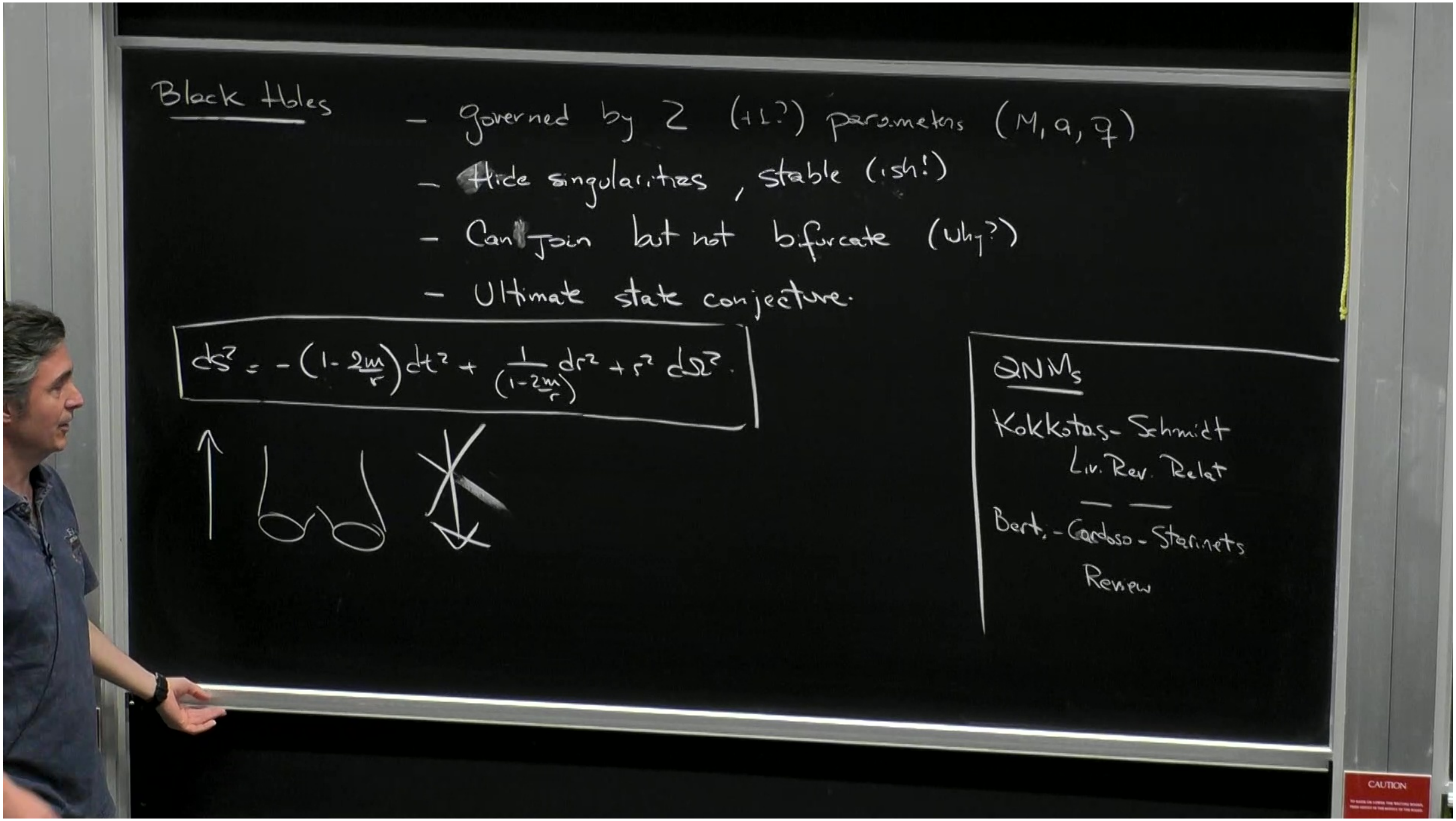

Errata
2) Post Newtonian basics
frequency / wavelength


Brief Review & Ex
- Waves & propagation
{□ h̄_ab = 0 ; ∂_a h̄^ab = 0} h̄_ab = Ā_ab e^{i k_c x^c}
k^c k_c = 0 ; k^c A_ab = 0
z - prop. k = (∂/∂t)^a + (∂/∂z)^a , Also k̃^a = γ k^a is null !
⇔ k̃_a x^a = γ t + γ z
[e^{i k̃_a x^a} + c.c] ~ sin(γ t + γ z)
??
sin(ωt + kz)
⇒ Above eqns don't fix frequency / wavelength


