The Neutrino “Livingston” Plot

INSS 2017. Fermilab. 2017. Aug. 17.

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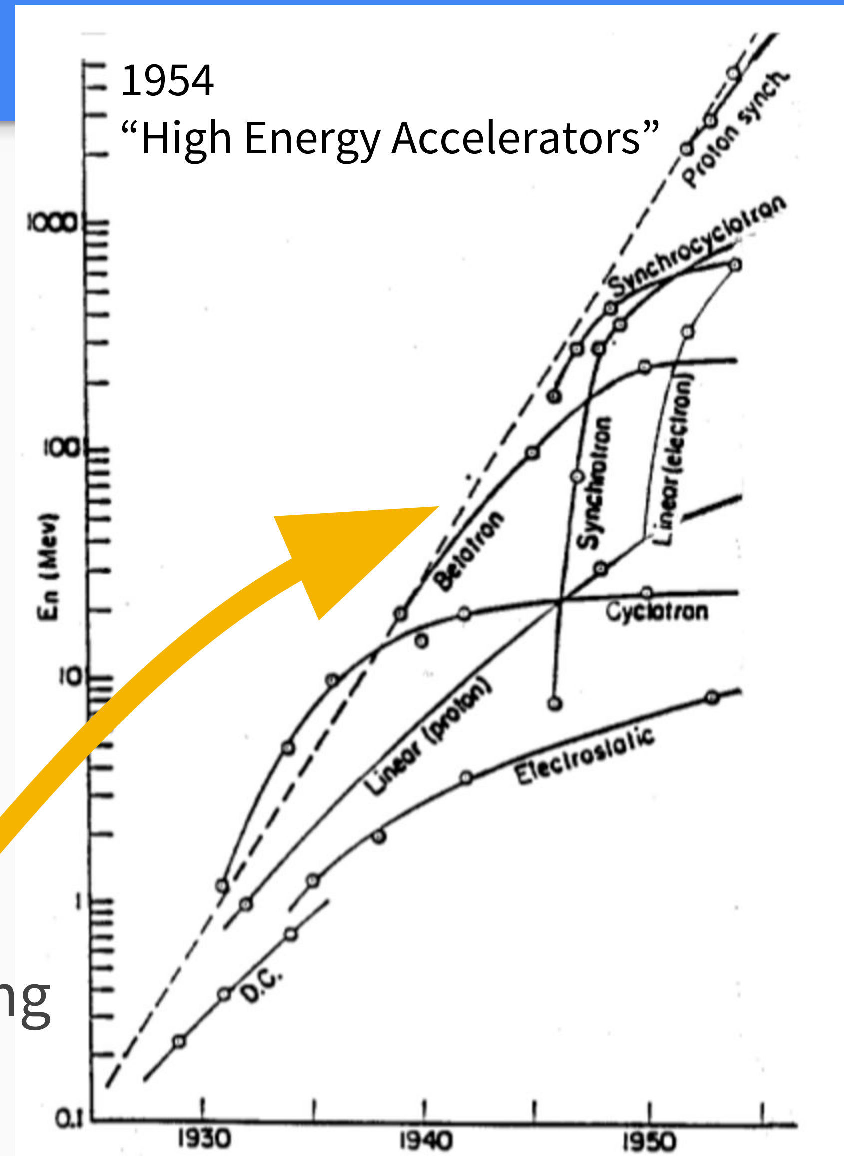
The Original

M. Stanley Livingston

- FNAL director 1967-1970

Accelerator CoM energy was doubling every six years!



