The NUTEV DIS $\sin^2\theta_W$ Anomaly

or

Beware of Mass Singularities

($\ln(M/m_f)$ terms)

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Lunch Discussion

BROOKHAVEN
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Based on: ***Oldies but Goodies***

WJM & A. Sirlin (1973) ***electron-muon universality***

WJM (1975) ***Dim. Reg. of mass singularities***

D. Albert, WJM, Z. Parsa, D. Wyler (1980) ***W & Z Decays***

*A. Sirlin and WJM (1981) ***Neutrino DIS & $\sin^2\theta_W$***

More Recent

A. Czarnecki, WJM, G.P. Lepage (2000) ***Muonium Decay***

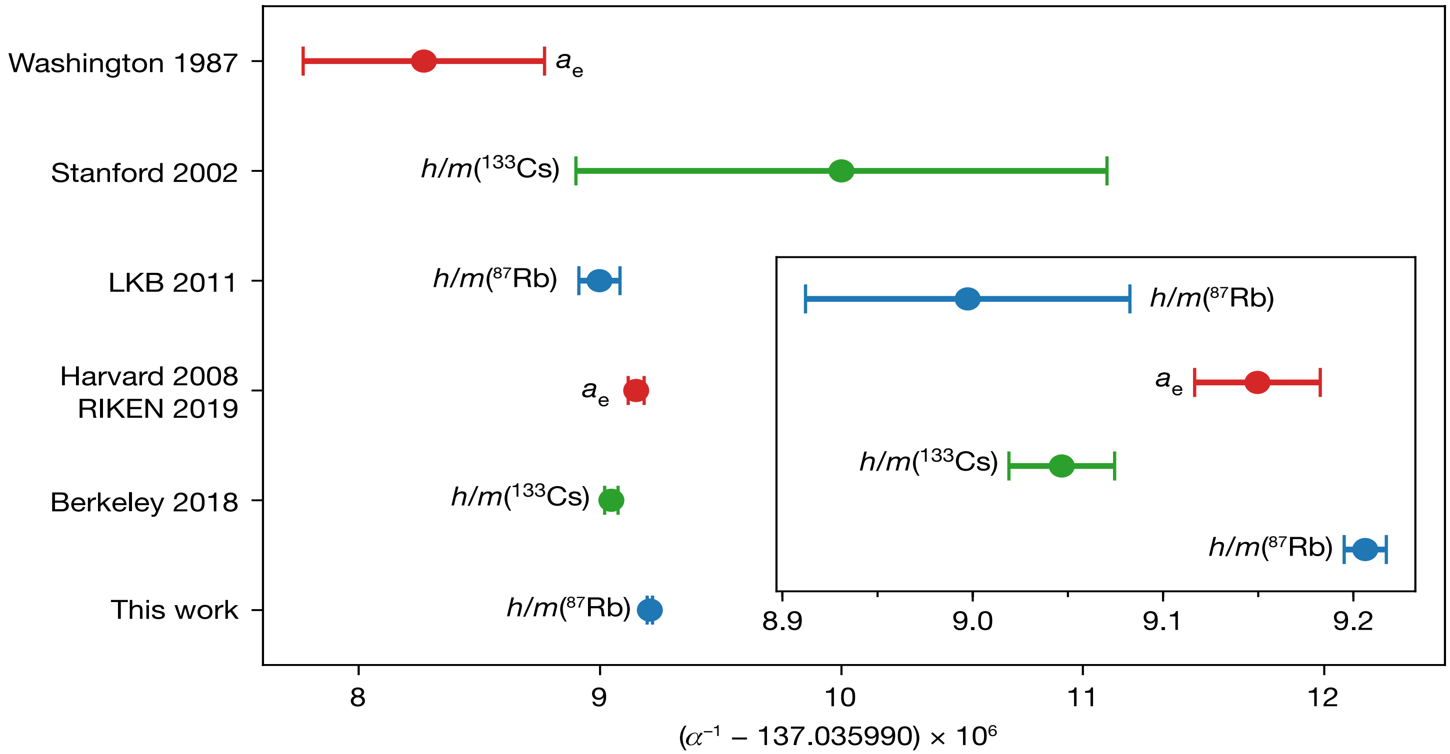
2020 Nobel Prize Connection

Black Holes and BNL

Precision EW Parameters (status):