- generation $\bar{h}_{ab} = \frac{2G}{c^4 r} \ddot{Q}_{ab}(t-r)$
- at a given r!
(in previous ex, at a given z
so "match")
Prop
$h = A e^{i\omega t + kz_{obs}} = e^{i\omega t} \left(A e^{ikz_{obs}}\right)$
gen
$h(t, z_{obs}) = \frac{2G}{c^4 r} \ddot{Q}(t-r)$


Ex
M2
M1
x
Q ≈ ∫ ρ x² ~ ∫ M R² (sin² Ωt)
(sin Ωt) cos(Ωt)
~ sin (2Ωt) dependence
ρ = M1 δ(r-R) δ(φ-Ωt)
+ M2 δ(r-R) δ(φ-Ωt-π)
L ≈ L0 (1 + 1/2 hxx)
① Compute amplitude [Bonus "heart" 2BH M = 10M☉ D = 100M☉]
② " Energy
③ " rate of change of distance
[Bonus: 2 BHs, M = 10⁸ M☉
L = 0.05 pc
how long for ΔL/L ~ 1% ?]
Liv. Rev. Relat


Black Holes
– governed by 2 (+1?) parameters (M, a, q)
– Hide singularities, stable (ish!)
– Can join but not bifurcate (why?)
– Ultimate state conjecture.
ds² = −(1 − 2m/r) dt² + 1/(1 − 2m/r) dr² + r² dΩ².
QNMs
Kokkotas - Schmidt
Liv. Rev. Relat
Bert. - Cardoso - Starinets
Review
CAUTION

Geodesics

$u^a u_a = -1$ $\qquad k^a k_a = 0$

$\left(\frac{\partial}{\partial t}\right)^a$; $\left(\frac{\partial}{\partial \phi}\right)^a$ $\qquad E = \left(1 - \frac{2M}{r}\right)\frac{dt}{d\tau}$; $L = r^2 \frac{d\phi}{d\tau}$

trajectories: massive particle $\qquad \frac{1}{2}E^2 = \frac{1}{2}\left(\frac{dr}{dt}\right)^2 + V(r)$

with $V(r) = \frac{1}{2} - \frac{M}{r} + \frac{L^2}{2r^2} - \frac{ML^2}{r^3}$

Circular orbits

$\rightarrow \exists$ circ. orbits "stable" if $r \geq 6M$

$L = 0.05\,pc$

for $\frac{\Delta L}{L} \sim 1\%$?

(M, a, q)

