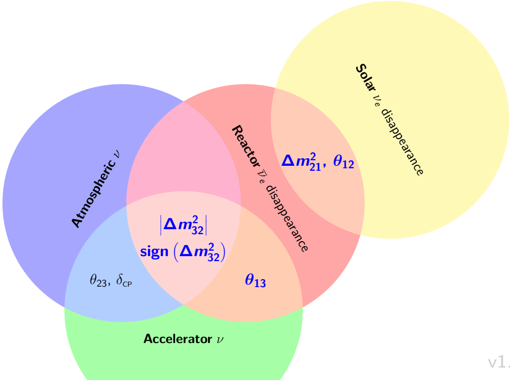
Neutrino oscillation physics in JUNO

Maxim Gonchar on behalf of the JUNO collaboration

Joint Institute for Nuclear Research

EPS-HEP
July 26, 2021



RSF grant #21-42-00023

v1.1.3

1 Introduction

- Neutrino mixing and oscillations
- Reactor $\overline{\nu}$ oscillations

2 JUNO and TAO

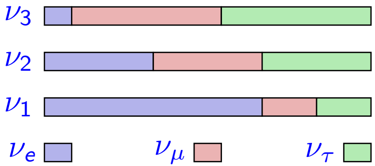
- Detectors
- Status

3 Oscillation physics

- Reactor $\overline{\nu}_e$
- Solar ν_e from $^8\mathrm{B}$
- Atmospheric $\nu_\mu/\overline{\nu}_\mu$
- Reactor $\overline{\nu}_s$

4 Summary

Mandatory slide I: Neutrino mixing



Weak and mass eigenstates differ:

$$|\nu_\alpha\rangle = \sum U^*_{\alpha i}|\nu_i\rangle$$

α – flavor states

i – mass states

Mixing parametrized by:

- three mixing angles: $\theta_{12}, \theta_{23}, \theta_{13}$,
- CP-violating phase: δ_{CP}.

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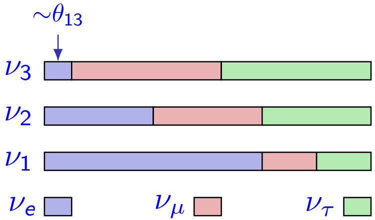

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Pontecorvo-Maki-Nakagawa-Sakata (PMNS) mixing matrix:

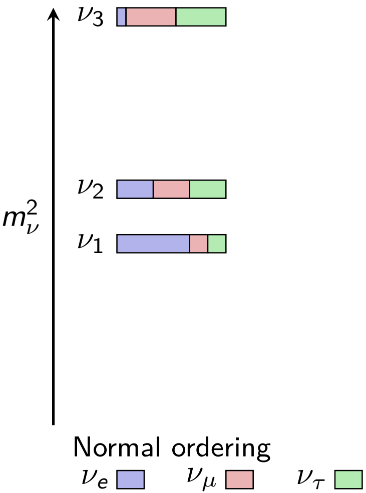
✓ $\theta_{23} \approx 45^\circ$ established through atmospheric and accelerator experiments: possibly maximal.

✓ $\theta_{12} \approx 34^\circ$ established through solar experiments and KamLAND: large, but not maximal.

✓ $\theta_{13} \approx 8^\circ$ established by reactor: **Daya Bay**, RENO, Double Chooz.

- δ_{CP} unknown: NOvA and T2K.

Mandatory slide II: Neutrino mass and ordering



Mass splitting from oscillations

- $\Delta m^2_{21} = (7.53 \pm 0.18) \times 10^{-5}\,\mathrm{eV}^2$
- $\left|\Delta m^2_{32}\right| = (2.42 \pm 0.06) \times 10^{-3}\,\mathrm{eV}^2$
- $\left|\Delta m^2_{32}\right| / \Delta m^2_{21} \sim 32$

Numbers updated: 2020.04.17

Neutrino mass

- Mass limits, meV:

$m_2 >$	0		
$m_3 \neq$	0	oscillations	
$\sum m_\nu \gtrsim$	60		
$\sum m_\nu \lesssim$	120	cosmology	Planck
$m_{\nu_e} <$	1100	direct	KATRIN
$\langle m_{\beta\beta} \rangle <$	160	$0\nu\beta\beta$	GERDA
$m_{\text{light}} <$	440		

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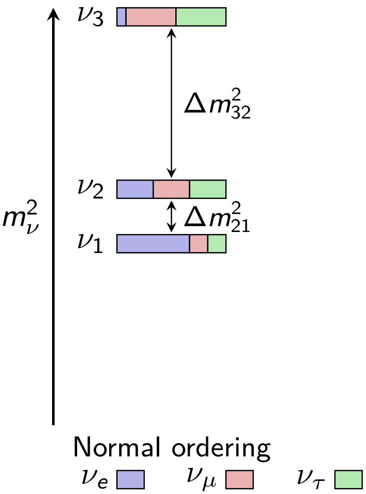

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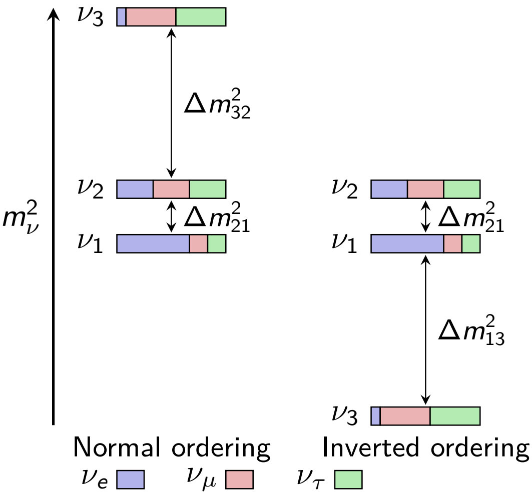

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- $|\Delta m^2_{32}| / \Delta m^2_{21} \sim 32$
- Mass ordering: is ν_1 lighter than ν_3?

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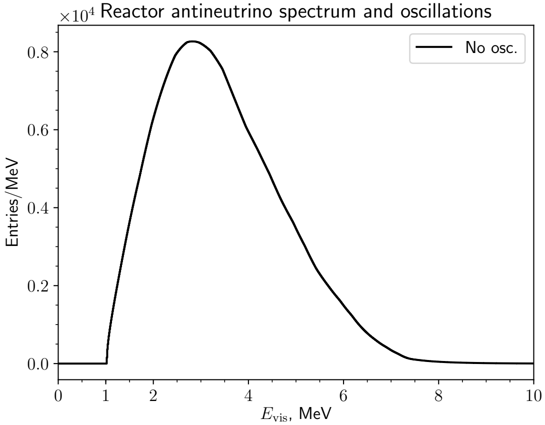
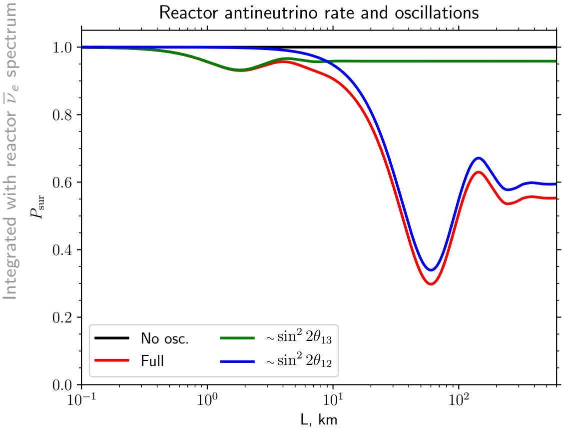
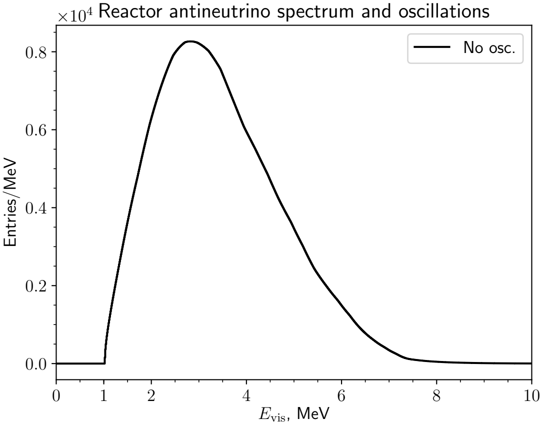


$E_{\mathrm{vis}} \approx E_\nu - 0.78\,\mathrm{MeV}$





$$1 - P_{\overline{\nu}_e\to\overline{\nu}_e} = \sin^2 2\theta_{13}\left(\sin^2\theta_{12}\sin^2\frac{\Delta m^2_{32}L}{4E} + \cos^2\theta_{12}\sin^2\frac{\Delta m^2_{31}L}{4E}\right) + \sin^2 2\theta_{12}\cos^4\theta_{13}\sin^2\frac{\Delta m^2_{21}L}{4E}$$

$\cancel{\delta_{\mathrm{CP}}, \theta_{23}}$

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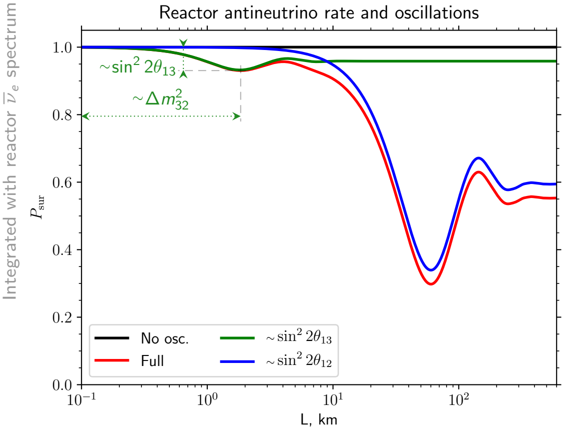

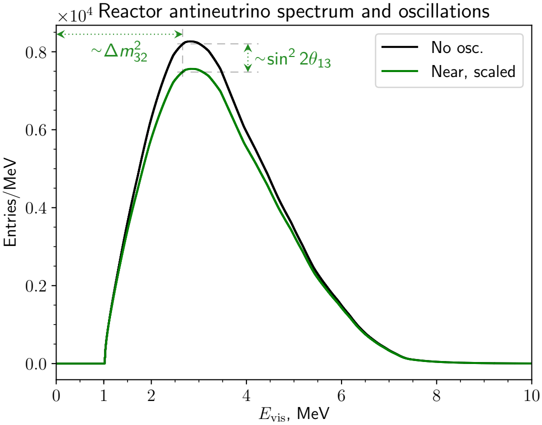

deficit value

minimum location

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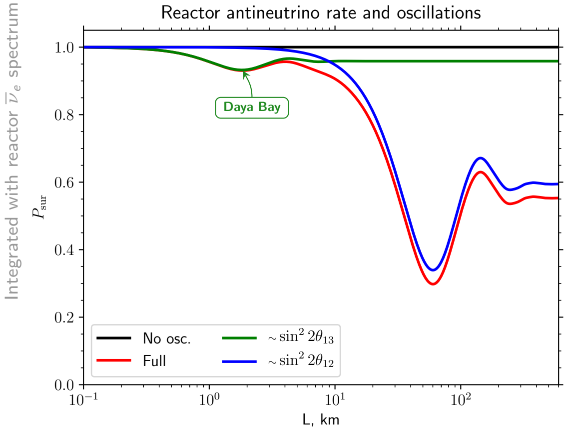