Quantity	2008 Value		2020 Value	Comment
α^{-1}	137.035999084(51)		***137.035999046(27)***	α^{-1}(Cs)
			137.035999150(34)	$\alpha^{-1}(a_e)$
			137.035999206(11)	α^{-1}(Rb) 5.5 σ tension New!
G_μ	$1.16637(1)\times10^{-5}\mathrm{GeV}^{-2}$		$1.1663787(6)\times10^{-5}\mathrm{GeV}^{-2}$	$\tau_{\mu+}$ PSI MuLAN 2010
m_Z	91 .1875(21)GeV		91.1876(21)GeV	-
$*m_t$	171.4(2.1)GeV	$\rightarrow$	172.9(0.4)GeV	FNAL/LHC
$*m_H$	>114GeV	$\rightarrow$	125.10(0.14)GeV	LHC
m_W	80.410(32)GeV	$\rightarrow$	80.379(12)GeV	LEP2/FNAL/LHC
			80.359(3)GeV	Global Fit Value
$\sin^2\theta_W(m_Z)$	0.23070(26)		0.23070(26)	SLAC A_{LR}
$\sin^2\theta_W(m_Z)$	0.23193(29)		0.23193(29)	CERN A_{FB}(bb)
(3 sigma difference?)				
$\sin^2\theta_W(m_Z)_{ave}$	0.23125(16)		0.23119(14)	Z Pole Ave.
			0.23120(6)	Global EW Fit

Comparison of recent α determinations from Nature (2020)
5.5 sigma difference between α(Rb) and α(Cs)
$\Delta a_e = a_e^{exp} - a_e^{SM}$ changes sign!



Comment on New α(Rb) value

$\Delta a_e = a_e^{exp} - a_e^{SM} = -87(28)_{exp}(23)_{\alpha}(2)_{th} \times 10^{-14}$ for Cs

$\Delta a_e = a_e^{exp} - a_e^{SM} = +47(28)_{exp}(9)_{\alpha}(2)_{th} \times 10^{-14}$ for Rb sign change

$\Delta a_\mu = a_\mu^{exp} - a_\mu^{SM} = +261(40)(26) \times 10^{-11}$

$\frac{\Delta a_\mu}{\Delta a_e} \sim 5553$ if m_μ^2/m_e^2 scaling holds, e/μ universality,