QNMs

Kokkotas - Schmidt
Liv. Rev. Relat

Bert. - Cardoso - Starinets
Review

Geodesics $\quad u^a u_a = -1 \qquad k^a k_a = 0$

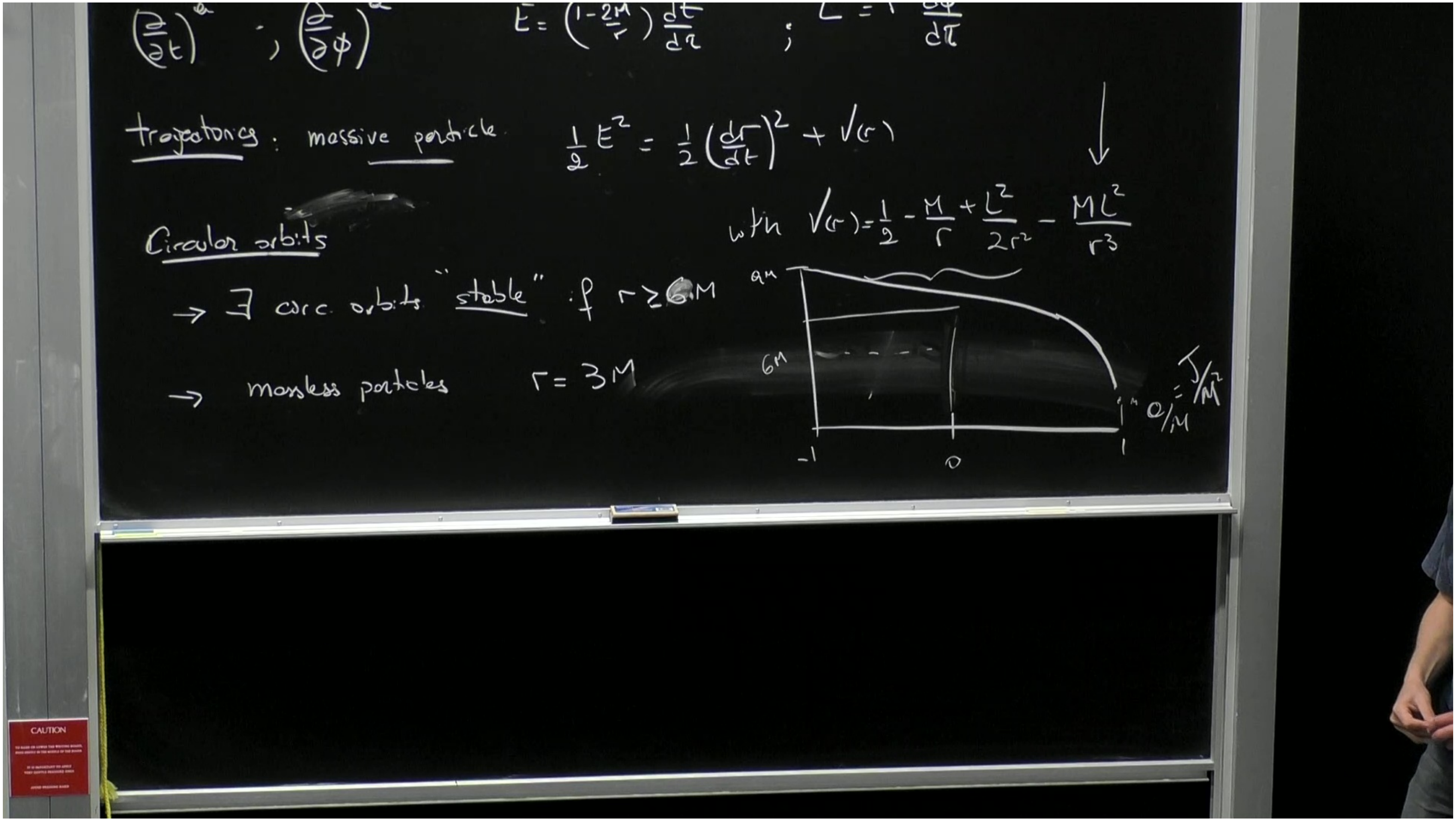
$$\left(\frac{\partial}{\partial t}\right)^a \; ; \; \left(\frac{\partial}{\partial \phi}\right)^a \qquad E = \left(1 - \frac{2M}{r}\right)\frac{dt}{d\tau} \quad ; \quad L = r^2 \frac{d\phi}{d\tau}$$

trajectories : massive particle $\quad \frac{1}{2}E^2 = \frac{1}{2}\left(\frac{dr}{d\tau}\right)^2 + V(r)$