Neutrino Detector Mass

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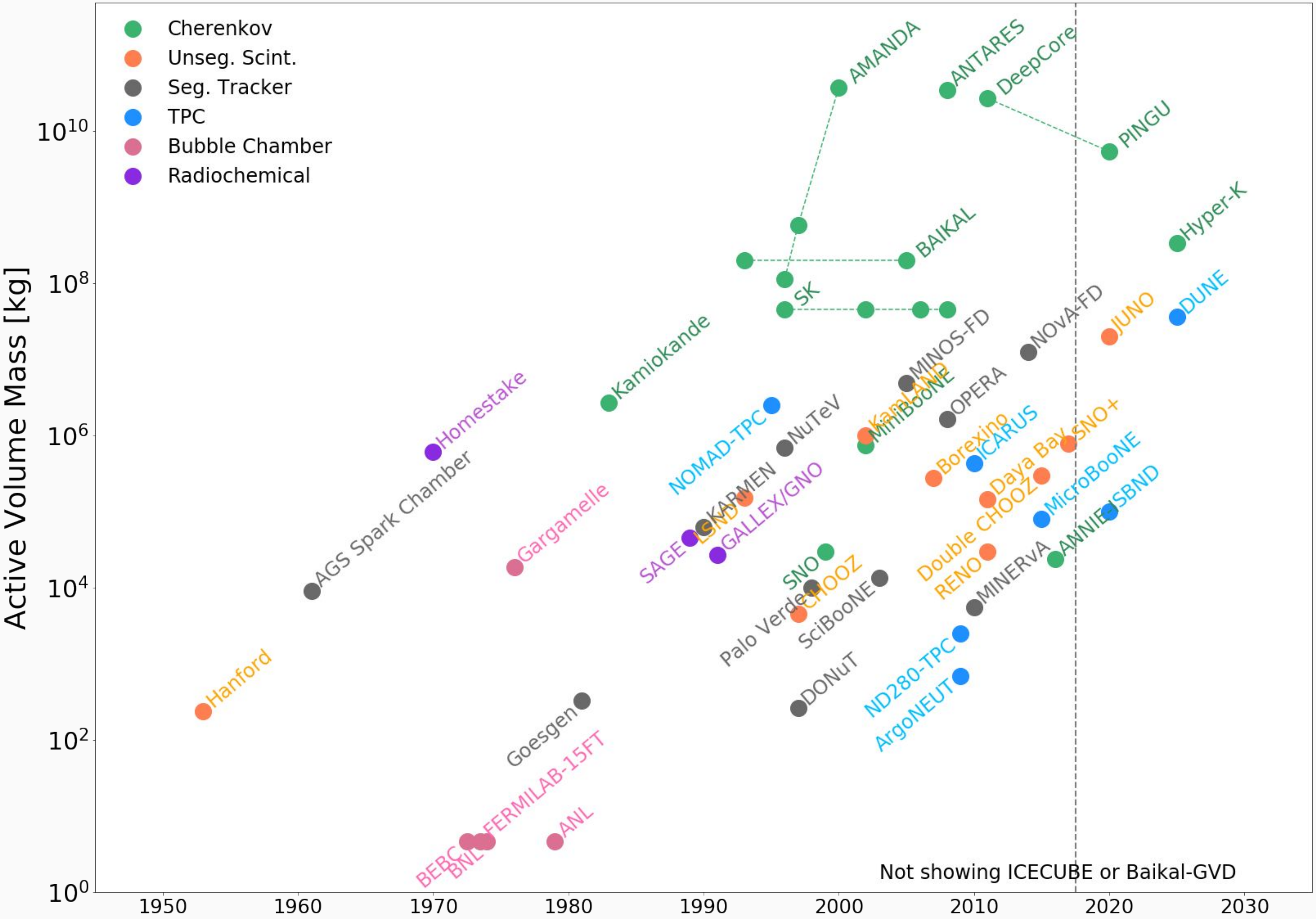
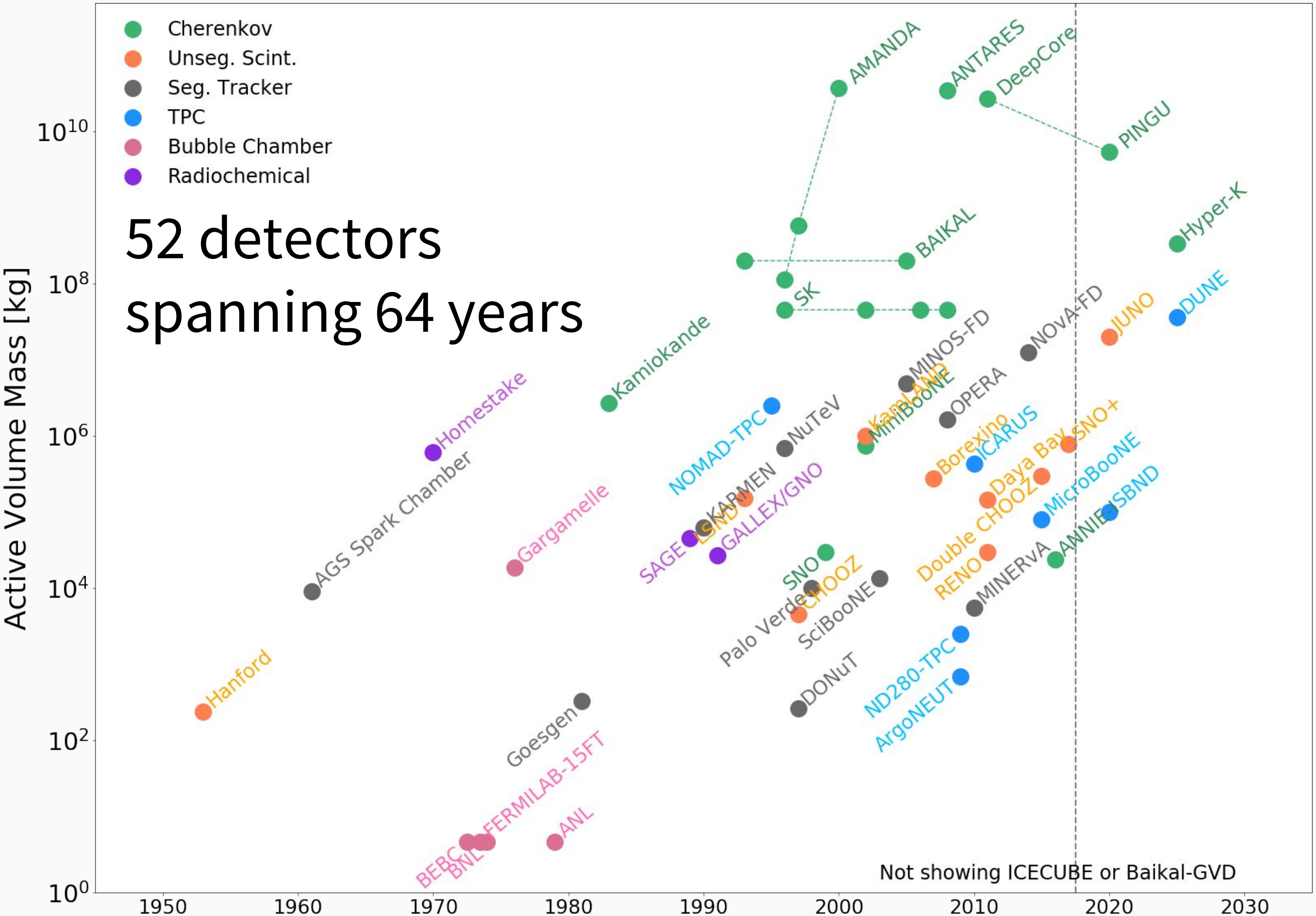
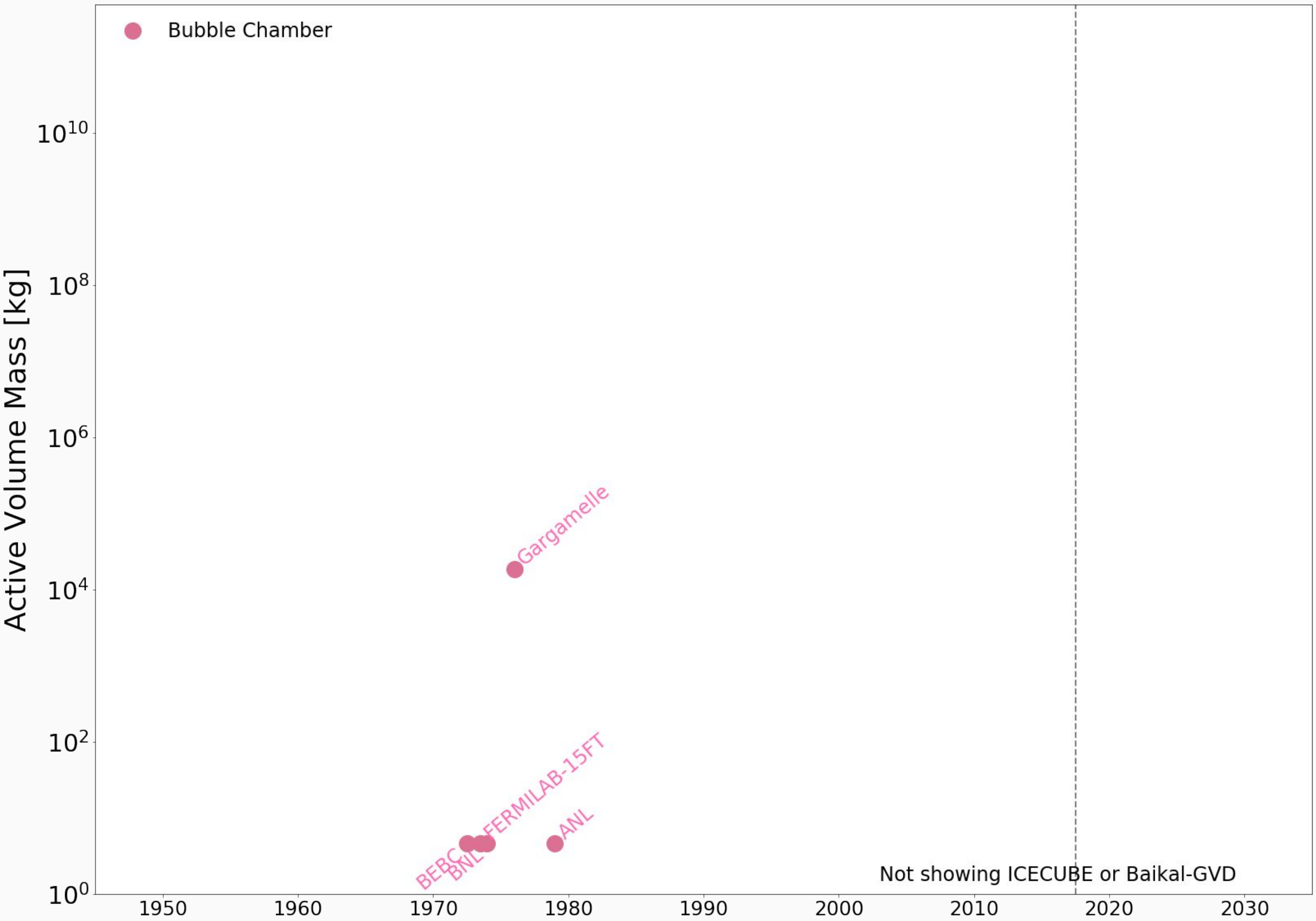