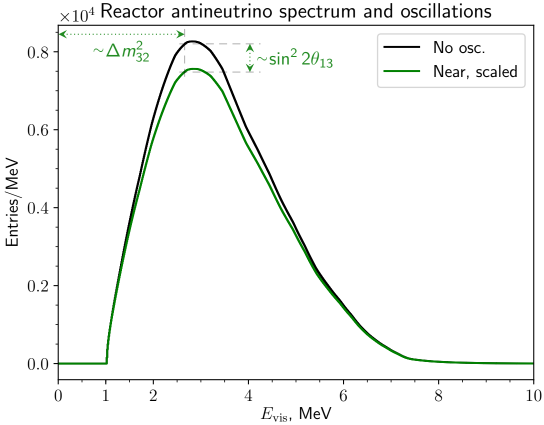

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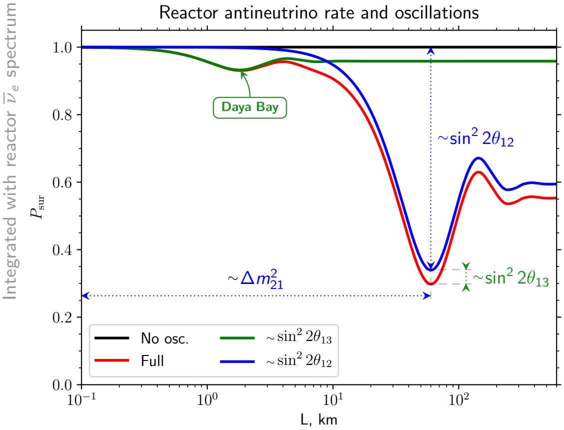

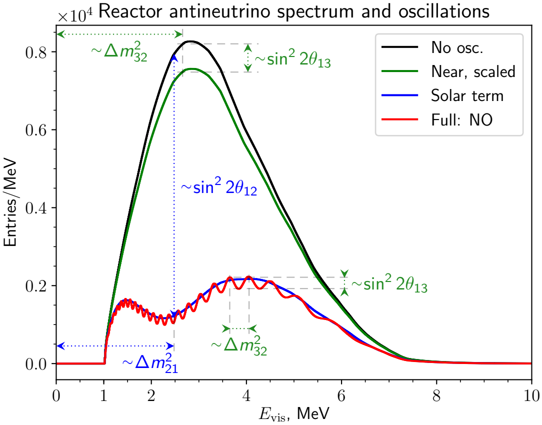

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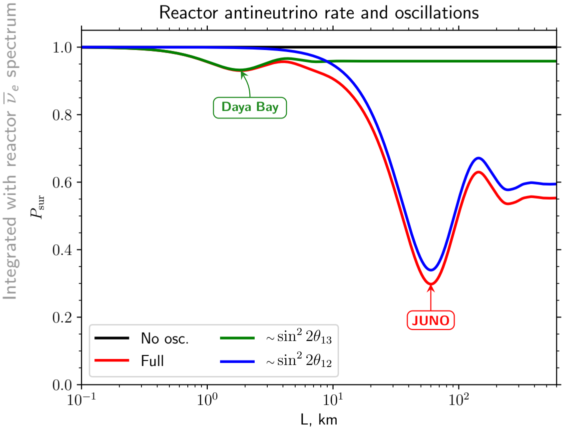

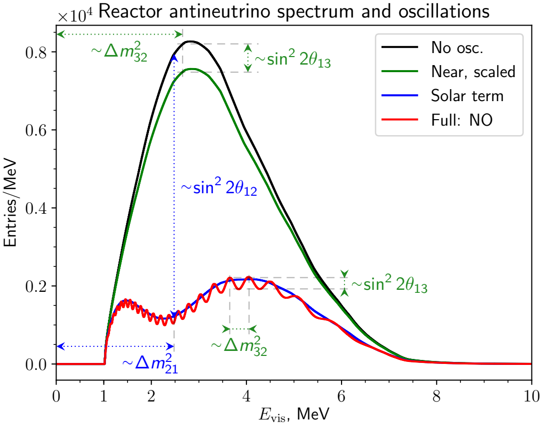

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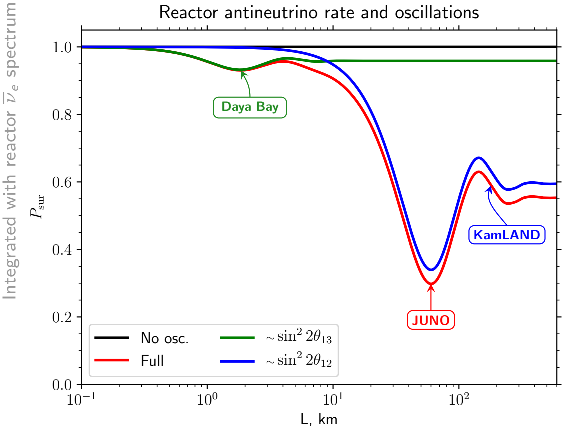

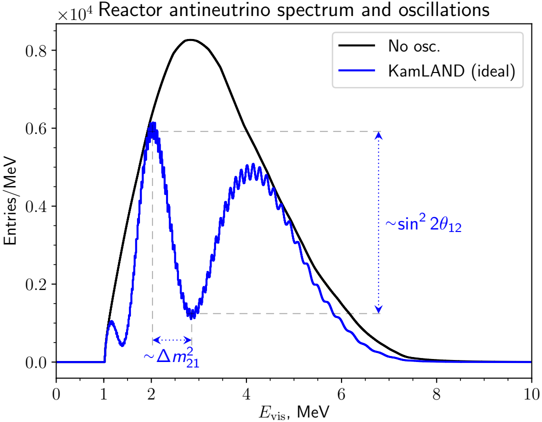

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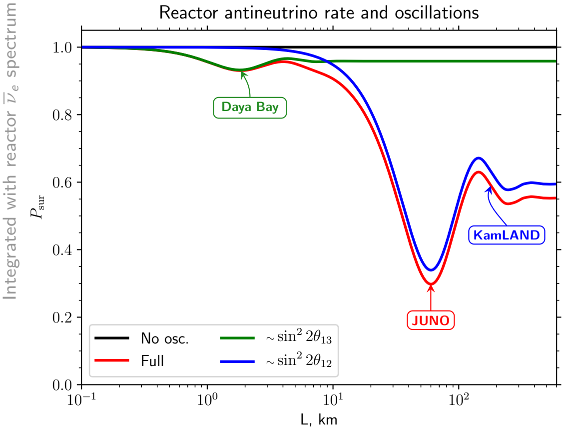

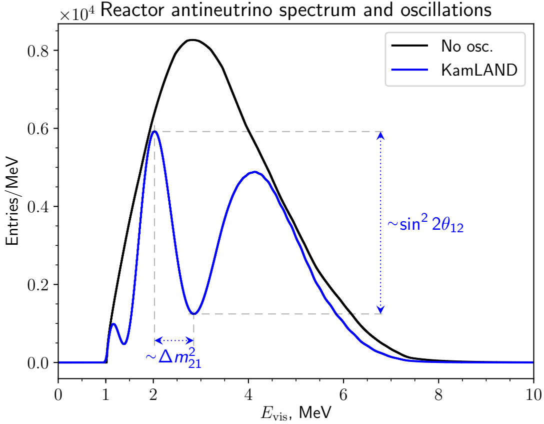

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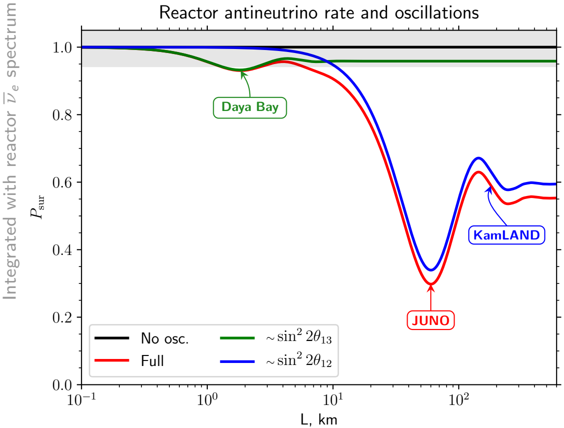
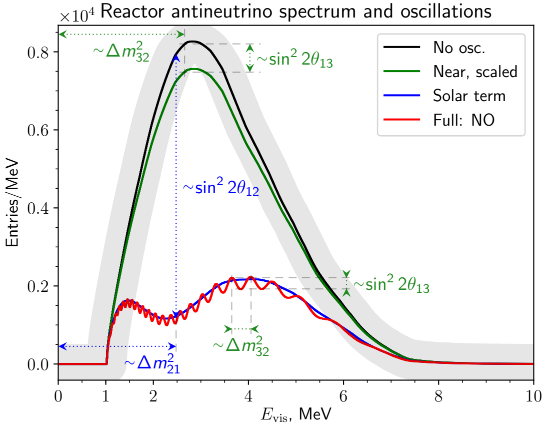
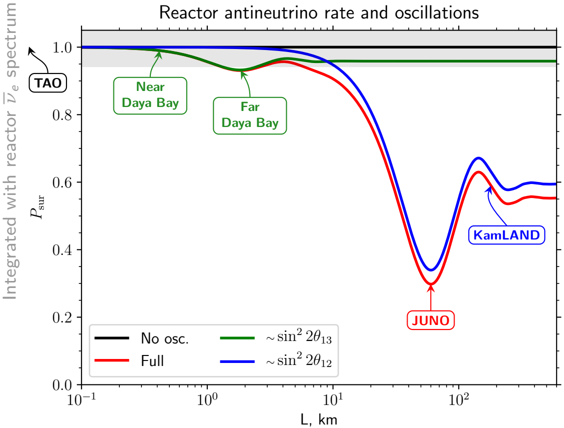


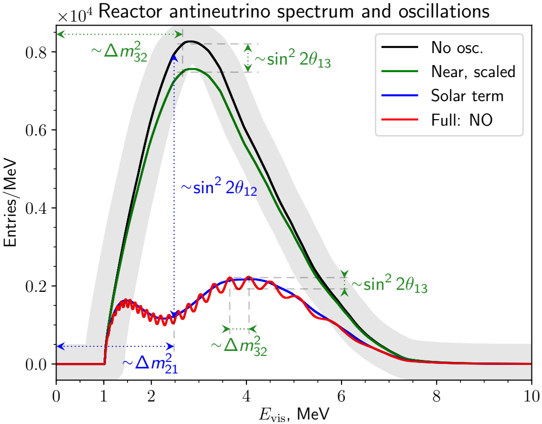


Challenges

- Unreliable antineutrino spectrum model: $\hookrightarrow$ know reference spectrum
- Energy resolution of the detector $\sigma < 3\%$ at 1 MeV: $\hookrightarrow$ resolve the peaks
- Energy scale of the detector (uncertainty $< 1\%$): $\hookrightarrow$ ensure the peak positions

$E_{\mathrm{vis}} \approx E_{\nu} - 0.78\,\mathrm{MeV}$





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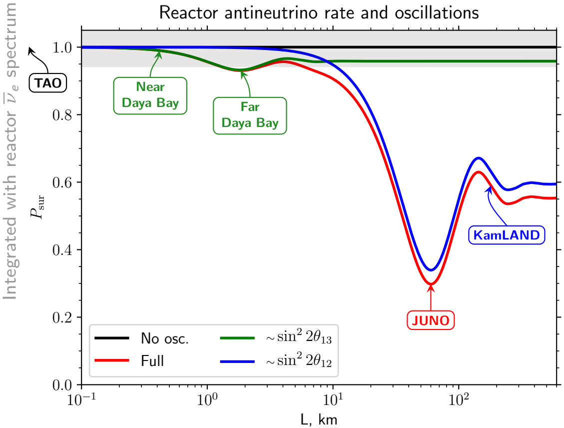

