Black Holes everywhere

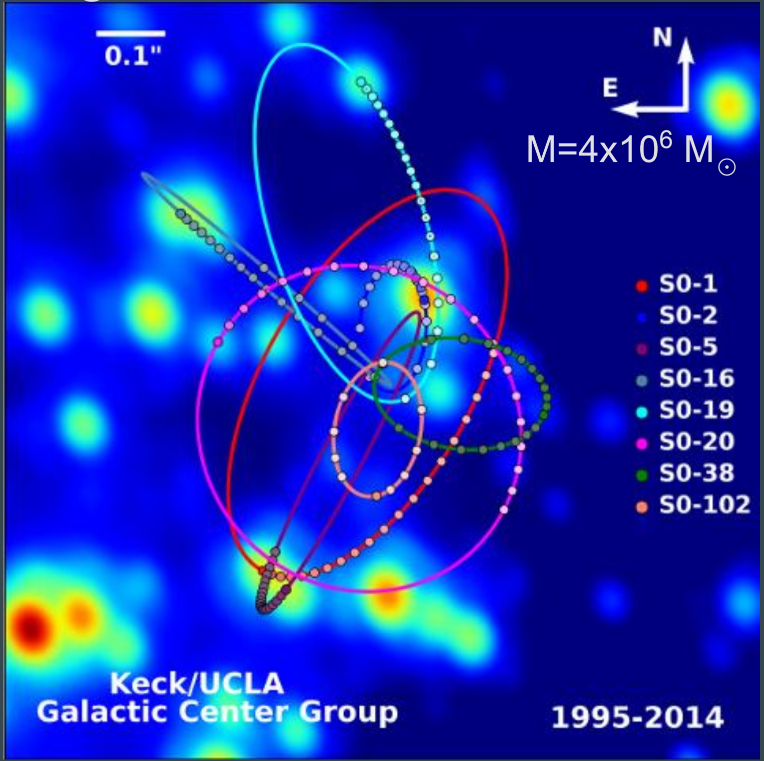
Alexander Kusenko
(UCLA and Kavli IPMU)

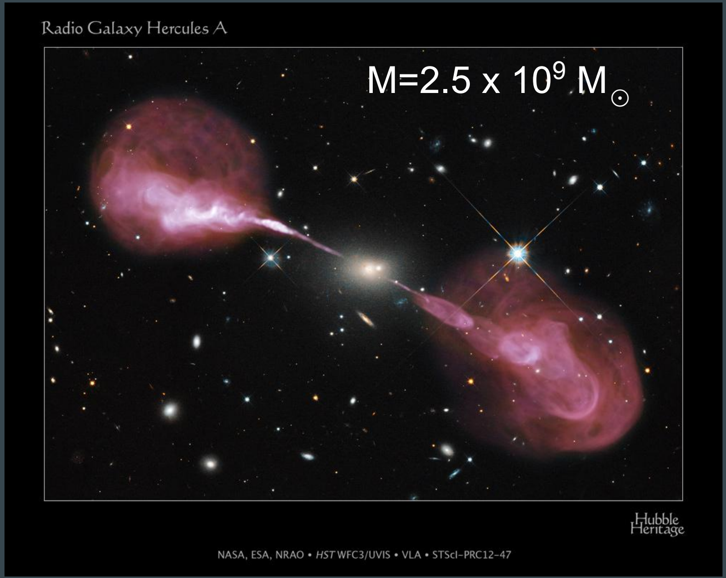
Kavli IPMU colloquium, November 26, 2019

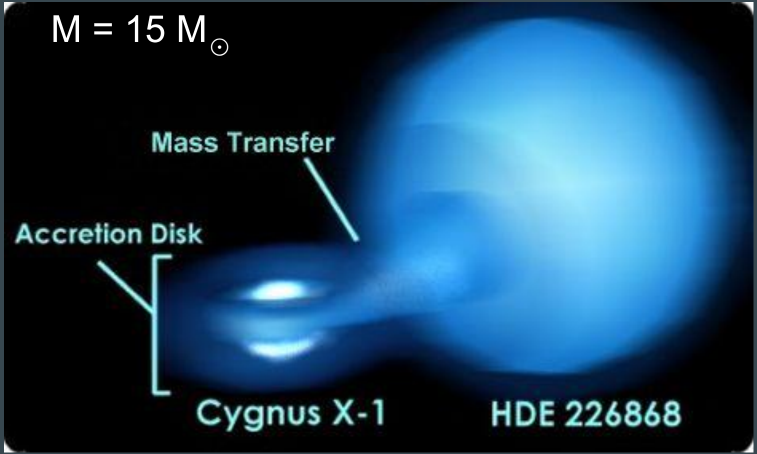
Supported by U.S. DOE Office of Science (HEP), and WPI, Japan

Some famous black holes

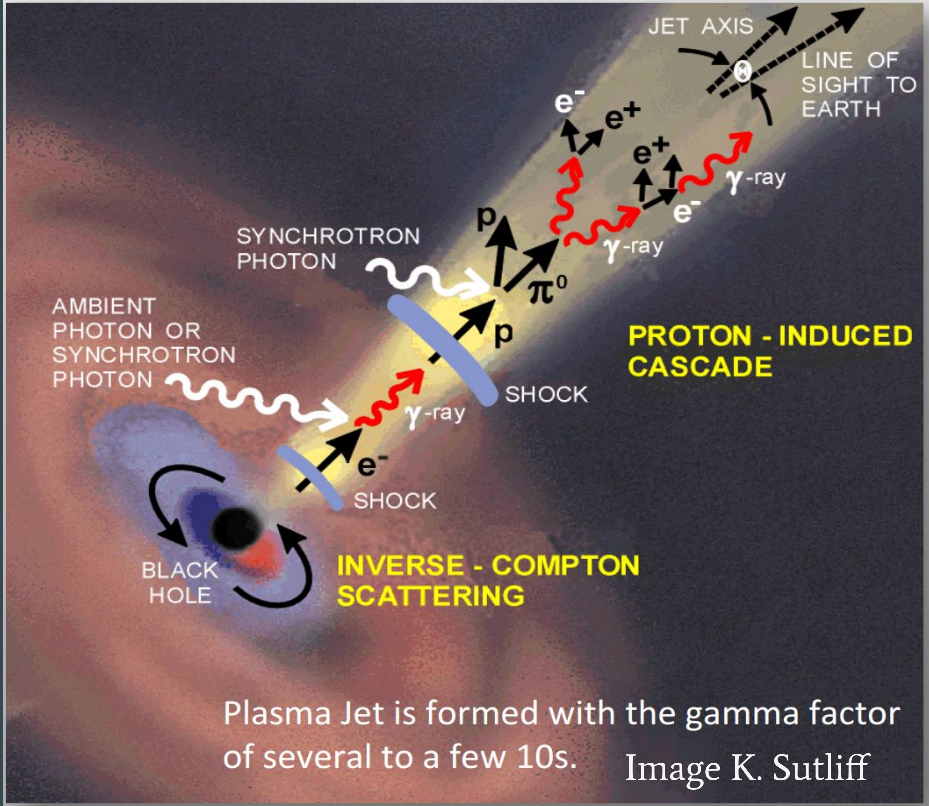
Sagittarius A*

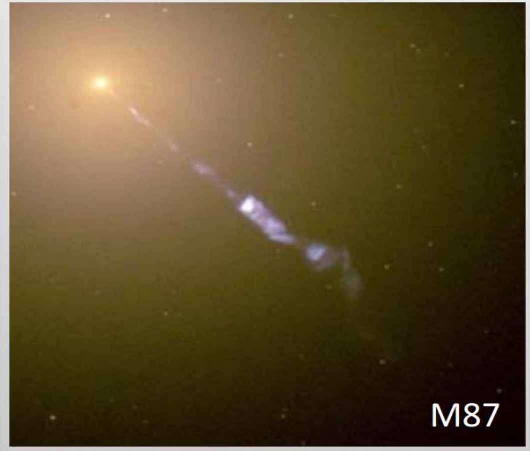


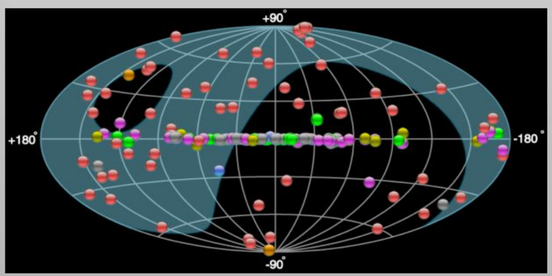




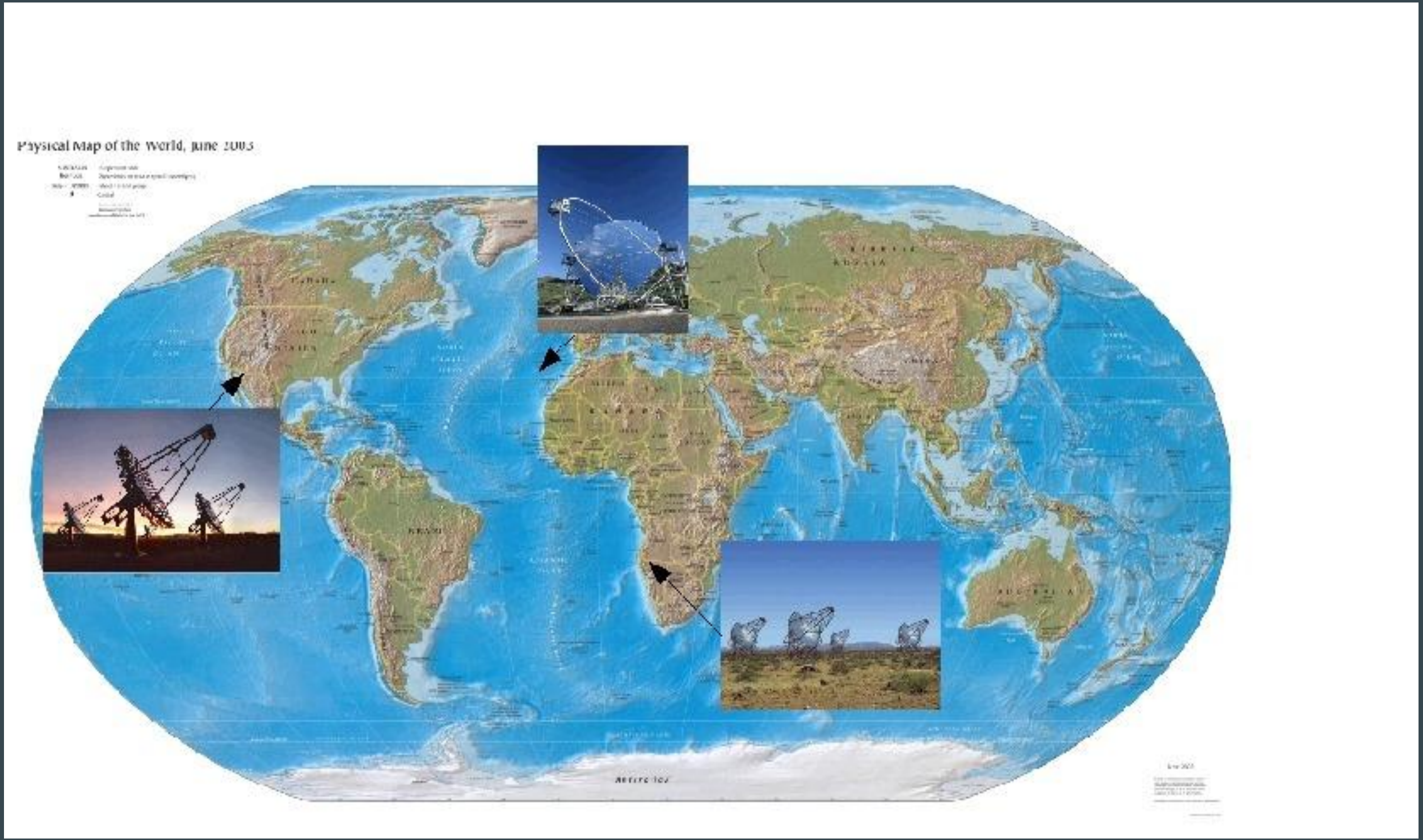
Blazars: supermassive black holes with a jet



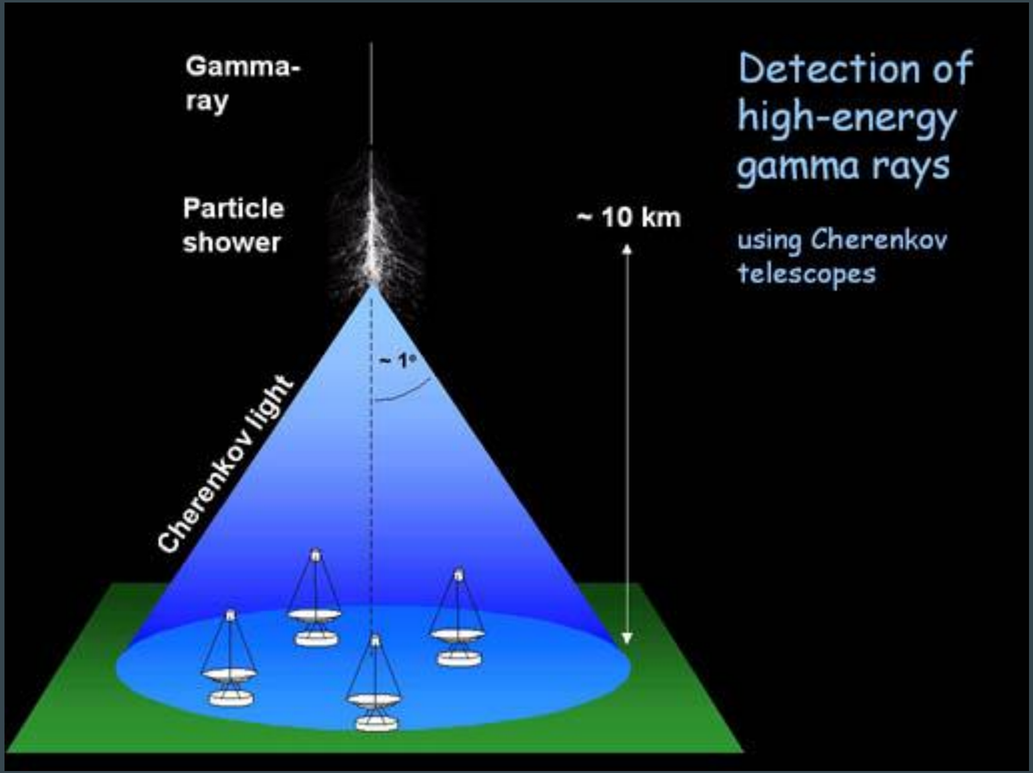




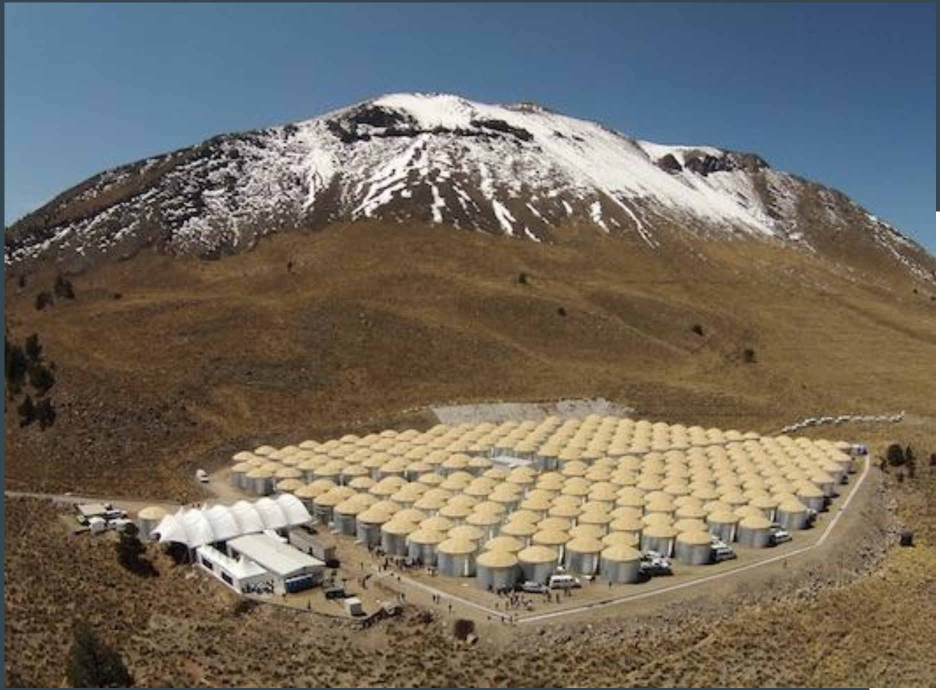
Atmospheric Cherenkov Telescopes

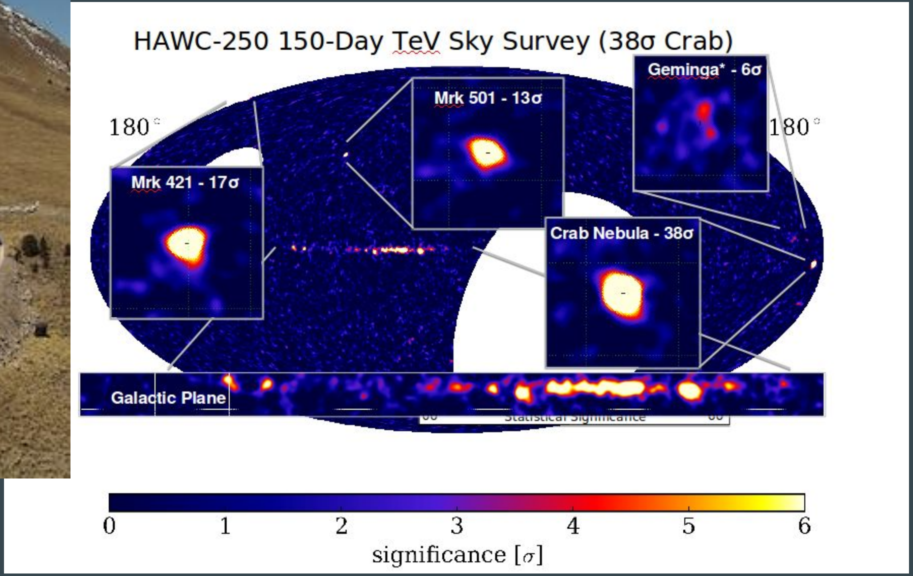


Atmospheric Cherenkov Telescopes



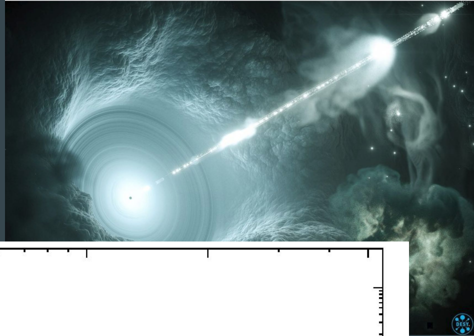
HAWC

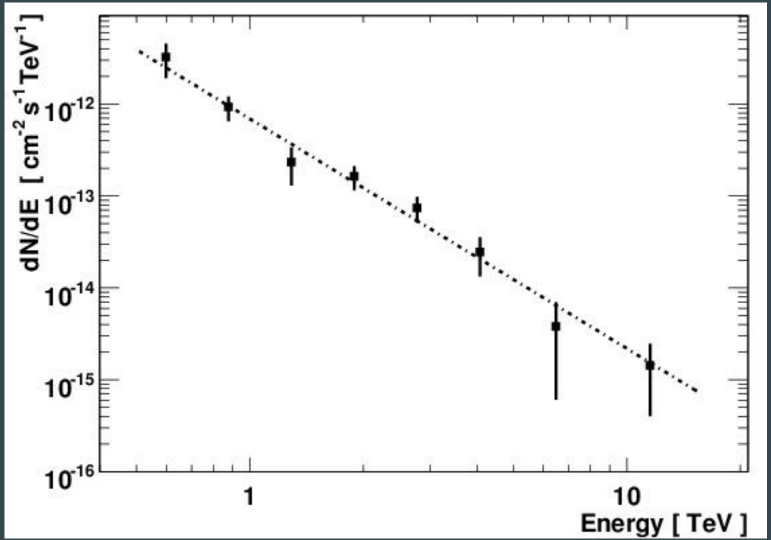



HAWC-250 150-Day TeV Sky Survey (38σ Crab)
Geminga* - 6σ
Mrk 501 - 13σ
180°
180°
Mrk 421 - 17σ
Crab Nebula - 38σ
Galactic Plane
0
1
2
3
4
5
6
significance [σ]