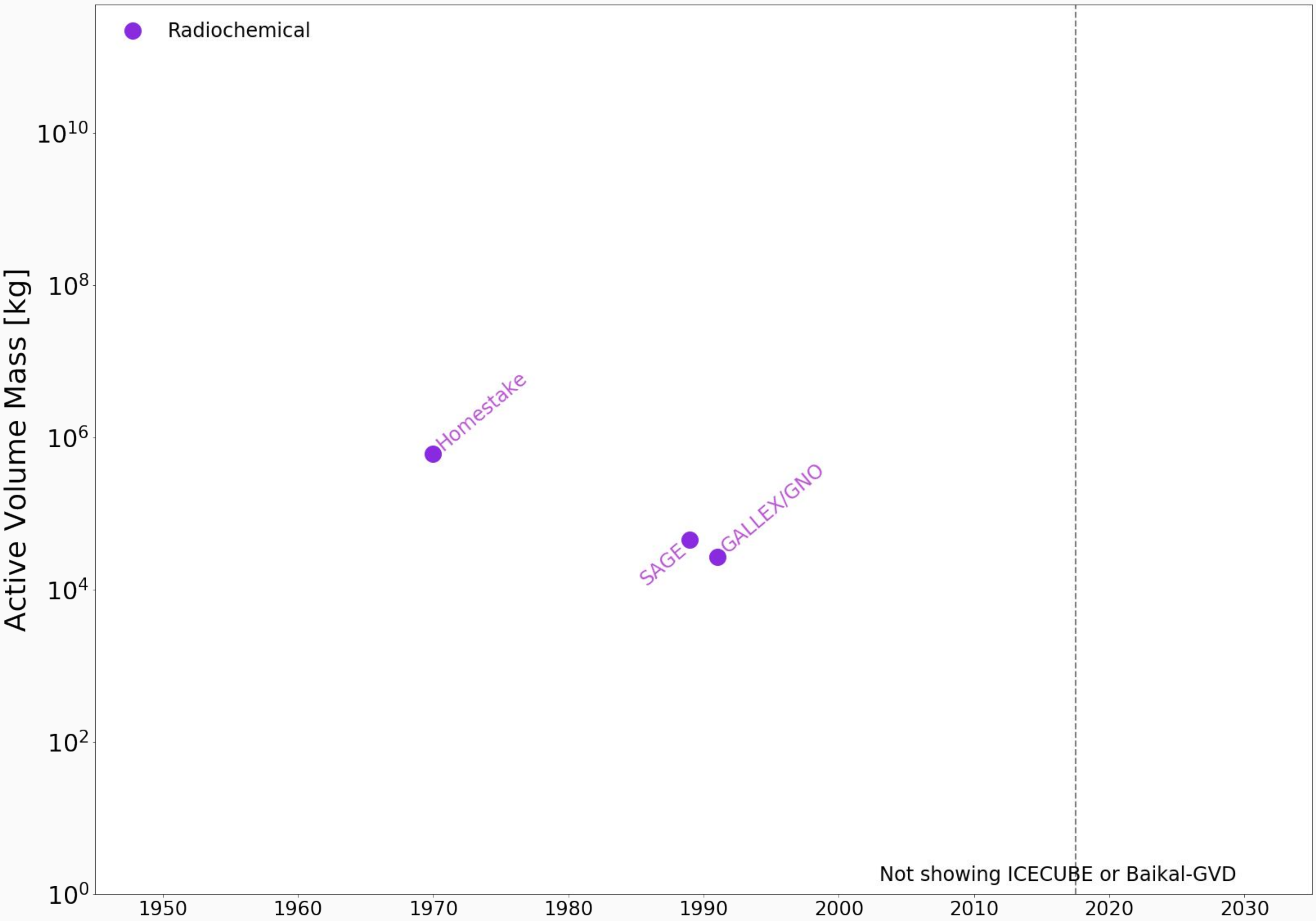
Neutrino Detector Mass



Neutrino Detector Mass – Bubble Chamber

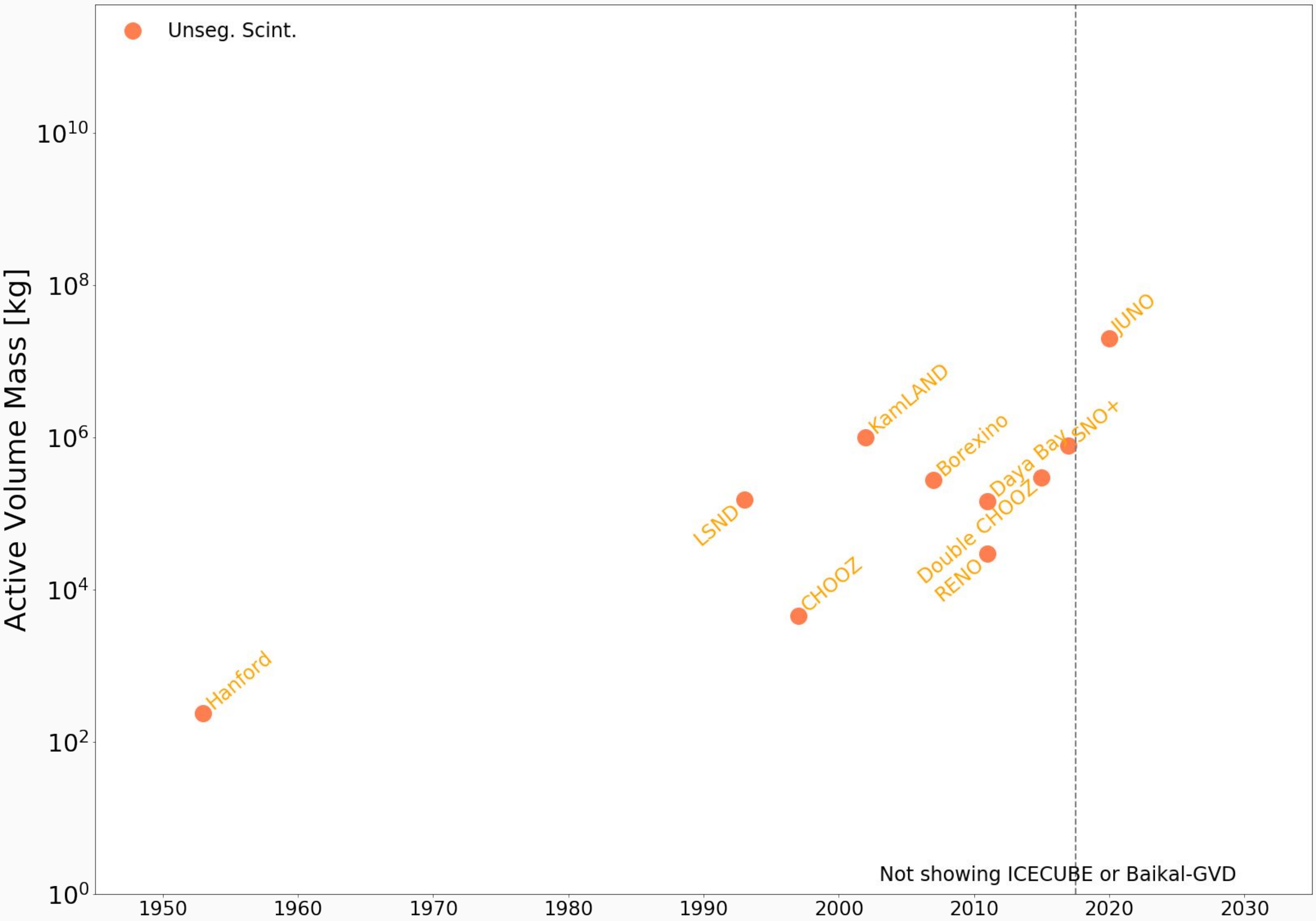


Neutrino Detector Mass – Radiochemical