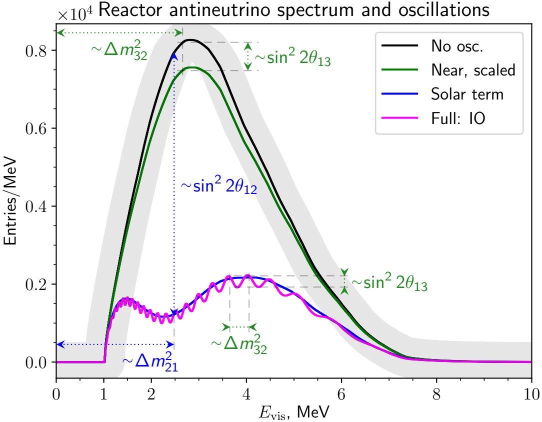

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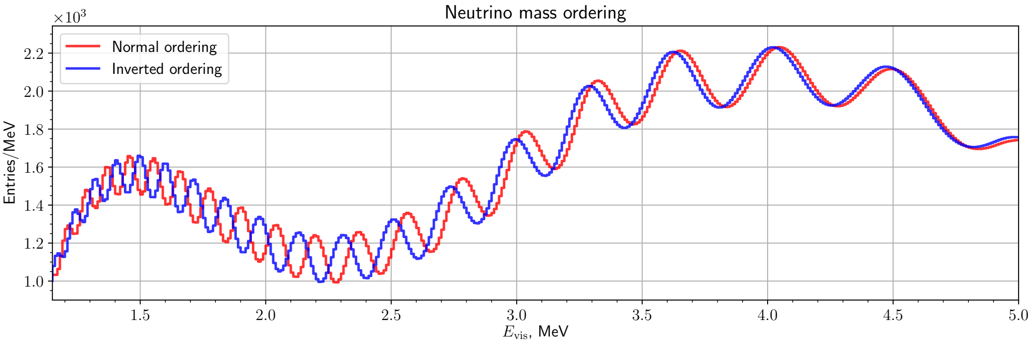
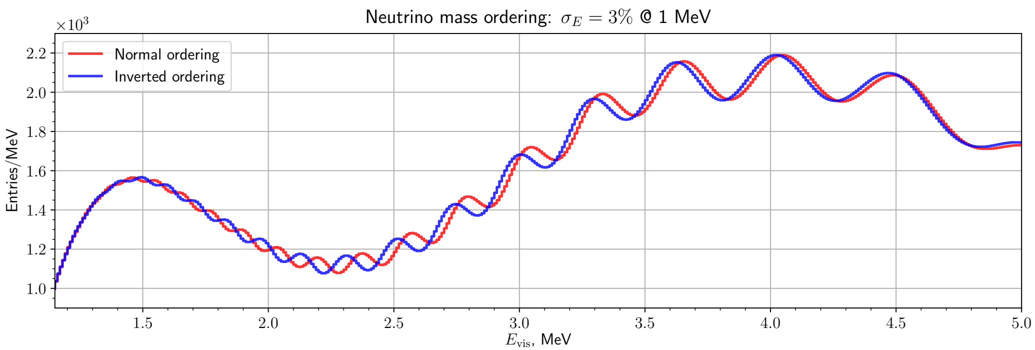


(plot: same Δm^2_{ee})

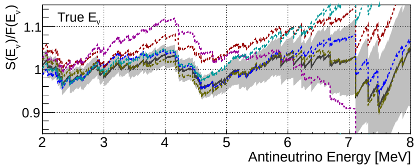
- Change of oscillation period with ordering $\ll$ energy resolution
- Cumulative effect across the most energy range

$E_{\mathrm{vis}} \approx E_\nu - 0.78\,\mathrm{MeV}$



(plot: same Δm^2_{ee})

- Change of oscillation period with ordering $\ll$ energy resolution
- Cumulative effect across the most energy range
- Possible threat: fine structure in reactor $\overline{\nu}_e$ spectrum



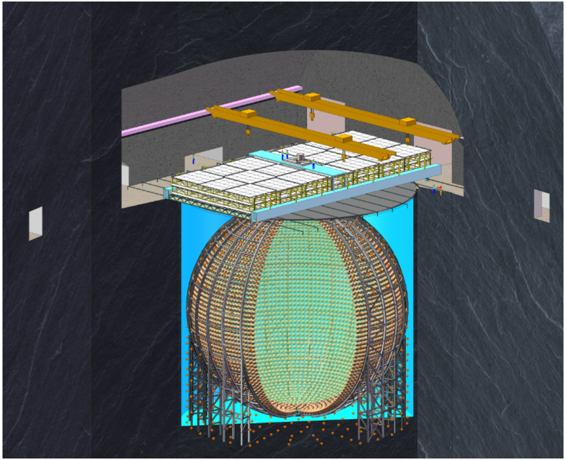
Dwyer&Langford [1407.1281], PRL114

$E_{\text{vis}} \approx E_\nu - 0.78\,\text{MeV}$

Oscillation physics with JUNO

Reactor $\overline{\nu}_e$ at $\sim$53 km

- Rate: $45\ \overline{\nu}_e/\text{day}$
- Features: spectrum shape
- Parameters: Neutrino Mass Ordering
  Δm^2_{31}, Δm^2_{21}, $\sin^2 2\theta_{12}$
- PMNS mixing matrix unitarity
- Mass splitting sum



Yellow Book (2015) [1507.05613], JPG43

Oscillation physics with JUNO

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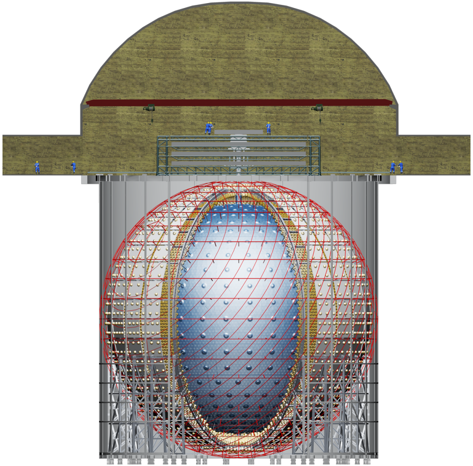
- Parameters: Neutrino Mass Ordering (NMO)
  Δm^2_{31}, Δm^2_{21}, $\sin^2 2\theta_{12}$

Solar ν_e from ^{8}B

- Rate: 17 ν_e/day
- Features: rate, day/night asymmetry
- Parameters: Δm^2_{21}, $\sin^2 \theta_{12}$



Solar ^{8}B [2006.11760], CPC45

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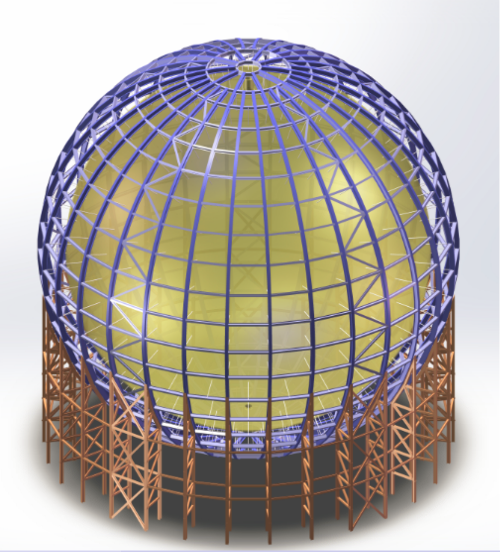
Solar ν_e from $^8\mathrm{B}$

- Parameters: Δm^2_{21}, $\sin^2\theta_{12}$

Reactor $\overline{\nu}_e$ at 30 m

s

- Rate at TAO: 2000 $\overline{\nu}_e$/day
- Features: spectrum shape
- Parameters: Δm^2_{41}, $\sin^2 2\theta_{14}$



TAO CDR [2005.08745]

Oscillation physics with JUNO

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Solar ν_e from ^{8}B

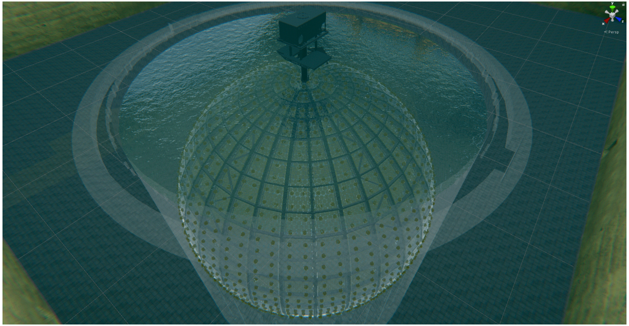
- Parameters: Δm^2_{21}, $\sin^2\theta_{12}$

Reactor $\overline{\nu}_e$ at 30 m

- Parameters: Δm^2_{41}, $\sin^2 2\theta_{14}$

Atmospheric $\nu_\mu/\overline{\nu}_\mu$

- 200 kton-years: 1233/1035 events
- Features: angular distribution
- Parameters: NMO, $\sin^2\theta_{23}$



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Oscillation physics with JUNO

Reactor $\overline{\nu}_e$ at $\sim$53 km

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Solar ν_e from ^{8}B

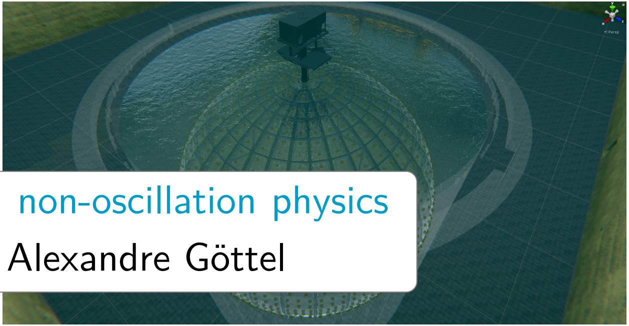
- Parameters:

Reactor $\overline{\nu}_e$ at 3

- Parameters: Δm^2_{41}, $\sin^2 2\theta_{14}$

Atmospheric $\nu_\mu/\overline{\nu}_\mu$

- Parameters: NMO, $\sin^2 \theta_{23}$

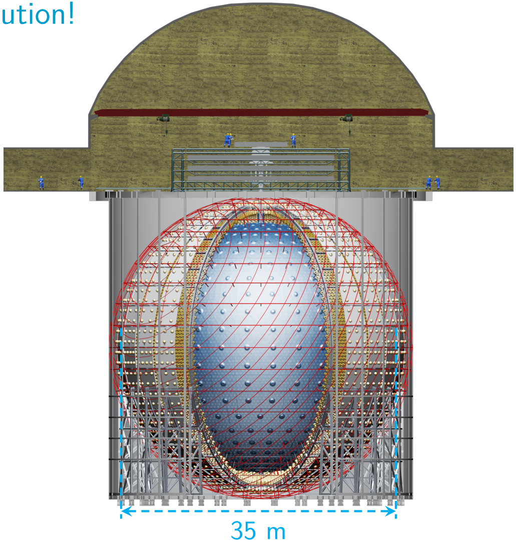


JUNO potential in non-oscillation physics

next talk by Alexandre Göttel

JUNO DETECTOR

More light → better resolution!



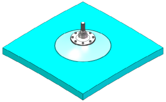
JUNO DETECTOR

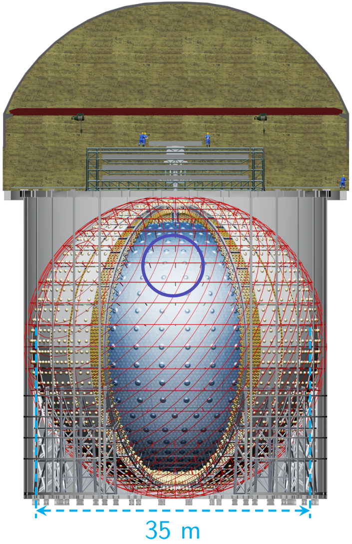
LS — Liquid Scintillator
LY — Light Yield

More light → better resolution!

Target

- 20 kt LS
- Optimized LY
- Acrylic sphere





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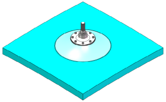
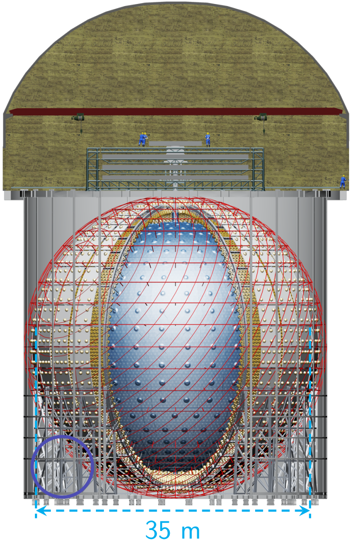


Support

- Stainless steel structure



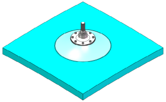
JUNO DETECTOR

LS — Liquid Scintillator
LY — Light Yield
PMT — PhotoMultiplier Tube
QE — Quantum Efficiency
p.e. — photo-electron

More light → better resolution!