$\Delta a_e = a_e^{exp} - a_e^{SM} \sim 6 \times 10^{-14}$ expected

Accommodate with a light Scalar

But first overcome Rb/Cs Difference

Best Off Z Resonance Measurements of $\sin^2\theta_W(m_Z)_{MS}$

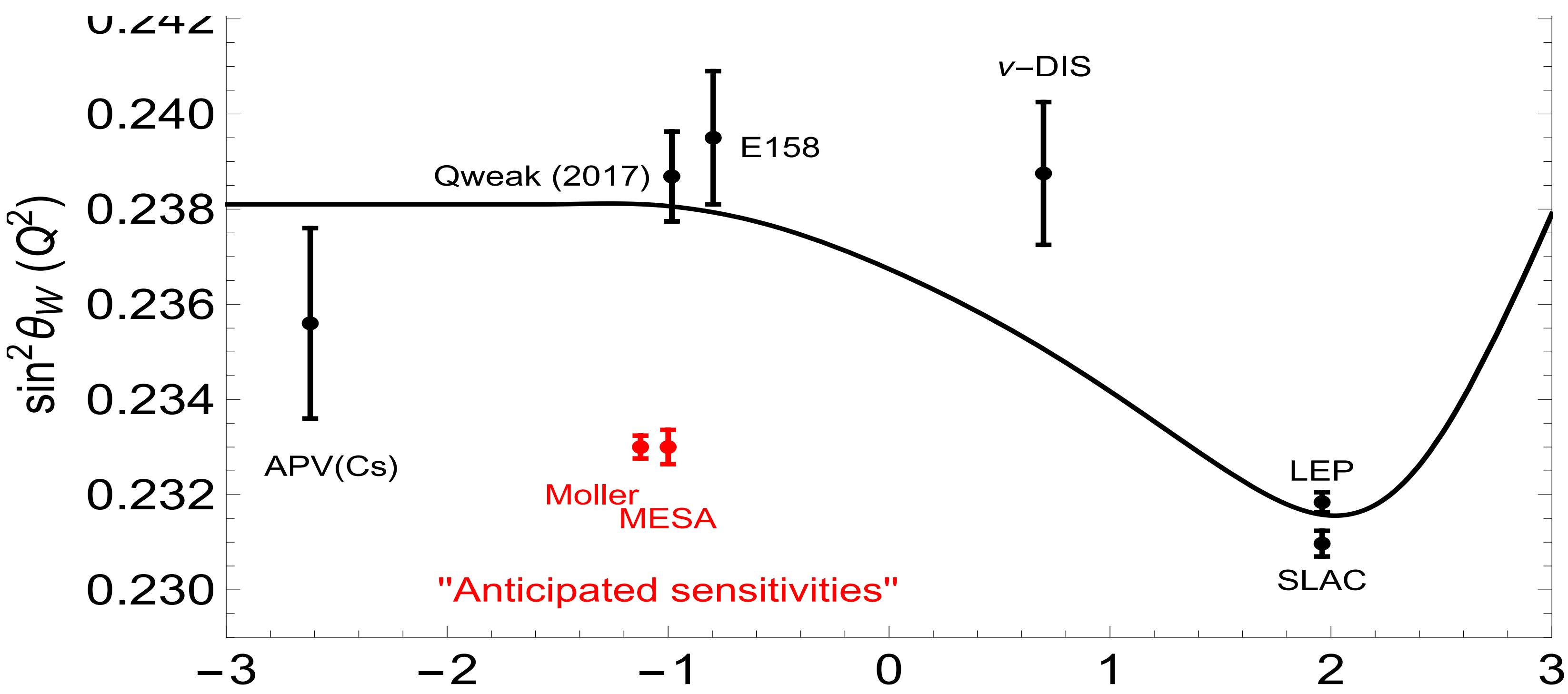
(Not Yet Competitive with Z Pole)

Reaction	$\sin^2\theta_W(m_Z)_{MS}$	<Q>
Cs APV	0.2283(20)	2.5MeV
E158 ee	0.2329(13)	160MeV
Q_{weak} ep	0.2310(11)	160MeV
Average	**0.23127(77)**	***Good Agreement***
Z Pole	0.23119(14)	
*NuTeV $\nu_\mu N$	0.23560(160)	10 GeV

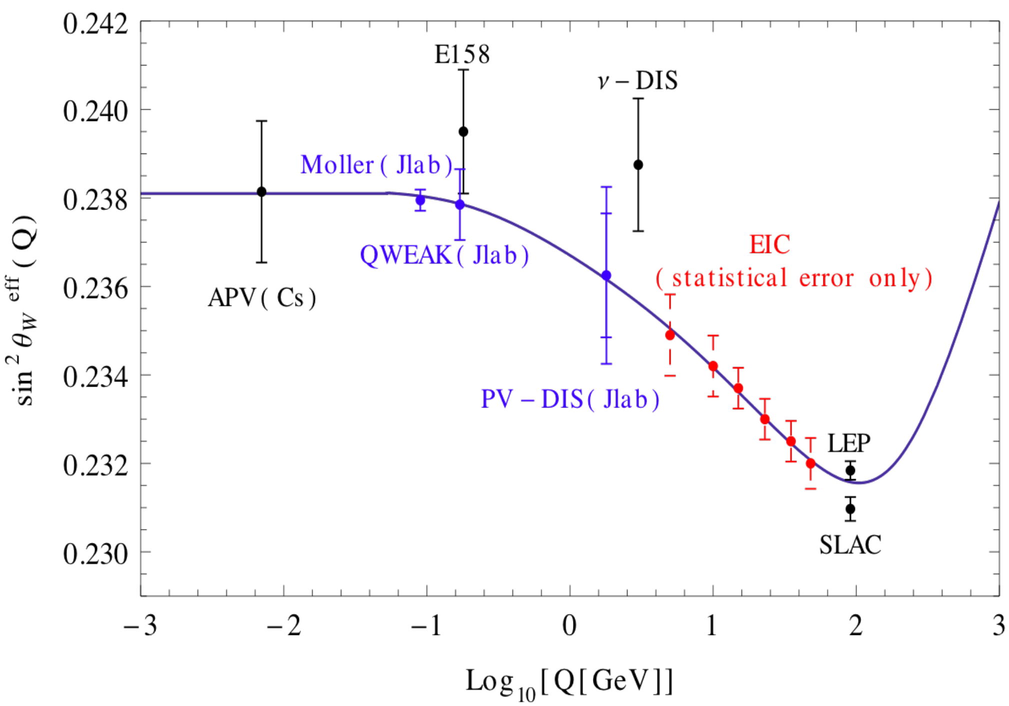
NuTeV high by about 2-3 sigma using $R_\nu^{exp}=\sigma_{NC}/\sigma_{CC}$ =0.3916(7)