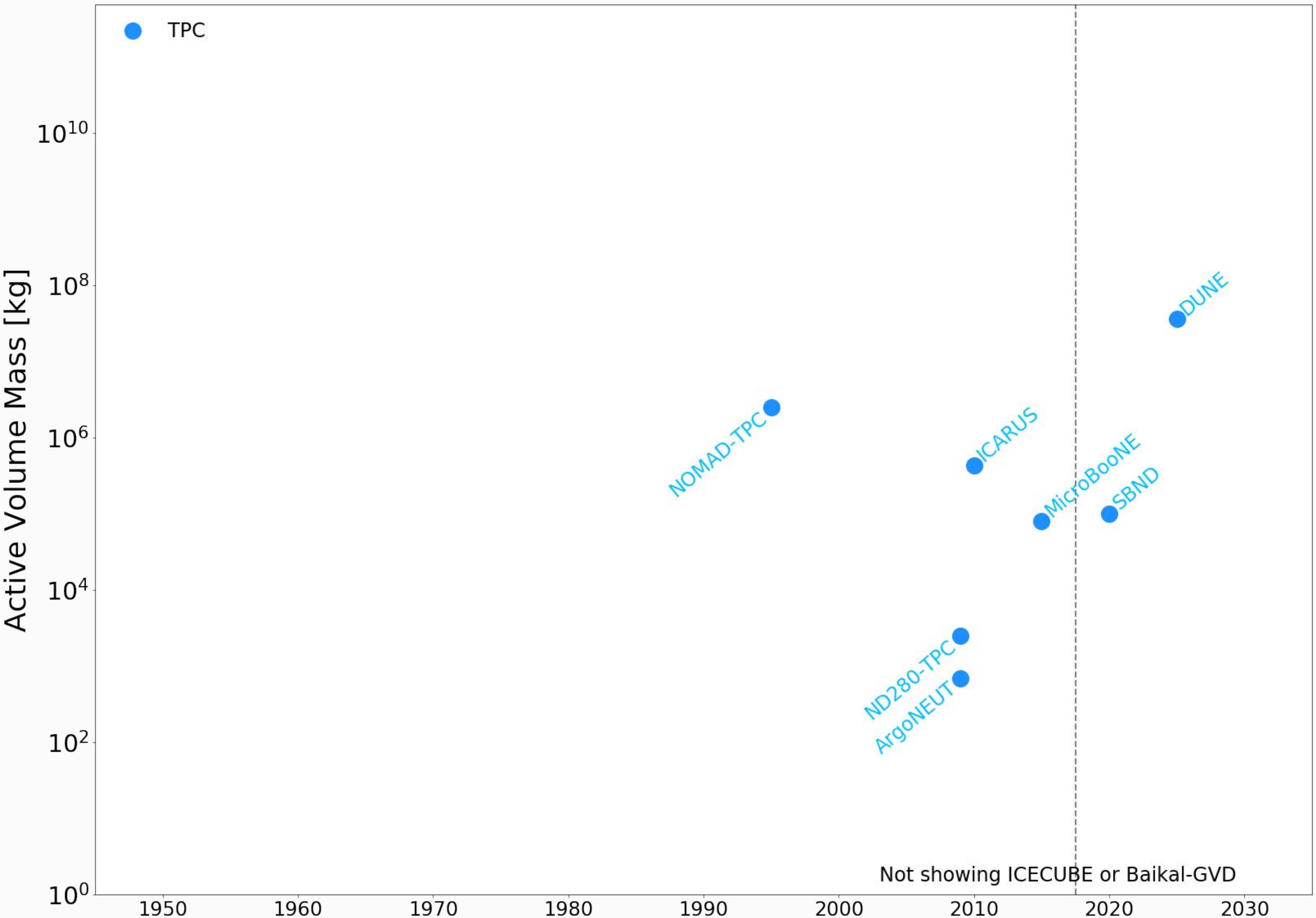


Neutrino Detector Mass – Segmented Tracker

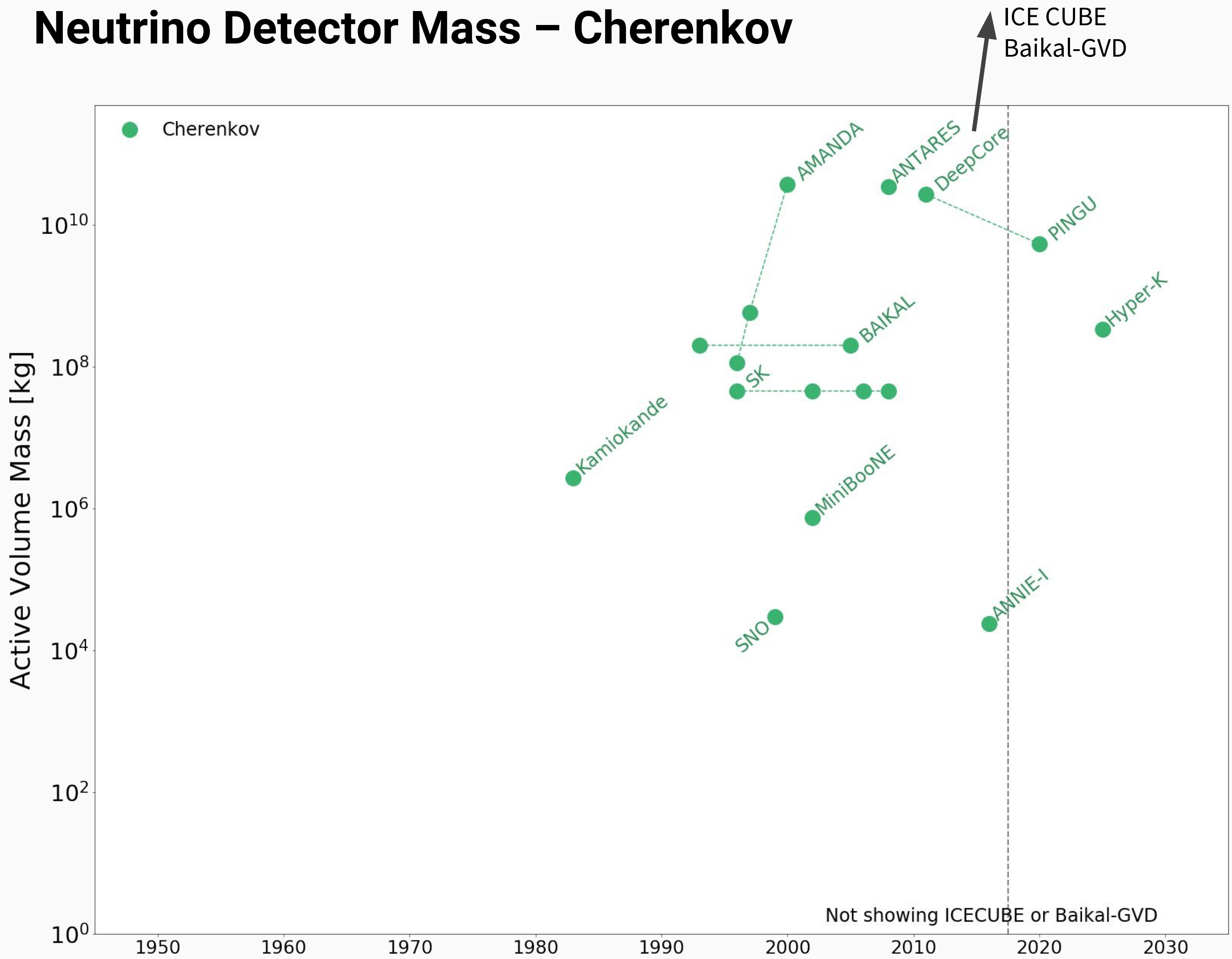
Neutrino Detector Mass – Unsegmented Scintillator