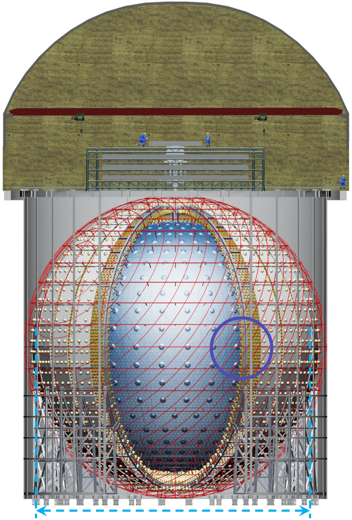
Target

- 20 kt LS
- Optimized LY
- Acrylic sphere



Support

- Stainless steel structure



Light collection

- 18k 20” PMTs
- High QE: 29.6%
- 1350 p.e./MeV
- +26k 3” PMTs

JUNO DETECTOR

More light → better resolution!

LS — Liquid Scintillator
LY — Light Yield
PMT — PhotoMultiplier Tube
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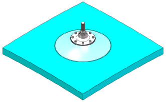
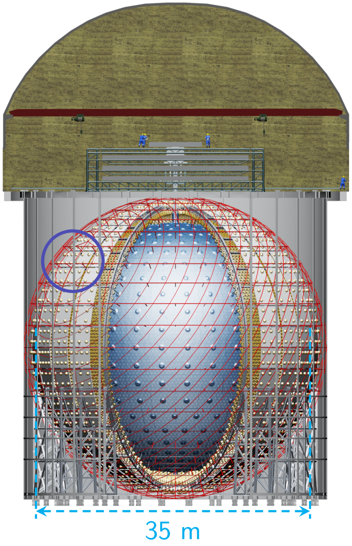


Coils

- Compensation of the Earth Magnetic Field

Support

- Stainless steel structure



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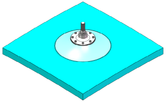


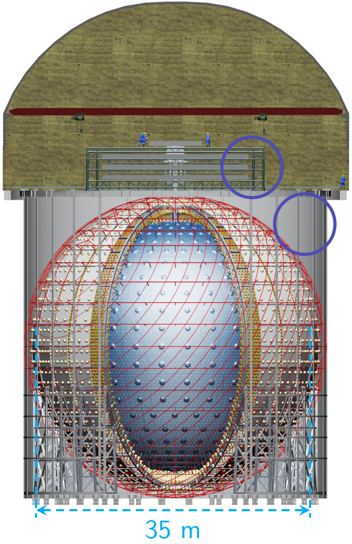
Coils

- Compensation of the Earth Magnetic Field

Support

- Stainless steel structure

Inverse Beta Decay (IBD) selection
Signal/Backgrounds



LS — Liquid Scintillator
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PMT — PhotoMultiplier Tube
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PS — Plastic Scintillator

Muon veto

- Top Tracker: 3 layers PS
- Water pool

Light collection

- 18k 20” PMTs
- High QE: 29.6%
- 1350 p.e./MeV
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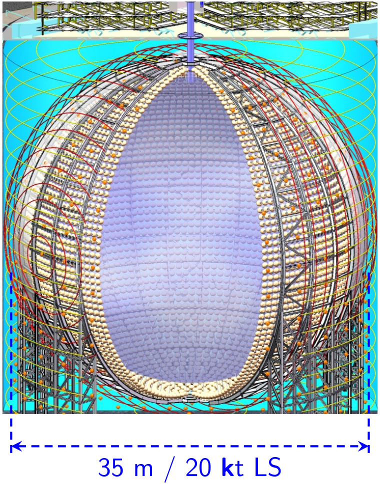
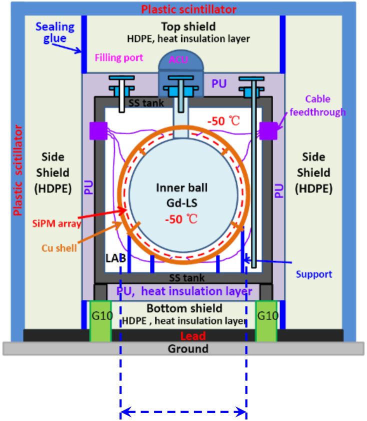
JUNO and TAO detectors



	JUNO
Attention	**Energy resolution $\sigma \searrow$**
Method	**Light collection $\nearrow$**
Scintillator	**LS**
PMTs	**18k 20"** **+26k 3"**
Coverage, %	**78**
Light col. p.e./MeV	~~1200~~ **1350**
σ_E at 1 MeV, %	**3**
Detectors	**1**
Thermal power, GW	~~35.8~~ **26.6**
Baseline	**52 km**
IBD/day/AD	~~60~~ **45**

Validity: June 2021

JUNO and TAO detectors



1.7 m / 2.6 t GdLS

	TAO	JUNO
Attention	**Energy resolution $\sigma \searrow$**	
Method	**Light collection $\nearrow$**	
	Dark noise $\searrow$	
Scintillator	**GdLS @ -50°C**	LS
PMTs	**SiPM**	18k 20”
	1.5M 5 mm	+26k 3”
Coverage, %	**94**	78
Light col. p.e./MeV	**4500**	~~1200~~ 1350
σ_E at 1 MeV, %	**2**	3
Detectors	**1**	1
Thermal power, GW	**4.6**	~~35.8~~ 26.6
Baseline	**30 m**	52 km
IBD/day/AD	**2000**	~~60~~ 45

Validity: June 2021

JUNO and TAO location

- JUNO — Jiangmen Underground Neutrino Observatory
- TAO — Taishan Antineutrino Observatory

	Yangjian (YJ)	Taishan (TS)
Thermal power, GW	2.9×6	4.6×~~4~~2
Total, GW	~~35.8~~ 26.6	
	signal	

...

Validity: June 2021

JUNO and TAO location

- JUNO — Jiangmen Underground Neutrino Observatory
- TAO — Taishan Antineutrino Observatory

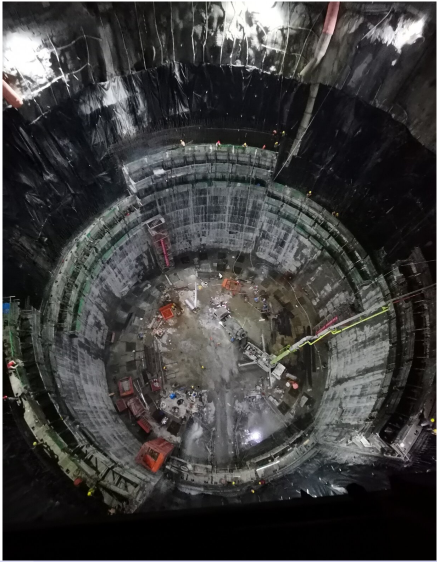
	Yangjian (YJ)	Taishan (TS)	Daya Bay/Ling Ao	Huizhou (HZ)	World
Thermal power, GW	2.9×6	4.6×~~4~~2	2.9×6	2.9×6	
Total, GW	~~35.8~~ 26.6		17.4	~~17.4~~	...
	signal		background		

Civil construction

✓ Civil construction: done.

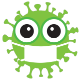
Civil construction

- ✓ Civil construction: done.
- ✓ Underground lab: done.
- ✓ Installation: soon.



JUNO schedule

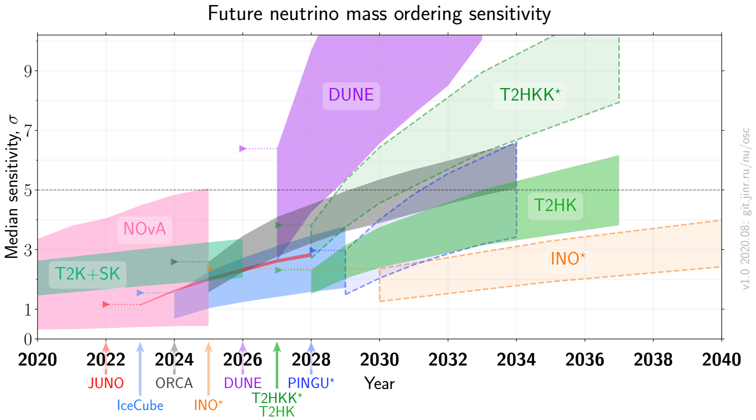
We are here



- **2014**: Complete conceptual design. International collaboration established.
- **2015**: Start civil construction, PMT production line.
- **2016**: Bidding of detector components.
- **2017**: Start PMT mass production. First electronics prototypes.
- **2018**: PMT mass production and testing.
- **2019**: Start PMT potting.
- **2020**: End of civil construction. Electronics mass production.
- **2021**: PMT installation. Detector and veto construction.
- **2022**: **Start of data taking**

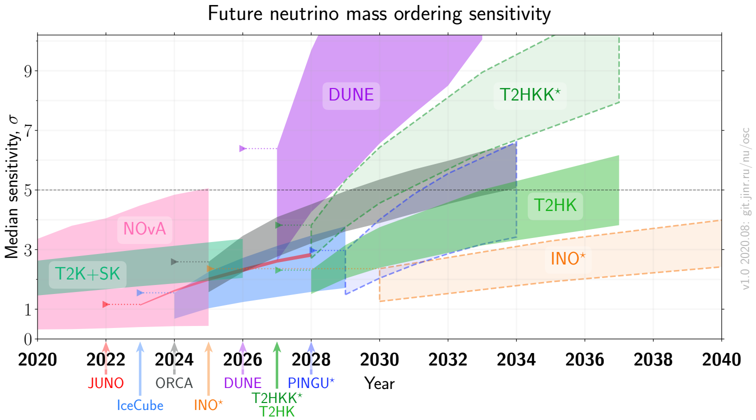
Oscillation physics

Sensitivity to Neutrino Mass Ordering



Yellow Book (2015) [1507.05613], JPG43
JUNO+IceCube [1911.06745], PRD101

Sensitivity to Neutrino Mass Ordering



- ✓ JUNO alone, 6 years: $\sim 3\sigma$
- ✓ +external constrain on Δm^2_{32}: $\sim 4\sigma$
- ✓ Combined with accelerator or atmospheric experiment: $> 5\sigma$

$\hookrightarrow$ sensitivity boost due to tension for wrong ordering

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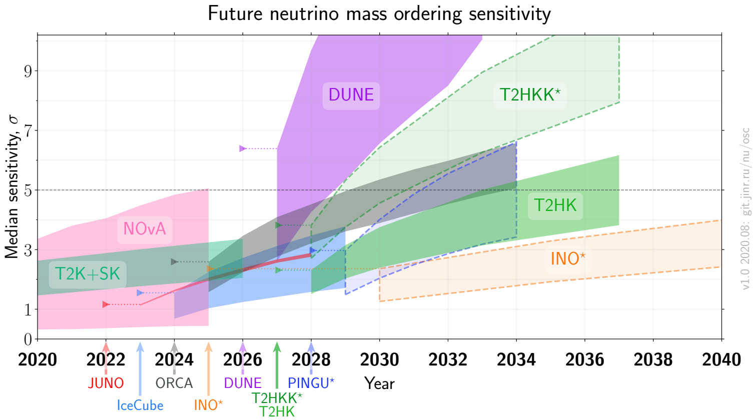

Changes since 2015

- Less favorable Δm^2_{32}
- No TS-3/4 cores less signal

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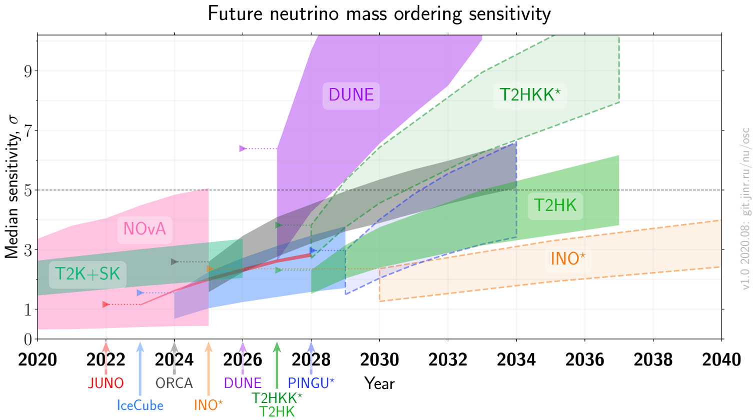