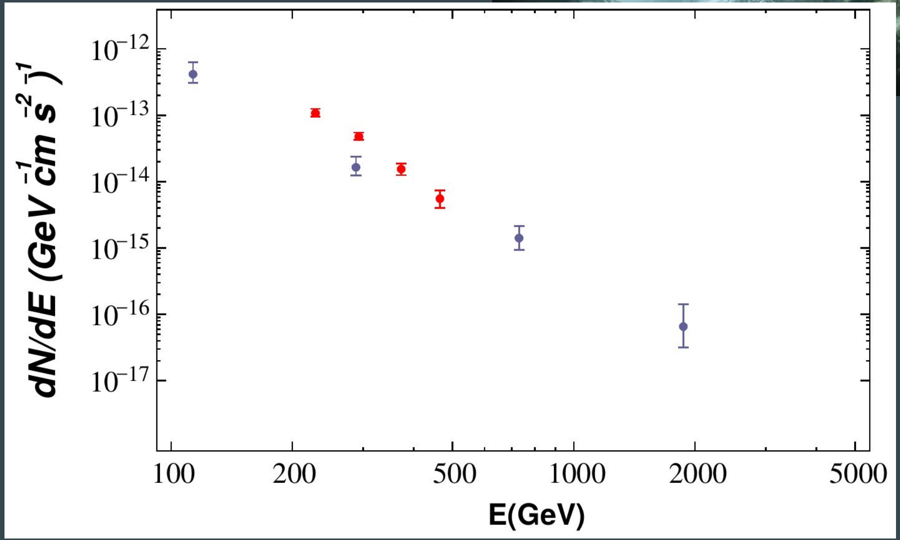
Fermi gamma-ray space telescope

HESS(black), MAGIC (blue), VERITAS (red)



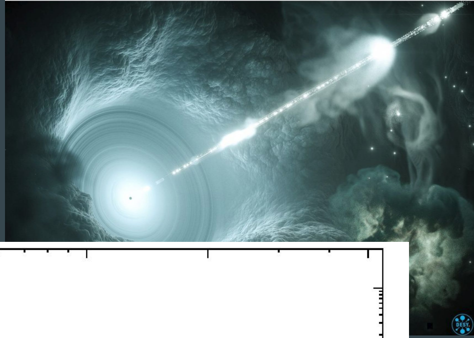


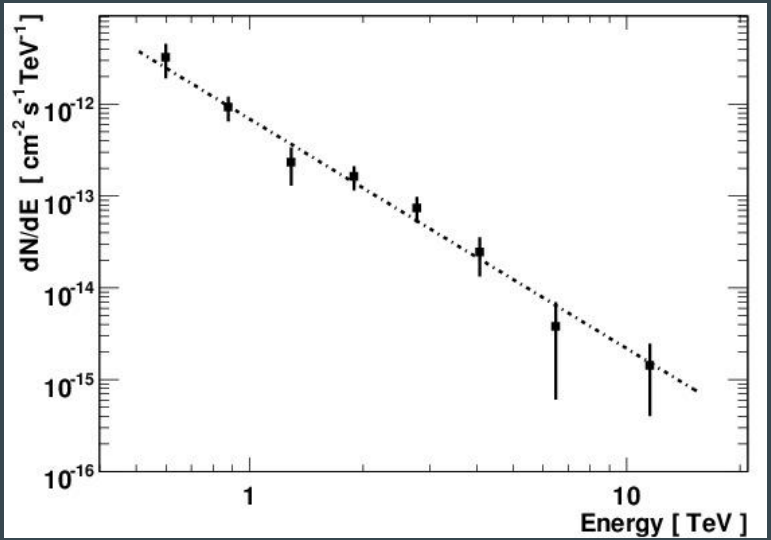
1 ES0229+200 (z=0.14)



3C66A (z=0.44)

HESS(black), MAGIC (blue), VERITAS (red)





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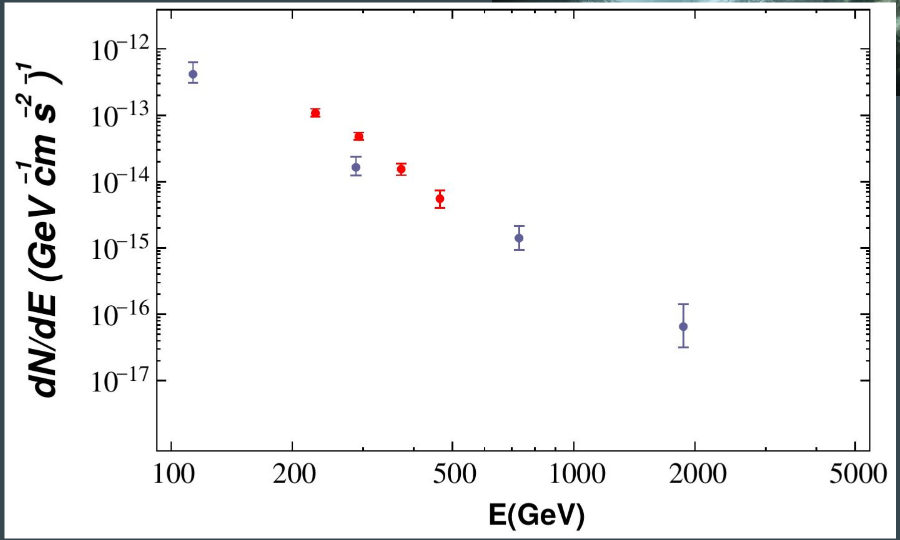
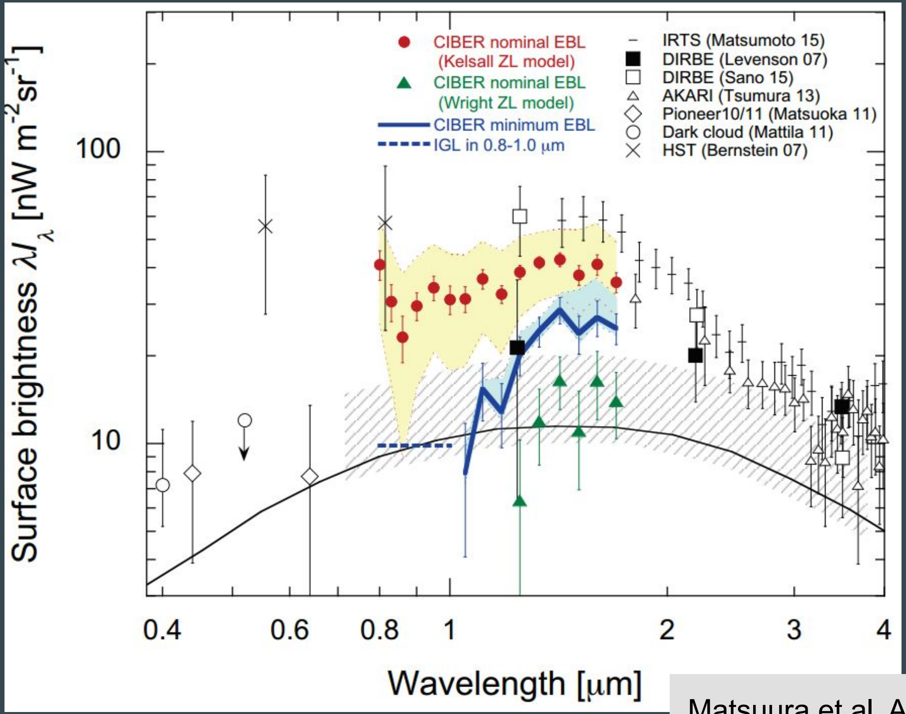


3C66A (z=0.44)

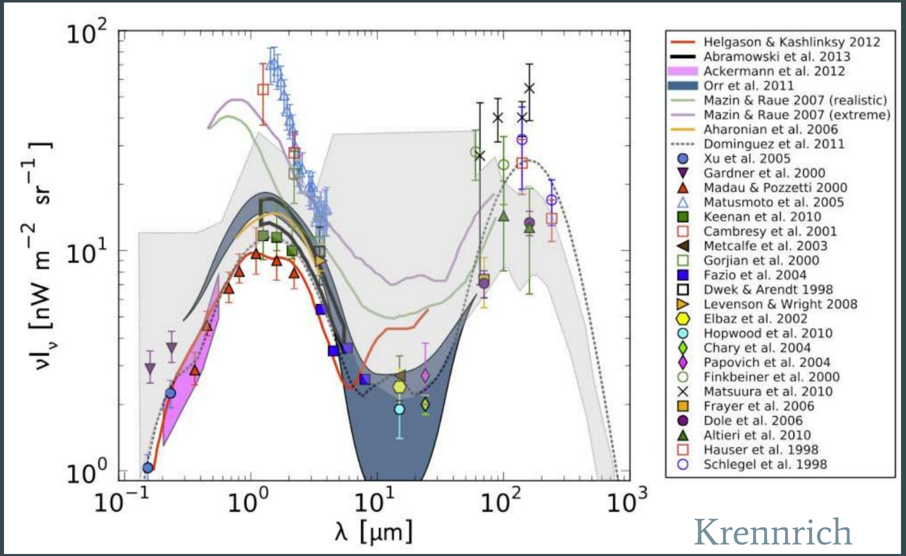
Theory: "we predict a sharp cutoff between 0.1 and 1 TeV" Stecker, et al. (1992)

Data: no sign of absorption due to $\gamma\gamma_{EBL} \rightarrow e^{+}e^{-}$

Extragalactic background light



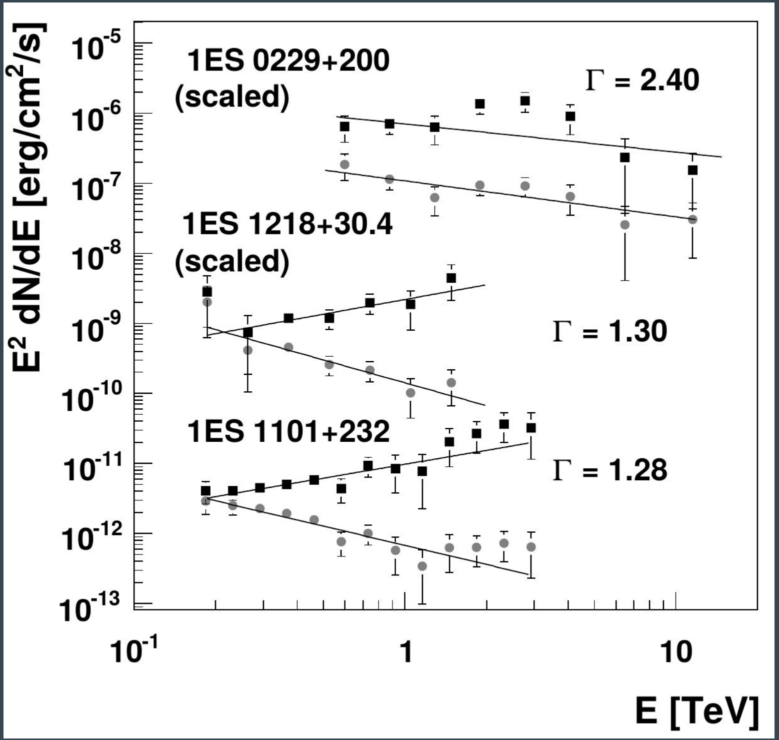
Matsuura et al. ApJ 839,7,2017



Krennrich

Interactions with EBL must degrade the energies of TeV photons: $\gamma\gamma_{EBL} \rightarrow e^+e^-$

Distant blazars: implausibly hard spectra?

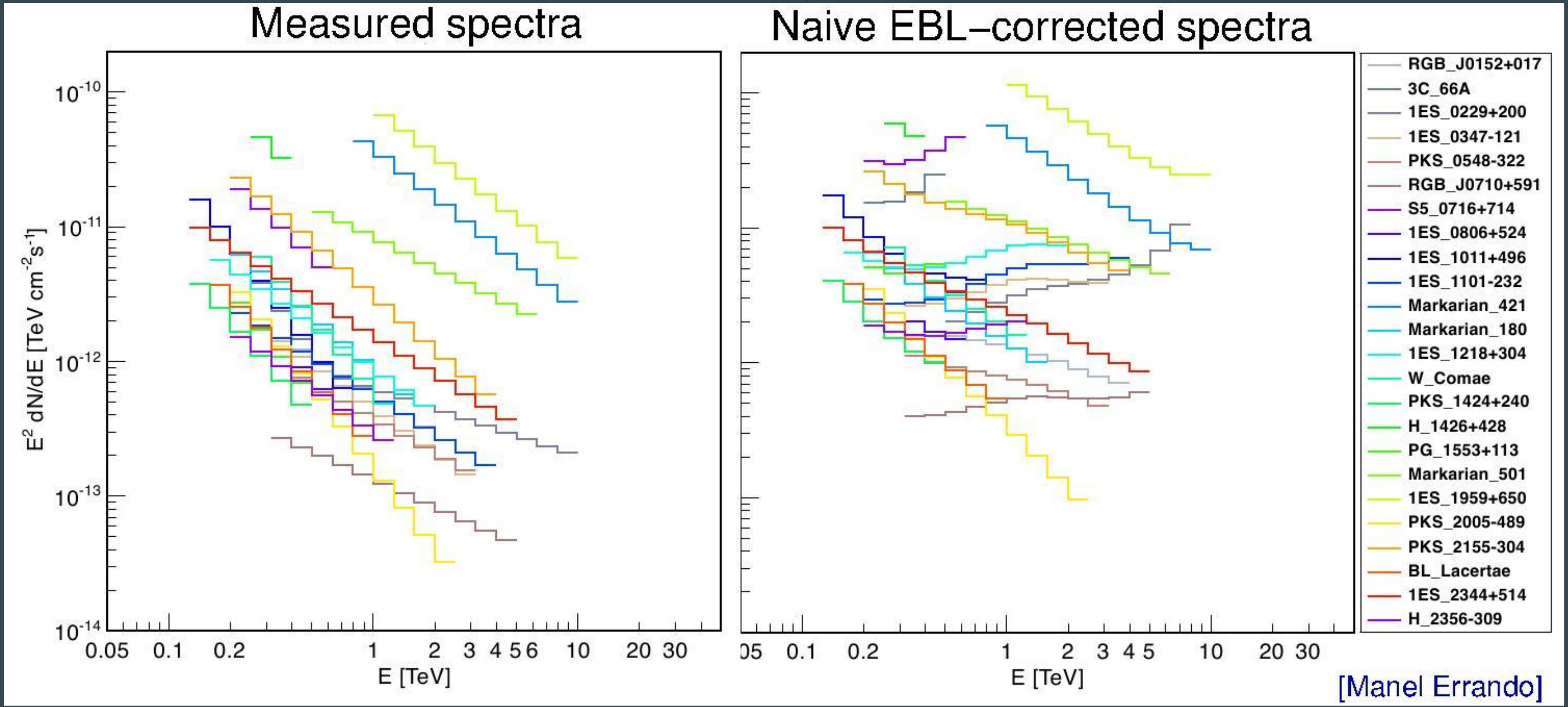


Absorption-corrected spectra would have to be extremely hard for distant blazars:

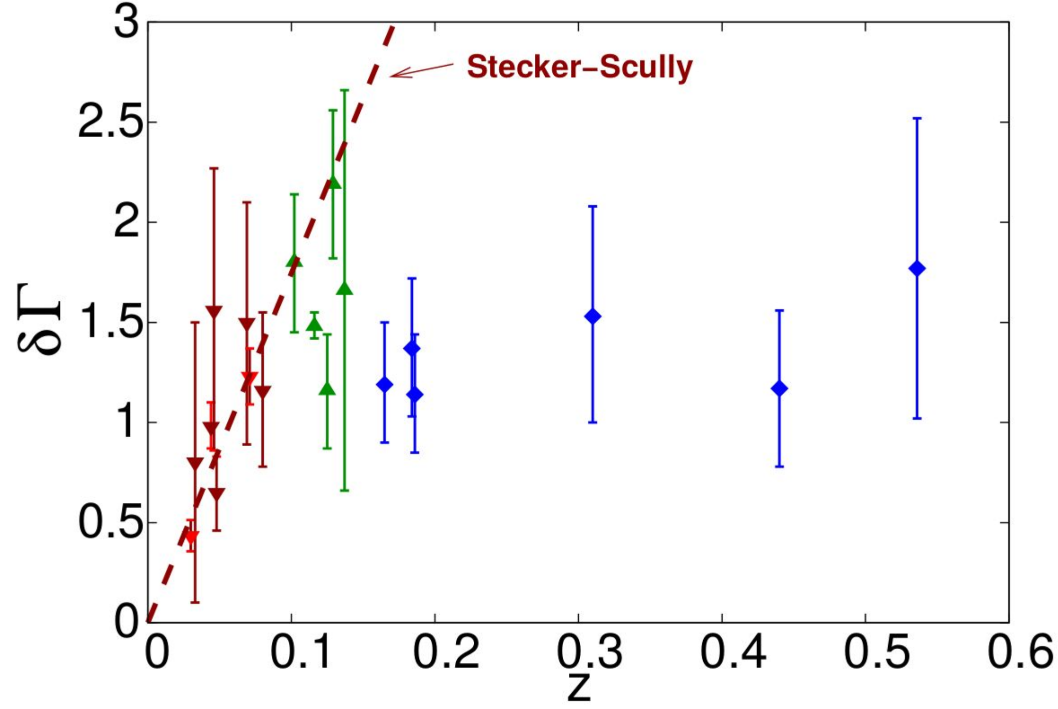
$$\Gamma < 1.5$$

[Aharonian et al.]