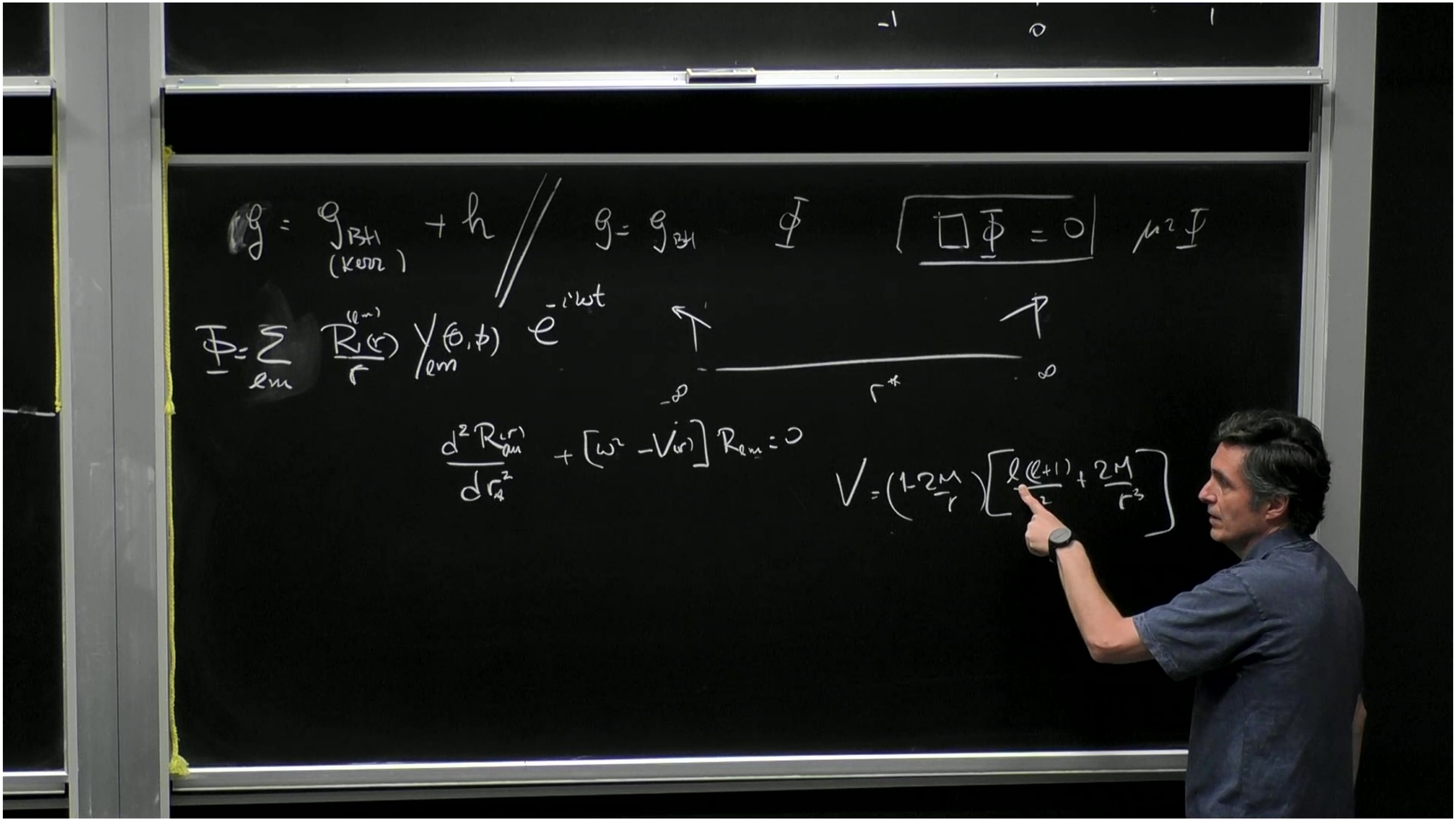
Circular orbits $\qquad$ with $V(r) = \frac{1}{2} - \frac{M}{r} + \frac{L^2}{2r^2} - \frac{ML^2}{r^3}$