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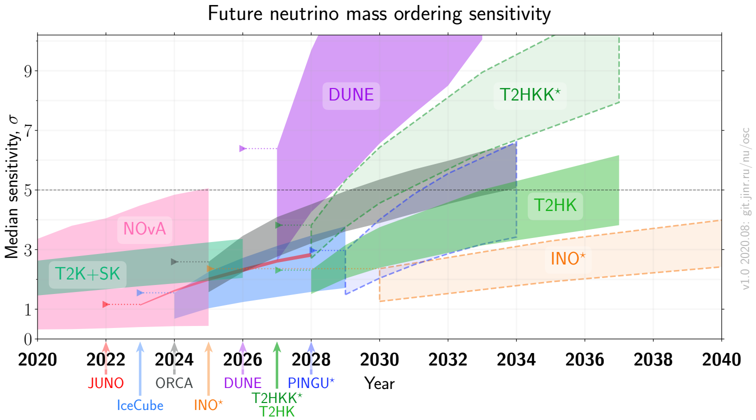

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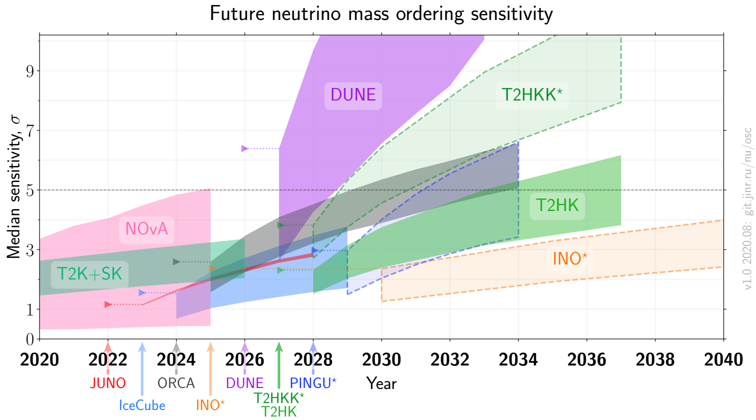

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- ▲ No HZ cores ↓ background
- ▼ World reactors ↑ background

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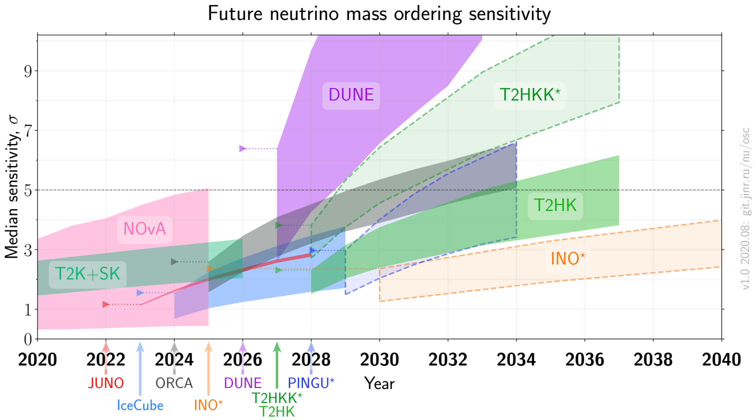

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- Dedicated publication in 2021

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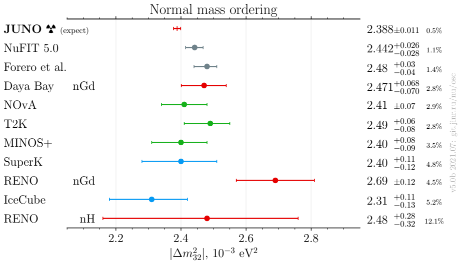
JUNO AND NEUTRINO OSCILLATION PARAMETERS

- JUNO will measure $\Delta m^2_{31}/\Delta m^2_{32}$, Δm^2_{21} and $\sin^2 2\theta_{12}$ with per-mille level precision.



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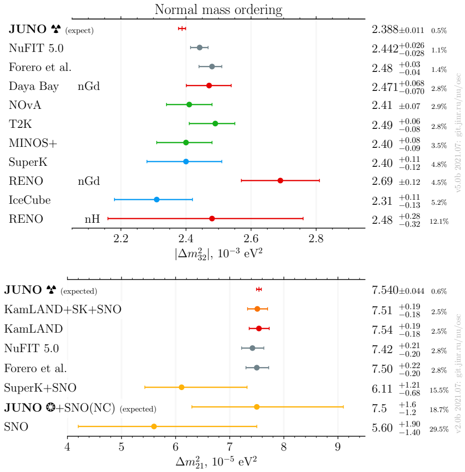

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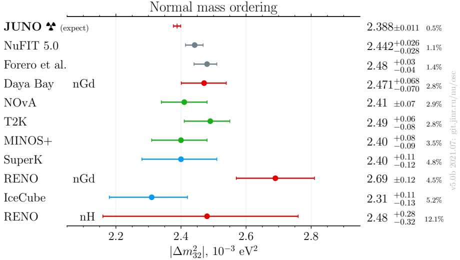

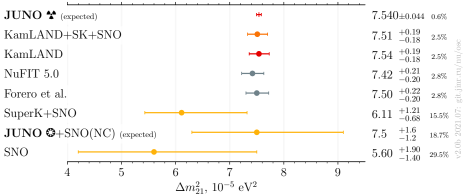

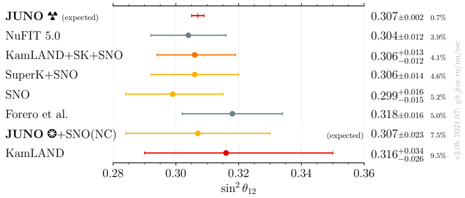

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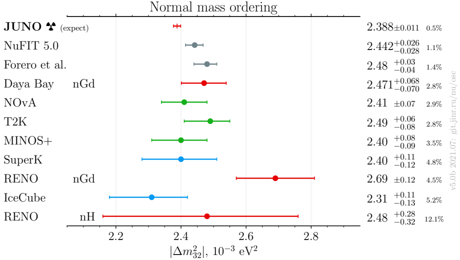
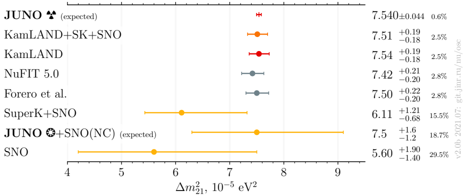
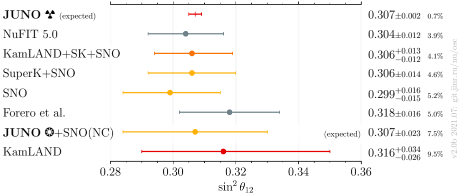
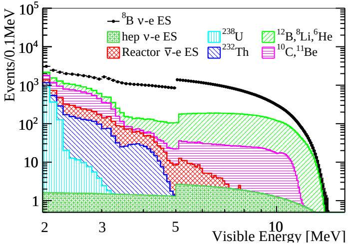


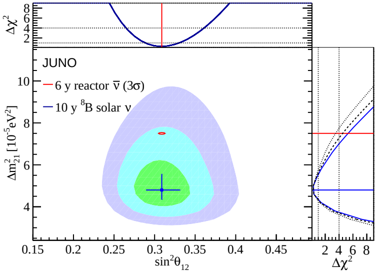




Paper on precision measurement with reactor $\overline{\nu}_e$ expected soon!

Oscillation physics with solar ^{8}B ν_e





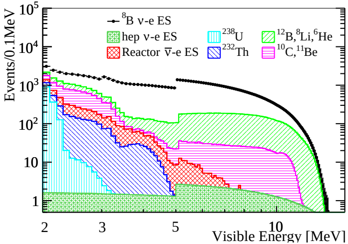
Oscillations

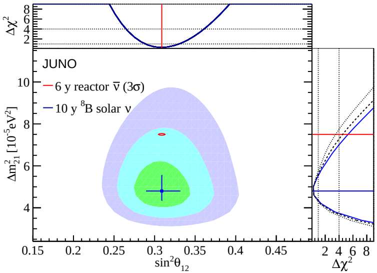
- ^{8}B ν_e are sensitive to the matter effect: Day/Night asymmetry

Extra

Solar ^{8}B [2006.11760], CPC45

Oscillation physics with solar $^{8}\mathrm{B}\ \nu_e$





Oscillations

- $^{8}\mathrm{B}\ \nu_e$ are sensitive to the matter effect: Day/Night asymmetry

Detection

- Signal: ν_e elastic scattering off e^-
- Expected rate: 17 ν_e/day
- Limiting factors: LS purity, cosmic ray related background
- Baseline $^{238}\mathrm{U}/^{232}\mathrm{Th}$ contamination: 10^{-17} g/g

P845: OSIRIS

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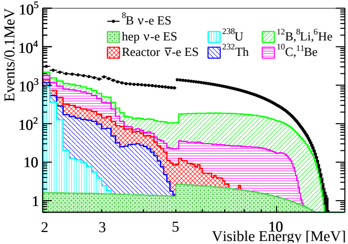

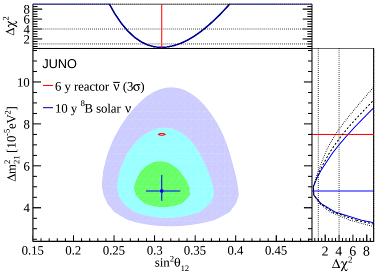

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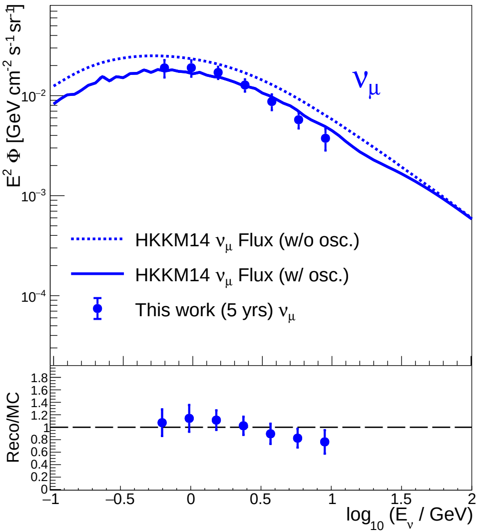
Data and analysis

- Events binned vs zenith angle $\cos\theta_z$ and ν_e energy
- $\sim$ 20% sensitivity to Δm^2_{21} and 8% sensitivity to $\sin^2\theta_{12}$
- Rate constrained with SNO (NC)

Extra

Solar ^{8}B [2006.11760], CPC45

Oscillation physics with atmospheric $\nu_\mu/\overline{\nu}_\mu$



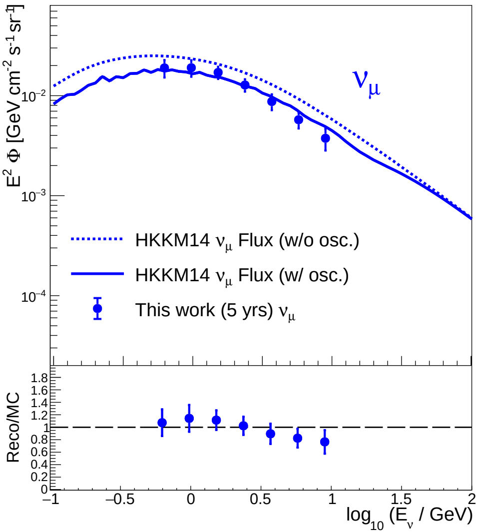
Extra

Atmospheric ν_μ/ν_e spectra [2103.09908]

Oscillations

- Matter effect: θ_z dependence

Oscillation physics with atmospheric $\nu_\mu/\overline{\nu}_\mu$



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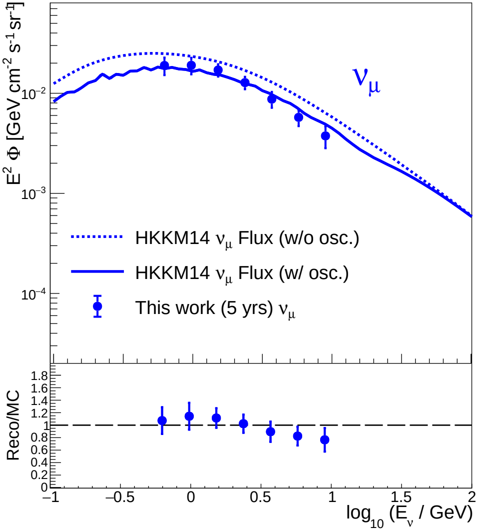
Oscillations