Blazar spectra



Spectral softening: problem with distant blazars



$\delta\Gamma = \Gamma_{\mathrm{GeV}} - \Gamma_{\mathrm{TeV}}$ [Stecker, Scully]

Analytical predictions for the spectral softening
work well for the nearby blazars,
but not for distant blazars

The mysterious transparency of the Universe...

- Hypothetical axion-like particles: photons convert into them in magnetic fields near the source, and they convert back to gamma rays? [de Angelis et al.]
- Violation of the Lorentz invariance suppresses the pair production? [Stecker, Glashow; etc.] $\gamma\gamma_{EBL} \rightarrow e^+e^-$

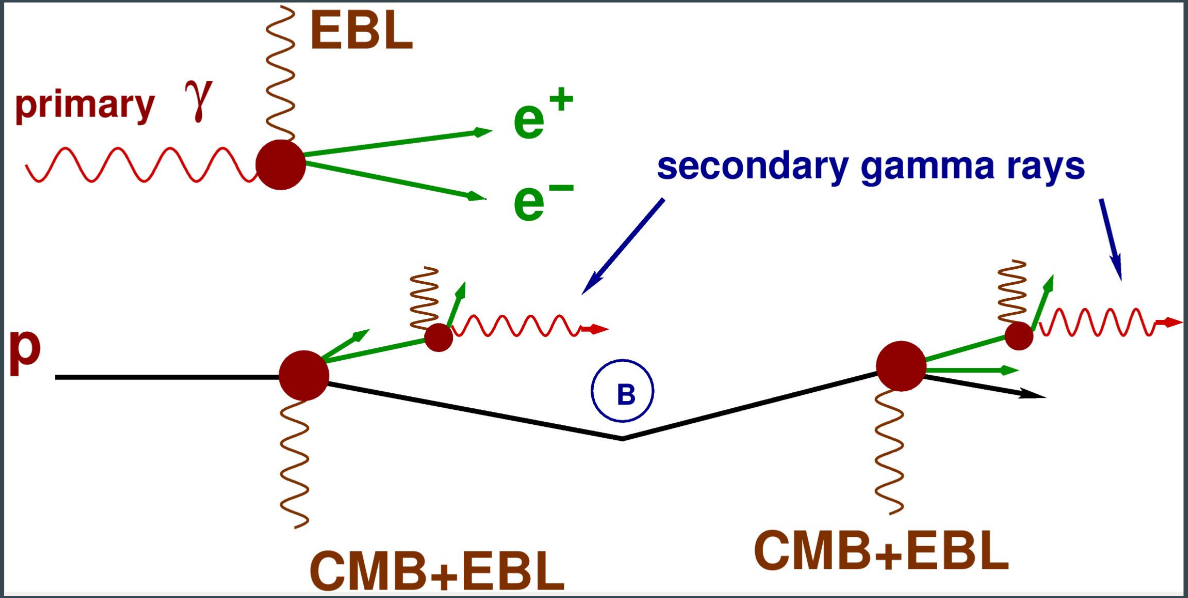
New physics is an exciting possibility,

but can there be a more conventional explanation?

Warren Essey

then UCLA graduate student

Gamma rays and cosmic rays



Secondary gamma rays from line-of-sight interactions of CRs

[Essey & AK (2010)]

Different scaling

$$F_{\text{primary},\gamma}(d) \propto \frac{1}{d^2}\exp\{-d/\lambda_\gamma\}$$

$$F_{\text{secondary},\gamma}(d) = \frac{p\lambda_\gamma}{4\pi d^2}\left[1 - e^{-d/\lambda_\gamma}\right] \propto \begin{cases} 1/d, & \text{for } d \ll \lambda_\gamma, \\ 1/d^2, & \text{for } d \gg \lambda_\gamma. \end{cases}$$

$$F_{\text{secondary},\nu}(d) \propto (F_{\text{protons}} \times d) \propto \frac{1}{d}.$$

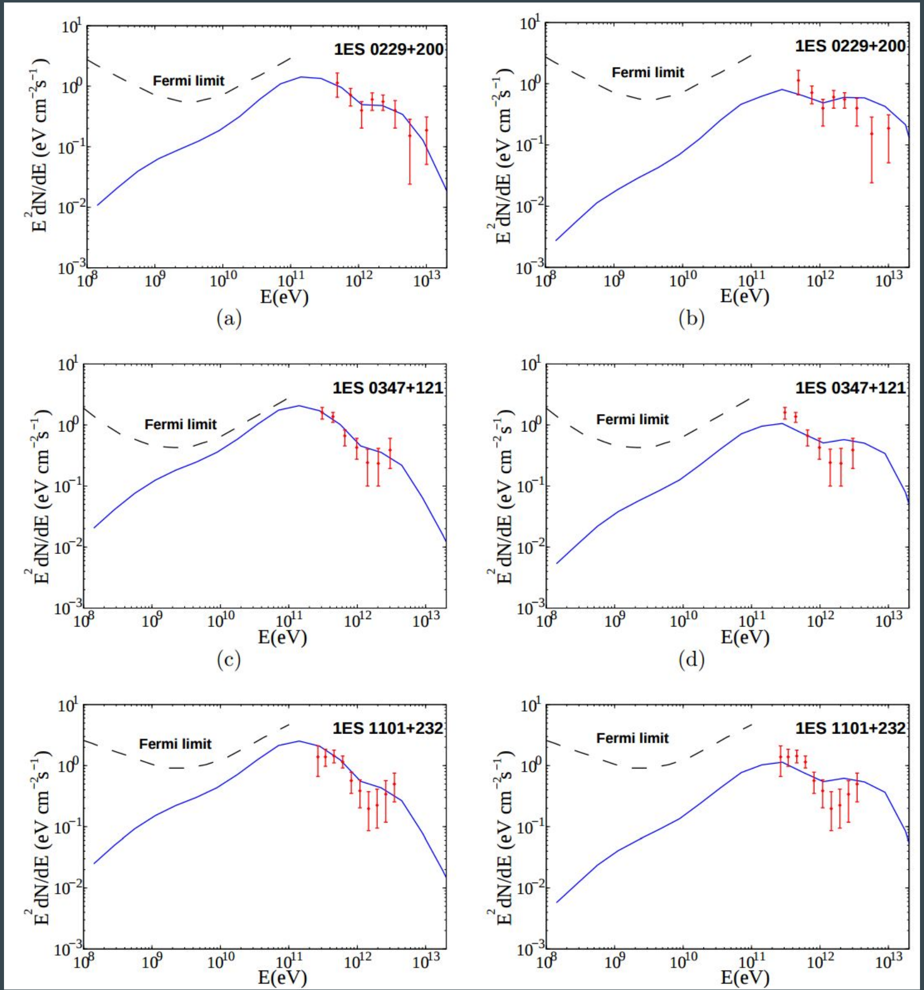
For distant sources, the secondary signal wins!

One-parameter fit (power in CR) for each source
[Essey & AK (2010); Essey, Kalashev, AK, Beacom (2011)]

Good agreement with data for high-redshift blazars (both “high” and “low” EBL models).

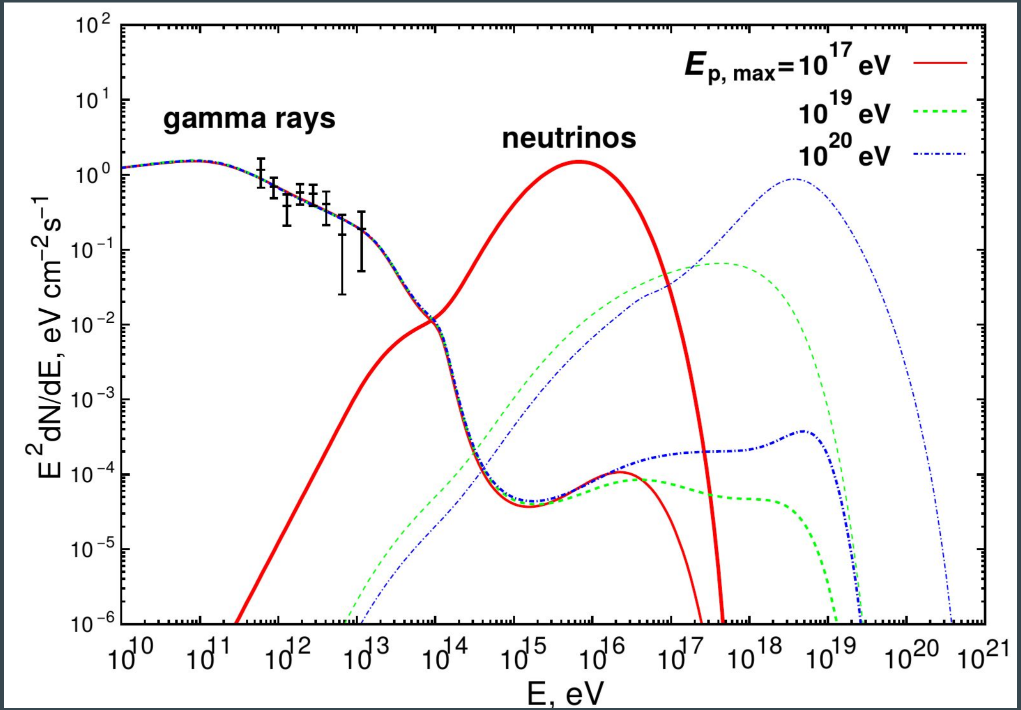
Reasonable CR power for a source up to z~1
[Aharonian, Essey, AK, Prosekin (2013);
Razzaque, Dermer, Finke (2012);
Murase, Dermer, Takami, Migliore (2012)]

Consistent with data on time variability
[Prosekin, Essey, AK, Aharonian (2012)]



Essey, Kalashev, AK, Beacom, ApJ (2011)

Secondary gamma, neutrinos from 1ES0229+200

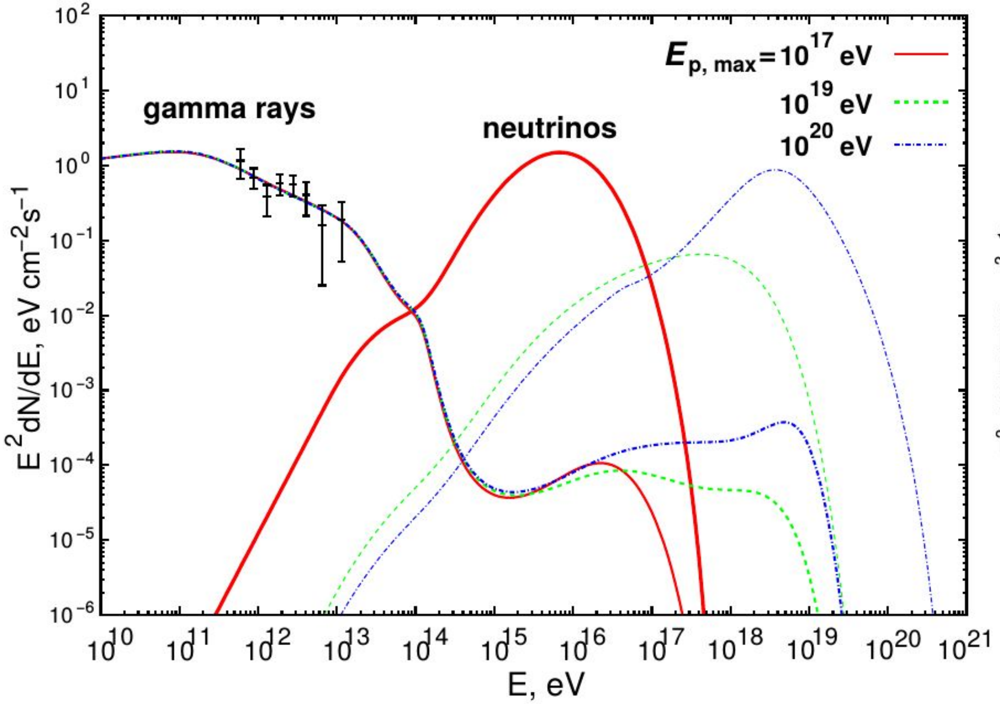


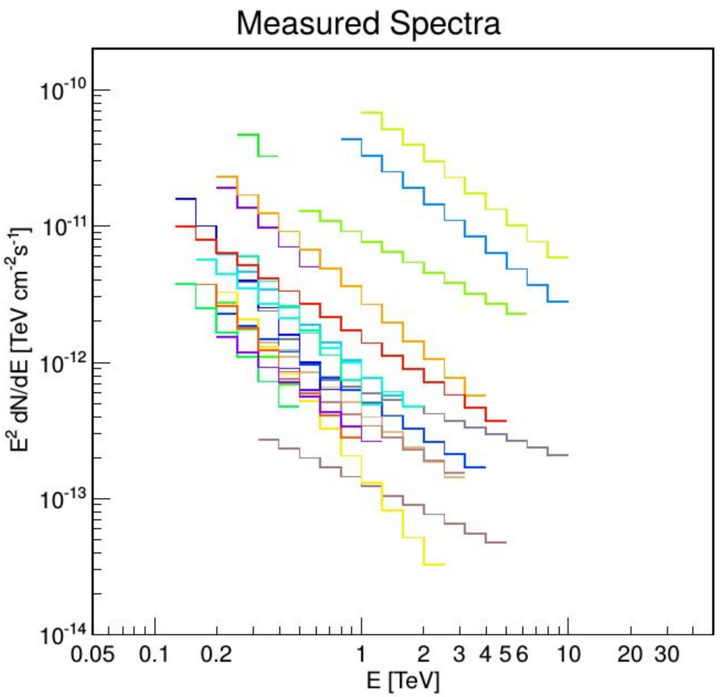
(z=0.14)

- Gamma-ray spectra **robust**
- Neutrino spectra **peaked**

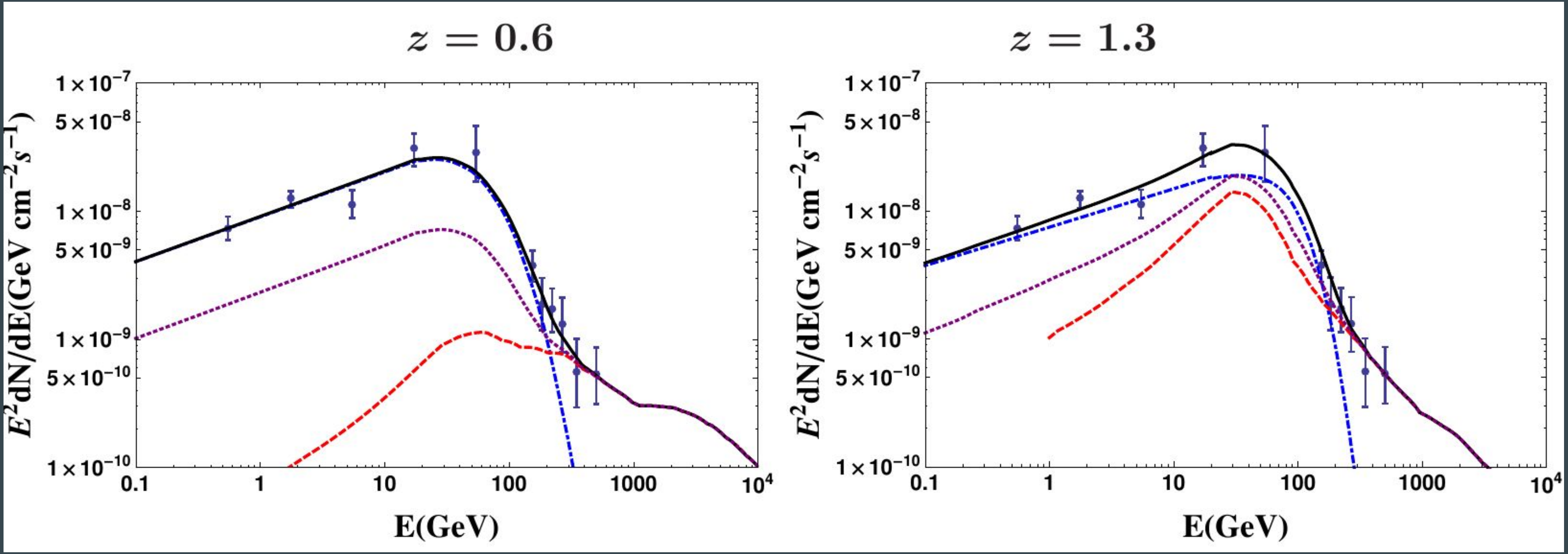
[Essey, Kalshev, AK, Beacom, PRL (2010)]

Robust shapes explain observed universality

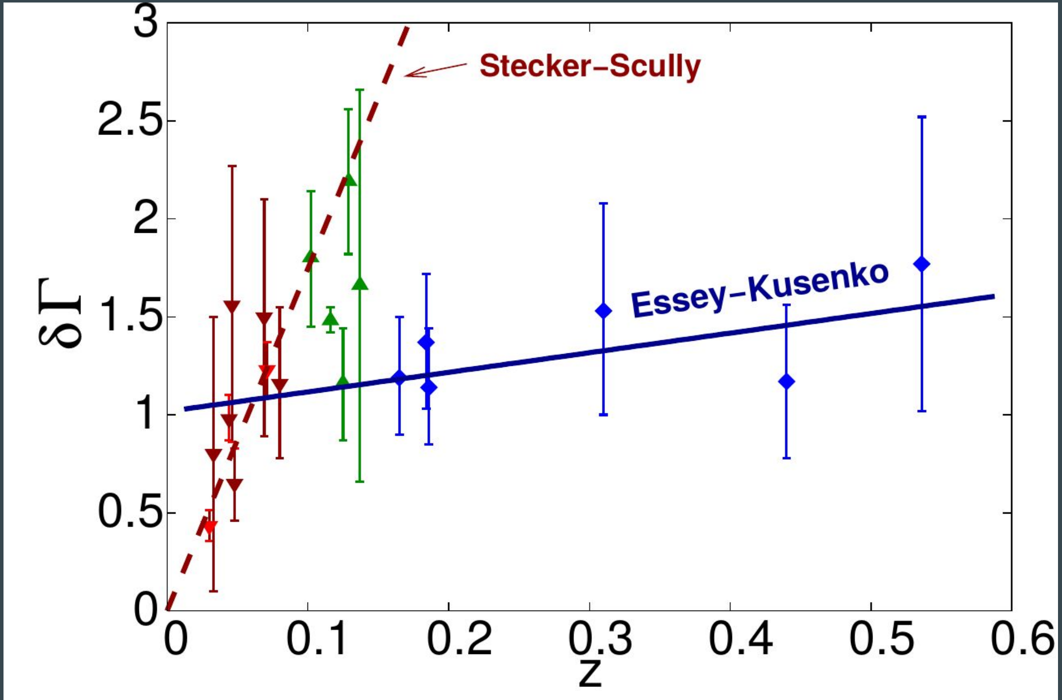




PKS 1424+240 at z>0.6 (the most extreme TeV blazar!)