Neutrino Detector Mass – TPC



Neutrino Detector Mass – Cherenkov



Neutrino Interaction Vertex Resolution

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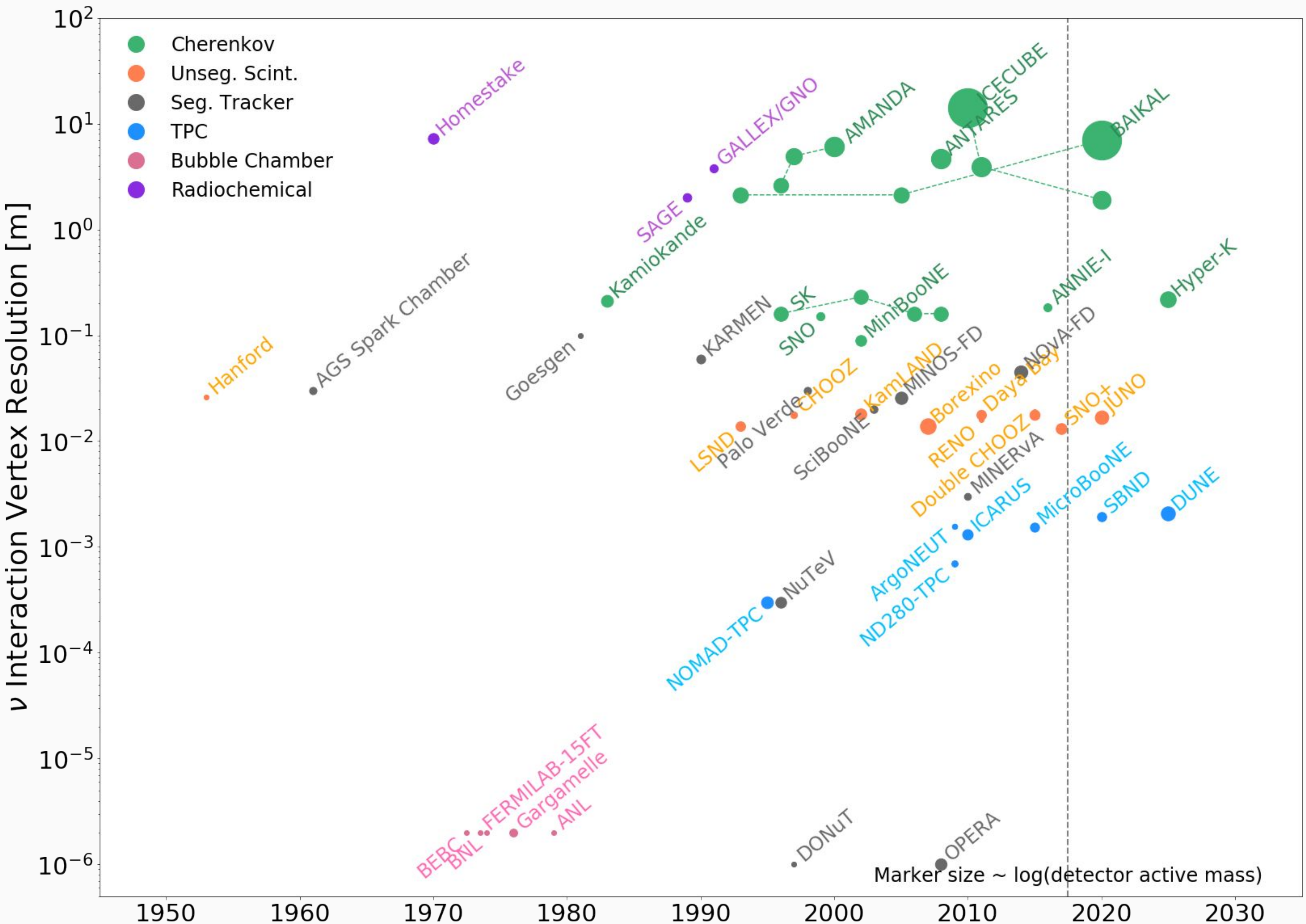
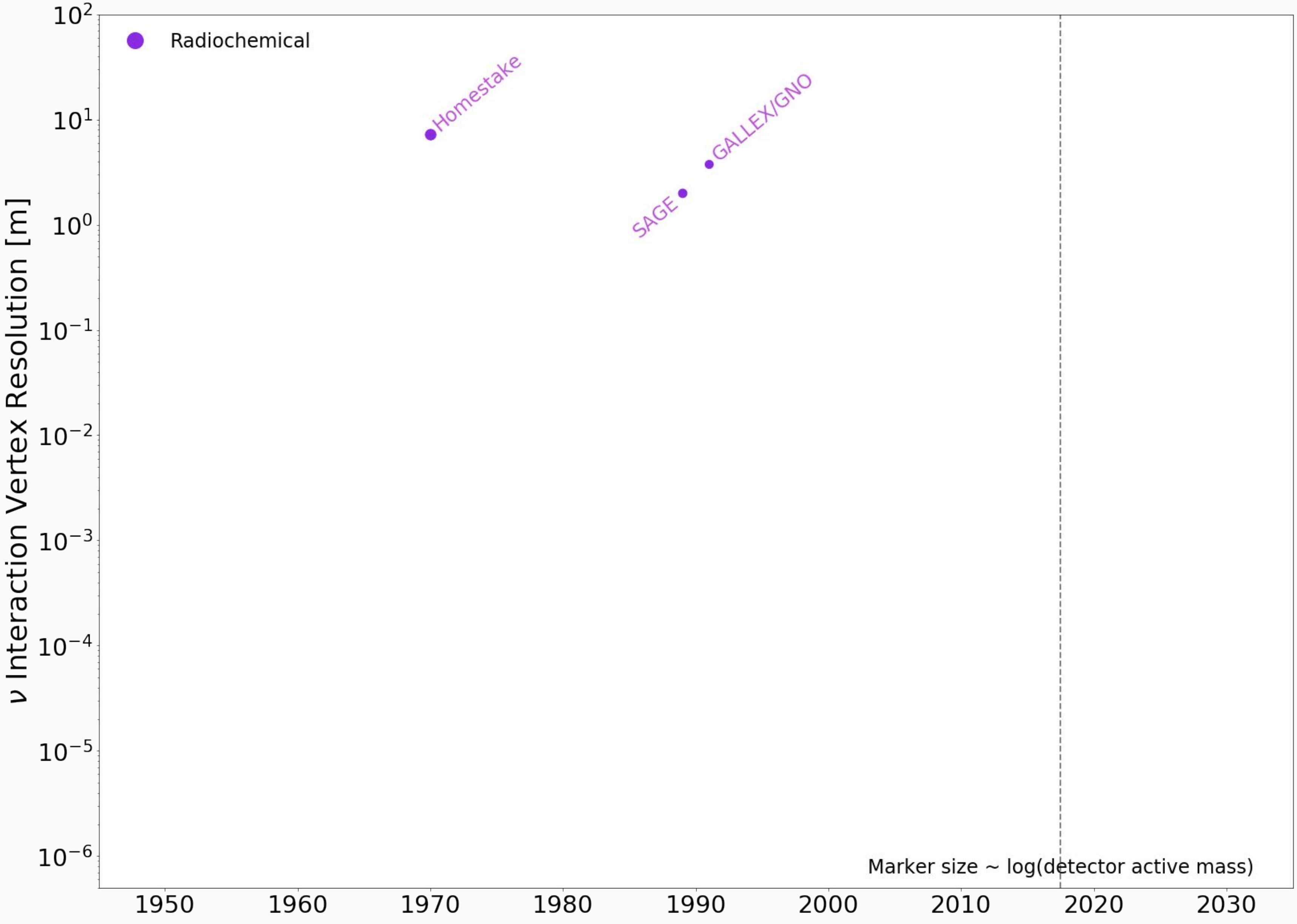
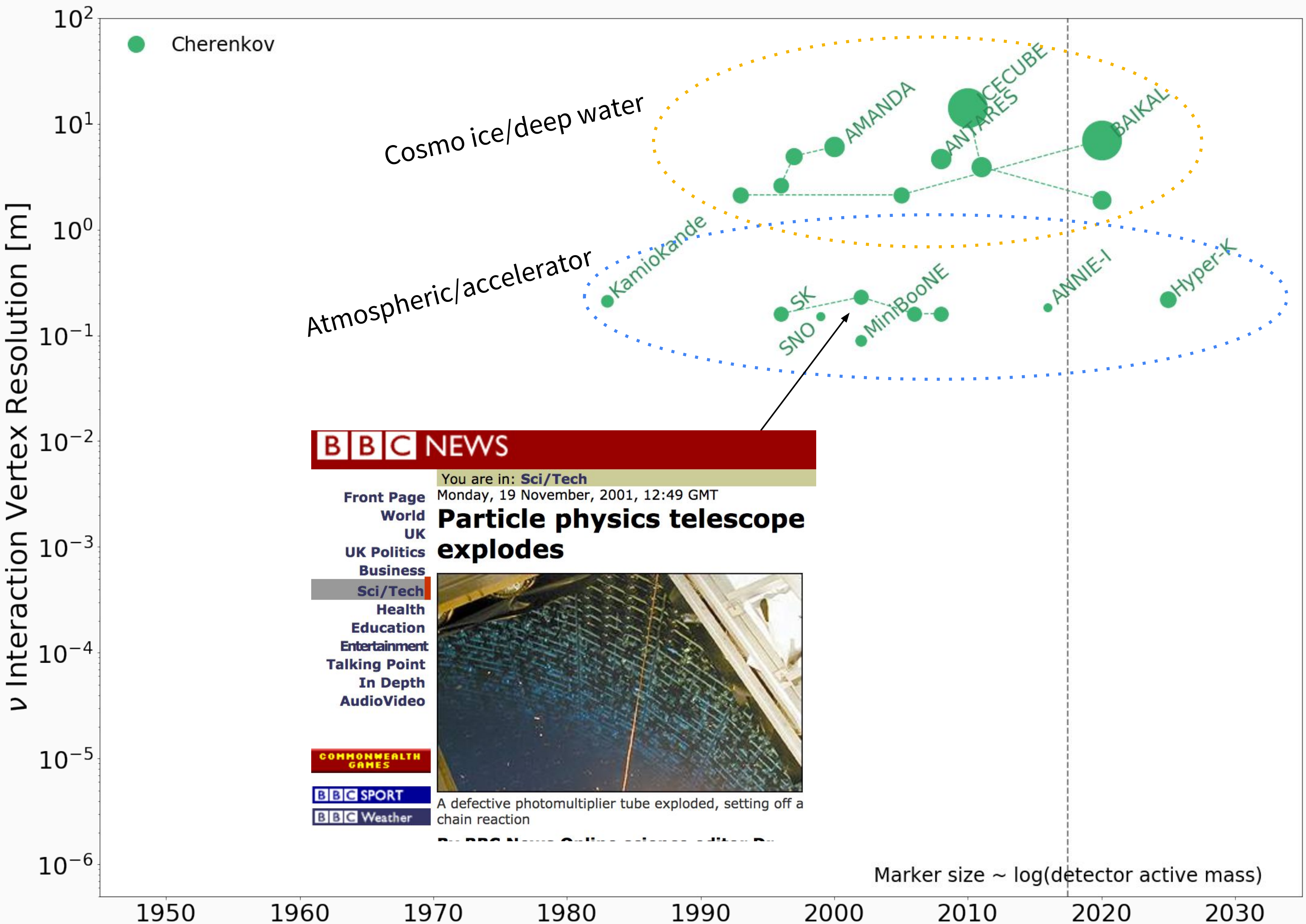


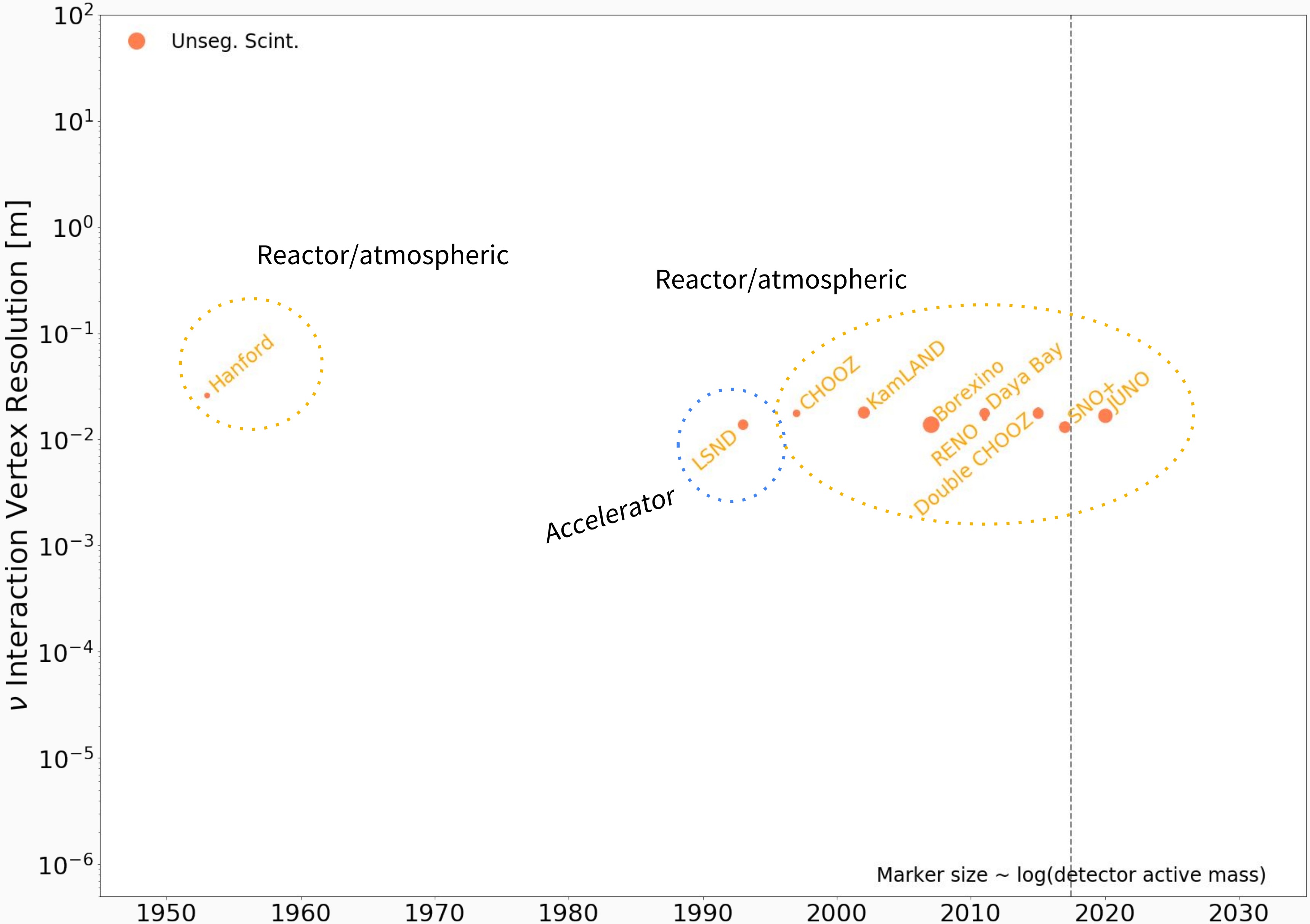
Neutrino Interaction Vertex Resolution – Radiochemical