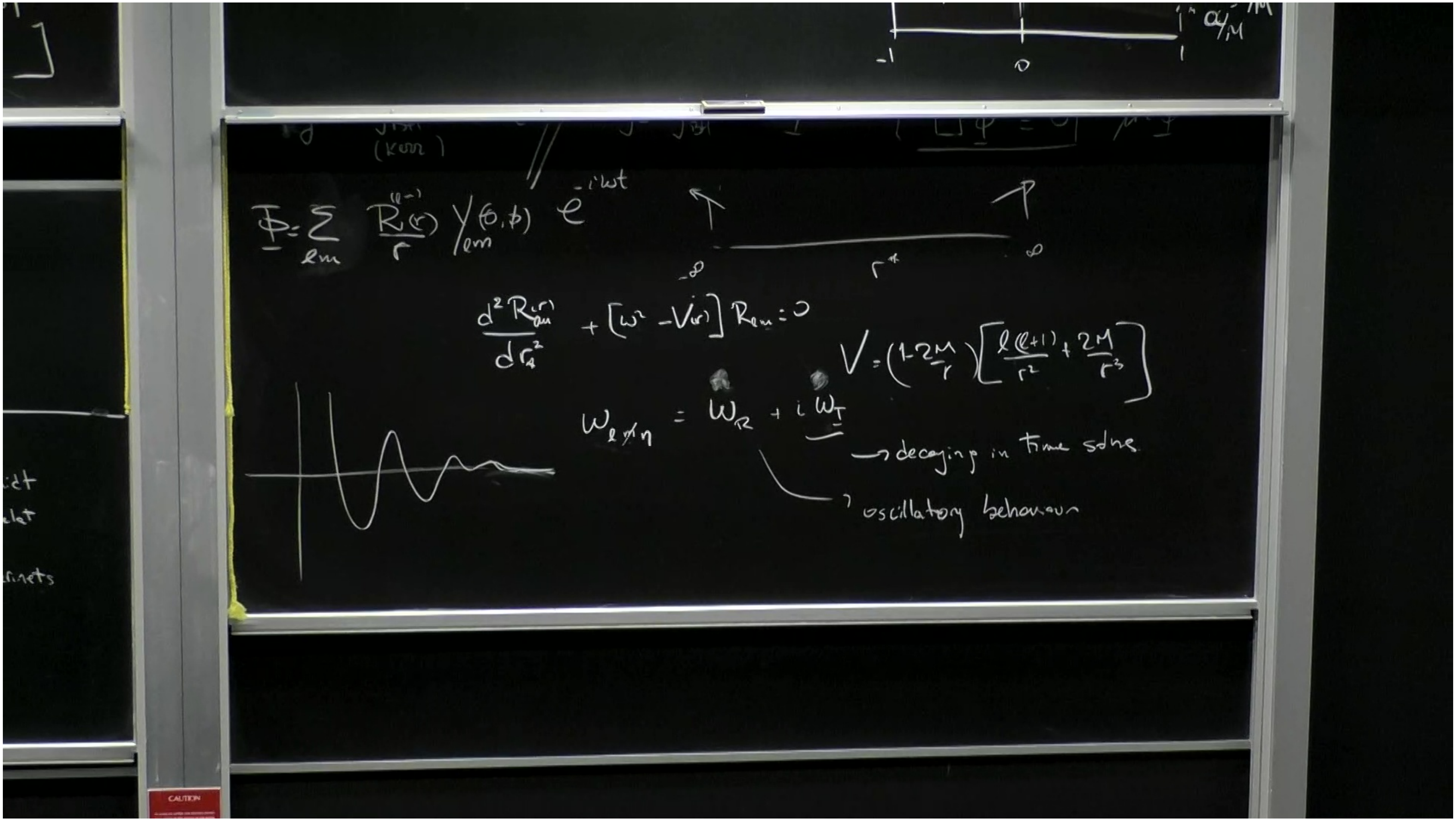
→ ∃ circ. orbits "stable" if $r \geq 6M$