Spectral softening



$\delta\Gamma = \Gamma_{\mathrm{GeV}} - \Gamma_{\mathrm{TeV}}$

Three populations in red, blue and green are seen in primary, secondary, or mixed components, respectively.

Predictions: no variability for TeV blazars at z>0.15. In good agreement with data. [Prosekin, Essey, AK, Aharonian]

CTA extragalactic survey discovery potential

Cherenkov Telescope Array (CTA)
extragalactic survey will see an enhancement in the number of distant TeV sources, thanks to secondary gamma rays.

[De Franco, Inoue, Sanchez-Conde, Cotter (2017)]

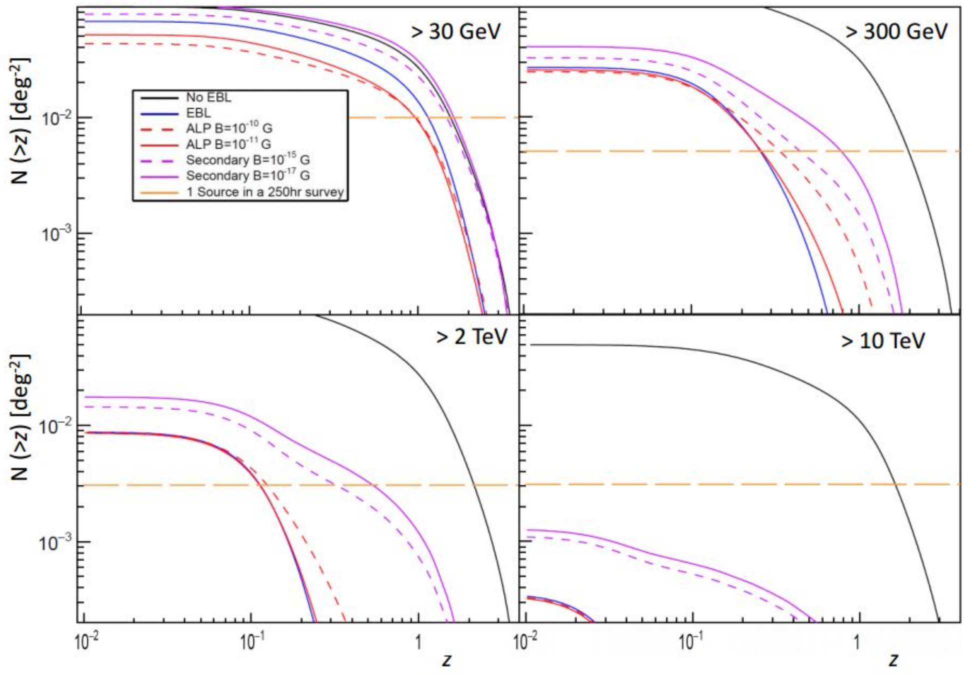
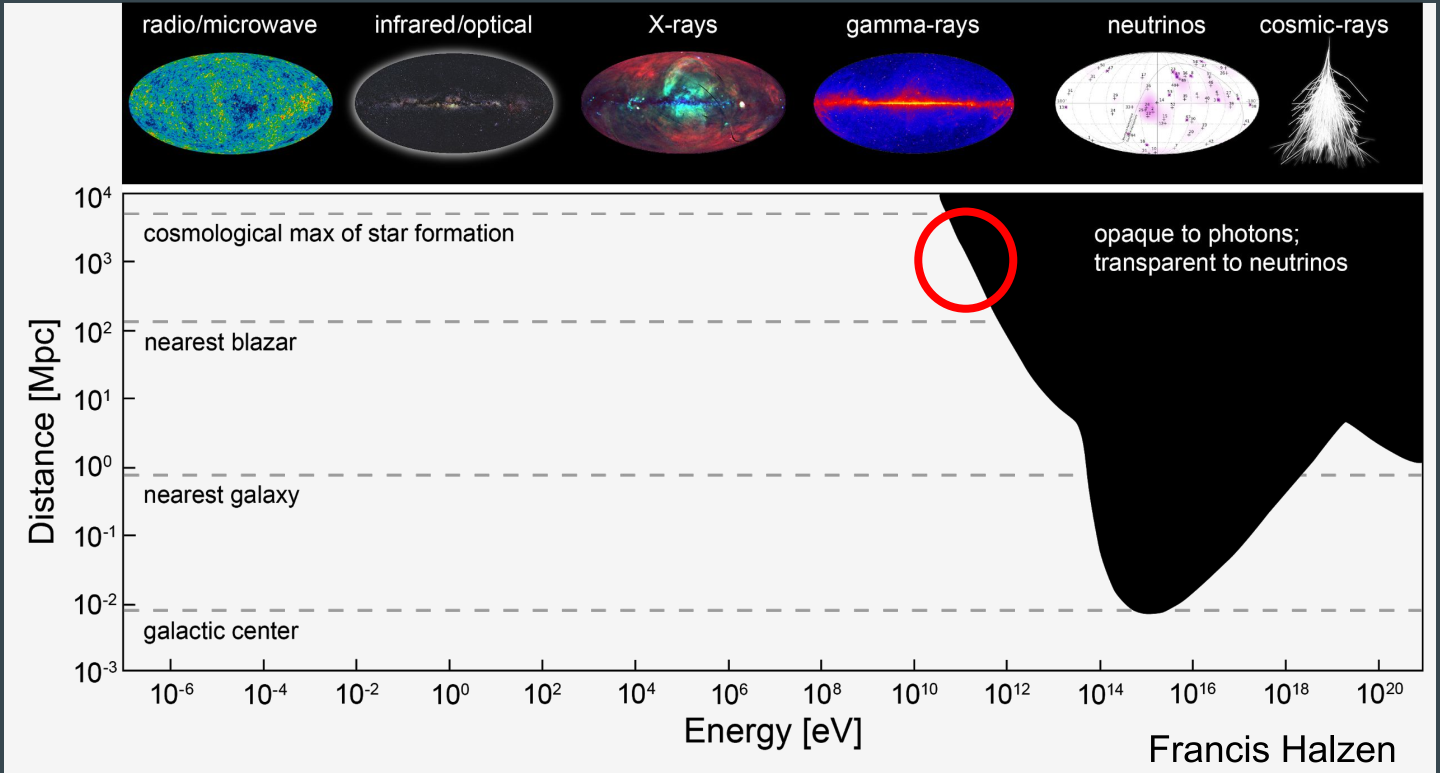


Figure 3: Cumulative source count as a function of redshift for CTA-South, assuming a 5σ integral flux sensitivity and 50 hr exposure observation. Dashed horizontal line represents 1 source detected in a 250 hr survey.

Seeing farther with secondary gamma rays

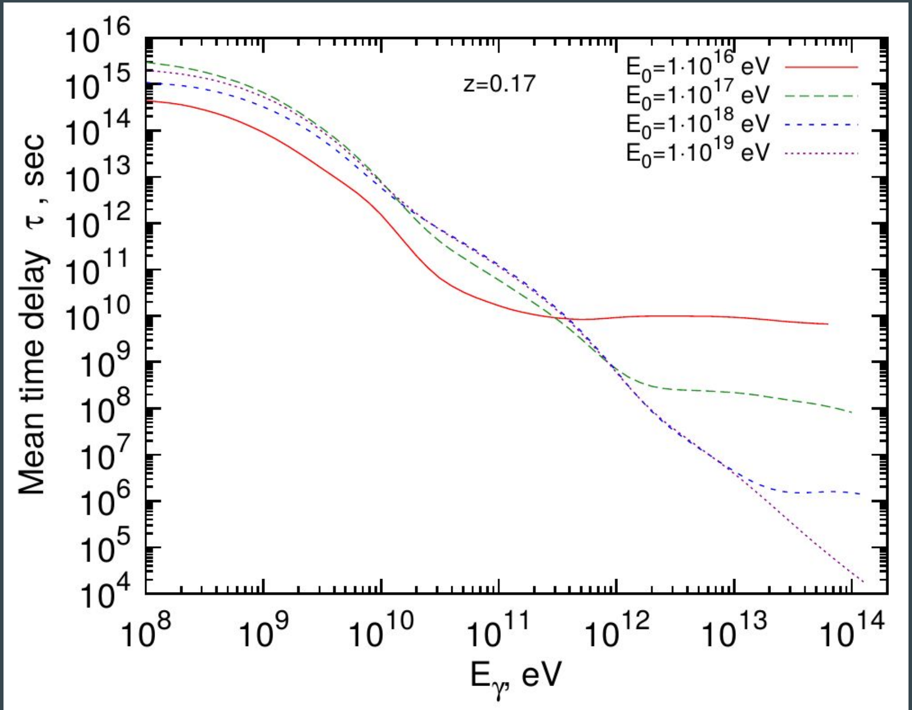


Erosion of time variability for *E>1 TeV, z>0.15*

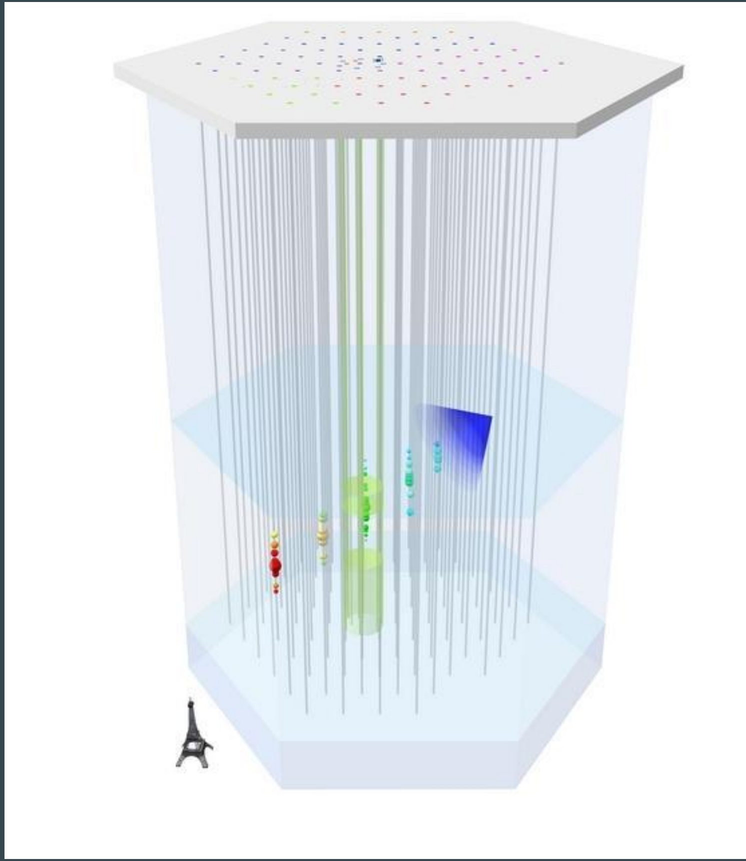
Nearby blazars are variable at all energies. Distant blazars are variable at lower energies, but there is no evidence of variability for, e.g., E>1 TeV, z > 0.15

Prediction: stochastic *pedestal* emerges at high energy, high redshifts, for distant blazars above which some flares may rise in a stochastic fashion.

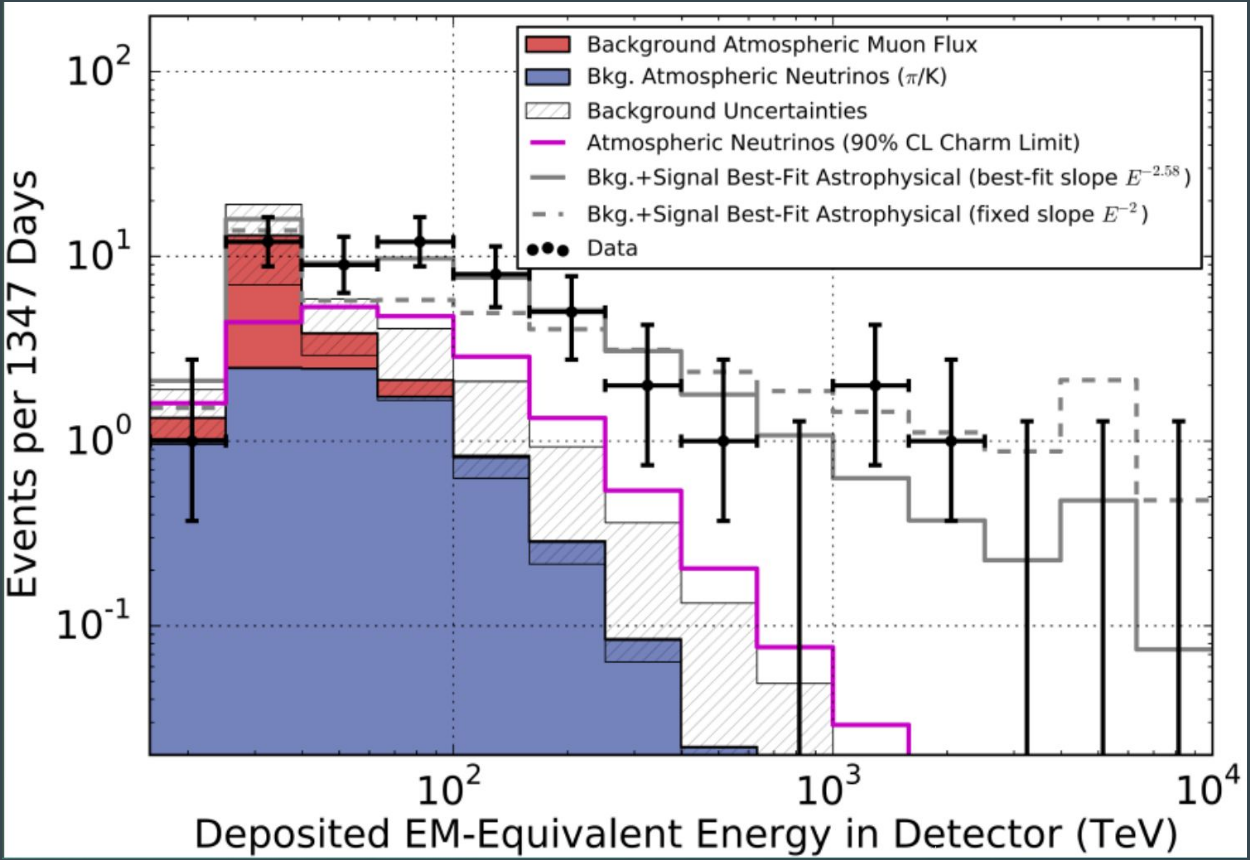
[Prosekin, Essey, AK, Aharonian, ApJ 757 (2012) 183]



IceCube detector



IceCube neutrinos: the spectrum

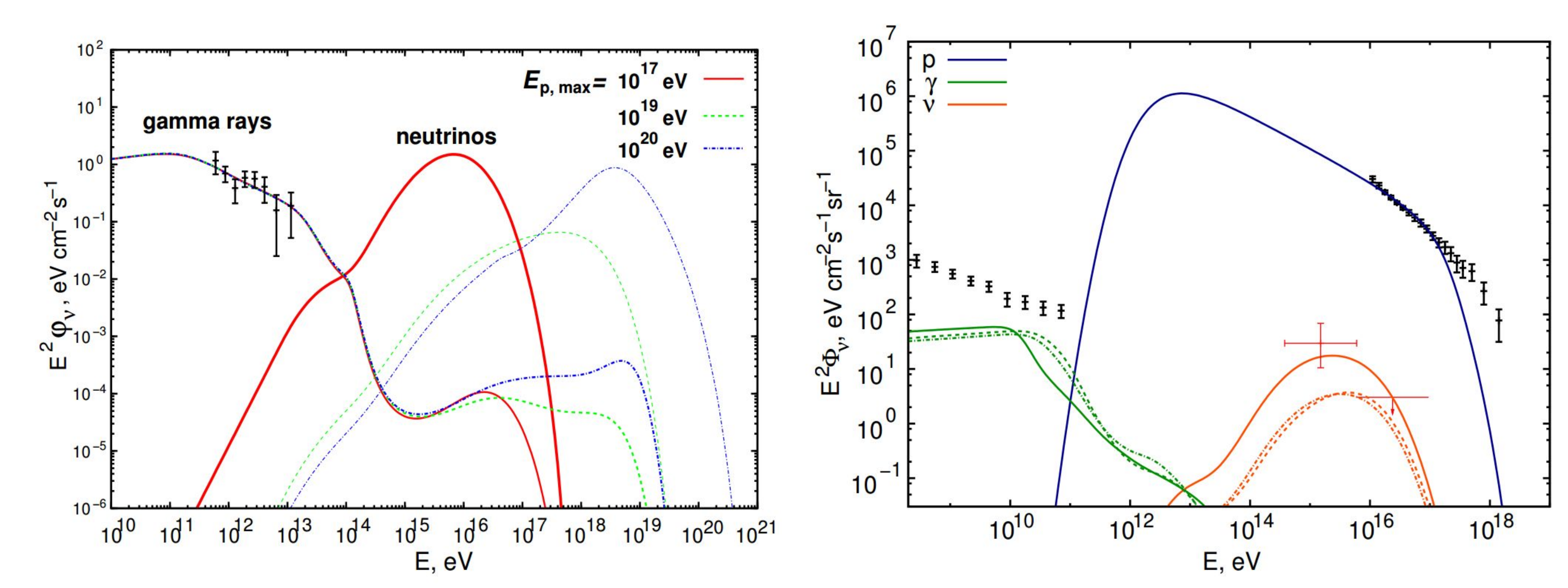


Power law with a cutoff?

Two components?

A peak at 1 PeV?