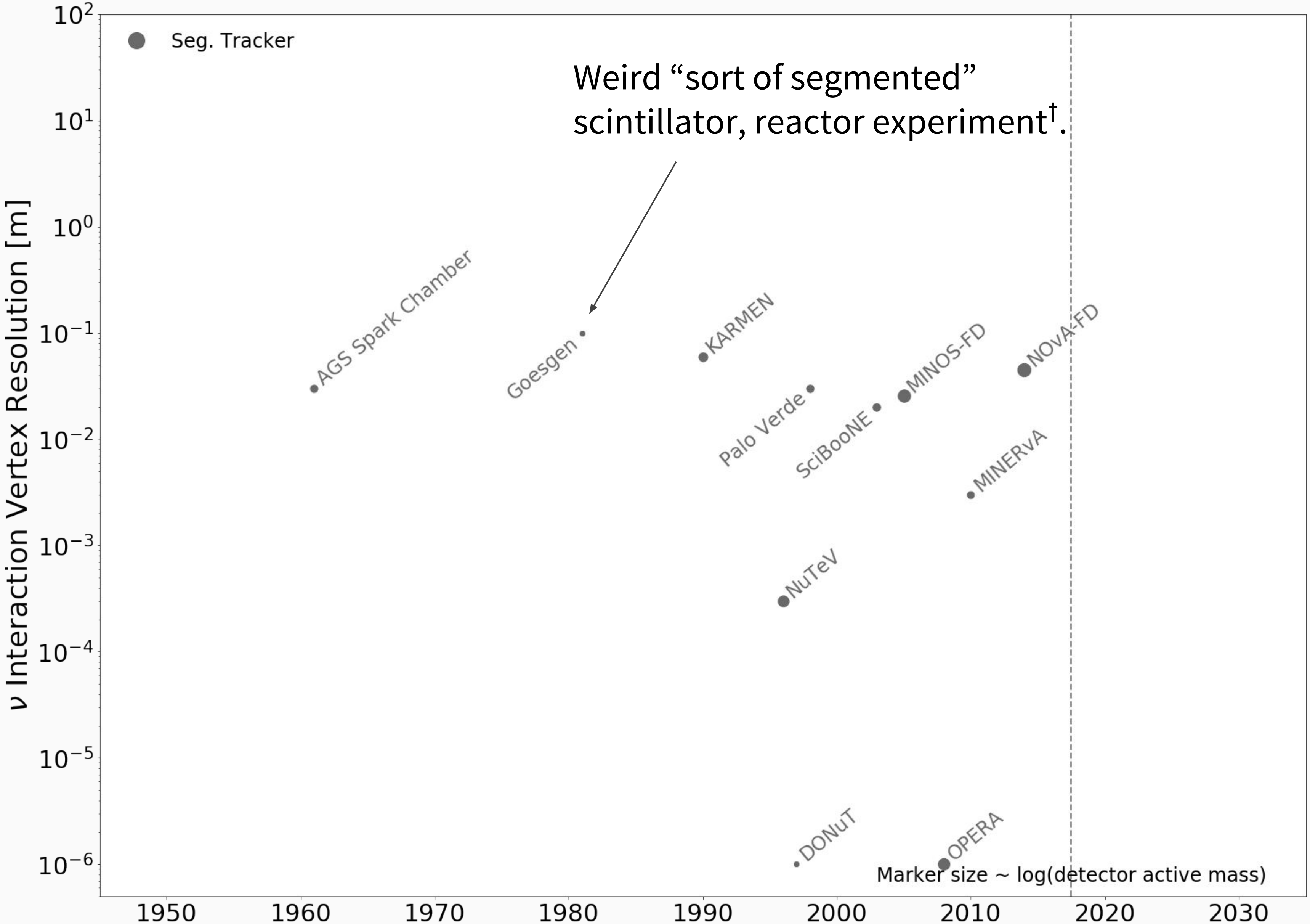
Neutrino Interaction Vertex Resolution – Cherenkov