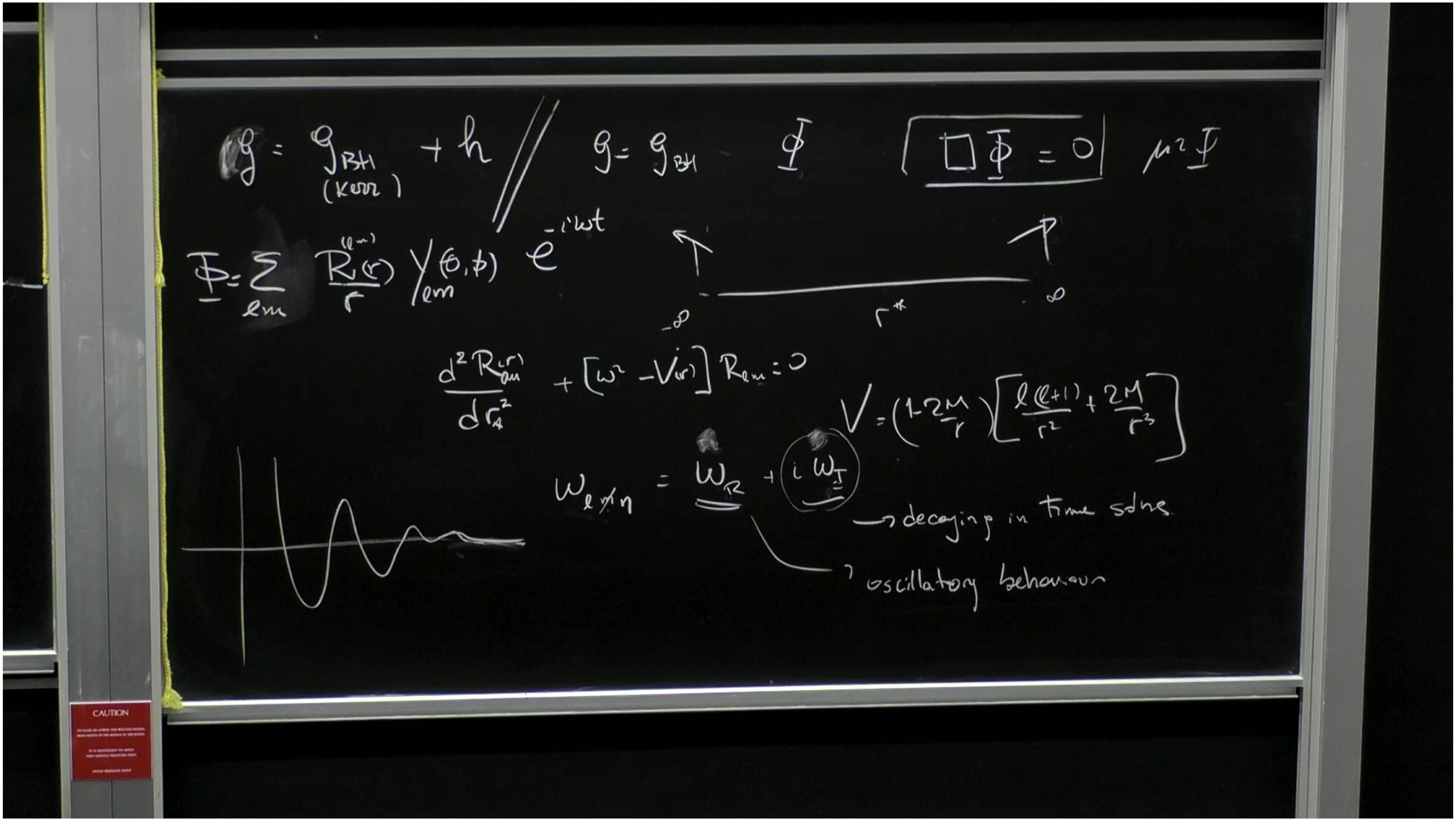
→ massless particles $\quad r = 3M \quad$ Light ring / photon sphere