BSM Unlikely? **R_ν incomplete Radiative Corrections? Likely!**

Running of the Weak Mixing Angle



Running of $sin^2\vartheta_W(Q)$ & Future Measurements



Radiative corrections to $R_{\boldsymbol{\nu}}$ (A. Sirlin &WJM 1981)

$R_\nu^{exp} \equiv \sigma(\nu_\mu N \to \nu_\mu X)/\sigma(\nu_\mu N \to \mu X')$ = 0.3916(7) NuTeV. (2002)

Radiative Corrections 1 loop + Bremsstrahlung (Monte Carlo)

Experiment: $\sin^2\theta_W \equiv 1 - \frac{m_W{}^2}{m_Z{}^2} = 0.2277(16)\ vs$ SM global fit → **0.2234(1)**

Main RC from Wγ Box $diagram$ $increases$ CC cross-section by $\frac{\alpha}{\pi}\ (ln\frac{m_Z{}^2}{2Q^2}$ +2) $\sim$1.8%

Suggests R_ν^{SM} needs additional correction by $\sim$ 0.9% to agree with Global average

Mass Singularities theorem (1959) No large $O(\frac{\alpha}{2\pi}\ln(\frac{2mNE_\nu}{m_\mu{}^2})) \sim 1\%$

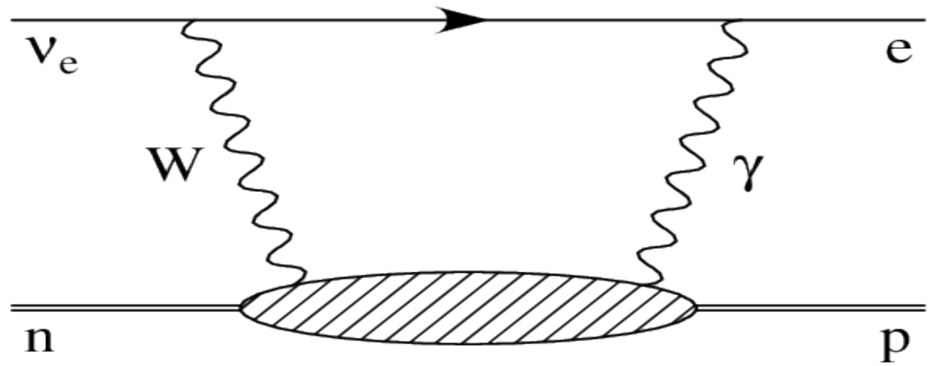
corrections for $\nu_\mu N \to \mu X'$ fully inclusive cross-section over all E_μ.

However, cuts on Bremsstrahlung induce mass singularities. Increase CC cross-section by about +0.8-0.9%. Just what is needed for agreement with SM. ***Already included??***

Predicted by A. Sirlin &WJM in 1981! ***Generic +0.7%***

Recently gifted to NuTeV Collaboration for consideration. The Jury is still out.