Line-of-sight interactions of CRs from blazars



Essey et al. Phys.Rev.Lett. 104 (2010) 141102; Kalashev et al., Phys.Rev.Lett. 111 (2013) 4, 041103

A peaked spectrum at 1 PeV can result from cosmic rays accelerated in AGN and interacting with photon backgrounds, assuming that secondary photons explain the observations of TeV blazars.

prediction: PRL 104, 141102 (2010)
consistency with IceCube: PRL 111, 041103 (2013)

PRL **104,** 141102 (2010) PHYSICAL REVIEW LETTERS week ending 9 APRIL 2010

Secondary Photons and Neutrinos from Cosmic Rays Produced by Distant Blazars

Warren Essey,[1] Oleg E. Kalashev,[2] Alexander Kusenko,[1,3] and John F. Beacom[4,5,6]
[1]*Department of Physics and Astronomy, University of California, Los Angeles, California 90095-1547, USA*
[2]*Institute for Nuclear Research, 60th October Anniversary Prospect 7a, Moscow 117312 Russia*
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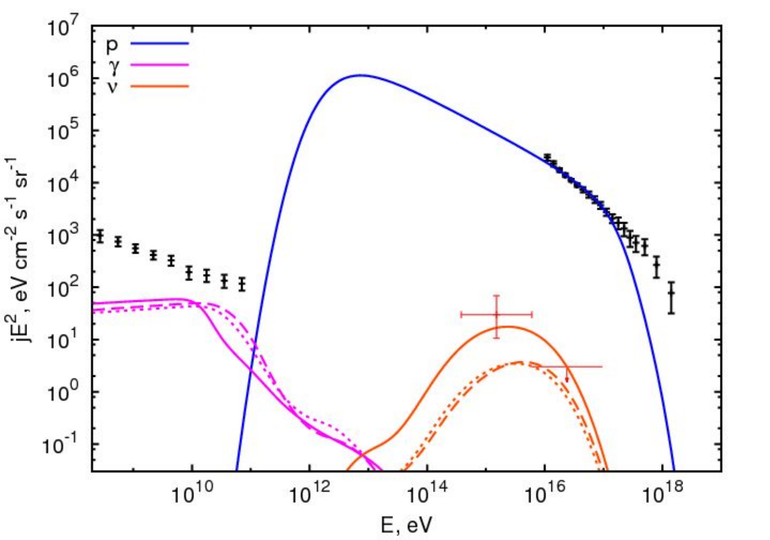
(Received 27 December 2009; revised manuscript received 22 February 2010; published 8 April 2010)

Secondary photons and neutrinos produced in the interactions of cosmic ray protons emitted by distant active galactic nuclei (AGN) with the photon background along the line of sight can reveal a wealth of new information about the intergalactic magnetic fields, extragalactic background light, and the acceleration mechanisms of cosmic rays. The secondary photons may have already been observed by gamma-ray telescopes. We show that the secondary neutrinos improve the prospects of discovering distant blazars by IceCube, and we discuss the ramifications for the cosmic backgrounds, magnetic fields, and AGN models.

DOI: 10.1103/PhysRevLett.104.141102 PACS numbers: 95.85.Pw, 98.54.Cm, 98.70.Sa, 95.85.Ry



PRL **111,** 041103 (2013) PHYSICAL REVIEW LETTERS week ending 26 JULY 2013

PeV Neutrinos from Intergalactic Interactions of Cosmic Rays Emitted by Active Galactic Nuclei

Oleg E. Kalashev,[1] Alexander Kusenko,[2,3] and Warren Essey[2]
[1]*Institute for Nuclear Research, 60th October Anniversary Prospect 7a, Moscow 117312, Russia*
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[3]*Kavli IPMU (WPI), University of Tokyo, Kashiwa, Chiba 277-8568, Japan*
(Received 28 February 2013; revised manuscript received 14 June 2013; published 24 July 2013)

The observed very high energy spectra of *distant* blazars are well described by secondary gamma rays produced in line-of-sight interactions of cosmic rays with background photons. In the absence of the cosmic-ray contribution, one would not expect to observe very hard spectra from distant sources, but the cosmic ray interactions generate very high energy gamma rays relatively close to the observer, and they are not attenuated significantly. The same interactions of cosmic rays are expected to produce a flux of neutrinos with energies peaked around 1 PeV. We show that the diffuse isotropic neutrino background from many distant sources can be consistent with the neutrino events recently detected by the IceCube experiment. We also find that the flux from any individual nearby source is insufficient to account for these events. The narrow spectrum around 1 PeV implies that some active galactic nuclei can accelerate protons to EeV energies.

DOI: 10.1103/PhysRevLett.111.041103 PACS numbers: 95.85.Ry, 98.54.Cm, 98.70.Sa

Implications for intergalactic magnetic fields

Magnetic fields along the line of sight:

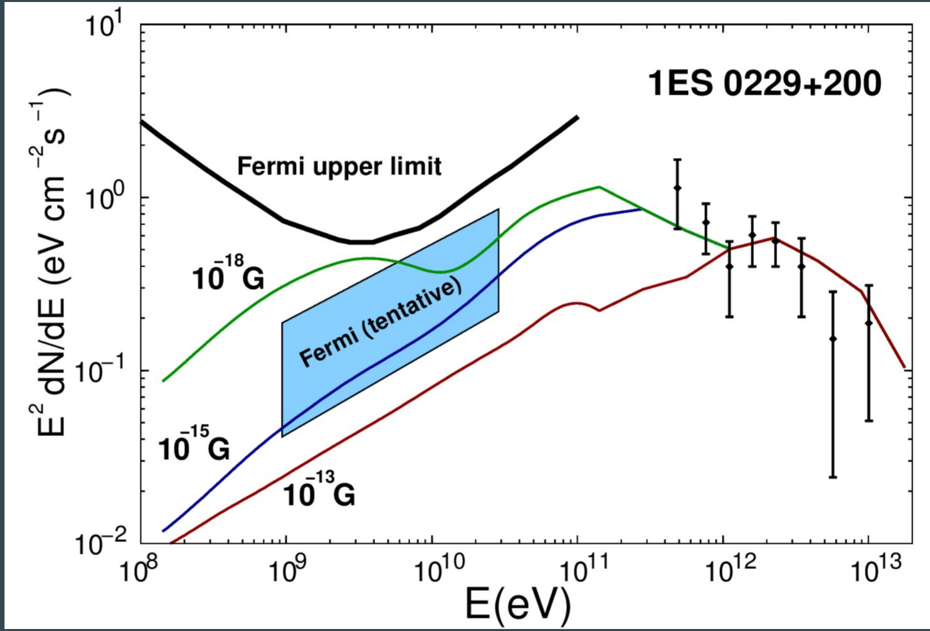
$$1 \times 10^{-17}\ \mathrm{G} < B < 3 \times 10^{-14}\ \mathrm{G}$$

Essey, Ando, AK (2011)

Lower limits: see also Finke et al. (2015)

If an intervening filament deflects protons, then no secondary component is expected.

However, even a source at z~1 has an order-one probability to be unobscured by magnetic fields, and can be seen in secondary gamma rays [Aharonian, Essey, AK, Prosekin, arXiv:1206.6715]



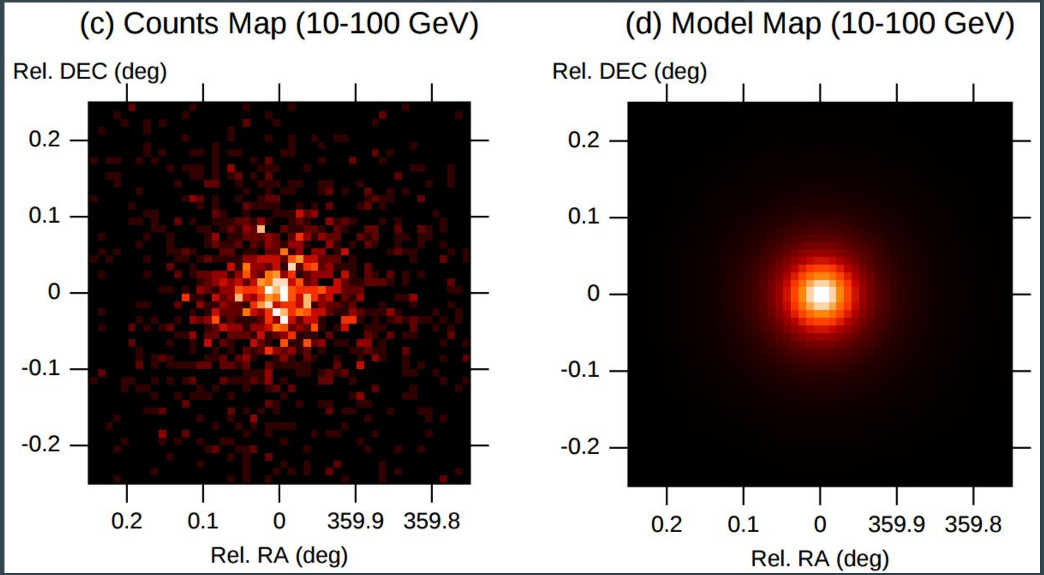
Essey, Ando, AK (2011)

Blazar halos: an independent measurement of IGMFs

Halos around stacked images of blazars implying

$B \sim 10^{-15}$ G

were reported (3.5σ) in 1st year Fermi data [Ando & AK, ApJL 722 (2010) L39].



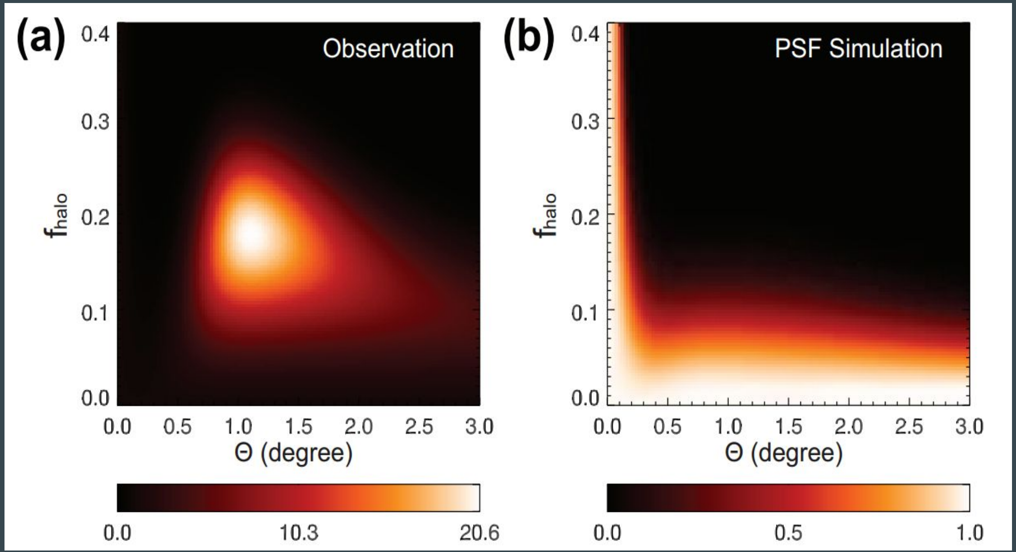
Ando & AK, ApJL 722 (2010)

Blazar halos: an independent measurement of IGMFs

Halos around stacked images of blazars implying **$B \sim 10^{-15}$ G** were reported (3.5σ) in 1st year Fermi data [Ando & AK, ApJL 722 (2010) L39].

Now the same technique was applied to the much larger Fermi data set, detecting lower energy halos of z< 0.5 blazars. The results, **$B \sim 10^{-17}$ -- 10^{-15} G** [Chen, et al. (2015)], confirm earlier results of Ando & AK, arXiv:1005.1924.

Consistent with independent measurement based on the gamma-ray spectra of blazars [Essey, Ando, AK, arXiv:1012.5313]



Chen, Buckley, Ferrer, Phys. Rev. Lett. (2015) confirm halos, IGMFs in the **$B \sim 10^{-17}$ -- 10^{-15} G** range

Extragalactic magnetic fields: a new window on the early universe?

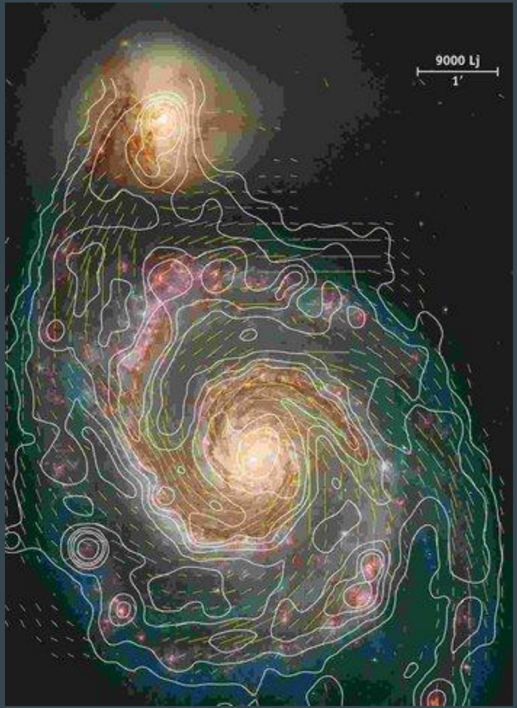
Magnetic fields and matter-antimatter asymmetry

Intergalactic magnetic fields away from galaxies may be representative of primordial seed fields.

Magnetic helicity

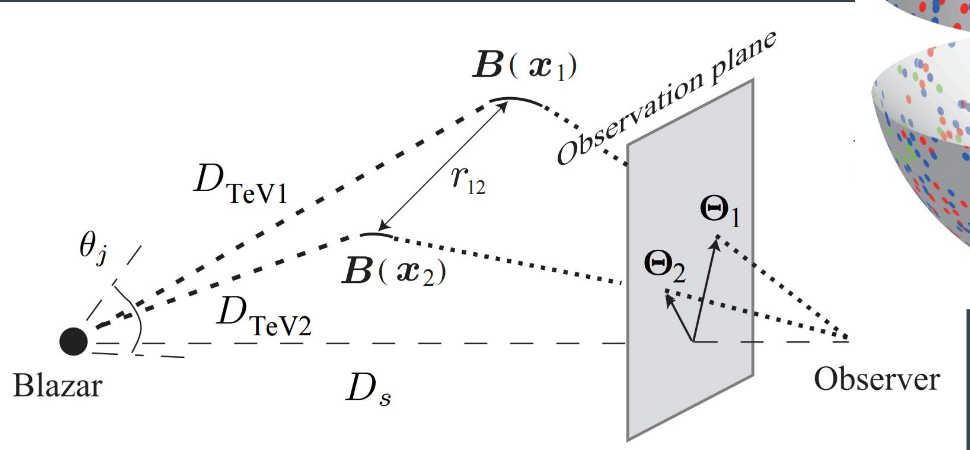
(~ Chern-Simons term for the U(1) of hypercharge)

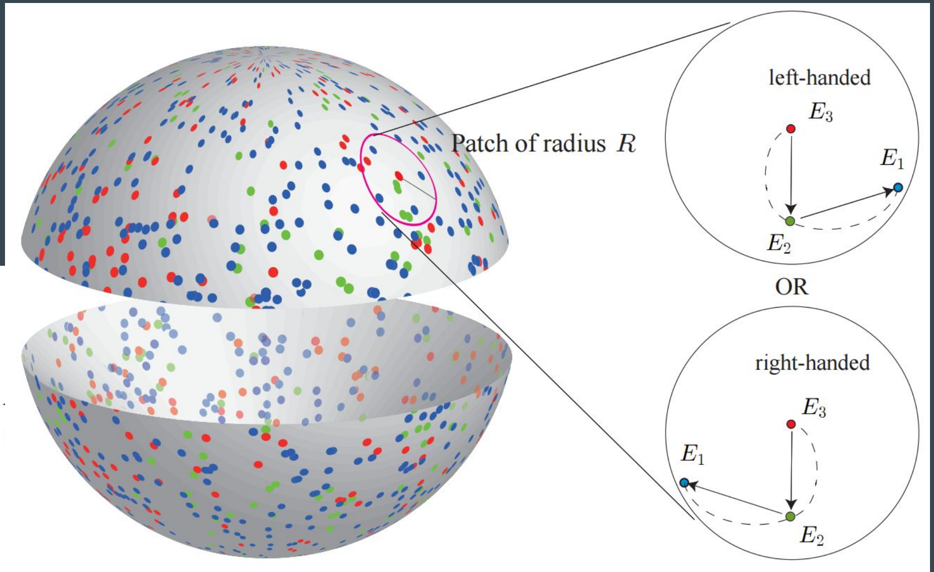
can break the symmetry between matter and antimatter and possibly explain the matter-antimatter asymmetry of the universe [Cornwall; Vachaspati et al.]



Magnetic helicity may be observable

[Vachaspati et al.] report 3σ evidence of non-zero helicity, with the *correct sign*





Tashiro, Chen, Ferrer, Vachaspati (2014)

Primordial black holes, formed in Big Bang?