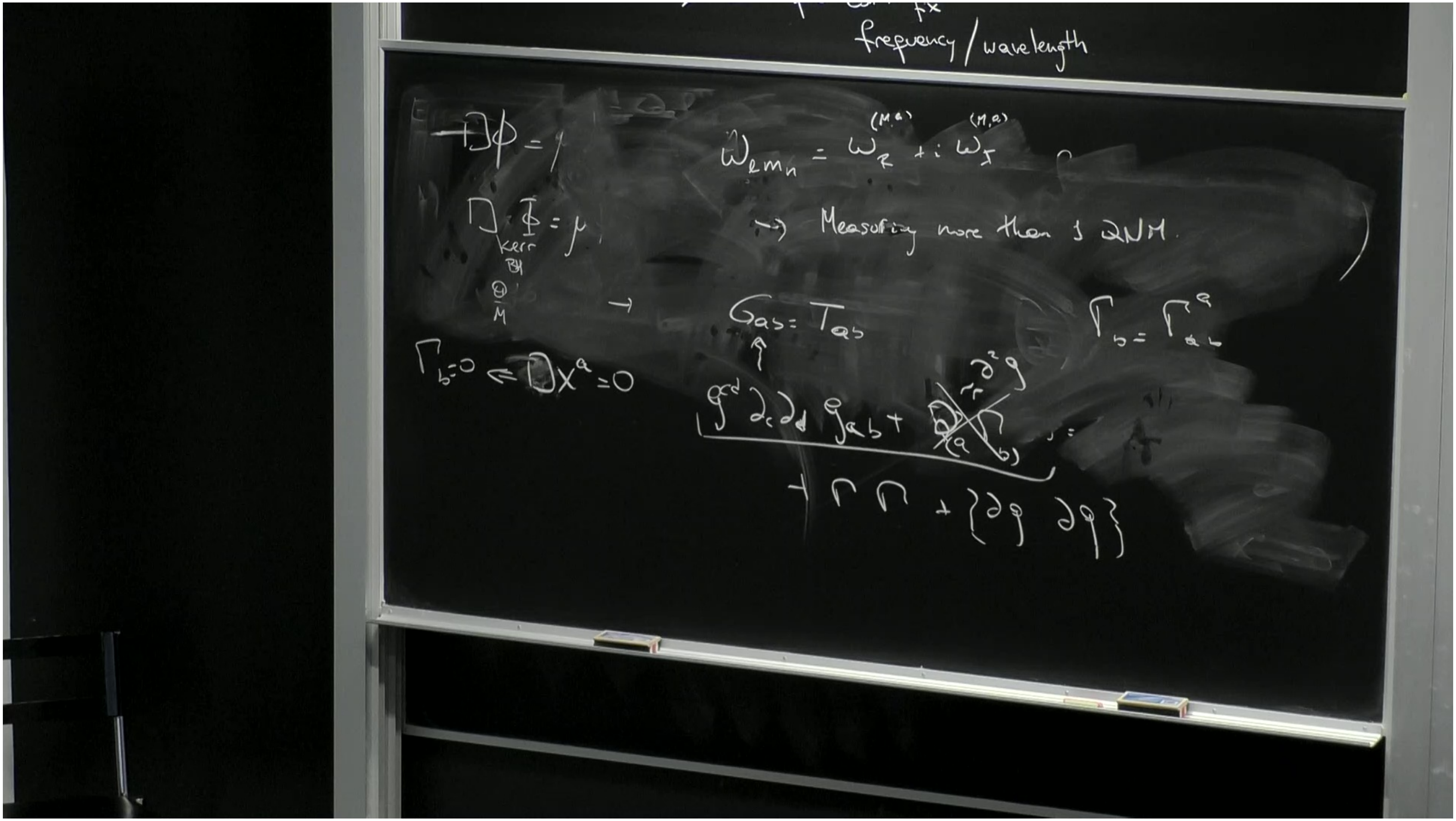


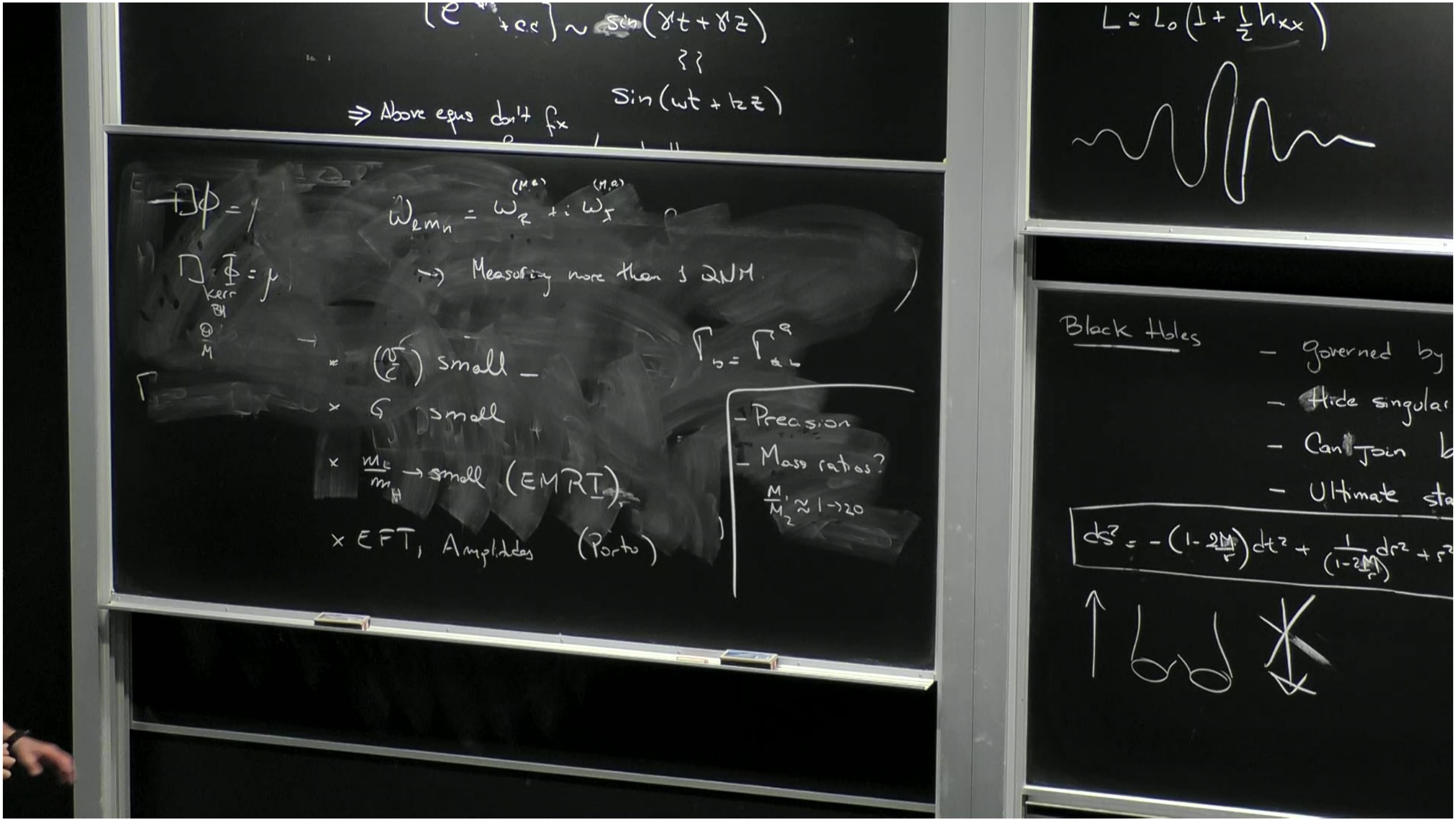
$\left(\frac{\partial}{\partial t}\right)^a$; $\left(\frac{\partial}{\partial \phi}\right)^a$
$E = \left(1 - \frac{2M}{r}\right)\frac{dt}{d\tau}$;
trajectories : massive particle
$\frac{1}{2}E^2 = \frac{1}{2}\left(\frac{dr}{dt}\right)^2 + V(r)$
with $V(r) = \frac{1}{2} - \frac{M}{r} + \frac{L^2}{2r^2} - \frac{ML^2}{r^3}$
Circular orbits
→ ∃ circ. orbits "stable" if r ≥ 6M
→ massless particles r = 3M
9M
6M
-1
0
1
J/M²
a/M