Box Diagram Loop Induced RC



Example of cuts: e/$\boldsymbol{\mu}$ Universality Breakdown in W→ $\boldsymbol{l\nu(\gamma)}$ decays ($\boldsymbol{l}$=e,$\boldsymbol{\mu}$)

Dimensional Regularization of both infrared div. & lepton mass sing. m_γ=0 m_l=0

Compare with $m_l \neq 0$ $calculation, neglecting\ O(\frac{m_l^2}{m_W^2})$ effects taking n→ 4

Inclusive Decay Rate=$g^2 \frac{m_W}{48\pi}(1-\frac{\alpha}{2\pi}(\frac{2\pi}{3}-\frac{77}{12}))\rightarrow \frac{\Gamma(W\rightarrow e\nu(\gamma))}{\Gamma(W\rightarrow \mu\nu(\gamma))} = 1+O(\frac{m_l^2}{m_W^2})$

Exclusive $E_{max} - \Delta E \leq E \leq E_{max}$ $\frac{\Gamma(W\rightarrow e\nu(\gamma),\Delta E)}{\Gamma(W\rightarrow \mu\nu(\gamma),\Delta E)}$ $=1 - \frac{\alpha}{2\pi}[(4\ln\frac{m_W}{2\Delta E} - 3)\ln\frac{m_\mu}{me}]$

Exponentiate $=(\frac{2\Delta E}{mW})^{0.0248}$ (1.018)

Cuts can afford Universality tests $=$ 0.93 for ΔE=1GeV

eg. B→ K$l^+ l^-$ New Physics? EXP?

e/ $\boldsymbol{\mu}$ detection differences

Precision Muon (μ^+) Lifetime $\rightarrow$ $\boldsymbol{GF}$

MuLAN experiment at PSI:

$\tau_{\mu+}$=2.1969803(22)x10^{-6}sec MuLAN 2010

(Most precise lifetime measurement ever!)

Lowered Previous World Average error by 1/20!

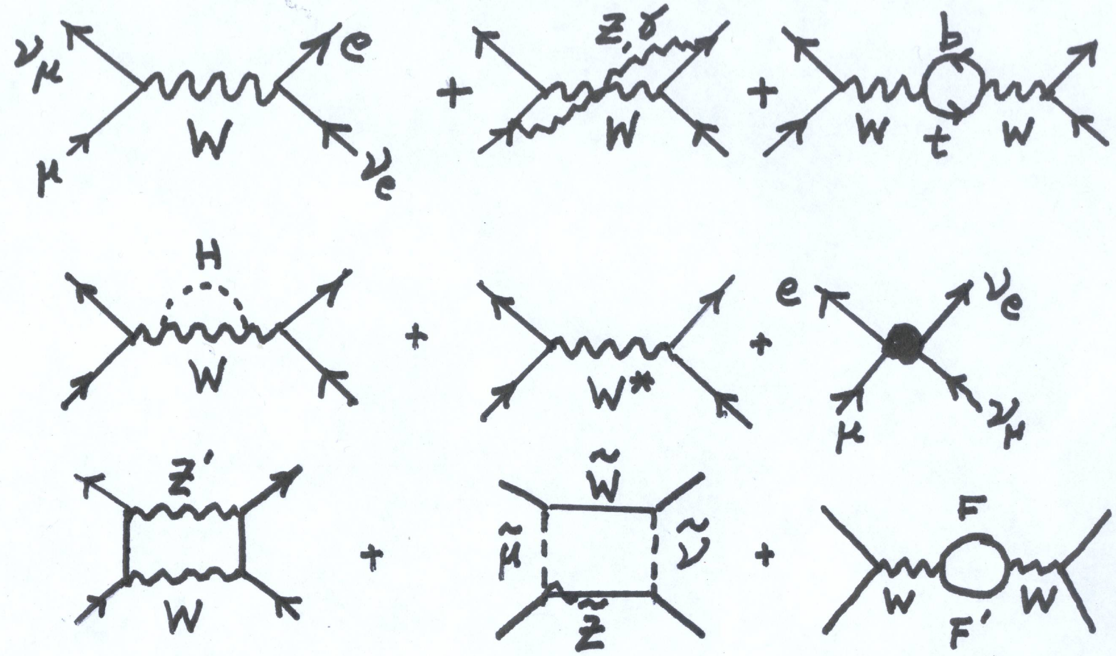
$\tau_\mu^{-1} = \Gamma(\mu^+ \rightarrow e^+ \nu_e \nu_\mu(\gamma)) = G_\mu^2 m_\mu^5 f(m_e^2/m_\mu^2)[1+RC]/192\pi^3$

RC $=\alpha/2\pi(25/4-\pi^2)(1+\alpha/\pi[2/3\ln(m_\mu/m_e)-3.7)\ldots]$ Fermi Th.