- Matter effect: θ_z dependence

Detection

- Primary channel: $\nu_\mu/\overline{\nu}_\mu$ CC
- Expected statistics, 200 kton-years: 1233/1035 events
- Limiting factors: angular resolution / PID purity

Oscillation physics with atmospheric $\nu_\mu/\overline{\nu}_\mu$



Extra

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Detection

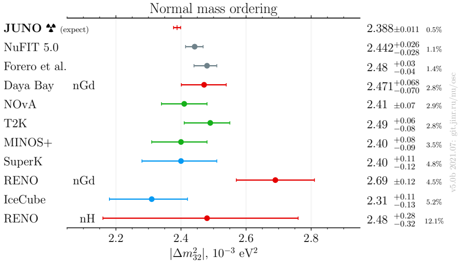
- Primary channel: $\nu_\mu/\overline{\nu}_\mu$ CC
- Expected statistics, 200 kton-years: 1233/1035 events
- Limiting factors: angular resolution / PID purity

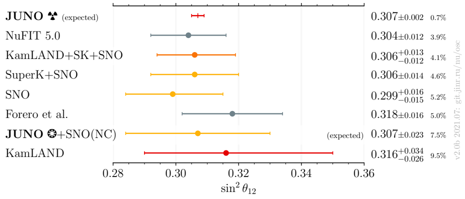
Data and analysis

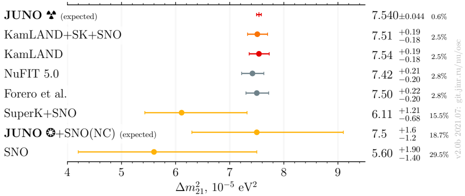
- Events binned vs zenith angle $\cos\theta_z$ (fine) and ν energy (coarse)
- $\sim 1\sigma$ sensitivity to ordering in 10 years
- Potential: combination with reactor analysis

JUNO and neutrino oscillation parameters

- JUNO will measure $\Delta m^2_{31}/\Delta m^2_{32}$, Δm^2_{21} and $\sin^2 2\theta_{12}$ with per-mille level precision.



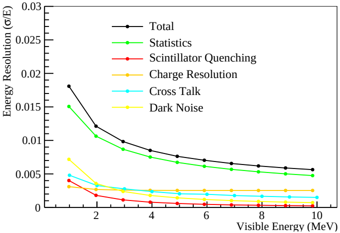


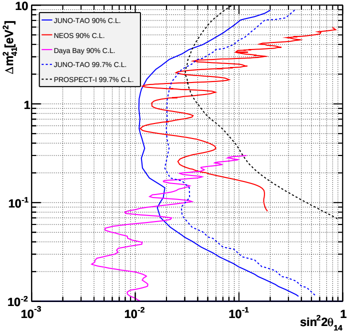


$\sin^2\theta_{23}$ sensitivity: to be estimated...

Paper on precision measurement with reactor $\overline{\nu}_e$ expected soon!

Sterile neutrino search with TAO and JUNO





Primary goal

TAO CDR [2005.08745]

- Reference reactor $\overline{\nu}_e$ spectrum with $\sigma = 2\%$ at 1 MeV.

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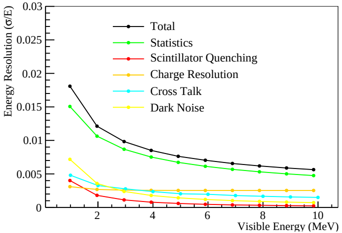
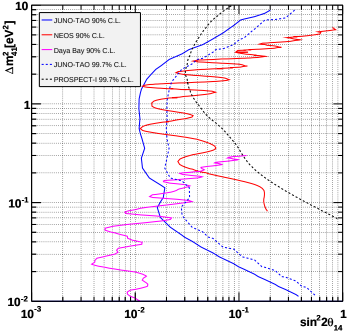




Primary goal

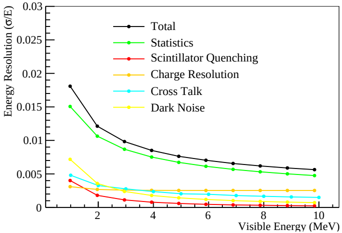
TAO CDR [2005.08745]

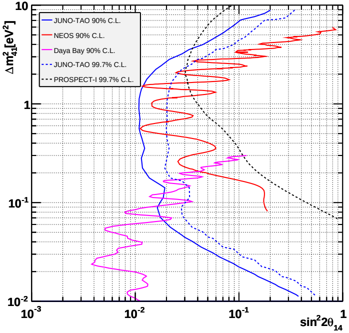
- Reference reactor $\overline{\nu}_e$ spectrum with $\sigma = 2\%$ at 1 MeV.

Oscillations: reactor at 30 m

- Relevant range: $0.5\,\text{eV}^2 \lesssim \Delta m^2_{41} \lesssim 5\,\text{eV}^2$
- ∼large L counterbalanced with high energy resolution

Sterile neutrino search with TAO and JUNO





Primary goal

TAO CDR [2005.08745]

- Reference reactor $\overline{\nu}_e$ spectrum with $\sigma = 2\%$ at 1 MeV.

Oscillations: reactor at 30 m

- Relevant range: $0.5\,\mathrm{eV}^2 \lesssim \Delta m^2_{41} \lesssim 5\,\mathrm{eV}^2$
- $\sim$large L counterbalanced with high energy resolution

Detection

- Inverse beta decay with nGd tag
- Expected rate: 2000 $\overline{\nu}_e$/day

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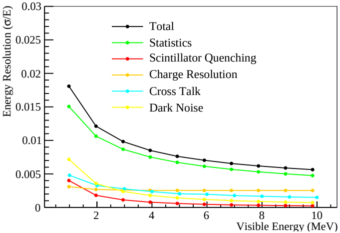

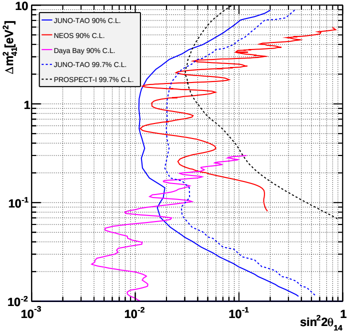

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Data and analysis

- Events, finely binned vs energy
- Simultaneous fit: TAO's 4 virtual subdetectors
- May verify Neutrino-4 best-fit: Δm^2_{41}=7.25 eV^2, $\sin^2 2\theta_{14}$=0.26

JUNO SUMMARY

- Determination of the neutrino mass ordering:
  - 3σ in 6 years via reactor $\overline{\nu}_e$
  - $> 5\sigma$ when combined with accelerator or atmospheric experiments
  - $+1\sigma$ via atmospheric $\nu_\mu/\overline{\nu}_\mu$ in 10 years

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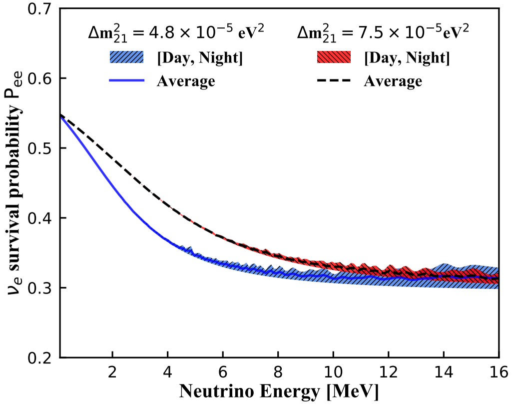
- Expected to start data taking in 2022!

Thank you for your attention!

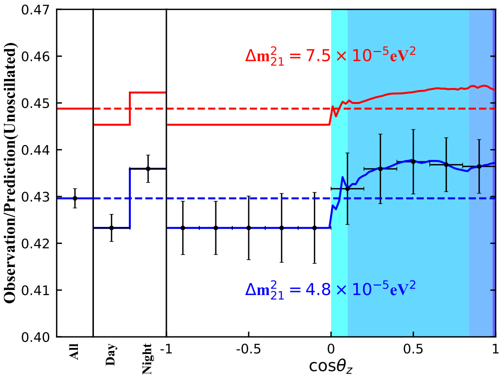
Spare slides:

Day/Night effect with solar ^{8}B ν_e

Expected ν_e spectrum from ^{8}B



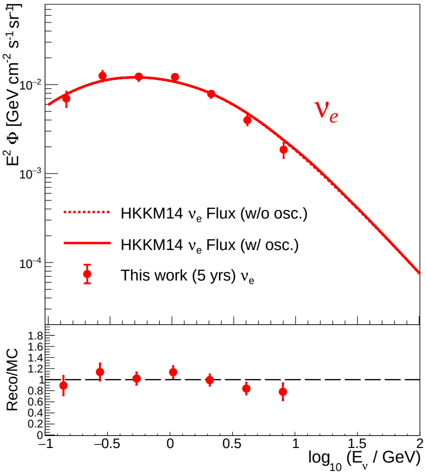
Day/Night asymmetry



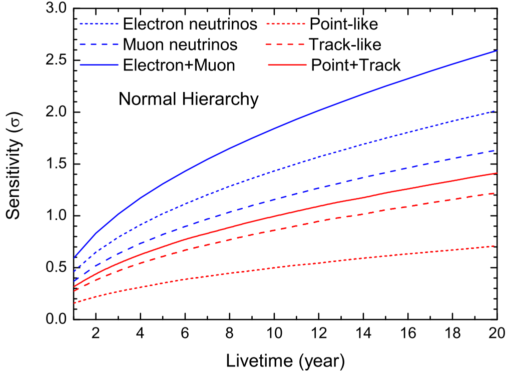
Solar ^{8}B [2006.11760], CPC45

Atmospheric neutrino oscillations

Atmospheric ν_e spectrum



NMO sensitivity vs time



Atmospheric ν_μ/ν_e spectra [2103.09908]

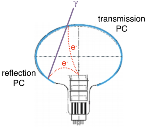
JUNO PMT STATUS

Large 20" PMT system

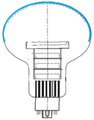
- 12'768 MCP PMTs by NNVT: delivered.
- 5'000 Dynode PMTs by Hamamatsu: delivered.
- Testing: mostly done.
- Protection cover: production started.