g = g_BH (Kerr) + h
g = g_BH
□Φ = 0
μ²Φ
Φ = Σ_lm R^(lm)(r)/r Y_lm(θ,φ) e^(-iωt)
-∞
r*
∞
d²R_lm(r)/dr*² + [ω² - V(r)] R_lm = 0
V = (1 - 2M/r) [l(l+1)/r² + 2M/r³]


(Kerr)
$\Phi = \sum_{lm} \frac{R_l(r)}{r} Y_{lm}(\theta,\phi)\, e^{-i\omega t}$
$-\infty$
r^*
∞
$\frac{d^2 R_{lm}(r)}{dr_*^2} + [\omega^2 - V(r)] R_{lm} = 0$
$V = \left(1 - \frac{2M}{r}\right)\left[\frac{l(l+1)}{r^2} + \frac{2M}{r^3}\right]$
$\omega_{lmn} = \omega_R + i\,\omega_I$
→ decaying in time solns
→ oscillatory behaviour


$g = g_{BH} + h$
(Kerr)
$g = g_{BH}$
Φ
$\Box \Phi = 0$
$\mu^2 \Phi$
$\Phi = \sum_{lm} \frac{R^{(lm)}(r)}{r} Y_{lm}(\theta, \phi) e^{-i\omega t}$
$-\infty$
r^*
∞
$\frac{d^2 R_{lm}(r)}{dr_*^2} + [\omega^2 - V(r)] R_{lm} = 0$
$V = \left(1 - \frac{2M}{r}\right)\left[\frac{l(l+1)}{r^2} + \frac{2M}{r^3}\right]$
$\omega_{lmn} = \omega_R + i\,\omega_I$
→ decaying in time scales
→ oscillatory behaviour


frequency / wavelength
Measuring more than 1 QNM
Kerr
BH
Gab = Tab


Above eqns don't fix
Measuring more than 1 QNM
small
small
small (EMRI)
EFT, Amplitudes (Porto)
Precision
Mass ratios?
Black Holes
Governed by
Hide singular
Can join
Ultimate