Other SM and "New Physics" radiative corrections absorbed into G_μ. Eg. 4th generation, Technicolor, W*…

$G_F \equiv G_\mu = 1.1663787(6)\times10^{-5}\,\mathrm{GeV}^{-2}$ precise & important normalization

Loop and Tree Level Corrections to Muon Decay



Z' Boson　　SUSY　　Technicolor

+ . . .

Lessons Learned From Muonium

in Vernon Hughes Memorial Symposium 2003

based on Czarnecki, Lepage & Marciano PRD61 (2000)

MuLan μ^+ Lifetime 1ppm measurement of $\tau_\mu \rightarrow G_\mu \rightarrow G_{Fermi}$

Stopped μ^+ in matter forms muonium $M=\mu^+e^-$ state

Phase space reduction cancels Final State Interaction!

Spectrum Changes $O(\alpha^2 m_e/m_\mu)$ from each

Cancel due to Lorentz & Gauge Invariance

Bound State Ward Identity

$\tau_M = \tau_\mu(1+ \frac{1}{2}\alpha^2 m_e^2/m_\mu^2$+higher order)

leading correction time dilation≈ $O(10^{-9})$

Muon lifetime G_μ should not be source of V_{ud} unitarity Problem

V_{ud}=0.97370(14): $|V_{ud}|^2+|V_{us}|^2+|V_{ub}|^2$=0.9985(5) 3 sigma tension

Phase Space Suppression cancels FSI e^+e^- (many examples)

Similar to Cancellation of Mass Singularities: Kinoshita & Sirlin (1959)

- Muonium $\pm 5\alpha^2 m_e/m_\mu$ linear contributions cancel
- General bound state theorem based on gauge invariance (QED and QCD)
- 1952 The Effect of Atomic Binding on Nuclear Reaction Energies Nuclear Beta Decay ***Serber & Snyder*** (first use of theorem)
- 1960 Muon capture Uberall (important potentially large effect)
- Bottom Decays (lifetimes) OPE Proof no $1/m_b$ effects
- **Superallowed Nuclear Beta Decays – Complicated at 0.1%**

Possible $O(Z^{4/3}\alpha^2 m_e/M)$ source of discrepancy?

Future Work

Inventors of Strong Focusing at BNL

Courant Livingston Snyder

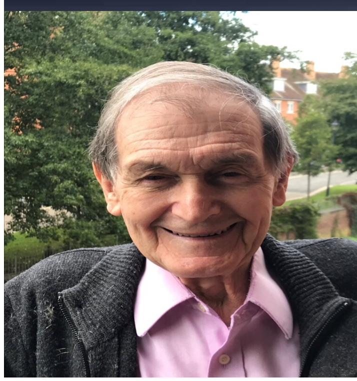
The Legacy Of Hartland Sweet Snyder
(A Human Interest Story)

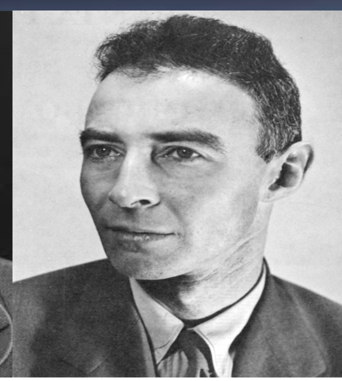
"The Effect of Atomic Binding on Nuclear Reaction Energies"
by R. Serber and H.S. Snyder PR87(1952). ***10 citations*** (I was last in 2004))

"The strong-focusing synchrotron: A new high-energy accelerator"
by Courant, Livingston & Snyder PR88(1952). ***135 Citations***

"Quantized space-time" H.S. Snyder PR71(1947)
1751 citations (100 in 2019!)

"On continued gravitation contraction" PR56(1939)
by J. Oppenheimer and H. Snyder ***(Classical Black Holes Exist!)*** ***876 citations***





2020 Physics Nobel Prize to Roger Penrose for Black Hole stability. Motivated by the early work of Snyder and Oppenheimer (1939)
(Ahead of its Time)

Roger Penrose   Hartland "sweet" Snyder   Robert Oppenheimer

Maurice Goldhaber and Ernest Courant
BNL Centenarians