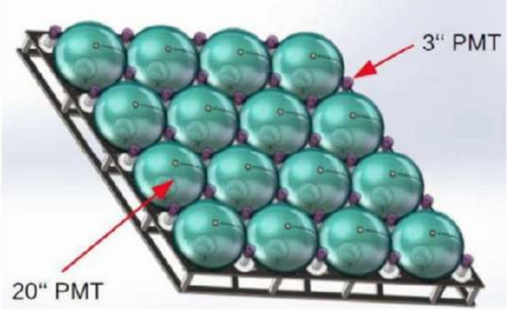
NNVT MCP

Photograph of MCP-PMT



Hamamatsu Dynode





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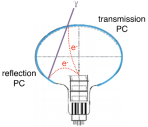

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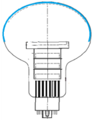

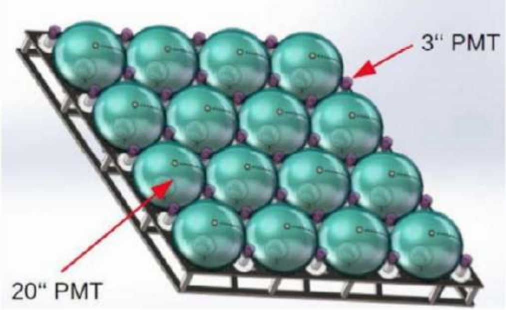

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	NNVT	Hamamatsu	HZC
PDE, %	28.3	28.1	24
TTS, ns	12	2.7	1.5

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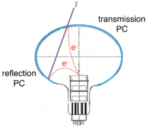

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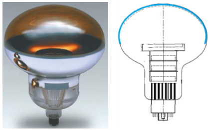
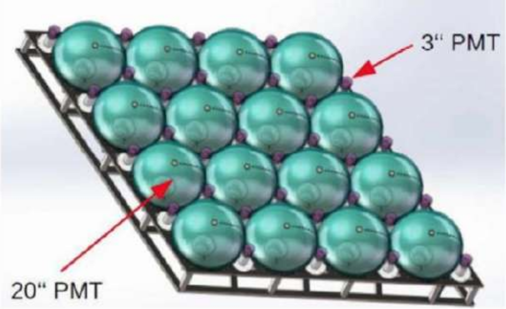
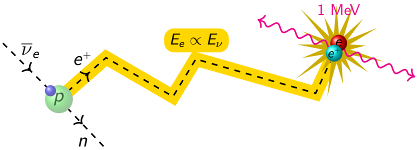




Inverse beta decay (IBD) and selection criteria



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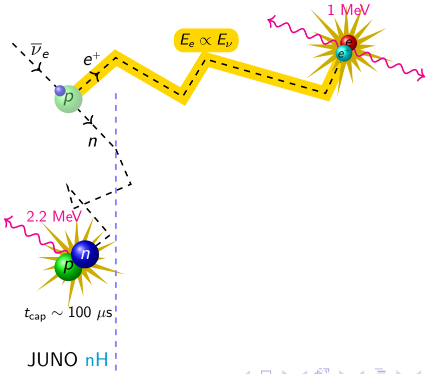

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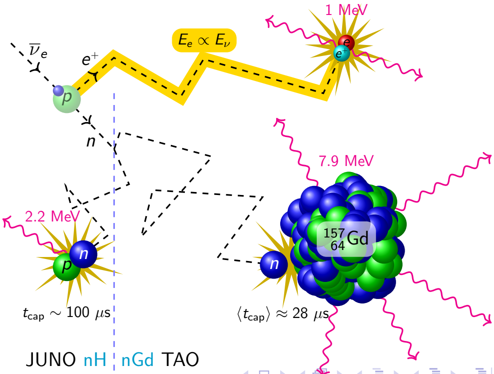

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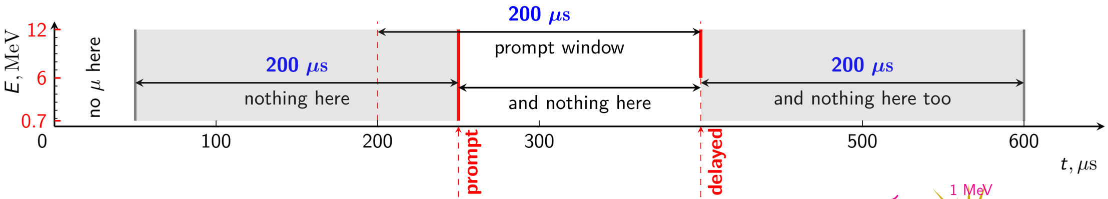

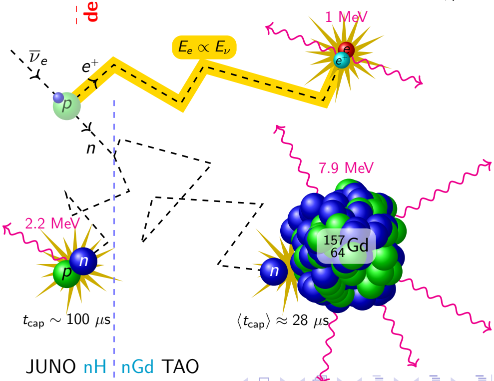

Plot: Daya Bay

Cherenkov: < 5%

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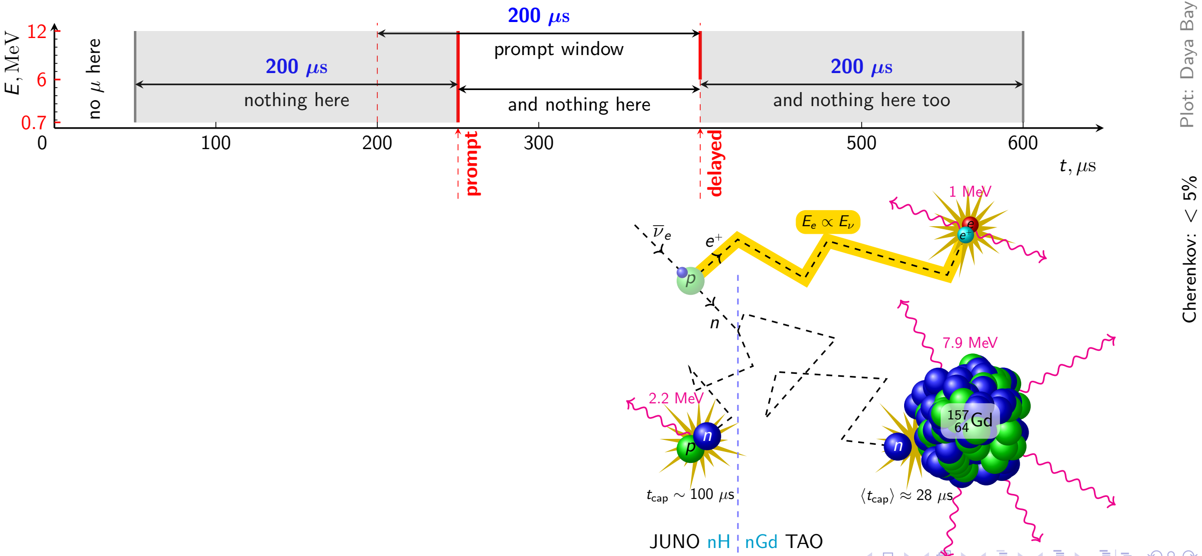

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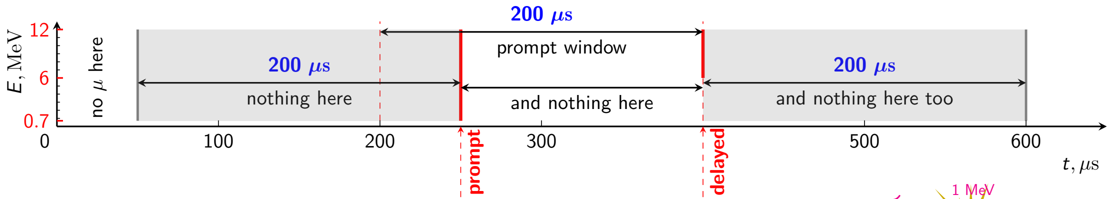
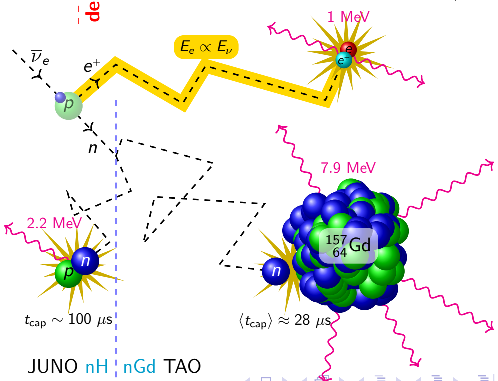


Cut	JUNO nH
Fiducial volume	$R < 17$ m
Time	1 ms
Prompt E, MeV	
Delayed E, MeV	1.9 – 2.5
Distance, m	1.5
Muon veto	TBD
Multiplicity veto, us	TBD



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Background events

Yellow Book (2015) [1507.05613], JPG43

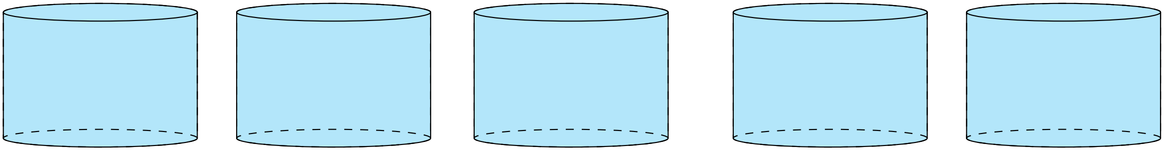
IBD rate corrected for missing reactors

Neutrino background sources

- Nearby reactors with $L \neq 53\,\mathrm{km}$: Daya Bay, Ling Ao
- World reactors
- Geo-$\overline{\nu}_e$

		JUNO S/N	Unc.
IBD	events/AD	45	
Geo ν	%	2.4	30
Accidentals	%	2.0	negligible
$^{8}\mathrm{He}/^{9}\mathrm{Li}$	%	3.6	20
Fast neutrons	%	0.3	100
$^{13}\mathrm{C}(\alpha, n)^{16}\mathrm{O}$	%	0.1	50
Total bkg	%	8.6	

Accidentals | β-n isotopes | Fast neutrons | $^{13}\mathrm{C}(\alpha, n)^{16}\mathrm{O}$ | ACU



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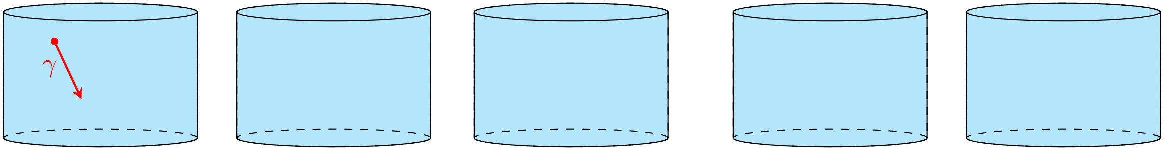

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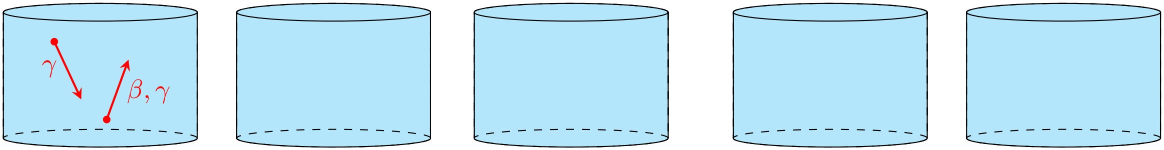

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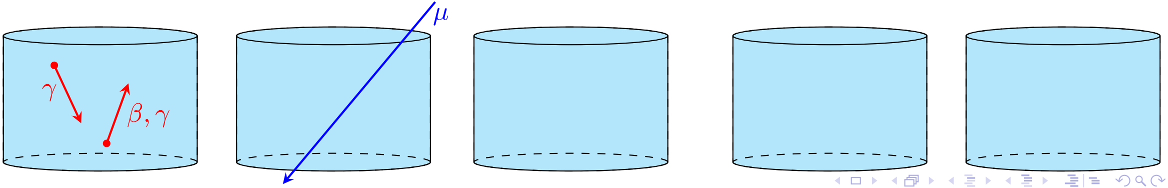

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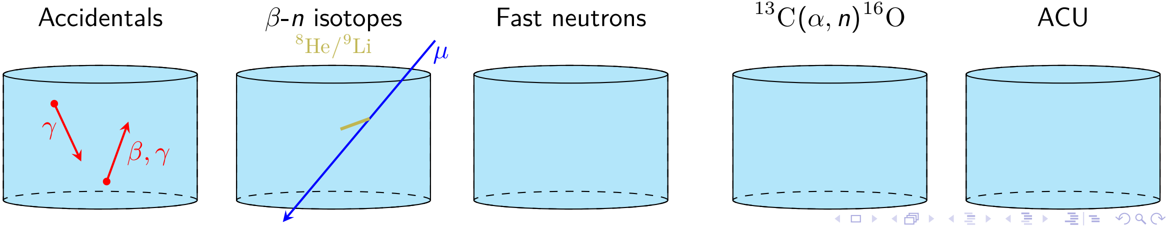