Neutrino Interaction Vertex Resolution – Unseg Liq Scin

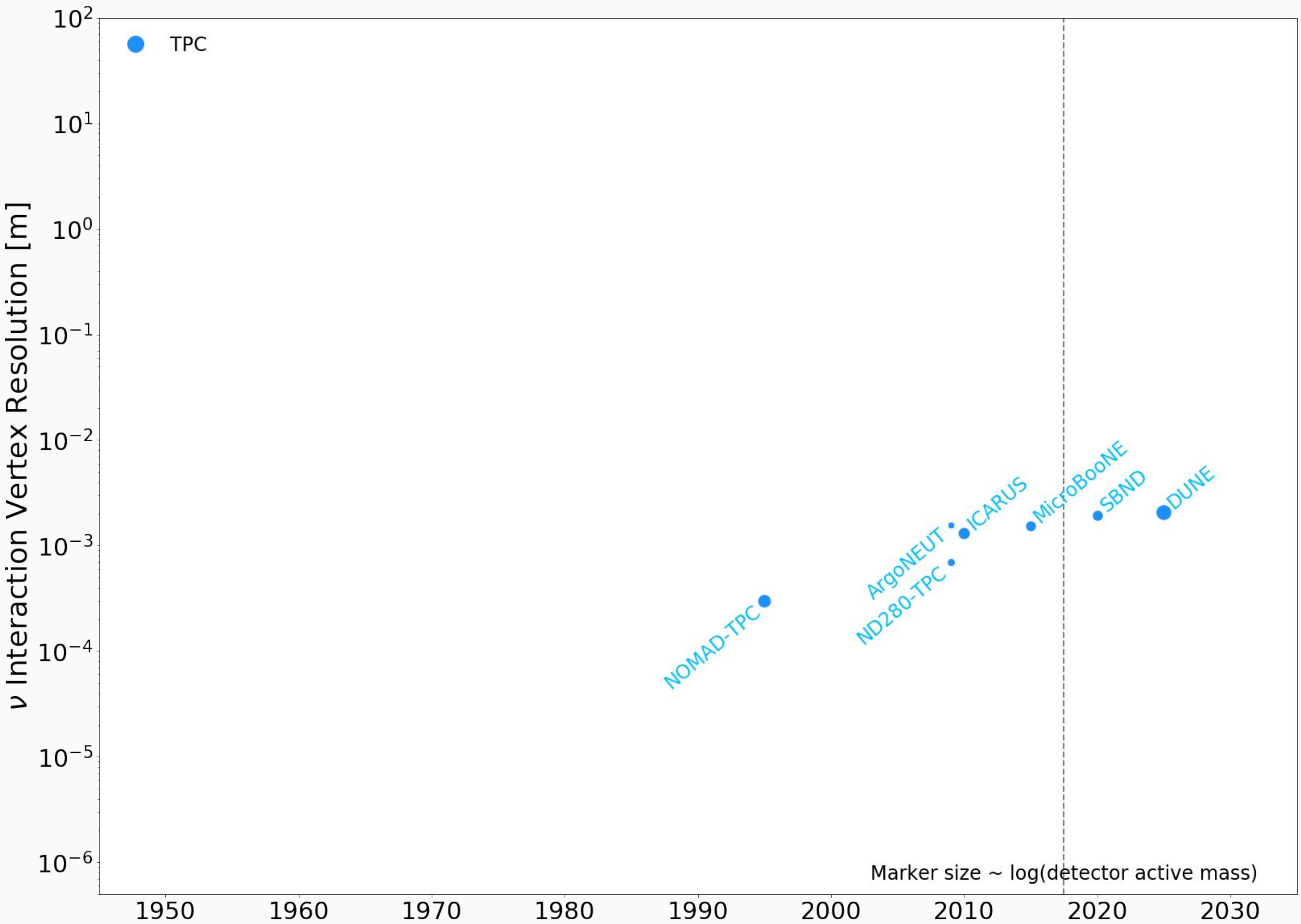


Neutrino Interaction Vertex Resolution – Seg Tracker

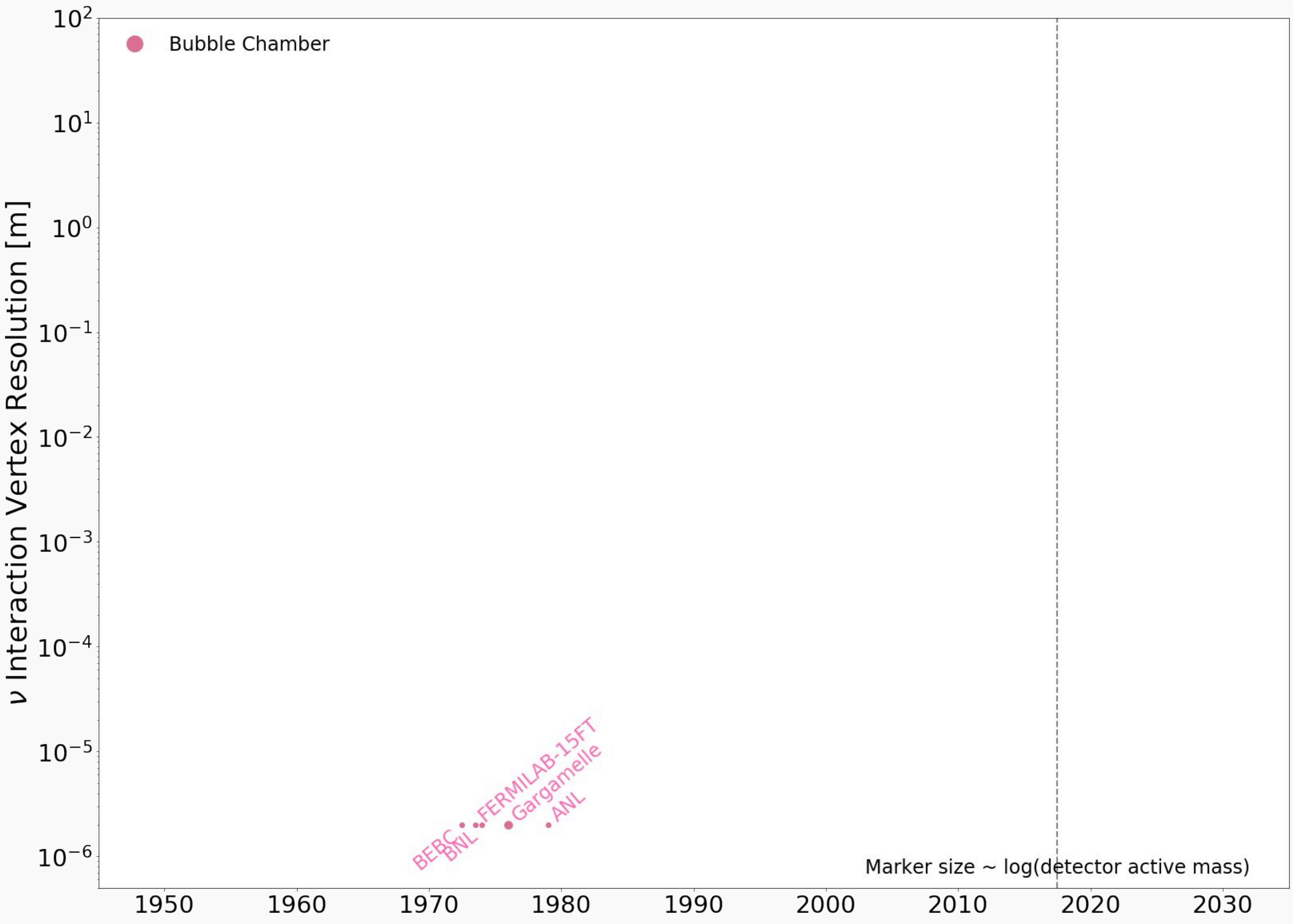


† https://journals.aps.org/prd/pdf/10.1103/PhysRevD.34.2621

Neutrino Interaction Vertex Resolution – TPC



Neutrino Interaction Vertex Resolution – Bubble Chamber



Conclusion

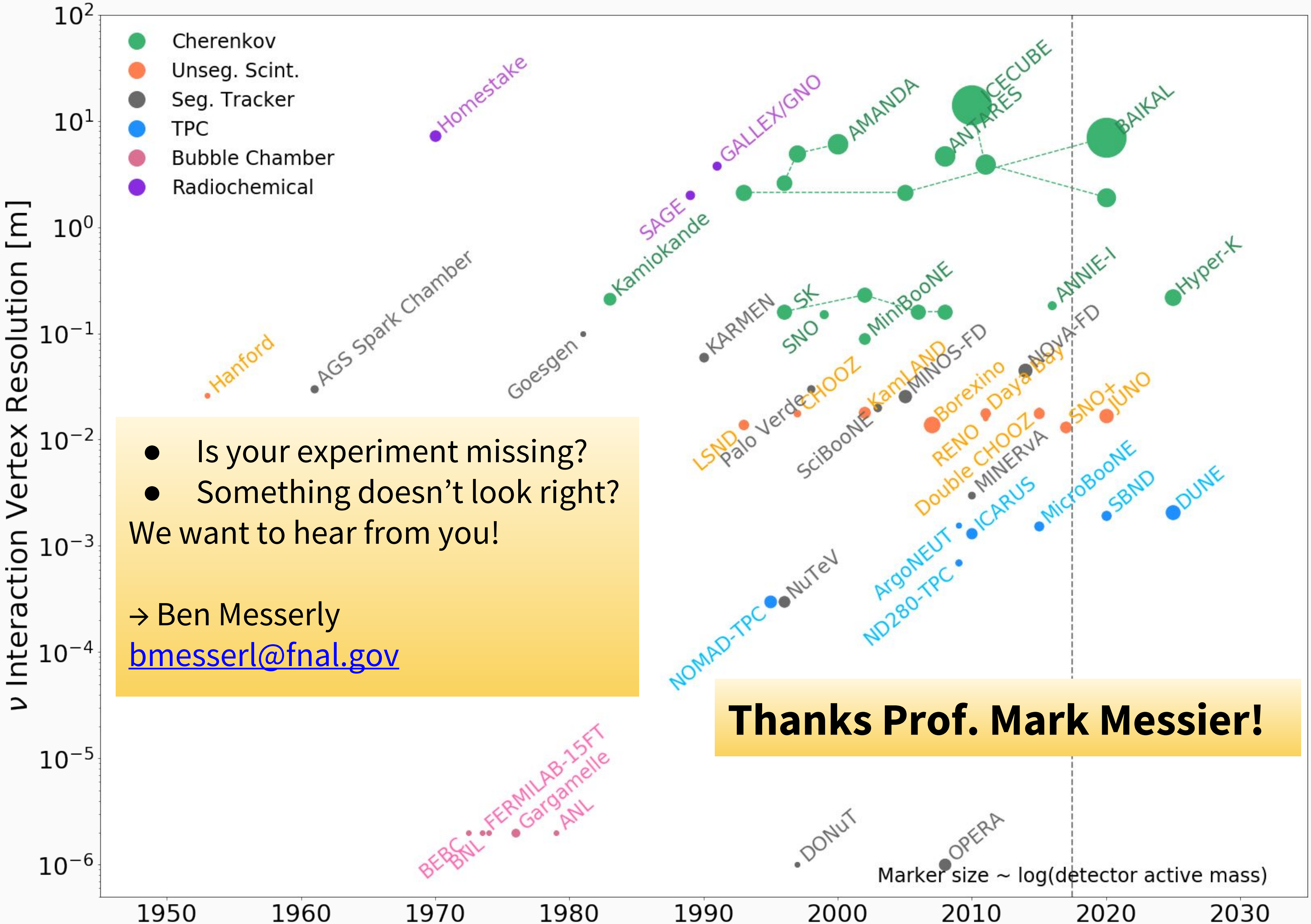
Our Data, Calculations, and Citations

B	C	D	E	F	G
Start	**End**	**Experiment**	**Detector Type**	**Location**	**mass [kg]**
1961	1962	**AGS Spark Chamber**	Tracking Calorimeter	BNL	9.07E+03
1996	2005	**AMANDA**	Cherenkov	South Pole	5.00E+09
1969	1979	**ANL**	Bubble Chamber	Argonne National Laboratory	2.3kg (H), 4.6kg (D)
2016	-	**ANNIE**	Cherenkov	Fermilab	
2008	-	**ANTARES**	Cherenkov	Mediterranean Sea	
2009	2010	**ArgoNEUT**	TPC	Fermilab	6.90E+02
1998	-	**Baikal**	Cherenkov	Baikal Lake, Russia	2.00E+08
1973	1984	**BEBC**	Bubble Chamber	CERN	
1974		**BNL 7ft**	Bubble Chamber	Brookhaven National Laboratory	

https://docs.google.com/spreadsheets/d/1HKEvm6tsoRX3EGpANM3n6nKIHn5NldHmfSU16YjVcoM/edit?usp=sharing

Notes on the method

- Many caveats + exceptions!
- Paper skimming, ancient pre-internet experiment archeology
- Extensive approximations, back-of-the-envelope calculations
- Where available use quoted resolutions instead of calculated resolutions
    - Calculations agree with quoted values within an order of magnitude; few exceptions.
    - See water cherenkov "*n.b.*" in backup slides.
- *Most* experiments don't care about and don't provide enough info to estimate resolution.