Can be produced in the early universe

Can account for dark matter. The only dark matter candidate that is not necessarily made of new particles. (Although new physics usually needed to produce PBHs)

Can seed supermassive black holes

Can probably contribute to the LIGO signal

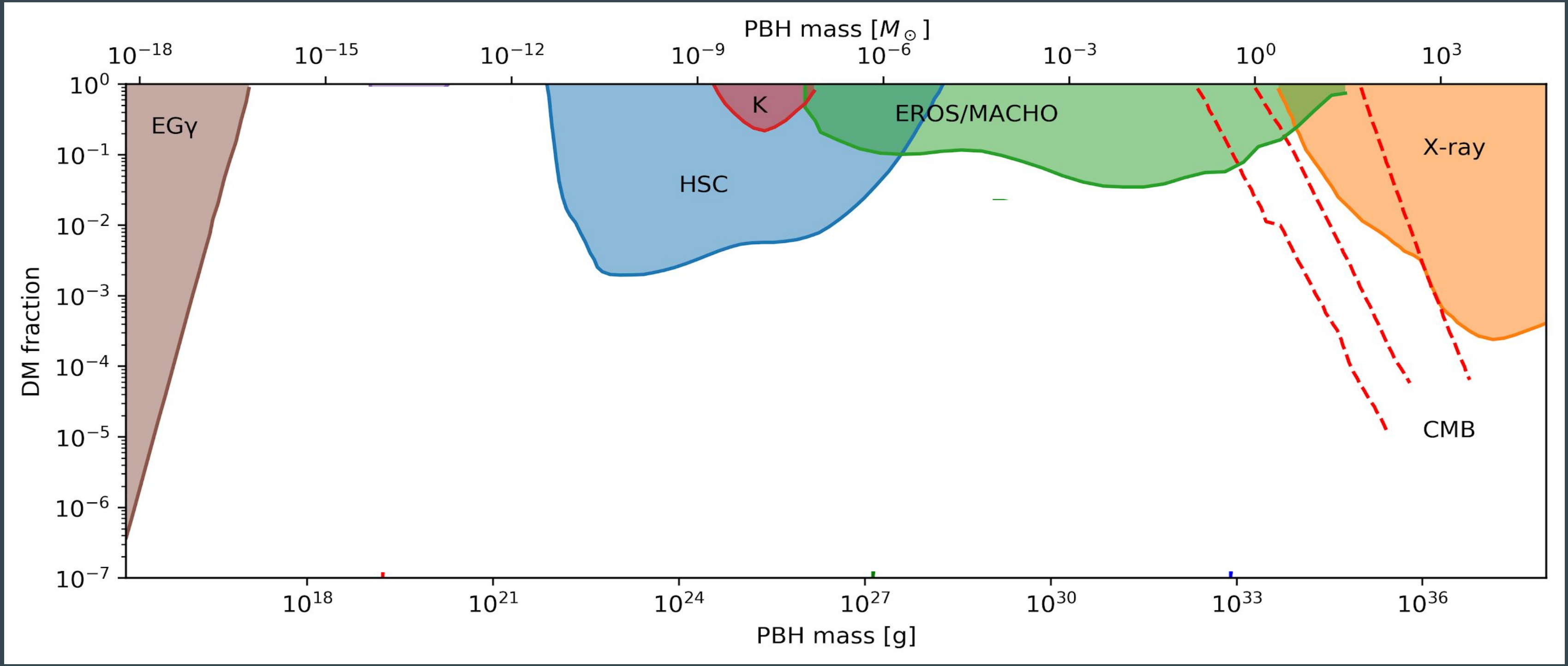
Can account for all or part of r-process nucleosynthesis

...and 511 keV line from the Galactic Center

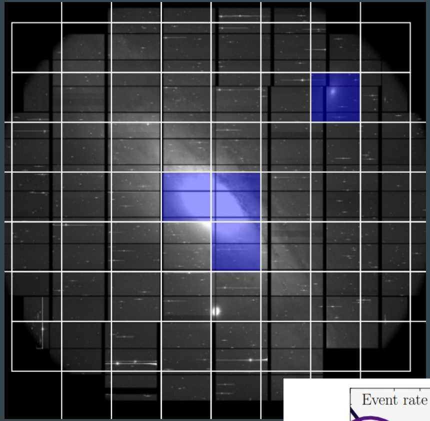
Formation:

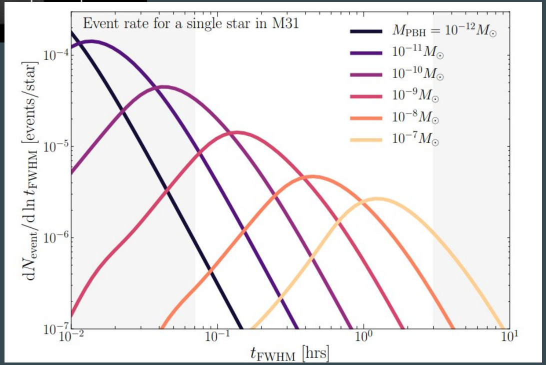
- Inflation [Garcia-Bellido, Linde et al.; Sasaki et al., ...]
  Spectrum of primordial density perturbations may not be scale invariant and may have an extra power on some scale: PBH are produced when the corresponding modes (re)enter horizon.
- Violent events, such as phase transitions
- Inhomogeneous Affleck-Dine baryogenesis [Kawasaki]
- Scalar field fragmentation: matter-dominated epoch with relatively few extremely massive particles per horizon ⇒ Poisson fluctuations [Cotner, AK,, Sasaki, Takhistov]

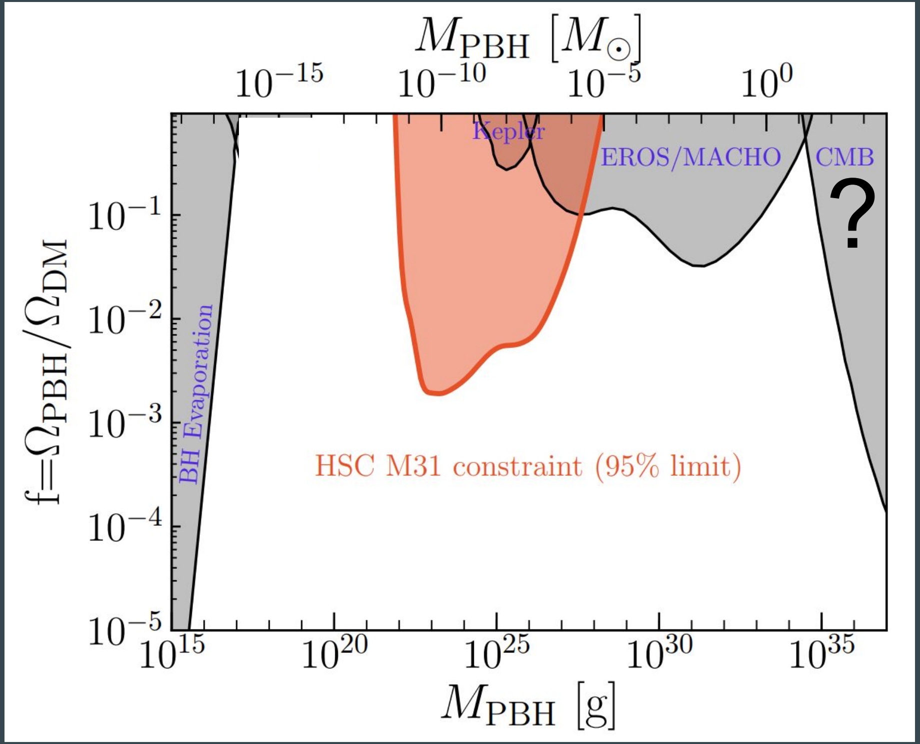
Experimental constraints



HSC search for PBH [Takada et al.]







A candidate microlensing event Subaru HSC obs. of M31

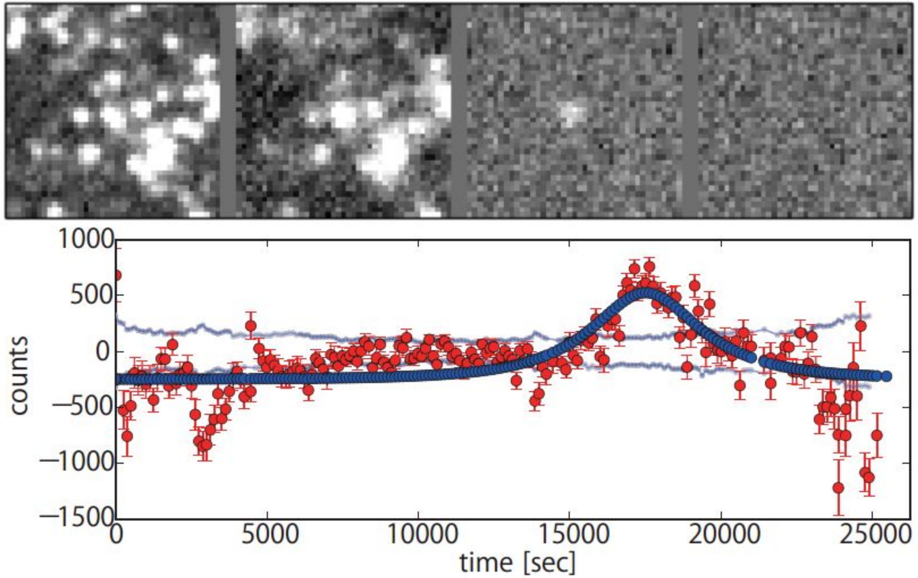


Figure 13. One remaining candidate that passed all the selection criteria of microlensing event. The images in the upper plot show the postage-stamped images around the candidate as in Fig. 7: the reference image, the target image, the difference image and the residual image after subtracting the best-fit PSF image, respectively. The lower panel shows that the best-fit microlensing model gives a fairly good fitting to the measured light curve.

Consistent with
PBH mass $\sim 10^{-7}\,M_{\odot}$
Need follow-up observations
[Niikura et al., Nature Astronomy arXiv:1701.02151]

Scalar fields

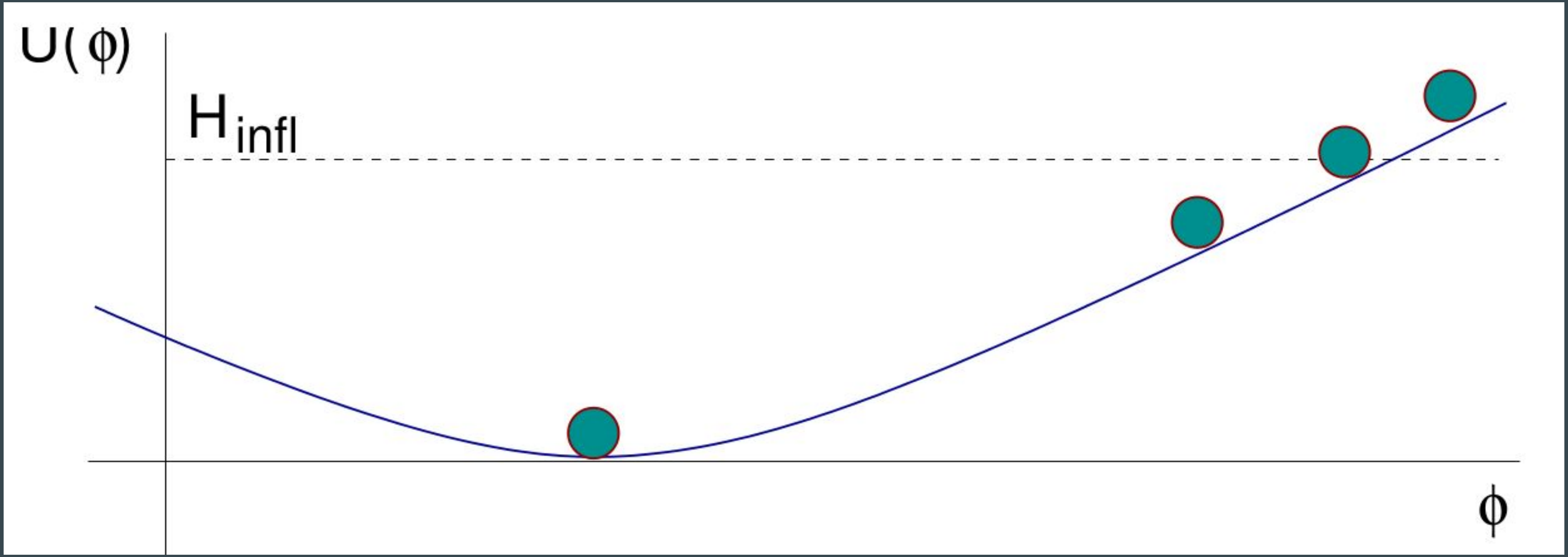
Simplest spin-zero object

Examples:

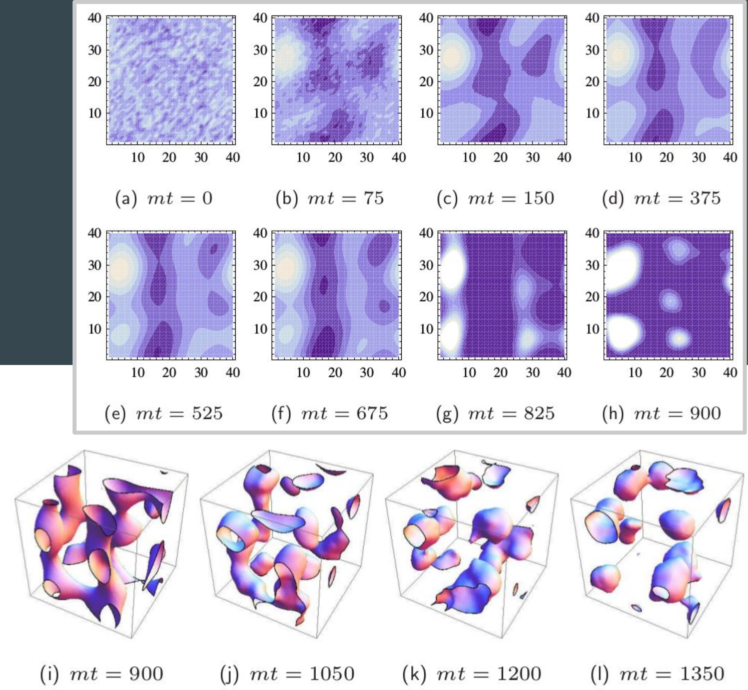
- Higgs field that gives an electron and other particles masses
- Supersymmetry - many scalar fields

Scalar fields in de Sitter space during inflation

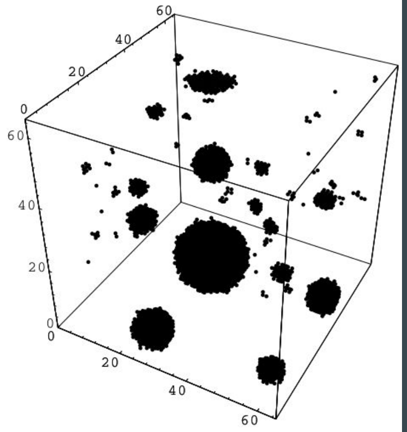
A scalar with a small mass develops a VEV
[Bunch, Davies; Affleck, Dine]



Numerical simulations of fragmentation



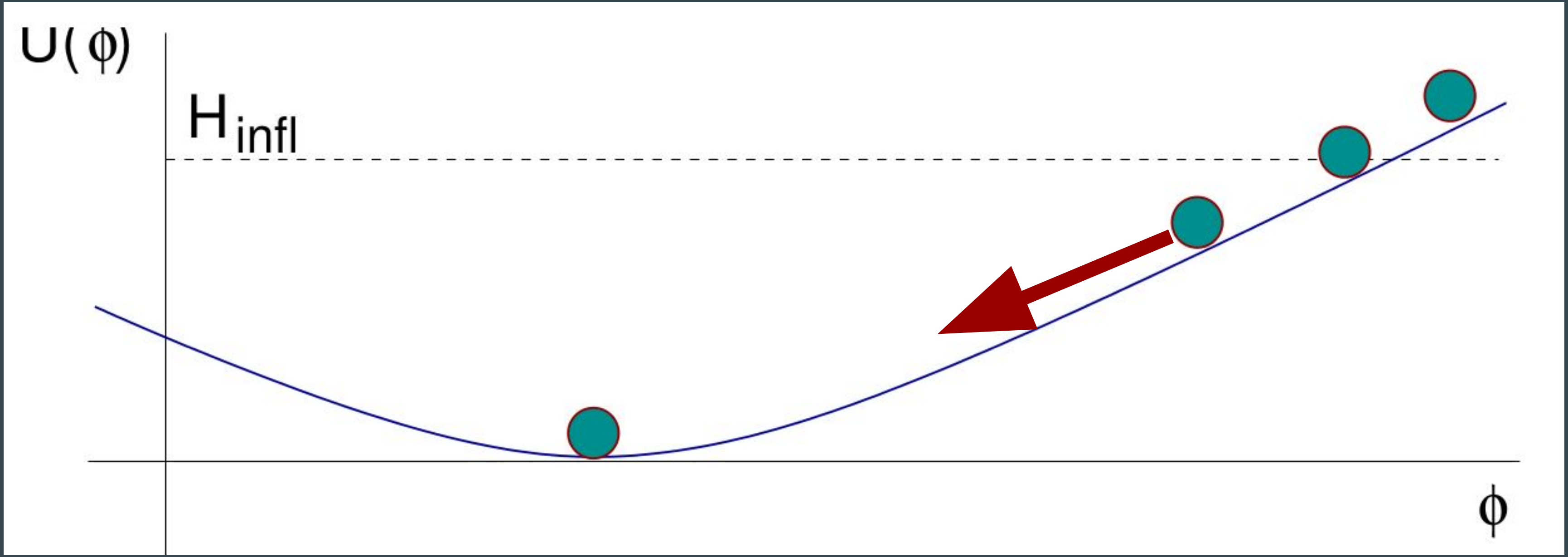
[Multamaki].



[Kasuya, Kawasaki]

Scalar fields in de Sitter space during inflation

A scalar with a small mass develops a VEV
[Bunch, Davies; Affleck, Dine]

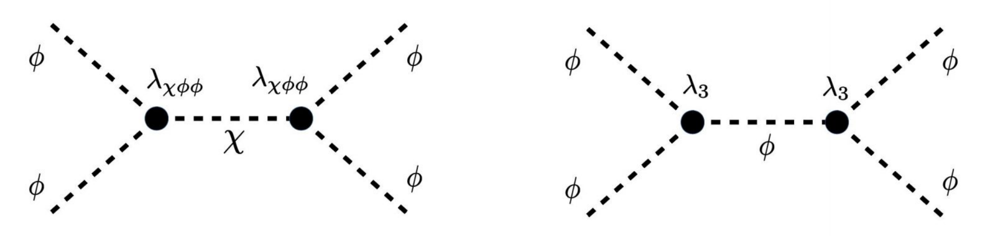


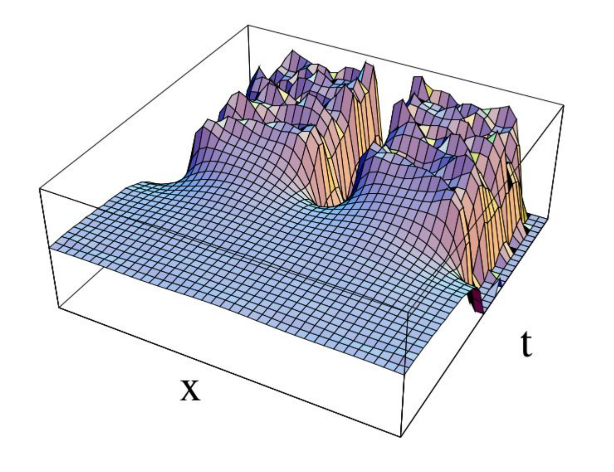
Scalar fields: an instability

Gravitational instability occurs due to the attractive force of gravity.