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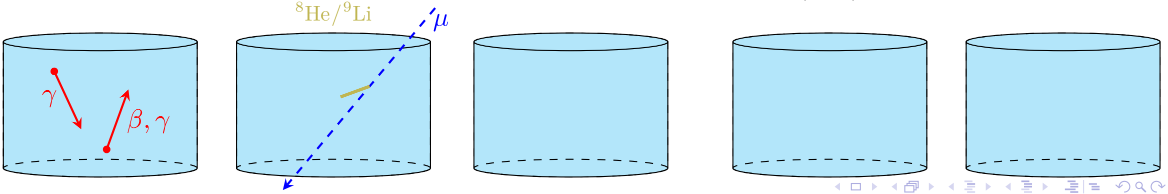

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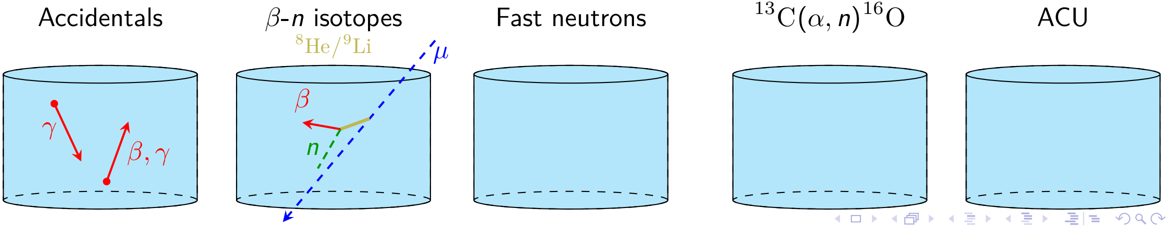

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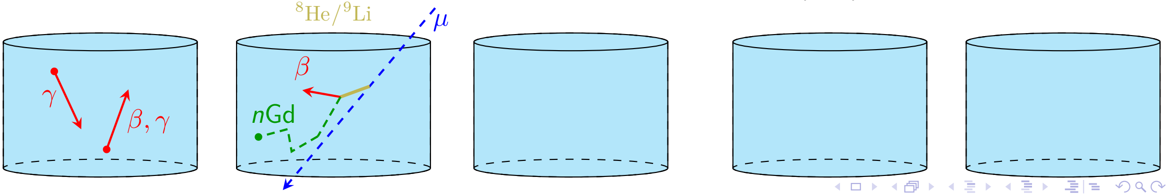

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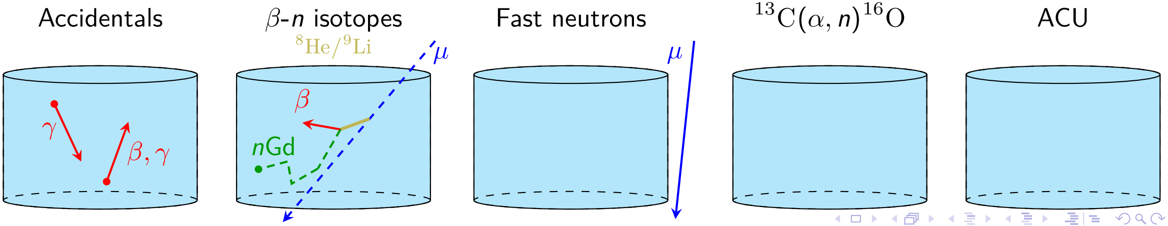

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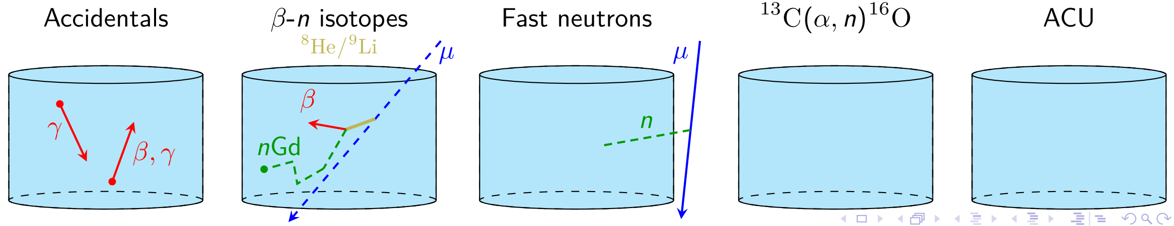

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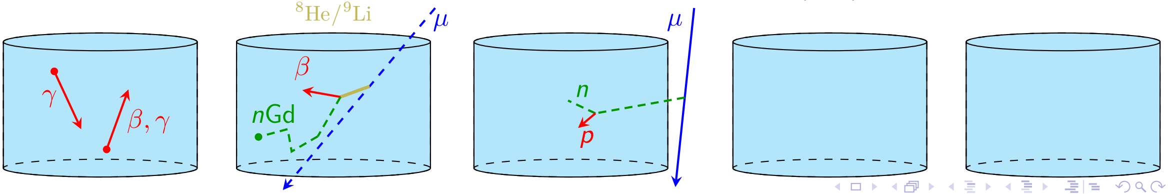
•	Total bkg	%	8.6	

Accidentals | β-n isotopes | Fast neutrons | $^{13}\mathrm{C}(\alpha, n)^{16}\mathrm{O}$ | ACU



Background events

Yellow Book (2015) [1507.05613], JPG43

IBD rate corrected for missing reactors

Neutrino background sources

- Nearby reactors with $L \neq 53\,\mathrm{km}$: Daya Bay, Ling Ao
- World reactors
- Geo-$\overline{\nu}_e$

			JUNO S/N	Unc.
•	IBD	events/AD	45	
•	Geo ν	%	2.4	30
•	Accidentals	%	2.0	negligible
•	$^{8}\mathrm{He}/^{9}\mathrm{Li}$	%	3.6	20
•	Fast neutrons	%	0.3	100
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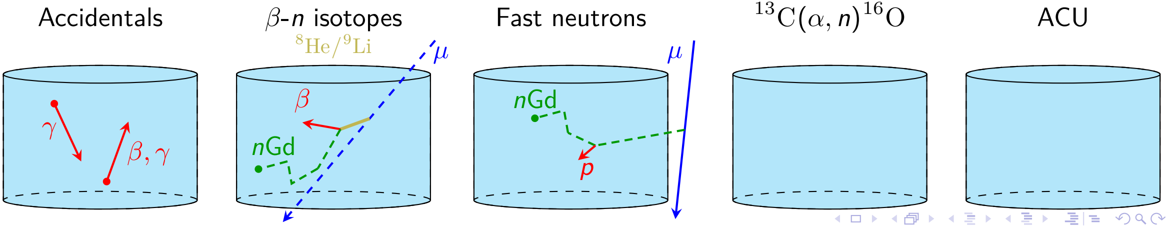

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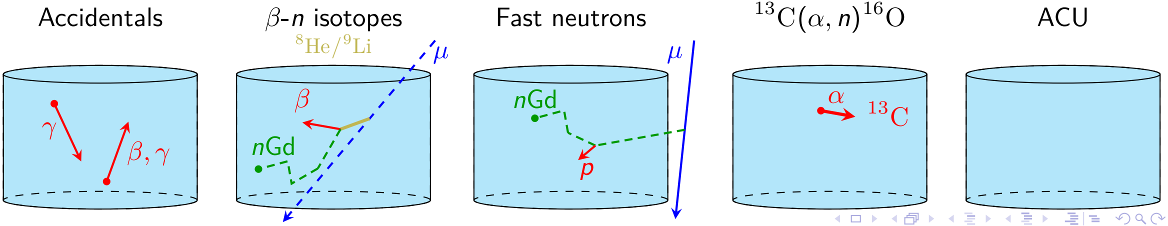

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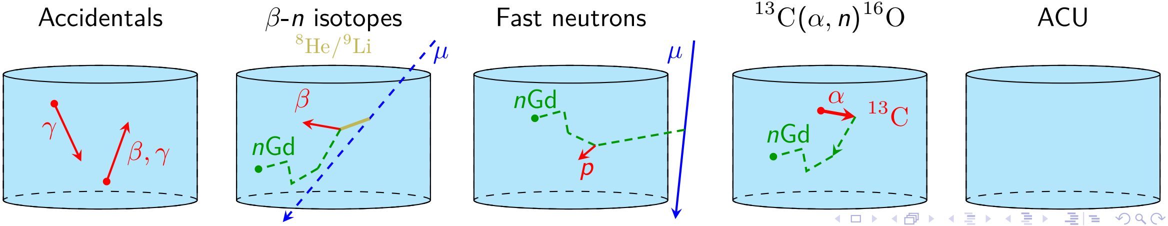

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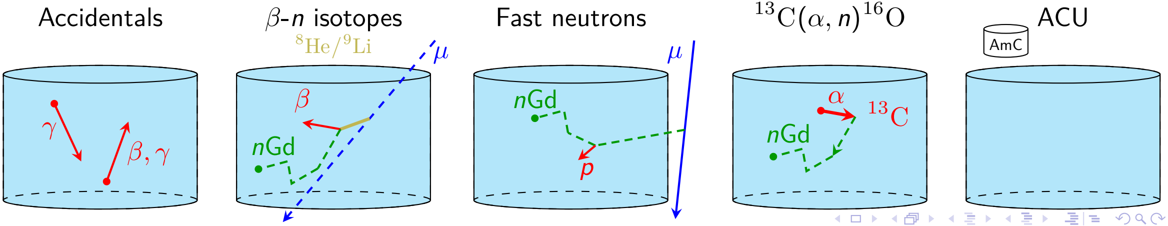

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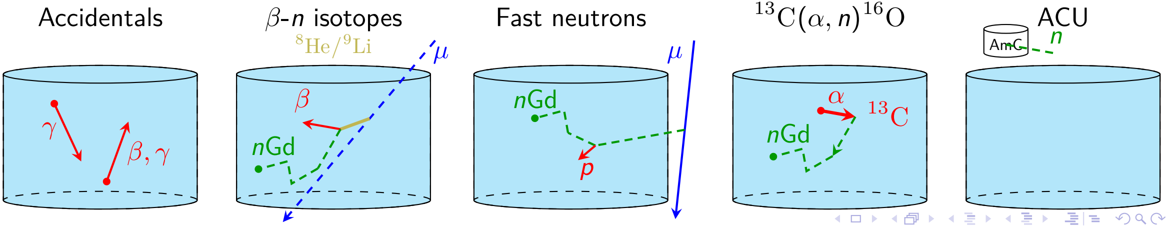

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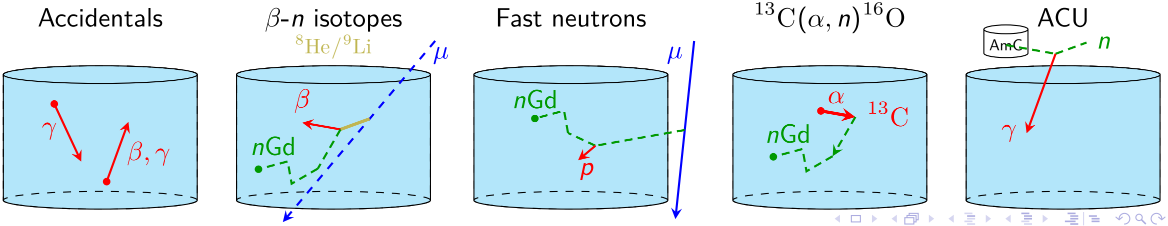

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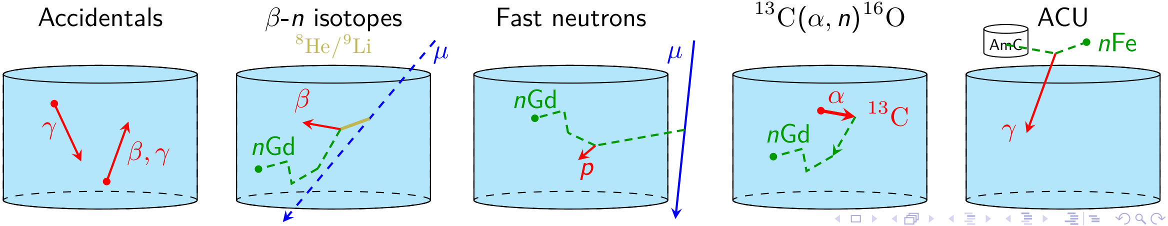

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