- Is your experiment missing?
- Something doesn't look right?

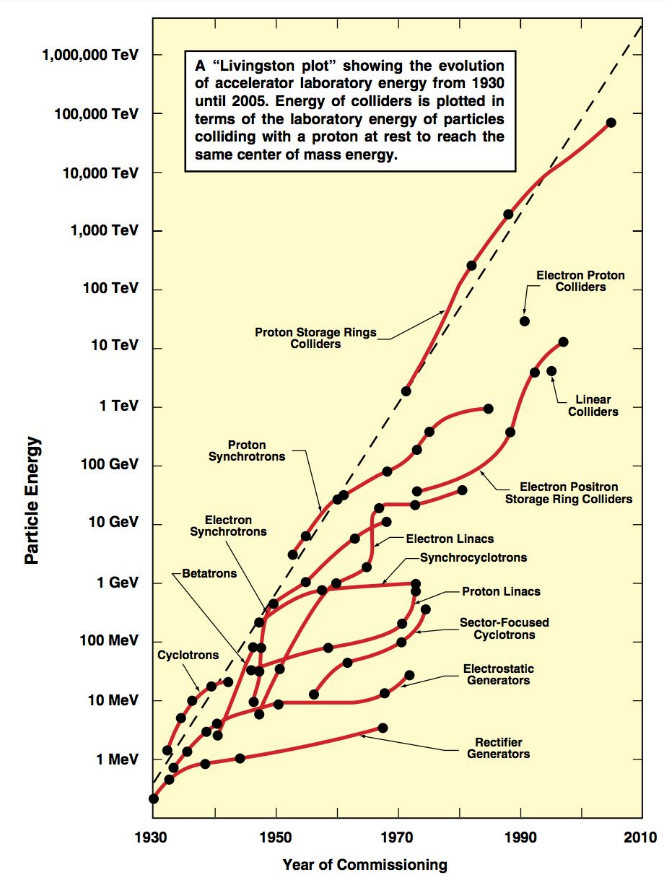
We want to hear from you!

→ Ben Messerly
bmesserl@fnal.gov

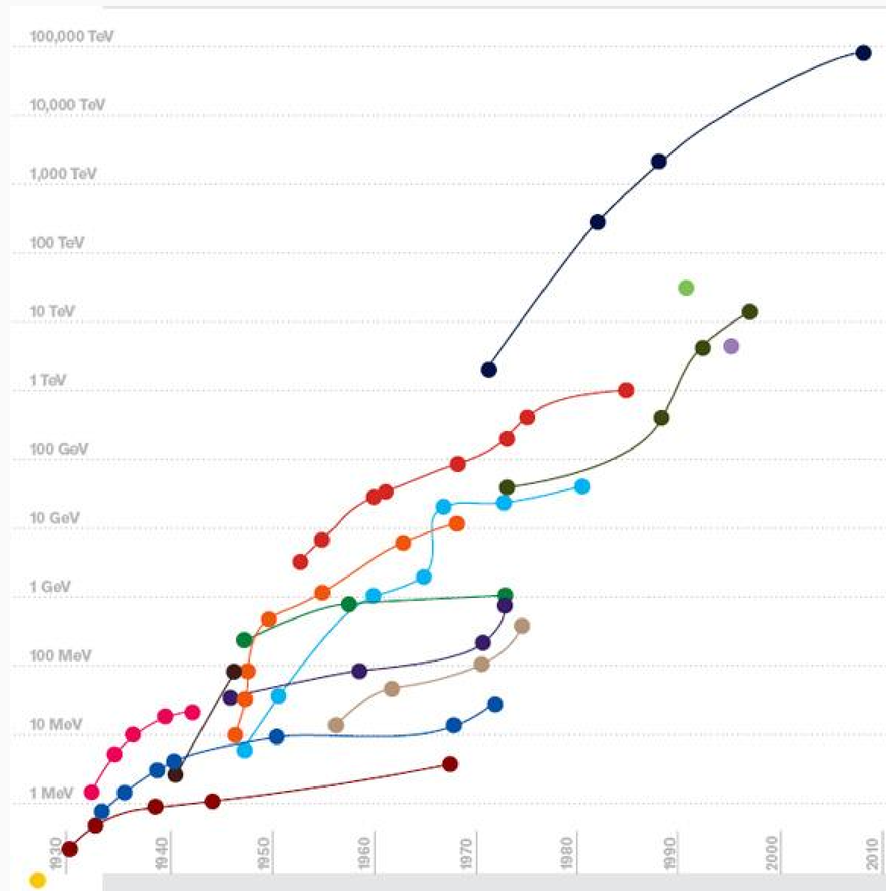
Thanks Prof. Mark Messier!

Backup

Many Iterations of the Livingston Plot



2001 Snowmass Accelerator R&D Report



Symmetry Magazine. Oct 1, 2009.

Calculation: Cherenkov and Unsegmented Scintillator

$$\text{Position Resolution} = \frac{\text{Resolution of a single PMT}}{\sqrt{\text{Photons detected}}}$$

$$\text{Resolution of a single PMT} = \text{timing resolution} \times c \times n$$

$$\text{Photons detected} = N_{\text{photons}} \times e^{-\frac{x_0}{\lambda_{Abs}}} \times \text{Quantum Eff} \times \text{PMT coverage}$$

$$N_{\text{photons}} = \frac{\text{photons produced}}{\text{track length}} \times \text{track length} \times sin^2(\theta_c)$$ (Cherenkov)

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- x_0 ~ detector scale
- λ_{Abs} ~ 10 m
- *Quantum Efficiency* = 20%
- PMT coverage ~ 10-40%
- Coverage = Σ $(SA_{PMT})/SA_{det}$. For Ice Cube-style detectors ~ Σ_{plane} $(SA_{PMT})/SA_{det}$

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N.B. For all detectors in these two categories, we used a **10 MeV electron** for photon source.

Not what reactor or solar experiments (E_ν ~ 1MeV) had in mind when they were determining their resolutions!

Generally: higher energy track → more photons → better resolution.

Calculation: Cherenkov and Unsegmented Scintillator

$$\text{Position Resolution} = \frac{\text{Resolution of a single PMT}}{\sqrt{\text{Photons detected}}}$$

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(Cherenkov)

E.g. we found that using a 10 MeV electron for a reactor experiment (E_ν ~ 5 MeV) lead to a calculated resolution ~ an order of magnitude better than the quoted resolution.

Similarly, 10MeV too small for cosmo experiments.

For consistency, used 10 MeV electron, though next iteration might adjust.

Calculation: Cherenkov and Unsegmented Scintillator

$$\text{Position Resolution} = \frac{\text{Resolution of a single PMT}}{\sqrt{\text{Photons detected}}}$$

$$\text{Resolution of a single PMT} = \text{timing resolution} \times c \times n$$

$$\text{Photons detected} = N_{\text{photons}} \times e^{-\frac{x_0}{\lambda_{Abs}}} \times \text{Quantum Eff} \times \text{PMT coverage}$$

$$N_{\text{photons}} = \frac{\text{photons produced}}{\text{particle energy}} \times \text{particle energy}$$

(Scintillator)

TPCs

New Experiments

Resolution ~

wire spacing (*x*&*y*) * drift distance/(drift time*sampling rate)

Segmented Tracking

Category Includes:

- Spark Chamber (1962 ν_μ discovery)
- ν_τ Emulsion (OPERA, DONuT)
- Standard Scintillator Trackers (NuTeV, MINERvA, MINOS, NOvA)

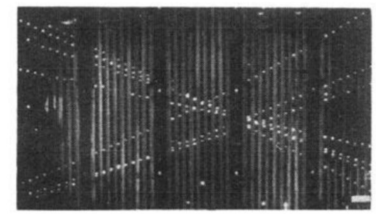
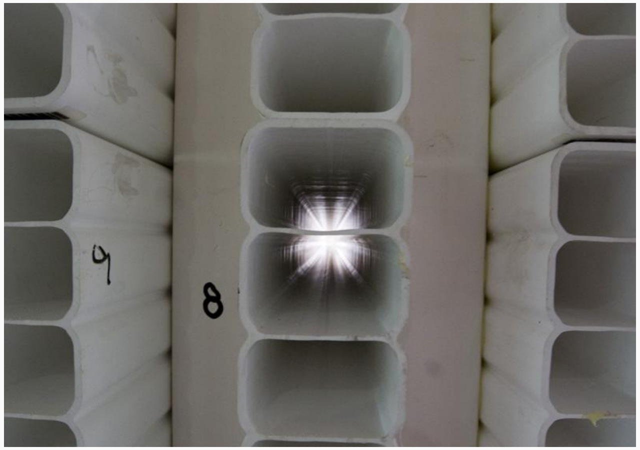


FIG. 4. Land print of Cosmic-ray muons integrated over many incoming tracks.



Resolution:

- Largely determined by dimensions/spacings of segments
- Though experiments had their own fancy methods which could improve resolution.