Similar instability can occur due to scalar self-interaction which is **attractive**:

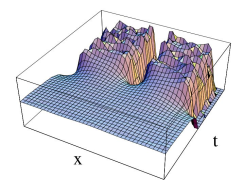
$$U(\phi) \supset \lambda_3 \phi^3 \quad \text{or} \quad \lambda_{\chi\phi\phi} \chi \phi^\dagger \phi$$





[AK, Shaposhnikov (1997)]

Early Universe



Inflation

origin of primordial perturbations

radiation dominated

$p=(1/3)\,\rho$

$\rho \propto a^{-4}$

structures don't grow

matter dominated

$p=0$

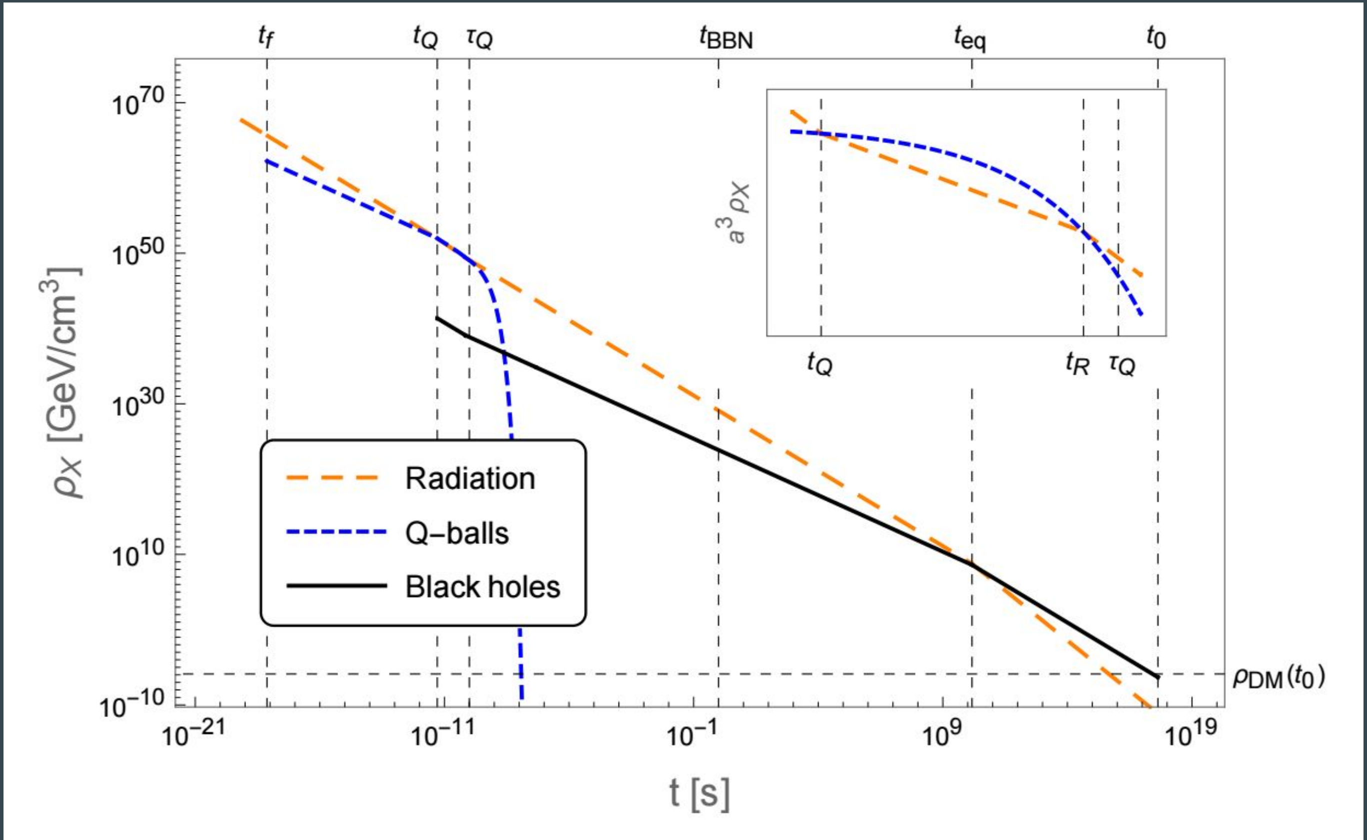
$\rho \propto a^{-3}$

structures grow

modern era (dark energy dominated)

[Cotner, AK, Sasaki, Takhistov]

Scalar lump (Q-ball) formation can lead to PBHs

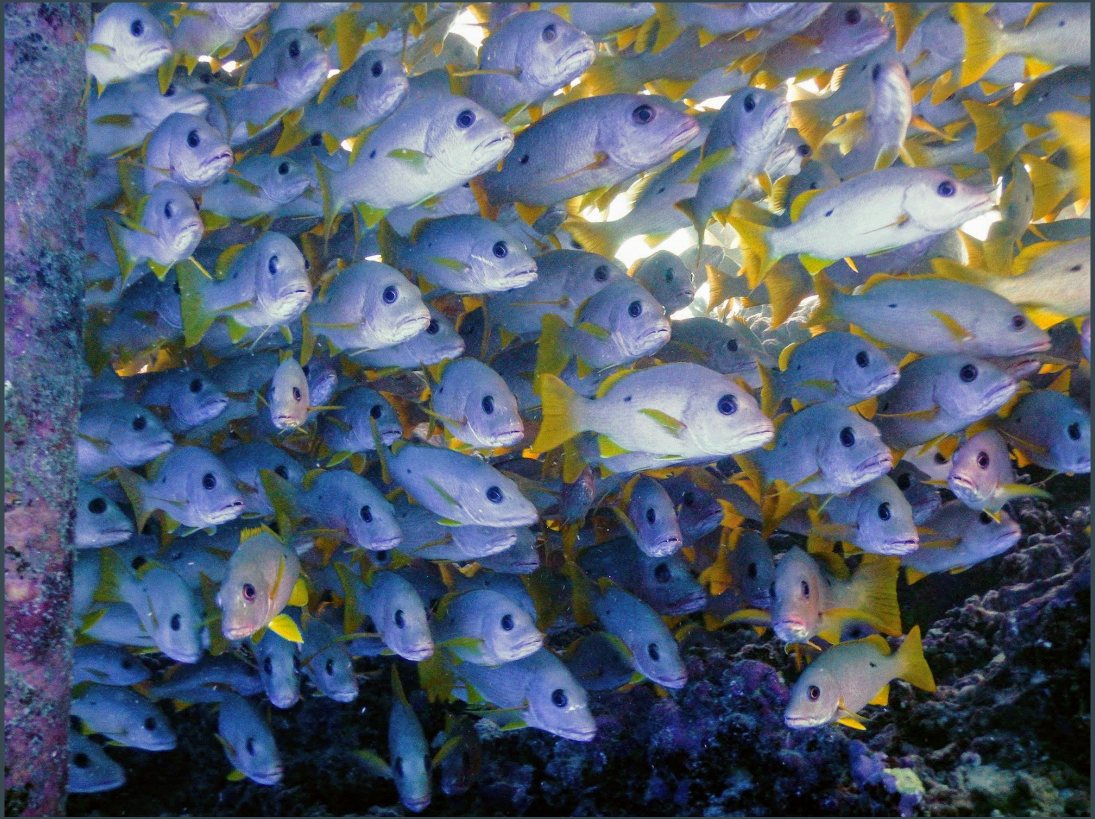


Intermittent matter dominated epoch in the middle of radiation dominated era

[Cotner, AK, Phys.Rev.Lett. 119 (2017) 031103]

[Cotner, AK, Sasaki, Takhistov, JCAP 1910 (2019)]

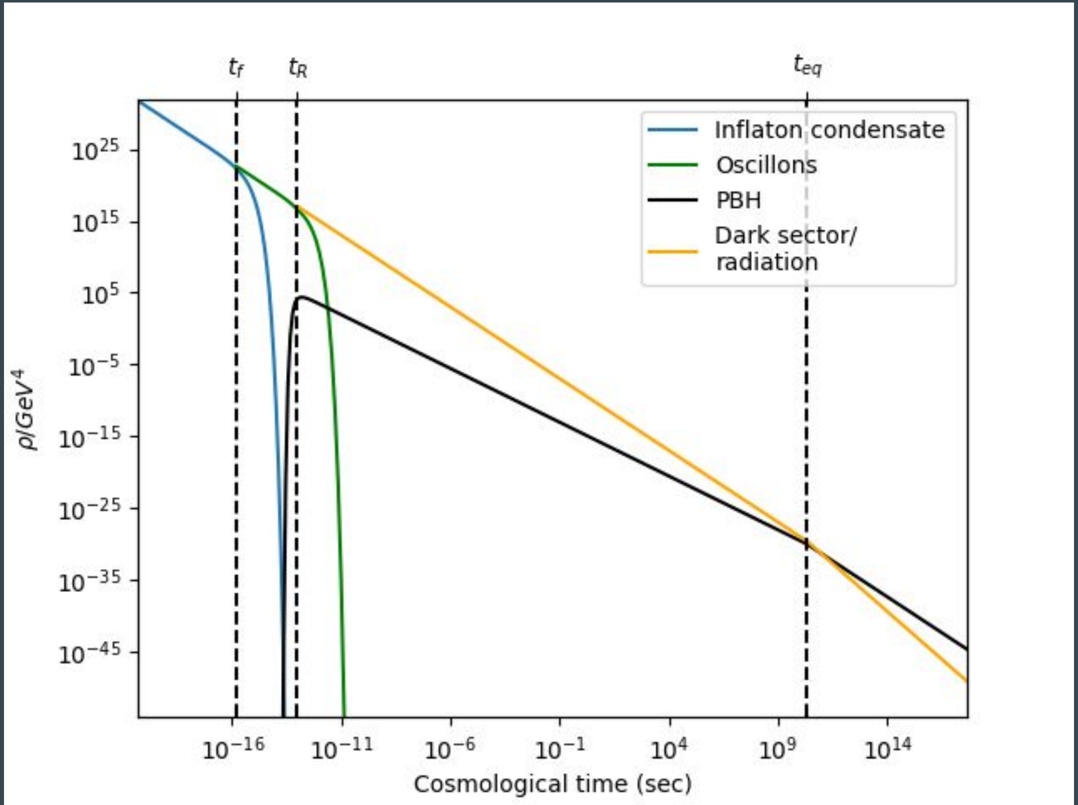
Many particles ⇒ only small Poisson fluctuations



FEW GIANT PARTICLES ⇒

LARGE POISSON FLUCTUATIONS

Scalar lump (oscillon) formation can lead to PBHs



Intermittent matter dominated epoch immediately after inflation

[Cotner, AK, Takhistov, Phys.Rev. D98 (2018), 083513]

[Cotner, AK, Sasaki, Takhistov, JCAP 1910 (2019)]

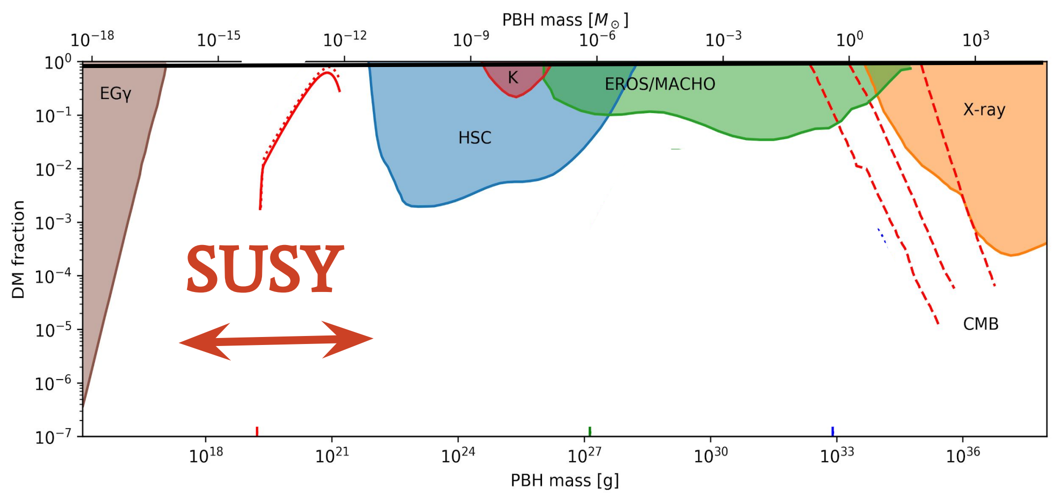
PBH from Supersymmetry: natural mass range

Flat directions lifted by SUSY breaking terms, which determine the scale of fragmentation.

$$10^{17}\text{g} \lesssim M_{\text{PBH}} \lesssim 10^{22}\text{g}$$

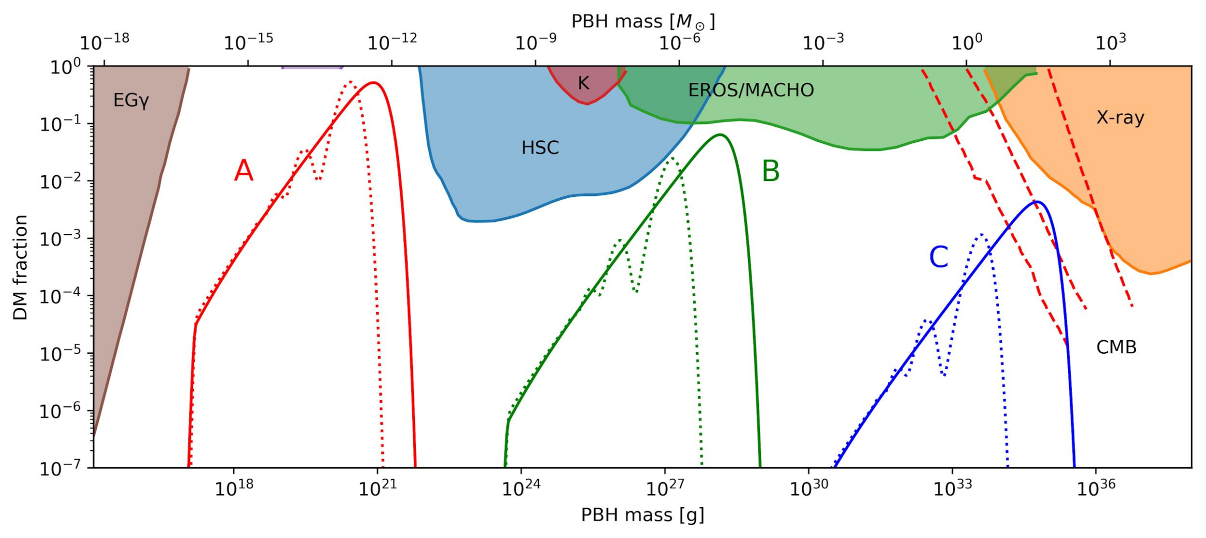
$$M_{\text{hor}} \sim r_f^{-1/4} \left(\frac{M_{\text{Planck}}^3}{M_{\text{SUSY}}^2}\right) \sim 10^{22}\text{g} \left(\frac{100\ \text{TeV}}{M_{\text{SUSY}}}\right)^2$$

$$M_{\text{PBH}} \sim r_f^{-1/4} \times 10^{22}\text{g} \left(\frac{100\ \text{TeV}}{M_{\text{SUSY}}}\right)^2$$



[Cotner, AK, Sasaki, Takhistov 2019]

Scalar lump formation can lead to PBHs

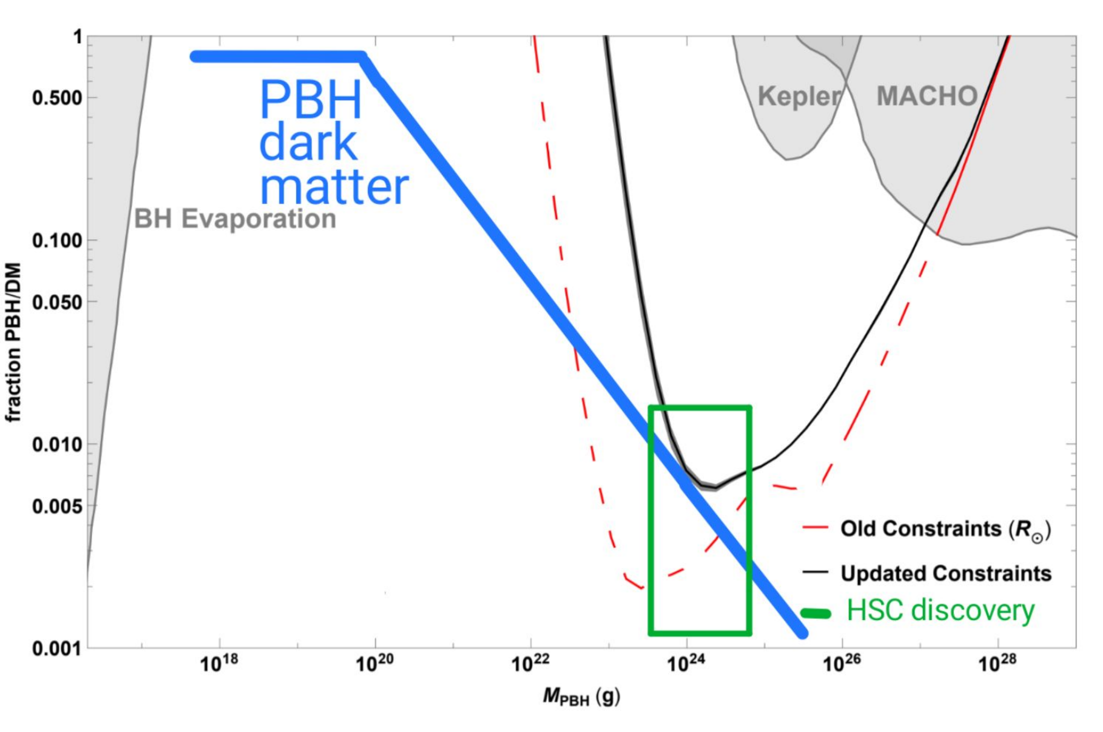


Mass function,

Ω_{PBH}=1, 0.2, 0.001

[Cotner, AK, Phys.Rev.Lett. 119 (2017) 031103]

Other models exist, and they can be probed by HSC

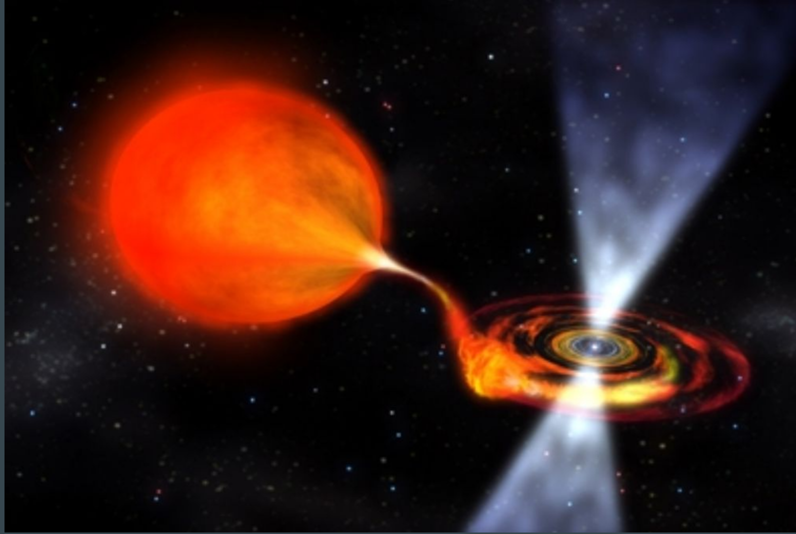


In class of models, the spectrum of PBH dark matter is extended, and the HSC can probe this signal using the high-mass tail. With a few hundred hours of observations, DM can be discovered, or the entire class of models can be ruled out.

[**talk by Vitagliano next week**]

PBH and neutron stars

- Neutron stars can capture PBH, which consume and destroy them from the inside.
- Capture probability high enough in DM rich environments, e.g. Galactic Center
- Can set limits? No NSs in GC (except for one very young magnetar), no NSs in dwarf spheroidals, … A hint?!
- What happens if NSs really are systematically destroyed by PBH?



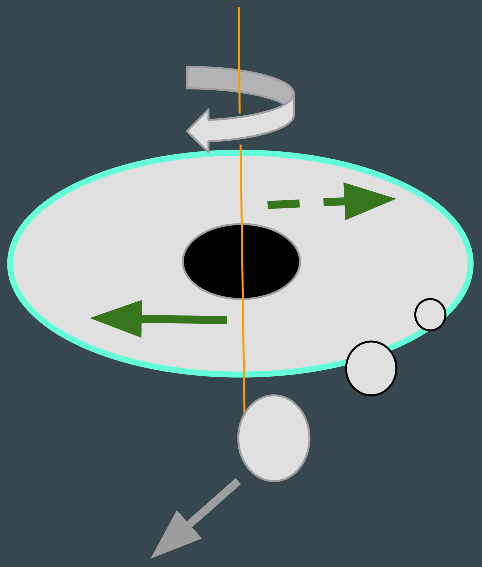
Fast-spinning millisecond pulsar. Image: NASA/Dana Berry

Neutron star destruction by black holes

⇒r-process nucleosynthesis, 511 keV, FRB

[Fuller, AK, Takhistov, Phys.Rev.Lett. 119 (2017) 061101]

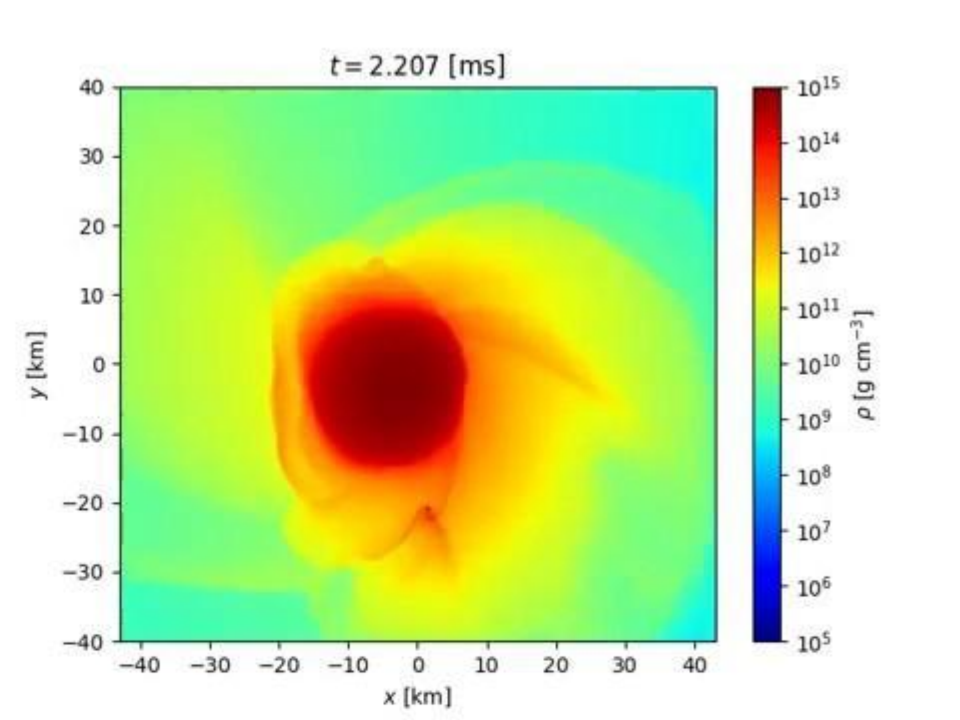
MSP spun up by an accreting PBH



- MSP with a BH inside, spinning near mass shedding limit: elongated spheroid
- Rigid rotator: viscosity sufficient even without magnetic fields [Kouvaris, Tinyakov]; more so if magnetic field flux tubes are considered
- Accretion leads to a decrease in the radius, increase in the angular velocity (by angular momentum conservation)
- Equatorial regions gain speed in excess of escape velocity: ejection of cold neutron matter

[Fuller, AK, Takhistov, Phys. Rev. Lett. 119 (2017) 061101] also, *Viewpoint* by H.-T. Janka

Numerical simulations by David Radice (Princeton)



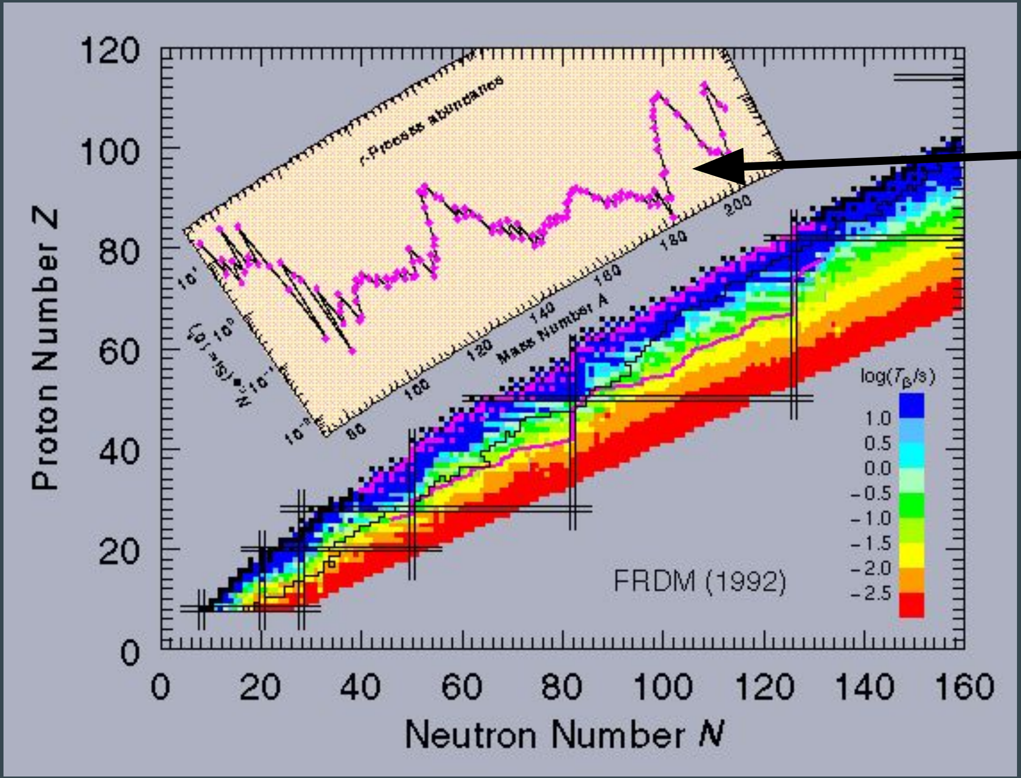
Preliminary results by
David Radice (Princeton U. and IAS)

Initial PBH mass for this simulation:

$M_{PBH} = 0.03\ M_\odot$

(preliminary results)

r-process nucleosynthesis: site unknown



- s-process cannot produce peaks of heavy elements
- Observations well described by r-process
- Neutron rich environment needed
- Site? SNe? NS-NS collisions?..

Image: Los Alamos, Nuclear Data Group

r-process nucleosynthesis: site?

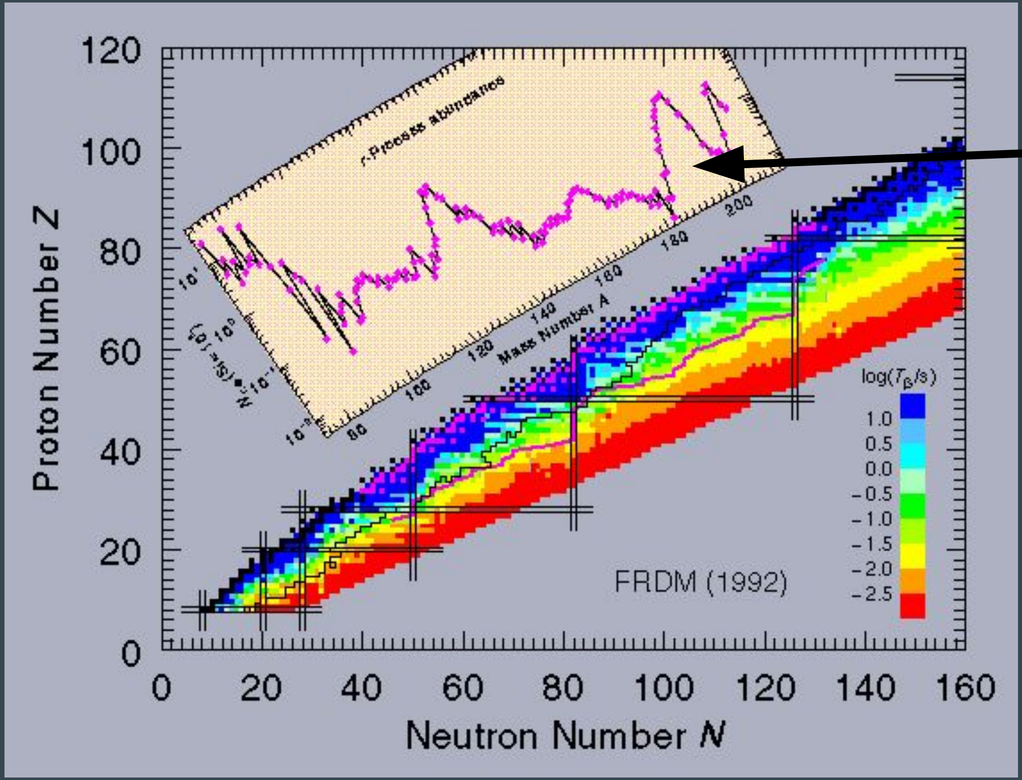
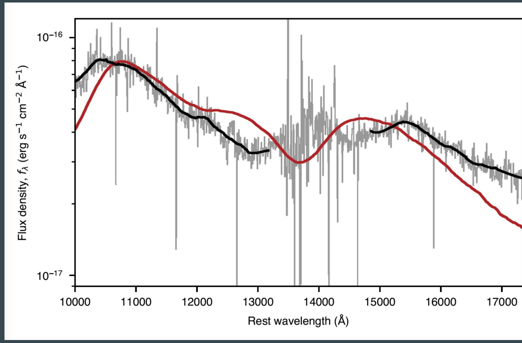


Image: Los Alamos, Nuclear Data Group

- **SN**? Problematic: neutrinos
- **NS mergers**? Can account for all r-process?



r-process material: observations

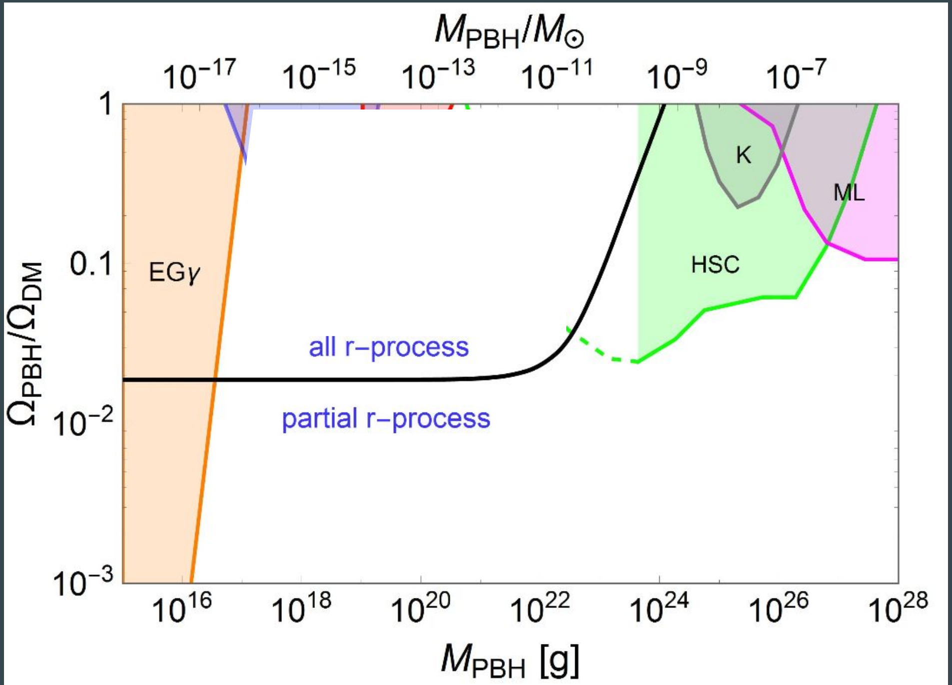
Milky Way (total): **$M \sim 10^4\ M_\odot$**

Ultra Faint Dwarfs (UFD): most of UFDs show no enhancement of r-process abundance.
However, **Reticulum II** shows an enhancement by factor **10^2-10^3**!

“Rare event” consistent with the UFD data: one in ten shows r-process material [Ji, Frebel et al. Nature, 2016]

NS disruptions by PBHs

- Centrifugal ejection of cold neutron-rich material (~0.1 $M_\odot$) MW: **$M \sim 10^4$ $M_\odot$** ✓
- UFD: a rare event, only one in ten UFDs could host it in 10 Gyr ✓
- Globular clusters: low/average DM density, but high density of millisecond pulsars. Rates OK. ✓



Talk by Takhistov next week

[Fuller, AK, Takhistov, Phys. Rev. Lett. 119 (2017) 061101]

also, a *Viewpoint* article by Hans-Thomas Janka

Kilonova without a GW counterpart -- signature of PBHs

- **Kilonova** event without a GW counterpart, but with a possible coincident FRB
- No GW signal characteristic of NS mergers
- No significant neutrino emission
- Fast Radio Bursts
- 511 keV line

[Fuller, AK, Takhistov, Phys. Rev. Lett. 119 (2017) 061101]

Table 2
Expected Number of KNe Found in Each Sample

Survey	# KNe[a]	Survey Years	KN Redshift Range
SDSS	0.13	2	0.02–0.05
SNLS	0.11	4	0.05–0.20
PS1	0.22	4	0.03–0.11
DES	0.26	5	0.05–0.20
ASAS-SN	<0.001	3	...
SMT	0.001	5	0.01–0.01
ATLAS	8.3	5	0.01–0.03
ZTF	10.6	5	0.01–0.04
LSST WFD	69	10	0.02–0.25
LSST DDF	5.5	10	0.05–0.25
WFIRST	16.0	2	0.1–0.8

[Scolnic et al. (DES), ApJ 852:L3 (2018)

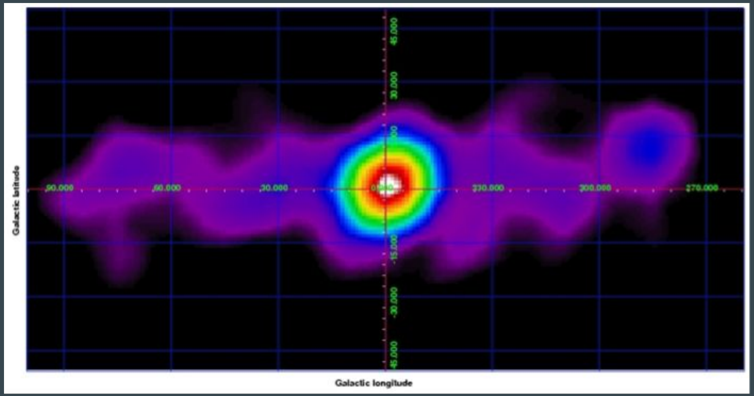
511-keV line in Galactic Center

Origin of positrons unknown. Need to produce 10^{50} positrons per year. Positrons must be produced with energies below 3 MeV to annihilate at rest. [Beacom,Yuksel '08]

Cold, neutron-rich material ejected in PBH-NS events is heated by β-decay and fission to T~0.1 MeV

→ **generate 10^{50} e^+/yr** for the rates needed to explain r-process nucleosynthesis.

Positrons are non-relativistic.

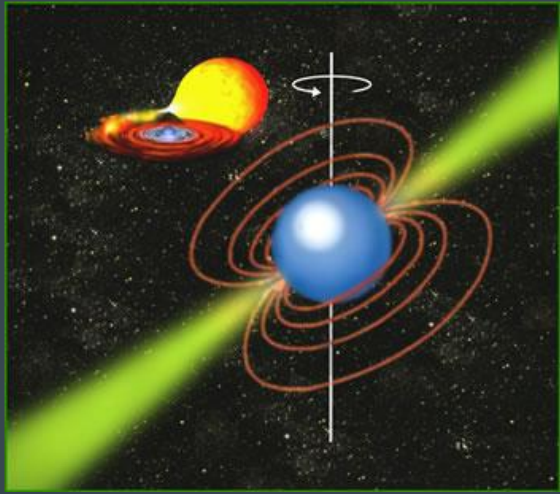


ESA/Bouchet et al.

$$\Gamma(e^+e^- \to \gamma\gamma) \sim 10^{50}\text{yr}^{-1}$$

[Fuller, AK, Takhistov, Phys. Rev. Lett. 119 (2017) 061101]

Fast Radio Bursts (FRB)



Origin unknown. One repeater, others: non-repeaters. ~ ms.

PBH - NS events: final stages dynamical time scale ~ ms.

NS magnetic field energy available for release: $\sim 10^{41}$erg
Consistent with observed FRB fluence.

Massive rearrangement of magnetic fields at the end of the NS life, on the time scale ~ms produces an FRB.
(Of course, there are probably multiple sources of FRBs.)

GW detectors can discover small PBH...

PBH + NS

⇓

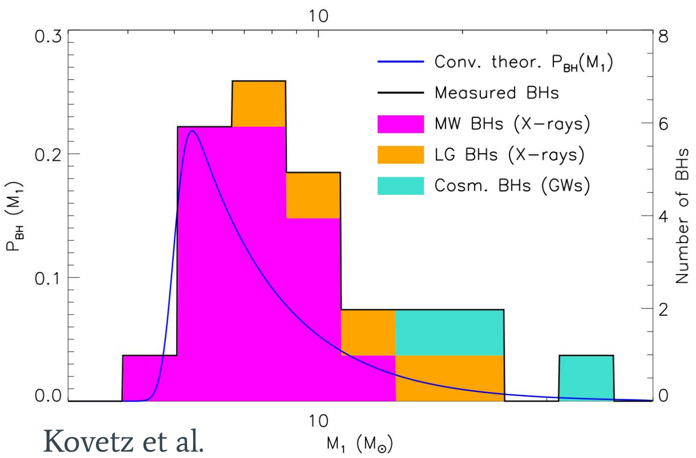
BH of 1-2 $M_\odot$

[Takhistov, arXiv:1707.05849]

...if it detects mergers of

1-2 $M_\odot$ black holes

(not expected from evolution of stars)



Kovetz et al.

Conclusion

- Signals of supermassive black holes in AGN are decoded yielding new information about the universe
- Small black holes formed in the early universe can be dark matter and can contribute to synthesis of heavy elements by destroying neutron stars. The NS disruption events can be discovered by future surveys as Kilonovae unaccompanied by GW signatures.
- Focus Week on Primordial Black Holes

  2-6 December 2019

  Kavli IPMU, Kashiwa, Japan

  Asia/Tokyo timezone